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To cite this version:

D. Payan, A. Sicard-Piet, J.C. Matéo-Vélez, D. Lazaro, S. Bourdarie, et al.. Worst case of Geostationary charging environment spectrum based on LANL flight data. Spacecraft Charging Technology Conference 2014 (13th SCTC), Jun 2014, PASADENA, United States. hal-01081993

HAL Id: hal-01081993

https://hal.science/hal-01081993v1

Submitted on 12 Nov 2014

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Worst case of Geostationary charging environment spectrum based on LANL flight data

D. Payan[1], A. Sicart-Piet[2], J.C. Mateo-Velez[2], D. Lazaro[2], S. Bourdarie[2], P. Sarrailh[2], N. Balcon[1]

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Abstract— Ground tests and computer simulations about satelittes charging effects require the definition of worst-case environment spectra representative of those encountered in orbit. For this, it is necessary to take into account the entire energy spectrum having an effect on both the gradient voltage build-up or mitigation on dielectrics and the absolute potential for each satellite.
Section II deals with the methodology and the criteria used to define worst-case environments, based on the physics of plasma material interaction, including the radiation induced conductivity. (RIC)

We have computed different classes of fluxes, all based on six LANL flight data for a period over 15 years. Section II presents how electron differential fluxes are extracted from LANL measurements, taking into account spacecraft potentials, including specific and necessary corrections
Then we also take into account the dose effect which affects the conductivity of all exposed dielectrics. Section III specifies different environments considered as possible worst-case environments, following the approach given in Section I.
This paper finally presents a synthesis of the spectra obtained and gives perspectives for their use for ground tests and for numerical assessment of worst-case spacecraft surface charging. Section IV provides a summary of the outcome of this paper, including impacts on experimental and numerical estimations of the charging risk in GEO.

Keywords—ESD, Charging, WorstCase, Spectrum

I. INTRODUCTION: "WHAT IS A WORST-CASE? "

The definition of a worst-case spectrum first depends on the different orbit. The risk on LEO is not the same than in GTO or GEO nevertheless design and requirements are still often the same.
One could think that to find a worst-case spectrum for space irradiation is really easy: Take a mono-energetic flux (something like 30keV and 1nA/cm²), irradiate a suspicious dielectric like a FEP Teflon® as shown Fig. 1 (dark black line) and you can immediately see that your sample reach a voltage above -7000 Volts in some minutes.
Thus, we can define design rules where you can forbid the use of your dielectric. You can also use it as a worst-case for all your preliminary software simulation made to predict the good behaviour of your spacecraft, in specific charging environment. And you will probably not see any difference because most of available software are unable to take into account charge deposition in the depth of dielectrics with an estimation of the conductivity taking into account charge deposition in the depth (different layers) of your dielectric.

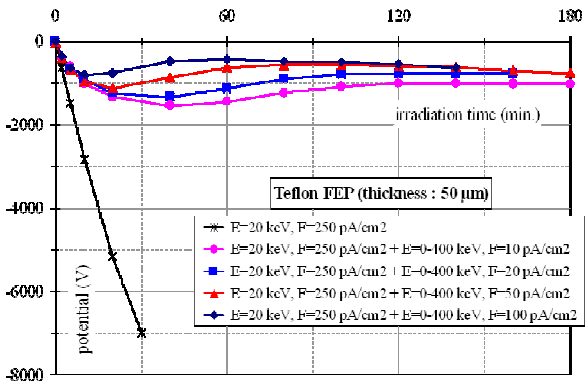

Fig. 1. Comparison of different irradiation on FEP Teflon®

Unfortunately if you test a two mil Kapton® under your just define worst-case environment, the result of this single irradiation will lead to hazardous voltage and a great number of ESD.

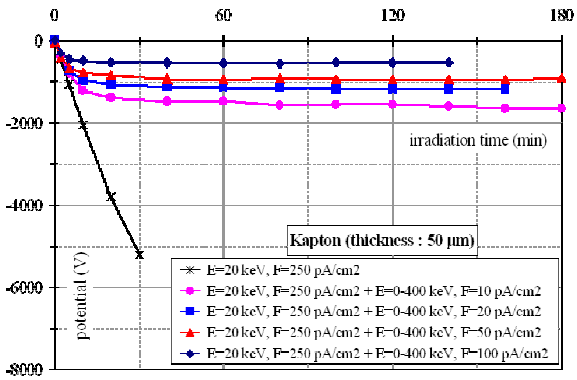

Fig. 2. Comparison of different irradiation on 2mils Kapton®

With such kind of worst-case spectrum, all dielectrics would be forbidden. Only metallic or very conductive parts would be

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allowed, everything would be equipotential and the charging concern on spacecraft solved…

On the other side, spacecraft are designed to resist more and more (we hope so) to various and large charging environments. And the more your spacecraft is well protected the more its own behaviour is decoraleted from a standard worst-case spectrum.

In other words it is a very specific spectrum, without any specific strong component, that will charge over months your forgotten thick dielectric deep inside your spacecraft. And this specific spectrum is your concern and without any effect on the spacecraft of your worst competitor.

Thus the definition of a Worst case spectrum depends on the spacecraft used.

This point out the difficulty to define a generic worst-case spectrum that could be universally used by each of us.

I. PART I

A. Radiated Induced Conductivity

Originally (in the 80's, in France), our materials were irradiated with mono-energetic spectra around 30 keV, charging only the external surface of dielectrics. Such irradiations systematically led to ESD on the majority of dielectrics, including 2 mils Kapton®. We were certainly in the presence of an unrepresentative worst case spectrum.

Since the end of the 80's[1] and during the 90's[2], European agencies and industries have used multi-energy spectra, to warranty an irradiation in the whole thickness of dielectrics under test. So we were able to reproduce in laboratory charge in space (Scatha, …), evaluate a real risk and qualify dielectrics. Today, temperature and dose (instantaneous and total) are also simulated to represent eclipse and Beging, Middle or End Of Life (BOL, MOL, & EOL) behaviours.

In space during storm, environment's particles spectra are different. The question that rises up is to know if there any chance to find a spectrum that could be define as a worst one and used everywhere?

Nevertheless, it was observed during our tests that a factor of ten in the high energetic part of the flux leads only to a factor of two on the surface potentials (Fig. 1 & Fig. 2). There is mitigation on the effect that let us hope that the definition of a worst case is possible. In other words, the main point is to have the full spectrum including high energetic flux more than the flux intensity itself.

B. Rough data correction

The correction is needed first because each particle detector has is own sensitivity. To solve that, it was necessary to calibrate detectors by correlating in space and time their flight measurements, which is better than a ground calibration. Second, space irradiation also induces an absolute potential on the spacecraft which directly affects the incoming particles energy on detectors. Hundreds or thousands volts negative spacecrafts modifies the energy distribution function in the same range of energies. It was solved using an analytical approach based on the Liouville's theorem.

C. Dose effect

Electrostatic charging concern is a question of minutes, while dose effect is in the range of month/year. In between we have to know what is the week or month worst spectrum and compare them to the worst of the year or the decade. In other words, how many times a spectrum equivalent to the annual worst one can be encountered during this year and are they comparable to others.

D. Worst case definition

The results of this work rely on different strategies. First, the highest fluxes at each energy were evaluated (i.e. post-storm irradiation). Second, based on the fact that high energetic fluxes promote the Radiated Induced Conductivity (RIC) efficiency, it is proposed to select spectra with high fluxes of low energetic particles (charge deposition) and high flux of energetic particles (RIC generation, as.e.g. during pre-storm irradiation). Third, we studied worst case spectrum leading to the highest measured absolute voltage, which were computed thank to particles energy measured on onboard detectors.

II. CHARGING ENVIRONMENT RETRIEVAL

This part aims at determining worst-case electron spectra for spacecraft surface charging, through the analysis of 15 years of particle measurement on-board Los Alamos National Laboratory (LANL) geosynchronous (GEO) spacecrafts. Figures were plotted using the IPSAT software version SVN 599. IPODE database was used to compute spectra.

A. LANL data in GEO

Available LANL GEO data are taken from 14/09/1989 to 30/11/2005 spread on 7 satellites: 1989-046, 1990-095, 1991-080, 1994-084, LANL-97A, LANL-01A et LANL-02A. Three particle instruments are used: MPA (Magnetospheric Plasma Analyzer), SOPA (Synchronous Orbit Particle Analyzer) and EPD (Energetic Particle Detector), this latter being embarked from 1996. MPA measures low energy electrons from 1 eV to 40 keV. In this paper, only 100 eV to 40 keV bins are used because lower energy bins are probably subject to secondary electron contamination in some cases. SOPA measures electron fluxes with energy between 50 keV and 1.3 MeV. Finally, EPD measures high energy electrons from 1 to several MeV. LANL-01A data have not been used because they are not fully reliable. Data have been initially filtered to get rid off contamination, noise and glitch. They have also been inter-calibrated. The time resolution of MPA is 86 seconds, while SOPA and EDP resolution is 10 seconds. The spacecraft potential is determined through SOPA. As a result, the time period is 86 s over the 15 years and SOPA/EDP measurements have been averaged on that period.

B. Spacecraft potential measurements

Spacecraft potential measurements taken from low energy proton flux measurements by MPA have been filtered to get rid off numerical errors. The default algorithm searching the energy of the proton flux peak can have problems in some

[1] First SIRENE Facility GEO 0-220keV Spectrum, ONERA, FRANCE
[2] Actual SIRENE Facility GEO 0-400keV Spectrum ONERA, FRANCE

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cases. An illustration of the filtered results is given in Fig. 3, where error lines have been successfully removed. From a physical point of view now, we obtain a classical result: large spacecraft charging is more probable around midnight of the Magnetic Local Time (MLT).

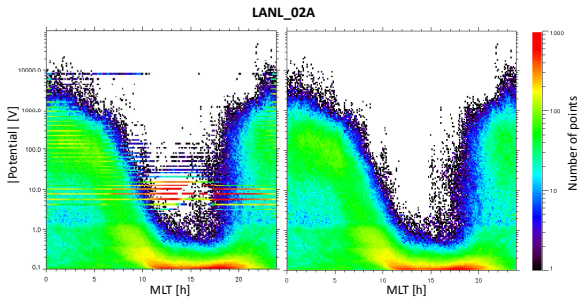

Fig. 3. LANL-02A potential from 10/01/2002 to 30/11/2005. Left: rough default computation. Right: filtered data.

C. *Electron differential flux determination*

In this section, we present the method used to transform the rough electron flux spectrograms measured and computed from the instruments into the undisturbed initial velocity distribution. We use the Liouville's theorem that states that the value of the distribution function in velocity space is conserved along a particle trajectory. As done in a companion paper [1], assuming 1/ an isotropic velocity distribution f_∞ in the undisturbed plasma (*i.e.* without spacecraft), 2/ all trajectories at detector entrance are filled (*i.e.* come from the undisturbed plasma and not from the detector or spacecraft), 3/ collisionless plasma; we conclude that for any particle velocity V_d on the detector corresponding to V_∞ at infinite:

$$f_D(V_D) = f_\infty(V_\infty) \tag{1}$$

expressed in [m^{-6}.s^3]. In addition, the total energy conservation of the particle writes:

$$V_D = \sqrt{V_\infty^2 - \frac{2q\phi_D}{m}} \tag{2}$$

where q is the electrical charge unit, ϕ_D the detector entrance grid potential and m the particle mass. Finally, we must get rid of particles which have a negative total energy on the detector. The measured omni directional fluxes *flux* expressed in unit [cm^{-2}.s^{-1}.sr^{-1}.MeV^{-1}] are transformed in a temporary distribution f_p and then in the desired f unit [m^{-6}.s^3] through the series of equations (3) to (6):

$$f_p(p) = 4\pi \frac{flux.10^4}{p^2} \tag{3}$$

$$n = 4\pi \int f_p(p) p^2 dp = 4\pi \int f_v(v) v^2 dv \tag{4}$$

$$f_v(v) = \left(\frac{m_0}{10^6 q}\right)^3 f_p(p) \tag{5}$$

$$f_v(v) = 4\pi \left(\frac{m_0}{10^6 q}\right)^3 \frac{flux.10^4 c^2}{E_c(E_c + 2E_0)} \tag{6}$$

n being the total density in cubic meter, p^2 the particle impulse verifying $p^2=E(E+2E_0)/c^2$ in [MeV^2.m^{-2}.s^2] and $E=1/2mV^2$ with V and c the velocity of the particle and light respectively in [m.s-1] and $E_0=m_0c^2$, the electron energy at rest (511 keV). Then the Liouville's theorem is used.

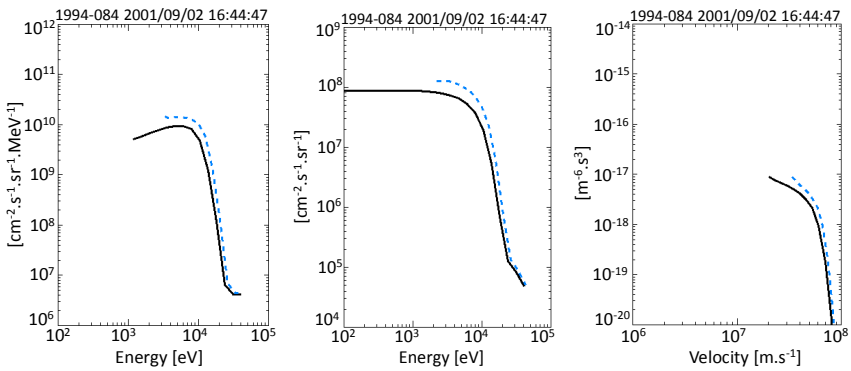

Fig. 4. Examples of flux transform using the Liouville's theorem approach for a spacecraft potential of -2000 V.
The solid black and dashed blue lines represent the distribution on the spacecraft (detection) and at origin (undisturbed plasma) respectively.
From left to right: differential omni directional flux, integrated omni directional flux and velocity distribution function.

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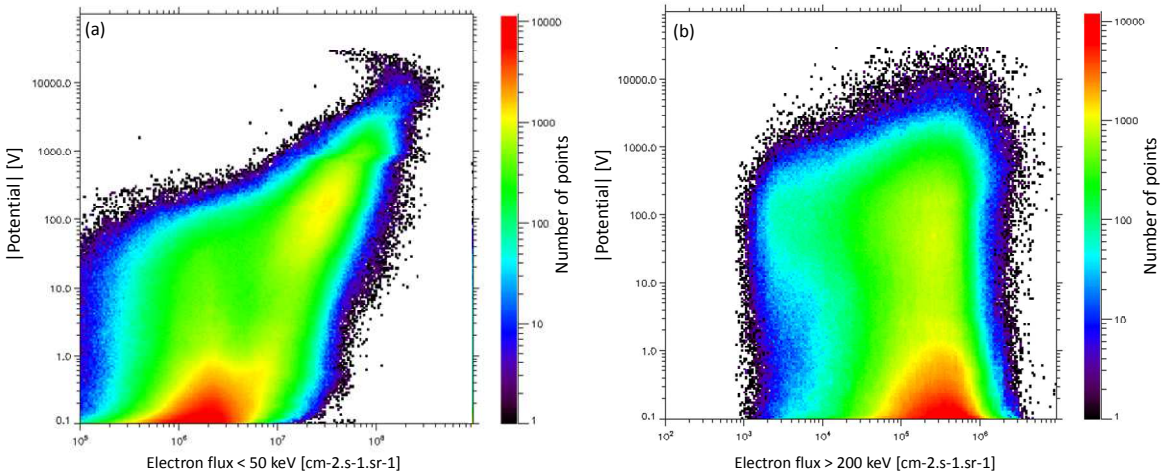

Fig. 5. Absolute spacecraft potentials as a function of electron flux at energy smaller than 50 keV and larger than 200 keV. Correlation between fluxes and spacecraft potential

The correlation between electron fluxes at energy smaller than 50 keV and larger than 200 keV is represented in **Erreur ! Source du renvoi introuvable.**. There is a clear correlation between low energy fluxes and the absolute potential. The high energy flux does not correlate with the absolute charging. However, they have an impact on differential charging, which was not measured on LANL spacecraft. This is why one should not conclude too rapidly that the high energy part is of no interest.

III. WORST-CASES SPECIFICATION

This section presents the electron worst-cases spectra computed from the 15 years data measurements, using three different criteria: 1/ Large flux at low energy and low flux at high energy; 2/ Large integrated flux; 3/ Large spacecraft absolute potential.

A. *Low electron flux at high energy*

This criterion is especially of interest when covering dielectrics are sensitive to radiation induced conductivity (RIC). As said earlier, the spacecraft absolute charging is mainly due to the integrated electron flux, which is maximum around some tens of keV during geomagnetic substorms. Differential charging is a fraction of absolute voltage for very resistive dielectrics. For other materials, such as kapton for instance [1], the induced conductivity leads to less severe differential charging. This was illustrated in a companion paper [3]. The criterion "RIC" used in this section considers the largest values of the parameter (7):

$$\frac{I_{E<50keV}}{I_{E>200keV}} = \frac{\int_{E=0}^{50keV} vf(v)v^2 dv}{\int_{E=200keV}^{\infty} vf(v)v^2 dv} \qquad (7)$$

a) Worst 5 minutes

All spectra presented in this paragraph correspond to averages over 5 consecutive minutes. The worst 5 minutes have been computed over the 15 years and also over each period of 5 years, 1 year and 1 month, leading respectively to 1, 3, 15 and 180 spectra. The one month period spectra are plotted in Fig. 6. There is a factor 10 to 100 between the flux magnitudes of the weakest and strongest events. This large dispersion is also observed on the spacecraft potential obtained during these events, from 100 to 10 000 Volts, see Fig. 7.

The summary of all period averages is plotted in Fig. 8. They are qualitatively similar. As expected, the 1 month worst case has however a lower flux at low energy and a larger flux at high energy.

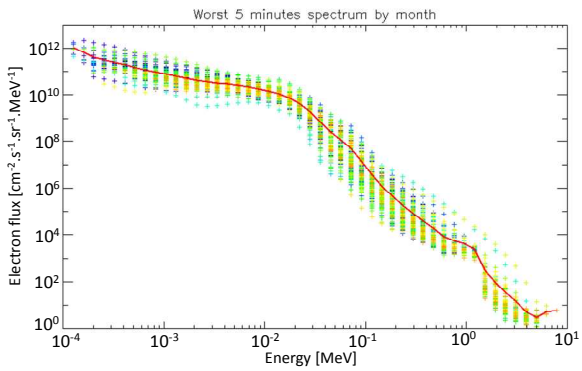

Fig. 6. Worst 5 minutes following the criterion RIC, for each month. Average value is solid red line.

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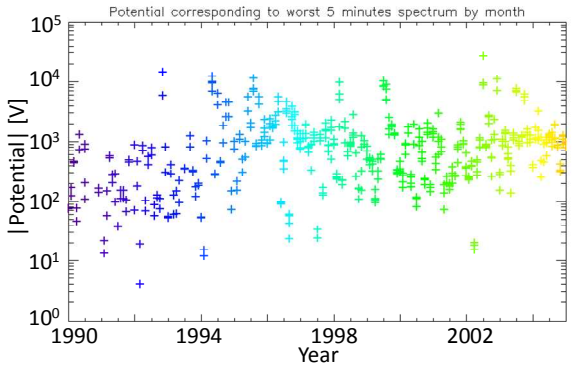


Fig. 7. Absolute spacecraft potential during the 5 minutes worst cases obtained each month; with criterion RIC

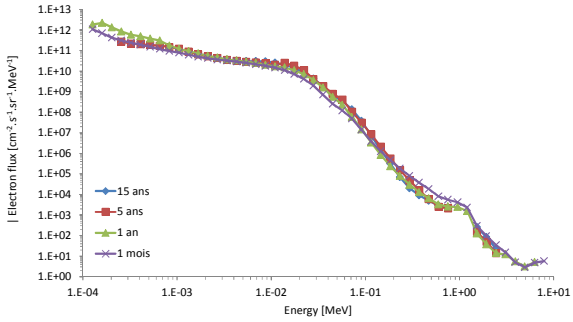


Fig. 8. Comparison between the 5 min worst cases obtained over different periods: 15 years, 5 years, 1 year and 1 month; with criterion RIC

b) Worst 15 minutes

The worst 15 minutes have been computed following the same approach and results are presented in Fig. 9

c) Worst instantaneous environment

Finally the worst instantaneous case is depicted in Fig. 10. The spacecraft potential was -2058 V during this event, hence with a risk of triggering surface ESDs.

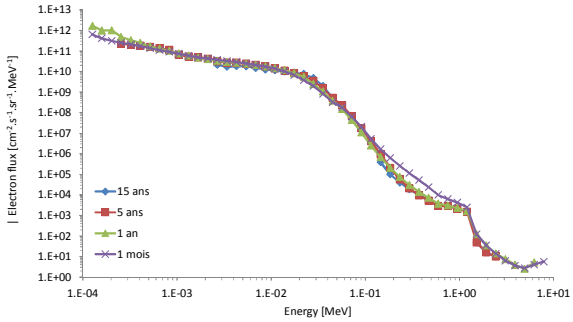


Fig. 9. Comparison between the 15 min worst cases obtained over different periods: 15 years, 5 years, 1 year and 1 month; with criterion RIC

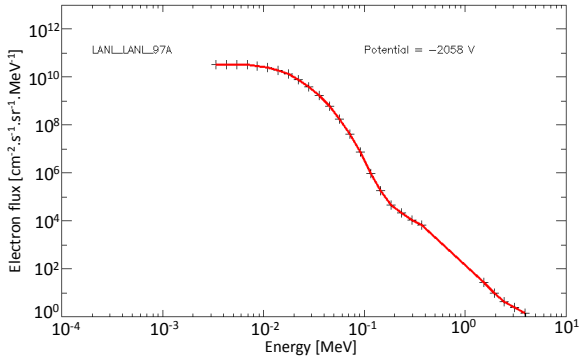


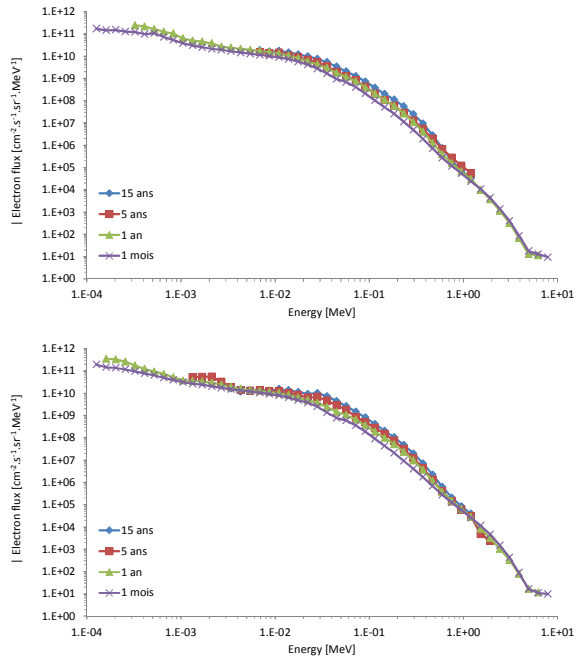
Fig. 10. Worst instantaneous case obtained over a period of 15 years of LANL data between 1990 and 2005, corresponding to criterion RIC

B. *Large integrated electron flux*

In this section with use a second criterion: the integrated electron flux over all energies. This criterion rather focuses on absolute charging than differential charging. The worst 5 minutes, 15 minutes and the worst instantaneous cases are represented in Fig. 11. The criterion considers large values of parameter (8):

$$I = \int_{E=0}^{\infty} v f(v) v^2 dv \tag{8}$$

The worst instantaneous case was obtained for a spacecraft absolute potential of -7480 V.



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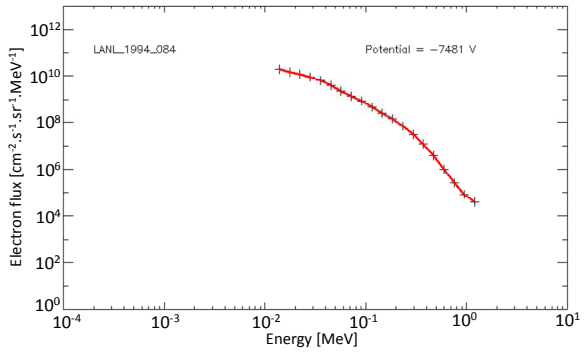

Fig. 11. Comparison between the 5 minutes (top) and the 15 min (middle) worst cases obtained over different periods: 15 years, 5 years, 1 year and 1 month. Worst instantaneous case.
All with the criterion base on integrated flux.

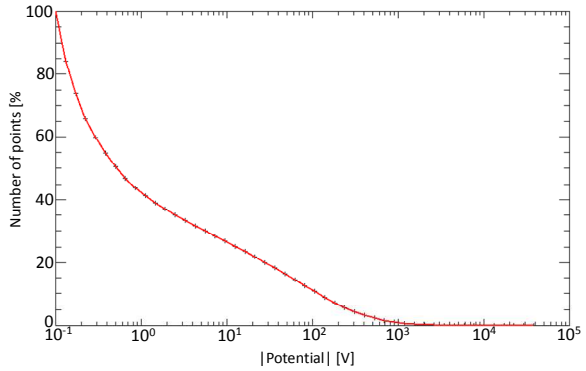

Fig. 12. Cumulative distribution function of the spacecraft potential over the 15 years of LANL spacecraft data.

C. *Large spacecraft potential*

The last criterion is based on the measured absolute spacecraft potential. The cumulative distribution function (CDF) of absolute potential is given in Fig. 12. It represents the percentage of measurement leading to a potential greater than the given voltage. Statistically, the spacecraft potential is rather small (less than -100 V) 90 % percent of the time. The negative potential has a probability to be larger than -500 V, -1000 V and -5000 V only 3%, 1% and 0.04 % of the time, respectively. For weakly negative potentials, the number and dispersion of spectra is large. For large negative potentials, as for instance larger than -5000 V in Fig. 13, the dispersion is about one order of magnitude at low energy (10 to 50 keV) and two orders at higher energy (50 keV to 1 MeV). This shows the wide range of environments that lead to large spacecraft absolute charging, and so on to differential charging.

The average spectra obtained for different potential thresholds are given in Fig. 14. The "<-30 000 Volt" spectrum is considered as the worst instantaneous spectra. Large spacecraft potentials correlate with the fluxes below 200 keV. The fluxes are quite similar at larger energy, which is a confirmation of the results of Fig. 5.

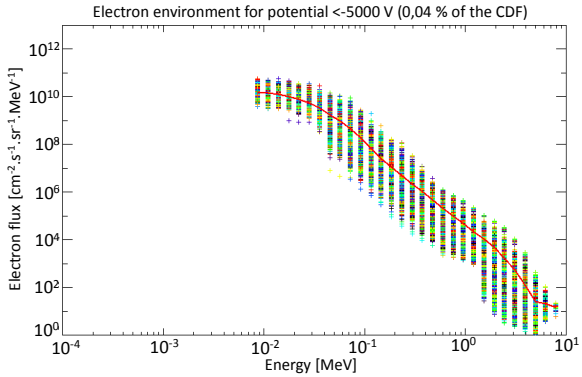

Fig. 13. Spectra corresponding to negative spacecraft potentials larger than -5000 V. Average spectra in solid red line.

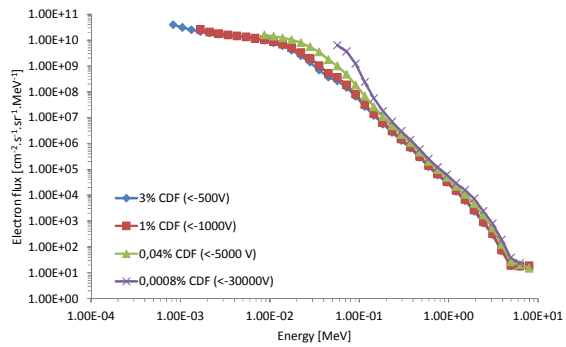

Fig. 14. Average spectra corresponding to negative spacecraft potentials larger than -500, -1000, -5000 and -30000 V

IV. SUMMARY

This paper showed the necessity to take account of different criteria for environment specification dealing with GEO spacecraft surface charging. The absolute charging is mainly due to low energy electron fluxes (below 50 to 100 keV). Past and recent experiments demonstrated that differential charging depends also on the intermediate and high energy part of the spectra (above 200 keV for thin dielectrics of a few hundreds of micrometers). A RIC criterion was thus proposed to minimize the conductivity induced by radiations. Worst case charging is indeed a combination between absolute and differential charging. A spacecraft whose sensitive dielectrics are made almost conductive due to radiations is theoretically safer. A third criterion was based on direct measurements of the potential, without any considerations on low and large energy fluxes. A comparison of the spectra obtained with the three criteria is presented in Fig. 15. This set of curves defines an envelope of electron environments to be used when dealing with worst case charging. Pending on spacecraft configuration and materials, design engineer may prefer using one or another. For instance, Kapton® charging being very sensitive to RIC, it is preferable to use the RIC criterion for estimating its charging at Sun shade (Kapton®') is photoconductive). A case by case approach seems necessary.

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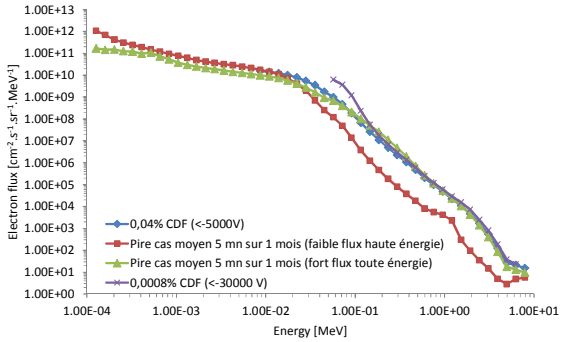

Fig. 15. Worst case spectra obtained for negative potentials larger than -5000 V and -30000 V (blue and violet lines respectively); for RIC criterion (red line) and for integrated flux criterion (green line)

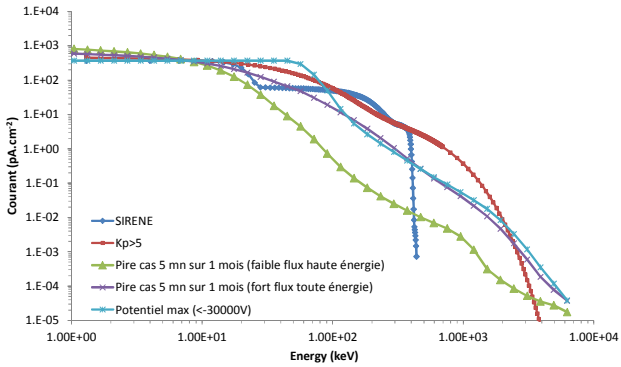

Fig. 16. Comparison between integrated current spectra (current density of electrons greater than): measured potential greater than -30 000V (light blue), RIC criterion (green), integrated flux criterion (violet), *kp* greater than 5 (red) and SIRENE facility (dark blue)

Finally, this study shows the necessity to accurately represent electron fluxes during ground experiments dealing with material charging estimation and conductivity measurements as seen Fig. 16. This would increase the set of simulated worst-case environments for GEO charging and add to the flight representativity. As a second perspective, we plan to study the proton flux spectra during strong events and to determine if they have a significant effect on spacecraft charging, as shown by numerical simulations of a companion paper [3]. Finally this study will be the basis for the definition of a worst case spectrum definition in an ECSS that will be used in Europe.

This activity was made at ONERA and funded by CNES R&D.

ACKNOWLEDGMENT

The authors thank I. Katz for helpful discussions concerning flight data and LANL especially R Friedel, G. Reeves, M. Thomsen for the long-term and good cooperation they have with ONERA and flight data providing.

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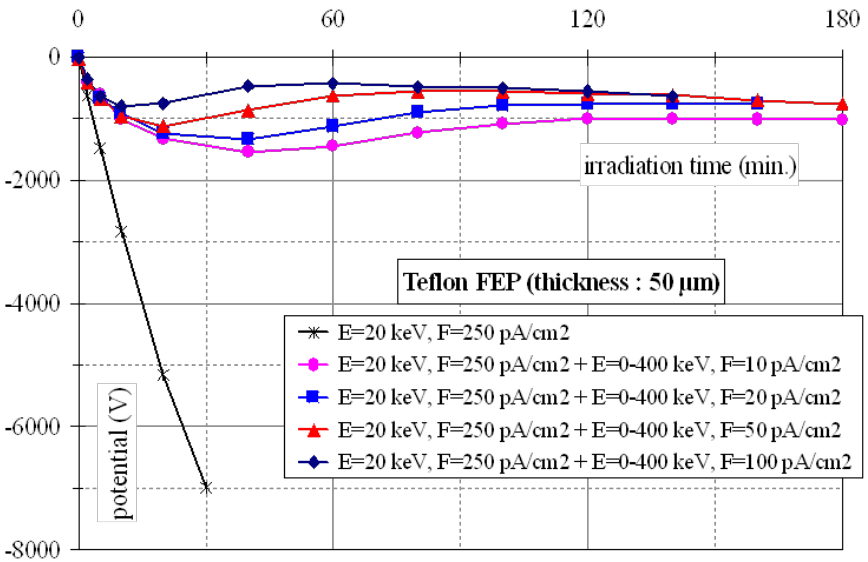
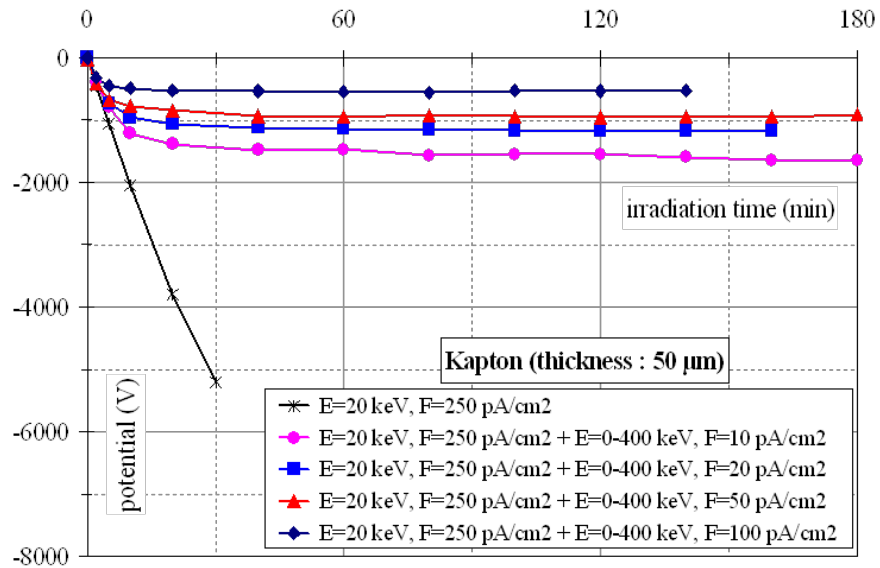
Worst–case monoenergetic flux

- The definition of a worst-case spectrum first depends on the different orbit..
- Is a mono-energetic flux (30keV and 1nA/cm²) a Worst-case?





Dielectric qualification with monoenergetic fluxes abandoned in France in the 80's

Worst-case Spectrum vs Spacecraft Specification

Spacecraft are designed to resist more and more to various and large charging environments.

- The more your spacecraft is well protected, the more its own behaviour is decoraleted from a standard worst-case spectrum.
- A very specific spectrum, without any specific strong component, that will charge over months your forgotten thick dielectric deep inside your spacecraft. And this specific spectrum is your concern and without any effect on the spacecraft of your worst competitor.

The definition of a Worst case spectrum depends on the spacecraft used.

This point out the difficulty to define a generic worst-case spectrum that could be universally used by each of us.

Our French Worst-case spectrum

We take into account

- Multi-energy spectra, to warranty an irradiation in the whole thickness of dielectrics under test.
- Temperature and dose (instantaneous and total),

→ Eclipse

→ Begin, Middle or End Of Life (BOL, MOL, & EOL) behaviours.

- Space spectra are different. Is there any chance to find a spectrum that could be define as a worst one and used everywhere?

→It was observed during our tests that a factor of ten in the high energetic part of the flux leads only to a factor of two on the surface potentials. There is mitigation on the effect that let us hope that the definition of a worst case is possible. In other words, the main point is to have the full spectrum including high energetic flux more than the flux intensity itself.

The LANL data

LANL data from 14/09/1989 to 30/11/2005 over 15 years, special thanks to R. Friedel, G. Reeves & M. Thomsen

7 satellites : 1989-046, 1990-095, 1991-080, 1994-084, LANL-97A, LANL-01A et LANL-02A.

3 particles measurement instruments

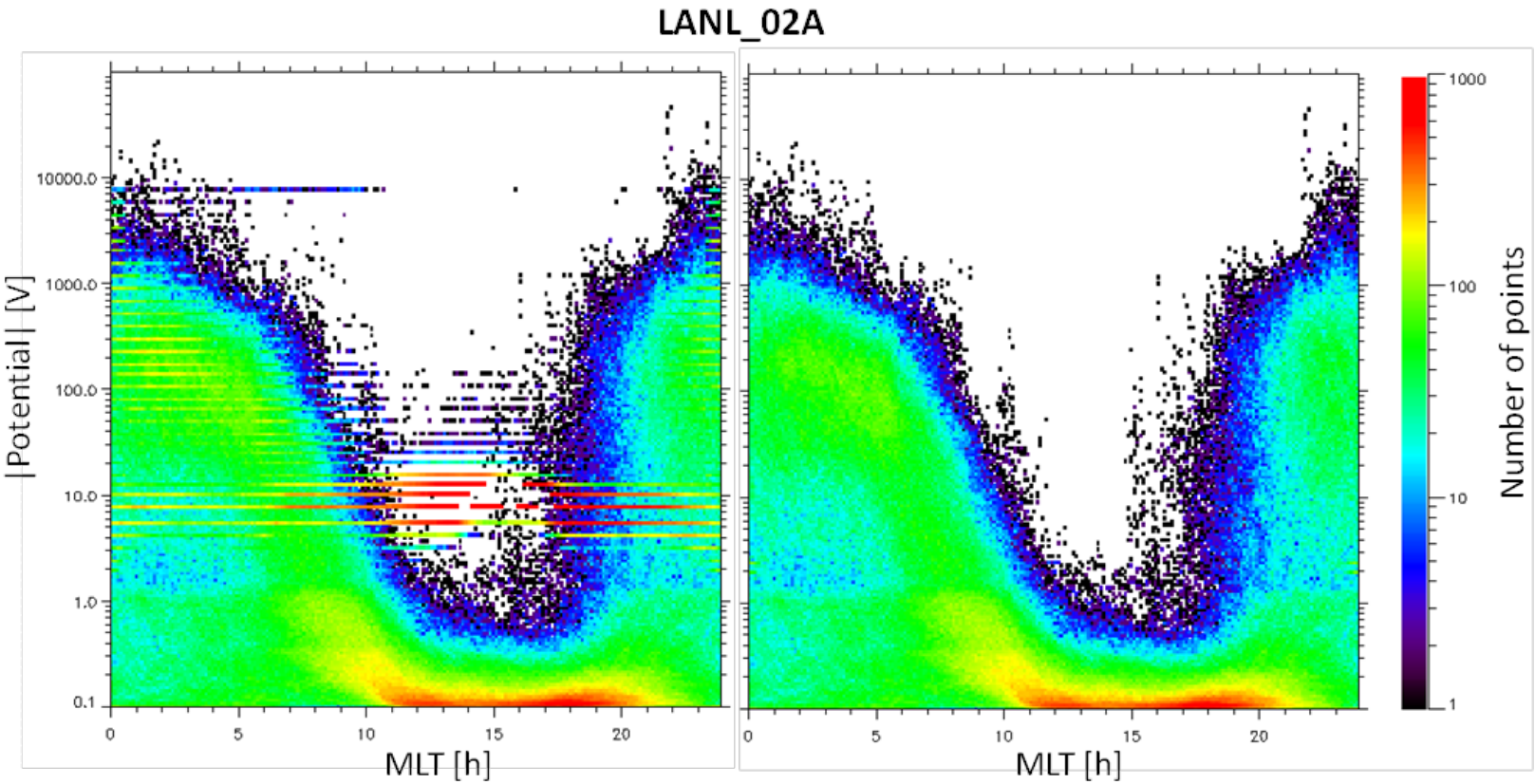
- MPA (Magnetospheric Plasma Analyzer) : from 1 eV (used from 100eV) to 40 keV, 86s resolution.
- SOPA (Synchronous Orbit Particle Analyzer) 50 keV to 1.3 MeV. 10s resolution, average taken on 86s.
- EPD (Energetic Particle Detector) since 1996 : from 1 MeV to several MeV. 10s resolution average taken on 86s.

Data from LANL-01A were not used:

Data where intercalibrated and cleaned from contamination, noise, glitche, ….,

The LANL Data

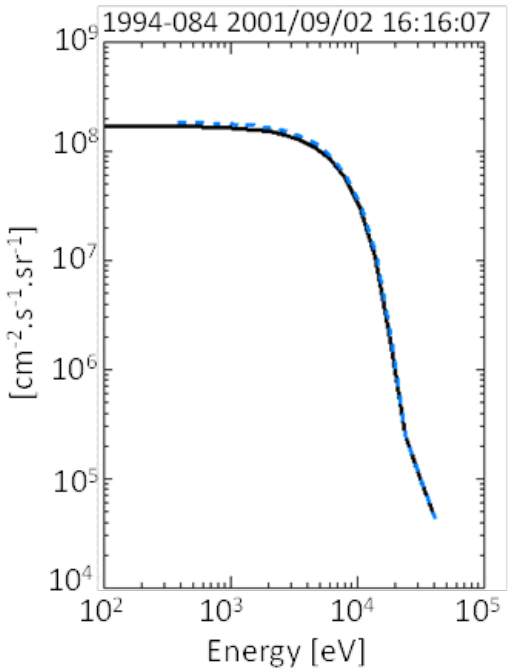
Rough data – Corrected data

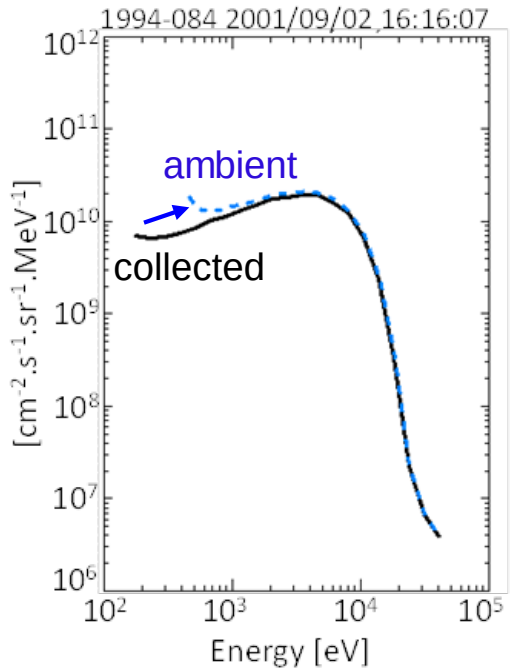


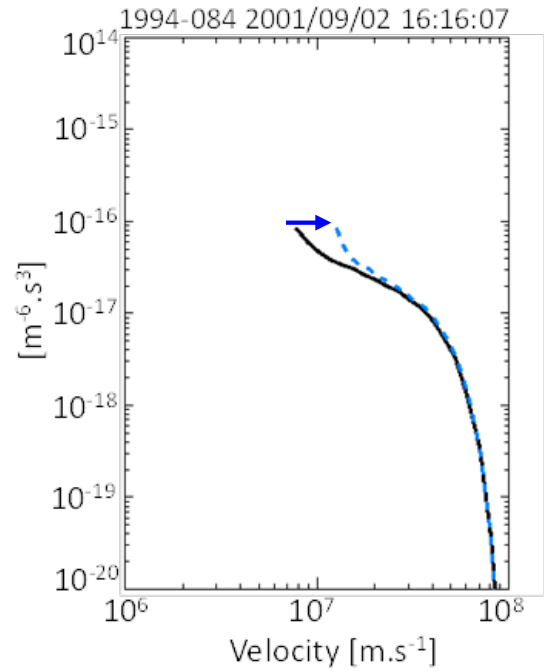
Absolute voltages vs Magnetic Local Time (MLT)

From collected data to ambient characteristics

Data are computed thanks to Liouville's theorem and Absolute voltage measured whith positive ion detectors

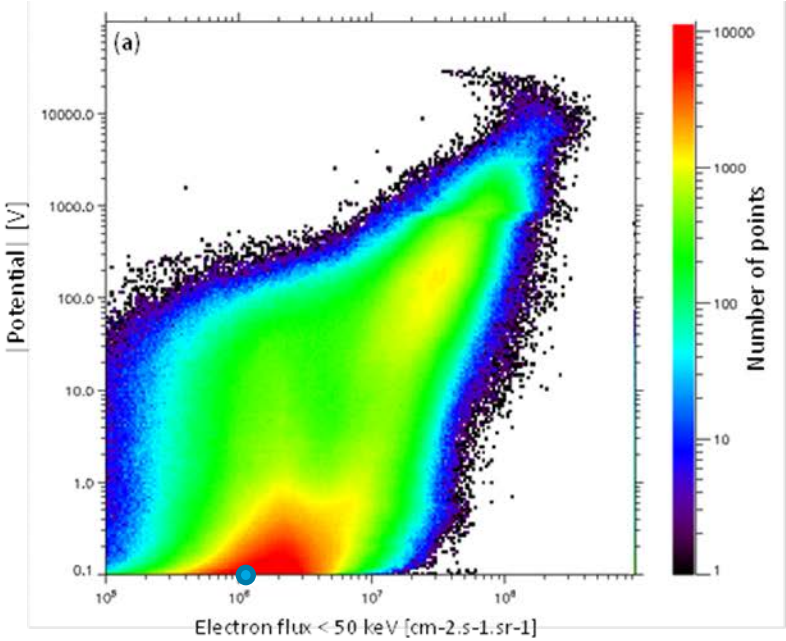


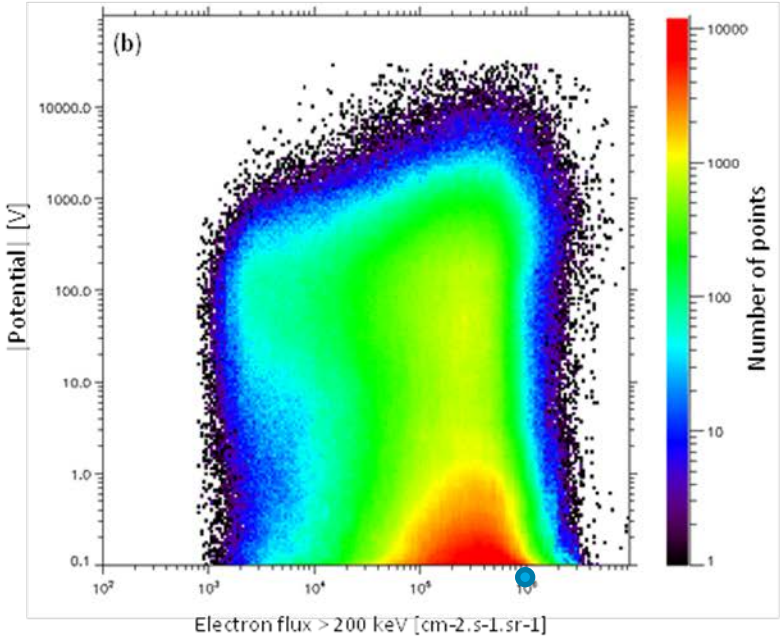




Correlation between electron fluxes at energy smaller than 50 keV and larger than 200 keV

Absolute spacecraft potentials as a function of electron flux at energy smaller than 50 keV and larger than 200 keV





There is a clear correlation between low energy fluxes and the absolute potential.
The high energy flux does not correlate with the absolute charging.
However, they have an impact on differential charging, which was not measured on LANL spacecraft. (have a look at Mr Mateo-Velez Poster)

- This is why one should not conclude too rapidly that the high energy part is of no interest.

The three worst-case scenarii

3 cases

1.The highest « low energy flux » (<50keV) and the lowest « high energy flux » called « Low RIC criterion »

2.The highest flux at each energy which correspond to the larger integrated electron flux

3.The spectra leading to the highest absolute potential

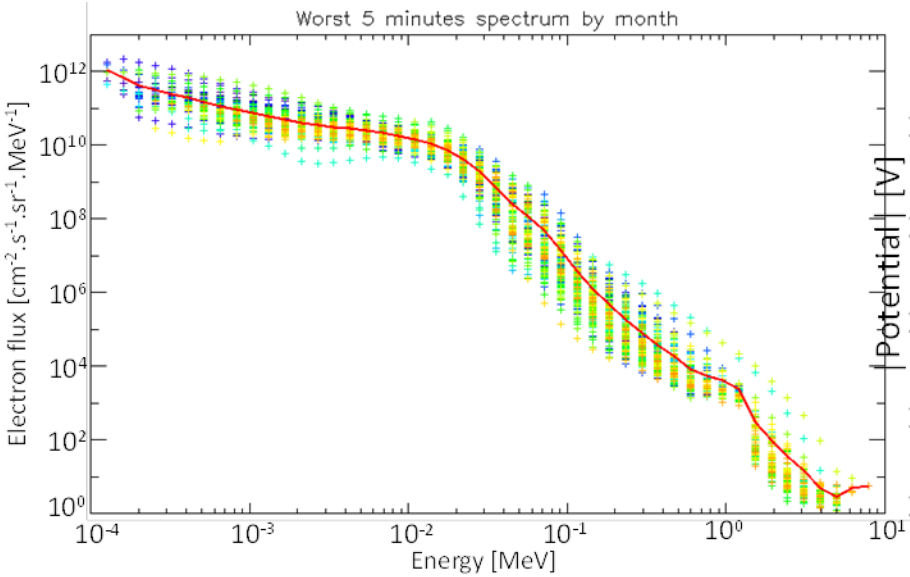
Studied in different cases

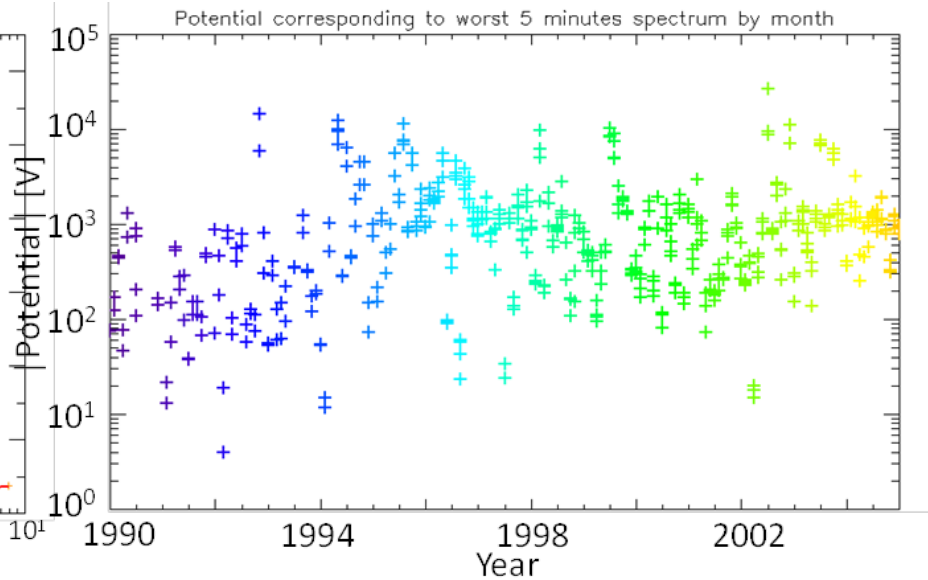
•The worst minute, the worst 5 minutes the worst 15 minutes,

•Every month, year, 5 years or 15 years

Only the 5 minutes cases are presented, all others are in the paper

1 - Low RIC criterion: Worst 5 minutes every month with

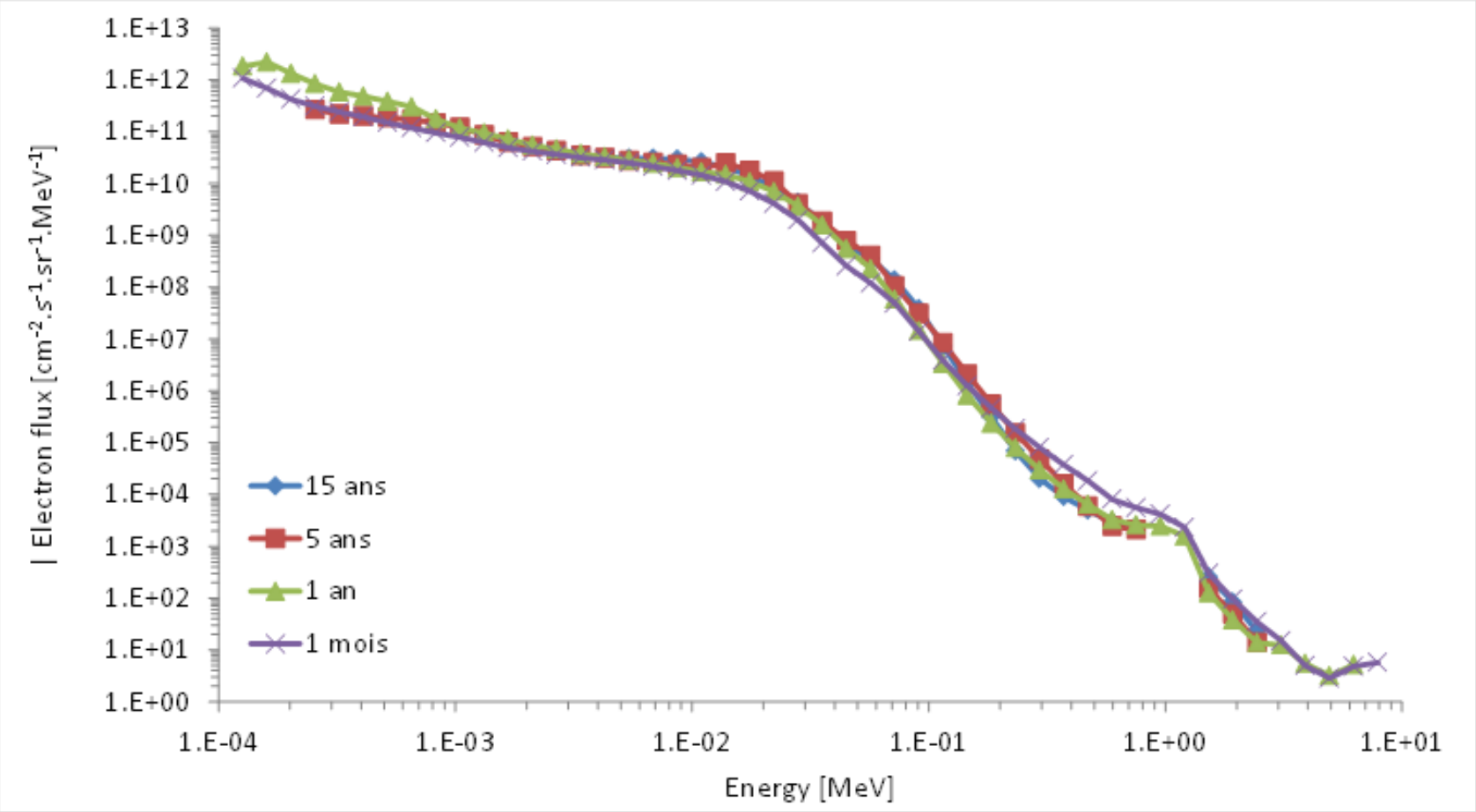




Worst 5 minutes following the criterion RIC, for each month. Average value is solid red line

Absolute spacecraft potential during the 5 minutes worst cases obtained each month; with criterion RIC

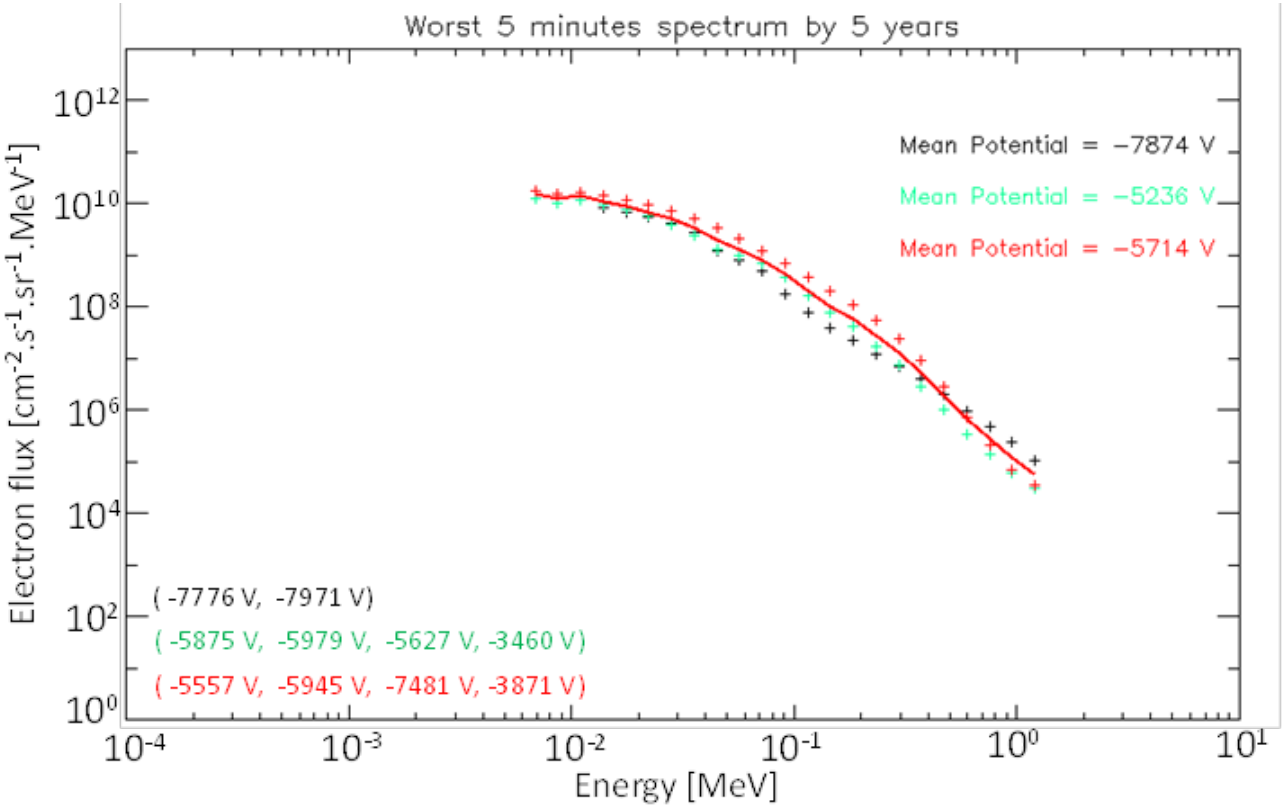
1 - Low RIC criterion: Worst 5 minutes every Month, Year, 5 Years and 15 Years



Comparison between the 5 min worst cases obtained over different periods: 15 years, 5 years, 1 year and 1 month

2 - Large integrated electron flux: Worst 5 minutes

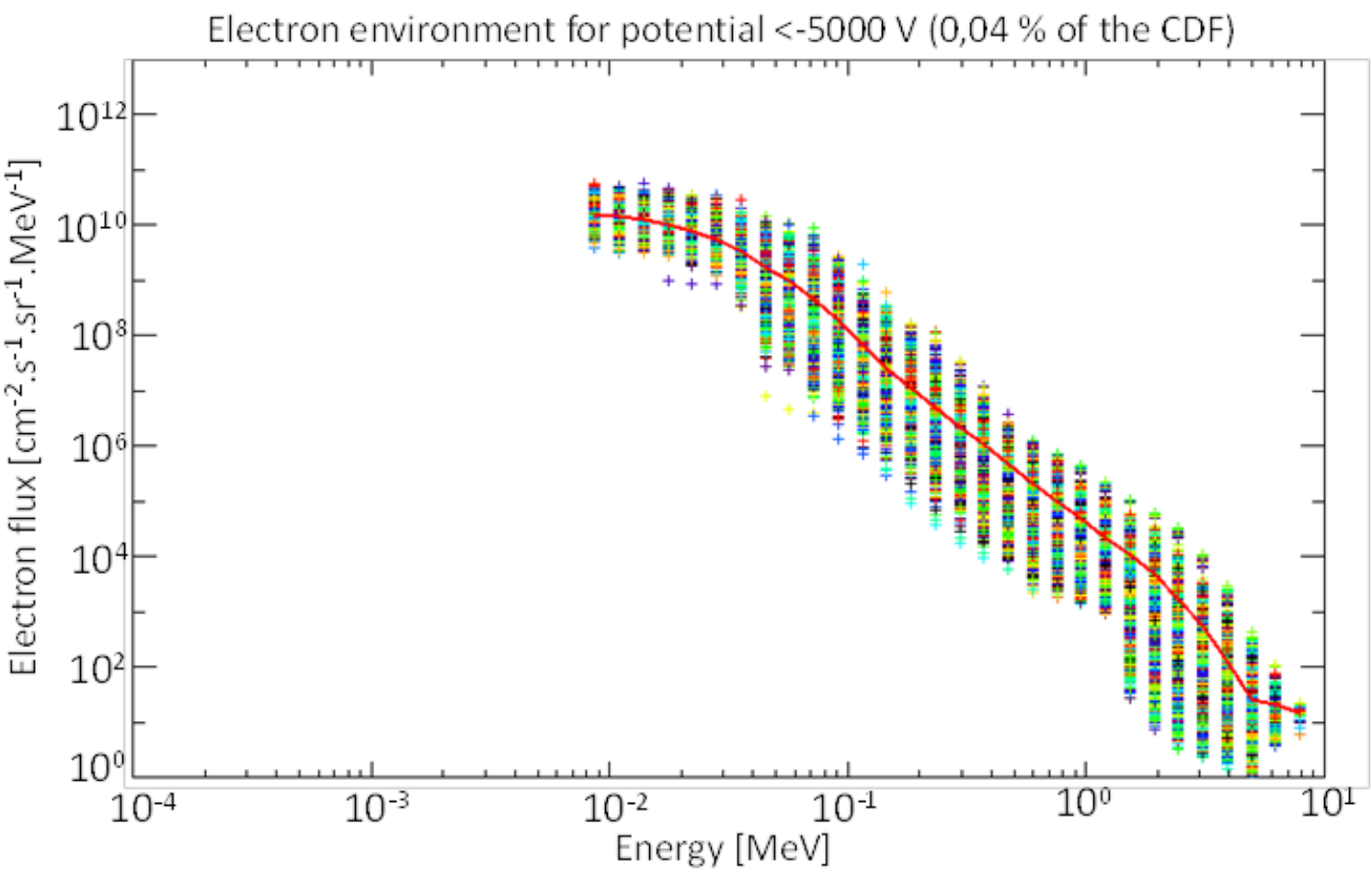
The second criterion: the integrated electron flux over all energies. This criterion rather focuses on absolute charging than differential charging.



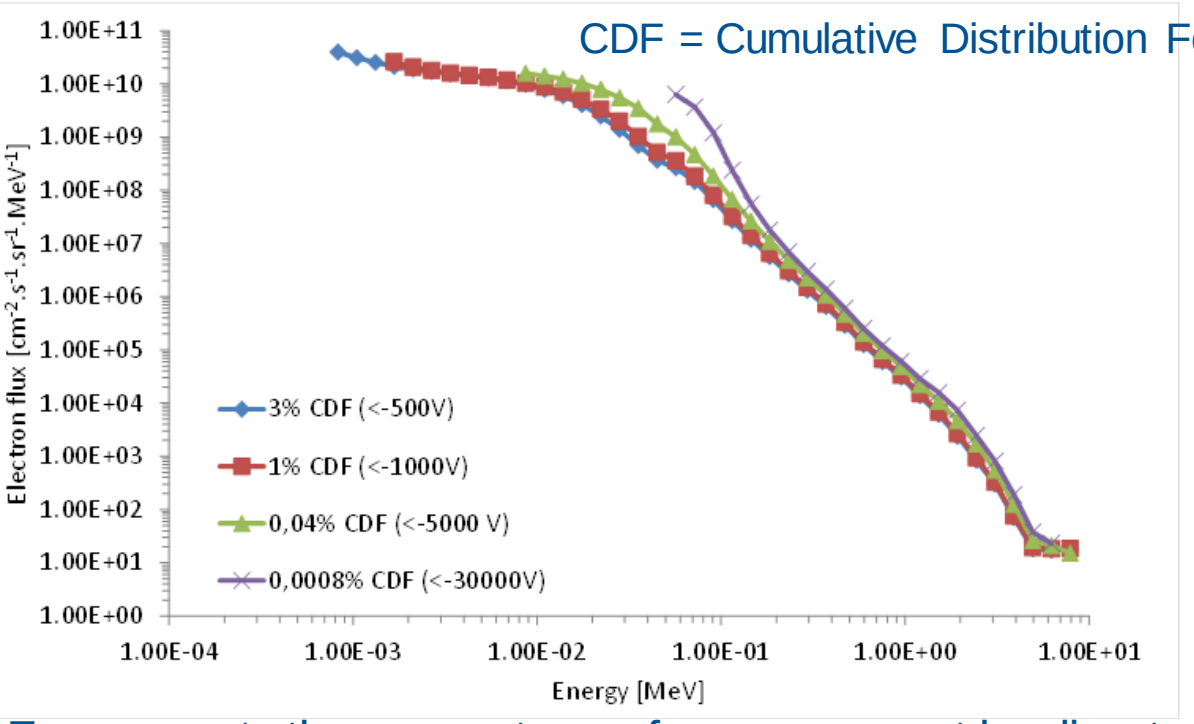
Worst of the worst-case measured on s/c at -5714V

3 - Largest spacecraft potential: Worst 5 minutes

Environment for Vsat<-5000V



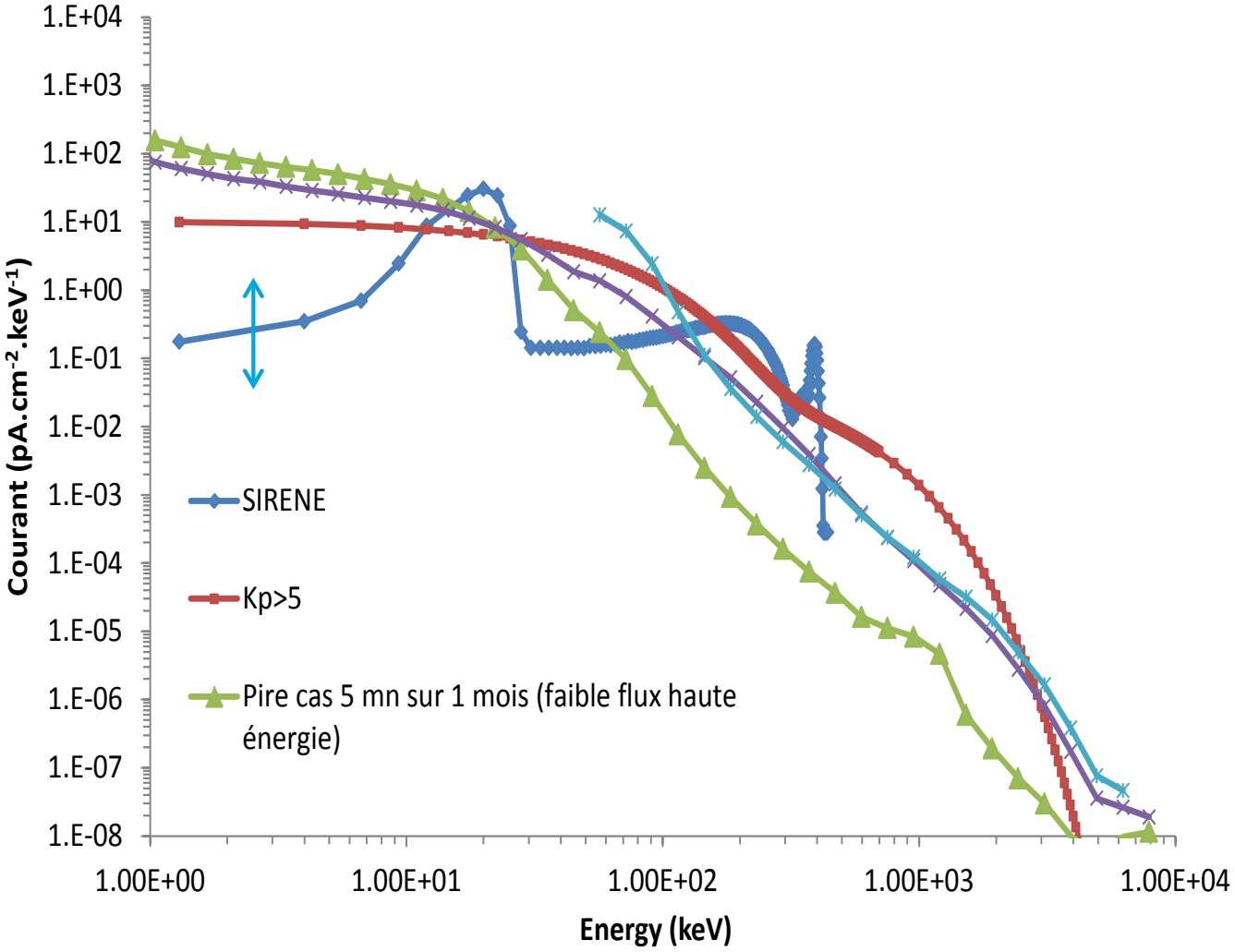
3 - Largest spacecraft potential: Worst 5 minutes



The CDF represents the percentage of measurement leading to a potential greater than the given voltage. Vs/c is :

- Rather small (less than -100 V) 90 % of the measurements,
- Larger than -500 V only 3%,
- Larger than -1000 V 1%,
- Larger than -5000 V 0.04 %,
- Larger than -30000V 0.0008% of the measurements

All fluxes comparison



Conclusion

This study shows the necessity **to accurately represent electron fluxes** during ground experiments dealing with material charging estimation and conductivity measurements and software simulations.

Ric cannot be no more forgotten. The capabilities of our software and irradiations facilities should be adapted to the knowledge we have of space irradiation (and not the contrary).

Spis for external dielectric, take into account a tens of different layers in each dose is computed for a good RIC estimation. Dielectrics can go under vacuum from SIRENE to GEODUR facilities and be iradiated from 0 up to 2 MeV.

From this study we have given **the limits in-between** your worst-cases are. This is the domain where we should work on.

I strongly recommend you to have a look on companion paper and poster this is a completion of this study

Next step for France studies: **Evaluate the effect Proton flux spectra** during strong events, on the voltage mitigation and ECSS on spectrum.

Thank you for your attention and …

… be careful this time, we got off the bus