LABORATORY STUDIES OF SPACECRAFT RESPONSE TO TRANSIENT DISCHARGE PULSES*

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A set of preliminary laboratory experiments was conducted to investigate several basic issues in connection with the in-orbit measurement of spacecraft discharge properties. These include design and fabrication of appropriate sensors and effects of spacecraft electromagnetic responses on the interpretation of the discharge data. Electric field sensors especially designed to respond to high-speed transient signals were installed on a mock-up of a satellite. The simple mock-up was basically a sheet of aluminum rolled to form a cylinder. A movable spark-discharge noise source designed to be electromagnetically isolated from its power supply system was used to induce transient signals at various locations on the "spacecraft's" outer surface. These measurements and their results and implications are described herein. It is concluded that practical orbital measurements to define discharge noise source properties should be possible, and that simple mock-ups of the type described below are useful in sensor system design and data interpretation.

INTRODUCTION

It was recognized about ten years ago that spacecraft charging occurs (ref. 1)** and constitutes a potential electromagnetic hazard to operational satellites (ref. 2). In spite of this awareness, surprisingly little orbital information has been generated to date regarding the electromagnetic properties of the discharge source (refs. 3,4). Such information is essential to the proper specification, design, and ground testing of satellites.

In designing an instrumentation system for the in-orbit measurement of discharge properties, it is necessary to recognize and take into account the effects of both the sensor and spacecraft in modifying the signal radiated by the discharge. In particular, since the sensor antennas and the spacecraft itself exhibit electromagnetic resonances, the received signal will not exactly

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**References are included at the end of this paper.

duplicate the signal at the source. To investigate the problems associated with orbital measurements, a rudimentary laboratory mock-up of a spacecraft was assembled and equipped with sensors and transient-measuring instrumentation. This work extended earlier laboratory measurements conducted to investigate the electromagnetic properties of discharges on spacecraft thermal-control materials (refs. 2,5,6). Provisions were made to excite the mock-up with an isolated spark source and to record the sensor responses to record simulated vacuum arc.

Tests on the mock-up indicate that, with proper sensor design and placement, it is possible to minimize the effects of sensor and vehicle resonances in masking important characteristics of the signals generated by the discharges. Furthermore, the tests indicate that the same simple instrumentation can be used in orbit to define certain important characteristics of arc discharges and to infer where on the spaecraft discharges are occurring.

<center>SENSOR DESIGN</center>

It is important to recognize that a discharge caused by spacecraft charging is a very brief transient phenomenon, and that excessive distortion of the measured data by successive reflections from the ends of the sensing antenna (ringing) must be prevented. Two possible solutions to this problem are illustrated in figure 1. First, the sensor element may be made long so that the interesting portion of the transient signal has been recorded before the reflection from the end of the sensor returns (fig. 1a). To minimize reflections, the far end of the sensor may be made lossy and terminated in its characteristic impedance. Alternatively, the dimensions of the sensor may be made electrically small so that the first sensor resonance occurs above the highest frequency of interest (fig. 1b). In this design, either the source spectrum does not contain appreciable energy at the ringing frequency or the measuring system bandwidth is too narrow to permit the ringing to be recorded. Although large antennas have been considered for the ground-based study of transient signals, electrically small sensors are the only ones practical for in-flight measurements.

The electrically small field sensor provides an output proportional to the electric or magnetic field or its derivative at the sensor's location. Equivalent circuits for the small electric dipole, evolved during the development of low-frequency avionic systems (refs. 7, 8) are shown in figure 2. The open-circuit voltage of the electric dipole is directly proportional to the local electric field (fig. 2a) while the short-circuit current is proportional to the derivative of the electric field (fig 2b). The short-circuit current can be measured using a broadband current transformer. With modern high-impedence FET-input amplifiers, it is possible to measure the open-circuit voltage over a wide range of frequencies. The experimenter is therefore free to choose between measuring E or D. In the laboratory experiment of refs. 5 and 6, a small dipole with a built-in FET preamplifier was used.

Equivalent circuits for the magnetic dipole are shown in figure 3. The open-circuit voltage of the magnetic dipole is proportional to the derivative of the magnetic field (fig. 3a) and the short-circuit current is proportional to the magnetic field (fig. 3b). To measure the short-circuit current, the measuring apparatus must have an insertion impedance that is small compared with $j\omega L$, the inductive reactance of the sensor, throughout the frequency range of interest. For a given antenna inductance, L, and system input impedance, R, this implies that:

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$$\omega > \frac{R}{L}$$

$$(1)$$

Thus, to measure I_{sc} at low frequencies, the loop inductance should be high. Unfortunately, simply increasing the loop inductance lowers the resonant frequency of the loop and reduces the effective sensitivity of the dipole. A modern current tranformer (such as the Tektronix CT-2) may have an insertion impedance of 0.04 Ω in parallel with 5 μH, thus allowing the design of loops responding directly to the tangential magnetic field intensity, H, over a bandwidth ranging from several kilohertz through HF.

If the loop inductance is reduced to extend the high-frequency response to VHF, the inductive reactance becomes small compared to the insertion impedance of available current probes over much of the frequency range of interest. Therefore, with magnetic field sensors intended for high-frequency studies, the open circuit voltage is usually measured, and so the response is proportional to $\dot{B}$.

At the surface of a good conductor, the magnitude of the surface current density, J, is equal to the magnitude of the tangential magnetic field intensity, H. Thus, a skin current density sensor may be either a magnetic dipole (small half-loop) or a current dipole (small slot). The loop antenna responds to the magnetic field at the surface of the conducting plane based on the elementary flux linkage concept (figure 4a). The loop may also be considered to respond to the current induced in the plane by the magnetic field. In the dynamic field case, the current in the ground plane and the surface magnetic field are inseparable. A slot interrupts the uniform current density, J, that would normally flow on the surface, forcing part of this current to flow through the short-circuited slot terminals (fig. 4b). The slot current is:

$$I = J\ell_e = H\ell_e$$

$$(2)$$

where ℓ_e is the effective height of the antenna.

The impedance of the small slot is primarily inductive reactance. Hence, the open-circuit voltage at the slot terminal is:

$$V = \ell_e L \frac{dJ}{dt} = \ell_e L \frac{dH}{dt}$$

$$(3)$$

The short-circuit current and open-circuit voltage of a small loop antenna are, respectively:

$$I = \frac{\mu A}{L} J \quad \text{and} \quad V = \mu A \frac{dJ}{dt}$$

$$(4)$$

where A is the area of the loop, $\mu = 4\pi \times 10^{-7}$ H/m, J is the surface current density, and L is the loop inductance.

Shielding is necessary to make the loop insensitive to the electric field. Conventional shielded loop design can be used for this purpose. Although loops are more sensitive than slots of comparable size, they protrude from the skin and may lead to mechanical interference problems. Since slots are flush with the skin, they may be installed anywhere a break in the skin can be allowed.

As indicated earlier, measuring the short-circuit current requires the measuring apparatus to have an insertion impedance that is small compared with the inductive reactance, $j\omega L$, throughout the frequency range of interest. Because L is small for a small half-loop and even smaller for a small slot, it is difficult to measure the late-time, short-circuit current directly. Therefore, the open-circuit voltage is usually measured in transient electromagnetic studies. Measurement of magnetic fields in the laboratory experiments of refs. 5 and 6 was implemented by using a series of slot antennas installed in the ground plane of the test set up.

The problem of developing and optimizing sensors for transient electromagnetic field measurements has been of great concern to the EMP community. Techniques for extending the performance of the basic sensors discussed above have been developed by Baum and others and have been published in the Sensor and Simulation Notes edited and authored by Baum (ref. 9). Portions of this work applicable to lightning measurement are contained in reference 10. Many of these sensors and sensor concepts can be adapted for spacecraft applications.

In addition to electromagnetic field measurements, the spacecraft experimenter is often interested in the currents and voltages induced in internal wiring. A variety of commercial current transformers are available covering the frequency range of interest. These transformers are well shielded and designed to minimize response to electric fields. Thus, current measurements are simple and straightforward to instrument.

Voltage measurements—particularly differential voltage measurements—may be more difficult to carry out. To measure the voltage between a particular wire and the frame, the probe must have adequate bandwidth, impedance, and dynamic range. Measuring the differential voltage between a pair of wires is more difficult. Not only must the probe be able to cover the dynamic range and bandwidth of interest, it must function in the presence of common-mode signals substantially larger than the desired signal. The present state of spacecraft charging research is such that differential voltage measurements are probably best deferred to the future.

SENSOR PLACEMENT (AIRFRAME EFFECTS)

An electromagnetic field sensor provides information about the electromagnetic fields at its location; unless special precautions are taken, the vehicle itself acts as an integral part of the sensor. At frequencies corresponding to the vehicle resonances, the antenna/spacecraft system can exhibit complex interactions. At VHF and above, the antenna/spacecraft system has the characteristics of the antenna element mounted on a large, complex ground plane. These problems have been studied in substantial detail for aircraft and rockets in connection with antenna design and investigation of EMP susceptibility (ref. 11). In particular, for the case of a slender cylinder, it is possible to derive a formula for the time domain response to a unit-step driving pulse. The results of such a calculation, shown in Figure 5, demonstrate several interesting affects: the ringing of the system at a frequency determined by the length of the cylinder is clearly evident. Also, it should be noted that the current is maximum at the center of the cylinder (u = 0) and decreases as one moves toward the ends (u = 1/4). Thus, in the case of a slim cylinder such as an aircraft or rocket, a substantial degree of decoupling from the airframe resonances can be achieved by locating the magnetic sensor at the end of a structural member (e.g., at the nose of the fuselage) where the current is zero.

Conversely, since the electric field is maximum at the ends of a conductor, E-field sensors are most strongly affected at the extremities.

SATELLITE MOCK-UP EXPERIMENTS

Although the time waveforms in Figure 5 indicate that substantial ringing can occur when a body is excited by a transient impulse, it must be recognized that the data in the figure are valid for a slender cylinder. In general, electromagnetic theory indicates that, for fatter bodies, the ringing dies out much more rapidly (i.e., fat bodies have a lower Q). Thus, it was possible that the signals excited on a satellite by a transient discharge might be much less complicated than one would infer from figure 5. To investigate the electromagnetic properties of a body resembling a satellite, and to gain insight into the feasibility of discharge source characterization, the laboratory "satellite" mock-up shown in figures 6 and 7 was assembled. Figure 6 shows the general size and form of the mock-up, which is simply a hollow uncapped cylinder made of sheet aluminum. It is approximately 1.8 m in diameter and 1.2 m high and stands upright on a 0.75-m high non-conductive, large-area wooden table. For the initial tests, two small electric-dipole sensors (equipped with high input impedance preamplifiers so that they respond directly to the local E field as was discussed earlier) were mounted 180° apart on the outside curved surface along the circumferential center line of the cylinder. The sensor cables were routed to the inside of the cylinder through small holes near the sensors. The signals from the two sensors were recorded simultaneously using a 400-MHz bandwidth dual-beam oscilloscope which was mounted inside the conductive cylinder where it was well shielded from external fields.

Transient electromagnetic fields were generated on the exterior of the mock-up using a dc spark-gap formed by positioning a 10-cm-diameter hollow copper sphere on an insulating support at a distance of approximately 3 mm from the outer cylinder surface at selected simuated arc locations. To prevent measurement errors resulting from transients radiated from, or field perturbations caused by the presence of the high-voltage cables, the copper sphere was connected to a 20-kV power supply located 4 m away, using special "electromagnetically-transparent," high-resistance wire as shown in figure 7. The required dc return path between the cylinder and the high-voltage supply was provided in this same way. Thus, electromagnetically, at RF the spark source appeared to be a completely isolated sphere charged to a high voltage. The spark source produces a unidirectional current pulse with an amplitude of roughly 400 A, and total duration of the order of 2 ns. It should be noted from figure 6 that the mock-up experiments were conducted in the middle of a laboratory area with no effort to shield the setup from ambient noise.

Some of the results of the satellite mock-up experiments are shown in figure 8. For the experiments illustrated, the spark source was moved to various positions along the equator of the "satellite" and the signals induced in the two sensors were recorded. When the spark source is near sensor #1 (as in fig. 8a), substantial signal is induced in this sensor, and a barely perceptible response is induced in sensor #2.

It should be noted that the initial pulse in sensor #1 is clearly defined, and that it is uncontaminated by the reflected pulses arriving late in time. This behavior is vastly different from the pronounced ringing illustrated in figure 5, when a slender cylinder is excited by a transient. Thus, the laboratory experiments

indicate that satellite electromagnetic characteristics are such that flight experiments intended to characterize discharge noise source characteristics in orbit should not be unduly plagued by satellite and sensor responses, provided the system is properly designed and configured.

In figure 8b, the spark noise source was positioned roughly equidistant from the two sensors, and signals of roughly equal amplitude are induced in the two systems. Again, it should be noted that the direct signal from the source is clearly defined, and not contaminated by ringing and reflections from discontinuities on the satellite.

In the course of these preliminary experiments, the satellite configuration was changed to include a boom, and the sensors and noise source were moved to a number of different positions. The resulting responses differed from those presented here, but were all explainable by electromagnetic considerations.

CONCLUSIONS

By applying proper electromagnetic principles to sensor design, it is possible to develop systems capable of responding to fast transients of the sort expected from spacecraft charging. The form many of practical satellites is such that they will not unduly contaminate the signals radiated by spark discharges. Accordingly, it should be possible to design flight systems for the study of spacecraft discharge characteristics. Finally, a simple satellite mock-up such as that used in the present experiments is easy to assemble, inexpensive, and adequate to provide important guidance during system design and for data interpretation.

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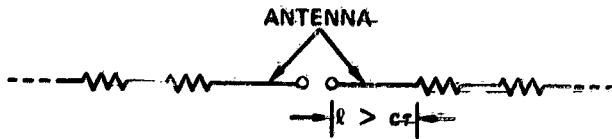
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where   c = velocity of light
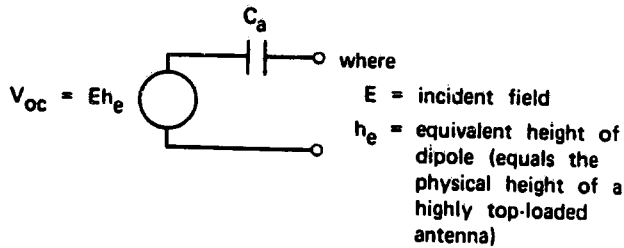
          τ = transient duration

(a) USE OF LONG ANTENNA TERMINATED IN LOSSY
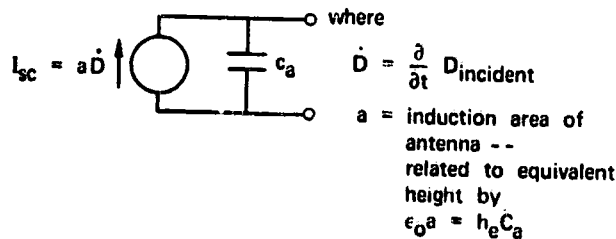MATERIAL TO INHIBIT REFLECTIONS
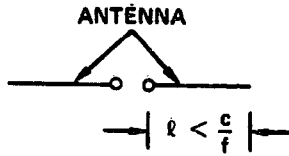
ANTENNA

where   c = velocity of light

          f = upper frequency limit
of recording system

(b) USE OF SHORT ANTENNA SYSTEM -- RINGING
OCCURS ABOVE HIGHEST FREQUENCY RECORDED

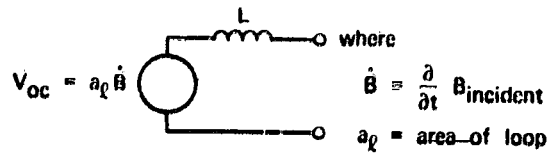Figure 1. - Approaches to transient field sensor design.

$V_{oc} = Eh_e$ C_a

where

E = incident field

h_e = equivalent height of
dipole (equals the
physical height of a
highly top-loaded
antenna)

(a) THEVENIN EQUIVALENT CIRCUIT
OF ELECTRIC DIPOLE

$I_{sc} = a\dot{D}$ C_a

where

$\dot{D} = \frac{\partial}{\partial t} D_{incident}$

a = induction area of
antenna --
related to equivalent
height by
$\epsilon_o a = h_e C_a$

(b) NORTON EQUIVALENT CIRCUIT
OF ELECTRIC DIPOLE

Figure 2. - Equivalent circuits of small electric dipole.

where

$$\dot{B} = \frac{\partial}{\partial t} B_{incident}$$

$$a_\ell = \text{area of loop}$$

$$V_{oc} = a_\ell \dot{B}$$

(a) THEVENIN EQUIVALENT CIRCUIT OF MAGNETIC DIPOLE

where

H = incident field

ℓ_e = effective length of antenna -- regulated to loop area by

$$\mu a_\ell = \ell_e L$$

$$I_{sc} = \ell_e H$$
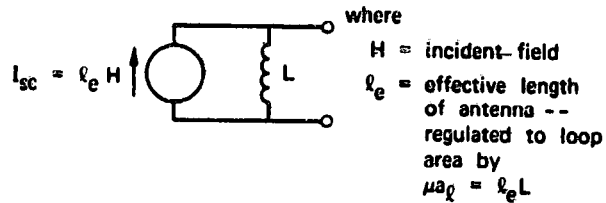
(b) NORTON EQUIVALENT CIRCUIT OF MAGNETIC DIPOLE

Figure 3. – Equivalent circuits of small magnetic dipole.

$$I = \frac{\mu A}{L} H$$

$$H = J$$
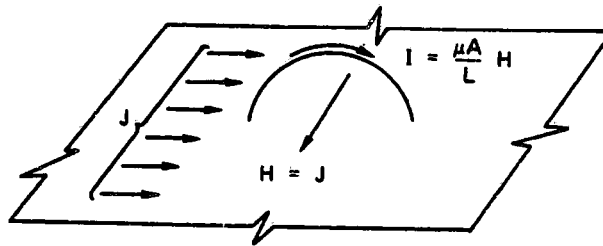
(a) HALF-LOOP OVER GROUND PLANE

$$H = J$$

$$I = H\ell_e$$
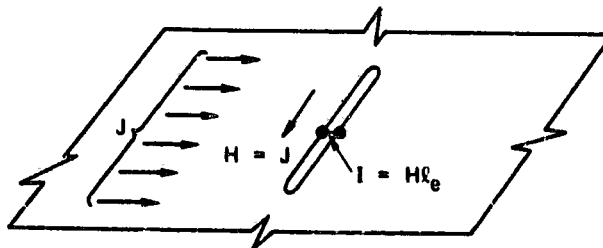
(b) SLOT IN GROUND PLANE

Figure 4. – Field, current density, and short circuit current relations for loop and slot antennas.

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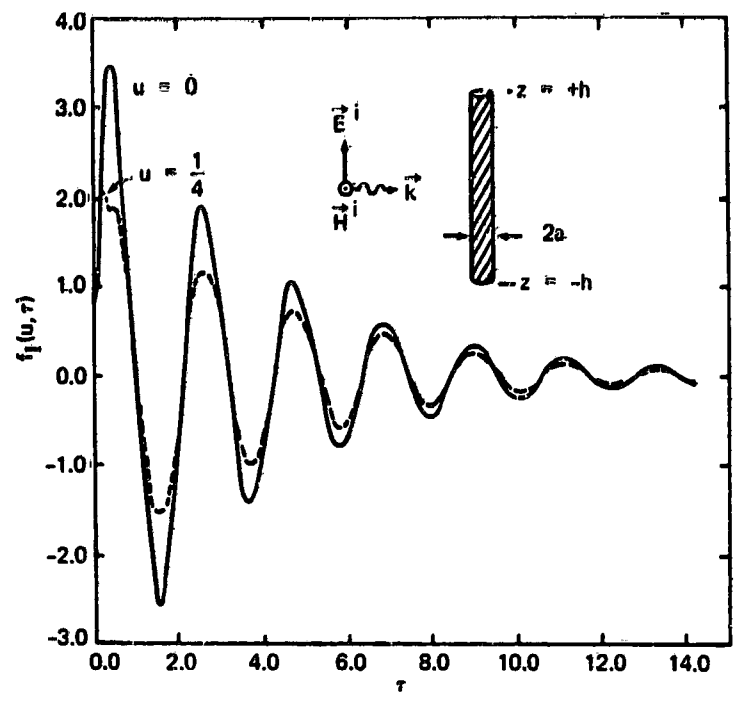
Figure 5. - Normalized axial current at two positions along a cylinder for a unit-step incident pulse (u = z/L, τ = ct/L, L = 2h).
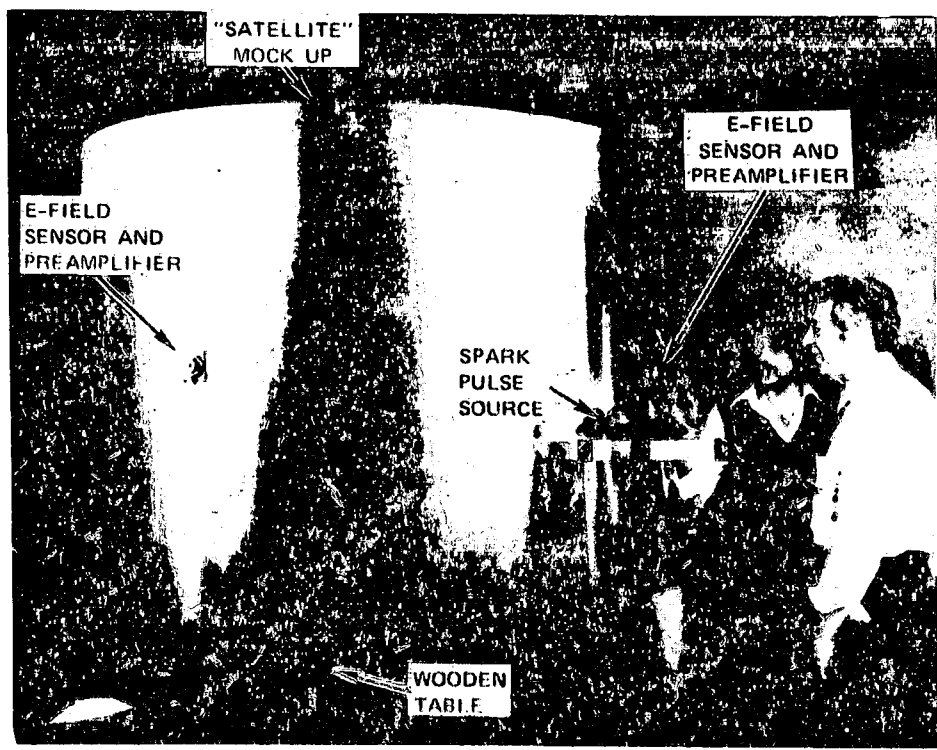
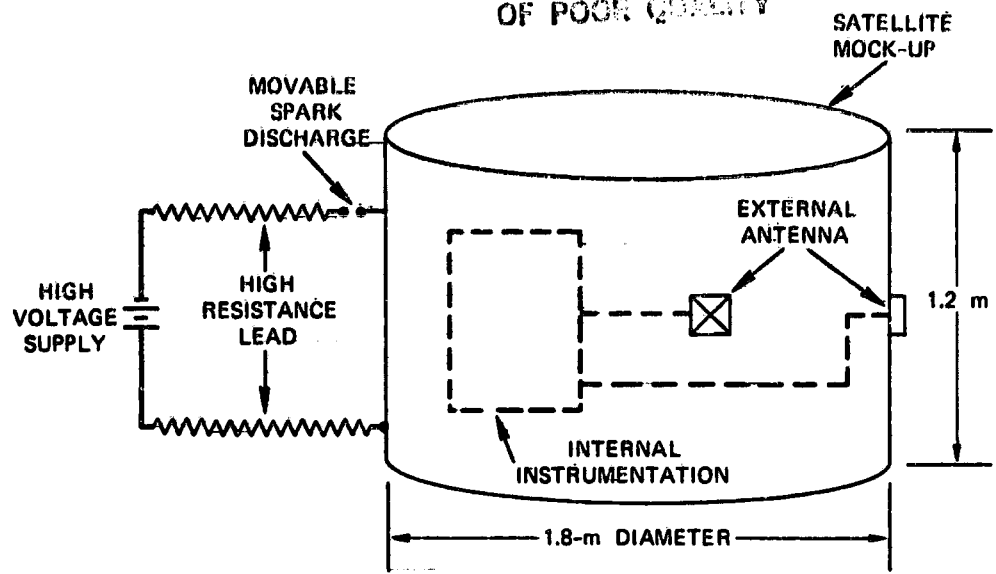

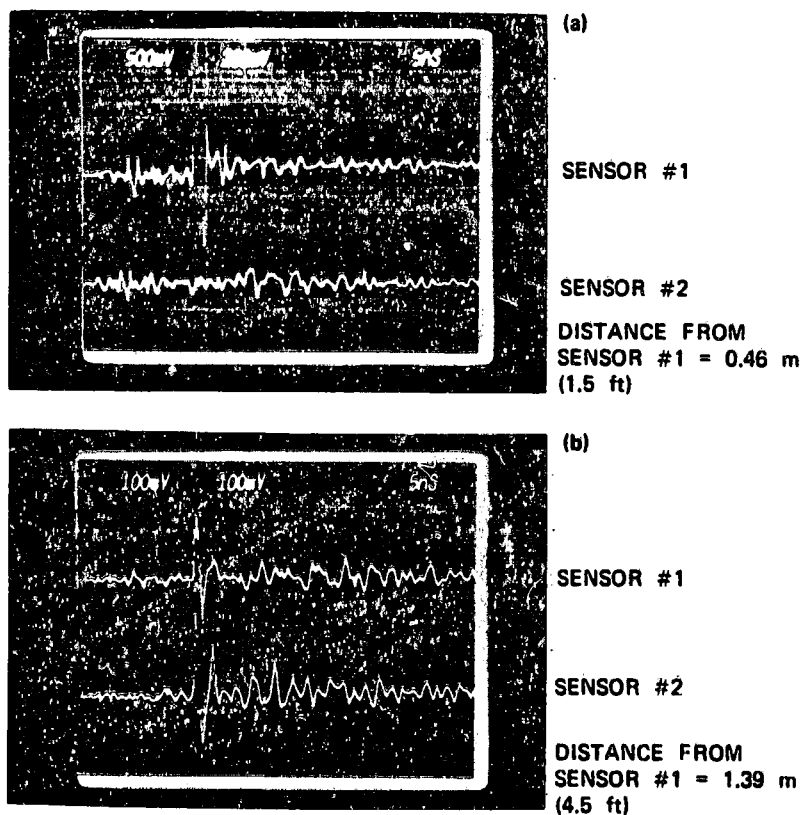Figure 6. - Satellite mock-up.

Figure 7. - SRI laboratory test of discharge localization technique.

Figure 8. - Sensor responses.