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THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING

DEPARTMENT OF ELECTRICAL ENGINEERING

Radiation Laboratory

INVESTIGATION OF PHYSICAL MODEL FOR
SATELLITE DETECTION

Final Report
March 1, 1961 - May 31, 1962

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The work described in this report was partially supported by the ADVANCED RESEARCH PROJECTS AGENCY, ARPA Order Nr. 120-61, Project Code Nr. 7400.

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THE UNIVERSITY OF MICHIGAN

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Prepared by

R. J. Leite

OBJECT

Formulate by theoretical analysis, the nature of the disturbances, the existence of passive RF radiation, and the nature of the radiating mechanism resulting from a satellite passing through the ionosphere.

TABLE OF CONTENTS

1. PURPOSE

The purpose of the work being performed under the present modification of the basic contract is to determine whether the emission of passive microwave radiation at measurable intensities above the normal atmospheric noise background results from the passage of a satellite through the ionosphere. This information is to be obtained by theoretically analyzing the nature of the disturbances to determine whether or not there is passive radiofrequency radiation and to analyze the nature of the radiating mechanism.

2. ABSTRACT

Brief summaries of published reports of the theoretical work are given. Two types of plasma problems were considered, namely, investigations of mechanisms which could produce passive microwave radiation from the immediate neighborhood of a vehicle in partially ionized, free-molecule, or near-free-molecule flow, and, fundamental studies of the photon transport properties of a non-relativistic plasma. Theoretical results exceeded all original expectations.

The nature of two experimental programs aimed at detection of the microwave emission from the wake of a body in free-molecule flow is described. Since neither program approached completion due to circumstances beyond the control of The University of Michigan, no discussion or evaluation of results could be made.

Conclusions concerning the theoretical results are given. Also included are detailed recommendations for theoretical and experimental extensions of the present work which appears to provide the only passive means of detecting and tracking a "silent" vehicle traversing the ionosphere.

3. REPORTS AND CONFERENCE PAPERS

3.1 "Kinetic Equations for Plasmas", R. K. Osborn, 2764-8-T, October 1961, UNCLASSIFIED.

3.2 "Wake of a Charged Prolate Spheroid at an Angle of Attack in a Rarefied Plasma", W. Sawchuk, 2764-9-T, March 1962, UNCLASSIFIED.

3.3 "Evolution of an Inhomogeneous Rarefied Plasma and Associated High Frequency Electromagnetic Radiation", R. K. Ritt, 2764-10-T, April 1962, UNCLASSIFIED.

3.4 "Electromagnetic Radiation from Shockwaves in a Low-Density Weakly-Ionized Medium", C. J. Mason, 2764-11-T, April 1962, UNCLASSIFIED.

3.5 "A Theory of Photon Transport in Dispersive Media", E. H. Klevans, 2764-12-T, May 1962, UNCLASSIFIED.

3.6 "The Determination of the Electron Density Perturbations Resulting from the Mixing of Two Different Plasmas", F. V. Schultz, 2764-14-T, June 1962, UNCLASSIFIED.

3.7 "Relativistic Transport Equations for Plasmas"*, Ecrument Ozizmir, The University of Michigan Report No. IP-571, June 1962, UNCLASSIFIED.

3.8 "Study of Microwave Radiometry Detection Techniques"- Final Report (15 April 1958 to 14 August 1961), B. A. Harrison and R. J. Leite, 2764-13-F, May 1962, SECRET.

3.9 "Photon Transport in Dispersive Media," E. H. Klevans, presented at the American Physical Society Meeting, Plasma Physics Division, Colorado Springs, Colorado, November 15 - 18, 1961, UNCLASSIFIED.

4. TECHNICAL WORK

4.1 Introduction

Detailed descriptions of the theoretical work performed under Modification 7 of the basic contract is well documented in published technical reports (See 3.1-3.7), therefore only brief summaries of the contents of each report will be presented here. Two experimental programs were initiated but neither advanced sufficiently to permit publishing of results, therefore, only descriptions of the intended program and the progress made will be presented here.

4.2 Theoretical Work

4.2.1 General

Two general types of plasma problems were undertaken, namely, theoretical investigations of physical mechanisms which might produce partially coherent

*This work was supported in part by other sources.

microwave radiation due to the configuration of the flow field associated with a vehicle in the free-molecule or near-free-molecule flow regimes and investigations of a fundamental nature concerning the transport properties of non-relativistic plasmas. Topics considered under the former investigations are 3.2, 3.3, 3.4 and 3.6 while those considered under the latter are 3.1, 3.5, and 3.7. The following summaries indicate the nature of the subject matter contained in each publication.

4.2.2 Wake of a Charged Prolate Spheroid at Angle of Attack in a Rarefied Plasma, The University of Michigan Report 2764-9-T.

The electron-ion charge distribution in the surrounding flow field and the surface potential of a perfectly conducting prolate spheroid moving in a rarefied and unbounded partially ionized plasma were determined. Asymmetrical characteristics of the flow field produced by such an object for angles of attack of 0^{o}, 45^{o}, and 90^{o} were considered. Both the earth's magnetic field and the photo-electric effect were ignored in the calculation. Consideration was given to steady state flow conditions only. At the altitude considered, (500 km), free molecular concepts were used and the problem was formulated in terms of the collision-free Boltzmann equations and Poisson's equation. With regard to particle-surface interactions, it was assumed that most of the ionized particles were neutralized at or near the satellite surface. The satellite potential for each angle of attack was determined by equating the total ion and electron fluxes. The values obtained are -0.36, -0.33, and -0.29 volts for angles of attack of 0°, 45°, and 90°, respectively. Since it was assumed that the positive ion density distribution is not influenced by the satellite potential field, the ion wake results mainly from the shadowing effect of the satellite. The ion density at any point in space was found by integrating its Maxwellian distribution function over limited velocity space whose bounds are determined from the geometry of the shadow cone in configuration space. This procedure results in a double integral which was evaluated numerically on IBM 709 and 7090 electronic computers.

The electrons were assumed to be always in equilibrium in the potential field surrounding the satellite. Poisson's equation was solved numerically using the Gauss iterative procedure on the IBM 709 computer. The present program was written to utilize computer core storage. This restricted the fineness of the mesh due to limited core capacity which reduced the accuracy of electron density computions in the vicinity of the satellite.

Results of numerical calculations for a prolate spheroid having a major axis of 4 meters and a minor axis of 2 meters and moving at 8 km/sec at an altitude of 500 km have been plotted for angles of attack of 0°, 45°, and 90°. These include separate plots for the positive ion and electron density distributions and a plot of the net charge distribution in the wake for each angle of attack.

4.2.3 Evolution of an Inhomogeneous Rarefied Plasma and Associated High Frequency Electromagnetic Radiation, The University of Michigan Report 2764-10-T.

The theoretical exploration for a physical mechanism which would be capable of generating electromagnetic emission at microwave frequencies within the flow field comprising the wake of a satellite in free-molecule flow was initiated by Kun-Mu Chen* at the suggestion of K. M. Siegel.** A theory was developed based upon the fact that an electron layer will always be formed at a sharp boundary between a plasma and a rarefied region such as that generated in the wake of a body moving through the ionosphere. Due to the high speed of the electrons relative to the ions and molecules, the time scale of transport phenomena in the electron layer is much smaller than that of similar phenomena in the plasma. Therefore, any oscillations within the electron layer resulting from perturbations will have a higher frequency than the plasma frequency characterizing the plasma region. Since this phenomena would occur within the cavity generated by the motion of the satellite at speeds greater than that of the ionic and molecular constituents of the medium, the emission resulting from these electron layer oscillations will propagate through

*"Investigation of Physical Model for Satellite Detection," Appendix A, Semi-Annual Report, February 15, 1961 - August 15, 1961, The University of Michigan Report 2764-34-P, Contract No. DA 36-039 SC-75041. UNCLASSIFIED.

**"Experimental Field Measurements of Passive Microwave Radiation," S. T. Harmon and W. E. Vivian, The University of Michigan Report 2764-2-T (January 1960), Contract No. DA 36-039 SC-75041. SECRET.

the external plasma and be detectable by external sensors.

Subsequently, a more exact mathematical treatment of the problem was undertaken by R. K. Ritt. His work (3.3) is summarized in the following discussion.

A gas, consisting of electrons and positive ions, is assumed, at t = 0, to have the following properties:

(a) The ion distribution number, N(x), has the form

$$N(x) = \begin{cases} 0, & -a \leqslant x \leqslant a \\ N_0, & |x| > a \end{cases}$$

where the ions are stationary, and are assumed to remain fixed throughout the evolution of the system.

(b) The electron distribution is N(x) V(v), V(v) being the distribution

$$\frac{1}{\sqrt{2\pi}\,\sigma} e^{-v^2/2\sigma^2}$$

The subsequent behavior of the electron distribution is investigated. This is done by assuming that the electron distribution function, f(x, v, t) satisfied the Vlasov equation and the above initial conditions.

The first question that arises concerns the existence of a solution to the problem as it has been formulated. Due to certain mathematical difficulties, the Vlasov equation is replaced by a nonlinear functional equation which has a unique solution, obtainable by a Picard type iteration. Further, it can be shown that the solutions have limits as $t \longrightarrow \infty$, and that the limiting values satisfy the requirements of the system in which the derivatives exist almost everywhere. A general solution of this system then yields the electron distribution for all values of x. For $|x| > a$, the electron number density approaches N_0 exponentially. It reaches a minimum at $|x| = a - h$, where h is the Debye length. Thus the formation of an electron sheath is described.

The next step consists of replacing the Vlasov equation by the Maxwell-Boltzmann equations and seeking perturbation solutions. Assuming that the true electron distribution for finite time is a perturbation from the limiting distribution, it is found that the perturbation equations can be satisfied by transverse electromagnetic waves having certain discrete frequencies. These frequencies fall into two classes, one inversely proportional to the thickness of the electron sheath and the other inversely proportional to the half-width of the cavity. The latter frequency is found to be more highly damped than the former.

The analysis shows that as the electrons approach an equilibrium distribution, highly attenuated, transverse electromagnetic waves are generated, having discrete high frequencies dependent only upon the Debye length of the ambient electron distribution. It should be emphasized that there is no implication here of high frequency plasma oscillations. The phenomenon described here is one in which the ion-electron configuration serves as a filter which passes discrete frequencies from the noise spectrum of the electromagnetic field produced by the electron motion.

It can be shown that similar results can be obtained for cylindrical geometry as well as the two-dimensional case considered here.

4.2.4 Electromagnetic Radiation from Shockwaves in a Low Density Weakly Ionized Medium, The University of Michigan Report 2764-11-T

The possibility of the emission of partially coherent electromagnetic radiation during the formation of the shock wave associated with a hypersonic re-entry vehicle moving in a low-density weakly-ionized medium was investigated. The nonlinear differential equations governing the formation of the shock wave and the associated jump conditions were obtained by employing kinetic theory techniques and the Boltzmann equation for the plasma. An application of these equations to a plane shock wave was made. Owing to a premature termination of the program, no attempt has been made to solve the equations since certain terms appearing in them have yet to be evaluated. Consequently, no conclusions are drawn.

4.2.5 The Determination of the Electron Density Perturbation Resulting from the Mixing of Two Different Plasmas, The University of Michigan Report 2764-14-T

The time-dependent perturbation of electron density arising from the mixing of two collisionless plasmas, characterized initially by unequal densities and equal electron temperatures, in a field-free region was investigated. It was assumed that changes in electron gas pressure, taken to be a scalar, occur adiabatically and that, for the time interval considered, the ions are immobile. Viscosity and heat conduction were neglected.

It is found that the following phenomena occur in the more-dense medium within a distance of about 1.5 Debye lengths from the interface: (1) The electron density at the interface immediately assumes a value about midway between the two unperturbed electron densities; (2) a rarefaction wave of increasing amplitude propagates into the more-dense medium with a velocity equal to the adiabatic acoustical velocity; (3) after the passage of this wave, rapidly damped electron density oscillations at the two plasma frequencies occur; and (4) after the oscillations die out, the electron density varies smoothly from a value of about one-half the difference in the unperturbed densities at the interface to the unperturbed value far from the interface. Similar phenomena are expected to occur for the less-dense medium.

4.2.6 Kinetic Equations for Plasmas, The University of Michigan Report 2764-8-T

This study produced a unified development of kinetic equations describing particle and photon transport in plasmas subjected to nonconstant and nonuniform external fields. It is found that the equations for the particle distributions are a generalization to the plasma of the equations postulated by Uehling and Uhlenbeck for neutral quantum gases. Since the equations describing photon transport have been developed and discussed previously,* only a brief discussion of these was incorporated in the report of the study for completeness. It was shown that the present description of the plasma is sufficiently complete and consistently developed to such a degree that an H-theorem is demonstrable.

4.2.7 A Theory of Photon Transport in Dispersive Media, The University of Michigan Report 2764-12-T

A systematic, self-contained development of an equation describing photon transport in a dispersive, nonrelativistic medium was evolved. The postulate-deduction procedure was developed along lines similar to those used by Ono in his quantum-statistical theory of neutral gas transport phenomena. The photon balance equation was exhibited as a time rate of change of a coarse-grained photon distribution function. The photons described have an energy-momentum relation $\hbar\omega = \frac{\hbar c |k|}{\mu}$, where μ is the index of refraction. Transport of these photons is characterized by a photon speed which is different from the speed of light. Transition probabilities for scattering, emission and absorption processes were computed to the lowest nonvanishing order.

*"Photon Transport Theory", R. K. Osborn and E. H. Klevans, The University of Michigan Report 2764-5-T (August 1960). UNCLASSIFIED.

The development of the transport equation is self-contained in the sense that the transverse dispersion relations for different systems of interest are determined within the context of the analysis. With respect to these calculations, a method employed by Mead in his discussion of the neutral gas has been employed. Whenever comparison is possible, the dispersion relations are found to be in agreement with those computed by other methods. Except for propagation parallel to the magnetic field, the method is not applicable to the plasma in an external magnetic field.

Radiation from a plane plasma layer was studied and reasonably good agreement with experiment was obtained, although the radiative transfer equation for the dispersive medium was not found to be in agreement with the more conventional equation which was developed by phenomenological balance considerations.

Emission and absorption coefficients are modified as a result of the dispersive medium. For bremsstrahlung in a fully ionized gas, for instance, as the photon frequency approaches the plasma frequency the emission is reduced and absorption enhanced. The possibility of Cenenkov radiation for a plasma in an external magnetic field was also indicated.

Photon transport through an Einstein model crystal was considered. The scattering cross section developed in x-ray scattering theory was obtained. In the limit of the infinite homogeneous crystal, the Bragg scattering condition emerges.

The transport equation which was developed is expected to be valid when (a) the medium is isotropic; (b) spatial variation of particle and photon distributions is slow over regions characterized by a length many times larger than the maximum wavelength of photons under consideration; (c) the frequency should be sufficiently above resonance regions (or the plasma frequency for the fully ionized gas) that radiation damping effects can be ignored. These conditions are only intended to be sufficient for the validity of the equation, but may not be necessary.

4.2.8 Relativistic Transport Equations for Plasmas, The University of Michigan Report IP-571

In this study, transport equations appropriate to high temperature plasmas based upon second-quantized Dirac theory of electrons were formulated. For the study of the statistical aspects of the problem an invariant phase space distribution was introduced in analogy with the Wigner distribution function, suitable to the study of spin 1/2 particles described by the Dirac equation. A coupled set of equations between this function and the spin distributions was derived which reduces to the covariant form of the Vlasov equation as $\hbar \longrightarrow \infty$. A Boltzmann equation for electrons in a system consisting of electrons, positrons and photons was also derived. The S-Matrix formalism was used and was restricted to the lowest non-vanishing order in the perturbation expansion. The equilibrium properties of the system are discussed. An H-theorem was proved and the equilibrium solutions were displayed. The results are in agreement with those obtained strictly from thermodynamical considerations. The kinetic equations describing the system and its approach to equilibrium based upon a field theoretic formalism have been obtained, and it has been shown that these equilibrium distributions are attained irreversibly. The kinetic equations for relativistic systems based upon a classical formalism had necessarily ignored such processes as pair creation and annihilation. It has been shown that it is necessary to consider these processes for a complete description of the system.

An interesting feature of this result is that for very high temperature systems ($kT \sim mc^2$) the density of the electron-positron pairs in the system is very large compared to the usual densities of the atomic electrons in the system. This, for instance, would have a profound effect upon the propagation of electromagnetic waves in such systems. In the study of the plasma oscillations in relativistic systems, other workers have made reference to extreme-relativistic limits without a consideration of the electron-positron pairs which would be present in such systems. Therefore, caution would be necessary in interpreting these results from the point of view of actual physical systems at extreme relativistic temperatures. Finally, the derivation of a Boltzmann-Vlasov equation for an electron-positron system taking pair creation and annihilation into account was sketched.

4.3 Experimental Work

4.3.1 General

The Radiation Laboratory participated in two experimental efforts. Both endeavors were aimed at detection of the microwave emission predicted by the theory which is summarized in 4.2.3. One method employed the use of a 60-foot antenna at USASRDL to receive signals emitted during the passage of a suitable satellite. The other experiment involved the installation of a microwave radiometer aboard a re-entry vehicle to observe the emission at its source. The former will be referred to as the tracking experiment and the latter the piggyback experiment in the summaries that follow.

4.3.2 Tracking Experiment

To provide a means of checking proposed theories of microwave emission from the wake of a satellite, it was proposed that USASRDL use existing receiving antenna facilities as detection devices. In order to do this, suitable tracking data had to be computed for each satellite to be observed. In addition, it was thought that the emitted frequencies would be dependent upon the altitude of the satellite. Therefore, a general satellite look-angle program using satellite ephemeris data from NASA Goddard Space Flight Center and an IBM 709 computer was assembled to provide the following quantities, as functions of time-of-day, for observations from any given site: elevation, azimuth, slant range, altitude above earth, elevation of sun, and illumination. Provisions were made to furnish this information in in either a punched card or a print-out form.

In order to make the format of the computer output compatible with that required for input to the antenna programmer, an interpolation sub-routine was appended to the computer program. A choice of read-out interval is now available by appropriate adjustment of sub -routine.

Due to the delays in the delivery of new antenna feeds and the microwave radiometer receivers experienced by USASRDL, no radiometric data was obtained before the termination of The University of Michigan contract. Prior to this termination, the Radiation Laboratory suggested that USASRDL use the 108 Mc tracking feed on the antenna to track appropriate satellites and record their elevation and azimuth as functions of time-of-day. This would provide a means of verifying the look-angle program and also reveal the presence of systematic errors in the experimental tracking system.

During October 1961, USASRDL obtained azimuth and elevation data as functions of time-of-day for three passes of Tiros II and one pass of Tiros III by using the 108 Mc tracking feed on the 60-foot antenna. Upon comparison with computer data, it was found that for Tiros II the computed azimuth angles were approximately 13 degrees greater than the observed azimuth angles while there was relatively good agreement between computed and observed elevation angles. The computed time of occurrence of a particular orbital position preceded the observed time by approximately 1.3 minutes. For Tiros III, the comparison was essentially the same as above except that observed times preceded computed times by approximately one minute.

While the comparisons indicated the apparent existence of some systematic errors, additional tests will be required to verify this fact. It is important that similar tests be performed when the radiometer and programmer are completely assembled and the system becomes operational so that final adjustments can be made.

In addition to supplying the tracking data of appropriately chosen satellites, The University of Michigan was given the responsibility to reduce and analyze the radiometer output data and subsequently select new satellites to be observed, based on interpretations of previous results. Since the USASRDL radiometric site did not become operational before the termination of The University of Michigan contract, there was no opportunity to satisfy these responsibilities.

4.3.3 Piggyback Experiment

At the request of AVCO Corporation and with the approval of ARPA and USASRDL, the Radiation Laboratory agreed to participate in two flight tests using the Titan Mark IV, Mod. 4 re-entry vehicle.* The purposes of the tests were to investigate ionization characteristics of the wake cavity by means of a Langmuir

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*See "A Proposal for Task VII Flight Test Experiments (Piggyback)" MS-9-60-41, AVCO, Research and Advanced Development Division, (Sept. 1960). SECRET.

probe and to detect emissions from the wake by means of a microwave radiometer. The duration of each test was intended to span the interval between re-entry vehicle separation and telemetry blackout.

After approximately two months of accelerated procurement of essential components and material, rapid completion of final design of flight equipment, and initial construction of components, the flight tests were cancelled because of the imposing of additional flight test requirements which could not be met within the time and financial schedules of the program. Upon cancellation of the program, all work pertaining to it was abandoned.

5. OVERALL CONCLUSIONS

5.1 Theoretical Work

Upon the completion of the preliminary phase of each of three studies, (4.2.2, 4.2.3 and 4.2.5) and upon defining a third problem (4.2.4), in addition to the work on the two basic studies (4.2.6 and 4.2.7), it was concluded that the theoretical portion of the work had been highly successful and that the aims of the contract had been achieved.

It was concluded also that any major extension of this work, beyond the present results, should be accompanied by simultaneous experimental programs. The theory has been extended to a point where experimental inputs would be of considerable assistance in any practical extensions of the theoretical work.

5.2 Experimental Work

Since neither experimental effort has been completed, no final conclusions concerning the experimental programs can be formulated. The lack of opportunity to cross-check theoretical results with experimental data during the course of this study has been a major disappointment to The University of Michigan personnel.

The USASRDL passive detection experiments using the 60-foot dish at Fort Monmouth will monitor frequencies between approximately 250 Mc and 2000 Mc. According to the theoretical model described in 4.2.3, frequencies in this passband would be emitted from the wakes of vehicles traversing the earth's atmosphere at altitudes between approximately 1800 Km. and 8500 Km. At these altitudes the free-molecule flow model which postulates the formation of a cavity becomes questionable and requires further examination, and, in addition, the occurrence of photo-emission of electrons from the surface becomes appreciable, thereby necessitating a re-evaluation of the theory to determine its effect upon plasma equilibrium and wake configuration. In addition, the atmosphere is so rarefied that the formation of any well-defined plasma boundary and its subsequent electron sheath might be doubtful. The probability of detecting radiation resulting from the mechanisms described in 4.2.3 is small due to the above uncertainties and the fact that only a small amount of emitted power can be expected from such a rarefied plasma and the fact that there is considerable power attenuation due to the inverse distance squared relationship. It is more probable that any passive radiation observed by the USASRDL system will emanate from satellites at much lower altitudes through the radiation mechanism associated with the characteristic dimensions of the cavity and therefore of the vehicle. It should be noted that these frequencies are independent of altitude; however, the emitted power will depend upon ambient density which varies approximately inversely with altitude.

It is the opinion of the author that in-flight tests provide the only reliable method of determining the characteristics of the emission and of checking the more fundamental aspects of the theoretical model. Land-based observations will be more feasible after the in-flight tests have established the identity of the signals and defined the nature of their signatures. Conclusions to be drawn from the results (or lack of results) of land-based experiments should be held in abeyance until carefully planned in-flight tests have been conducted.

6. RECOMMENDATIONS

The following are logical extensions of some of the efforts initiated under this contract. It should be emphasized that the present work is essential in satellite detection probiems where "silent" vehicles are involved. Very few alternative avenues of approach are available. Because of the promising nature of the theoretical results, the need for an experimental program is apparent. It is urgently recommended, therefore, that a space vehicle based program be initiated immediately to ascertain the practical limits of this satellite detection scheme.

6.1 Microwave Emission from the Wake of a Satellite; Extension of 4.2.3

6.1.1 Perform experiments to determine the frequency spectrum and energy level of the expected emission from the wake of space vehicles. The experiment would make use of microwave radiometers located at the rear of the vehicle to scan the wake region.

6.1.2 Using inputs from 6.1.1 calculate the energy spectrum of the emission. (This calculation might be performed now, however, experimental inputs would help to establish bandwidth limits and thereby reduce the number of calculations required).

6.2 Wake of a Non-Spherical Satellite; Extension of 4.2.2

6.2.1 Perform calculations at several other angles of attack to attain better understanding of wake flow field transitions.

6.2.2 Reduce flow field grid size to obtain more accurate solutions in immediate vicinity of the satellite.

6.2.3 Find grid size limit which will permit the plasma sheath on frontal surface of a vehicle in free molecule flow to be defined and then examine the thickness of this sheath as a function of accommodation coefficient.

6.2.4 Using Langmuir probes, experimentally determine nature of plasma sheath on frontal surface of a vehicle in free molecule flow.

6.2.5 Examine change in flow field as function of variation of eccentricity of prolate spheroid.

6.3 Emission at the Onset of Re-entry; Extension of 4.2.4

6.3.1 Complete numerical solution of nonlinear differential equations to obtain description of steady-state shockwave structure.

6.3.2 Extend above case by including time variation, obtain unsteady shockwave configuration, and examine electromagnetic emission characteristics of diffuse, unsteady shockwave.

6.3.3 Using Langmuir probes, experimentally determine the nature of the density build-up at the front of a vehicle during re-entry into the atmosphere of the earth.