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Forecasting the Earth's Radiation Belts for Satellites Undergoing Electric-Orbit Raising

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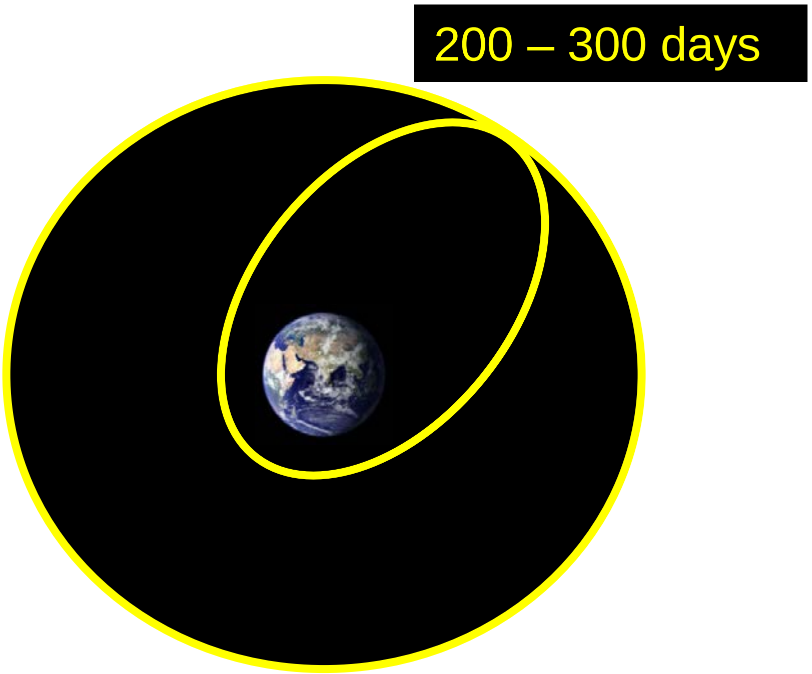
Outline

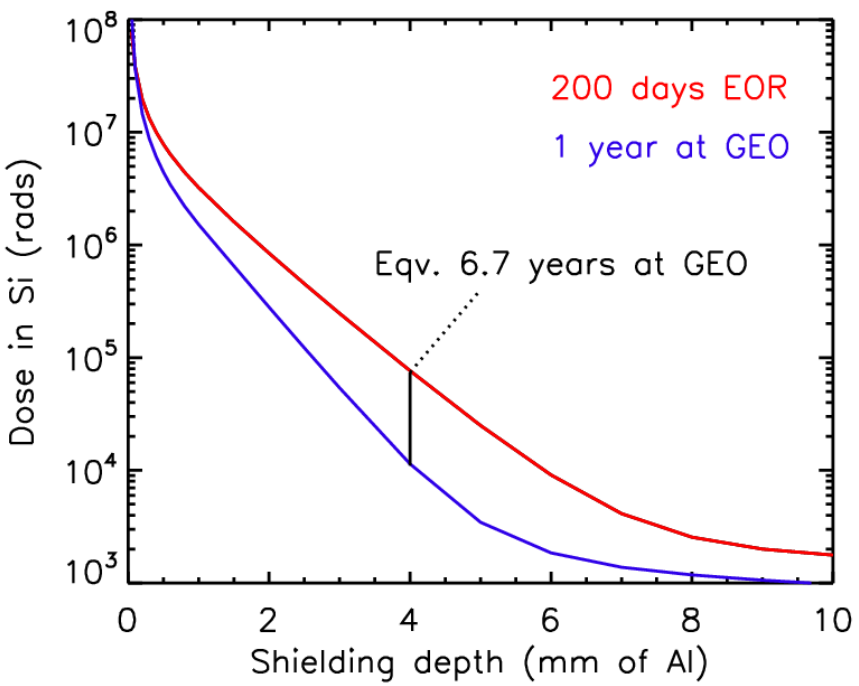
- Electric orbit raising
- Variability of the radiation belts
- Physical model for forecasting
- The system and examples

Key New Driver

- Boeing: All-electric satellite propulsion for commercial satellites
- Half the cost of launch to ~ US$ 60m
- But takes 200-300 days to reach geostationary orbit
- Radiation protection for Medium Earth Orbit?



Horne and Pitchford [2015]



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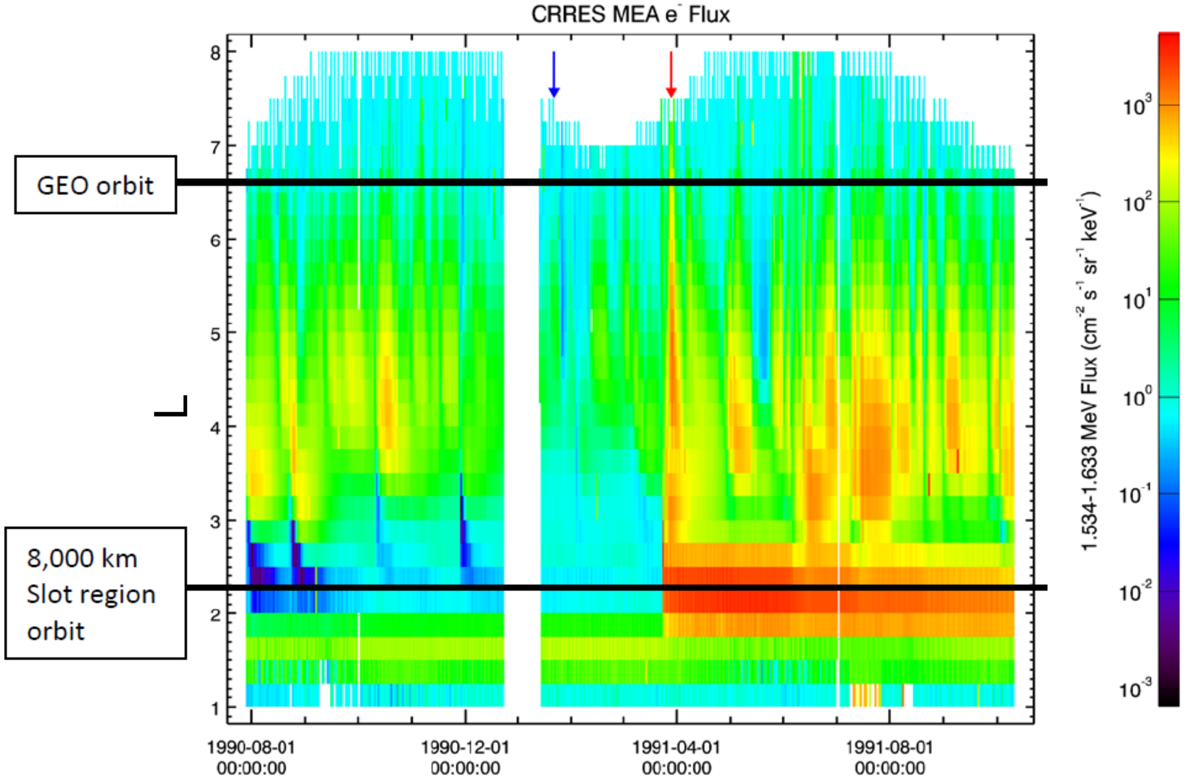
Medium Earth Orbit – Highly Variable

- Risk of internal charging, surface charging, solar array degradation, ionising dose
- GPS/Galileo, Electric orbit raising, slot region orbits
- Growth area - need for Space Situation Awareness



Horne and Pitchford [2015]

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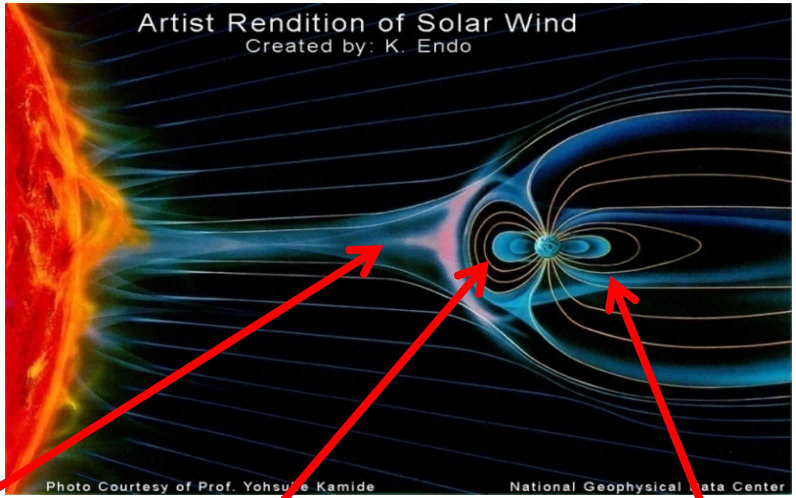
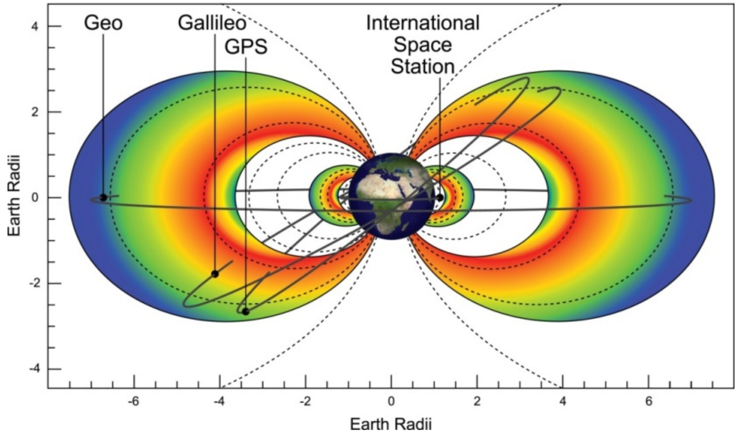
Space Weather - Forecasting Concept

- It takes ~ 40-60 minutes for the solar wind to flow from the ACE satellite to the Earth
- Access ACE satellite data in real time and use it to drive our forecasting models
- Focus on internal satellite charging
- 100 keV – 10 MeV electrons



ACE satellite

Satellite orbits and the van Allen radiation belts



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British Antarctic Survey Radiation Belt Model BAS-RBM

- BAS-RBM solves the Fokker-Planck equation for phase-space density (f) in pitch-angle (α), energy (E) and L* (L) coordinates

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

Radial transport | Pitch angle diffusion | Energy diffusion | Losses

- Drift & bounce averaged diffusion coefficients D_{LL}, $D_{\alpha\alpha}$, D_{EE} are activity, location and energy dependent

- Details in: Glauert et al. [2014]

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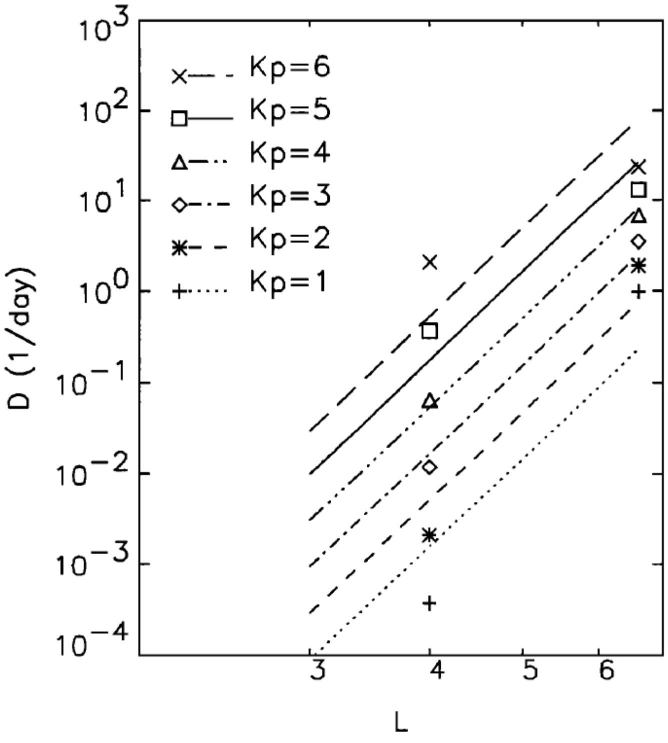
Models and Assumptions

- We use a Physical model – as in Meteorological Forecasting

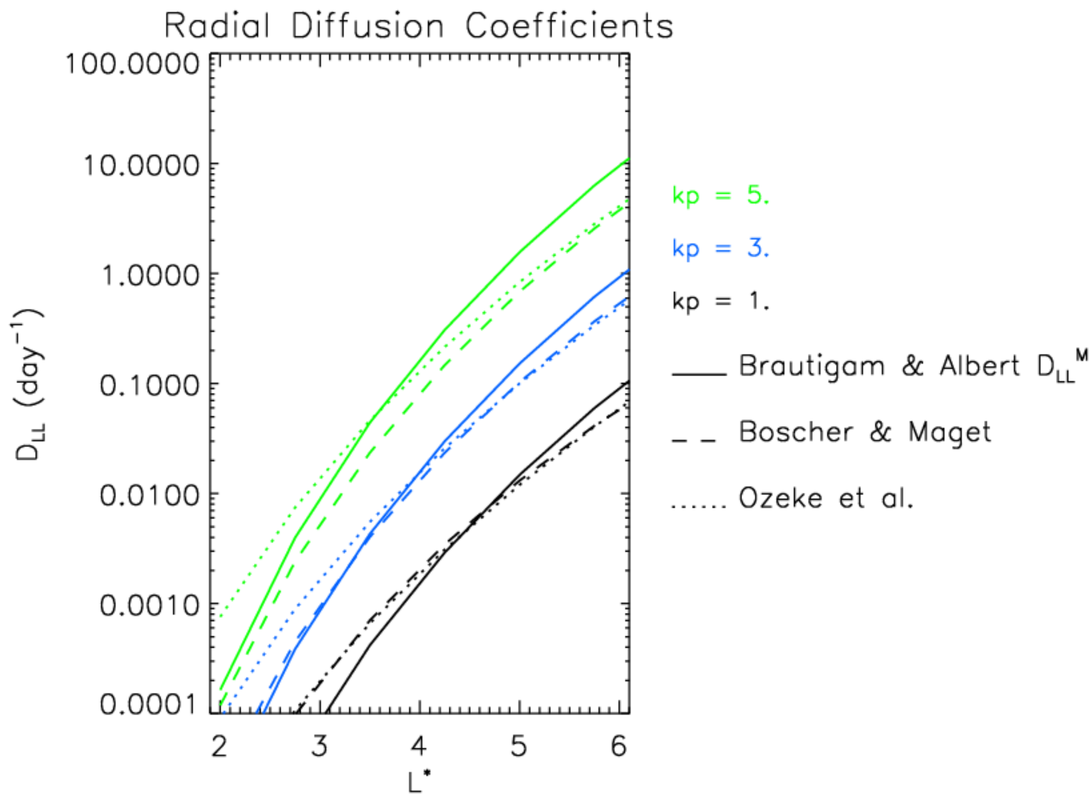
- Sub models
  - Magnetic field model
  - Atmospheric collision model
  - Radial diffusion model
  - Magnetopause model
  - Plasma density model
  - Wave models – Wave-particle interactions
    - Chorus waves
    - Hiss waves
    - Lightning generated whistlers
    - EMIC waves

Radial Diffusion Coefficients D_{LL}

Brautigam and Albert [2000] ~L^{10}



B&A, Ozeke et al.,



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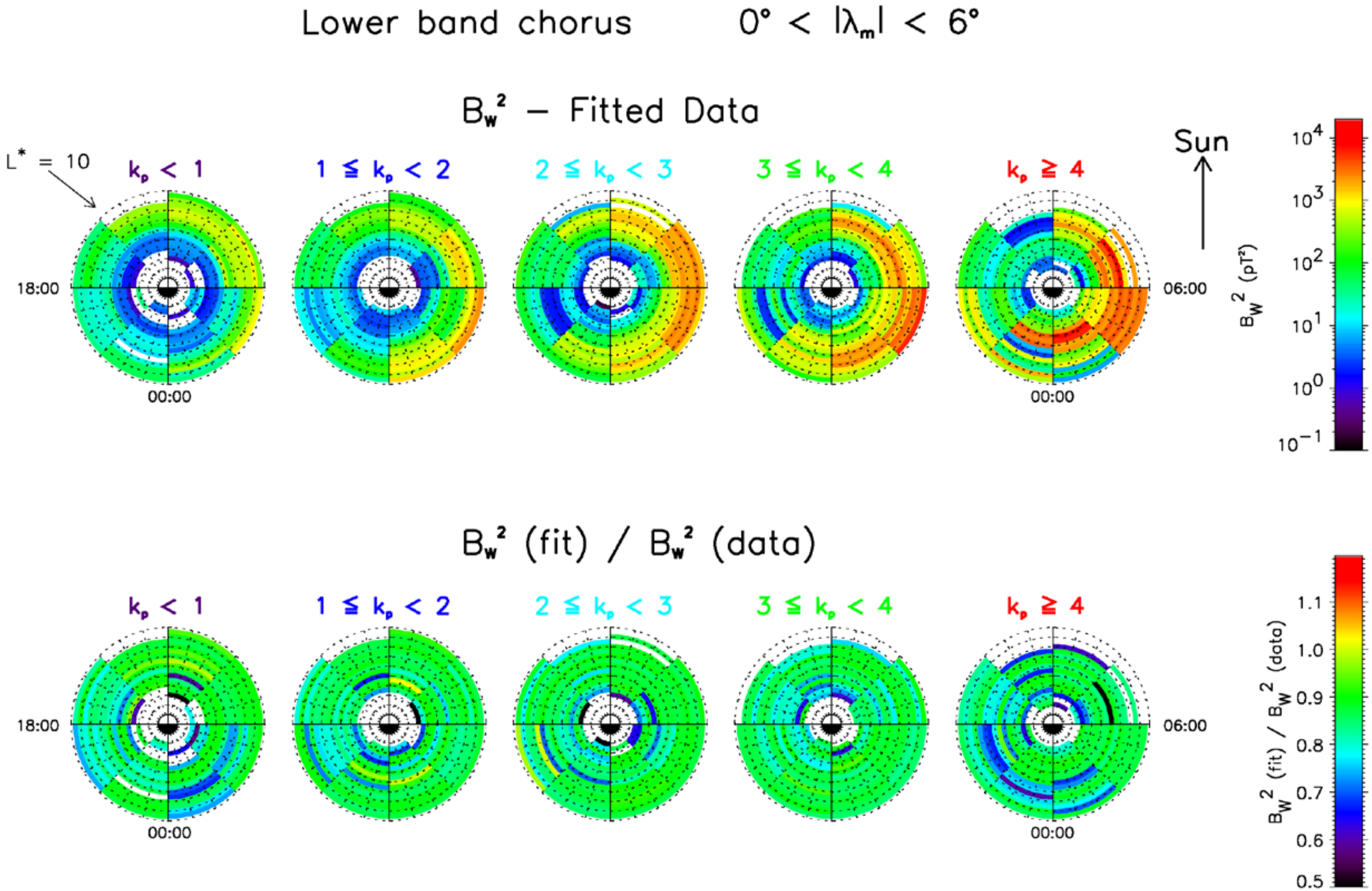
Chorus Wave Data – From 7 Satellites



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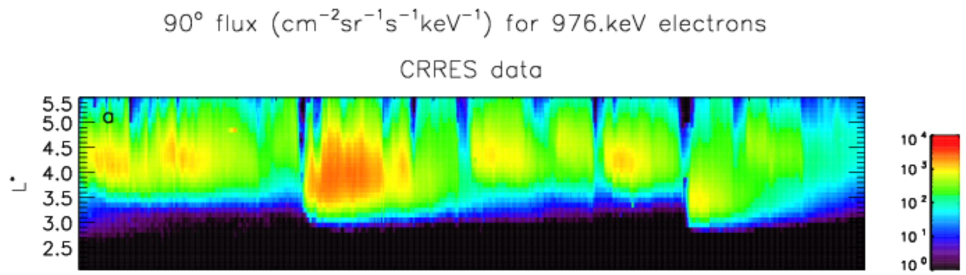
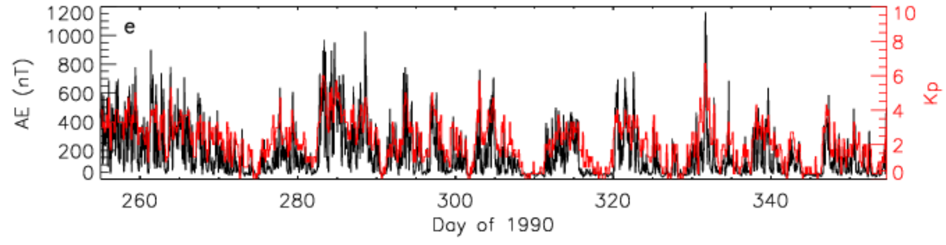
Importance of Wave-Particle Interactions

Satellite data - Electrons





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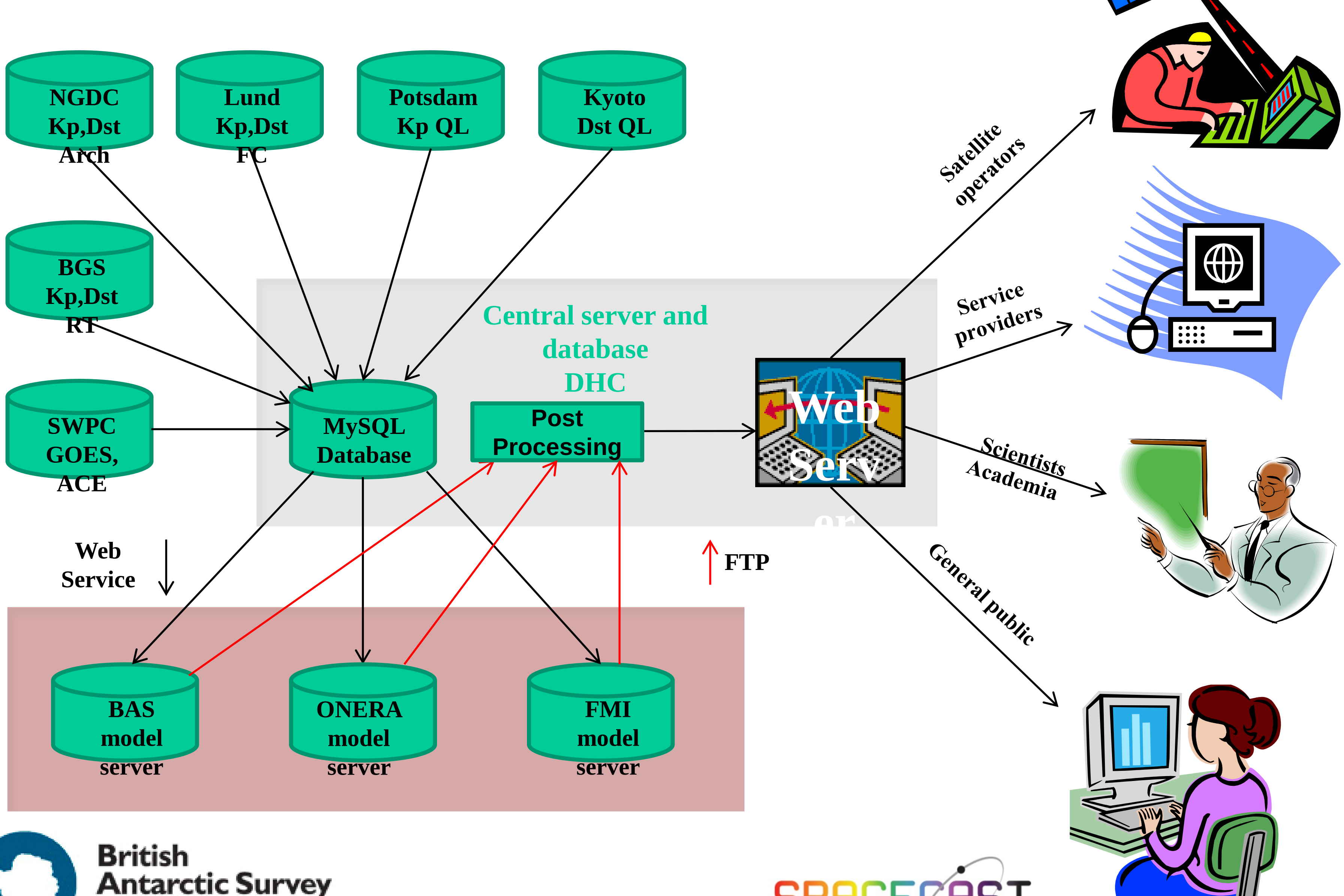
Achievements - SPACECAST Forecasting System



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Boundary and Initial Conditions (Forecasting)

- Initial conditions
  - Steady state that matches GOES >800 keV electron flux

- Boundary conditions
  - Outer boundary – L* = 8, J(E) depends on Kp (CRRES)
    - If last closed drift shell < 8, J = 0 with loss timescale
  - Inner boundary – L* = 2, J(E) depends on Kp (CRRES)
  - Low energy – J depends on Kp (CRRES)
  - High energy – J = 0
  - Small pitch angles – set df/dα = 0
  - Large pitch angles – set df/dα = 0

- All boundary conditions depend on Kp – need a forecast of Kp

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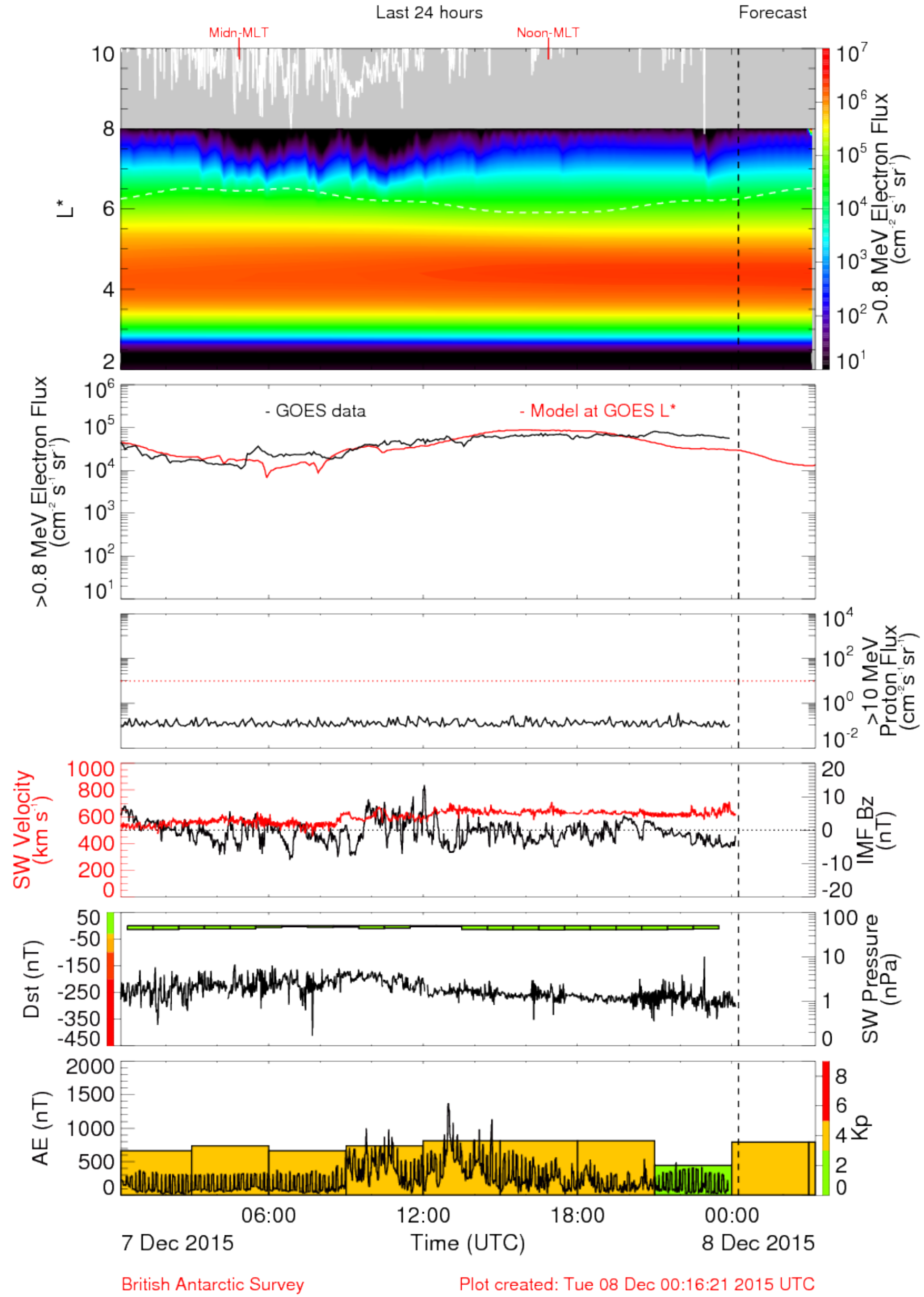
Space Weather

- Forecast the radiation belt electron flux >800 keV
- Including wave-particle interactions give better forecasts and situation awareness [Horne et al., 2013]
- Risk of satellite internal charging
- www.spaceweather.ac.uk



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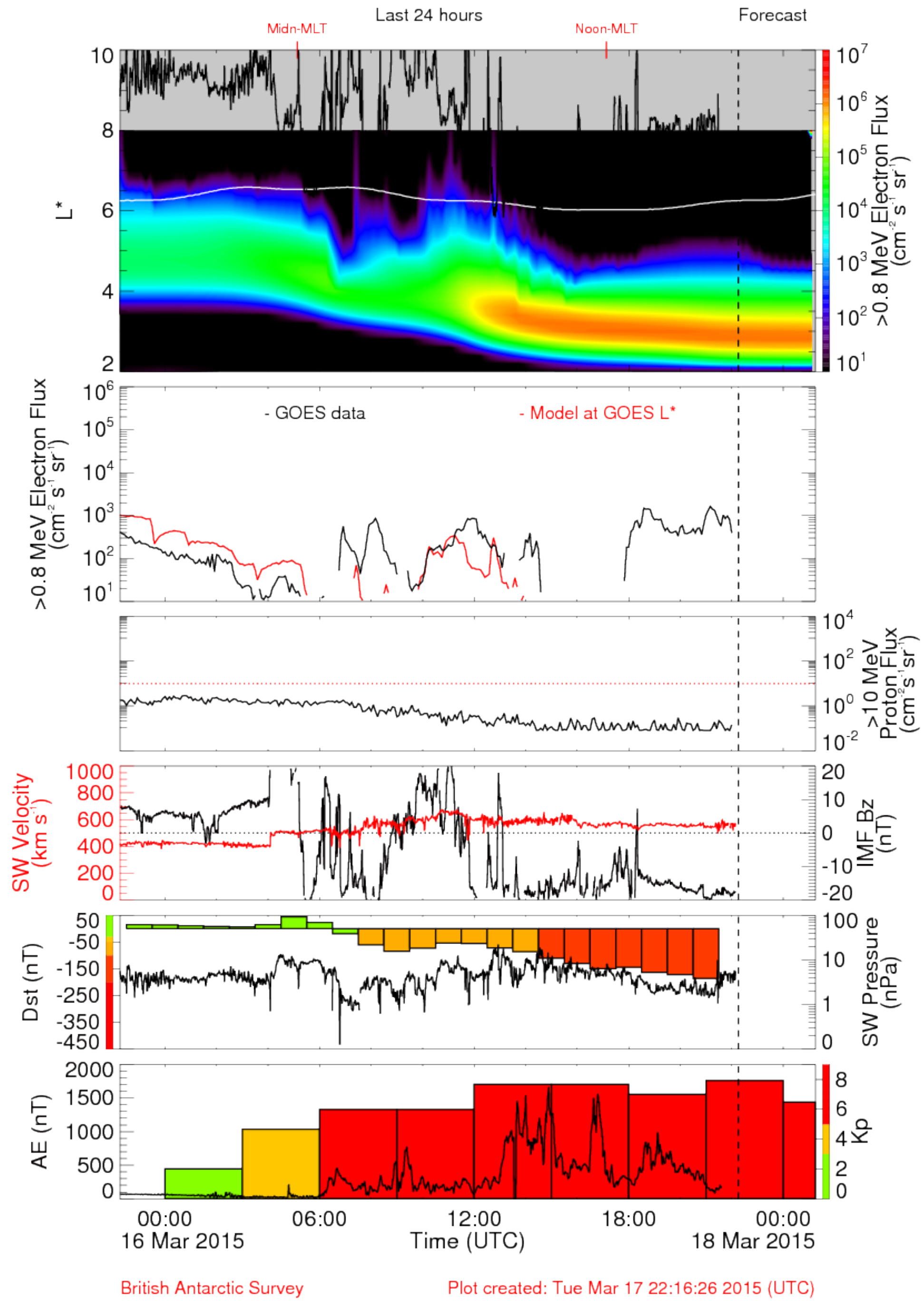
Storm Event

- Magnetopause inside GEO
- Electron loss by outward Radial diffusion and precipitation
- Risk of satellite internal charging in Medium Earth Orbit – not GEO
- Losses too high in latter part of event – work to do
- www.spaceweather.ac.uk



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Summary

- Medium Earth Orbit (MEO) is becoming more important
  - Electric orbit raising, GPS/Galileo, Slot region orbits

- Need for better space situation awareness and forecasting

- SPACESTORM project uses physical models to forecast the whole outer radiation belt – updated every hour (www.fp7-spacecast.eu and www.spaceweather.ac.uk)

- Including wave-particle interactions enables better Space Weather forecasting and situation awareness

- Need for more model development and testing against research data

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Acknowledgements

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