How to Really Measure Low Energy Electrons in Space

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There is little argument in the space plasma physics community that in-situ, low energy electron measurements are technically challenging. The primary obstacle has been the effects of spacecraft charging on the measured three-dimensional electron velocity space distribution. A successful spacecraft charging correction algorithm used with the three-dimensional electron instrument aboard the Ulysses spacecraft has clarified the role of spacecraft and instrument parameters in the eventual reconstruction of low energy electron distributions. Suggestions for instrument and spacecraft modifications that can minimize spacecraft charging effects are presented in this paper. The emphasis is on designs that lend themselves to robust correction algorithms.

INTRODUCTION

The objective of in-situ particle measurements of space plasmas is to provide enough information to fully characterize the plasma particle distributions. The details of both the ion and the electron distributions are needed to understand the growth of instabilities and the partitioning of energy within the plasma. The space environment and typical spacecraft resources, however, can significantly affect the extent to which accurate particle distribution measurements can be obtained. Fundamentally, it is charging of the spacecraft that distorts measurements of the ambient plasma velocity space distributions. As charged particles approach a plasma instrument, their velocities and trajectories are modified by the plasma sheath surrounding the spacecraft. It has been shown [Scime et al., 1994; Parker and Whipple, 1970], that the ambient plasma velocity space distribution can be accurately reconstructed if the plasma sheath structure and the spacecraft potential are known.

The focus of this paper is a discussion of the role played by instrument design, instrument calibration, and spacecraft design in the velocity space distribution reconstruction process. Not all spacecraft shapes or instrument designs are equivalent. For the purposes of discussion, only those techniques that lead to more accurate plasma measurements without a significant increase in instrument resources (mass, power, telemetry) are considered.

To avoid the complications of multiple species and subsonic distributions, discussions will be limited to low energy electrons measured from positively charged spacecraft. It is true that for a positively charged spacecraft, very low energy ions are completely reflected and it is not possible to recover the low energy ion data. In such a case, the spacecraft design must emphasize the complete elimination of the charging of the spacecraft. The instrument modifications and spacecraft designs suggested in this paper for charged spacecraft are also relevant for low energy ion measurements from negatively charged spacecraft, or measurements of low energy particles whose energy exceeds that of a similarly charged spacecraft (e.g., ambient 4 eV electrons measured from a spacecraft charged to -3 V).

2. SPACECRAFT CHARGING

For a plasma in which the electron temperature is greater than a few percent of the ion temperature, the electron flux to the surface of an object immersed in the plasma exceeds the ion flux. In the absence of any other effects, e.g., photoelectron emission or secondary electron emission by
ion or electron impact, the excess electron flux results in a negative floating potential for the object [Langmuir and Blodgett, 1924]. This situation occurs only rarely in magnetospheric and heliospheric plasmas. Solar ultraviolet radiation liberates enough photoelectrons from the surface of a typical spacecraft that the photoemission overwhelms the ambient electron flux and the spacecraft floats positive. Because the magnitude of the spacecraft potential is a function of the ambient plasma density, spacecraft illumination (solar ultraviolet level and spacecraft orientation), age of the spacecraft surface, and ambient plasma temperature, a priori calculations of the spacecraft potential are accurate only to within a few volts [Mandell et al., 1978]. When a spacecraft enters the full shadow of a celestial body, such as the Earth or the Moon, the photoelectron emission ceases and the spacecraft can charge to large negative potentials [Rosen, 1976; Whipple, 1981]. Due to their plasma densities and distances from the Sun, different regions of space have different characteristic spacecraft potentials. Figure 1 shows typical spacecraft potentials for the ionosphere, magnetosphere, and heliosphere.

Once it becomes positively charged, a spacecraft will attract negatively charged particles. That the negative charged particles (electrons) will accelerate towards the spacecraft and gain additional kinetic energy equal to the spacecraft potential is obvious. The effects on the details of the measured particle distributions, however, are more subtle. The spacecraft potential distorts the trajectory of the ambient electrons entering the instrument (Figure 2). A positively charged spacecraft will focus ambient electrons. A negatively charged spacecraft will defocus ambient electrons. In the limit of a thin sheath (or a sheath whose equipotential surfaces are parallel to the spacecraft body near the instrument), the relationship between the true incident angle for an electron far from the positively charged spacecraft (θ₀) and the measured angle of incidence (θ) is given by:

$$\sin \theta = \frac{\sin \theta_0}{\sqrt{1 - \frac{U}{E_A}}}.$$  

(1)

where $U$ is the spacecraft potential and $E_A$ is the energy of the electron measured by the instrument [Scime et al., 1994]. For $E_A = U$, electrons emitted from the spacecraft body itself ($\theta = 90^\circ$) can appear to come from the ambient plasma. The result is an energy-dependent geometric factor for the instrument that is also a function of the local plasma density and solar illumination. Low energy electrons are collected from an enormous field of view and only the higher energy electrons are collected from the intended instrument field of view. It should be added that magnetic field focusing effects should be considered if low energy particle instruments are placed close to high current spacecraft power systems.

This focusing effect has been described by a number of authors [Garrett, 1981; Singh and Baugher, 1981; Sojka et al., 1984; Scime et al., 1994], but only recently have correction techniques been implemented during routine data analysis [Comfort et al., 1982; Scime et al., 1994]. Left uncorrected, this focusing effect leads to substantial errors in the calculation of the electron density and all the vector moments of the electron distribution, e.g., velocity and pressure tensor. After using a thin sheath (local Debye length small compared to spacecraft scale size) spacecraft charging model that corrects for both the acceleration and focusing of the ambient electrons, the difference between ion and electron density measurements from the Ulysses spacecraft dropped from 60% to less than 0.5% [Scime et al., 1994]. The details of the three-dimensional electron velocity space distribution measured by Ulysses also improved with the thin sheath correction. For example, unless the magnetization of the electrons is systematically

![Figure 1. Typical spacecraft potential (θ) for different regions of the near-Earth space environment [Garrett, 1981; Scime et al., 1994; Frank et al., 1993].](image1)

![Figure 2. Example of trajectory focusing effect for a positively charged spacecraft attempting to measure ambient, low energy electrons. Measured angle of incidence is θ, while true angle of incidence is θ₀ (see Eq. (1)).](image2)
destroyed during an electron gyroperiod (through some type of anisotropic collision effect in the plane perpendicular to the magnetic field), the electron distribution will be isotropic, gyrotropic, in the plane perpendicular to the magnetic field. Before the thin sheath correction (Figure 3a), the measured electron distributions were clearly non-gyrotropic. After the correction, the distributions were appeared remarkably gyrotropic (Figure 3b).

To perform the thin sheath correction, the angular distribution of the ambient electron distribution must be measured. Without measurements from a differential plasma instrument, corrections for sheath focusing effects cannot be performed. Single aperture instruments, such as simple Faraday cups, combine the electron fluxes from different angles of incidence and there is no way to reconstruct the paths through the sheath for individual low energy electrons. Corrections for the overall geometric factor can be estimated [Scime et al., 1994], but the vector moments cannot be accurately repaired.

Accurate measurements of the spacecraft potential are also needed to perform the sheath focusing correction. In many cases, the cloud of photoelectrons surrounding a positively charged spacecraft can be used. Photoelectrons emitted with kinetic energy less than the spacecraft potential are reflected back to the spacecraft and can be detected by onboard plasma instruments. Figure 4 shows a typical electron energy spectrum measured with an electrostatic analyzer aboard the positively charged Ulysses spacecraft. The data in Figure 4 are from a single sampling direction from the spinning spacecraft. As indicated in the figure, both photoelectrons and ambient electrons are detected by the analyzer. The discontinuity in the slope of the energy spectrum (the two portions of the spectrum have different temperatures) distinguishes the accelerated ambient electrons from the trapped photoelectrons and indicates the spacecraft potential. Although this technique is quite useful, when the ambient electron temperature is low, as in the outer solar system, the discontinuity in the slope of the electron spectrum vanishes. Without some other measurement of the spacecraft potential, correction for charging effects is not possible in the outer heliosphere or on negatively charged spacecraft.

It is the difficulty in correcting for space environmental effects that has lead many researchers to treat electron measurements as unreliable and instead “calibrate” them to agree with ion or plasma wave data once the spacecraft is on orbit (e.g., Frank et al. [1993]); ignoring both plasma-dependent variations in the responses of different measurement techniques and the careful ground-based calibration of the electron instrument. Since the objective of in-situ electron measurements is to investigate the details of the electron distribution, simply scaling moments of the distribution can obscure non-systematic errors due to variations in spacecraft charging effects. Improper correction of charging effects can result in misinterpretations of plasma parameter gradients. For example, density increases can appear to be density decreases because of the reduced effects of spacecraft charging [Scime et al., 1994].

Unfortunately, mitigating space environmental effects to increase measurement accuracy is not the driving factor in modern instrument design. Future space instruments must be "lighter, smaller, and cheaper." Therefore, new instrument designs must improve accuracy while reducing resource requirements.

1. SPACECRAFT MODIFICATIONS

Without modifying any plasma instruments, a dramatic reduction in the effects of spacecraft charging can be obtained by simply minimizing the charging. This can be accomplished with plasma contactors or ion guns that emit positive ions from the spacecraft. Active spacecraft potential control has been used on a number of spacecraft including CATHA [Olsen et al., 1990] Geotail [Schmidt et al., 1995] and Polar [Moore et al., 1995]. Active potential control is typically employed to allow the detection of very low energy positive ions that would be reflected away from a positively charged spacecraft [Olsen et al., 1982; Moore et al., 1995]. Recent results from an indium metal based ion emitter aboard the Geotail spacecraft indicate that the spacecraft potential can be maintained between 2 Volts and
10 Volts positive in the near-Earth space environment [Schmidt et al., 1995]. Although the Geotail potential control system has been fairly successful, there are significant spacecraft resource penalties for using an emitter or contactor for active potential control. These include: a source of ions is required (adding mass to the spacecraft and increasing power consumption); long term missions such as Voyager, Pioneer, or Ulysses exceed the expected one to two year lifetime of these devices [Schmidt et al., 1993]; contamination of the local ion and electron populations by the emitted ions; the generation of particle beam induced electromagnetic waves [Olsen et al., 1990]; and the effects of plasma contactors on other scientific instruments are not thoroughly understood. If sufficient resources are available and the scientific objectives of the mission are not compromised, active spacecraft potential control can certainly play a crucial role in reducing the adverse effects of the space environment on low energy plasma measurements. However, even when a plasma emitter is used, the residual few volt spacecraft potential can still significantly affect measurements of an ambient particle distribution with a few eV temperature, e.g., the bulk electron population in the heliosphere [Phillips et al., 1993] or the bulk ion population in the plasmasphere [Moldwin et al., 1995].

Another way to improve the measurement process without modifying the plasma instrument itself is to choose a more appropriate spacecraft geometry. Since it is the "view through the sheath" that affects the trajectories of incident particles, spacecraft charging effects can cause identical instruments in the same plasma environment but aboard spacecraft of different shapes to measure the ambient plasma distribution differently. Figure 5 shows the focusing of 9 eV electrons for two different spacecraft. Each spacecraft is charged to a potential of +7 Volts. In both cases, the electrons appear to have an energy of 16 eV when measured at the spacecraft. The electrons that appear to originate at an angle of 45° with respect to the aperture normal are strongly focused. The difference in the focusing effects for the two spacecraft (planar and spherical) is due entirely to the shape of the spacecraft. Figure 5 shows the advantages of a simple planar spacecraft geometry when it is time to reconstruct the actual ambient particle distribution. These simulations used the NASCAP computer code [Katz et al., 1981; Mandel et al., 1978] to modeling the sheath focusing effects.

Because environmental effects such as shown in Figure 5 are ignored during typical instrument calibration, it is critical to have a complete understanding of the sheath structure near a plasma instrument once it is in space. This is probably best accomplished by a combination of computational and experimental modeling. If the instrument (or a close facsimile) and the nearby spacecraft structure are placed in a carefully designed calibration facility that can simulate the appropriate space plasma environment, the focusing effects of the sheath can be quantitatively assessed and compared to computational models. The models can then be used with confidence during the actual mission and subsequent particle distribution reconstruction process.

Since it is the photoelectron emission current that defines the plasma Debye length near the spacecraft (typical photoelectron emission currents [Schmidt et al., 1995] yield electron densities of approximately $10^7$ cm$^{-3}$), it would not be difficult to construct model spacecraft that maintain the ratio of Debye length to spacecraft structural scale size. In space, the photoelectron dominated Debye length is approximately 0.2 m. Typical low density laboratory plasma Debye lengths are approximately 0.05 m. Thus a one-forth scale model of the relevant spacecraft surfaces and a miniature spacecraft potential...
plasma instrument could be used to map the focusing effects of different spacecraft shapes as well as benchmark codes such as NASCAP. Miniature plasma instruments have already been flown on rockets for ionospheric measurements [Pollock et al., 1996].

Having reviewed the effects of the plasma sheath on the ambient particle distribution, it is important to remember that, without an accurate measurement of the spacecraft potential, even a perfect in-situ calibration cannot be used to accurately reconstruct the measured electron velocity space distribution once the spacecraft is in space. Therefore, instruments intended for accurate low energy plasma measurements must be modified to provide accurate measurements of the spacecraft potential.

4. INSTRUMENT DESIGN

Accurate spacecraft potential measurements can be obtained passively or actively from a positively charged spacecraft. The passive approach is to measure the electron distribution with closely spaced energy steps around the spacecraft potential so that photo and ambient electron distributions can be cleanly separated. Regardless of the type of plasma instrument, electrostatic analyzer (e.g., Bame et al., 1992) or Faraday cup (e.g., Ogilvie et al., 1995), the energy steps through which a plasma instrument is scanned are usually logarithmically spaced. This practice permits efficient coverage of a broad energy range. Unfortunately, it also results in relatively coarse coverage in the 0.1 eV to 20 eV range. As shown in Figure 4, finely spaced energy steps are needed to accurately determine the spacecraft potential. The increased telemetry requirements that would result from additional measurement steps could be eliminated by onboard spacecraft potential calculations. With sufficiently detailed information aboard the spacecraft, it should be possible to only transmit the value of the spacecraft potential and data from the energy steps above it. This would actually reduce the telemetry needs of the final instrument. Such an instrument, the PEACE instrument, was to be flown on the ill-fated Cluster mission [Johnstone et al., 1988].

The active approach is to directly measure the spacecraft potential with an electron emitter. Electrons expelled by an electron emitter aboard a positively charged spacecraft will be reflected back to the spacecraft until the emission energy exceeds the spacecraft potential. By sweeping the energy of the emitted electron beam until the signal from an appropriately positioned detector vanishes, the spacecraft potential can be determined accurately and quickly (see Figure 6). The minuscule emission currents needed for such a measurement would not affect the spacecraft potential. Telemetry requirements of the instrument could be reduced by using the spacecraft potential measurements in the analyzer power supply control circuitry and the data processing system to avoid transmitting, or not even measure, energy steps below the spacecraft potential. The additional mass, power, and volume resources used by the emitter must be weighed against the improved scientific return of a plasma instrument for which the low energy particle distributions can be accurately reconstructed. Inclusion of the emitter and detector assembly will increase the mass of the electron analyzer. The best placement for an emitter could be determined by a combination of simulation and laboratory experimentation.

5. DISCUSSION

Analysis of low energy electron data from the Ulysses spacecraft indicates that the ambient electron distribution can be accurately reconstructed with an accurate measurement of the spacecraft potential and a thorough understanding of the spatial structure of the sheath in front of the instrument. This information can be integrated with data processing and instrument control systems aboard spacecraft to reduce telemetry requirements and increase measurement speed of future instruments. Control of the spacecraft potential with ion guns or plasma contactors can play an important role in minimizing space environmental effects, but accurate measurements of low energy plasma populations still require accurate spacecraft potential measurements. The spacecraft potential can be determined...
passively, as is typically done, or actively with the use of an electron emitter aboard the spacecraft. Although the emitter increases the mass and weight of a prospective instrument, the improved scientific reliability of the data may justify employing less capable instruments to stay within mass and power requirements. Finally, laboratory testing of instruments in a plasma filled chamber as a function of spacecraft potential and ambient plasma density are needed to investigate the coupling of ambient plasma parameters and sheath focusing effects while simultaneously benchmarking modeling codes.

The space environment plays an important role in low energy plasma measurements and the need for more detailed distribution measurements will continue to motivate the development of new approaches to minimize space environmental effects. "Really measuring low energy electron distributions in space" requires careful consideration of the impact of spacecraft and instrument designs on the eventual distribution reconstruction process.

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REFERENCES


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