A REVIEW OF SPACECRAFT EFFECTS ON PLASMA MEASUREMENTS

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Abstract

The spacecraft induced environment includes, secondary particles generated by primary radiation, outgassing material, particles emitted by thrusters or emitters, spacecraft generated electric and magnetic fields. All of these components may severely affect the behaviour of sensors and especially scientific instruments. In this presentation various effects are reviewed and methods to cope with, or to mitigate, them are discussed.

Introduction

This paper deals with unwanted effects on space plasma measurements related to the perturbation that spacecraft induces on the environment or directly on sensor themselves. These effects could be organised in several categories as follows:

- spacecraft system anomaly (with various possible origins e.g., human, thermal, radiation...).
- electromagnetic or magnetic perturbations;
- electrostatic perturbations from spacecraft charged surfaces;
- contamination by neutral or secondary particles originating from the spacecraft;
- space charge effects from spacecraft electrostatic sheath.

Spacecraft anomalies may obviously affect the measurements via interrupting them or limiting the spacecraft resources available for them. Sensors themselves are subject to anomalies or degradation due to radiation, thermal and human error problems. The rest of the effects mentioned above are due to spacecraft induced environments such as secondary particles, generated by primary radiation, outgassed material, particles emitted by thrusters or emitters, spacecraft generated electric and magnetic fields. A list of the induced environment components is given in Table 1 below together with their effects on particle detectors.

This review is focused on three of the main effects on plasma instruments: contamination by spacecraft generated charged particles, surface charge effects and space charge effects on particle detection. A discussion of other effects can be found in previous reviews including the ones from Berthelier [1998], Pedersen et al. [1998], Hasting [1995], Laframboise and Sonmor [1993], Garret [1981] and Whipple [1981].

Table 1. Spacecraft induced environments and main effects on space systems.

Type and energy range when applicable	Main effect
Secondary charged particles (eV to MeV depending on primary radiation energy)	Background and false signal Space charge interference
Charged particles from thrusters and emitters	Space charge Secondary particles
Outgassed, sputtered and emitted neutral material	Deposit on surfaces and affect their properties
Electric and magnetic field	Affect field sensors and electronic Affect particle trajectories

Detector Contamination by Spacecraft Generated Garticles

Nearly all kind of particles ion, electron, atomic, molecular or photon can be generated by spacecraft surfaces artificially, spontaneously or under external influences. Spacecraft generated electron and ion can perturb sensors creating background and artefacts. Such effects are discussed in this section.

Photo-electrons are generated by primary UV and X photons impinging spacecraft material. The photo-electron yield varies very much with surface material (cf [Grard 1973 and Grard et al. 1983]) and the resulting flux leaving spacecraft surface depends of the electrostatic potential environment but saturation current level is typically of the order of a few tens of micro-Ampere per square meter. In addition, variation with time spent in space has been observed. This is explained by the contamination of surfaces by outgassed material or by atmospheric constituents.

There are numerous reports of photo-electron contamination of particle sensors [e.g., Wrenn and Heikkila, 1974, Szita et al., 2001] including Langmuir probes [Cauffman and Maynard, 1974; Pedersen et al., 1984, 1998; Hilgers et al., 1992, Hilgers 1995]. Photo-electrons generated inside the detectors can be minimising via the control of the amount of exposed internal surface to sunlight. Photo-electrons generated elsewhere over the spacecraft are much more difficult to avoid since they can travel a rather long distance away from the surface before being turned back to it.

An example is shown on Figure 1 on the electron energy spectrograms as a function of time as measured by PEACE electron detector onboard Cluster [Torkar et al., 2001]. The spacecraft generated photo-electrons appear as a low energy population with a well defined cut-off at the spacecraft potential (solid black line).

It must be noted that the photo-electron trajectories may be strongly influenced by the spacecraft generated electrostatic potential distribution (cf next section) and as result the photoelectron cloud can expand in the whole space around the spacecraft up to very long distances. Example of the photo-electron cloud expansion around a positively charged spacecraft is shown on Figure 2. The simulations were performed using the PicUp3D charging code [Forest et al., 2001; Thiébault et al., 2003a]. It can be seen that although the photo-emission takes place only on half of the cylindrical surface of the spacecraft, the photo-electrons easily propagate in all directions (including the anti-sunward one) and the isodensity contours nearly follow the spacecraft surface iso-distance beyond a few spacecraft radii.

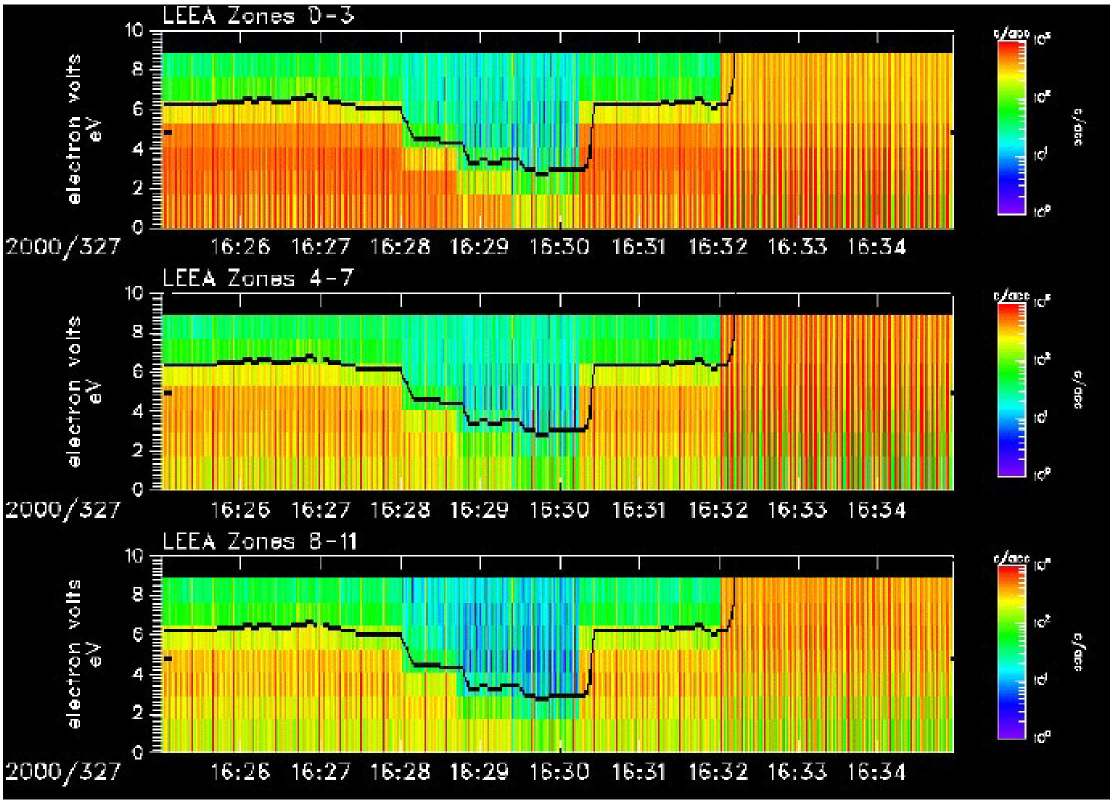

Figure 1. Electron energy spectrograms as a function of time as measured by PEACE electron detector on Cluster [Torkar et al.2001].

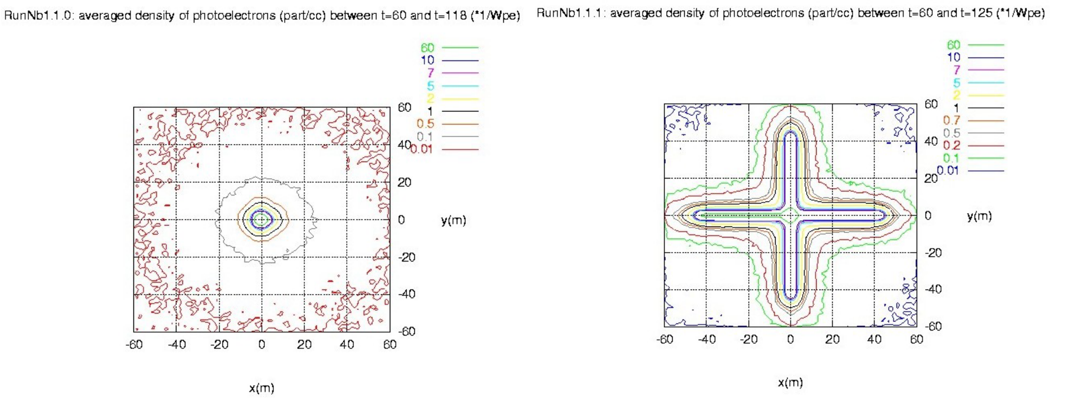

Figure 2. Photo-electron density contours in a plan perpendicular to a cylinder emitting photo-electron from its surface toward negative values of x as simulated with the 3D PIC code PicUp3D without boom antennas (left panel) and without (right panel).

Electrons are also emitted by spacecraft surface under irradiation by high energy particles (ions and electrons). One can distinguish the backscattered electrons from the secondary electrons. The former ones are electrons reflected by surfaces with nearly the same energy as the primary electrons and in specular direction. The secondary electrons are generated at much lower energy (typically a few eV) than the primary ones and in a broader range of directions. Secondary electron effects and behaviour are similar than for the photo-electrons except that currents are usually smaller and the emission occurs on nearly all external surfaces because the high energy charged particle environment is far more isotropic than the photon environment. The number of secondary electrons emitted per incoming particles (yield) is a function of the incident particle energy. The yield can vary from nearly zero for incident particle with low energy (below 10 eV) or very high energy (above a few keV) to near one (and sometimes more than unity) around a few hundred eVs.

Since secondary electron and photo-emitted electron yields strongly depend of the surface material it is in principle possible to select material to be used according to such a property. However, it may be conflicting with other material requirements (e.g, conductivity and thermal properties). In addition, the yield may change with time spent in space due to material degradation and contamination.

Ions generated on spacecraft have been reported in data from various space missions including the Application Technology Spacecraft ATS-5 and ATS 6, the US Air force P78-2 (SCATHA) spacecraft and the magnetospheric science spacecraft ISEE 1 [Deforest, 1973; Olsen et al., 1981; Olsen and Norwood, 1991; Olsen and Whipple, 1988]. All these papers report observations when the spacecraft ground potential was very negative (typically more than 100 V) compared to the ambient plasma and the spacecraft generated ions were identified by a secondary peak at an energy typically lower than the primary accelerated ion peak through the potential drop.

Two mechanisms have been proposed to explain these ion populations. The first one invokes sputtering by energetic ions and the second one outgassing. Sputtered ions can be generated by high energy ions (pre-existing or from low energy ion population accelerated by negatively charged surfaces). Olsen and Norwood [1991] found that 10 to 100 keV Oxygen ions on glass could produce a yield of 0.5 to 1. particle per incident ions and roughly 2-4% of this yield is ionised. Outgassed material may be ionised by UV and X radiations. In principle, this type of spacecraft generated ions may be generated also in non high level charging conditions but should decrease with mission time.

Electric thrusters and ion and electron guns are designed to emit a significant amount of charged particles. Usually, they are emitted with a high enough energy and in an appropriate direction such that they are not turned back to particle detectors (unless especially designed this way). It must be noted, however, that certain electric thrusters devices also emit a significant amount of cold neutral gas which interact with the energetic ions via charge exchange and can be further scattered back to the spacecraft. A numerical model of these charge exchange ions around a simplified model of SMART 1 spacecraft predicts that the plasma cloud density outside of the main plume can be of the order of 10^{11} m^{-3} [Tajmar, 2001]. An example of such a numerical simulation is shown in Figure 3 for a spacecraft at the same potential as the plasma.

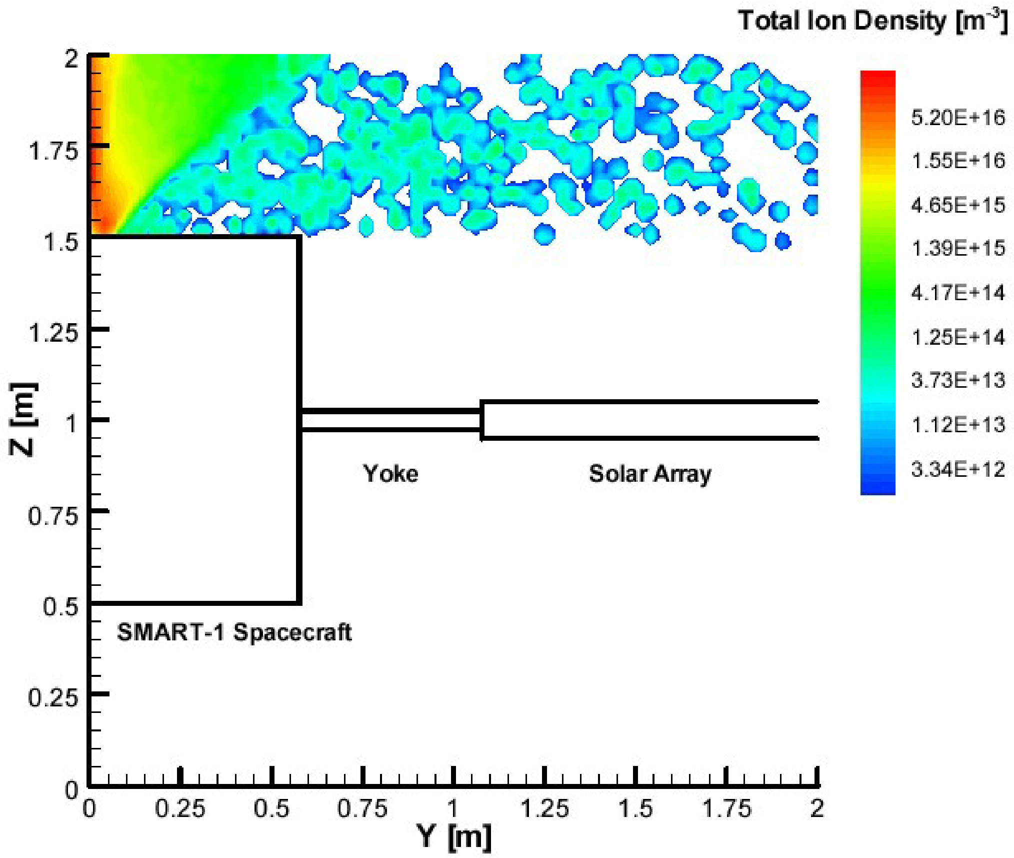

Figure 3. PIC simulation of SMART-1 ion plume density showing charge exchange ions backscattered toward the spacecraft [from Tajmar, 2001].

Surface Charge Effects

Electric charges (electrons and ions) of the plasma are free to move and may eventually get trapped on material surface. They cannot leave a surface as easily as in the atmospheric environment because the vacuum is far less conductive regarding this process. Also, secondary ion and electron emission processes (including photo-emission) contribute to change surface charges. The accumulation of charge (positive or negative) leads to the creation of an electric field distribution that eventually will prevent further charge accumulation by repelling the species of a given polarity and attracting the species of opposite polarity (cf sketch Figure 4). Indeed, the spacecraft is like a complicated electrical circuit with both active and passive elements that is non-linearly coupled to electrical current from space via its whole surface. Often, but not always, this system reaches an equilibrium corresponding to an overall current balance.

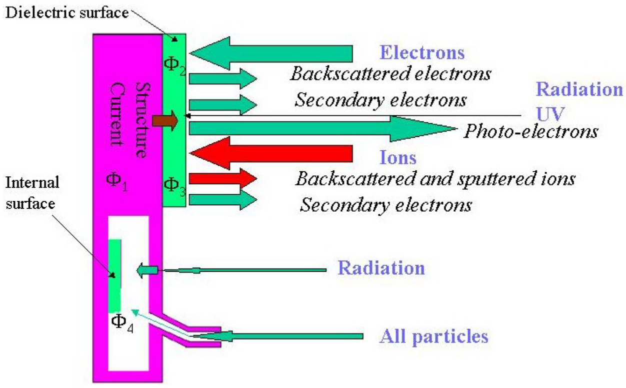

Figure 4. Sketch of the various electron and ion currents leading to charge deposition on a spacecraft surface element.

Because of the higher mobility of the electrons compared to the ions, surfaces in space plasma tend to charge negatively when the photo-electron current is negligible, i.e., in eclipse or in high density (ionospheric plasma). An equilibrium state would be mainly achieved by current balance of incoming ions and electrons, with possibly secondary and backscattered electrons when a significant amount of primary particles have energy around a few 100 eV (i.e., near maximum of the secondary electron yield; cf section 2). When the energy of the electrons is typically above a few keV (e.g., in the aurora or in storm and substorm accelerated particle environments) the secondary electron emission process is less efficient in mitigating the primary charging current and surfaces may reach very high negative potential level (of the order of 1 kV) in eclipse [Deforest, 1972; Garret and Rubin, 1978; Prokopenko and Laframboise, 1980; Olsen et al., 1983; Gussenhoven et al. , 1985; Wrenn and Johnstone, 19986; Yeh and Gussenhoven, 1987; Lai, 1991; Wahlund et al., 1999]. Spacecraft potential may severely affect spacecraft measurements [Olsen, 1982, Olsen et al. 1983] and in extreme case may also be a hazard to spacecraft system because of related electrostatic discharges [Katz and Mandel, 1982; Anderson and Koons, 1996].

On Figure 5 the time series of several plasma parameters are shown around a period of negative electrostatic charging on the Freja spacecraft [Wahlund et al. 1999]. Measurements of three different ion species are shown on the first three panels whereas electron measurements are shown on the two last panels. The energy range is shown on the vertical axis and the color level indicate the flux magnitude. The charging event is identified by an increase of the ion energy for all three ion species and all directions. This is because the ions are suddenly accelerated through the difference of potential toward the spacecraft and caught with the corresponding kinetic energy by the detector. One can see that such an event occur during a period where high energy electrons are observed. This type of electrons population is typically observed during auroral arc crossings at low altitudes (~800 to 10,000 km). Electron populations of similar energy are observed at higher altitudes on lower latitudes where high level negative charging may also occur, usually when the spacecraft is in eclipse.

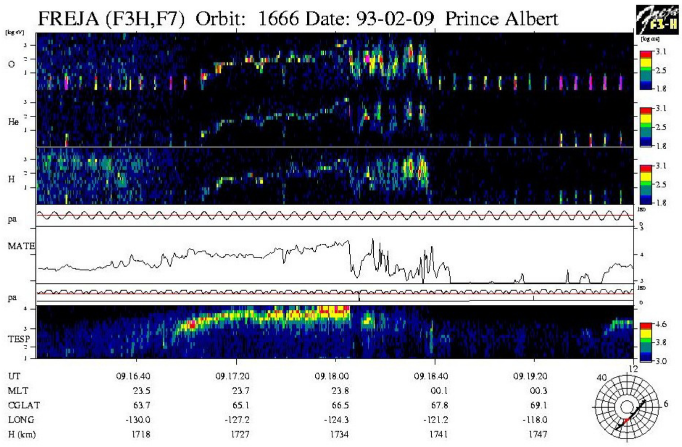

Figure 5. Time series plot of the particle measurement (from Wahlund et al., 1999).

It can be noted, however, that there have been a few reports of high level negative charging in sunlight {Mullen et al., 1986, Olsen and Whipple, 1988]. The event examined by Olsen and Whipple [1988] has been attributed to differential charging due to a degradation of the conductive coating of the spacecraft. As a result non-sunlit surfaces may have charged negatively and created negative potential barrier blocking photo-electron emission on the sunlit surfaces which in turn tend to charge negatively as well.

In general, sunlit surfaces, especially in the low density magnetosphere and the solar wind, are usually driven positively by photo-electron emission and so is the whole surface of a well conductive spacecraft. The positive voltage is about a few volts in the solar wind, the magnetosheath and the plasmasheet and a few tens of volts in very depleted magnetospheric regions (the so called magnetospheric lobes).

Even moderate positive potentials can strongly affect the accuracy of the measurements and re-calibration may require very sophisticated post-processing, e.g., relying on 3D modelling of the spacecraft potential and the electrostatic sheath. Several examples are given in the following.

An obvious effect is the repelling of ions with energy too low with respect to the required electrostatic potential to reach the detector. As a consequence the total number of density will be difficult to evaluate [Olsen, 1982; Olsen et al., 1986].

To cope with such a problem, it is sometimes possible to polarize negatively the detector. In this case however the trajectory of the lower energy ions is strongly perturbed and information is practically lost regarding their original direction of arrival which is a critical information for reconstructing the angular velocity distribution [Hamelin et al., 2002]. An illustration of the problem is given Figure 6 taken from Hamelin et al. [2003] where ion trajectory are computed for a spacecraft potential at +12 V and a detector at –4 V. The ion trajectories are strongly influenced by the potential on spacecraft surface and made even more complicated due to the complex geometry of the surface. Similar studies have been performed in order to simulate the response of the ion detector ROSINA onboard Rosetta spacecraft [Roussel and Berthelier, 2001; Nyffenegger et al., 2001]. One interesting aspect of this series of studies is that it includes comparison between numerical simulations and ground testing in plasma chambers [Roussel, 1998; Berthelier and Roussel, 2001].

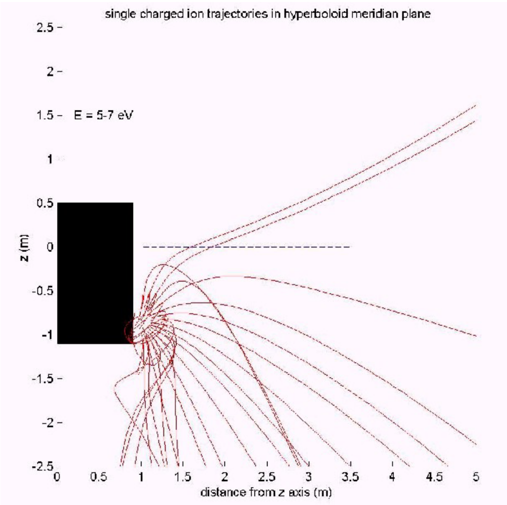

Figure 6. Projection of 3D ion trajectories on the A16 analyser plane for Vs = 12 V and Vh = 4 V [Hamelin et al., 2001].

Conversely, attracted species may experience a focusing effects. This effects on electron measurements has been investigated by a few authors [Garrett, 1981; Sing and Baugher, 1981; Sojka et al., 1984; Comfort et al., 1982]. Recently, Scime et al. [1994] have shown that taking into account electron trajectory bending by the spacecraft generated electrostatic field may considerably improve electron measurements.

Finally, it must be noted that if the spacecraft geometry is simple and its surface conductive enough the potential current relation of the spacecraft can be derived (using e.g., [Laframboise, 1966]) and the spacecraft potential can be used as a plasma diagnosis techniques [cf. e.g., Escoubet et al., 1997].

Space Charge Effects

In the cold ionospheric plasma or high speed streaming solar wind the relative velocity between the spacecraft and the plasma is such that the flow around the spacecraft is meso-sonic which means with relative speed higher than the thermal ion velocity but lower than the electron thermal velocity. It results an ion depleted region in the wake behind the spacecraft. The properties of spacecraft wakes on low Earth orbits have been recently reviewed by Hasting [1995]. In addition, to the plasma rarefaction effect which makes surfaces in the wake more prone to charging, there is a region with an excess of negative charge with more or less complicated structure [e.g., Parker, 1978, Singh et al., 1997]. The related electrostatic potential distribution may also affect the measurements of particles.

Some wake effects are intrinsically related to the Earth geomagnetic field. For instance, it has been noted that polar cap flow of cold ionospheric plasma may create a magnetic field aligned wake behind the spacecraft and that such a wake would be increased by the positive spacecraft potential usually observed in such regions. The resulting space charge is suspected to induce spurious electric field with double probe system measurements [Pedersen et al., 1984; Engwall et al., 2003]. Similarly, Langmuir probe current decreases observed when the probe and the spacecraft are magnetically connected have been interpreted as a field aligned magnetic wake of the spacecraft hub [Hilgers and Holback, 1993; Hilgers, 1995].

As already mentioned in section 2 above, several spacecraft are equipped with active plasma or particle emitter devices which may be active scientific experiments or systems used for propulsion or surface charge mitigation. The injected plasma is usually of much higher density compared to the ambient plasma and can significantly influence the electrostatic potential around the spacecraft even when there is no net space charge injected. In the case of the POLAR spacecraft, Singh et al. [2001] have shown on the basis of numerical simulations that while the use of a plasma contactor efficiently reduces the positive potential of the spacecraft the ion measurements were nevertheless significantly affected by the electric field generated by the expanding plasma.

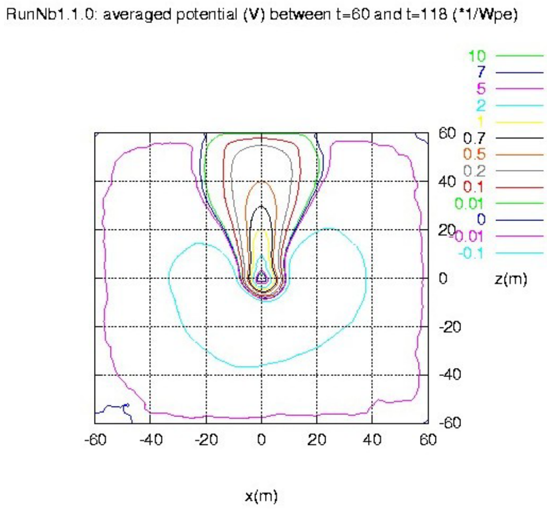

Figure 7. Electric potential contours around a spacecraft at 7 V in a plasma with a density of 1 cm^{-3} and a temperature of 10 eV.

An alternative system also used for charged mitigation but relying on ion emitter has been discussed by Torkar et al. [2001]. The space charge influence of the resulting ion beam in absence of neutraliser has been investigated via PIC plasma simulation method by Thiébault et al. [2003a]. An example of simulated electric potential contours around the ion plume when the spacecraft is at 7 V in a plasma with a density of 1 cm^{-3} and a temperature of 10 eV is shown in Figure 7. The effect of the ion beam space charge is clearly seen along the Z axis (perpendicular to the sun and to the spine plane). However, it can be seen that it is very efficiently shielded by the ambient plasma electrons and the photoelectrons in direction perpendicular to the Z axis. The positive potential typically vanishes within a few meters. A negative potential barrier appears instead which is created by the photo-electron space charge.

The existence of negative potential barriers around spacecraft generated by secondary or photo electrons induced space charge has been speculated for many years [cf e.g Whipple 1976 and reference therein]. Such barriers may affect the current balance on spacecraft surfaces especially via their limiting effect on secondary electron emission and/or the access of particles to detectors. Evidence in space are marginally conclusive [Whipple, 1976; Zhao et al., 1996] but some numerical simulations tend to confirm their existence [Schroeder, 1973; Sasot et al. 2003, Thiébault et al., 2003a, 2003b]. An example of simulation results from Thiébault et al. [2003b] is shown in Figure 7 in a 100 cm^{-3} density and 1 eV temperature plasma environment around a spherical body with isotropic secondary electron emission for three values of the potentials; -1 V, 0 V and +1 V suggesting that potential barriers could be observed over a relatively broad range of potential and can be of the order of the secondary electron emission and ambient plasma thermal energy.

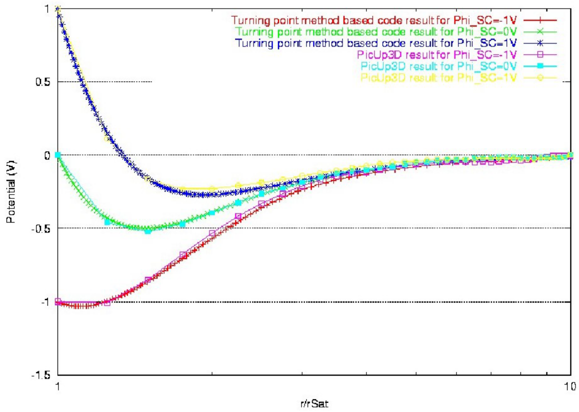

Figure 8. Simulation of the potential profile in a 100 cm^{-3} density and 1 eV temperature plasma environment around a spherical body with isotropic secondary electron emission for three values of the potentials; -1 V, 0 V and +1 V.

Conclusion

There are several spacecraft effects which may limit significantly the scientific return of plasma instruments. Some mitigation techniques exist. For instance positive surface potential can be mitigated by ion emission or plasma contactors, improvement can be obtained by mounting detectors on booms and/or making spacecraft geometry as simple as possible, spacecraft surface materials may be chosen according to their specific properties. However, some trade-off analyses are often necessary due to the possible impact the mitigation techniques may have on cost and/or the performance of other systems. Modelling is still required for optimising the set-up and/or retrieving a 'clean' signal. To this end numerical plasma simulation, laboratory testing and detailed space-based observation for validation would be useful. Currently, the analyses are mainly limited by the lack of information on material properties in space, and of space-based observations in general. Also numerical tools are in general not accurate enough to cope with the thin details required for simulating detector signals. Various recent initiatives are trying to address these issues, especially in the framework of ISSI working group on plasma instrument calibration, SPINE activities [Forest et al., 2001, Roussel et al., 2003] and ECSS standard on spacecraft charging [Rodgers and Hilgers, 2003].

Acknowledgments

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