# Spacecraft Charging - Welcome and the NASA Glenn Perspective
# Or
# My World and Welcome to It


Dale C. Ferguson
NASA Glenn Research Center
Cleveland, Ohio, USA 44135
216-433-2298, fax 216-433-6106, email ferguson@grc.nasa.gov



## ABSTRACT

Here, we welcome participants to the 7$^{th}$ Spacecraft Charging Technology Conference - A Spacecraft Charging Odyssey, and lay out the NASA Glenn Research Center perspective on spacecraft charging - past, present, and future.


## WELCOME

Spacecraft Charging as a discipline has more than twenty years of history and tradition as we meet in the Netherlands this week. From the very early spacecraft charging failures, such as Marecs-A, to the recent "anomalies" such as those experienced on the Tempo-2 and PAS-6 satellites, it is important to note that hundreds of millions of dollars and sometimes the fate of entire large corporations depend on the fast resolution of problems with satellites on-orbit. This is not easy to do, because usually the satellites cannot be recovered for investigation, and sometimes the only clues are literally what time of the day it is, or whether there was a solar flare. Much preferable, of course, is to prevent such calamities from happening in the first place. As participants in this conference, our investigations, both scientific and engineering, are important to keep telecommunications alive and well in the space age.

## THE NASA GLENN CONNECTION

What is now NASA Glenn Research Center at Lewis Field, in Cleveland, Ohio, USA, was formerly NASA Lewis Research Center. It was named for the first administrator of NACA, the precursor to NASA in the USA. The name change was to honor John Glenn, an Ohio boy who became the first US citizen to orbit the earth. Thus, our very name is now associated with earth-orbit. Since about 1974, NASA Glenn has been the NASA center most deeply involved in spacecraft charging issues. It continues to be the Center of choice for spacecraft charging testing and experimentation, flight experiments and models. NASA Lewis was the co-sponsor of the first Spacecraft Charging Technology Conference (SCTC) in 1977. In the following, memory was the greatest resource. I apologize in advance for those who have inadvertently been omitted.

## EARLY HISTORY

Early spacecraft charging investigations at NASA Lewis were done by Bob Lovell, John Stevens, Frank Berkopec, Carolyn Purvis, John Staskus, Norm Grier, Stanley Domitz, Joe Kolecki, Jim Roche and others. Some involved participation in design and construction of flight experiments, such as SCATHA (Spacecraft Charging at the High Altitudes), ATS-6 (Advanced Technology Satellite) and SPHINX (Space Plasma High-Voltage Interactions Experiment), etc. Some of these experiments were successful, but SPHINX went in the drink. Others involved laboratory experimentation, such as SCATSAT (a model satellite for looking at arc current propagation), or the high voltage experiments done in large vacuum chambers at JSC and elsewhere. Still others were theoretical models of charging, that eventually led to the NASCAP codes, but were also applied initially to charging studies for the Galileo spacecraft and others. Steve Gabriel and Henry Garrett were important players in these early studies.

Once the basic physics of charging had been worked out, the emphasis of the group turned to the complex modeling necessary to do charging calculations, to determining the physical properties of materials important to charging, and to production of guidelines for spacecraft design. These areas of work involved the participation of outside companies and universities.

in 1984, it has been used around the world for detailed charging analyses. Instrumental in its development were Ira Katz and Myron Mandell, still extremely active in spacecraft charging studies. Later, Gary Jongeward, Victoria Davis, John Lilley, Bob Kuharski, and Barbara Gardner took up the cause and made major contributions.

Case Western Reserve University was contracted to determine the basic charging parameters of materials, such as secondary electron yields and photoelectric effect yields of spacecraft materials. Dick Hoffman, Bill Gordon, and Tom Eck come to mind as important contributors. Other universities, such as the University of Iowa, Colorado State University, Utah State, MIT and many more made important contributions as well, as did the Naval Postgraduate School, where Chris Olsen hosted one of the early SCTCs. Special mention must be given to Gerry Murphy (Iowa), Paul Wilbur (CSU), and Dan Hastings (MIT) for their work with, for, and important to spacecraft and their plasma interactions. Guidelines were written, with the first and most widely used being that of Carolyn Purvis and John Stevens of NASA Lewis, and Al Whittlesey and Henry Garrett of JPL.

## SDIO IS COMING! SPACE STATION IS COMING!

In the early eighties, it became clear that a permanent space station would be built, and that it would need, for efficiency's sake, a high voltage solar array. Now a new spacecraft charging focus became important - the necessity of preventing high voltages from arcing spacecraft in the Low Earth Orbit (LEO) environment, rather than the GEO (Geosynchronous) environment that was important for communications satellites.

At about the same time, SDIO (the so-called Star Wars effort) made orbiting high power platforms of a military nature necessary in LEO. Here, the tremendous demands for power might lead to nuclear generators that might even run open-loop, putting out tons of effluents per second. It was inevitable that such systems would interact with the orbital environment.

NASA Lewis geared up for these two big LEO efforts. New scientists and engineers were hired, including David Snyder, Dale Ferguson (the author), Joel Galofaro, and others. All of these have gone on to make contributions to spacecraft charging in LEO.

Orbiting LEO experiments were performed, including PIX (Plasma Interactions Experiment) and PIX-II. These were piggyback experiments on Delta carriers whose primary purpose was to launch other satellites. PIX showed that high voltage arcing and the so-called snapover phenomena, which had been seen in laboratory tests, could also occur in space. PIX-II showed the dependence of those things on solar array area, plasma conditions, voltage, etc.

Meanwhile, modeling efforts led to codes such as EPSAT (Environments Power System Analysis Tool), which went on in the 90's to become the Environments Workbench (EWB) of today. It integrates nearly all LEO environments and interactions into a single tool. Unfortunately, export control restrictions still prevent it from being distributed outside of the USA.

One of the still unanswered questions was first posed during this era - how can solar arrays arc at potentials which at first glance are not sufficient to produce breakdown strength electric fields? Some of the papers at this conference are on this very topic.

## SPACE STATION ELECTRICAL GROUNDING

An early space station-oriented flight experiment was called VOLT (for Voltage Operational Limits Test). It was designed, built, and tested to determine the highest voltage (and thus the highest efficiency) that could be used in the space station solar array design. Unfortunately, official announcement of the Space Station Program meant that all space station-related work was rolled into the Space Station funding pot, before there was any money in it to support the work. Suffice it to say that VOLT died for lack of funding, and the Space Station chose a 160 V power system, safely below the solar cell arcing thresholds found on PIX-II.

Star Wars-related suborbital flight experiments with which NASA Lewis was involved were called SPEAR (Space Power Experiments Aboard Rockets). SPEAR-I and SPEAR-III were successes, and gave information about the interactions of power systems in space up to 20 kV. SPEAR-II was blown up by range officers when its attitude control failed, but it was nevertheless considered by BMDO to be 85% successful, based on ground-tests conducted in its development! Solar cell experiments on SPEAR-III failed because they were accidentally placed in the wake of the suborbital rocket body throughout the flight.

Theoretical studies of Space Station arcing were done by Jongeward and Don Parks at S-Cubed and by Roger Metz of Colby College, funded by NASA Lewis. These showed how arcs might get started at only 200 volts or so, and how they would couple to the Space Station power system if they occurred. David Snyder of Lewis measured peak arc strengths and total energies as a function of voltage and capacitance.

About this time, an opportunity to hire new personnel presented itself at NASA Lewis. Some of those hired were Civil Servants, and some were contractor personnel. New hires included Ricaurte Chock, Joel Herr, Tom Morton, and Russ Cottam. Since that time, each has distinguished himself with important work in spacecraft charging.

Originally, the Space Station was to have had a 20 kHz AC power system, which would have effectively decoupled the solar arrays from the secondary power system onboard the Space Station modules. When decisions were made by an interim Space Station Administrator to use a DC 160 V power system and to ground the Space Station to the negative end of the solar arrays, an outcry went out from the plasma interactions community, led by the author and David Snyder of LeRC and Ralph Carruth at MSFC. It was clear to anyone familiar with LEO spacecraft charging that this would cause the Space Station to charge to high negative voltages with respect to the ambient plasma, and make the arcing problem into a systems problem, not just a solar array problem.

The Space Station responded by starting the Electrical Grounding Tiger Team, to examine the issue. After a year of studies, involving most plasma experts throughout the US and Canada, the conclusion that was reached was that dielectric breakdown would denude the Space Station anodized aluminum in a matter of a few years unless a hollow cathode plasma contactor was used on Space Station to actively control its floating potential. These conclusions were based on plasma chamber testing done at Lewis, MSFC (primarily by Jason Vaughn), and other places. Later, when the Space Station became the International Space Station (ISS), plasma contactor work was continued, and now Plasma Contacting Units (PCUs) are operating as the primary charge control technique on ISS.

As part of this effort, Ricaurte Chock of NASA Lewis, using NASCAP/LEO, showed that the electron collection of the ISS solar arrays was a strong function of the test electron temperature. This result was verified by testing done by Bernie Sater and Marian Felder on a full ISS solar array panel pair at NASA Lewis. Their tests also confirmed the efficacy of plasma contactors to control the potential of large areas on the Space Station.

Hollow cathodes had been used at NASA Lewis to neutralize electric propulsion beams for some time, and were proposed for use on the international TSS (Tethered Satellite System) electrodynamic tether experiments. While those experiments eventually flew without hollow cathodes, the PMG flight experiment (Plasma Motor Generator) of Jim McCoy at JSC proved the concept with hollow cathodes at both ends of a 500 m tether. Flight plasma diagnostics were provided by Roy Torbert and others at the University of New Hampshire, and modeling was done by John Raitt and others at Utah State, and by John Lilley and Ira Katz of S-Cubed using EWB, now the "official plasma interactions tool" of the Space Station program. PMG flew as a piggyback on a Delta GPS launcher. Emission currents as high as 0.3 amp were measured.

In 1994, the SAMPIE flight experiment flew in the payload bay of STS-62. SAMPIE stood for Solar Array Module Plasma Interactions Experiment. SAMPIE had originally been proposed as a joint experiment of ESA and NASA, but ESA pulled out. SAMPIE tested Space Station solar cells, some of which were modified to minimize plasma interactions. It also had some well characterized samples of pure metals, with known separations, an anodized aluminum sample, and a Vbody and Langmuir probe to characterize its plasma environment. Analysis of SAMPIE data improved our understanding of LEO plasma interactions greatly, and were even used by Boris Vayner, a new Lewis NRC fellow, to discover ion acoustic waves produced by arcing. Barry Hillard, hired by NASA Lewis to be the SAMPIE Project Scientist under the P.I. Dale Ferguson (the author), branched out into charging and Paschen discharge in the Martian environment.

NASA Lewis was also involved in 1994 in the Air Force orbital flight experiment called PASP Plus (Photovoltaic Array Space Power Plus Diagnostics). This experiment, developed by Don Guidice at Hanscom Air Force Base, tested over a dozen solar cell designs in the LEO space environment for arc thresholds, current collection, radiation damage, etc. Data obtained from it were invaluable in space- qualifying new cell and array designs and making basic measurements of long-term array performance in space. Many of the arrays were plasma tested in LeRC chambers, and LeRC even contributed to sample buildup in many cases.

## OOPS, GEO CHARGING AGAIN!

NASA Glenn has been involved with agency, interagency, and national committees dealing with space environmental effects from their inception. For instance we have been a part of the Space Technology Interagency Group dealing with space environments. Later, when the Space Environment Effects (SEE) Program was started, the Chair of the Plasmas and Fields Working Group was placed at NASA Lewis, and remains at NASA Glenn today. MSFC is the seat of the entire SEE program. The leadership of SEE has now passed from Steve Pearson to Billy Kauffman, and the Plasma Co-chairs are Dale Ferguson (the author) and Jody Minor of MSFC. Much of the SEE activity has been done by universities and companies under contracts awarded as part of SEE NASA Research Announcements.

Because of the identification of the NASA Glenn Research Center with spacecraft charging problems, we were among the first notified when in 1997, severe anomalies were seen on two Space Systems/Loral satellites. Entire solar array strings were shorting out and becoming unusable. At the rate at which the strings were going, it was only a matter of time before the satellites were severely impacted. As a member of the anomaly resolution team, David Snyder of NASA Glenn agreed to do plasma testing of the Loral arrays in our plasma chambers.

The hypothesis that the failures were spacecraft charging-related was made based on the coincidence of the failure times with high levels of geomagnetic activity as measured by satellites in similar orbits. However, not enough energy was contained in the capacitance of one solar array string to destroy a string. After much testing, it was decided that arcs were jumping from one solar array string to another, and were becoming continuous, powered by the entire solar array. At Glenn, we showed that seemingly small changes in the design of the Loral solar arrays had placed them at risk of destroying themselves. The cells had been moved closer together. The coverslides had been made thinner and less conductive. And, the solar array string voltage had been increased to the 100 V range.

All of these changes contributed to the arcs. The change in coverslides had made the electric fields stronger, as had the increased voltages. PASP Plus had shown that similar cell coverslide designs could arc at voltages as low as 75 volts. The strings were now close enough together that if one arced into the plasma, it would "couple" to the adjacent string, and the arcs could become continuous. Eventually, the Kapton array substrate charred, forming a permanent short. Since the arrays in question were the first Loral had flown with GaAs solar cells, it was important that the cell material be exonerated, for another half-dozen satellites with the identical cell design were waiting on the launchpad. The happy ending was that Glenn testing performed by Snyder, Vayner, and Galofaro showed the cause of the problem, corrective measures were taken on all the Loral solar arrays, and there have been no similar problems on any of the Loral satellites launched since.

## LEO, TOO?

Word spread about the Loral problems, and it wasn't long before Glenn received a phone call from the EOS-AM1 team at Goddard. Their solar arrays were virtually identical to the Loral arrays, but had an even higher string voltage! Could they arc in the same way? Glenn testing showed they could. In the Loral case, three corrective actions were taken - the high voltage adjacent cell gaps were grouted, the string layout was changed to reduce interstring adjacent voltages, and diodes were put in place to prevent strings not involved in the arcing from feeding current to the arc-sites. The EOS-AM1 case was different. The only option available was flat-pack diodes to prevent arcs from drawing enough current to become continuous. Power traces then had to be covered with Kapton to prevent arcs from occurring on the wrong sides of the diodes. Glenn testing showed this fix to be effective, EOS-AM1 (now Terra) was launched, and no solar array arcing problems have occurred.

## DEEP SPACE 1

Another fallout event from the Space Systems Loral problems was last-minute changes on Deep Space 1 (DS-1). We at Glenn had been consulted on the solar cell and array design on DS-1, but had not seen the power systems design until immediately prior to flight. DS-1 used a power system with total currents and voltages in the range for the Loral-type problems to occur. However, the arrays were concentrator arrays, and the cell and string designs had no high voltage cells adjacent to each other. Upon further examination, however, it was found that the main power traces had exposed conductors separated by a small distance, where arcs, if they happened, could jump from one trace to the other, shorting out the entire power panel. Each power panel provided half the DS-1 power.

At the time this was discovered, one of the power panels was already attached to the spacecraft. Nevertheless, the decision was made to modify both power panels by covering the suspect power traces with RTV, so there could be no arcing from one to the other. Robb Frederickson at JPL was influential in convincing DS-1 to make this decision. The attached panel was removed, and both panels were modified. As you must know by now, DS-1 was launched and was a phenomenal success, and its ion engines have been operating now continuously for years on its interplanetary mission.

## ELECTROSTATIC CHARGING ON MARS

NASA Glenn had several experiments on the Mars Pathfinder Sojourner Rover on the surface of Mars. One of these, the Wheel Abrasion Experiment, was supposed to find the abrasion of thin metallic layers on one of the rover wheels when it spun in the Martian dust. Those at Glenn who were involved in this experiment included the author, Joe Kolecki, and David Wilt. As with most good experiments, this one not only shed light on its desired goal, but also taught us about other phenomena. In particular, dust adhering to the wheel showed that electrostatic charging had occurred, an effect that had been predicted (in fact, we had put discharging points on the rover to prevent this from causing unwanted discharges). In the case of the Sojourner Rover, the dust only stuck to the wheel at points on the wheel where the photoelectric effect had not discharged the wheel, and only occurred when actual roving was taking place, not when the wheel spun in-place. It is estimated that about 80 V of charging occurred on Sojourner.

## ISS AGAIN AND FPP

As the year 2000 rolled around, the ISS plan was to control its potentials by using one PCU, and after about two years, the other PCU on orbit was to be substituted, and after 2-4 years, both would be replaced. This would mean bringing new PCUs to orbit, and returning and refurbishing the orbital units. The initial PCUs were to be put up on flight 3A, in June of 2000, and would be operational when the main solar arrays (the main ISS charging devices) went up on flight 4A in November. When one of the PCUs failed its acceptance test in early 2000, the flight deadline loomed, and the program seriously considered delaying orbital deployment of the PCUs. A report to the ISS Safety Review Panel even went so far as to cite that since there would be no ISS problems in the absence of the PCUs except for slowly developing surface destruction, there would be no operational constraint on ISS if the PCUs were not on-orbit until after 4A.

A telephone call to the author from Ray Degaston (one of the original ISS Electrical Grounding Tiger Team participants, but now with the ISS Independent Assessment Office) alerted NASA Glenn to the problem in February, and a 4 hour presentation to the ISS team at JSC was made. In it, the author showed the newly found possibility of continuous arcing from the arc sites on ISS if the PCUs were not operating, and pointed out possible problems to EVA astronauts from exposure to such large arcs. A hurried call to address the ISS Vehicles Office followed, and its Steve Porter thereafter called for a PCU Tiger Team effort to explore these issues, beginning in March, 2000. The Analysis and Testing Tiger Team group was led on the NASA side by Ralph Carruth, of MSFC, and on the Boeing side by Jim Lambert.

The ISS PCU Tiger Team, through analysis and testing, showed that the danger of continuous arcing on ISS was not real, because the threshold is too high, but that EVA astronauts could become part of the arc current path, and parts of their EVA suits would become the preferred arc-sites (with a threshold of 68 volts or less). Even capacitance-fueled arcs on an astronaut would put one amp through the astronaut's heart, well above lethal levels. The spacesuit components testing was done by Todd Schneider at MSFC, while a threshold of 74 volts was found by David Snyder at Glenn for ordinary ISS anodized aluminum. Thus, the arcing hazard on ISS was elevated to a catastrophic hazard, capable of killing personnel. Such a hazard demands two fault tolerance, meaning that three independent controls must be in place.

Two approaches were then taken by the ISS program. The PCUs were placed on the fast-track, with emphasis on launch no later than flight 3A. They were tested in a vacuum chamber to guarantee that both PCUs could be operated at once. This provided one fault tolerance during EVAs. The other approach was to turn the ISS solar arrays into their own plasma wakes during EVAs. This approach demanded experimental verification that it would, indeed, control the ISS potential, and experiments had to be done to determine how far into the wake they had to be pointed to do so. But the ISS had no way of measuring its potential relative to the plasma. A device had to be flown, and had to be flown by flight 4A, when the high voltage solar arrays would be deployed.

The NASA Glenn solution was to design, build, test, and fly probes to measure the ISS potential relative to the ambient plasma. This had to be done by November, while the decision to fly was made only in June. Could it be done in time? Only if the interfaces were kept as simple as possible, and only manned flight-qualified components were used. The device was called FPP (for Floating Potential Probe). Dale Ferguson was (and is) the Principal Investigator, and the Project Scientist is Barry Hillard. The probes FPP would use were previously flown on the SAMPIE experiment in 1994. A flight qualified motherboard was selected. Power would come from 2 test samples of ISS design solar arrays, of 16 cells each. Communications would be provided by a Wireless Instrumentation System, to telemeter data from the FPP, located up on P6 near the solar array canisters, far away from the PCUs and modules, to an antenna on the Unity Node some 20 meters away. Then it would be sent to Earth on regular communications passes over ground stations. Such a system had been used several times previously on the Space Shuttle. Astronauts would have a real-time display on a laptop computer inside ISS. The design and construction of the probes and main FPP unit was done by Design_Net Engineering, headed by Gerry Murphy. Invocon (headed by Kevin Champaigne) provided the communications system. Plasma testing was done at Glenn by David Snyder. The project was pushed through by Ben Sellari, of the JSC ISS team.

FPP met its flight deadline, was deployed by astronauts on flight 4A, and immediately started telemetering ISS floating potentials and the ambient plasma plasma parameters from its Langmuir probe.

Since its deployment, FPP data (as analyzed importantly by Ira Katz and Barbara Gardner) has already shown the following:

1. vxB charging of ISS can sometimes be the most important mechanism, and can push 0.1 amp currents through the structure.
2. The solar arrays on ISS collect much less current than had been anticipated from the SAMPIE and PASP Plus measurements. With PCUs operating, a maximum of about 0.3 amps has been observed, compared with about 1.2 amps predicted before launch.
3. Snapover is clearly seen in the electron currents collected by the ISS solar arrays, and its minute-long decay timescale to steady state currents has been seen.
4. The electron and ion collection timescales for the ISS structure have been measured to be <0.3 second and > 2 seconds, respectively, in rough agreement with pre-flight estimates of ISS capacitance. This verifies that arcs, if they occur on ISS, will involve large amounts of energy (several Joules per arc).
5. There exist about 2 square meters of ion-collecting area on the ISS solar array masts, and about 10 square meters on the main ISS structure which were unaccounted for before launch.
6. With its PCUs off, the maximum charging of the 6A stage on ISS is only about 40 volts, much less than had been anticipated, but still enough to make EVA hazard controls necessary.
7. Shunting one of the ISS solar arrays at sunrise is an effective control against charging to more than 40 volts for the current ISS configuration.
8. Turning the ISS solar arrays 97 degrees or more from the full ram condition effectively controls ISS charging.
9. Shuttle docking and undocking events have characteristic signatures in the ISS floating potential.
10. If ISS is ever allowed to arc, the signature will be seen in the FPP data.

## NEW INITIATIVES

Although all things are subject to change with the new US administration, NASA seems to have a particular interest in the following problems at the present time:

1. Space weather and effects of the solar cycle. A new initiative called Living With a Star will orbit several satellites to measure spacecraft charging (and other effects) caused by the solar wind, solar UV, and other time-variable solar effects. As part of this initiative, a Space Environments Testbed will be orbited to check out new technologies to mitigate spacecraft charging and other effects.
2. The exploration of Mars. Paschen discharge may be important on Mars, and the possibility that roving spacecraft may charge to Paschen discharge levels must be tested.
3. High voltage solar arrays in space. The Space Solar Power program has baselined very high voltage power systems and solar arrays and is paying to develop such systems. Already, several designs for solar arrays the may operate reliably at up to 1000 volts in space have been produced, and will soon be tested in laboratory experiments.
4. Electric propulsion. The high Isp of Hall and ion thrusters makes them particularly attractive for use in interplanetary and earth-orbiting missions with large orbital changes. The mass of such propulsion systems could be cut in half if they could be driven directly by high voltage solar arrays. Hall thrusters require >300 V

and ion thrusters >1000 V arrays for direct-drive use in space. Variable Isp designs also require high voltages.

## THE LONG-TERM PROSPECTS

The famous American philosopher Yogi Berra once said prediction is very difficult, especially the future. What must be evident though, is that spacecraft charging problems have not and will not go away. Advances in solar arrays and spacecraft designs often exacerbate these problems, rather than helping them. Cooperation of NASA with universities, industry, and, yes, space agencies of other countries will undoubtedly be important in the future. NASA Glenn, and indeed all of NASA, will be poised to take on all challenges, and ready to cooperate with the entire world, to solve our future spacecraft charging problems.