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APOLLO PLASMA SHEATH IN-FLIGHT DIAGNOSTICS

BY

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ABSTRACT

The principal problem associated with the predictions of the Apollo reentry radio blackout is a lack of understanding of the ion forming chemistry in the Command Module flow field. In-flight plasma diagnostic probes are discussed as a direct method to obtain precise data on the plasma sheath. These data can serve to validate the results of laboratory investigations and to evaluate the effects of material addition. Observation of RF signal degradation is also considered as a necessary adjunct of a program on plasma diagnostics for correlation with electron density probe measurements. On missions of the Apollo Block I Command Module there will be an opportunity to evaluate the effectiveness during reentry of a beacon antenna located on the aft body radiating through the separated flow region. For this investigation the application of an in-flight electron density probe is urged for correlation with signal observations.

The characteristics of several electron density probes are discussed for their potential application to Apollo in-flight plasma sheath diagnostics. A description is given of the microwave resonant type probes developed at the General Applied Science Laboratories (GASL) for measurement of electron density in shock tubes and shock tunnels. The GASL internal cavity probes operate in supersonic flow and the dielectric waveguide type probes operate along the stagnation streamline of separated flow. These probes are considered to be adaptable for in-flight application. A wedge-shaped Langmuir type probe developed at the Stanford Research Institute for diagnostics of supersonic plasma flow is briefly described.

APOLLO PLASMA SHEATH IN-FLIGHT DIAGNOSTICS

INTRODUCTION

The physical factors involved in Apollo reentry communication blackout predictions are varied and numerous. The principal limitation now on predictions is a lack of knowledge of the plasma sheath.

To determine the properties of the sheath, the flow field around the spacecraft must be calculated including an analysis of the nonequilibrium chemistry of the high temperature gas. A most difficult task for the study of the degradation of the Apollo reentry radio link is to understand the detailed chemical reactions in the flow field.

Flight data have contributed negligibly to the understanding of the plasma sheath. There have as yet been no in-flight measurements to determine directly the local electron density in the flow field of manned reentry vehicles. RF signal strength attenuation data have been used to infer the level of reentry plasmas by comparing measured signal attenuation with calculations based on theoretical models. However, many uncertainties are involved in the data interpretation so that only crude information about the plasma sheath can be drawn. At the onset and termination of blackout the common deduction is that electron density along the signal propagation path has attained the critical plasma frequency corresponding to the RF signal. Oftentimes, though, no reliable history is available on the spacecraft attitude to make a proper correlation of signal propagation path in the plasmas with signal strength variation. As a result signal attenuation data are only indicative of the gross integrated propagation effect and offer little for detailed plasma diagnostics.

But even these limited means for assessing electron density level are absent during blackout when no measurable signal is present. In the skip type trajectory of the Apollo reentry flight there are two extended blackout intervals with which to reckon. Flight data on the dense plasma sheath during the blackout intervals are especially important for comparison with laboratory investigation.

In view now of the restricted information which has been adduced concerning the plasma sheath from RF signal attenuation data it would be of distinct value to have a diagnostic probe that can be immersed directly into the Apollo flow field to yield unambigous measurements of the local electron density.

The definitive data on the plasma sheath would serve for direct application in validating laboratory methods of plasma sheath predictions and correlation of the plasma data with the RF radio system performance during reentry. The effects of material additions on the plasmas level could also be realistically evaluated.

In this article the applicability of in-flight diagnostic probes for the Apollo plasma sheath are discussed for these purposes. In addition, observation of RF signal degradation is considered as a necessary adjunct of a program on plasma diagnostics for correlation with electron density probe measurements. Therefore, both probes and RF antenna sources onboard the Command Module are treated. The differing antenna types and their locations on the Apollo Command Module are described in order to illustrate the variety of physical problems that can be explored.

The characteristics of several electron density probe types are discussed for their potential application to Apollo in-flight plasma sheath diagnostics. A research program under GSFC sponsorship (NASA Contract No. NAS5-9881) is currently being conducted by the General Applied Science Laboratories, Inc. (GASL) on the development of plasma diagnostics probes for laboratory application in the Apollo flow field. The GASL probes are designed for shock tube and shock tunnel investigation* of the Apollo flow field at the Cornell Aeronautical Labotarory (CAL) and are considered as well to be adaptable for in-flight application. The results of the GASL developmental test are described below in some detail. A wedge-shaped Langmuir type probe developed at the Stanford Research Institute (SRI) under the Langley Research Center sponsorship (NASA Contract No. NAS1-3942) is briefly reviewed for its characteristics as an electron density probe for reentry plasma diagnostics.

RF SIGNAL-PLASMA SHEATH DIAGNOSTICS

The plasma sheath is the controlling factor for the reentry radio link of the Apollo Command Module with the ground stations, but since this plasma envelope is highly non-uniform the degree of degradation varies widely depending on antenna location. The generation of the plasma sheath and the interaction of the antenna signals with the non-uniform plasma medium are the major, complex factors for the prediction of the reentry radio system behavior. The important regions of antenna plasma interaction are identified from the antenna locations and signal propagation paths. With these regions delineated in-flight electron density probe experiments can be formulated.

*GSFC sponsored Contract No. NAS5-9978.

The observations of antenna signals can also be utilized for diagnostics, provided the difficulties of determining the signal path through the reentry flow field can be overcome. The diagnostic experiments should call for a close coordination of the acquisition of probe data with ground observation of signal attenuation. As a preliminary then to a discussion on the application of plasma probes, the antennas are described in order to show the opportunities for added plasma diagnostics offered by the varied signal transmission characteristics.

Command Module Antennas

The Unified S-Band System (USBS) is the tracking and communication radio link for the Apollo-lunar missions. The Command Module of the early Apollo missions, except for the first, A/S #201, has dual C-band and S-band beacon tracking systems for the check-out of the Unified S-Band System. The C-band antennas are incorporated as a backup support for the S-band antennas and to act as the primary beacon tracker until final verification of the USBS. In this proving stage, several antenna types and differing antenna locations on the Command Module are involved. A summary of data on the antenna is given in Table I to aid in understanding some essential features of the antennas for the reentry radio tracking and communication for the early Apollo mission.

Table I
Beacon-Type Antennas for Early Apollo Missions

Apollo Missions (A/S)	Air Frame No. (Block I)	Heat Shield Block Type	C-Band Antenna Location Designation (Ref. 1,2)	S-Band Antenna Type	
				USBS	Scimitar
201	9	I	1	–	–(1)
202	11	I	General-2(3)	–	X
204	12	I	General-2	–	X
205	14	I	General-2	–	X
501	17	II	General-2	X	–(2)
502	20	II	General-2	X	–(2)

(1)The scimitar structure housing the VHF antenna is present, but the S-band antenna is absent.

(2)The scimitar structure housing the VHF antenna is transferred from the Command Module to the Service Module.

(3)See Figure 2b.

The Apollo missions having a Block I air frame configuration are A/S #201(AF-9), 202(AF-11), 204(AF-12), 205(AF-14), 501 (AF-17), and 502(AF-20). The latter two, #501 and 502, have Block II heat shield whereas the other air frames carry Block I heat shields.[1]

The missions A/S #202, 204, and 205 are to have two VHF/S-band antennas (Fig. 1). The radiating element of the VHF is the thin metallic sheet of a scimitar configuration. The S-band antenna radiates through a notched slot in the scimitar. The antennas are housed in protective ablative material, erected on the vehicle surface a few inches aft of the Command Module shoulder. One of the scimitars located on the leeward side, 17° from the pitch plane has a 1-1/2" thickness of ablative material and is designated the "surviving" antenna while the other located on the windward side, 3° from the pitch plane has a 3/4" thickness of ablative material and is designated the "non-surviving" antenna.

The overall length of the antenna housing is about 18.4" and the extension of the structure from the surface is about 7-1/2". A consideration for the re-entry antenna performance is the disturbance of the flow field by the housing and the location of S-band antenna radiating element relative to the disturbed plasma sheath. The notched slot provided for the S-band antenna is about 5" above the vehicle surface and 15" behind the shoulder.

The missions A/S #501 and 502 have four USBS flush-mounted cavity-backed slot antennas equally spaced around the torus of the Command Module (Fig. 2a). The angular locations are 45° from the pitch plane. This positioning of the USBS antennas is to provide an effectively omni-directional radiation pattern.

The A/S #201 has no S-band antennas, but has four flush-mounted cavity-backed C-band antennas in the location described for the USBS antennas. On the other missions, A/S #202, 204, 205, 501, and 502 the four C-band antennas will instead have locations shown in Fig. 2b. Three of these antennas are on the torus, positioned midway between the USBS antennas. The fourth C-band antenna is in the aft section of the vehicle on the windward side, 14° off the pitch plane and about 30" from the torus.

Plasma Sheath Regimes

The relation of the various plasma regimes of the Apollo Command Module to the antennas can be studied by reference to Figure 3. The flush-mounted

(1) On later Apollo missions (A/S #207, AF-101; #503, AF-102) the C-band antennas are dropped leaving only USBS antennas. The heat shield and air frame are both of the Block II type.

C-band and USBS antennas at the torus are covered by the boundary layer flow and by the overlay of the dense plasma prevailing in the surrounding invisicid flow. RF signals from these antennas are in general dominated by the invisicid regions along the signal line of propagation.

The plasma conditions around scimitar S-band antennas will differ from that of flush-mounted antennas. The extent to which the protruberance modifies the plasma distribution is not known nor is it clear whether the S-band antenna will be immersed in the inviscid or separated flow.

The free shear layer and wake region plasmas are traversed by signals propagating in the aft direction. The long signal path length in these regions can be significant for absorptive attenuation.

In order to properly assess the importance of a flow region for RF interference, it is necessary to know in detail the aspect angle and bank angle history of the Command Module relative to the ground trackers. The flight path angle during reentry amounts to only a few degrees, so the velocity vector is nearly parallel to the local horizon. Accordingly when the lift vector is positive, the antennas on the leeward side of the vehicle have the direct view of the ground stations, and are favored over the windward antennas; while for negative lift the windward side antennas are favored. For a given trajectory point and vehicle attitude relative to the ground station, a careful analysis is still required to determine precisely which of the multiple USBS antennas has the strongest signal transmission.

Good reentry flight data on the Command Module attitude and bank angle history will help identify propagation paths through the plasma sheath and will therefore make attenuation data useful for diagnostics of the various plasma regimes. The several antenna beacon systems in the Apollo missions can then usefully serve as differing transmission sources through the plasma sheath. The radiation from the notched slot of the scimitars will act as S-band signal sources imbedded in the plasma sheath. These can be compared with the S- and C-band signals radiated from cavity-backed slot antennas mounted flush on the toroidal segment of the vehicle surface. Also, observations of signal variations from the aft located C-band antenna would be of value for exploring the plasma level in the separated flow regions provided these signals are distinguishable from the other C-band antenna signals.

APOLLO PLASMA SHEATH PROBLEMS

The Apollo spacecraft, like Mercury and Gemini, has a capsule type configuration. The vehicles have a strong, broad, normal shock wave and a separated flow behind the vehicle shoulder. The distinguishing features for the Apollo plasma sheath arise from the superorbital reentry velocity of 36 kft/sec and large angle of attack, 20°. Investigation of the Apollo sheath is therefore difficult since it involves three-dimensional flow around a body of relatively complex geometry and high temperature reacting air.

This report stresses the desirability of obtaining in-flight data to improve the description of the plasma sheath and to aid the laboratory investigations relating thereto. Attention is given below to listing of flow field and plasma sheath problems important for Apollo radio communication for which in-flight plasma diagnostics with electron density probes would be of value.

Inviscid Flow Plasma

Methods for calculating the Apollo three-dimensional inviscid flow field have been developed by Cornell Aeronautical Laboratory (CAL), yet there exists major problems in determining the nonequilibrium real gas flow.

The direct, nonsteady method of Bohachevsky (CAL) has proved to be a powerful direct means for calculating the inviscid nonequilibrium flow for Apollo (Ref. 3). The plasma free electron density is, however, known to be a sensitive function of the nonequilibrium state and of the kinetics of the ion forming reactions. The lack of knowledge of the mechanism and pertinent ion reaction rate constants is then the limiting factor in the calculation of plasma properties in the inviscid flow (Ref. 4). Laboratory experiments have been planned and are currently under way at CAL to reduce the uncertainty involved in flow field ion chemistry (Ref. 5). Results of the CAL investigation are to provide the basis for predicting the Apollo plasma sheath.

Diagnostic probing in the inviscid flow near the shoulder of the Command Module would be a favorable location for comparison with CAL prediction methods. The region neighbors the site of the beacon antennas and is characterized by rapidly expanding flow with strong gradients in the plasma parameters. Data on the electron density near the aperture of the antenna is of special importance for correlation with observed signal strength attenuation.

Separated Flow Plasma

Separated flow has been the most difficult flow to analyze. Rigorous analytical methods for calculating three-dimensional separated flow for Apollo have not been possible because of the highly nonlinear character of the flow. A commonly used model assumes a uniform enthalpy level within separated flow, but even then there remains an uncertainty in the prevailing enthalpy level.

The investigation of separated flow is in general beset by the difficulty of developing rigorous computational methods and a deficiency of appropriate experimental data. There has been recent noteworthy progress by Dr. Holden at CAL in the application of theoretical methods to two-dimensional separated flow (Ref. 6). One difficulty at least in the application of this investigation to Apollo will be the need to develop suitable scaling laws. It appears inescapable that one is compelled to turn to in-flight plasma diagnostics in order to get accurate data on the separated flow plasma.

Material Injection

In the ablation of the Apollo heat shield, material is released into the boundary layer and dispersed in the afterbody flow of the free shear layer and separated flow regions. The contribution of the ablation material and its impurities to the free electron density in the plasmas sheath has not been adequately studied for Apollo. There is considerable difficulty in making a thorough, realistic laboratory analysis. In-flight plasma diagnostics of the boundary layer and separated flow plasmas could offer definite data on this effect.

Water injection already performed on GT3 has demonstrated its capability of substantially alleviating the RF-attenuating effects of the plasma sheath (Ref. 7). Should a plasma ameliorative experiment be further pursued in the Apollo program it would be desirable to obtain precise data with a plasma probe on modifications of local electron density.

The importance of in-flight diagnostics for the separated flow is further emphasized by the complexity added by these mass injection problems. As already noted the early Apollo missions are especially favored for the study of the separated flow region because of the C-band antenna positioned in this region.

GASL ELECTRON DENSITY PROBE DEVELOPMENT

GASL has developed plasma probes to measure quasi-local electron densities in an ionized inviscid supersonic flow (Ref. 8). The probes were designed and tested for operation in shock tubes and shock tunnels. They are also considered to be adaptable for in-flight application in the environment of the Apollo reentry flow field. These probes may then afford the needed means of obtaining precise data points of electron densities in the Apollo plasma sheath.

The immediate application for the probes is for employment in the CAL shock-tube tunnel to assist in the investigation of the ion reactions of the Apollo plasma sheath. The CAL facility has the unique capability of simulating a flow field environment at an enthalpy level approaching those of spacecraft return from lunar missions. The GASL probe design is particularly suited to diagnose this environment. The aerodynamic shaping of the probe confers on it the capability to entrain discrete streamtubes with a minimum flow disturbance and to precisely measure the electron density of the sampled flow. In the expanding flow of the shock-tunnel nozzle there can be large gradients in the flow parameters. The interferometer technique has the disadvantage of yielding only an integrated electron density along a path, therefore necessitating an assumption about the electron density profile. Here the superior spatial resolution of the GASL probe has an advantage.

The following paragraphs summarize material from the GASL technical reports on NASA contract numbers NAS5-3929 (Ref. 8) and NAS5-9881 (Ref. 9) relating to electron density probe development.

Internal Cavity Type Probe

Two internal cavity type probes have been developed having a nominal microwave resonant wavelength of 3 cm and 10 cm. The probes (Fig. 4 and 5) are characterized by a central flow channel which is part of a resonant cavity. With the probe immersed in an ionized supersonic flow the channel fills with a streaming plasma, and induces a shift in the resonant frequency. For a dilute plasma the frequency shift is linearly related to the electron density n; viz,

$$\frac{\Delta f}{f_0} = k \frac{n}{n_c} \qquad (1)$$

where f_0 is the unperturbed resonant frequency, n_c is the associated critical electron density for f_0, and k, the proportionality constant, is designated the probe sensitivity. The critical electron density is an upper bound to the range of measurements of the probe while the minimum measurable electron density is determined by Q, the figure of merit of the cavity. The parameter k is determined from calibration testing described below. The probe characteristics are summarized in Table II.

Table II
Probe Electromagnetic Characteristics

Probe (Wavelength)	n_{min} (e/cm^3)	n_c (e/cm^3)	f_0 (Mc/sec)	Q	k
10 cm	7×10^7	5.4×10^{10}	2080	3200	0.118
3 cm	8.5×10^8	9.0×10^{11}	8684	2000	0.270

Aerodynamic Factors

A basic factor in the aerodynamic design of the internal cavity probe is that the flow properties of the streamtube within the central channel are not to be significantly disturbed. A normal stand-off shock at the entrance of the channel would, of course, greatly perturb the free electron density. A knife edge at the lip of the entrance circumvents these perturbations. A disturbance that is necessarily present in the channel is boundary layer flow. To minimize this effect the channel is given a slight divergence (2.5° half-angle) to compensate for boundary layer growth.

The probe is designed for operation in Apollo reentry conditions. GASL noted that the inviscid aerodynamic flow immediately behind the shoulder of the vehicle is approximately Mach 2.5 to 3.0 over a large part of the Apollo trajectory. The conditions of nearly uniform Mach numbers in this region were taken as a desirable local environment for determining the aerodynamic design of the probe. The probe is considered to be capable of operating in hypersonic flow up to Mach 6 also.

In arriving at the final probe design, GASL found the requirements for favorable aerodynamic factors and electromagnetic characteristics were in conflict. The aerodynamics favors a short channel length to minimize boundary layer growth, whereas electromagnetics favors a long channel for a high Q. A large diameter channel is needed to increase the probe sensitivity, but a small diameter is desired for increased spatial resolution in sampling the flow. The final design was a compromise between these demands.

Electromagnetic Calibration

Several methods were employed in order to cover the wide operating range of the probes and also for intercomparison and added verification. The calibration results given below include data on preliminary models, which establish calibration characteristics applicable as well to final probe design.

Dielectric Rod Method – The electromagnetic calibration was confined to the linear range of operation of the probe. Thus, the calibration required only determination of the sensitivity parameter k of Eqn. (1). This determination was performed using a dielectric rod (plastic foam) as a standard to simulate the plasma. The dielectric constant of the standard rod $\epsilon_r = 1.0036$, was measured in a special test resonant cavity. Apart from sign, the frequency shift induced by the dielectric rod is equivalent to that of a dilute plasma. Results of the probe calibration are shown in Fig. 6.

Electron Beam Method – An electron beam of accurately known electron density was used as a check on the dielectric rod calibration method. The test probe used in this calibration was of a preliminary design.

The electron beam, collimated by an axial magnetic field, uniformly filled the probe channel with an electron cloud. The minimum electron density in the calibration, 10^7 e/cm^3, was the minimum measurable electron density for the test probe as determined by the Q of the cavity. The maximum electron density used, about 10^8 e/cm^3, was fixed by the capacity of the electron gun. The results of this calibration (Fig. 7) show the linear response of the probe and agree with the dielectric rod method.

Shock Tube Method – The final calibration test of the 3 cm and 10 cm wavelength probes was performed in an aerodynamic environment at approximately Mach 2.5 flow, within the GASL low pressure shock tube. The calibration test for the 10 cm probe consisted of a comparison of probe electron density measurements with the GASL shock tube electron density calibration chart, stated by GASL to be accurate to within a factor of two. The data are given in Fig. 8.

The calibration test of the 3 cm probe consisted of simultaneous measurements of electron density within the probe cavity and of the undisturbed electron density upstream of the probe with a 1 cm wavelength interferometer. The test data are shown in Fig. 9.

For both probes there is a good agreement between the aerodynamic data points and the solid line calibration determined by the dielectric rod method.

Aerodynamic Test of Channel Flow

The objective of the aerodynamic test was to verify that channel flow within the probe was not significantly different from ambient conditions when the probe is placed in a supersonic Mach 2.5 inviscid flow like that at the Apollo shoulder.

The schematic for the test is shown in Figs. 10 and 11.* The channel of the aerodynamic model has a length-diameter ratio of five with a 2.5° half-angle expansion. The channel diameter of the model is 0.2 inches. Since this is smaller than both the 0.70 inches and 0.45 inches of the 10 cm and 3 cm probes, the aerodynamic test results are to be viewed as conservative, relative to the larger diameter of the final probe designs.

The probe was tested in a Mach 2.5 flow at a Reynolds number approximately simulating flow at 150,000 ft altitude. The axial pressure gradient was measured with static pressure taps along the channel. A sample of the axial static pressure measurements with the Pitot tube removed is shown in Fig. 12 for various free stream Reynolds numbers nondimensionalized with respect to the ambient pressure. For the probe at 0° and 5° angles of attack the pressure is within 30% of the free stream value.

The series of pressure measurements demonstrated that the flow within the channel was undisturbed by a normal shock, that the flow is slightly expanded in the channel, and that the static pressure remains nominally at the free stream value at a 5° angle of attack for the test.

Separated Flow Probe

GASL is currently developing a microwave resonant type electron density probe for operation in separated flow (Ref. 9). As shown in Fig. 3 a separated flow region forms behind the vehicle shoulder adjacent to the wall of the afterbody. The near zero velocity conditions along the stagnation streamline offers a favorable location for the electron density probe. There is a minimum of aerodynamic disturbance along the stagnation streamline which frees the probe from aerodynamic constraints and permits use of an open microwave device.

The basic design of the prototype being developed is an open cylindrical dielectric waveguide structure (Fig. 13). Boron nitride having a dielectric constant four is being used as the dielectric cylinder. The cylinder has a length of 2.52 inches†, outer diameter of one inch, and an inner diameter of three-eighth of an inch. The diameter of the metal end plates is 1-1/2 inches.

The probe operates in a non-radiating TE_{016} mode which propagates axially between the metal end plates. Radial wires have been imbedded in the dielectric rod to suppress the propagation of undesired modes. A basic feature of the probe operation is an evanescent wave of the TE_{016} mode extending beyond the cylinder. When immersed in a plasma the perturbation of the wave and corresponding shift of the resonant frequency is used to measure the electron density

*The probe in this schematic was a preliminary design.

†The probe of most recent design is of one inch length.

near the cylindrical wall. A theoretical curve showing this characteristic of the probe is given in Fig. 14. The probe has an unperturbed resonant frequency of 8.455 kMc with a corresponding critical electron density $N_c = 8.92 \times 10^{11}$ e/cm^3. The Q of the probe, 2100, determines a minimum measurable electron density of $10^{-2}\ N_c$.

The sensitivity of the probe depends on the depth into the plasma to which the electromagnetic field penetrates. This is shown in Fig. 15 for the azimuthal electric field component E_θ. The radial magnetic field component H_R is related to E_θ by a constant factor. The longitudinal magnetic field component, H_Z is shown in Fig. 16. For an underdense plasma the depth of penetration is about a centimeter. The skin depth in the presence of an overdense plasma is, however, only about a millimeter which makes the measurements very sensitive to boundary conditions of the surrounding plasma medium.

The electron density in the boundary layer adjacent to the probe will be perturbed from the ambient level due to plasma dynamic interactions with the wall. This factor will constitute a limit to the maximum measurable electron density. It is worth noting though that the absence of a radial electric field in the resonant mode will tend to keep to a minimum current flow between plasma and probe. In order for the probe to measure the unperturbed ambient electron density it is necessary that the boundary layer thickness be small compared to the penetration depth. To evaluate this effect GASL is investigating charge diffusion and thermal boundary layer effects at the probe wall. It is expected that the upper limit to probe measurement is $10^{+2}\ N_c$.

The experimental verification of the theoretical curve of Fig. 14 will be conducted by GASL in a shock tube using a reflected shock wave. Additional tests will also be done by GASL in a glow discharge tube.

STANFORD RESEARCH INSTITUTE WEDGE-TYPE PROBE

A Langmuir type probe of wedge-shape configuration has recently been investigated at the Stanford Research Institute (SRI). The investigation shows the probe to possess the capability for plasma diagnostics in supersonic flow. The properties of this probe are summarized here for comparison purposes with the GASL microwave internal cavity type probe (Ref. 10).

The wedge-shaped probe design is to minimize flow field perturbation. The wedge configuration has the advantage as well of having substantial structural strength for reentry flow while offering minimal disturbance to flow. SRI has found that the current collected by this probe can be interpreted by free molecular flow theory even under continuum conditions where the wedge base dimensions are 30 mean free paths.

The probe is a wedge shape of 10° half-angle (Fig. 17) having an edge length of 1/2" and a side length of 1/4". The side is partly insulated allowing only a 1/8" leading edge for the collecting electrode. The probe is supported by a 1/16" diameter insulated cylinder.

The test of the wedge probe was performed in a shock tube at flow velocities from 13,000 to 23,000 ft/sec with an ambient pressure of 0.1 mmHg. The verification of the electron density level was performed with a Langmuir type cylindrical rod probe of 0.01" diameter which had in turn been checked with a 33 Gc/sec interferometer.

The wedge probe electron density data normalized by the 0.01" probe data are compared with the 0.01" probe measurements in Fig. 18. In interpreting current measurements for the lowest electron densities, a modest correction was made for the increased area of current collection due to the presence of a sheath (space charge). The wedge probe measurements show agreement with the 0.01" probe to within a factor of two in the range from 10^{10} to 5×10^{13} e/cm^3.

Also shown in Fig. 18 are data for 1/4" and 1/16" diameter cylindrical rod probes. These probes were studied along with 0.01" diameter rod to assess the limits of applicability of free molecular probe theory. It was found that free molecular theory gives accurate results for probe radii as large as three times the neutral near free path of the flowing gas.

The results of the SRI investigation show that the wedge probe has a favorable structural and aerodynamic configuration for operation in supersonic plasma flow and is capable of accurate measurement over a broad range of electron densities.

CONCLUSION

Diagnostic probes for the Apollo plasma sheath are needed for several reasons. One is to obtain precise data on the ion forming processes in the inviscid and separated flow. In-flight measurement of electron density is in fact the only realistic way to validate laboratory prediction methods on the plasma sheath. Besides, an unambiguous interpretation and analysis of the degradation of the RF system performance requires definitive plasma sheath data. Still another need for probe diagnostics will arise in the event that a plasma ameliorative technique is explored in flight. An electron density probe should be an integral part of this type experiment.

The GASL and SRI probes both have a potential for in-flight application, but it is still necessary to demonstrate fully the adequacy of their aerodynamic performance. They require further extensive testing over the broad range of aerodynamic conditions encountered in Apollo reentry flight.

The early Apollo Block I spacecraft will have a C-band antenna mounted at an aft body location. This antenna radiates through the separated flow region. Simultaneous measurement of electron density with a probe and observation of signal attenuation would be a distinct asset. The opportunity for exploring the advantages of the aft antenna location in a reentry environment will be limited to flights of the Block 1 configuration, since only these flights are to have the aft mounted C-band antenna.

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REFERENCES

1. Antenna Equipment, S-Band, Flush Mounted, Omni; NAA Specifications, SISD, Prepared by W. Rumsey and G. Blanchette, No. MC481-0048, Sept. 3, 1965.

2. Antenna Equipment, Beacon; NAA Specifications (Approved), SISD, Prepared by W. Rumsey and R. Taylor, No. MC481-0005, Sept. 10, 1965.

3. Bohachevsky, I. O. and Mates, R. E., A Direct Method for Computation of Nonequilibrium Flows with Detached Shock Waves, Part II, Axisymmetric Blunt-Body at an Angle of Attack, AIAA 2nd Aerospace Sciences Meeting, New York, N. Y., January 25-27, 1965.

4. Dunn, M. G., Daiber, J. W., Lordi, J. A., and Mates, R. E., Estimates of Nonequilibrium Ionization Phenomena in the Inviscid Apollo Plasma Sheath, CAL Report No. A1-1972-A-1, Sept. 1965, Cornell Aeronautical Laboratory.

5. Quarterly Progress Reports for Project Apollo, NASA Contract No. NAS5-3976, June 1, 1964 – Dec. 1, 1965, Cornell Aeronautical Laboratory.

6. Holden, M. S., An Analytical Study of Separated Flows Induced by Shock Wave – Boundary Layer Interactions, CAL Report No. A1-1972-A-3, Dec. 1965, Cornell Aeronautical Laboratory.

7. Beckwith, I. E., and Bushnell, D. M., Depletion of Free Electrons Due to Water Injection into Hypersonic Flow Fields, 3rd Symposium on the Plasma Sheath, AFCRL, Bedford, Mass., Sept, 21-23, 1965.

8. Development of an Electron Density Probe, Final Report, NASA Contract No. NAS5-3929, March 1965, General Applied Science Laboratories, Inc.

9. First Quarterly Report for Electron Density Probe, General Applied Science Laboratories, Inc., NASA Contract No. NAS5-9881, August 1965.

10. Scharfman, W. E., The Use of Langmuir Probes to Determine the Electron Density Surrounding Reentry Vehicles, Final Report, NASA Contract No. NAS1-3942, SRI Project 5034, June 1965.

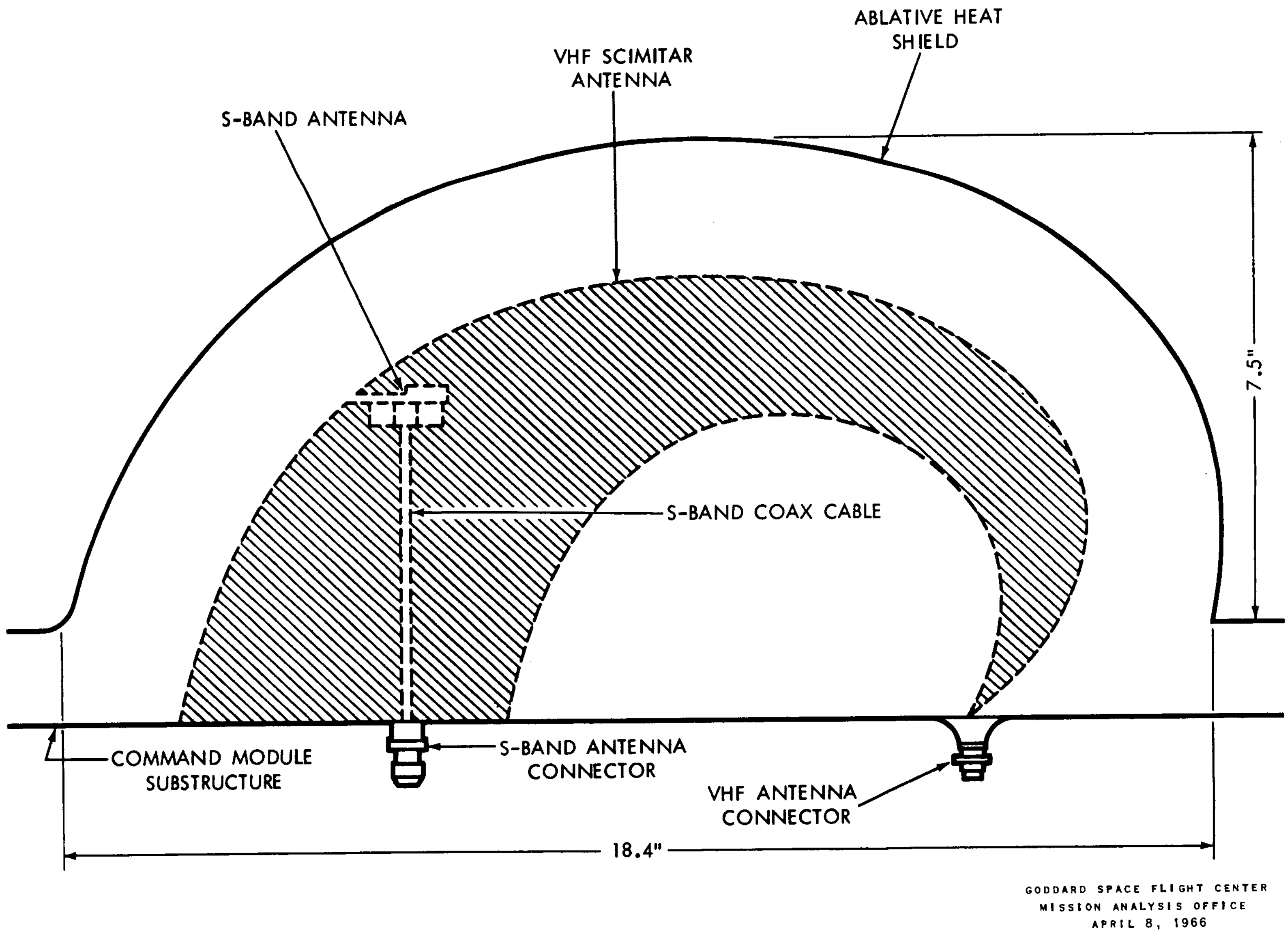


Figure 1–VHF/S-Band Scimitar Antenna

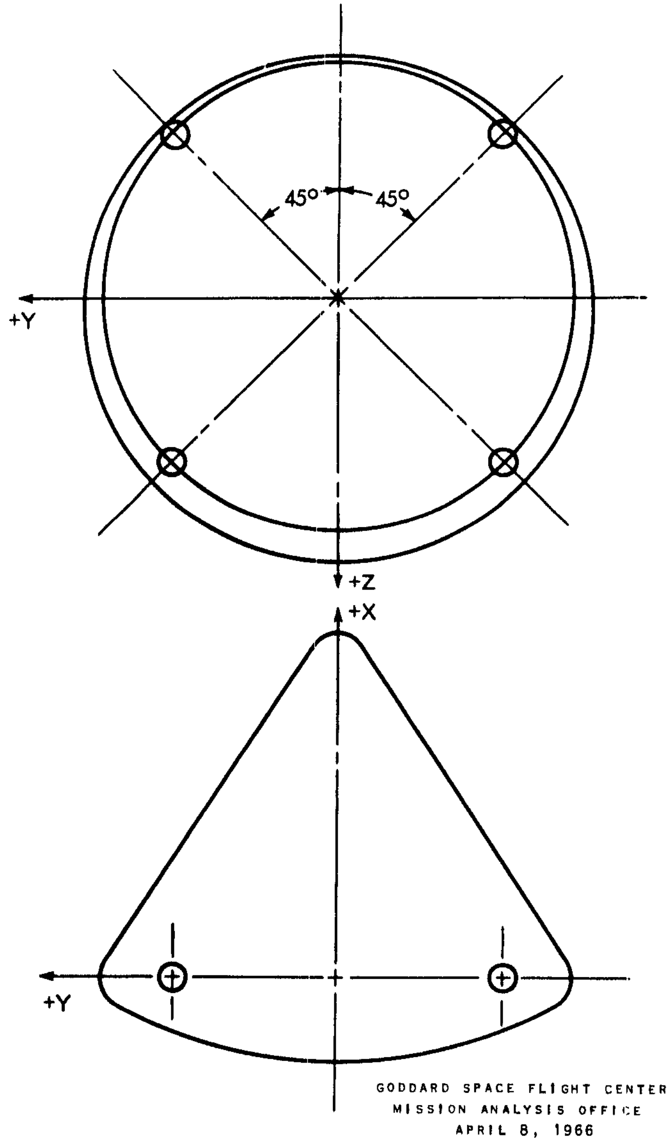


Figure 2a–USBS Antenna Locations

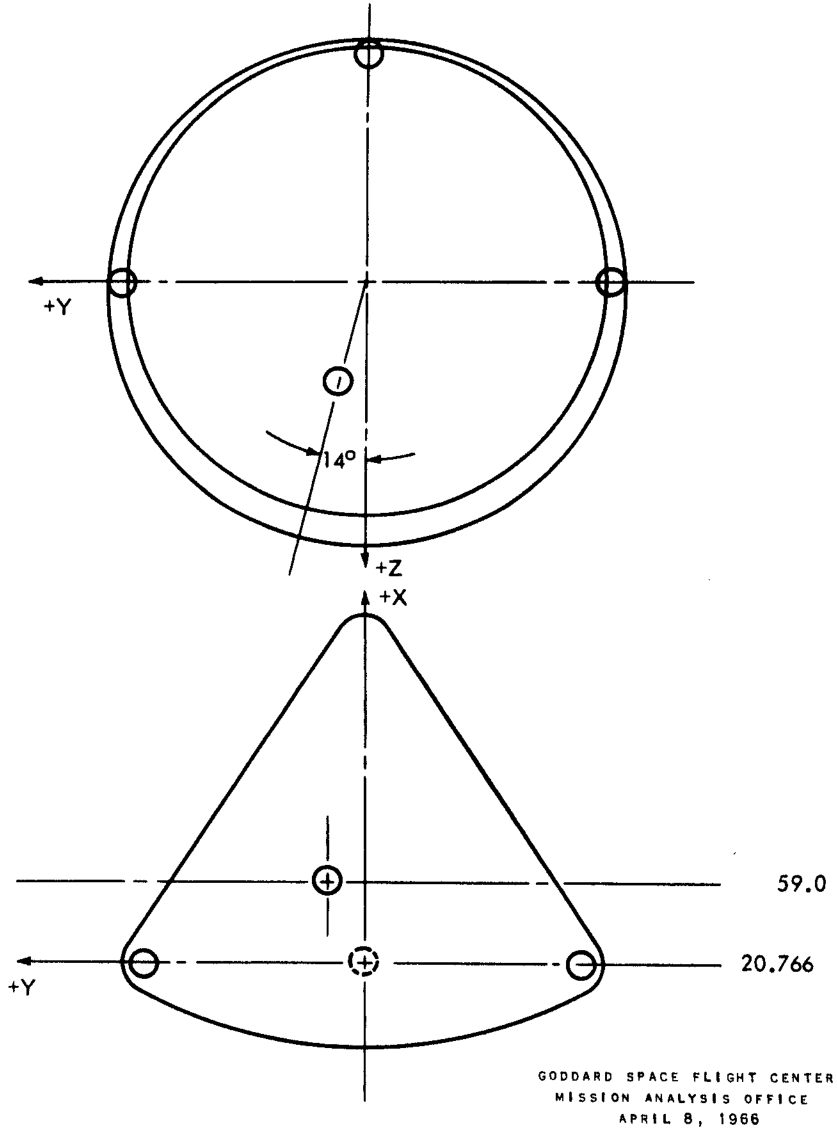


Figure 2b–C-Band Antenna Locations

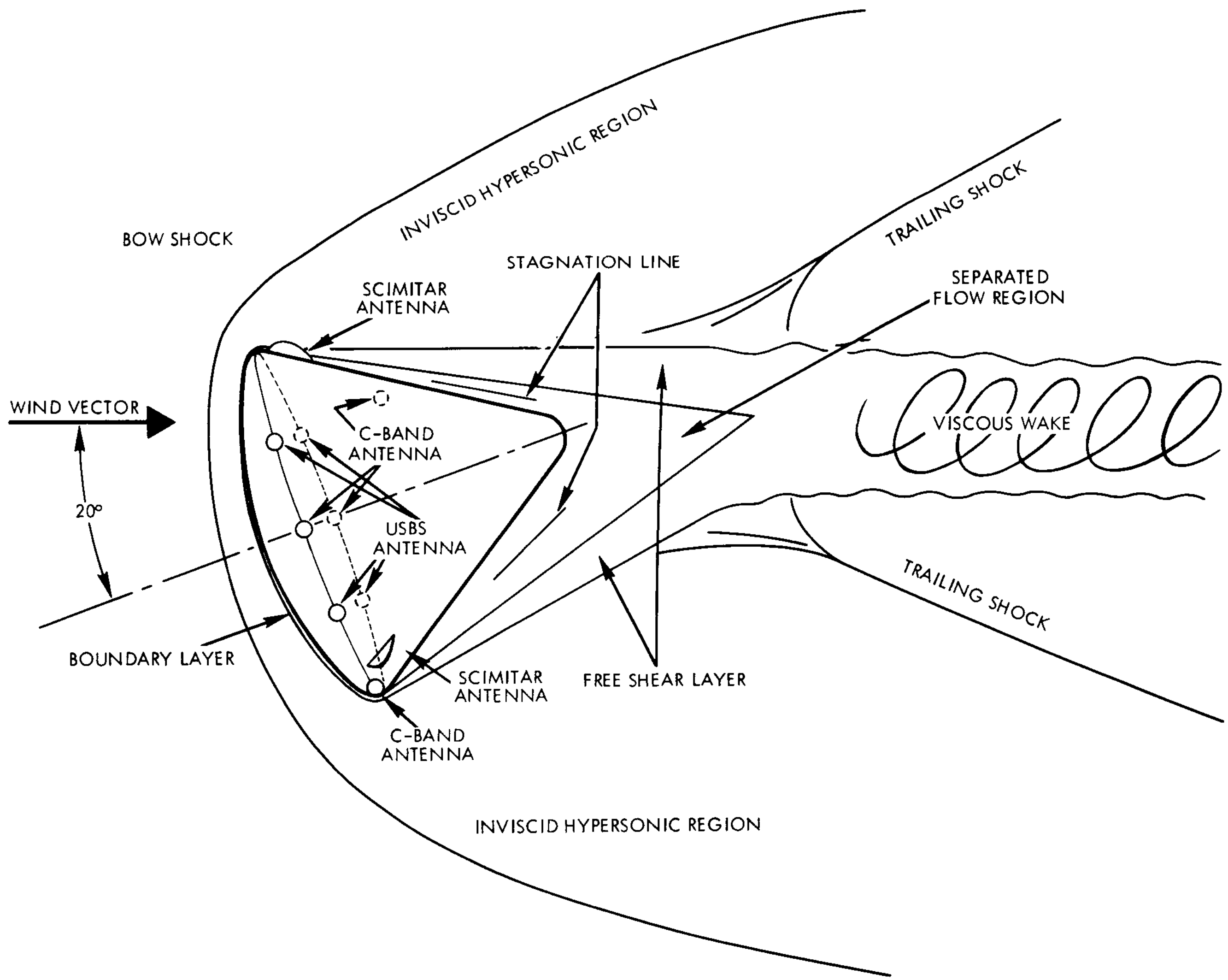
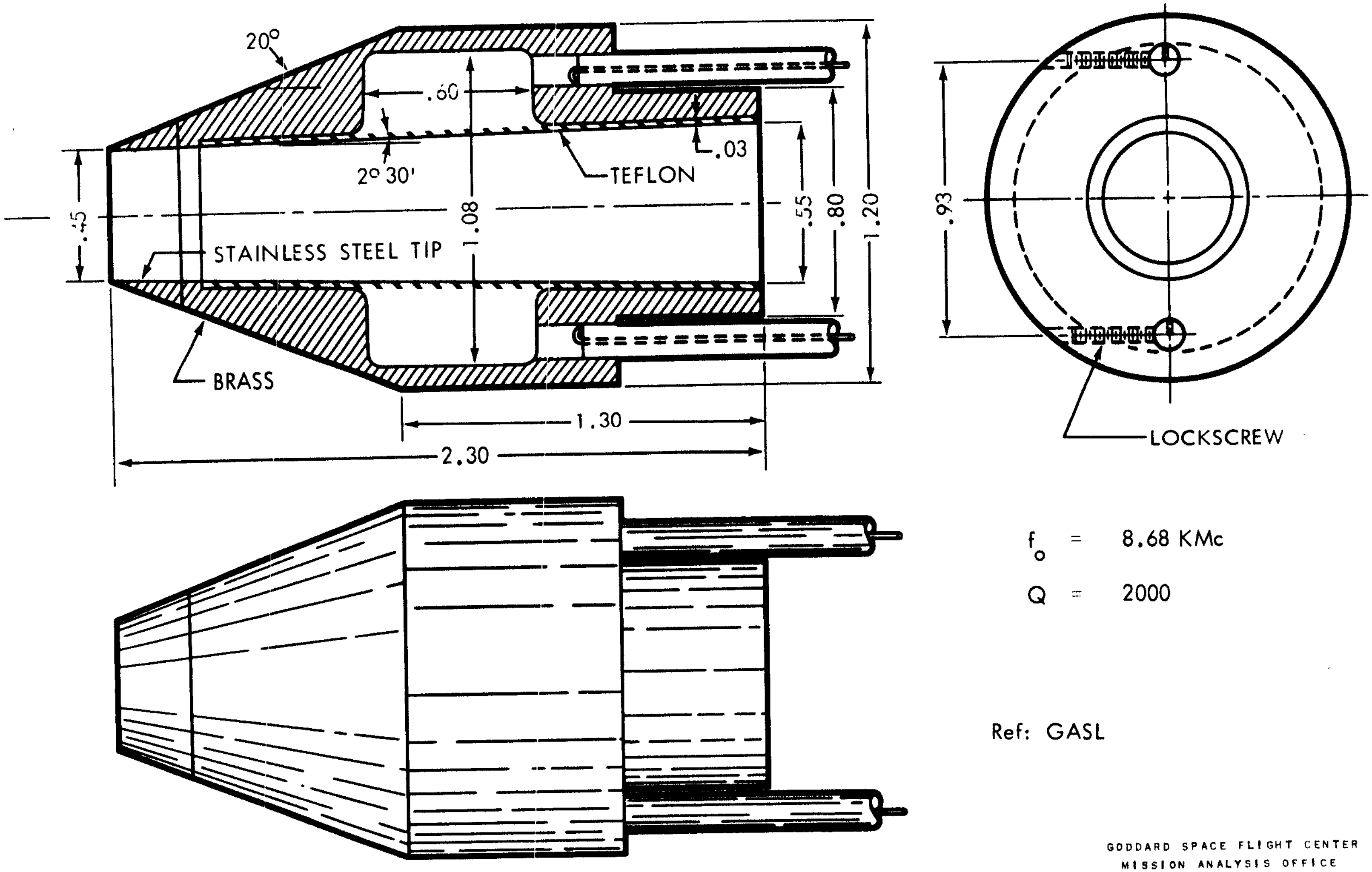


Figure 3-Beacon Antenna Locations and Reentry Flow Regions of the Apollo Command Module - Block I. (USBS and S-Band Scimitar Antennas are not present on the same vehicle.)



f_o = 8.68 KMc

Q = 2000

Ref: GASL

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Figure 4–3 cm Wavelength Probe

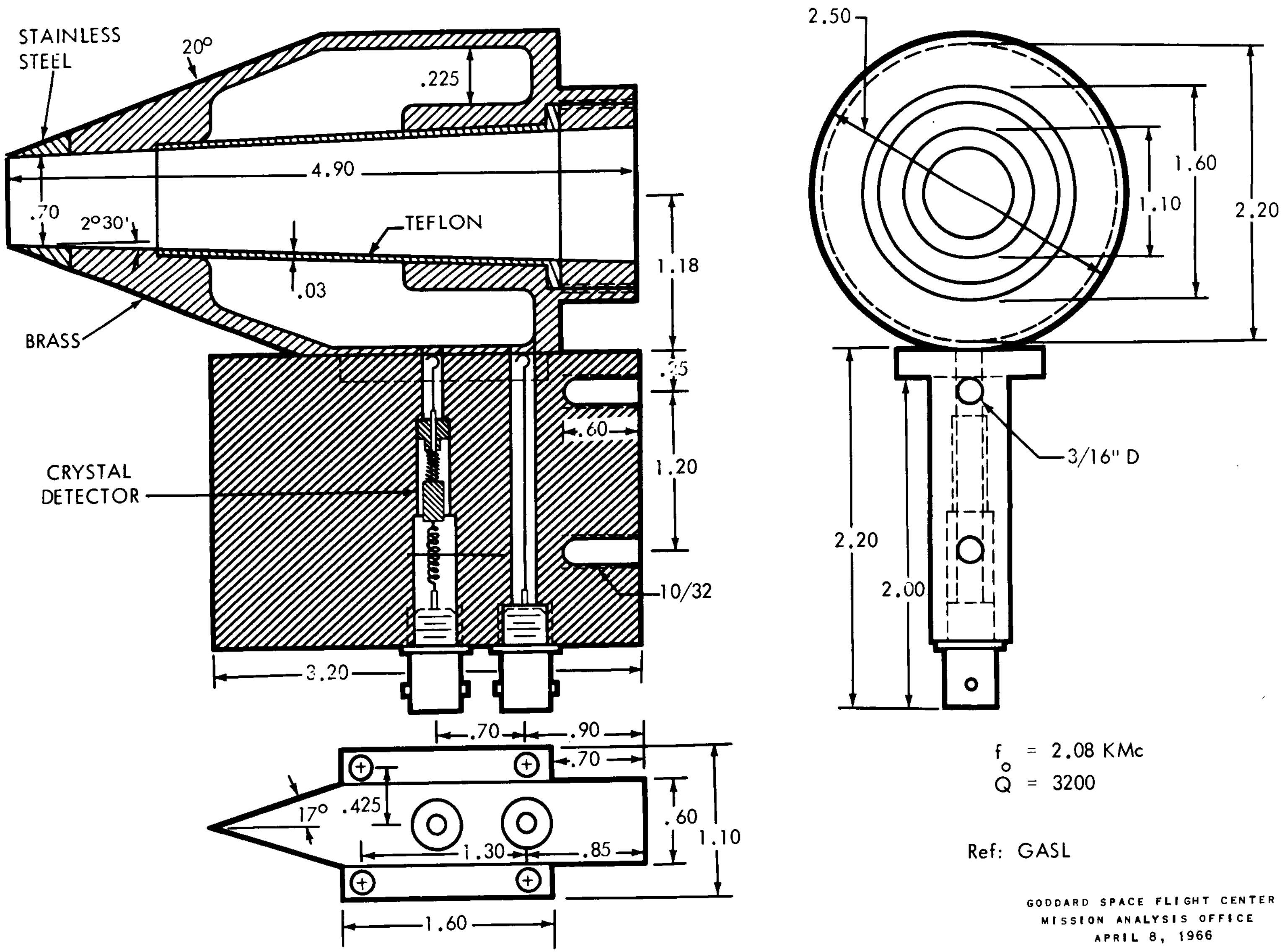

Figure 5–10 cm Wavelength Probe and Mounting

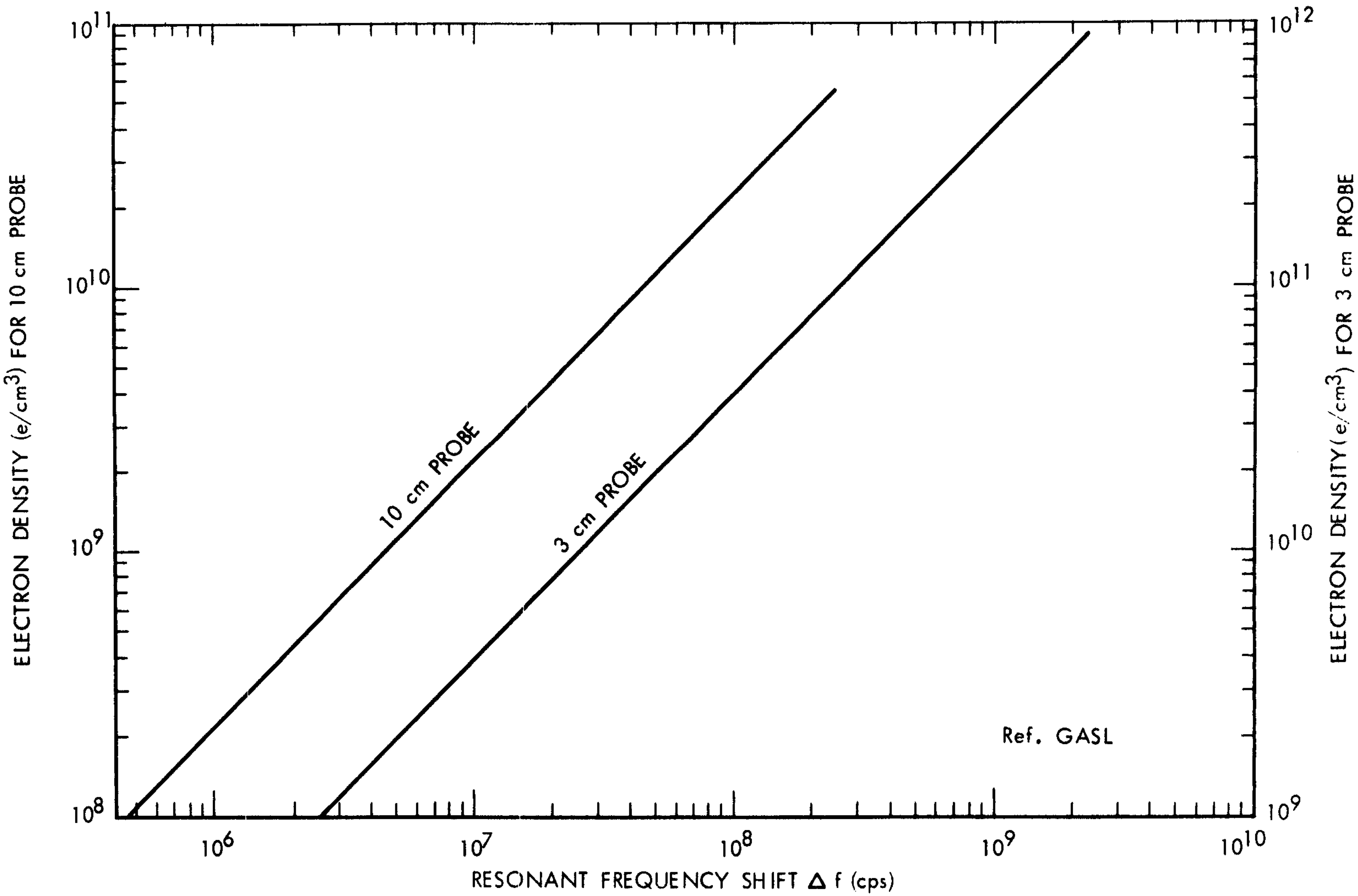

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Figure 6–Electromagnetic Calibration Chart

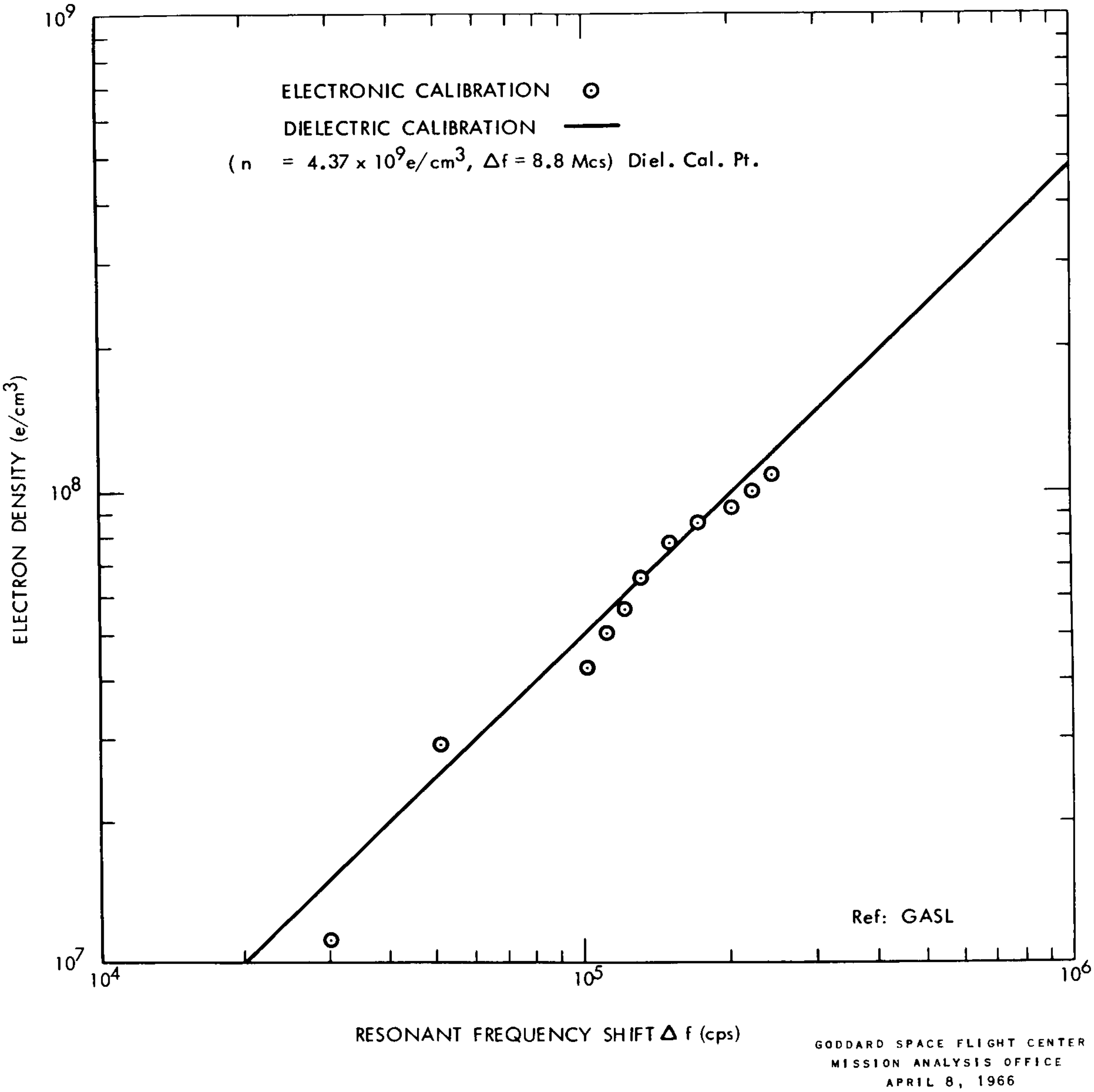

Figure 7–Comparison of Dielectric Calibration with Electronic Calibration

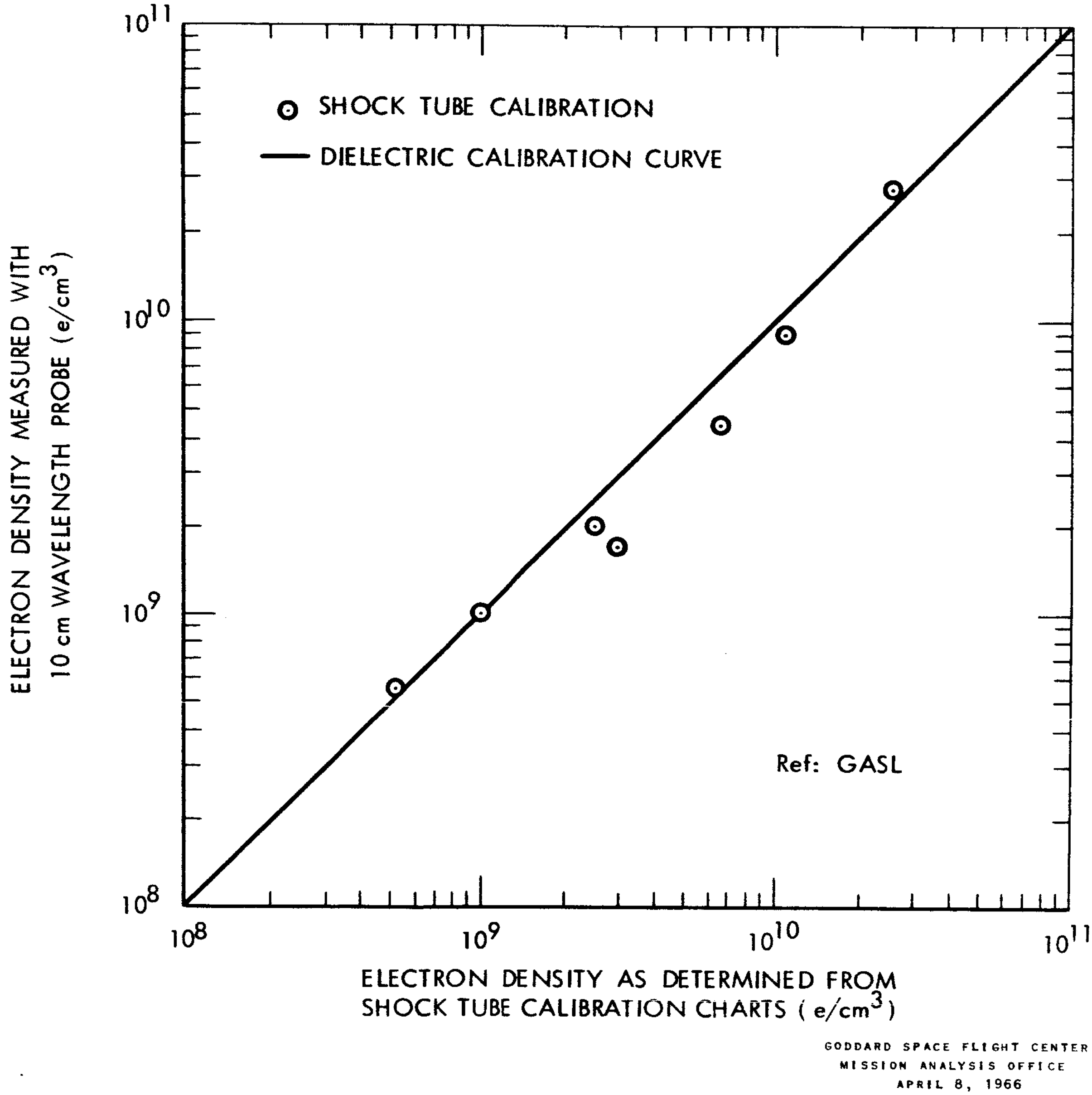

Figure 8—Correlation of Electron Density Indications for the 10 cm Wavelength Probe

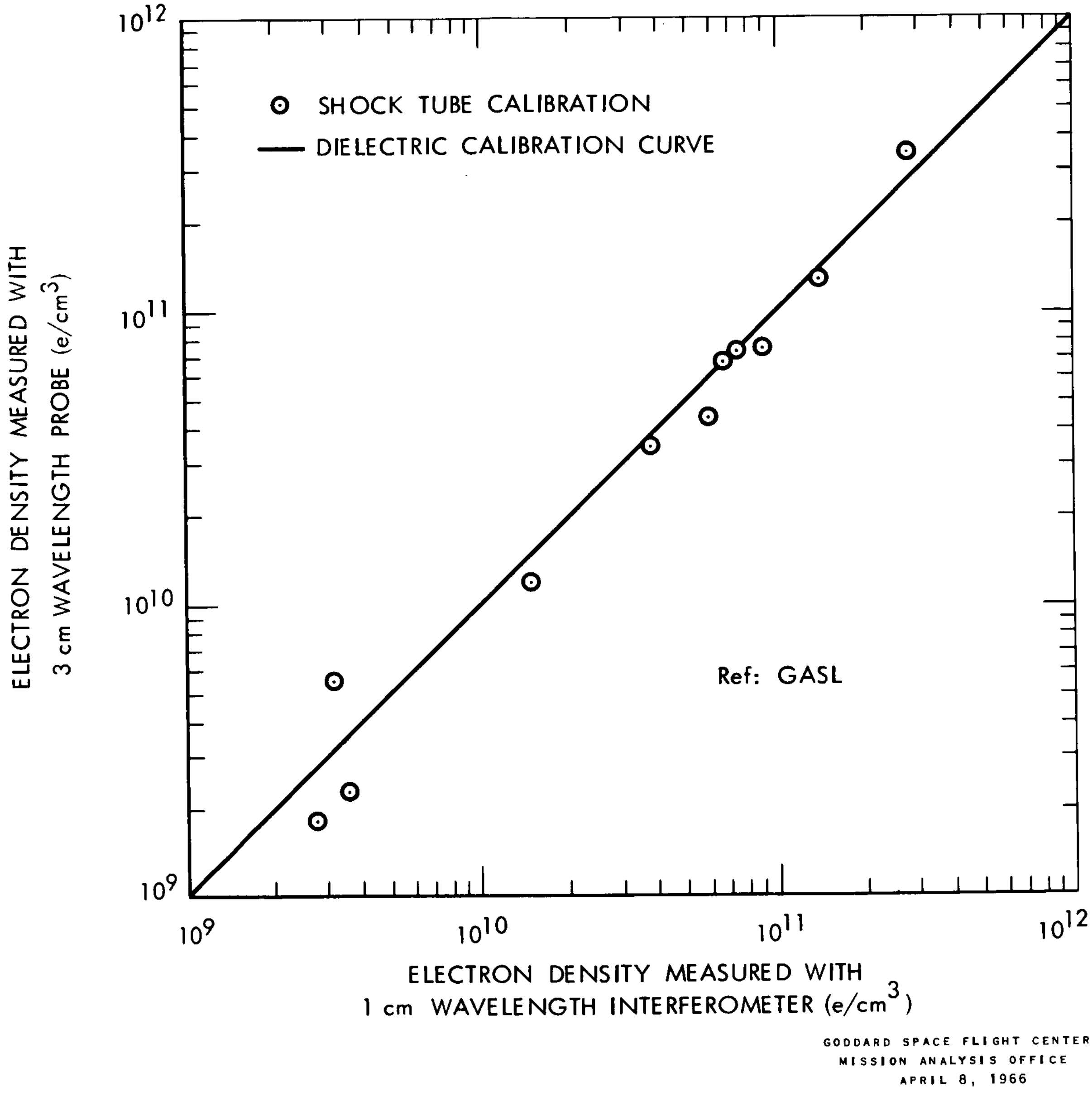

Figure 9–Correlation of Electron Density Indications for the 3 cm Wavelength Probe

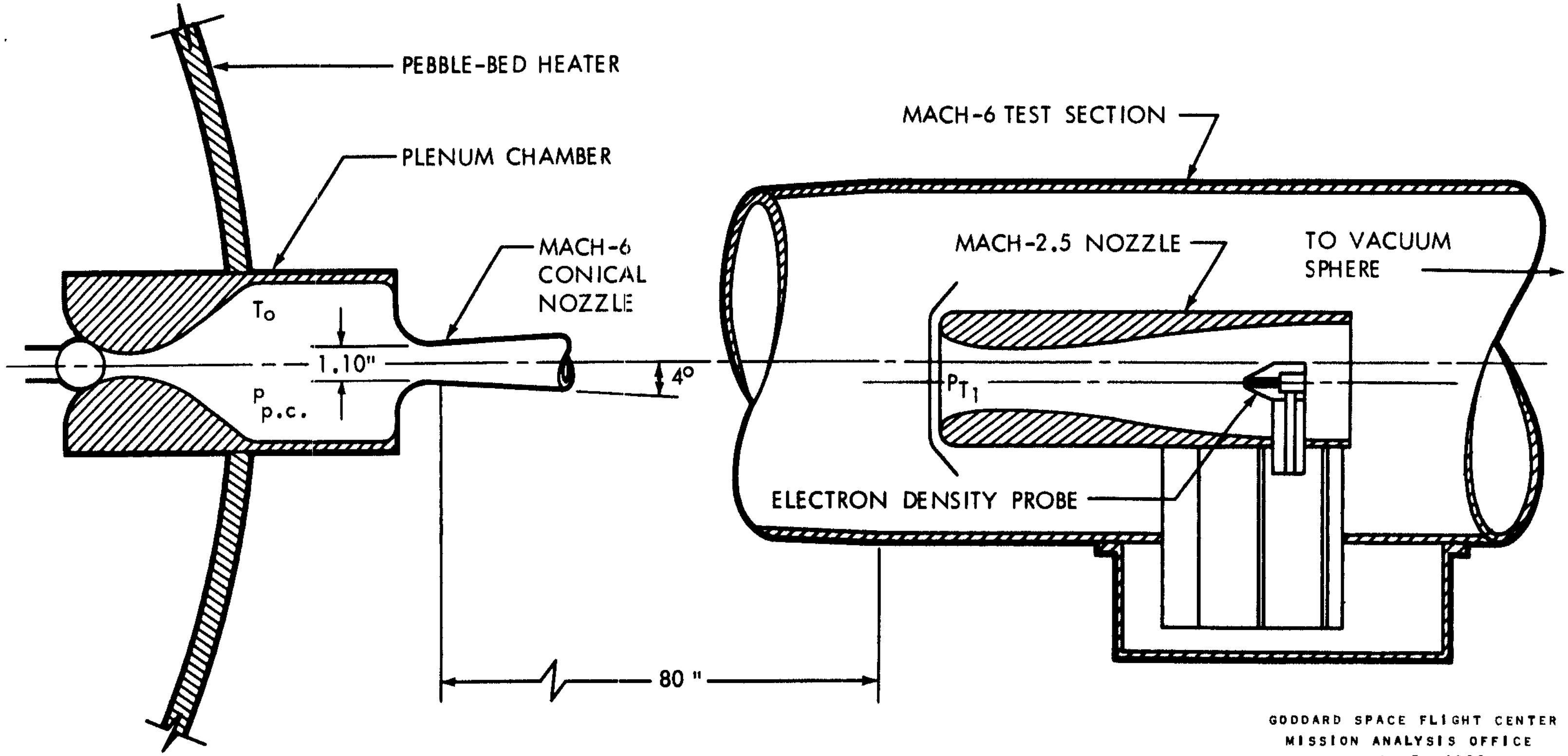

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Figure 10—Aerodynamic Test Facility – Schematic

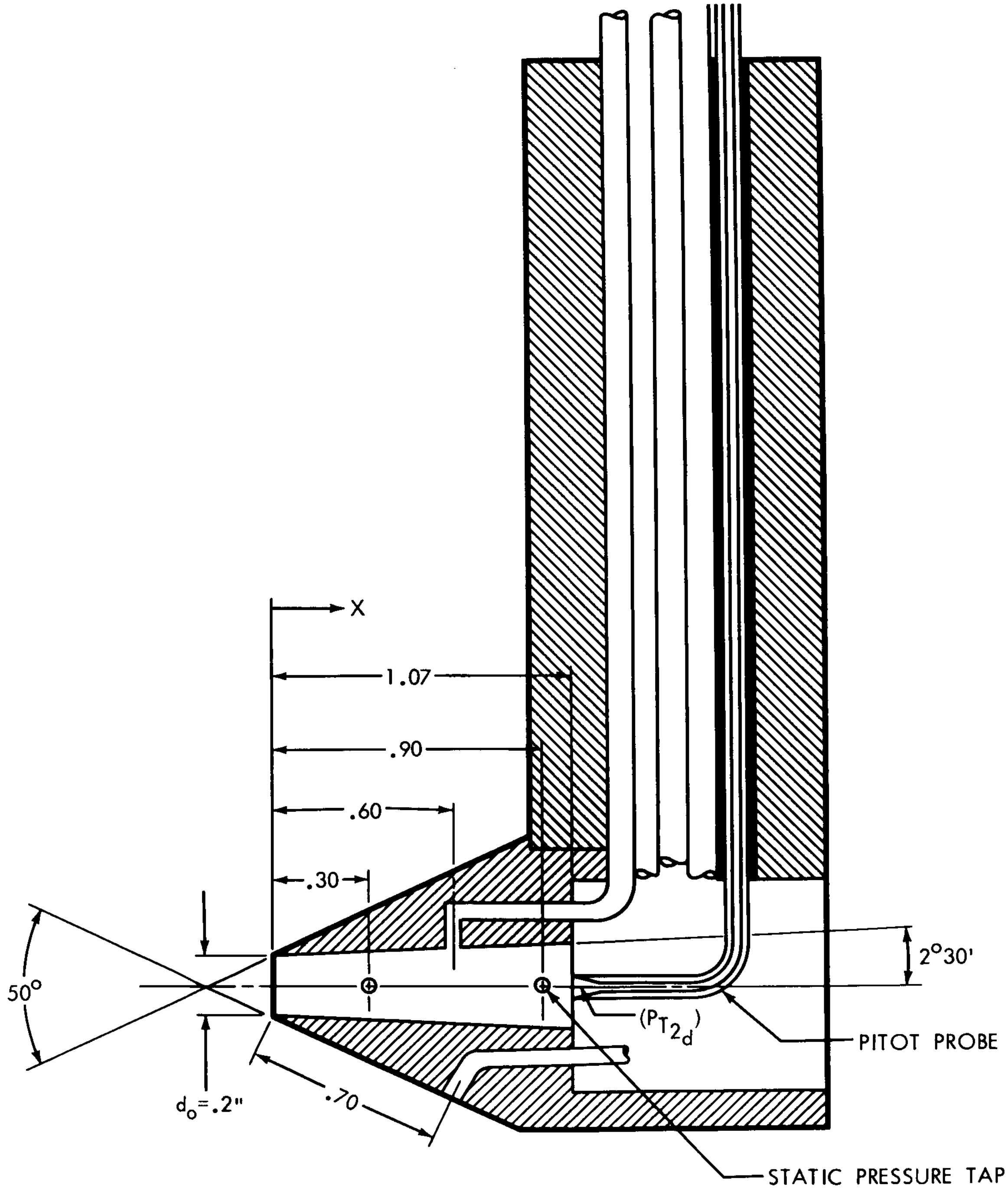

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Figure 11–Aerodynamic Model of the Electron Density Probe

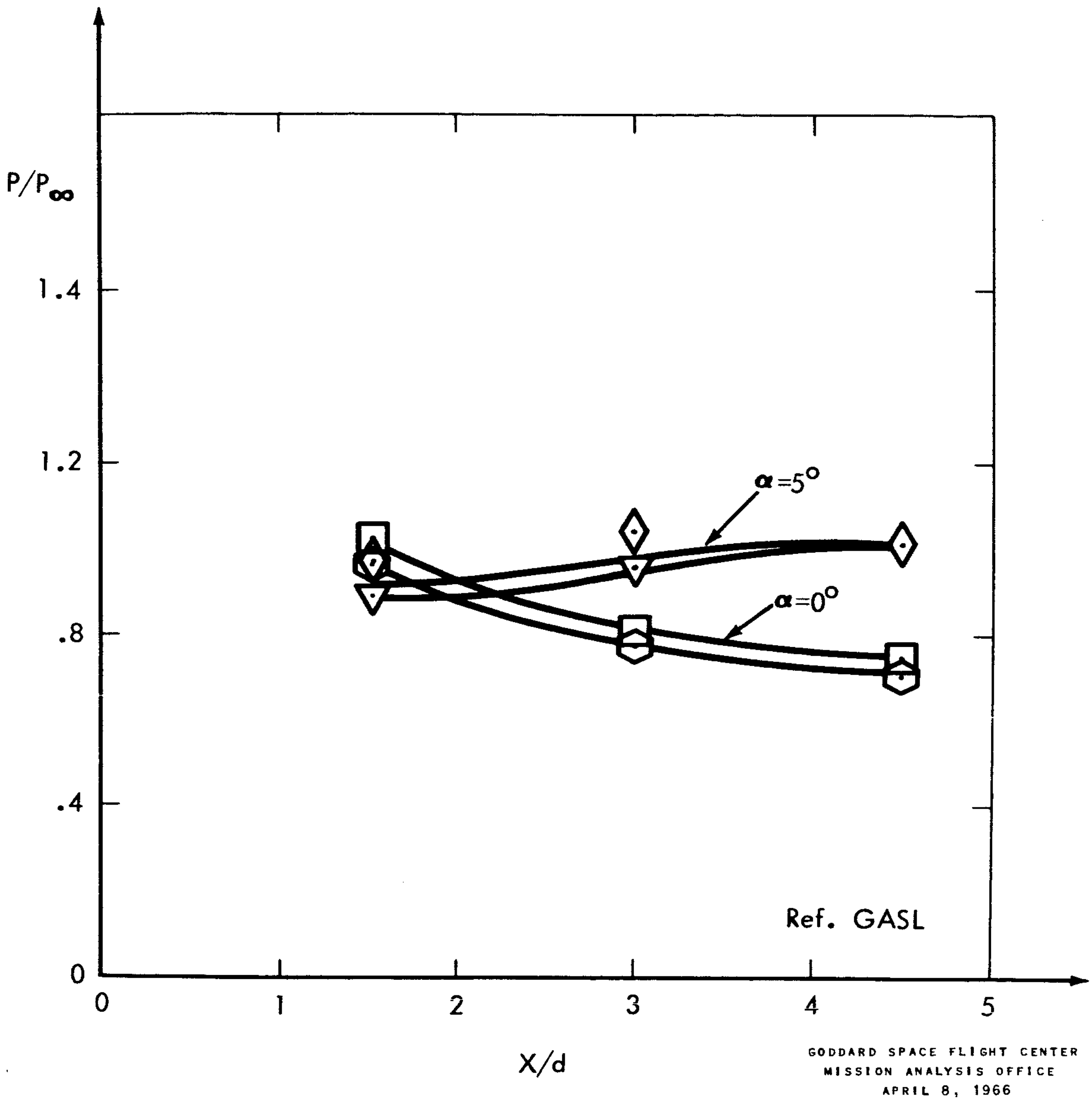
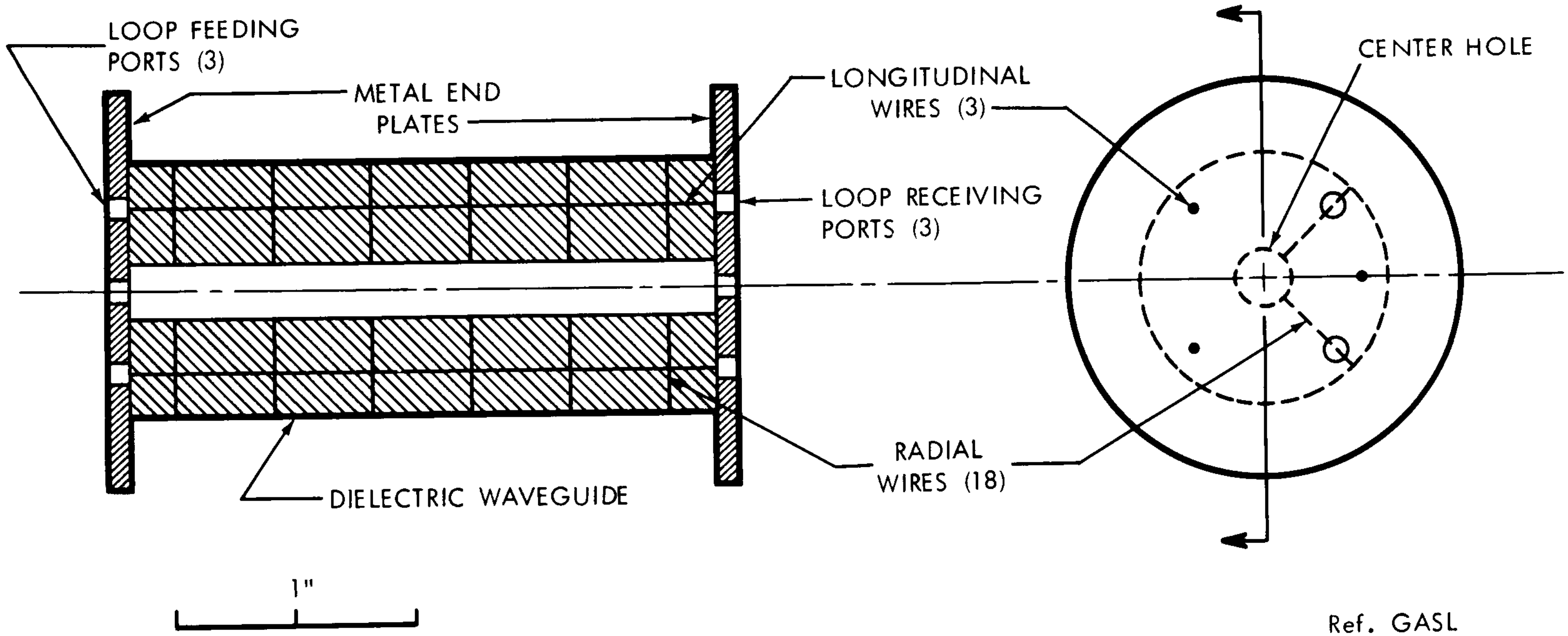


Figure 12–Static Pressure Distribution in Duct



Ref. GASL

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Figure 13–Prototype Dielectric Waveguide Type Probe

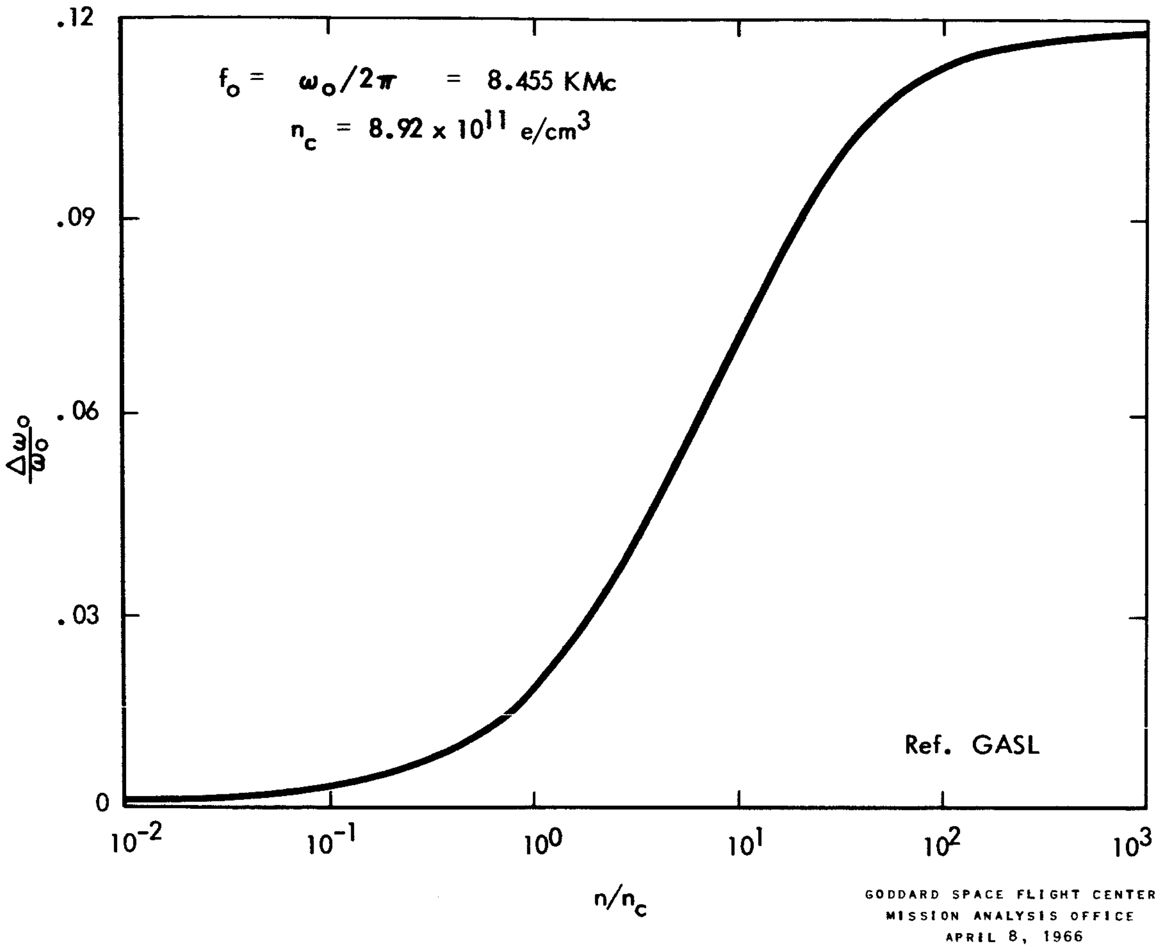

Figure 14–Characteristics of Dielectric Waveguide Type Probe

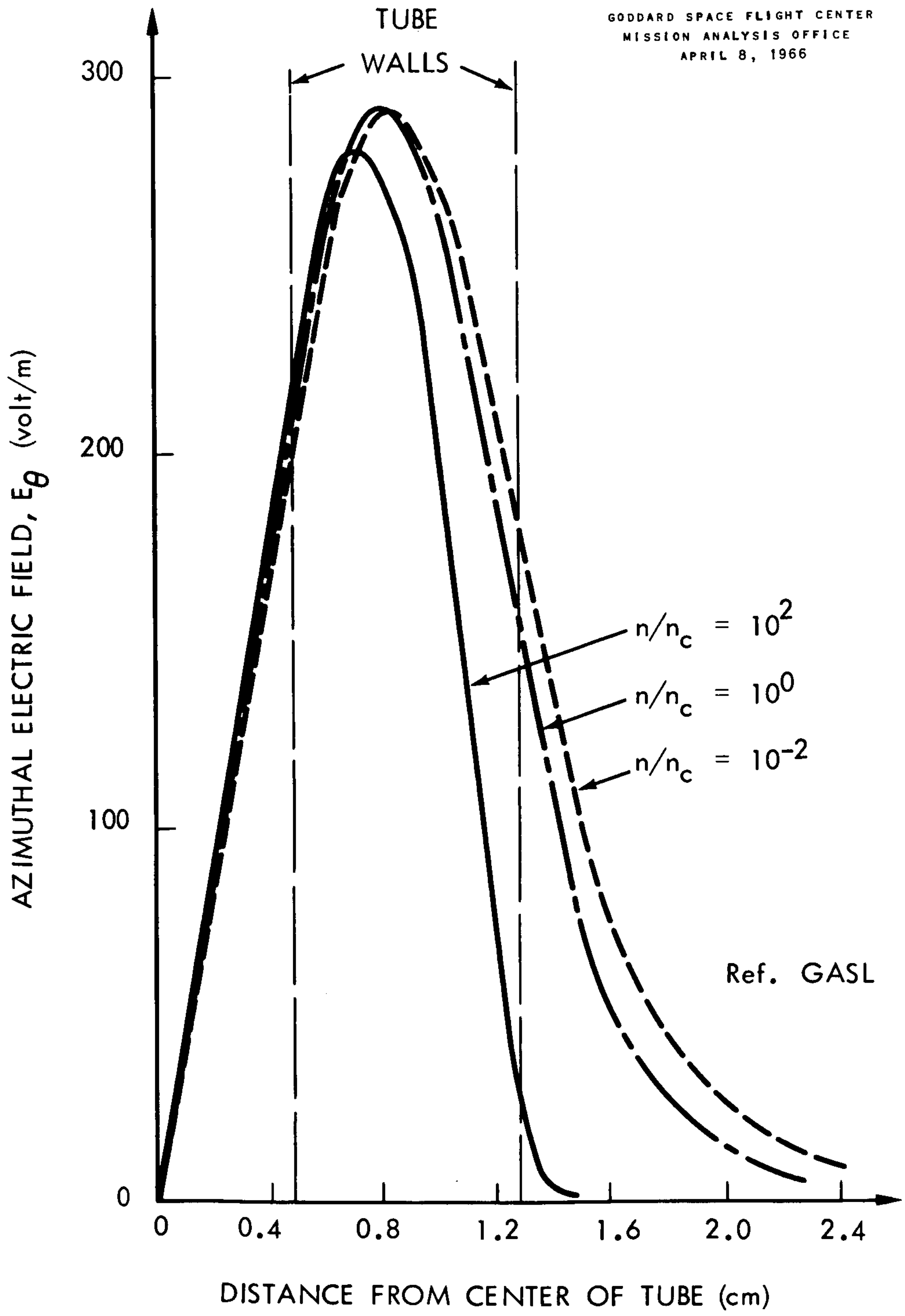

Figure 15–Electric Field Distribution for the Dielectric Waveguide Type Probe

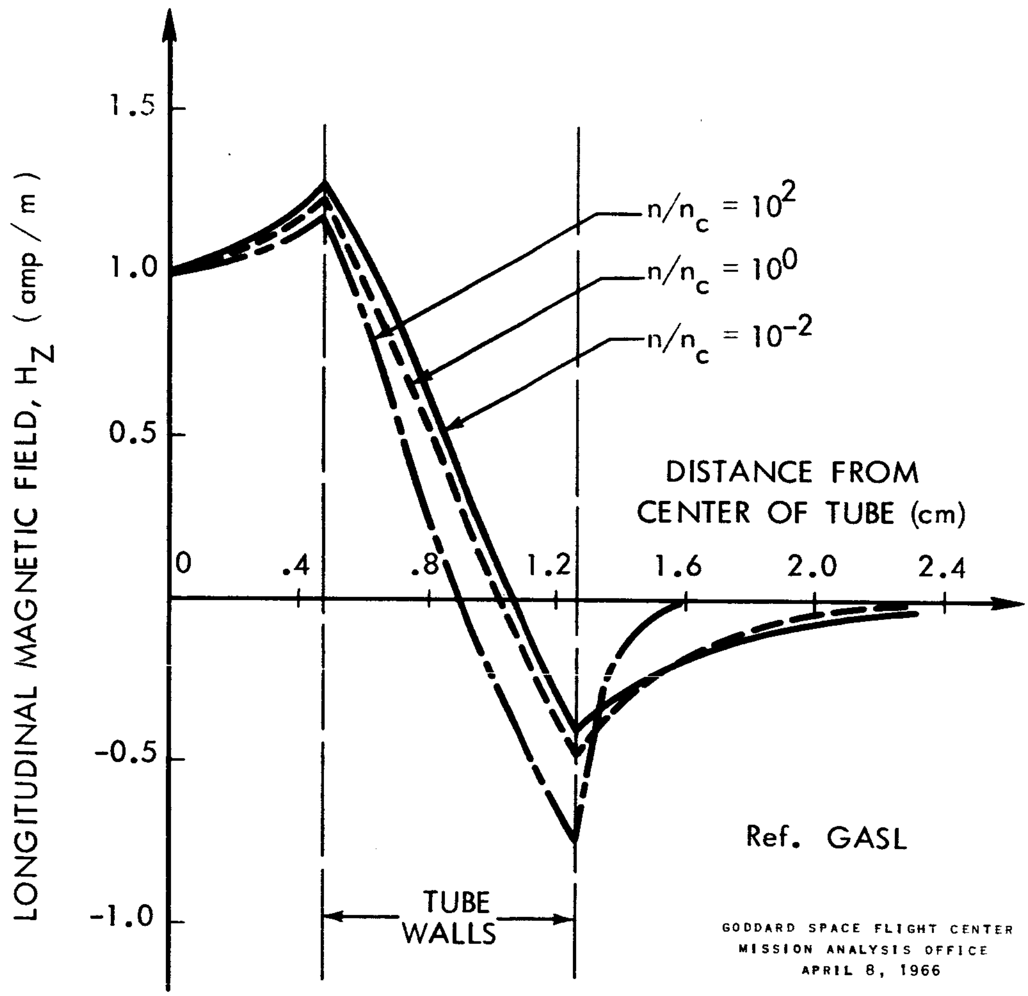

Figure 16–Magnetic Field Distribution for the Dielectric Waveguide Type Probe

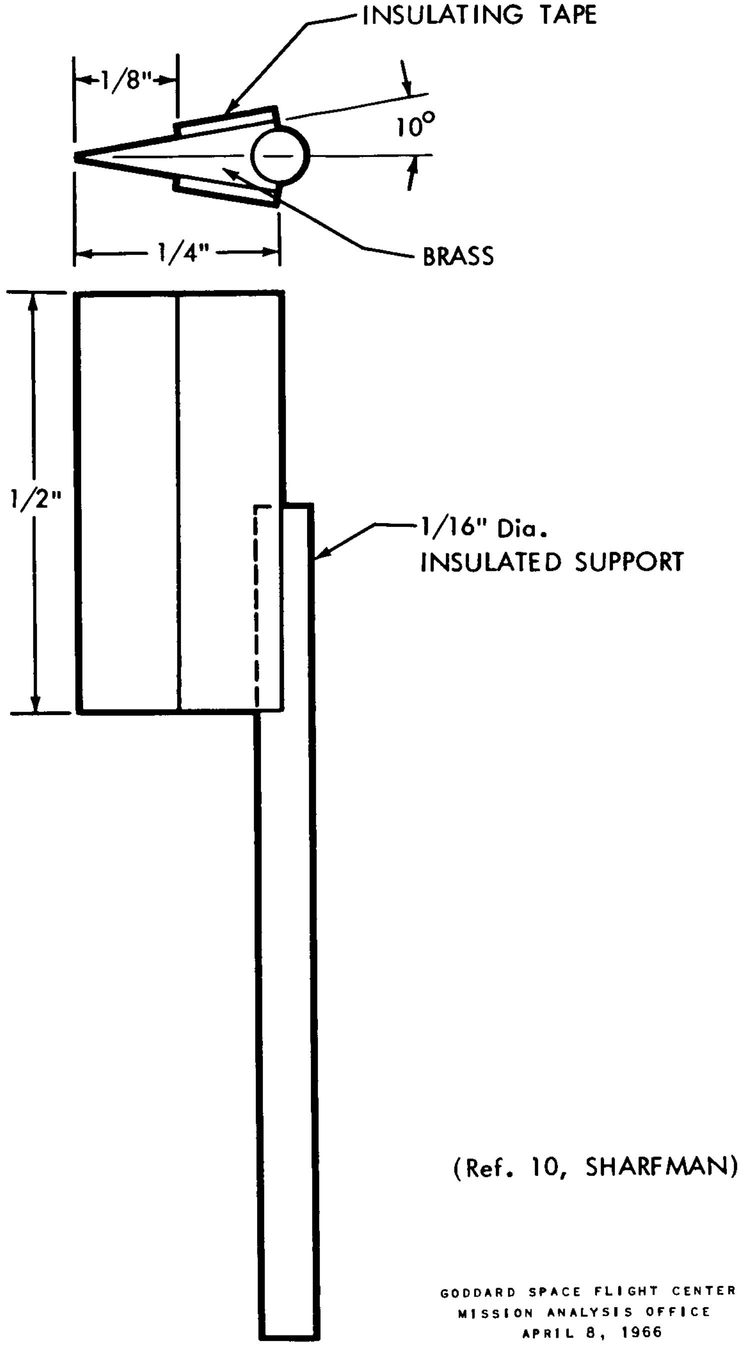

Figure 17–SRI Wedge-Shaped Probe Configuration

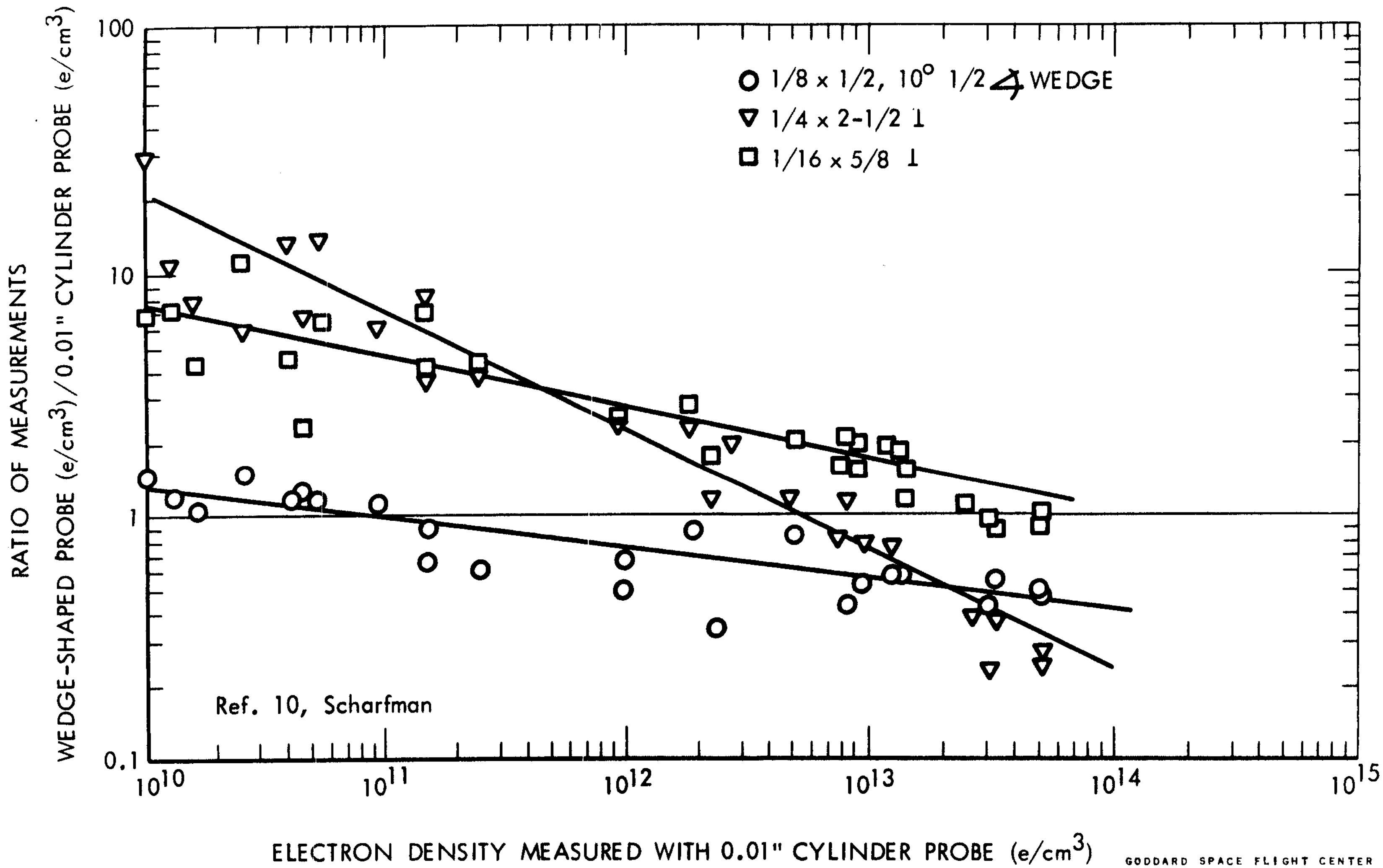

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Figure 18–Comparison of Wedge-Shaped Probe Electron Density Measurements with 0.01" Cylinder Probe Data