ACTIVE SPACECRAFT POTENTIAL CONTROL: RESULTS FROM THE DOUBLE STAR PROJECT

Satellite On Orbit Investigations

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Abstract

Ion emitter instruments ASPOC (Active Spacecraft Potential Control) have been used successfully in several magnetospheric missions including the ESA Cluster Project. An improved version has been developed for the equatorial spacecraft of the Chinese-European Double Star mission (TC-1) launched in December 2003. The modifications include a new design of the ion emitter modules. As a result, higher currents than in previous missions can be achieved. The main objective of the investigation lies in a reduction of positive spacecraft potential in order to minimize the perturbations to the plasma measurements on board, in particular to the plasma electron instrument PEACE. These data show an almost complete suppression of photo-electrons when ASPOC is emitting at 30 to 50 μA beam current. The angular distribution of the electrons in the presence of the ion beam is investigated in detail. The measurement of ambient electron distributions is highly improved.

1. Introduction

1.1 The mission

Double Star is the first mission launched by China to explore the Earth’s magnetosphere and to study the effects of the Sun on the Earth's environment. Double Star involves two satellites designed, developed, launched, and operated by the Chinese National Space Administration. The program is jointly conducted with the European Space Agency. A key aspect of Europe's participation in the Double Star project is the provision of eight instruments, seven of which are identical to those simultaneously flying on the four Cluster spacecraft. A further eight experiments are provided by Chinese institutes.

The first of the two spacecraft (TC-1), the 'equatorial' one, was launched on 29 December 2003 at 19:06 UT. The orbit is elliptical (580 x 78952 km, corresponding to a geocentric apogee height of 13.4 Earth radii) and is inclined at 28.2 degrees to the equator. Not only the payload, but also the spacecraft bears some similarities with Cluster, albeit the overall dimensions are smaller. It has cylindrical shape with 1.4 m height and 2.1 m diameter and is spin-stabilized at 15 rpm. The height of the body-mounted solar array is 740 mm. The configuration of the spacecraft is with two 2.5 m experimental rigid booms and two axial telecommunication antenna booms. The projected area of TC-1, which determines the photo-electron current, is 22% smaller than for Cluster, neglecting ≈1 m² from the surface of the wire booms on the Cluster spacecraft, which are absent on TC-1. All outer surfaces of the spacecraft are electrically conductive.
1.2 Scientific Objectives

This paper presents preliminary data obtained on board of TC-1 by the electron analyzer PEACE in conjunction with operations of the active spacecraft potential control instrument (ASPOC), which has the main purpose of maintaining a low spacecraft potential in order to improve the electron measurements at low energy. The near-equatorial region of the Earth's magnetosphere within ≈13 Earth Radii - which is the part covered by the TC-1 orbit - is populated with plasma of different type, at apogee on the dayside, the spacecraft is rather likely located in the magnetosheath or even in the solar wind, whereas on the nightside large parts of the orbit will lead into the tail lobe or the tail plasma sheet. As a result of the different plasma densities and temperatures along the orbit and throughout all seasons, the electric potential of the spacecraft will vary over a considerable range. Laakso (2002) has statistically studied the potential of the NASA Polar spacecraft, and found for the equatorial region that the average potential in the tail reaches ≈20 V. Obviously, with larger plasma densities on the dayside and especially in the magnetosheath the average potential is between 5 and 10 V.

It is well known that low-energy particle measurements on board a charged spacecraft suffer from the modification of the particle trajectories and energies in the sheath around the spacecraft. In addition, the bulk of the photo-electrons at a few eV energy will return to the spacecraft and some will inevitably enter into the detectors, where micro-channel plates suffer from the resulting high count rates. The presence of large quantities of photo-electrons makes the interpretation of the data becomes even more difficult.

The TC-1 spacecraft carries the instrument ASPOC, which produces a beam of ions at energies of several keV. Its current acts to reduce the equilibrium potential of the spacecraft when the ambient plasma is too tenuous to support a substantial current to compensate the photo-electron current. Thereby, the potential is reduced to a few volts positive, and at the same time the amplitude of variations of the potential caused by changes in the plasma environment is minimized. According to the maximum total photo-electron flux generated at the surface of the spacecraft, the required ion emission current lies in the range between 10 μA and 50 μA. This technique has been applied earlier and very successfully in the missions Geotail (Schmidt et al., 1995), Equator-S (Torkar et al., 1999) and Cluster (Riedler et al., 1997, Torkar et al., 2001).

2. Instrumentation

2.1 The electron analyzer

A key element of the TC-1 payload is the electron analyzer PEACE, which has the task of measuring the electron velocity distribution function at the satellite in three dimensions with good time, energy, and angular resolution for electron energies up to ≈25 keV. The design is based on the Cluster PEACE instrument (Szta et al., 2001). The sensor is built to the "top hat" design: with hemispherical electrostatic energy analyzers and a semi-annular micro-channel plate with a position-sensitive readout as the detector. Figure 1 shows the data processing unit and the sensor.

Figure 1. PEACE data processing unit and sensor for Double Star TC-1
In the most commonly used operating mode, measurements are taken during 32 consecutive parts of the spin (later on referred to as azimuthal sectors). During each part, the data are acquired simultaneously from 12 polar angle bins (anodes), and over 30 separate energy intervals. Thus the full $4\pi$ solid angular coverage is composed of a grid of 12 polar bins by 32 azimuthal bins; each bin is $15^\circ$ in polar by $11.25^\circ$ in azimuth. The measurements presented here cover the range from $\approx 1$ eV to 1 keV. The energy steps are roughly linearly spaced below $\approx 10$ eV, and logarithmically above. The energy range that is covered in a single spin is a subset of the full energy range the instrument can measure. In the time intervals presented here, a scheme which alternates between energy ranges has been used. In this case a complete 3-D distribution over the full energy range is obtained every 8 seconds.

Figure 2 shows the orientation of the sensor on the spacecraft. Anode number 0 receives electrons entering the sensor from "below", i.e., moving nearly parallel to the northward pointing spin axis. Anodes 5 and 6 point almost radially outwards, and anode number 11 receives electrons from "above" (i.e., North). Most of the circumference of the spacecraft is covered by indium oxide coated, and therefore electrically conductive, solar arrays.

![Figure 2. Sketch of the spacecraft configuration with polar zones of PEACE; the ASPOC ion beam is indicated at the bottom panel of the spacecraft.](image1)

2.2 The ion emitter instrument

![Figure 3. Schematic of the ion emitter.](image2)

The ion emitter instrument ASPOC for TC-1 is based on the design for the instruments for the Cluster mission (Torkar et al., 2001). In brief, it utilizes 4 ion emitters on the principle of solid needle-type Liquid Metal Ion Sources with Indium as charge material. A needle with a $\mu$m-scale tip radius is wetted by a film of liquid Indium. When a potential between 4 and 9 kV is applied between the needle and an extractor electrode, an ion beam is formed. Figure 3 shows the schematic of an emitter with the Indium reservoir and the small heater element which keeps the Indium liquid together with the electrical supplies. The main differences to the previous design consist of completely separated ion
optics for each emitter and the absence of a focusing system, which leads to a wider beam of about $\pm 30^\circ$ width (FWHM). The emitters on TC-1 are operated at constant emission currents between 10 and 50 $\mu$A.

3. Results from three case studies

3.1 Case 1

Figure 4 shows the orbits of TC-1 in March 2004. The apogees are located in the magnetosheath under nominal conditions. The first case describes a turn-on of the ASPOC ion beam on 6 March 2004 at 04:56 UT amidst the outward leg of the orbit, i.e., outside the radiation belts but still inside the magnetopause. The magnetic field magnitude was $\approx 400$ nT.

![Image of orbit diagram]

**Figure 4.** Double Star TC-1 orbits in March 2004, in GSE co-ordinates (courtesy NASA Satellite Situation Center SCCWeb, http://sscweb.gsfc.nasa.gov)

Figure 5 displays the electron energy flux measured on 6 March 2004 at 04:56 UT before and after turn-on of the ASPOC ion beam with a current of 30 $\mu$A. The green, blue, and red lines show anodes 11, 5, and 0, respectively. The thin lines refer to the situation without ion beam. The energy range below 8 eV is dominated by photo-electrons. The spectrum at higher energies is almost featureless. After turn-on of the ion beam, the photo-electron signatures are reduced by up to one order of magnitude in flux. Whereas the original angular distribution was almost isotropic in polar angle (albeit with some enhancement of fluxes parallel to the spacecraft surface), the modified distribution is more intense in anode 11 than in the two other directions shown. By controlling the spacecraft potential with the ion beam which is emitted downwards from the spacecraft, photo-electrons arriving from above the sensor appear to be the least reduced. Between 8 eV and a few tens of eV (i.e., above the energy where we can assume that photo-electrons dominate) we see a minor reduction of the flux when the ion beam is active.

We can assume that the ion beam has reduced the spacecraft potential. As there are no independent direct measurements of the potential, we have to derive it from features in the electron data. In order to analyze the case quantitatively, we plot the same measurement as distribution function in phase space (Fig. 5). A shift of the potential would a) decrease the cut-off energy for photo-electron detection (photo-electrons with higher energy would not return to the spacecraft), and b) reduce the energy of ambient electrons arriving at the sensor by the equivalent amount. One can indeed verify the latter effect in Fig. 7. A constant shift of energy by 2 eV occurs for PSD between $10^{14}$ and $10^{13}$ m$^{-6}$ s$^{-3}$ (belonging to initial energies $>8$ eV), being indicative of a change of the spacecraft potential by 2 V. The shift of the cut-off energy which we expect to see for the photo-electron regime is probably smeared out by anisotropies in the original distribution. These anisotropies appear very clearly in the dependence of the energy flux on azimuth and polar angle shown in Fig. 8.
Figure 5. Electron energy flux measured on 6 March 2004 at 04:56 UT before and after turn-on of the ASPOC ion beam with a current of 30 μA (see text).

Figure 6. Data from Fig. 5 displayed as phase space density.

Figure 7. Energy shift calculated from Fig. 6
Figure 8. Electron energy flux as a function of viewing angle at four energy steps before the turn-on of the ion beam.

Figure 8 shows four panels with electron energy flux at constant energy as a function of viewing angle in sensor co-ordinates, before the ion beam is turned on. The energies are 5.3, 11, 59, and 137.8 eV, respectively. Azimuth angle is given in 32 steps of 22.5° each, whereby step 7 corresponds to a look angle towards the Sun, step 15 looks towards $+Y_{	ext{CODE}}$, and step 23 looks anti-sunward. The pointing of the 12 anodes ranges from nearly southward (anode 0) to nearly northward (11).

Figure 9. Electron energy flux as a function of viewing angle at four energy steps after the turn-on of the ion beam.

Noteworthy features include:

- higher fluxes in anodes 0 and 11 (this is expected, as the photo-electron contamination should be more intense at look angles tangential to the surface)
- flux in anode 11 is higher than in anode 0 (expected, as the sensor is located below the central plane of the spacecraft and anode 11 has a larger spacecraft surface area in front of it)
- a flux enhancement in sectors looking towards the Sun, in particular at the two lowest energies
- a magnetic field-aligned population at E=11 eV and E=59 eV (azimuth 15 & anode 4 and azimuth 31 & anode 7)
• trapped electrons at 59 eV and 138 eV
• an anti-sunward feature at 11 eV (azimuth 23 & anode 6)

Let us compare this with the situation when the 30 μA-ion beam is turned on (Fig. 9). We see the following changes:
• fluxes at 5 eV are strongly reduced in all directions except those looking into the Sun (note the different ranges of the color scales)
• the anti-sunward feature which had been present at 11 eV now becomes visible at 5 eV, too.

There are no visible effects at energies above 11 eV, i.e., the measurements do not suffer from any distortion of the distributions by the ion beam. The changes due to the lower spacecraft potential remain as the only visible effects.

The description of case 1 ends by showing in Fig. 10 the energy flux spectra taken over azimuth angles excluding the sunward sector, in comparison to the azimuth-averaged spectra from Fig. 5. The striking features are
• The photo-electron population is almost completely removed when the ion beam is active. This may indicate that the reduction of the spacecraft potential by the beam may indeed be stronger than the azimuth-averaged data had suggested.
• The resulting distribution in polar angle is almost isotropic. One may speculate that the photo-electrons measured in the case without ion beam were responsible for the anisotropy. With the ion beam turned on, all measured electrons may be ambient.

![Figure 9. Electron energy flux as a function of viewing angle at four energy steps after the turn-on of the ion beam.](image)

3.2 Case 2

On 14 April 2004 at 08:30 UT the ion beam was switched between 0, 16, and 30 μA within a few minutes. The spacecraft was close to the magnetosheath, but still inside the magnetopause (B<30 mT). The plasma density was lower than in case 1, which can be seen by the wider energy band in the distribution function (Fig. 10) which is populated by photo-electrons. Without potential control this band extends to 16 eV. An ion beam with 16 μA current shifts this threshold to 3 eV, presumably associated with a likewise reduction of the spacecraft potential. As in case 1, the data from the hemisphere with look angles away from the Sun shown here reproduce the spacecraft potential variations very clearly.

Figure 11 shows the further reduction of the spacecraft potential by increasing the beam current to 30 μA. Whereas the previous turn-on of the ion beam with 16 μA caused a spacecraft potential reduction by ≈13 V, this
subsequent increase of the beam current by 14 μA results only in a small further drop by ≈1 V. This confirms the fact that almost exponentially increasing beam currents are needed to reduce the potential to values very close to zero. However, a reduction to a few volts positive can be achieved already with beam currents of 10 to 20 μA (for a spacecraft of the size of TC-1).

Figure 10. Phase space density measured on 14 April 2004 at ≈08:30 UT without and with an ion beam current of 16 μA (see text).

Figure 11. Phase space density measured on 14 April 2004 at ≈08:30 UT with ion beam currents of 16 μA (thin lines) and 30 μA (bold lines).
3.3 Case 3

Case 3 aims at a deeper look into effects of even higher beam currents (up to 50 \( \mu \text{A} \)). The measurements were taken on 4 April 2004 between 04 and 05 UT. The spacecraft was again located in the magnetosheath region, in this case already temporarily entering the magnetosheath with higher plasma densities. Figure 12 gives an overview.

![Figure 12. Top panel: Energy-time spectrogram of energy flux measured on 4 April 2004, at 04-05 UT; bottom panel: red curve shows ASPOC beam current.](image)

Figure 13. Energy flux spectra (top panels) taken for two selected time intervals (bottom panels). Left side: at increased ambient plasma density, right side: for low density, and comparing cases without ion beam and with 10 \( \mu \text{A} \) beam.

Figure 13 demonstrates that a 10 \( \mu \text{A} \) ion beam in a low plasma density environment leads to a similar spacecraft potential as the uncontrolled value in a moderately dense plasma. Finally, Figure 14 shows that a 50 \( \mu \text{A} \) beam current very efficiently removes photo-electron signatures from the measurements.

4. Conclusion

The results from the ASPOC spacecraft potential control instrument on the Double Star TC-1 spacecraft demonstrate that the applied method efficiently improves plasma electron measurements by reducing the effect of photo-electrons and by reducing the influence of the spacecraft sheath on ambient electrons. Ion beam currents of the
order of 10 to 20 \( \mu \text{A} \) provide a reduction of the potential which is sufficient under most circumstances, but also higher currents up to 50 \( \mu \text{A} \) have been tested. In no case any disturbance of the plasma electron measurements by the ion beam has been found.

![Energy flux spectrum](image)

Figure 14. Energy flux spectrum (top panel) taken for a selected time interval (bottom panel), for low ambient density, comparing cases with ion beam currents of 10 and 50 \( \mu \text{A} \).

5. References


