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PLASMA EFFECTS ON APOLLO RE-ENTRY COMMUNICATION

by Richard Lehnert and Bernard Rosenbaum

Goddard Space Flight Center
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SUMMARY

Effects of plasma formation on electromagnetic wave propagation during the Apollo spacecraft re-entry from lunar missions are considered for nominal and emergency re-entry trajectories. Concepts of the Apollo re-entry ground support network are discussed in the light of effects of RF signal blackout on tracking and communication. The degree of predictability of blackout areas and the generation of ameliorative methods against blackout are of primary concern. Goddard Space Flight Center's previous efforts on this subject are summarized and future plans of action along this line are outlined.

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INTRODUCTION

Tracking and communication problems caused by RF signal blackout during the re-entry phase of the Apollo spacecraft returning from a lunar mission will be considered in this paper. Re-entry into the earth's atmosphere is generally defined to commence at an altitude of 400,000 ft. Upon deeper penetration of a spacecraft into the regimes of exponentially increasing air density, atmospheric drag converts much of the spacecraft's kinetic energy into heat, largely by compression in the stagnation region and partially by skin friction in the boundary layer (the shear layer). Temperatures in the heat cap between the bow shock and spacecraft surface rise to such magnitudes that the environmental air dissociates and ionizes. Consequently the flow field surrounding the spacecraft becomes highly conductive, markedly attenuating RF signals. In the most critical case radio communication is completely blacked out.

This signal blackout has already been experienced during the re-entry of Mercury spacecraft. A much more serious condition of tracking and communication blackout is expected during re-entry of Apollo spacecraft, because the Apollo re-entry velocity, 35,000 ft/sec, will be higher than the Mercury re-entry velocity, 24,000 ft/sec. This condition will be particularly critical since it will coincide with the maneuver phase of the re-entry flight. It may eliminate ground support during a vital portion of the maneuver phase or even during the entire regime of effective maneuverability, depending on the re-entry trajectory.

In the interest of generating the most efficient and reliable re-entry ground support, it is necessary to recognize all re-entry trajectories possible within existing constraints, and to establish the degree of ground assistance needed to assure complete success for any re-entry mission. In this regard, tracking and communication capabilities must be investigated in light of the RF signal blackout problem; and a solution of this problem must be sought for trajectories wherein proper signal transmission may decide the success or failure of the re-entry mission.

RE-ENTRY

The re-entry phase of the Apollo Command Module flight is considered to be bounded by an upper altitude of 400,000 ft (conventional re-entry altitude) and a lower altitude of 50,000 ft, as determined by the programmed termination of the operation of the on-board automatic guidance system.

*This report supersedes Goddard Space Flight Center document X-513-64-8. It was presented at the NASA Conference on Communication Through Plasmas of Atmospheric Entry and Booster Exhaust, Langley Research Center, Hampton, Virginia, January 14-15, 1964.

The presently considered range variation of nominal Apollo re-entry trajectories to be flown with the Massachusetts Institute of Technology automatic guidance and control system extends from approximately 1000 to 5000 naut. mi. (Reference 1). Control maneuvers during re-entry can be performed only by rolling the Command Module. By means of the roll maneuver the lift vector is rotated into a desired direction. Lift is generated in the pitch plane of the Command Module at a trim angle (α = 33 degrees), attained by a prescribed displacement of the center of gravity from the longitudinal axis of rotational symmetry. At this trim angle, where a lift-to-drag ratio of L/D = 0.5 is established, the overturning moment and the aerodynamic restoring moment are in equilibrium. Consequently, maneuvers depend on adequate aerodynamic forces and are restricted to altitudes where the air density ρ and velocity v are sufficiently high to insure an effective dynamic pressure, $\rho v^2/2$. The threshold value for the dynamic pressure can be determined from a minimum effective drag reference level (Reference 2). This drag reference level is attained at about 300,000 ft.

Typical Apollo re-entry trajectories are presented in Figure 1* for ranges of 5000, 3000, and 1000 naut. mi. at a nominal re-entry flight path angle of γ = - 6.4 degrees. For a given landing site the trajectories can vary from a characteristic skip trajectory (1 in Figure 1) to a typical

*Information for the trajectories presented in Figures 1-4 was obtained from References 1 and 3. The blackout bounds from Reference 3 by North American Aviation, Inc. (NAA) are included for comparison.

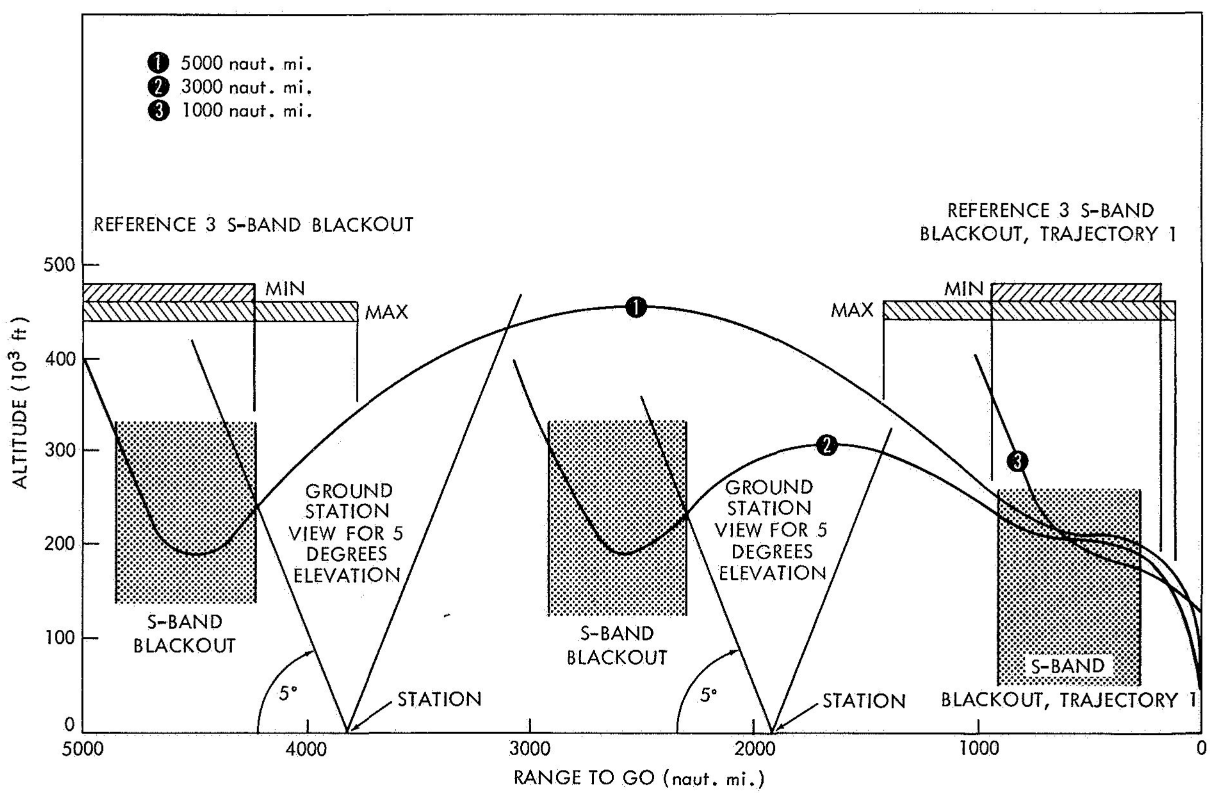

Figure 1—Apollo re-entry trajectories for γ = -6.4 degrees.

direct descent trajectory (3 in Figure 1), depending on the ground distance of the re-entry point from the landing area. For the skip trajectory the on-board automatic guidance and control mode calls for maneuvers to correct range and cross-range in two areas. Maneuver control is most effective in the dip-in region of the trajectory commencing shortly after the re-entry point and fading out at an altitude near 300,000 ft, upon skip out. Above this altitude the dynamic pressure is so small that a ballistic trajectory prevails until the Command Module again enters a region of effective aerodynamic forces. This second area of maneuverability lends itself only to minimal corrections on account of the rapidly decreasing velocity and the remaining short range-to-go. The lower bound of maneuverability is determined where the automatic guidance system program terminates (Reference 4).

The direct descent type of trajectory (3 in Figure 1) does not have a skip-out phase. It has only one upper and one lower bound for maneuverability, coinciding with the original onset and ultimate termination of the maneuver capability expected for the skip trajectory. Consequently, most of direct descent re-entry is a controlled flight.

Figure 2 shows the variation of the altitude vs. range profile within a re-entry flight path angle corridor of γ = -5.4 to -7.4 degrees, for a nominal 5000 naut. mi. Apollo re-entry

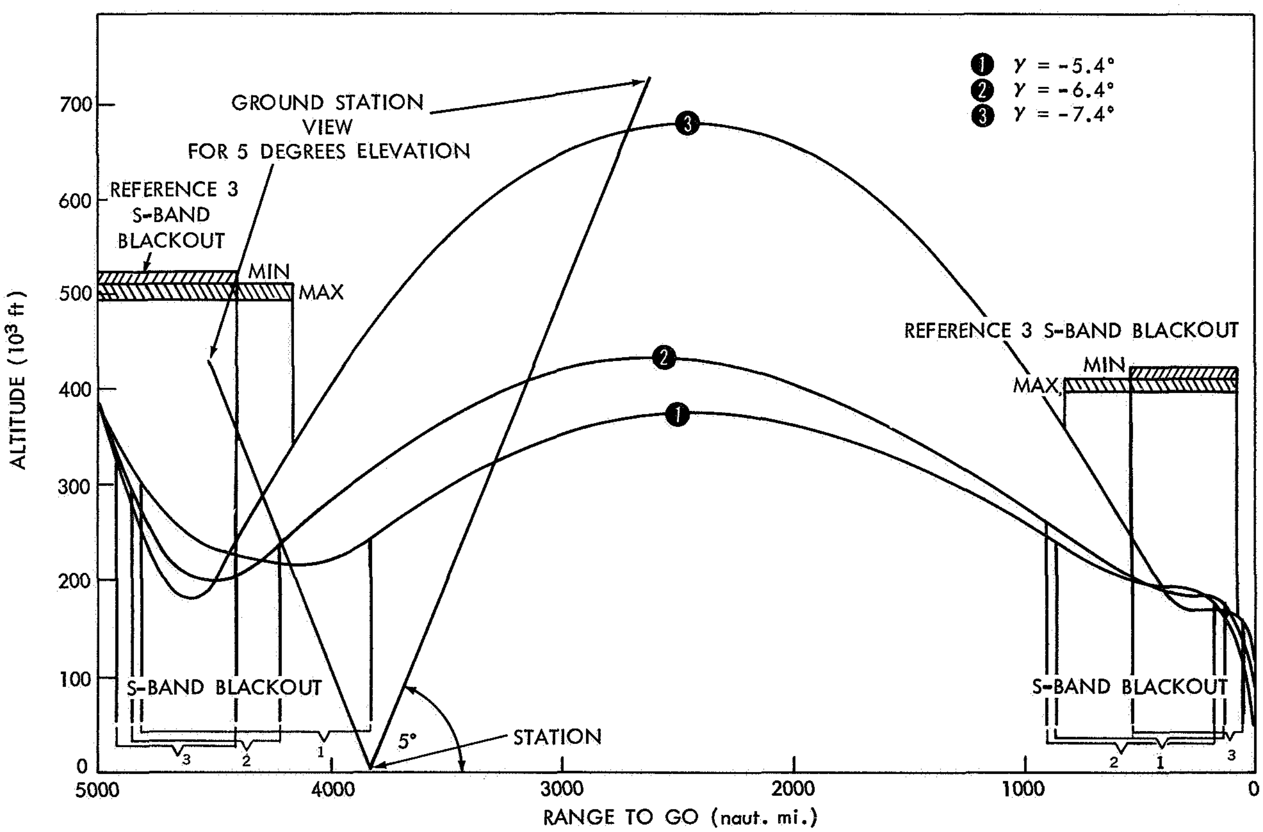

Figure 2—Apollo 5000 naut. mi. re-entry trajectories.

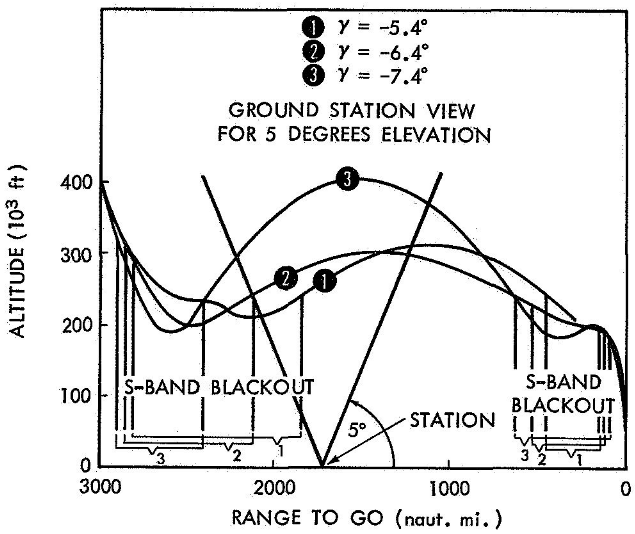

Figure 3—Apollo 3000 naut. mi. re-entry trajectories.

trajectory. Particularly noteworthy is not only the large change in the maximum altitude as a function of extreme re-entry angles but also the shift in the range-to-go from the point of deepest initial penetration for different re-entry angles amounting to a maximum of 500 naut. mi. The latter is a basic factor in ground support coverage.

An example of the effect of the re-entry flight path angle on shorter skip trajectories (3000 naut. mi.) is given in Figure 3. Although the maximum altitude variation with γ is much less than that for the 5000 naut. mi. trajectory, the maximum downrange variation of the minimum altitude in the initial dip of the flight still amounts to 500 naut. mi. The direct descent trajectories shown in Figure 4 are not expressly affected by the re-entry flight path angle.

In view of the requirements for the safety of the astronauts a manual emergency re-entry mode is being considered as a back-up for the on-board automatic guidance and control system. It is based on an independent semi-automatic on-board system consisting of an accelerometer which senses in-flight path direction and a real time display of the accelerometer output in terms of g vs. velocity, v. The velocity is obtained by integrating the accelerometer output. Figure 5 shows a schematic diagram of the g vs. v display which is an integral part of the pilot's control board. The pilot, takes over the roll control of the Command Module, using the g vs. v display

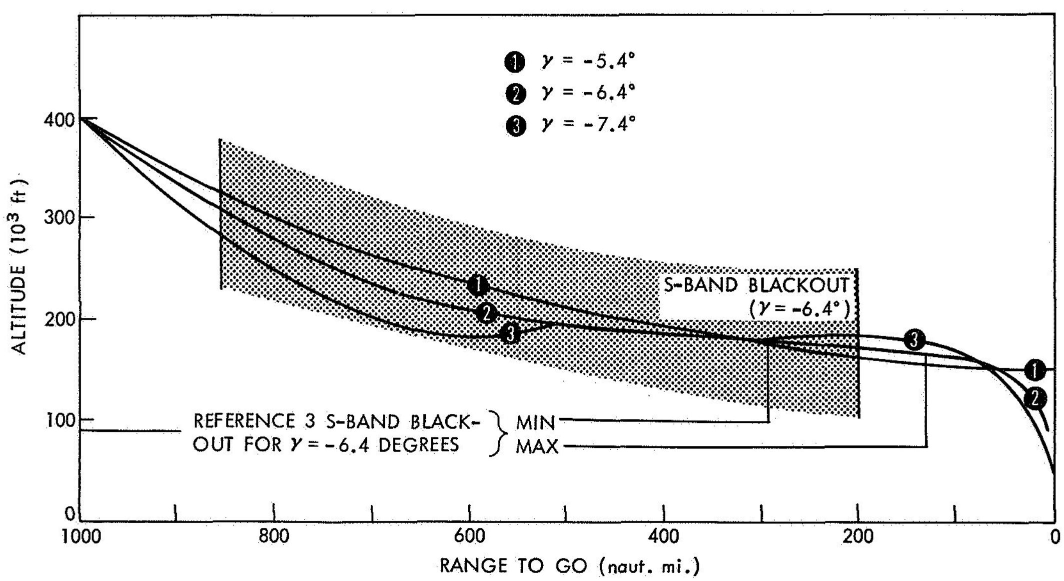

Figure 4—Apollo 1000 naut. mi. re-entry trajectories.

as a guide for staying within prescribed g-limits and for gradually reducing his velocity to slightly below orbital speed in order to avoid a fatal skip-out. During the manual emergency mode, the astronauts have no on-board indication of spacecraft position, and range and cross-range deviations from the prescribed flight path become incidental. As an example, three 5000 nautical mile trajectories generated with the automatic guidance system have been plotted in the g vs. v display for re-entry angles of -5.4, -6.4, and -7.4 degrees (Figure 5). They all demonstrate that the g and v constraints have been properly taken into consideration.

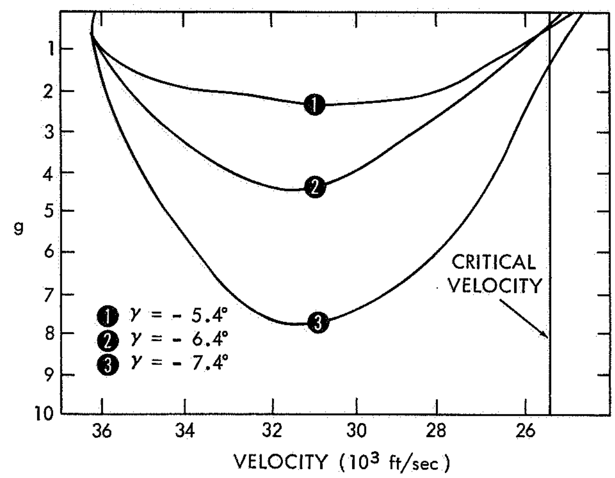

Figure 5—Manual emergency re-entry mode for 5000 naut. mi. trajectories.

Present investigations* indicate that with the manual re-entry emergency mode it is possible to fly trajectories ranging up to 7500 naut. mi. within the prescribed g and v constraints. The apparent incompatibility with the maximum range of presently considered nominal automatically guided re-entry flights is being studied.

BLACKOUT AREAS

With the predictions on hand for Apollo RF signal blackout, preliminary estimates of blackout areas during typical re-entry trajectories can be made. It should be pointed out that the predictions given here, based on unpublished information from AVCO† and the Cornell Aeronautical Laboratory‡ and the previous work of Goddard Space Flight Center (References 5-8), are made under very simplifying assumptions. These assumptions suggest *summa summarum* that all conditions of the RF signal blackout for a given operational frequency during any Apollo re-entry trajectory are prescribed by two parameters, velocity and ambient air density. (For a standard atmosphere density profile, the second determining parameter becomes the altitude.) Under these assumptions, blackout areas have been coordinated with characteristic Apollo re-entry trajectories. An example of an altitude vs. velocity presentation of the trajectories considered in Figure 1 is given in Figure 6. Plotted in this diagram are two sets of parameter family curves, 4 and 5, indicating predicted blackout bounds for operational frequencies of 250 Mc, 2 Gc, and 5 Gc. The predictions for curves 4 by AVCO† are based on equilibrium flow assumptions and an antenna location on the windward side (attached inviscid flow) of the conical Apollo afterbody. Curves 5 were obtained

*Informal discussion between North American Aviation, Inc. (NAA), Massachusetts Institute of Technology, and Goddard Space Flight Center. NAA is prime contractor for the Apollo project.
†Memorandum from the Director of Electronics and Control, NASA Headquarters to the Director of Langley Research Center, August 17, 1962.
‡Memorandum from P. V. Marrone to A. Hertzberg, Cornell Aeronautical Laboratory, May 11, 1962, and private discussion with A. Hertzberg.

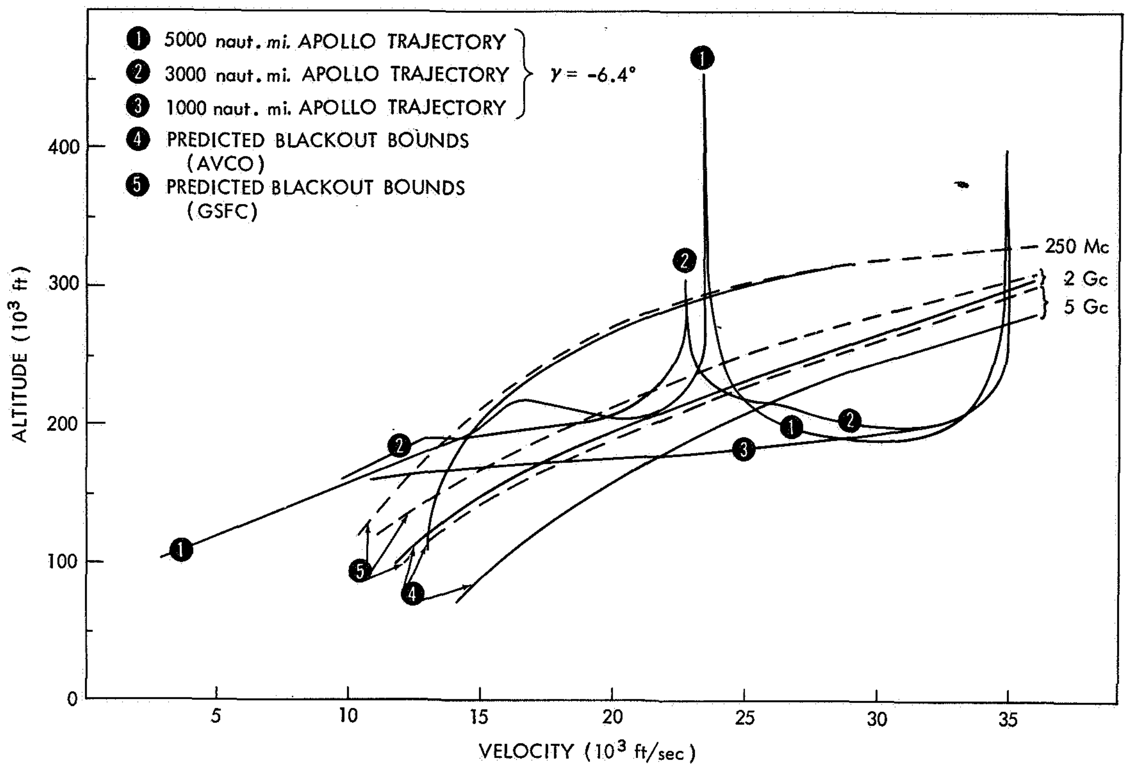

Figure 6—Blackout bounds for typical Apollo re-entry trajectories.

by adjusting the geometry factors of Tischer's flow field model for an antenna location on the leeward side (separated flow) of the Apollo afterbody for nonequilibrium conditions in the stagnation region.

By using the scheme in Figure 6 as a tentative approach, S-band blackout areas have been determined for all trajectories given in Figures 1-4. Figure 1 shows the estimated S-band blackout regions for nominal 5000 and 3000 naut. mi. re-entry trajectories at a re-entry flight path angle of γ = -6.4 degrees. Trajectory 1 has two areas of blackout within the two regimes of spacecraft maneuver described earlier. The first blackout commences upon initial Apollo penetration into the atmosphere at about 310,000 ft and prevails throughout the major portion of the maneuverable flight to approximately 250,000 ft during skip-out.

The second blackout takes place in an altitude region from about 250,000 to 180,000 ft while the spacecraft returns from the skip. For comparison, predictions of S-band blackout by North American Aviation, Inc., have been plotted (Reference 3) which are based on equilibrium flow field and plane wave propagation calculations, with an assumed antenna location on the windward side of the Apollo spacecraft more commensurate with the Mercury C-band antenna position. Electron density or plasma frequency, calculated along the wave propagation path, has been supplied with an uncertainty factor of plus and minus an order of magnitude. This uncertainty factor may include the neglected effects of nonequilibrium flow, three-dimensional wave propagation, and ablation.

Taking into account this order of magnitude variation of the electron density, Reference 3 gives the maximum and minimum extent of S-band blackout for the two described areas of blackout for trajectory 1. It is interesting to note that, with the exception of the initial onset of blackout, the Reference 3 minimum blackout area predictions are in fairly good agreement with the GSFC estimates (see also Figure 2). This agreement, however, should not be overemphasized because the effects of ablation may further enhance attenuation, when they are taken into account.

General tendencies of S-band blackout for the Apollo skip trajectories may be recognized by inspecting Figures 1-3. The duration of the first blackout area varies, but the second blackout region is affected very little by changes of the trajectory profile.

The contributing parameter for the changes in the extent of the first blackout area is the re-entry flight path angle. Practically independent of the range of skip trajectories, the maximum variation of the length of the blackout area within the considered re-entry angle corridor amounts to as much as 600 naut. mi.

The most serious blackout effect is imposed on short range direct descent re-entry trajectories (see Figure 4). Practically the entire maneuverable portion of the re-entry flight appears to be in the S-band blackout region. Comparison with NAA blackout data shows that the Goddard Space Flight Center prediction of the termination of blackout for a re-entry angle of -6.4 degrees lies about halfway between the NAA lower altitude bounds of maximum and minimum blackout. It is interesting to note that almost the entire flight phase for the manual emergency re-entry mode (see Figure 5) is immersed in S-band blackout.

EFFECT OF BLACKOUT ON GROUND SUPPORT

A critical matter in re-entry will be the initial phase of deceleration to suborbital velocity. Precise guidance and maneuvering are essential. It is also important that the ground network provides a monitoring capability for the prime guidance system and functions as an integral link between the spacecraft and control center should the vehicle be flying in a manual emergency mode. For the manual emergency re-entry mode the re-entry network should also be able to predict the locale of an emergency landing.

As mentioned, the re-entry environmental conditions have a debilitating effect on communication and tracking. Consequently, the ground network must be reviewed in light of the strong interaction between the radio signal and the ionized flow field surrounding the re-entering spacecraft and its radio antenna. This interaction degrades the overall performance of the radio channel. The S-band transponder signal level as well as the other radio channels can be attenuated severely. The proximity of the plasma to the antenna introduces a severe impedance mismatch which can drastically weaken the signal power, reducing the channel capacity of the telemetry system and making voice communication impossible. Tracking errors also will arise from a degradation of Doppler range rate measurements. Even skin tracking can be unsatisfactory because of the confusion introduced by the ionized vehicle trail and precursor ionization in front of the shock.

The development and implementation of methods circumventing blackout is a prime need of the re-entry phase. Ways of eliminating blackout in the severe Apollo re-entry flight conditions have not yet been developed within the Apollo mission requirements. Methods suggested for modifying the flow field chemistry include seeding the flow field with electronegative materials and injecting a fluid into the boundary layer. The injection of fluid has been successfully demonstrated in the RAM project (Reference 9) during an actual flight experiment. To evaluate the effect of fluid injection for Apollo, experiments need to be conducted which take into account the stagnation condition attending super-orbital re-entry and the complex fluid mechanical problems stemming from the geometry of the Command Module.

In the event that techniques are not developed to overcome blackout, the Apollo ground support must function within the restrictive communication conditions imposed by blackout. A critical interval can develop as the spacecraft descends to 200,000 ft and initiates the skip out of the atmosphere. Emergency conditions at this juncture make it necessary to execute corrective maneuvers quickly because the vehicle soon will be in an ascending phase and aerodynamic conditions are not favorable for maneuvers. Decision time is at a premium. This is where the ground support may be able to help, but is at present handicapped by the blackout state. The precise limit of the communication rupture also will have a critical bearing on the placement of a tracking ship and other communication problems. For instance, for a continental landing in the southern part of the United States a tracking ship would be placed in a most effective strategic position in the Pacific Ocean as indicated by the generalized term "ground station view" in Figures 1-3. The range of a nominal re-entry trajectory is approximately known well in advance. For each prescribed trajectory range the tracking ship has to have a position such that the spacecraft can be acquired immediately after escaping blackout. However, the precise limit of communication rupture occurs in an area whose location relative to the re-entry point is a function of the re-entry flight path angle and the performance of the on-board automatic guidance system during the blackout. The re-entry flight path angle can be determined fairly well by the Manned Space Flight Network after the last major midcourse correction, about a day prior to the re-entry phase. However, according to recent information additional midcourse maneuvers can be performed until 1 hr prior to landing. Such maneuvers would affect the re-entry angle considerably. Consequently, a change in trajectory profile on short notice will have a significant effect on the positioning of the tracking ship. The present uncertainty in blackout termination during skipout also poses a problem to the positioning of the ship and consequent acquisition and tracking capabilities. As yet, it is not possible to accurately predict where blackout will end in the ascent phase, but 250,000 ft may be a reasonable estimate.

To optimize the Apollo tracking network and meet its requirements during re-entry, the plasma effects on communication must be understood and degrading effects accurately evaluated. Analytical methods of investigating the signal degradation on re-entry are encumbered by two fundamental problems common to all re-entry communication problems. One is the determination of the plasma properties of the hypersonic ionized flow field, the so-called plasma sheath. The other is the behavior of an antenna clad by the plasma sheath. The treatment of these problems is very difficult because of the multiplicity and complexity of the phenomena involved and also because of the lack of physical data and, in some instances, the intractable mathematical problems. The plasma properties in particular are a very sensitive function of complex physico-chemical processes in the shock layer and the calculation of these processes is subject to error because of the uncertainty in the basic physical parameters. The reaction rate constants of many of the numerous chemical reactions are only very crudely known. Recombination rate constants theoretically predicted by various authors differ by as much as three orders of magnitude. Therefore, most efforts at evaluating the blackout problem are primarily handicapped by the uncertainty in the crucial plasma properties. Furthermore, the behavior of an antenna immersed in a plasma can be very difficult to analyze. When observed signals have been attenuated 20 db or more, the changes in signal propagation caused by the plasma sheath are so drastic that the antenna radiation pattern will be quite unlike the pattern in the absence of a plasma.

Since the effective radiation pattern is influenced by the presence of the plasma, the positioning of a tracking ship also will be affected. However, the plasma influence on the radiation pattern has not yet been evaluated and so this factor is not considered here. The Goddard Space Flight Center efforts to investigate this problem are discussed in the next section.

The major effect of the plasma is to attenuate the signal strength available for communication between the ground and the spacecraft. In the high altitude regimes of the Apollo flight the critical parameter controlling attenuation is the ratio of signal frequency to the maximum plasma frequency in the antenna region. The attenuation in general is relatively high or low in accordance with a ratio less or greater than unity. The positions in the vehicle trajectory where the ratio equals unity are used in this paper for determining the blackout limits. The rule of thumb condition for blackout then predicts that, for the planned skip trajectories, blackout will occur in two intervals, one for each entry phase (see Figures 1-3).

To determine the effect of the plasma sheath on radio communication during re-entry the free electron density distribution in the antenna region must be known. This is a function of the airflow and reaction kinetic between the stagnation region and antenna region. During the re-entry flight Apollo will be surrounded by an asymmetric flow field because of its trim angle of 33 degrees. Since the trim angle does not change during roll maneuvers, the flow field will remain unchanged. As a consequence there will only be one possible flow field for Apollo for a given altitude and vehicle velocity. The flow field asymmetry can be examined by viewing a cross-section of the flow field in the plane containing the symmetry axis and lift vector (Figure 7). A stagnation point develops in this plane at a position near the vehicle's upper shoulder. The expanded airflow around one shoulder will have, at altitudes above 170,000 ft., an inviscid attached flow with a presumably laminar boundary layer. About the other shoulder the airflow will be unable to follow the converging vehicle contour and a separated flow regime will follow. The free electron density distribution in the aftersection of the vehicle can differ appreciably for the two flow patterns described. The antennas on the vehicle wall bordering these flow regimes can have different radio characteristics and their blackout intervals will not be the same. The separated flow regime has circulatory flow and is broad in extent, with a relatively large quantity of ablation products and hence high electron concentration. The thermochemical state of this region is difficult to describe. The flow field around the shoulder having an attached flow field is more

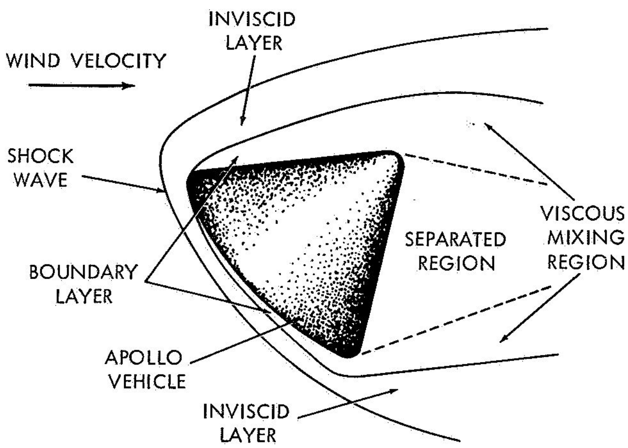

Figure 7—Apollo hypersonic flow regions.

amenable to analysis. A stream-tube analysis can be used for the inviscid flow regions to calculate the electron density distribution in the antenna region. The plasma sheath properties for Apollo are a sensitive function of the nonequilibrium conditions in the stagnation region. Therefore, the finite rate reaction kinetic of species in this region must be considered. A sudden expansion of the airflow about the Apollo shoulder will inhibit electron-ion recombination and maintain the electron concentration at a high level. An accurate evaluation of the downstream electron distribution will involve an analysis of a multitude of coupled chemical reactions.

GODDARD SPACE FLIGHT CENTER EFFORTS

In connection with preparation of the Apollo ground support network in general and the Apollo re-entry network in particular, GSFC became concerned with the plasma effects on re-entry tracking and communication. The guiding idea for the attack on this problem was the establishment of a quick-look program which would provide approximate predictions of blackout areas and would lend itself to later refinements. These refinements could be based, for instance, on more elaborate theoretical treatments of wave propagation as well as on more commensurate experimental data of chemical kinetics not presently predictable with an accuracy better than several orders of magnitude.

With this guideline in mind, F. J. Tischer developed simplified mathematical models of electrical flow field properties and wave propagation, with applications to the Mercury and Apollo re-entry problems. Results of these investigations, which have been published in References 5-8, will be reviewed briefly in the following paragraphs.

The attenuation level of signals and the blackout conditions during re-entry can be approximately determined in terms of plasma properties in the antenna region. Tischer described the plasma sheath properties in an analytic form which facilitates a direct calculation of signal attenuation. With this representation the properties of the sheath at the antenna region are governed by two factors: (1) The plasma properties in the stagnation region; and (2) a modulating factor which essentially lumps the controlling physical effects on the plasma prevailing between the stagnation region and the antenna location. Thus

$$N_e = N_s(h, V)\, F\left(\frac{X}{D}, \frac{Y}{\Delta}, h, V, B, A, \cdots\right), \tag{1}$$

$$\nu = \nu_s (h, V) G\left(\frac{X}{D}, \frac{Y}{\Delta}, h, V, B, A, \cdots\right) , \tag{2}$$

where N_e and ν are the electron density and collision frequency in the shock layer, N_s and ν_s are these parameters in the stagnation region, and F and G are the form factors. X and Y are distances along a near-body streamline originating from the stagnation region and along a body normal, respectively. D and Δ are the vehicle nose radius and the shock layer thickness, h is the altitude, V the vehicle velocity, B the body configuration, and A the spacecraft attitude. The advantage of this representation is that it allows the known properties of the plasma sheath to be included in the calculation of the signal attenuation.

For the wave propagation problem a method of successive approximation is used. The attenuation R^{db} is written

$$R^{db} = R_0^{db} + \sum_{\nu} \Delta R_{\nu}^{db} ,$$

where R_0^{db} is a first order approximation based on a plane wave propagating in a stratified medium. The higher order terms which account for reflection, multiple scattering, and antenna configuration are calculated by a recursion method. Thus, the approximate equation for the db attenuation for the plasma sheath characteristic of a blunt-nosed vehicle becomes

$$R_0^{db} = 0.012 \ N_s \ (h, V)_s \ F_1 \left(\frac{X}{D}, \frac{Y}{\Delta}, B\right) G_1 \left(\frac{X}{D}, \frac{Y}{\Delta}, B\right) \frac{\delta_{eq}}{f^2} ,$$

where F_1 and G_1 are slowly varying geometrical form factors describing the variation of electron density in the aft section of the vehicle, δ_{eq} is an equivalent thickness of the plasma sheath, and f is the operational frequency. This formula was tested with the MA-6 flight attenuation data. By utilizing the in-flight-observed C-band data, which show a brief marginal blackout interval, and considering F_1 and G_1 constant, a prediction for the limits of the VHF blackout altitude range is obtained. This was in reasonable agreement with the observed data. Figure 8 presents an altitude vs. velocity plot of the MA-6 re-entry trajectory. The blackout curves are adjusted for the observed blackout bounds of RF signals at operational frequencies of 250 Mc and 5 Gc. The blackout curve for 2 Gc was obtained by using the geometry factors of the flow field model established for 5 Gc. The plasma and collision frequencies upon which the blackout predictions for the MA-6 were based are given in Figure 9 (Reference 5). In this figure fp_s is the plasma frequency at the stagnation point under the assumed equilibrium conditions and fp_1, fp_2, and fp_3 are the plasma frequencies at different antenna locations; ν_s is the collision frequency at the stagnation point and ν_1 the collision frequency, assumed to be constant, for all considered positions of antennas. Figure 10 is a plot from Reference 5 of the maximum plasma frequency during the MA-6 re-entry; fp_s again is the stagnation point plasma frequency, curve A, and $fp^{(-2.5)}$, curve B, is the plasma frequency for the C-band antenna location calculated with the flow field geometry factors adjusted for actual in-flight-measured C-band signal attenuation. From C-band data modified by the longitudinal electron density variation between the C-band and telemetry

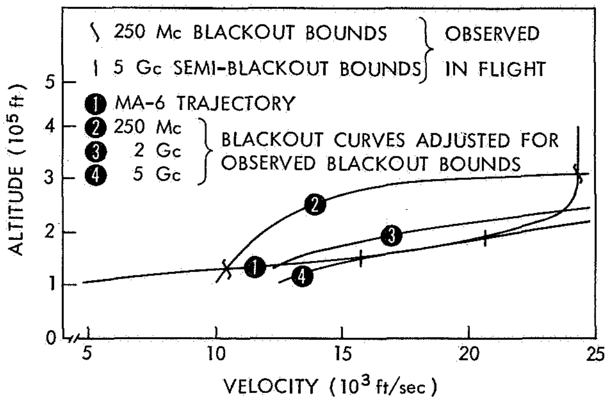

Figure 8—Re-Entry Trajectory for MA-6.

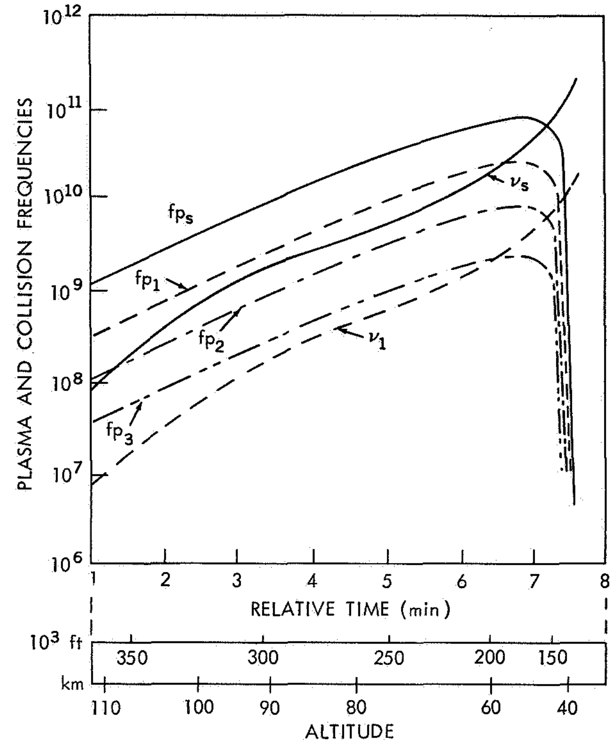

Figure 9—Plasma and collision frequencies in the flow field near the Mercury after-body.

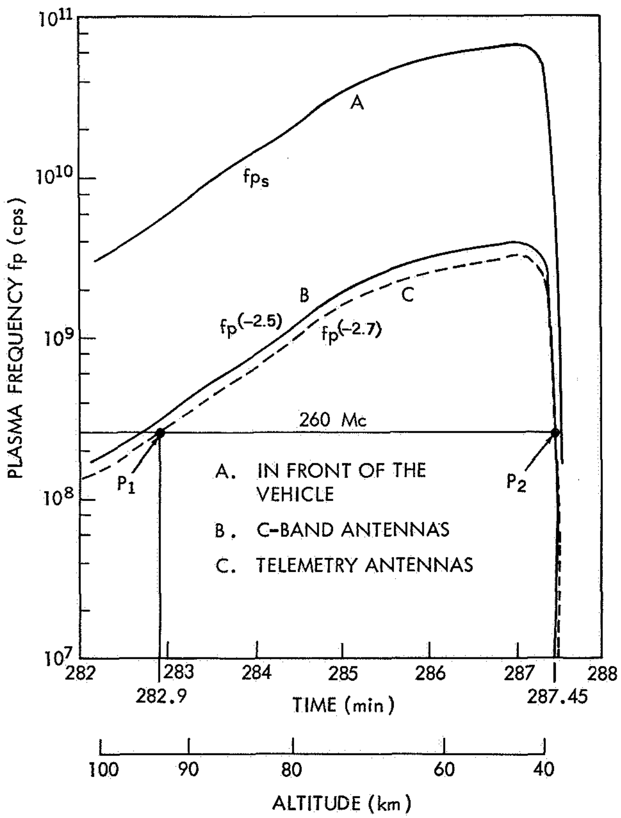

Figure 10—Maximum plasma frequency during MA-6 re-entry.

antennas the plasma frequency $fp^{(-2.7)}$, curve C, was obtained. Points P_1 and P_2, the intersects of curve C with the 260 Mc line at altitudes of 306,000 and 125,000 ft., respectively, give the VHF blackout bounds, which agree in general with in-flight observations.

There are numerous and crude approximations in the present application of the method discussed. However, the intuitive appeal of the method and its heuristic character have been the basis for further investigation along this path and the search for more refined calculations. F.J. Tischer*is currently conducting one-and two-dimensional calculations based on analytical methods and numerical procedures. In the current reformulation the impedance mismatch between the antenna and plasma is assumed to be an impedance input of the antenna system. This offers to be a more satisfying concept of

*NASA research grant NsG-608, "Investigation of Electromagnetic Wave Propagation Through the Ionized Flow Field Around Spacecraft Re-Entering Planetary Atmospheres," given to the University of Alabama Research Institute, Huntsville, Alabama.

the antenna problem and considerably simplifies the wave propagation and radiation pattern calculations.

Cornell Aeronautical Laboratory (CAL), working on "Re-Entry Radiation and Air Flow" under contract NAS r-119 for NASA, has done some nonequilibrium flow field calculations pertaining to the characteristic re-entry conditions of the Mercury spacecraft.* By using a stagnation region solution, with application of their finite rate normal shock program, plasma frequencies have been computed for the Mercury re-entry altitude range. Figure 11 shows the results and compares them with those for equilibrium conditions and an estimate of nonequilibrium viscous effects for high altitudes. A single ionization model (one dominant ionization reaction) with 8 species and 10 chemical reactions was used for the low altitude conditions, and a complex kinetic model consisting of 12 species and 28 chemical reactions (19 ionization reactions) was applied for the high altitude case.

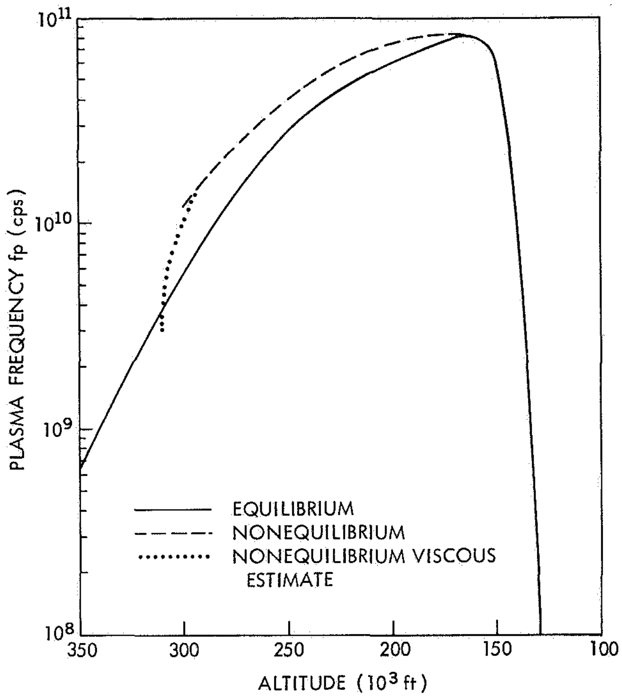

Figure 11—Plasma frequency at the MA-6 stagnation point.

For super-orbital velocities as many as eleven additional electron forming reactions have been considered. These reactions are closely coupled to a multitude of other reactions involving numerous atomic and molecular chemical species. A computational program has been developed for an equilibrium composition of air behind a normal shock for flow velocities up to 50,000 ft/sec. The program comprises 20 chemical species and 40 reactions. Application to Apollo would require a detailed calculation of the nonequilibrium state. The investigation of these problems is, however, handicapped by the uncertainty and lack of basic physical data on reaction rate kinetics of ions and neutral chemical species.

The CAL has formulated an experimental program whose purpose is to fill this need. The investigation will utilize a shock-tube tunnel capable of developing the stagnation condition of high enthalpy at the nozzle throat, corresponding to super-orbital re-entry velocities. This will permit the study of nonequilibrium ionization in an aerothermo-chemical environment appropriate to stream tubes about the Apollo vehicle. The objective of this program is to obtain basic data on reaction rate kinetics and develop methods for calculation of the plasma sheath properties for the lunar re-entry mission. A more accurate and meaningful prediction of the plasma effects then will be possible.

*Memorandum from P. V. Marrone to A. Hertzberg, Cornell Aeronautical Laboratory, May 11, 1962, and private discussion with A. Hertzberg.

Techniques for eliminating blackout, like fluid injection, often rely on modifying the non-equilibrium chemistry and ionization level. The basic studies of CAL* are expected to provide more effective procedures for developing and evaluating these remedial methods.

CONCLUSIONS

Plasma effects on tracking and communication during Apollo re-entry from a lunar mission have been reviewed. Several characteristic re-entry trajectories have been studied for RF signal blackout areas expected to occur during skip and direct descent re-entry flights. The presently existing uncertainties of the electrical properties in the Apollo plasma sheath and the plasma effects on antenna performance have led to widely differing estimates of blackout area predictions. The most desirable case of continuous tracking and communication throughout the entire re-entry phase could be achieved only by developing ameliorative methods for preventing blackout. To accomplish this, both the complex physico-chemical phenomena of the asymmetric ionized flow field peculiar to Apollo, and the three-dimensional wave propagation through the highly inhomogeneous plasma sheath must be more clearly understood. However, the development and implementation of preventive techniques must conform with the overall system requirements.

For the establishment of a most economical and effective Apollo re-entry gound support network, it will be necessary to know precise blackout bounds for all possible types of re-entry trajectories. The accuracy or uncertainty of the prediction of blackout area bounds are determining factors in the assessment of the gound support capabilities during Apollo re-entry. In order to aid in this effort the CAL will be given the task of investigating the basic reaction kinetics of chemical species in high temperature air flow under conditions simulating Apollo re-entry from lunar missions. The effect of ablation impurities in the plasma sheath will also be subject to studies by CAL in their high-enthalpy shock-tunnel facilities. In addition, ameliorative techniques such as fluid injection, found to be very successful for RAM flights (ICBM re-entry conditions) by Langley Research Center, will be considered for testing with respect to applicability to Apollo re-entry in CAL facilities. To aid in determining precise blackout bounds GSFC has given a grant to the University of Alabama Research Institute for the development of refined ionized flow field and wave propagation models pertaining to specific characteristics of the Apollo spacecraft.†

For an ultimate confirmation of predictions based on theoretical treatment and experimental investigation in ground facilities, the posibility of incorporating coordinated experiments in the Gemini and early Apollo flight programs is being considered. Although environmental conditions pertaining to re-entry velocities cannot be met in these programs, flight experiments of the suggested kind may give valuable confirmation of predicted blackout bounds within altitude and velocity regimes common to the near-earth and lunar missions.

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*Contract to be let by GSFC.

†NASA research grant NsG-608, "Investigation of Electromagnetic Wave Propagation Through the Ionized Flow Field Around Spacecraft Re-Entering Planetary Atmospheres," given to the University of Alabama Research Institute, Huntsville, Alabama.

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