Modelling Space Weather Events and Mitigating their Effects on Spacecraft with SPACESTORM

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Given by

S. Dubyagin

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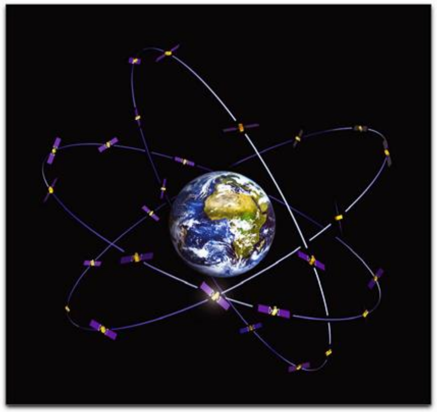
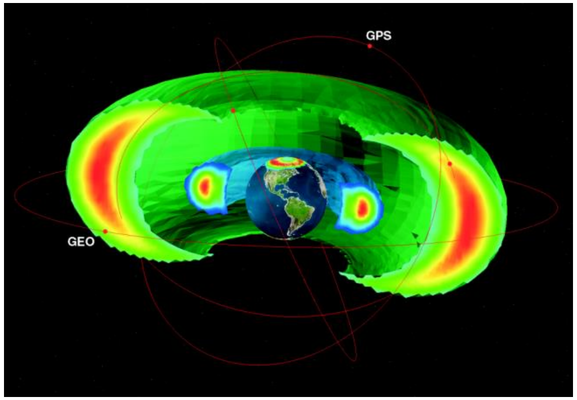
ISROSES, Golden Sands, Bulgaria, 16th September, 2016

SPACESTORM - The Goal

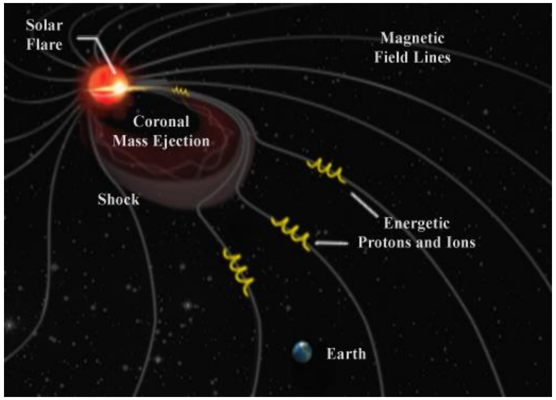
Satellites



Radiation Belts



Solar Energetic Particles



- ***Goal***
  - *To model severe space weather events and mitigate their effects on satellites by developing better mitigation guidelines, forecasting, and by experimental testing of new materials and methodologies to reduce vulnerability.*

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Selected Highlights of the Project So Far

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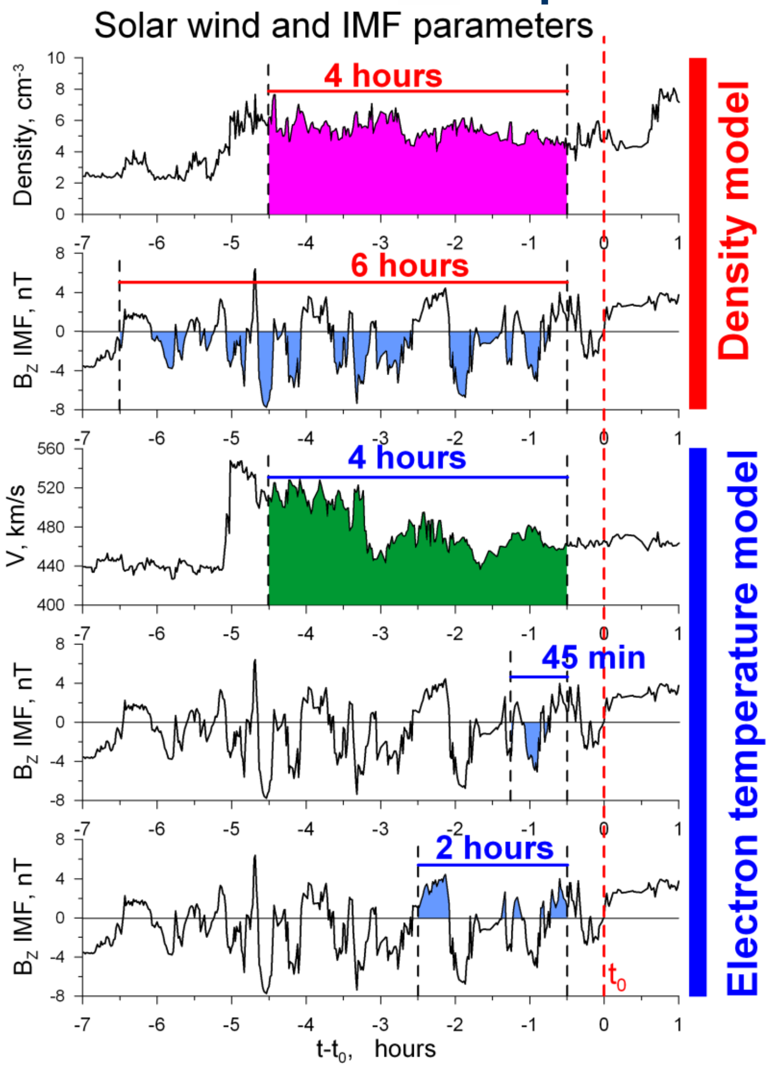
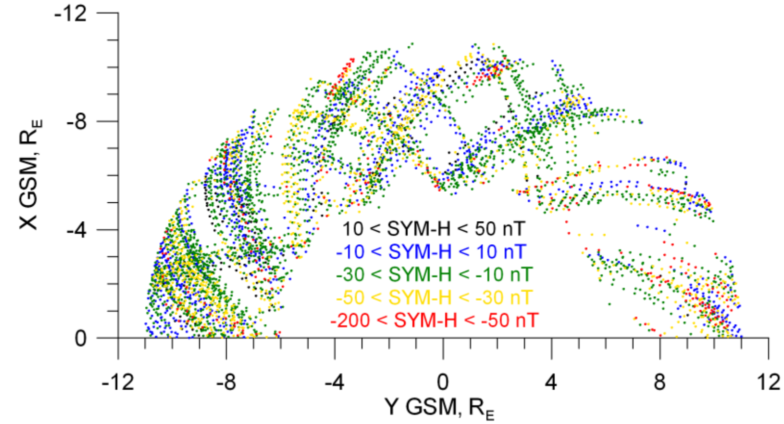
New Empirical Plasma Sheet Model





- Analysed THEMIS data 6–11 Re
- Developed an empirical model with time lags
- Input
  - solar wind data (proton density, IMF Bs, velocity
- Output:
  - el density, temperature

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Dubyagin et al., JGR, 2016

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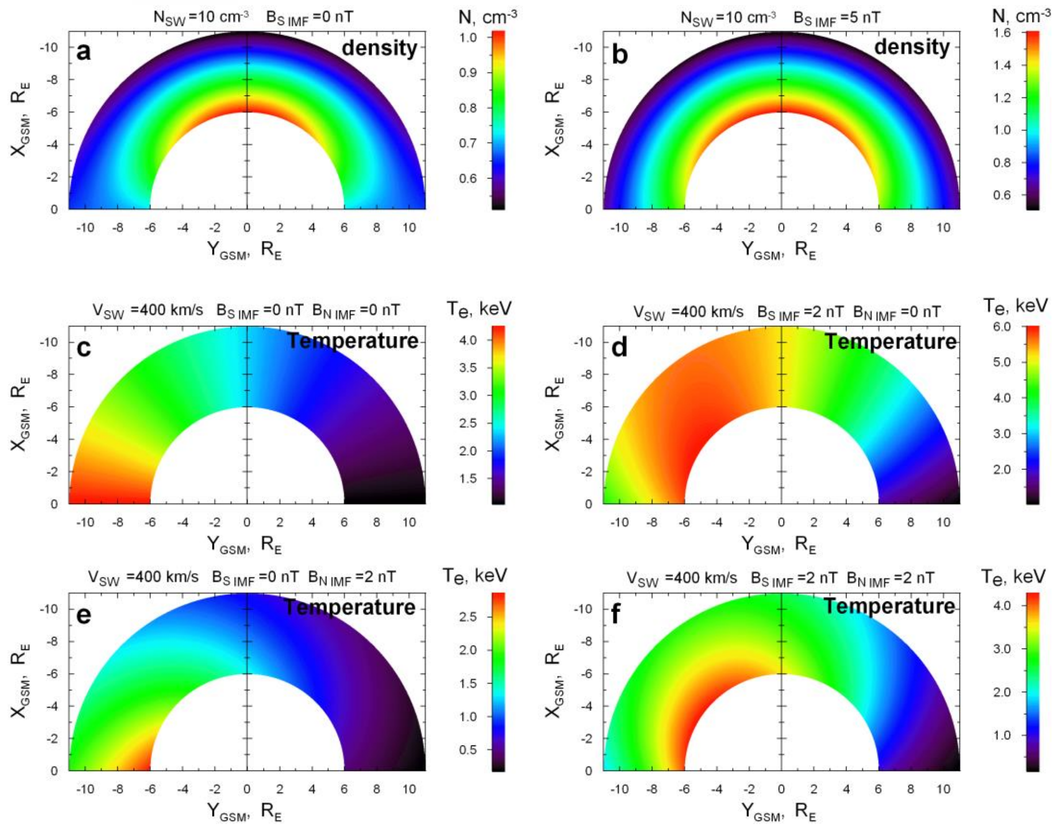
Dubyagin et al., JGR, 2016

Examples



- Note asymmetry in electron Temperature
- Model output can be used as a source for modelling inward transport of < 150 keV electrons using IMPTAM

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Modelling 30 Years of Radiation Belts

- Use >2 MeV electron flux from GOES as boundary condition for 30 years of data

- Developed a set of spectra binned by >2 MeV flux and using lower energy channels >800 keV and >2 MeV from GOES 15 to get the flux for the outer boundary

- Used asynchronous regression [O'Brian et al., 2001]
  - To map the flux measurement at any MLT, to the flux that would be measured by the same instrument at a fixed, reference local time

  - Hence - map data to a fixed L for the outer boundary condition

BAS Radiation Belt Model

- Diffusion equation for the drift averaged phase-space density
- Includes:
  - Radial transport
  - Wave-particle interactions
  - Loss to the atmosphere
  - Loss to the magnetopause
- Waves:
  - Plasmaspheric hiss
  - Lightning generated whistlers
  - Upper band, lower band and low-frequency chorus
  - EMIC waves

$$\frac{\partial f}{\partial t} = \frac{1}{g(\alpha)}\frac{\partial}{\partial \alpha}\bigg|_{E,L} g(\alpha)\left(D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\bigg|_{E,L} + D_{\alpha E}\frac{\partial f}{\partial E}\bigg|_{\alpha,L}\right) + \frac{1}{A(E)}\frac{\partial}{\partial E}\bigg|_{\alpha,L} A(E)\left(D_{EE}\frac{\partial f}{\partial E}\bigg|_{\alpha,L} + D_{\alpha E}\frac{\partial f}{\partial \alpha}\bigg|_{E,L}\right) + L^2\frac{\partial}{\partial L}\bigg|_{\mu,J}\left(\frac{1}{L^2}D_{LL}\frac{\partial f}{\partial L}\bigg|_{\mu,J}\right) - \frac{f}{\tau}$$

$$g(\alpha) = \sin 2\alpha\left(1.3802 - 0.3198\left(\sin\alpha + \sin\alpha^{1/2}\right)\right)$$

$$A(E) = (E + E_0)\left(E(E + 2E_0)\right)^{1/2}$$

Glauert et al. [2014a, 2014b], Horne et al. [2013], Meredith et al. [2014], Kersten et al. [2014]

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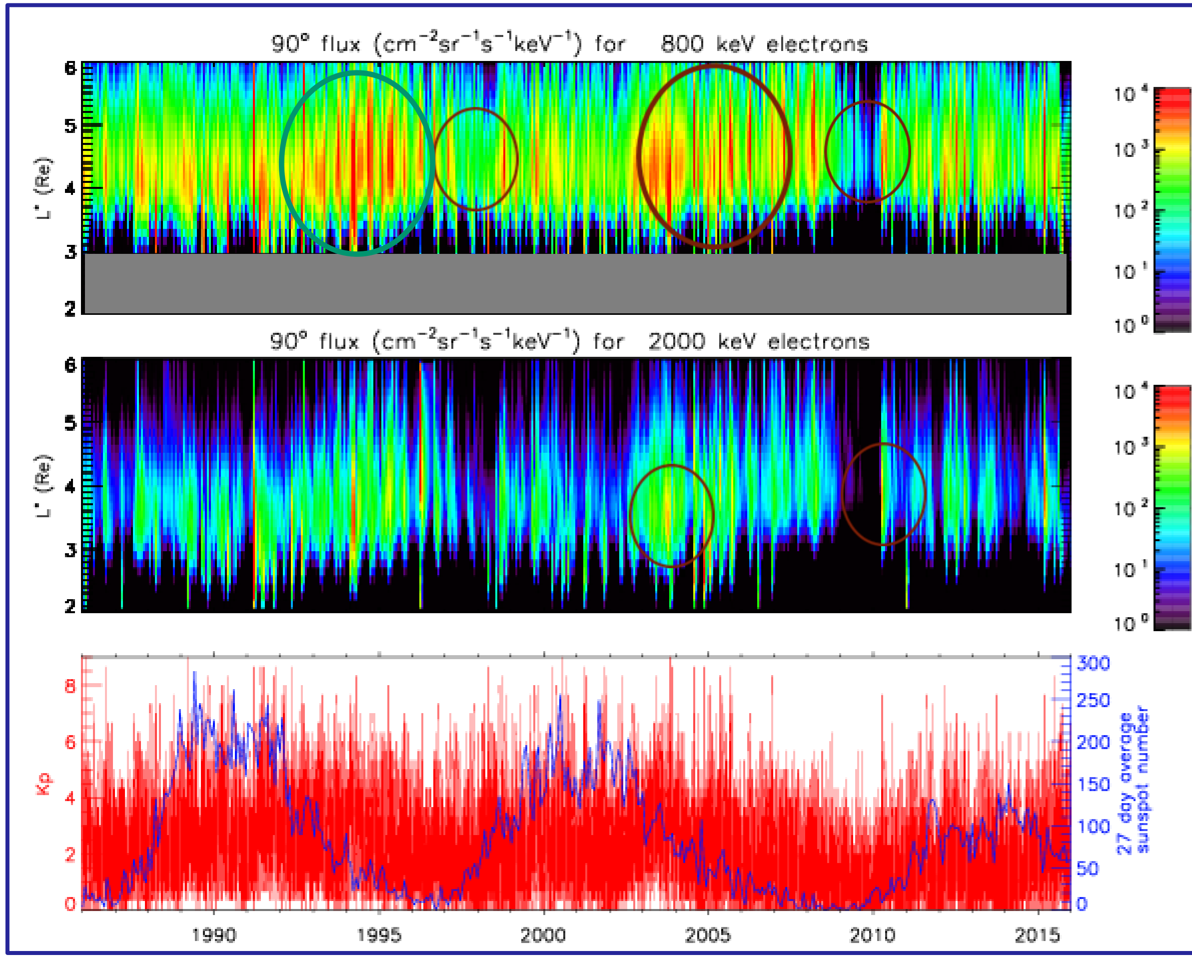
30 year simulation

- Long term variability
  - Most intense in declining phase 1993-1994, 2003-2005
- Quiet start to new cycle
  - 1998, 2009
- 2 MeV at L*=3.5
  - peak flux can be several orders of magnitude different for extended periods



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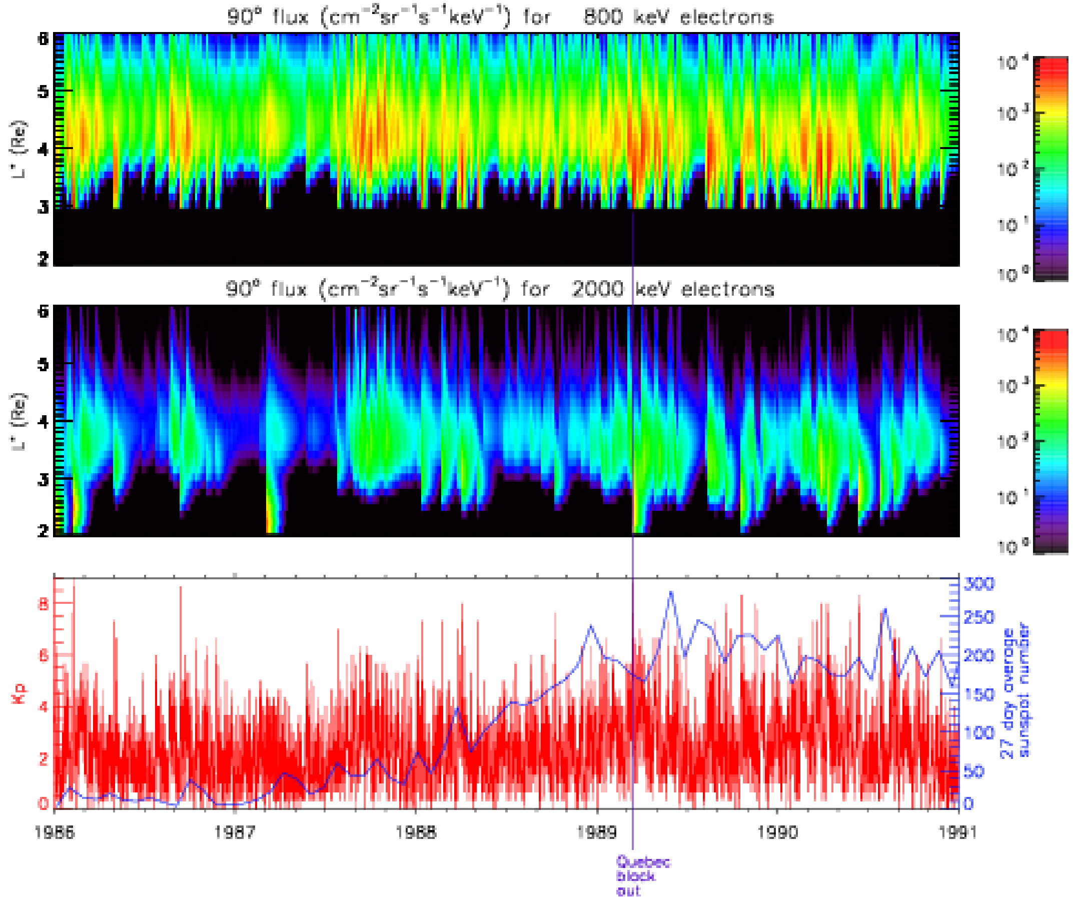
1986-1991

Example – reconstructed the March 1989 storm



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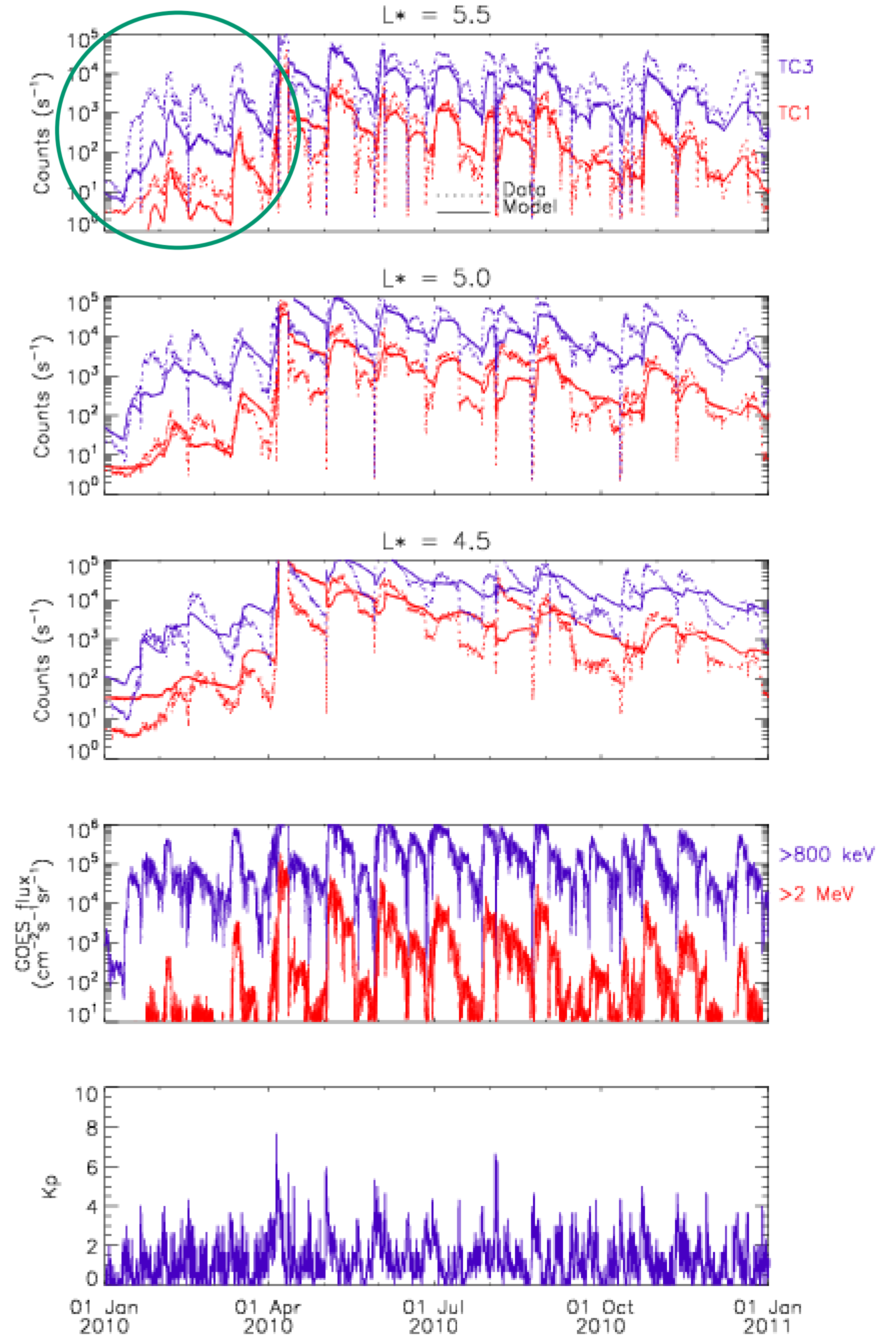
Comparison with GIOVE-B

- At L* = 4.5, 5 and 5.5
- Best agreement when the flux is high
- Poor agreement at start of year
  - End of 'electron desert'
  - Fluxes lower than those used to construct spectra (GOES 15)
  - Need better spectrum for these conditions



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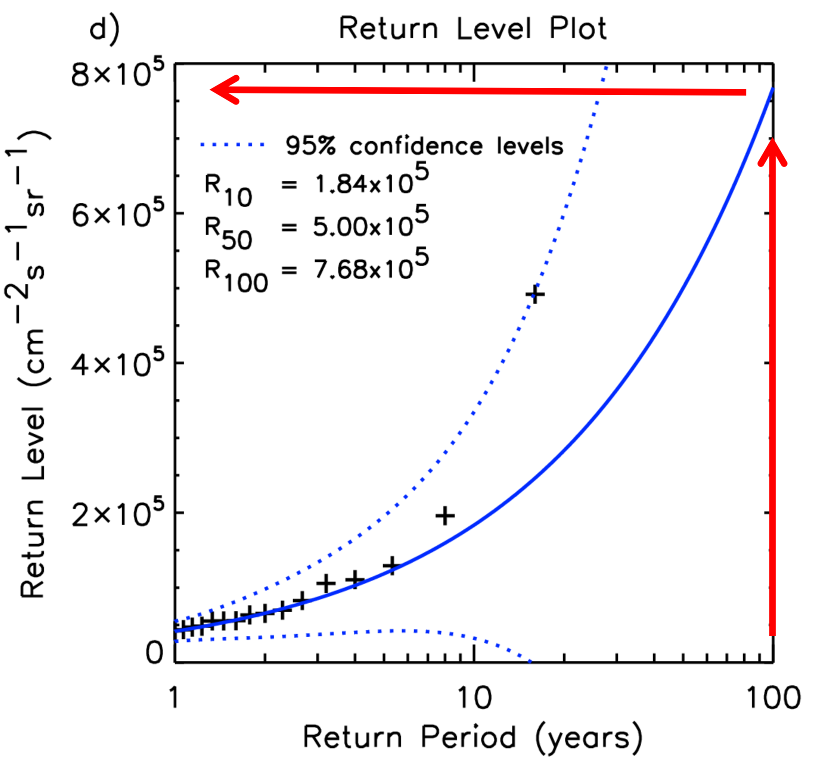
1 in 100 Year Event – GOES West

- Statistical analysis of GOES > 2 MeV electrons
- 1995 – 2014, 7 GOES satellites
- 1 in 100 year flux of daily-averaged E > 2 MeV electrons at GEO orbit is 7.68×10^5 $cm^{-2}s^{-1}sr^{-1}$
- 7 times larger than Koons [2001] at GOES West
- Reason:
  - Applied dead time correction
  - Sorted by satellite longitude
  - GOES E and W are at different L



- Meredith et al., SW [2015]

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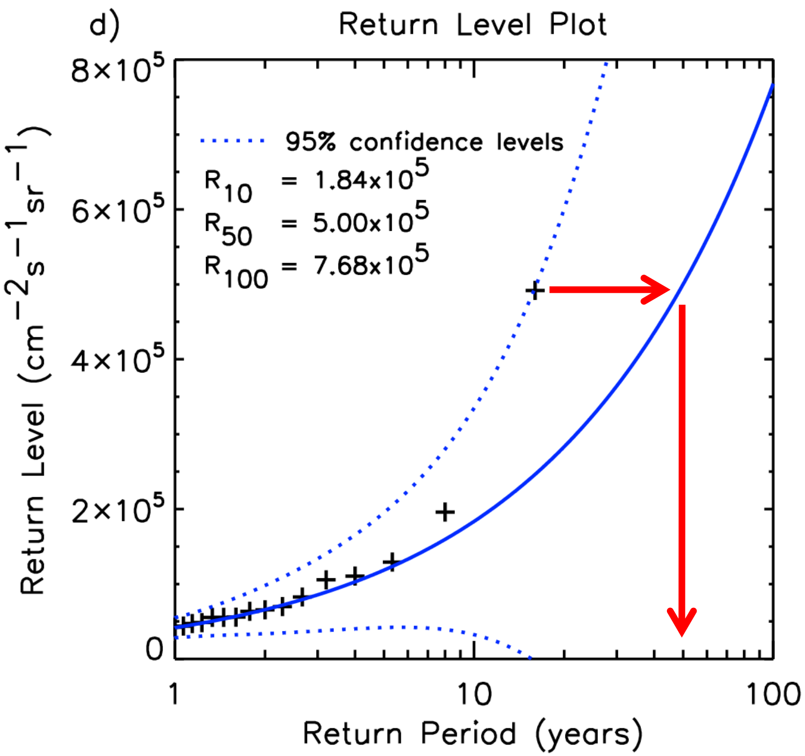
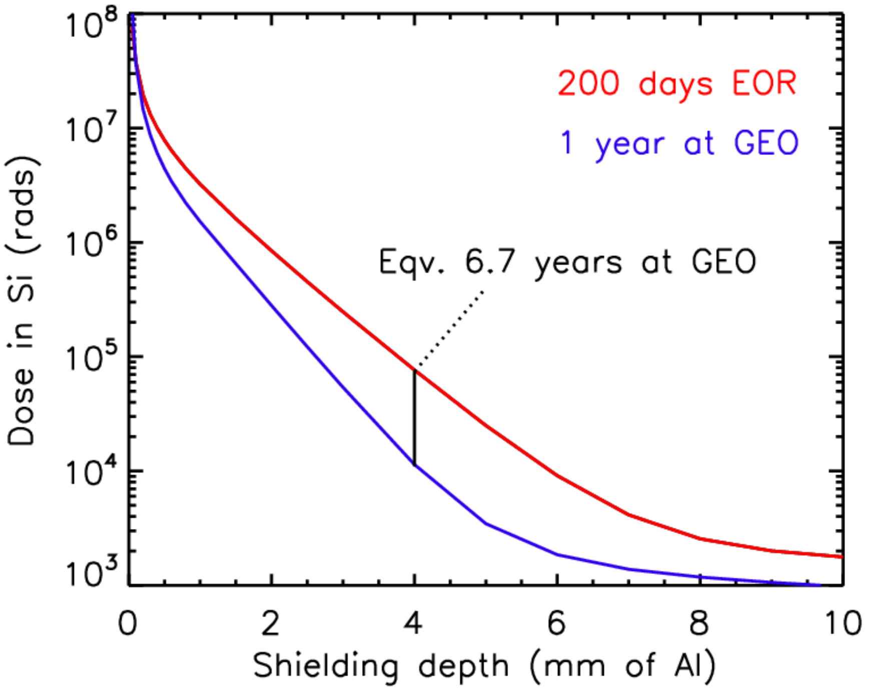
29 July 2004 – 1 in 50 Year Event

- We also identified a 1 in 50 year event
- Occurred on 29 July 2004
- Galaxy 10R lost its secondary xenon ion propulsion system
- This reduced its lifetime significantly resulting in an insurance payout of US $75.3 M



Electric Orbit Raising

- BOEING - New method of launching commercial satellites using electric thrusters
- 200 – 300 days to reach geostationary orbit
- Much longer in the radiation belts
- Radiation dose during orbit raising is equivalent to 6.7 years operation at geostationary orbit
- Need to ensure radiation protection



Horne and Pitchford, SW, 2015

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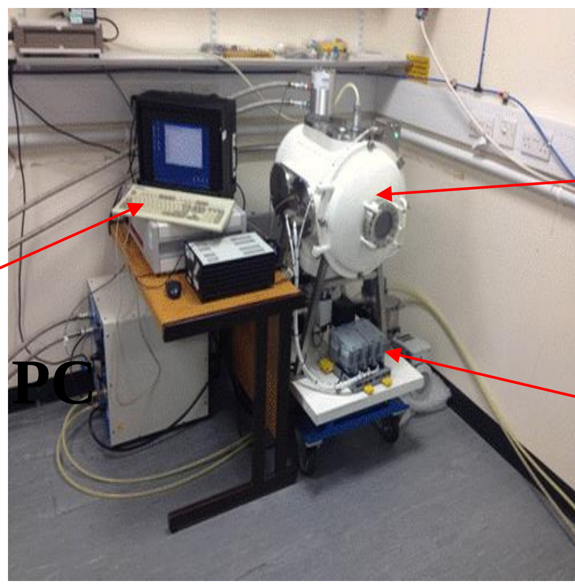
Low Intensity Long Duration Irradiation Expts.

- Use Realistic Electron Environment Facility (REEF)
- Uses Sr-90 (pure β emitter) to 'emulate' trapped electron spectrum in Van Allen belts

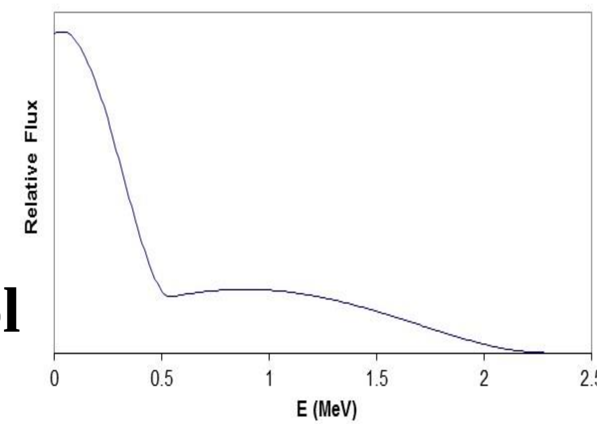
PSU / Control PC



Vacuum Chamber

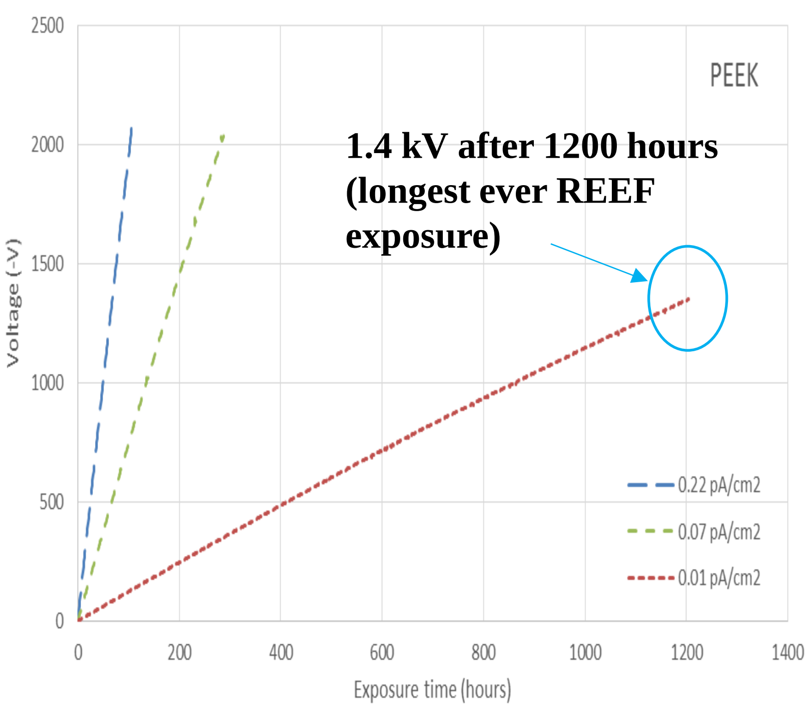
Axis control

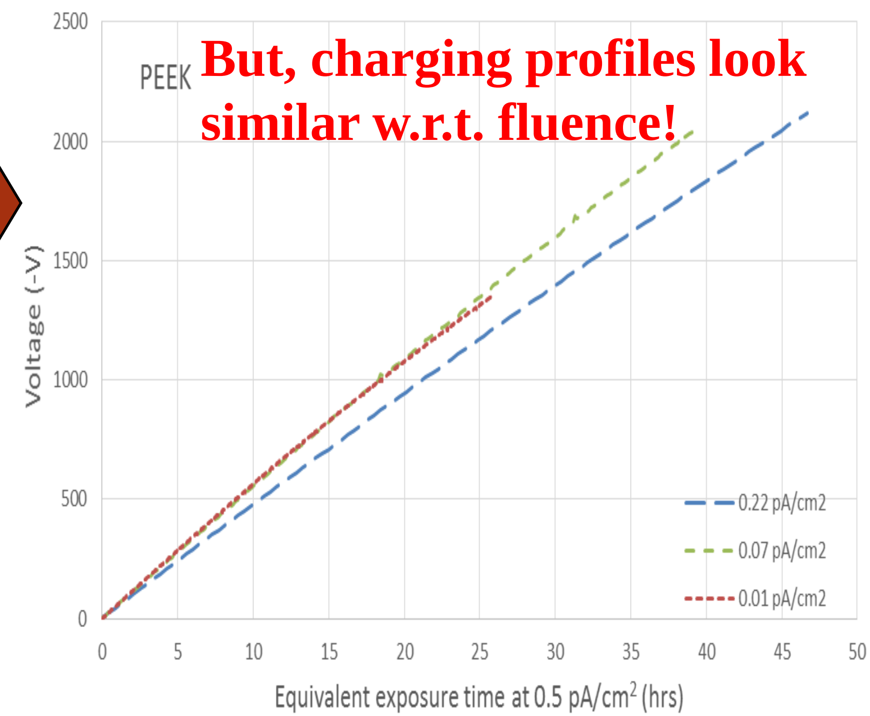
Sr-90 spectrum extends up to ~2.2 MeV:



PEEK Results

- Irradiated Poly-ether-ether-ketone
- Measured the voltage on surface using a non-contact probe
- Might expect radiation induced conductivity to affect the charging profile
- But – not for this material

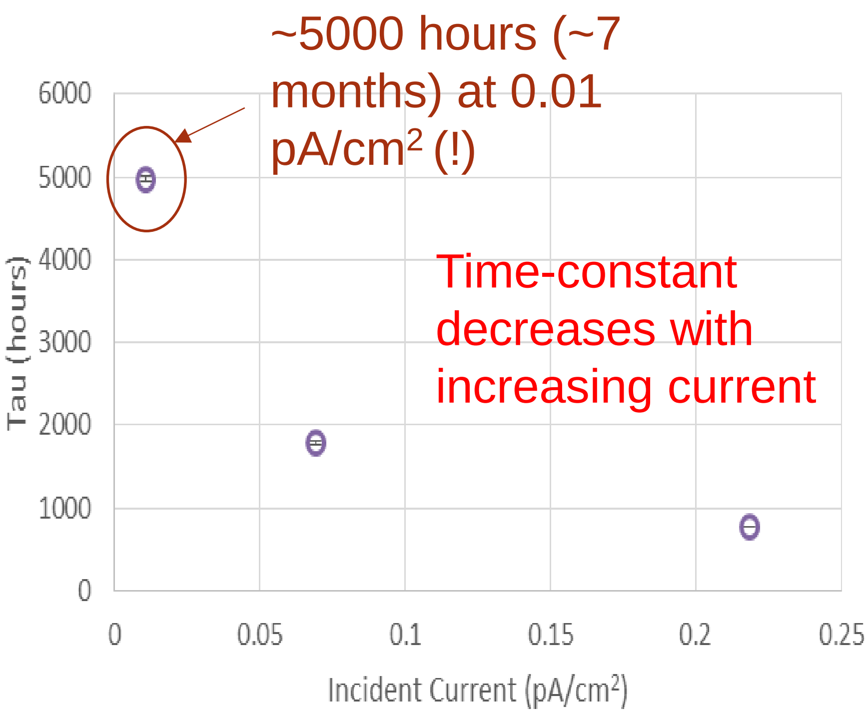


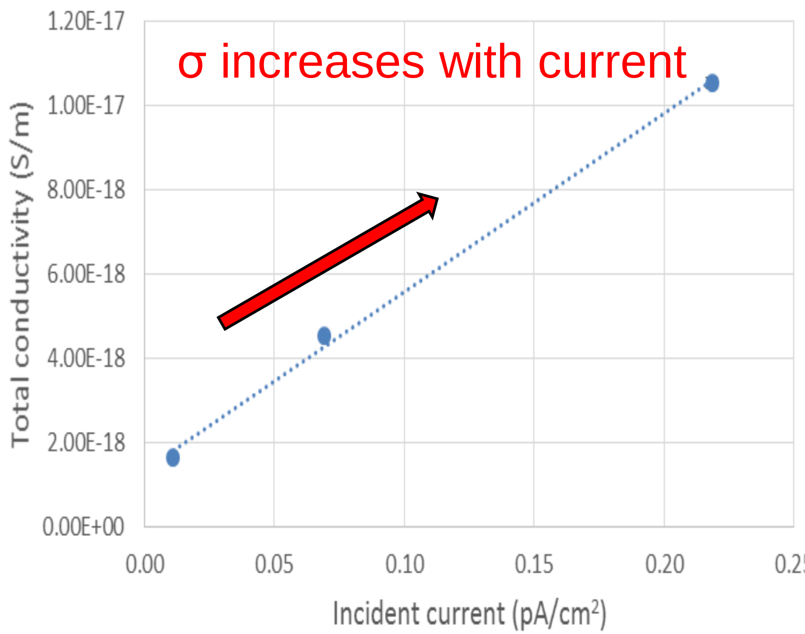


Charging Parameters

$$\tau = \frac{\varepsilon_0 \varepsilon_r}{\sigma}$$

- Measured the time constant from Voltage-time plots – hence conductivity
- Time constant decreases with increasing irradiation current
- Conductivity increases with current

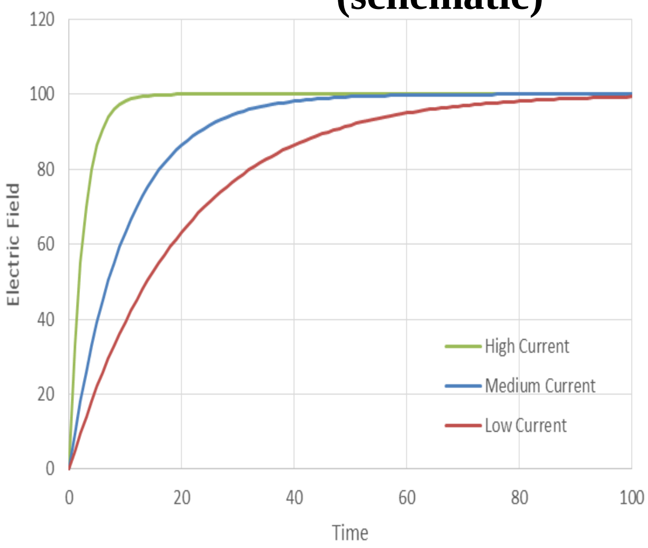




Implications

- Key findings of long-duration irradiations of PEEK:
  1. Radiation-induced conductivity >> bulk conductivity for high electron current > 0.1 pA/cm^2
  2. Radiation Induced conductivity index (Δ) is approximately 1
- Implication is that total conductivity is, to first approximation, inversely proportional to current
- Therefore the maximum electric field in the material is independent of the intensity of the environment

(schematic)



$$E = \frac{J_d}{\sigma} . \left(1 - e^{-t/\tau}\right)$$

Plateau ~ constant (environment affects only the time taken to reach equilibrium)

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Surface Charging Risk Assessment

Low energy electrons (1-100 keV) are responsible for spacecraft surface charging. This is however limited by electron emission by the spacecraft surfaces due to the impact of electron, proton and photons.

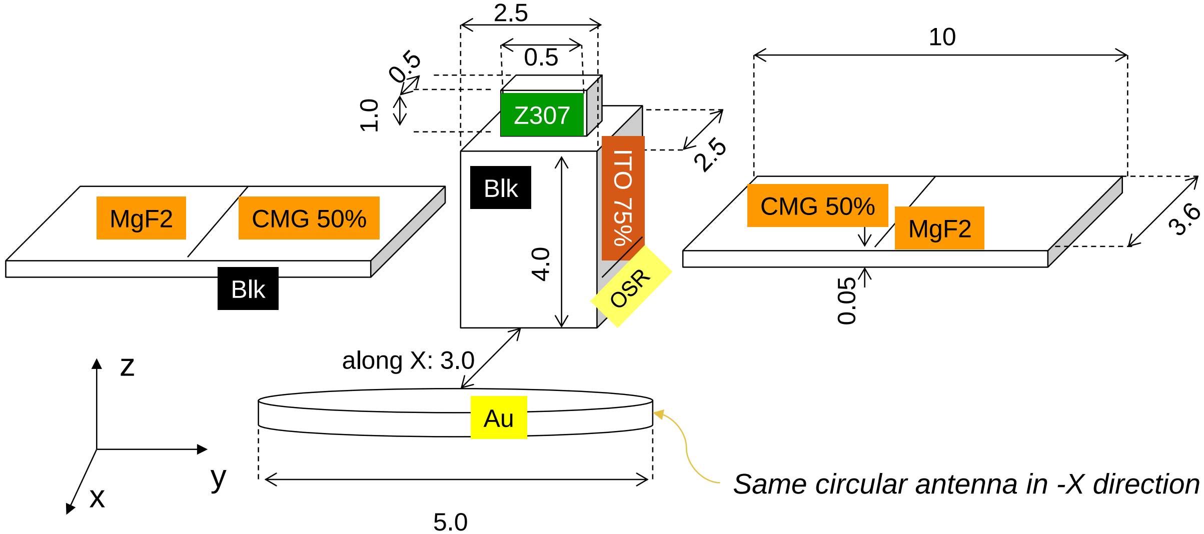
Generally photoemission is sufficient at keeping the spacecraft slightly positive, with no hazard for spacecraft.

Risks often occur during eclipse and at eclipse exit. However, large negative potentials are regularly observed at Sun.

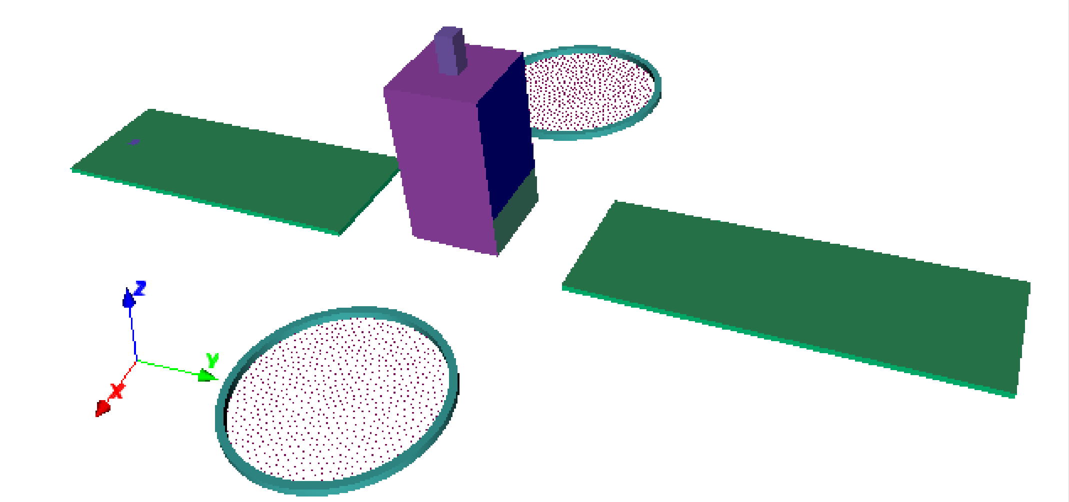
Understanding charging risks requires :

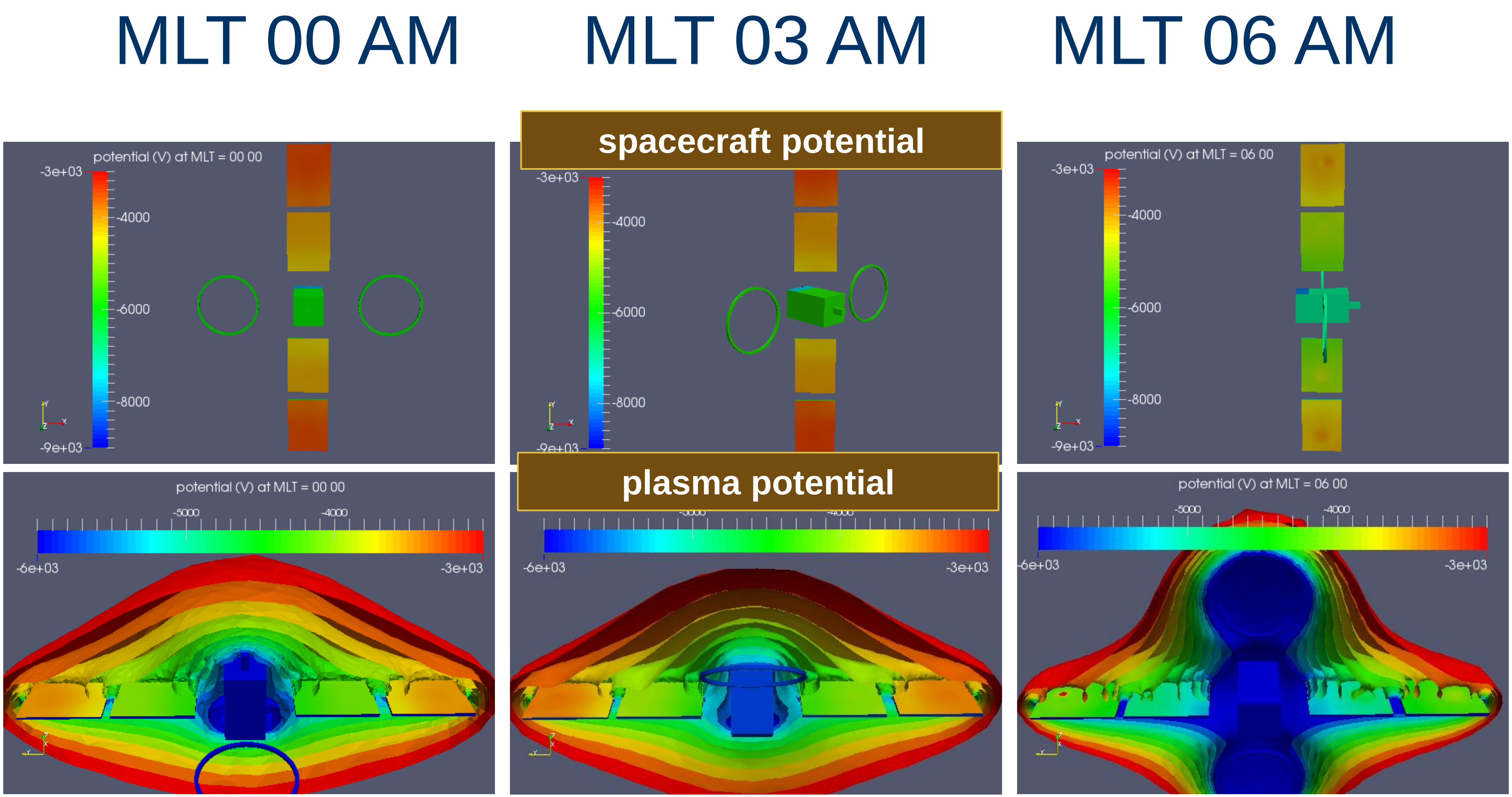
- full 3D spacecraft simulations
- accurate evaluation of electron and proton fluxes

Charging at GEO under ECSS worst case



SPIS software (www.spis.org)
3D CAD
Time dependent electrostatics code
Plasma dynamics
Interaction with materials
Charging estimates





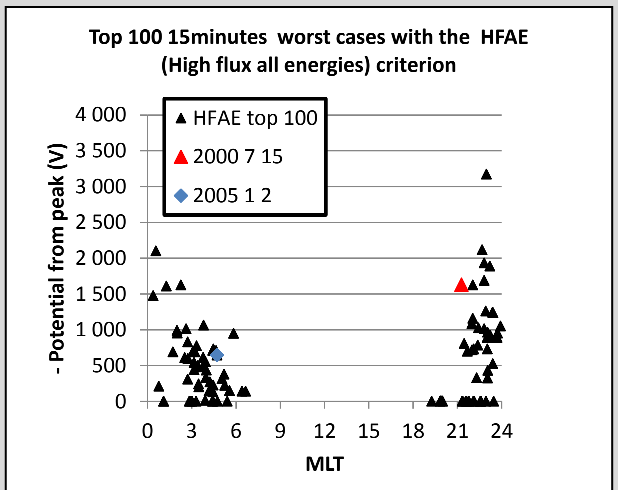
Mateo-Velez et al 2016, 14th SCTC

With the same environment : Charging risk are more important at 06 AM

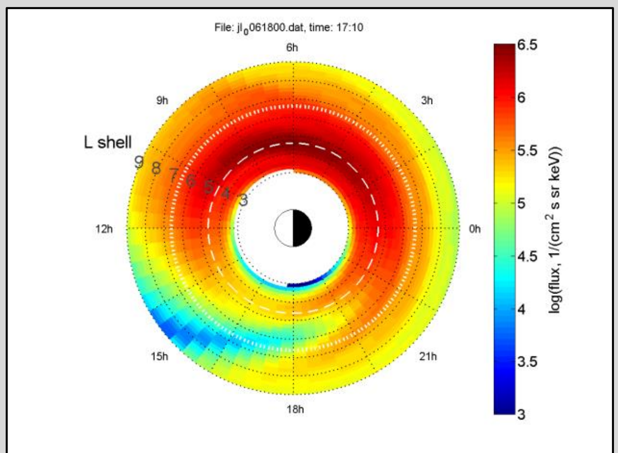
The spacecraft attitude and of the area of conductive materials exposed to sunlight are very important

Charging at MEO

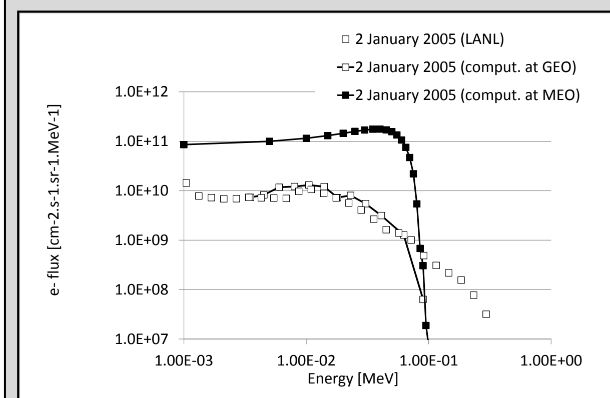
- Few data available
- Method to obtain MEO worst case flux
  1. Use the results of CNES/ONERA R&D activities (2010-2016) to select dates of charging events at GEO LANL spacecraft
  2. Use the IMPTAM software developed at FMI to transport electrons from GEO LANL to MEO L = 4.6
  3. Select time and position of worst case electron fluxes at MEO after



1. GEO LANL (courtesy of CNES)



2.IMPTAM



3. Specification at MEO

Mateo-Velez et al 2016, 14th SCTC

Next step : SPIS simulation

Acknowledgements

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