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CHARGING MITIGATION EXPERIMENTS ON SOUNDING ROCKETS

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Abstract. This paper introduces the general means, mitigation and measurement of spacecraft charging. The results from the NASA/ISAS CHARGE and DoD SPEAR sounding rocket programs are used to illustrate the effectiveness of different techniques to mitigate the electrical charge on the spacecraft. The two techniques of neutral gas or plasma release in addition to the emission of electron fluxes are demonstrated in several flights. Due to under-performance of the plasma release devices the results obtained show that, in general, neutral gas release is an effective means of mitigating electrical charge of either polarity. Electron beams are effective if the acceleration is provided by an internal power supply rather than the field produced by the charged spacecraft. Although differential biasing of sections of a spacecraft was employed as a charging technique it is pointed out that this can also be used as a charge mitigation technique for spacecraft charging processes independent of the differential biasing.

Introduction

Sounding rockets provide a relatively inexpensive method to study active techniques of charging space vehicles, studying how they interact with the ambient ionosphere and investigating methods of mitigating the electric charge induced on them. The lifting capability of commonly used sounding rocket motors limits the observations to be primarily at low earth orbit (LEO) altitudes or lower. In this paper I will address charge mitigation techniques which have occurred on two series of active experiment sounding rocket payloads, the NASA/ISAS Cooperative High Altitude Rocket Gun Experiments (CHARGE) and the DoD Space Power Experiments Aboard Rockets (SPEAR). In some cases the charge mitigation was serendipitous as a result of unsynchronized gas jet operations for attitude adjustments. Other payloads were specifically designed to study the efficacy of different techniques for charge mitigation.

The paper will summarize the relevant processes leading to spacecraft charging; establish that viable techniques exist to measure the vehicle potential which is a manifestation of the charging; discuss the general techniques that can be employed to mitigate space vehicle charging and present results obtained for both serendipitous and deliberate charge mitigation on sounding rockets.

Background

At LEO altitudes space vehicles can acquire a net electrical charge by a variety of causes. The electrical potential, which is a consequence of the charge accumulation on the space vehicle, will stabilize when the net current flowing to the vehicle is zero [*Garrett*, 1981; *Whipple*, 1981].

Passive charging will result from the spacecraft being immersed in a plasma with the electron thermal speeds being much greater than the ion thermal speeds resulting in a small negative charge on the vehicle to equalize the positive ion and electron fluxes and thereby achieve current balance.

Photo- emission and secondary emission from space vehicle frame surfaces will drive the vehicle potential to a positive potential large enough to collect ionospheric electrons to equal the net photo- and secondary electron fluxes.

Absorption of energetic charged particle fluxes will drive the potential to be the same sign as the particle flux to a level where other currents negate that carried by the energetic charged particle flux which may, in turn, be reduced by the retarding potential on the spacecraft.

Finally, current fluxes to the vehicle can be artificially induced by the use of active charging schemes such as the emission of locally generated charged particle beams and the application of a differential electrical bias between different parts of the space vehicle. Again the vehicle will adjust its electrical potential until the currents from all sources are in balance.

At LEO altitudes the ionospheric plasma density is high enough that the current balance to the vehicle frame is generally dominated by currents from the ionospheric plasma and the currents artificially induced by active charging systems [*Raitt et al.*, 1999].

When the vehicle acquires a net charge, the electric field it produces is confined to a charge sheath around the vehicle. The size of the sheath varies from centimeters to meters depending primarily on plasma density and vehicle potential. It is, therefore, reasonable to use the undisturbed ionospheric plasma outside the sheath as a conductive ground reference in relation to charge mitigation methods. These techniques are sometimes referred to as vehicle grounding.

General Techniques

There are three general techniques that may be employed to mitigate the electrical charge on a space vehicle. The implementation and effectiveness of the techniques are somewhat dependent on the space vehicle environment.

The impedance between the ionosphere and the spacecraft can be reduced thereby allowing a sufficiently large current to flow between the spacecraft and the ionosphere to neutralize the spacecraft charge. This generally needs steps to be taken to increase the number density of charge carriers in the vicinity of the spacecraft above that provided by the ionosphere. This is normally achieved by the release of either neutral or ionized gas into the immediate environment of the spacecraft. Examples of the effectiveness of these techniques will be described later.

Another method that has been used to mitigate spacecraft charging has been to induce current flow from the spacecraft ground to the surrounding ionosphere using an internal power supply. The current flow is normally achieved by the use of charged particle accelerators commonly configured as electron or ion guns. Again examples of the application of this technique using electron guns will be described later.

Finally it is possible to arrange a configuration whereby differential biasing by a source of emf can be used to transfer ionospheric charge carriers from a deployed collector to neutralize excess charge in another part of the spacecraft system. This can be achieved by tethered payload sections to be discussed later.

Measurement of Spacecraft Charging

In order to assess the effectiveness of charge mitigation techniques, it is necessary to be able to measure the degree of charging of a spacecraft. This is achieved by measuring the electrical potential of the surface of the spacecraft relative to the undisturbed ionosphere. There are four main techniques to make this measurement, two rely on the modification of ambient charged particle distribution functions at the spacecraft surface due to its electrical potential, and two rely on a direct measurement of the electric potential difference between the charged spacecraft and the undisturbed ionosphere.

For small potentials it is possible to measure the change in the bulk drift energy of electrons or positive ions using the Langmuir Probe or Retarding Potential Analyzer instruments respectively. The expected features on the current voltage characteristics are offset by an amount equal to the potential of the spacecraft ground relative to the ionosphere [*Raitt et al.,* 1973].

Higher vehicle potentials can be measured by the use of floating potential probes located outside the charge sheath around the space vehicle. Since this may extend to distances of the order of meters, the floating probe needs to be deployed on a system such as a boom or a tether. If the floating potential (typically ~0.5V in the ionosphere) is small compared to the vehicle potential, the potential difference between the floating probe and the vehicle ground then provides a direct measure of the vehicle potential [*Fahleson,* 1967; *Falthammar,* 1989]. In order for the deployed probe to remain at floating potential during the measurement, the current drawn by the voltage monitor must be small compared to the charged particle thermal fluxes at floating potential. Examples of this type of measurement will be shown later when the measured efficacy of different spacecraft charge mitigation techniques will be discussed.

Larger potentials can also be measured using differential energy analyzers for either electrons or positive ions depending on the polarity of the spacecraft charge. In principle the spectrum of the charged particles accelerated through the spacecraft charge sheath should be peaked at the energy corresponding the potential drop across the sheath, that is the spacecraft potential. This is generally true for positive ion spectra resulting from a negatively charged spacecraft, but the peaking is not so pronounced in the spectrum of electrons returning to a positively charged spacecraft [*Burke et al.,* 1998; *Gentile et al.,* 1998]. The generation of secondary electrons from the surfaces usually results in large differential fluxes at low energies that mask the peak. For electron fluxes, the signature that can be used is the high energy cut-off that is close to the vehicle potential.

Another instrument that has been used to measure spacecraft potential is often referred to as a Charge Probe. This can be a compact, surface mounted sensor consisting of a metallic plate below a sheet of insulator exposed to the spacecraft environment [*Williamson et al.,* 1982]. The plate is maintained at spacecraft ground, and the transient charge flowing to/from the plate is measured by a charge sensitive amplifier. The flow of charge can then be related to the change of potential of the spacecraft assuming the capacitance of the probe is known, and that the ambient ionospheric plasma maintains the outer surface of the insulator at the fixed floating potential. This instrument has the advantage that it can be designed to have a rapid time response, but it needs resetting from time to time which makes it difficult to maintain a record of the absolute potential of the spacecraft.

Experimental Programs

All payloads in the CHARGE [*Raitt,* 1995], SPEAR-1 [*Raitt,* 1991] and SPEAR-3 [*Raitt,* 1996] programs referred to earlier were flown on versions of the Black Brant sounding rocket that lifted the payloads to altitudes in the range 250 – 300km. The flights were conducted at night under no-moon conditions to facilitate observation of optical effects produced by particle beams and/or high voltage charging.

Chronologically the programs were as follows:

CHARGE-2

This was a Mother-Daughter tethered payload, using a conducting, insulated tether that deployed to a maximum separation of Mother and Daughter of ~400m during the flight time above 80km altitude. Charging was induced by electron emission from an electron gun with a maximum beam current of ~100mA at an electron energy of 1000eV and an internal power supply could also be used to differentially bias the Mother and Daughter payload sections through the tether up to 500V [*Myers et al.*, 1989].

SPEAR-1

This payload used an internal power supply to bias two spheres deployed about 3m from the payload. The biasing arrangement allowed the spheres to be biased at different positive voltages up to 45kV relative to the payload ground. The deployment booms were designed to have a graded potential drop for several sphere radii from the attachment points thereby avoiding strong electric fields near the attachment points. The bias voltage was derived from high voltage capacitors charged to a programmed voltage that was determined by the time they were connected to a constant current high voltage power supply. Current limitation was set by a series resistor of 2 kΩ connected between the capacitors and the deployed spheres. A low-light-level television camera was placed to observe light emission in the vicinity of the biased spheres. The potential of the payload ground was intended to be held close to the potential of the local ionosphere by a plasma contactor. Unfortunately the plasma contactor cover never deployed, and the payload was therefore driven to high negative potentials [*Allred et al.,* 1989].

SPEAR-3

A second flight was made using a similar configuration to SPEAR-1, but with only one deployed sphere and a lower biasing voltage of 10kV. The goals of SPEAR-3 were to study several different techniques of charge mitigation on a negatively charged spacecraft at potentials of up to -2kV. Two material release techniques were included, a plasma contactor and cold gas release. Also two electron emission devices were used, a thermionic cathode and an array of field emission devices. In both electron emission cases, the intent was to use the sheath field resulting from the charge on the payload to accelerate the electrons away from the payload. The various grounding devices were employed cyclically to test them at different altitudes. In addition comparison of the effects of a rapid application and a ramped application of the high voltage bias were studied.

CHARGE-2B

The primary objective of CHARGE-2B was to generate electromagnetic waves by modulating an ampere level electron beam at frequencies in the VLF range. However, since the beam would result in charging of the payload, a charge mitigation device was included. Based on earlier experience a cold gas release system was used, and proved to be successful in lowering the payload potential while the electron gun was emitting currents of up to 1.5A. The payload was configured as a tethered Mother/Daughter arrangement similar to CHARGE-2. In addition a free flying section of the payload was included. The tether was used solely as a means of measuring the potential of the Mother relative to the distant, deployed Daughter assumed to be close to the ambient ionospheric potential [*Raitt et al.,* 1995].

Impedance Reduction Results

In all of the programs under discussion in this paper, the most effective way of reducing the impedance between the charged spacecraft and the ionosphere was found to be by releasing cold gas into the charge sheath. Collisional ionization of the dense gas near the release point appears to be the mechanism to produce the additional ionization to allow sufficient current to flow from the charged spacecraft to the ionosphere to reduce its charge level to a low value.

For positively charged spacecraft, the ionospheric electrons accelerated to the surface will ionize the released gas directly until the potential is lowered to the point at which the ionization rate is at the value needed to produce just sufficient plasma to maintain the current to the ionosphere equal to that charging the spacecraft.

If the spacecraft is charged negatively, the ionization of the released gas results from secondary electrons from the spacecraft surface generated by impact of the positive ions accelerated through the spacecraft sheath. The secondary electrons are in turn accelerated away from the spacecraft by the sheath field and eventually acquire sufficient energy to ionize the released gas thereby generating the additional plasma needed to lower the sheath impedance.

Plasma contactors were included as the only (SPEAR-1) or alternate (SPEAR-3) means of charge mitigation, but in both cases the devices did not operate correctly. In both cases means to power up quickly to have them operational in ~5 minutes for the payload to reach its working altitude may have been at the root of the problems. The SPEAR-1 instrument employed a cover used to maintain cleanliness of the cathode during the pre- and immediately post-launch periods which did not deploy during flight. The exposure of the SPEAR-3 hollow cathode to the atmosphere just before launch when local purging had to cease may have poisoned the cathode resulting in the very low emission current of the plasma contactor during the SPEAR-3 flight.

CHARGE-2

CHARGE-2 provided an early indication of the effectiveness of cold gas release on spacecraft charge mitigation. The deployment of the tether was assisted by cold gas thrusters mounted on the Daughter and oriented to provide a separation force. The thrusters were timed to operate for three seconds every thirty seconds.

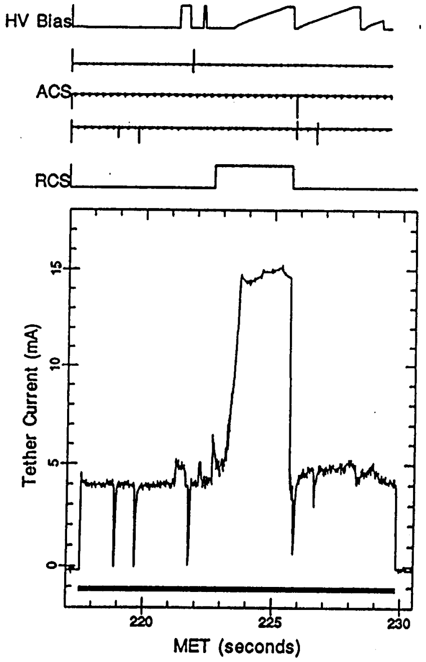


Figure 1. Collected current enhancement due to cold gas release [*Gilchrist et al.,* 1990].

During one such thruster operation, by chance the electron gun was operating and charging the Mother positively and the power supply differential bias supply was connected resulting in the Daughter being charged to close to +1000 V relative to the ionosphere. Figure 1 shows the marked increase in tether current as a result of the gas release [*Gilchrist et al.,* 1990]. The plot shows the time history of the tether current which increases to 4.5 mA when the electron gun begins emitting, this current being the part of the return current collected by the Daughter biased through the tether. The current then increased to ~10 mA when the separation thruster (labeled RCS) operated for three seconds. The 10 mA was equal to the electron beam current providing a direct indication of the reduction in the sheath impedance at the Daughter allowing much greater current flow between the charged spacecraft section and the ionosphere.

In addition to the extended release of gas from the separation thruster, the shorter bursts of gas from the Mother attitude control system (ACS) can be seen to mitigate the charge on the Mother for the brief periods of gas release. The times of the ACS operations are shown on the panel marked ACS, and the corresponding reduction in tether current is clearly seen. In this case the Mother charge sheath impedance is greatly reduced allowing the return current to compensate for the emitted beam current to be provided primarily through the Mother charge sheath without the need for additional current collected by the Daughter.

SPEAR-1

During the operation of the SPEAR-1 experiment, there was one occasion when a change in attitude coincided with the application of the high voltage bias to the spheres. At this time there was a lot of activity in the ACS system with numerous short pulses of gas being emitted. Figure 2 show two of the currents monitored in the high voltage circuits during this event. The currents are plotted as a function of time, the exponential decay envelope reflecting the exponential decay of the voltage on the biasing capacitor. The spikes show the changes in current due to charge mitigation by the gas release. The upper panel shows the total current delivered from the capacitor, while the lower panel shows the current flow through the potential grading boom.

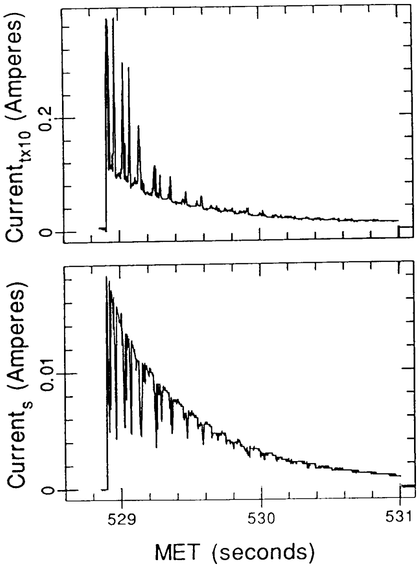


Figure 2. Enhanced current collection by SPEAR-1 payload due to ACS gas jet operation.

The external impedance from the sphere back to the payload skin consists of the sheath impedances of the sphere and the payload in series. The results shown in figure 2 are interpreted as a significant reduction in the payload sheath impedance due to the ACS gas release which then increases the total current and diverts more current through the external path than through the essentially fixed impedance of the grading boom.

SPEAR-3

The gas release results discussed earlier arose from serendipitous operation of spacecraft charging mechanisms and system gas release jets. In the SPEAR-3 program the gas release means of mitigating the spacecraft charge was synchronized with the means of charging the spacecraft. Figure 3 summarizes one of the charge mitigation experiments with gas release.

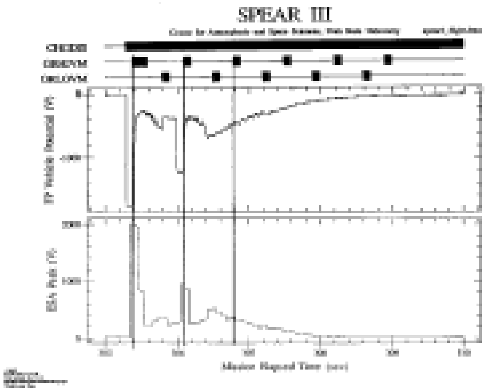


Figure 3. Mitigation of negative charge on the SPEAR-3 payload by neutral gas release.

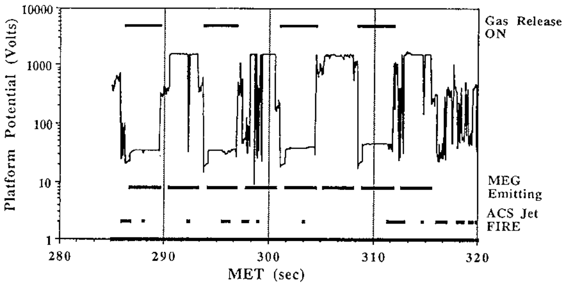
The upper panel shows the duration of the charge period and the operation of high (GRHIVM) and low (GRLOVM) gas flow rates from nozzles similar to those used on sounding rocket ACS systems. The actual flow rates for the two cases were 2 cc/sec and 0.2 cc/sec respectively. The lower panels show the potential of the payload relative to the ionosphere measured by two of the techniques discussed earlier. The upper of the two potential panels shows a measurement by a deployed floating probe, while the lower panel shows the potential measured by an ion collecting electrostatic differential energy analyzer. The scale of the electrostatic analyzer shows the modulus of the potential, the floating probe indicates polarity. The range of the floating probe instrument was set to respond to lower voltages on the payload, so the measurement saturates below the highest voltage of 2000V measured by the electrostatic analyzer.

Without charge mitigation, the shape of the potential variation with time would mirror the exponential decay of the voltage on the biasing capacitor. The faster sampled floating probe results in Figure 3 show that the high flow rate gas release reduced the potential of the payload to about -300V if the potential before gas release was between ~1000V and ~600V. This is seen by the fact that after the third high flow gas release the potential is not affected. It is presumed that this means that insufficient secondary electrons are released and/or they are not energized sufficiently to produce enough additional plasma in the dense region of the gas plume.

CHARGE-2B

The CHARGE-2B payload also used gas release synchronized with the operation of an electron gun to mitigate the charging of the payload resulting from the electron flux emitted from the payload. The electron beam energy was 3 keV and the current was ~1.5A derived from the operation of two emitters in parallel.

Figure 4 shows an example of the electron gun operation and the payload charge mitigation resulting from cold gas emission. The central plot shows the payload potential relative to the deployed Daughter measured through the tether joining the Mother and Daughter sections of the payload. The high potentials correspond to no gas release and the lower potentials to operation of the gas release system. The gun operations are denoted by the bars labeled "MEG emitting" and the gas release by the bars labeled "Gas release on". It can be seen that the payload charged up to ~1000V in the absence of any charge mitigation system. However when the gas flow was initiated the payload potential dropped to ~30V. At this potential the sheath impedance was reduced sufficiently that the 30V across it was sufficient to allow a current equal to the beam current to flow through the sheath. In this case it is likely that the gas ionization by returning electrons was aided by the large flux of electrons being emitted from the electron gun.



Effect of CHARGE–2B gas releases on vehicle potential.

Figure 4. Mitigation of positive charge on the CHARGE-2B payload by cold gas release.

The ragged nature of the central plot is the result of serendipitous reduction of the payload potential by the unsynchronized operation of the ACS jets that occurred at times indicated by the bars labeled "ACS jet fire".

Charge Emission Results

Three examples of spacecraft charge mitigation by electron beam emission will be discussed. In the first case the electron beam emission was produced by acceleration of electrons in an electron gun powered by an independent power supply. There was no current control for the beam and we will see that in this case there was excess compensation for the accumulated negative charge resulting in positive charge accumulation on the spacecraft. In the second case the electric field resulting from the negative charge on the spacecraft aided by a small negative bias on the thermionic cathode accelerated the electrons away, and in this case the potential was reduced to be close to zero. A similar result to the second case was obtained using electrons generated by field emission from an array of tips located in the spacecraft charge sheath.

CHARGE-2

Figure 5 shows variations of potential of the Mother and Daughter sections of CHARGE-2 during electron beam emission from the Mother and positive biasing of the Daughter section through the tether by the internal power supply.

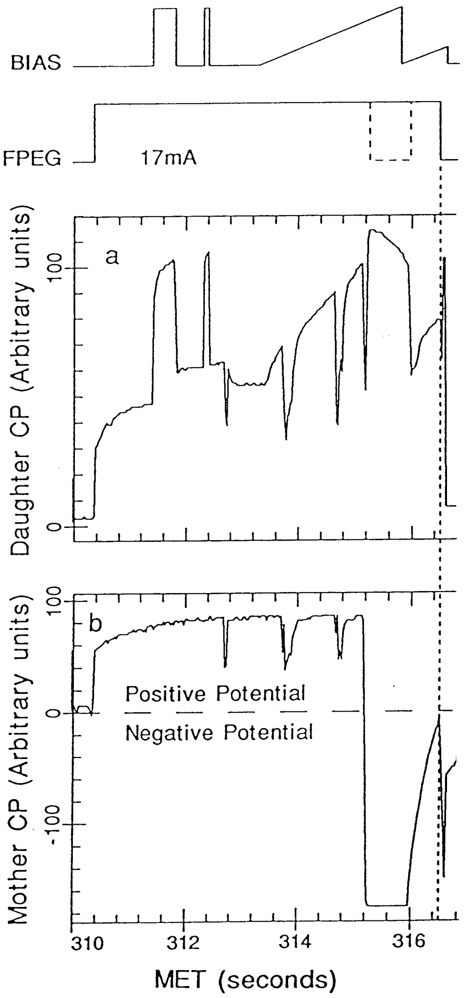


Figure 5. Overmitigation of negative vehicle charge by electron beam emission on CHARGE-2.

The top panels show the sequence of bias potentials and the operation of the electron gun (labeled FPEG) as functions of time. The broken line region at the right side of the FPEG emission plot indicates a period when the electron gun shut down due to arcing caused by excessive local gas pressure inside the gun head. The lower panels show variations in the potentials of the Daughter and

Mother respectively as functions of time measured by the charge probes on each payload section.

The charge mitigation aspect is most clearly shown in the lower panel. When the electron gun begins emitting, the Mother potential is driven positive to increase electron collection from the ionosphere to match the emitted beam current of 17mA. At 315.2 seconds the electron emission ceases due to an arc shutdown and the Mother is driven to a high negative potential resulting from the bias provided by the internal power supply. Thus, in terms of illustrating charge mitigation by electron beam emission, it is more descriptive to read the lower plot in Figure 5 backwards. It shows that a large negative bias on the Mother resulting from differential charging is over-mitigated by the electron beam emission. This is because the electron beam emission current is determined independently from the degree of charging of the spacecraft.

SPEAR-3

The SPEAR-3 payload included two electron sources with provision to release the electrons into the charge sheath around the spacecraft.

One system used a thermionic emitter with a small negative potential relative to spacecraft ground applied to the filament to induce the charge cloud around the heated filament to drift to the spacecraft charge sheath. Figure 6 shows one discharge cycle in which the electron gun was activated.

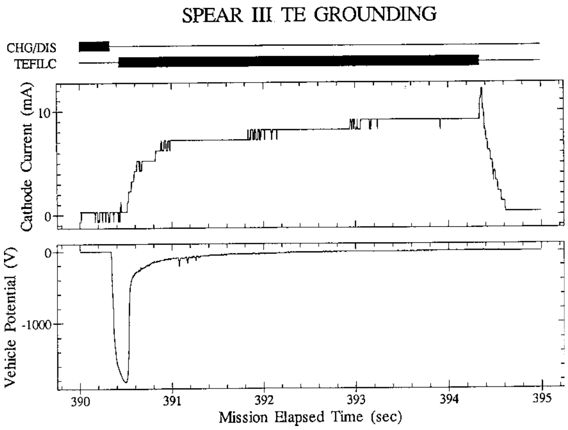


Figure 6. Negative charge mitigation of the SPEAR-3 payload by electron emission from a Thermionic Emitter (TE).

The upper bar plots show the application of the differential high voltage, and the operating period of the electron gun. In order that the electron gun was not active during other experiments its filament was normally turned off. Thus the first part of the plot shows the increase in cathode current as the filament heats up. The lowest panel shows the spacecraft potential initially being driven negative by the differential bias, then this charge being mitigated by the electron emission as the filament heats up to its emission temperature. There is no indication of a return to negative bias on the spacecraft when the electron gun is turned off because by this time the differential bias from the charged capacitor was very low

The other electron emission system consisted of an array of field emission devices with a nominal current capacity of 100mA. The electron extraction field energized the emitted electrons to 300eV and their flow was oriented to be into the spacecraft charge sheath.

Figure 7 shows an example of the Field Emission Device (FED) mitigating the negative charge on the spacecraft induced by the differential bias source. The format of the figure is similar to Figure 6, but the activation of the FED is shown in the top panel, and the lower panels show the time history of the FED activation and the spacecraft potential.

It can be seen that the initiation of the biasing drives the spacecraft to a high negative potential. Then, as the field emission is ramped up as shown by the cathode current to the FED the negative charge on the spacecraft is mitigated and its potential moves much closer to zero. At the end of the charging period there is no induced spacecraft charging when the FED is switched off because the voltage on the charging capacitor had decayed to near zero.

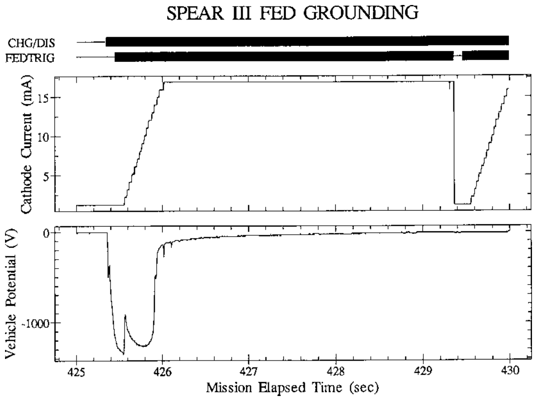


Figure 7. Negative charge mitigation of the SPEAR-3 payload by electron emission from a Field Emission Device (FED).

Both of the results shown in Figures 6 and 7 were not repeatable near apogee when the ionospheric density was highest. This is due to the inability of either electron-emitting device to provide enough current to compensate for the higher current collected by the deployed, biased sphere under those conditions. It appears that the perveance of the systems using the sheath as the electron accelerating region is not sufficiently high to provide the current needed to mitigate the negative charging when the ionospheric density is ~10^{11} m^{-3}.

Differential Biasing Results

In the examples used in this paper to illustrate various charge mitigation techniques and their effectiveness differential biasing was used only as a means of charging the spacecraft before mitigation techniques were used. However, the fact that electrical potentials of spacecraft can be controlled by differentially biasing the spacecraft relative to a deployed current collector is shown in Figures 2, 3, 5, 6, and 7. It therefore follows that by adjusting the magnitude and polarity of the differential bias, it will be possible to draw sufficient current from the ambient plasma to neutralize the charge excess on the charged spacecraft.

It seems, therefore, that differential biasing in conjunction with the measurement of spacecraft potential could be utilized to provide an automatic, continuous method of mitigating charge excess on the spacecraft. This technique does require electrical power to operate the bias supply and a means of deploying the biased electrode to a distance where the charge sheaths of the spacecraft (before mitigation) and the biased electrode do not intersect. However, it will then operate without the production of effluent clouds of neutral or charged matter around the spacecraft. The use of spacecraft potential monitoring to control the differential bias allows the spacecraft potential to be controlled to be either positive or negative as well as close to zero depending on the scientific and technological requirements.

Conclusions

The results obtained from the various experiments described in this paper have shown that an effective way of reducing the charge on either positively or negatively charged spacecraft is the release of neutral gas into the charge sheath. This reduced the potential of positively charged vehicles from kV levels to about 30V and negatively charged vehicles to about -300V. It is likely that plasma contactors would have been equally effective, but unfortunately in both trials of this device it failed to generate a plasma cloud.

An electron gun in which the electrons were accelerated away from the vehicle by an internal power supply biasing internal electron optics mitigated negative charge on a spacecraft. However, if the accelerating region of the electron gun was formed by the electric field in the charge sheath it was found the perveance was too low to provide adequate electron emission to mitigate charging at altitudes near the peak density of the ionospheric F-region.

Although differential charging of spacecraft sections by internal power supplies was primarily used to charge those sections, it seems that this technique could be used to mitigate charge on spacecraft that are being charged by external influences. This technique used in conjunction with a spacecraft potential monitor could provide a rapid acting precise control of vehicle charging at a required charging level.

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References

Allred, D., J. D. Benson, H. A. Cohen, W. J. Raitt, D. A Burt, I. Katz, G. A Jongeward, J. Antonaides, M. Alport, D. Boyd, W. C Nunnally, W. Dillion, J. Pickett, and R. B. Torbert, The SPEAR-1 Experiment: High voltage effects on space charging in the ionosphere, *IEEE Transactions on Nuc. Sci., 35,* 1386, 1989.

Burke, W. J., W. J. Raitt, D. C. Thompson, J. S. Machuzak, L. C. Gentile, B. E. Gilchrist, C. Y. Huang, D. L. Cooke, D. A. Hardy, D. G. Olson, J.-P. Lebreton, and C. Bonifazi, Shuttle charging by fixed energy beam emissions, *Geophys. Res. Lett., 25,* 725, 1998.

Fahleson, U., Theory of electric field measurements conducted in the magnetosphere with electric probes, *Space Sci. Rev.*, 7, 238, 1967.

Falthammar, C-G., Electric fields in the magnetosphere – A Review, *Planet. Spa. Sci., 37,* 899, 1989.

Garrett, H. B., The charging of spacecraft surfaces, *Rev. Geophys. and Space Phys., 19,* 577, 1981.

Gentile, L. C., W. J. Burke, C. Y. Huang, J. S. Machuzak, D. A. Hardy, D. G. Olson, B. Gilchrist, J.-P. Lebreton, and C. Bonifazi, Negative shuttle charging during TSS-1R, *Geophys. Res. Lett., 25,* 433, 1998.

Gilchrist, B. E., P. M. Banks, T. Neubert, P. R. Williamson, N. B. Myers, W. J. Raitt, and S. Sasaki, Electron collection enhancement arising from neutral gas jets on a charged vehicle in the ionosphere, *J. Geophys. Res., 95,* 2569, 1990.

Myers, N. B., W. J. Raitt, B. E. Gilchrist, P. M. Banks, T. Neubert, P. R. Williamson, and S. Sasaki, A comparison of current-voltage relationships of collectors in the earth's ionosphere with and without electron beam emission, *Geophys. Res. Lett., 16,* 365, 1989.

Raitt, W. J., D. C. Thompson, B. E. Gilchrist, and V. M. Aguero, Electrical charging of space platforms at low earth orbit altitudes, *Adv. in Space Res., Active Experiments in Space Plasmas,* in press, 1999.

Raitt, W. J., Space power experiments aboard rockets SPEAR-3, Final Report, *DNA-TR-95-8*, 1996.

Raitt, W. J., Sounding tethered payload experiments: The NASA CHARGE program, Proceedings, *Fourth International Conference on Tethers in Space*, Vol. II, 107, Washington, D. C., 10-14 April 1995.

Raitt, W. J., J. Ernstmeyer, N. B. Myers, A. B. White, S. Sasaki, K-I. Oyama, N. Kawashima, A. C. Fraser-Smith, B. E Gilchrist, and T. J. Hallinan, VLF wave experiments in space using a modulated electron beam, *J. Spacecraft and Rockets, 32,* 670, 1995.

Raitt, W. J., SPEAR-1 Payload and SPEAR-2 External Diagnostic Package, Final Report, *DNA-TR-91-132*, 1991.

Raitt, W. J., J. Blades, T. S. Bowling, and A. P. Willmore, A satellite-borne positive ion mass spectrometer, *J. Sci. Inst. E, 6,* 443, 1973.

Whipple, E. C., Potentials of surfaces in space, *Rep. Prog. Phys., 44,* 1197, 1981.

Williamson, P. R., W. F. Denig, P. M. Banks, W. J. Raitt, N. Kawashima, K. Hirao, K-I., Oyama, and S. Sasaki, Measurements of vehicle potential using a mother-daughter tethered rocket, *Artifical Particle Beams in Space Plasma Studies,* Ed. B. Grandal, Plenum, 645, 1982.