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IMPEDANCE OF PLASMA COATED AXIAL SLOT ANTENNA

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INTRODUCTION

A general research program is being conducted at the NASA Langley Research Center to study plasma sheath effects on the communication systems of reentry vehicles. Methods of minimizing the blackout effect are being investigated. This program is called Project RAM, for Radio Attenuation Measurements, and combines both theoretical and experimental investigations of the plasma sheath. One of the principal areas of investigation involves the study of electromagnetic wave interaction with plasma by using electron density profiles supplied by flow field analysis.

As part of this research effort a research vehicle was launched from Wallops Island, Virginia on April 10, 1964 in which the prime experiment was to verify flow field predictions from electron density measurements by using on-board microwave reflectometers at discrete locations along the nose cone.

Another major objective of the flight was to measure the input impedance of a narrowband and broadband VHF antenna in order to observe changes in the impedance caused by the proximity of the plasma sheath. This experiment was conducted, primarily, to observe detuning effects caused by the plasma sheath. Prior to the flight, it was generally concluded that plasma diagnostic data for the VHF range could not be obtained since electrically small antennas had to be used. This conclusion was made due to the fact that cavity-backed slot antennas are less amenable to a sound theoretical analysis. However, the slot antenna impedance measurements during flight plasma conditions did present interesting

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results. This antenna experiment is discussed in detail in reference 1. The flight test and the use of impedance data for plasma diagnostic purposes are discussed briefly herein.

FLIGHT EXPERIMENT

The nose-cone slot-antenna location and the RAM payload are shown in figure 1. Antenna performance was monitored by an impedance ring from which phase information was obtained; the voltage standing-wave-ratio was determined by the use of a bidirectional coupler. The slot antenna was cavity backed as shown in figure 2. Due to the lack of sufficient payload volume, the antenna dimensions were restricted to a length of 0.25λ and a cavity depth of 0.0625λ. Because an antenna with these physical dimensions is electrically small, the radiation efficiency was reduced considerably, and capacitive loading was necessary to improve the radiation efficiency. The resulting far-field radiation pattern is shown in figure 3. Capacitive loading not only improved the radiation efficiency but also decreased the bandwidth. The narrow bandwidth characteristics can be seen in the impedance curves in figure 4. The real and imaginary components of the slot aperture impedance are also presented as a function of the slot length to wavelength (L/λ) ratio.

The impedance of the slot antenna was also measured with a lossy dielectric shroud placed over the nose cone. The lossy dielectric material was composed of silicone rubber impregnated with graphite and a dielectric constant of 10 and a loss tangent of 0.10 were exhibited. The shroud was designed so that it could be placed over the RAM nose cone and slot aperture. The 1.50-inch shroud is shown alongside the RAM nose cone in figure 5. The slot impedance with the dielectric shroud is shown in figure 6 and it can be seen that (f_r) the slot resonant frequency is decreased as the L/λ ratio is decreased.

The flight impedance measurements during plasma conditions are given in figure 7. An interesting result is the slot resistance as a function of flight time. The resistance reached a maximum at 110 seconds as the reactance goes through resonance approaching a highly inductive value. Comparing the flight results of figure 7 with the free-space impedance characteristics of figure 4, the plasma impedance is similar to the free-space characteristics of the slot antenna for an increasing L/λ ratio. An increase in L/λ during plasma conditions indicates that the resonant frequency of the antenna is increasing as the electrical dimensions of the slot is decreased. The reduction in the electrical length of the slot is due to the proximity of the plasma sheath about the antenna aperture. The shift of the resonant frequency f_r in the plasma was compared with the shift in a dielectric medium and it was readily determined that f_r shifts one way for a dielectric and the opposite way for a plasma.

The flight impedance data implied that plasma resonance $\left(\frac{\text{Plasma frequency}}{\text{Signal frequency}} = \frac{\omega_p}{\omega_s} = 1\right)$ could have occurred in the vicinity of 110 seconds at the time of peak resistance or at a minimum aperture conductance. A theoretical flow-field analysis was conducted by North American Aviation (ref. 2) and the calculated electron densities were compared with the reflectometer flight results. The results of these inputs indicated that the critical electron density for the VHF experiment could be extrapolated and found to occur in the vicinity of the time in question. The flight impedance measurements lead to further investigations into the impedance method of plasma diagnostics.

Shortly after the flight of the RAM vehicle, significant progress was made in the theoretical treatment of the input impedance of antennas covered with a plasma and other dielectric material. Galejs (ref. 3) and Compton (ref. 4) studied the problem of the rectangular waveguide opening onto a plasma-covered, conducting, flat ground plane. R. C. Rudduck (ref. 4) computed the terminal admittance Y_T of the structure, assuming a semi-infinite medium, from the expression

$$Y_T = \frac{2p}{|V_o|^2} = \frac{2b}{a} \frac{\iint_{\text{aperture}} \left(\vec{E} \times \vec{H}\right) \cdot dS}{|V_o|^2}$$

where V_o is the applied voltage on the slot, p is power, b and a are length and width of aperture, S is area, and the electric field $\vec{E}$ was assumed to be of the same form as the dominant TE_{01} mode in the waveguide. The magnetic field $\vec{H}$ depends upon the dielectric constant ϵ_r of the plasma, hence, upon the electron density. The change in admittance as a function of the dielectric constant, that is, as ω_p/ω increases, is shown in figure 8. Also shown in this figure for a qualitative comparison only is the admittance of the VHF cavity slot antenna during flight plasma conditions.

In addition to the rectangular waveguide computed in reference 2, the admittance of a long axial slot on a coated cylindrical ground plane coated with a nonhomogeneous medium has been computed in reference 5 by Knop, Swift, and Hodara. The admittance of a gap antenna on a coated cylindrical ground plane was also computed and is presented in reference 5. The interesting result of these antenna investigations was that the conductance of each antenna approached zero as the ratio of the plasma frequency to the signal frequency $\left(f_p/f_s\right)$ approached unity and remained small as $\left(f_p/f_s\right)$ exceeded one. Hence this result appears to be independent of the type of antenna.

LABORATORY PLASMA TESTS

Since the admittance trend of the VHF slot antenna during plasma conditions was similar to the rectangular waveguide, more information concerning the plasma diagnostic capability of this electrically small antenna was desired. Preliminary investigations have been made in a plasma facility to measure the impedance of the VHF slot antenna as a function of the plasma electron density. Since the facility could not accommodate the physical size of a VHF antenna, the slot and cavity dimensions were scaled to a frequency of 1.90 GHz, reducing the size by a factor of 12.85. The test facility is shown in figure 9. The antenna was very similar to the flight antenna and was mounted on a flat ground plane. The ground plane and slot opening were covered with a thin sheet of mylar to prevent the plasma from entering the cavity. The ground plane and antenna were placed in the vacuum tank under the plasma slab as shown in figure 9. The free-space impedance characteristics of the antenna are given in figure 10, and narrowband characteristics are evident.

The electron density in the slab was determined by measuring the saturation current of a floating double probe stationed close to the slot. The electron density was then obtained by the following expression (from ref. 6):

$$N_p = \frac{\left(1.34 \times 10^{27}\right)}{A} i_s \sqrt{M/T_p}$$

where i_s is saturation current

M is mass of the positive ion

A is probe area

T_p is plasma temperature

N_p is electron density

The critical electron density for the operating frequency was determined from the expression:

$$N_p = \left[\frac{\omega_p}{2\pi(8970)}\right]^2$$

A limited number of tests have been conducted thus far to determine whether the condition that $f_p/f_s = 1$ occurred at the peak resistance point of the antenna impedance. During one test, a saturation current of $i_s = 52$ microamperes was measured by the double probe and indicated an electron density of approximately 4.1×10^{10} particles/cm^3. The normalized slot resistance measured for this value of electron density was 2.10 which indicated that plasma resonance had not yet occurred. A normalized slot resistance of 2.61 was needed for corresponding critical electron density of 4.5×10^{10} particles/cm^3. Further tests are anticipated in which steps will be taken so that the slot impedance through critical density can be measured.

CONCLUSION

In conclusion, the flight results obtained by using an electrically small slot antenna and the analytical results discussed indicate a promising method of plasma diagnostics, that is, the input impedance method. This method would be especially useful when plasma information is required of antennas less amenable to a sound theoretical analysis.

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5. Knop, C. M.; Swift, C. T.; and Hodara, H.: Radiation Patterns and Admittance of an Axial Slot on a Plasma Covered Cylinder. Presented at Third Symposium on the Plasma Sheath of Hypersonic Flight, September 21-23, 1965.
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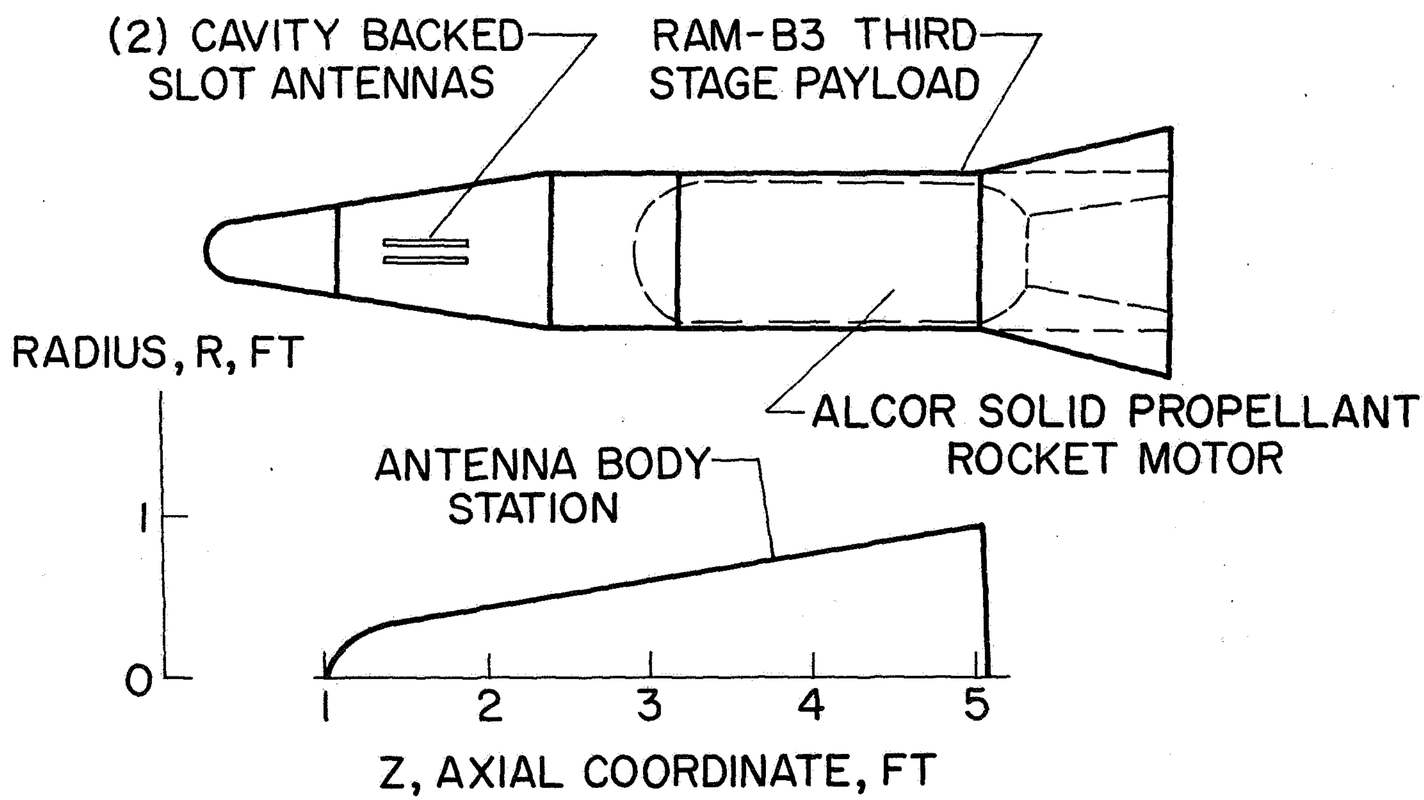

Figure 1.- RAM-B3 payload configuration and coordinate system.

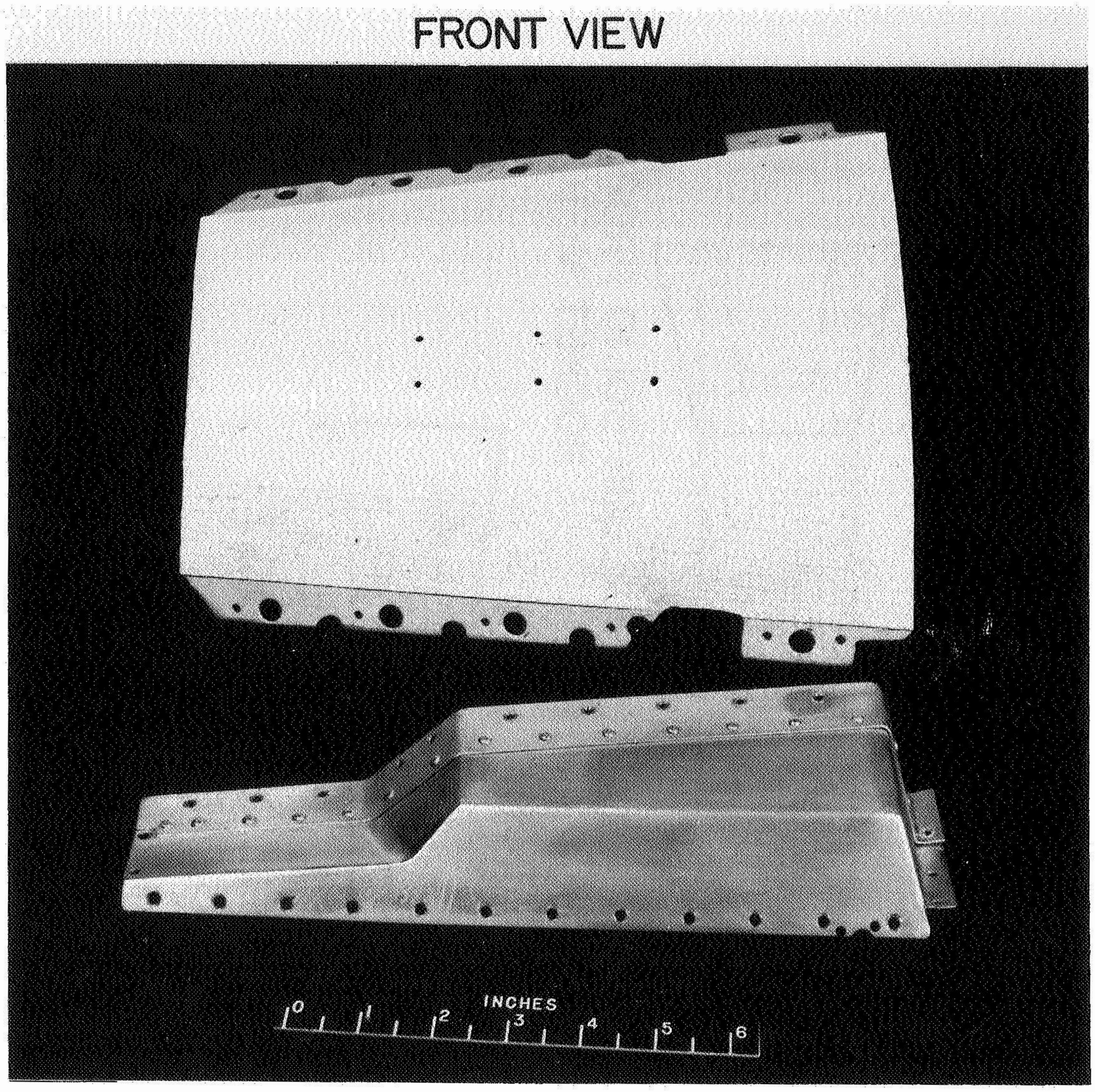

Figure 2.- RAM payload cavity backed slot antenna configuration.

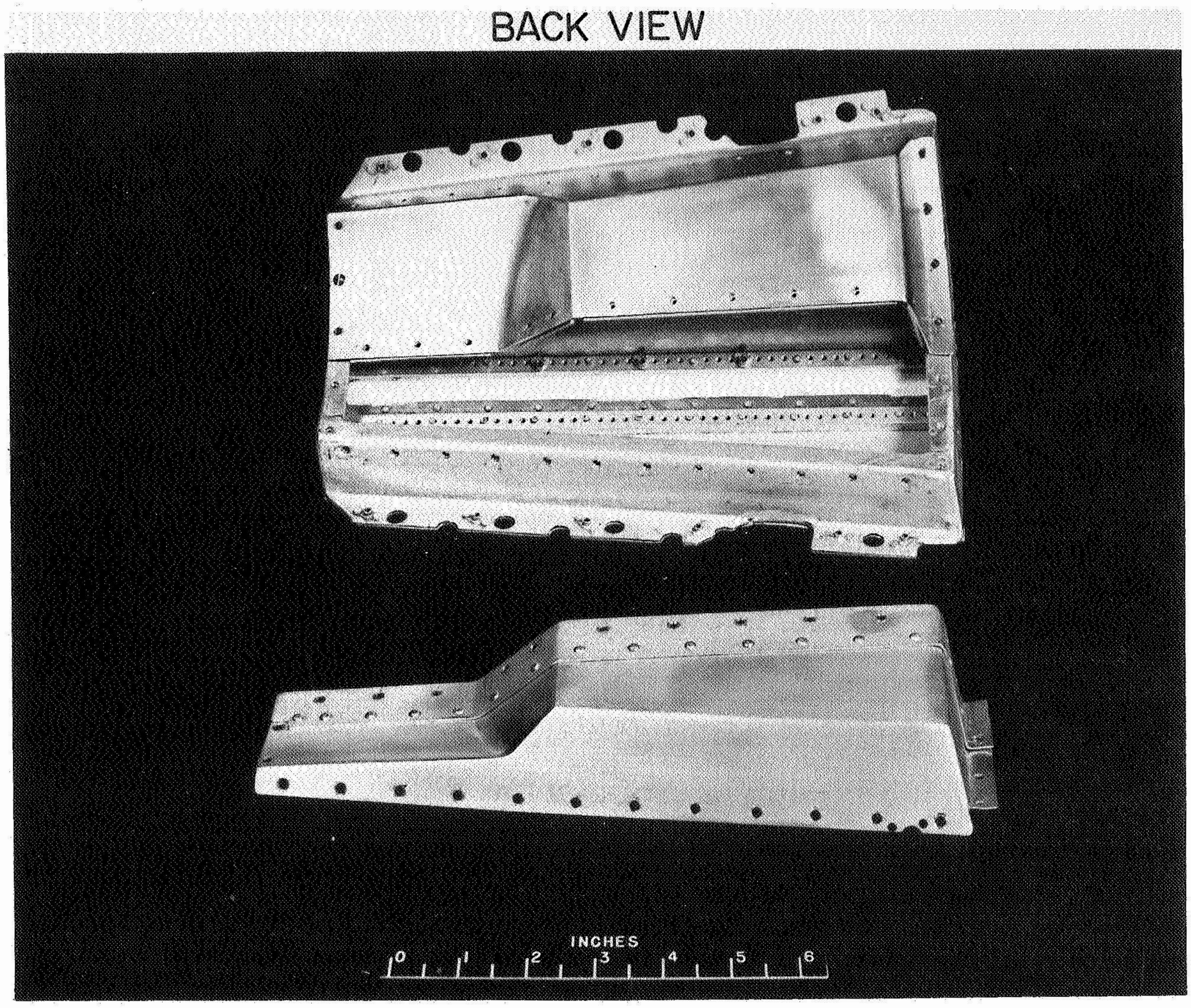

Figure 2.- Concluded.

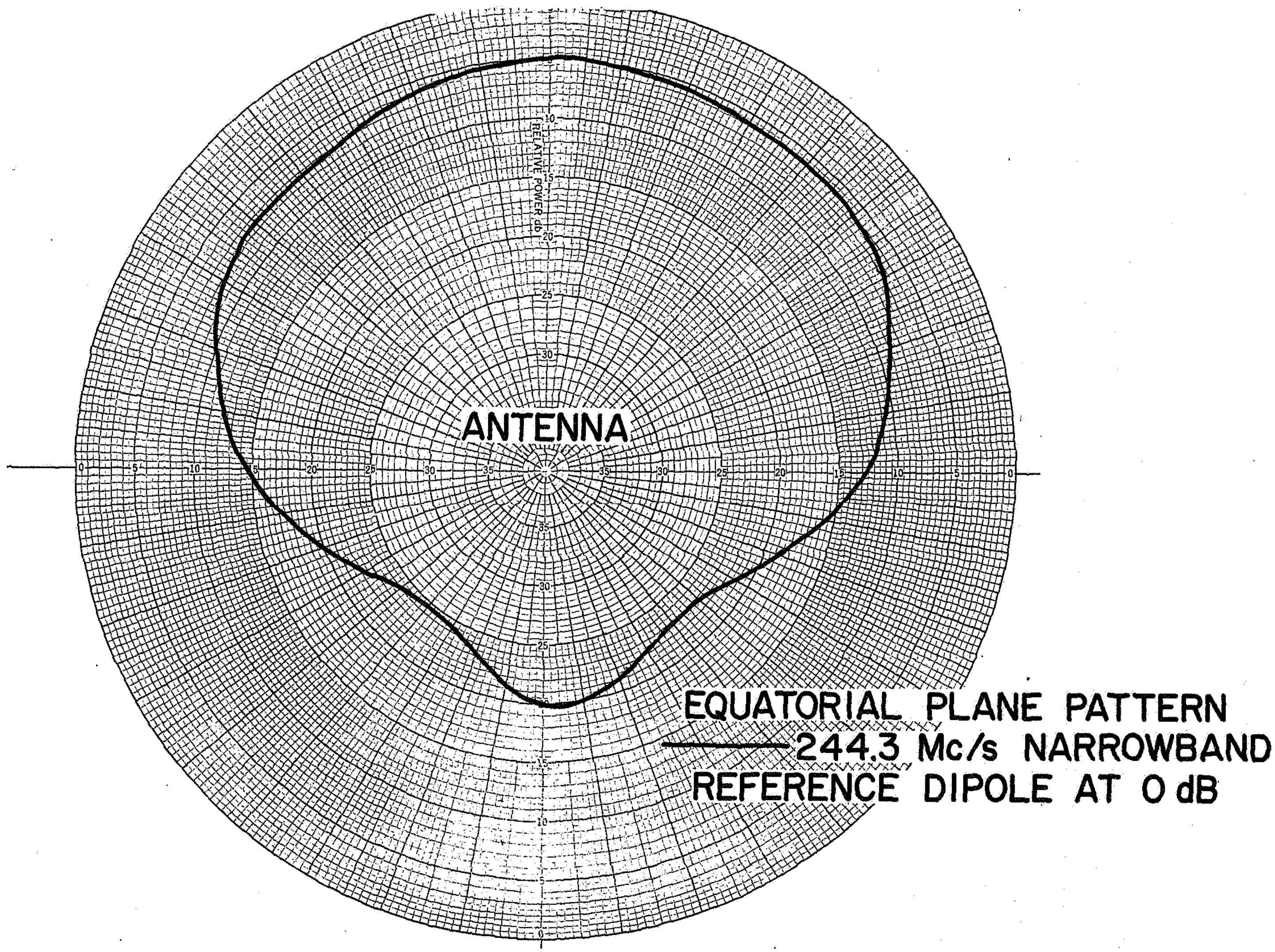

Figure 3.- Equatorial plane radiation pattern of the RAM slot antenna.

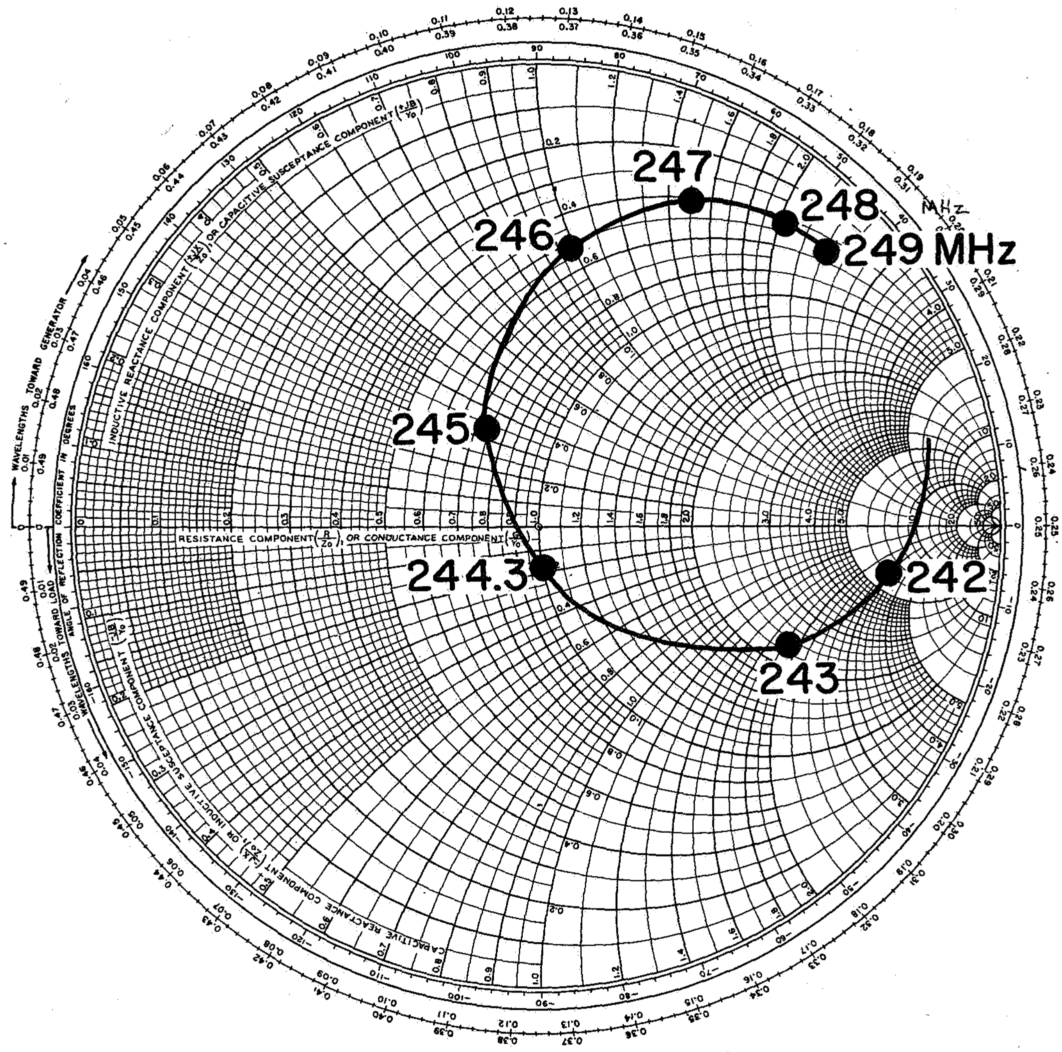

Figure 4.- Narrowband slot free-space impedance characteristics.

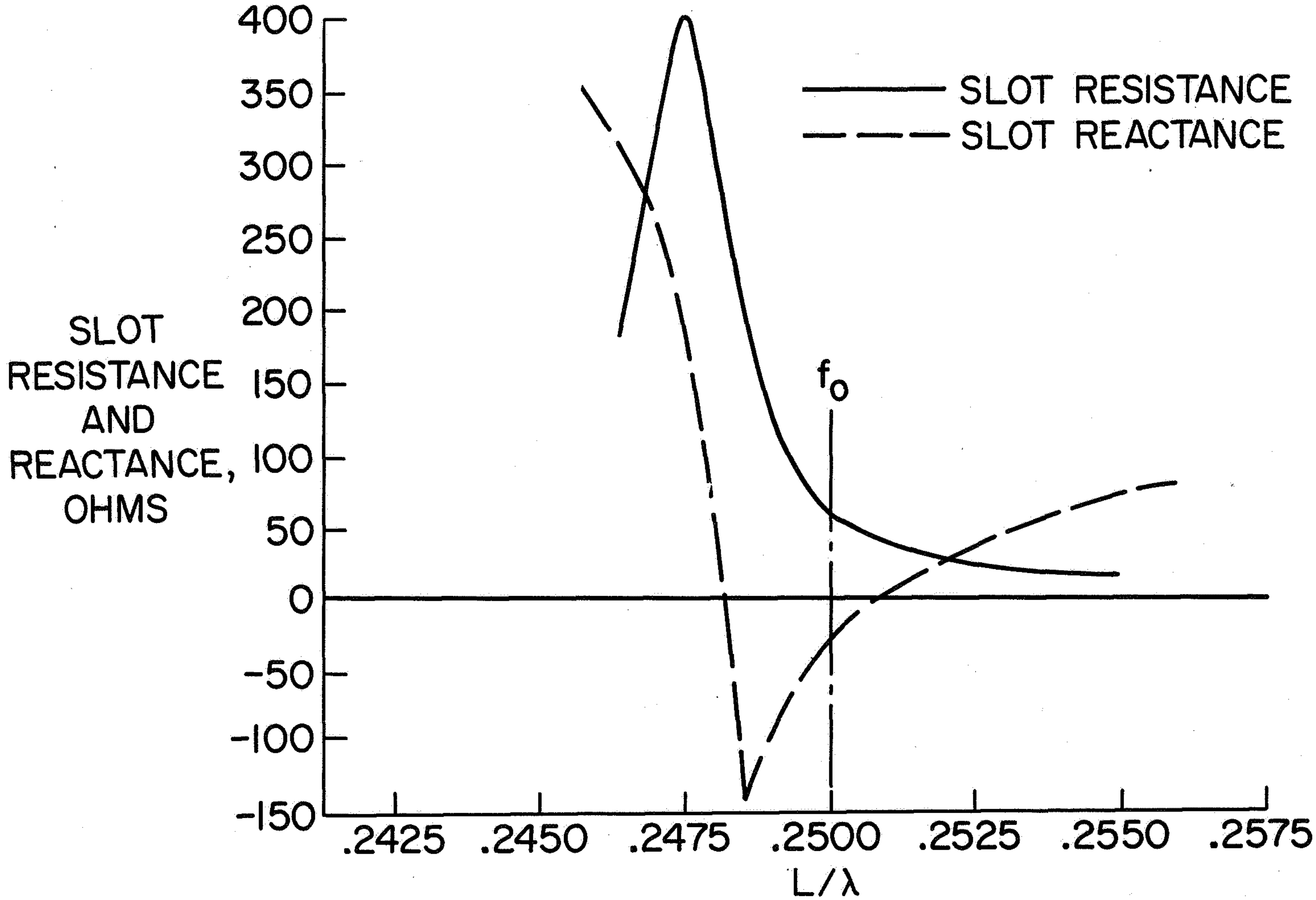

Figure 4.- Concluded.

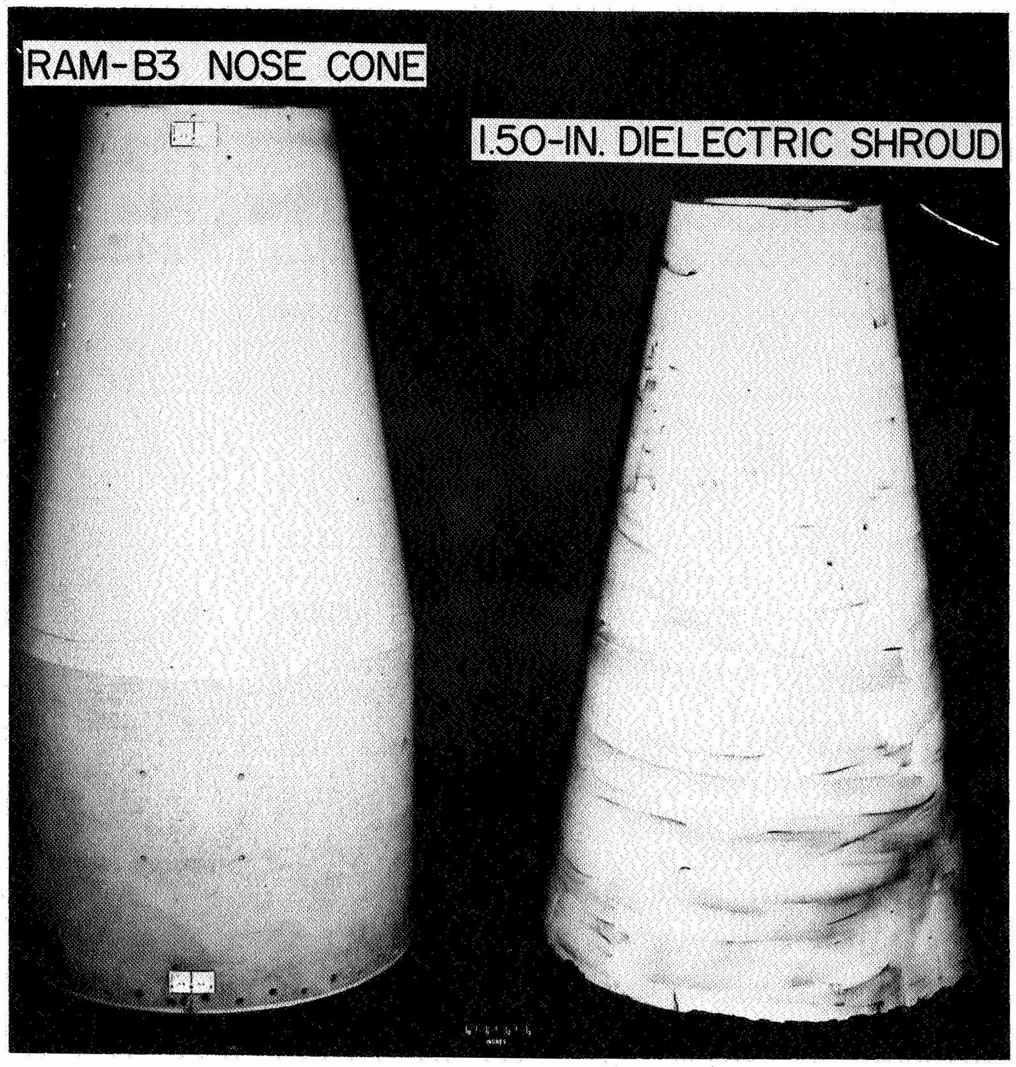

Figure 5.- RAM nose cone and the dielectric shroud.

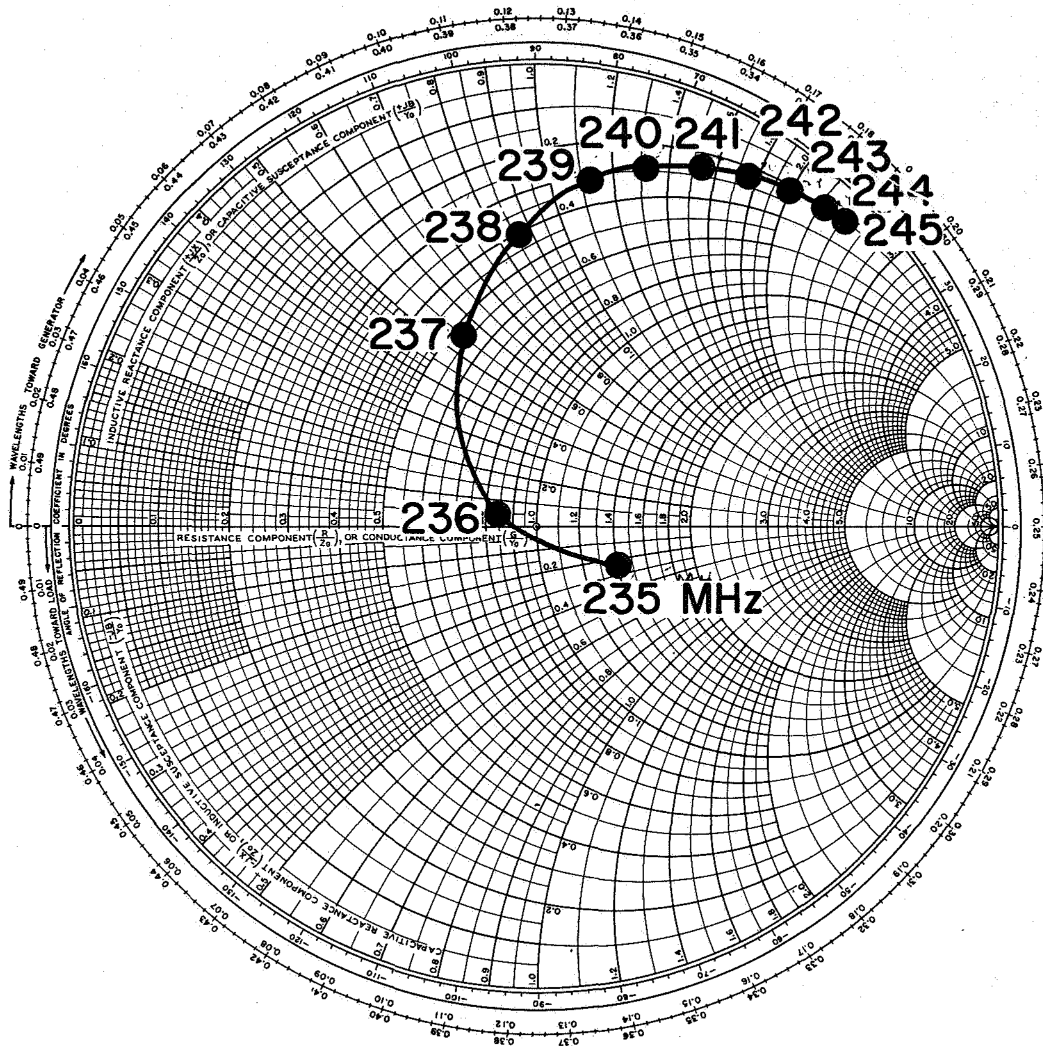

Figure 6.- Impedance of slot antenna covered with dielectric shroud.

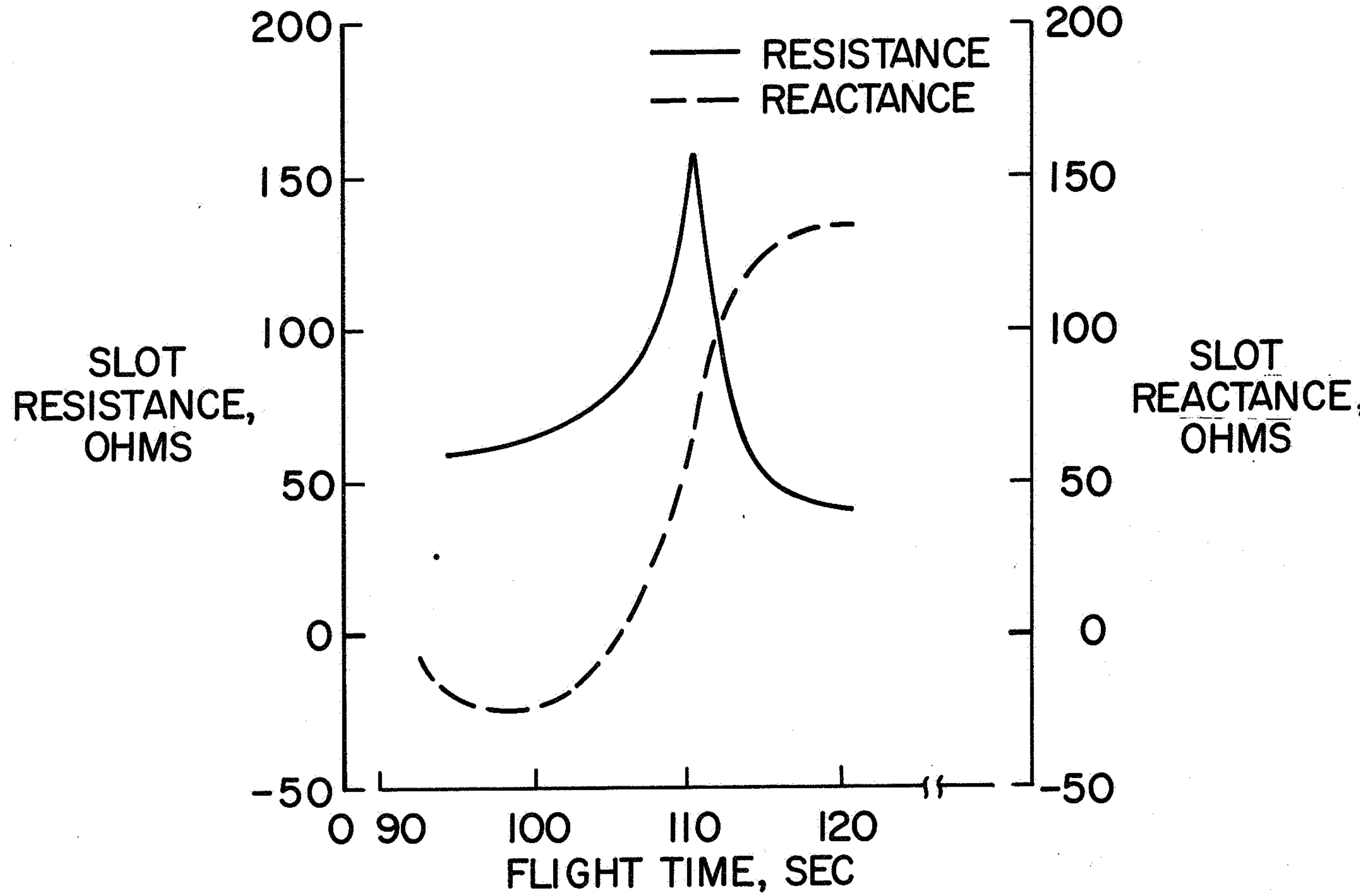

Figure 7.- RAM-B3 antenna experiment flight results.

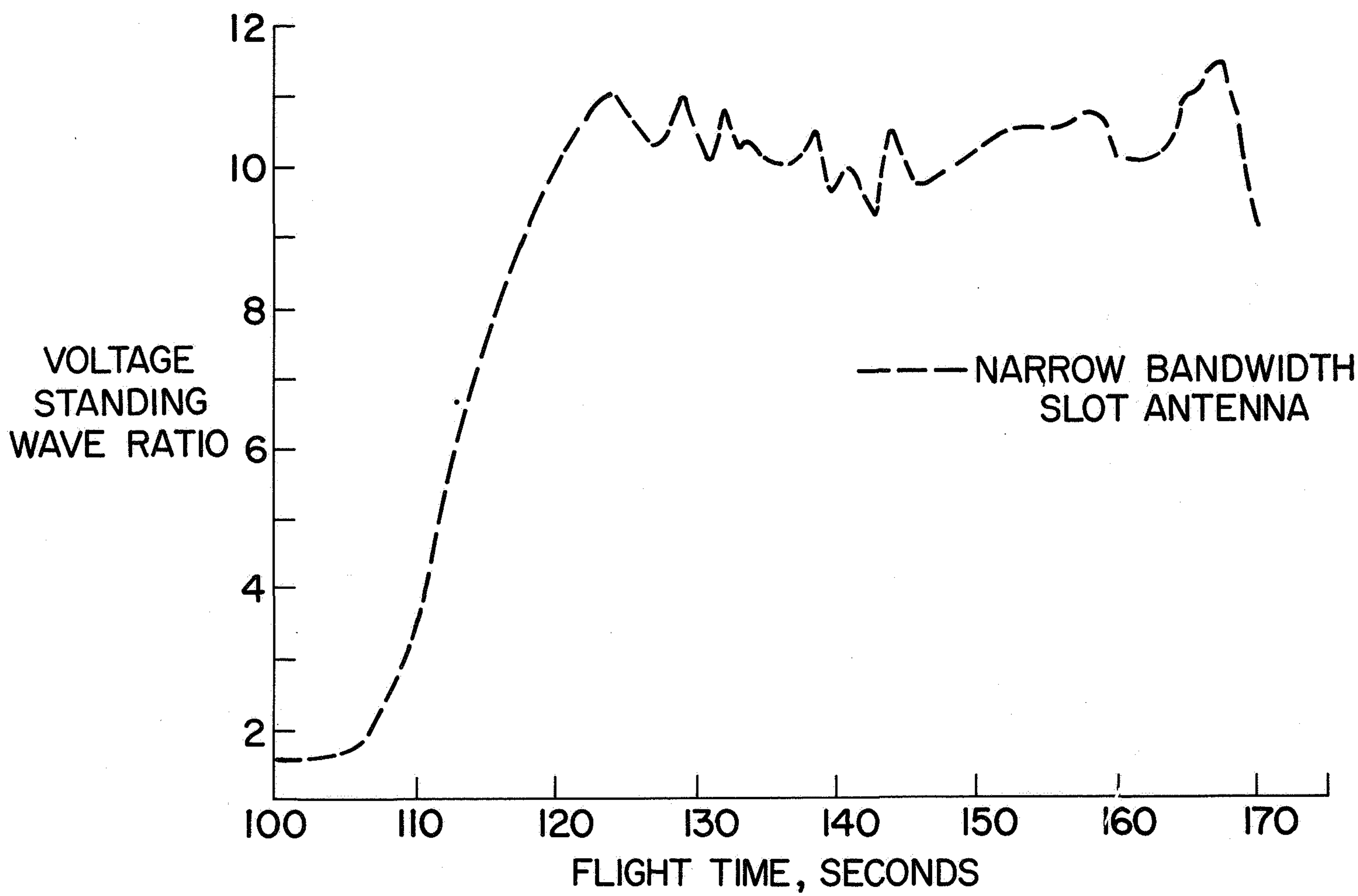

Figure 7.- Concluded.

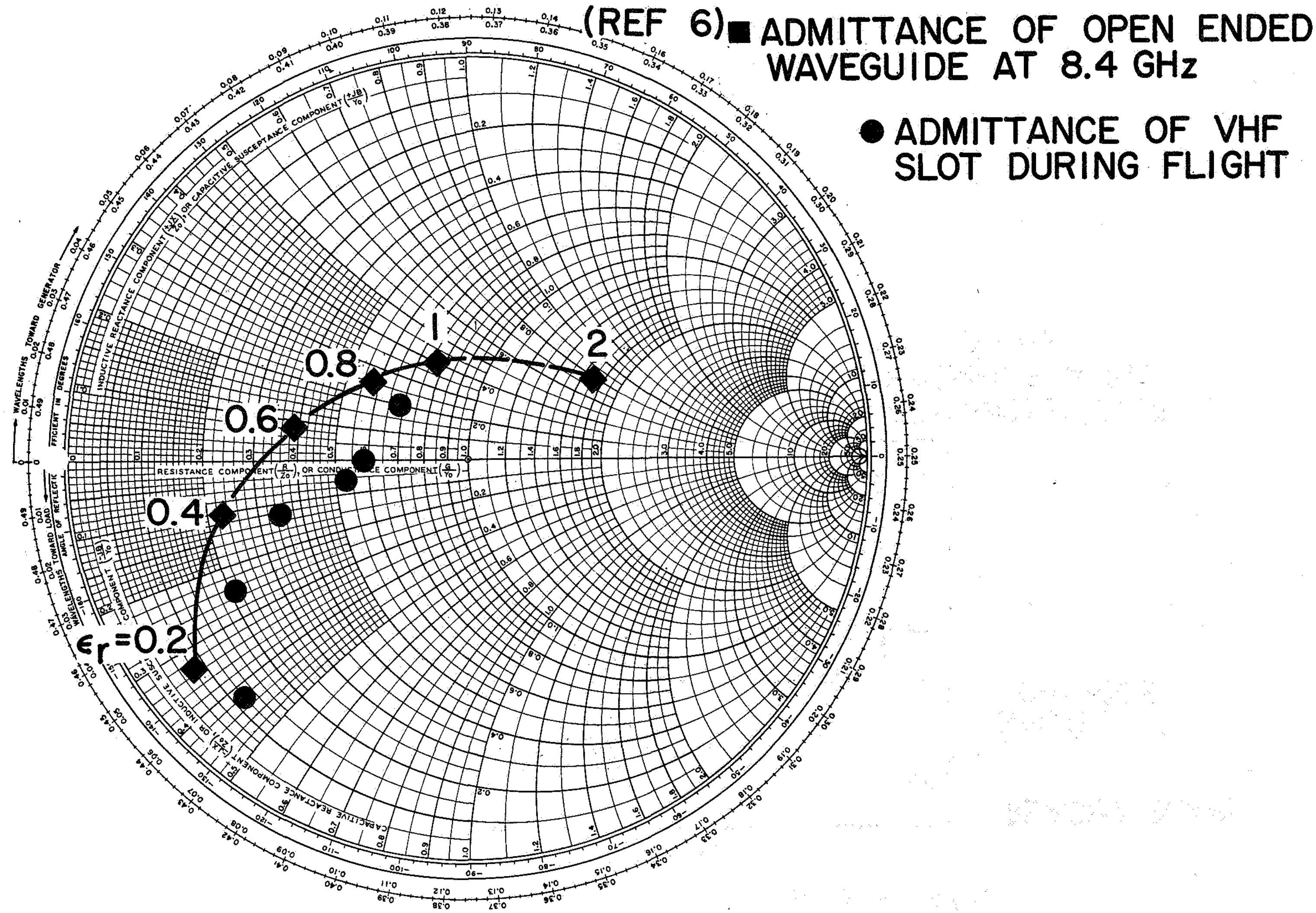

Figure 8.- Aperture admittance of open ended waveguide as a function of plasma frequency.

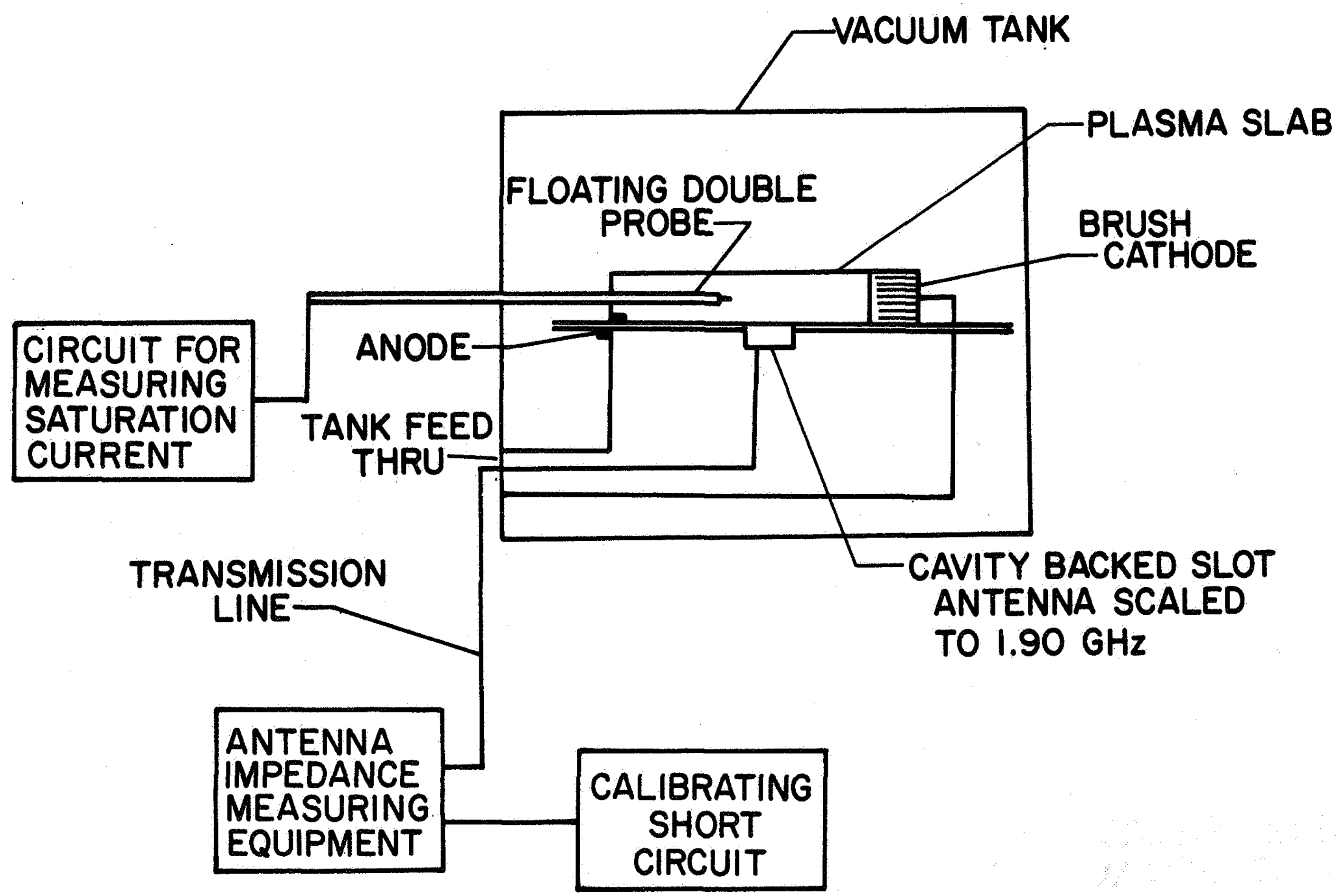

Figure 9.- Langley plasma slab facility.

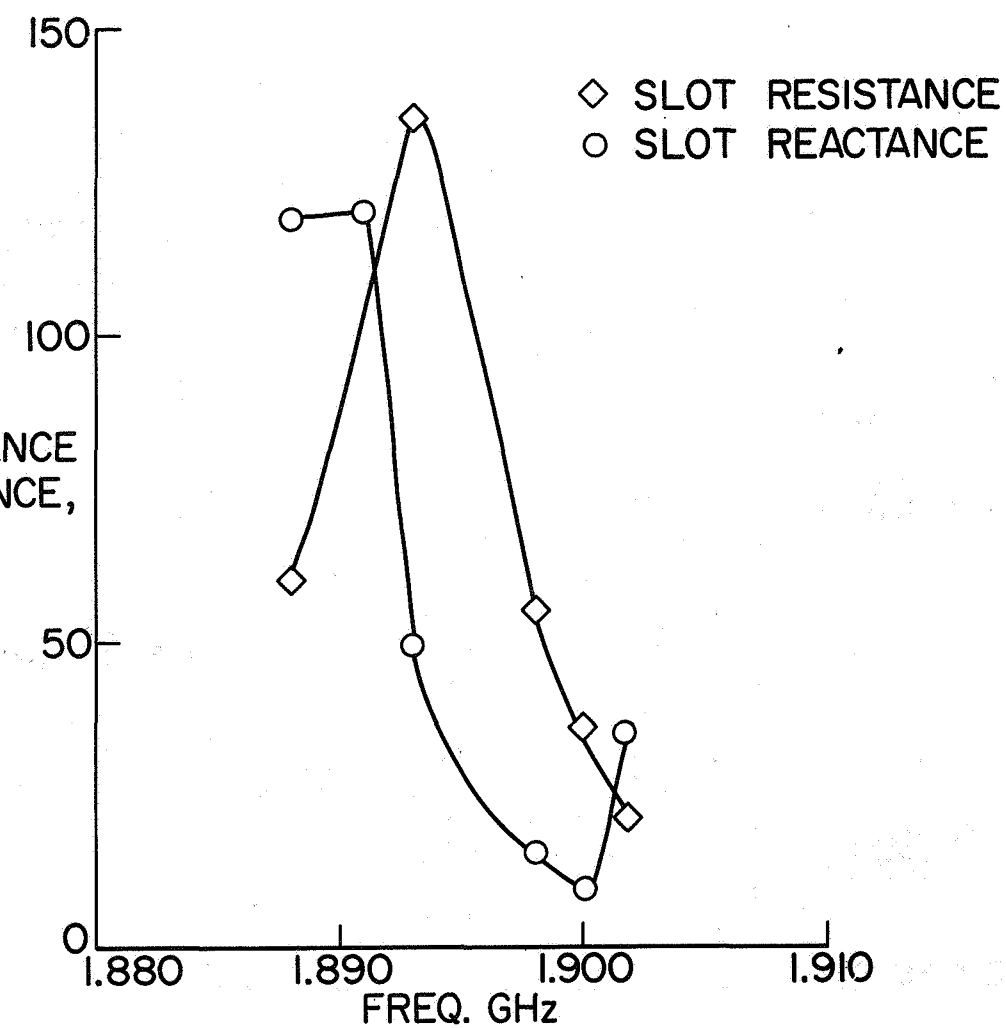

Figure 10.- Impedance of RAM payload VHF slot antenna scaled to 1.90 GHz.

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