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Engineering Notes

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Spacecraft Potential Control by the Plasma Source Instrument on the POLAR Satellite

R. H. Comfort*
University of Alabama in Huntsville, Huntsville, Alabama 35899
T. E. Moore†
NASA Goddard Space Flight Center, Greenbelt, Maryland 20771
P. D. Craven‡
NASA Marshall Space Flight Center, Huntsville, Alabama 35812
C. J. Pollock§
Southwest Research Institute, San Antonio, Texas 78284
F. S. Mozer¶
University of California, Berkeley, Berkeley, California 94720
and
W. S. Williamson**
Hughes Research Laboratories, Inc., Malibu, California 90265

Introduction

IT is increasingly recognized that the low-energy core plasma is a critically important part of magnetospheric plasma transport, yet this plasma cannot be accurately measured from spacecraft at potentials much different from that of the ambient plasma. In low-density regions such as the polar cap and lobes, spacecraft charge positively, excluding core ions from the spacecraft and accelerating core electrons so much that their velocities cannot be measured with any accuracy. In regions of high electron pressure and temperature, spacecraft charge negatively, excluding the ambient core electrons and accelerating the core ions so much that their velocity cannot be accurately measured. Plasma contactors have been used on a number of spacecraft operating in low-plasma-density regions to prevent charging of spacecraft to high potentials, particularly when exposed to high fluxes of energetic particles. This concern has prompted extensive studies by NASA[1] for use of plasma contactors on the international space station, where solar arrays may significantly affect the spacecraft potential.[2–4] The Japanese/NASA Geotail spacecraft has also successfully employed active potential control to enable the observation of low-energy-plasma particles.[5] The Plasma Source Instrument (PSI), a vitally important part of the Thermal Ion Dynamics Experiment (TIDE), corrects both positive and negative charging problems through the emission of electrons and xenon ions as needed to regulate the potential to near that of the ambient plasma.

This Note has three purposes. The first is to demonstrate that PSI is effective in controlling the spacecraft potential to low positive values, thereby permitting observations of low-energy plasma, which would otherwise be unobservable. The second is to demonstrate the effects of PSI operation on TIDE observations and those made by other instruments on the POLAR satellite. The final objective is to present a possible physical explanation for the distortion of some particle observations during PSI operations and thereby to provide a basis for developing a quantitative model to compensate for these effects.

Operational Characteristics

The TIDE-PSI complement is on board the POLAR satellite, which is part of the U.S. International Solar–Terrestrial Physics (ISTP) group of spacecraft making observations in the vicinity of the Earth.[6,7] POLAR was launched in February 1996 into an elliptical polar orbit, with apogee near $9R_E$ and perigee near $2R_E$ geocentric. Before the activation of most of the POLAR instruments, PSI underwent an activation period during which operating procedures were refined and improved. Since then, PSI has been operated a number of times, simultaneously with TIDE, in a mode that effectively regulates the POLAR floating potential.

The PSI is made up of a hollow cathode, anode, keeper electrodes, grounded shields, and a magnetic structure designed to enhance ionization and to minimize the gas flow required. The instrument is described in detail in Ref. 7; its function is to ionize the gas flow, providing a medium-density plasma that will provide an electrically conducting bridge between the ambient plasma and the satellite and prevent differential charging between surfaces on the satellite. Xenon is used to provide an inert-gas plasma. A saturation ion current of 1.0 mA is obtained with a gas flow of 0.5 std cm^3 min^{-1} (0.37 μmole/s). The anode voltage can be varied through a bias power supply. With this power supply, the cathode and keeper can be biased relative to the spacecraft, permitting vernier control of the spacecraft potential.

During one of the periods of activation and in conjunction with the Electric Field Instrument[8] (EFI) team, the bias voltage of the anode was stepped from 0 to -10 V and back to 0 V and then from 0 to $+6$ V and back to 0 V. A second sweep to -10 V was performed to check the repeatability of the results. The effect of these voltage ramps on the potential between the spacecraft and the EFI booms is shown in Fig. 1. Note that while PSI is operating at a fixed bias of -4 V, the spacecraft potential is quite steady at near $+1.8$ V, except when the bias is being ramped to other voltages. When PSI is turned off (after 1320), the spacecraft potential returns to about $+22$ V. The capability to exert fine control over the POLAR floating potential using the bias supply integral to PSI is shown in Fig. 2, which is drawn from the data taken during the voltage ramps noted in Fig. 1. The positive range was limited to $+6$ V because determination of the spacecraft potential by EFI becomes questionable when the magnitude of this potential is below about 0.5 V. It is imperative to maintain a slightly

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*Professor, Physics Department and Center for Space Plasma and Aeronomic Research. Member AIAA.
†Head, Interplanetary Physics Branch, Code 692, Building 2, Room 138.
‡Astrophysicist, Space Sciences Laboratory, Code ES 83.
§Vice President, Building 178, P.O. Drawer 28510, 6220 Culebra Road.
¶Professor, Space Sciences Laboratory.
**Research Project Manager, Sensors and Materials Laboratory, 3011 Malibu Canyon Road. Senior Member AIAA.

positive potential to keep xenon ions from returning to the spacecraft and possibly contaminating instrument surfaces.

The PSI routine operating point has been chosen to minimize its emission of white noise, which raises the plasma wave background of the Plasma Wave Instrument[9] (PWI). This is a particular problem in the 1–10-kHz range, as illustrated in Fig. 3, which shows data taken during the same period as Fig. 1. At this time it is not certain whether PSI actually emits white noise or alters the coupling of the probes to the spacecraft and other electronic systems or some combination of the two. Without this noise constraint, the potential could be maintained at a lower magnitude, as long as it remained demonstrably positive (see preceding discussion).

The PSI also affects the EFI probe measurements of low-frequency electric fields. In particular, the spin-plane components of the electric field are altered by spurious potentials of approximately 500 mV over the 100-m tip-to-tip separation, as shown in Fig. 4. Though somewhat contrary to the expectation of a reduced sheath thickness with PSI operating, the existence of residual electric fields of small amplitude is a natural consequence of localized charge separation in the plasma plume near the spacecraft, as discussed later.

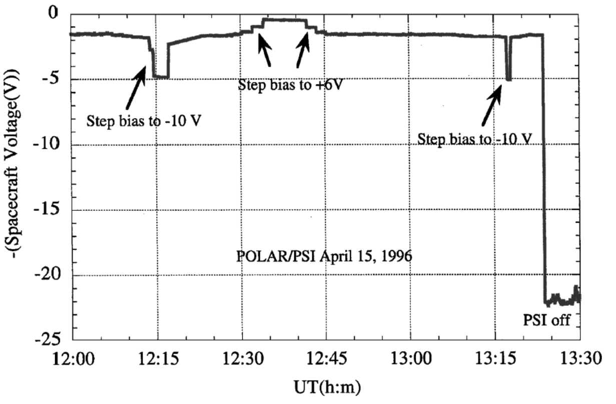

Fig. 1 Effect of the PSI on the POLAR spacecraft potential near apogee. The vertical scale is the negative of the spacecraft potential. Biases refer to changes in the bias voltage applied to PSI circuitry (see Fig. 2). Measurements were made by the EFI on POLAR on April 15, 1996.

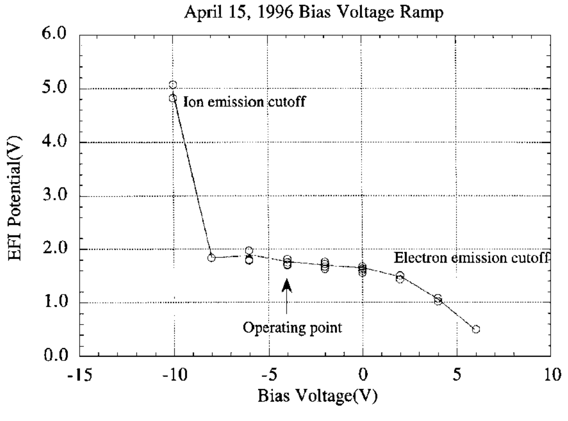

Fig. 2 Effect of the PSI bias voltage on the POLAR spacecraft potential. These are the combined data from the different steps of the bias voltage indicated in Fig. 1.

Science Results to Date

The POLAR spacecraft can float as much as 40–50 V positive during passes over the polar cap, as shown in Fig. 5. PSI operations drastically change this situation, stabilizing the potential at

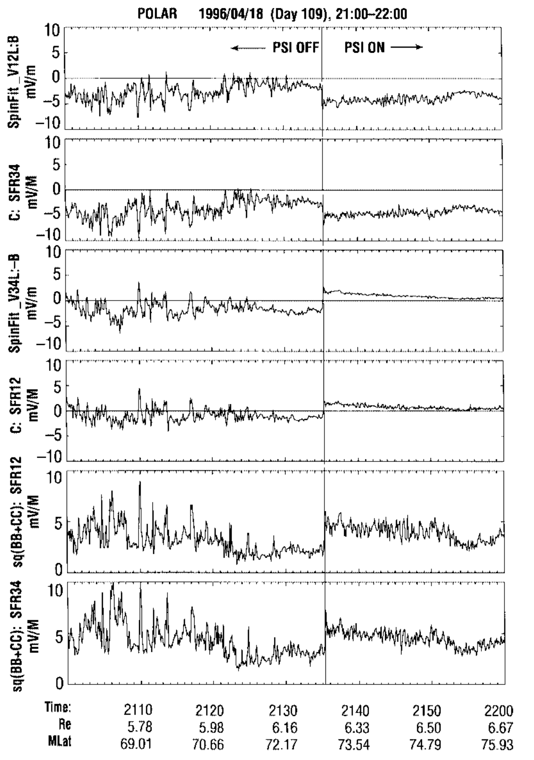

Fig. 4 Electric field measurements from the EFI on April 18, 1996. A small change in the electric field is clearly evident when the PSI turns on at 2134.

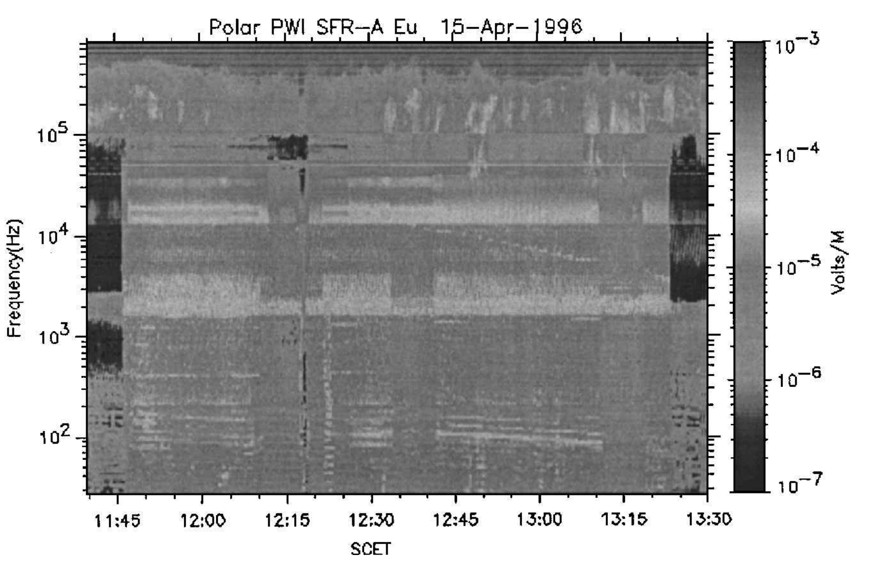

Fig. 3 PWI frequency spectrogram for the same time period as Fig. 1. The PSI is on from about 1147 to 1324. Effects of the PSI are seen especially in the middle-frequency range of 1–10 kHz.

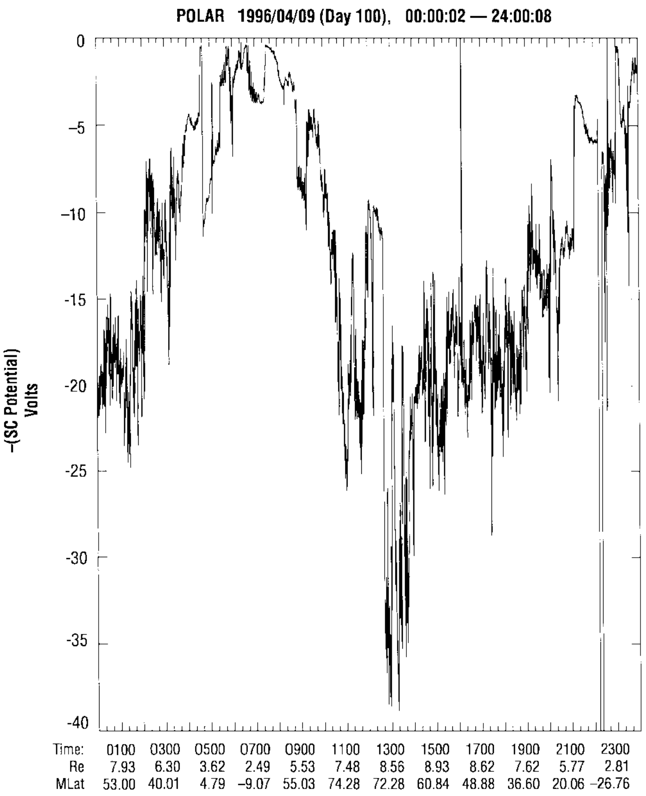

Fig. 5 Spacecraft potential for a 24-h period on April 9, 1996, without the PSI operating, as measured by the EFI. The negative of the spacecraft potential is plotted. The spacecraft potential is at a minimum (<1 V) near perigee (where ambient current densities are highest) and at a maximum (>35 V) near apogee (where ambient current densities are lowest). Both apogee and perigee are over the polar caps, where ambient plasma densities are generally low.

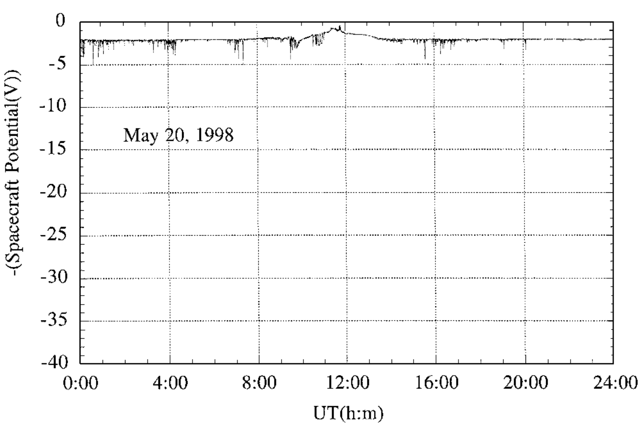

Fig. 6 Spacecraft potential for a 24-h period on May 20, 1998, with the PSI operating, as measured by the EFI. This figure may be compared with Fig. 5, which displays the same potential range. In this pass, perigee occurs just before 1200, where ambient current densities are seen to overcome the effects of the PSI. Small positive spikes appear to occur where variable populations of energetic particles are encountered.

$+2.4 \pm 0.13$ V. Figure 6 demonstrates how well PSI clamps the spacecraft potential over the course of a complete day (more than a complete orbit). Typically, the potential is clamped quite closely around apogee, where densities are very low and there is little variability. The only place where the spacecraft potential becomes closer to zero is near perigee, where ambient plasma current densities are higher. The most pronounced deviations (in the positive direction, typically remaining less than 5 V) occur with encounters of energetic particle populations in auroral regions; these are brief excursions to which the PSI adjusts once conditions become steady. The ± 0.13-V uncertainty noted earlier is the standard deviation of the variability of the spacecraft potential in Fig. 6 over the period displayed.

With the PSI running, the TIDE is able to observe high-Mach-number, field-aligned flows that extend throughout the polar cap, as shown in Fig. 7. It turns out that these flows have energies in the range of tens of electron volts in the case of H+, somewhat higher for heavier species, and with a downward trend from dayside to nightside.[10] In this example, substantial fluxes of field-aligned H+ with energies below 10 eV are evident; without the PSI, these would be unobservable, as is generally the case over the polar cap when the PSI is not operating. This is evident when the PSI is turned off just after 2300; the particle population below 40 eV is no longer visible.

The disturbance of the electric field sensed by the EFI indicates that operation of the plasma source disturbs the sheath electric field around the spacecraft, introducing a field that will deflect low-energy particles to some degree as they approach it. The preceding plasma flow observations indicate a high-Mach-number, magnetic-field-aligned flow that bears little evidence of any strong deflections by the disturbed spacecraft sheath and is loosely consistent with a purely radial sheath field. Nevertheless, we know from the EFI measurements that the electric field around the spacecraft is disturbed by PSI plasma emission, and it is essential to assess the magnitude of this effect on the particles being observed.

Sheath Model

The TIDE-PSI team is in the process of developing a quantitative model of the PSI sheath that will provide the three-dimensional potential associated with the PSI plasma plume.[11] In the absence of quantitative results, it is useful to consider the characteristics of the model, using the EFI measurements to provide a quantitative normalization sufficient to assess the magnitude of particle deflections. The physical model described next is intended to aid understanding of the anisotropy detected in the potential structure around the spacecraft and to provide an independent, qualitative check on the detailed numerical model that is under development. It will also help guide the scale requirements for how large the model space must be to include all of the significant physical processes.

The basic physical model of the disturbed sheath is illustrated in Fig. 8, which shows two schematic views of the POLAR spacecraft at different scales. The left-hand panel is a view along the local magnetic field with the spin axis directed toward the left, whereas the right-hand panel is a somewhat zoomed-out side view of the spacecraft with the local magnetic field oriented from left to right. The essential features of the potential distribution near the spacecraft can be understood as a cleavage of the electrons from the ions of the PSI plasma emission. The source electrons have gyroradii with a distribution that peaks in the vicinity of 30 m, whereas the xenon ions have a distribution that peaks around 20 km. Thus, in the vicinity of the spacecraft, there is a region of positive space charge that is spread very broadly above the plasma emission direction in this view, whereas there is a region of negative space charge that is centered below the plasma emission direction and in the vicinity of the EFI probe that is most nearly perpendicular to the local magnetic field at any given time.

After separating, the PSI-emitted electrons and ions depart from the spacecraft vicinity along the magnetic field, merging back together so as to form a nearly neutralized column over a distance scale that is unknown, then conforming to whatever plasma flow and drift are present in the flux tube. This is illustrated in the right-hand panel of Fig. 8. Clearly, a region exists in which ions are deflected in the sense illustrated.

Based on the EFI electric field observations, we can estimate the magnitude of the potentials near the spacecraft. Because the EFI booms are roughly an electron gyrodiameter away from the spacecraft, the probe on the electron side of the spacecraft is bathed in the largest space charge concentration anywhere in the disturbed sheath. Because the xenon gyroradius is so much larger, the positive space charge is relatively diffuse, and there is little space charge in the vicinity of the probe on the ion side of the spacecraft. Thus the 500 mV from tip to tip is largely concentrated on the electron side

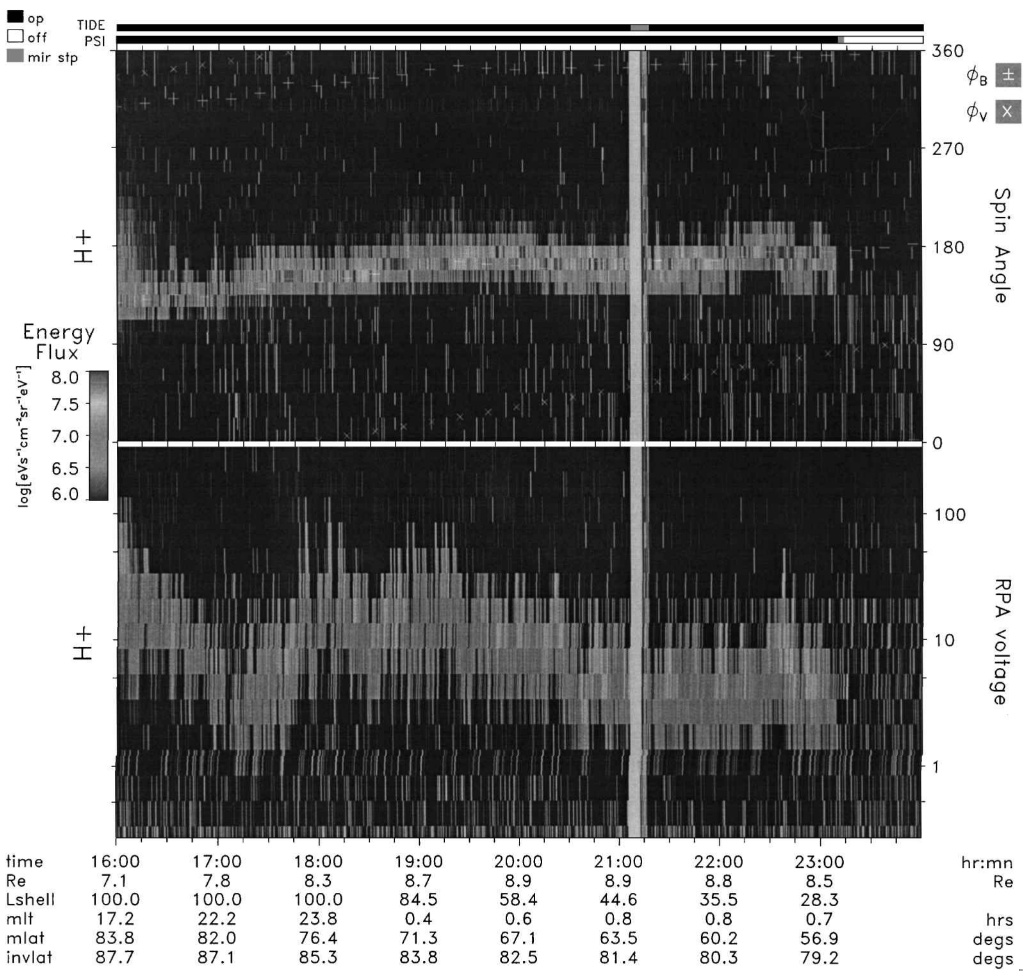

Fig. 7 TIDE spectrogram for the apogee portion of the pass on April 19, 1996. During the pass, the PSI is turned off at 2303, after which ions with energies below 40 eV are no longer seen. (Between 2102 and 2104 the TIDE is in a calibration mode.)

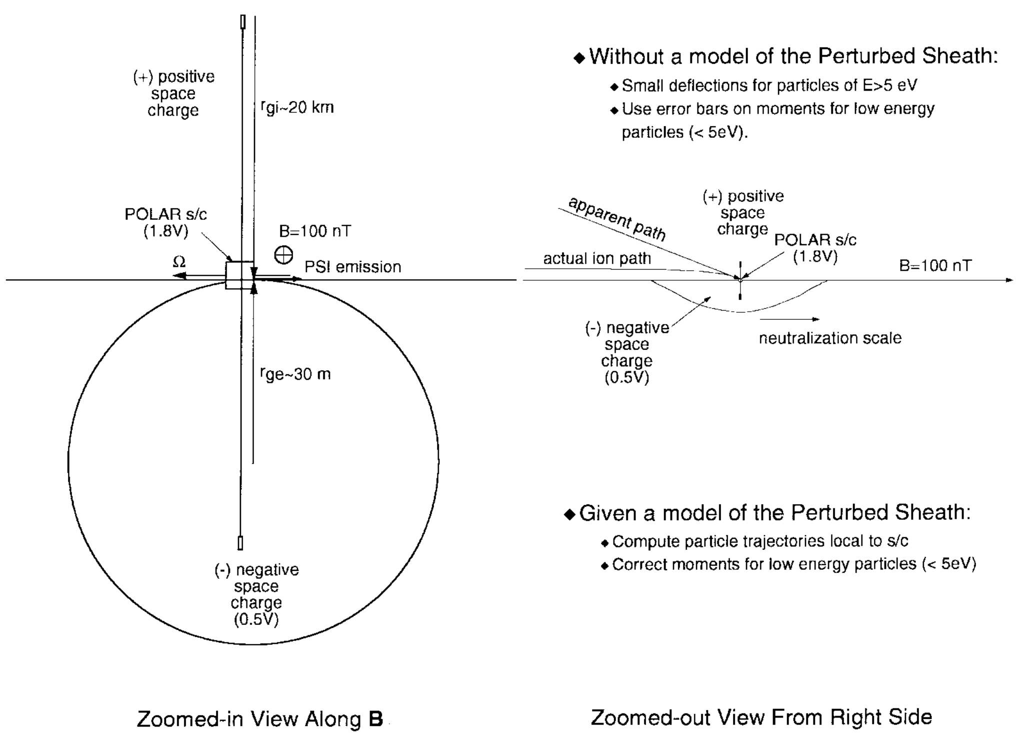

Fig. 8 Sheath model associated with the plasma contactor running. The geometry of the PSI emission relative to the geomagnetic field is a key factor in this model. The orbit of POLAR and the orientation of the spacecraft make this type of geometry common throughout much of the orbit.

of the spacecraft, and we can infer that the negative space charge concentration on that side of the spacecraft leads to a local potential on the order of 500 mV relative to the spacecraft.

This being the case, a criterion for vanishing deflection of the particles is that they have energies of greater than about 10 times the value of 500 meV. Thus, 5-eV and higher-energy particles are relatively unaffected by the disturbed sheath, except that they do, of course, lose (or gain) about 2 eV of energy upon approach to the spacecraft in the case of the ions (or the electrons). Clearly, we have no reason to expect that the high-Mach-number ion flows observed by the TIDE should be significantly deflected by the PSI sheath disturbance. On the other hand, the ambient electrons accompanying these ion flows have much smaller flow energy, larger thermal velocity, and lower Mach number. Clearly, the core electrons below 5 eV ($\sim$7-eV measured energy) should exhibit detectable effects of deflection in these disturbed sheath fields. Subtle departures from electron gyrotropy may be observed at somewhat higher energies as well. These values can be used to interpret the observations from the TIDE as well as other instruments and to guide numerical model development to gain a quantitative understanding of the details of the potential structure. This model can in turn be used to develop empirical expressions to compensate for the effects of the PSI on observations of the natural environment.

Conclusions

Observations clearly demonstrate that the PSI has had the desired effect on the TIDE measurements: Low-energy ions that would otherwise be unobservable are seen. Equally clear is that the PSI modifies the sheath structure around the POLAR spacecraft in ways that also affect measurements made by other instruments, such as the PWI and the EFI. This implies that it will also have quantitative consequences for the TIDE observations. The EFI observations suggest that the TIDE core ion measurements will not be significantly affected unless ion energies are much less than 5 eV. Core electrons are more affected by the PSI sheath, and at lower outflow speeds the ions will also be influenced, requiring a better understanding of the sheath. A physical model has been presented that explains qualitatively the origin of the anisotropy found in observations with the PSI operating. This model can be used to guide the development of a detailed and accurate numerical model, which in turn can be used to develop modifications to the analysis to compensate for the PSI effects. The best understanding of the PSI sheath will come from synoptic operations of the PSI and dedicated analysis of the complete POLAR plasma data set.

Acknowledgment

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References

[1]Williams, J. D., and Wilbur, P. J., "Experimental Study of Plasma Contactor Phenomena," *Journal of Spacecraft and Rockets*, Vol. 27, No. 6, 1990, pp. 634–641.

[2]Ferguson, D. C., and Hillard, G. B., "In-Space Measurement of Electron Current Collection by Space Station Solar Arrays," AIAA Paper 95-0486, Jan. 1995.

[3]Chaky, R. C., and Lambert, J. C., "The ISS Plasma Contactor," AIAA Paper 96-0627, Jan. 1996.

[4]Patterson, M. J., Verhey, T. R., Soulas, G., and Zakany, J., "Space Station Cathode Design, Performance, and Operating Specifications," 25th International Electric Propulsion Conf., IEPC Paper 97-170, Cleveland, OH, Aug. 1997.

[5]Schmidt, R., Arends, H., Pedersen, A., Rudenauer, F., Fehringer, M., Narheim, B. T., Svenes, R., Kvernsveen, K., Tsuruda, K., Mukai, T., Hayakawa, H., and Nakamura, M., "Results from Active Spacecraft Potential Control on the Geotail Spacecraft," *Journal of Geophysical Research*, Vol. 100, No. A9, 1995, pp. 17,253–17,259.

[6]Acuna, M. H., Ogilvie, K. W., Baker, D. N., Curtis, S. A., Fairfield, D. H., and Mish, W. H., "The Global Geospace Science Program and Its Investigations," *Space Science Reviews*, Vol. 71, 1995, pp. 5–21.

[7]Moore, T. E., Chappell, C. R., Chandler, M. O., Fields, S. A., Pollock, C. J., Reasoner, D. L., Young, D. T., Burch, J. L., Eaker, N., Waite, J. H., Jr., McComas, D. J., Nordholdt, J. E., Thomsen, M. F., Berthelier, J. J., and Robson, R., "The Thermal Ion Dynamics Experiment and Plasma Source Instrument," *Space Science Reviews*, Vol. 71, 1995, pp. 409–458.

[8]Harvey, P., Mozer, F. S., Pankow, D., Wygant, J., Maynard, N. C., Singer, H., Sullivan, W., Anderson, P. B., Pfaff, R., Aggson, T., Pedersen, A., Falthammar, C.-G., and Tanskannen, P., "The Electric Field Instrument on the Polar Satellite," *Space Science Reviews*, Vol. 71, 1995, pp. 583–596.

[9]Gurnett, D. A., Persoon, A. M., Randall, R. F., Odem, D. L., Remington, S. L., Averkamp, T. F., Debower, M. M., Hospodarsky, G. B., Huff, R. L., Kirchner, D. L., Mitchell, M. A., Pham, B. T., Phillips, J. R., Schintler, W. J., Sheyko, P., and Tomash, D. R., "The Polar Plasma Wave Instrument," *Space Science Reviews*, Vol. 71, 1995, pp. 597–622.

[10]Su, Y.-J., Horwitz, J. L., Moore, T. E., Chandler, M. O., Craven, P. D., Giles, B. L., Hirahara, M., and Pollock, C. J., "Polar Wind Survey with TIDE/PSI Suite Aboard POLAR," *Journal of Geophysical Research* (to be published).

[11]Leung, W. C., Singh, N., and Moore, T. E., "Numerical Model of the Plasma Sheath Generated by the Plasma Source Instrument Aboard the Satellite in the Magnetosphere," 1998 Spring Meeting of the American Geophysical Union, Paper SA22A-06, Boston, MA, May 1998; also *EOS, Transactions, American Geophysical Union*, Vol. 79, April 1998, p. S234.

A. C. Tribble
Associate Editor

Computational Prediction of Pitch Damping for Supersonic Blunt Cones

D. K. Ludlow* and N. Qin†
Cranfield College of Aeronautics, Cranfield, Bedfordshire, England MK43 0AL, United Kingdom

Nomenclature

C_m, C_n	= pitching and side moment coefficients, respectively, (moment)/$\frac{1}{8}\pi\rho V^2 D^3$
C_{m_q}, $C_{m_{\dot\alpha}}$	= individual pitch damping coefficients: the rate of change of C_m with q and $\dot\alpha$, respectively
$C_{m_q} + C_{m_{\dot\alpha}}$	= pitch damping coefficient sum
C_p	= pressure coefficient, (pressure)/$\frac{1}{2}\rho V^2 - 2/(\gamma M^2)$
D	= projectile diameter, m
M	= freestream Mach number
p	= spin rate of body nondimensionalized by $2V/D$
q	= transverse angular velocity of body nondimensionalized by $2V/D$
Re	= Reynolds number based on D
T	= freestream temperature, K
V	= freestream velocity, m/s
x	= coordinate distance from (blunt) nose tip along body's longitudinal axis in D
x_{cg}	= axial location of center of gravity of body from (blunt) nose tip in D
α	= angle of attack, deg
$\dot\alpha$	= rate of change of α with respect to time nondimensionalized by $2V/D$
β	= side slip angle, deg
γ	= gas constant for air (1.4)
ρ	= freestream density, kg/m^3
Ω	= angular rate of noninertial coordinate frame about inertial frame, nondimensionalized by $2V/D$

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*Research Officer, Flow Control and Prediction Group.

†Senior Lecturer, Flow Control and Prediction Group. Senior Member AIAA.