Bootstrap Charging on the DSCS Satellite

Shu T. Lai, David Cooke, Bronek Dichter, Kevin Ray, Alex Smith
Space Weather Center of Excellence
Space Vehicles Directorate
Air Force Research Laboratory
Hanscom AFB., MA 01731-3010

and

Ernest Holeman
Boston College
Chestnut Hill, MA 02167

Abstract

Charging of surfaces surrounded by larger surfaces on spacecraft requires special treatment. The usual Mott-Langmuir current collection formula does not apply because of the lack of spherical symmetry. It is insufficient to consider the interaction between each surface and the ambient plasma. It is necessary to include the interaction between surfaces. In the bootstrap mechanism, if the surrounding surfaces are at higher negative potentials than that of the surrounded small surface, a local potential well forms above the small surface. The potential well prevents the secondary electrons from leaving the small surface. On the other hand, the secondary electrons from the surrounding surfaces can land on the smaller surface. As a result, the small surface's potential swings negative, approaching an equilibrium potential which equals that of the surrounding surfaces. The time scale of the approach depends on the relative capacitances of the interacting surfaces. The simultaneous measurements of the potentials of two small surfaces and the spacecraft ground surface on DSCS offer an excellent opportunity for studying spacecraft surface interactions in space plasmas. In this paper, we report on the first observation of bootstrap charging in space.

1. Introduction

It is well known that current collection by an ideal spacecraft in the geosynchronous orbit environment is given by the orbit-limited Mott-Langmuir probe equation:

$$I_i(0)\left(1-\frac{e_i\phi}{kT_i}\right)-I_e(0)\exp\left(-\frac{e_e\phi}{kT_e}\right)=0 \qquad \textbf{(1)}$$

where the first term represents the incoming ambient ion current $I_i(\phi)$ and the second term the incoming ambient electron current $I_e(\phi)$. In eq(1), e_i = e, and e_e =-e, where e is the elementary charge. The spacecraft potential ϕ in eq(1) is assumed negative, which occurs when the space plasma is energetic. The secondary electron current $I_s(\phi)$, the backscattered electron I_b, and the photoelectron current $I_{ph}(\phi)$, should also included in the current balance equation, if they are present.

$$I_i(\phi)-I_e(\phi)+I_s(\phi)+I_b(\phi)+I_{ph}(\phi)=0 \qquad \textbf{(2)}$$

The secondary electrons and photoelectrons are of low energy, their temperatures being about 1 to 2 eV only. Depending on the surface material, $I_s(\phi)$ may exceed the incoming electron current $I_e(\phi)$. The photoelectron current $I_{ph}(\phi)$ often exceeds all other currents, except during very stormy events. Both $I_s(\phi)$ and $I_{ph}(\phi)$ are important**;** neglecting either one of them would affect the charging solution of eq(2). The backscattered electrons are less abundant and less important.

Differential charging may occur on a spacecraft with many surfaces and different surfaces properties. That is, the surfaces may charge to different potentials. The surfaces, at different potentials, interact with each other, resulting in new potentials self-consistently. This is where bootstrap charging occurs as discussed in the next section.

2. Bootstrap Charging

Suppose a small surface starts with a potential initially. As the potential of the neighboring large surface changes in time, the potential of the small surface may be affected. This is the theoretical idea of bootstrap charging [*Mandell*, et al., 1978]. We believe that no explicit space observation has been reported before**;** this is the first time.

To illustrate the process of bootstrap charging, let us discuss an example. Figure 1 shows a small surface at an initial potential ϕ_1 = -2 V, say, surrounded by a large surface at ϕ_2 = -900 V, say. That is, the large surface is at -898 V relative to the small one. The potential contours (up to hundreds of Volts negative) from the large surface extend to above the small one.

A potential well, with a potential barrier and a saddle point, is formed above the small surface. As a remark, we note that an analytical expression of a potential well due to a circular surface surrounded by a larger one has been given by *Sherman and Parker* (1971).

In Figure 1, the secondary electrons from the small surface cannot leave the potential well, because secondary electrons have a few eV only in energy whereas the potential well is hundreds of Volts deep. On the other hand, the ambient electrons, which are of keV, or tens of keVs, in energy depending on the geomagnetic condition, can keep on coming in at will through the potential barrier onto the small surface. Furthermore, the secondary electrons from the larger surface are attracted towards the smaller surface which is relatively positive in potential. The incoming electrons charge the small surface negatively, until the potentials of the two surfaces are about equal. When they do, there will be no more barrier, the secondary electrons from the small surface can leave, and the secondary electrons from the larger surface will no longer be attracted towards the smaller one. Thus, an equilibrium or self-consistent set of potentials form. This illustrates the process of bootstrap charging.

The time scale of change in potentials depends on the ratio of the capacitances of the interacting surfaces [*Mandell, et al.*, 1978]. In the geosynchronous orbit environment, it takes a ms to charge a typical uniform satellite [*Garrett*, 1981]. A small surface of $1 cm^2$ in area surrounded by a spacecraft ground of $1 m^2$ in area, would have a small capacitance ratio of 1 over 1000. Thus, the potentials change rapidly.

The potential of the small one is affected significantly by that of the large surface, but not vice versa. As an analogy, transferring water from the sea to a bottle can raise the latter's water level significantly, but transferring water from the bottle to the sea would not affect the sea level.

3. Symptoms of Bootstrap Charging

As a corollary of the above illustration, the salient features are as follows. (1) If a small surface develops a negative potential relative to the neighboring large one, we expect no modification of the potentials. This is because the small surface cannot develop potential barriers over the large one. In nature, a small system can hardly affect a large one. (2) If the small surface potential becomes positive relative to the large one (even if both potentials are negative relative to the space plasma), bootstrap charging occur. When it does, the small surface potential changes rapidly until it is approximately the same as that of the large one.

4. The DSCS Satellite

The DSCS satellite experiment measures the potentials of two small dielectric surfaces relative to that of the spacecraft ground [Figure 2]. The relative potentials are measured directly by a device behind each of the small surfaces [*Mullen et al., 1997*].

A precaution is in order. The zero potentials of the small quartz and kapton surfaces are not registered as zero, but as about -1500 V. This is due to an instrument problem, which was known before launch [*Mullen*, private communication]. That is, the entire scale of the small dielectric surface potential should be shifted such that -1500 volt means 0 volt truly. In sunlight, the shift amount is about -1200 volt. In this paper, we have avoided this confusion by labeling the quartz and kapton potentials during quiet geomagnetic conditions as zero V. As a result, this precaution is not needed.

A low energy plasma source is also onboard. The source generates a partially ionized neutral xenon gas at thermal energies on command. The purpose is for testing charging mitigation. However, our purpose here is to look for evidence of bootstrap charging of the two small surfaces, during periods when the plasma source is off.

The two small surfaces are each of about $1 cm^2$ in area; that of the spacecraft ground exceeds $1 m^2$. One small surface is made of kapton; the other is quartz fabric. Behind each of them, the voltage difference between the small surface and the spacecraft ground is measured directly [*Mullen, et al.*, 1997]. The spacecraft is approximately rectangular in shape and is in a geosynchronous orbit. The small surfaces are both on the ram side of the spacecraft and are in sunlight for several hours a day. About half of the spacecraft body surface is in sunlight unless in the Earth's shadow.

6. Spacecraft Charging on DSCS

When the incoming electron flux exceeds the outgoing secondary and backscattered electron fluxes, charging onset occurs. The secondary electrons are much more abundant than the backscattered electrons. The charging level is governed by the balance of currents, as discussed in an earlier section. If the secondary electron current is suppressed, the current balance changes and, as a result, the charging level changes.

In sunlight, the (outgoing) photoelectron current may exceed the (incoming) ambient electron currents. As a result, sunlight tends to suppress negative charging. Indeed, the negative level charging events of the two small surfaces on DSCS occur only when they are not facing the sun.

However, half of the DSCS spacecraft conducting body (ground) is always in sunlight unless during eclipse. Negative level charging of the DSCS ground can occur in sunlight, but only when the space plasma is exceptionally energetic. In order to better identify the driving force and the system response, we select periods when the spacecraft is in eclipse.

A standard method to measure the negative potential of spacecraft ground is to identify the shift of the peak of the positive ion flux spectrum. The ions are accelerated towards the negatively potential of the spacecraft, thereby shifting the ion distribution function by an amount equal to the energy due to the spacecraft potential [Figure 3]. The ion flux spectrum is obtained from the ion distribution function multiplied by the ion velocity and integrated over appropriate look angles. This is the method used in measuring the charging level of the DSCS spacecraft ground [Figures 4,5]. We will discuss Figures 4,5 in details in the Sec.6.

The ion peak method is an indirect method but usually works well. However, for equatorial orbits, such as in the case of DSCS, a precaution is in order. In the DSCS data, there are occasional peaks due to equatorial ion beams. These ions bounce back and forth along a daytime magnetic flux tube connecting the north and south auroral regions. There are two characteristics for identifying these bouncing equatorial ions. (1) The typical energy of these ions detected on DSCS is around 300 eV. (2) The energy rises steadily and then falls steadily as the satellite travels into, across, and then out of the flux tube. Such peaks due to bouncing equatorial ions can be easily mis-interpreted as spacecraft potentials. Such ion beams are outside the scope of this paper.

6. Bootstrap Charging on DSCS

Figure 4 shows a bootstrap event on DSCS. We first explain the three data panels. The upper panel shows the ion flux spectrum. The middle panel shows the release rate of the low energy ionized neutral gas (plasma) for mitigation. The lower panel shows the relative potentials of the small kapton surface (green line) and the small quartz surface (red) with respect to the spacecraft ground, and the incoming electron flux (white) which includes electrons of all energies.

From about 1600 to 11900 sec UT, both surfaces (green, red) are at negative potentials. From about 1900 to 5100 UT, the low energy plasma release is on as indicated by the (partially ionized) low energy gas release rate in the middle panel and also by gas on-off indicator (plateau) in the lower panel in the same period. The low energy ionized gas (or plasma) reduces, but not completely, the potentials of the kapton and quartz surfaces. When the gas release stops, the potentials climb up quickly again. There are three yellow vertical lines and later one light blue vertical line in the top panel. They are data glitches due to unknown reason and can be ignored.

What is interesting is that at just before 12000 UT, the spacecraft ground potential (also called frame charging) reaches about -2 kV as indicated by the bright yellow ion peak in the upper panel. At that moment, both the kapton and quartz potentials relative to the ground fall to zero rapidly with an apparently exponential rate.

We contend that this is an evidence of bootstrap charging. Initially, the small surface (kapton and quartz) are at around -1 kV. At about 12000 UT, the large spacecraft ground reaches about -2 kV, which exceeds -1 kV of the small surfaces. The bootstrap process occurs, which rapidly changes the potentials of the small surfaces to about the same potential as the large surface (ground). Therefore, the relative potentials becomes zero. The rate is exponential with a time constant given by the ratio of the surface capacitances, as discussed in Sec.3.

Another clear evidence of bootstrap charhing is presented in Figures 5. The kapton and quartz surfaces charge to about -1 to -2 kV initially. Then, at about 11700 UT, the spacecraft ground charge to beyond -2 kV. The small surfaces rapidly charge to the same potential as the ground, resulting in a zero relative potential.

Finally, we remark that in all four years of DSCS data, we have not seen a single case in which the spacecraft ground charges to a higher negative potential than the small surfaces. As soon as the ground charges tries to a higher negative potential, the small surfaces rapidly charge to the same potential, resulting in a zero relative potential.

7. Summary and Conclusion

We began by explaining the theoretical idea of bootstrap charging. Heretofore, no experimental evidence of bootstrap charging has been reported. The DSCS spacecraft charging data of two dielectric (kapton and quartz) surfaces and of the ground provide an excellent opportunity to study the charging interactions of these surfaces. In this paper, we have reported the first observations of bootstrap charging in space.

References

Garrett, H.C., "The Charging of Spacecraft Surfaces," *Rev. Geophys. & Space Phys.*, Vol.19, 1981, pp.577-616.

Mandell, M.J., Katz, I., Cassidy, J.J., Schnuelle G.W., and Steen, P.G., "The Decrease in Effective Photocurrents due to Saddle Points in Electrostatic Potentials," *IEEE Trans. Nucl. Sci.*, Vol. NS-25 (6), 1978, pp.1313.

Mullen, E.G., A.R. Frederickson, G.P. Murphy, K.P. Ray, E.G. Holeman, D.E. Delorey, R. Robson, and M. Farar, An autonomous charge control system at geosynchronous altitude: flight results for spacecraft design consideration, *IEEE Trans. Nucl. Sci.*, Vol.44, No.6, 2188-2194, 1997.

Sherman C. and L.W. Parker, Potential due to a circular double disk, *J. Appl. Phys.*, Vol.42, 870-872, 1971.

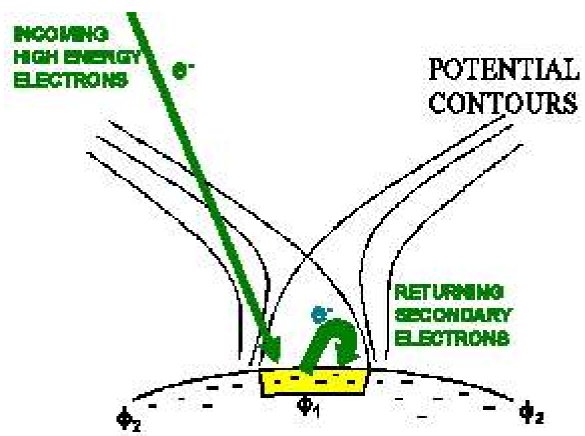

Figure 1. A potential well with a saddle point above a small surface surrounded by a large surface, which is at a higher level negative potential relative to the well. The secondary electrons from the small surface are trapped in the well.

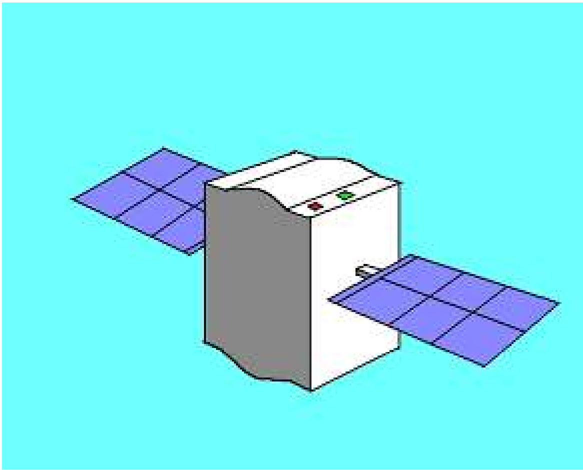

Figure 2. A schematic diagram of the DSCS satellite. The small kapton and quartz surfaces and the ion flux detector (not shown) are on the ram side of the satellite.

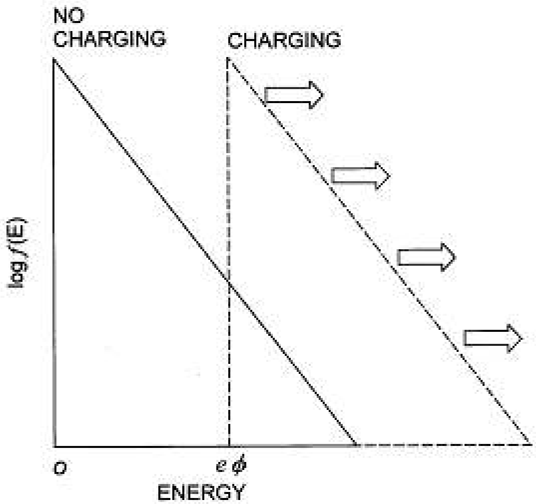

Figure 3. Shift of the Maxwellian distribution function of the repelled charge species. The magnitude of the shift indicates the charging level.

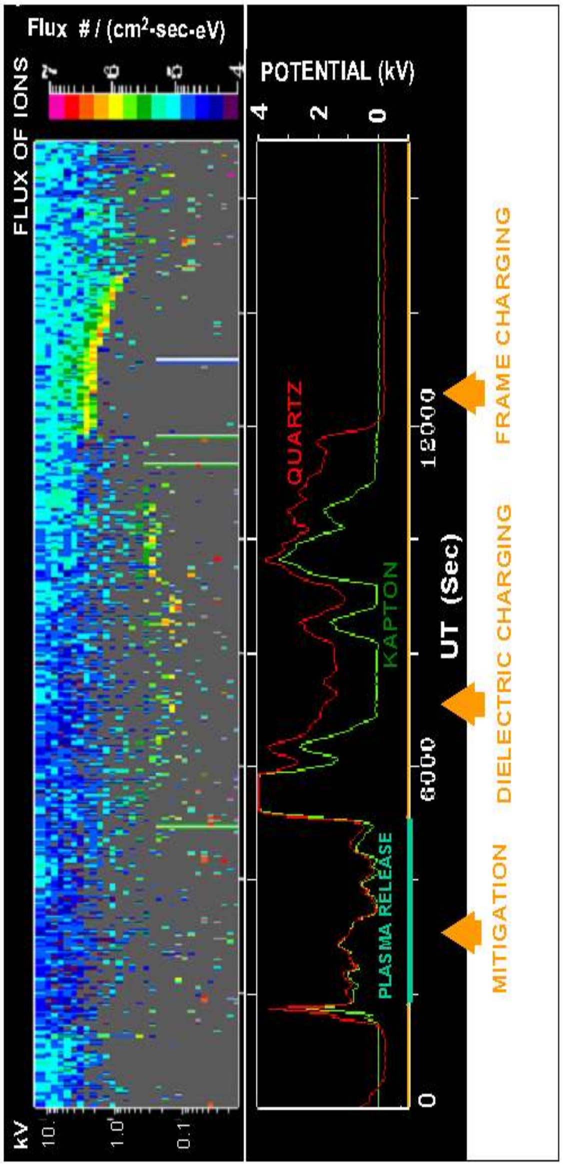

Figure 4. A sequence of events showing the small dielectric surfaces charging, mitigation by the release of low energy xenon plasma, the small dielectric surfaces charging again, and high level negative charging of the spacecraft ground (or frame).

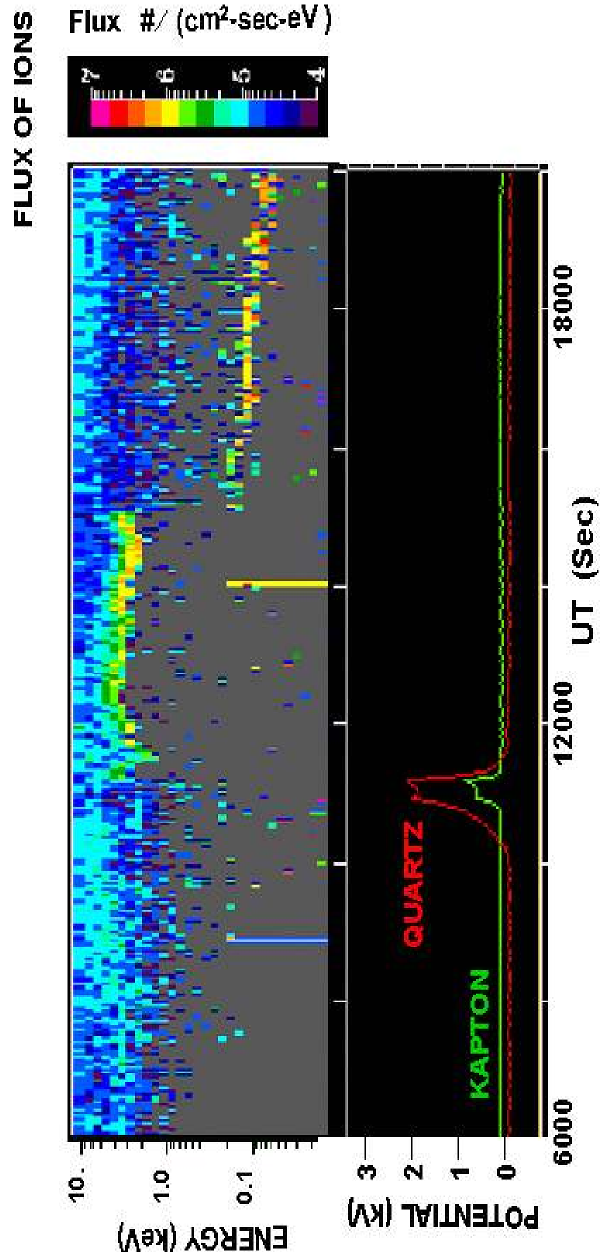

Figure 5. A sequence of events showing the small dielectric surfaces charging followed by ground charging. The two vertical lines (blue and yellow) at about 8400 and 14000 UT are noise glitches.