Determination of the 1 in 100 year space weather event in medium Earth orbit

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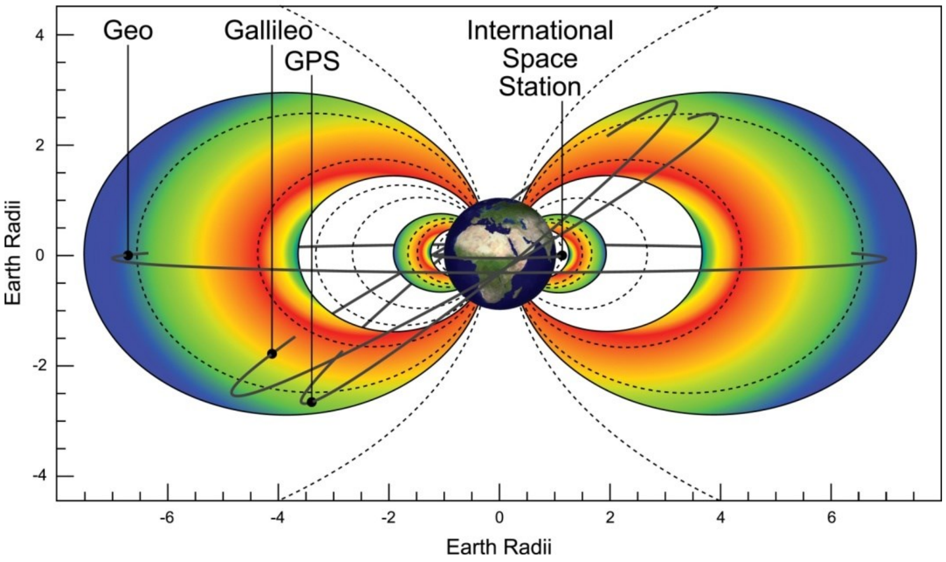
Earth's Radiation Belts

- Our critical infrastructure extends to 6.6 Earth radii
- Over 1300 satellites in Earth orbit
- Most are exposed to relativistic electrons (E > 1 MeV) in the Earth's radiation belts
- These so-called "killer electrons" are a major cause of radiation damage

Satellite orbits and the van Allen radiation belts

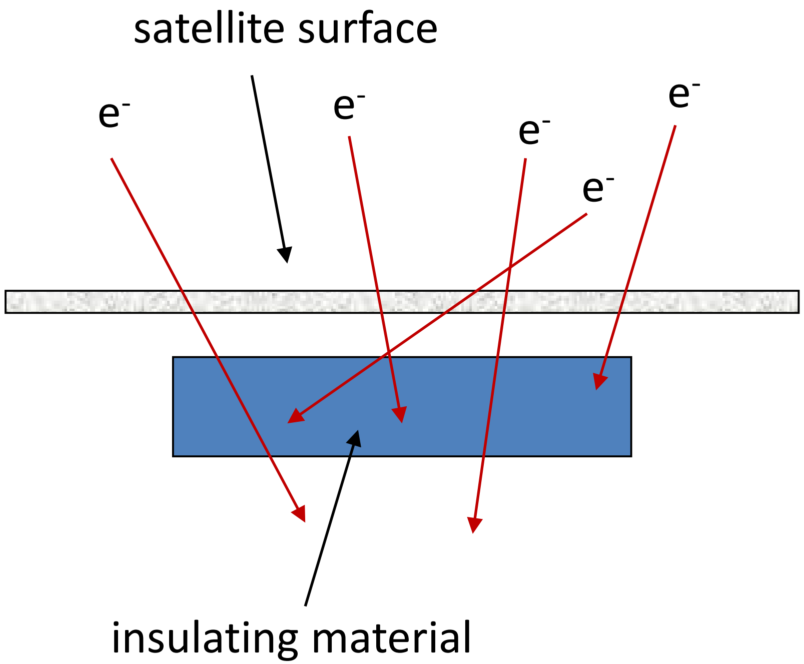


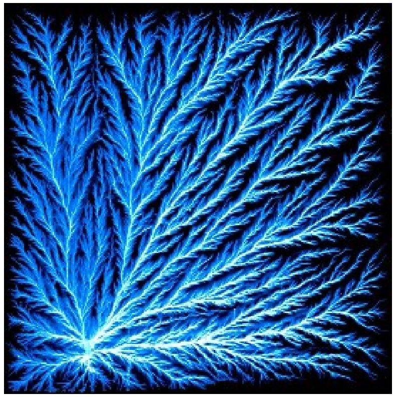
Radiation Damage

- Relativistic electrons can penetrate satellite surfaces and embed themselves in insulating materials

- The charge can build up and eventually exceed breakdown levels

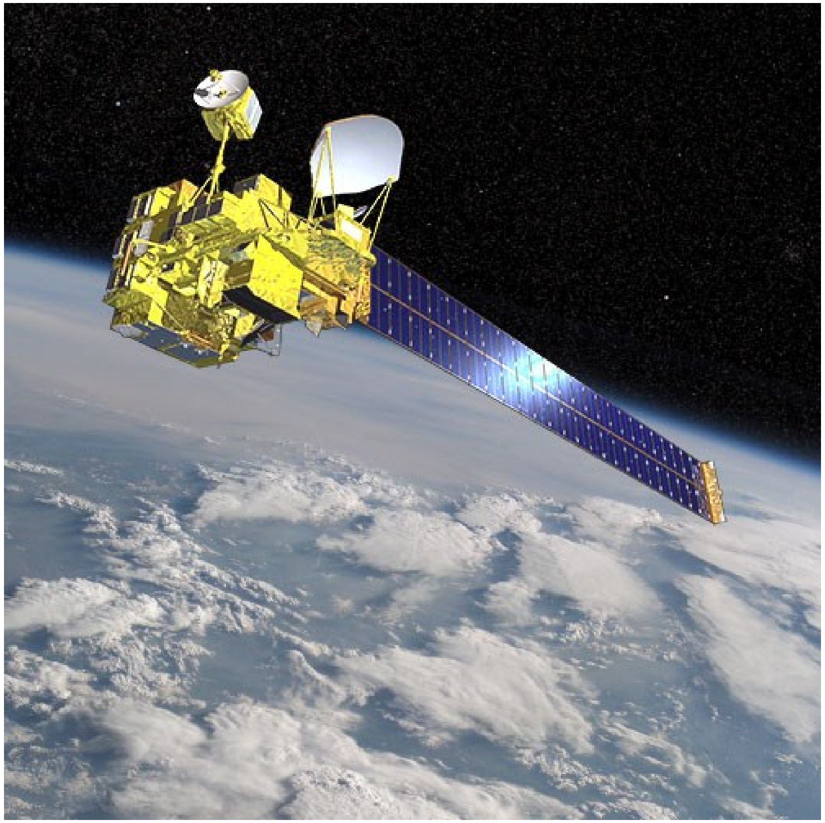
- The subsequent discharge can damage components and even destroy a satellite





Space Weather Effects on Satellites

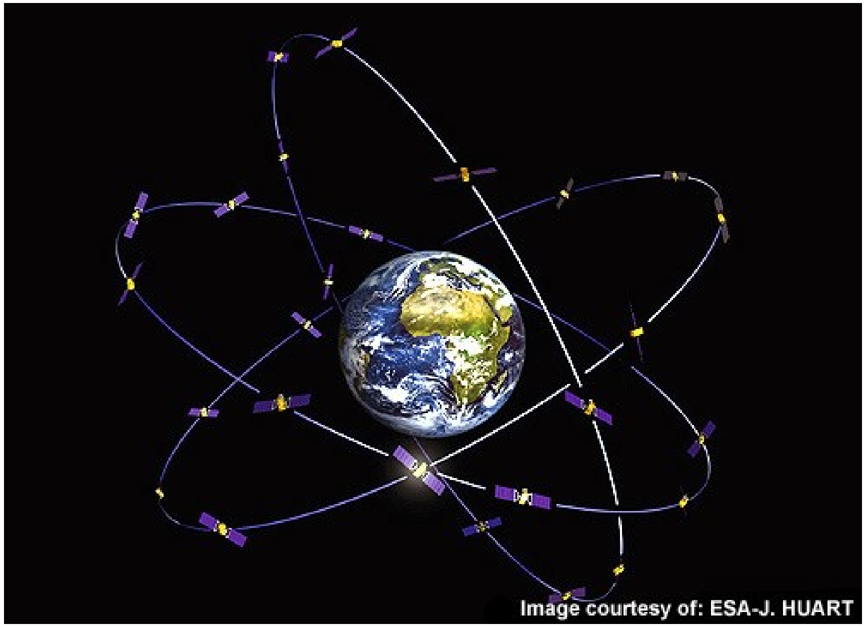
- The impacts of space weather on satellite operations range from momentary interruptions of service to total loss of capabilities when a satellite fails
- During a major storm in 2003
  - 47 satellites experienced anomalies
  - more than 10 satellites were out of action for more than 1 day
  - the US$ 640 M Midori-2 satellite was a complete loss



Artists impression of Midori-2 satellite

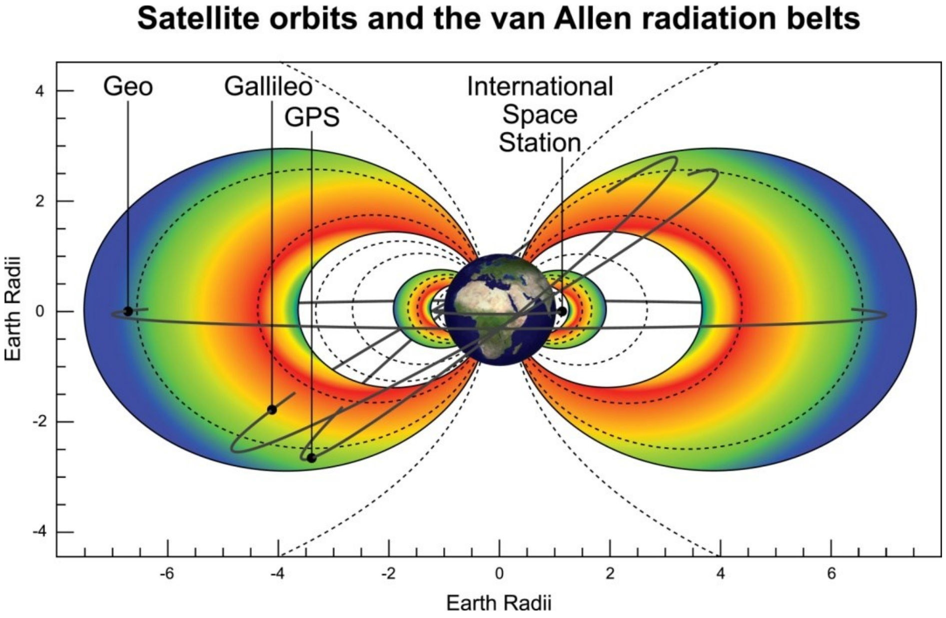
Motivation

- Europe is investing heavily in the Galileo global navigation satellite system
- There are currently 14 operational satellites in the developing constellation
- When fully operational in 2020 it will consist of 30 satellites with 10 satellites spread in three different orbital planes



Motivation

- Satellites in the Galileo constellation
  - operate in circular orbits
    - altitude: 23,300 km
    - inclination: 56^o
  - pass through the heart of the outer radiation belt
  - may be exposed to large fluxes of relativistic electrons



Motivation

- Satellite operators and engineers require realistic estimates of the highest charging currents that are likely to be encountered in MEO
  - to assess the impact of an extreme event
  - to improve resilience of future satellites

- Satellite insurers require this information
  - to ensure satellite operators are doing all they can to reduce risk
  - to help them evaluate realistic disaster scenarios

Objective

- The objective of this study is to calculate the 1 in 10, 1 in 50, and 1 in 100 year internal charging currents in medium Earth orbit

Giove-A

- Study uses data from ESA's Giove-A satellite
- This satellite was the first test satellite of the Galileo GNSS
- It was launched in December 2005 to
    - test technology in orbit
    - claim frequencies allocated to Galileo

credit: ESA

Orbital Parameters	
Altitude:	23,300 km
Inclination:	56°
Period:	14 hours

Giove-A

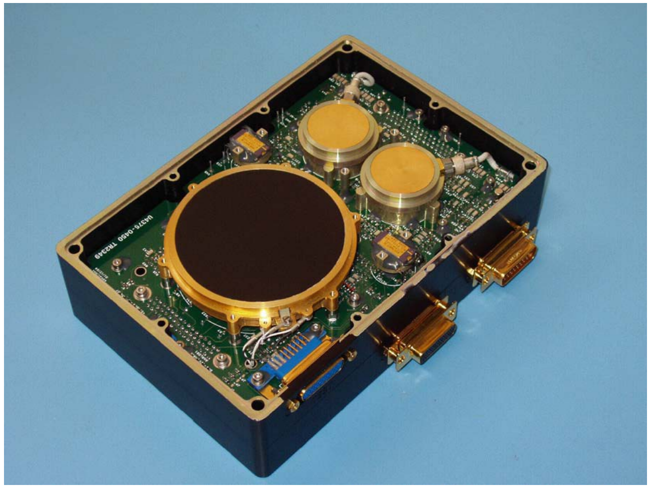
- Giove-A was initially designed with a lifetime of 27 months
- This lifetime has been greatly exceeded and the satellite continues to acquire good data
- For this study we use data from the SURF internal charging monitor
- Use data from 29th December 2005 to 5th January 2016

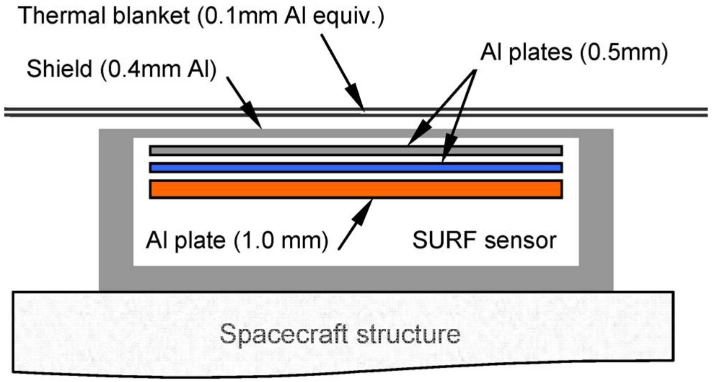
credit: ESA

Orbital Parameters	
Altitude:	23,300 km
Inclination:	56^{o}
Period:	14 hours

SURF Internal Charging Monitor

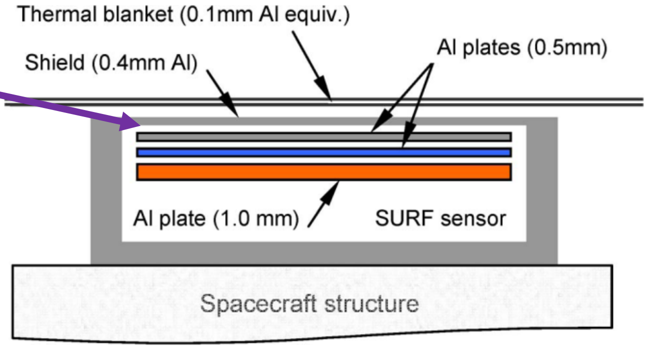
- SURF is designed to measure the small currents which penetrate spacecraft surfaces and cause internal charging
    - consists of three aluminium collector plates mounted in a stack
    - each plate is connected to an electrometer to measure the deposited current
    - measured currents lie in the range of $fAcm^{-2}$ to $pAcm^{-2}$





SURF Internal Charging Monitor

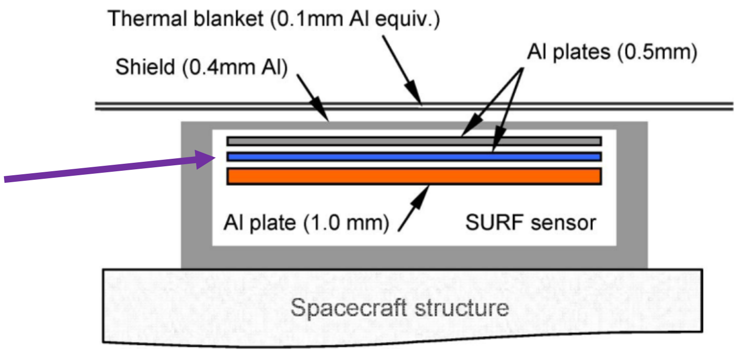
- The top plate is 0.5 mm thick and lies underneath 0.5 mm Al-equivalent shielding
  - responds to electrons above 500 keV with a peak response between 700 and 900 keV



SURF Internal Charging Monitor

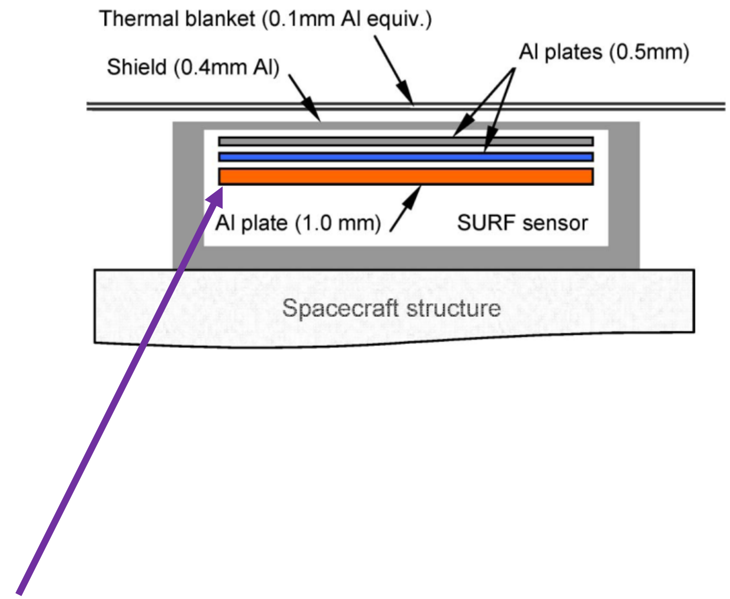
- The top plate is 0.5 mm thick and lies underneath 0.5 mm Al-equivalent shielding
  - responds to electrons above 500 keV with a peak response between 700 and 900 keV

- The middle plate is 0.5 mm thick and lies underneath 1.0 mm Al-equivalent shielding
  - responds to electrons above 700 keV with a peak response between 1.1 and 1.4 MeV



SURF Internal Charging Monitor

- The top plate is 0.5 mm thick and lies underneath 0.5 mm Al-equivalent shielding
  - responds to electrons above 500 keV with a peak response between 700 and 900 keV
- The middle plate is 0.5 mm thick and lies underneath 1.0 mm Al-equivalent shielding
  - responds to electrons above 700 keV with a peak response between 1.1 and 1.4 MeV
- The bottom plate is 1.0 mm thick and lies underneath 1.5 mm Al-equivalent shielding
  - responds to electrons above 1.1 MeV with a peak response between 1.6 and 2.1 MeV



SURF Database

- The SURF plate current data were provided at a 5 minute time resolution
- For each time step we calculated L* using the Olson-Pfitzer quiet time model and the IGRF field at the beginning of the appropriate year

Data Analysis

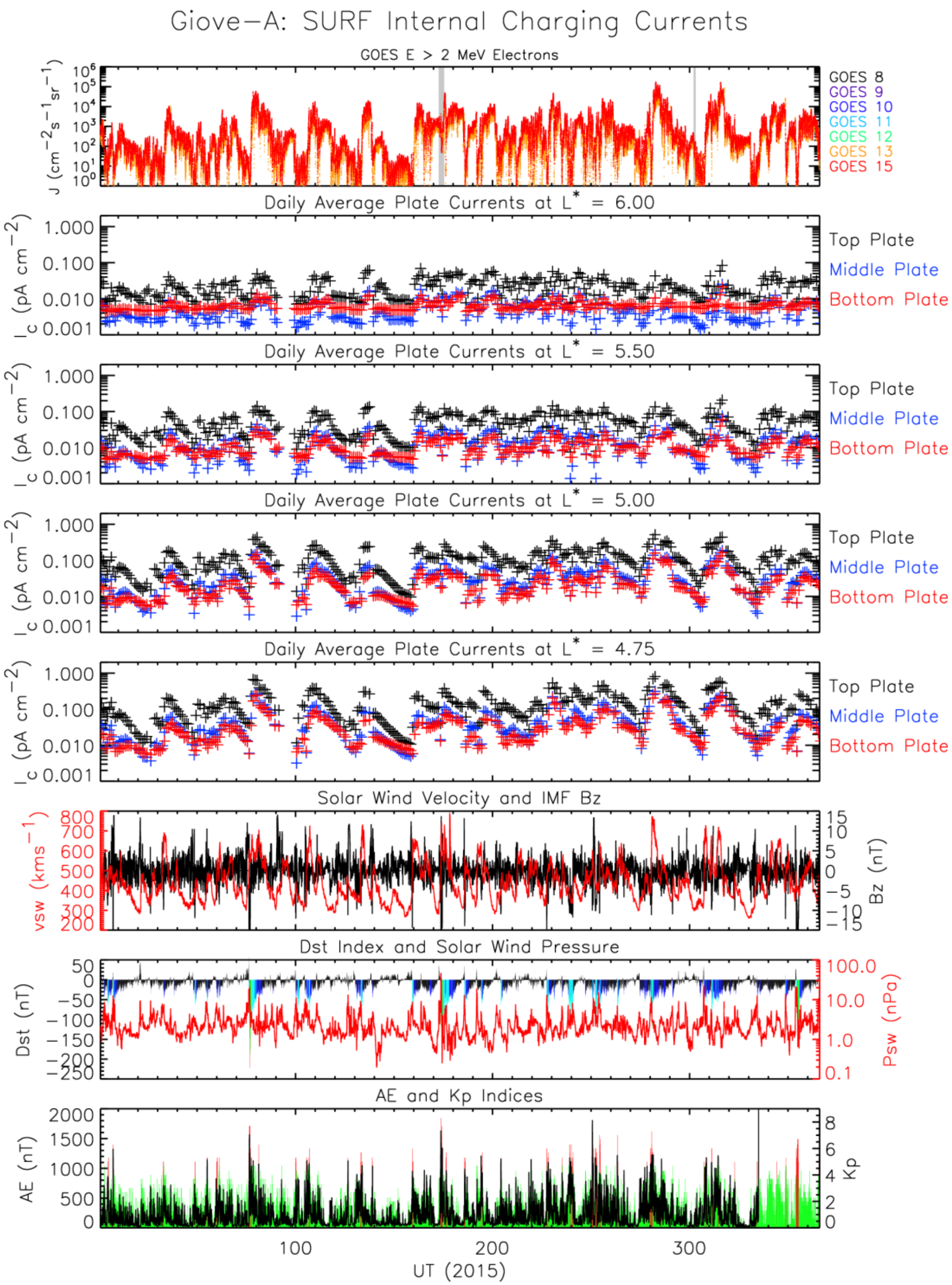
- We determined the daily-averaged plate currents as a function of L* for 10 evenly spaced values of L* from L*=4.75 to L* = 7.00
    - ~3025 good quality data points at each L* corresponding to 8.3 years of operational data

Data Analysis

- We determined the daily-averaged plate currents as a function of L* for 10 evenly spaced values of L* from L*=4.75 to L* = 7.00
  - ~3025 good quality data points at each L* corresponding to 8.3 years of operational data
- To compare with engineering standards we also calculated the daily averaged plate currents averaged along the orbit path
  - to ensure good coverage used days with > 80% coverage
  - 2223 good quality data points corresponding to 6.1 years of operational data

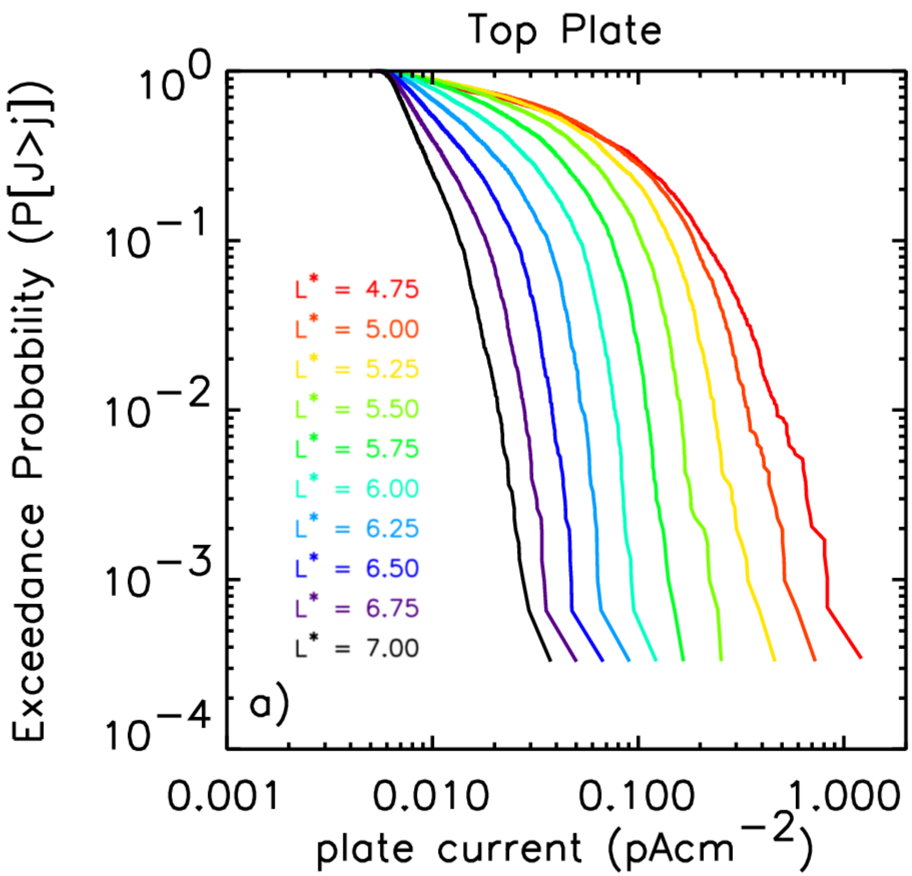
Summary Plot

- To inspect the data we produced annual summary plots
- We plotted the SURF data at 4 representative L* values together with the GOES E > 2 MeV fluxes
- Data confirmed to be very clean and no outliers were found



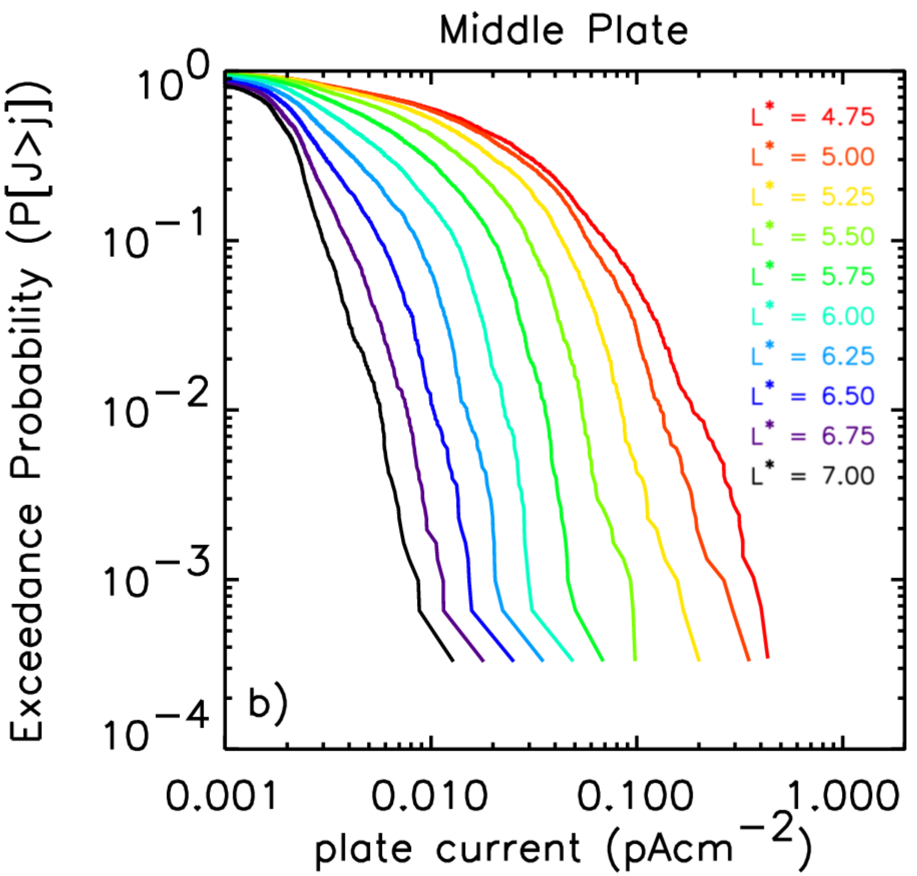
Exceedance Probability

- Top plate currents cover two orders of magnitude ranging from 0.005 to 1.2 $pAcm^{-2}$
- Largest observed top plate currents range from 0.04 $pAcm^{-2}$ at L* = 7 to 1.2 $pAcm^{-2}$ at L* = 4.75



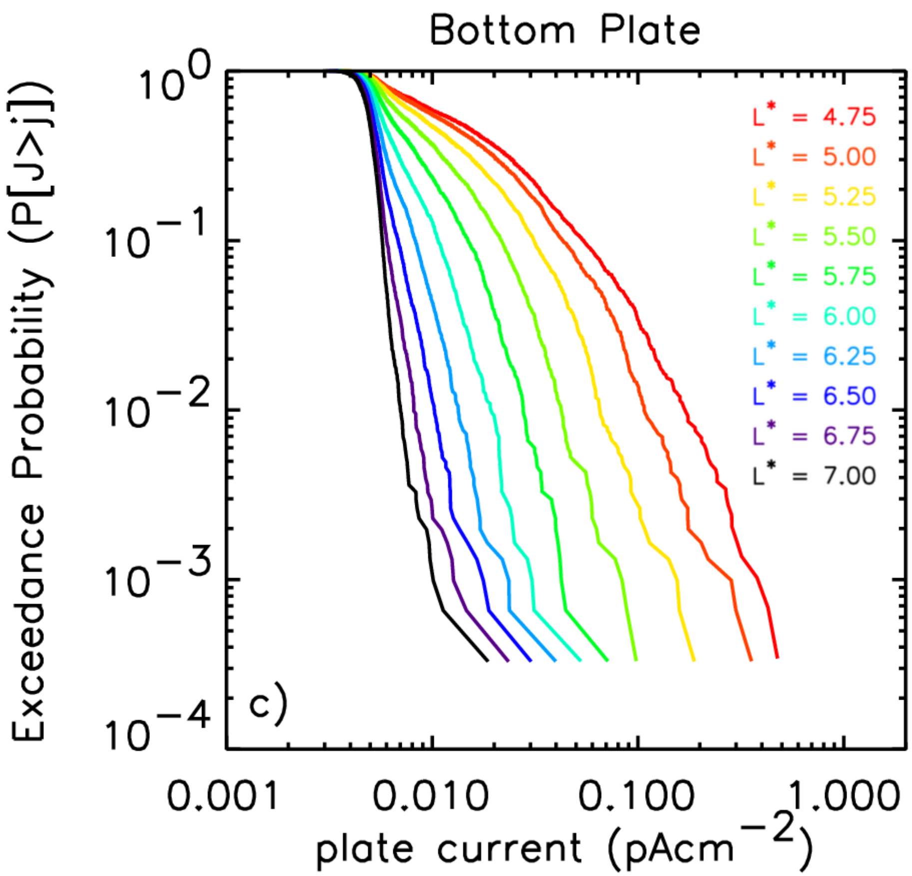
Exceedance Probability

- Middle plate currents cover two orders of magnitude ranging from 0.001 to 0.43 $pAcm^{-2}$
- Largest observed middle plate currents range from 0.01 $pAcm^{-2}$ at L* = 7 to 0.43 $pAcm^{-2}$ at L* = 4.75



Exceedance Probability

- Bottom plate currents cover two orders of magnitude ranging from 0.004 to 0.48 $pAcm^{-2}$
- Largest observed bottom plate currents range from 0.02 $pAcm^{-2}$ at L* = 7 to 0.48 $pAcm^{-2}$ at L* = 4.75



Extreme Value Analysis

- Two main methods for extreme value analysis
  - block maxima
  - exceedances over a high threshold

- The exceedances over the threshold approach makes the best use of the available data and has been successfully applied in many fields

- For this approach the appropriate distribution function is the Generalised Pareto Distribution (GPD)

Declustering

- Values can exceed the threshold on consecutive days
- The statistical analysis requires that the individual exceedances are independent
- Technique to deal with this is known as declustering

Declustering

- Use an empirical rule to define clusters of exceedances
- Consider cluster to be active until 3 consecutive daily averages fall below the threshold
- Identify the maximum excess in each cluster
- Fit the GPD to the cluster maxima

Generalised Pareto Distribution

- The GPD may be written in the form

$$G(x-u) = 1 - (1+ \xi(x-u)/\sigma)^{-1/\xi}$$

where: x are the cluster maxima above the chosen threshold u

ξ is the shape parameter which controls the behaviour of the tail

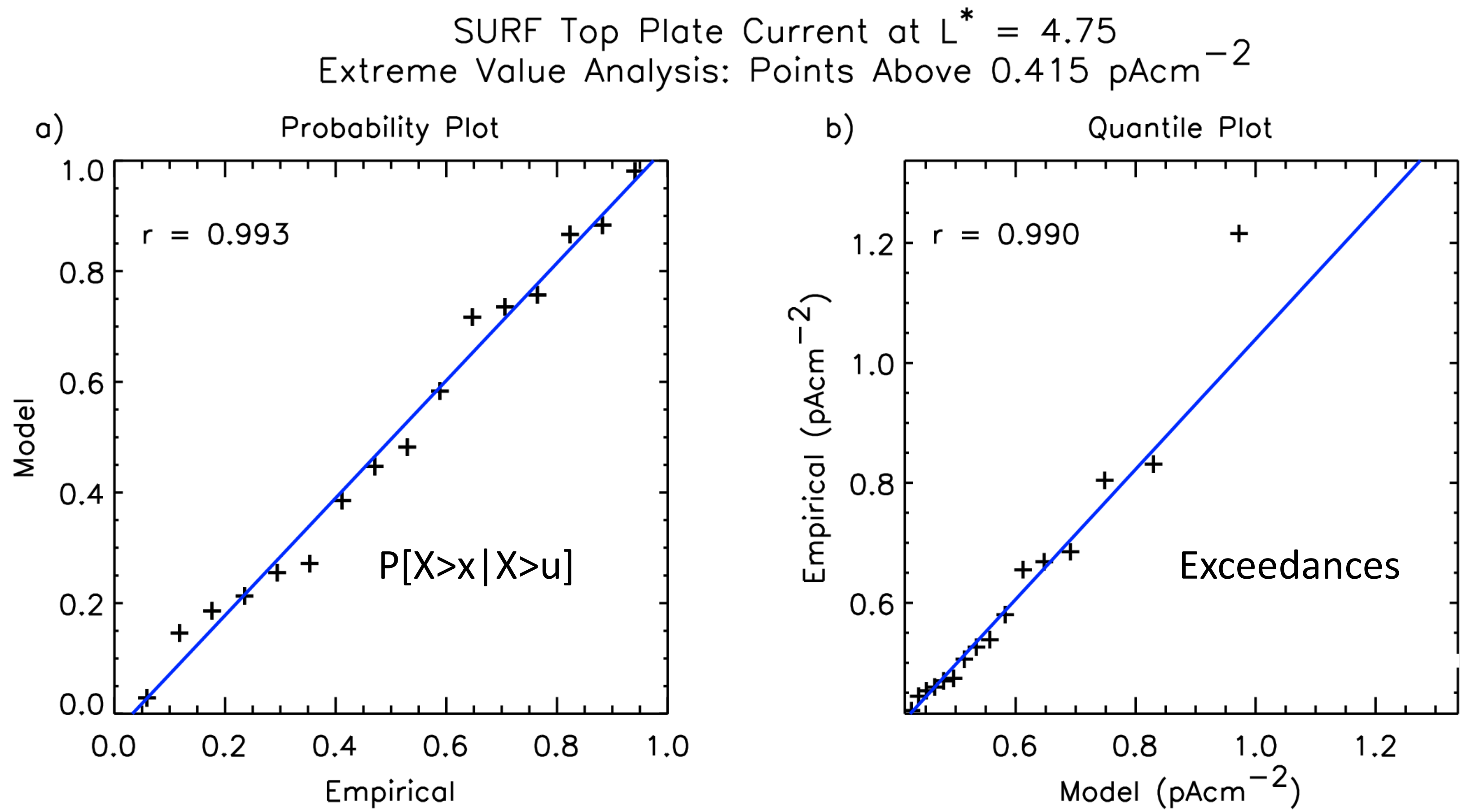
σ is the scale parameter which determines the dispersion or spread of the distribution

- We fit the GPD to the tail of the distribution using maximum likelihood estimation

Quality Checks

- We may assess the quality of a fitted GPD model by comparing the empirical and modelled probabilities and quantiles
- If the GPD model is a good method for modelling the exceeedances then both the probability and quantile plots should be linear

Probability and Quantile Plots



- The probability and quantile plots are both approximately linear showing that the GPD is a good method for modelling the exceedances

Determination of the 1 in N Year Event

- Our major objective is to determine the 1 in N year space weather event

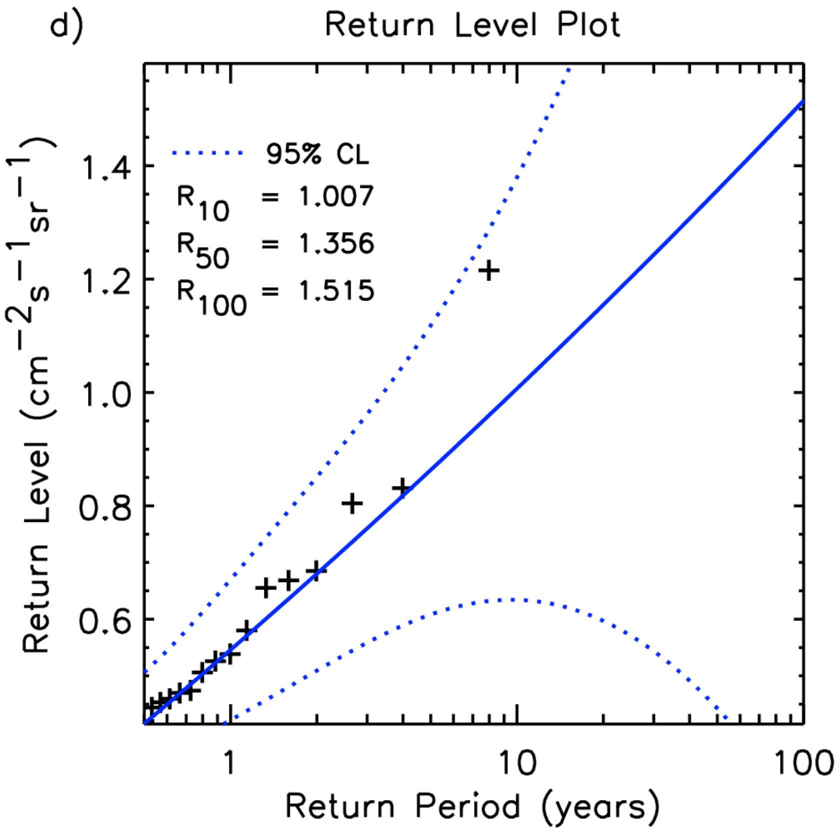
- The plate current that is exceeded on average once every N years can be expressed in terms of the fitted parameters σ and ξ as:

$$x_N = u + (\sigma/\xi)((N n_d n_c/n_{tot})^{\xi} - 1))$$

where n_d is the number of data points in a given year, n_c is the number of cluster maxima and n_{tot} is the total number of data points

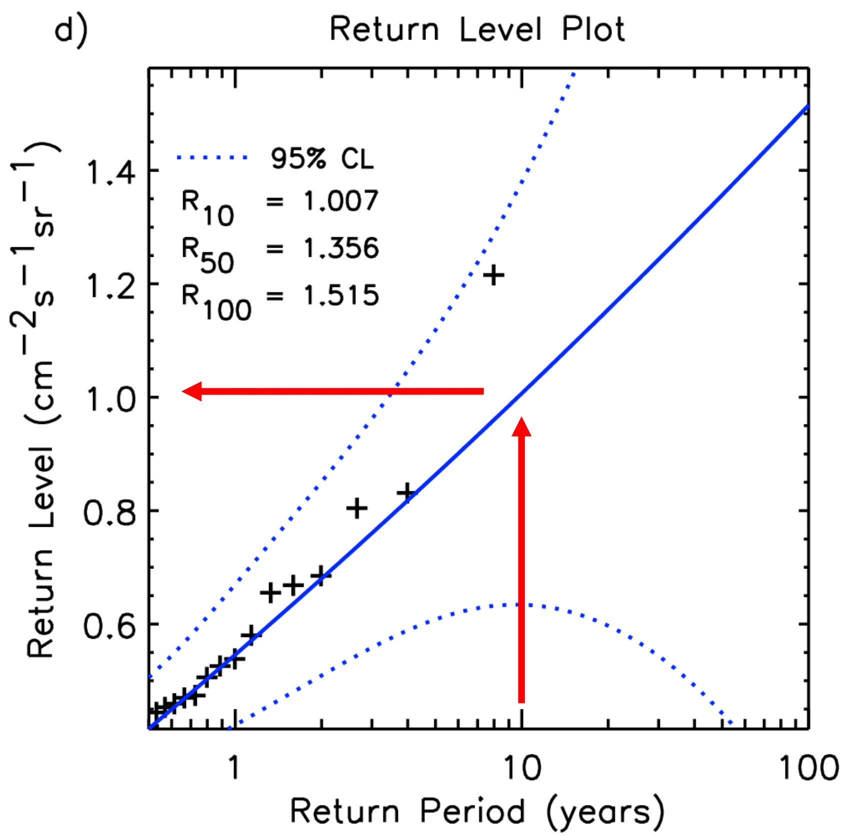
- A plot of x_N against N is known as a return level plot

Top Plate: Return Level Plot at L* = 4.75



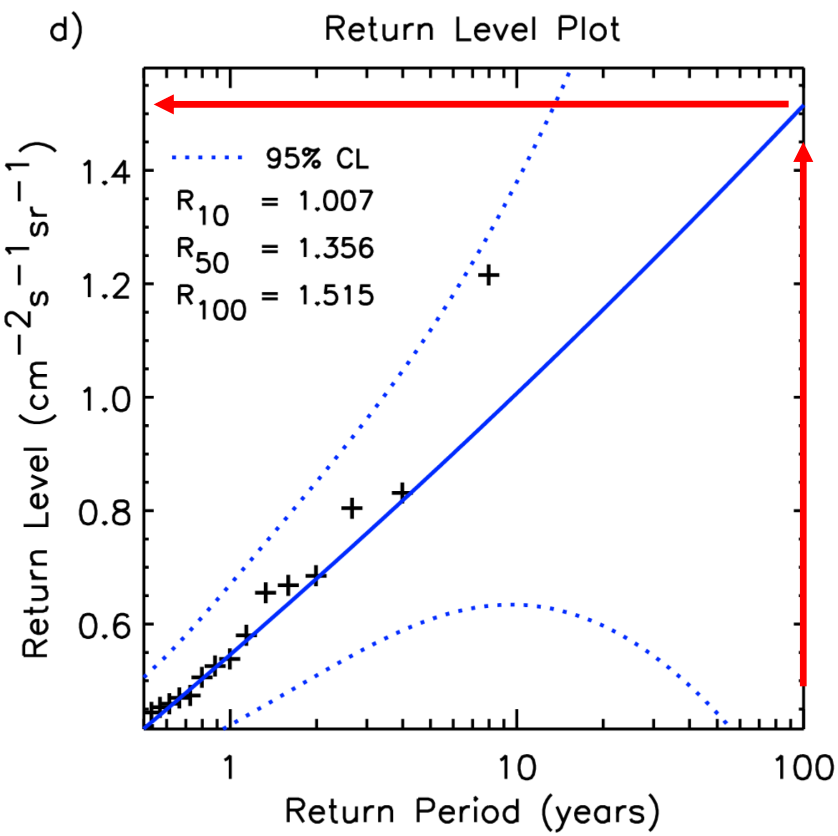
Top Plate: Return Level Plot at L* = 4.75

- 1 in 10 Year plate current
  - 1.0 pAcm^{-2}



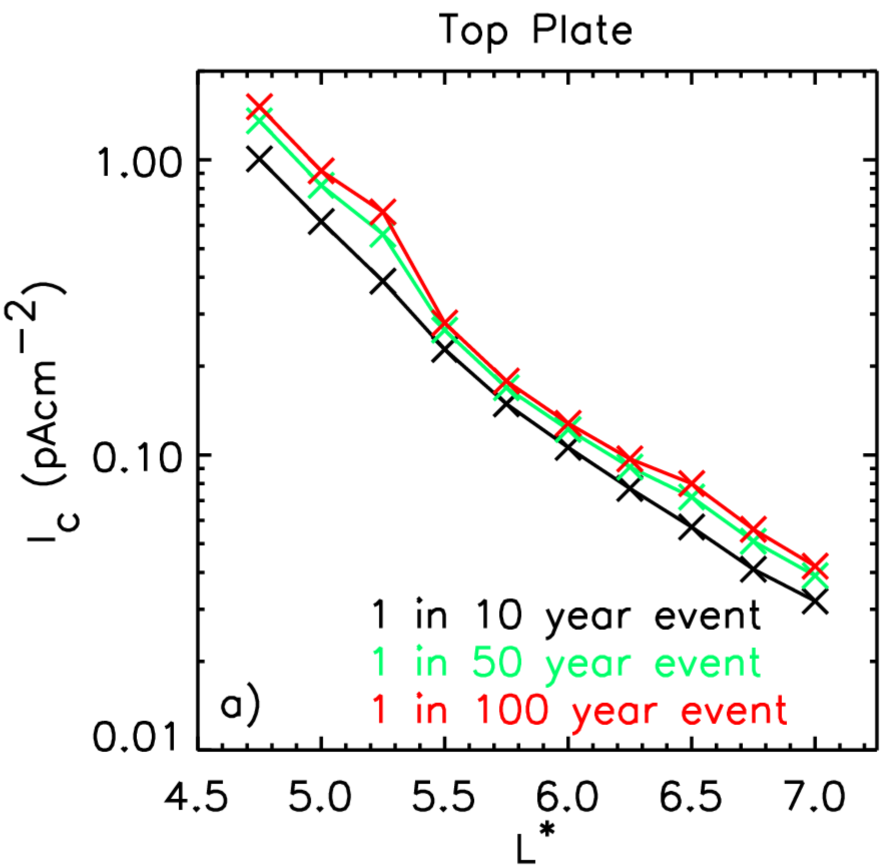
Top Plate: Return Level Plot at L* = 4.75

- 1 in 10 Year plate current
  - 1.0 $pAcm^{-2}$
- 1 in 100 Year plate current
  - 1.5 $pAcm^{-2}$



Top Plate: 1 in N Year Event Levels

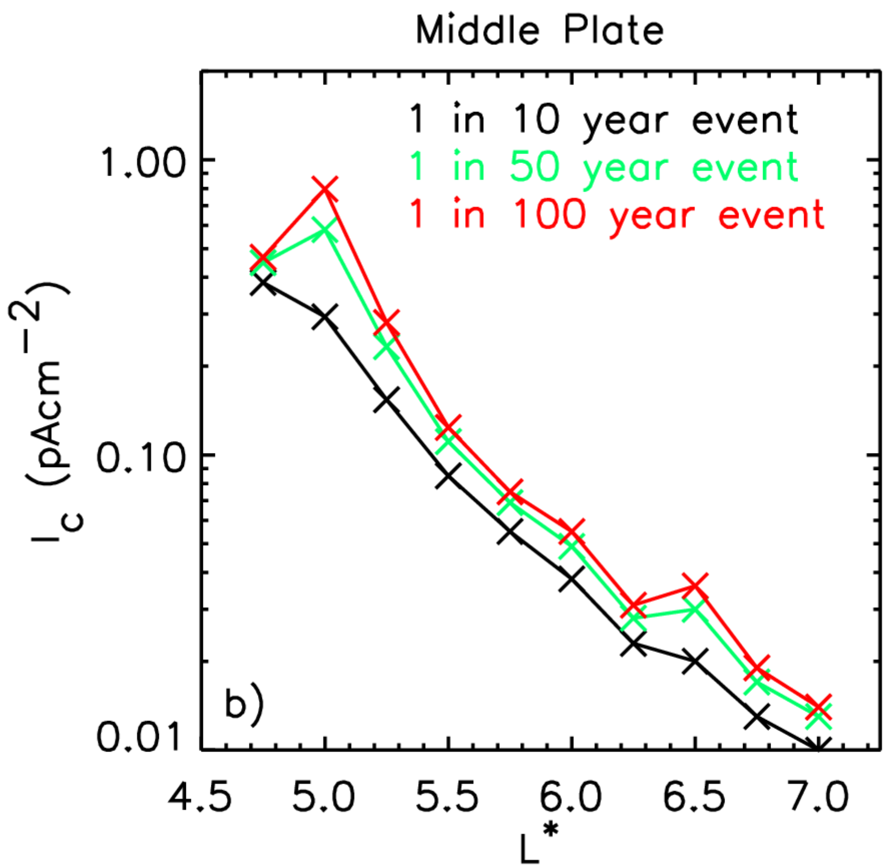
- 1 in 10 year top plate current
  - increases with decreasing L*
  - ranges from 0.03 $pAcm^{-2}$ at L*= 7.0 to 1.0 $pAcm^{-2}$ at L* = 4.75
- 1 in 100 year top plate current
  - lies in the range 0.04 to 1.5 $pAcm^{-2}$
  - is generally a factor of 1.2 – 1.8 times larger than the 1 in 10 year event



Middle Plate: 1 in N Year Event Levels

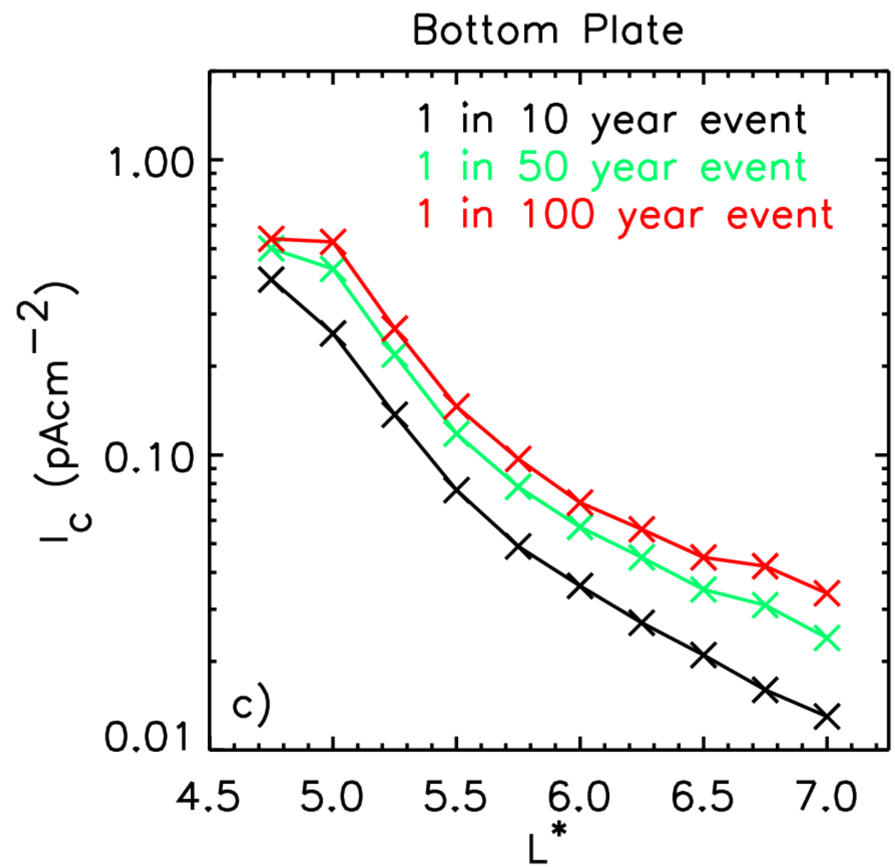
- 1 in 10 year middle plate current
  - increases with decreasing L*
  - ranges from 0.01 $pAcm^{-2}$ at L*= 7.0 to 0.4 $pAcm^{-2}$ at L* = 4.75

- 1 in 100 year middle plate current
  - lies in the range 0.015 to 0.8 $pAcm^{-2}$
  - is generally a factor of 1.2 – 2.7 times larger than the 1 in 10 year event



Bottom Plate: 1 in N Year Event Levels

- 1 in 10 year bottom plate current
  - increases with decreasing L*
  - ranges from 0.01 $pAcm^{-2}$ at L*= 7.0 to 0.4 $pAcm^{-2}$ at L* = 4.75
- 1 in 100 year bottom plate current
  - lies in the range 0.03 to 0.5 $pAcm^{-2}$
  - is generally a factor of 1.4 – 2.6 times larger than the 1 in 10 year event

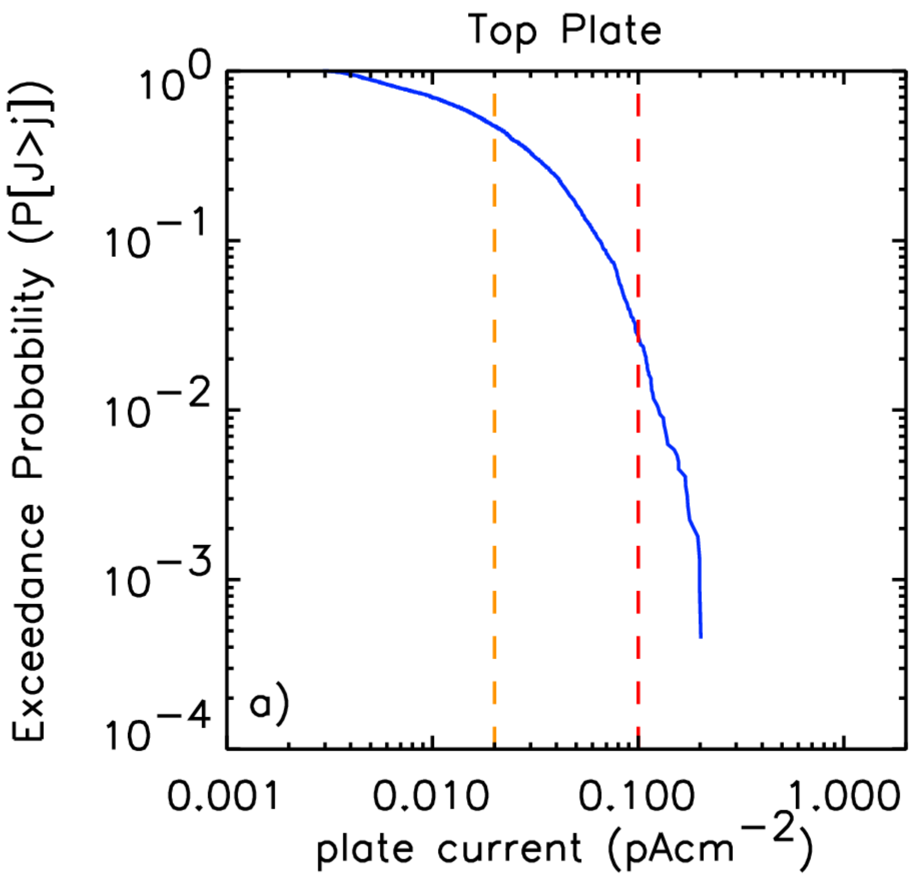


Comparison with Engineering Design Standards

- Both NASA and the European Cooperation for Space Standardization (ECSS) have guidelines on charging current
  - a maximum average current of 0.1 $pAcm^{-2}$ over a 24 hour period is commonly adopted
- For dielectrics operating at temperatures less than 25^{o}C the ECSS have adopted a threshold of 0.02 $pAcm^{-2}$
- For comparison with engineering design standards we repeated the analysis using daily-averaged plate currents over the entire orbit path

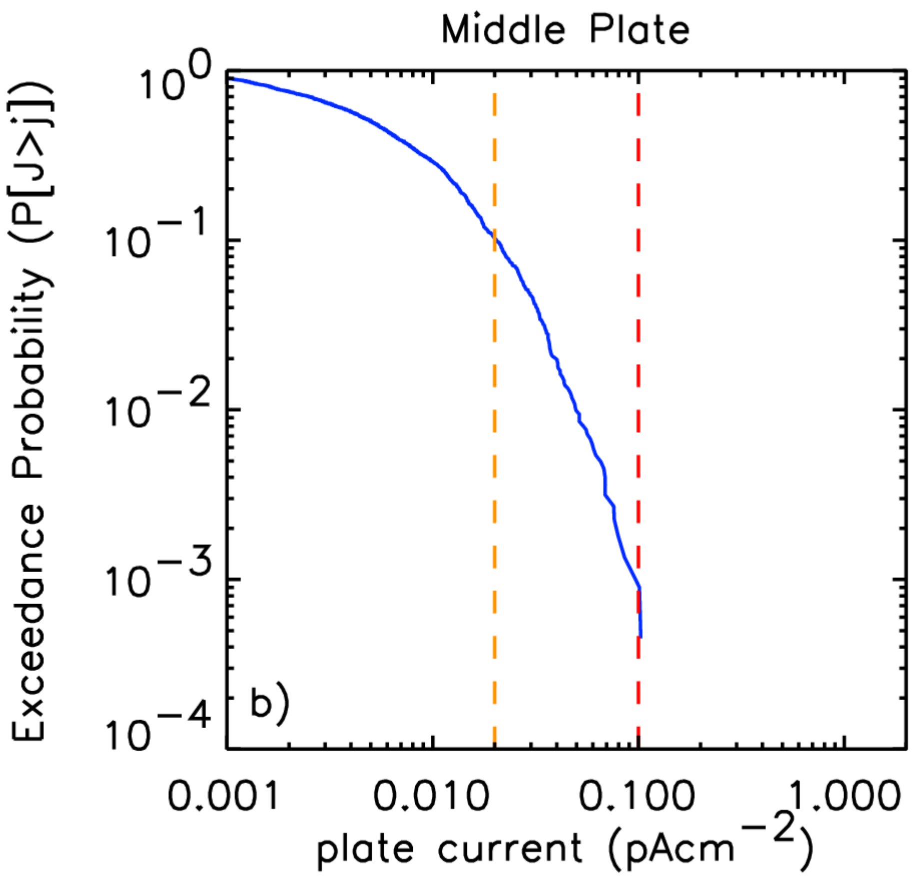
Daily-Averaged Top Plate Currents Averaged Along Orbit Path

- Top plate currents cover just under two orders of magnitude ranging from 0.003 to 0.2 $pAcm^{-2}$
- Lower design threshold is exceeded on 1045 days (47% of days)
- Upper design threshold is exceeded on 60 days (2.7% of days)



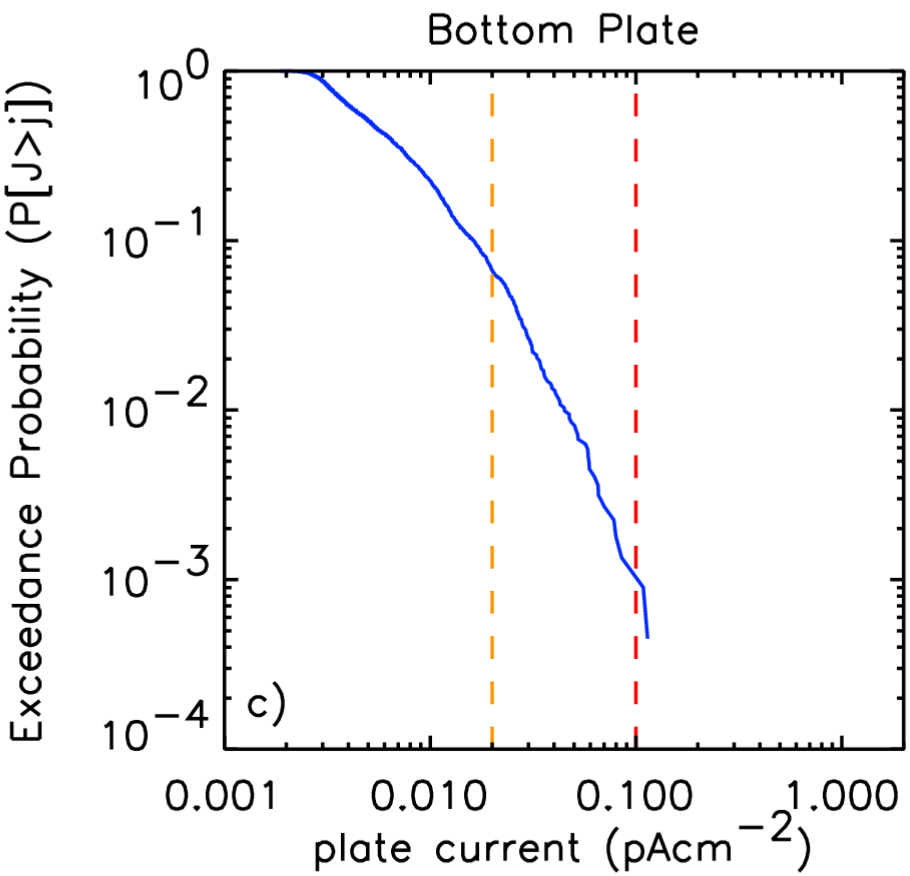
Daily-Averaged Middle Plate Currents Averaged Along Orbit Path

- Middle plate currents cover two orders of magnitude ranging from 0.001 to 0.1 $pAcm^{-2}$
- Lower design threshold is exceeded on 222 days (10% of days)
- Upper design threshold is exceeded on 3 days (0.1% of days)



Daily-Averaged Bottom Plate Currents Averaged Along Orbit Path

- Bottom plate currents cover just under two orders of magnitude ranging from 0.002 to 0.1 $pAcm^{-2}$
- Lower design threshold is exceeded on 149 days (6.7% of days)
- Upper design threshold is exceeded on 3 days (0.1% of days)



1 in N Year Events Averaged Along Orbit Path

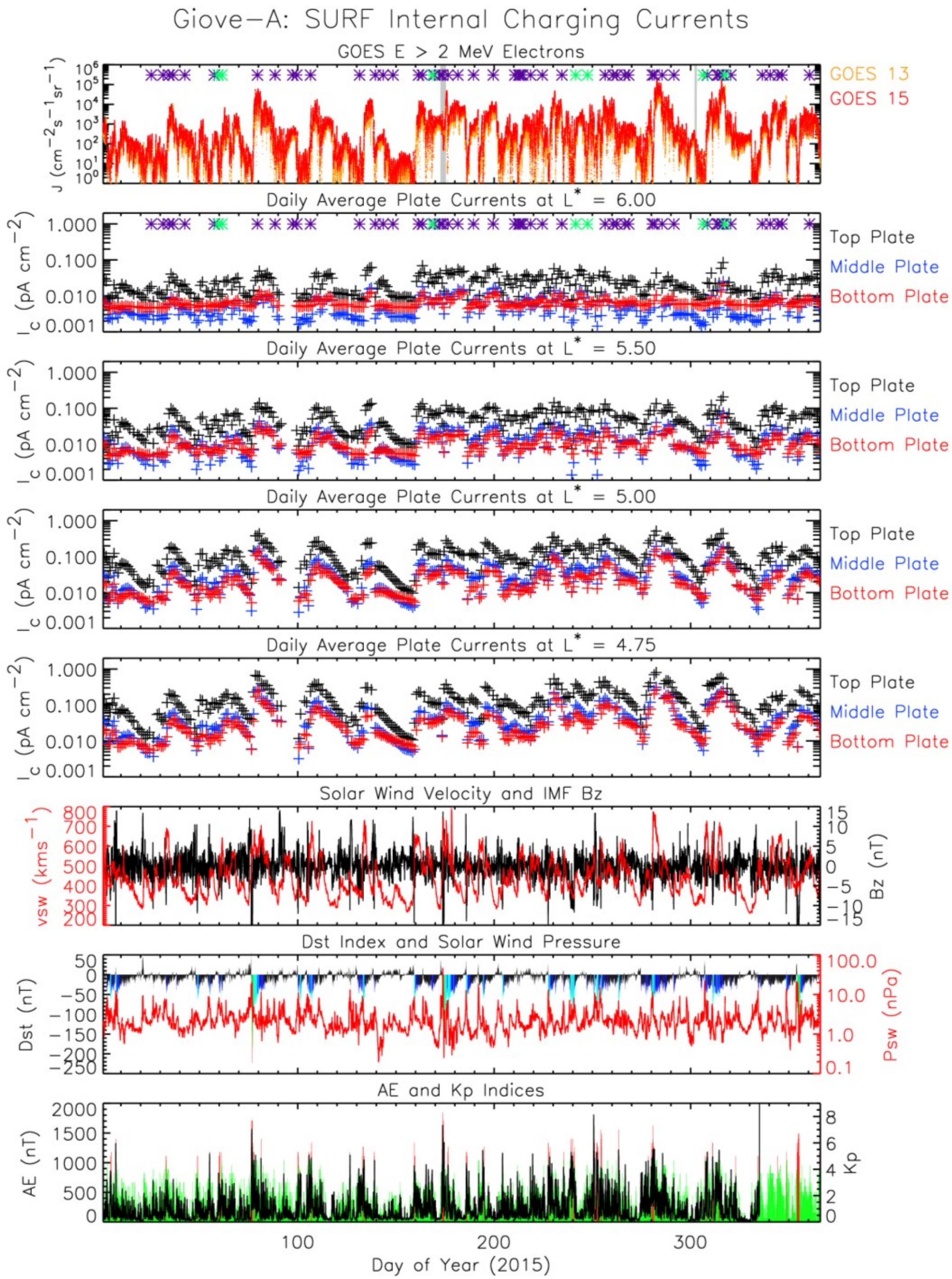
- We also conducted an extreme value analysis of the daily-averaged plate currents averaged along the orbit path
- The 1 in 10 year top plate current is a factor of 2.1 times the upper design threshold
- The 1 in 10 year middle and bottom plate currents are equal to the upper design threshold

Plate	1 in 10 year current ($pAcm^{-2}$)	1 in 100 year current ($pAcm^{-2}$)
Top	0.21	0.24
Middle	0.1	0.14
Bottom	0.1	0.16

Satellite Anomalies

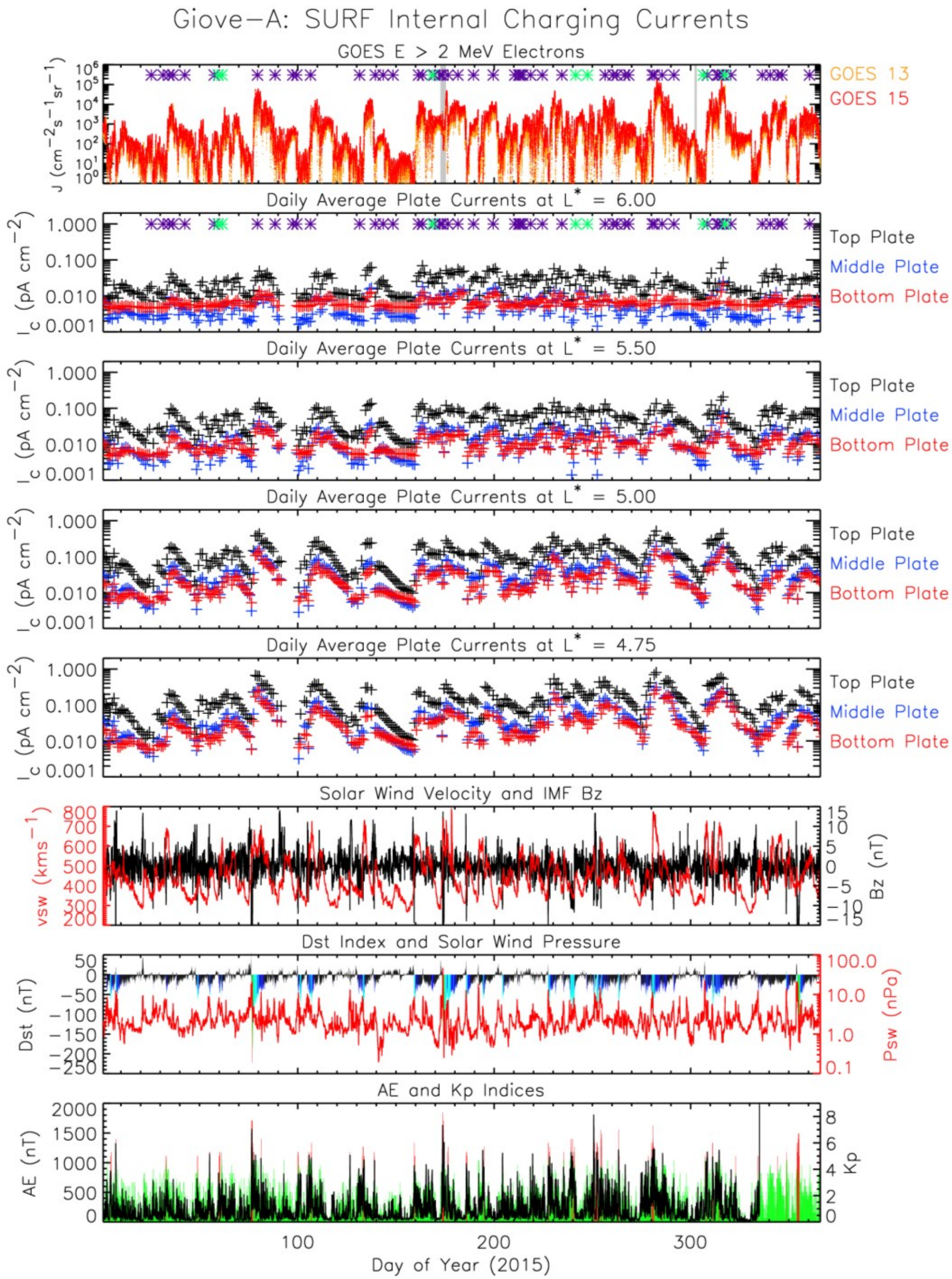
- There has been a significant increase in satellite anomalies at GEO thought to be due to IESD in the second half of 2015 [D. Pitchford, private communication]

- Overall 19 satellite anomalies at GEO were identified in the first 160 days and 40 in the next 160 days



Satellite Anomalies

- The GOES E > 2 MeV flux and the SURF plate data at L* = 6.0 can be used to investigate the relationship between the satellite environment and satellite anomalies
- Days with one or two anomalies thought to be due to IESD are marked as purple and green asterisks respectively
- Most, but not all, anomalies are associated with high fluxes of relativistic electrons and large plate currents



Conclusions

- We have determined the 1 in 10, 1 in 50 and 1 in 100 year plate currents as a function of L* and along the orbit path
- The 1 in 10 year top, middle and bottom plate currents maximise at L* = 4.75 and are determined to be 1.0, 0.43 and 0.48 $pAcm^{-2}$ respectively
- Averaged along the orbit path the 1 in 10 year top, middle and bottom plate currents are 0.21, 0.1 and 0.1 $pAcm^{-2}$ respectively

Conclusions

- The 1 in N year plate currents serve as “yardsticks” or “benchmarks” to compare against current or previous space weather conditions

- The results may also be used to compute the return period of any given space weather event as a function of plate current and L* to determine if the event was particularly extreme at any given plate current or location.

Acknowledgements

- We would like to thank Sam Rason and Richard Hebden at SSTL for their work in extending the Giove-A operations and enabling us to receive the data

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