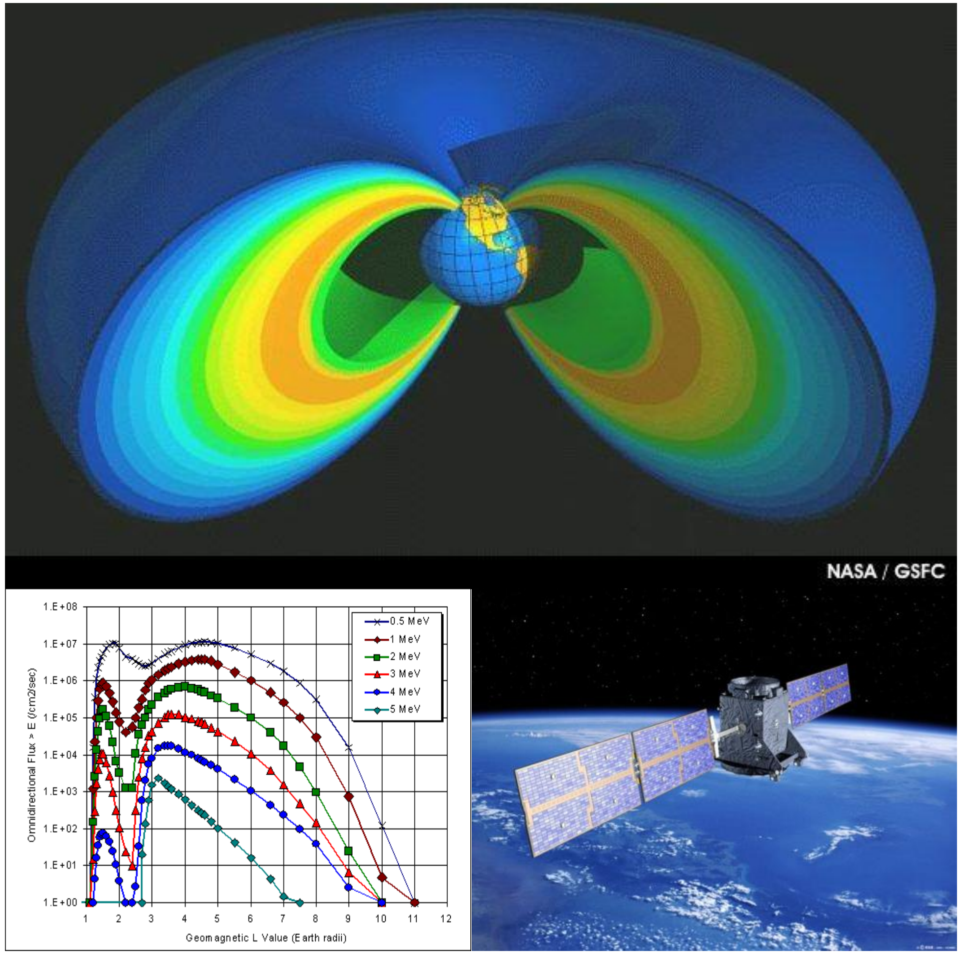
Data and Models for Internal Charging Analysis

Alex Hands
University of Surrey, UK

5^{th} September 2017
SEESAW Conference
Boulder CO

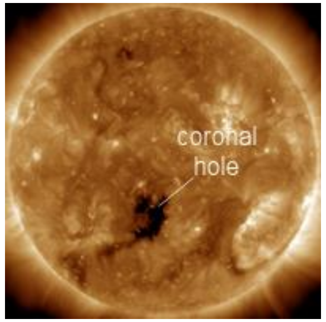
Outline

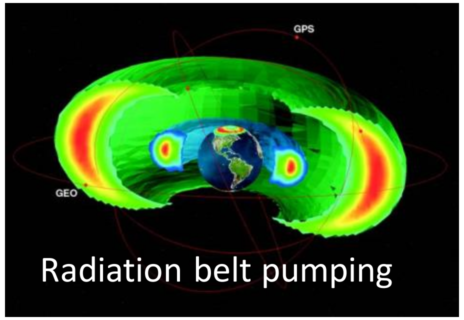
- Background
  - Internal Charging
- Data
  - Focus on SURF instrument
- Environment Models
  - Focus on FLUMIC and MOBE-DIC
- Charging Models
  - Focus on DICTAT
- Experimental Approach
- Future Work

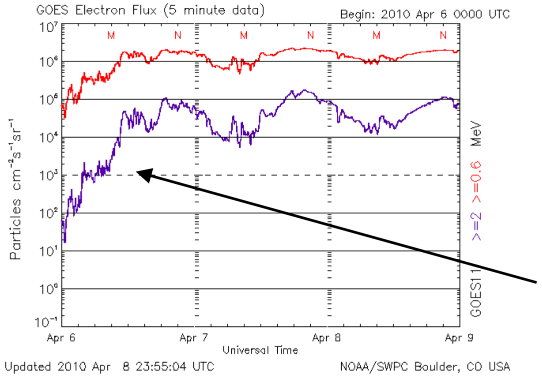


Internal Charging

- Energetic trapped electrons in Van Allen belts pose a threat to satellites through internal charging of dielectric materials:
- The outer electron belt is extremely dynamic - large changes in flux occur over short timescales, driven by coronal holes and coronal mass ejections (CMEs)



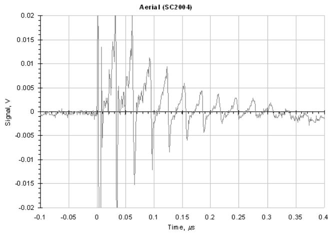




e.g. April 2010:

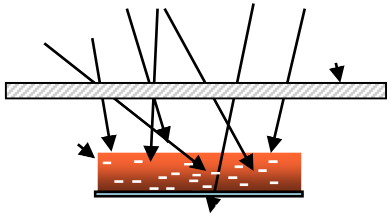
>2 MeV flux at GEO increases by ~4 orders of magnitude in a few hours!

Satellite anomaly / outage /failure



Energy coupling into circuit

Electrostatic discharge

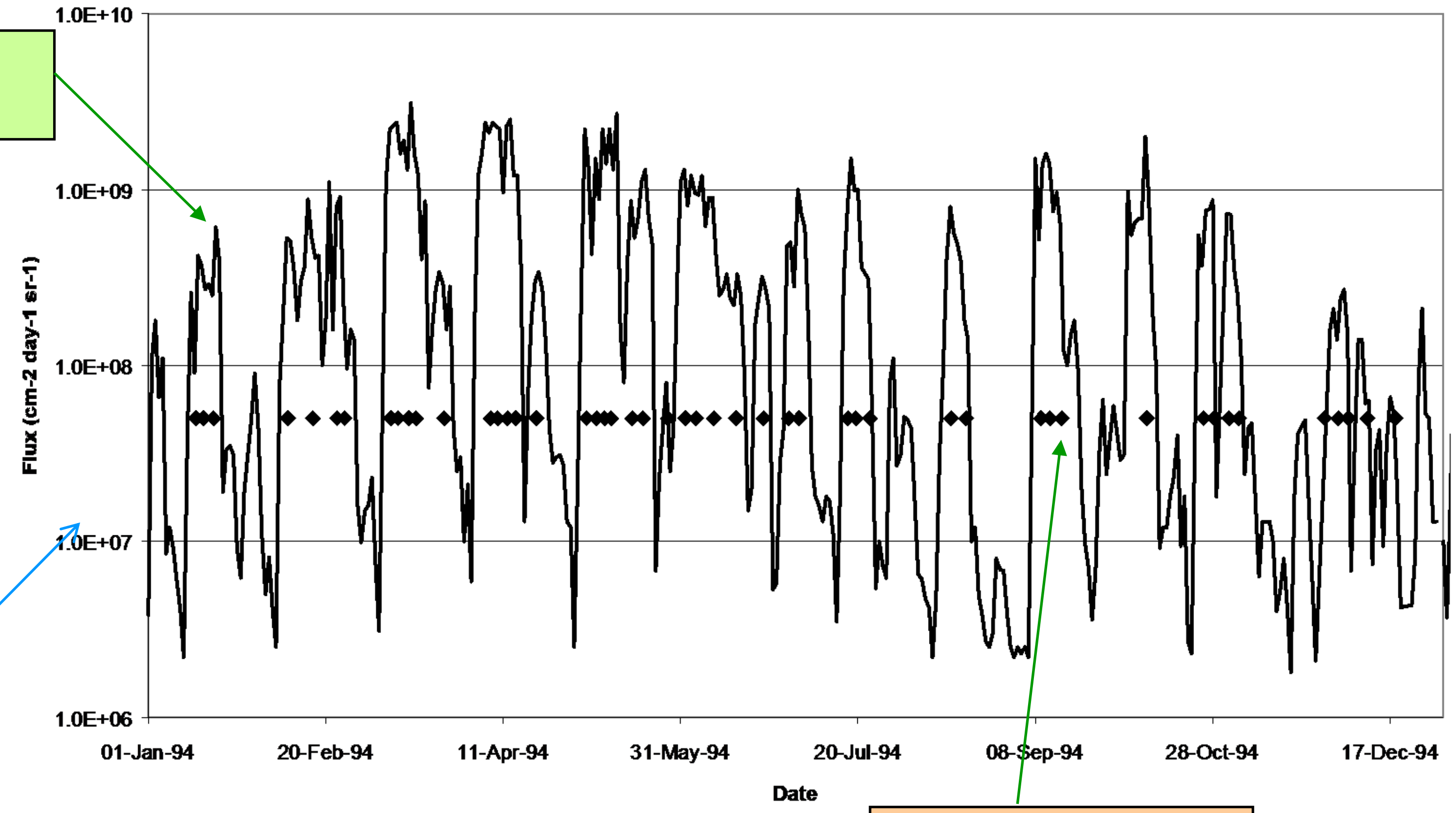


Electrostatic charging of spacecraft materials

Satellite Anomalies

- Example of correlation with GOES >2 MeV electron flux:

Anik E1 & E2, Intelsat K disabled

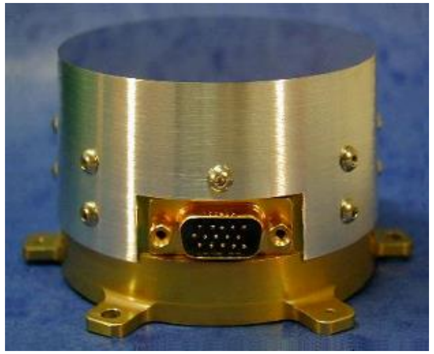


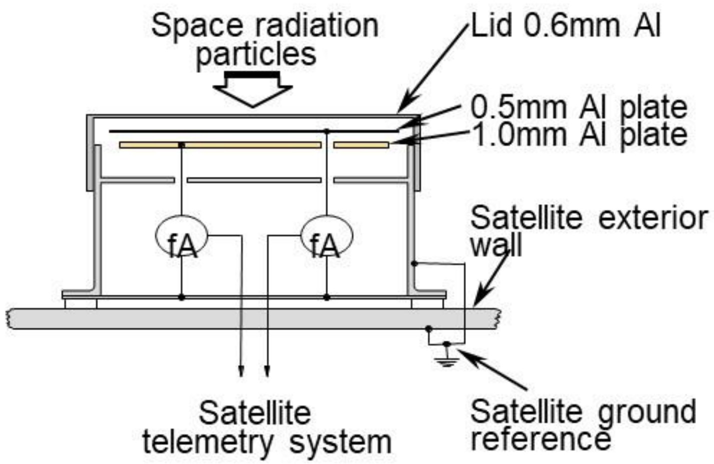
Note log scale – outer belt is highly dynamic due to buffeting by the solar wind

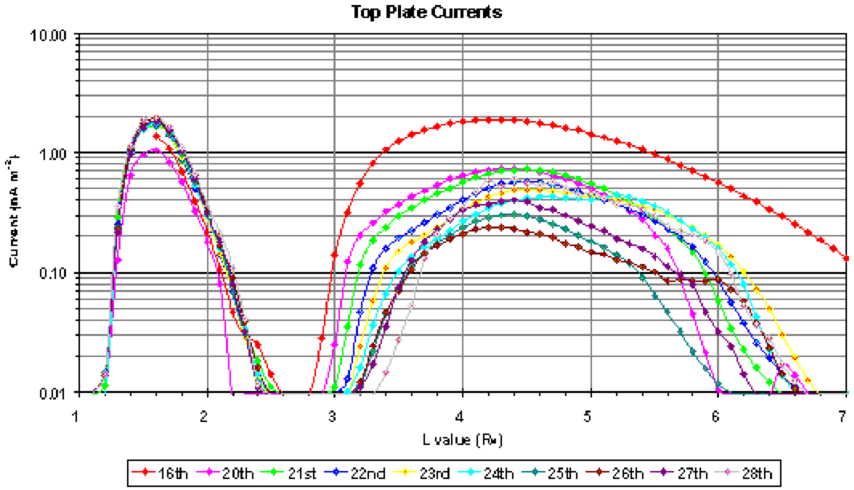
DRA-Δ anomalies

In-situ measurements of electron current

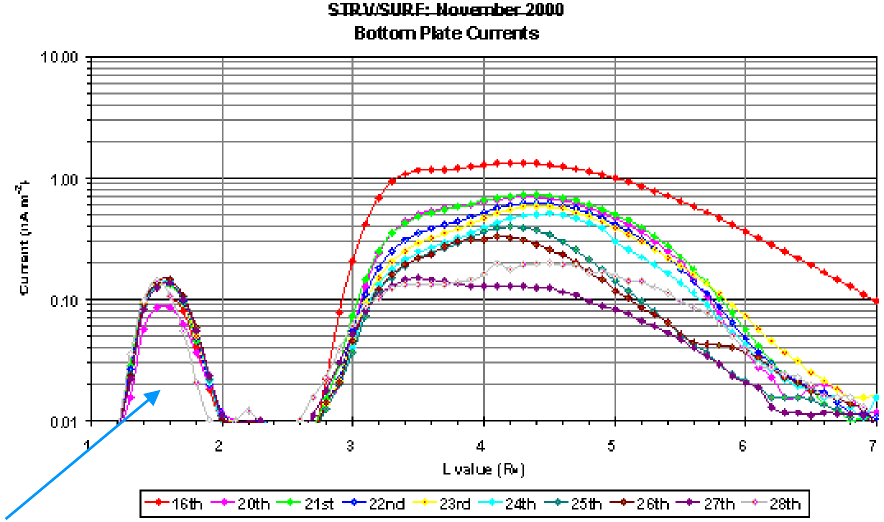
SURF Instrument (carried on STRV1d GTO mission)







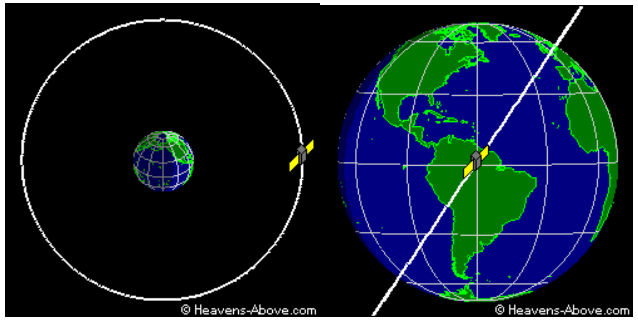
Inner & outer belts clearly visible



~MeV electrons in inner belt
(in 2000 but no longer?)

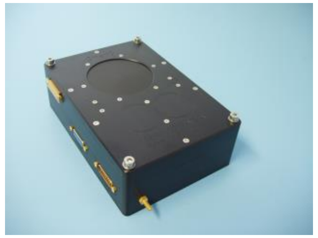
UNIVERSITY OF SURREY

Giove Spacecraft

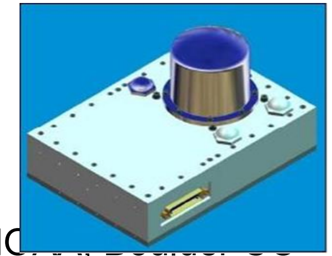


- Technology Demonstrator Satellites for Galileo Constellation
- Each Carries Space Environment Monitor(s)
- Medium Earth Orbit (~23,500 km, 56°)

Giove-A:
- Launched Dec 2005
- Two instruments:
  - Merlin



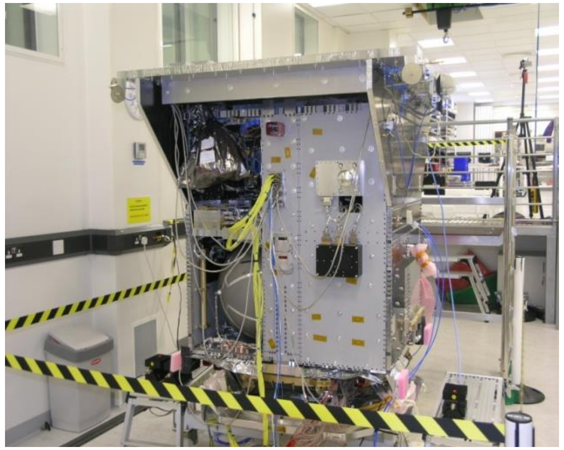
  - Cedex

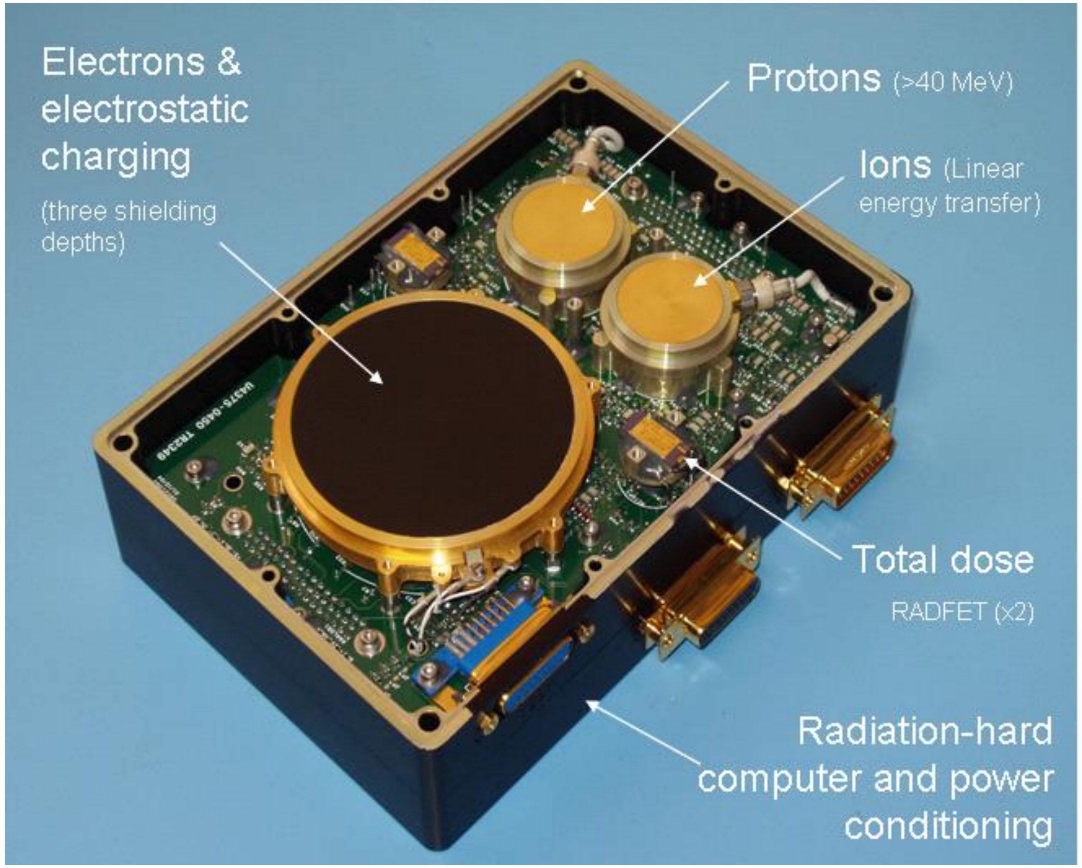


Giove-B:
- Launched Apr 2008
- One instrument:
  - SREM

Merlin radiation monitor

- Suite of detectors
- Launched in 2005 on Giove-A
- Still operating successfully





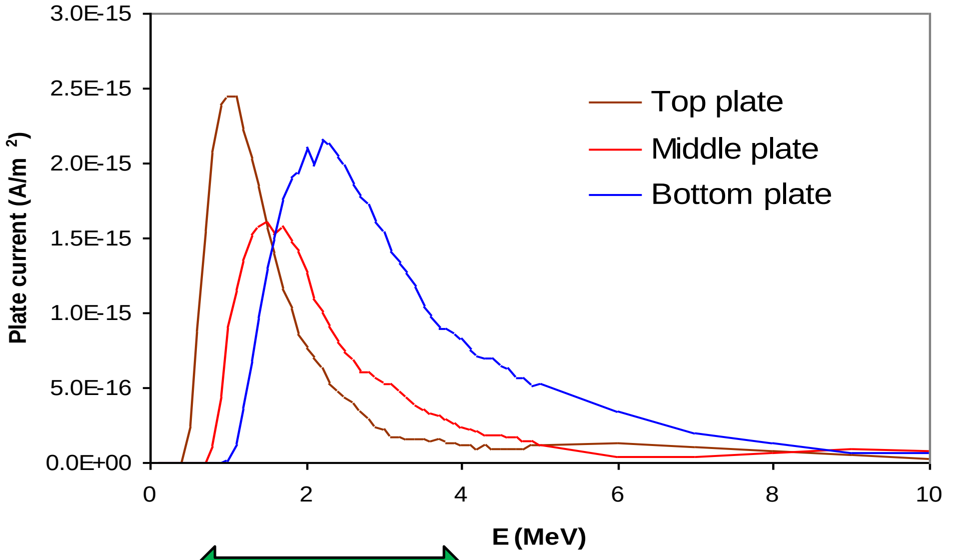
"The Merlin Space Weather Monitor and its Planned Flight on the Galileo System Testbed Satellite (GSTB-V2/A)," K. A. Ryden, C. S. Dyer, P. A. Morris, R. A. Haine and S. Jason IAC paper IAC-04-IAA.4.9.3/U.6.04, Published in Proceedings of IEC Congress Vancouver, Canada, 2004.

Merlin-SURF

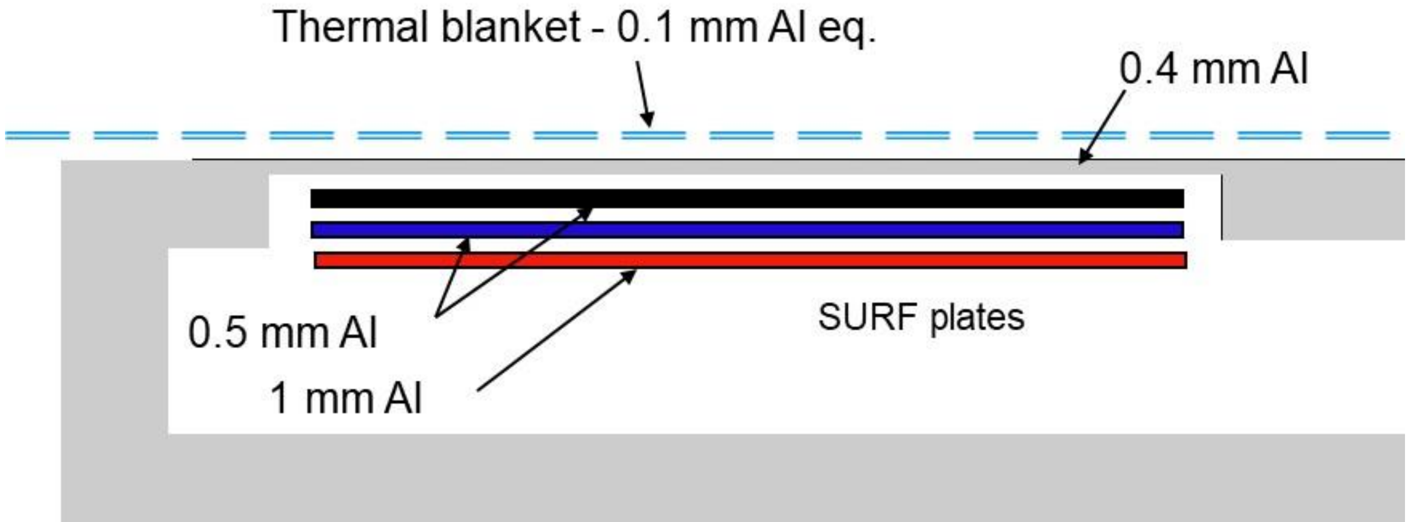
Successor SURF detector now has three charging plates

- Top Plate: 0.5mm thick, 0.5mm Al shielding above
- Middle Plate: 0.5mm thick, 1.0mm Al shielding above
- Bottom Plate: 1.0mm thick, 1.5mm Al shielding above

Response functions



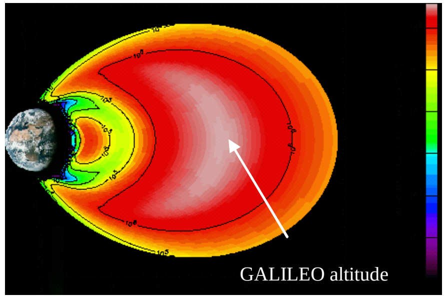
Peak response ~0.5 – 4 MeV



Free from proton contamination (v. small opposite polarity currents during SEPE)

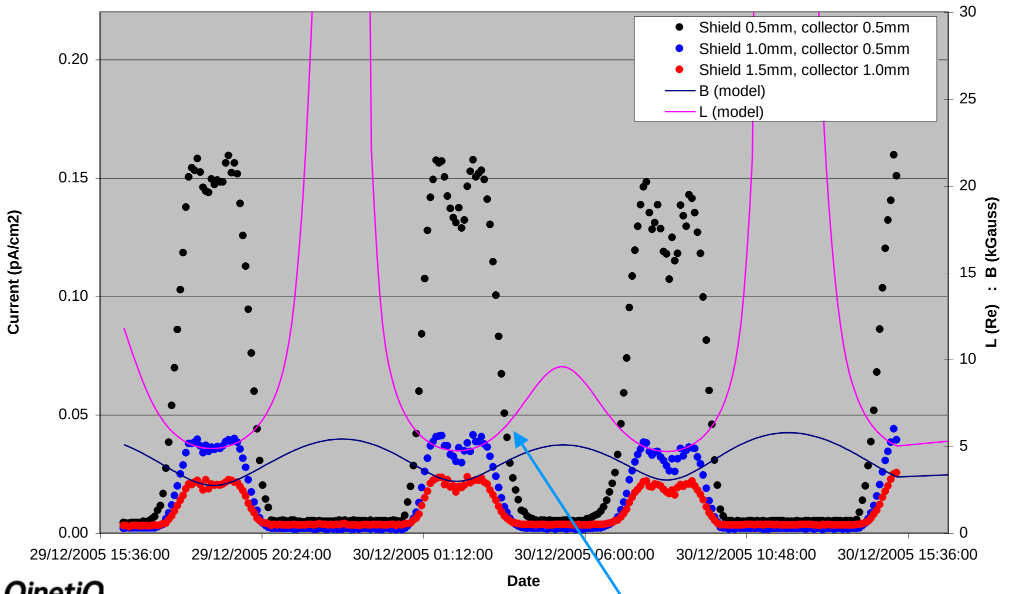
SURF Data

- Giove-A / Galileo orbit is in the heart of the outer belt
- Perfect location for internal charging currents



First Day:

MERLIN-GIOVE A: CHARGING CURRENTS DUE TO TRAPPED ELECTRONS

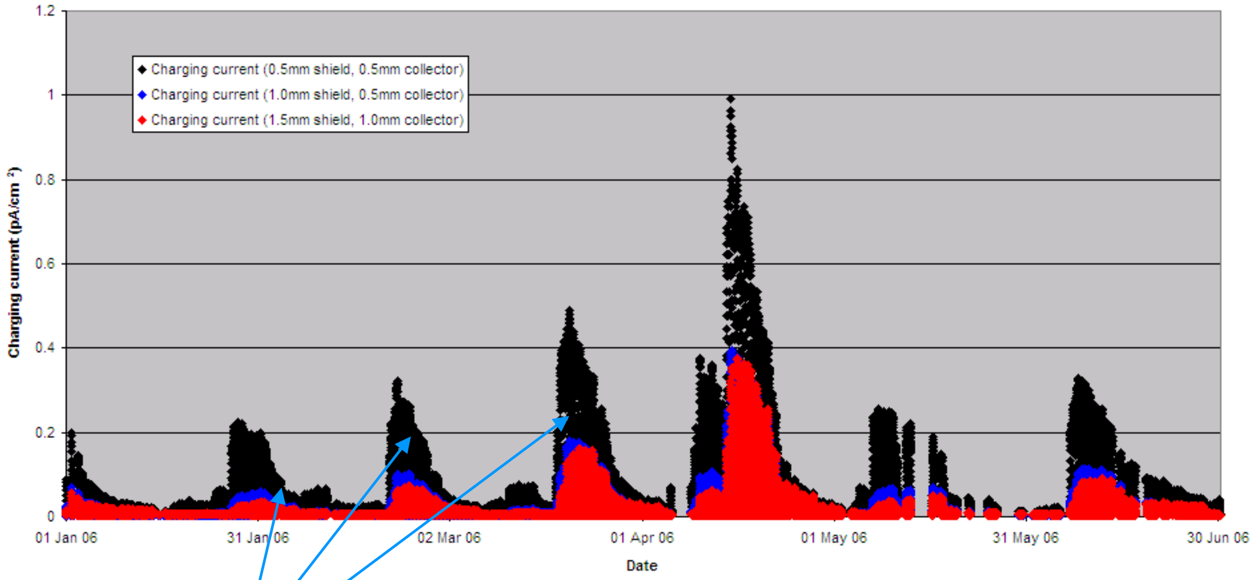


QinetiQ

Samples peak of belt every ~7 hours

First 6 months:

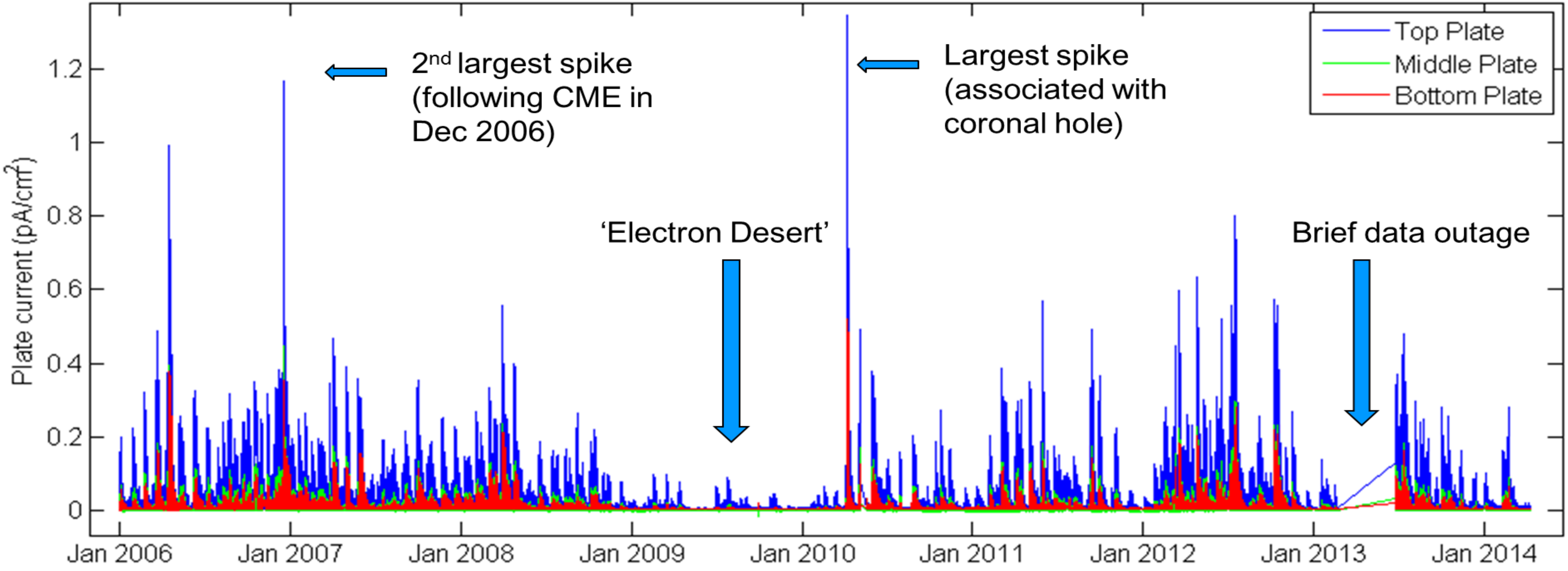
Merlin Giove A



Recurrence of coronal hole

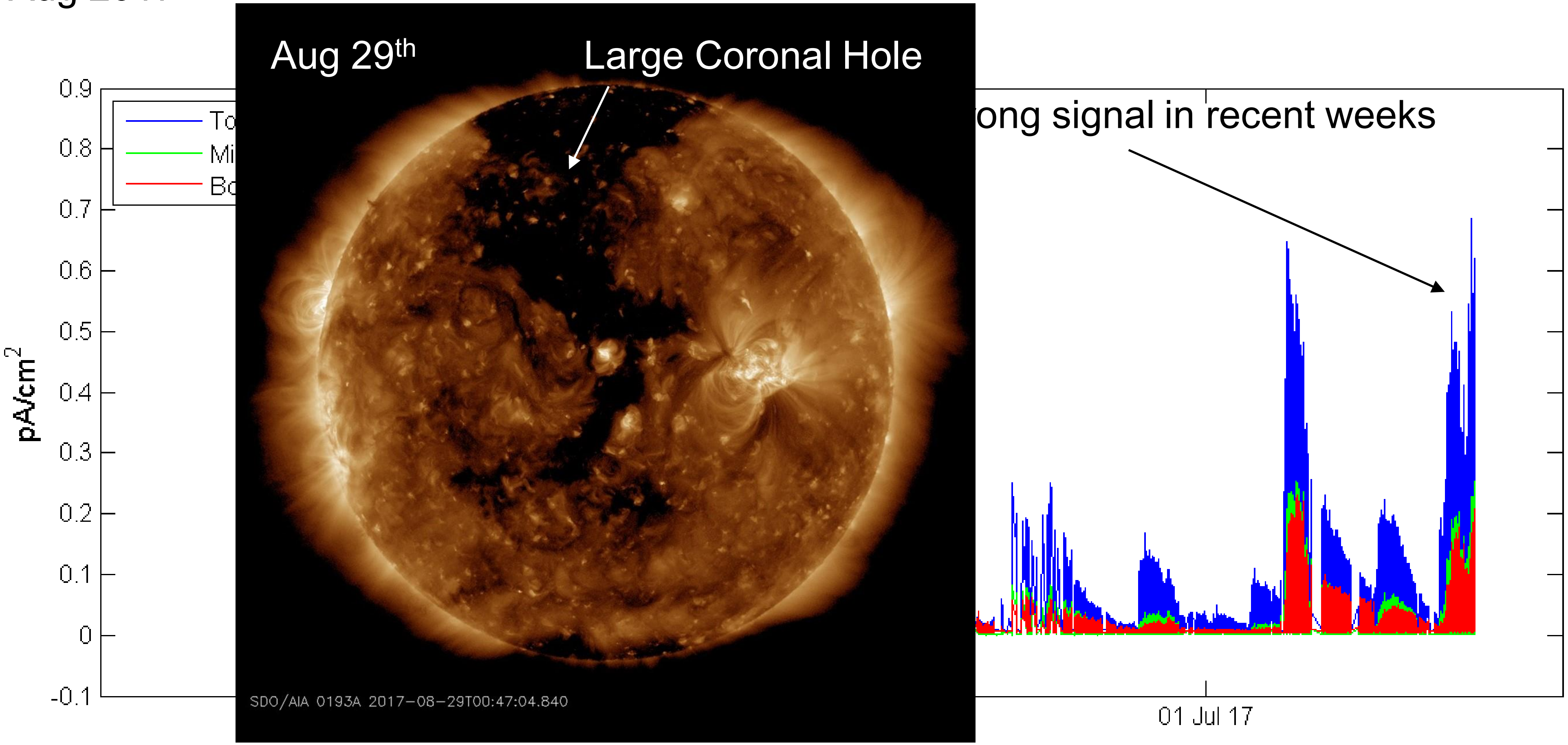
SURF Data

- 2005 – 2014:



Most recent SURF data

Jan – Aug 2017



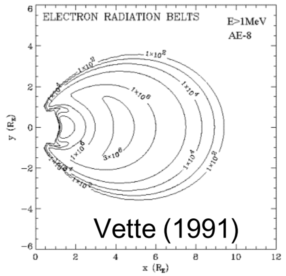
Existing Environment Models

- Several models describe the Van Allen belts:
- AE8:
  - Industry standard for decades
  - Static model – no flux variability
  - Inadequate for internal charging
- AE9:

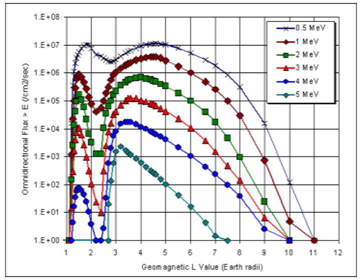
This Talk

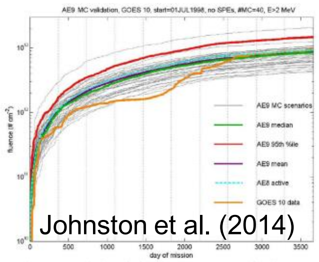
ces

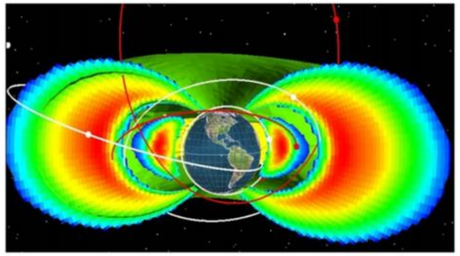
  - Comprehensive statistics
  - Complex (many input parameters & run options)
- FLUMIC:
  - Worst-case model for internal charging
  - Based primarily on GEO data (not near peak)
  - User-friendly but not up-to-date
- MOBE-DIC:
  - Based on MEO data
  - Extrapolated to other parts of outer belt
- Various others targeted at specific environments/orbits

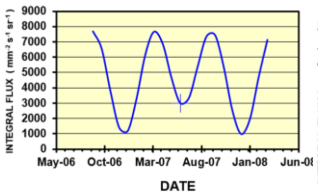


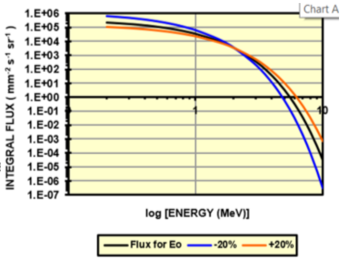
Vette (1991)

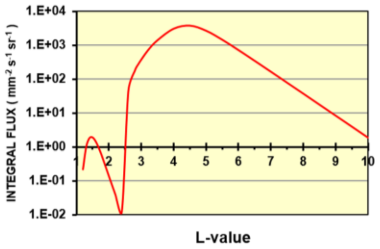



Johnston et al. (2014)





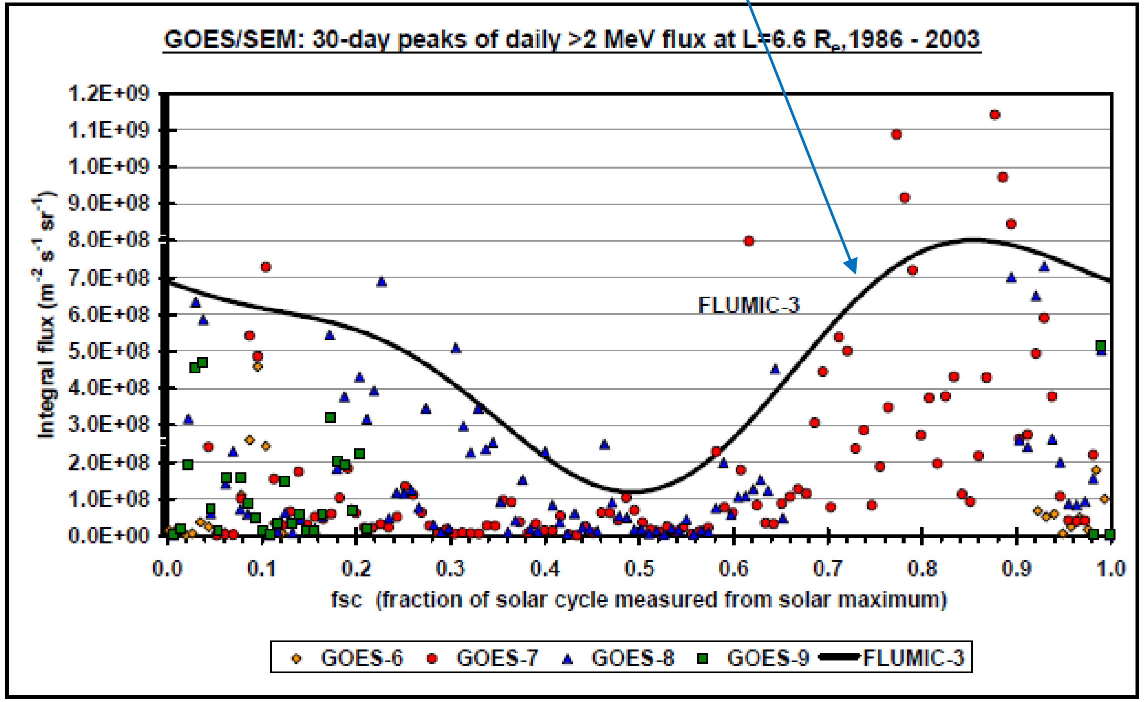




FLUMIC

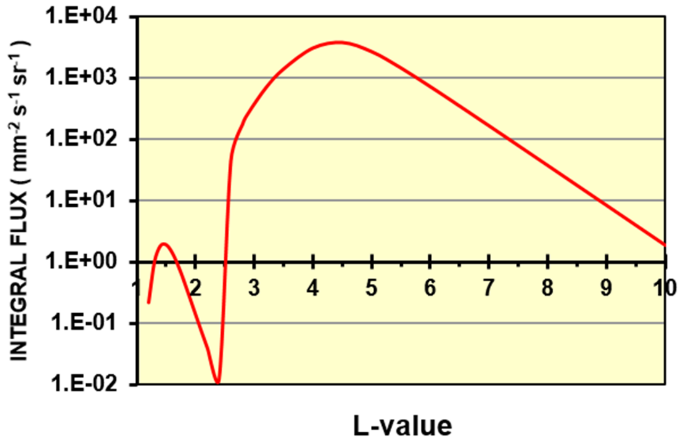
- Empirical model developed specifically for internal charging (2000)
- Based mainly on data from STRV and GOES in 1980s and 1990s
- Give 'worst-case' 1-day flux envelope as function of:
  - B
  - L
  - fraction of solar cycle
  - fraction of year (seasonal)
- Latest version 3.0 (available on SPENVIS)
- ALE (Anomalously Large Event) version for 'worst case'

Flux envelope varies with apparent solar cycle modulation in GOES data

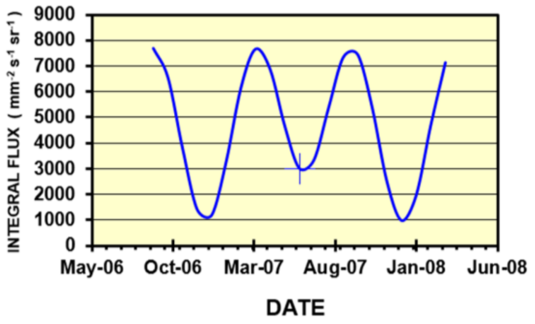


FLUMIC – key features

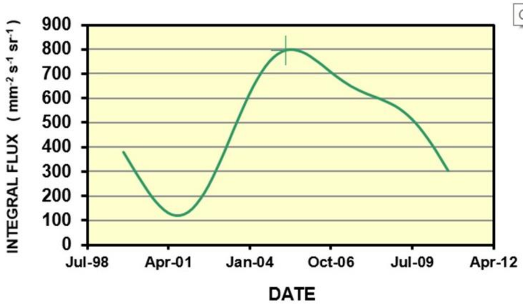
1. Covers inner and outer electron belts



2. Flux output depends on date

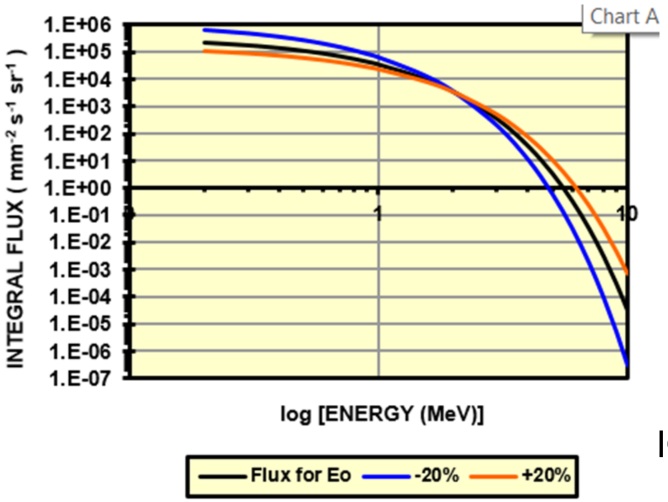


Seasonal modulation



Solar cycle modulation

3. Simple exponential spectrum

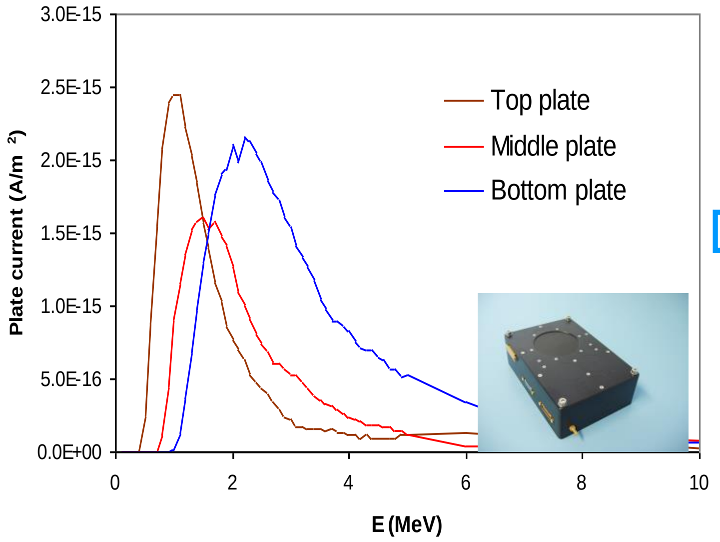


4. It's easy to use!

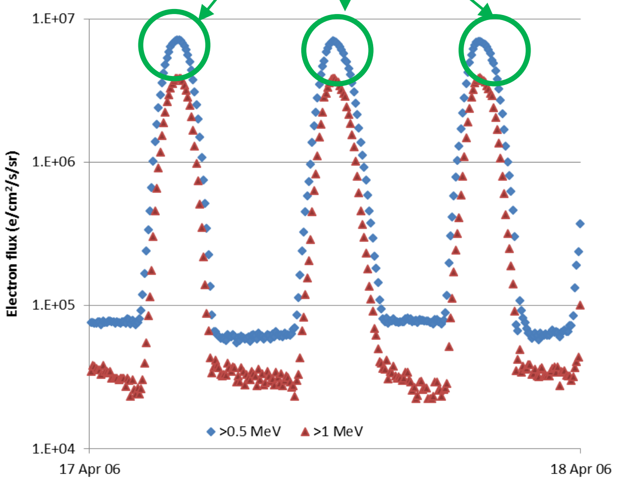
Model of Outer Belt Electrons for Dielectric Internal Charging (MOBE-DIC)

- New model based on MEO Electron fluxes extracted from SURF data

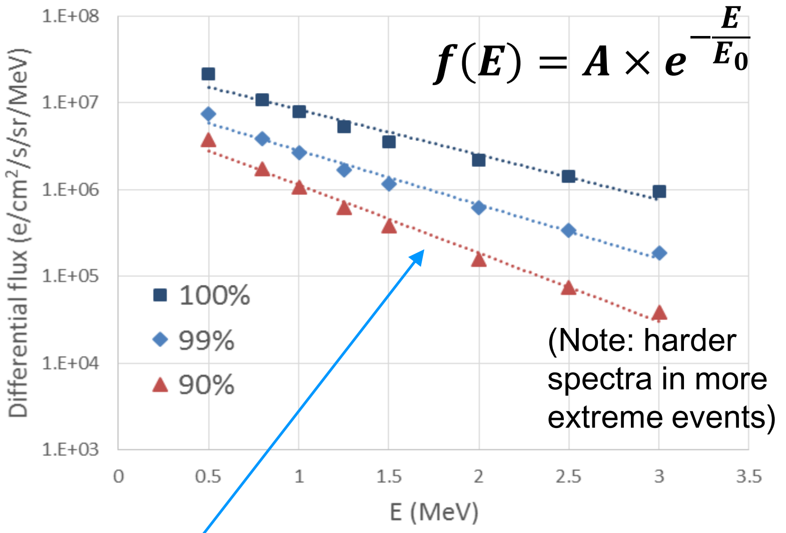
Instrument response functions used to derive flux based on assumed exponential spectrum



Create reduced series of average flux at equatorial peaks (L≈4.7)



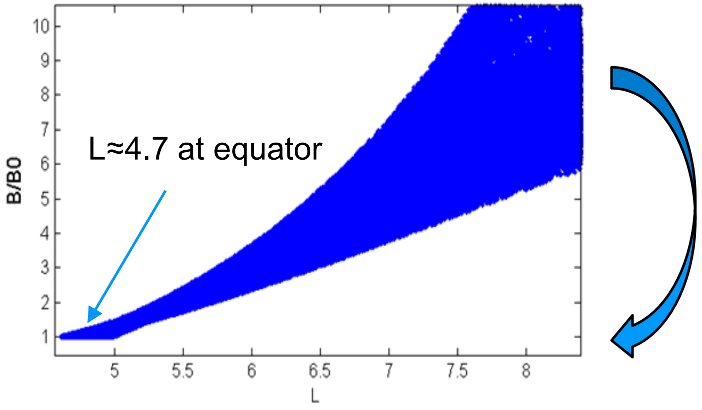
Fit baseline spectra at three exceedance probabilities - 90%, 99% & 100%



These three spectra form the basis of the MOBE-DIC model

Extrapolating to other L-Shells

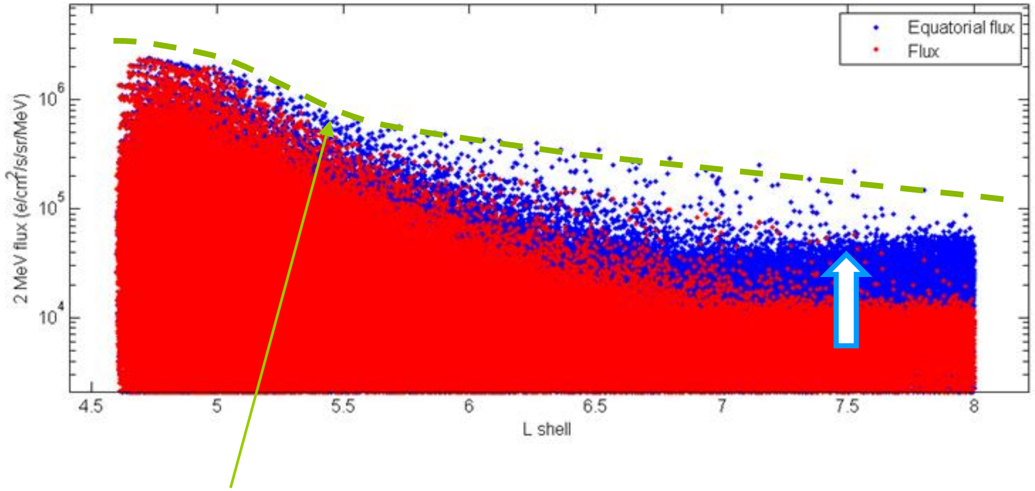
- Inclination of Giove-A orbit means higher L shells only encountered at higher latitudes
- Need to renormalise non-equatorial fluxes:



Assume Vette function (like AE8 and FLUMIC)

[Scaling is (slightly) L-dependent but not energy-dependent]

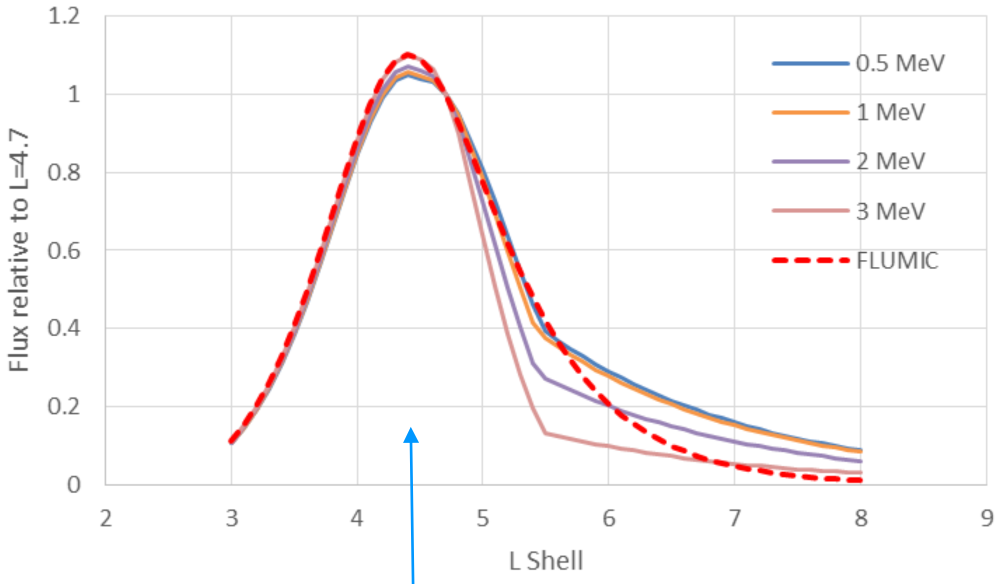
1. All Flux ⇨ Equatorial Flux



2. Fit 'envelope' to renormalised data (at each energy)
→ Energy-dependent L-Shell profile

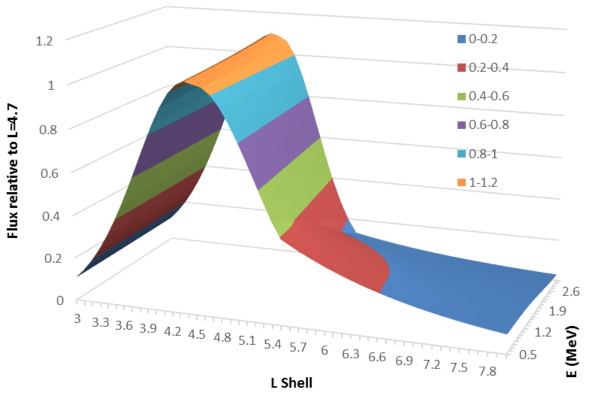
Extrapolating to other L-Shells

- Final (energy-dependent) L-shell profile (3 < L < 8)

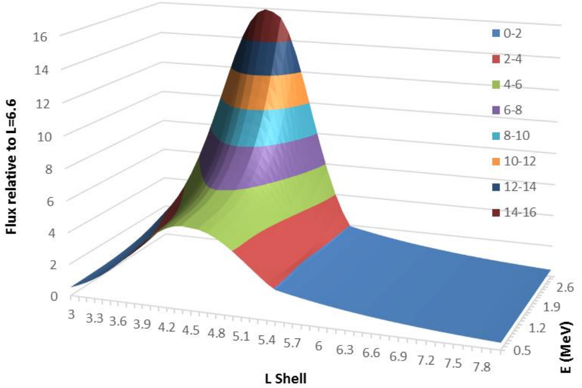


FLUMIC function used below L=4.5 (no Giove data)

Normalised to L=4.7:



Normalised to L=6.6:



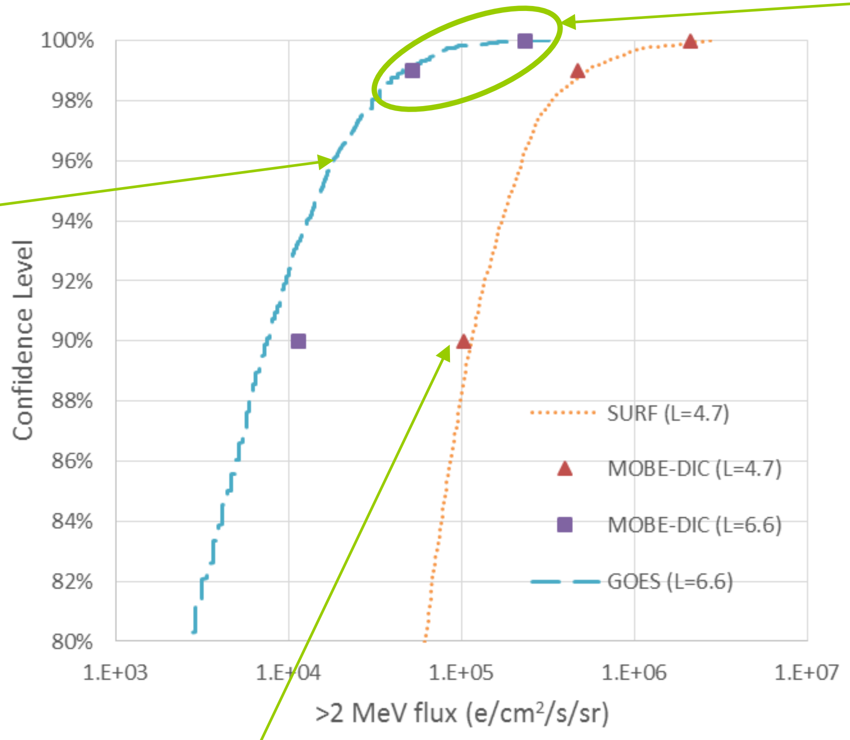
(NB slightly modified version used for integral flux)

Comparison to GOES data

- Compare model to cumulative probability density functions from data:

>2 MeV flux adjusted to L=6.6 and for dead-time effects

(Meredith et al., 2015)



Unsurprisingly, excellent consistency at L=4.7 (MEO)

Good agreement between MOBE-DIC and GOES at 99% and 100% (slightly worse at 90% due to conservative L-shell envelope)

MOBE-DIC prediction for '100%' (worst case) at GEO for >2 MeV flux is:

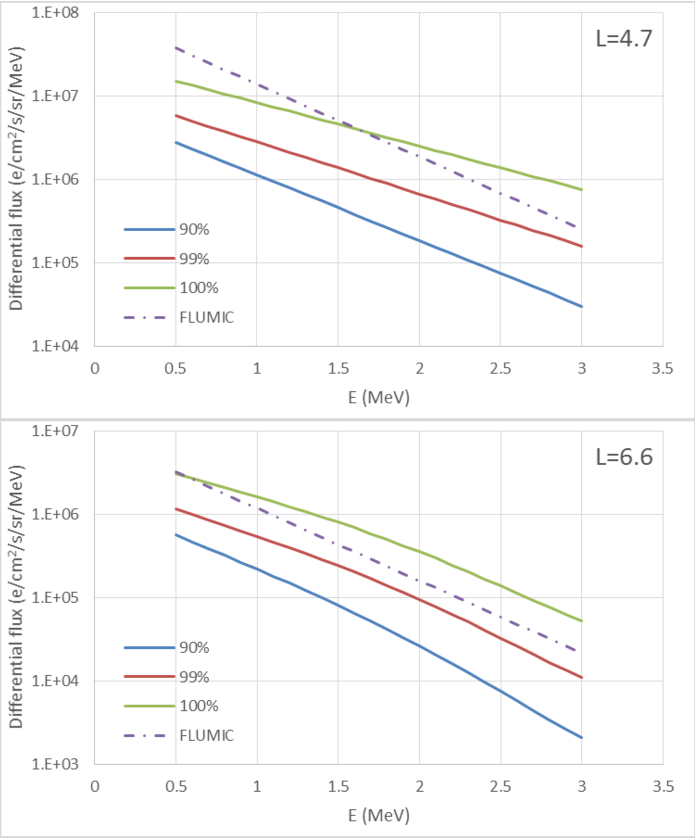
2.34×10^5 e/cm^2/s/sr

Theoretical upper limit (Koons et al. 2001)…

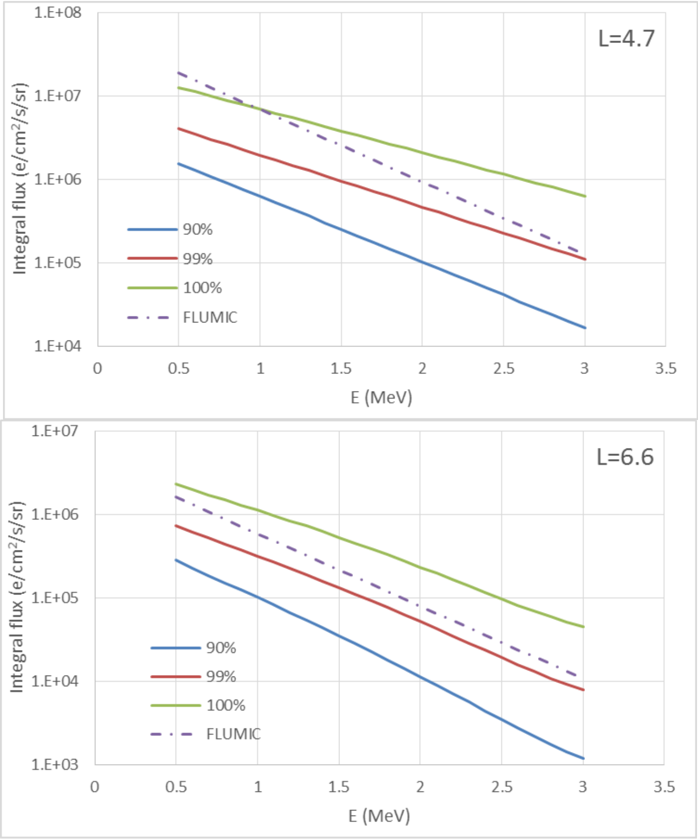
2.34×10^5 e/cm^2/s/sr !!

Comparison to FLUMIC

Differential Spectra



Integral Spectra

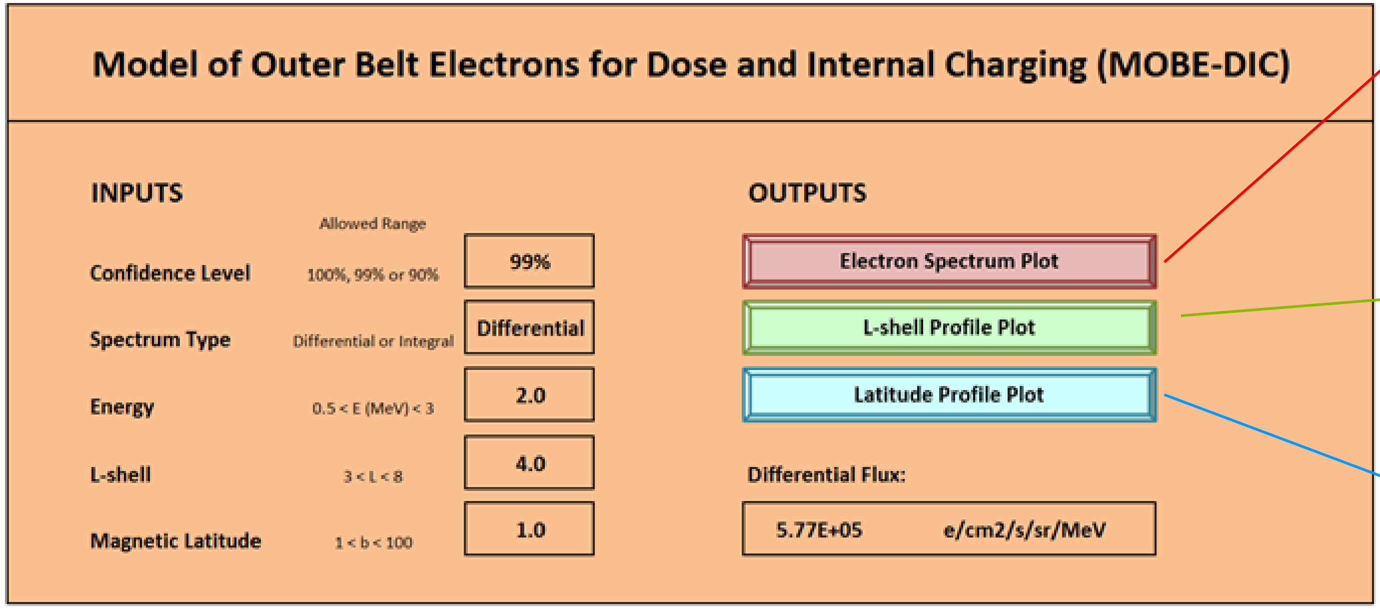


MOBE-DIC gives harder spectrum at peak of MEO (close to 100% level at 1 MeV)

Good agreement at GEO (FLUMIC in between 99% & 100% MOBE-DIC level)

MOBE-DIC: Implementation

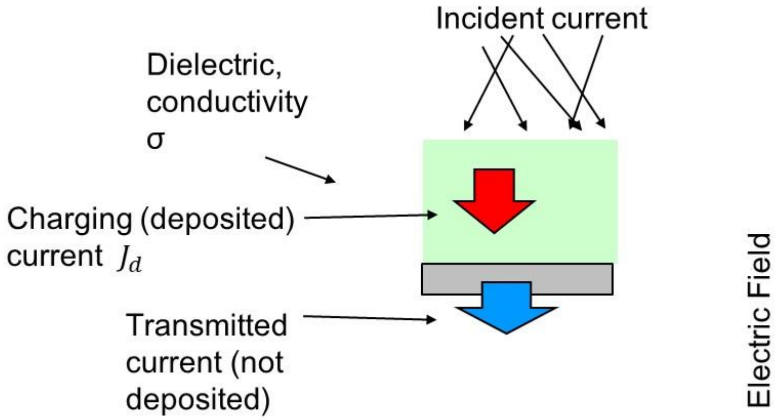
- MOBE-DIC model is defined by a set of parameters and simple equations
- At present simple spreadsheet implementation:

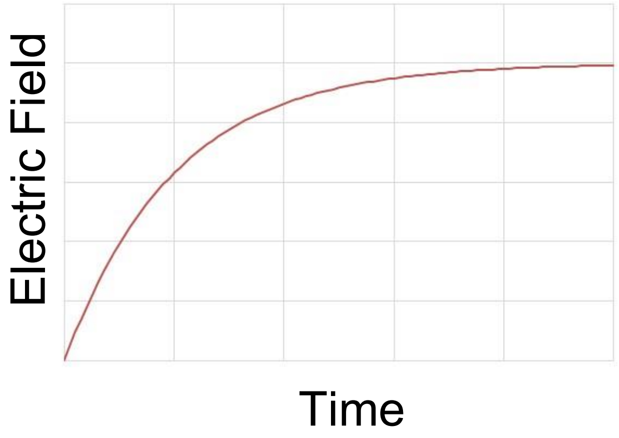


- Public version available on request (a.hands@surrey.ac.uk)
- To be made available via Spenvis…

Internal Charging Models

- Various models exist for calculating internal charging (1-D and 3-D)
- For example:
  - DICTAT
  - NUMIT (1-D & 3-D)
  - MCICT
  - SPIS-IC
- Based on same basic electrostatic equations:



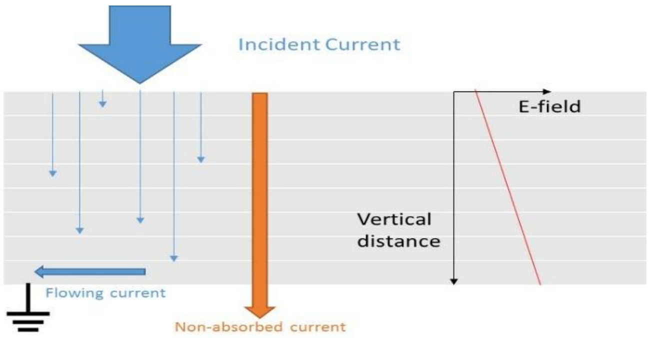


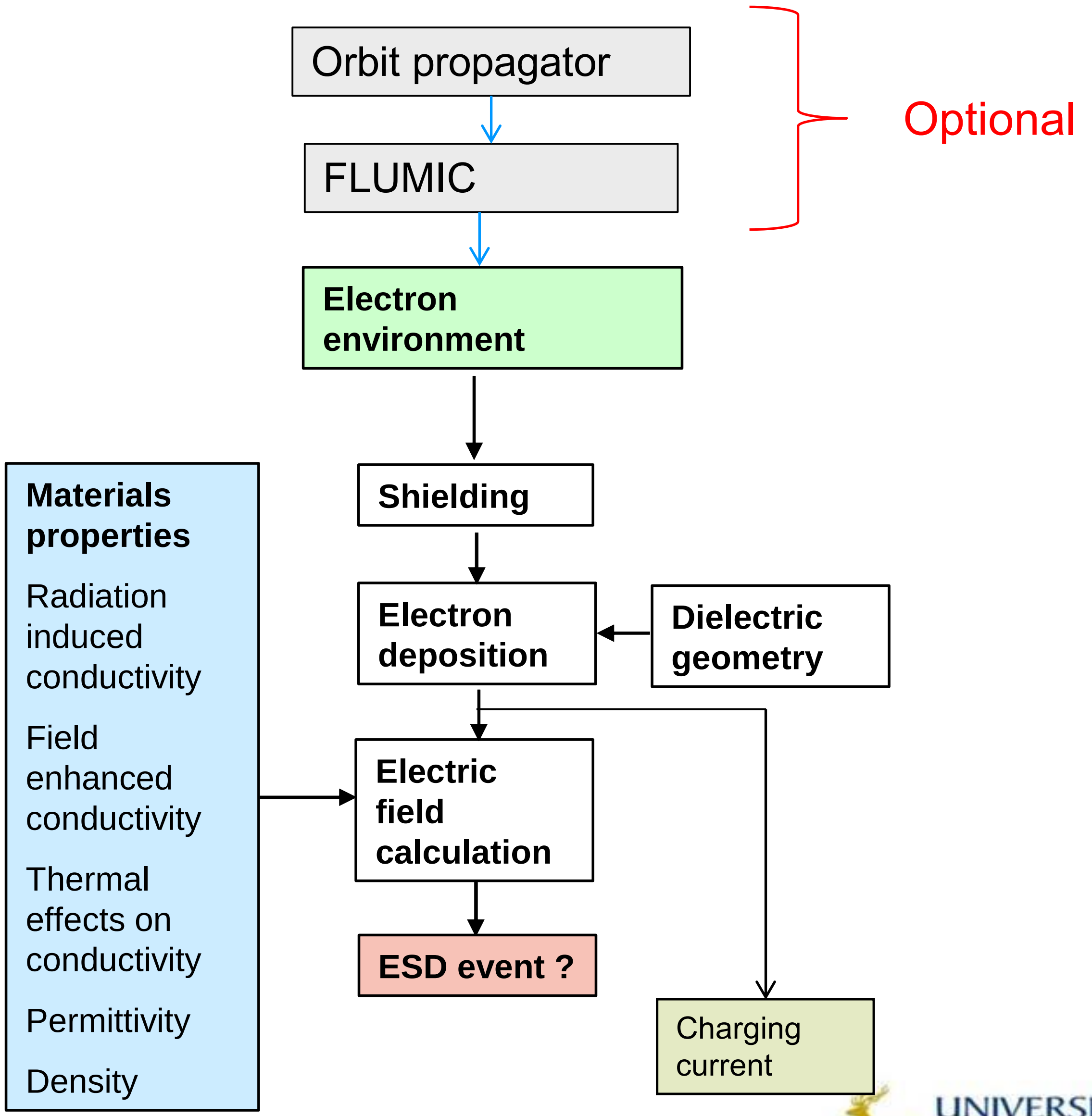
Exponential build-up of electric field (or surface voltage), eventually reaching equilibrium

$$E = \frac{J_d}{\sigma}.\left(1 - e^{-t/\tau}\right) \qquad \tau = \frac{\varepsilon_0 \varepsilon_r}{\sigma}$$

DICTAT

- 1-D structure
- Electron transport – Weber & Sorensen formulae
- Temperature effects
- Radiation induced and field enhanced conductivity
- Cable and Flat geometries
- Various grounding arrangements
- Electric field calculated in ten layers





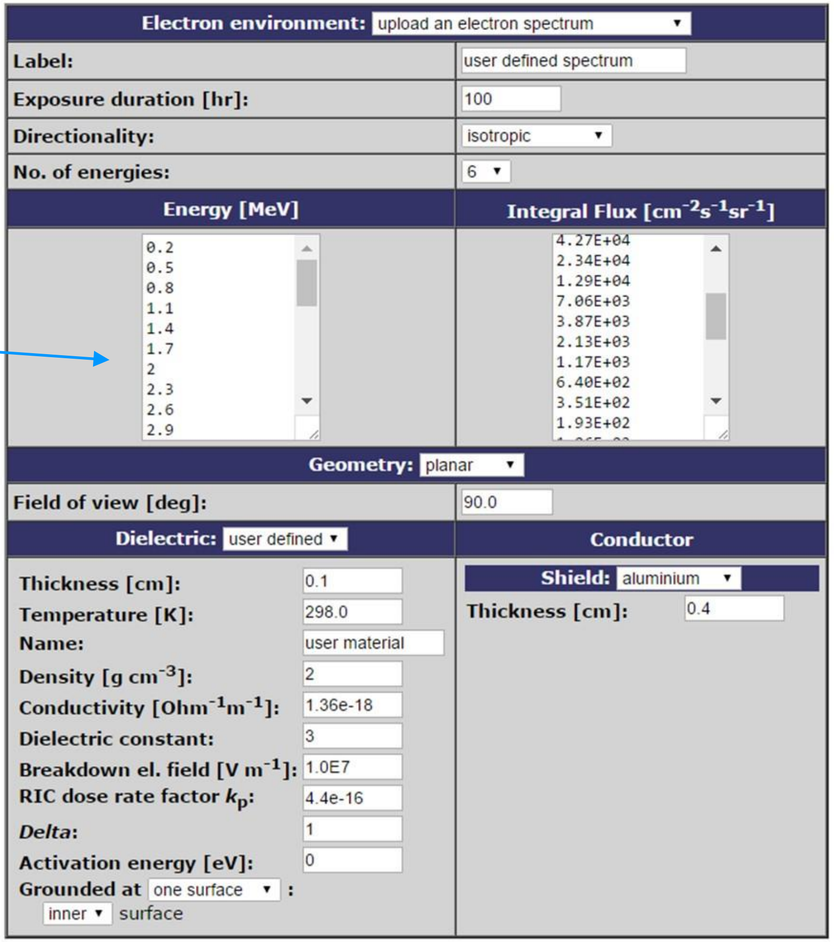
22

DICTAT

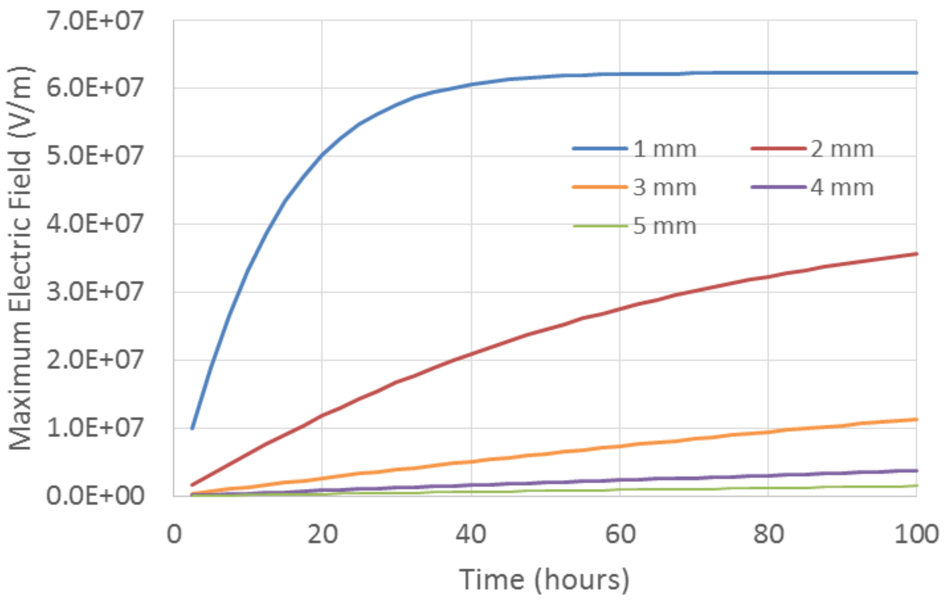
- Structure on SPENVIS:

Spectrum

Material parameters



E-field as a function of time
(e.g. for varying shielding thickness)



Sensitivity Analysis

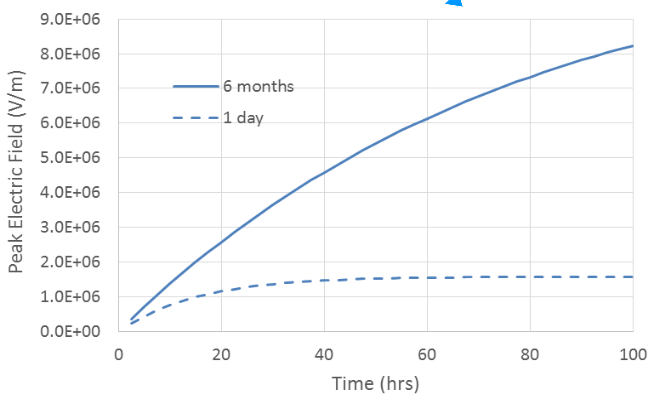
Material properties have dominant impact on charging behaviour:

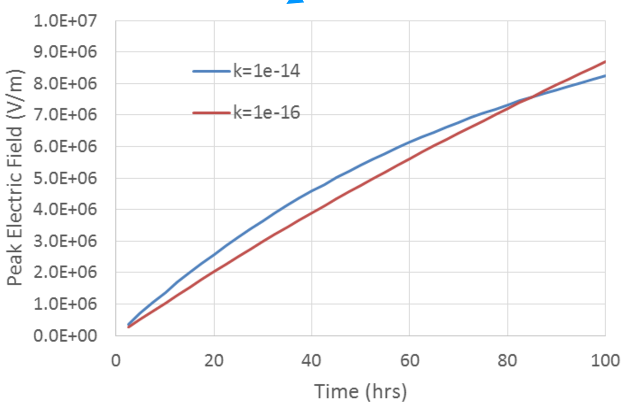
Key conductivity equations:

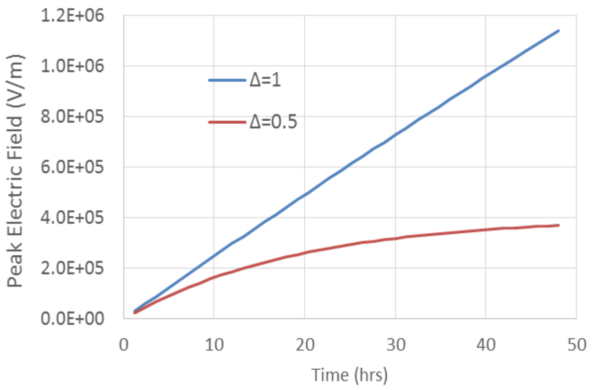
$$\sigma_{total} = \sigma_T + \sigma_{RIC}$$

$$\sigma_{RIC} = k_p . \dot{D}^{\Delta}$$

(RIC = radiation-induced conductivity)



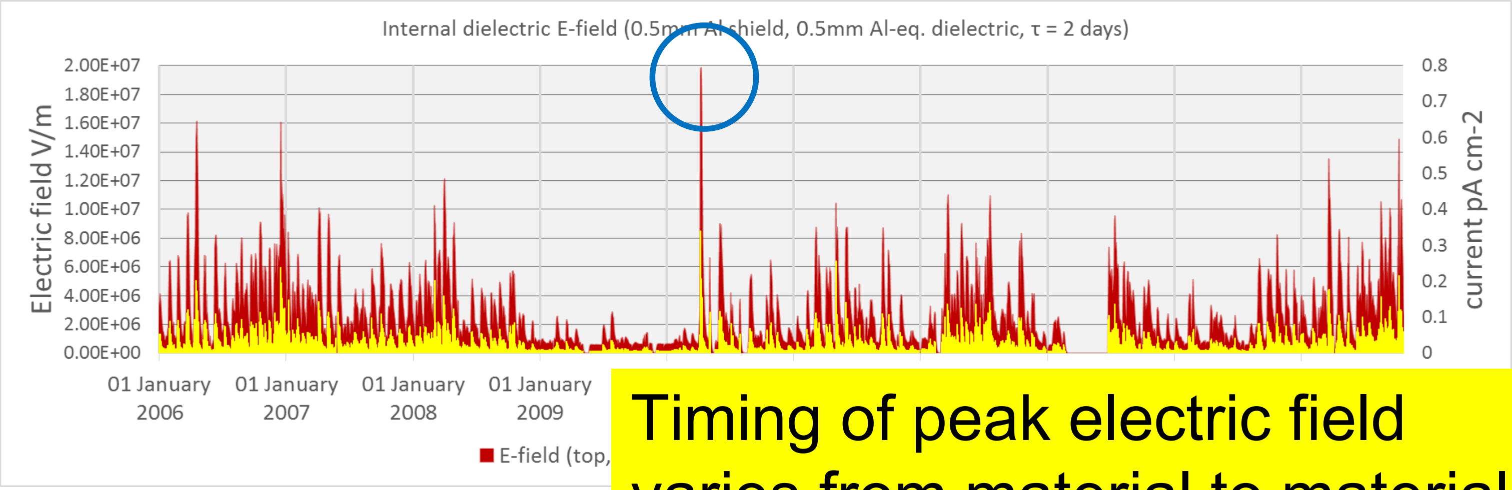




All very important factors even *without* environment variation

Real Environment Variability

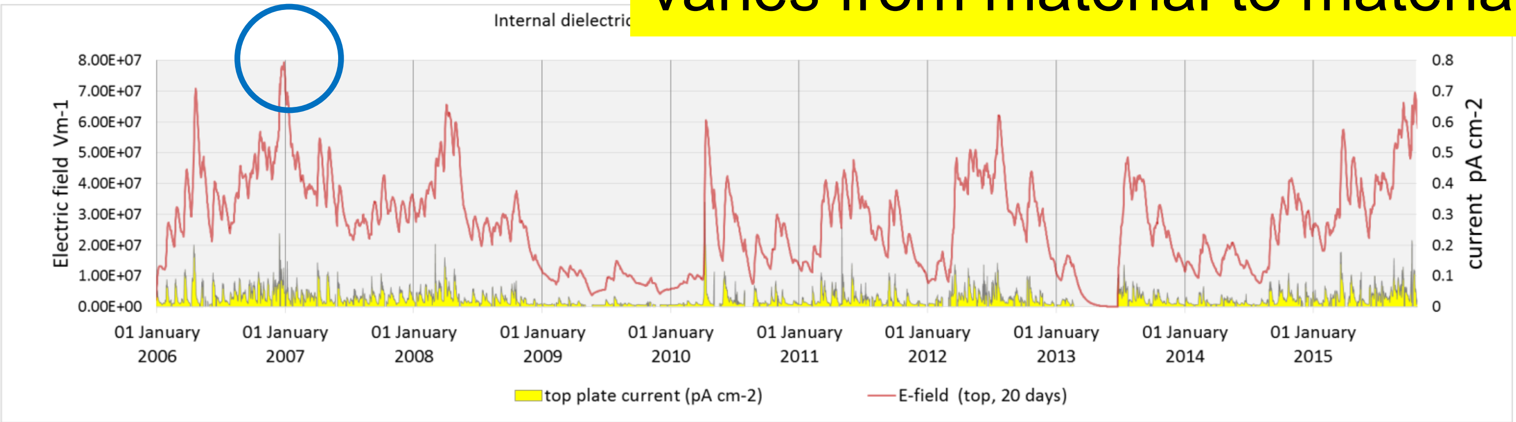
- Ryden et al. (following similar work by Bodeau) used SURF currents to analyse charging response to real environment under different conductivity assumptions:



Relaxation time constant: **2 days**

Peak E-field = April 2010

Timing of peak electric field varies from material to material !

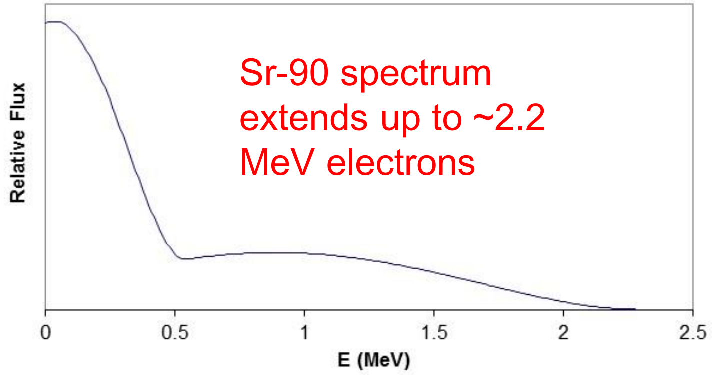


Relaxation time constant: **20 days**

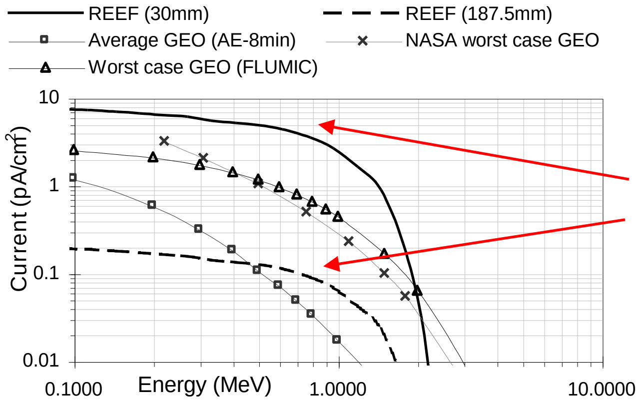
Peak E-field = December 2006

Experimental Approach

- Internal charging behaviour can be recreated in the lab – e.g. using electron accelerator or, alternatively, radioactive beta source
- At Surrey University we use strontium-90 in Realistic Electron Environment Facility (REEF):



Sr-90 spectrum extends up to ~2.2 MeV electrons

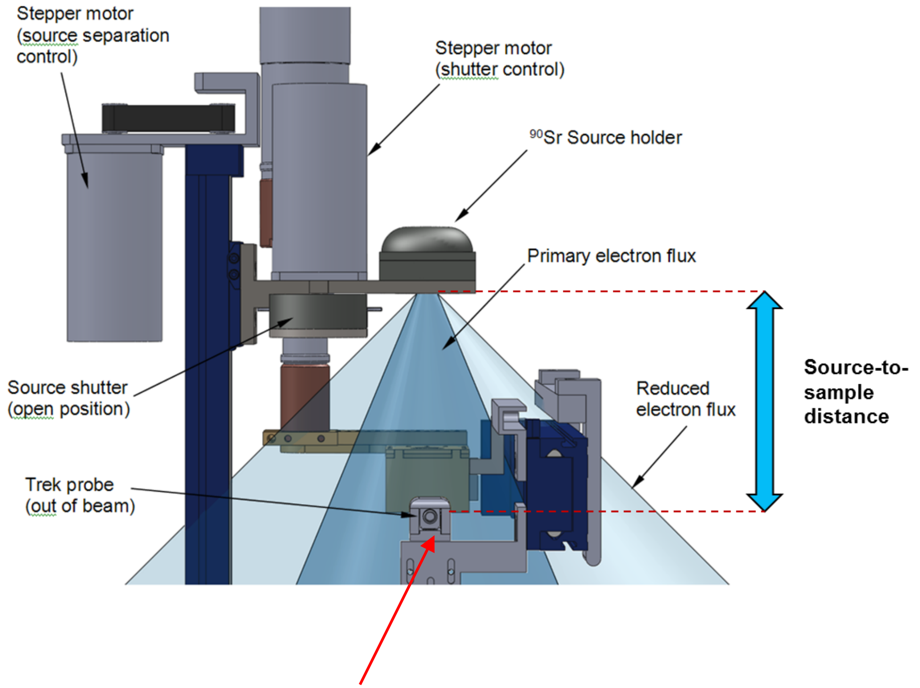


Dynamic range encompasses worst case

Vacuum Chamber housing ~3 GBq source

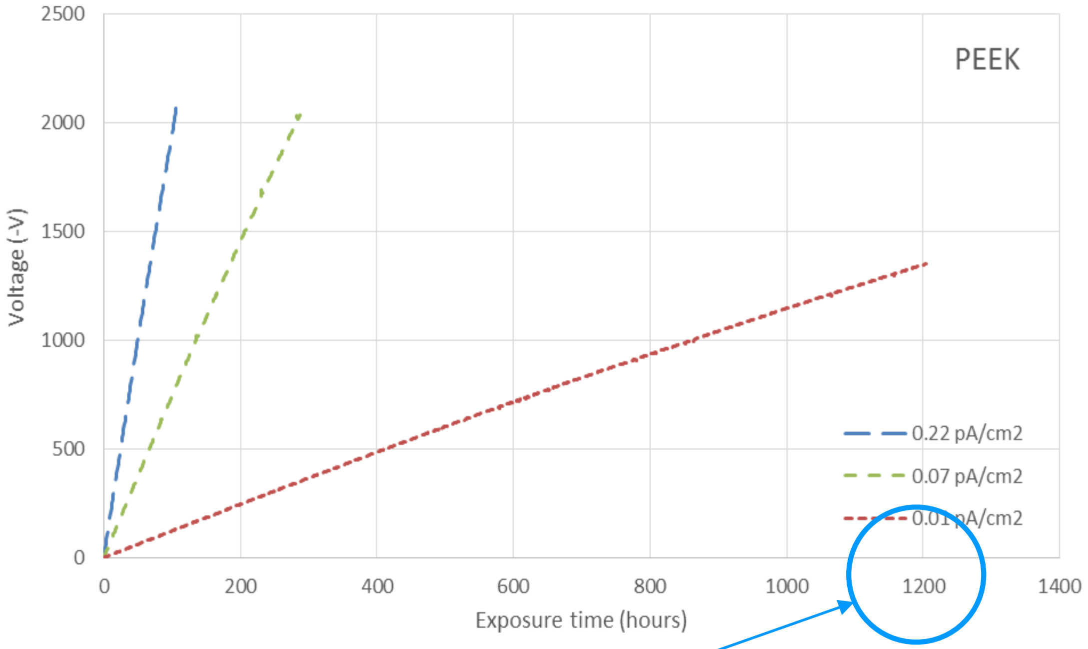
REEF Setup

- Intensity varied by raising/lowering source housing:



(Surface potential measured with non-contact Trek probe)

Long-term measurements of charging response:



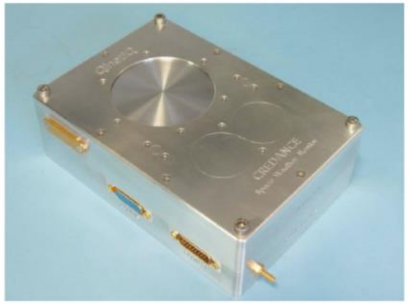
1200 hours ≈ 2 months continuous exposure

Future Plans: EMU & CREDANCE

- Merlin-SURF instrument has been operating successfully for >11.5 years (and still going!)
- Continuous direct measurement of MEO charging currents
- Successor instrument – Environmental Monitoring Unit (EMU) launched on one of FOC Galileo GNSS satellites in November 2016
  - Eight charge-collecting plates
  - Wider energy response: 0.1 to >10 MeV
  - Data will be analysed as part of ESA GALEM project
  - Upgrade to MOBE-DIC planned
- Cosmic Radiation Environment Dosimetry and Charging Experiment (CREDANCE) – to be launched in 2018 on SpaceX Falcon Heavy Rocket as part of Space Environment Testbed (SET-1) payload on AFRL DSX Spacecraft
  - Merlin-type instrument
  - Eccentric orbit covering slot region: 6000 x 12000 km
- SPHERE monitor under development (Surrey Proton, Heavy Ion & Electron Radiation Monitor) – collaboration between SSC and SSTL

EMU

CREDANCE

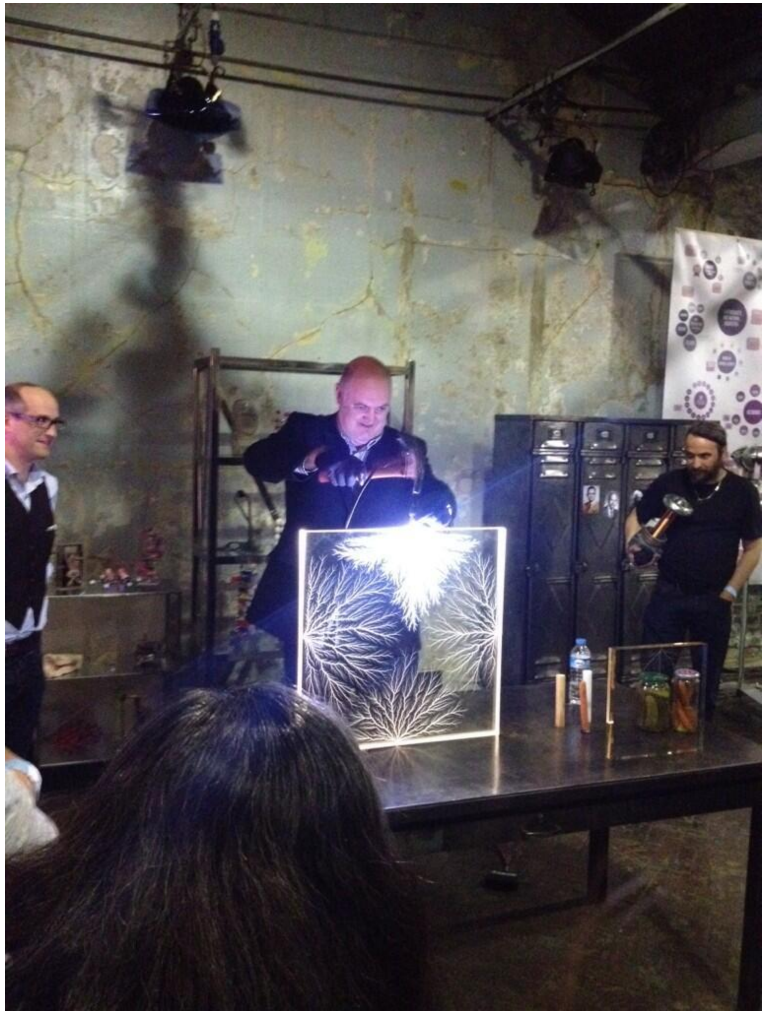


UNIVERSITY OF SURREY

Summary

- Internal Charging remains a significant threat to spacecraft operating in the trapped radiation belts
- SURF detector continues to provide direct and uncontaminated measure of *in situ* charging currents
- FLUMIC and MOBE-DIC models aim to provide user-friendly guide to worst case environment for charging effects
- DICTAT provides simple 1-D analysis of charging behaviour based on user-supplied material properties
- Lack of accurate knowledge of material parameters is a key uncertainty in modelling internal charging behaviour & risk assessment of satellite vulnerability
- Laboratory testing can help both by discovery of material properties and realistic measure of charging behaviour in low intensity environments
- Future instruments will help reduce environment uncertainty

Thank You !



Spare Slides

31

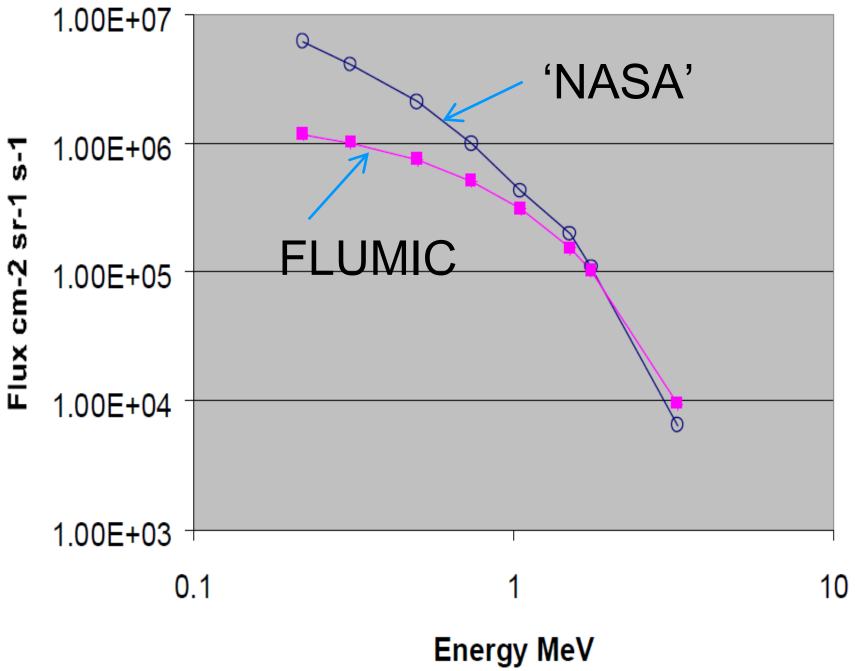
Electron environment specification

Interested in 'worst case' electron environments (>10 hours)

Models based on measurement over long periods

- Orbit specific e.g. NASA HDBK spec, MEO model
- Extrapolated to all regions e.g. FLUMIC, AE9 (new!)

Note: AE8 and other average models are not applicable



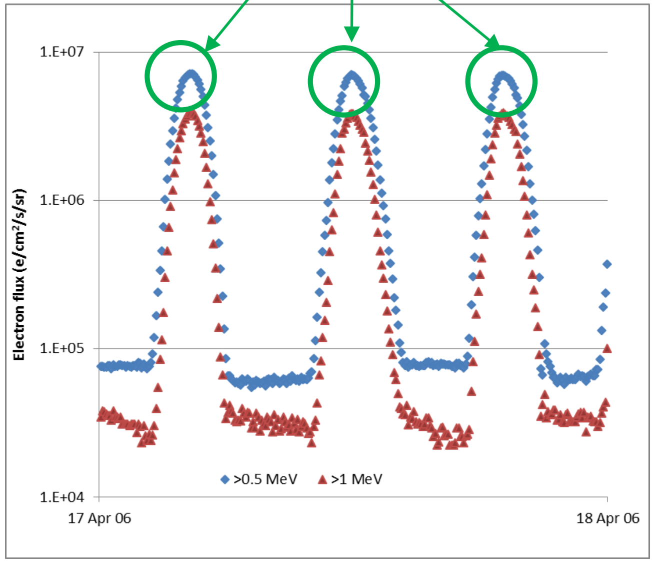
NASA recommended 'worst case' geostationary electron flux spectrum (circles) alongside the anomalously large event (ALE) spectrum defined in the FLUMIC3 model (squares).

32

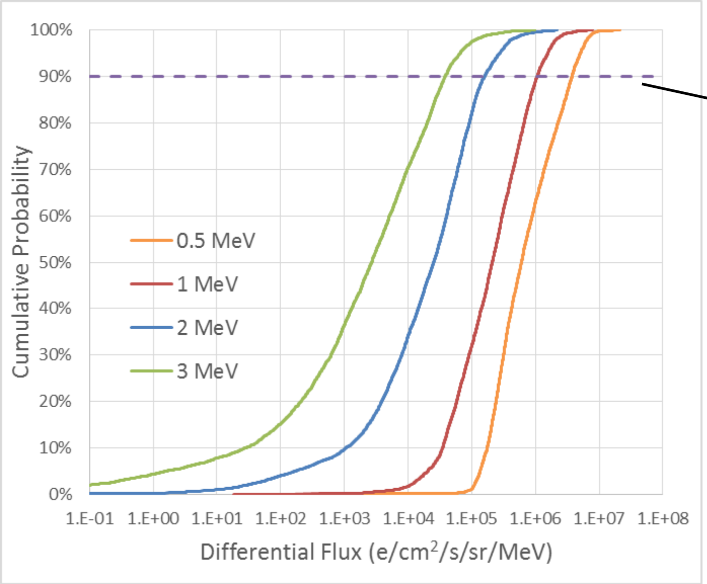
Worst Case Statistics

- Use derived flux time series to create cumulative distribution functions (CDFs) at discrete energies in the range 0.5 – 3 MeV (peak of instrument response)

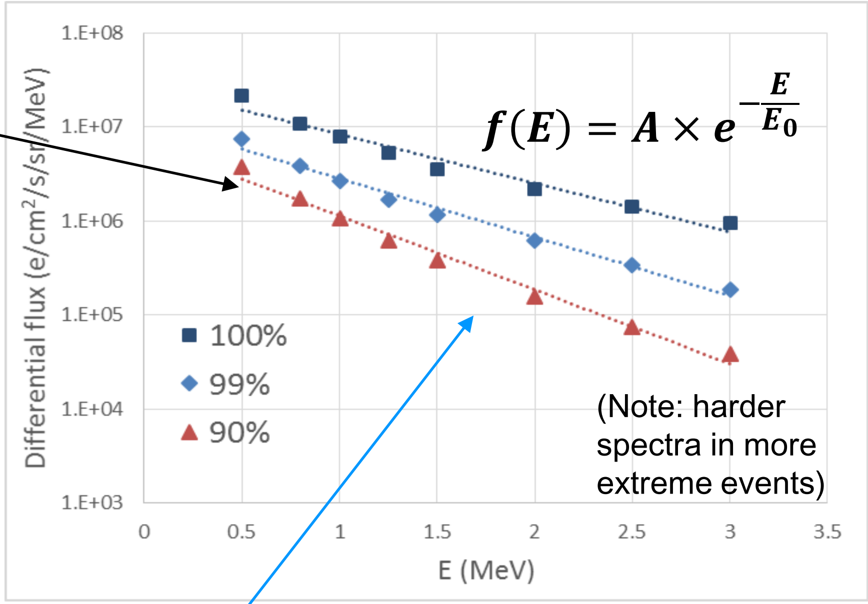
Create reduced series of average flux at equatorial peaks (L≈4.7)



CDFs based on equatorial flux:



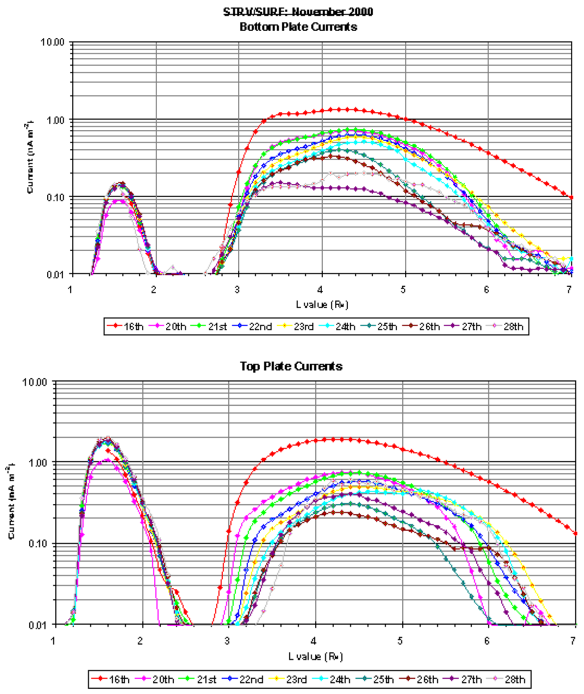
Fit baseline spectra at three confidence levels - 90%, 99% & 100%:



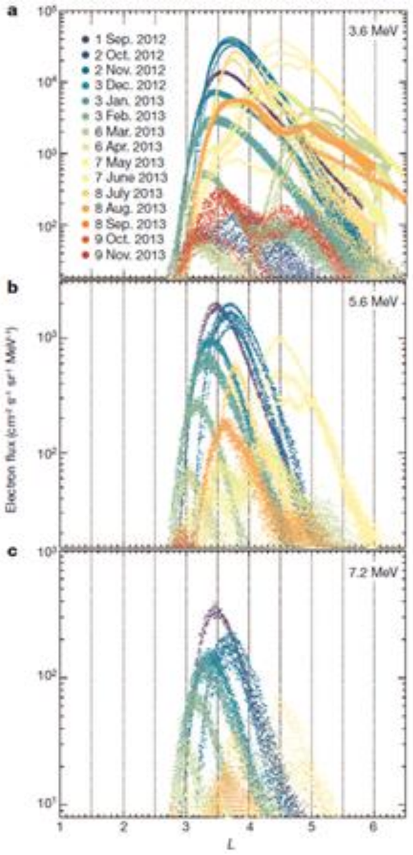
These three spectra form the basis of the MOBE-DIC model

Extrapolating to other L-Shells

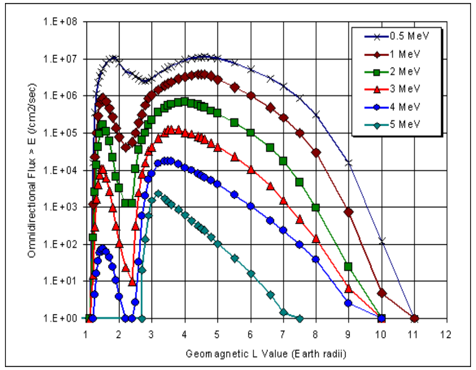
- Equatorial spectra at L≈4.7 form the basis of the model
- Need to derive profile of L-shell to extrapolate, however…
- L-Shell profile is <u>not</u> stable, e.g.:



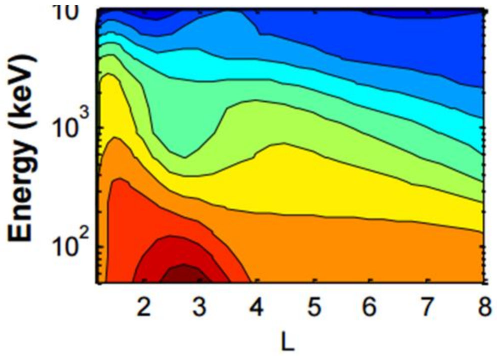
SURF on STRV1d (Ryden et al. 2001)



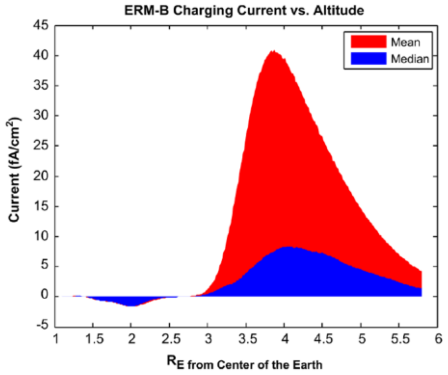
Van Allen Probes, REPT (Baker et al. 2014)



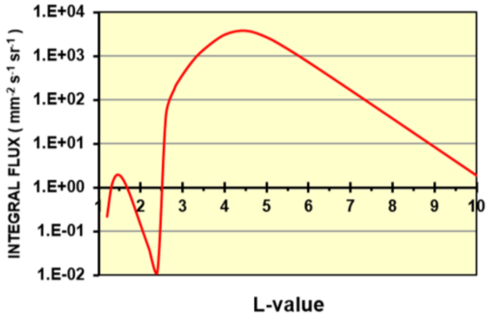
AE8



AE9



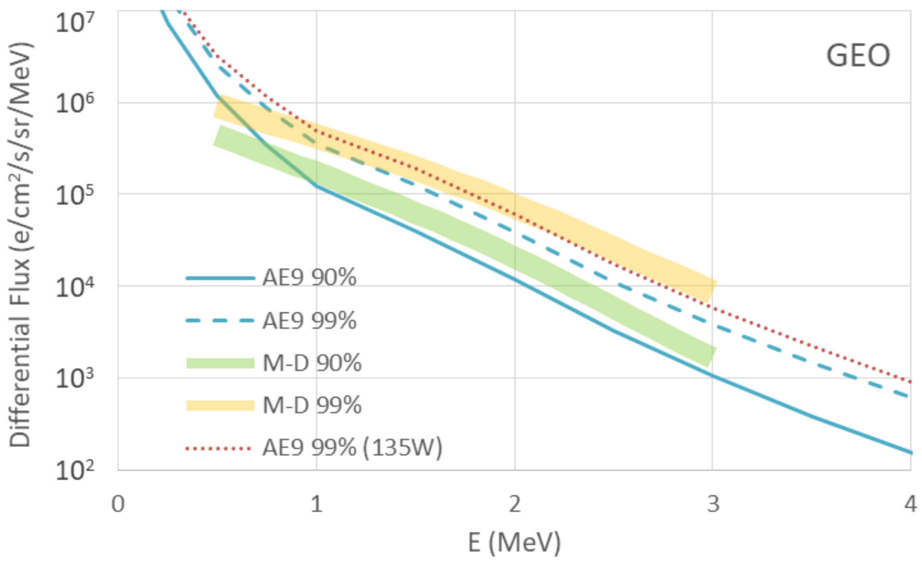
Van Allen Probes, ERM (Maurer et al. 2013)

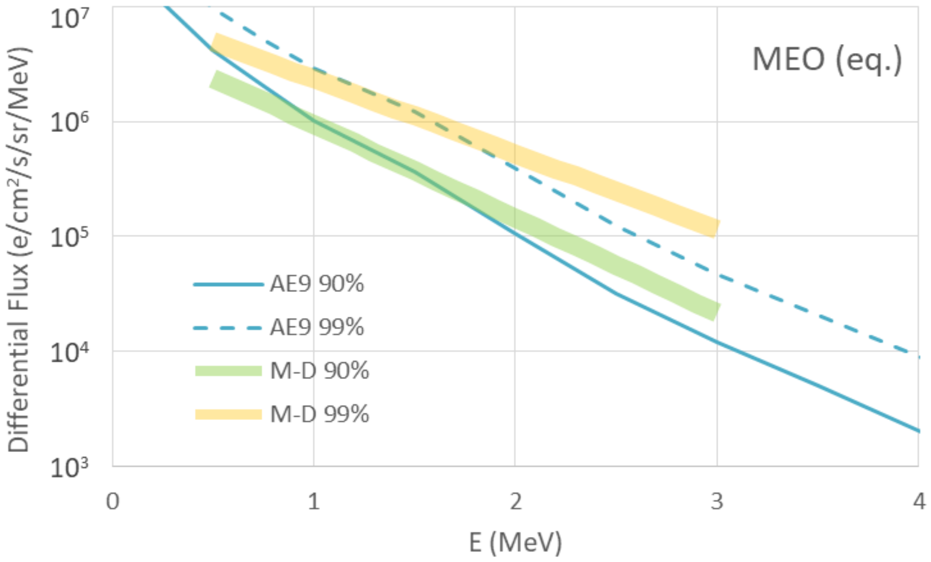


FLUMIC

Comparison to existing models

- AE9:





- NASA Handbook 4002A