Analysis of the Ion Current Collection in the Plasma Wake During the Charging Hazards and Wake Studies (CHAWS) Experiment

by

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Submitted to the Department of Aeronautics and Astronautics on October 21, 1996 in partial fulfillment of the requirements for the degree of Master of Science in Aeronautics and Astronautics

Abstract

The Charging Hazards and Wake Studies (CHAWS) experiment characterized the ion current collection to a negatively biased Langmuir probe mounted in the wake of the Wake Shield Facility (WSF) during both the STS-60 (CHAWS I) and STS-69 (CHAWS II) missions. A recalibrated version of the CHAWS I data is presented and a semi-analytical model developed under the previous data calibration for high voltage (>1750 V) wake side probe current prediction is shown to remain adequate. Application of the model to the new and exhaustive CHAWS II data confirms its validity over typical LEO ambient plasma density, ion temperature, and angle of attack parameter spaces.

The results from a previously developed fully three dimensional hybrid PIC code are compared to sample high voltage wake side current-voltage sweeps and found to under-predict the observed current by about a factor of two. Additional analysis demonstrates that uncertainties in the ion density, ion temperature, electron temperature, secondary species (H+) contribution, and secondary electron coefficient determination may be sufficient to reconcile the code-data difference. The code is further confirmed through employment in the low voltage (<1100 V) analysis. It was found that the secondary species (H+), at about 0.5% to 2.5% of the total ambient ion density, dominated current contribution by virtue of its having a much lower Mach number than the dominant O+ species. The low voltage analysis also determined that photo-emission was at most one milli-ampere and that the turn-on voltages, which were previously thought to be either masked or non-existent, were locatable and consistent with pre-flight and PIC code prediction. Code analysis of the wake current dependence on electron temperature confirms the model finding that the wake side current collection was orbit motion limited.

Analysis of the small set of ram side data (i.e. when the shield was inverted and the probe was aligned directly into the plasma flow) demonstrates that the space charge limited collection theory by Laframboise and the code are in agreement if the data is corrected for end effect. The results, combined with a comparison of the CHAWS densities to IRI prediction, suggest that the CHAWS detectors may have underestimated the ambient density by as much as a factor of two. The ram side analysis also suggests that electron heating ($T_e \sim 5T_i$) was observed in the ram direction of the WSF.

The dominant dependencies of the developed model are presented and its employment for geometries other than CHAWS confirm that the dependencies are identical to those of the PIC code. Both the general model and the code may now be applied in engineering within the wake of LEO space vehicles and the general model may be easily incorporated into spacecraft design tools such as Environmental WorkBench (EWB).
Acknowledgments

After completion of a task as large as this it is difficult to ensure that all involved are properly acknowledged. Indeed, it is a testament to human imperfection should someone be forgotten and I offer my sincerest apologies if such is the case.

First on my list is Dr. Daniel Hastings. The rare combination of a jovial presence and professional manner made him a pleasure to work with. His advice was integral to both the success of this work and in MIT’s opening of my eyes to a larger reality.

The technical assistance offered by Dr. Dave Cooke and the other CHAWS project members was also greatly appreciated. I think Dave will be a terrific father to his new offspring and sincerely hope he keeps his amazing van.

The camaraderie and assistance of those in the Space Systems Lab will never be forgotten. Thanks to Graeme for constructing the indestructible model and to Gabriel, whom I’ve never met in person but talked with over the e-mail on many occasions, for providing the original simulation code. Thanks to Czepiela for being blunt, Yashko for being subtle, Dave for his insight, and the CASL people and network maintainers for all the computer time and patience. Thanks to Chris for the trips to Larry’s and late night pool, Ray for softball, Rob S. for the satellite know-how, and Rob B. for lots of battery margin, Guy for the great laugh at the Miracle, Angie for the cheap parking, Doug for being a swell dresser, Folushio for the brain teasers and chess matches, Tolu for late night ER, and TELAC for their tools.

My parents must be mentioned. They let me learn about life for myself and take its lessons to heart. Thanks for the love, patience, and letting me find my own way. Dad, I bet you never thought that a few harmless sci-fi books and star-gazing BBQ’s in my pre-teens would take root so firmly!

And to Janelle, for traveling the world only to find herself here with me.
THE OAK AND THE REEDS

A violent storm uprooted an Oak that grew on the bank of a river. The Oak drifted across the stream, and lodged among some Reeds. Wondering to find these still standing, he could not help asking them how it was they had escaped the fury of a storm which had torn him up by the roots.

"We bent our heads to the blast," said they, "and it passed over us. You stood stiff and stubborn till you could stand no longer."

_Stoop to conquer._

-The Fables of Ἐsop (–600 B.C.)

Sir Toby: Does not our life consist of the four elements?
Sir Andrew: Faith, so they say; but I think it rather consists of eating and drinking.

-William Shakespeare, _Twelfth Night_
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Nomenclature

\( \bar{c}_e \)  Mean electron velocity  
\( \bar{E}_m \)  Motional electric field  
\( \bar{v}_d \)  Drift velocity  
\( \theta \)  Angle of attack  
\( \sigma \)  Charge density  
\( \phi \)  Electric potential  
\( \alpha \)  Angle measured from center of WSF  
\( \beta \)  Fitted parameter  
\( \gamma \)  Secondary yield function  
\( \Theta \)  Aspect angle of ion detector  
\( \alpha_{\text{int}} \)  Angle to intersection point of sheath and WSF edge  
\( \lambda_m \)  Debye length  
\( \Omega \)  Ion/electron gyro frequency  
\( \varepsilon \)  Permittivity of free space  
\( \Phi_0 \)  Probe bias  
\( A_c \)  Collection area  
\( B \)  Magnetic field  
\( \text{cps} \)  Counts per second  
\( C_s \)  Ion acoustic velocity  
\( d \)  Distance from probe to WSF center  
\( e \)  Elementary charge  
\( E_{\text{orbit}} \)  Orbital energy  
\( eV \)  Electron volt  
\( f_c \)  Maxwellian distribution function  
\( I \)  Current  
\( J \)  Angular momentum  
\( j_a \)  Net current density  
\( j_e \)  Electron current density  
\( j_i \)  Ion current density  
\( j_{\text{pho}} \)  Photoemission current density  
\( J_{\text{ram}} \)  Ram flux  
\( k \)  Boltzmann’s constant  
\( l_p \)  Probe length  
\( M \)  Ion Mach number  
\( m_i \)  Ion mass  
\( n_- \)  Plasma density  
\( n_e \)  Electron density  
\( n_i \)  Ion density  
\( n_n \)  Neutral density  
\( q_i \)  Ion charge  
\( R \)  WSF radius  
\( r \)  Distance from probe  
\( r_c \)  Sheath radius
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_p )</td>
<td>Probe radius</td>
</tr>
<tr>
<td>( S )</td>
<td>Speed ratio</td>
</tr>
<tr>
<td>( t )</td>
<td>Time</td>
</tr>
<tr>
<td>( T_e )</td>
<td>Electron temperature</td>
</tr>
<tr>
<td>( T_i )</td>
<td>Ion temperature</td>
</tr>
<tr>
<td>( U )</td>
<td>Potential energy</td>
</tr>
<tr>
<td>( v )</td>
<td>Velocity</td>
</tr>
<tr>
<td>( v_o )</td>
<td>Orbital velocity</td>
</tr>
<tr>
<td>( v_x, v_y, v_z )</td>
<td>Velocities in x, y, z</td>
</tr>
<tr>
<td>( \omega_{pe} )</td>
<td>Ion/electron plasma frequency</td>
</tr>
<tr>
<td>( x, y, z )</td>
<td>Coordinate directions</td>
</tr>
</tbody>
</table>
Chapter 1: Introduction

1.1 Overview

The need to understand the nature of and design for the interaction between spacecraft operating in low Earth orbit and the plasma environment has been recognized since the advent of space flight. The issue has received additional attention in recent years since charging phenomena associated with this interaction may be enhanced by increases in spacecraft size, power, flight duration and in the frequency of multi-vehicular interaction. The most notable example is Space Station Alpha which will be the largest structure ever flown in space with an unprecedented power of about 75 kW. In the best case isolated surfaces and even the entire vehicle can attain significant potentials relative to the plasma, altering the response characteristics of detectors and complicating scientific investigation. In more severe cases there may be electrical discharge between isolated surfaces or even nearby objects. This arcing may have a wide variety of detrimental effects including damaging of mission critical electronics, electromagnetic noise, surface erosion and outright structural damage. Spurious signals may also be generated within the vehicle electronics with potentially disastrous consequences. Spacecraft charging has been linked directly to anomalous satellite behavior and implicated in complete losses of others [1].

One of the least understood and difficult aspects of spacecraft charging has been interactions occurring on the wake side of vehicles without symmetrical geometry and with complex surface
and biased object configurations. In low Earth orbit the flow around an orbiting object is mesothermal. That is, the electron thermal velocity is much greater than that of the spacecraft while the ion thermal velocity is much less. This causes the formation of a region behind the spacecraft which is essentially devoid of ions but electron rich. Objects or electrically isolated surfaces within the wake can become negatively charged with respect to other spacecraft components and begin to suffer the previously mentioned difficulties. For objects operating at significant voltage levels such as power supplies, wires, or even other spacecraft, charging effects can be much more pronounced and correspondingly more dangerous.

Previous work on spacecraft wake interaction has consisted of numerical simulation and laboratory work but there has been no in situ data available with which to verify the validity of those investigations. In order to ameliorate this the Charging Hazards and Wake Studies experiment (CHAWS) was implemented. The CHAWS project attempted to achieve the following objectives:

1. Flight test a new generation of miniaturized particle detectors by using them to measure the ambient low energy ion population on the ram and wake side of the Wake Shield Facility.
2. Determine and understand the current-voltage characteristic of a negatively biased object in a plasma wake under a wide variety of changing environmental conditions and compare the results to numerical simulation.
3. Derive a general (i.e. applicable to geometries other than CHAWS) model consistent with both the data and the simulation from which future spacecraft may be designed to avoid hazards posed by wake charging.

This thesis concentrates on the last two objectives but is also concerned with the first as a necessary consequence. The analysis of the data from both CHAWS flights (STS-60 and STS-69) along with a fully three dimensional numerical simulation completes development of a general and consistent model for the observed phenomena and permits engineering with the highly biased objects within the LEO wake environment.

1.2 Theory and Background

1.2.1 Low Earth Orbit Environment

The ionosphere is defined as the region from about 60 km to about 1000 km above the surface of the Earth. It is sub-divided into several regions: D (60 to 100 km), E (100 to 150 km)
and F (150 to 1000 km). The ionosphere owes its existence to ionization of the neutral atmosphere by ultraviolet, X-ray, and corpuscular heat radiation. Since the neutral atmosphere density decreases with height and the radiation flux increases there is a balance which leads to the layer formation. Almost all satellites which operate in LEO do so in the F region, usually at an altitude of 300 to 400 km. CHAWS was designed to provide data which is applicable within that range of utilization and subsequent discussion is limited to that regime. Typical LEO ambient environment parameters are provided in Table 1.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital velocity, v_o (km/s)</td>
<td>7-8</td>
</tr>
<tr>
<td>Plasma density, n_e=n_i=n_p (m^-3)</td>
<td>$10^{10}$-$10^{12}$</td>
</tr>
<tr>
<td>Ion temperature, T_i (eV)</td>
<td>0.05-0.15</td>
</tr>
<tr>
<td>Electron temperature, T_e (eV)</td>
<td>~2 T_e</td>
</tr>
<tr>
<td>Plasma composition at ~350 km</td>
<td>O+&gt;95%, H+&lt;5%</td>
</tr>
<tr>
<td>Neutral density, n_n (m^-3)</td>
<td>~$10^{14}$</td>
</tr>
<tr>
<td>Magnetic Field, B (G) (equatorial)</td>
<td>~0.3</td>
</tr>
</tbody>
</table>

Studies performed on the ionosphere and spacecraft interaction with it employ several useful and convenient parameters. Some of the more typical ones, their formulation and typical LEO values are provided in Table 1.2. Some, such as the Debye length, describe bulk properties of the plasma while others pertain to the behavior of individual constituents.
Table 1.2: Basic plasma parameters.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Expression</th>
<th>Typical Value at LEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debye length (cm)</td>
<td>( \lambda_D = \sqrt{\frac{e^2 kT_e}{n_e e^2}} ) (1.1)</td>
<td>0.2-2</td>
</tr>
<tr>
<td>Ion thermal velocity (km/s) (Maxwellian distribution)</td>
<td>( v_{th,i} = \sqrt{\frac{3kT_i}{m_i}} ) (1.2)</td>
<td>1-1.5 (O+) 4-6 (H+)</td>
</tr>
<tr>
<td>Mean electron velocity (km/s)</td>
<td>( \bar{v}_e = \sqrt{\frac{8kT_e}{\pi m_e}} ) (1.3)</td>
<td>( \bar{v}<em>e \gg v_o, v</em>{th,i} )</td>
</tr>
<tr>
<td>Ion Mach number</td>
<td>( M = \frac{v_o}{v_{th,i}} ) (1.4)</td>
<td>5-7 (O+) 1-2 (H+)</td>
</tr>
<tr>
<td>Ion acoustic velocity (km/s)</td>
<td>( c_s = \sqrt{\frac{kT_e}{m_i}} ) (1.5)</td>
<td>( \sim 1 ) (O+)  ( \sim 4 ) (H+)</td>
</tr>
<tr>
<td>Ion/electron plasma frequency (s(^{-1}))</td>
<td>( \omega_{pi,e} = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_{i,e}}} ) (1.6)</td>
<td>( \omega_{pi} \approx 2 \times 10^4 ) ( \omega_{pe} \approx 4 \times 10^6 )</td>
</tr>
<tr>
<td>Ion/electron gyro frequency (s(^{-1}))</td>
<td>( \Omega_{e,i} = \frac{eB}{m_{e,i}c} ) (1.7)</td>
<td>( \Omega_e = 1.5 \times 10^6 ) ( \Omega_i = 30 )</td>
</tr>
</tbody>
</table>

1.2.2 Spacecraft Charging

An excellent and comprehensive summary of spacecraft charging is available in the book *Space Environment Interactions* by D. Hastings [2]. This section summarizes the major points contained therein and emphasizes charging aspects of direct interest to the CHAWS experiment.

In a space plasma a spacecraft acts like an isolated electric probe. It will collect charge and attain an electric potential as dictated by Maxwell’s equations. Electrically isolated surfaces of a spacecraft behave in the same manner. The magnitude of this potential depends on, among other things, the nature of the ambient plasma and on how the object travels though it. Overall, the current density to a surface at the plasma potential is given by

\[ j_a = -(j_i - j_e) \] (1.8)

In LEO the motion of the spacecraft is mesothermal. That is, the electron speed ratio, defined in equation (1.9), is much greater than unity while the ion speed ratio is less than unity. Hence, the spacecraft is traveling though the plasma at an orbital velocity greater than the thermal velocity of the ions but is effectively at rest with respect to the electrons.
\[ S_e = \frac{v_o}{v_{sh,e}} \]  \hspace{1cm} (1.9)

\[ S_i = \frac{v_o}{v_{sh,i}} \]  \hspace{1cm} (1.10)

If it is assumed that the electrons obey a Maxwellian distribution function

\[ f_e = n_e \left( \frac{m_e}{2nkT} \right)^{\frac{3}{2}} \exp \left( \frac{-m_e v^2}{2kT} \right) \]  \hspace{1cm} (1.11)

where \( n_e \) is the plasma density and \( T \) is the characteristic electron temperature then the electron current density to a surface is

\[ j_e = \frac{n_e \vec{v}_e}{4} \]  \hspace{1cm} (1.12)

The ion flux to a surface is given by

\[ j_i = j_e \left( e^{-M_n^2} + M_n \sqrt{\pi} (1 + \text{erf}(M_n)) \right) \]  \hspace{1cm} (1.13)

where \( M_n \) is the component of the flow along the normal to the surface and

\[ j_e = n_e \sqrt{\frac{kT}{2\pi m}} = \frac{1}{2} \frac{n_e}{\sqrt{\pi}} v_o \]  \hspace{1cm} (1.14)

For a Mach number greater than about 3 and an aperture facing into the xam direction equations (1.13) and (1.14) simplifies to

\[ j_i = e n_e v_o \]  \hspace{1cm} (1.15)

while an aperture on the wake side of a satellite would see an ion flux dictated by

\[ j_i = j_e e^{-M_n^2} \]  \hspace{1cm} (1.16)
For significant Mach number values it is clear that (1.15) far exceeds the flux predicted by equation (1.16). Therefore, for the LEO environment equation (1.8) becomes

\[ j_a = -e \left( n_o \nu_o - \frac{n_o e}{4} \right) \quad (1.17) \]

There are two secondary current sources which should be considered: photoelectric and secondary electron emission. Many materials employed on the surfaces of spacecraft emit photoelectrons when illuminated by the UV component of the solar spectrum. It is a function of satellite material, solar flux, solar incidence angle and satellite potential. The two functions necessary to determine the photoelectric yield are the solar flux energy spectrum, S(E) and the photon electron yield, W(E). Hence, for a spacecraft surface that is at zero or lower potential the photoemission current density is found through

\[ j_{\text{pho}} = - \int_0^\infty W(E)S(E)dE \quad (1.18) \]

Hastings [2] has tabulated the total possible photoelectron current density at 1 AU for a variety of materials (refer to section 5.3).

Ions or electrons which impact a surface with sufficient energy may cause the emission of a secondary electron. The amount of secondary electron current depends on many factors, including the incident particle energy, the nature of the surface material and the angle of incidence. Increasing the surface bias negatively has been observed to increase the effective secondary electron current yield [2]. The secondary electron flux can even exceed the incident fluxes under some circumstances and is obviously of importance to spacecraft charging control.

The magnetic field has also been observed to have a significant effect on the current collection [2]. The magnetic field at LEO is strong enough to introduce anisotropies in both charged particle flux and by imposition of a motional electric field along the spacecraft. The latter is a result of the object moving across the Earth’s magnetic field and is given by

\[ \vec{E}_m = \vec{v}_o \times \vec{B} \quad (1.19) \]

This motional field is a consequence of the transformation of Maxwell’s equations under translation and arises from the relativistic requirement that light move at the same speed in all reference frames. Hence, the object has no unique reference potential relative to the plasma since
the induced emf will vary with position on the surface of the spacecraft within the magnetic field. The motional emf is highest in LEO and is of the order 0.25 V/m.

The Earth’s magnetic field also causes anisotropies in the particle fluxes. The force on a charged particle traveling within magnetic and electric fields is given by

$$\vec{F} = \vec{F}_B + \vec{F}_E = q(\vec{v} \times \vec{B} + \vec{E})$$  \hspace{1cm} (1.20)

where q is the particle charge. In the absence of an electric field the force on a charged particle is always perpendicular to the particle’s instantaneous velocity vector and the magnetic field vector. Hence, a particle in a uniform magnetic field must move in a circle in a plane perpendicular to the magnetic field vector. The radius of this circle is

$$\rho_p = \frac{m_p v_\perp}{qB}$$  \hspace{1cm} (1.21)

where $m_p$ is the particle mass and $v_\perp$ is the component of the velocity perpendicular to B. The frequency of this gyration is defined in Table 1.2. It is possible for the gyrating particle to move parallel to the magnetic field vector. In essence, the superposition of the particle gyration with the parallel velocity causes it to describe a helix centered on a magnetic field line. Since the ion mass is much greater than the electron mass its gyration radius is much larger and, compared to typical spacecraft dimensions, its motion appears ballistic for charge collection concerns. The electron motion towards the spacecraft, however, is the E cross B drift under the motional electric field along the magnetic field line to which it is confined. The drift evaluated on the motional field is

$$\vec{v}_d = \frac{\vec{E}_i \times \vec{B}}{B^2} = \frac{(\vec{v}_e \times \vec{B}) \times \vec{B}}{B^2} = -\vec{v}_e$$  \hspace{1cm} (1.22)

Hence, relative to the spacecraft, the electrons appear to flow towards it with its orbital velocity while in a Earth reference frame the electrons appear to be gyrating around a fixed field line. Likewise, charged particles released from the spacecraft at low relative velocities would become trapped on a field line and appear to be swept away from the craft with a velocity $v_e$.

The flux anisotropy induced by the magnetic field makes electron collection from the $-\vec{v}_e$ and $\vec{B}$ directions much easier than collection from the $\vec{v}_e \times \vec{B}$ direction. Previous work [3] on the effects of these magnetic field induced anisotropies on spacecraft charging found that the electron flux can be reduced by as much as a factor of two on some surfaces. Section 1.2.3 considers the
current collection to probes and surfaces which are significantly biased with respect to the plasma potential.

1.2.3 Review of Relevant Langmuir Probe Theory

In general the current collected by a body in an unmagnetized plasma depends on the properties of the body, the plasma and any neutral particles present. The most important parameter is the Debye length, defined in Table 1.2, since it determines the degree of space charge effects. The Debye length is also the length scale below which the ‘quasi-neutrality’ of a plasma is violated. If it is small compared to the characteristic dimension of the spacecraft then the ‘thin sheath’ approximation is appropriate while if the opposite is true then the ‘thick sheath’ approximation should be considered. Each limit provides for specific simplifying assumptions which allow computation of the collected current.

As an illustration consider the simplest case of a spherical Langmuir probe in a collisionless plasma operating in the thick sheath attractive potential limit. In this case the attractive potential is given simply by Coulombs law. If the plasma streaming towards the probe is a mono-energetic beam there will be two quantities which will be constants of the motion within the conservative field: angular momentum (J) and energy (E). As the angular momentum of the particles is varied there will be a critical trajectory which will just graze the surface of the probe as shown in Figure 1.1.

![Effective Cross Section](image)

**Figure 1.1: Orbit motion limited collection.**

This impact parameter defines an effective collection cross section for the incident beam of charged particles. This consideration allows the derivation of an analytical linear current-voltage relationship.
\[ I = I_0 \left( 1 - \frac{e\Phi_p}{kT} \right) \] (1.23)

This formulation holds as long as trajectories exist at all energies which originate from an infinite distance and graze the probe. This is the definition of orbit motion limited current collection. Moreover, since any velocity distribution may be represented by the superposition of many mono-energetic beams then equation (1.23) holds for all physical velocity distributions.

For the case where the Debye length is similar to or less than the characteristic dimension of the spacecraft then the additional potential barrier to collection posed by charged particle shielding of the probe potential must be considered. In this case not all initial energies have trajectories which will graze the surface of the probe and there will be a non-impacting critical trajectory which defines the closest approach, as shown in Figure 1.2. This boundary is often times referred to as the adsorption boundary. Particles without sufficient angular momentum to avoid collection will impact the probe with angles of incidence greater than zero. The presence of the additional potential boundary to particles collection dictates that the sheath limited current will always be less than the orbit motion limited collection.

![Figure 1.2: Sheath limited current collection.](image)

Excellent summaries of theories applicable to electric probes immersed stationary and flowing plasmas are available in Paul M. Chung et al’s *Electric Probes in Stationary and Flowing Plasma* [4], the paper by B.M. Annaratone et al [5], and by Hastings [2]. The theories presented here are not applicable to the CHAWS wake measurements but they may provide insight into collection dependencies and could be directly applicable to data taken when the shield was briefly inverted and the probe was aligned directly into the plasma flow. Theories which are relevant to the
CHAWS situation predict ion current collection in a collisionless plasma. Reproduced below is a table presented in [5] which lists such ion collection theories and their basic attributes in order of increasing sophistication. In all the cases where the collection is space charge limited, i.e. sheaths which are finite in extent or where the concept of an adsorption radius is introduced, the theories were based on some form of numerics. The orbit motion limited case, i.e. a sheath which may be considered effectively infinite in extent, considered by Mott-Smith and Langmuir is analytical.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Hypothesis</th>
<th>Symmetry</th>
<th>Ion Current Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bohm</td>
<td>Thin sheath ( r_p/\lambda_p = \infty )</td>
<td>Plane</td>
<td>Independent of Probe Bias</td>
</tr>
<tr>
<td>Allen, Boyd and Reynolds (Chen)</td>
<td>( 0.5 \leq r_p/\lambda_p \leq 70 ) , radial motion , ( T_i=0 )</td>
<td>Spherical and cylindrical</td>
<td>Results presented in a graphical form</td>
</tr>
<tr>
<td>Mott-Smith and Langmuir</td>
<td>Infinite sheath ( T_i=0 ) , No absorption radius</td>
<td>Spherical and cylindrical</td>
<td>Analytical solution: ( j_e \propto (1-eV_p/kT_i) ) where ( V_p&lt;0 ) (spherical) ( j_e \propto (1-eV_p/kT_i)^{1/2} ) where ( V_p&lt;0 ) (cylindrical)</td>
</tr>
<tr>
<td>Bohm, Burhop and Massey</td>
<td>Thin sheath , mono-energetic ions absorption radius</td>
<td>Spherical</td>
<td>( J_i = \kappa ne \left( \frac{kT_e}{m} \right)^{1/2} ) where ( \kappa ) depends slightly on the ion energy, independent of ( V_p )</td>
</tr>
<tr>
<td>Bernstein and Rabinowitz (Chen)</td>
<td>Thick sheath ( 5 \leq r_p/\lambda_p \leq 15 ), ( T_i=0 ) , mono-energetic ions adsorption radius</td>
<td>Spherical and cylindrical</td>
<td>Results presented in graphical form.</td>
</tr>
<tr>
<td>Laframboise (Kiel; Peterson and Talbot)</td>
<td>Wide range of: ( r_p/\lambda_p ), ( T_i/T_e, \Phi_p ) , Maxwellian distribution of ions</td>
<td>Spherical and cylindrical</td>
<td>Results presented in graphical form but several approximate fits.</td>
</tr>
</tbody>
</table>

In another body of work Al'pert at al [6] performed a detailed computational and theoretical consideration of current collection to biased bodies in both the thin and thick sheath regimes. He found that for a spherical probe
\[ j = j_0 \left( 1 + \frac{|\Phi_p|}{kT} \right) \]  \hspace{1cm} (1.24)

provided the collection is orbit motion limited, as defined by

\[ \frac{e|\Phi_p|}{kT} \ll \left( \frac{\lambda_D}{r_p} \right)^8 \]  \hspace{1cm} (1.25)

The space charge limited current was found to be

\[ j = 0.951j_0 \left( \frac{e|\Phi_p|}{kT} \left( \frac{\lambda_D}{r_p} \right)^4 \right)^{6/7} \]  \hspace{1cm} (1.26)

provided

\[ \frac{e|\Phi_p|}{kT} \gg \left( \frac{\lambda_D}{r_p} \right)^8 \]  \hspace{1cm} (1.27)

Equation (1.26) is obtained from

\[ j = 1.47 j_0 \left( \frac{r_c}{r_p} \right)^2 \]  \hspace{1cm} (1.28)

where \( r_c \) is the space charge limited sheath radius given by

\[ r_c = 0.803 \lambda_D \left( \frac{e|\Phi_p|}{kT} \frac{r_p}{\lambda_D} \right)^{3/7} \]  \hspace{1cm} (1.29)

Equation (1.13) also applies in the thin sheath limit if the potential on the body is very high, as defined by

\[ \left( \frac{e|\Phi_p|}{kT} \right)^4 \geq \frac{r_p}{\lambda_D} \]  \hspace{1cm} (1.30)
1.2.3 Spacecraft Wake

The mesothermal motion of objects in LEO creates behind them a region which is evacuated of ion but is, owing to their much greater mobility, electron rich. The main features of the wake are provided in [7] and are illustrated in Figure 1.3 for a spherical body.

- Immediately behind the body the electron and ion densities will be much higher than if the particles were treated as neutral particles. The electron density will be much larger than the ion density.
- Focusing of charged particles will occur behind the body. The region of maximum rarefaction lies on a conical surface with an opening angle of \( \sin^{-1}(C_i/v_o) \). This is similar to a Mach cone behind a supersonic aircraft.
- Under some conditions the focusing of charged particle behind the body may exceed the ambient density.
- The focusing effect depends strongly on the potential of the back surface of the spacecraft as well as the electron-ion temperature ratio \( T_e/T_i \).
- At great distances from the body, but slightly off axis, two enhanced regions may appear.
- Under the influence of an ambient magnetic field the structure of the far field wake becomes smoothed at a distance of the order \( v_o/\Omega_i \).

![Diagram of spacecraft wake characteristics](image)

**Figure 1.3:** Illustration of basic spacecraft wake characteristics.
1.2.6 Previous High Voltage Wake Studies

The general analytic solution of the plasma wake behind a complex spacecraft is impossible and becomes even more complicated if there are high voltage devices such as wires or power supplies operating within it. Insight into high voltage wake interaction with spacecraft can be gained through the consideration of a flat biased plate in a typical LEO mesothermal plasma flow [8]. In this case the sheath cannot be ignored and the wake structure must be found numerically [8]. The results of a detailed two dimensional PIC calculation for the plate at zero angle of attack is shown in Figure 1.4.

![Wake behind a highly biased plate at zero angle of attack.](image)

**Figure 1.4: Wake behind a highly biased plate at zero angle of attack.**

The plate is 400 Debye lengths, at a potential of -80kT/e and immersed in a Mach 8 flow of O+ ions. It is clear that there are two ion streams of which are pulled around and into the wake region. These streams are composed of the ions which just pass by the edge of the plate and receive an impulsive kick into the wake [8]. The local current density can even exceed the ambient ion current density and are of sufficient energy to cause sputtering from typical materials employed in spacecraft construction.

The structure of the wake formed by the biased plate can be defined qualitatively using two parameters: the non-dimensional plate voltage $e\Phi_{\text{plate}}/kT_e$ and the nondimensional sheath ratio $d_{sh}/L_{\text{plate}}$ where $L_{\text{plate}}$ is the plate length. The latter ratio is given by

$$
\frac{d_{sh}}{L_{\text{plate}}} = 1.3 \left( \frac{e\Phi_{\text{plate}}}{kT_e} \right)^{\frac{3}{4}} \left( \frac{\lambda_p}{\sqrt{M_o \sin \alpha L_{\text{plate}}}} \right)
$$

(1.31)
where $M_e$ is the Mach number and $\alpha$ is the angle that the plane of the plate makes with the flow vector. The first parameter is a measure of the effective energy the plate can provide the particles as it rounds the plate. The second provides a measure of how far the plate can reach transverse to the edge in modifying the particle trajectories.

Several other high voltage wake studies have been performed. Enloe et al [9] undertook laboratory simulation of a small negatively charged body behind a shielding disk. The most important results of this work are that it predicted a linear current-voltage characteristic and the existence of a threshold potential below which no current is collected. Numerical simulations which complement the laboratory work are available in [10][11].

In this thesis an analysis of the totality of the CHAWS I and II data is presented. Numerical simulation and in situ observation are employed in an oftentimes complementary fashion and lead to the confirmation of and additional confidence in a model describing current collection to highly biased objects in the wake of spacecraft. Chapter 2 presents the CHAWS experiment, overviews its operation in LEO and presents the plasma ambient parameter detector calibration. In Chapter 3 the collected data is presented and necessary reduction methods are described. A fully three dimensional numerical simulation of CHAWS and the semi-analytical wake engineering model which it inspired are presented in Chapter 4, along with their applicability to the observed data. Both Chapters 5, the pre-threshold voltage analysis, and Chapter 6, the ram side analysis, confirm the simulation developed in Chapter 4 in distinctly different collection regimes. Chapter 5 also provides insight into the significance of secondary species in LEO wake interactions while Chapter 6 demonstrates the consistency of the CHAWS ram side data, existing current collection theory and numerical simulation. Chapter 7 generalizes the model for use in future wake engineering of spacecraft and confirms its dominant dependencies for geometries other than that of CHAWS.
Chapter 2: The Charging Hazards and Wake Studies (CHAWS) Experiment

Material in this chapter is drawn heavily from the paper "The Charging Hazards and Wake Studies (CHAWS) Experiment" [12] presented by C.L. Enloe at the AIAA 33rd Aerospace Sciences Meeting, Reno, January 1995 and also from the Masters thesis by Graeme Shaw [13].

2.1 Overview of CHAWS

The Wake Shield Facility (WSF) is a 12-foot diameter stainless steel disk which creates an ultra-high vacuum environment in space. It was designed, built and managed by the Space Vacuum Epitaxy Center (SVEC) in cooperation with its principle industry partner Space Industries Inc. at a cost of 30 million dollars. SVEC is a NASA center for the commercial development of space based at the University of Houston. The shield is a self-contained spacecraft, or free flyer, with cold gas propulsion for separation from the shuttle robotic arm, a momentum bias attitude control system and sixty kilowatt-hours of energy stored in silver zinc batteries. The principle mission of both the first and second WSF flights was to achieve and characterize for the first time an uncontaminated ultra-vacuum in Low Earth Orbit (LEO) and to demonstrate the feasibility of epitaxial growth of high quality semi-conductor thin films required for advanced electronic and optoelectronic devices. The process control and vacuum characterization equipment are located on the back, or wake side, of the shield while the controller electronics, attitude control system,
batteries and support equipment are located on the front, or ram side. The WSF communications system routes telemetry and commands to and from the shuttle payload bay shield mount which relays to both WSF ground personnel and the flight crew. The free flyer weighs about 4350 pounds and occupies about one-quarter of the payload bay. It is shown pictorially in Figure 2.1.

![Image of WSF in the grappled deployment](image)

**Figure 2.1: The WSF in the grappled deployment.**

The Charging Hazards and Wake Studies Experiment (CHAWS), designed by the Air Force Phillips Laboratory at Hanscom AFB, MA, was intended to study the interaction between the spacecraft and the wake environment. It took advantage of the geometric simplicity, the minimum amount of hardware on the wake side of the shield and that low outgassing materials were specified for use there to avoid contamination of the primary experiment. The position of various CHAWS components on the shield is shown in Figure 2.2.
Figure 2.2: CHAWS components mounted on the WSF.

CHAWS studied the wake environment by recording the positive ion collection to a highly biased probe mounted on the back of the shield while simultaneously observing environmental parameters with sensors mounted on the ram side.

2.2 CHAWS Hardware

The CHAWS flight hardware consisted of three components: the Ram Side Sensor (RSS), a wake side Langmuir probe and a ram side micro-processor. The RSS contained stepping power supplies and three thermal ion detectors while the microprocessor contained the counters, A/D converters and control circuitry for CHAWS. The probe contained three more thermal ion detectors and also measured the total current collected.

2.2.1 Ram Side Sensor

The RSS provided measurements of the plasma environment through which the WSF was traveling. The outside configuration if shown in Figure 2.3.
The casing housed the electronics and raised the three thermal ion detectors sufficiently to ensure that they had access to their complete field of view (FOV). The detectors are microchannel-plate based particle counters [14]. Since the ions make a 180 degree turn inside the detector it have an inherently high a high solar rejection as photons are lost in the baffle at the back of the detector. This feature is also a drawback since high energy particles can not make the turn and become lost in the baffle. The detector field of view is greater than 80° for ions of energy less than 32 eV and is reduced for particles of up to 200 eV. The detector plates are halved or quartered so that on either side of the shield eight digital readings of the particle flux are obtained. The location and field of view of the 16 channels is shown in Figure 2.4. By comparing the counts into each detector on the ram side the orientation of the plasma flow velocity can be determined over a range of ±40°×±5°.
Each of the RSS apertures is fitted with a retarding potential analyzer (RPA) which allows determination of the incoming stream energy distribution and hence allows observation of the flow velocity, ion temperature and, in principle, composition. The retarding potential was varied from 0 to 32 V in 1024 discrete steps over 7.5 seconds.

2.2.2 Langmuir Probe

The Langmuir probe, shown in Figure 2.5, consists of a grounded central structure and a negatively biased stainless steel outer shell.

![Figure 2.5: Schematic of the Langmuir Probe.](image)

The power supply does not sink the current so when the probe was not in operation it could float slightly negative due to interaction with the electron rich wake environment. There was a total of 256 voltage steps available for application to the probe. The first 64 go from 0 to 63 V in 1 V steps while the remaining steps cover 75 to 4750 V in 25 V steps. A logarithmic current amplifier measures the total probe current collected across to a resistance of 500 MOhms.

Also mounted on the probe are three thermal ion detectors identical to those on the RSS. One faces outboard towards the plasma stream, another inboard towards the center of the shield and the third detector faces outward from the tip of the probe. When the power supply is not applying bias to the probe the detectors have a retarding bias applied and take measurements in the same manner as the ram side detectors. However, when the high voltage status of the probe is enabled the ion detector retarding potential grid in grounded out making them simple counters.
2.2.3 Micro-processor

The Micro-processor controller controlled all aspects of the CHAWS hardware operation. All the thermal ion detectors can be individually activated and the 32 V sweep bias applied to their apertures can be grounded. It also controls the application of the negative bias to the Langmuir probe shell. The bias application is broken down into eight pre-defined sweeps of voltage ranges 0 to 31, 62, 325, 775, 1550, 2325, 3100 or 4825 V. Each sweep has 32 points.

Data acquisition occurred whenever there was power applied to CHAWS. Data enters into an onboard buffer until it is polled by the WSF computer. The 7.5 second RPA sweep sets the base clock for the CHAWS data collection. Particle counts from the wake side are placed into the data stream as 8-bit logarithmically compressed counts via a method which provides 4 bit precision. The ram side particle count data are sent as uncompressed 16-bit values. Each high voltage sweep of the probe takes one minute while eight RPA sweeps of 160 count measurements each are taken on the RSS and the wake detectors. Each high voltage sweep of the probe had to initiated from an external trigger via the WSF from either ground control of the shuttle crew.

2.3 Flight Operations

In the CHAWS experiment several parameters influencing the amount of current collection to the probe varied. These include shield angle of attack, plasma density, configuration (grappled or free-flying), ion temperature, electron temperature, shield bias due to both \((\vec{v} \times \vec{B}) \cdot \vec{T}\) and interaction with the surrounding plasma, and probe bias. Figure 2.6 defines the angle of attack convention employed throughout this work.

![Figure 2.6: Sign convention for WSF angle of attack.](image)

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2.3.1 STS-60 Overview

STS-60 Discovery was launched from pad 39A at Kennedy Space Center on February 3rd 1994. The shuttle was placed in an orbit with an altitude of 350 km and an inclination of 57°. This large inclination was chosen for political reasons since a mission specialist, Sergei Krikalev, became the first Russian cosmonaut to fly into orbit on a US space vehicle and it was therefore politically desirable to have the shuttle ground track pass over Russia. From the aspects of policy and public relations this US-Russian cooperation was the most significant mission component. The flight duration was 6 days and landed at Kennedy Space Center Shuttle Landing Facility on February 9th 1994.

The main payloads carried into orbit were the Spacehab-2 laboratory module and the Wake Shield Facility (WSF-1). The mission plan [15] specified that the WSF be deployed and released on flight day three. The shield was to maneuver away from the orbiter to a distance of around 45 miles. The principal experiment on WSF-1 was to be the growth of thin-film semiconductor using the Molecular Beam Epitaxy (MBE) and Chemical Beam Epitaxy (CBE) process equipment mounted on the wake side [16]. The ultra-vacuum environment in the wake would allow the growth of virtually defect-free thin film layers of gallium arsenide, indium phosphide and other semiconductor materials on wafer substrates. Meanwhile the crew would work in the Spacehab-2 module on 12 separate experiments. After two days the shuttle was to rendezvous with the shield and retrieve it with the robotic arm. During this retrieval phase of the mission the CHAWS experiment was to conduct active measurement. The WSF was to be held by the arm for an entire day of CHAWS operation.

Unfortunately the plan could not be followed. The WSF horizon sensor failed shortly before the shield was to be deployed. It was decided not to release the shield since retrieval might not be possible. Instead, the WSF remained grappled to the manipulator arm, as shown Figure 2.7, while all the experiments were conducted. The additional contamination from the orbiter degraded the vacuum required for the epitaxy experiments [17]. On February 8th, after the epitaxy experiments had been completed, the high voltage CHAWS operations were enabled.
Figure 2.7: Orientation of the WSF and the shuttle in the grappled deployment. The Earth is downwards while the velocity vector is into the page for the left picture and to the right for the other.

2.3.2 CHAWS I Operations

The CHAWS operations fell into two categories: passive and active measurement. For approximately 13.5 hours the detectors made passive measurements while the primary epitaxy experiment was carried out. The probe high voltage sweeps were not enabled during this time to avoid perturbing the wake environment. Active operations began after the last wafer was stowed and lasted 4.5 hours. Unfortunately, these operations were restricted by a failure in the high voltage power supply. An unexpected low impedance to ground caused the supply to overheat and limited the maximum applicable potential to -125 V. Twelve high voltage sweeps were conducted before the failure and 41 truncated sweeps were done after. The 41 low voltage sweeps were later found [18] to be suspect due to the low impedance to ground and are not considered in this work. Shaw [13] limited his work to solely the high voltage analysis since that regime is generally more important to spacecraft design.

2.3.3 STS-69 Overview

STS-69 Endeavor was launched from Kennedy Space Center Pad 39-A on September 2nd 1995 at 11:09 am. It flew at a nominal altitude of 370 km at an inclination of 28.4°. This was the
ninth mission for shuttle Endeavor and the 71st shuttle flight. The mission duration was 10 days and 20.5 hours and landed at Kennedy Space Center on September 18th at 7:37 am.

The mission had two primary payloads to deploy: the WSF and Spartan 201, both of which were free flyers. STS-69 marked the third flight of Spartan 201 whose mission is a scientific research effort aimed at the investigation of the Sun and the charged particle solar wind. In addition to the free flyers the crew had perform a 6 hour spacewalk to test both assembly techniques for the international Space Station and thermal improvements to space suit design. Many other experiments had to be performed and monitored. These included:

- The Extreme Ultraviolet Hitchhiker (IEH-1). The first of five planned flights to measure long-term variation in the magnitude of the absolute extreme UV radiation from the sun and also the Jupiter- Io plasma torus.
- Testing of the combined Capillary Pumped Loop/Gas Bridge Assembly cooling system.
- The EPICS (Electrolysis Performance Improvement Concept Study) which tested the electrolysis of water to obtain hydrogen and oxygen. The onboard generation of oxygen should reduce the Space Station resupply by 12000 pounds annually.
- The TES-2 (Thermal Energy Storage) which studied the microgravity behavior of thermal energy storage salts.
- Several biomedical and bioprocessing experiments.

The Spartan 201 free flying experiment was performed for the first three days of the Shuttle flight. On flight day 4 the Spartan satellite was retrieved and the WSF was released from the shuttle. Four days later the shuttle grappled the shield with shuttle remote manipulator system (RMS) and on the following day the shield was stowed in the payload bay for return to Earth.

2.3.4 CHAWS II Operations

The primary experiment aboard the WSF was the ultra-pure epitaxial growth investigation. The first day of free flight operation was employed to verify operational capability. An attitude control problem caused a distinct wobbling in the shield and resulted the loss of one days worth of measurements. During the two days of epitaxial operation the CHAWS sensors made passive measurements of the ram and wake environment since sweeping by the Langmuir probe would have disrupted and possibly contaminated the wake environment. After the final wafer grown by the molecular beam epitaxy experiment was safely stowed CHAWS began active operation. The free flight data obtained by the CHAWS experiment on flight days 7 and 8 were constrained due to
time pressure resulting from the attitude control system problem and the data from day 7 was lost
due to bad telemetry between the shuttle and the shield. In total about one hour of active free flight
data was obtained. On flight day nine the CHAWS experiment was run for a period of over three
hours while the shield was mounted onto the shuttle arm.

2.4 Post-flight Calibrations

The method by which the raw counts per time interval incident upon a given RPA aperture
are converted into a flux value is defined as the instrument calibration. This conversion is essential
for a meaningful determination of the ambient plasma density and temperature but does not have
any effect on the current-voltage sweeps measured by the Langmuir probe. Unfortunately, this
calibration has been done twice since the genesis of the CHAWS project. Post CHAWS I
experimentation with these detectors [19] determined a rough constant value conversion factor.
Preparation work for CHAWS II along with some modifications which were not complete until the
beginning of 1996 found a more accurate [20] calibration function. Both of these calibrations are
outlined briefly below.

2.4.1 CHAWS I Instrument Calibrations

Immediately following the CHAWS I flight the CHAWS hardware was flown to Phillips
Laboratories for post-flight calibration. These calibrations were performed in a vacuum chamber
with an argon ion engine used as a plasma source. The work had two primary purposes. First,
the difference in sensitivity between the detectors due to slightly different apertures and channel
efficiencies [21] was measured so the raw counts could be adjusted. Second, a conversion factor
for determination of ram flux, \( J_{\text{ram}} \), in \( \text{cm}^2\text{s}^{-1} \) into the aperture from the observed detector count rate
(cps) was measured and is given by

\[
J_{\text{ram}} = \frac{\text{cps} \times 495484}{\cos(\theta)} \tag{2.1}
\]

In this calibration the effect of the detector orientation was assumed to be purely geometrical.
The projected area of the detector was reduced by a factor \( \cos(\theta) \) where \( \theta \) is the angle that the
detector made with the plasma stream. Any other changes in the FOV were neglected [14]. The
self-impedance of the probe was also found in order to calibrate the total current measurements.
2.4.2 CHAWS II Instrument Calibrations

These calibrations were determined by Dr. Dave Cooke at the Air Force Phillips Laboratory at Hanscom AFB, MA at the beginning of 1996. The calibration factors are given by

\[ \text{flux} = \text{cps} \times \text{flux\_cal\_factor} \quad (2.2) \]
\[ \text{density} = \text{cps} \times \text{den\_cal\_factor} \quad (2.3) \]

where

\[ \text{flux\_cal\_factor} = \frac{1}{G(\text{Mach, azimuth, elevation}) \times G0 \times P\text{factor}} \quad (2.4) \]

\[ \text{den\_cal\_factor} = \frac{1}{G_{-N}(\text{Mach, azimuth, elevation}) \times G0 \times P\text{factor} \times Vd} \quad (2.5) \]

An aperture azimuth of zero is defined to be the direction in the plane of the aperture which is radially outward from the shield center. The azimuth increases in the counter-clockwise direction about the normal to the aperture. Aperture elevation is defined as the angle from the aperture normal. The G0, P\text{factor} and Vd are all constants of the calibration and are implemented in CHUNKS. Vd is the drift velocity of the ambient plasma stream, G0 is the correction for a Mach zero flow and the P\text{factor} simply corrects the units to be consistent with the desired output. Both G and G\_N, the effective area for the detector, encompass all the detector sensitivities to Mach number, azimuth and elevation and hence attain a higher level of detail and accuracy than the purely geometric consideration of the previous section. The determination of the G and G\_N functions and the calibration constants is provided in Appendix A where the report by Dr. Dave Cooke is reproduced.

This calibration is thought to be more accurate and is verified by the ability of all three apertures, despite being at different angles to the flow, to provide close to the same measurement of the ion density and temperature. The new calibration substantially altered the ambient plasma parameters and necessitated re-visiting the work done by G. Shaw [13] before proceeding with analysis of the CHAWS II flight data. For comparison, both the old and the new calibration ambient parameter values are included in the CHAWS I summary in Table 3.1.
2.5 Emission Experiments

2.5.1 Secondary Electron

The energies of the incident ions were much greater than the work function of the probe material and raised concerns that secondary electron emission from the Langmuir probe cover was contributing to the total current measured. A team at Northeastern university performed a series of vacuum chamber experiments to quantify the amount of secondary electron emission [22]. Figure 2.8 shows their experimental configuration. The probe was placed within an isolated stainless steel grid and into a vacuum chamber with gas flow control. The grid-probe separation was 1 cm. Ar ion current could be identified from the SEE current by changing the polarity between the grid and the probe. A potential difference of -30 V was sufficient to prevent any secondary electrons from leaving the surface of the probe. Determination of the amount of secondary electron current was made by observing the difference in the total measured current for each grid polarity. The secondary electron yield could then be calculated and be applied directly to the CHAWS data to remove the secondary electron contribution. Note that the probe cover itself did not provide the Ar ions with their impact energy; this was provided by the accelerator grid shown in the Figure. Hence use of this yield value in CHAWS data analysis assumes that the effective secondary electron yield does not depend on the surface field or bias which was actually present in the on-orbit operation of the probe.

![Figure 2.8: Experimental configuration for secondary yield measurement [22].](image-url)
Chapter 3: CHAWS Results and Data Reduction

The CHAWS experiment measured the ambient plasma parameters with the Ram Side Sensor and interrogated ion collection into the wake with a high voltage Langmuir Probe. The shield orientation and relative position were recorded by the orbiter. Following each flight of the experiment the totality of the CHAWS data was transferred to a Sun workstation at the Hanscom Air Force Base Phillips Laboratory. The data was accessible via two computational shells: CHAPS and CHUNKS [23]. CHAPS provides a general graphical overview of CHAWS data and follows the timeline of the actual data collection while CHUNKS, via UNIX shell script, outputs any aspect of the recorded data over a specified time period in a tabular format for further analysis. Each executes some degree of data reduction, such as density determination from the RPA sweeps, however, some additional data reduction was performed and is outlined in this chapter.

Due to a failure in the high voltage power supply CHAWS I captured only 12 high voltage sweeps. Of those, 4 had large data drop-outs and were removed from consideration. The low voltage CHAWS I sweeps were corrupt as a result of a lower than expected impedance to ground [18] and were also removed from consideration.

The re-flight of CHAWS, after persevering through a malfunctioning attitude control system and despite time pressure due to difficulty with the primary WSF experiment, managed to return a wealth of data. In total, there were over 80 Langmuir Probe voltage sweeps taken. These varied from 32 to almost 5000 volts in maximum voltage size and were taken at a wide variety of shield orientation and position. One measurement period was continuous for almost two orbits and
experienced a wide variety in ionospheric parameters. While the majority of measurements were taken with the probe positioned within the wake of the WSF, some trials were performed with the shield inverted so that the probe was facing directly into the plasma flow. Others were run with the shield within the deep wake of the shuttle and some quite dramatic observations were made with the shield following the orbiter as the main OMS engine was fired. The analysis contained within this report examines primarily the wake side and ram side Langmuir probe current-voltage measurements in both the high (>100 Vl) and low (<100 Vl) voltage regions.

3.1 Ambient Parameter Determination

This determination has been the subject of some controversy in the CHAWS project. As reported in section 2.4 there was a re-calibration of the Ram Side Sensor (RSS) prior to the flight of CHAWS II. The results detailed in this section and employed in the remainder of this work are based completely on the results of the newest and more accurate [20] release of the instrument calibration.

The Ram Side Sensor described in section 2.2.1 contained three Retarding Potential Analyzers (RPA). The ideal planar RPA employs a retarding potential \( V_r \) which defines the minimum normal energy, \( 1/2m_{ion}(v_{normal})^2 \), with which an ion can pass through the aperture and be detected. Ramping \( V_r \) and recording the flux density of the ions yields the ion energy distribution with respect to the shield. In the CHAWS experiment the RPA's were swept through a retarding potential of 0 to 32 volts over a 7.5 second period in 160 discrete voltage steps. For each step interval the number of counts was recorded. It was assumed temporal aliasing of the plasma parameters was small over the RPA sweep period. After the measured raw counts were converted into actual flux readings via the calibration outlined in section 2.4.2 a particle energy spectrum such as the one shown in Figure 3.1 was obtained. For each current-voltage curve of the CHAWS experiment up to eight of these spectra were taken on each of the three ram side RPA's. These are included in Appendix B.
From these spectra the ion density, temperature and WSF potential relative to the plasma could be found.

3.1.1 Ion Density

The ion density was determined from the peak of the flux versus energy plot. The orbital velocity of the CHAWS experiment was about 7600 m/s. This provides the O+ ions in the plasma stream an effective kinetic energy of about 5 eV. Hence, except at high angles of attack, at the low RPA voltages every ion incident upon the detector aperture has sufficient velocity normal to the aperture plane to be detected. CHUNKS and CHAPS averaged the first three points of each RPA sweep to determine $J_{\text{max}}$ and then simply calculated the local ambient ion density according to equation (3.1).

$$n_{i,w}(m^{-3}) = \frac{J_{\text{max}}(cm^{-2} \cdot s^{-1}) \times 10^4}{v_o(m \cdot s^{-1})}$$  \hspace{1cm} (3.1)
3.1.2 Ion Temperature and WSF Floating Potential

The thermal energy of the ions determines the spread of the distribution function and also the slope of the energy spectrum. The physics of the ion collection to the RPA has been well considered [13] and is reproduced below.

The plasma stream was assumed to have a drifting Maxwellian velocity distribution

\[ f_i = n_i \cdot \frac{m_i}{2 \pi k T_i} \left( \frac{m_i}{2 \pi k T_i} \right)^{3/2} \exp \left( -\frac{m_i ((v_x - \cos(\theta) \cos(\phi) v_{orb})^2 + v_y^2 + v_z^2)}{2 k T_i} \right) \]  

(3.2)

where \( \theta \) is the angle of attack and \( \phi \) is the yaw angle.

An integral over the velocity-space of this function will give the theoretical flux to the surface of the detector, as follows:

\[ J_{ram} = \int \int_{v_x, v_y} \int_{\frac{2 e \Phi_{ra}}{m}}^\infty f_i v_x d^3v \]  

(3.3)

The \( v_x \) lower limit is set at \( \frac{2 e \Phi_{ra}}{m} \) to screen out all ions with

\[ \frac{1}{2} m_i v_x^2 < e \Phi_{ra} \]  

(3.4)

The integral was evaluated with suitable changes in variables to give [24]

\[ J_{ram} = n_i \cdot \left( \frac{\cos(\theta) \cos(\phi) v_{orb}}{2} \right) \text{erfc}(\Gamma) + \sqrt{\frac{k T_i}{2 \pi m_i}} \exp(-\Gamma^2) \]  

(3.5)

where

\[ \Gamma = \frac{\sqrt{e \Phi_{ra}} - \frac{1}{2} m_i (v_x \cos(\theta) \cos(\phi))^2}{\sqrt{k T_i}} \]  

(3.6)

It was necessary to modify the above equation since the spacecraft was not grounded with respect to the plasma. In this more general case,
\[ \Phi_{total} = \Phi_{rpa} + \Phi_{wsf} \] (3.7)

where \( \Phi_{wsf} \) is the floating potential of the wsf.

The function described by equation (3.5) can be fit to the data to determine the values for the two unknowns, \( kT_i \) and \( \Phi_{wsf} \). This was accomplished using a gradient expansion least squares technique [25][26]. The fit of equation (3.5) to each RPA sweep is also provided in Appendix B. The procedure also provides an uncertainty in the fitted ion temperature value. Typically, the \( kT_i \) uncertainty was within about 0.03 eV.

Other techniques have been developed [20] which apply the same physics but are computationally simpler than the direct fit employed above. Essentially, these algorithms estimate the maximum slope value of the energy spectrum and employ the derivative of \( J_{rain} \) with respect to the ion energy. While their computational efficiency makes them ideally suited for use on actual spacecraft, where processing power is limited, these methods are less accurate than the direct fit to the data. One of the techniques developed by [20] was implemented in CHUNKS; this work employed the more accurate temperature determination method. A comparison of the results from each method is provided in Figure 3.2.

![Figure 3.2: Comparison of ion temperature results for a) direct fitting to the RPA sweep ('FIT') and b) slope estimation ('SLOPE') for Day 256 (CHAWS II).](image)

45
The CHAWS experiment was not equipped to measure the electron temperature of the plasma and it was assumed in the subsequent high voltage analysis and Debye length calculation that the electron temperature was twice that of the ion temperature.

### 3.1.3 Summary

The ion density and temperature determination methods described in the previous sections were applied to each of the several RPA energy spectra taken for each Langmuir probe current-voltage curve. Table 3.1 presents the ambient parameter values averaged over each of the eight CHAWS I probe sweeps.

<table>
<thead>
<tr>
<th>Sweep</th>
<th>GMT</th>
<th>(V_{\text{MAX}}) (V)</th>
<th>Tilt (deg)</th>
<th>Ion Temp (eV)</th>
<th>wsf bias (V)</th>
<th>Density ((m^{-3}))</th>
<th>Debye ((cm))</th>
<th>Density ((m^{-3}))</th>
<th>Ion Temp (eV)</th>
<th>Debye ((cm))</th>
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</table>

Included for comparison are the ambient parameter values found for the older version of the instrument calibrations. In general, the newer density values are between 2% and 25% lower while the new ion temperature values differ from the old by as much as 30%. As a result, the calculated Debye length increased by as much as 25% in the earlier sweeps and dropped to almost no change by sweep 12. These changes were significant enough to warrant re-consideration of the high voltage CHAWS I work performed by Shaw [13].

The CHAWS II ambient parameters are summarized in Tables 3.2, 3.3 and 3.4. On days 256 and 257 the WSF was free flying while on day 258 it was grappled to the robotic manipulator system of the shuttle.
Table 3.2: CHAWS II High Voltage Sweep Parameters (Day 256)

<table>
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<th>Sweep</th>
<th>GMT</th>
<th>$V_{\text{MAX}}$ (V)</th>
<th>Tilt (deg)</th>
<th>Ion Temp (eV)</th>
<th>wsf Bias (V)</th>
<th>Density (m$^{-3}$)</th>
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Table 3.3: CHAWS II High Voltage Sweep Parameters (Day 257)

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<th>Tilt (deg)</th>
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<td>Ion Temp (eV)</td>
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<tr>
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</tr>
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<td>2.6E+11</td>
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<tr>
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<td>325</td>
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<td>0.11</td>
<td>NA</td>
<td>6.5E+10</td>
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<td>NA</td>
<td>8.0E+10</td>
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<td>0.09</td>
<td>NA</td>
<td>1.2E+11</td>
<td>0.9</td>
</tr>
</tbody>
</table>

None of the wake side sweeps had significant yaw angles except for sweeps 86 and 87 which were at -18.5 and -18.7 degrees, respectively. Sweeps 88 and 89 were taken with the plane of the shield parallel to the plasma stream flow vector and are hence denoted as being at the 'SIDE' orientation. Likewise, sweeps 113 through to 116 were taken with the shield inverted such that the
probe was pointed directly into the flow and are hence denoted as being at the 'INV' orientation. For both the inverted and the side sweeps the RPA's could not obtain satisfactory energy spectra. The asterisk beside each indicates that the ambient parameters were determined through the estimation process described in section 6.1.1. Sweeps 103 to 112 were taken with the shield in the deep wake of the shuttle and the ion collection to the probe in this circumstance was beyond the scope of this study.

Once the environmental values were obtained it was of interest to compare the parameter space covered by CHAWS I and II. Figures 3.3 to 3.5 make evident that CHAWS II covered many of the areas covered by CHAWS I but did so in much greater detail. In addition, CHAWS II took sweeps at voltage levels not achieved in CHAWS I, explored a greater breadth of attack angle, and obtained some sweeps at lower ion temperatures. The CHAWS II data clearly offers a more varied and comprehensive test of both the computational and analytical models developed in pre-flight and post-CHAWS I periods. The inverted and sideways oriented sweeps are not included. 'FF' refers to the free-flight while 'G' indicates that the data was taken when the shield was grappled.

![Figure 3.3: Parameter space covered by angle of attack.](image-url)
3.2 Wake Data

Exploration of the ion collection to a negatively biased high voltage source in the wake of a satellite was the primary goal of the CHAWS flights. This section provides the CHAWS high and low voltage sweeps obtained and explains their basic characteristics. The division between the low voltage and the high voltage regions is the turn-on voltage, predicted by CHAWS simulation [10][27] to be about -100 volts. This is a natural division since the collection mechanism for each region may be fundamentally different.
3.2.1 High Voltage I-V Sweeps

A representative current-voltage characteristic is shown in Figure 3.6. All the raw CHAWS sweeps are included in Appendix C. The error in the current measurement is due to the estimated 5% incremental accuracy in the logarithmic amplifier.

![Graph](image)

Figure 3.6: Sample high voltage I-V sweep (sweep 10).

The more surprising aspects of both the CHAWS I and CHAWS II sweeps was that they were non-linear and that there was no abrupt turn-on voltage. Pre-flight modeling [10] and additional particle-in-cell simulation (refer to section 4.1) predicted a linear characteristic and a turn-on voltage of about -100 volts. At the lower voltages it was expected that the potential would have yet to expand outside of the shield wake and therefore very few O+ ions would be collected. Once the potential became sufficient to extend beyond the edge of the shield the collection of O+ would begin, defining the turn-on voltage. The masking of the turn-on voltage may be due to a low Mach number component of the frontal stream which can, by equation (1.16), more easily penetrate the wake and be collected. This is discussed in Chapter 5. Above a few hundred volts [12] the curves could be fit to a power law

\[ I = AV^\alpha \]  

(3.8)

where A is just a constant of proportionality and \( \alpha \) was typically between 1.5 and 1.6.

All curves with a full range of data between the values of -300 to -1500 volts were fit to this law with the results presented below in Table 3.5.
Table 3.5: Power law fits to the CHAWS high voltage sweeps.

<table>
<thead>
<tr>
<th>CHAWS I</th>
<th>A</th>
<th>α</th>
</tr>
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<tbody>
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<td>iv006</td>
<td>5.83E-09</td>
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</tr>
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<td>iv011</td>
<td>1.42E-09</td>
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</tr>
<tr>
<td>AVERAGE</td>
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</tr>
<tr>
<td>STD DEV</td>
<td>1.73E-09</td>
<td>0.08</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAWS II</th>
<th>A</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>iv058</td>
<td>1.72E-09</td>
<td>1.57</td>
</tr>
<tr>
<td>iv059</td>
<td>1.88E-09</td>
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<td>1.74E-09</td>
<td>1.56</td>
</tr>
<tr>
<td>iv087</td>
<td>1.53E-09</td>
<td>1.56</td>
</tr>
<tr>
<td>iv085</td>
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<td>1.56</td>
</tr>
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</tr>
<tr>
<td>AVERAGE</td>
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<td>1.55</td>
</tr>
<tr>
<td>STD DEV</td>
<td>7.1482E-10</td>
<td>0.03</td>
</tr>
</tbody>
</table>

The power value of these fits was found to exhibit no detectable dependence on plasma density, ion temperature, or angle of attack. The degree of non-linearity is constant at a given voltage, indicating that the cause is a fixed property of the experiment. One possible explanation is the coefficient of secondary electron emission. Provided in Figure 3.7 are the results of the SEE coefficient measurement performed at Northeastern University for the CHAWS I stainless steel Langmuir probe [22].
The results of the SEE experiment were initially surprising. It was observed that as the Ar+ ion beam scoured clean the probe surface the emission coefficient decreased. After the CHAWS I flight the probe was found to have a brown tarnish on much of its surface. This contamination was identified as gallium arsenide from the epitaxy experiment. Unfortunately, the probe was tested at Northeastern University almost a year after the CHAWS I flight. By this time the surface contamination was thought to have been composed not only of gallium arsenide but also its oxides and possibly oxides of the steel itself due to exposure to the atmosphere. Hence, a true measurement of the SEE coefficient for the CHAWS probe at the time of flight could not be captured. Rather, only the bounds within which the true flight SEE may lie could be defined. The dashed line [13] was the best estimate of the flight SEE coefficient.

Consideration of the CHAWS II data may justify re-visiting this estimate. For the second flight the probe returned without any visible surface contamination. Therefore, the CHAWS II data should have been more linear than that of CHAWS I. Interestingly enough, the \( \alpha \) value average for each flight over the same voltage range are statistically equivalent. If the CHAWS II probe were clean for the entire flight then this power law result suggests that the flight level of contamination may have been too severe a correction for the CHAWS I data. It is also possible that the CHAWS II probe was contaminated at roughly the same level as the CHAWS I probe and that it was sputtered clean while performing the ram side sweeps towards the end of the mission. The likelihood that each flight had the same contamination level is small and hence suggests that the
contamination on the CHAWS I probe had little effect on the data at the time of flight. Since this is not a conclusive result both levels are considered throughout this work. Presented in Figure 3.8 is the sample sweep of Figure 3.6 corrected for both the flight and clean levels of contamination.

![Graph](image)

**Figure 3.8:** Sample of I-V sweep (sweep 10) corrected for both flight and clean SEE levels.

The removal of the secondary electron component of the probe current has almost linearized the data and, considering the possible error in the SEE measurement and estimation, may even provide at least qualitative agreement with the linear pre-flight prediction. An extrapolation of the corrected data down to zero current for various data sweeps predicts that the O+ collection onset voltage is between -200 to -400 volts, which, while encouraging, is at the high end of the pre-flight POLAR code prediction of -30 to -300 volts and above the result of about -100 volts from the particle in cell code described in section 4.1. If, however, the lower portion of the sweeps, say -500 V to -1000 V, were linearly extrapolated back to zero current the onset voltage range shifts about 100 V positive and brings the data into agreement with both code predictions. If the code predictions are correct then this suggests that the SEE correction is insufficient to fully linearize the data.
3.2.2 Low Voltage I-V Sweeps

Figures 3.9 and 3.10 present the low voltage CHAWS II data, distinguished by whether the wake shield was grappled or free flying. The figures contain only those sweeps which were of 32 and 62 volts in size. Other data points which are below the turn-on voltage but are contained within curves of greater size, such as the 325 volt curves, are available in Appendix C.

![Graph of CHAWS II low voltage free flight data.](image)

**Figure 3.9:** CHAWS II low voltage free flight data.
Figure 3.10: Grappled CHAWS II low voltage sweeps at low (a and b) and high (c) angles of attack.

In both the free flight and the grappled WSF deployments the data obtained was linear. The large dip in sweep 103 (Figure 3.10b) and the jump in sweep 98 (Figure 3.10a) both correspond to a proportional change in the ion density detected by the RPA’s. The sweep in Figure 3.10c was taken at a large negative angle of attack and hence saw current several times that of sweeps with similar ion density but of near zero attack angle. The sweeps for both deployments have no obvious differences in form or magnitude.
3.3 Ram Side Data

The term ram side refers to both the inverted and sideways oriented current-voltage characteristics. This data set is the most limited of the CHAWS data since sweeps where the probe was immersed directly into the plasma flow were of secondary interest to investigation of the wake. In addition, analysis of this data is more detailed and less exact since the RPA's could not capture sweeps of the plasma flow and therefore could not provide ambient parameter information. In total, there were four ram side sweeps of 325 volts and two of 32 volts. Only one of each the 325 volt and the 32 volt curves was oriented sideways to the flow. These sweeps are presented in Figures 3.11 and 3.12.

![Graph showing current-voltage characteristics for ram side data](image)

**Figure 3.11:** Inverted and sideways sweeps with a maximum probe bias of -325 volts.
Figure 3.12: Inverted and sideways sweeps with a maximum probe bias of -32 volts.

The power law fit results to the ram side data are presented in Table 3.3.1.

<table>
<thead>
<tr>
<th>SWEEP</th>
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</tr>
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<tbody>
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</tr>
<tr>
<td>89</td>
<td>2.1E-6</td>
<td>0.68</td>
</tr>
<tr>
<td>113</td>
<td>3.6E-6</td>
<td>0.65</td>
</tr>
<tr>
<td>114</td>
<td>7.3E-6</td>
<td>0.49</td>
</tr>
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<td>115</td>
<td>5.2E-6</td>
<td>0.64</td>
</tr>
<tr>
<td>116</td>
<td>7.0E-6</td>
<td>0.59</td>
</tr>
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</table>

The 325 volt sweeps had power values of about 0.64 while the 32 volts sweeps had power values of about 0.50. The fit results suggest that as the sweep size increases the power law dependence becomes weaker the data becomes increasingly linear.
Chapter 4: High Voltage Analysis

The high voltage analysis forms the centerpiece of this work. The CHAWS project was intended to explore the charging interaction between a low Earth orbit spacecraft and its wake. It was also meant to fly and test revolutionary new ion detectors and provide data with which to verify numerical simulation of complex unsymmetric systems. The ultimate goal of CHAWS is to provide with confidence a means to properly engineer with the spacecraft wake - be it to avoid differential charging of surfaces or to save on spacecraft mass by taking advantage of the insulating properties of the wake by placing high voltage uninsulated power supplies and wires within it.

Much of the work contained herein has been performed by previous researchers on the CHAWS project but none of their results or predictions have been applied to the CHAWS II data. This chapter reviews both the particle-in-cell (PIC) code developed to simulate the experiment and the semi-analytical model developed by G. Shaw [13] and goes on to perform an examination of the results. Much of this analysis is complemented by results found in the low voltage analysis of the following chapter and by the ram side analysis of Chapter 6.

4.1 Particle-in-Cell Code

The PIC simulation was originally developed by Dr. Gabriel Font, a post-doctoral researcher employed at the MIT Space Systems Laboratory until Spring of 1995. Much of the information
4.1.1 Governing Equations

The essential problem addressed by the PIC code is the computation of the electric potential from the available simulation information via the scalar Poisson equation:

$$\frac{1}{\varepsilon_0} \nabla^2 \phi = \sigma$$  \hspace{1cm} (4.1)

where $\varepsilon_0$ is the permittivity of free space, $\phi$ is the electric potential and $\sigma$ is the charge density. In a plasma the charge density is related to the concentration of the electrons and ions by

$$\sigma = e n_e + q_i n_i$$  \hspace{1cm} (4.2)

where $n_i$ and $n_e$ are the ion and electron number densities. This simulation employed only singly ionized oxygen atoms, O+, and therefore $q_i$ equals $e$. The potential in equation (4.1) can be non-dimensionalized with the electron thermal energy:

$$\hat{\phi} = \frac{e \phi}{k T_e}$$  \hspace{1cm} (4.3)

where $k$ is Boltzmann's constant and $T_e$ is the electron temperature. The spatial derivatives are non-dimensionalized with the Debye length

$$\hat{x} = x \left( \frac{\varepsilon_0 k T_e}{n_e e^2} \right)^{-1} = \frac{x}{\lambda_D}$$  \hspace{1cm} (4.4)

and the densities are normalized by the ambient density.

$$\hat{n} = \frac{n_i e}{n_0}$$  \hspace{1cm} (4.5)

Equation (4.1) may then be expressed as
\[
\frac{\partial^2 \hat{\phi}}{\partial \hat{x}^2} + \frac{\partial^2 \hat{\phi}}{\partial \hat{y}^2} + \frac{\partial^2 \hat{\phi}}{\partial \hat{z}^2} = (\hat{n}_e - \hat{n}_i)
\]  

(4.6)

The ions were followed by the computation and their density is directly determined. The electrons, however, were assumed to be a Boltzmann fluid in equilibrium with the potential and hence their density is given by

\[
n_e = n_\infty \left( \frac{\text{e}^+}{\text{e}^-} \right) = n_\infty \text{e} \hat{\phi}
\]

(4.7)

For the CHAWS simulation this assumption is valid since the electron thermal speed is much greater than both the WSF orbital and the O+ ion thermal speeds. Equation (4.6) then simplifies to the non-dimensional non-linear Poissons equation:

\[
\frac{\partial^2 \hat{\phi}}{\partial \hat{x}^2} + \frac{\partial^2 \hat{\phi}}{\partial \hat{y}^2} + \frac{\partial^2 \hat{\phi}}{\partial \hat{z}^2} = \text{e}^\hat{\phi} - \hat{n}_i
\]

(4.8)

Once the potential has been determined the electric field influencing the particle motion can be found by

\[
\hat{E} = -\nabla \hat{\phi}
\]

(4.9)

where the electric field has been normalized by the ion mass, ion charge, the Debye length and the plasma frequency:

\[
\hat{E} = \hat{E} \left( \frac{q}{m_i \lambda_D \omega_{pi}^2} \right)
\]

(4.10)

The particle velocities can then be updated via Newton’s second law

\[
\hat{m}_i \frac{\partial \hat{v}}{\partial \hat{t}} = \hat{q}_i \hat{E}
\]

(4.11)

The time step has been normalized with the ion plasma frequency

\[
\hat{t} = t \cdot \omega_{pi}
\]

(4.12)
while the velocity has been normalized with the ion thermal velocity

\[
\hat{v} = v \left( \frac{kT_i}{m_i} \right)^{-1} = \frac{v}{C_i}
\]  

(4.13)

The velocity computed by equation (4.11) can then be used to move the particles to their next location.

4.1.2 Computational Scheme

The simple procedure followed by the code is provided in Figure 4.1.

![Diagram](image)

**Figure 4.1: Computational Sequence**

The density is weighted onto the grid node points using a linear interpolation method. The solution to the potential distribution is then found with a 3-D ADI scheme. The field is then found by differentiating the potential and back-interpolating the result to the particles. The particle velocities and positions are then updated through a time-centered leap-frog scheme which maintains second order accuracy.
4.1.3 Computational Model

The computational geometry of the WSF is provided in Figure 4.2.

![WSF Computational Geometry Diagram](image)

Figure 4.2: WSF computational geometry.

Much of the apparatus seen in Figure 2.2 has been removed. These objects should not become significantly biased relative to the probe and therefore their presence should constitute only a second order effect.

The computational grid is Cartesian and the node points are equally spaced in all directions. The simulation is 50 cells long and 75 cells in the other two dimensions. The flow entrance is located 1/3 of a body radius in front of the WSF while the upper boundary is one body radius above the top edge of the shield. The exit plane is one body radius behind the shield while the other side boundaries are each 1/3 of a body radius from the edge of the WSF. These and the other boundaries were chosen through trial and error until alteration of the boundary size did not affect the simulation results. All boundaries and surfaces were assumed to be fully accommodating.

The particles are loaded randomly in space with a Maxwellian distribution of velocities. The orbital velocity of the WSF is then superimposed onto the distribution. The simulation is run for one convective time period to allow the flow field to become established and then another time
period is allowed to run with the results being averaged over it. Trial runs determined that 5 super-particles per cell are sufficient to allow the true physics to be captured. The simulation uses a total of about 1.5x10^6 super-particles.

To ensure convergence the values of the individual cell length \( L \) and the iteration time step \( \Delta t \) were conservatively estimated from trial and error to be 0.0815 m and 9.56x10^-7 s. For a given set of simulation input parameters the \( S \) and \( dt \) factors would be altered according to equations (4.14) and (4.15) to ensure that \( L \) and \( \Delta t \) remained unchanged and hence preserved the code characteristics.

\[
L = \lambda_D S = \sqrt{\frac{\varepsilon_0 k T_e}{n_e e^2}} \cdot S \tag{4.14}
\]

\[
\Delta t = \frac{dt}{w_{pi}} = \sqrt{\frac{e m_i}{n_e e^2}} \cdot dt \tag{4.15}
\]

For example, if the code were run for an O+ ion density of 1x10^{11}, an ion temperature of 0.1 eV and an electron temperature of 1.5 times the ion temperature then \( S \) must be 9.00 and \( dt \) must be 0.100. Neither of these parameters depend upon the probe potential.

The probe potential is held fixed for a given simulation and is measured with respect to the plasma. The shield potential is found by observing the flux to its surface and enforcing the zero net current collection condition.

### 4.1.4 Results

The visual renderings of the code results contained in this section and elsewhere in this work were produced using the visualization package VISUAL 3 developed by Bob Haines at the Massachusetts Institute of Technology Aeronautics and Astronautics Department. VISUAL 3 has a general structure which that allows it to visualize almost any type of continuous field, be it scalar, vector or unsteady. VISUAL 3 allows use of its routines through well defined access points and is ideally suited for representing the simulation results.

Simulations employing only O+ at probe biases between -500 and -2000 volts were carried out for the WSF computational geometry. The simulation results presented in this section were found for an orbital velocity of 7600 ms\(^{-1}\), an ambient density of 1x10^{11} m\(^{-3}\), an ion temperature of 0.1 eV and an electron temperature of 0.15 eV. These conditions were considered representative of the plasma parameters experienced by the WSF when it was in low Earth orbit.
The expansion of the electric potential contours is shown in Figures 4.3 and 4.4 for a probe bias of -1500 V. In Figure 4.3 the contours spread out behind the shield and below the probe. Above the probe the contours are more confined and spread out less as the space charge of the frontal stream is contacted. Nevertheless, the contours expanding into the stream are in the negative 10's of volts. Figure 4.4 depicts the contours as seen from behind. They are not as wide in the area above the probe and demonstrate the magnitude of the potential values that extend into the frontal stream.

Figure 4.3: Visual 3 centerline potential contour cross section for a probe bias of -1500 volts.
Figure 4.4: Potential isocontours behind the WSF for a probe bias of -1500 volts.

The ion densities are shown in Figures 4.5 and 4.6 for the same bias and trial parameters as the potential displays. Figure 4.5 is a centerline cross section of the O+ density. At the lower edge of the shield there is the expected Mach expansion of ions around the shield. However, the upper edge has a crescent shaped area which is cleared of ions and this may be the most important observation resulting from the high voltage PIC analysis. This is shown quite clearly in Figure 4.6 which is a cut plane parallel to the plane of the shield but one half of a body radius behind it. The ion evacuation region compares precisely with the potential contour expansion shown in Figure 4.4.
Figure 4.5: Visual 3 O+ centerline density cross section for probe bias of -1500 volts.

Figure 4.6: O+ centerline ion density distribution one-half of the body radius behind the WSF for a probe bias of -1500 volts.
The ions which enter the crescent area are diverted from the frontal stream into the wake and impact the WSF, as shown in Figure 4.7. The lighter gray area below the probe on the rear of the wake shield is and area where the incident ion flux is about half that of the ram side ion flux. The white areas on the probe correspond to an incident flux of about five times the ion flux. The sample trajectories which all begin in the plane of the shield in different locations all converge at nearly the same point. The electric field forms the flow into sharply defined beams. A comparison of the total current to the probe to both CHAWS I and II data is provided in section 4.3.

Figure 4.7: Sample O+ ion collection trajectories for a probe bias of -1500 volts.

In summary, a three dimensional PIC code was developed to simulate the plasma flow around the WSF for conditions similar to those experienced during both flights. The code confirmed ion focusing in the wake, that the bulk of the probe current is collected on the inboard side of the probe and that there is a clear relationship between the ion density distribution and the potential field. The area where the potential extends into the frontal stream is evacuated of ions. These ions are focused into the wake and are responsible for the current collected by the probe.
4.2 Semi-Analytical Model for Current Collection

The model described in this section was originally developed by a colleague, Graeme B. Shaw [13], using the CHAWS I data and the code results presented in the previous section. The subsequent re-calibrations of the plasma sensors necessitated that the process that was originally followed by Shaw be repeated using the CHAWS I data. This section re-presents the model proposed by Shaw, re-does the semi-analytical application to the CHAWS I data and expands the exploration to the extensive CHAWS II data.

4.2.1 Model Rationale

The simulation provided critical insight into the ion collection dynamics and the potential structure surrounding the Langmuir probe. The code suggested the existence of a well defined collection boundary that separates the ions which pass downstream from those which get collected to the probe. Figures 4.4 and 4.6 show that the boundary edge is closely related to the potential structure which extends outside of the wake region. This result allows the development of an analytical model for the current collection to the probe which is based on the particle flux through the crescent shaped area.

The collection boundary discovered by the code is similar to the absorption boundary or effective cross section defined for classical space charge and orbit motion limited theory. The CHAWS situation is complicated by the presence of two current collecting bodies, one of which is located in the wake of the other. It may be imprudent to assume that every particle which enters the collection boundary is collected. Some particles may enter the collection sheath and become trapped in a bound orbit from which it can never be removed in collisionless modeling. Calculations by Al'pert [7] and also by Virmont [28] demonstrates that neglecting the trapped particle population is a good approximation since its size is insignificant compared to the current which is actually collected. Other work by Biasca and Wang [11] on the current collection to charged objects in the wake of larger objects shows that for some situations a significant portion of the ions incident upon the collection area follow a trajectory which orbits the charged object a few times and then passes downstream. The simulation of section 4.1 found that while such trajectories exist their number is insufficient to be a significant source of error. However, as shown in Figure 4.7, the flux of ions to the rear of the wake shield itself can not be neglected. Hence the use of a definite collection boundary will incur some imprecision. However, the model should give the basic trends of the collection characteristics and allow reasonable estimates to be made for the amount of ion current collected within acceptable engineering error bounds.
The basics of the model proposed by Shaw are:

- The wake boundary is formed along a Mach expansion/rarefaction region if no bias is applied to the probe.
- The wake boundary is characterized by a region of large ion density gradient. Therefore, within the wake it is assumed that the plasma is significantly non-quasineutral.
- The lower density in the wake allows the potential contours to expand outside the shadowing body provided the density in the protruded region is sufficiently depleted.
- The direction of motion of the ambient stream is unaltered ahead of the WSF. Any acceleration imparted to the ions prior to their entering the wake is assumed to be linear, directed parallel to their motion.
- The current to the probe can be quantified by the flux of ions through the section of the wake boundary which extends around the outside of the WSF. This extended wake region defines the collection boundary. The current will therefore be proportional to the area of this region, projected normal to the direction of the stream.

The model is displayed in Figure 4.8.

![Diagram](image_url)

**Figure 4.8: The basic model.**
4.2.2 Collection Area and Radius

The results of the simulation found that the potential structure was cylindrical near the probe and spherically symmetric outside of a few probe radii. Further from the probe the metallic shield and the frontal ion stream begin to distort to spherical contours. In order to develop the model it was necessary to assume that the field between these two extremes was isotropic. An analysis by Shaw of the potential decay radially outward from the simulation probe found this to be a valid assumption.

The geometry of the model and an illustration of the areas to be calculated are shown in Figures 4.9 and 4.10, respectively. Note that in this section of the report the θ sign convention is reversed. The details of the area calculation are provided in the work by Shaw; only the main results are presented here.

Figure 4.9: Geometry of the model.
The angle $\alpha_{\text{crit}}$ is given by solving

$$A \sin \alpha_{\text{crit}}^2 + B \sin \alpha_{\text{crit}} + C = 0 \quad (4.16)$$

where

$$A = -R^2 \sin \theta^2 \quad (4.17)$$

$$B = -2R \cos \theta (d \cos \theta + l_p \sin \theta) \quad (4.18)$$

$$C = (d \cos \theta + l_p \sin \theta)^2 + R^2 - r_c^2 \quad (4.19)$$

The $\alpha_{\text{crit}}$ may then be found through
\[ \alpha_{\text{crit}}' = \arctan \left( \frac{(R \sin \alpha_{\text{crit}} - d) \cos(\theta) - l_p \sin(\theta)}{R \cos \alpha_{\text{crit}}} \right) \] (4.20)

and the final collection area can be written as

\[ A_c = \frac{1}{2} \frac{r_e^2}{r} (\pi - 2\alpha_{\text{crit}}') + \left| R \cos \alpha_{\text{crit}} (d \cos \theta + l_p \sin \theta) \right| - \frac{1}{2} R^2 (\pi - 2\alpha_{\text{crit}}) \cos \theta \] (4.21)

With the collection region defined, under the previously discussed assumptions the current to the probe should be given by

\[ I = \text{Flux} \times A_c = n_v \cdot v_{\text{orbit}} \cdot e \cdot A_c \] (4.22)

In order to completely specify the collection area an expression for its radius must be determined. Hence the physics behind the ion collection must be considered. In both the space charge and orbit motion limited theories described in Chapter 1 a collection boundary was defined through angular momentum considerations. It is true in general that ions with an energy less than the potential

\[ U(r) = e \phi(r) + \frac{J^2}{2mr^2} \] (4.23)

are collected. The CHAWS situation, however, is complicated by two factors: the presence of the metallic shield which distorts the electric field near its surface and the wake edge which represents a discontinuity in the electric field. As a consequence of both complexities it is unlikely that \( U(r) \) falls off in a monotonic fashion and therefore demands solving the coupled Poisson and Vlasov equations. It is therefore not possible to quantify \( U(r) \) and a deterministic solution for a collection radius based on energetics can not be found.

In many situations an approximation of the collection boundary may be made through application of conservation of angular momentum. This is characteristic of force centered problems and is the standard solution for orbit motion limited situations. This analysis has been carried out for geometries similar to that found in the CHAWS experiment [11][9] but these findings show that this method is not valid for CHAWS since the shadowing body and the extended probe result in an unsymmetric electric field and also allow conservation of angular momentum to be violated since the ions may be accelerated ahead of the shield.
Another avenue of approximation is to consider the sheath edge to be the actual collection boundary. The results of the simulation in Figures 4.4 and 4.6 clearly demonstrate that the collection boundary corresponds directly to the potential structure extending beyond the edge of the shield. The error in approximating the sheath edge to be the collection boundary should be small in comparison to the total size of the collection region. The determination of the radius expression for the sheath edge is still non-trivial but is far simpler than invoking a numerical solution of the Vlasov equation.

Al'pert [6] showed that for a probe with \( r_p \gg \lambda_D \) in a stationary plasma which satisfies

\[
\frac{e|\Phi_p|}{kT} \gg \left( \frac{\lambda_D}{r_p} \right)^8
\]  

(4.24)

the size of the space-charge region is given by

\[
r_c = 0.803 \lambda_D \left( \frac{e|\Phi_p| r_p}{kT \lambda_D} \right)^\frac{3}{7}
\]  

(4.25)

This equation predicts the size of the collection region if the behavior is completely space charge limited and there are no wake effects. Despite the presence of the wake edge the functional form of \( r_c \) should be reasonably well suited to the problem. Shaw modified the expression by altering \( r_p \) to be \( l_p \) since the CHAWS probe is extended and employed the orbital energy (\( \sim 5eV \)) instead of the \( kT \) (\( \sim 0.1 \)) value since the orbital energy is dominant and is hence more important to the energetics of ion collection. Since the wake density is less than the ambient density the probe potential should drop off more slowly and hence the collection may be closer to the orbit motion limit case. Therefore the exponent with which the radius depends on the voltage may have a value between 3/7 and 1/2. However, at small Debye lengths equation (4.25) would predict \( r_c \) values which are too low. The calculated value would correspond to the amount of Debye shielding which is occurring outside the wake when within the wake the collection conditions are less affected by the ambient parameters. In these cases Shaw argues that numerical simulation would become necessary. Restricting use of the new \( r_c \) expression to the thick sheath limit would avoid complications and allow a simple analytical function to estimate the boundary of the collection area.

In order to determine the most suitable expression for \( r_c \) two alternatives were considered. The validity of each was tested by a fit to the data. The predicted dependencies on density, ion temperature and angle of attack are far more complex than anything implied by \( r_c \). The proposed one parameter functions are
\[ r_{e,sc} = r_p + \beta_1 \lambda_D \left( \frac{e|\Phi_p| I_p}{E_{orbit} \lambda_D} \right)^\frac{3}{7} \]  \hspace{1cm} (4.26)

\[ r_{e,oml} = r_p + \beta_1 \lambda_D \left( \frac{e|\Phi_p| I_p}{E_{orbit} \lambda_D} \right)^\frac{1}{2} \]  \hspace{1cm} (4.27)

where \( \beta_1 \) is a constant found by the fitting procedure. The expression which depends on the probe bias to the 3/7 describes space charge limited collection while the expression which depends on the 1/2 power corresponds to orbit motion limited collection. The value for the probe radius is included since the co-ordinate system has its origin at the center of the cylindrical probe. Similar expressions which employed two fitting parameters were also considered by Shaw and were of the form

\[ r_c = r_p + \beta_0 I_p + \beta_1 \lambda_D \left( \frac{e|\Phi_p| I_p}{E_{orbit} \lambda_D} \right)^x \]  \hspace{1cm} (4.28)

where \( x \) is the power corresponding to each type of collection and both \( \beta_0 \) and \( \beta_1 \) are fitting factors. Shaw found that these two parameter fits were not useful due to the extensive uncertainty in the I-V and ambient parameter measurements as well as the error incurred from several unqualified assumptions present in the analysis. These include the SEE correction estimation and the assumption that the electron temperature was twice that of the ion temperature. It was also noted that the contribution of the \( \beta_0 \) term to the \( r_c \) value was consistently much less than that of the \( \beta_1 \) term. In the one parameter expressions the ratio of the electron to ion temperature is of no significance since any error in the original assumption is simply absorbed directly into the fit factor.

In the following re-performance of the work by Shaw each one parameter expression was fit to the CHAWS I and CHAWS II data. At each data point the values used for the ambient density, ion temperature and angle of attack were those found by the methods described in Chapter 3. The fitting procedure used a non-linear gradient expansion algorithm [25][26] to determine the \( \beta_1 \) values. This algorithm minimizes the \( \chi^2 \) value with respect to the fitting parameters. \( \chi^2 \) is a goodness of fit parameter which measures the dispersion between the measured and the predicted values. It is defined by
\[ \chi^2 = \frac{1}{N - \text{DOF}} \sum_{j=1}^{N} \frac{(I_{\text{exp}} - I_{\text{mod}})^2}{\sigma_i^2} \] (4.29)

where \(N\) is the number of data points and \(\text{DOF}\) is the number of degrees of freedom in the fit. \(\sigma_i\) is the variance in the measured current which is 5% for CHAWS. A \(\chi^2\) value of exactly one indicates that the fit lies just within the error range of the data being fit. A value less than one therefore does not necessarily indicate a better fit to the data but does mean that the predicted values are closer to the actual data points than a fit with a \(\chi^2\) of exactly one. A \(\chi^2\) value much greater than one shows that a function fits poorly to the data. Since the \(\chi^2\) value distribution is unknown it can not be used as an absolute measure of the fit goodness but only as a comparator.

### 4.2.3 Model Results for CHAWS I Data

The results of the model fits to the CHAWS I sweeps are provided in Table 4.1. As discussed in section 3.1.3 the work by Shaw had to be re-evaluated due to a re-calibration of the ambient parameter sensors which altered the values of ion density and temperature significantly. In the fits of Table 4.1 the data was corrected for the flight level of secondary electron current since equations (4.26) and (4.27) are intended to describe the ion current collection to the probe. The range of the fit was begun at -300 V to avoid the effects of low Mach number contribution to the current. A more detailed discussion of the starting point for the fit is included in section 4.2.4.

| Table 4.1: \(\chi^2\) comparison of space charge and orbit motion limited model fits for the flight level of SEE. |
| --- | --- | --- | --- | --- | --- | --- | --- |
| | Sweep 3 | Sweep 5 | Sweep 6 | Sweep 7 | Sweep 8 | Sweep 10 | Sweep 11 |
| SC \(\chi^2\) | 63.4 | 34.8 | 16.0 | 32.2 | 0.2 | 52.4 | 1.7 |
| OML \(\chi^2\) | 11.7 | 0.3 | 0.2 | 0.3 | 2.0 | 0.3 | 3.5 |

In the work by Shaw it was found that the last three sweeps were fit much better by the space charge formulation of equation (4.26) while the first four sweeps clearly matched the orbit motion limited description. The tentative conclusion was that the collection was orbit motion limited but for situations of lower Debye length, as seen for the last three sweeps, space charge effects become significant. As Table 4.1 demonstrates, the orbit motion limit behavior is a good descriptor of all the CHAWS I sweeps. However, sweeps 11 and 8, which had the two lowest Debye lengths of the considered sweeps, are fit slightly better by the space charge description and this may indicate that space charge effects can become significant. Nevertheless, it is clear the orbit motion limited
description of the current collection offers the best overall description of the ion current collection to the probe. It is also noteworthy that sweeps 10 and 7, which had Debye lengths similar to that of sweep 8, were fit much better by the orbit motion limited equation. Fits to sweep 12 failed in both cases since the Debye length was too small and, as discussed in the previous section, prevents the collection radius from extending into the frontal stream by artificially exaggerating the true amount of Debye shielding present in the wake and therefore violates the thick sheath limitation defined at the outset of the model creation.

Table 4.2 presents the orbit motion limit fits to the data when the sweeps are corrected for only the clean level of secondary electron emission which, as suggested by the discussion in section 3.2.1, may be worthy of further consideration.

<table>
<thead>
<tr>
<th></th>
<th>Sweep 3</th>
<th>Sweep 5</th>
<th>Sweep 6</th>
<th>Sweep 7</th>
<th>Sweep 8</th>
<th>Sweep 10</th>
<th>Sweep 11</th>
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<tbody>
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<td>OML $\chi^2$</td>
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<td>0.3</td>
<td>0.1</td>
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The fits to sweeps 3, 8 and 11 improved while the fits to sweeps 5, 6 and 10 became worse. The sweep 7 fit quality was unaffected by the change. The space charge fits were generally poorer and are not included. These results do not demonstrate that the model fits better for one level of correction as opposed to the other. The difference between the two corrections may be too small to be discernible from a sample size of only seven sweeps and this issue is re-examined in the following section. Figure 4.11 presents the $\beta_1$ values resulting from the fits presented in the previous tables. The minimum and maximum Debye lengths which were permitted within the bounds of the error in both density and ion temperature were also fit to the data and these $\beta_1$ values are also included. In general the minimum and maximum Debye lengths yielded fits which were considerably poorer than the mean values.
Figure 4.11: OML $\beta_1$ values for flight SEE conditions.

It was initially surprising that both the maximum and the minimum Debye length values resulted in higher values for $\beta_1$ than the mean Debye lengths. For the maximum Debye lengths the density is lower and therefore the collection area must be larger to match the data. In the minimum Debye length case the density is high enough that the model over-predicts the amount of space charge to be overcome and this condition also necessitates that the $\beta_1$ value be higher to again match the data. This fits demonstrates that $\beta_1$ may vary between about 0.9 and 1.2; however, for the purposes of future modeling based solely on the CHAWS I data the average Debye length $\beta_1$ value, which also returned the lowest goodness of fit values, is the most appropriate. The clean secondary electron level corrected OML model fits associated with this section are included as Appendix D.

4.2.4 Model Applied to CHAWS II Data

As discussed in section 3.1.3 the parameter space covered by the CHAWS II high voltage sweeps was larger and more detailed than that of CHAWS I. The much greater extent of the CHAWS II data offers a much better opportunity to test the model proposed by Shaw and to investigate contribution to the current by both secondary electron emission and low Mach number flow. Table 4.3 compares the goodness of fit for both the OML and space charge model formulations.
Table 4.3: Space charge and orbit motion limited model fits to the CHAWS II data.

<table>
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<tr>
<th>SWEEP</th>
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<th>\chi^2 (CLEAN)</th>
<th>\chi^2 (CLEAN)</th>
<th>\chi^2 (FLIGHT)</th>
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<td>NF</td>
<td>NF</td>
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</tbody>
</table>

In general, the space charge limited fits to the data are poorer than those of the OML equation. The NF symbol refers to 'no fit' and means that the attempted fit failed. The space charge theory had several no fit results and also indicates that it is ill-suited for description of the ion current collection. It is therefore concluded that the CHAWS II data is orbit motion limited in nature. It should be noted that the 775 V sweeps, of which CHAWS I had none, consistently
yielded either no fit or very high values for $\chi^2$. Sweeps 55, 94 and 96 yielded no fit results for both the space charge and OML fits. In the other higher voltage fits, all of which are included in Appendix E, it was found that OML model almost always under-predicted the amount of current below about the 1700 V1 value. Hence, based on the poor fit results and the under-prediction in this range by the higher voltage fits it is believed that there is additional current present in the data that is not accounted for by the high voltage model. The most probable source of this current, as discussed in Chapter 5, is H+ ions which by virtue of their lower Mach number more easily enter the wake and become collected. Due to the significant levels of low Mach number current contamination at the lower voltages the 775 V curves are excluded from further consideration in this high voltage analysis. Also included in Table 4.3 is a comparison of the goodness of fit values in the OML formulation for both levels of secondary electron emission correction. In twelve of the sweeps the clean level provides a better match with the data while the other six prefer the flight level correction. If it is believed that the model has captured the dominant dependencies of the ion collection then this result is in tentative agreement with the likelihood that the CHAWS II probe was not contaminated and, since the power law fits of section 3.2.1 are statistically equivalent, may also suggest that the contamination observed on the CHAWS I probe was not significant. The $\beta_1$ values found for the OML fit at the clean level of correction are shown in Figure 4.12.

![Figure 4.12: OML $\beta_1$ values for the average Debye length at the clean level secondary electron emission.](image-url)
The average value of $\beta_i$ is 1.05 but with a standard deviation of 0.1. This places the fit results of CHAWS II in good agreement with those found in CHAWS I where the clean level fit parameters are scattered near a value of 1.

Figure 4.13 displays the variance of the goodness of the OML model fit with the fit start point. The work contained in this section and performed by Shaw started the fit at a value of -300 V. It may be that the high voltage dependencies of the model are still being partially masked beyond -300 V by the collection of low Mach number flow from within the wake. This possibility is supported by work in section 5.2.3 which suggests H+ collection may be significant up to several hundred volts and by the previously discussed 775 V sweeps.

![Figure 4.13: The $\chi^2$ factor for each sweep as the start voltage for each fit is increased. The factor is normalized by the $\chi^2$ value found at -300 V for each sweep.](image)

In general, the $\chi^2$ values improve with increasing start value. Moreover, in many cases the change from -300 to -550 V resulted in a larger improvement than in the step from -550 to -800 V. Since the start point was increased in equal intervals it appears that the goodness of fit depends less on the starting point as its value is increased and this is in agreement with the assessment in Chapter 5 that the low Mach number flow component contributes less to the current collection at
the higher voltages. The average Debye length OML model fits to the data for the clean level of secondary electron emission are included in Appendix E.

### 4.3 Code-Data Comparison

#### 4.3.1 Simulation of Two Sweeps

The PIC code presented in section 4.1 also measured the total current to the probe. The simulation was run for parameters that corresponded to a CHAWS I sweep (sweep 10) and a CHAWS II sweep (sweep 68), as shown in Table 4.4.

<table>
<thead>
<tr>
<th>Table 4.4: Simulation and actual sweep parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Density (m$^3$)</td>
</tr>
<tr>
<td>CODE</td>
</tr>
<tr>
<td>SWEEP 10</td>
</tr>
<tr>
<td>CODE</td>
</tr>
<tr>
<td>SWEEP 68</td>
</tr>
</tbody>
</table>

The difference in density between the code and sweep 10 is due to the instrument recalibration since this run was performed just after the CHAWS I flight. The second code run was done following the CHAWS II flight and employed the proper value. The primary reason for choosing to simulate these sweeps was that the ambient parameters remained almost constant during the 60 second current-voltage sweep.

The total current results of the simulations are shown in Figures 4.14 and 4.15. In both plots the data has been corrected for the estimated amount of secondary electron emission current. Both the simulation and the data are linear but both simulation results underestimate the observed data by a considerable amount. The amount of difference appears to be less for the CHAWS II case than for CHAWS I. This may be due to the larger CHAWS I difference between the parameters the simulation employed and those that were actually measured. If the code were to use the newer density value of 1x10$^{11}$ m$^3$ and use an angle of attack of -10 degrees then the difference would be slightly smaller and be close to the difference found in the CHAWS II case which is slightly less than a factor of two.
4.3.2 Discussion

The factor of two difference between the code and the data was quite surprising and while it may be acceptable from an engineering perspective scientifically it warrants in-depth consideration.
Possibilities for this discrepancy include systematic code error, incorrect or inaccurate inputs to the code or an additional source of current which is present in the data but is not accounted for in the code-data comparison.

A systematic error in the code is unlikely. Another simulation code, POLAR (Potential of Large objects in the Auroral Region), developed by the Air Force Geophysical Laboratory [10] was designed to model the interaction of spacecraft with LEO plasma. POLAR is a three dimensional steady state Poisson-Vlasov solver and is therefore different than codes based on PIC methodology. Shaw [13] demonstrated that the two codes yielded identical current-voltage prediction for the same set of input parameters. That each code would possess the same systematic error is improbable and removes any type of systematic error in the PIC code from consideration.

An error in the code inputs translates into an error in the environmental parameters and hence in the detectors or in the analysis of the detector data. The considerable expertise and experience that contributed to developing and analyzing the detectors makes such errors unlikely. The density values are considered good to within a factor of two [13] and the temperature values, which have only a secondary effect on the data, were found in section 3.1.2 to be good to within about 30%. Despite the reported accuracy of the detectors it is of interest to compare the predictions of the IRI atmospheric model to the detector data. The IRI (International Reference Ionsosphere) computer model, based mainly on ground based observations of total electron content, provides electron and ion densities and temperatures as functions of longitude, latitude, altitude, solar activity and time. Figure 4.16 displays the comparison between the CHAWS measured ion densities found on Day 258 and the IRI model prediction. The IRI model values were found through Environmental WorkBench (EWB), a software package used for assessment of various spacecraft-environment interactions developed by Maxwell’s S-CUBED Division for NASA Lewis Research Center.
Figure 4.16: Comparison between CHAWS density values and the IRI model. The two vertical lines enclose one period of the data.

Qualitatively, given the possible factor of two density error and the statistical nature of the IRI model the data and the model agree. The noon peaks (time ~33500 s) differ substantially but laboratory testing [18] demonstrates that the detector did not saturate. Overall, it is unlikely that the density values are in error beyond a factor of two and additional runs of the code have demonstrated that the ion temperature error of 30% is still a secondary consideration.

Another input of concern is the ratio of the electron temperature to the ion temperature, which was not measured directly in the experiment. As will be shown in Chapter 6, Laframboise theory [29] for space charge limited current collection to a cylindrical probe aligned with the plasma flow is quite sensitive to this ratio. The fits of Laframboise theory to the ram side sweeps (Chapter 6) suggested that the ratio of the electron temperature to ion temperature may be greater than the assumed factor of 1.5. Additional references [30][31] have also noted an increase in the electron temperature within the wake of a spacecraft and place this ratio as high as three times the 1.5 ratio. Hence, the code was run for higher ratios with the results included in Figure 4.17.
Figure 4.17: Current dependence on electron temperature for sweep 10 simulation at a probe bias of -1000 V.

The figure demonstrates quite clearly that electron temperatures as high as five times that of the ion temperature only increase the computed current by 10%. This insensitivity of the current collection to the electron temperature is confirmation that the wake side collection is orbit motion limited in nature. The remaining possibility for the code-data difference is an additional source of current which is not accounted for in the code-data comparison but is present in the data.

The contribution to the current by Low Mach number components of the flow, i.e. H+, is examined in Chapter 5. It was found that the proportion of the flow which is composed of H+ is at most 2.5%. Previous work using the Dynapac [32], a three dimensional electrostatic code, performed a limited amount of work with H+. The results are included in Table 4.5.

<table>
<thead>
<tr>
<th>Pro/`e Bias (V)</th>
<th>Density (m(^{-3}))</th>
<th>Current ((\mu\text{A}))</th>
<th>Current ((\mu\text{A}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No H+</td>
<td>10 % H+</td>
</tr>
<tr>
<td>-20</td>
<td>1x10(^{11})</td>
<td>0</td>
<td>1.7</td>
</tr>
<tr>
<td>-100</td>
<td>1x10(^{11})</td>
<td>0.8</td>
<td>12.1</td>
</tr>
<tr>
<td>-2000</td>
<td>1x10(^{11})</td>
<td>115</td>
<td>144</td>
</tr>
</tbody>
</table>

These results, which were all found zero angle of attack, clearly show that H+ contributes disproportionately to the current. Seeding the ambient density with 10% H+ resulted in a current...
increase of 25% over the results containing solely O+. The results of Chapter 5 also demonstrated that the current due to H+ increases linearly with the ambient H+ density so a value of 2.5% H+ may be estimated to contribute only about 6% more to the simulated current found by the PIC code.

The final remaining possibility is additional negative charge emission from the stainless steel probe surface. There are several types of surface emission which may be relevant to our situation. These are SEE, photo-emission, field emission and sputtering.

SEE from an unbiased stainless steel probe surface has been covered in detail in the CHAWS context and, while explaining most of the data non-linearity, it does not explain the missing current.

Photo-emission, as described in Chapter 1, is simply the ejection of electrons from a surface due to impact of photons of sufficient energy. The results of the low voltage analysis demonstrate that this is limited to about a micro-ampere. This is clearly too small and also does not explain why data taken when the probe is shielded from the sun, for example sweep 10, also has the missing current.

Field emission is another possibility. Field emission typically begins at surface field values of about 1x10^8 to 1x10^10 V/m. Based on equation (5.1) the surface field on the CHAWS probe is about 9000 V/m at -1000 V bias. Hence, field emission may be safely ignored.

The final surface process to consider is sputtering. Sputtering is simply the ejection of probe atoms by the impact of particles with sufficient energy. While the sputtering yield is not known for stainless steel it may be approximated to be that of its main constituent, iron. Table 4.6 shows the iron sputtering yield values for energies between 100 eV to 600 eV.

<table>
<thead>
<tr>
<th>Energy</th>
<th>100 eV</th>
<th>200 eV</th>
<th>300 eV</th>
<th>600 eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>0.20</td>
<td>0.53</td>
<td>0.76</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Sputtering as it is commonly understood is a neutral particle process. The particles emitted from an unbiased surface have no reason to take extra charge with them. However, a biased surface may cause the emitted atoms or particles to pick up a negative charge as it leaves. Augmented negative charge emission, i.e. current far above that which would be accounted for through SEE, from a biased surface may have been observed by Chung Chan et al [33] at energies and biases similar to CHAWS but with surface fields about 225 times greater. A literature search has found no prior work dealing specifically with augmented negative charge emission from biased surfaces when ions of sufficient energy to initiate sputtering are incident upon them. However, unpublished work by Dr. Steve Meassick of the New Mexico Highlands University using copper
suggests that the CHAWS surface fields were not large enough to allow augmented charge emission to be significant.
Chapter 5: Low Voltage Analysis

The low voltage data is defined as the sweeps and sweep segments which were between 0 V and the onset voltage which is thought to be approximately -100 V, as based on section 4.3.1 and pre-flight modeling [10]. While this analysis was not of direct interest to high voltage wake-spacecraft interaction it offered the opportunity to resolve some issues raised in the high voltage analysis. The high voltage PIC code simulations were below the data by approximately a factor of two. Possible explanations for this included low Mach number flow components, additional negative charge emission and code error. As shown in Figure 3.7, in the low voltage region particle energy and probe bias are insufficient to cause significant negative charge emission and hence removes this area of uncertainty. In addition, the collection to the probe is not a mixture of high and low Mach number components; rather, it should, by equation (1.16), consist exclusively of low Mach number flow. Simulation and comparison to the actual data should provide both an improved assessment of the PIC code validity and a greater understanding of the high voltage significance and composition of the low Mach number flow. Investigation of low Mach number flow invasion of the spacecraft wake is of significance not only to the CHAWS experiment but to any application, such as ultra-pure epitaxial growth, which attempts to operate in the wake environment.
5.1 Low Mach Number Flow Composition

Unfortunately, the CHAWS experiment did not have an ion mass spectrometer aboard so a direct determination of the low Mach number flow composition was not possible. The Mach number definition demonstrates that candidates for the low Mach number component could either possess a higher thermal velocity than the main stream O+ or net velocity relative to the shield which is lower than the orbital velocity. Candidates which satisfy one of those criteria may include contamination of the shield environment by the shuttle, turbulent O+, and frontal stream H+.

First the possibility of contamination from the nearby orbiter is considered. Previous work [34] has found that when plasma parameters have been measured from the bay of the orbiter the ambient O+ signature was almost always masked by an enhanced population of molecular ions, O₂+ or NO+. The WSF epitaxy experiment (CHAWS I) was shown to be contaminated with water vapor from the shuttle [17]; however, the similarity of both the RPA (Appendix B) and low voltage I-V data for both the free flight and grappled low voltage data (section 3.2) demonstrate that ionized contamination from the shuttle was not significant compared to the current collection observed. More directly, CHAWS I-V sweeps taken with the probe pointing into the payload bay while within the deep wake of the shuttle found currents about an order of magnitude below both the free flight and grappled sweeps. Hence, shuttle contamination is not considered to be the source of the low Mach number flow component and both turbulent O+ and H+ remain possibilities.

In the CHAWS context, plasma turbulence is defined as the generation of charged particle density fluctuations near the WSF body. It has been found [35] that turbulence occurs for both large body (space shuttle) and smaller bodies (standard ionospheric satellites) and is not confined to the wake of the body. The amount of turbulent plasma was also found to correlate directly with the total ambient plasma density. This is consistent with a proposed turbulence creation mechanism [36] where about 1% of the ions incident upon a ram-facing surface are elastically reflected and this reflected stream causes buffeting in the original plasma flow. While this offers a possible explanation for the noise found in the RPA sweeps it does not explain how, in a plasma with an ion collision length of many kilometers, this back stream can drastically reduce a component of the Mach 5 or so flow down to speeds which can pass the restriction set by equation (1.16).

Another candidate is the H+ component of the frontal stream. While it may be assumed that H+ has the same temperature as the O+ [37] its lower mass provides it with a thermal velocity four times that of O+. Hence, according to equation (1.16), at an ion temperature of about 0.1 eV about one third of the H+ ram side flux would reach the back of the shield while only about one O+ ion
would impact the shield rear every million years. This was explored qualitatively by the PIC code in Figure 5.1 where results of runs for O+ and H+ at equal densities for zero probe bias are presented.

Figure 5.1: PIC ion density distribution results for O+ (left) and H+ (right) where each run had a density of $n_n$ of $1 \times 10^{11}$ m$^{-3}$, a $T_i=0.1$ eV and $T_e=0.15$ eV.

Use of the IRI model via the Environmental Work Bench (EWB) software developed by S-Cubed Inc. estimates H+ to be between 5 and 30% of the total ambient ion density at low earth orbit. However, many other references, such as [31], [38], and [39], which are based on earlier measured values, estimate the H+ density to be less than 0.1%. Other more recent references [32] place this value between 1 and 10%.

In principle, the RPA sweeps should be able to assist in a final determination of low Mach number flow density and composition. The frontal stream O+ ions have, by virtue of the shield’s orbital velocity, an effective energy of about 5 eV. H+, being one sixteenth as massive as O+, will have an effective energy of about 5/16 eV. Assuming the H+ is Maxwellian and that it has a temperature similar to that of O+ then there should be a roll-off in the RPA sweeps similar to that caused by O+. However it should be at an energy of 5/16 eV and it should be smaller in size owing to the lower H+ density.
Unfortunately, the WSF almost always floated positive relative to the plasma by a few volts (refer to section 3.1.3). Hence, the 5/16 eV roll-off, if it existed, would only be seen in the few RPA sweeps where the shield bias was below 5/16 of a volt. Some of these sweeps are reproduced in Figures 5.2 to 5.5. Each plot represents the average of the 8 RPA sweeps taken for the indicated I-V sweep. The circled region indicates where the H+ signal was expected.

Figure 5.2: Averaged RPA sweep for sweep 82. $\Phi_{WSF}=0.2$ V.
Figure 5.3: Averaged RPA sweep for sweep 83. $\Phi_{WSF} = 0.1$ V.

Figure 5.4: Averaged RPA sweep for sweep 84. $\Phi_{WSF} = -0.6$ V.
Figure 5.5: Averaged RPA sweep for sweep 85. \( \Phi_{WSF} = -0.8 \) V.

The RPA sweeps do not contain the expected H+ signal. They do contain noise which is attributable to turbulence which would mask any H+ signal with a density below about 10% of ambient. Hence, the RPA sweeps do not offer a final determination of the source of the low Mach number flow source but do provide a ceiling of about 10% on the H+ density.

Overall, the simplest and most explicable composition of the low Mach number flow is H+. Environmental contamination from the shuttle may be safely excluded from consideration and the lack of a satisfactory physical mechanism for a drastic slowing of a component of the frontal stream O+ removes turbulence from consideration.

5.2 PIC Simulation

A simulation was performed of the low voltage sweeps using H+ as the low Mach number flow component. The numerical results can not be directly compared to any particular low voltage sweep since an independent measure of the H+ density could not be obtained. The simulation objectives were to obtain results which qualitatively resemble the data and hence to both increase confidence in the code and support the H+ hypothesis.
5.2.1 Estimation of H+ Density and Temperature

A limited amount of previous work employing H+ [32] has been performed and it assumed an H+ density of 10%. These results are reproduced in Table 4.4.2.1. Based on those results and the low end of the IRi model prediction it was decided to take an H+ density of 5% of the total ambient density. To obtain a low voltage PIC I-V curve that could be compared to the high voltage simulation of sweep 10 the total ambient density was assumed to be $1 \times 10^{11}$ m$^{-3}$ which resulted in an H+ density of $5 \times 10^9$ m$^{-3}$. The H+ temperature was assumed to be that of O+ [37].

5.2.2 PIC Modification

The low voltage collection should, by equation (1.16) be dominated by H+. The assumption that ion species act independently in their expansion into the wake of a satellite made modification of the code to contain both H+ and O+ unnecessary. Previous theoretical and experimental work has demonstrated that this is an excellent assumption [40]. Hence, the modification to the PIC code consisted simply of changing the particle mass to that of H+ from O+ and ensuring that both the cell size and time step remain constant by altering the stretch factor of equation (4.14) and the time factor in equation (4.15). The quantitative results become meaningless once the potential expands into the frontal stream since the composition and density there are not representative of the CHAWS experiment. However, for the purpose of simulating the low voltage region these modifications retain the accuracy and characteristics of the original code.

5.2.3 Results

Following are sample Visual 3 renderings of the PIC code results. Simulations were run at potentials of 0, -10, -20, and -50 V and employed an ion temperature of 0.1 eV, an electron temperature of 0.15 eV, and an H+ ambient density of $5 \times 10^9$. Figure 5.6 is a cut plane through the center of the shield perpendicular to the shield plane showing the H+ ion density. The probe is clearly collecting from many different directions as the H+ ions penetrate the wake. Figure 5.7 demonstrates that at -50 V the collection sheath is approaching, but does not enter, the frontal stream.
Figure 5.6: Visual 3 rendering of H+ density profile with a probe bias of -50 volts.
Figure 5.7: A cross section of the probe potential structure at a bias of -50 volts proving that frontal stream ions are not candidates for collection.

Qualitatively, these results agree with the high voltage simulation assessment that there should be a turn-on voltage and shows that low Mach number flow can easily reach the probe. It also graphically demonstrates that the low Mach number flow collection should not end immediately following turn-on. Rather, it will continue to increase until all low Mach number flow entering the wake is collected. This result is in agreement with the high voltage analysis assessment that at about the less than 1700 V range there is an additional component to the current.

Figure 5.8 is a line plot of the potential extending outward from the center of the probe to the near edge of the shield. It clearly establishes that the potential in the PIC code has yet to expand past the edge of the shield. Plotted for comparison is the potential that would be seen from a finite line of charge without any space charge present. This potential can be simply derived and is given by

\[
V(r) = \frac{\lambda}{2\pi\varepsilon_o} \ln\left(\frac{L + \sqrt{r^2 + L^2}}{r}\right) \tag{5.1}
\]
where $L$ is half the length of the CHAWS probe, $\lambda$ is the charge density, and $r$ is the radial distance from the center of the probe. Knowing that $V(r_{\text{probe}}) = \Phi_{\text{probe}}$ allows a value for $\lambda$ to be determined.

![Graph](image)

**Figure 5.8:** Comparison of PIC potential and a simple line charge potential demonstrating that space charge effects are significant.

Despite being in the ultra-high vacuum wake region of WSF, the penetration of H+ space charge is sufficient to reduce the potential expansion well below that predicted by equation (5.1). Had space charge effects been insignificant the use of the ADI explicit scheme to solve numerically for the potential in the low voltage analysis would not have been necessary and prediction of the current to the probe at the would have been greatly simplified.

Figures 5.9 and 5.10 show the quantitative comparison of the code result to the free flight and grappled low voltage data, respectively.
Both the code and the data are linear and this qualitative agreement confirms the code. Moreover, it appears that the use of an H+ density of $5 \times 10^9 \text{ m}^{-3}$ was a good estimate, placing the code results within the range covered by both the grappled and the free flight data. This supports the proposed understanding of low Mach number flow and suggests that with further analysis it may be possible to use the data in conjunction with the code to arrive at an estimate of the H+ as a
percent of the total ambient density and therefore ascertain its true significance at the higher voltages.

5.3 Estimation of H+ Density

This section describes the estimation the H+ density as a percentage of the total ambient density through use of information found from both the code and the low voltage data.

5.3.1 Data Current versus Density Trend

Figure 5.11 is a plot of probe current versus the measured ambient density at a probe bias of -30 V.

![Graph showing current versus ambient density](image)

**Figure 5.11:** Current versus ambient density at -30 V probe potential. Points with the 'S' annotation were taken with sunlight directly incident upon the probe.
The three photo-emission denoted points are noticeably above the trend followed by all the others. As shown in Table 5.1 the photo-emission points are each almost a micro-amp above the trend.

<table>
<thead>
<tr>
<th>SWEEP NUMBER</th>
<th>SUN ANGLE (degrees)</th>
<th>MEASURED CURRENT (µA)</th>
<th>TREND CURRENT (µA)</th>
<th>ESTIMATED PHOTO EMISSION (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>89.9</td>
<td>1.9</td>
<td>1.2</td>
<td>0.7 (±0.2)</td>
</tr>
<tr>
<td>90</td>
<td>93.9</td>
<td>2.4</td>
<td>1.6</td>
<td>0.8 (±0.2)</td>
</tr>
<tr>
<td>91</td>
<td>92.6</td>
<td>2.3</td>
<td>1.5</td>
<td>0.8 (±0.2)</td>
</tr>
</tbody>
</table>

The sun angle is the angle between the axis of the probe and the sun on a plane defined by the probe axis and the center of the sun. A sun angle of zero degrees is defined as the instance when the end of the probe mated with the shield is pointing directly at the sun. Hence, the points in the above table were all taken when the outboard side of the probe was facing the sun and therefore correspond to the maximum photo-emission condition. Hastings [2] has estimated that for stainless steel at 1 AU the photoemission current density from the illuminated surface should be 20 µA/m². The cross sectional area of the probe at the above sun angle is 0.046 m² and therefore predicts that the total amount of photoemitted current should be 0.92 µA. Hence the experimentally observed photo-emitted current is in good agreement with the theoretical estimation. All other points in Figure 5.11 were taken when the WSF was in on the night side of the Earth. The similarity of the sun angle and the constant difference between the ‘S’ points and the trend formed by the other points further confirms that photo-emission was observed. The deduction of photo-emission from the plot increases confidence that the trend is real and that the ratio of H+ to the ambient density may be approximated as constant.

The current observed at the -30 volt probe bias increases roughly with the measured ambient density. The slope of the linear fit to the trend is probably good to within a factor of 1.5. The spread of the points about the fit line is at least partly due to temperature variation between the sweeps and to some variation in the H+ to ambient density ratio.

Previous work and basic kinetic theory demonstrates that the amount of a species found within the wake should be directly proportional to the ambient density of that species. Hence, the current to the probe at the low voltages should, since Figure 5.11 has shown that the current scales in a manner proportional to the ambient density, also scale proportionately with the ambient H+ density. While the H+ density could not be determined directly from the CHAWS data the current versus H+ density trend should be attainable through employment of the PIC code.
5.3.2 PIC Current versus Density Trend

Figure 5.12 shows the current versus density trend found from the PIC code. The ion temperature and electron temperature were held constant at 0.1 eV and 0.15 eV, respectively. The H+ density values run were 2.5x10⁹ m⁻³, 5.0x10⁹ m⁻³ and 7.5x10⁹ m⁻³.

Figure 5.12: PIC current versus H+ density prediction at a probe bias of -30 volts.

As expected, the trend was linear. This again confirms the code and enables an estimation of the H+ as a percentage of the total ambient density to be performed.

5.3.3 Estimation and Discussion

Sections 5.3.1 and 5.3.2 determined the low voltage current to the probe as a function of both the ambient measured density and the H+ density. Both trends were of the same form as was expected from basic kinetic theory. An estimate of the ambient H+ density can therefore be made simply by dividing the slope of the data current-density line by the slope of the H+ PIC current-density trend. This yields
\[ H + (\%) = \frac{slope(current\_versus\_ambient\_density)}{slope(current\_versus\_H + \_density)} = \frac{2.95(\pm 1) \times 10^{-18} \text{A} \cdot \text{m}^3}{2.29(\pm 1.1) \times 10^{-16} \text{A} \cdot \text{m}^3} = 1.3(\pm 0.8)\% \]

(5.2)

The maximum H+ percent provided for by this analysis is therefore about 2.5%. A value this low is also consistent with the RPA sweeps, where turbulence would mask any H+ signature below about 10% of ambient.

This result is of great significance to the high voltage analysis. [32] found that if 10% of the frontal stream were H+ then current would disproportionately increase by 25% at a probe bias of -2000 V (refer to Table 4.5). The value found in this analysis places the maximum H+ content at about one forth of that utilized by the Dynapac and relegates H+ to a less than 10% effect. Therefore, secondary species (low Mach number flow) can not be responsible for the high voltage code-data discrepancy found in Chapter 4 of this report.

### 5.4 Turn-on Voltage Determination

Previous work with the CHAWS I data concluded that the turn-on voltage was masked by the collection of low Mach number flow to the probe at the low voltages [13]. This section demonstrates that with consideration of the PIC code results and careful examination of the I-V sweeps with a 325 V maximum obtained on CHAWS II, these turn-on voltages can be located and compares them to both PIC code turn-on and pre-flight prediction.

### 5.4.1 PIC Consideration and Data Confirmation

The PIC code has predicted linear I-V behavior in both the low voltage and the high voltage analysis. This is in agreement with both the free flight and grappled low voltage data and, once secondary electron effects were removed, with the behavior of the high voltage data. It is hence logical to presume that at the onset of frontal stream ion collection there will be a discontinuity in the slope of the I-V characteristic. This is illustrated in Figure 5.13 where the PIC trials of Figures 4.15 and 5.9 are extrapolated over the range of 0 to -350 V and summed.
Figure 5.13: Superposition of extrapolated O+ (Figure 4.15) and an H+ (Figure 5.9) PIC trials.

The turn-on for the high voltage collection was predicted to be -84 V for the above PIC trial. This indicates that the 32 V and 62 V range I-V sweeps were not sufficient to observe the expected turn-on voltage. However, the 325 V curves are of sufficient range and have enough low voltage points that if the turn-on is sharp enough then it should be observable. Examination of these curves (Appendix C) in the -50 to -100 V region demonstrated that such a kink exists.

5.4.2 Location and Values

The onset of O+ ion collection is illustrated by simply plotting the slope between the data points as a function of voltage. This was done for all the 325 V I-V sweeps on the left side of Figures 5.14 through to 5.20. Evident on these plots is a dramatic shift in the slope of the characteristic which usually occurred between about -50 and -100 V. It was difficult to determine the location of the actual turn-on voltage from these plots; however, they do provide an estimate of the range over which the event occurs. The right side of each figure is a more precise determination of the onset voltage. It was found by simply fitting the linear portions of the curve before and after the kink. Typically these portions were between -20 and -40 V for the low voltage section and between -100 and -325 V for the high voltage section. The intersection of these lines provided the onset voltage value while the range of occurrence on the slope versus voltage plots.
provided an estimate of the error. The results for all the CHAWS II 325 V I-V sweeps are summarized in Table 5.2.

![Figure 5.14: Turn-on location for sweep 48.](image1)

![Figure 5.15: Turn-on location for sweep 52.](image2)
Figure 5.16: Turn-on location for sweep 53.

Figure 5.17: Turn-on location for sweep 69.
Figure 5.18: Turn-on location for sweep 74.

Figure 5.19: Turn-on location for sweep 76.
Figure 5.20: Turn-on location for sweep 80.

Table 5.2: Summary of identified turn-on voltages.

<table>
<thead>
<tr>
<th>SWEEP NUMBER</th>
<th>DENSITY (#/m²)</th>
<th>TURN-ON VOLTAGE (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>43</td>
<td>6.3e10</td>
<td>74</td>
</tr>
<tr>
<td>52</td>
<td>NA</td>
<td>69</td>
</tr>
<tr>
<td>53</td>
<td>NA</td>
<td>73</td>
</tr>
<tr>
<td>69</td>
<td>1.47e11</td>
<td>73</td>
</tr>
<tr>
<td>70</td>
<td>1.70e11</td>
<td>82</td>
</tr>
<tr>
<td>74</td>
<td>2.95e11</td>
<td>89</td>
</tr>
<tr>
<td>76</td>
<td>2.71e11</td>
<td>92</td>
</tr>
<tr>
<td>80</td>
<td>1.58e11</td>
<td>74</td>
</tr>
</tbody>
</table>

5.4.3 Discussion

Table 5.2 also contains the densities measured for each sweep. The analysis of sections 5.2 and 5.3 indicate that even at a 1% H+ ambient content the potential expansion within the wake of the WSF will still be significantly reduced by space charge penetration. The analysis also demonstrated that the degree of space charge invading the wake is proportional to the ambient density. Hence the turn-on voltage should increase with increasing ambient density. This trend is evident in Figure 5.21 and confirms the presence of H+ space charge within the wake even at a low percent of the ambient density. However, the dependence of the turn-on voltage on the density, while proportional, is slight. Overall, it appears that the distance to the edge of the shadowing body is the dominant factor influencing the turn-on voltage.
The significant error in the data in Figure 5.21 prevents a more detailed analysis of this effect. The turn-on voltage from the PIC code is also included, verifying that the code and data in the 325 V I-V sweeps are in agreement. Section 3.2, however, found that while the SEE corrected curves were near linear the linear extrapolation of the resulting curves to zero current found that turn-on should be in the range of about -200 V to -400 V. Pre-flight modeling using POLAR [10] found that the turn-on voltage should be between -30 and -300 V. One possibility for this difference is that the SEE correction of the high voltage curves, as discussed in section 3.2.1, is not sufficient to completely linearize the data.

This pre-flight modeling also predicted that angle of attack would have an even greater effect on the turn-on voltage. Unfortunately this can not be confirmed since all of the 325 V I-V sweeps were all taken at a near zero angle of attack.
Chapter 6: Ram Side Analysis

A detailed consideration of the ram side data offered the opportunity to complement the high and low voltage wake side analysis of the last two chapters and to assist in a comprehensive assessment of the total threat posed to spacecraft by interaction with their environment. To fully understand and predict the charging hazards to spacecraft it must be shown that theory and simulation describing ion collection to charged surfaces oriented into the plasma stream are adequate. This chapter attempts to provide additional verification of the PIC code by employing it in the inverted position and comparing the results to both pre-existing theory and to the CHAWS data. Moreover, the application of existing theory to the ram side data may also provide an independent verification of the ambient parameter measurement by the RPA’s and furnish insight into other aspects of interaction between the shield and the space environment.

6.1 Estimation of Ambient Parameters

As shown in Chapter 3, the CHAWS II flight performed four voltage sweeps with the probe aligned directly into the plasma stream just before being stowed on the shuttle. Three of these sweeps were 325 V in magnitude while the fourth was of only 32 V. Since the ram side sensor was oriented into the wake when the shield was inverted there are no direct ambient parameter measurements available for the ram sweeps. Hence to at least qualitatively verify the simulation and pre-existing theory estimation of these parameters is necessary.
Figure 6.1 shows the predicted IRI model ion densities and the measured CHAWS II ion densities for the shield orbit on day 258. The period shown covers more than one orbit. The highest peak corresponds to a local time of noon while the two sub-peaks correspond to a local time of midnight. Since the terminator advances across the Earth by one orbital period for each shuttle orbit the plasma density period is the sum of an orbital period plus the time it takes the shuttle to travel the distance that the terminator moved (about 10 minutes). The period of the plasma density is indicated by the two vertical lines in the figure. The IRI prediction and the detector data are in qualitative agreement: each has the largest peak at local midday and sub-peaks at local midnight. However, the detector data is consistently below that of the IRI model. Since IRI is a statistical model based on the average of many earlier measurements of the ionosphere and given the possible variance of space ‘weather’ it is possible that the CHAWS measurements and the IRI prediction are in satisfactory agreement. The periodicity of the CHAWS density data is the key to estimating the ram side density for sweeps 113 to 116.

The ram side sweeps were taken almost one orbit following the last useful RPA sweeps. Hence a simple linear extrapolation of the last density measurements is not sufficient to render a density estimate. Rather, it would be more prudent to use density values located one density period prior to the time of the ram sweeps. The density period value used in this estimation was that of the IRI model in order to avoid the uncertainty of estimating it from the actual data. This should not cause any more uncertainty since the density period is determined by simple orbital mechanics. The time of each ram side sweep had subtracted from it a density period and at the resulting time value the density was interpolated. Since the density data was continuous for more than one orbit it was possible to leap frog back another density period and obtain an even earlier value for the density. The density value one period prior to the ram sweeps was taken as the actual estimate while the even earlier density value was used to estimate the uncertainty, which was usually about 50%. The ion temperature, although not as periodic as the density, was estimated through the same technique. Subsequent analysis demonstrates that the ion temperature is of no consequence to the ram side analysis. Table 6.1 displays the estimated values.
Figure 6.1: Comparison of EWB (IRI MODEL) prediction to CHAWS ion density measurements.

Table 6.1: Estimated ambient parameters for the inverted sweeps.

<table>
<thead>
<tr>
<th>SWEEP NUMBER</th>
<th>TIME (UT)</th>
<th>EST. DENSITY (m⁻³)</th>
<th>EST. ION TEMP (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>113</td>
<td>40230</td>
<td>6.5e10</td>
<td>0.11</td>
</tr>
<tr>
<td>114</td>
<td>40334</td>
<td>8.0e10</td>
<td>0.11</td>
</tr>
<tr>
<td>115</td>
<td>40482</td>
<td>1.0e11</td>
<td>0.09</td>
</tr>
<tr>
<td>116</td>
<td>40616</td>
<td>1.2e11</td>
<td>0.09</td>
</tr>
</tbody>
</table>

The sideways sweeps were taken between the first trough and the midday peak in Figure 6.1. The values shown in Table 6.2 were found through simple linear interpolation with the error estimated to be about 50%. Since pre-existing theory does not accommodate probes other than those aligned directly with the plasma flow these sweeps it was not possible to consider these sweeps.

Table 6.2: Estimated ambient parameters for sideways sweeps.

<table>
<thead>
<tr>
<th>SWEEP NUMBER</th>
<th>TIME (UT)</th>
<th>EST. DENSITY (m⁻³)</th>
<th>EST. ION TEMP (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>88</td>
<td>32251</td>
<td>1.9e11</td>
<td>0.07</td>
</tr>
<tr>
<td>89</td>
<td>32355</td>
<td>2.3e11</td>
<td>0.06</td>
</tr>
</tbody>
</table>
6.2 Relevant Theory

The situation of a probe aligned into a plasma flow has received considerable attention. Indeed, the Langmuir probe and associated theory are often employed as a diagnostic tool for determination of plasma temperature and density. Ion collection to various probes of simple geometry was discussed briefly in section 1.2.5. From equation (1.25) for typical CHAWS parameters it is clear that the collection by the probe is space charge limited. The assumption made by Bernstein and Rabinowitz [41] and also by Allen, Boyd and Reynolds [42] that the electron temperature is much greater than the ion temperature is not valid in the low Earth orbit space environment. Typically the value of the electron to ion temperature in undisturbed LEO plasma is about two [37]. Hence the more sophisticated work undertaken by Laframboise, which allows for lower electron-ion temperature ratios, is the most applicable to CHAWS ram side data.

Laframboise [29] extended the Bernstein and Rabinowitz formulation [41] to the physically more reasonable case of a ion Maxwellian distribution. He performed extensive numerical computations for the ion current collection to both spherical and cylindrical probes over a wide range of Debye ratio \( \xi_p = R/\lambda_p \), temperature ratio \( \varepsilon = T_i/T_e \) and probe potential. These calculations are sufficient for determining the current-voltage characteristics of spherical and cylindrical probes over essentially the entire range of practical operation conditions in the collisionless limit. The analysis and computation details are available in [29].

Several approximate fits have been made to Laframboise’s numerical results. The one which will be employed in this work is that developed by Peterson and Talbot [43]. The non-dimensional current density is given as a function of the non-dimensional potential by

\[
 j_{ion}^* = (\beta + |\chi_p^*|)^\alpha
\]  

(6.1)

where the normalizations are given by

\[
 j_{ion}^* = \frac{I_{ion}}{A_p} \left[ \frac{n_e e (kT_{ion})^{1/2}}{2 \pi m_{ion}} \right] \left[ \frac{e \phi_p}{kT_e} \right]^{1/2}
\]  

(6.2)

\[
 \chi_p^* = \frac{e \phi_p}{kT_e}
\]  

(6.3)

The \( \beta \) and \( \alpha \) parameters are functions of the ion-electron temperature and Debye ratios and are given by
\[ \alpha = \frac{a}{b + \ln \xi_p} + ce^m + d \]  
(6.4)

\[ \beta = e + e(f + g(\ln \xi_p)^3) + \ln \xi_p \]  
(6.5)

where the constants are

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.900</td>
<td>2.300</td>
<td>0.070</td>
<td>-0.340</td>
<td>1.500</td>
<td>0.850</td>
<td>0.135</td>
<td>0.750</td>
</tr>
</tbody>
</table>

The fit is good to within 3% and offers the clear advantage of providing a means for interpolating and extrapolating the results of Laframboise.

All of the expressions for cylindrical probe ion collection in Table 1.3 assumed that the probe had a sufficiently high \( l_p/r_p \) to avoid current contribution from the end. This ‘end effect’ can, as shown by Lederman et al [44] and Chung [4], increase the observed current density several times above that found for probes of effectively infinite length. The proportion of the total current found due to end effect increases with the \((l_p/r_p)^{-1}\) and the sheath size, which is contributed to by plasma density, electron temperature and probe bias. Probes with \( l_p/r_p \) ratios below about 100 to 300 may be susceptible depending on the plasma parameters and the probe bias employed. The CHAWS probe has a \( l_p/r_p \) of only 9 and is therefore a likely candidate for end effect collection. Additional work by Basu and Sen [45] has presented a conceptually simpler but approximate expression for the radius of the collection sheath about a cylindrical probe in the same situation described by Laframboise’s theory. It is consistent with the results by Laframboise and clearly demonstrates that the sheath about the probe in the absence of end effect should be cylindrical.

### 6.3 Ram Side Simulation

The PIC code was run to simulate the ram side ion collection to the probe when it was aligned directly into the plasma flow. Simulation was necessary to explore the extent of any end effect and hence determine whether the theory by Laframboise could be safely applied. The code current-voltage characteristic could also be compared to the data for the given estimated parameters and hence provide an independent verification of the ion detector measurement. Finally, the Visual 3 renderings of the code output should provide insight into the ion collection and the sheath characteristics.
6.3.1 PIC Modification

The modifications made to the original code produced by G. Font [27] are relatively simple. Instead of re-entering the shield coordinates to invert the shield the flow direction was reversed. All surfaces and boundaries are still fully accommodating but the particles are loaded at the opposite side of the simulation. The presence of the shield behind the plate should pose only a second order effect since the flow is transonic and the shield itself is not significantly biased in comparison to the probe.

6.3.2 Results

The simulation was initially run for the sweep 115 estimated ion density of $1 \times 10^{11}$, an ion temperature of 0.057 eV and an electron temperature 1.5 times that of the ion temperature. The voltage range explored was 0 to -300 V since that was covered by the actual CHAWS ram side data. The ion temperature of 0.057 eV, rather than the 0.09 eV estimated for sweep 115, was employed since it was the result of an earlier and less accurate estimation method. The effect of a slightly higher ion temperature on the results was, as a consequence, also explored by an additional simulation run. Figures 6.2 to 6.4 present Visual 3 renderings of the probe ion density profile for -20, -100 and -300 V.
Figure 6.2: PIC Ion density profile for a probe bias of -20 V.
Figure 6.3: PIC ion density profile for a probe bias of -100 V.
Figure 6.4: PIC ion density profile for a probe bias of -300V.

In each cross section there is a region evacuated of ions which expands with increasing probe bias. In the -20 V case the sheath around the probe is cylindrical around the half of the probe closest to the shield and tapers off towards the tip. In both the -100 V and -300 V cases the sheath is clearly not cylindrical but almost hemispherical. In all cases the sheath is symmetric about the probe and the shield has had no obvious influence on the ion collection. Figure 6.5 plots the 3-D potential isocontours for the -300 V case and clearly demonstrates the hemispherical nature of the sheath at the higher voltages.
Figure 6.5: Potential isocontours about the probe for $\Phi_{\text{probe}} = -300$ V. The outer contour is at -2 V while the inner one is at -100 V.

The almost hemispherical sheath is in disagreement with the assessment by the Laframboise and Basu prediction that the collection sheath should be cylindrical. However, the code is consistent with a probe which is suffering from a very significant end effect. Indeed, it appears that the CHAWS probe, with its low $I_p/r_p$ ratio, is acting almost exclusively as an ‘end’ at the higher voltages. In the -20 V simulation the sheath appeared to be at least partially cylindrical indicating that the end effect may not have been as severe at the lower voltages and this is consistent with the findings of Lederman et al [44]. Section 6.4 presents the comparison of the quantitative PIC code results and compares them to both the actual CHAWS data and the Laframboise predictions.

6.4 Comparison of Theory, Data, and Simulation

Figure 6.6 compares the PIC code results to the prediction of Laframboise theory.
Figure 6.6: Comparison of the current-voltage characteristics of the CHAWS ram side sweeps, the PIC simulation and Laframboise theory.

The PIC code current is several times greater than that predicted by Laframboise for the same parameters. Moreover, as the bias increases the difference becomes much larger and demonstrates that the end effect component of the total computational current is becoming increasingly significant. Both these observations are consistent with findings by Lederman [44] and others and confirms that the CHAWS probe is suffering from a large end effect current.

Also included is the current found by a simulation run at -300 V for an ion temperature of 0.093 eV, the actual ion temperature estimated in section 6.1. The resulting current actually decreased slightly from that found for the lower ion temperature. This has been observed by Allen [46] and is consistent with the general finding in space charge limited ion collection that the sheath size is dictated by the electron temperature and not the ion temperature. The ability of the code to resolve the slight decrease in current due to an increase in ion temperature is encouraging. Unlike the wake side data analysis of Chapter 4, the importance of the electron temperature in the ram side collection can not be neglected and necessitates re-visiting the assumed electron-ion temperature ratio in following discussion.

Also included in Figure 6.6 are the CHAWS ram side data sweeps 115 and 116. While the code and the data share the same qualitative form the code is almost a factor of two less than the PIC simulation. Since the probe biases are too low for significant emission of negative charge the difference must be due to error in the ambient parameter inputs to the code. These inputs are the plasma density, ion temperature and electron temperature. The code and space charge limited
collection theory demonstrate that the ion temperature is of essentially no consequence and therefore can be neglected as the source of the code-data difference. The uncertainty in the ion density estimation of section 6.1 is 50%. However, the uncertainty in the estimated error itself could be considerable. Therefore, in order to determine if density alone may provide an explanation for the difference, the code was run at -300 V for a density twice that initially employed. The resulting current is also displayed on Figure 6.6 and shows that while much of the gap was closed the code and data are still not in good agreement. However, a combination of increased in density and the electron temperature may be sufficient to match the code and the data. Unfortunately, performing a two parameter fit between the PIC code, which generally takes over two days to run on an SGI Indigo II with 256 megabytes of RAM for one data point, and the data would be beyond the computational resources available to the CHAWS project. An alternate method which employs a combination of the code and the theory to fit the data for ion density and electron-ion temperature ratio is presented in the following section.

6.4.1 Predicted Ambient Parameter Values for Ram Side Sweeps

As demonstrated by the computational simulation the ram side sweeps have a significant amount of current due to end effect. The theory by Laframboise assumed that the probe was essentially infinite in length and hence there can be no end effect contribution to the current. Therefore, the difference between the PIC code current-voltage characteristic and the model prediction for the same input parameters should be solely the end effect current. The dominant parameters determining the extent of the end effect are the \( l_p/r_p \) ratio and the probe bias. Hence, to a first approximation, the factor by which the code is greater than the theory at a given voltage, \( f_{end}(\Phi_p) \), are the same for situations of similar ion density and electron temperature. Hence, it should be possible to correct the data itself for end effect by reducing it by \( f_{end}(\Phi_p) \), assuming the density and ion temperature values used to derive \( f_{end}(\Phi_p) \) are not significantly different from those of the plasma when the sweep was taken. Once corrected for end effect current the next iteration ion density and electron-ion temperature ratio can be found by fitting the Laframboise theory to the data. The new parameters would differ somewhat from the original code and theory values for which \( f_{end}(\Phi_p) \) was first determined. Hence it was necessary to re-determine the end effect correction factors for the new ambient parameters. This process, as outlined in Figure 6.7, could be continued until the code and data current-voltage curves converged.
This process allows determination of the same ambient parameter values as a brute force two parameter fit of the PIC code to the data but involves orders of magnitude less computational time. Unfortunately, even the process of Figure 6.7 involves a considerable amount of processing. The first set of correction factors were determined directly from Figure 6.6 for sweep 115 and the data was corrected for them. The subsequent first iteration theory fit to the corrected sweep 115 is included in Table 6.3. Also included in Table 6.3 are the fits to the other two sweeps corrected using the sweep 115 $f_{end}(\Phi_p)$. Use of the sweep 115 factors on the other two sweeps was necessary due to processing time constraints and incurs some additional imprecision in the resulting ambient parameters for those sweeps. For the next iteration, the code was then run at -100 V for the new density and electron temperature values and, as shown in Figure 6.8, the gap between the PIC code and the sweep 115 data closed appreciably. The new correction factor at -100 V was then found and was 0.75 of the first $f_{end}(100 \text{ V})$. Instead of running the code at the other voltages it was assumed that all the first iteration correction factors could be modified by the 0.75 to obtain the second iteration correction factors. Hence, $f_{end(second \ iteration)}(\Phi_p) = 0.75 f_{end(first \ iteration)}(\Phi_p)$. The results of the theory fit to the data after correction in the second iteration are also
included in Table 6.3. The amount of uncertainty in assuming that the 0.75 factor prevents a third iteration from being safely undertaken in the same manner before the entire $f_{\text{end(second iteration)}}(\Phi_p)$ is found. Fortunately, as shown in Figure 6.8, the code and data were in good agreement after the second iteration at -100 V. The final results of the fits are also provided in Table 6.3 in the two columns on the right side. The first and second iteration fits of the theory to the end effect corrected data are shown in Figures 6.9 to 6.11.

<table>
<thead>
<tr>
<th>SWEEP</th>
<th>INITIAL EST. T/T_i</th>
<th>INITIAL EST. n_0 (m^{-3})</th>
<th>1st FIT n_0 (m^{-3})</th>
<th>2nd FIT n_0 (m^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>113</td>
<td>1.5</td>
<td>6.5x10^{10}</td>
<td>2.9</td>
<td>8.2x10^{10}</td>
</tr>
<tr>
<td>115</td>
<td>1.5</td>
<td>1.0x10^{11}</td>
<td>3.6</td>
<td>1.4x10^{11}</td>
</tr>
<tr>
<td>116</td>
<td>1.5</td>
<td>1.2x10^{11}</td>
<td>3.3</td>
<td>1.8x10^{11}</td>
</tr>
</tbody>
</table>

The 32 V sweep, since the PIC code was run at only 0, -20, -100 and -300 V, was not fit in this analysis since the linear interpolation between the PIC points for correction factor determination at voltages below 120 V incurred too much error to permit a meaningful fit by the theory.

Figure 6.8: Demonstration of agreement between the code and the data by the second iteration.
The results found after the second iteration are sufficient to make two key observations. First, the density values estimated from section 6.1 differ from the fit results by more than 50%. This indicates that the detectors were underestimating the true amount of ion density present by as much as a factor of two. This is consistent with the IRI comparison made in Figure 6.1 where the CHAWS measured density is consistently below the IRI prediction. A factor of almost two increase in the ion density would also be sufficient to explain much of the high voltage analysis code-data difference (refer to Chapter 7). The H+ density estimate of Chapter 5 would also decrease by a factor of two, further removing H+ from high voltage consideration.

Second, the electron-ion temperature ratio in the disturbed plasma is about two or three times greater than that estimated for an undisturbed plasma. Samir, in his review of plasma disturbances caused by the space shuttle and small satellites [35], states that it is quite clear that the electron temperature behavior in the wake and ram side of satellites is a controversial subject. He believes that it is not clear under which plasma and body conditions the temperature enhancement may occur and that it is not obvious whether it is a universal phenomena or one which is limited to certain types of spacecraft. He suggests that a series of laboratory and in situ experiments should be performed in order to better understand the phenomena and says that ideal in situ candidates are free fliers, tethered satellites and RMS-mounted satellites. The results shown in Table 6.3 demonstrate that a ram side stainless steel Langmuir Probe mounted onto a flat stainless steel disk operating in low Earth orbit on the shuttle robotic arm observes electron heating. It is not clear that this heating also occurred in the wake since the results of Chapter 4 demonstrate that the ion collection to the probe while it was in the wake was orbit motion limited and therefore, as shown in Figure 4.17, is quite insensitive to electron temperature.
Figure 6.9: Fits of Laframboise’s space charge theory to end effect corrected sweep 113.

Figure 6.10: Fits of Laframboise’s space charge theory to end effect corrected sweep 115.
Figure 6.11: Fits of Laframboise's space charge theory to end effect corrected sweep 116.
Chapter 7: Wake Engineering

Thus far the analysis of spacecraft high voltage wake interaction has been confined to the CHAWS experiment. Previous chapters confirmed the fully three dimensional PIC code in a wide variety of CHAWS situations and also provided a model for and understanding of the ion current collection to the Langmuir probe. This chapter extracts aspects of the CHAWS analysis and presents generalizations of the results so that they can be employed in future spacecraft design. Questions such as whether the wake of a LEO spacecraft can provide free insulation for high voltage power supplies and how much ion, or feedback, current can be expected to objects of differing geometric location and size are addressed. The non-dimensionalized dominant dependencies of the model will be presented and are confirmed by additional runs of the PIC code and the advantages and disadvantages of both the code and model for future design work are discussed.

7.1 Model-Code Comparison

The model presented and confirmed in Chapter 4 is, as shown in Appendix E, in good agreement with the data and may be employed in general with a $\beta_1$ parameter of about 1. A comparison between the code, which typically under-predicted the data, and the model for $\beta_1=1$ is shown in Figure 7.1.
Figure 7.1: Comparison between model ($\beta_1 = 1$) to the PIC code for the sweep 68 ambient parameters ($n=1.53\times10^{11}$ m$^{-3}$, $T_{ion}=0.09$ eV).

As expected, the code under-predicts the model at the higher voltages. Aside from the possible error incurred through the derivation of the model (refer to Chapter 4), there are several possible sources of error which could, in combination, explain why the code is below both the data and the semi-analytical model fit to it. These are summarized in Table 7.1.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>ERROR</th>
<th>MAXIMUM IMPACT ON PIC CURRENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_e$</td>
<td>±100%</td>
<td>±50% (likely increase)</td>
</tr>
<tr>
<td>$T_i$</td>
<td>±30%</td>
<td>±10%</td>
</tr>
<tr>
<td>$T_e$</td>
<td>~2 to 5$T_i$</td>
<td>0 to 10% increase</td>
</tr>
<tr>
<td>$H^+$ n</td>
<td>-</td>
<td>5 to 10% increase</td>
</tr>
<tr>
<td>SEE coefficient</td>
<td>±5?%</td>
<td>±5?%</td>
</tr>
</tbody>
</table>

The largest source of error is in the density observation and results from detector uncertainty. The comparison of CHAWS ion densities with those predicted by the IRI model in Figure 6.1 and the results of the ram side analysis both suggest that the measured density values were below the actual values by as much as a factor of two. Hence, the density input to the code may have been too low and may explain as much as half of the gap between the model and simulation. The error
in the ion temperature is a true uncertainty in that none of the previous analysis indicated that it could be a systematic error present in either the detectors or in the analysis of the RPA sweeps. It may be responsible for as much as a 10% increase in the PIC current. The electron temperature was assumed in the PIC code to be 1.5 times that on the ion temperature. The work by Papadopoulos [36] is at least suggestive of the possibility that electron heating may occur in the wake of satellites and could raise their temperature to as high as 5 times the ion temperature. This was investigated (Chapter 4) using the PIC code and found that even at 5 times the ion temperature the current to the probe would increase by only 10%. H+ is also considered a source of error since, by virtue of its lower mass and higher thermal velocity, it may pass into the wake more easily and be collected and therefore contribute disproportionately to the current (refer to Chapter 5). The analysis in section 5.3 found the H+ density to be typically about 0.5% to 2.5% of the total ambient ion density and hence H+ consideration could effectively raise the PIC current by as much as 10%. Finally, while the secondary electron coefficient has been the subject of considerable discussion throughout this work, the error in the SEE coefficient determination from Figure 3.7 is a true uncertainty. There is also the possibility of augmented negative charge emission (refer to Chapter 4), which would obviously artificially raise the observed experimental current by an unknown amount if it is occurring, and places a potentially large uncertainty on the SEE coefficient error estimation itself. The combination of all the heretofore mentioned sources of error in the manner by which they are expected to affect the PIC current effectively bring the code and the model into agreement.

7.2 Generalized Model

7.2.1 Restatement of CHAWS Model

The work of Chapter 4 demonstrated that the developed semi-analytical model agreed with both the CHAWS I and II flight data for $\beta_1=1$. In summary, the current to the wake side probe may be estimated from

$$I = Flux \times A_c = n \cdot v_{\text{orbit}} \cdot e \cdot A_c$$

(7.1)

where

$$A_c = \frac{1}{2} r_e^2 (\pi - 2\alpha_{\text{crit}}') + \left| R \cos \alpha_{\text{crit}} (d \cos \theta + l_p \sin \theta) \right| - \frac{1}{2} R^2 (\pi - 2\alpha_{\text{crit}}') \cos \theta$$

(7.2)
\[ r_{c,omi} = r_p + \beta_1 \lambda_D \left( \left| \frac{d \Phi_p}{l_p} \right| \frac{l_p}{E_{\text{orbit}} \lambda_D} \right)^{\frac{1}{2}} \] (7.3)

\[
\begin{align*}
R &= \text{Wake Shield radius} \\
d &= \text{Distance from probe to center of WSF} \\
l_p &= \text{Probe length} \\
r_p &= \text{Probe radius} \\
\theta &= \text{Angle of attack} \\
\Phi_p &= \text{Probe bias} \\
E_{\text{orbit}} &= \text{Orbital energy}
\end{align*}
\]

and where \( \alpha_{\text{crit}} \) is given by

\[ A \sin \alpha_{\text{crit}}^2 + B \sin \alpha_{\text{crit}} + C = 0 \] (7.4)

where

\[ A = -R^2 \sin \theta^2 \] (7.5)

\[ B = -2R \cos \theta (d \cos \theta + l_p \sin \theta) \] (7.6)

\[ C = (d \cos \theta + l_p \sin \theta)^2 + R^2 - r_c^2 \] (7.7)

The \( \alpha_{\text{crit'}} \) may then be found through

\[
\alpha_{\text{crit'}} = \arctan \left( \frac{(R \sin \alpha_{\text{crit}} - d) \cos(\theta) - l_p \sin(\theta)}{R \cos \alpha_{\text{crit}}} \right)
\] (7.8)

These equations capture the dominant dependencies of the ion current collection to the CHAWS wake side probe and can be used to predict the current to the probe for a given set of environmental parameters.
7.2.2 Proposed Dominant Non-Dimensional Groups

Shaw [13] proposed, based on the presented model, the following non-dimensional groups as being those which dominate the ion current collection to the Langmuir probe. It was not possible to determine a simple closed form for the angle of attack dependence.

\[
\frac{I}{I_{\text{ram}}} = \frac{r^2}{R^2} = \left( \frac{\lambda_{\text{CLR}}}{R^2} \right) \left( \frac{e^2\Phi_p}{E_{\text{orbit}}} \right)
\]

Equation (7.1) states that the non-dimensional current to the wake probe scales proportionately with the Debye length, the probe potential, the characteristic probe dimension, and varies with the inverse square of the shadowing body's radius. These non-dimensional groups in combination with the CHAWS specific model constitute a general model for wake engineering. For a simple example, consider a probe with twice the length of the CHAWS probe mounted in the same location on the WSF. To determine the current to the new probe for a given set of environmental parameters, the model in section 4.2 can be employed to determine the current to the original CHAWS probe and then this value can be modified for a probe of twice the length using the dependencies of equation 7.1. In this case the modifier is simply a factor of two. Unfortunately, these geometric dependencies can not be verified from the CHAWS experiment since they were not varied. However, it is possible to confirm them through use of the PIC code. The limitations and restrictions of employing the model in the more general fashion are presented in the next section.

7.2.3 Limitations and Restrictions on the General Model

Before it is possible to confirm the geometric dependencies of equation (7.1) and in order to ensure proper application of the general model its limits and restrictions are outlined below:

1. No segment of the current collecting body may be immersed in either the ion rarefaction region (defined in Figure 4.8) or the frontal plasma stream. In essence, all biased surfaces must be confined to strictly the wake region.

2. Moreover, the electric field penetrating the frontal plasma stream must be spherical in nature. This does not necessitate that the wake object be of a simple geometry. Rather, it must be possible to approximate the field originating from it as that of a point charge in a distance less than that from the object to the edge of the shadowing body.
3. The angle of attack dependence can not be determined for general application. It depends strongly on object geometry and location within the wake. The methodology for such a determination is provided in section 4.2.2. Care must be taken that at significant angles of attack that neither condition 1 or condition 2 are violated.

4. The shadowing body itself can not be significantly biased with respect to the ambient plasma. Bodies such as the wake shield which are allowed to equilibrate to a potential of a few volts positive or negative relative to the plasma are not sufficiently biased to invalidate use of the model. It is not sufficient to simply shift the probe bias to correct for a shadowing object which does have a significant bias.

5. At Debye lengths below about 0.04 cm the model over-predicts the collected current. However, since the purpose of this model is to facilitate LEO spacecraft design and such designs must consider the worst case currents over the design life of the object, i.e. long Debye length and therefore OML collection situations, this restriction is of no engineering consequence.

6. At object potentials insufficient to cause sheath penetration into the frontal plasma stream the model is not generally applicable. This dictates that \( \frac{e|\Phi_s|}{E_{orbit}} \gg 1 \).

7. The model assumes the O+ ion is the dominant constituent of the ambient plasma. H+, by virtue of its lower mass and higher thermal velocity, contributes disproportionately to the current. Fortunately, at LEO the H+ component is generally less than 10% of ambient and the most it can increase the current to a wake side high voltage object operating within the above parameters is about 25% (refer to section 4.3 and Chapter 5).

7.2.4 PIC Code Confirmation of Non-dimensional Current Dependencies

The variance of the current with the probe bias and Debye length was established in Chapter 4. However, the predicted variance of the current with geometric properties of probe length and the shadowing body’s radius can obviously not be confirmed within the CHAWS data since neither the probe length nor shield radius could be varied. The code, having been confirmed in the body of this work to agree with both the data and model within the bounds of possible experimental error, was used instead to verify these proposed aspects of the current dependence.

Two different cases were run. The first kept the probe in the same location on the rear of the shield but doubled its length while the second moved the probe to the center of the shield. Both trials used the sweep 68 ambient parameters in order to allow direct computational comparison to the CHAWS simulation of Chapter 4. The results are presented pictorially in Figures 7.2 and 7.3.
Figure 7.2: PIC isopotential contours (left) and ion density cross section (right) for $I_p=2I_{CHAWS}$ ($\Phi_p=-2000$ V, $n_e=1.5 \times 10^{11}$ m$^{-3}$, $kT_{ion}=0.09$ eV).

Figure 7.3: PIC isopotential contours (left) and ion density cross section (right) for a shield center probe. ($\Phi_p=-3000$ V, $n_e=1.5 \times 10^{11}$ m$^{-3}$, $kT_{ion}=0.09$ eV).
The isopotential contours and collection sheath of Figure 7.2 demonstrate that the region extending into the wake is spherical in nature and the elongated probe does not extend directly into the ion rarefaction region created by the frontal stream as it passes the shield. Hence none of the precepts outlined in section 7.2.1 for application of the bubble model are violated.

Figure 7.3 demonstrates that the potential expansion is clearly spherical in nature before it reaches the edge of the rarefaction region. Indeed, the sheath extends into the frontal stream by only a small amount but it is sufficient to avoid violation of the sixth restriction presented in section 7.2.2.

Equation (7.1) predicts that doubling the probe length should double the observed current while moving the probe to the center of the shield should, since it can be regarded to a first approximation as increasing the shield radius by 1.4 m, decrease the observed current by about a factor of three. Table 7.2 summarizes the main results of the numerical work and compares them with the amount of current change predicted by equation (7.1).

<table>
<thead>
<tr>
<th>Geometric Configuration</th>
<th>Voltage (V)</th>
<th>PIC Current (mA)</th>
<th>PIC Current Change Factor</th>
<th>Model Current Change Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHAWS Experiment</td>
<td>-3000</td>
<td>0.20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Probe at Shield Center</td>
<td>-3000</td>
<td>0.062</td>
<td>0.31</td>
<td>0.35</td>
</tr>
<tr>
<td>CHAWS Experiment</td>
<td>-2000</td>
<td>0.13</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Twice the Probe Length</td>
<td>-2000</td>
<td>0.27</td>
<td>2.08</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Overall, it is clear that the model and code share the same dominant dependencies and that both the model, within the limits set in section 7.2.1, and the code may both be satisfactorily employed for more general wake engineering purposes.

The variation predicted by the general model in the collected current with changes in geometry are provided in Figures 7.4 and 7.5 for a sample set of environmental parameters. For the general model, characteristic length is defined as the perpendicular distance from the shadowing body’s wake side surface to the object point farthest from the surface.
Figure 7.4: Predicted current versus radius ($\Phi_p=-1000$ V, $n_\infty=1\times10^{11}$ m$^{-3}$, $kT_i=0.1$ eV, $d=1.4$ m).

Figure 7.5: Predicted current versus object length ($\Phi_p=-1000$ V, $n_\infty=1\times10^{11}$ m$^{-3}$, $kT_i=0.1$ eV, $d=1.4$ m).
7.3 Discussion

There are several questions and applications that should be considered in light of the proposed wake engineering tools. First, the flux to wake side surfaces should be considered. Unfortunately, despite being located within the wake, the flux to a particular surface depends strongly on the object geometry, location in the wake and on the bias of objects located therein. The use of the PIC code by G. Font [27] confirmed that the ram ions which pass the shield may be focused into beams which are turned into the wake and impact the wake side surface with local fluxes as much which may exceed the ram flux by as much as twenty times. The location of beam impact will differ from design to design and can only be evaluated properly with careful use of numerical simulation.

The presence of multiple biased objects within the wake should also be considered. Obviously, if any one object is the closest to the edge of the shadowing body and is the most significantly biased then it will dominate the current collection. The model may also be employed to consider multiple objects which are separated by a distance great enough to prevent significant overlap of their potentials which extend into the frontal stream. This amounts to an additional restriction on the model employment. In the event that several objects of similar bias are located in almost the same area they may be considered separately by the model. However, this could underestimate the total expansion of the net sheath into the wake region and hence underestimate the net feedback current to the rear of the spacecraft. In such cases it is recommended that numerical simulation be employed. Clusters of biased objects which, in total, simplify to a point source field once the edge of the shield is reached can be assessed through direct use of the model provided to current to each object within the cluster is not required.

In the WSF-I (STS-60) flight the epitaxial growth experiment was found to be contaminated, presumably by water vapor from the orbiter. Another possibility for this contamination is H+ which, since it has a Mach number of about 1 to 2, can penetrate the shield wake quite easily. When no highly biased objects are operating within the wake of the WSF, which was the case during the epitaxial growth experiment, about one third of the H+ ram flux could, by equation (1.16), impact the rear of the WSF. In comparison, about one O+ ion every million years would be likely to impact the rear of the shield. In the WSF-II flight it was noted that the WSF free flying epitaxial growth experiment, which was over 20 miles from the orbiter, suffered similar contamination. It is unlikely that at such a large distance from the orbiter that the contamination was again water vapor from the shuttle. Indeed, H+ becomes a much more likely suspect. One method for avoiding such contamination in the future and for providing perhaps an even better than anticipated vacuum for ultra-pure epitaxial growth would be to ring the epitaxial apparatus in
negatively biased CHAWS-type probes. In effect, these would act much like terrestrial ion pumps only no energy would be required to ionize the offending atoms since this is performed naturally. Numerical simulation would be required to assess whether there would be any ion beam formation which could impact the epitaxial growth area and would also allow the Langmuir probes to be configured in an optimal manner.

Finally, the question of whether the wake may be employed as a natural insulator can be addressed. A general comparison between the CHAWS ram and wake side currents as a function of probe bias is provided in Figure 7.6.

![Figure 7.6: General comparison between the ram and wake side probe currents as a function of probe bias.](image)

The above comparison was made between an extrapolation of a power law fit to the ram side sweep 115 and the model for the estimated ambient parameters for sweep 115. For the lower biases, the CHAWS probe clearly collected more current while oriented into the ram direction. This is simply because of the greater ion density in the immediate object vicinity when it is oriented into the ram. In such situations it is logical, if given the choice, to locate power supplies and wires within the wake of the spacecraft. Beyond the cross-over point, however, the space charge present in the ram direction begins to provide more insulation than the wake, where the ion collection is orbit motion limited in nature and hence continues to increase. Hence, for such situations it is logical to locate power supplies and wires on the ram side of the satellite. To generalize beyond the CHAWS situation the ram side theory of Chapter 6 and the general model outlined in this chapter
must be considered so that to generate a design plot such as Figure 7.6. For situations where the power supply or wire is of a bias below the cross-over point there must be a trade study performed between the cost of designing for a feedback current and the cost of adding insulation.
Chapter 8: Conclusions

The objectives of the CHAWS project were the following:

1. Flight test a new generation of miniaturized particle detectors by using them to measure the ambient low energy ion population on the ram and wake side of the Wake Shield Facility.
2. Determine and understand the current-voltage characteristic of a negatively biased object in a plasma wake under a wide variety of changing environmental conditions and compare the results to numerical simulation.
3. Derive a general (i.e. applicable to geometries other than CHAWS) model consistent with both the data and the simulation from which future spacecraft may be designed to avoid hazards posed by wake charging.

This work achieved these objectives through a comprehensive analysis of the data from both CHAWS flights. The analysis was sub-divided into four distinct categories: ion density and temperature determination from the RPA data, high voltage wake current collection (>100I), low voltage wake current collection (<100 VI) and ram side current collection. In the last three items a fully three dimensional PIC code simulation was compared to the data in order to confirm the code in a wide variety of ion collection regimes and also to provide insight and even quantification of data aspects which were not available from the experimental data.

In the high voltage analysis a semi-analytical model previously developed using only the CHAWS I data under an older and less accurate RPA instrument calibration was presented. The
model, which is based on classical probe theory, approximates the spherical sheath edge observed in the PIC simulation as the ion collection boundary. Re-application of this 'bubble' model to the CHAWS I data under the new calibration demonstrated that the original model is still valid and that the wake side ion collection is orbit motion limited. Successful model application to the much more extensive CHAWS II data confirmed OML collection and proved model validity over typical LEO ion densities, temperatures and spacecraft angle of attack. The bubble model assumes that the plasma is predominantly O+ and was found, as a result, to under-predict the ion current collection below about 1750 Vl, where H+ collection was significant. PIC code simulation of the ion collection under-predicted the ion current by about a factor of two. However, subsequent analysis of uncertainties in ion density, ion temperature, electron temperature, secondary species contribution (H+) and the SEE coefficient determination found that the error bound is sufficient to bring simulation and data into agreement. PIC consideration of elevated electron temperature on ion current found that even values of T_e>5T_i result in only a small current increase (<10%) and further confirmed that the ion collection is orbit motion limited.

In the low voltage analysis the importance of H+ was examined. It was found that H+, by virtue of its lower Mach number, penetrates the wake much more easily than O+ and is the dominant component of the ion current in the low voltage region. PIC simulation employing H+ at the low voltages had the same I-V characteristic form as the data. Based on that result, additional simulation estimated the maximum H+ density to be 2.5% of the total ambient density. The small amount of H+ allowed it to be neglected in the high voltage analysis beyond ~750 Vl and greatly simplified bubble model considerations. The low voltage analysis also identified the amount of photo-emission from the probe to be about a milli-ampere and located the turn-on voltages (~100 V) predicted by pre-flight modeling and the PIC code.

Analysis of the small set of ram side data (i.e. when the shield was inverted and the probe was aligned directly into the plasma flow) demonstrated that the space charge limited collection theory by Laframboise and the PIC code are in agreement if the data is corrected for end effect. The results, combined with a comparison of the CHAWS densities to IRI prediction, suggest that the CHAWS detectors may have underestimated the ambient density by as much as a factor of two. This was accounted for in the high voltage analysis. The ram side analysis also suggested that electron heating (T_e ~ 5T_i) was observed in the ram direction of the WSF.

With confirmation of the simulation in a wide variety of situations and to within the bounds of possible uncertainty, it could, in principle, provide all the information necessary to engineer for highly biased objects within the wake of LEO spacecraft. Its run time for only one data point, however, would be several days on computational resources typically available to the engineering community. This obviously prevents its implementation into the design cycle. Hence, the semi-analytical model developed in the CHAWS high voltage analysis was expanded into a more general
model which is applicable to geometries other than CHAWS. The ion current was found to scale linearly with the biased object extension into the wake and inversely with the square of the shadowing body radius. These geometric dependencies of the general model were confirmed using the numerical simulation. The overall simplicity of the model should make its addition to existing spacecraft design tools, such as Environmental WorkBench, simple and hence allow future spacecraft to be designed for high voltage wake charging interactions.

In summary, the CHAWS project was a resounding success. The current voltage characteristic of a highly biased negative object in the wake of a satellite was obtained over a wide range of LEO ion density, temperature and angle of attack. This work achieved an understanding of all critical aspects contributing to probe current through analysis of the high, low and ram side data in conjunction with a fully three dimensional hybrid particle-in-cell code. The comprehensive understanding allowed completion and verification of a semi-analytical model which captured all the dominant dependencies of the ion current collection. Both the generalized version of the model and the numerical simulation are sufficiently predictive to allow future LEO spacecraft to be tailored to take full advantage of, and avoid charging hazards posed by, wake charging interactions.

Future work should follow two avenues. First, specific applications of the model, such as the wake side ion pump for achievement of improved vacuums or prediction of feedback current to a high voltage wake side power system, should be developed. This gives spacecraft designers examples which can provide guidelines for successful model employment. Second, while this work explored the critical geometric dependencies of the code and the model, a more comprehensive comparison over a wider variety of non-CHAWS situations would provide additional insight into the model restrictions and, in essence, provide for a small amount of fine tuning.
APPENDIX A: CHAWS RPA CALIBRATION REPORT AND ANALYSIS (by David Cooke of the Hanscom AFB Phillips Lab)
CHAWS RPA Calibration Report and Analysis

The Geometric Function

The detectable flux of ions into a detector may be modeled as the flux, \( F_a \), an aperture with inward normal \( \hat{n} \), which is transmitted or detected with an efficiency described by the geometric function \( g(v) \) or \( G(v) = A g(v) \), where \( g \) has values less than or equal to one, and \( A \) is the area of the aperture. At the entrance of the aperture, or for a perfect detector, \( g=1 \) everywhere, and \( G=A \). For a less than perfect detector, \( G \) will vary over its parameter range, which depends on the nature of the instrument. For a mass spectrometer, we might need to consider detection efficiency as a function of mass. The CHAWS detectors are planar retarding potential analyzers where the detection efficiency at a minimum depends upon particle velocity \( v \), and the retarding potential \( V_R \) which defines the minimum normal energy \( (1/2mv_n^2) \) with which an ion can pass through the instrument and be detected. The detected flux of ions, \( F_d \) (#/sec) is thus:

\[
F_d = F_d(f(v,M),G(v,V_R),\hat{n}) = \iiint d^3v f(v,M)G(v,\hat{n},V_R)v \cdot \hat{n}
\]  

(A1)

where \( f(v,M) \) is the particle distribution function which is assumed to be flowing with a characteristic Mach number \( M \). The objective of calibration is to determine \( G \). With \( G \) known, the objective of analysis is to 'guess' the \( f(v) \) responsible for our measurement \( F_d \). In some cases, the convolution of \( G \) with \( f(v) \) in equation A1 is analytic, and we may be able to algebraically solve for the relevant properties of \( f(v) \). When the convolution yields no tractable analytic form, it is common to look for practical approximations. Here we will avoid this until we can evaluate the approximations by considering the full solution. We are thus posed with an analysis problem that is model dependent and somewhat theoretical in nature. It is worth noting that a 'differential' detector with a limited field of view can be calibrated with by single valued geometric factor. Such an instrument is much simpler to calibrate and analyze, however its data conveys proportionally less information about the bulk properties of the plasma.

The Assumptions

To simplify the present discussion we will assume that \( G \) is independent of the particle speed, \( v \), and restrict the retarding potential to be zero. The first assumption should be revisited, and the latter is reasonable since we will both calibrate and determine the plasma density at a single voltage, \( V_R = 0 \). Thus \( G \) becomes \( G=G(\theta,\phi) \), where \( \theta \) and \( \phi \) are spherical polar angles about \( \hat{n} \).
Additionally, we will usually be interested in determining the bulk properties of the space plasma, which for Low Earth Orbit ionosphere, may be assumed to be Maxwellian and seen by an orbiting detector as drifting. It will provide for a more focused, albeit less general discussion if we specialize to that particle distribution now. The drifting Maxwellian distribution function is

\[ f = N \left( \frac{m}{2\pi kT} \right)^{3/2} e^{-\frac{(v-v_0)^2}{2kT}} = pe^{-(v-M)^2} = p e^{-\frac{(v-x-M_x)^2-(v-M)^2}{2kT}} \]  

(A2)

where \( N \) is the plasma density, \( m \) is the particle mass, \( k \) is Boltzman's constant, \( T \) is the plasma temperature, \( p=N(m/2\pi kT)^{3/2} \), and \( V=v/(2kT/m)^{1/2}=v/v_o \) where \( v_o \) is the characteristic particle speed. The drift velocity, \( v_d \), now becomes the Mach vector \( M=v_d/v_o \). All three forms will be used at some time, and we usually choose \( \hat{z} = \hat{n} \). Using this \( f \) in equation A1 with \( g=1 \), we find that the flux density to an aperture is

\[ J_a = J_o \left[ e^{-M^2} + M_n \sqrt{\pi} \left( 1 + erf(M_n) \right) \right] = Nv_o J_a \]  

(A3)

where we identify the Maxwellian thermal flux density \( J_o \), and \( M_n \) is the projection of \( M \) onto \( \hat{n} \).

\[ J_o = N \sqrt{kT/2\pi m} = 1/2N \pi^{-1/2} v_o \]

\[ J_a = 1/2 \pi^{-1/2} \left[ e^{-M^2} + M_n \sqrt{\pi} \left( 1 + erf(M_n) \right) \right] \]

In applying equation A3, it is important to remember that \( M_n \) retains its sign. Thus for \( M \geq 3 \), an aperture facing into the ram direction has \( M_n=M \), and \( J_a=NMv_o \). Facing into the wake, the aperture sees \( J_a = J_o e^{M^2} \).

**Method of Analysis**

We can see that for the assumed velocity distribution the aperture flux depends on \( N \), \( T \), and \( M_a \). Ideally, our instrument should measure these three quantities, plus the total Mach vector, \( M \). The CHAWS detectors have been designed to do this. Analysis of the count rate as a function of \( V_R \) will yield \( M_n \), and \( T \). Inside of the detectors, the ion collection 'surface' is quadratured about \( \hat{n} \), and from the ratios of the quadrant fluxes and knowledge of \( M_n, M \) can be determined. Thus, knowing \( T \), and \( M \), equation A3 will give us \( N \) if we know \( F_a \), which we will now determine from the calibration and \( F_d \). For the present discussion, we will assume that \( M \) and \( M_n \) are known,
or in practical units, $V_d$, T, $\theta$, and $\phi$, where ( and $\phi$ are now the spherical angles resolving M about $\hat{n}$. For this section, we also assume that $G(v)$ has been determined.

Our goal now is to find $F_{sub \ a}$ from our knowledge of $G(v)$ and $F_d$, and from $F_a$, to find $N$. To accomplish this, we could perform the integration in equation A1 for each measurement and find $N$ as the scale factor that matches equation A1 to the measurement. As this would be quite tedious, we adopt an approach where we precalculate and tabulate equation A1 over an expected range. This is identical to determining the average geometric factor $\overline{G}$,

$$
\overline{G}(M) = \frac{F_d}{J_a} = \frac{\iiint G(v)f(v,M)d^3v\cdot \hat{n}}{\iiint f(v,M)d^3v\cdot \hat{n}} \quad (A4)
$$

where we have explicitly stated the dependence of the distribution function on the Mach number, M. If we know or have otherwise correctly guessed M and thus $\overline{G}(M)$, we can then invert the equation A4 to find $J_a$, and then find $N$ from equation A3. There is a practical modification to equation A4 obtained by the following expansion.

$$
\overline{G}(M) = \frac{\overline{G}(M)}{G_0} = \frac{G(M)}{G_0} \bar{g}_0 P = \bar{g}_r(M) \bar{g}_0 P \quad (A5)
$$

where $\bar{G}_0 = \overline{G}(M=0) = \varepsilon A \bar{g}_0 = P \bar{g}_0$ is the averaged geometric factor for an isotropic distribution. We have also combined the aperture area A and any overall efficiency factor, $\varepsilon$, into a prefactor P. It is $\bar{g}_r(M)$ that is to be computed and tabulated. The reason for this modification is to provide a convenient 'self-normalization' for $\overline{G}$ which removes all the uncertainties and laboratory scale factors from the tables into the two number $\bar{g}_0$ and P. Thus we may simply determine the aperture flux as

$$
J_a = F_d / \bar{g}_r(M) \bar{g}_0 P \quad (A6)
$$

An additional advantage of introducing $\bar{g}_0$ is that it is the most intuitive average of the geometric function so that at the aperture or for a perfect hole $\bar{g}_0 = 1$. $\bar{g}_0$ can be used to analyze a measurement where there is no good guess for M. Such a situation can arise when considering wake measurements. On the ram side M may be known, but is sufficiently large (M $\geq 5$) that the predicted wake fluxes are much lower than what is observed. In this case, the particle population responsible for the observed wake fluxes could be locally generated and possibly non-flowing.
In the above discussion, it is implied that we should determine \( J_a \), and invert equation (A3). This however will require much recomputation of the exponential and error function. Further, since exactly these terms were used in normalizing \( \overline{G} \), and given the precision problems presented by these functions, it would be a serious source of error to normalize with one computer program, truncate on output, then reapply with another computer and program. We resolve this difficulty by observing that from equation (A3),

\[
N = \frac{J_a^m}{v_o J_a} = \frac{F_d^m}{G(M)v_o J_a} = \frac{F_d^m}{\overline{G}_N(M)} = \frac{F_d^m}{\overline{G}_N(M)\overline{g}_o P v_o}
\]  

(A7)

where the superscript 'm' is used to distinguish a measured quantity and we defined the density geometric factor, \( \overline{G}_N(M) \), and tabulate the matrix,

\[
\overline{g}_N(M) = \overline{G}_N(M) / \overline{g}_o P v_o = \overline{G}(M) J_a / M \overline{g}_o P = \overline{G}_F(M) J_a / M
\]  

(A8)

Note that for \( M=0 \), \( \overline{g}_N(M) \) is undefined. That is because to have \( M=0 \), the population must either be nondrifting so that \( v_o \) is undefined with respect to the nonexistent drift velocity, or the temperature is infinite. This singularity is artificial since in equation A7, we chose to divide by the orbital velocity, \( v_o \). In this case we agree to set \( M=1 \) so that,

\[
\overline{g}_N(M) = \overline{G}(M=0) J_a / (M=1)\overline{g}_o
\]

and we must realize that the density has been calculated with the assumption that \( v_a=v_o \), and so must use \( v_o \) when applying A7.

### Measurement of \( G \)

The coordinate system for the measurement and analysis of \( G \) is shown in Figure A1. The CHAWS detectors were calibrated using the CALSYS system in the MUMBO facility at PL/GPS. The CALSYS system measures detector response in the spherical polar system shown in Figure A1 with the system pole and the instrument normal oriented such that \( \phi_s = 0 \), and \( \theta_s = \pi/2 \). Measurements are reported in terms of the zenith angle compliment, \( \theta_{sc} = \theta_s - \pi/2 = 0 \). If it were possible, we might consider calibration with a facility capable of simulating the full range of LEO environments. In this case, we would directly measure \( \overline{G} \), instead of \( G \). This is, however neither practical or desirable, so \( G \) is determined with a narrow or cold ion beam ( \( M \) approx 66). Although it is CALSYS that physically moves, it leads to simpler notation to think of the beam as
moving about the detector normal. With the beam incident on the detector from $\theta_b \pm \Delta \theta, \phi_b \pm \Delta \phi$, the detected flux is,

$$F_d = (\delta \theta \delta \phi \sin \theta_b) \cos \psi G(\theta_{bc}, \phi_b) \int_{0}^{\alpha} f(v) v^3 dv \quad (A9)$$

Where $\psi$ is the angle between the beam and $\hat{n}$. Here, we have employed the fact that the beam distribution $f$ is very narrow to reduce the angle integrals, and we have identified $\delta \theta \delta \phi \sin \theta_b$ as $\delta \Omega$, the solid angle that just 'captures' the beam. Meanwhile, a Faraday cup is used to monitor the beam and measures,

$$F_c = A_c \delta \Omega \int_{0}^{\alpha} f(v) v^3 dv \quad (A10)$$

So, the differential distribution function $G$ is determined from the measured flux rate as,

$$G(\theta_b, \phi_b) = \frac{F_d A_c}{F_c \cos \psi} = \frac{F_d A_c}{F_c \cos \phi_b \sin \theta_b} \quad (A11)$$

**Coordinates and Transformations**

Although practical in the laboratory, the CALSYS choice of angles is not convenient for analysis, where we prefer a system with the pole aligned with the detector normal (see Figure A1). The following equations transform the coordinates of any point in the 'old system' (unsubscripted) to a new system (subscript $a$) where the old coordinates of the new pole are subscripted $n$.

$$\cos \theta_a = \cos \theta \cos \theta_n + \sin \theta \sin \theta_n \cos(\phi - \phi_n) \quad (A12)$$

$$\tan \phi_a = \sin(\phi - \phi_n)/(\sin \theta_n \cot \theta - \cos \theta_n \cos(\phi - \phi_n)) \quad (A13)$$

Since we want the pole of the new analysis system to be aligned with the detector normal, the subscript $n$ above represents both the coordinates of the normal and new pole. When substituted this gives,

$$\cos \theta_a = \sin \theta \cos \phi = \cos \theta_c \cos \phi \quad (A14)$$

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\[ \tan \phi_s = \tan \theta \sin \phi = \cot \theta_s \sin \phi \quad (A15) \]

For equation A1 and spherical coordinates,

\[ v \cdot \hat{n} = v \cos \psi = v(\cos \theta \cos \theta_s + \sin \theta \sin \theta_s \cos (\phi - \phi_s)) = v \cos \theta_s \quad (A16) \]

where \( \psi \) is the 'slant angle' between \( v \) and \( \hat{n} \)

**Calibration Data**

The CHAWS RPA detectors were calibrated both before and after flight. Difficulties with the preflight calibrations and repairs to the detectors made recalibration essential. Although the preflight data is still valuable, for simplicity of presentation, this report will concern itself with postflight calibration only. Further, the details of the laboratory procedures required to calibrate the detectors, and the methods used in manipulating the data are subjects of separate reports. Here, we will briefly discuss the process in general and present the final product as it is input to the simulation process described in this report.

The coordinate system for the data collected by CALSYS is described above and shown in Figure A1. The calibration system uses an \( N_2 \) ion beam with a 2 degree angular distribution so that measurements are effectively differential on larger scales. Data is collected on a predefined regular grid of \( \theta, \phi \) points with a typical spacing of 2 to 5 degrees over as large an extent as is possible. This last constraint is significant for the CHAWS detectors as their field of view is often wider than can be accommodated by CALSYS. Because of the unmeasured regions of the detector field of view, we were forced to investigate a number of methods for extrapolating \( G \) before the integrations described previously could be performed. The first idea was to characterize the detector response and extrapolate using that characteristic. This proved unsuccessful because of the significant variations between detectors. We finally employed the following procedure. First the lab data was transformed from the CALSYS coordinates to the analysis coordinates. In this form, we were able to identify 'rays' of detector count rates varying in \( \theta \) along lines of constant \( \phi \). From the complete rays that approached constant low count rates at high \( \theta \), an averaged background was chosen and subtracted from the complete data. Finally, the incomplete rays were completed by selecting nearby complete rays as a profile, and scaling that profile to complete the ray. What is presented in the following figures is the final \( G(v) \) product sampled at the same angular interval as the \( g_F \) and \( g_N \) plots and tables. In the case of the rams side data, considerably
finer resolution was preserved going into the integration process. For the wake data, the laboratory data was quite sparse so that a great deal of intuition was employed in completing the data sets.

The units of the data are chosen for convenience. On the ram side, it is counts/\( \tau /I_c \), where \( \tau \) is the accumulation period (= 5.0 sec) and \( I_c \) is Faraday cup current in units of pico Amps. On the wake side, the units are counts/\( \tau /I_c /1000 \), \( \tau =7.5 \) sec. To calculate the prefactors described above, we must also know the effective area of the Faraday cup \( A_c =48.0 \text{ cm}^2 \). Thus we have,

\[
P_{\text{ram}} = A_c 1.6 \times 10^{-19} 10^{12} / 5.0 = 1.54 \times 10^{-6} \text{ cm}^2 \text{ pAmp} \quad (A17)
\]

\[
P_{\text{wake}} = A_c 1.6 \times 10^{-19} 10^{12} 1000 / 7.5 = 1.02 \times 10^{-3} \text{ cm}^2 \text{ pAmp}
\]

Notice that it is not necessary to explicitly include the detector aperture area as it is measured and included somewhere in \( P \times \overline{G}_0 \). For reference these areas are: Ram, all = 5.0 \times 10^{-3} \text{ cm}^2; Wake, end = 5.6 \times 10^{-1} \text{ cm}^2; Wake, in/out = 1.5 \times 10^{-1} \text{ cm}^2.

The 'data' being discussed and processed is the sum of all of the sub-channels (either 2 or 4) of each detector. This represents that maximum data available. The detectors were designed such that the subchannel information could also be used to determine the Mach angles. This treatment is difficult, lengthy and the subject of another report. A primary reason for this difficulty is the gross variations between the detector and sub-channel responses.

**Determining \( \overline{G} \)**

The determination of \( \overline{g}_F(M) \) and \( \overline{g}_N(M) \) is described by following the logic of the Fortran simulation, cal.f. First the calibration file for the detector to be simulated is read into Common by the subroutine loadg.f. During the simulation the subroutine plotg samples \( G \) at frequent angular intervals, and outputs the geometric response \( g(\theta,\phi) \) for plotting. This is done as a check, since this is the geometric response of the detector from this point on. Next, a series of "do loops" are performed as follows:

1. Choose \( M \)
   - Loop on Mach number = 1, 5, and 10
   - Loop on Mach azimuth angle (10 degree steps, 0 to 360)
   - Loop on Mach polar angle (5 degree steps, 0 to 180)
2. Calculate the particle flux
Loop on particle velocity polar angle (2 degree steps, 0 to 80)
Loop on particle velocity azimuth angle (variable steps ~ 2 degrees)
Sample G(v) (the data)
Loop on particle speed
ΔFluxG=δvδΩf(M, v)G(v)
ΔFlux0=δvδΩf(M=0, v)G(v)
End v loops
\[ J_s = \frac{1}{2\pi^{1/2}} \left[ e^{-\frac{M_\text{a}^2}{M_\text{a}^2}} + M_\text{a}^2 \pi^{1/2} \text{erfc}(\frac{-M_\text{a}}{\sqrt{2}}) \right] \]
\[ \bar{g}_o = \sum (\Delta \text{Flux0})/(1/2\pi^{1/2}) \]
\[ \bar{g}_F = \sum (\Delta \text{FluxG})/J_s/\bar{g}_o \]
\[ \bar{g}_N = \sum (\Delta \text{FluxG})/\bar{g}_o/M \]
Output \( \bar{g} \) s
End Mach loops

The results of this process are presented in Figure A2 for the Ram side center detector. The \( \bar{g}_o \) results and the prefactors are presented in table 1. Both the ram side inboard and outboard detectors were repaired after the first flight and recalibrated, so separate calibrations should be needed for each flight. As of this report, only the post repair calibration data has been fully processed. On the wake side, there were no repairs. The ram/wake inboard/outboard simulations results are not presented here, but are included in the flight support programs CHAPS and CHUNKS.

<table>
<thead>
<tr>
<th>Detector</th>
<th>( \bar{g}_o )</th>
<th>P cm² pA</th>
<th>( P \bar{g}<em>o v</em>{\text{orb}} ) cm³ pA sec⁻¹</th>
<th>Aperture Area cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>v_{\text{orb}}=7.4×10⁵ cm/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ram inboard</td>
<td>0.141</td>
<td>1.54×10⁶</td>
<td>0.161</td>
<td>5.0×10⁻³ cm²</td>
</tr>
<tr>
<td>Ram center</td>
<td>0.187</td>
<td>1.54×10⁶</td>
<td>0.213</td>
<td>5.0×10⁻³ cm²</td>
</tr>
<tr>
<td>Ram outboard</td>
<td>0.163</td>
<td>1.54×10⁶</td>
<td>0.186</td>
<td>5.0×10⁻³ cm²</td>
</tr>
<tr>
<td>Wake inboard</td>
<td>0.393</td>
<td>1.02×10³</td>
<td>296.0</td>
<td>1.5×10⁻¹ cm²</td>
</tr>
<tr>
<td>Wake center</td>
<td>0.887</td>
<td>1.02×10³</td>
<td>669.0</td>
<td>5.6×10⁻¹ cm²</td>
</tr>
<tr>
<td>Wake outboard</td>
<td>0.011</td>
<td>1.02×10³</td>
<td>8.30</td>
<td>1.5×10⁻¹ cm²</td>
</tr>
</tbody>
</table>
Figure A1: Coordinate system for analysis and measurement of G.

Figure A2: The CHAWS ram side sensor detector response. The top graph shows a horizontal projection of a 3D plot of the ram side center detector geometric
function $G(\theta, \phi) \times \cos(\theta)/G(0)$ as measured with CALSYS. This is equivalent to $g_r(M=66)$. The vertical axis is $g_r(M)$, and the two horizontal axis are $x=\cos(\theta)\sin(\phi)$. The x and y tick marks are 30 degrees and the vertical ticks are 1 unit. Moving down the page we show $g_r(M)$ for $m=9, 5, 3, 1$. 
APPENDIX B: SAMPLE CHAWS RPA SWEEPS
IV 3 sample RPA sweep

IV 5 sample RPA sweep

IV 6 sample RPA sweep

IV 7 sample RPA sweep
IV 8 sample RPA sweep

IV 10 sample RPA sweep

IV 11 sample RPA sweep

IV 12 sample RPA sweep
IV 43 sample RPA sweep

IV 44 sample RPA sweep

IV 45 sample RPA sweep

IV 46 sample RPA sweep
IV 47 sample RPA sweep

IV 48 sample RPA sweep

IV 54 sample RPA sweep

IV 55 sample RPA sweep

KT = 0.128
Uncertainty = 0.068

KT = 0.084
Uncertainty = 0.016

KT = 0.091
Uncertainty = 0.052

KT = 0.059
Uncertainty = 0.012
IV 56 sample RPA sweep

IV 57 sample RPA sweep

IV 58 sample RPA sweep

IV 59 sample RPA sweep
IV 60 sample RPA sweep

IV 61 sample RPA sweep

IV 62 sample RPA sweep

IV 63 sample RPA sweep

KT = 0.056
Uncertainty = 0.011

KT = 0.069
Uncertainty = 0.041

KT = 0.027
Uncertainty = 0.006

KT = 0.059
Uncertainty = 0.036
IV 64 sample RPA sweep

IV 65 sample RPA sweep

IV 66 sample RPA sweep

IV 67 sample RPA sweep
IV 68 sample RPA sweep

IV 69 sample RPA sweep

IV 70 sample RPA sweep

IV 71 sample RPA sweep
IV 72 sample RPA sweep

IV 73 sample RPA sweep

IV 74 sample RPA sweep

IV 75 sample RPA sweep
IV 76 sample RPA sweep

IV 77 sample RPA sweep

IV 78 sample RPA sweep

IV 79 sample RPA sweep
IV 84 sample RPA sweep

IV 85 sample RPA sweep

IV 86 sample RPA sweep

IV 87 sample RPA sweep
IV 94 sample RPA sweep

IV 95 sample RPA sweep

IV 96 sample RPA sweep

IV 97 sample RPA sweep
IV 98 sample RPA sweep

IV 99 sample RPA sweep

IV 100 sample RPA sweep

IV 101 sample RPA sweep
IV 102 sample RPA sweep

$K_T = 0.040$

Uncertainty = 0.010
APPENDIX C: CHAWS I AND II RAW HIGH VOLTAGE CHARACTERISTICS
APPENDIX D: MODEL FITS TO CHAWS I SWEEPS
APPENDIX E: MODEL FITS TO CHAWS II SWEEPS
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