SOME EUROPEAN ACTIVITIES ON SPACECRAFT/PLASMA INTERACTIONS IN LOW EARTH ORBIT

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ABSTRACT

This paper describes some current European activities on the topic of spacecraft/plasma interactions in low Earth orbit.

One programme is concerned with a study of the mechanisms governing the formation of plasma wakes by large bodies. The work involves both simulation in the laboratory and computational studies using existing computer codes. Although aimed at attaining a better understanding of these mechanisms, the study will provide input to large platform design studies, and into the requirement for the second activity, described below.

The second programme is concerned with spacecraft/plasma interactions and electromagnetic effects in low Earth and polar orbits. It involves the study of plasma wake formation and spacecraft charging phenomena. Again, both experimental and computational work is involved. A suite of computer codes to model various aspects of the interactions is being developed. The intention is to produce an engineering tool for use in spacecraft design studies, and for the assessment of the impact of the space environment on the spacecraft. Cross-validation of the experimental and computational results is seen as an important aspect of this work.

1. INTRODUCTION

In the first decades of the space age, European organisations were active in studying the topic of spacecraft/plasma interactions (SPI) in low Earth orbit (LEO). The work was in support of both space science studies and spacecraft design efforts. Activity ranged from measurements in space (Samir and Willmore, 1965; Samir and Wrenn, 1972), through laboratory simulation (Cox, 1965; Clayden and Hurdle, 1967; Agnello, 1969; Pigache, 1971), to computational studies (Martin, 1974).

After this initial period where interest was concentrated on LEO, the emphasis then moved to the study of phenomena occurring in geostationary orbit, and in particular of spacecraft charging and discharging in the space environment. Several European spacecraft suffered from flight anomalies, causing computer upsets and spurious commands, and a significant amount of effort was expended in this area. A recent, comprehensive summary paper is available (Frezet et al, 1989).

More recently still, with the advent of large-scale programmes such as Colombus, MTFF, and Polar Platform, the focus of interest has moved once again, returning to LEO and the questions of the SPI of large, active, long-lived structures in LEO in general, and the polar orbit environment in particular (Thiemann and Bogus, 1986; Martin, 1986; Coggiola et al, 1988; Coggiola, 1988). These studies represent a significant area of activity in Europe at present, and indeed several contributions arising from the work appear in these Proceedings (Wrenn and Sims, 1989; Soubeyran and Levy, 1989).

This paper describes two programmes of work on SPI under way at present in Europe, among other on-going activities just mentioned. The first programme is being carried out by Culham Laboratory (A.R. Martin, R.A. Bond, P.M. Latham) on behalf of the Royal Aerospace Establishment (RAE) at Farnborough in the United Kingdom (Project Monitor, G.L. Wrenn). This is concerned with a study of the mechanisms governing the formation of plasma wakes by large bodies. The work involves both simulation in the laboratory and computational studies using existing computer codes.

The second programme is being carried out on behalf of the European Space Agency (ESA; Project Monitors, E.J. Daly and J. Hamelin). Culham Laboratory is heading a consortium including the Mullard Space Science Laboratory (MSSL) of University College London (A.D. Johnstone, D.J. Rodgers, R.L. Kessel), the Norwegian Defence Research Establishment (B.M. Maehlum, J. Troim) the Technical University of Graz in Austria (W. Riedler, M. Friedrich, K. Torkar), and RAE Farnborough (G.L. Wrenn, A.J. Sims).

The ESA programme is concerned with SPI and electromagnetic effects in LEO and polar orbit, involving the study of plasma wake formation and spacecraft charging phenomena. Following a review and identification of the important interactions, experimental and computational simulations are being carried out, and a suite of computer codes is being developed with the intention of providing an engineering tool for use in spacecraft design studies, and for the assessment of the impact of the space environment upon spacecraft.

The two programmes are harmonised and co-ordinated to produce a cohesive and comprehensive study. The programme contents are described in more detail in the remainder of this paper.

2. LARGE BODY PLASMA WAKE FORMATION

2.1 Introduction

A spacecraft moving through the LEO plasma does so at a velocity which is hypersonic with respect to the ambient ions, but subsonic with respect to the electrons. This flow condition is referred to as mesothermal, and the motion of the spacecraft will give rise to "plasma aerodynamics" effects. The wake structure caused by the spacecraft, and the associated potential distribution perturbations about the body, will play a critical role in such areas as spacecraft charging, the excitation of turbulence and electromagnetic noise, diagnostic equipment positioning, communications links, etc.

A thorough understanding of the fundamentals of the interaction of large bodies in the LEO ionosphere is a necessary first step towards the study of spacecraft charging and other problems of current interest. Likewise, the conditions in the ionosphere (and in particular in polar orbit) must be quantified and rationalised in order for any computational or experimental work to result in accurate simulation and prediction of the spacecraft - ionosphere interactions.

A large amount of work, both theoretical and experimental, has gone into the study of plasma wakes around vehicles moving in the ionosphere. However, the vast majority has been for the case where the body dimensions are of the order of, or less than, the Debye length λ_D, in the ambient plasma. For the case of large spacecraft, where the R/λ_D ratios are of the order of 100 or more, then there is little previous work to rely on, with the exception of some very recent STS data.

Experimentally, the largest bodies that have been investigated generally had a dimension to Debye length ratio of 40-50, and were simple cylinders or spheres. The wake behaviour was probed axially downstream of the body. While not as complex as the wake produced by small obstacles, there was still structure to be seen and the general characteristics were sufficiently different to those of smaller bodies to discourage extrapolation from one to the other. The potentials applied to the bodies were also modest and not representative of those anticipated in a polar orbit. In addition, the parameter variations (Debye length, ion speed ratio, etc.) were limited.

Computationally and theoretically the situation is somewhat more optimistic. Until relatively recently the largest body modelled has been of the order of 25 Debye lengths. However, in the past few years larger body dimensions have been investigated. At present this has only been carried out using one method of computation and comparison with results from a different mathematical approach is needed. Again, the parametric variation has been limited.

Work carried out for ESA/ESTEC (Coggiola et al, 1988) has shown that the case where the rear of a large spacecraft is shielded from ion fluxes, as a result of the wake set up by its motion through the plasma, and where a large, energetic electron stream is being collected can result in differential charging levels of many kilovolts. This in turn, has the effect of modifying further the potential and density contours about the body and leads to a very complicated flow-field structure. It is this structure that must be better investigated and understood before extensive programmes of work into the detailed mechanisms of the charging problem are embarked upon.

2.2 Computational Simulation

The computational simulation work uses an existing computer code SATIN3, which is a much enhanced version of a code used in previous work (Martin, 1974).

This program represents the distribution of ions by a cold beam and the distribution of electrons by the Boltzmann factor i.e. "cold ion" approximation. The method of solution of the coupled Vlasov-Poisson equations for particle density and electric potential is via the use of flux-tubes. In this method the flux of particles in the tube is constant, and the tube is defined by two neighbouring trajectories. Since the cross-sectional area of the tube is known from trajectory calculations, and the particle velocity is also known, the particle density at any point in the tube can be computed. The flow field being investigated is represented by a mesh array of points and the calculated density is assigned to the nearest grid point along the path of the tube. The flux tube evolution is followed from far away towards the body, and the solution method is therefore one of the family of "outside-in" techniques.

The program can solve for the cases of a disc, with axisymetric rotation about the centre axis, or for a long plate (both bodies are transverse to the plasma flow). Input variables such as ion mass, satellite velocity, body potential etc. are provided for control of the modelling. Large bodies (of the order of 100 Debye lengths) have been modelled in work to date. The limit will probably be set by computer time (and cost) considerations, but this is offset to some extent by the relatively fast computational speed of the program.

The major disadvantage of the code is that the method of solution fails if trajectories attempt to cross over or to reverse direction; a condition which is velocity dependent but in practice occurs at dimensionless body potentials of - 35 to - 40, where this is defined as the body potential divided by the electron temperature (in electron volts). However, the code will also tackle the case of a second body (or surface) immediately in the shadow of the main body i.e. representative of a high level of differential charging at the rear of the body. In this case, second body potentials as low as - 5,000 have been modelled.

The code has a wide range of graphical output options, including colour contour plotting using customised subroutines. Figure 1 shows an example of the ion density contours and an isometric representation of this and Figure 2 shows the potential and density contours for a disc, with a dimensionless body potential of - 4 and an area immediately behind this with a potential of - 5,000.

As well as this numerical work, the output from the computer runs are being used as data for input into the development of semi-empirical models (Martin, 1974; Stone, 1981) which predict the wake dimensions and shape as a function of parameters such as body size, spacecraft Mach number and spacecraft potential. As an example, Figure 3 shows a comparison of numerical data (points) with semi-empirical model fits (solid lines), for the variation of the length of the wake behind a body as a function of Mach number, for three different sized bodies.

2.3 Experimental Simulation

The experimental work is being carried out in a large LEO plasma simulation facility at Culham. Some relevant details of the facility are given in Table 1, together with the corresponding characteristics of the test facility at the Norwegian Defence Research Establishment (NDRE) (Troim, 1989), used in work to be discussed in the next section.

Facility calibration has been carried out with a range of diagnostics mounted in the facility to determine the range of plasma temperatures and densities which can be produced. This allows the corresponding range of orbital altitudes which can be simulated in the facility to be evaluated. In terms of LEO plasma environment simulation, altitudes between 200 km and around 1,000 km can be simulated. Ion Mach numbers of M = 10 can be simulated, which is somewhat higher than conditions found in LEO. The hypersonic characteristic of the flow should be well modelled, nevertheless.

The experimental programme will map the interaction of large bodies with the above simulated environment. A range of spacecraft size, spacecraft velocity (Mach number) and body potential will be used. The plasma flow fields will be mapped, both axially and radially. The validity of the simulation (scaling laws, facility background pressure effects, etc.) will be investigated. A comparison will then take place of numerical and experimental wake interaction results, together with a critical assessment of the validity or otherwise of each approach.

Critical issues raised by the numerical and experimental work will then be identified, and their impact upon large bodies in LEO, and the proposed Polar Platform in particular, will be investigated. Areas of incomplete assessment will be indicated, together with proposals to rectify this.

3. SPI AND ELECTROMAGNETIC EFFECTS

3.1 Introduction

The second programme of work to be described is wider ranging than that discussed in Section 2 above, and involves the coverage of a wide range of SPI topics.

As background to the study, the concern and activity in Europe over high levels of spacecraft charging in geostationary orbits was referred to above. Interest in the behaviour in LEO was started by the realisation that auroral precipitation zones could cause the same types of effects, with impact on spacecraft, and particularly on large structures (Parks and Katz, 1980). These early numerical studies were followed by evidence from sensors on-board the DMSP spacecraft that suggested that charging up to kilovolt levels did indeed occur (Gussenhoven et al, 1985). Preliminary laboratory experiments (Coggiola et al, 1988; Coggiola, 1988) suggested that high levels of charge could be sustained on a model spacecraft, even in conditions where a relatively high plasma background level was present.

A wide-ranging review of the available literature was carried out, to identify and focus on the effects that may be of great concern for future missions. Topics covered included the effects caused by the hypersonic spacecraft motion through the plasma, the effects caused by exposure to high energy auroral electron fluxes, effects on solar arrays operating in the relatively dense plasmas in LEO, the effects of contamination (both of the spacecraft itself, and by the spacecraft on the ambient neutral and plasma environment), and effects leading to the generation and emission of plasma waves and electromagnetic radiation.

This review, which was written as a detailed and self-contained document, formed the basis for the choice of content of the current programme of work, described in more detail below.

3.2 Computational Simulation

The interaction of a space vehicle with its surroundings in low Earth orbit is a complex phenomena and no simple description will allow all the features to be adequately quantified. The use of computer codes, does, however, provide the spacecraft designer with a powerful tool to analyse some of the effects since many of the physical processes occurring may be included in such codes. Nevertheless, despite the potential of computational methods, it is not realistic, at present, to design a code which includes all the physical processes that may be present in a rigorous and self-consistent manner. Instead it is proposed that a suite of codes be provided each of which will perform an analysis of the spacecraft/plasma interaction on the basis of a specific but restricted set of assumptions. While each code individually will allow only part of the problem to be addressed the entire suite will allow a much more complete picture to be obtained.

The software being developed will consist of a suite of programs, written in a modular manner, allowing further program additions to take place without disrupting the overall software package. Each program within this suite is assigned to a particular level, generally reflecting the complexity of the program, and of the problem being studied, and also reflecting the level of familiarity required to run and interpret a particular program. Three levels are proposed and these are described in more detail below.

Level 1 is the simplest level of software. It is intended to allow someone unfamiliar with the subject of spacecraft/plasma interactions to define a particular spacecraft and mission requirement, in outline terms, and the software should then determine the characteristics of the space environment which may then be used in more specialised programs in order to study the problem further. Input to the software will consist of, information on the orbital characteristics (altitude, inclination), mission characteristics (time of launch, duration) and spacecraft characteristics (size, materials, solar array dimensions).

The software will interpret this input in terms of plasma interaction parameters relevant to the problem assessment (densities, temperatures, Debye length, high energy particles) as a function of the input parameters (altitude, inclination, time of launch, mission duration).

Level 2 represents a more complicated set of software than Level 1, but still consists of programs which a non-specialist should be capable of running and interpreting. It will consist of several independent programs, each simulating a particular aspect of spacecraft/plasma interactions. At the initial stage, each program will be stand alone, requiring separate dedicated input. The programs will, however, be written in such a way that future enhancements to the software should allow a common data input set to be used with the programs, and commonality of data input will be implemented from the outset.

The types of software intended to be provided at Level 2 are as follows:

a) A program which gives an estimate of the charge that a body would acquire in a plasma. Analytical relationships will be used, and the code should have a rapid turn-around. Different materials and plasma conditions should be able to be input by the user.

b) A program which gives an estimate of the current collection, and associated power loss, that a solar array would experience in a plasma. Empirical relationships, from laboratory simulations and in-orbit testing will be used. Different voltages and plasma conditions should be able to be input by the user.

Additional programs may be added to this level at a future date. An example would be:

c) A program which gives an estimate of the wake extent and structure that a body would create in moving through a plasma. Semi-analytical relationships from laboratory simulations and in-orbit experiences would be used. Different body characteristics and plasma conditions should be able to be input by the user.

Level 3 represents the most complex set of software, requiring specialist knowledge to run and interpret. It will consist of several independent programs, each simulating a particular aspect of the spacecraft/plasma interactions in detail. The programs may be large and may require substantial amounts of CPU time to run, but anticipated continuing improvements in computer power may alleviate this problem in the medium term. Each program will stand alone, and will require a dedicated data input set.

The types of software intended to be provided at Level 3 are as follows:

a) A program which gives a self-consistent solution, using particle-mesh numerical methods, to the charge that a body would acquire in a plasma. Different materials and plasma conditions should be able to be input by the user. The output will be written to dedicated files, and a wide range of post-processing options will be available, particularly graphical representation.

b) A program which gives a self-consistent solution, using particle-mesh numerical methods, to the particle and potential distribution about a body moving through a plasma. Different body characteristics and plasma conditions will be able to be input by the user. The output will be written to dedicated files, and a wide range of post-processing options will be available, particularly graphical representation of the output to enhance interpretation.

As in Level 2 other programs could be integrated into this level.

The proposed structure of the Spacecraft/Plasma Interactions and Electromagnetic Effects program suite is illustrated in Figure 4. Five codes will be developed encompassing all three levels. These codes are as follows:

LEOPOLD	Determination of the characteristics of the low Earth and polar orbit environments. This software is being written at Culham.
EQUIPOT	Analysis of material charging in the low Earth and polar orbit environments. A 0-d code. This package is being written at RAE (Wrenn and Sims, 1989).
SOLARC	Analysis of the current collection and associated power loss of solar arrays in the LEO and polar orbit environments. Again a 0-d code. This software is being written at Culham.
PICCHARGE	Detailed analysis of spacecraft charging and local plasma modification in the LEO and polar environments. A 2-d or 2.5-d code. This package is being written at MSSL.
SAPHIRE	Detailed analysis of ram and wake flows due to a charged spacecraft in the LEO and polar orbit environments. A 2-d code. This package is being written at Culham.

(It should be noted that the code names are at this stage only tentative.)

As an example of the way the codes in the suite interelate, it is envisioned that the user will use the Level 1 software code LEOPOLD to generate the basic space environment data such as particle densities, temperatures and average ion masses that may then be used as part of the input data to the codes at higher levels. Whilst initially and within the current study this will be performed manually, further development will allow this operation to be performed automatically.

As as further example, the use of the Level 2 code EQUIPOT will allow the user to obtain rapid information as to the extent of charging likely for a given material. If a more detailed analysis is required the user will then use PICCHARGE to obtain a detailed and accurate picture of the charging level to be expected.

3.3 Experimental Simulation

The content and scope of the proposed experimental programme will be such that model geometries, plasma conditions, and diagnostic measurements will provide a direct comparison with the output of the computational codes being developed in parallel with this work. The comparison of experimental data and computational output is an essential part in the evolution of accurate, reliable, and validated computational tools. The experimental programme will also aim to provide a complete and self-consistent set of measurements, and to characterise the plasma phenomena over as wide a range of relevant parameters as is feasible within the constraints of the study.

Two main areas of prime concern are being investigated. The first of these is a study of the interaction of a streaming plasma with various bodies of relatively simple geometry, in conditions relevant to the ionosphere. The second area is the charging of bodies with conducting and dielectric materials subjected to the high energy electron bombardment characteristic of the auroral regions, both with and without the presence of a streaming plasma.

The experimental work will be carried out in the LEO plasma simulation facilities at Culham and NDRE, some details of which were given in Table 1. At Culham, the facility has the advantage of greater size, much greater pumping speed, and lower base pressure (several orders lower than the typical working pressure quoted in Table 1). In general more detailed measurements will be taken than at NDRE. The effect of pressure variation on the slow ion fraction in the facility will be investigated, to validate the wake measurements. The wake measurements themselves will be performed for a variety of relevant operating parameters.

The complete list of parameters to be varied, measurements to be made, and the diagnostic requirements which these imply, is necessarily limited by the scope of the overall study, and a trade-off between the experimental and other major aspects of the study must be made. In particular, the balance between the software development requirements, and the need for experimental understanding and validation of codes has been considered carefully.

At NDRE the facility has the ability to vary the ambient magnetic field in the plasma, via the use of an array of Helmholtz coils. The main objective will be to establish the effects of the magnetic field on the properties of the wake region behind a body. The field will be varied to give less than 0.02 gauss throughout the controllable region, 1 gauss in the y-direction, 1 gauss in the z-direction, and a field duplicating the fixed field measured in the Culham facility.

For the charging studies, two models are proposed to provide direct comparison with the computer codes. The first of these consists of a metal plate, illustrated in Figure 5, which can be biased by an external supply. Along the centreline are positioned a number of isolated plugs, designed so that the insulator is not directly irradiated by the electron gun. The charging of these under different conditions will be measured externally using a high impedance probe.

The second model is also a metal plate, illustrated in Figure 6, which can be biased by an external supply, or left electrically floating. Provision will be made for attaching one or more smaller segments of a variety of dielectric materials. The aim is to determine how the presence and irradiation of a significant area of dielectric alters the charging of the model under various conditions.

The measurements to be made in each of the above cases consist simply of the potentials either of the metal plugs or the model as a whole. As with the wake simulation studies, the range of parameters to be varied must necessarily be restricted.

While the experimentation will be carried out at Culham and NDRE, the data will also be made available to MSSL and Graz. All four organisations will participate in data analysis and interpretation. The latter two organisations are also providing diagnostic equipment to be used in addition to the standard diagnostics already available.

MSSL are developing a miniature microchannel plate analyser with good angular resolution and excellent charge/mass and energy resolution, of such a size that perturbation of the ambient plasma should be kept to a minimum. Such an analyser should give far greater sensitivity than a conventional retarding potential analyser and this should be very valuable when measuring ion directional information by rotating the analyser.

The Technical University of Graz has produced a compact probe consisting of a small sphere surrounding by a grid. This is a scaled down version of a diagnostic which has been successfully flight tested. When biased negative in the ion saturation region, the sphere acts as an ion probe, providing data on ion current and density. It can also be used as a Langmuir probe, by applying a sweeping voltage and measuring the current response. This should provide the electron temperature and an estimate of the electron density and plasma potential. To minimise stray fields, the correct grid potential and open area are clearly important.

In addition to the main programme described above, it is proposed to perform two other simulations at Culham, with interpretation taking place at all locations. The charging of a second body, such as a small sphere in the wake of a larger body, subject to electron irradiation will be investigated. This relatively simple experiment may elucidate the two body problem, and provide information and a starting point for future investigations.

It is also proposed to investigate the effects on the wake of ejecting a stream of gas from the downstream side of one of the existing models. The aim is to simulate crudely the effects of outgassing or thruster firing. As with the two body charging experiments, the extent of any measurements will be limited. Previous investigations (Martin and Barton, 1974) suggest that the effects on the wake of introducing the gas locally are quite different to those obtained by raising the ambient gas pressure. Again, this work would aim to determine whether further or more detailed investigations are warranted.

4. CONCLUSIONS

As input to the two studies described above a wide range of spacecraft/plasma interactions and their effects have been discussed. Many hold potentially serious implications for future large, long lived, active structures in space, and in some cases could adversely affect the operation and safety of such systems.

Laboratory experiments can adequately simulate the space environment and its interaction with spacecraft, but attention must be paid to the validity of the simulation. Plasma wake studies have generally only covered small to medium vehicles. A reasonable data base on solar array interactions exists. Spacecraft charging studies in polar orbit conditions are in their infancy.

Numerical and computational studies can aid in interpretation of the interaction phenomena and, to a lesser extent, in spacecraft design. The assumptions inherent in several codes limit their application to design activities, until a more fundamental understanding of the basics behind the interactions has been achieved.

There is a large literature concerned with space-based experiences, but interpretation is, at times, difficult and contradictory. Vehicle charging in polar orbits has been indicated, and the adverse effects that active beam emissions can have on vehicles are well established. Again, a reasonable data base on solar array interactions exists, but it should be noted that this is in conflict with ground data.

It is hoped that the work described in this paper will make a significant contribution to the study of spacecraft/plasma interactions, and to the methods used in designing future spacecraft.

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Table 1 LEO Plasma Simulation Facility Characteristics

Parameter	Culham Facility	NDRE Facility
Maximum diameter (m)	1.3	0.96
Total length (m)	5.9	2.0
Total volume (m^3)	7.8	1.45
Type of pumping	Liquid helium and turbopump	Liquid helium and turbopump
Pumping speed (N_2) (ℓ/sec)	75,000	1,500
Working pressure (mbar)	5×10^{-6}	6×10^{-6}
Magnetic field	Earth	Variable

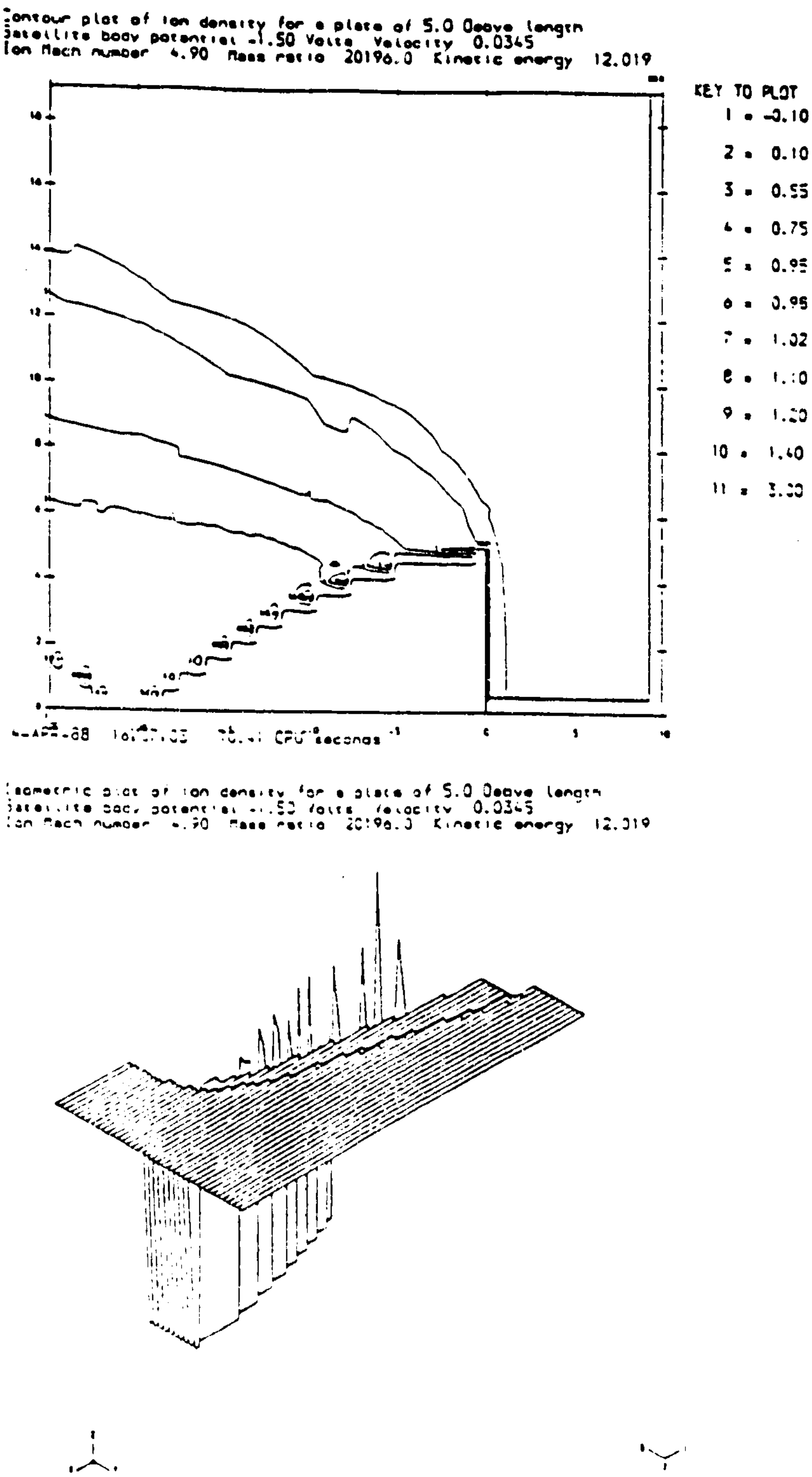

Figure 1 <u>**An example of density data generated by SATIN3.**</u>

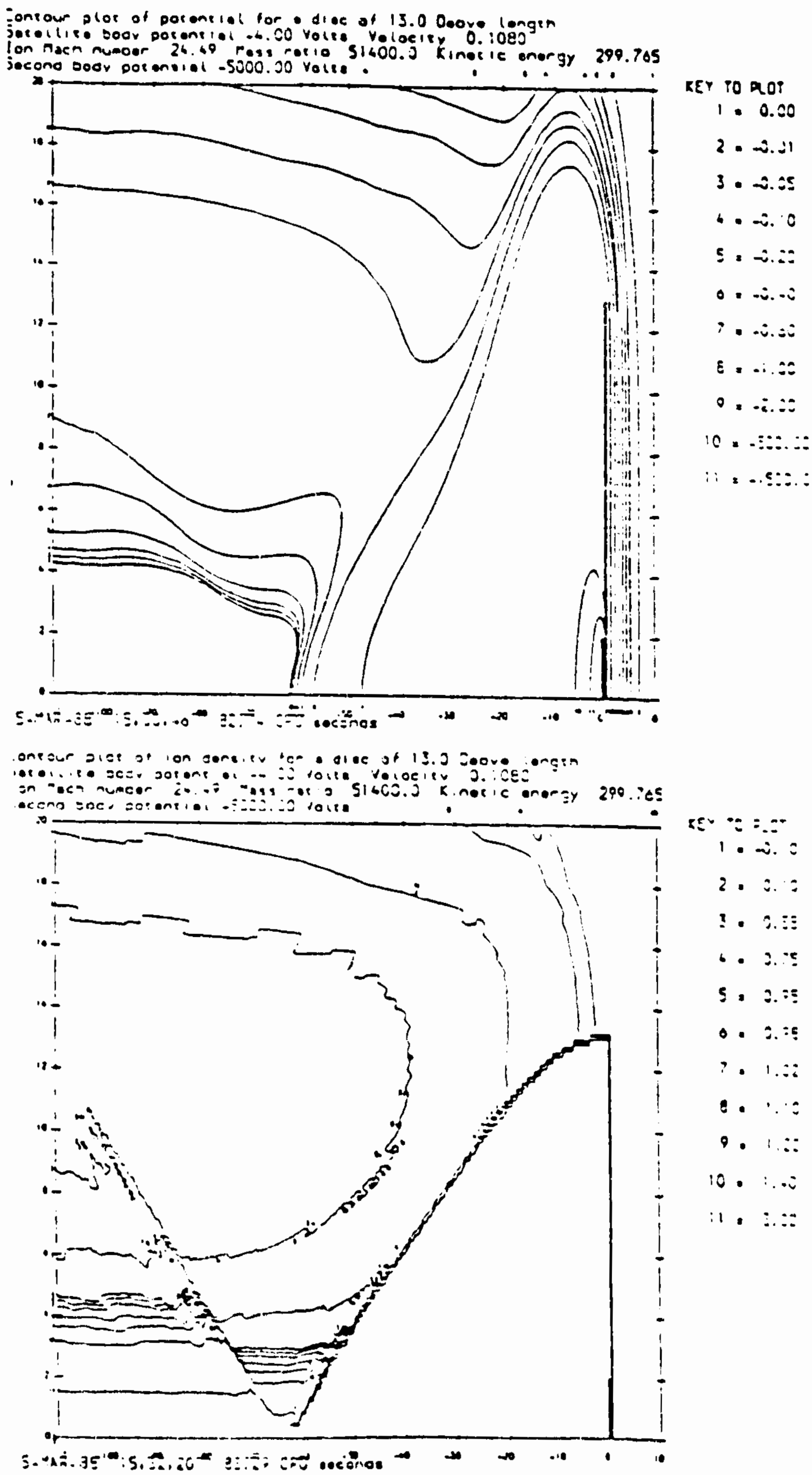

Figure 2 <u>**SATIN3 simulation of a body with differential charging.**</u>

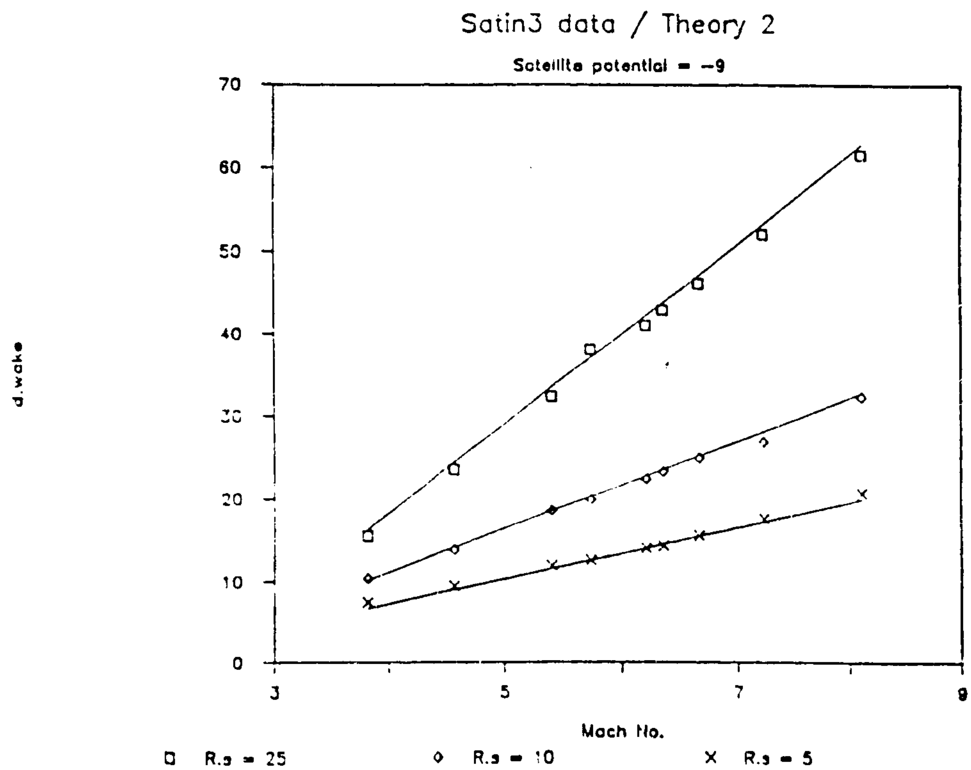

Figure 3 Comparison of SATIN3 data with a semi-empirical model for the wake dimension.

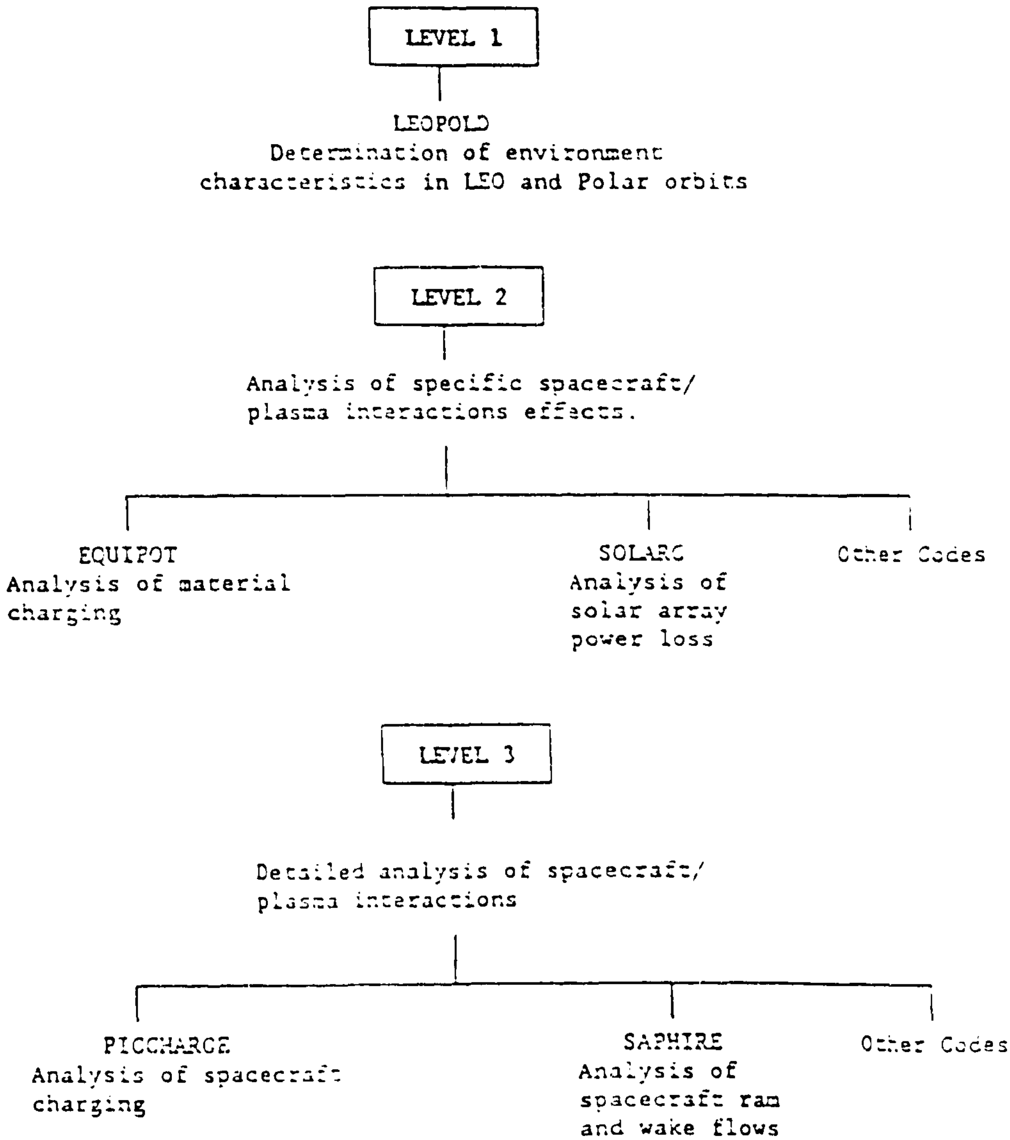

Figure 4 <u>**Spacecraft/plasma interactions and electromagnetic effects program suite.**</u>

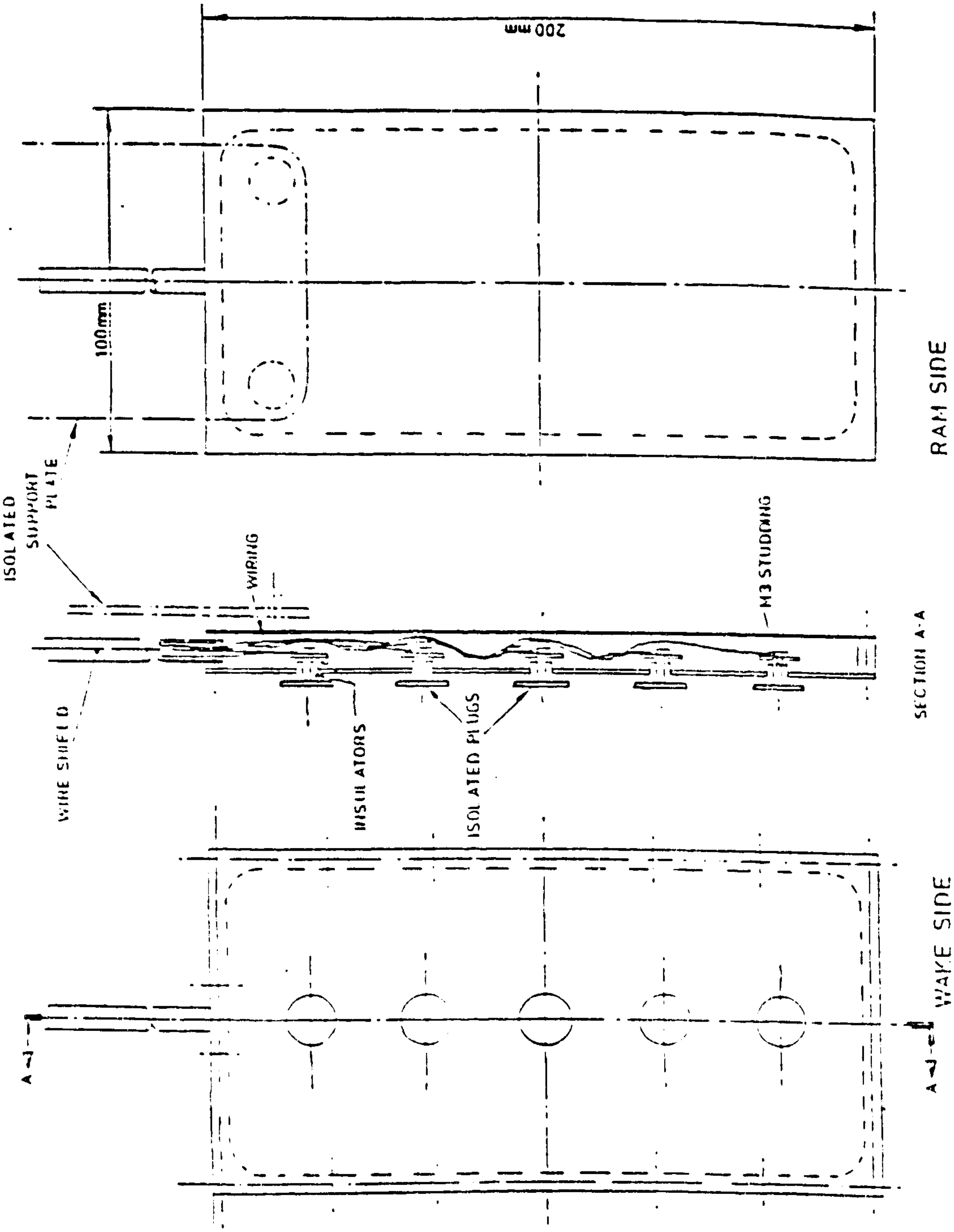

Figure 5 **Schematic diagram of the model with isolated plugs, to be used in charging experiments.**

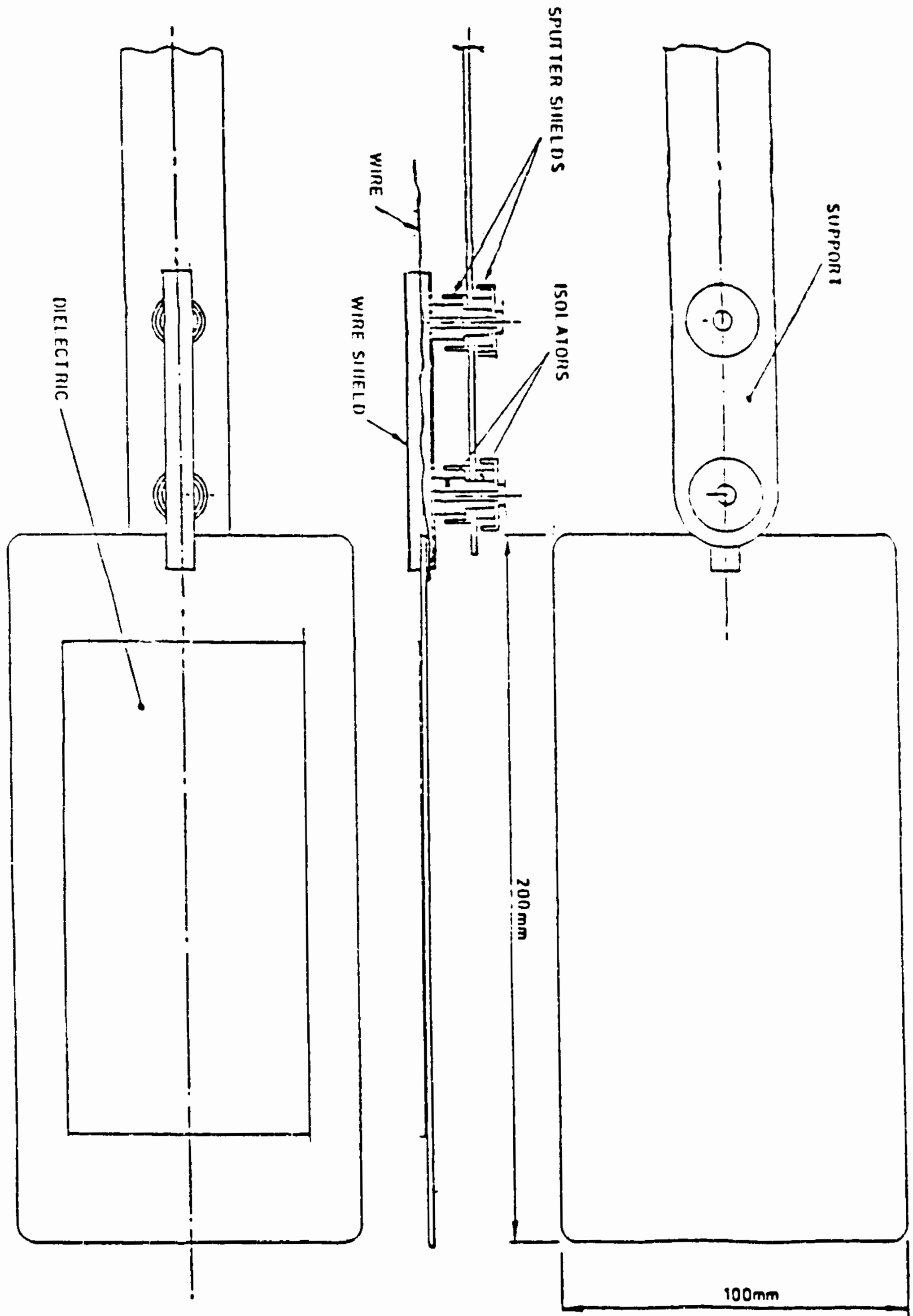

Figure 6 **Schematic diagram of the model with dielectric segments, to be use in charging experiments.**