SIMULATIONS OF SOLAR WIND PLASMA FLOW AROUND A SIMPLE SOLAR SAIL

INTERACTIONS OF SPACECRAFT AND SYSTEMS WITH THE NATURAL AND INDUCED PLASMA ENVIRONMENT

Henry B. Garrett
The Jet Propulsion Laboratory,
The California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-2644
Henry.Garrett@jpl.nasa.gov

Joseph Wang
Department of Aerospace and Ocean Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0203
540-231-8114
jowang@mail.vt.edu

Abstract

In recent years, a number of solar sail missions of various designs and sizes have been proposed (e.g., Geostorm). Of importance to these missions is the interaction between the ambient solar wind plasma environment and the sail. Assuming a "typical" 1 AU solar wind environment of 400 km/s velocity, 3.5 cm^{-3} density, ion temperature of ~10 eV, electron temperature of 40 eV, and an ambient magnetic field strength of 10^{-4} G, a first order estimate of the plasma interaction with square solar sails on the order of the sizes being considered for a Geostorm mission (50 m x 50 m and 75 m x 75 m corresponding to ~2 and ~3 times the Debye length in the plasma) is carried out. First, a crude current balance for the sail surface immersed in the plasma environment and in sunlight was used to estimate the surface potential of the model sails. This gave surface potentials of ~10 V positive relative to the solar wind plasma. A 3-D, Electrostatic Particle-in-Cell (PIC) code was then used to simulate the solar wind flowing around the solar sail. It is assumed in the code that the solar wind protons can be treated as particles while the electrons follow a Boltzmann distribution. Next, the electric field and particle trajectories are solved self-consistently to give the proton flow field, the electrostatic field around the sail, and the plasma density in 3-D. The model sail was found to be surrounded by a plasma sheath within which the potential is positive compared to the ambient plasma and followed by a separate plasma wake which is negative relative to the plasma. This structure departs dramatically from a negatively charged plate such as might be found in the Earth's ionosphere on the night side where both the plate and its negative wake are contiguous. The implications of these findings are discussed as they apply to the proposed Geostorm solar sail mission.

Nomenclature

$\lambda_D = \sqrt{\frac{KT_e}{4\pi ne^2}}$	plasma Debye length (based on electron temperature)
Φ	electric potential
Φ_s	solar sail to ambient plasma potential difference
B_o	solar wind magnetic field
d_{sh}	solar sail sheath thickness
L_x, L_y	solar sail size

n_{sw}	solar wind plasma density
T_e, T_i	electron and ion (proton) temperature, respectively
v_{sw}, v_{ti}, v_{te}	solar wind flow velocity, ion thermal velocity, and electron thermal velocity, respectively
$I_T(\Phi_s)$ =	Total current to/from solar sail; = 0 for current balance at potential $\Phi=\Phi_s$.
$J_e(\Phi_s)$ =	Average electron current per unit area to solar sail at potential Φ_s
$J_i(\Phi_s)$ =	Average ion current per unit area to solar sail at potential potential Φ_s
$JS_e(\Phi_s)$ =	Average secondary electron current per unit area from solar sail at potential Φ_s
$JBS_e(\Phi_s)$ =	Average backscattered electron current per unit area from solar sail at potential Φ_s
$JS_i(\Phi_s)$ =	Average ion induced secondary electron current per unit area from solar sail at potential Φ_s
$J_{pho}(\Phi_s)$ =	Photoelectron current per unit area from solar sail at potential Φ_s
A_e =	Ambient electron impact area
A_i =	Ambient ion impact area
A_{pho} =	Photoelectron emission area

Introduction

In recent years, a number of solar sail missions of various designs and sizes have been proposed. Indeed various groups, both private and governmental, are in the process of building either flight or prototype solar sails. Of potential importance to these missions is the interaction of the ambient solar wind plasma environment with the sail. To evaluate this interactions and establish a baseline for future studies, we will assume a "typical" 1 AU solar wind environment of 400 km/s velocity, 3.5 cm^{-3} density, ion temperature of ~10 eV, electron temperature of 40 eV, and an ambient magnetic field strength of 10^{-4} G. This environment will be used to carry out a first order estimate of the plasma interaction with square solar sails on the order of the sizes being considered for a Geostorm mission (50 m x 50 m and 75 m x 75 m corresponding to ~2 and ~3 times the Debye length in the plasma). As will be discussed in more detail below, the first step will be to carry out a crude current balance for the sail surface immersed in the plasma environment and in sunlight to estimate the surface potential of the model sails (the surfaces in this initial study are assumed to be made of thin, uniformly conducting aluminum). A 3-D, Electrostatic Particle-in-Cell (PIC) code is then used to simulate the solar wind flowing around the solar sail. Assuming that the solar wind protons can be treated as particles while the electrons follow a Boltzmann distribution, the electric field and particle trajectories are solved self-consistently to give the proton flow field, the electrostatic field around the sail, and the plasma density in 3-D. The sail is found to be surrounded by a plasma sheath within which the potential is positive compared to the ambient plasma and followed by a separate plasma wake which is negative relative to the plasma. The structure departs dramatically from a negatively charged plate such as might be found in the Earth's ionosphere on the night side where both the plate and its negative wake are contiguous. Finally, the implications of these findings are discussed as they apply to a sample mission, the Geostorm Solar Sail.

Basic Characteristics

Spacecraft in the interplanetary environment experience a number of effects from the sun: surface charging (either positive or negative) and/or deep dielectric charging that can result in damaging arcs, UV and radiation effects on materials, and plasma wake or sheath effects that could impact experiments or instruments on the spacecraft. Of importance here are plasma interaction effects due to the solar wind. The solar wind is a fully-ionized, electrically neutral, magnetized plasma that flows outward from the Sun. The solar wind plasma in interplanetary space can vary over a wide range: from <1 cm^{-3} to ~80 cm^{-3} in density, from ~200 km/s to over 2000 km/s in velocity, and from 0.5 eV to ~100 eV in temperature. Although the solar wind is highly variable,

in this study we will concentrate on the typical or average solar environment in order to establish a baseline for future studies. We will thus assume the following "average" solar wind parameters for our test environment:

$$v_{sw} \sim 400\ km/s;\ n_{sw} \sim 3.5\ cm^{-3};\ T_i \sim 10\ eV;\ T_e \sim 40\ eV;\ B_o \sim 10^{-4}\ Gauss$$

(For simplicity, here we only consider the core population for the solar wind electrons and ignore the halo population.)

Based on these solar wind parameters, the following basic plasma parameters can be determined:

$$\lambda_D \sim 25\ m;\ v_{te} \sim 2.65 \times 10^3\ km/s;\ v_{ti} \sim 30\ km/s;\ c_s = (T_e/m_p)^{1/2} \sim 62\ km/s$$

$$\Omega_i \sim 1\ rad/s;\ \Omega_e \sim 1.8 \times 10^3\ rad/s$$

The basic characteristics of the solar wind flowing around a solar sail are thus the same as that of a collisionless, mesothermal plasma flowing around an obstacle. That is, since the solar wind flow is such that $v_{ti} << v_{sw} << v_{te}$,, the plasma is mesothermal. Moreover, as both the ion gyroradius, $r_{ci} = v_{sw}/\Omega_i \sim 400$km, and the electron gyroradius, $r_{ce} = v_{te}/\Omega_e \sim 1.5$ km, are much larger than the typical solar sail dimension ($L_{sail} \sim 100$m), the solar wind flow may be considered as an unmagnetized, collisionless plasma flow for our problem.

The floating potential of the solar sail relative to the ambient solar wind plasma can be estimated from current balance (Garrett, 1981). That is, for a thin, conducting aluminum sheet, it is assumed that current balance is given by:

$$\begin{aligned} I_T(\Phi_s) = 0 = -A_e \cdot J_e(\Phi_s, T_e, n_{sw}) + A_i \cdot J_i(\Phi_s, T_i, n_{sw}) + A_e \cdot JS_e(\Phi_s, T_e, n_{sw}) + \\ + A_e \cdot JBS_e(\Phi_s, T_e, n_{sw}) + A_i \cdot JS_i(\Phi_s, T_i, n_{sw}) + A_{pho} \cdot J_{pho}(\Phi_s) \end{aligned} \quad (1)$$

An accurate calculation of the solar sail floating potential requires knowledge of the detailed spacecraft specification so that all the current sources can be properly accounted for. In this paper, we shall consider a very simple geometric model—a conducting flat plate. For the solar wind conditions listed in section I, the assumed model (Garrett, 1981) estimates that the floating potential in sunlight ranges $\Phi_s \sim -6$ V to ~ -14 V based on the details of the current collection (e.g., ion ram current, orbit limited, etc.). Hence, in this study, we take the sail potential to be $\Phi_s \sim -10$ V .

Simulation Model

A 3-D, Electrostatic Particle-in-Cell (PIC) code is used to simulate the solar wind flowing around a solar sail. In this code, the solar wind protons are treated as particles. The electron component is assumed to be an isothermal fluid and hence its density follows the Boltzmann distribution. The electric field and particle trajectories are then solved self-consistently. A dynamic alternating direction implicit (DADI) solver is used to solve the nonlinear Poisson's equation in a 3-dimensional space. More detailed description of the code can be found in Wang et al. (2001).

The model setup is shown in Fig.1. When geometric symmetry is considered, the simulation setup needs to include only a quarter of the sail. The $x = 0$ and $y = 0$ boundaries are symmetric surfaces while all other boundaries are "open" boundaries. Macro-particles representing the solar wind protons are injected into the simulation domain along the z axis at every time step. The solar sail is taken to be a conducting, thin plate with the assumed 10 V potential.

Simulation Results

As a base model, we consider a square conducting sail with dimensions of $Lx = Ly$. Table 1 listed the solar sail sizes being considered for the Geostorm mission: $Lx = 50$ m for Sail-1 and $Lx = 75$ m for Sail-2, respectively. If one normalizes the dimension by the electron Debye length, one finds that the two sail sizes are $Lx/\lambda_D \sim 2$ and $Lx/\lambda_D \sim 3$, respectively. For these dimensions and an assumed sail potential to be $\Phi_s \sim 10$ V, the model parameters for Geostorm simulations have been determined and are listed in Table 1 in both normalized units and physical units. A series of test runs with varying resolutions were performed to ensure that the results do not depend on the simulation parameters.

Geostorm Solar Sail Results

The simulations results for the two sails considered are shown in figures 2 and 3. In each figure, the top panel shows electric potential contours on a z-y plane cutting through the center of the sail; the middle panel shows potential contours on a x-y plane containing the sail surface, and the bottom panel compares the potential profile along a z-axis through the center of the sail surface and that along a z-axis through the center of the sail edge. The following conclusions can be drawn from the simulations:

- The sail is surrounded by a plasma sheath (within which the potential is positive compared to ambient) and followed by a plasma wake (within which the potential is negative).
- The plasma sheath in the ram side starts at a distance of ~2 λ_D in front of the sail, or a distance of ~50 m in front of the sail for the typical solar wind conditions listed in section 1.
- For the two solar sail sizes considered, the sail size has a minimum effect on the plasma sheath. (Although the potential in the wake region is significantly different.)
- While the plasma sheath extends to a distance of ~50 m in front of the sail, its effects on solar wind electron measurement made near the sail surface should be minimum. This is because the solar sail floating potential is only about 10 V while the solar wind electron temperature is $T_e \sim 40$ eV. However, the sheath may have some effects on solar wind proton measurements made within the sheath.

Parametric Simulation Results

To better understand the global structure of plasma sheath and wake, we have also performed parametric simulations for various sail sizes and floating potentials. To generalize the results for different solar wind conditions, we will present results in normalized parameters. (Note that the results scale with the plasma Debye length.) This section presents simulation results for a solar sail with a dimension of $Lx = Ly = 8\ \lambda_D$ (i.e., L ~200 m for the solar wind conditions listed in section 1. For comparison, we also include simulation results for a conducting plate with a negative floating potential. The parametric cases are summarized in Table 2. The results are shown in figures 4 through 8.

It is interesting to compare the plasma interaction of solar sail with that of a large space platform in the ionosphere. A spacecraft in low Earth orbit (LEO) also sees a collisionless, mesothermal plasma flow. However, a LEO spacecraft typically has a negative floating potential. The problem of ionospheric plasma flowing around a large, negatively biased structures has been studied extensively (for instance, *Wang and Hastings*, 1992a,b; *Wang et al.*, 1994, and references therein). In such a problem, the dominate physics is formation of a plasma wake. When the spacecraft flowing potential is low, the wake is formed through plasma expansion. An expansion fan will be generated at plate edge which serves as a presheath to connect the ambient plasma flow

and the plasma sheath surrounding the plate. Hence, for a negatively biased sail, the plasma sheath and wake is a unified structure, as shown in Fig.5. On the other hand, for a solar sail with a positive floating potential, the sheath and wake are two distinct regions. In this configuration, the protons are decelerated within the sheath but still undergo the same expansion process in the wake region.

Conclusions

We find, for base solar wind plasma conditions, that a solar sail is surrounded by a plasma sheath followed by a plasma wake (within which the potential is negative). The sheath thickness in front of the solar sail is a few Debye lengths thick for moderate charging potentials. Since the solar wind Debye length is in the range of $O(10)$ m to $O(10^2)$ m, comparable to typical solar sail dimensions, one would expect to observe some sheath effects within a distance of tens of meters on the ram side. However, since the solar sail floating potential is found to be moderate (a few volts), sheath effects on solar wind measurements performed near the sail are *not* expected to be significant.

Acknowledgements

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References

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Wang, J., and D.E. Hastings, Ionospheric plasma flow over large high voltage space platforms I: Ion-plasma time scale interactions on a plate at zero angle of attack, *Phys. Fluids B*, *4(6)*, 1597-1614, 1992a.

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Wang, J., P. Leung, H. Garrett, and P. Murphy, Multibody-Plasma Interactions: Charging in the Wake, *J. Spacecraft*, *31* (5, September-October), 889-894, 1994.

Wang, J., D. Brinza, and M. Young, Three-Dimensional Particle Simulations of Ion Propulsion Plasma Environment for Deep Space 1, *31* (3, May-June), 433-440, 2001.

Tables

Table 1: Geostorm Solar Sails

	$Lx \times Ly$ (λ^2_D)	Lx (m)	Φs (T_e)	Φs (V)	dsh (λ_D)	dsh (m)
Sail-1	2X2	50	0.25	10	~ 2	~ 50
Sail-2	3X3	75	0.25	10	~ 2	~ 50

Table 2: Parametric Cases

	$Lx \times Ly$ (λ^2_D)	Φ_s (T_e)
1	8X8	.25
2	8X8	-2.25
3	8X8	1.00
4	8X8	-1.00
5	8X8	-10.00

Figures

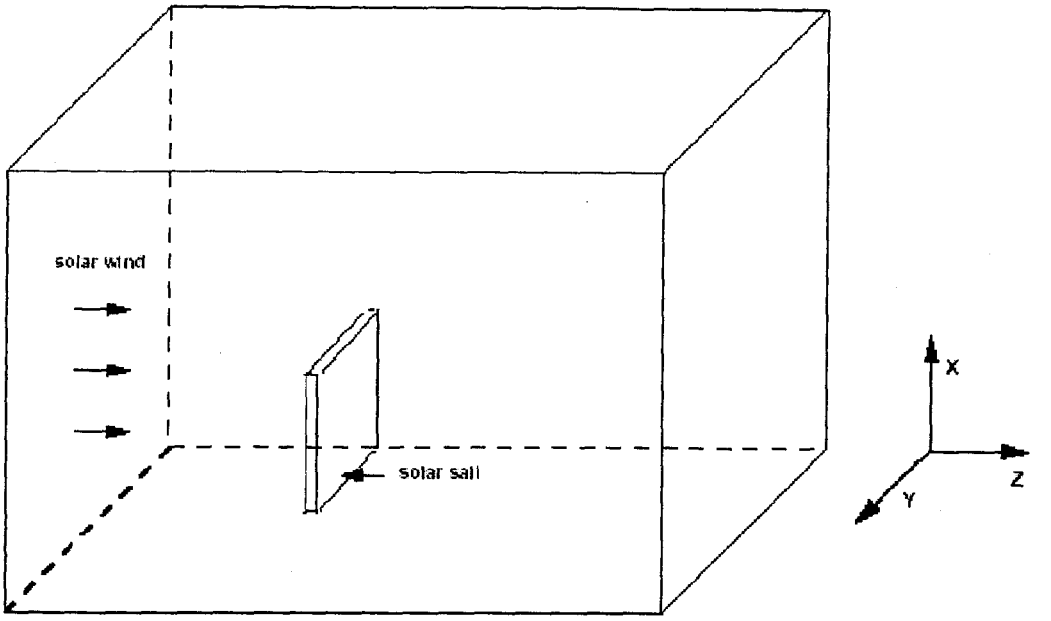


Figure 1: Simulation Setup. 3-D simulations are performed for a quarter size solar sail. Solar sail is modeled as a thin conducting plate with a potential. Solar wind is injected from the upstream surface along the z direction. Solar wind is modeled as particle protons and fluid electrons.

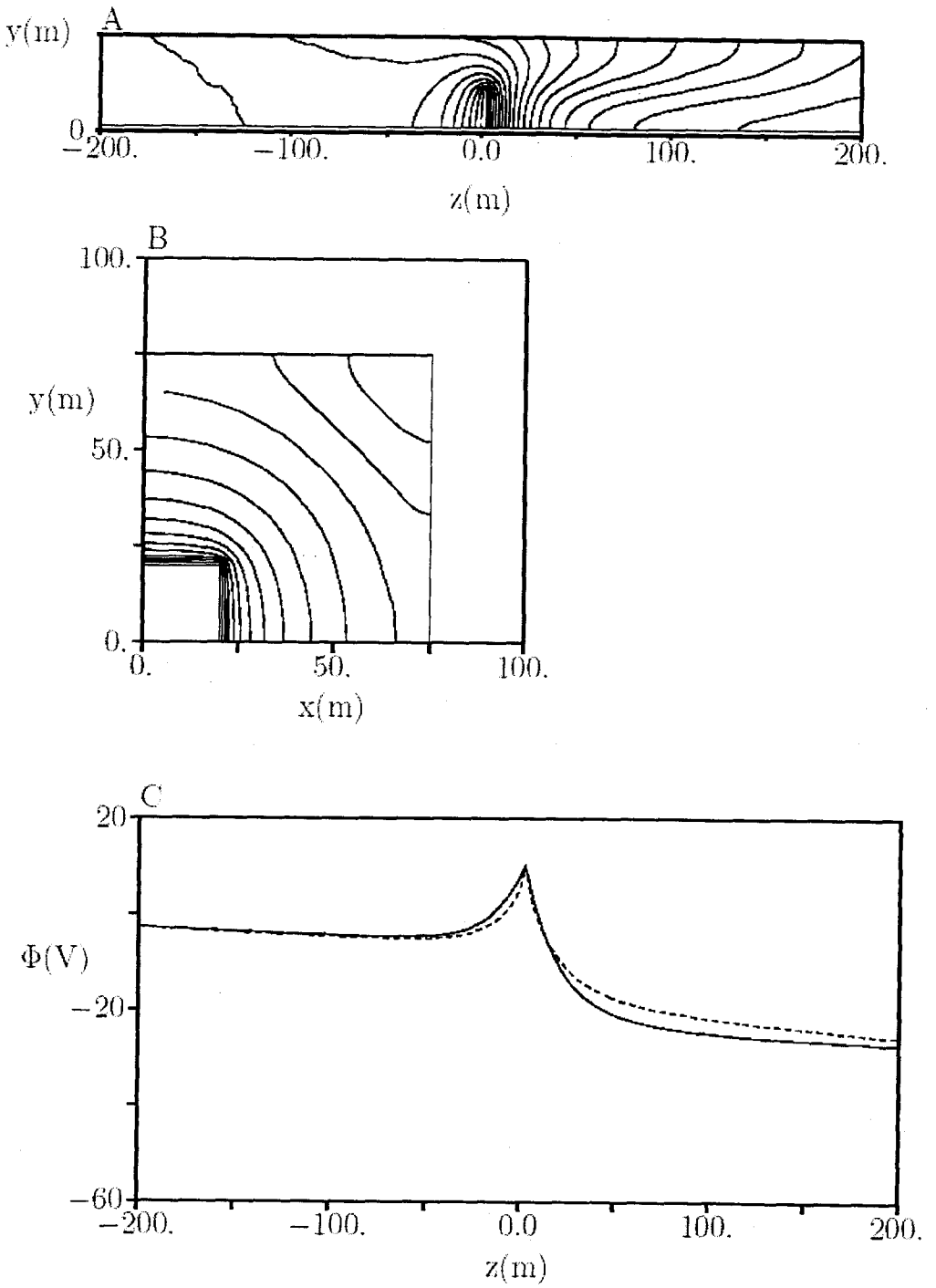


Figure 2: Simulation Results for Sail-1. Dimension: 50 m X 50 m. Sail Potential: 10V. A: electric potential contours on a z-y plane cutting through sail center. B: electric potential contours on a x-y plane containing sail surface. (contour level difference=2 V) C: potential profile along a z axis through the center of the surface and a z axis through the center of the edge.

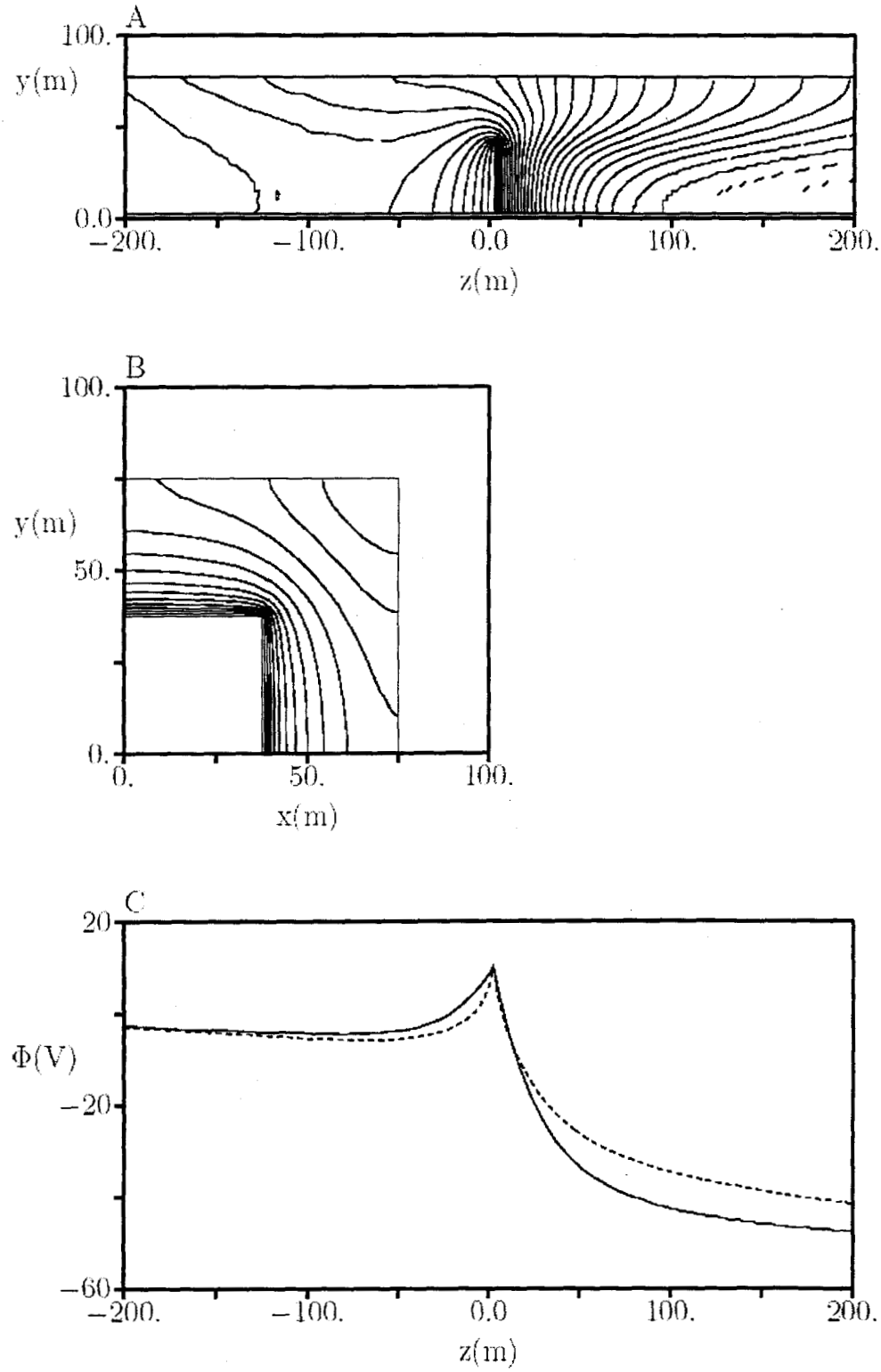


Figure 3: Simulation Results for Sail-2. Dimension: 75 m X 75 m. Sail Potential: 10V. A: electric potential contours on a z-y plane cutting through sail center. B: electric potential contours on a x-y plane containing sail surface. (contour level difference=2 V) C: potential profile along a z axis through the center of the surface and a z axis through the center of the edge.

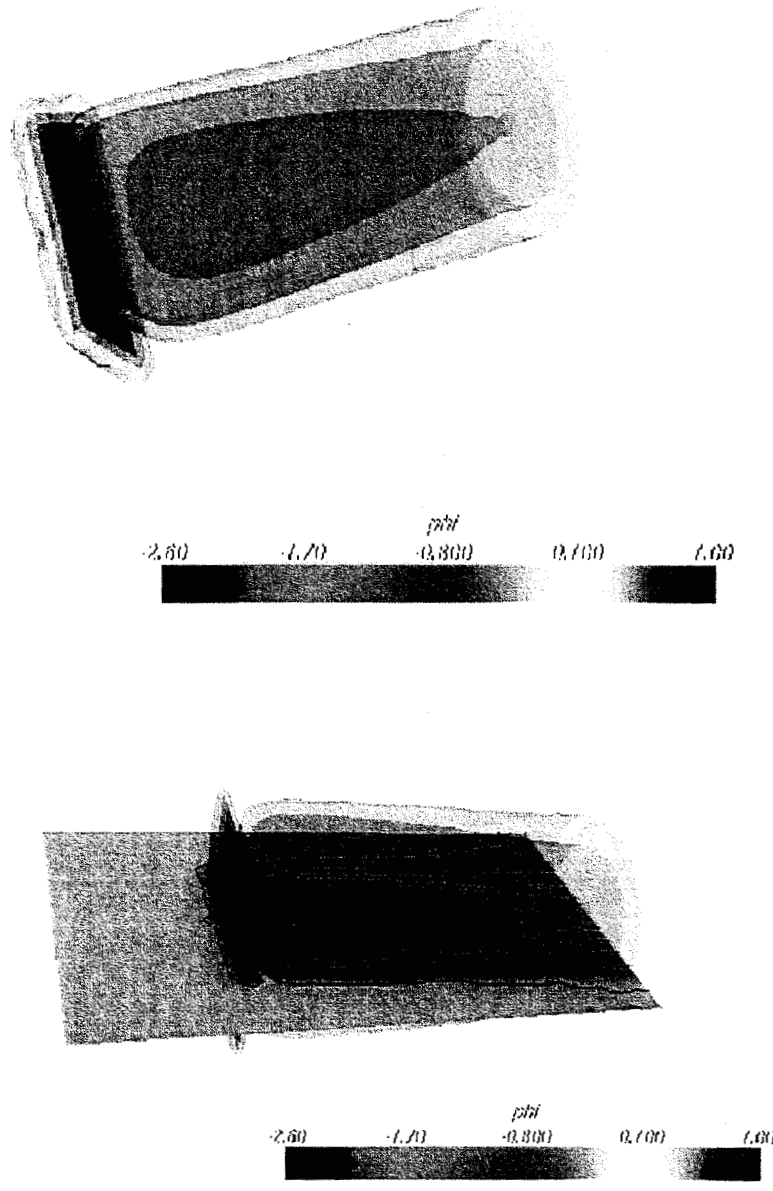


Figure 4: Parametric Case 1. (Potential Isosurfaces. Potential values are normalized by T_e. Sail potential : 0.25 T_e)

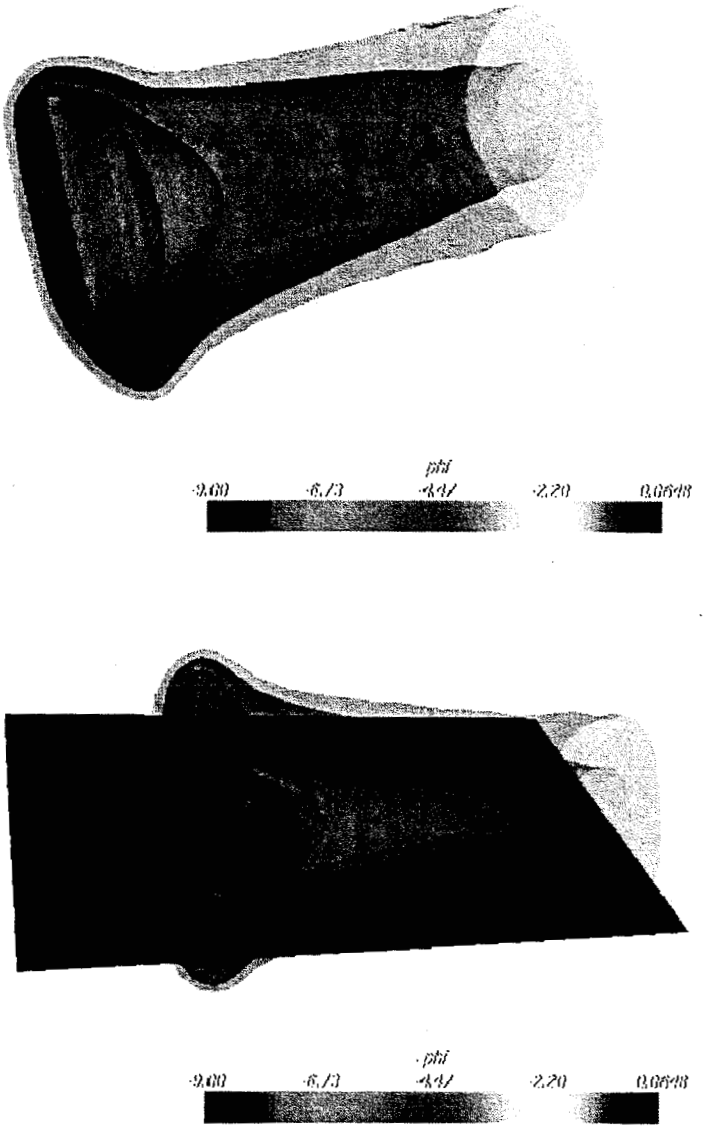


Figure 5: Parametric Case 2 (Potential Isosurfaces. Potential values are normalized by T_e. Sail potential : -2..25 T_e)

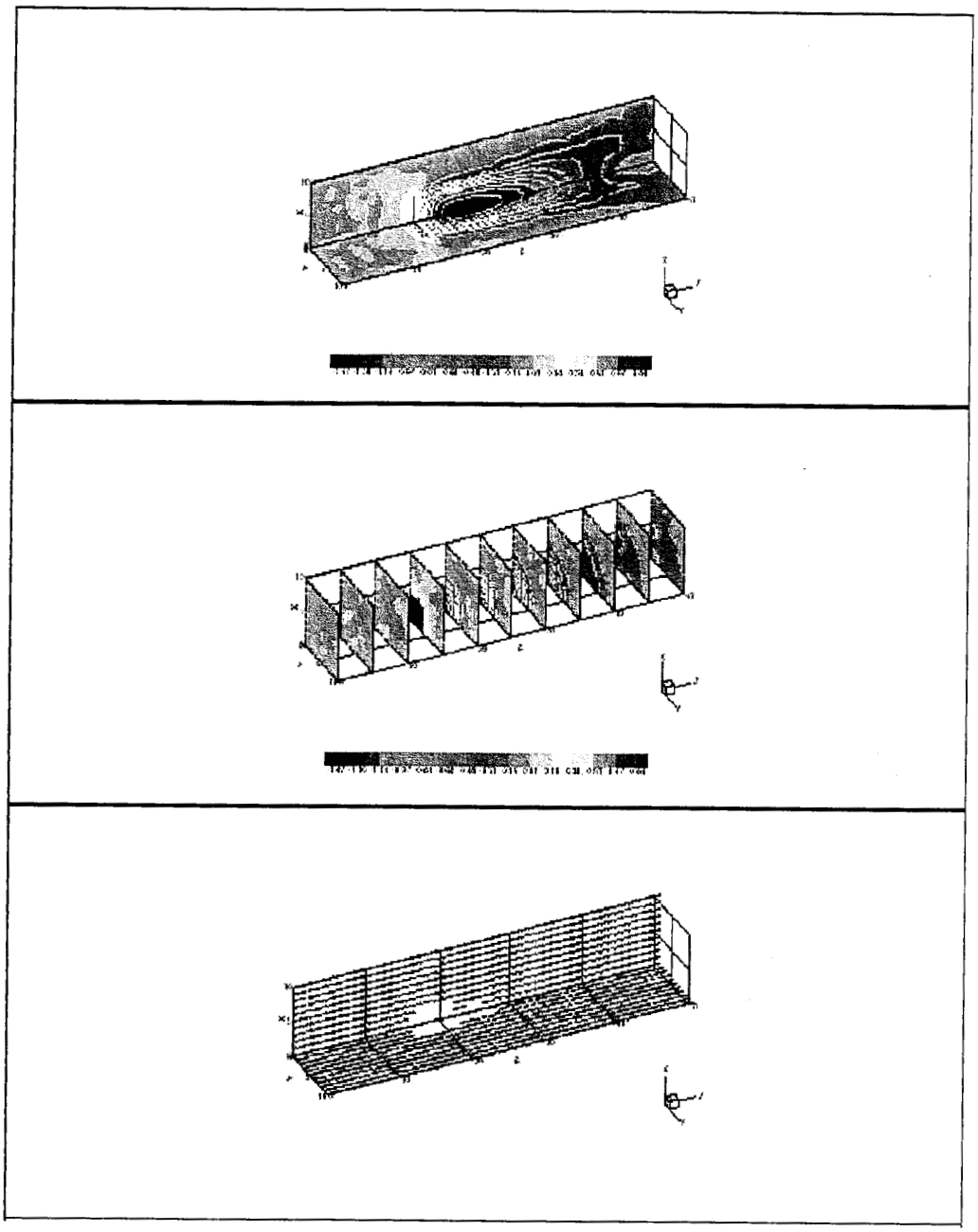


Figure 6: Parametric Case 3 (Potential contours and ion velocity vectors. Potential values are normalized by T_e. Sail potential : 1 T_e)

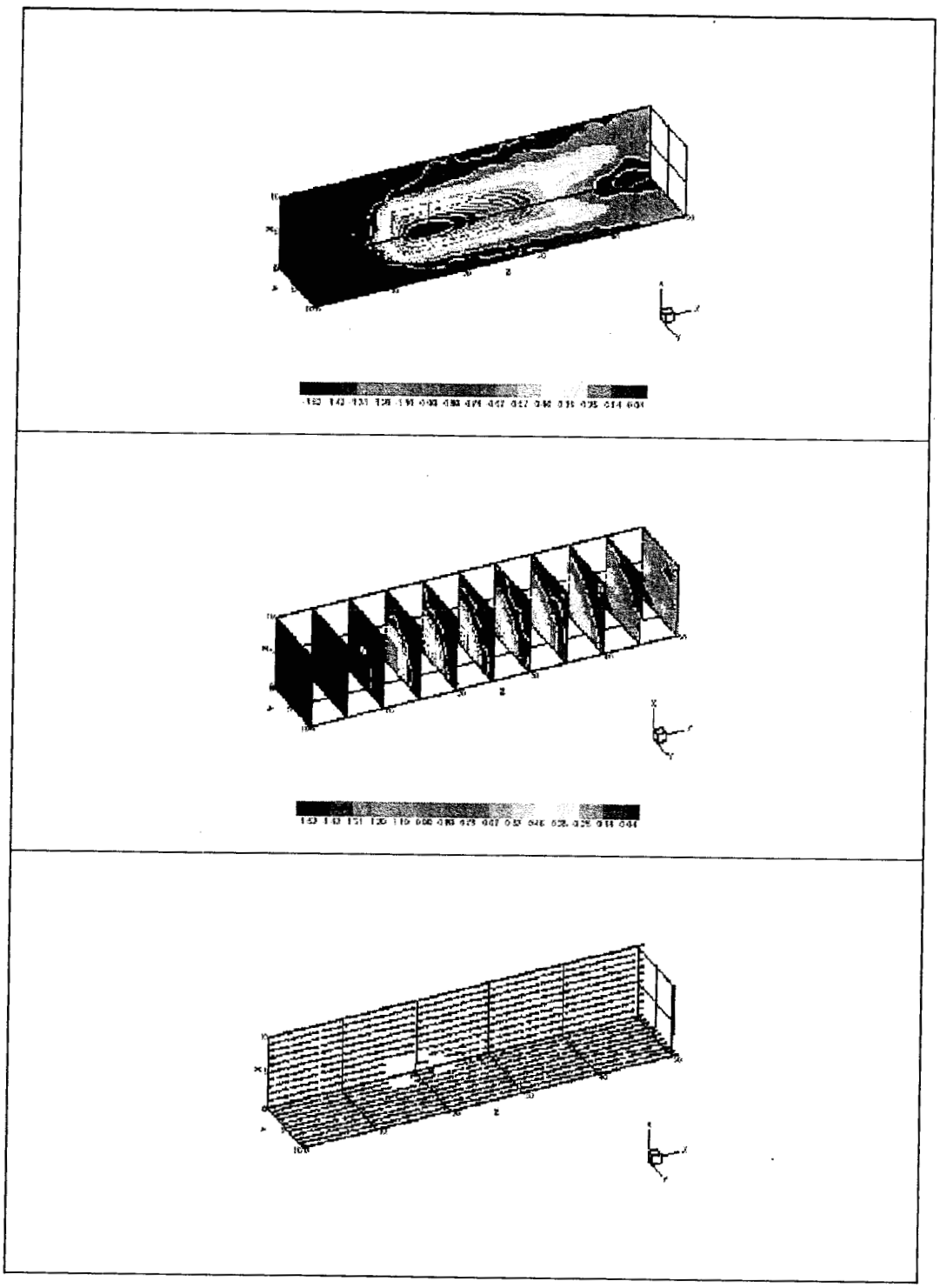


Figure 7: Parametric Case 4 (Potential contours and ion velocity vectors. Potential values are normalized by T_e. Sail potential : -1 T_e)

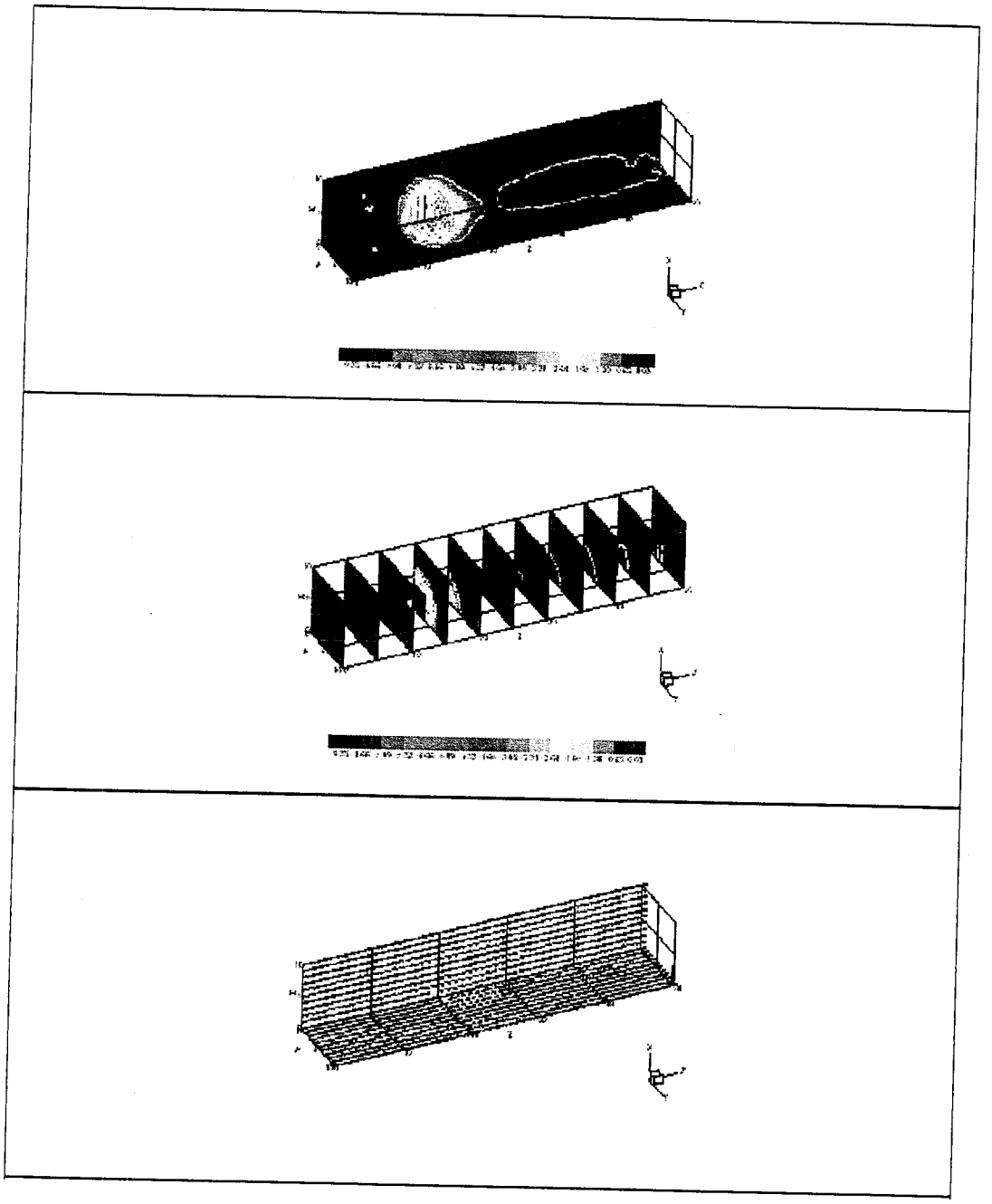
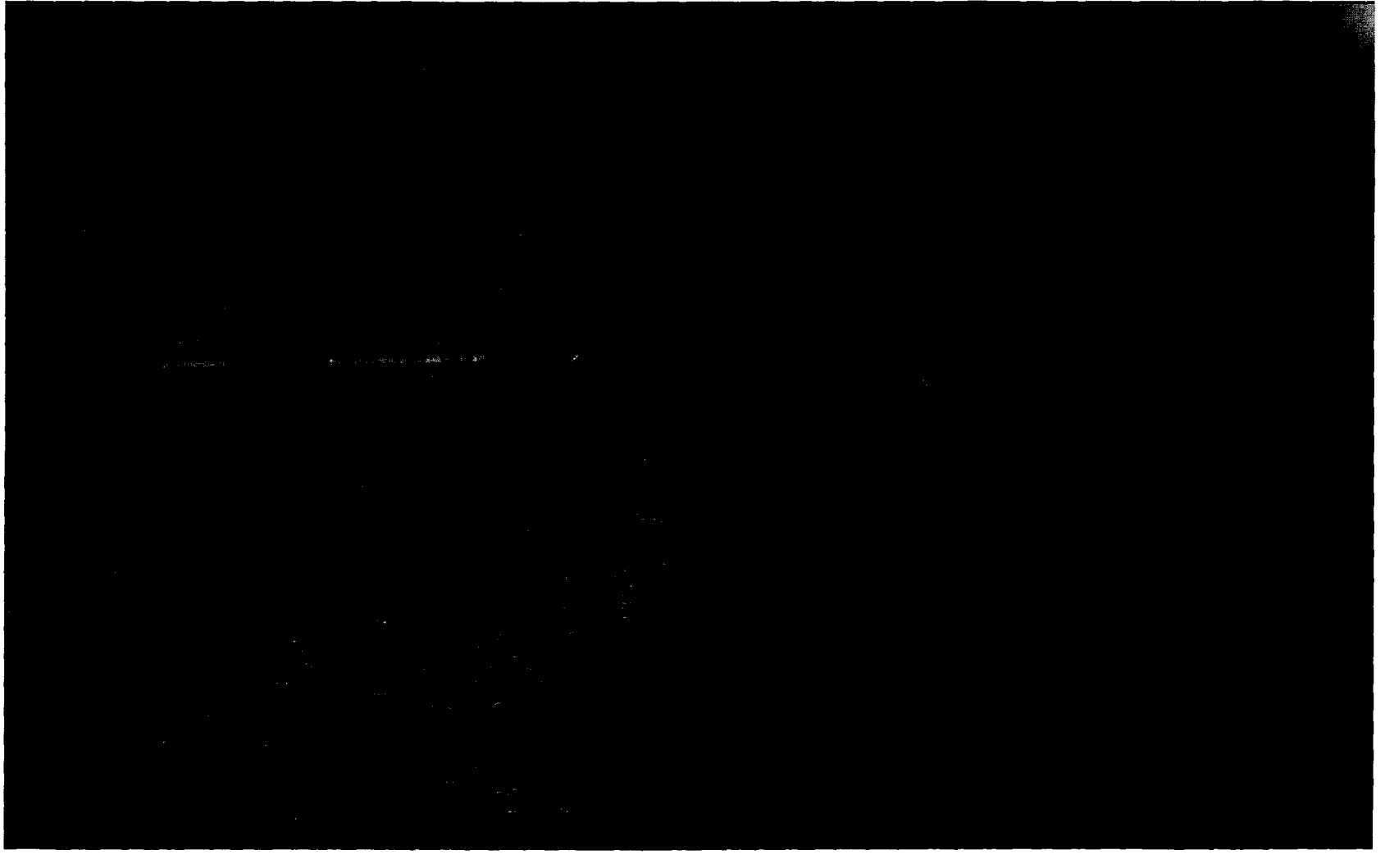


Figure 8: Parametric Case 5 (Potential contours and ion velocity vectors. Potential values are normalized by T_e. Sail potential : -10 T_e).

SAIL INTERACTIONS

SIMULATIONS OF SOLAR WIND PLASMA FLOW AROUND A SIMPLE SOLAR SAIL

INTERACTIONS OF SPACECRAFT AND SYSTEMS WITH
THE NATURAL AND INDUCED PLASMA ENVIRONMENT



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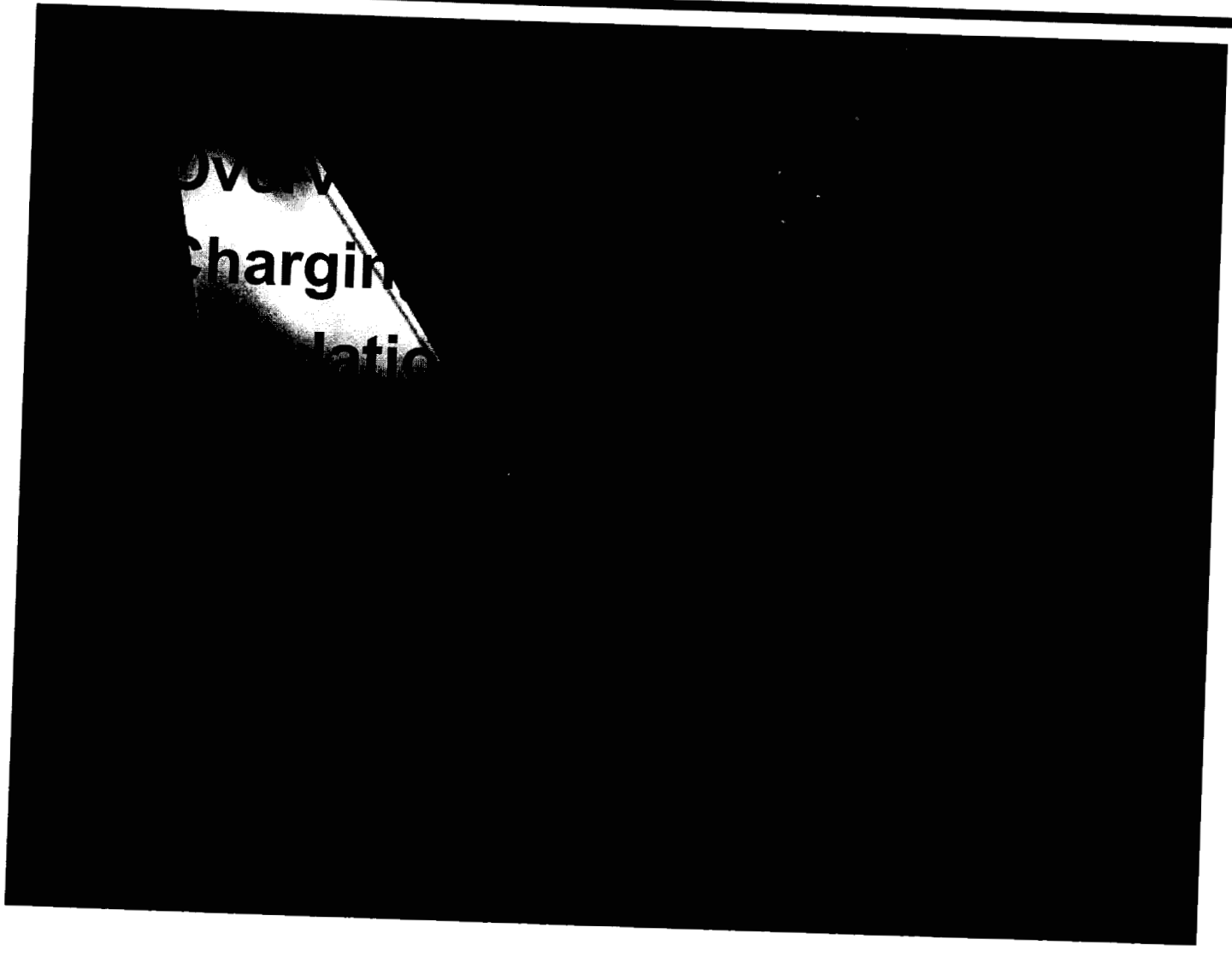


Geostorm Solar Sail Mission

GEOSTORM CONCEPT

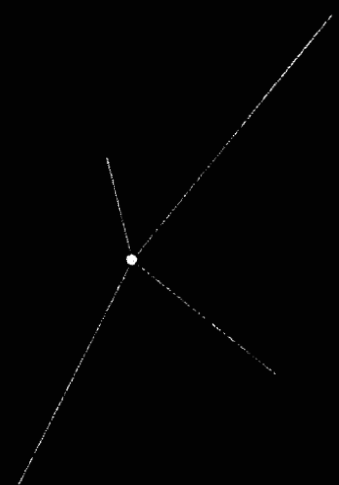
FABRICATION AND PACKAGING

DEPLOYMENT / JETTISON IN 0 g

ATTITUDE CONTROL

TRAJECTORY MANEUVERS AND NAVIGATION

SCIENCE MEASUREMENT AND ENGINEERING DIAGNOSTIC INSTRUMENTATION



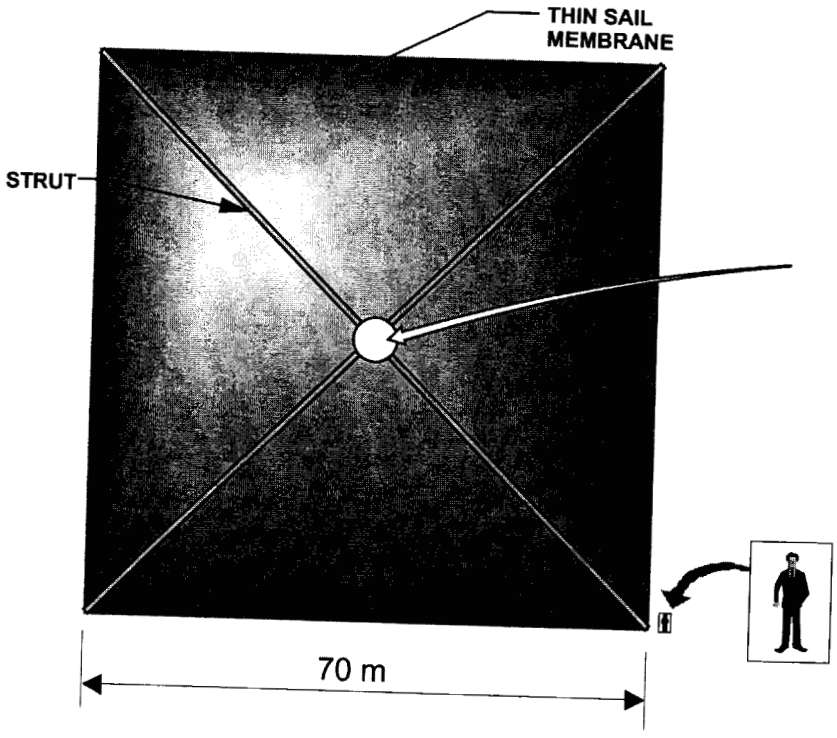
OPERATIONAL GEOSTORM WARNING MISSIONS / SOLAR SENTINEL MISSION

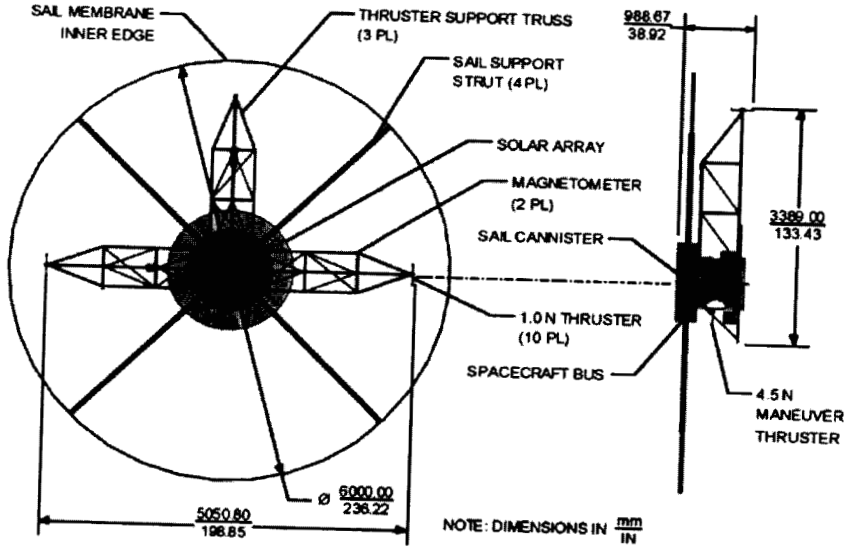
NON-KEPLERIAN EARTH ORBIT

SOLAR POLAR IMAGER

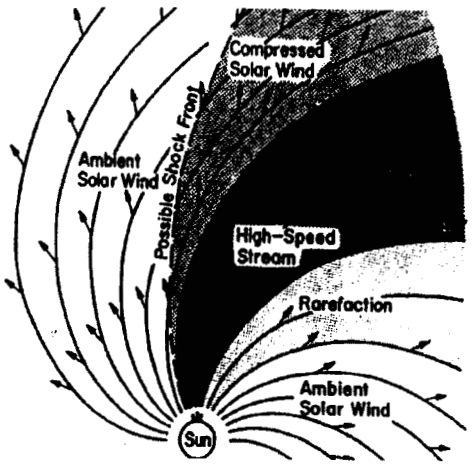
INTERSTELLAR PRECURSOR AND INTERSTELLAR MISSIONS

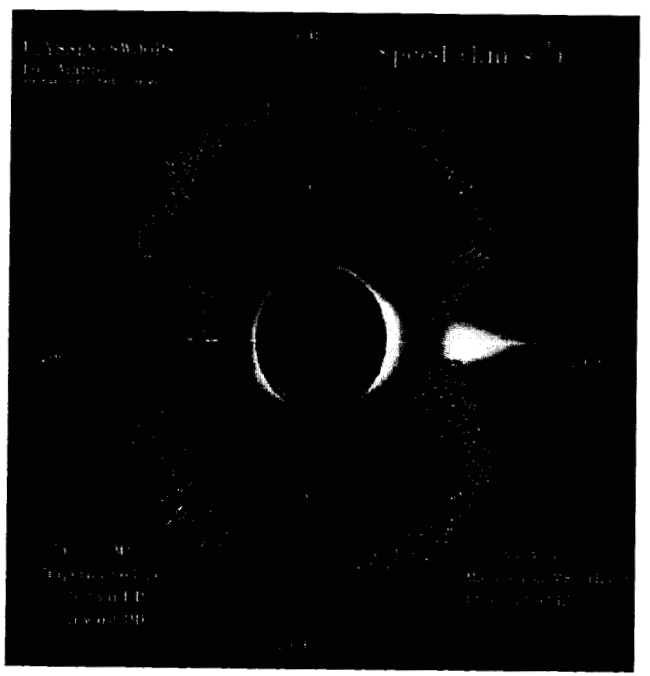
Geostorm Solar Sail Mission





SOLAR WIND PARAMETERS

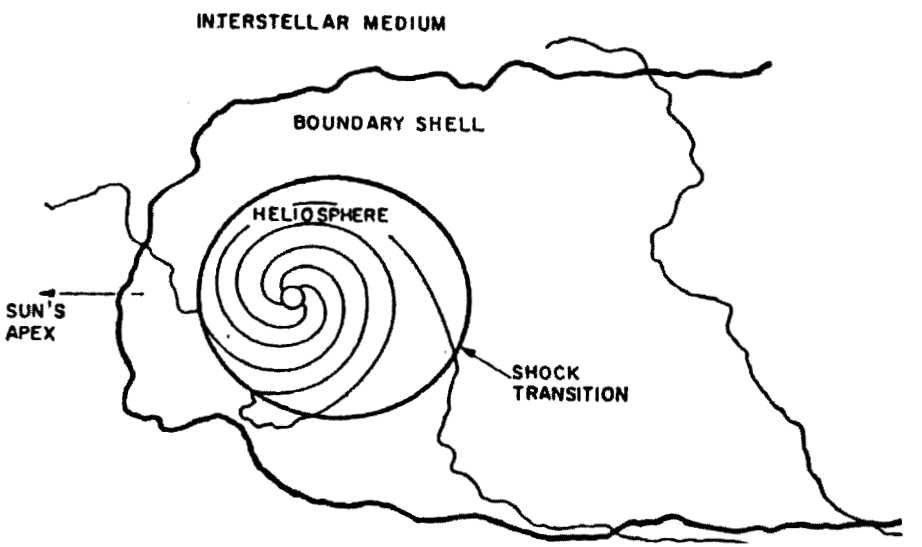




SOLAR WIND PARAMETERS AT 1 AU

	MIN	MAX	AVG
FLUX (NO#/CM^2-S)	10^8	10^{10}	2-3X10^8
VELOCITY (KM/S)	200	2500	400-500
DENSITY (NO#/CM^3)	0.4	80	5-10
T (eV)	0.5	100	20
T_{max}/T_{avg}	1.0 (isotropic)	2.5	1.4
HELIUM RATIO (N_{He}/N_H)	0.0	0.25	0.05
FLOW DIRECTION	±15° from radial		~2° East
ALFVEN SPEED (KM/S)	30	150	60
B (γ)	0.25	40	6

B VECTOR POLAR COMPONENT: AVG IN ECLIPTIC PLANE
PLANAR COMPONENT: AVG SPIRAL ANGLE ~45°



Model Assumptions

- **"Nominal" Solar Wind:**

  v_{sw} ~ 400 *km/s* n_{sw} ~3.5 cm^{-3}

  T_i ~10 *eV* T_e ~ 40 *eV*

  B_o ~ 10^{-4} *Gauss*

- **Plasma Parameters:**

  λ_D ~25 *m*; v_{te} ~2.65 x 10^3 *km/s*

  v_{ti} ~30 *km/s* $c_s = (T_e/m_p)^{1/2}$ ~62 *km/s*

  Ω_i ~1 *rad/s* Ω_e ~1.8 x 10^3 *rad/s*

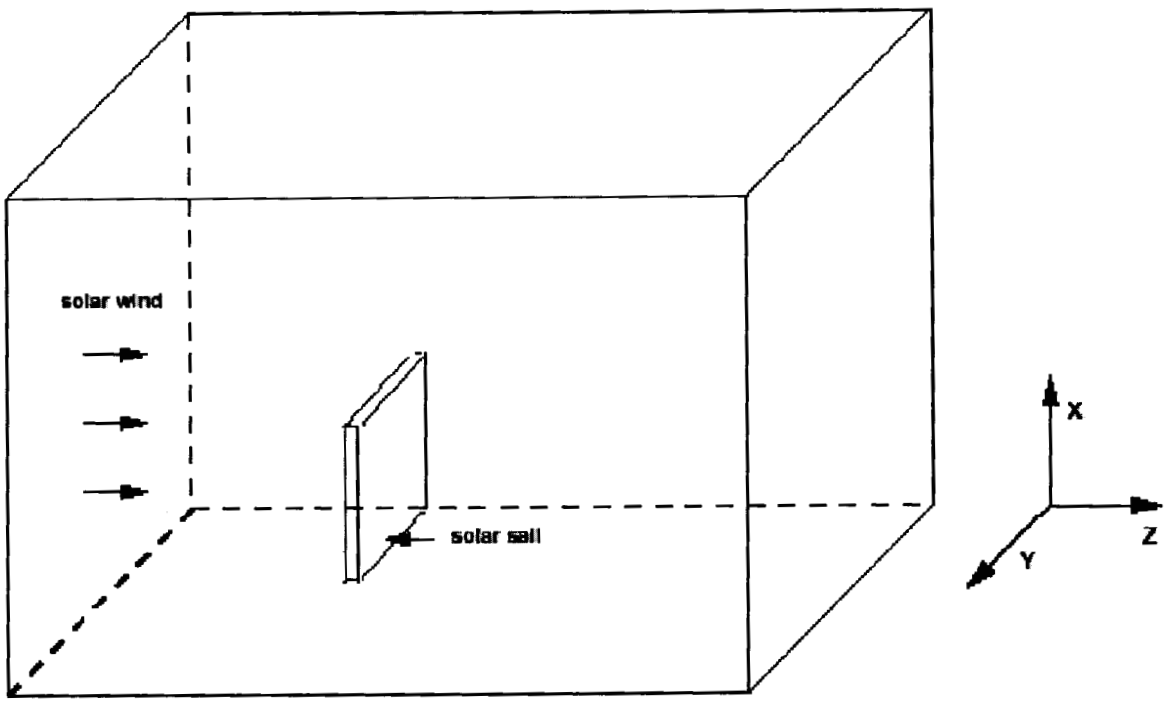
- **Spacecraft Potential (Sunlight):**

  Φ_s ~6 *V to* ~14 *V* *Assume* ~10 *V*

Model Assumptions

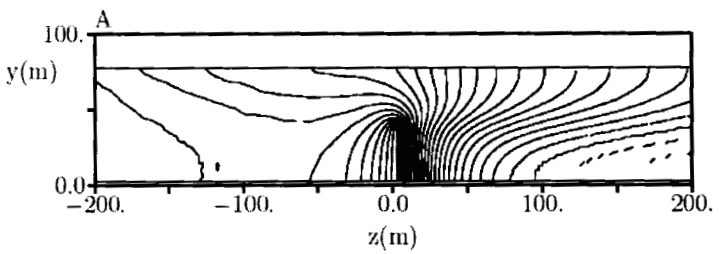
- 3-D, Electrostatic Particle-in-Cell (PIC) code
- Solar Wind protons treated as particles
- Solar Wind electrons treated as isothermal fluid (Boltzmann distributed)
- Electric field/particle trajectories solved self-consistently using dynamic alternating direction implicit (DADI) solver in 3-dimensions [Wang et al. (2001)]

Model Simulation Setup

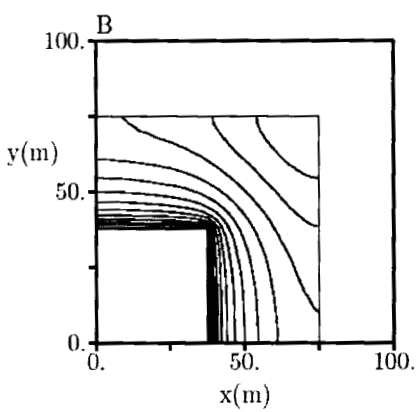


- 3-D simulations performed for quarter size Sail
- Solar Sail modeled as thin conducting plate with a potential
- Solar wind injected from upstream surface along z direction
- Solar wind modeled as particle protons and fluid electrons.

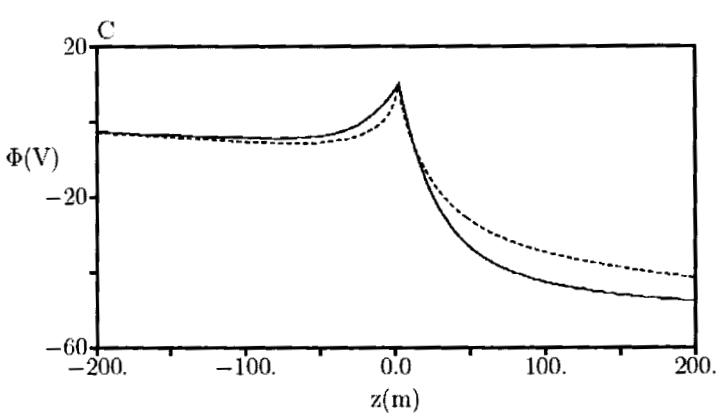
Simulation Results for Sail (75 m x 75 m) at 10 V Surface Potential



A: Electric potential contours on a z-y plane cutting through sail center.

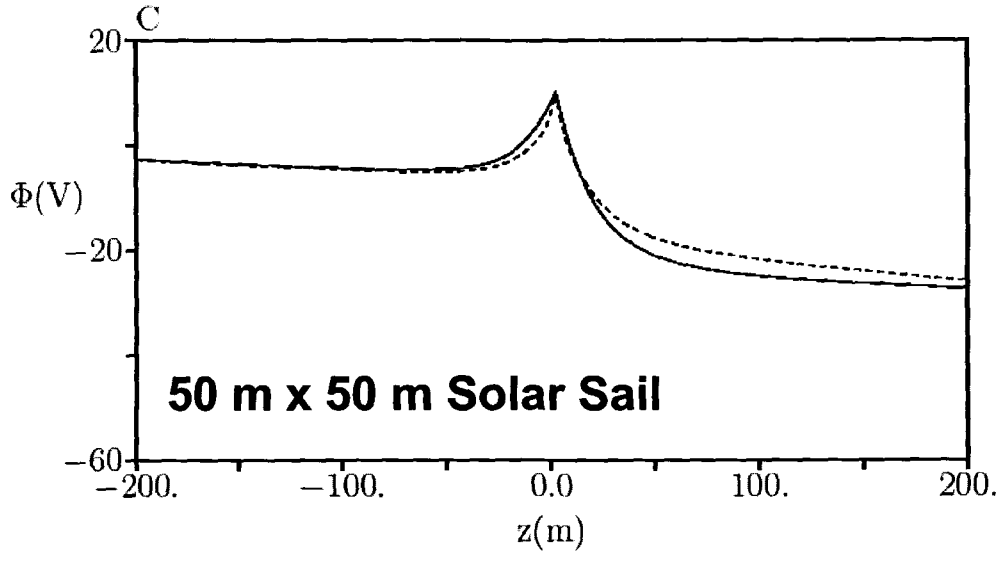


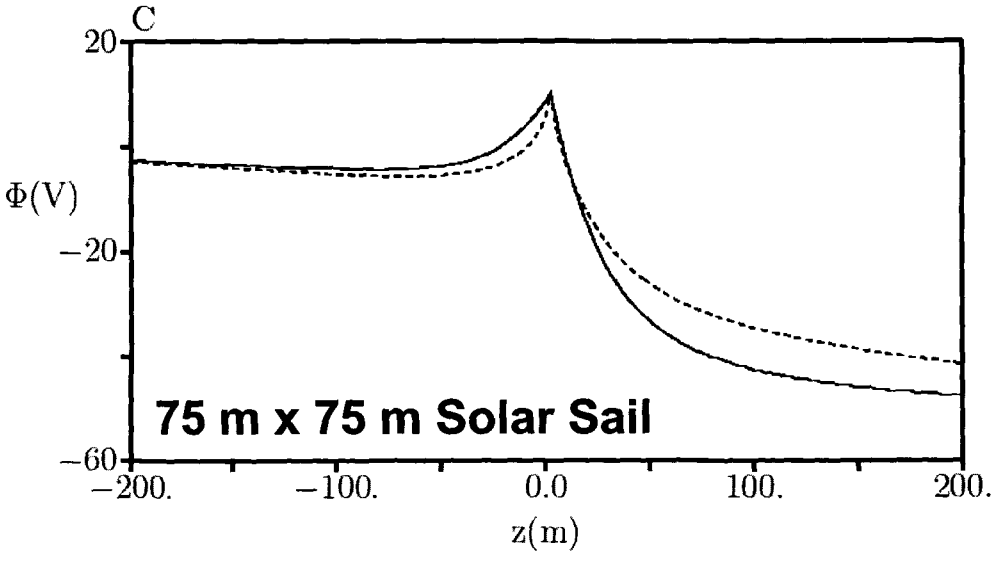
B: Electric potential contours on a x-y plane containing sail surface.



C: Potential profile along a z axis through the center of the surface and a z axis through the center of the edge.

50 m x 50 m Sail vs 75 m x 75 m Sail at 10 V Surface Potential

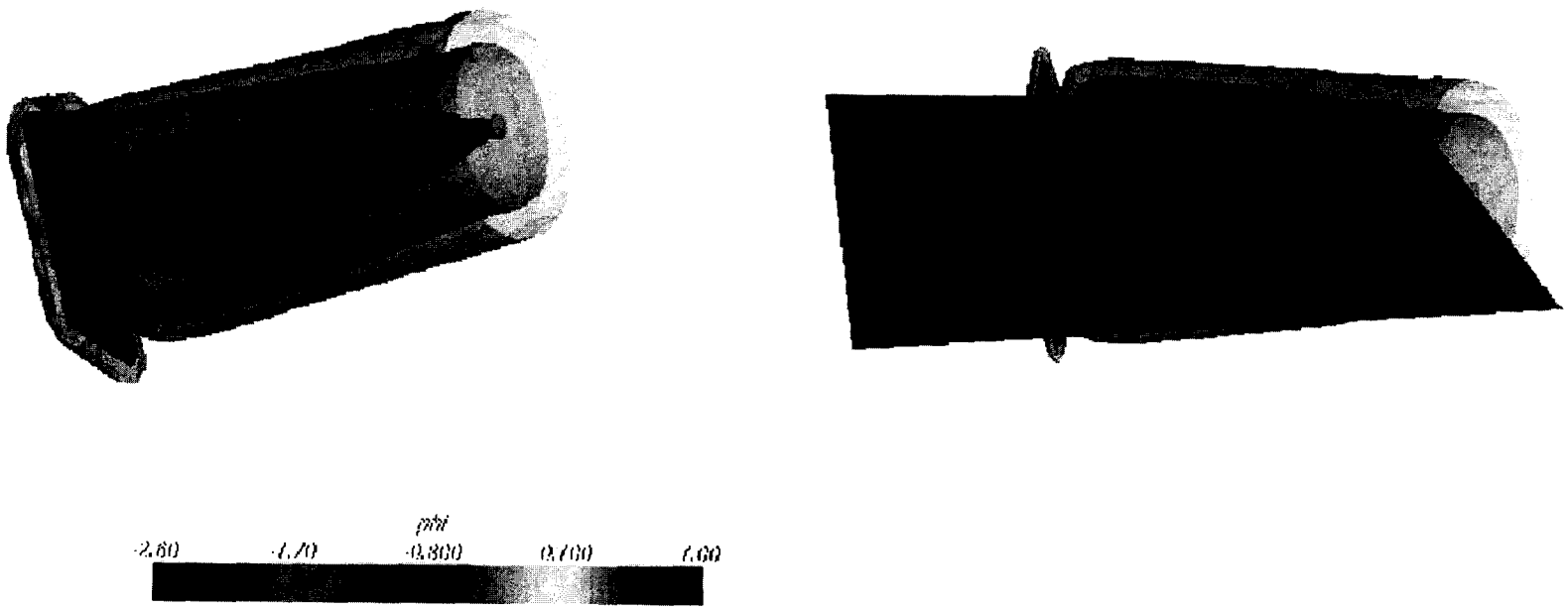




Solid line--Potential profile along z axis through center of the surface

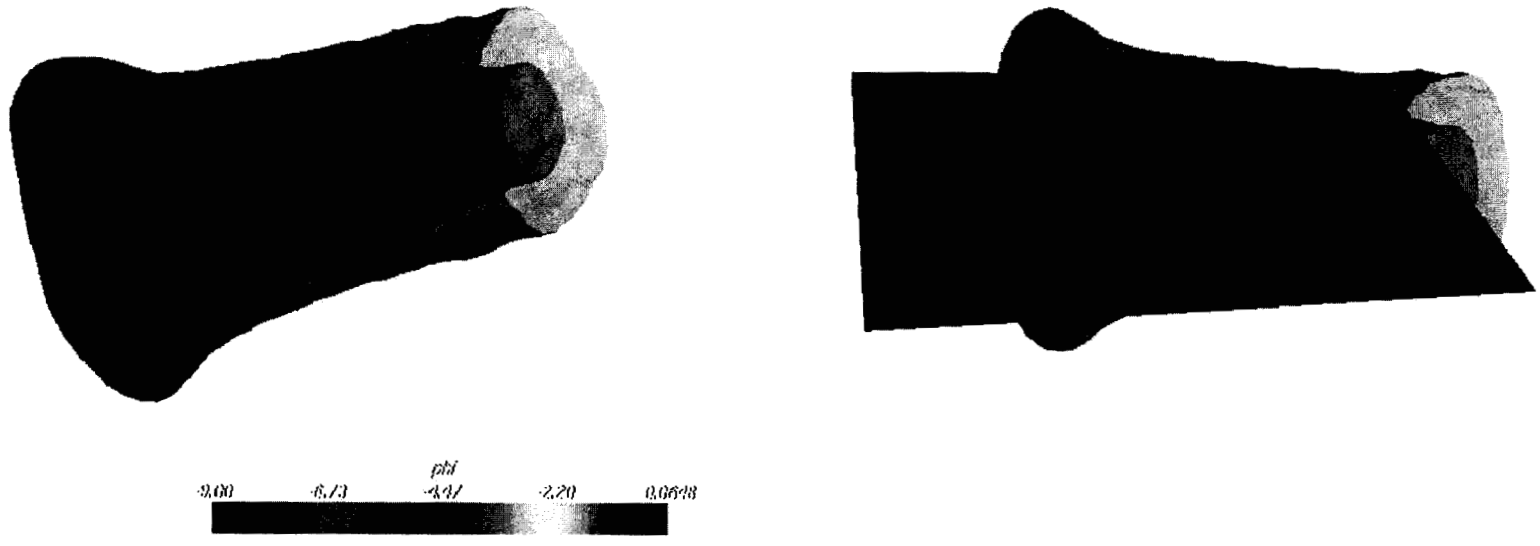
Dashed line--Potential profile along z axis through center of an edge

Parametric Case 1



Potential Isosurfaces. Potential values are normalized by T_e. Sail potential : 0.25 T_e

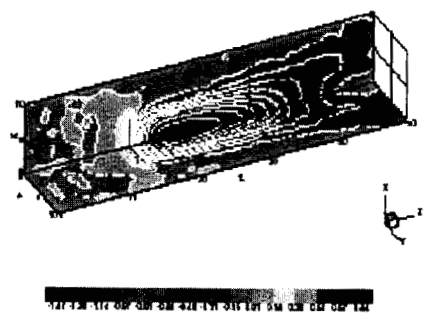
Parametric Case 2



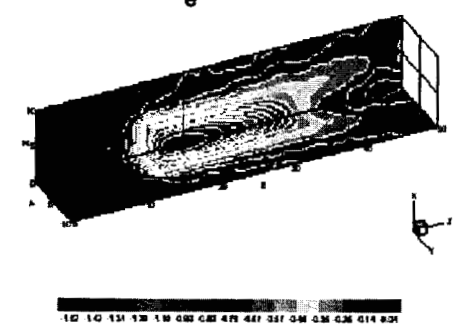
Potential Isosurfaces. Potential values are normalized by T_e. Sail potential : -2.25 T_e

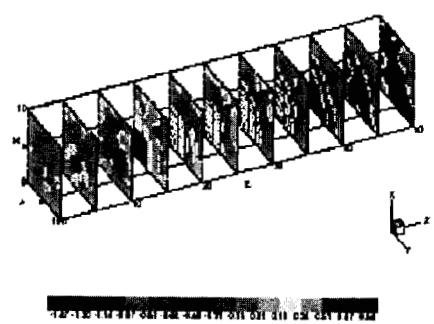
Panametric Cases for Potentials of $\pm T_e$

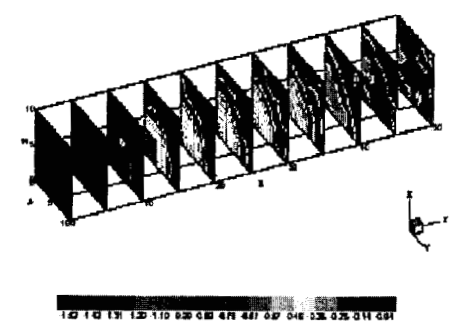
Sail potential : 1 T_e



Sail potential : -1 T_e







Potential contours. Potential values are normalized by T_e.

Conclusions

- Sail surrounded by positive plasma sheath followed by negative plasma wake.
- Plasma sheath on ram side starts at ~2 λ_D or ~50 m for "nominal" solar wind.
- For 50 m and 70 m sails, size minimally effects plasma sheath although wake potential is significantly different.
- Effects on solar wind electron measurements made near sail surface should be minimum as solar sail floating potential is ~10 V while T_e~40 eV.
- Sheath may effect solar wind proton measurements made within sheath.