# Calibration of Electron, Proton and Heavy-Ion Radiation Environment Data from Giove-A and Comparisons to Giove-B

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**3rd Space Radiation and Plasma Monitoring Workshop**

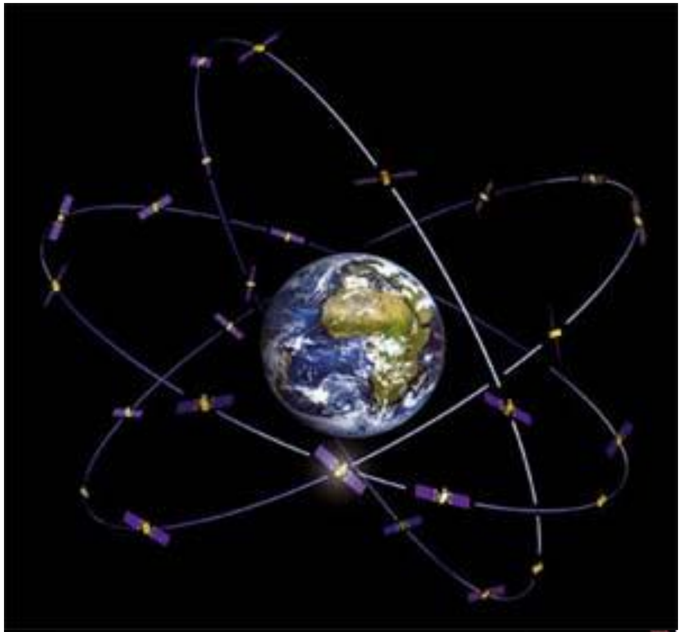
**May 13-14, 2012, ESA-ESTEC , Noordwilk, NL**

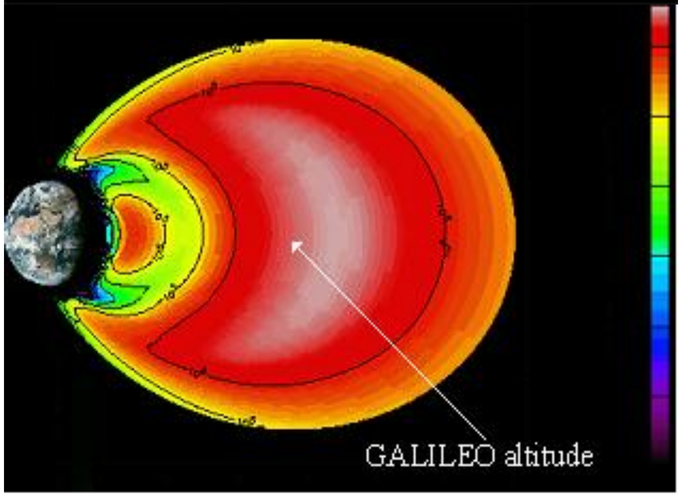
# Outline

- The Galileo Constellation; Giove-A and Giove-B
- The Radiation Monitoring Instruments
- Electron Results: SURF, CEDEX Dose-Rate Diodes
- Proton Results: MERLIN
- LET Spectra Results: CEDEX
- Conclusions

# Galileo

- Galileo – the European Global Navigation Satellite System
  - Europe's Independent, commercial system
  - Final constellation to consist of 30 satellites, 27 active, 3 spare in 3 orbital planes
  - Medium Earth Orbit: ~23,000 km, $56^{o}$
  - System initiated with two test bed spacecraft:
    - GIOVE -A (launched 2005) &
    - GIOVE-B (launched 2008)





# Giove-A

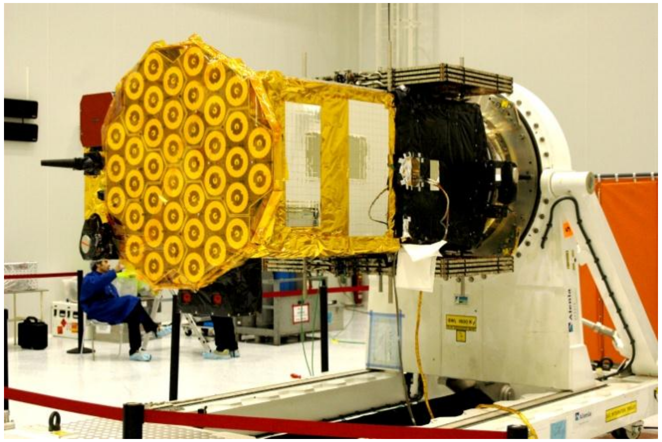
- Giove-A – Galileo Test-Bed
  - Objectives
    - Secure frequency filing
    - Demonstrate key payload technologies in orbit (23,222 km, $56^{o}$)
    - Provide Signal-in-Space for experimentation
    - Measure MEO radiation environment (MERLIN, CEDEX)
    - 30 month schedule – design-to-orbit

      Kick-Off – July ‘03; Launch – $28^{th}$ Dec. ‘05
    - $30M budget – designed/built by SSTL
    - 27 month planned mission lifetime
    - Retired 2012; currently **still operational**

# Giove-B

- Giove-B – Galileo Test-Bed
  - Objectives
    - Similar technology test-bed objectives to Giove-A
    - Provides full Galileo signal (MBOC)
    - Flies passive Hydrogen maser atomic clock as well as two Rubidium standards
    - Measure MEO radiation environment (SREM)
    - Launched 27$^{th}$ April 2008

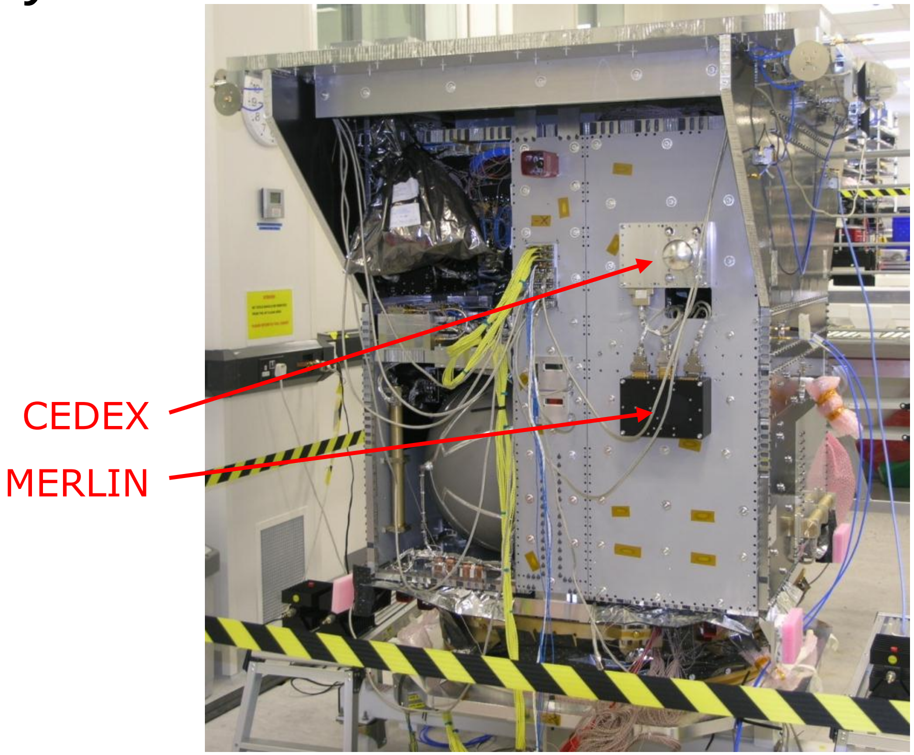
      23,222km MEO, 56$^{o}$ inclination
    - Retired July 2012
    - Now in Graveyard orbit ~600km higher.



# Radiation Monitors: Giove-A

- **CEDEX** – University of Surrey/SSTL
  - Cosmic-Ray LET Spectra
  - Proton Flux
  - Dose-Rate Induced Photocurrents

- **MERLIN** – QinetiQ
  - Cosmic-Ray LET Spectra
  - Proton Flux
  - Total Ionising Dose
  - Electrons/ Deep Charging Currents




GIOVE-A Flight Model AIT at the Surrey Space Centre, University of Surrey, 2005

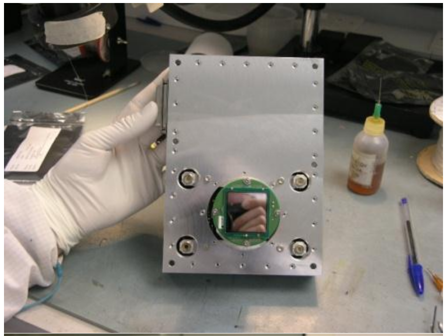
# CEDEX

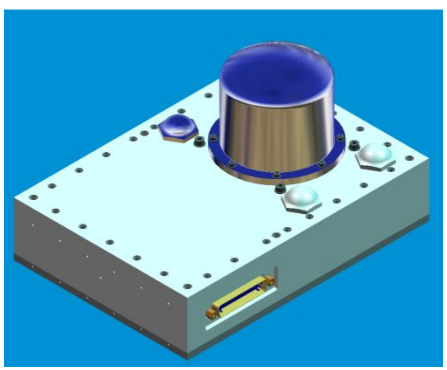
- Resources: <2.2 kg (including radiation shielding), <4.5W
- Heritage: Surrey's CRE Payloads – COTS electronics
- Measure Proton flux (45-50 MeV) and ion LET spectra
  - Combined proton and ion telescope employing large-area (3cm x 3cm x 300 $\mu$m deep) PIN diodes
  - Ion LET values binned into 512 linearly spaced channels

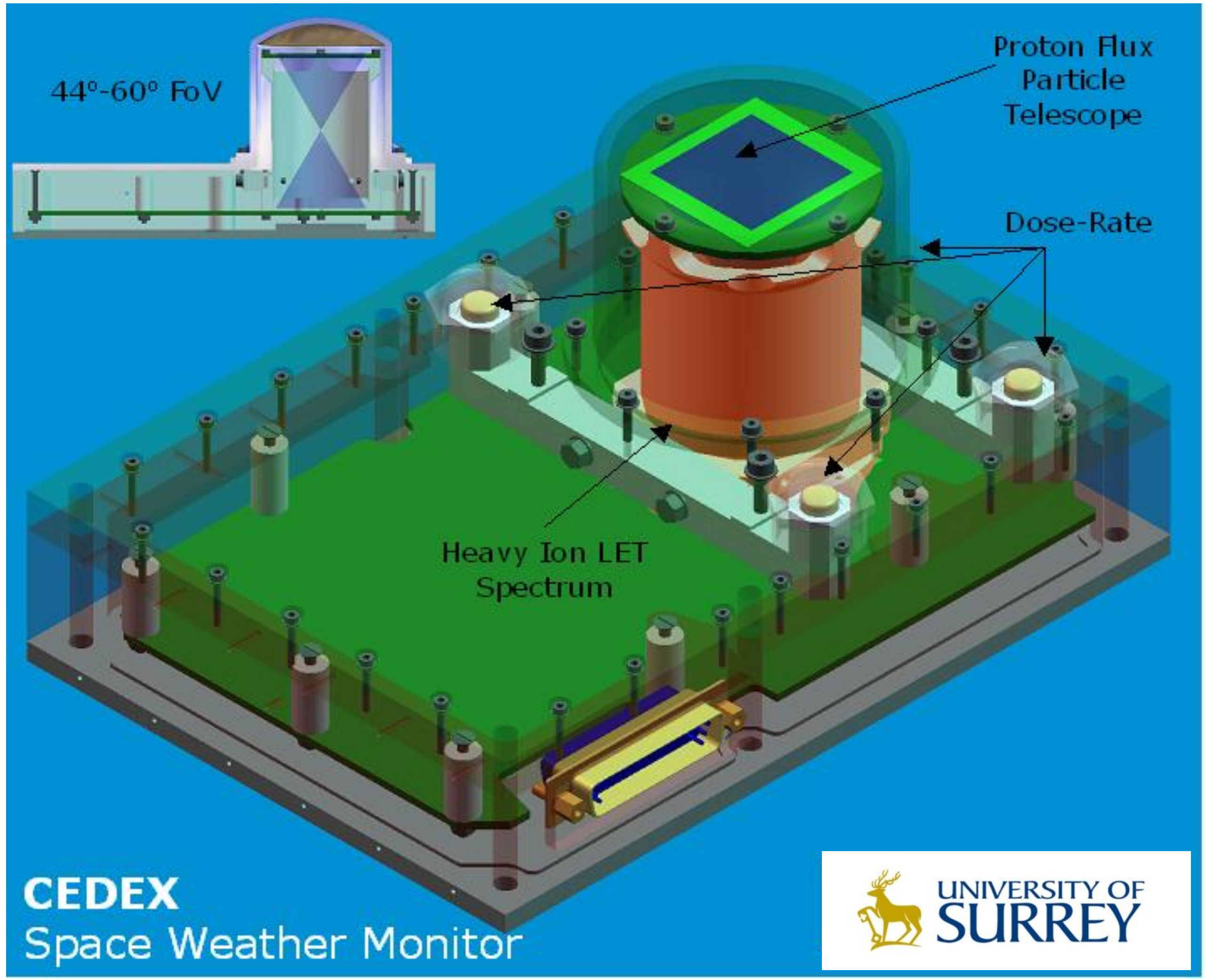
    32 to >10,000 MeV $cm^2$ $g^{-1}$.
- Measure ionising dose-rate induced photocurrents
  - Dose-rate-induced photocurrents measured in dome shielded PIN photodiodes (provides electron data) – dose response of diodes calibrated in QinetiQ's REEF Sr-90 Facility (7.6 pA per mrad $s^{-1}$; min. step = 0.4 pA ~0.05 mrad $s^{-1}$ ~5 rad(Si) $day^{-1}$)

    Four shielding depths: 2mm Al, 4mm Al, 2mm Cu, 4mm Cu

# CEDEX






44°-60° FoV
Proton Flux Particle Telescope
Dose-Rate
Heavy Ion LET Spectrum
CEDEX
Space Weather Monitor
UNIVERSITY OF SURREY

# Merlin

- Resources: <2 kg, < 3.5W
- Heritage: QinetiQ's CREDO and SURF Payloads
- Monitor internal charging effects
  - Measure current deposition in 3 shielded collector plates

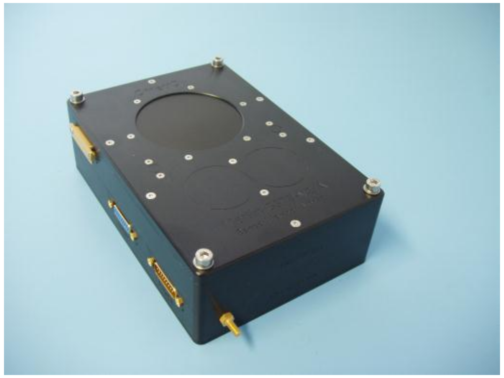
    (0.5mm, 1mm and 1.5mm Al shielding)
- Measure Proton flux (>40 MeV) and ion LET spectra
  - Independent proton and ion telescopes employing large-area diodes
  - Ion LET values binned into 32 logarithmically spaced channels

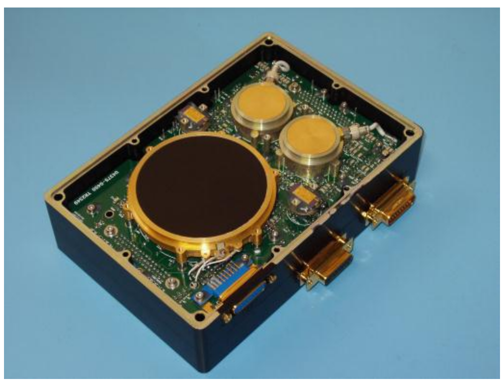
    95 to 28,500 MeV $cm^2$ $g^{-1}$.
- Measure total ionising dose
  - Total dose in rad($SiO_2$) using shielded RADFETS

    (3mm and 6mm Al shielding)

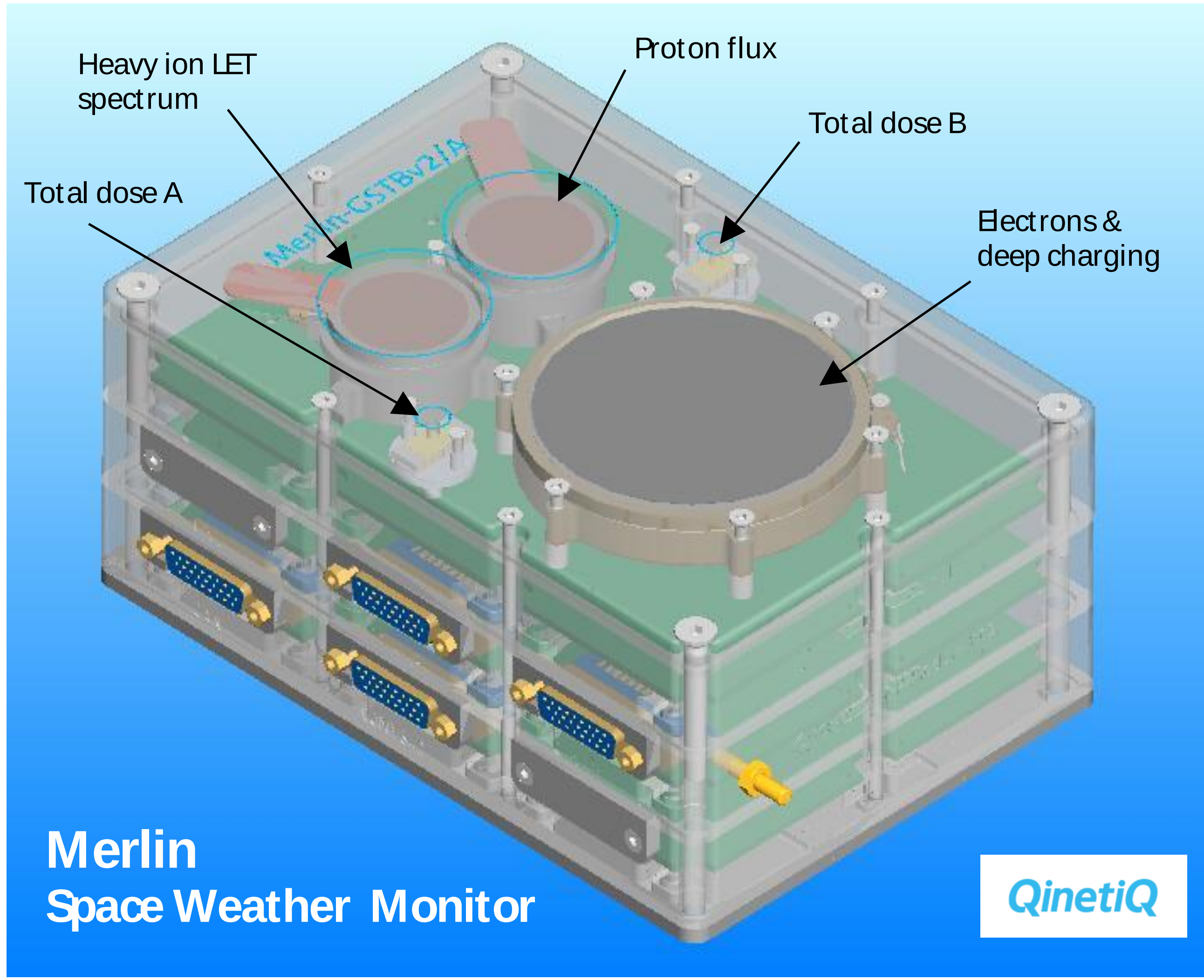
SURREY SPACE CENTRE

# Merlin





GIOVE-A Version
includes SSTL CAN data bus interface



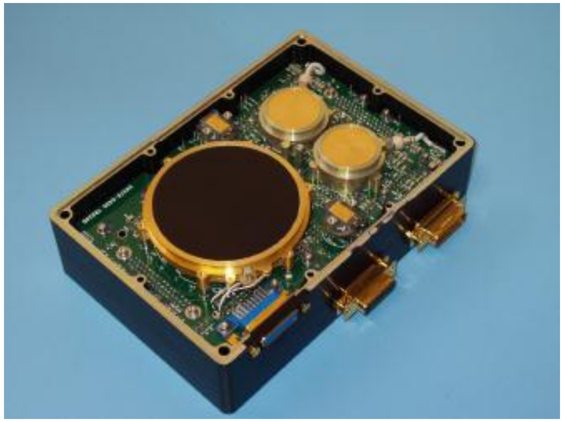
# Radiation Monitors: Giove-B

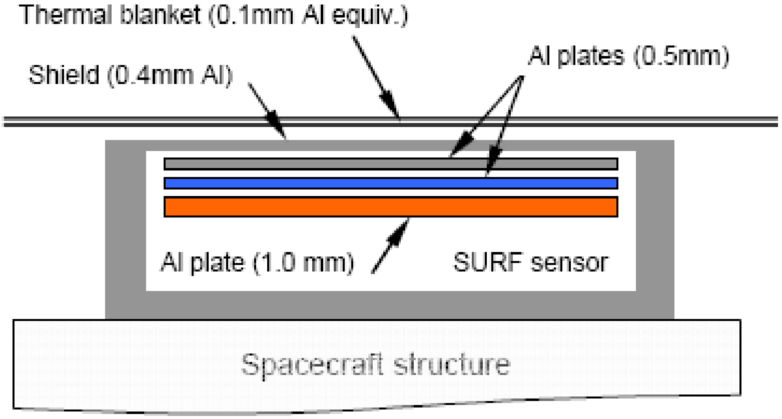
- **SREM** Oerlikon Space/ Paul Scherrer Institute
  - Electron/ Proton Counts/Fluxes
  - Total Ionising Dose
  - Mass: 2.5 kg
  - Dimensions: 96 mm x 122 mm x 217 mm
  - Power  Consumption < 2W
    Floating bus voltage 20 V to 50 V DC
  - TM/TC Compatibility with most spacecraft standards
  - Sensors: Three precision particle detectors (measurement error < 1%) – two arranged as a telescope separated by a double layer of aluminium and tantalum
  - 15 channels providing data on electrons and protons
  - Internal total dose measurement
  - Internal temperature measurement

GIOVE-B SREM Instrument
http://srem.web.psi.ch/html/srem_home.shtml

# Electron Results

- **MERLIN SURF**
  - The rate of charging is measured in three 70 mm diameter aluminium detector plates stacked one on top of the other.
    - The top two plates are 0.5 mm thick, and the bottom plate is 1 mm thick. The combined shielding effect of the sensor cover and thermal blankets is equivalent to 0.5 mm of aluminium.
  - For each plate there is a high sensitivity and low-sensitivity current channel, providing a wide dynamic range.
    - Low sensitivity channel provides a (dynamic) output of 10 mV $pA^{-1}$, and high-sensitivity (dynamic) output is 500 mV $pA^{-1}$





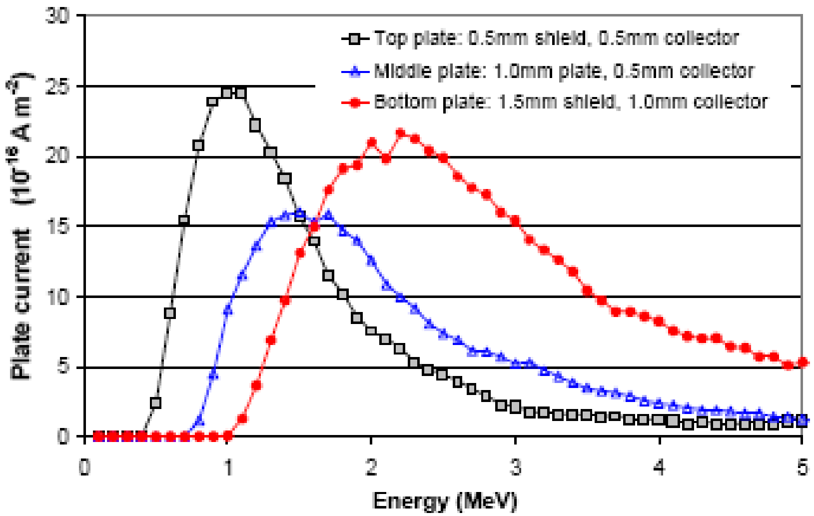
# Electron Results

- **MERLIN SURF**
  - Analysis shows no proton contamination from the MEO environments encountered – so the electron data is unambiguous – no need to subtract positive currents.
  - The peak electron energy sensitivity for the plates is approximately 0.8, 1.1 and 1.7 MeV respectively.

Plate Currents in fA $cm^{-2}$

| | Top plate | Middle plate | Bottom plate |
|---|---|---|---|
| 29-Sep-89 | 0.29 | 0.14 | 0.17 |
| 24-Oct-89 | 0.14 | 0.07 | 0.06 |
| 4-Aug-72 | 6.16 | 4.48 | 5.68 |
| CRÈME WW | 0.40 | 0.18 | 0.15 |
| CRÈME peak | 8.37 | 2.63 | 2.85 |
| AP8 @ L=1.62 | 5.46 | 1.65 | 1.11 |

Predicted 'positive' current contamination in the SURF plates during various solar particle event scenarios and at the peak of trapped proton belt. The units are fA $cm^{-2}$



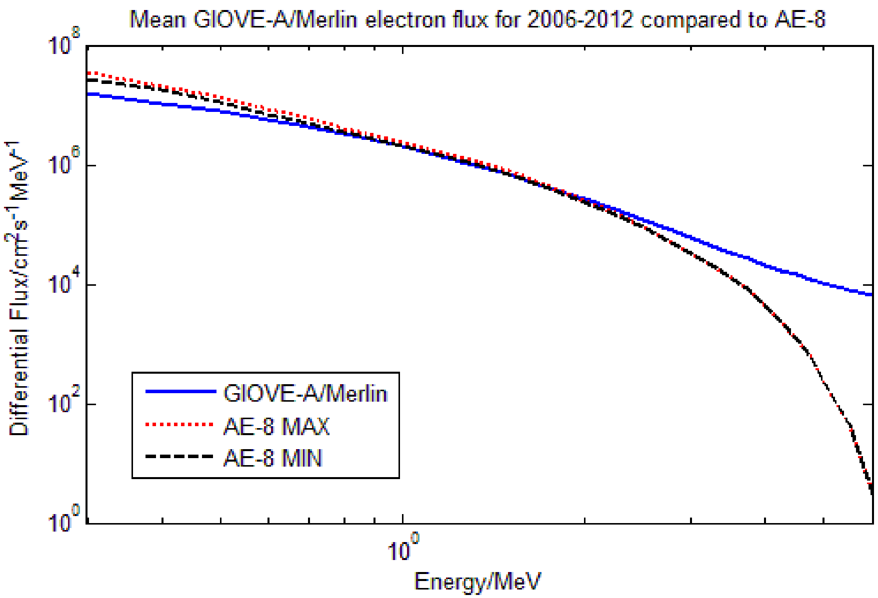

Response functions for the three SURF plates obtained using the DICTAT tool. (isotropic intensity of 1 e $cm^{-2}$ $s^{-1}$)

# Electron Results

- **MERLIN SURF**
  - Electron spectra were derived initially by using a simple exponential fit with units of $cm^{-2}s^{-1}sr^{-1}MeV^{-1}$ ($E_0$ = folding energy)

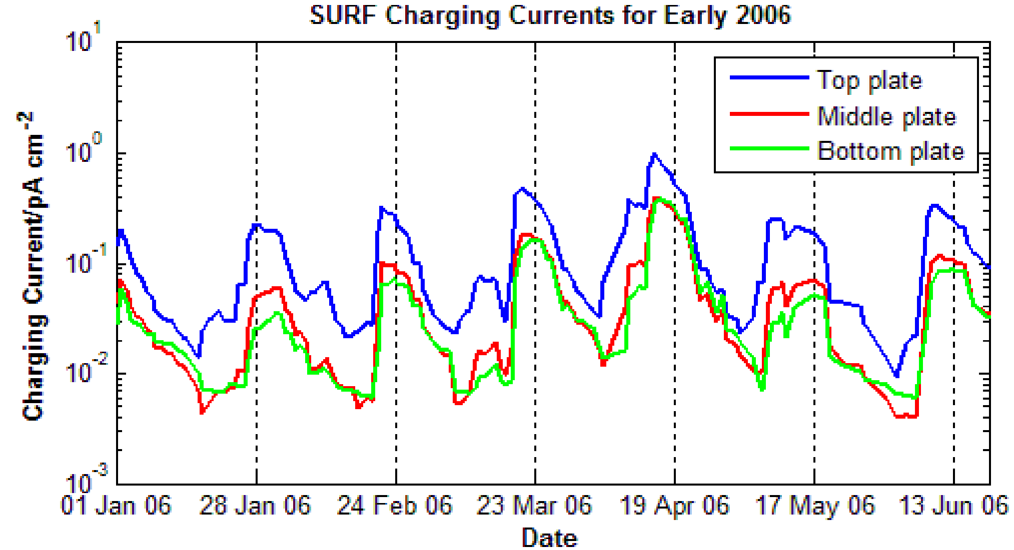
$$f(E) = Ae^{-\frac{E}{E_0}}$$

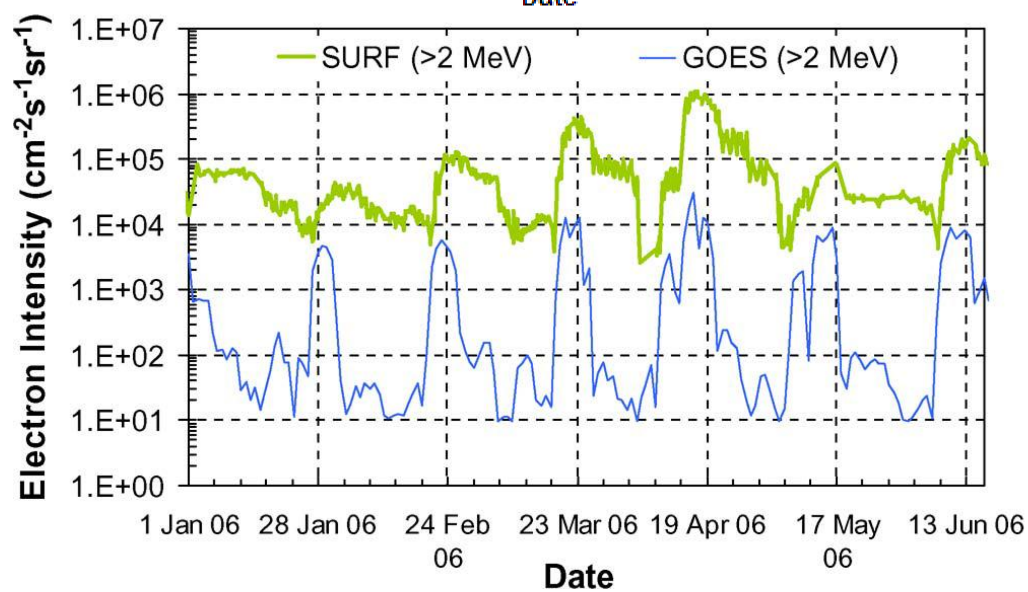
  - This gave a good match to AE-8 model predictions over the range 0.5-2 MeV.



# Electron Results

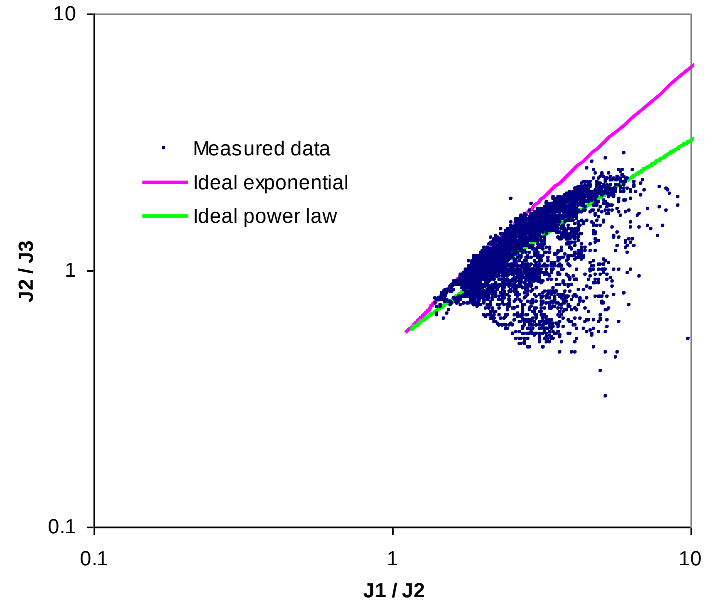
- **MERLIN SURF**
  - It also enabled comparisons to be made with GOES electron flux data.

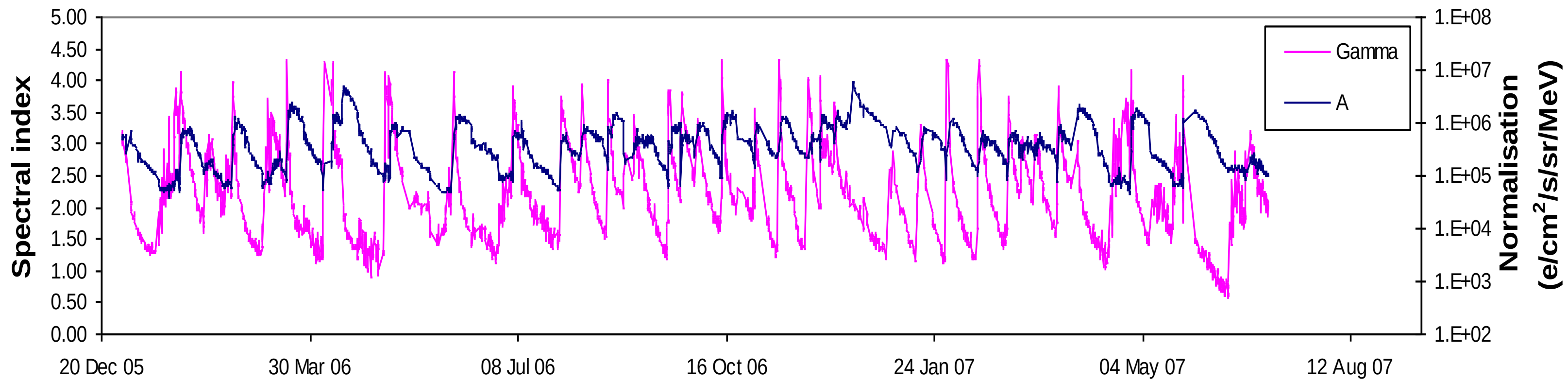


# Electron Results

- **MERLIN SURF**
  - By examining plate current ratios it became clear that a simple power law of the form:
    $f(E) = A.\ E^{-\gamma}$
    where $\gamma$ is the spectral index, gives a better fit to the data.
  - $E_0$, A, and $\gamma$ were found by a iterative method.



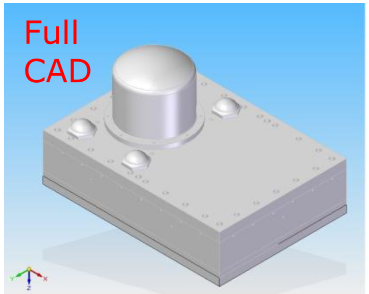
SURREY SPACE CENTRE

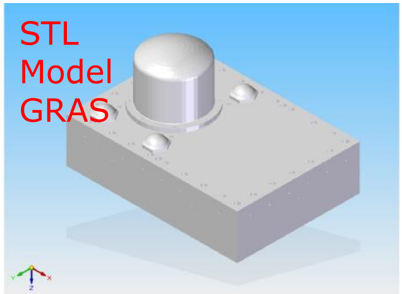
# Electron Results

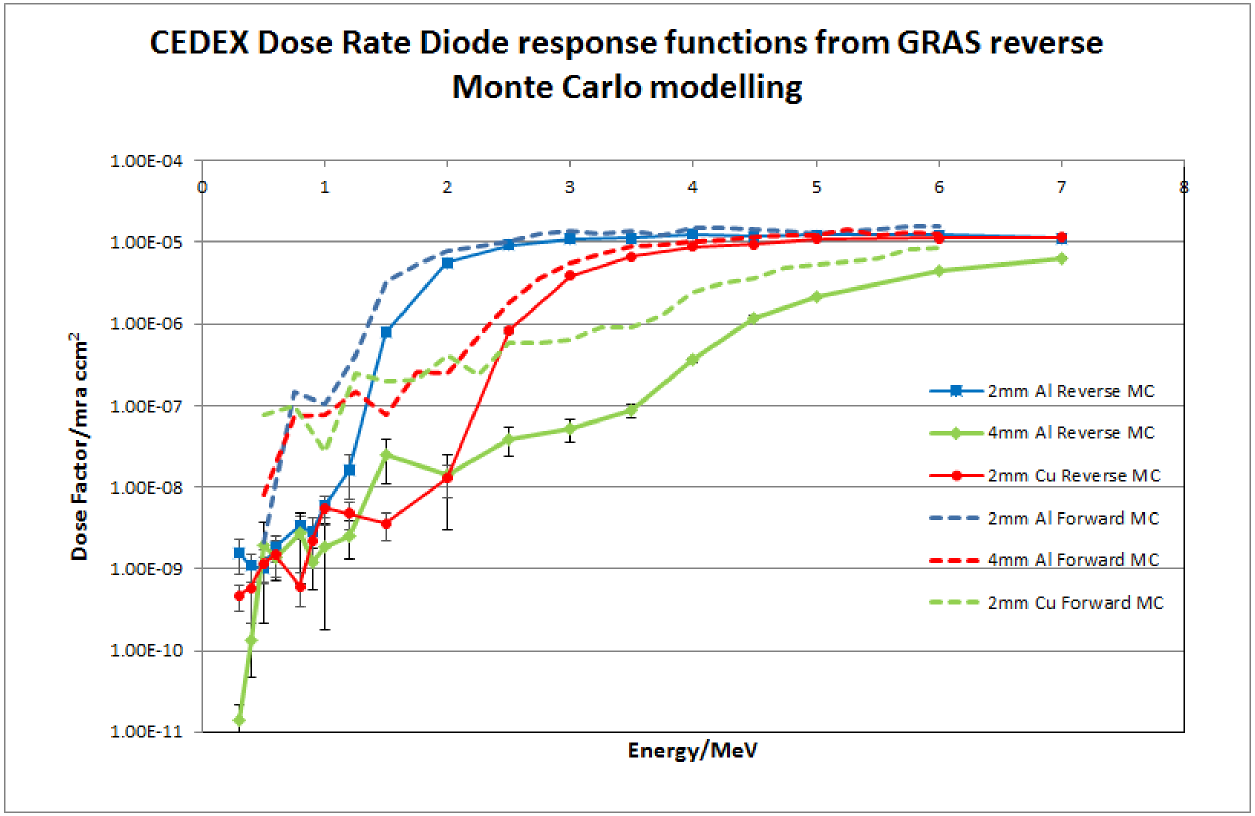
- **CEDEX Dose Rate Diodes**
- The four shielded (2mm, 4mm Al and 2mm, 4m Cu) dose rate diodes are sensitive to any ionising radiation.
- They provide a voltage which is proportional to “photo” current:
  - $V = 10^{10} I_{phot\ o}$
- However, they are strongly affected by temperature (dark current) and offset voltage changes due to spacecraft occasionally power cycling the payload.
- (GEANT4) GRAS modelling gave an initial response function using a forward Monte-Carlo (MC) approach and a simplified structural model of the spacecraft and payload.
- We attempted to improve this via a detailed CAD model of the payload (0.1mm) and reverse MC.

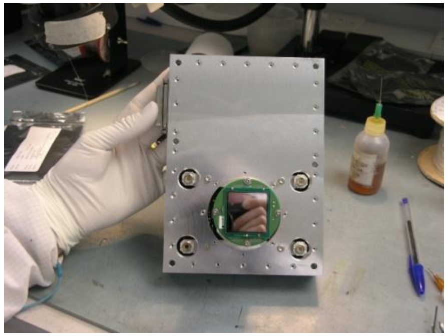
# Electron Results

- **CEDEX Dose Rate Diodes**



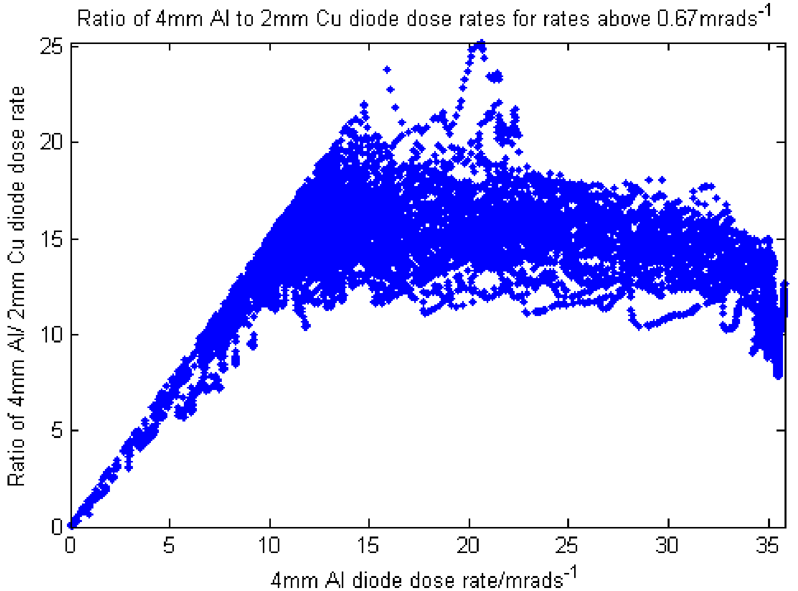



# Electron Results

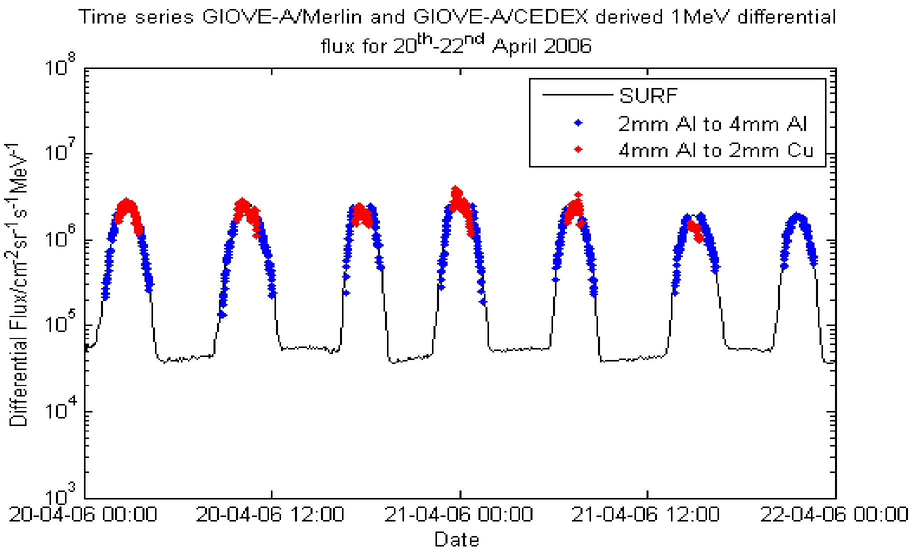
- **CEDEX Dose Rate Diodes**
- Proton contamination was dealt with by filtering data by L-Shell and by considering periods outside of solar proton events.
- Long term variations were filtered by a 2-hour moving average, and voltage offset jumps were detected and corrected.
- The 2mm Al shielded detector was affected by a negative offset, and the 4mm Cu detector only showed activity during major solar events, and so the data from the 4mm Al and 2mm Cu shielded detectors was used to form an exponential fit model.

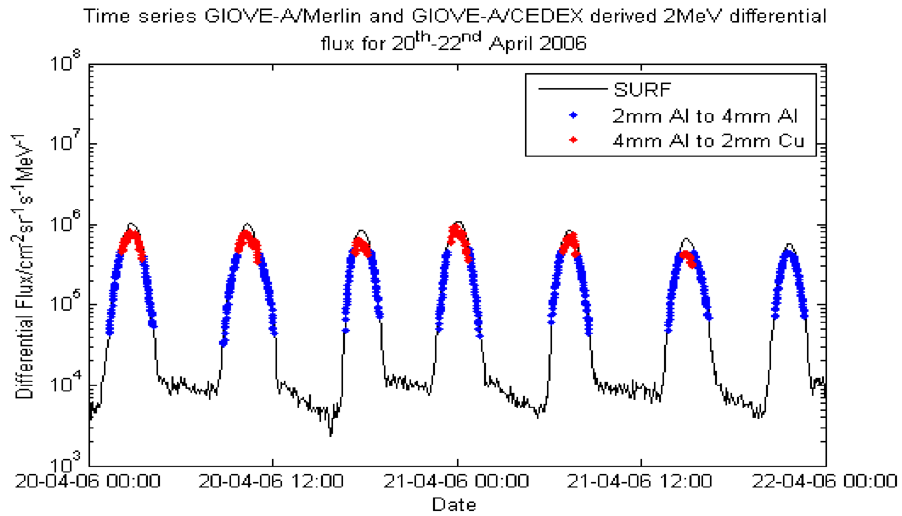
$$f(E) = Ae^{-\frac{E}{E_0}}$$



# Electron Results

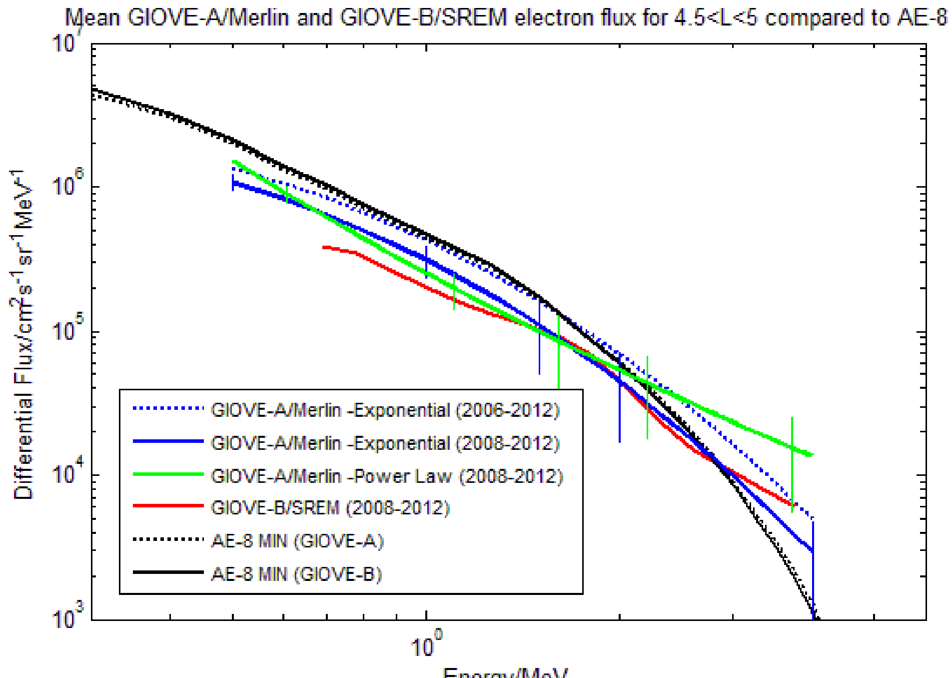
- **MERLIN and CEDEX Dose Rate Diodes**
- Comparisons with MERLIN SURF give good agreement:



# Electron Results

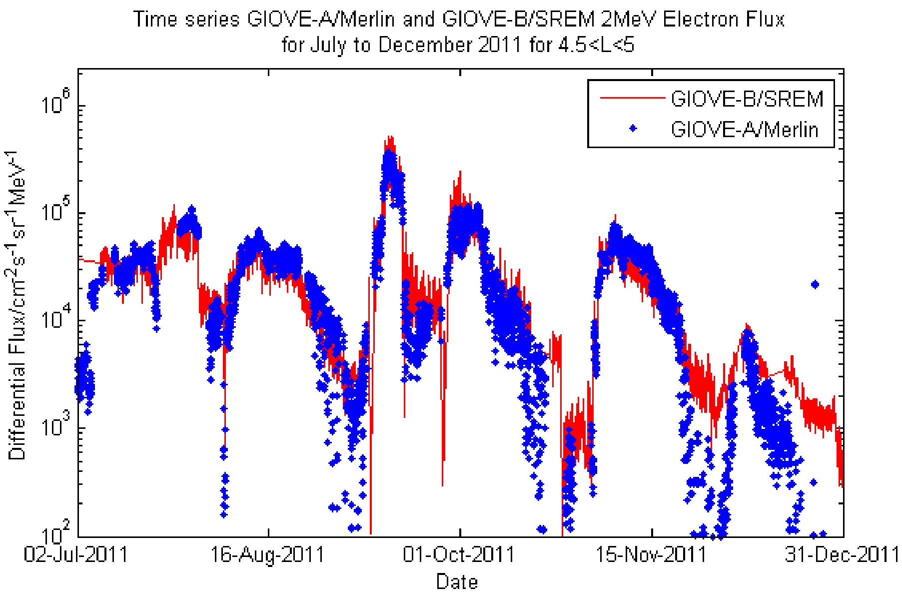
- **MERLIN and SREM Electrons**
- SREM data from Giove-B were processed according to the methods in “SREM Solar Particle Event Scientific Analysis” of the ESA Contract 21480/08/NL/NR – good agreement is achieved.

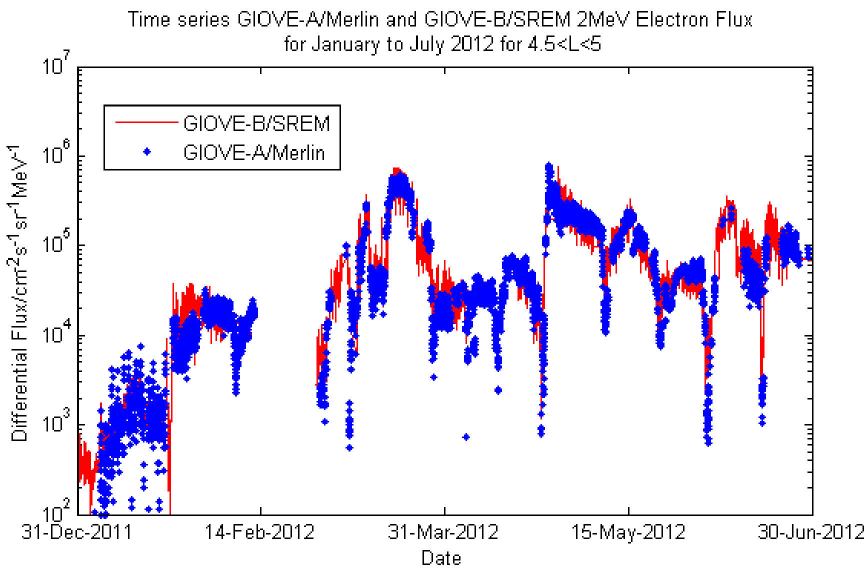



GIOVE-A/Merlin and GIOVE-B/SREM derived average differential flux spectra for the period 2006-2012 for 4.5<L<5

# Electron Results

- **MERLIN and SREM Electrons**
- Selecting 4.5<*L*<5 minimises the effect of any residual proton contamination in SREM.



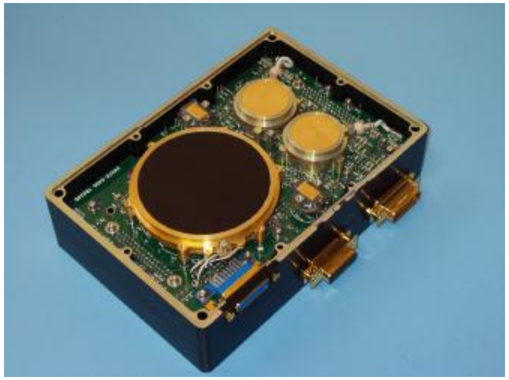



# Proton Results

- **MERLIN Proton Channel**
  - MERLIN is sensitive to protons > 40 MeV via one of its particle telescopes.
  - The geometric factor for a single-ended telescope (i.e. particles enter from one side only) with two identical circular co-axial detectors is given by Sullivan, 1971:

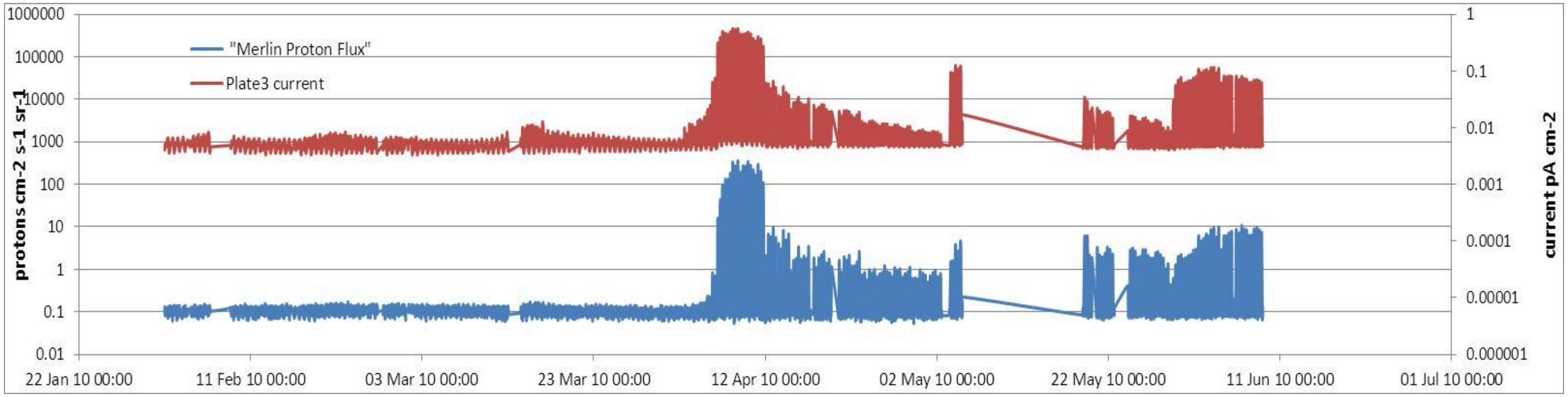
$$G = \frac{1}{2}\pi^2\left[2R^2 + L^2 - \{(2R^2 + L^2)^2 - 8R^2\}^{\frac{1}{2}}\right]$$

  - For Merlin, which has a detector diameter of 1.96cm and separation of 2.5cm, G has a value of 1.14 $cm^2$ sr.
  - Thus to convert to flux we have to take the co-incident counts per second and divide by 1.14 to give flux in $cm^{-2}$ $sr^{-1}$ $s^{-1}$



# Proton Results

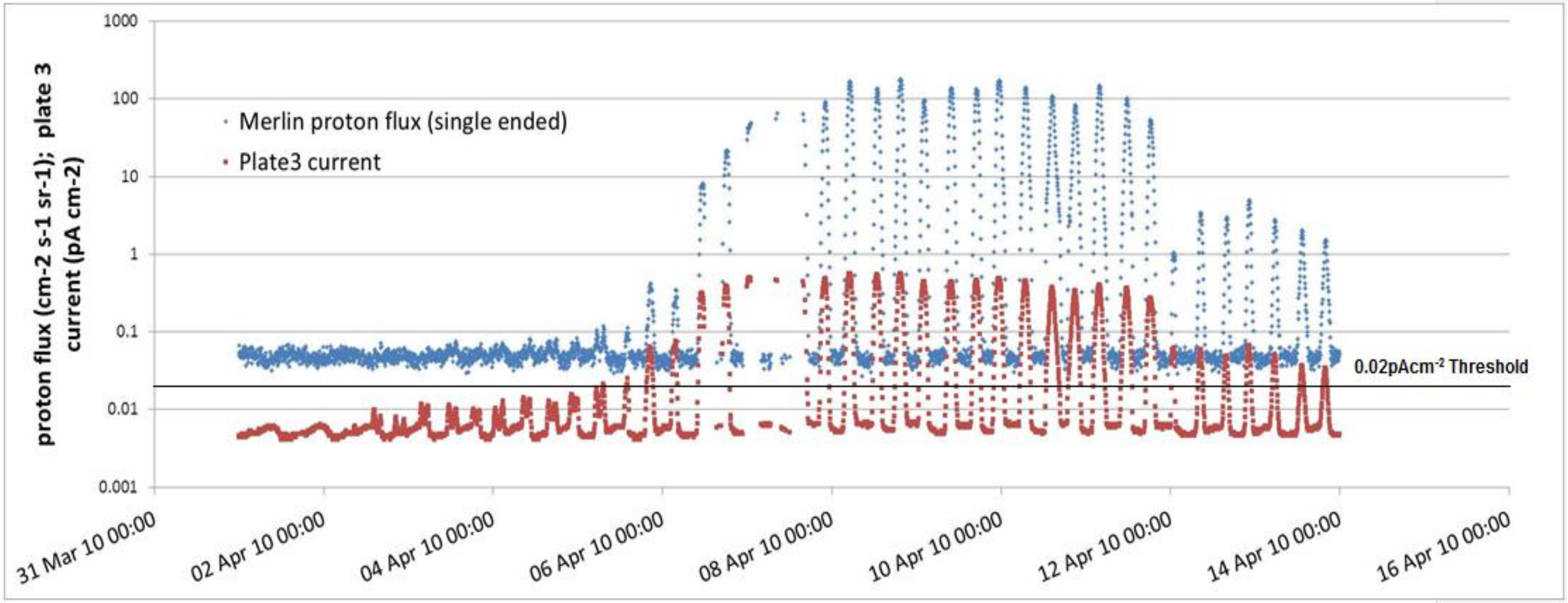
- **MERLIN Proton Channel**
  - Although relatively well shielded (~4mm Al), energetic electrons can still reach the detector diodes and while individual electrons will not deposit enough energy to cause a ‘count’, pile-up of multiple electrons could do so. Contamination might be expected during:
    - Transits through the heart of the electron belt
    - Periods of electron belt enhancements.




Proton telescope data and SURF plate 3 data :February to March 2010. No solar particle events occurred in this period so readings in the proton channel are contamination from electrons.

# Proton Results

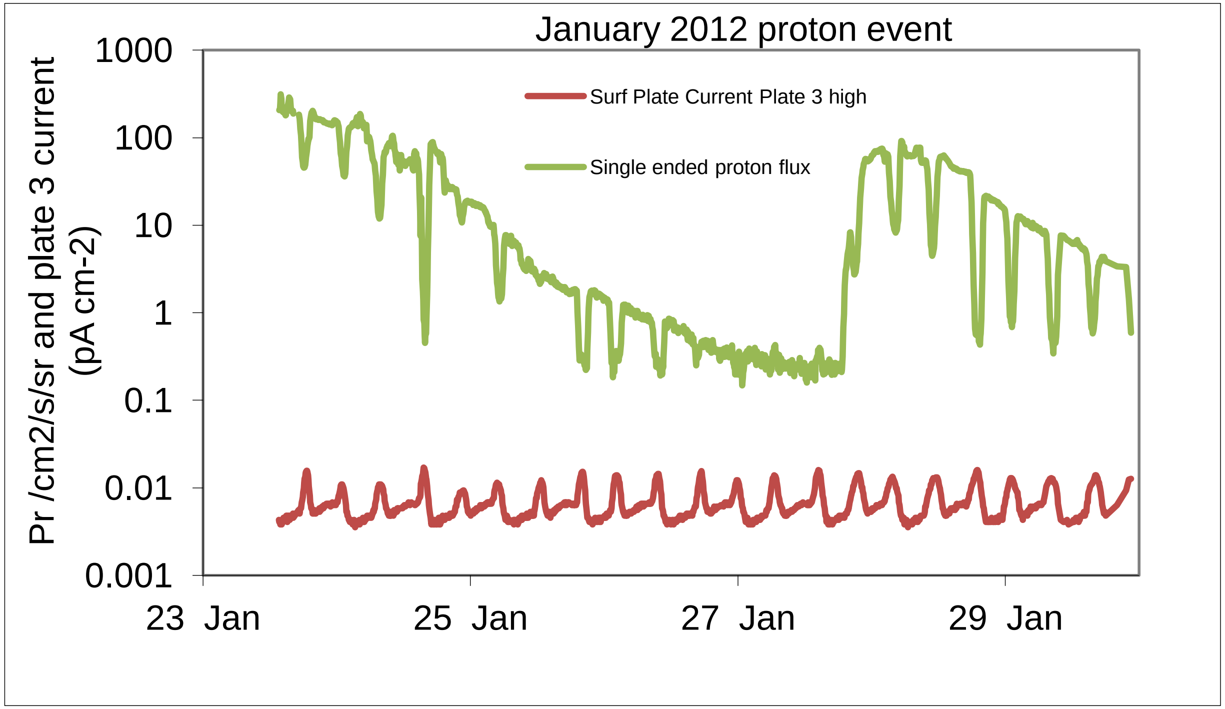
- **MERLIN Proton Channel**
  - We use SURF plate 3 data to indicate when the proton data are electron contamination free.
  - A threshold < 0.01 pA $cm^{-2}$ gives < 1 proton $cm^{-2}$ $s^{-1}$ $sr^{-1}$ contamination




SURF plate 3 current and proton channel flux during the strong April 2010 electron belt enhancement. 'Single ended' assumes particle entry at one end of the telescope only

# Proton Results

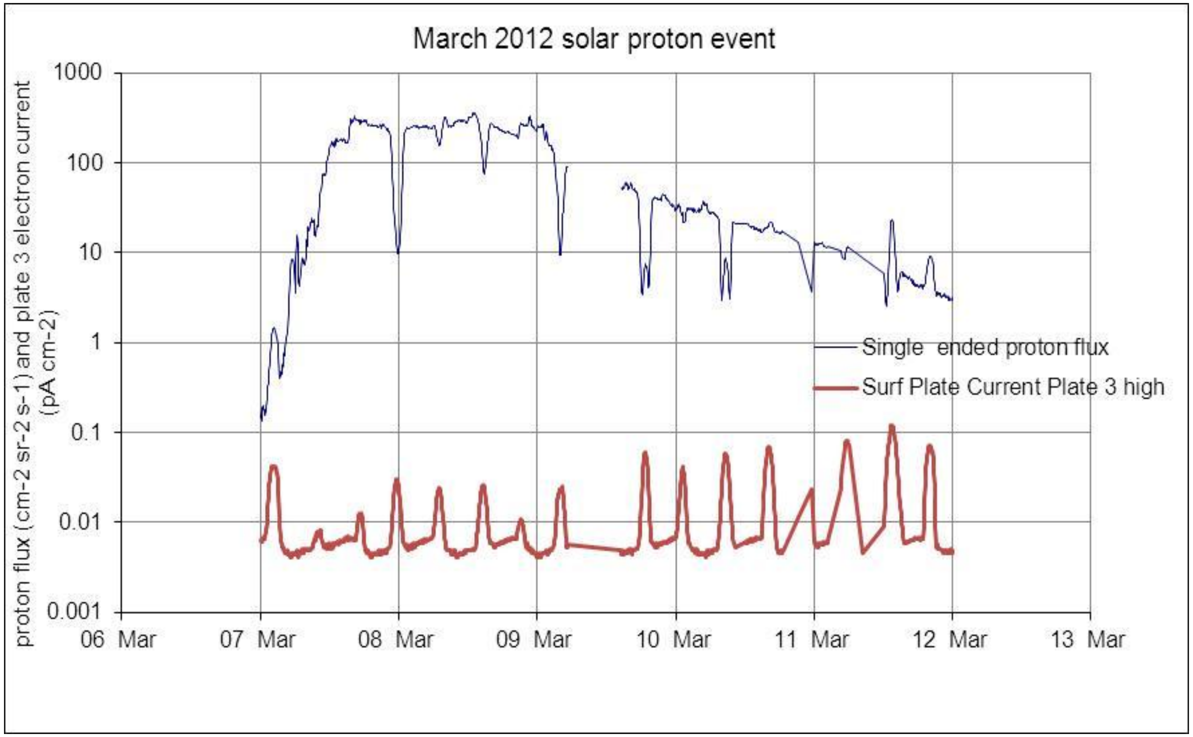
- **MERLIN Proton Channel**
  - Unfortunately (for us!) there were few SPEs during the observation period: January , March and May 2012.




The proton event in January 2012 occurred when the electron belt was at a low level and thus proton flux measurement was largely uncontaminated.

# Proton Results

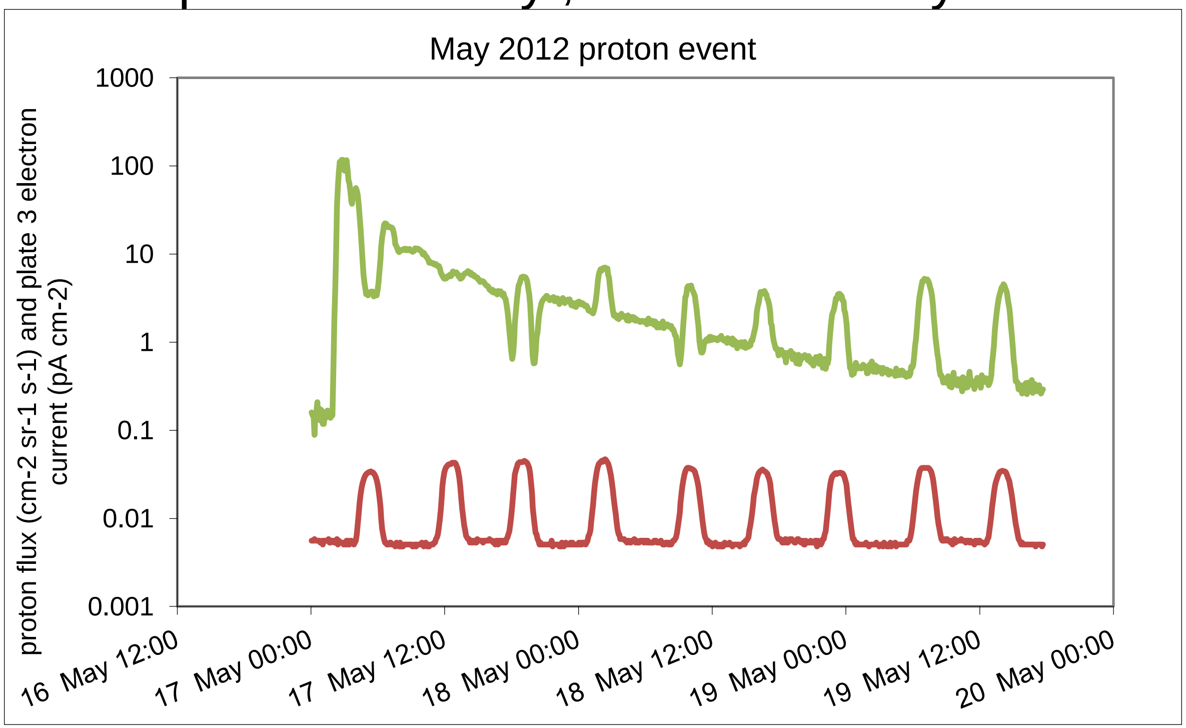
- **MERLIN Proton Channel**
  - Unfortunately (for us!) there were few SPEs during the observation period: January , March and May 2012.




The proton event in March 2012 occurred when the electron belt was at a relatively high level and some degree of contamination is evident.

# Proton Results

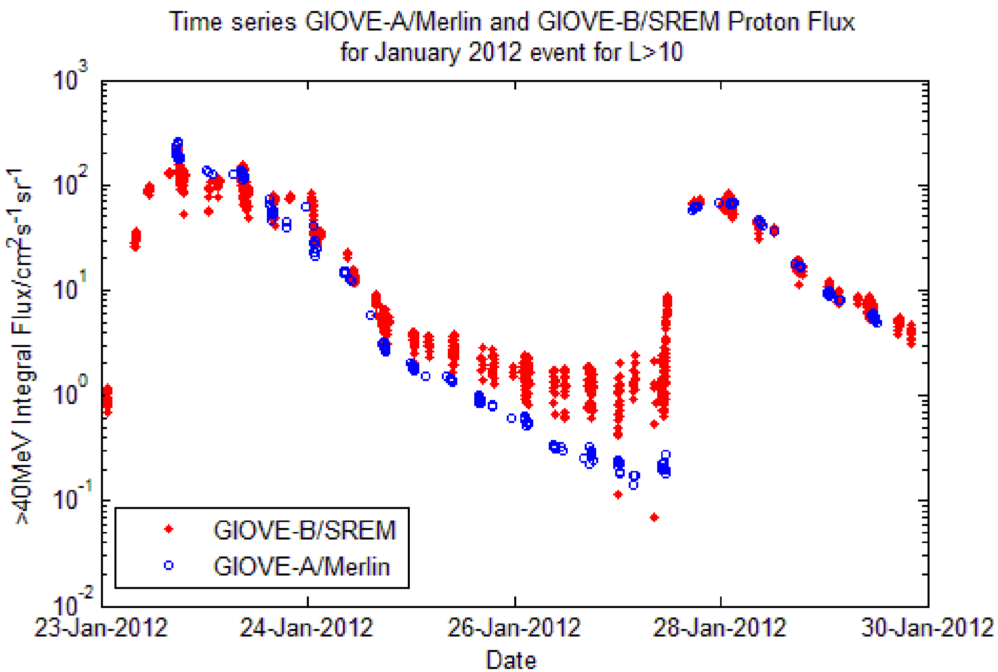
- **MERLIN Proton Channel**
  - Unfortunately (for us!) there were few SPEs during the observation period: January , March and May 2012.

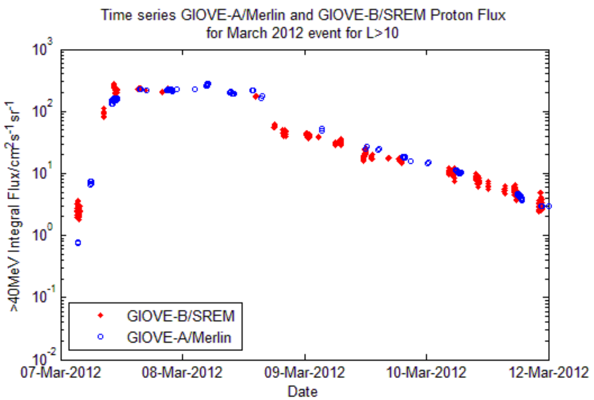


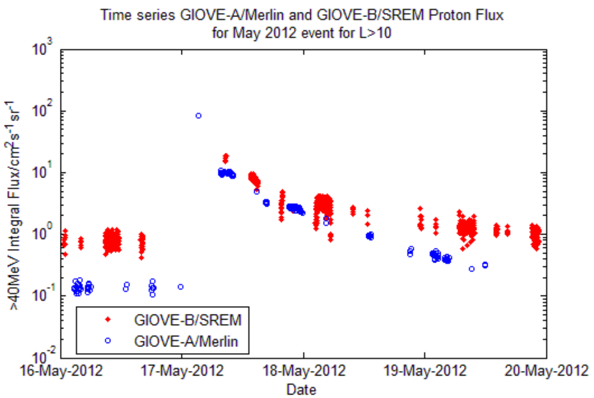

The proton event in May 2012. This occurred when the electron belt was at a high level and thus proton flux measurement was at times corrupted by electrons.

# Proton Results

- **MERLIN and SREM Protons**
- SREM data were processed as recommended[1], however residual electron contamination remained. Thus, only data for L-shells > 8 can be considered contamination free.
- Good agreement is seen for high proton fluxes




[1]Sandberg, I. et al "Unfolding and Validation of SREM Fluxes", IEEE Trans. Nucl. Sci., vol. 59, no. 4, pp. 1105-1112, August 2012),

# LET Spectra

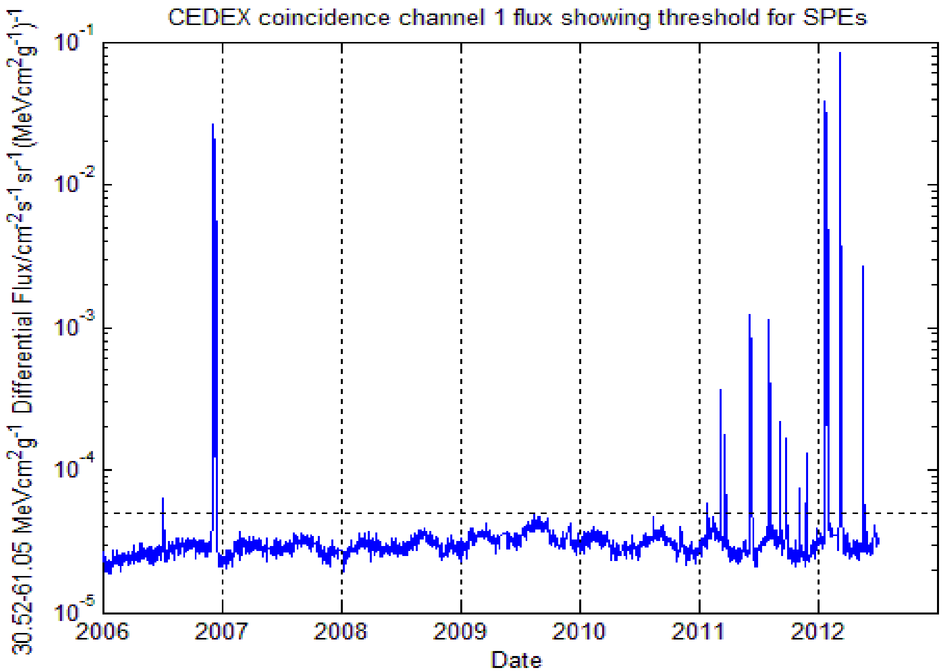
- **CEDEX LET Telescope**
  - The LET telescope on CEDEX consists of two 3x3cm, ~300μm thick PIN Silicon detectors with a spacing of 7.4cm. The detectors are placed behind a 2.5mm Copper dome, equivalent to 8mm Aluminium shielding.
  - Assuming particle incidence from both directions on the particle telescope, the geometric factor for coincident particle strikes is given by Thomas:

$$G_{co} = 2\left( 4\left(Z^2 + x^2\right)^{1/2}\left( x\tan^{-1}\left( \frac{x}{\left(Z^2 + x^2\right)^{1/2}} \right)\right) - 4Z\left( x\tan^{-1}\left(\frac{x}{Z}\right)\right) + Z^2 \ln\left( \frac{\left(Z^2 + x^2\right)^2}{Z^2\left(Z^2 + 2x^2\right)} \right)\right)$$

  - With spacing of Z=7.4cm and detector length on a side of x=3cm, $G_{co}$ = 2.6733cm$^2$ sr.
  - The geometric factor for the entire field of view of the prime detector from both sides, including coincidence counts, is simply given by: $G = 2\pi x^2$ G = 56.5487cm$^2$sr.

# LET Spectra

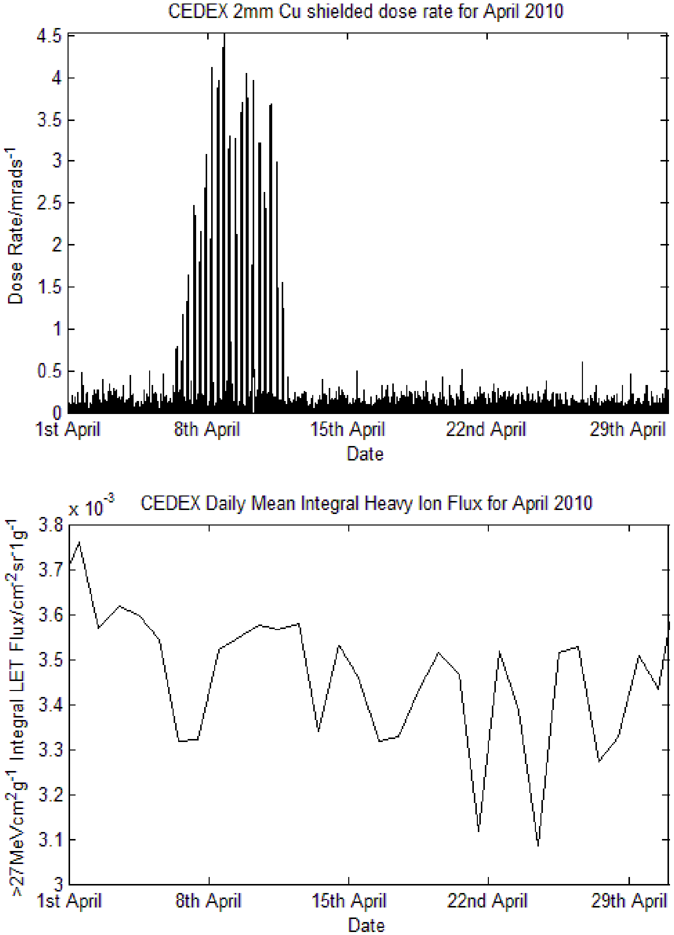
- **CEDEX LET Telescope**
  - By inspection, if the daily average Channel 1 count was above $5x10^{-5}cm^{-2}sr^{-1}s^{-2}(MeVcm^{2}g^{-1})^{-1}$, that data is considered to be part of a solar particle event.




Time series of daily mean CEDEX Differential flux showing threshold for SPE identification

# LET Spectra

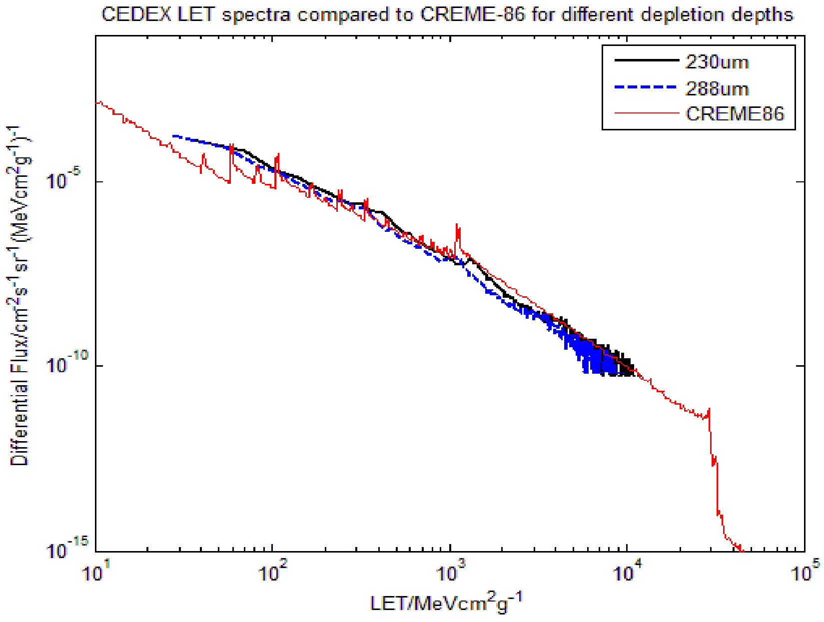
- **CEDEX LET Telescope**
  - CEDEX LET telescope is heavily shielded against electron contamination.
  - The shielding on the front end of the LET telescope on CEDEX consists of a 2.5mm thick Cu dome, approximately equivalent to 8mm Al. The back is shielded by the spacecraft .
  - Comparisons with the CEDEX Dose Rate Diode Data show that it is indeed unaffected by electrons.

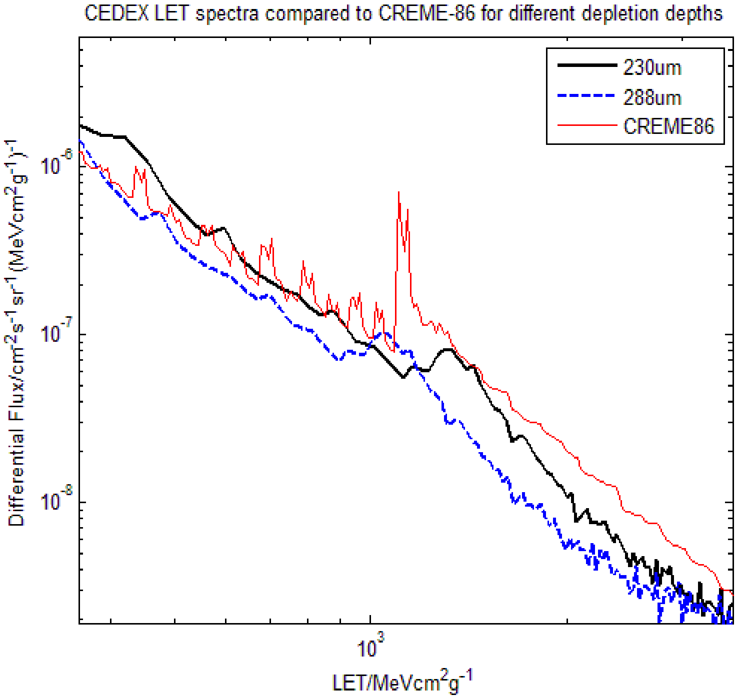



CEDEX 2mm Cu shielded dose rate for April 2010 compared to CEDEX integral LET flux for the same period

# LET Spectra

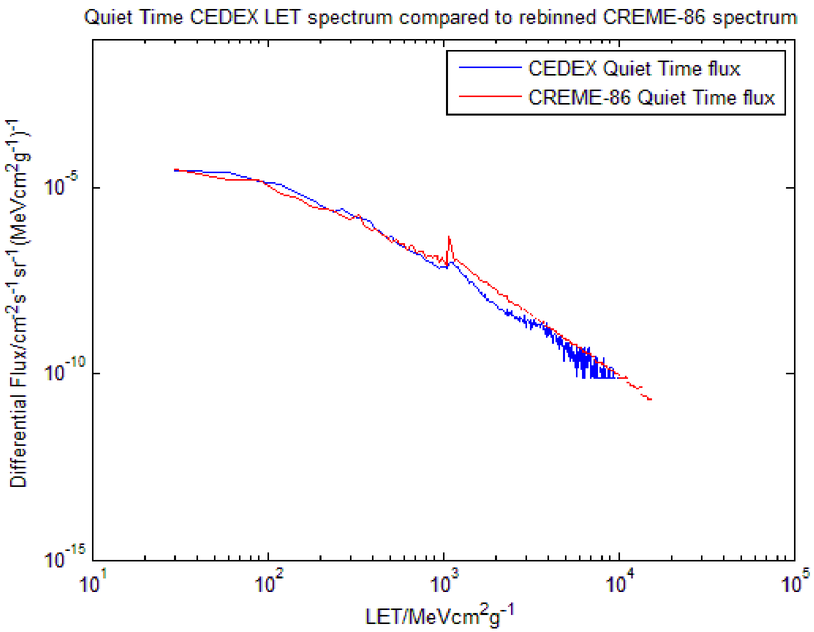
- **CEDEX LET Telescope**
  - CEDEX PIN diodes are ~ 300 μm thick – however, the charge collection depth is a little uncertain as the diodes are not operated at full depletion voltage. An effective depth of between 230 μm and 288 μm was modelled. The position of the Fe peak indicates a true effective depth of 270 μm.

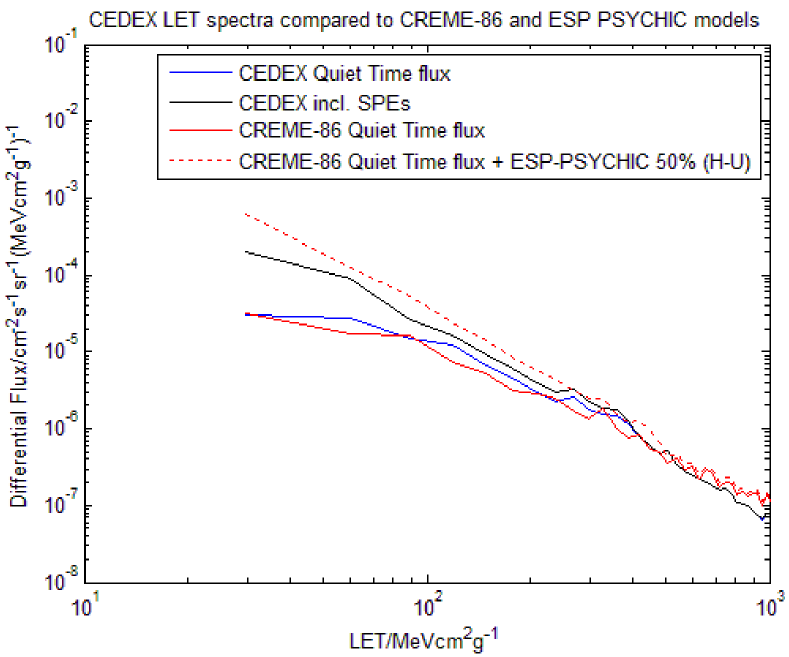


# LET Spectra

- **CEDEX LET Telescope**
  - CEDEX LET data show good agreement with CREME-86 Quiet Time flux.

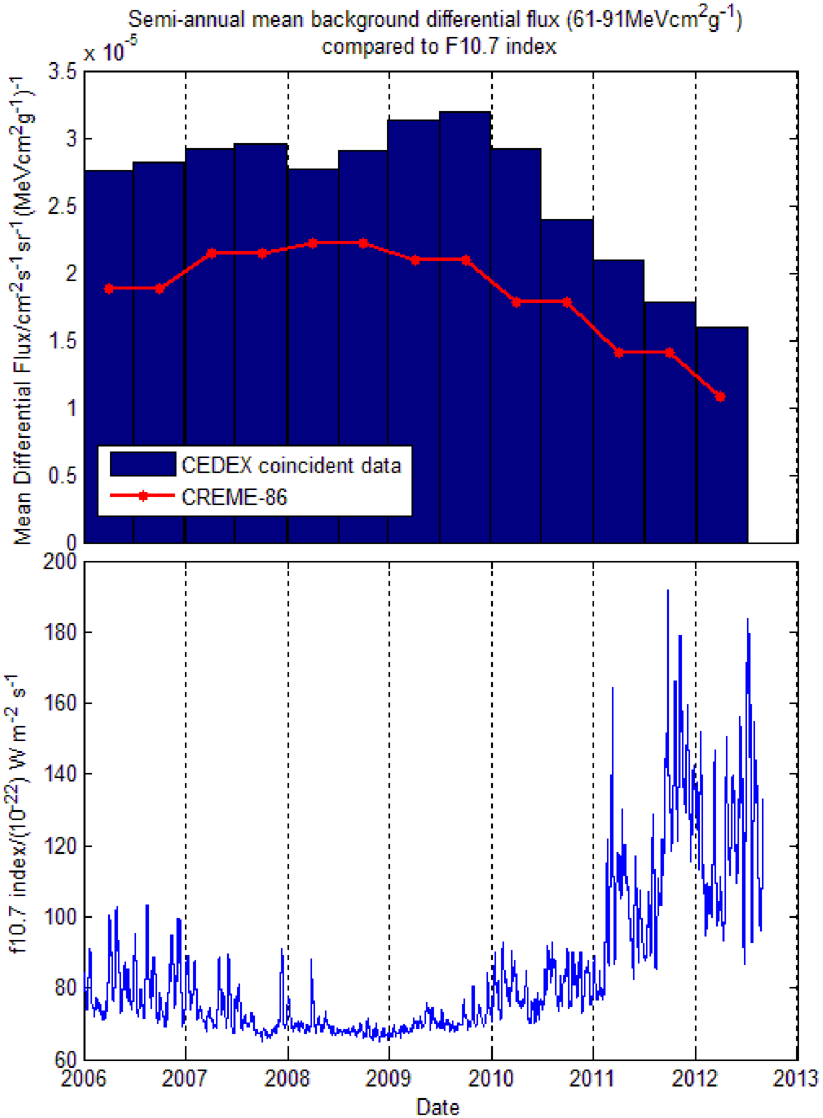



CEDEX coincidence derived mean differential LET spectrum for Solar quiet times and for January 2006 to July 2012, compared to CREME-86 and ESP-PSYCHIC 50% confidence predicted spectrum, re-binned to match coincident data

# LET Spectra

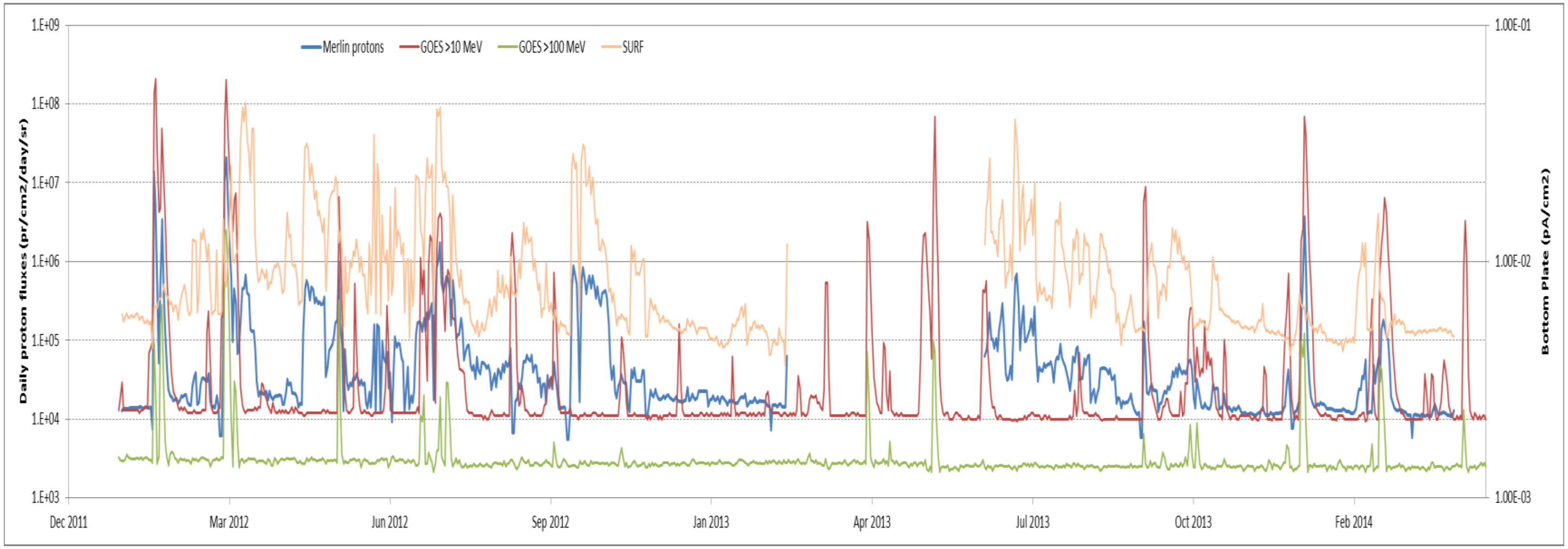
- **CEDEX LET Telescope**
  - Long term LET variation is observed over the solar cycle:




Semi-annual CEDEX coincidence derived mean differential LET spectrum for Solar quiet times 2006 to 2012, compared to CREME-86 and F10.7cm index showing actually and predicted variation over the solar cycle

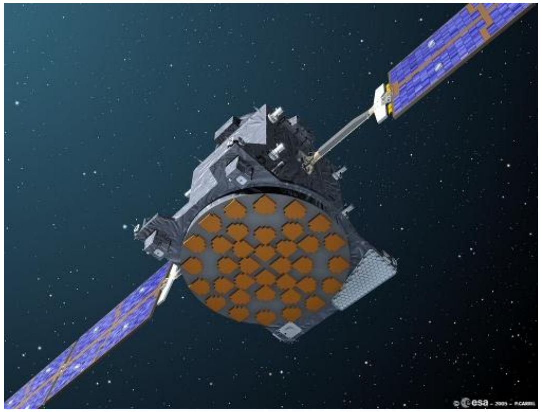
# Conclusions and Future Work

- The Giove Radiation Environment Sensors have given excellent data on the MEO environment.
- Inter-comparison of results show good agreement, as well as the value of flying a diversity of payloads to give robustness and confidence.
- Giove-A is still operational and MERLIN is still producing good data (CEDEX is now expired).



# Conclusions and Future Work

- Both CEDEX and MERLIN have produced a long sequence of data (2006-2012) and work is underway to derive a model of the MEO environment based on these flight results.
- Further comparisons of the flight data with other models are also in progress.
- Giove-A data will be logged as long as the spacecraft and payloads remain operational.




- **Acknowledgements:** Particular thanks go to Hugh Evans and Eamonn Daly of ESTEC for their support of this work, as well as to the Giove-B SREM team.
- This work is supported by ESA Contract Number: 4000105611.