Extreme Relativistic Electron Fluxes at Geosynchronous Orbit

N. P. Meredith¹, R. B. Horne¹, J. Isles¹ and J. V. Rodriguez²,³

¹British Antarctic Survey;
²University of Colorado Boulder; ³National Geophysical Data Center, Boulder

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Motivation

- Satellite operators, designers and insurers are interested in extreme space weather events to help them better understand the satellite environment and assess the impacts of an extreme event.
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- The objective of this study is to calculate the electron flux for the 1 in 10, 1 in 50, and 1 in 100 year space weather event at geosynchronous orbit.
Data Analysis

• Use GOES E > 2 MeV electron data from 1st January 1995 to 30th June 2014

• Study uses data from GOES 8, 9, 10, 11, 12, 13 and 15

• Use 5 minute resolution E > 2 MeV electron data from NOAA

credit: NOAA

Typical Orbital Parameters
Altitude: 35,800 km
Inclination: 0°
Data Analysis

- Electron data
  - have been corrected for proton contamination
  - for the first time the data have been corrected for dead time
  - dead time correction ranges from a factor of 1.0-1.15 for fluxes around 5000 cm$^{-2}$s$^{-1}$sr$^{-1}$ to ~2 for the largest fluxes observed

Typical Orbital Parameters
Altitude: 35,800 km
Inclination: 0°

credit: NOAA
Exclude Solar Proton Events

• The E > 2 MeV electron data may be contaminated during solar proton events

• We adopt the NOAA SWPC definition of a solar proton event and exclude the electron data whenever the flux of E > 10 MeV protons is greater than 10 cm\(^{-2}\)s\(^{-1}\)sr\(^{-1}\)

• Calculate daily average when > 90% of the day has good quality data in the absence of contamination from solar protons
Primary Geographic Longitudes

• GOES satellites operate at two primary geographic longitudes, GOES East at 75° and GOES West at 135° W

• The satellites are at different magnetic latitudes with GOES East at 11° N and GOES West at 4° N

• GOES East and GOES West are at different L shells

• Since the flux of energetic electrons generally decreases with L near geosynchronous orbit we conduct our analysis for GOES East and West separately

Figure adapted from Onsager et al., 2004
Good Quality Data Points

- In total there are 5844 good quality data points at GOES West, corresponding to approximately 16 years of operational data.

- There are 5649 good quality data points at GOES East corresponding to approximately 15.5 years of operational data.
GOES West: $E > 2$ MeV Electrons
• Probability that an individual sample J is greater than j (P[J>j])

Exceedance Probability

GOES E > 2 MeV Electrons
Exceedance Probability of Daily Averaged Integral Flux

Exceedance Probability (P[J>j])

j (cm$^{-2}$s$^{-1}$sr$^{-1}$) $10^4$ $10^5$

GOES East
GOES West
Exceedance Probability

- Probability that an individual sample $J$ is greater than $j$ ($P[J > j]$)

- Flux that is exceeded 0.1% of the time is
  - $4.5 \times 10^4$ cm$^{-2}$s$^{-1}$sr$^{-1}$ at GOES East
  - $1.35 \times 10^5$ cm$^{-2}$s$^{-1}$sr$^{-1}$ at GOES West
Exceedance Probability

- Fluxes at GOES West are typically a factor of 2.5 higher than those at GOES East.

- This is largely due to the fact that the satellite at GOES West is at a lower magnetic latitude and hence L shell.
Extreme Value Analysis

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

- For comparison with earlier work (e.g., Koons [2001]) we use the exceedances over a high threshold method

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

- The GPD may be written in the form

\[ G(x-u) = 1 - \left(1 + \frac{\xi(x-u)}{\sigma}\right)^{-\frac{1}{\xi}} \]

where: \( x \) are the data values above the chosen threshold \( u \)
\( \xi \) is the shape parameter which controls the behaviour of the tail
\( \sigma \) is the scale parameter which determines the dispersion or spread of the distribution

- The GPD is a distribution function

- \( 1-G(x-u) \) representing the probability that a random variable \( X \) exceeds some value \( x \) given that it already exceeds a threshold \( u \)
Declustering

- Values can exceed the threshold on consecutive days
- The statistical analysis assumes 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 and consider cluster to be active until 3 consecutive daily averages fall below the threshold

- Identify the maximum excess in each cluster and assume cluster maxima to be independent, with conditional excess given by the GPD

- Fit the GPD to the cluster maxima
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 exceedances then both the probability and quantile plots should be linear.
Return Levels

The return level, $x_N$, which is exceeded on average once every $N$ years can be expressed in terms of the fitted parameters $\sigma$ and $\xi$ as:

$$x_N = u + \left(\frac{\sigma}{\xi}\right)(Nn_d\zeta)^\xi - 1)$$

where $\zeta = n_c/n_{tot}$, the number of cluster maxima divided by the total number of data points and $n_d = \text{is the average number of data points in any given year}$
The probability and quantile plots are both approximately linear showing that the GPD is a good method for modelling the exceedances.
GOES West: Return Level Plot

- One in Ten Year Flux
  - $1.84 \times 10^5$ cm$^{-2}$s$^{-1}$sr$^{-1}$
GOES West: Return Level Plot

- One in Ten Year Flux
  - $1.84 \times 10^5 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$

- One in One Hundred Year Flux
  - $7.68 \times 10^5 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$
GOES West: Return Level Plot

- Largest observed flux is a one in fifty year event
GOES East: Extreme Value Analysis

GOES East $E > 2$ MeV Electrons
Extreme Value Analysis: Points Above $13500 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$

(a) Probability Plot

Model

\[ P[X>x|X>u] \]

Empirical

$r = 0.995$

(b) Quantile Plot

Empirical ($\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$)

Exceedances

Model ($\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$)

$r = 0.980$

- The probability and quantile plots are both approximately linear showing that the GPD is a good method for modelling the exceedances
GOES East: Return Level Plot

- One in Ten Year Flux
  - $6.53 \times 10^4 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$
GOES East: Return Level Plot

- One in Ten Year Flux
  - $6.53 \times 10^4 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$

- One in One Hundred Year Flux
  - $3.25 \times 10^5 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$
GOES East: Return Level Plot

- Largest observed flux is a one in fifty year event
Return Levels for Event with same Frequency as the Carrington Event

• Largest space weather event of the last 200 years is widely regarded to be the Carrington event of 1859

• When ranked by 5 different space weather effects it is the only event to appear at or near the top of each ranking [Clilver and Svalgaard, 2004]

• Historical auroral records suggest the return period of a Carrington type event is 150 years [Lloyds, 2013]

• The return levels for a 150 year event are $9.86 \times 10^5$ and $4.35 \times 10^5$ cm$^{-2}$s$^{-1}$ sr$^{-1}$ at GOES West and GOES East respectively
Comparison with Koons [2001] Study

- Our results are significantly larger than those presented in Koons [2001].

- The 1 in 10 year event at GOES West is about a factor of 2.7 times that estimated by Koons [2001].

- For more extreme events, the 1 in 100 year event at GOES West is about a factor of 7 times that estimated by Koons [2001].
July/August 2004

- Largest $E > 2$ MeV flux of $4.91 \times 10^5$ cm$^{-2}$s$^{-1}$sr$^{-1}$ observed at GOES-West on 29$^{th}$ July 2004

- Coincided with the largest $E > 2$ MeV flux of $1.93 \times 10^5$ cm$^{-2}$s$^{-1}$sr$^{-1}$ at GOES-East

- Independent measurements of this extreme flux event suggests the flux event is real

- GOES-West flux exceeded 10,000 cm$^{-2}$s$^{-1}$sr$^{-1}$ for nine consecutive days from 28$^{th}$ July to 5$^{th}$ August
July/August 2004

• Double Star TC1 and TC2 reported over 30 anomalies during the period from 27 July to 10 August [Han et al., 2005]

• These anomalies largely occurred in the Earth’s radiation belt and were attributed to internal charging [Han et al., 2005]
July/August 2004

- On 3 August, during the extended period of enhanced $E > 2$ MeV electron fluxes, Galaxy 10R lost its secondary xenon ion propulsion system [Choi et al., 2011].

- This reduced its lifetime significantly resulting in an insurance payout of US $75.3$ M.
What Caused the Extreme Event?

- Three consecutive storms
- IMF $B_z$ remained southward for significant periods during recovery phase of each storm
- Average value of AE index around 900 nT for first 10 hours of each recovery phase
- Such high and sustained levels of AE are likely to be associated with:
  - strong and sustained levels of whistler mode chorus
  - elevated seed electrons
  - strong acceleration of electrons to relativistic energies
Conclusions

• The daily average flux of E > 2 MeV electrons measured at GOES West is typically a factor of 2.5 higher than that measured at GOES East

• The 1 in 10, 1 in 50 and 1 in 100 year event at GOES West are $1.84 \times 10^5$, $5.00 \times 10^5$ and $7.68 \times 10^5$ cm$^{-2}$s$^{-1}$sr$^{-1}$ respectively
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• These flux levels can serve as “yardsticks” or “benchmarks” to compare against current or previous space weather conditions
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• These flux levels can serve as “yardsticks” or “benchmarks” to compare against current or previous space weather conditions

• The results can be used to determine the return period of any given event
  • our results suggest that the largest event seen during the study period was a one in fifty year event
Acknowledgements

- The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreements number 606716 (SPACESTORM) and is also supported in part by the UK Natural Environment Research Council.
GOES West: \( E > 2 \) MeV Electrons

Daily Averaged \( E > 2 \) MeV Electron Flux

Sunspot Number

UT (years)
GOES East: $E > 2$ MeV Electrons
Top Ten Flux Events at GOES West

<table>
<thead>
<tr>
<th></th>
<th>Flux (cm(^{-2})s(^{-1})sr(^{-1}))</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.92x10(^5)</td>
<td>29(^{th}) July 2004</td>
</tr>
<tr>
<td>2</td>
<td>3.31x10(^5)</td>
<td>28(^{th}) July 2004</td>
</tr>
<tr>
<td>3</td>
<td>2.31x10(^5)</td>
<td>30(^{th}) July 2004</td>
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<tr>
<td>4</td>
<td>1.96x10(^5)</td>
<td>18(^{th}) May 2005</td>
</tr>
<tr>
<td>5</td>
<td>1.36x10(^5)</td>
<td>17(^{th}) May 2005</td>
</tr>
<tr>
<td>6</td>
<td>1.29x10(^5)</td>
<td>17(^{th}) September 2005</td>
</tr>
<tr>
<td>7</td>
<td>1.25x10(^5)</td>
<td>18(^{th}) September 2005</td>
</tr>
<tr>
<td>8</td>
<td>1.14x10(^5)</td>
<td>19(^{th}) September 2005</td>
</tr>
<tr>
<td>9</td>
<td>1.11x10(^5)</td>
<td>19(^{th}) May 2005</td>
</tr>
<tr>
<td>10</td>
<td>1.11x10(^5)</td>
<td>17(^{th}) April 2006</td>
</tr>
</tbody>
</table>
## Top Ten Flux Events at GOES East

<table>
<thead>
<tr>
<th></th>
<th>Flux (cm$^{-2}$s$^{-1}$sr$^{-1}$)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.93x10$^5$</td>
<td>29$^{th}$ July 2004</td>
</tr>
<tr>
<td>2</td>
<td>1.18x10$^5$</td>
<td>30$^{th}$ July 2004</td>
</tr>
<tr>
<td>3</td>
<td>5.24x10$^4$</td>
<td>19$^{th}$ September 2005</td>
</tr>
<tr>
<td>4</td>
<td>4.93x10$^4$</td>
<td>18$^{th}$ September 2005</td>
</tr>
<tr>
<td>5</td>
<td>4.83x10$^4$</td>
<td>31$^{st}$ July 2004</td>
</tr>
<tr>
<td>6</td>
<td>4.67x10$^4$</td>
<td>19$^{th}$ May 2005</td>
</tr>
<tr>
<td>7</td>
<td>4.43x10$^4$</td>
<td>17$^{th}$ April 2006</td>
</tr>
<tr>
<td>8</td>
<td>4.37x10$^4$</td>
<td>18$^{th}$ May 2005</td>
</tr>
<tr>
<td>9</td>
<td>3.89x10$^4$</td>
<td>20$^{th}$ September 2005</td>
</tr>
<tr>
<td>10</td>
<td>3.79x10$^4$</td>
<td>21$^{st}$ September 2005</td>
</tr>
</tbody>
</table>
Appendix 1 - Exclusions

• The E > 2 MeV electron data may be contaminated during solar proton events

• We adopt the NOAA SWPC definition of a solar proton event and exclude the electron data whenever the flux of E > 10 MeV protons is greater than 10 cm$^{-2}$s$^{-1}$sr$^{-1}$

• Calculate daily average when > 90% of the day has good quality data in the absence of contamination from solar protons
Appendix 1 - Exclusions

• We also exclude

  • data from GOES 10 in February 2010 during a period of anomalously low fluxes attributed to count rates that had not been properly converted to fluxes [Su et al., 2014]

  • data from GOES 12 collected in September 2003 due to a 1.5 day offset between the 5 minute and 1 minute averages

  • data from GOES 12 after 28 November 2008 due to partial failure of the dome detector
Appendix 2 - Look Direction

- The single set of electron sensors on each of GOES 8-12 look westward with the exception of those on GOES 10 which looked eastward.

- There are two sets of electron sensors on GOES-13 and GOES 15. One set looks eastward and the other looks westward.

- In orbit GOES 13 is upright and we select data from the westward facing telescope.

- GOES 15 undergoes a yaw flip twice a year at the equinoxes which means the eastward looking telescope then looks westward and vice versa.
  - The manoeuvre lasts approximately half an hour and is discounted from the analysis.
  - We select the data from the appropriate westward facing channel for our analysis.
Appendix 3 - Missing Satellite Location

• The geographic longitude of the satellite is occasionally missing in the archived files when the data are of good quality.

• We inspected the data and found 20 intervals of missing geographic longitudes.

• With the exception of one missing interval the satellite was parked at a particular location.

• For the other missing interval, which lasted one day, GOES 15 was in the process of moving from 90 W to 135 W at about 1 degree a day.

• To obtain the satellite longitude during the missing intervals we linearly interpolate between the recorded longitudes before and after the missing intervals.
Appendix 4 - Yaw Flips

- GOES 15 undergoes a yaw flip twice a year at the equinoxes.
- The manoeuvre lasts approximately half an hour.
- Dates of yaw flips:
  - September 22, 2011 c. 1800 0 (upright)
  - March 20, 2012 c. 2100 1 (inverted)
  - September 20, 2012 c. 2100 0 (upright)
  - March 20, 2013 c. 2100 1 (inverted)
  - September 23, 2013 c. 2100 0 (upright)
  - March 20, 2014 c. 2100 1 (inverted)
- The EPEAD telemetry channels labeled ‘E’ look westward when the spacecraft is upright (yaw flip flag = 0) and eastward when the spacecraft is inverted (yaw flip flag = 1).
- The EPEAD telemetry channels labeled ‘W’ look eastward when the spacecraft is upright (yaw flip flag = 0) and westward when the spacecraft is inverted (yaw flip flag = 1).
## Appendix 5 – Sensitivity to Threshold Selection

### GOES West

<table>
<thead>
<tr>
<th>Event Interval</th>
<th>20000 cm$^{-2}$s$^{-1}$sr$^{-1}$ (cm$^{-2}$s$^{-1}$sr$^{-1}$)</th>
<th>30000 cm$^{-2}$s$^{-1}$sr$^{-1}$ (cm$^{-2}$s$^{-1}$sr$^{-1}$)</th>
<th>40000 cm$^{-2}$s$^{-1}$sr$^{-1}$ (cm$^{-2}$s$^{-1}$sr$^{-1}$)</th>
<th>50000 cm$^{-2}$s$^{-1}$sr$^{-1}$ (cm$^{-2}$s$^{-1}$sr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 in 10 year</td>
<td>1.64x10$^5$</td>
<td>1.88x10$^5$</td>
<td>1.84x10$^5$</td>
<td>1.84x10$^4$</td>
</tr>
<tr>
<td>1 in 50 year</td>
<td>3.75x10$^5$</td>
<td>6.26x10$^5$</td>
<td>5.00x10$^5$</td>
<td>5.01x10$^5$</td>
</tr>
<tr>
<td>1 in 100 year</td>
<td>5.33x10$^5$</td>
<td>1.06x10$^6$</td>
<td>7.68x10$^5$</td>
<td>7.67x10$^5$</td>
</tr>
</tbody>
</table>

### GOES East

<table>
<thead>
<tr>
<th>Event Interval</th>
<th>6750 cm$^{-2}$s$^{-1}$sr$^{-1}$ (cm$^{-2}$s$^{-1}$sr$^{-1}$)</th>
<th>10125 cm$^{-2}$s$^{-1}$sr$^{-1}$ (cm$^{-2}$s$^{-1}$sr$^{-1}$)</th>
<th>13500 cm$^{-2}$s$^{-1}$sr$^{-1}$ (cm$^{-2}$s$^{-1}$sr$^{-1}$)</th>
<th>16875 cm$^{-2}$s$^{-1}$sr$^{-1}$ (cm$^{-2}$s$^{-1}$sr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 in 10 year</td>
<td>5.85x10$^4$</td>
<td>6.77x10$^4$</td>
<td>6.53x10$^4$</td>
<td>6.45x10$^4$</td>
</tr>
<tr>
<td>1 in 50 year</td>
<td>1.23x10$^5$</td>
<td>1.94x10$^5$</td>
<td>1.98x10$^5$</td>
<td>1.66x10$^4$</td>
</tr>
<tr>
<td>1 in 100 year</td>
<td>1.67x10$^5$</td>
<td>3.09x10$^4$</td>
<td>3.25x10$^5$</td>
<td>2.49x10$^5$</td>
</tr>
</tbody>
</table>
Appendix 6 - Choice of Threshold at GOES West

- We want to fit to the GPD to the extreme values of the distribution
- Need enough points for a meaningful fit
- Quantile plot should be approximately linear
- For GOES West we set the threshold $4.0 \times 10^4 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$
Appendix 6 - Choice of Threshold at GOES East

- For GOES East we set the threshold at $1.35 \times 10^4$ cm$^{-2}$s$^{-1}$sr$^{-1}$
Appendix 7 - Is the Distribution Bounded?

• The shape parameter controls the behaviour of the tail
  if $\xi < 0$ the distribution has an upper limit
  if $\xi > 0$ the distribution has no upper limit

• The shape parameters for the fits at GOES West and GOES East are $0.61\pm0.44$ and $0.73\pm0.33$

• Our results suggest that there is no upper limit to the flux of $E > 2$ MeV electrons at geosynchronous orbit
Appendix 7 - Is the Distribution Bounded?

- Early work by Koons [2001] and O’Brien et al. [2007] suggests that the flux of $E > 2$ MeV electrons tends to a limiting value.

- We repeated our analysis using log fluxes as done by Koons [2001] and O’Brien et al. [2007].

- The new shape parameters became $0.019 \pm 0.28$ and $0.16 \pm 0.23$.

- The shape parameters for both log fits include negative values within their error bars suggesting that we treat the conclusion that the fluxes have no upper bound with caution.
Appendix 7 - Is the Distribution Bounded?

• The studies demonstrate the difficulty of determining the presence or absence of an upper bound from only 10-20 years data

• A definitive answer probably requires data covering many more decades

• In reality there is likely to be an upper bound set by some physical process but this is not evident from the statistical analysis here