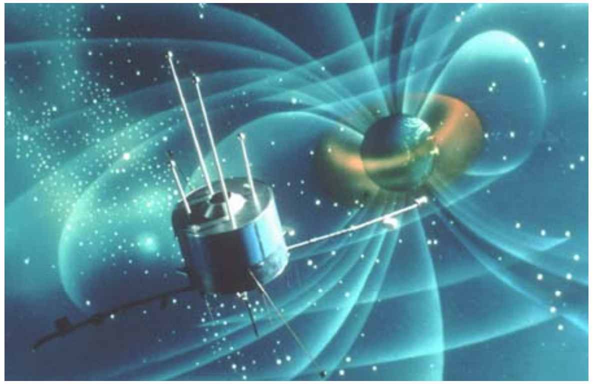
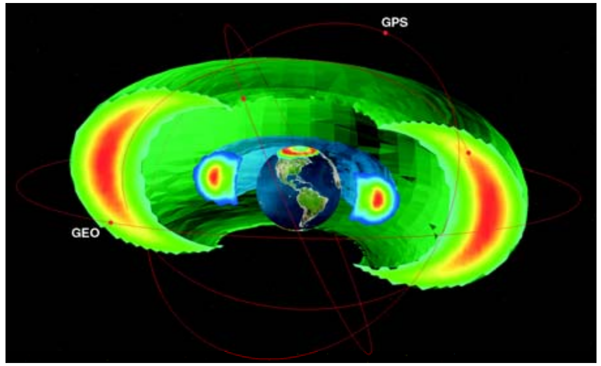
The BAS Radiation Belt Model



Sarah Glauert

Richard Horne

Nigel Meredith



British Antarctic Survey, Cambridge, UK

SPACECAST

SPACESTORM

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Met Office, January 16th 2015

Outline

- How & why the forecasts were developed
- Physical processes in the radiation belts
- The BAS Radiation Belt Model
- The forecasting system
- Forecasts
- Future developments

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Context

- Richard had a key role in showing the importance of wave particle interactions
  - PADIE code quantifies the effect of the interactions
  - BAS Radiation Belt Model (BAS-RBM) developed as research tool
- SPACECAST – EU FP7 project
  - Adapt BAS-RBM for forecasting
  - Aimed to get system up and running, then improve forecasts
  - Forecast whole radiation belt, 3 hours ahead, updated every hour
  - Finished February 2014
- SPACESTORM began April 2014
  - Focus on extreme events
  - Forecasting will continue
  - Improvements from SPACESTORM will be incorporated into forecasting

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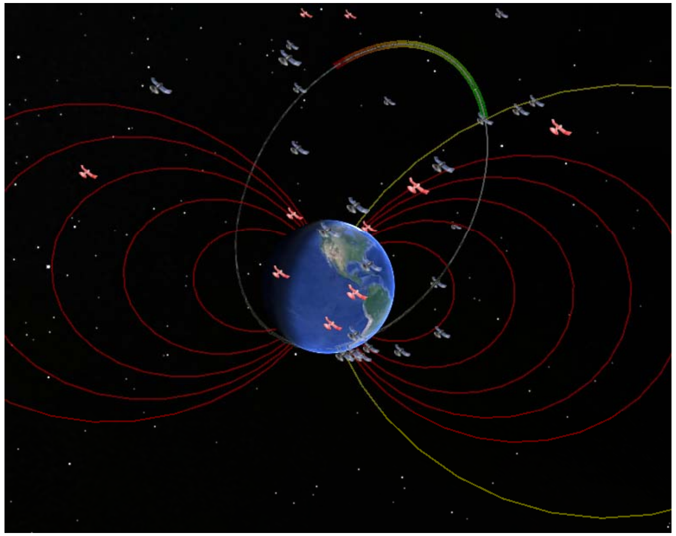
BAS Space Weather database and forecasts

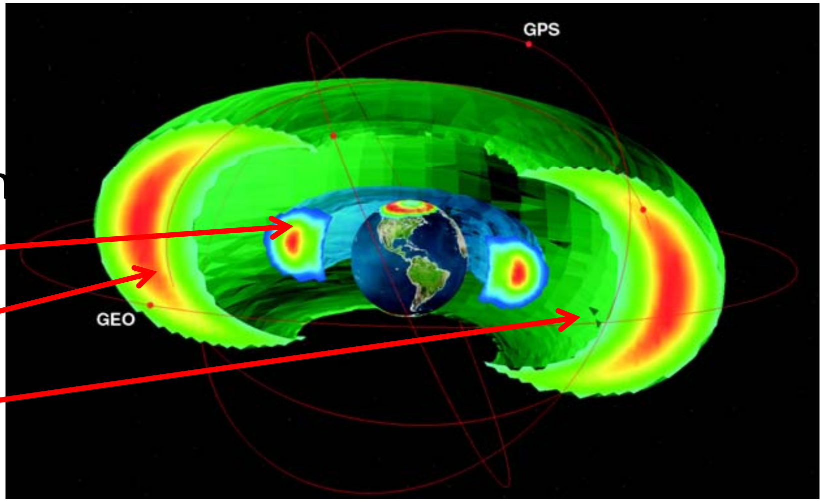
- Developed our own Space Weather database and website
- Independent from SPACECAST
- Forecasts use BAS-RBM
- Can tailor output for users
  - Orbit and/or energy



Space Weather
The satellite forecast

Electron Radiation Belts

- High energy electrons (E>500 keV) are trapped by Earth's magnetic field



- Form two torus shaped regions around earth
  - Inner belt 1.2 < L < 2 Fairly stable
  - Outer belt   3 < L < 7 Highly dynamic
  - Slot region lies between the two belts

- Electron flux in the outer belt is extremely variable
  - Can change by several orders of magnitude in hours
  - Real challenge for forecasting

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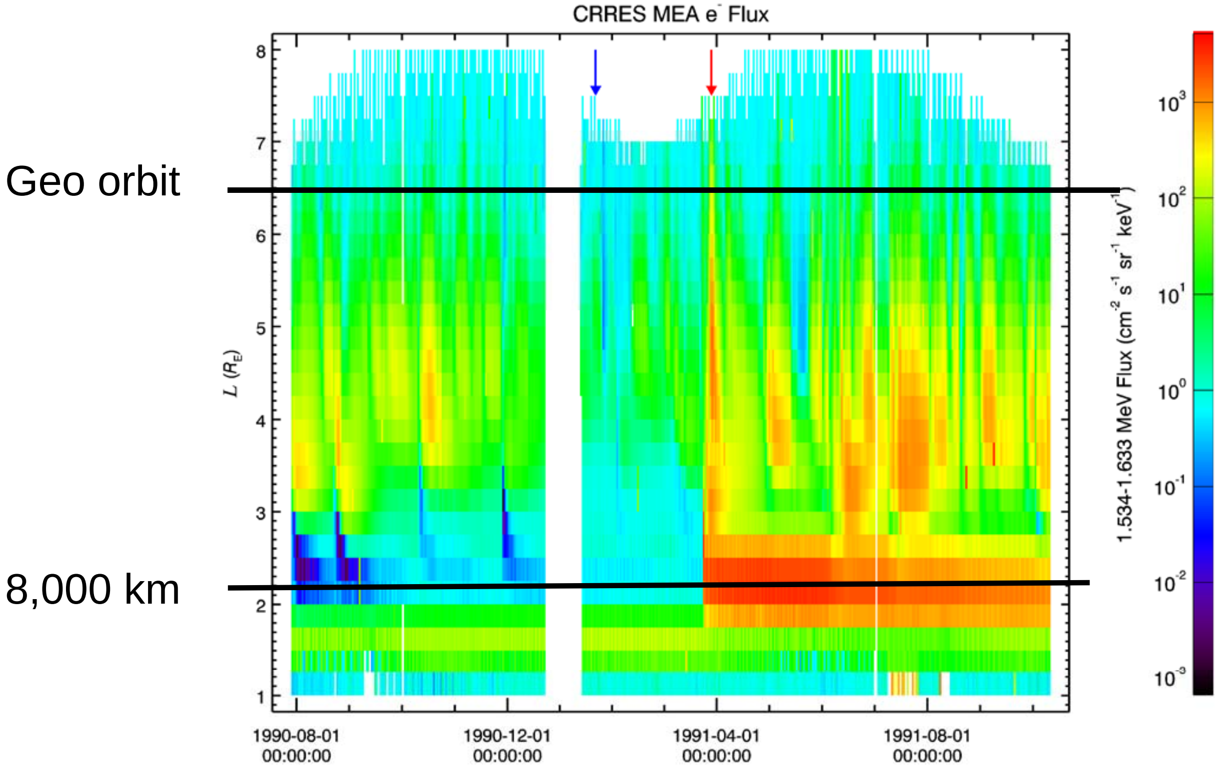
Slot Region

1.5 MeV electron flux from CRRES



- Much higher charging environment after March 1991
- O3B satellites will be at 8000 km.

- Heyndrickx [2014]

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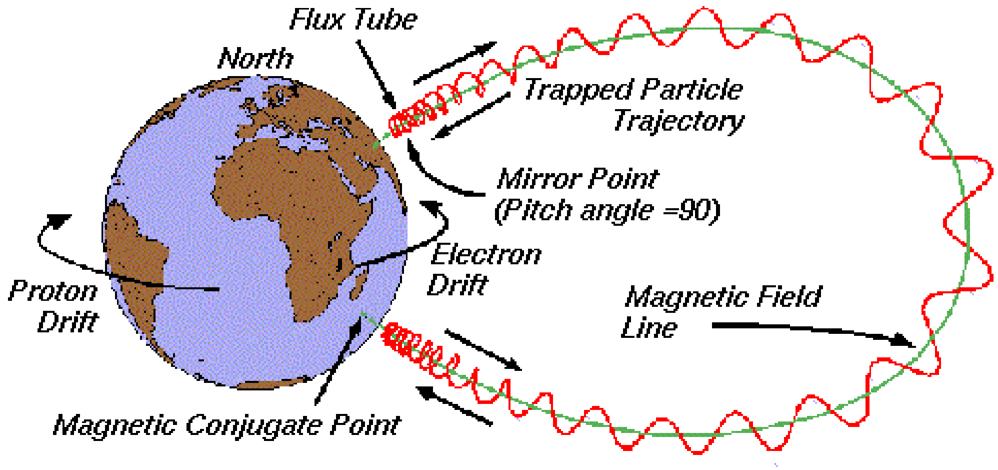
Motion of trapped electrons

An electron’s motion is constrained by the magnetic field

3 parts:

- Orbiting round the field line
- Bouncing along the field line
- Drifting between field lines



Modelling uses a coordinate system related to magnetic field:

- Pitch-angle, α - Angle between the particle’s velocity and the magnetic field
  Determines how far along the field line the particle travels
- L shell - Distance from the centre of the Earth to the equatorial crossing of the field line measured in Earth radii
- L* - Similar to L shell but takes non-dipole field into account

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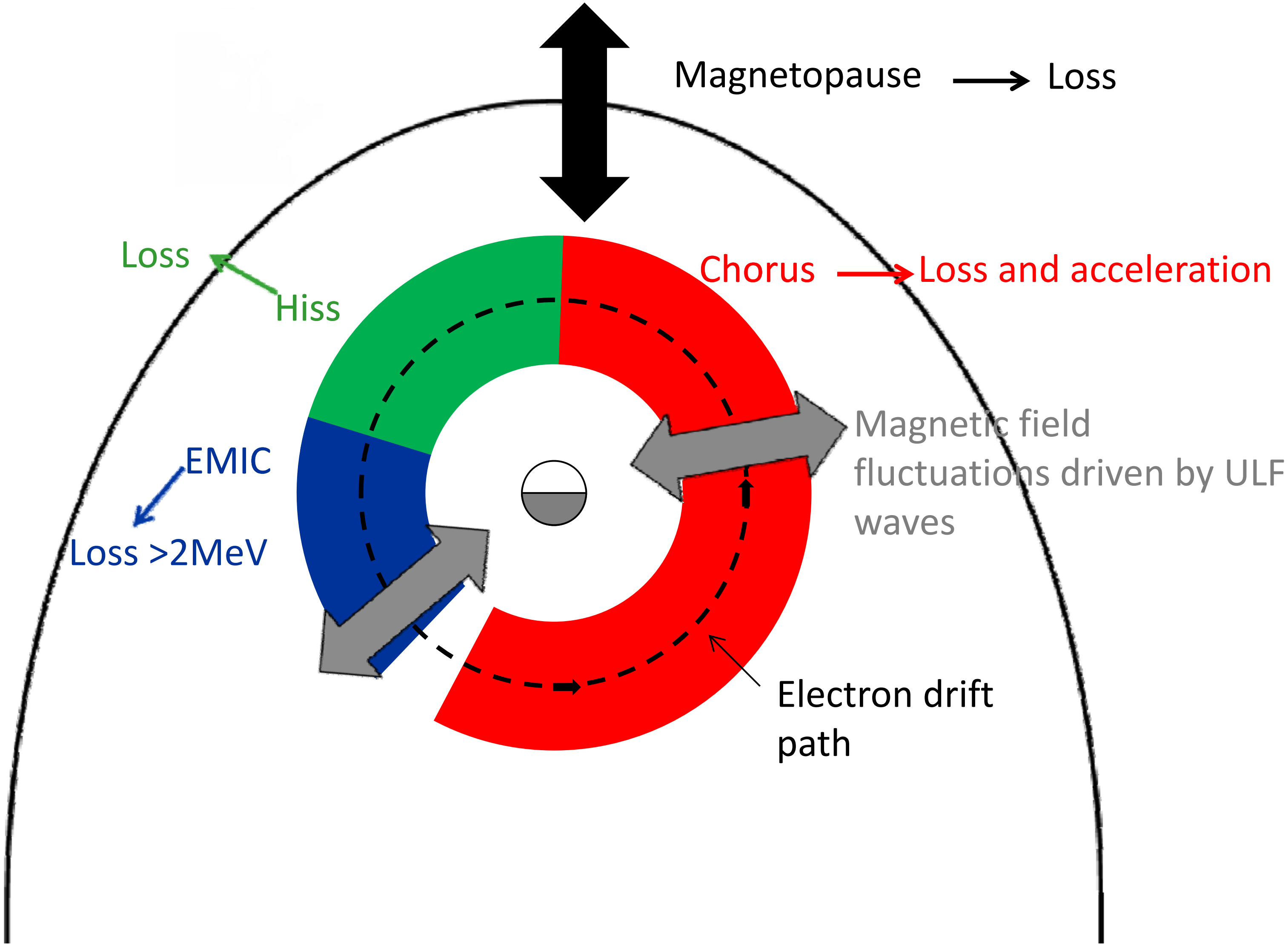
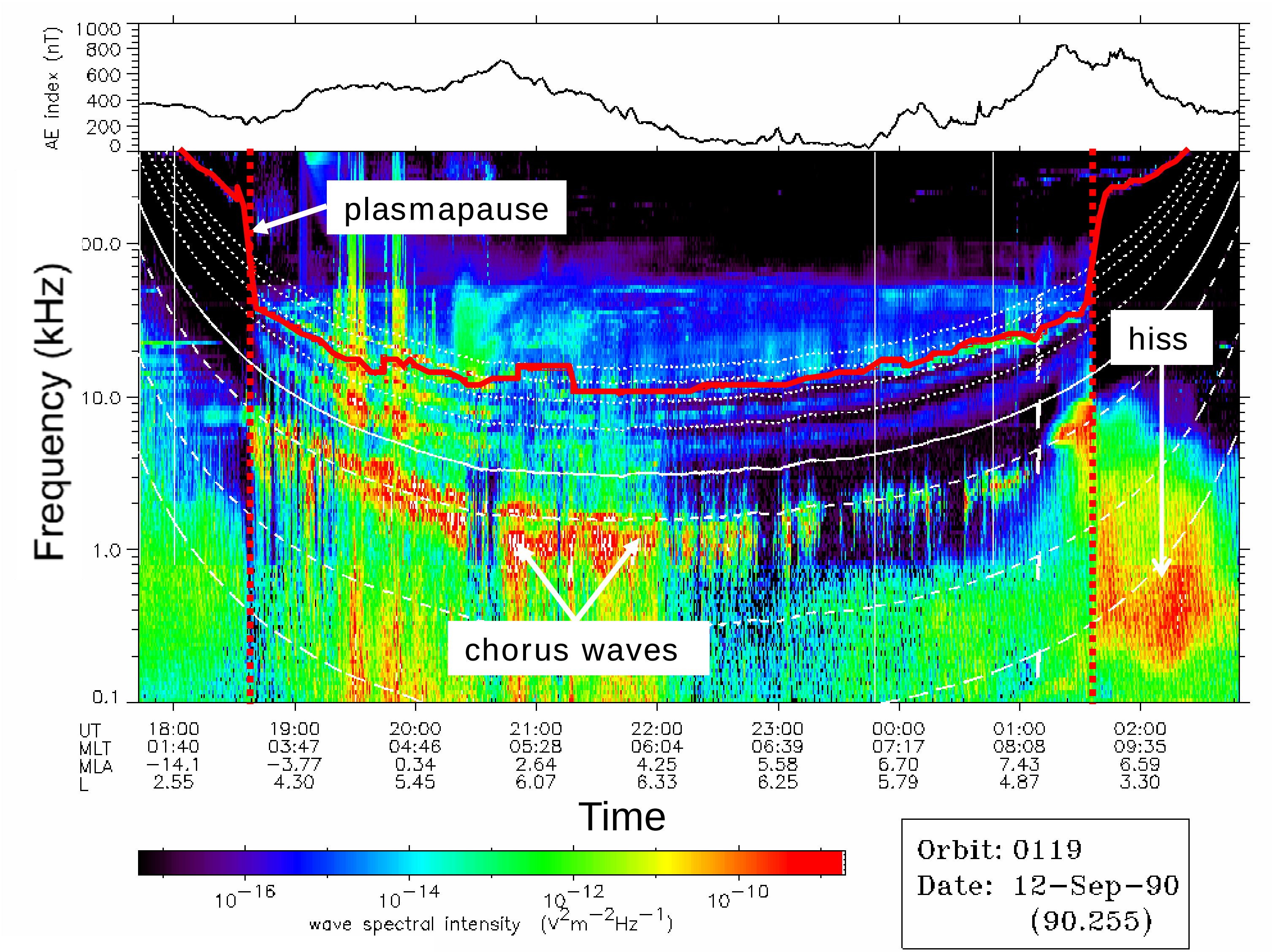
A few minutes in the life of an MeV electron



Everything is location, activity and energy dependent
Other processes too...

Chorus and Hiss



- Chorus - outside the plasmapause
- Hiss - inside the plasmapause

Electromagnetic Ion Cyclotron Waves

- Low frequency waves (0.1-5 Hz)
- Excited in bands below the proton gyrofrequency
- Mainly seen between the proton and helium gyro-frequencies and between the helium and oxygen gyrofreqencies
- Resonate with >2MeV electrons

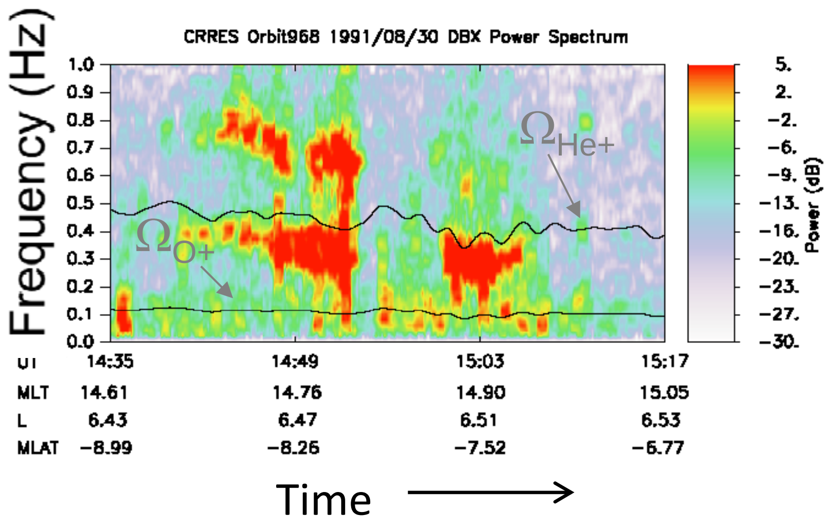


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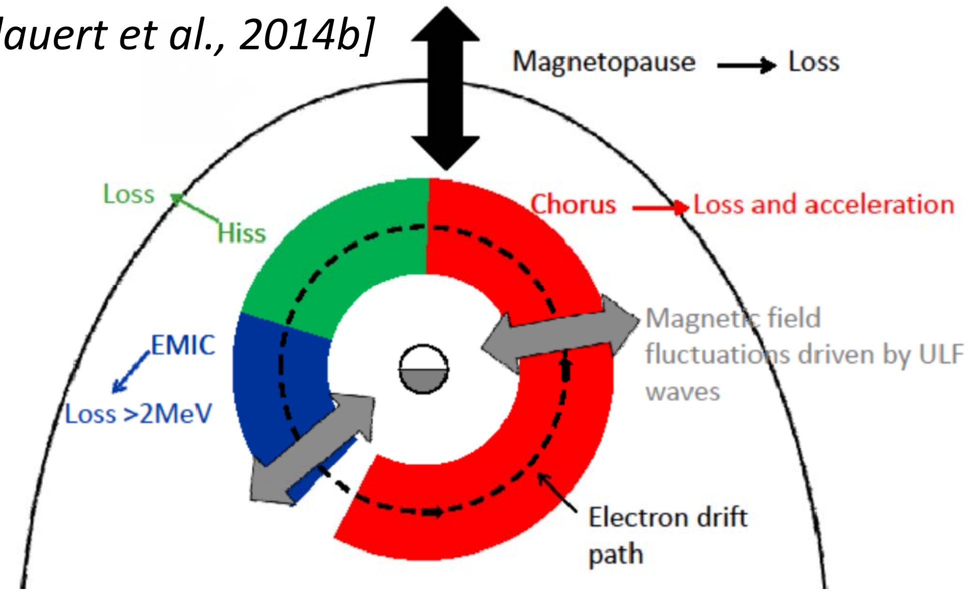
Figure courtesy of Brian Fraser

Physical processes in the BAS-RBM

- Radial transport *[Brautigam & Albert, JGR, 2000]*
- Upper & lower band whistler mode chorus waves *[Horne et al., 2013]*
- Plasmaspheric hiss & lightning-generated whistlers *[Glauert et al., 2014a]*
- EMIC waves *[Kersten et al., 2014]*
- Plasmapause *[O'Brian and Moldwin, 2003]*
- Collisions with atmosphere *[Abel & Thorne, 1998]*
- Losses to the magnetopause *[Glauert et al., 2014b]*



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BAS Radiation Belt Model

Change latitude range of the bounce

Fokker-Planck equation for phase-space density (f)

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right)\Bigg|_{\mu J} + \frac{1}{g(\alpha)}\frac{\partial}{\partial \alpha}\left(g(\alpha) D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\right)\Bigg|_{EL}$$

Losses

Radial transport

$$+\frac{1}{A(E)}\frac{\partial}{\partial E}\left(A(E) D_{EE}\frac{\partial f}{\partial E}\right)\Bigg|_{\alpha L} - \frac{f}{\tau(\alpha, E, L)}$$

α - equatorial pitch-angle

E - energy

L - L*

Acceleration

$$g(\alpha) = \sin\alpha\cos\alpha(1.30 - 0.56\sin\alpha)$$

$$A(E) = (E + E_0)(E + 2E_0)^{\frac{1}{2}} E^{\frac{1}{2}}$$

- Each type of VLF wave can contribute to $D_{\alpha\alpha}$ and D_{EE}
- Diffusion coefficients depend on activity (Kp or AE), location and energy
- Modelling depends on calculating the correct diffusion coefficients

Diffusion models

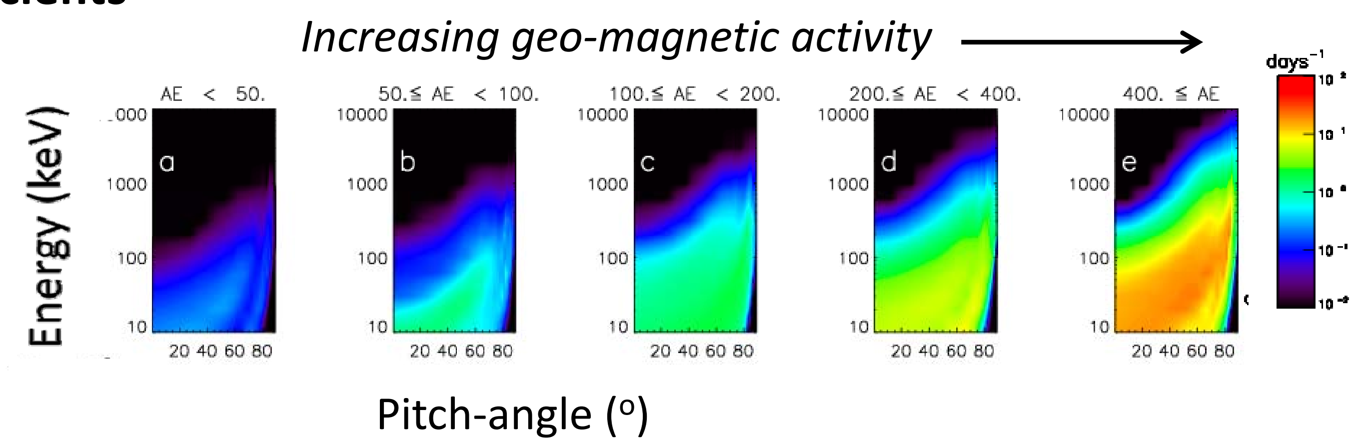
- The diffusion coefficients are key to modelling
- Use satellite observations to get data on the different waves
  - Variation with L*, MLT, latitude and geomagnetic activity
- Calculate diffusion coefficients with PADIE code *[Glauert and Horne, 2005]*
- Include chorus, hiss, lightning-generated whistlers and EMIC waves

Chorus diffusion coefficients

Pitch-angle diffusion

$D_{\alpha\alpha}$(days^{-1})

L* = 5



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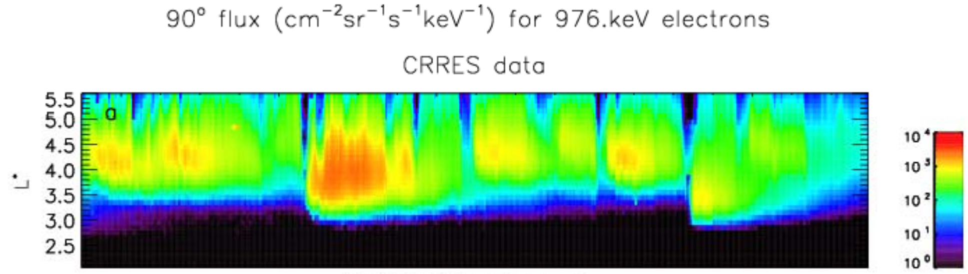
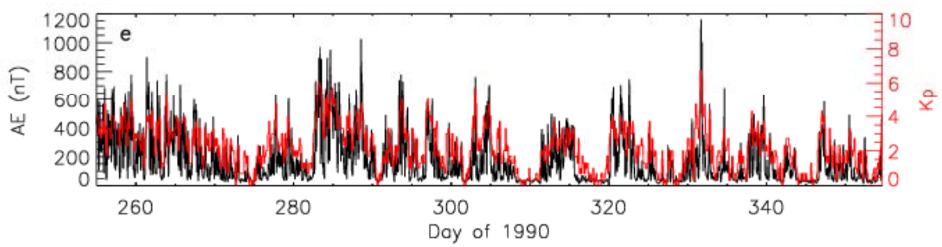
Role of radial diffusion, hiss and chorus

CRRES data





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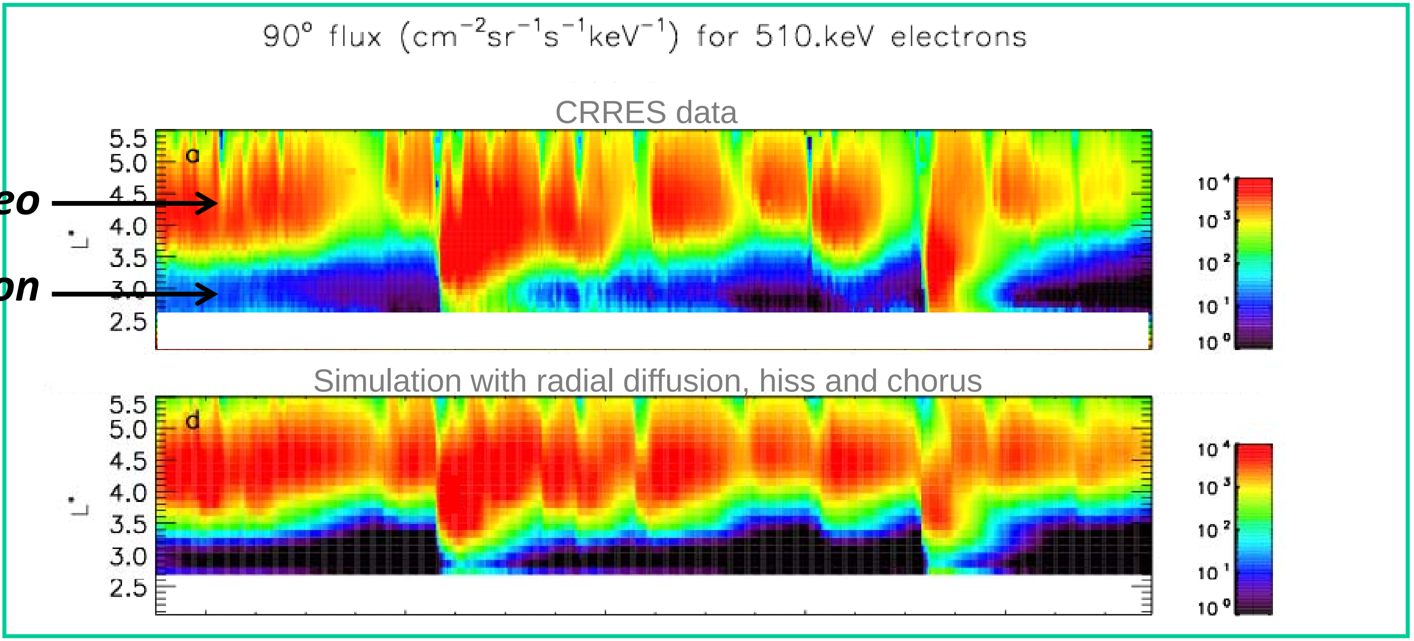
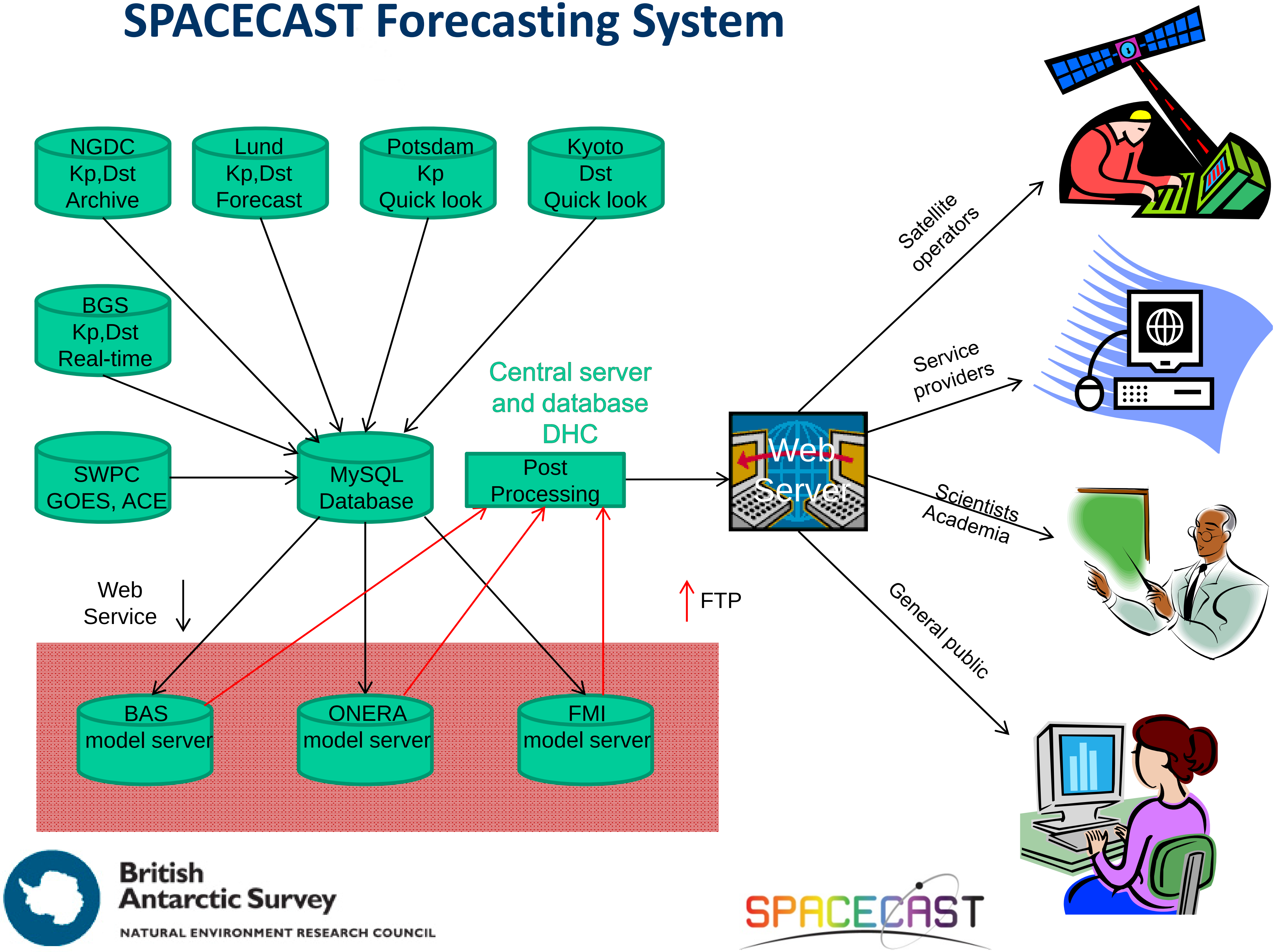
510 keV electrons

GPS , Galileo

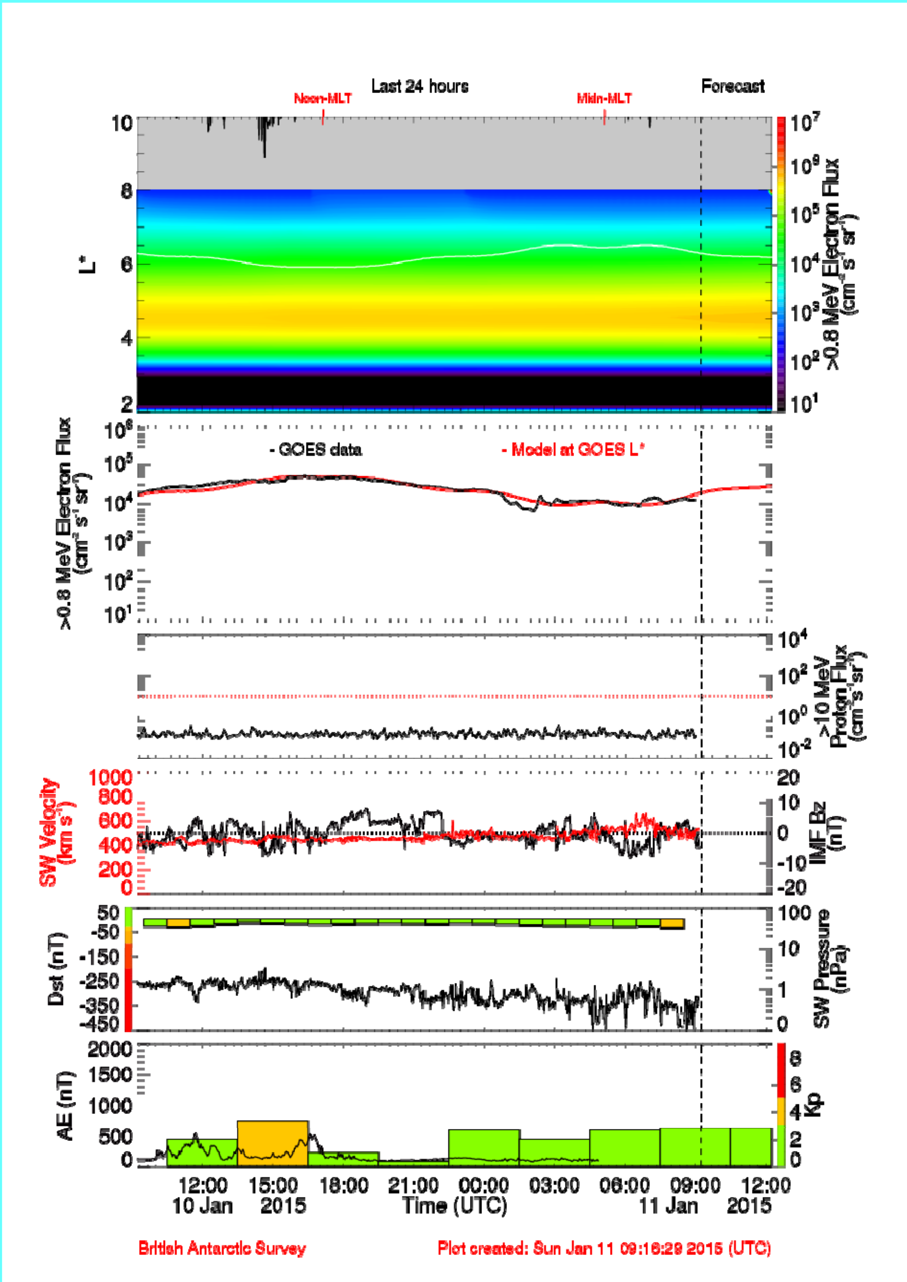
Slot region



SPACECAST Forecasting System

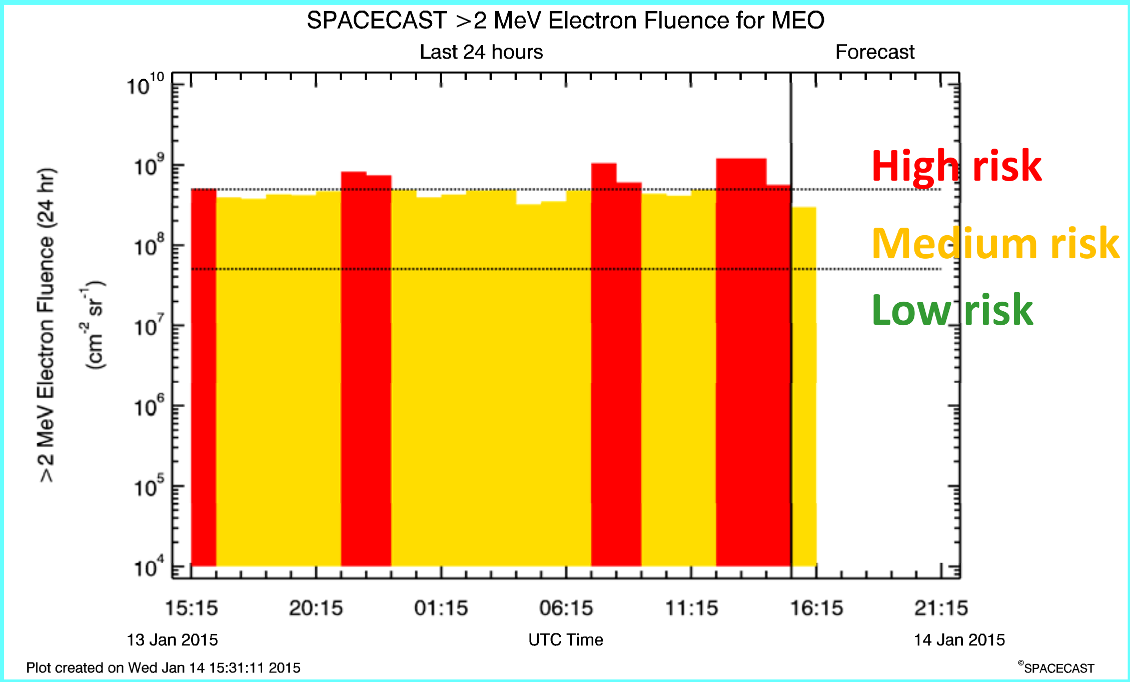


BAS Forecasts



- Detailed forecast
  - Simulation of last 24 hours
  - Forecast of next 3 hours
- Various energies available
  - 300, 800, 2000 keV
  - >100, >300, >800, >2000 keV
- Solar wind parameters and magnetic indices

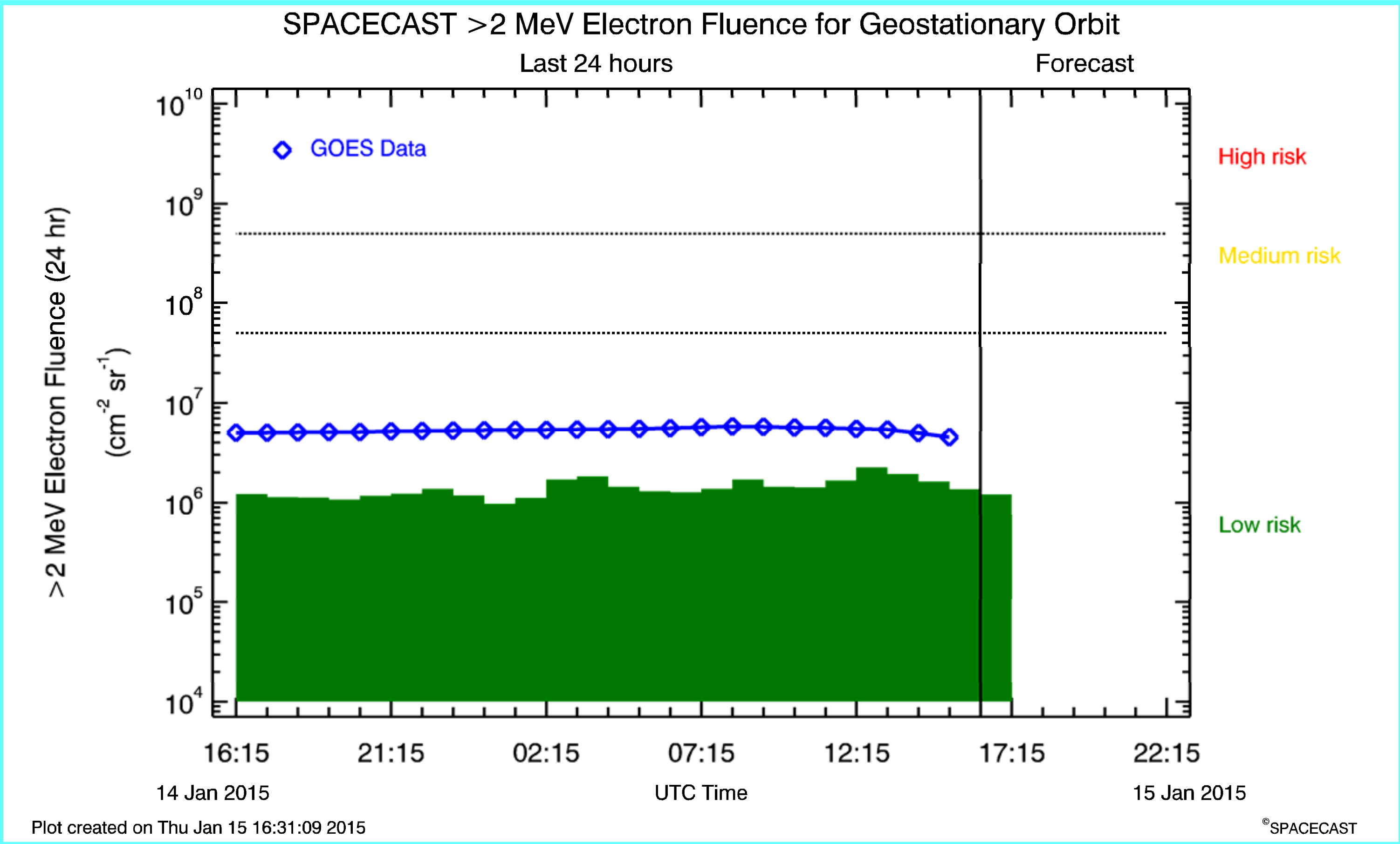
Fluence



- 24 hour fluence >2MeV
- Related to internal charging
- Produced for GEO, MEO and slot region orbits
- Could be calculated for a specific orbit

GOES Fluence

- Calculate >2 MeV electron flux from GOES data
- Data is unreliable at times
  - Solar proton events
  - Falls below background levels



SPACECAST risk index

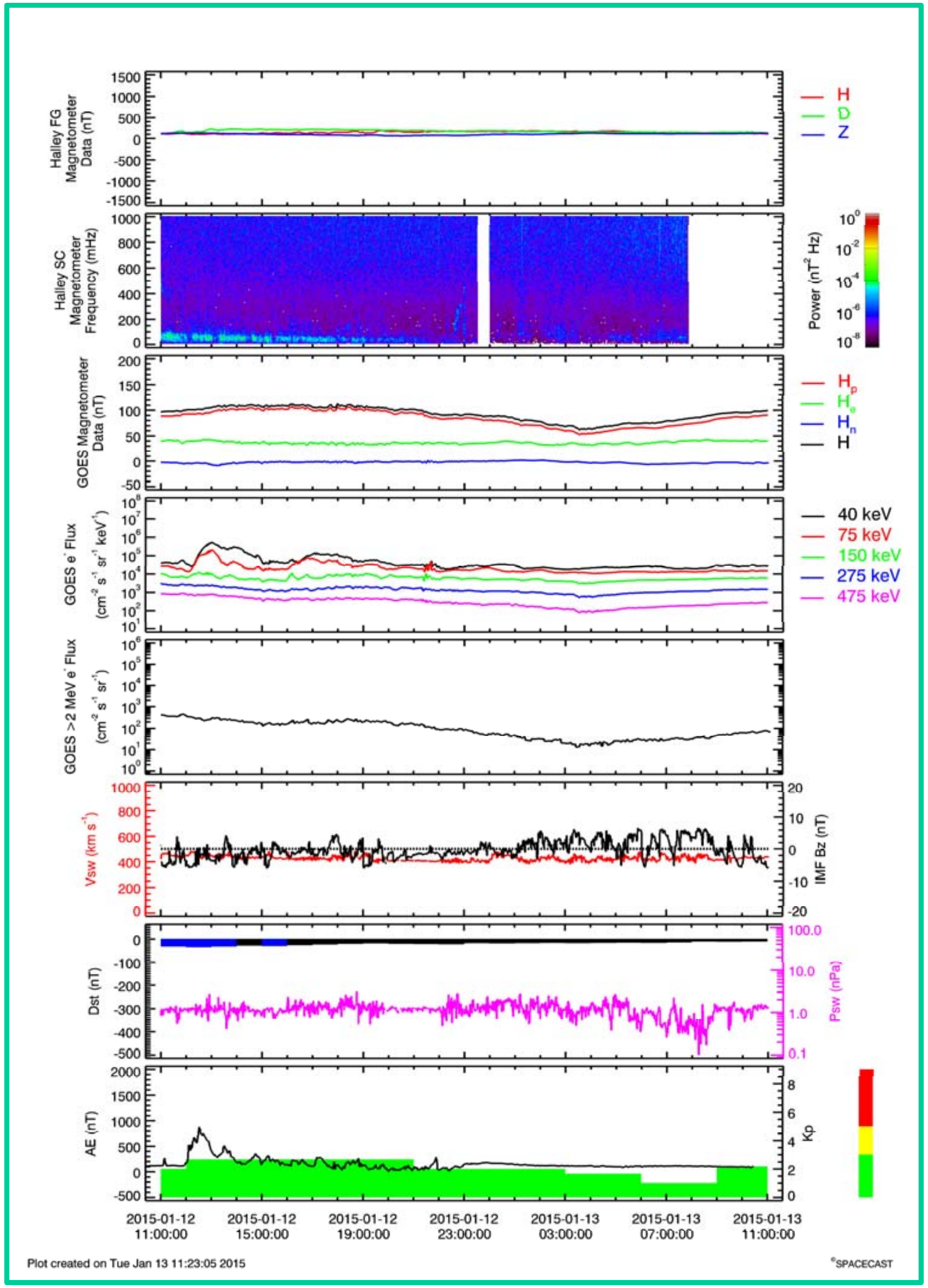
SPACECAST Satellite Risk (updated hourly)

	Internal charging	Surface charging
Geostationary orbit	Low	Low
Galileo/GPS orbit	Medium	Low
Slot region	Low	Low

Solar proton dose rate: Low

Risk index for internal charging

- Based on 24 hour fluence
- Shown for 3 typical orbits
- Could be tailored to a specific spacecraft



Ground based data

- BAS has real time magnetometer data from Halley
- Shows when substorms occur
  - If Halley is in correct location (near MLT midnight)
- Substorms are associated with injections of low energy electrons

Possible developments

- Develop graphics
  - Movies
  - Better versions of fluence for each orbit
  - Customise other plots
- Results for specific spacecraft
- Extend forecasting times
  - Longer forecast for Kp available from SWPC
  - Have to make assumptions about solar wind conditions

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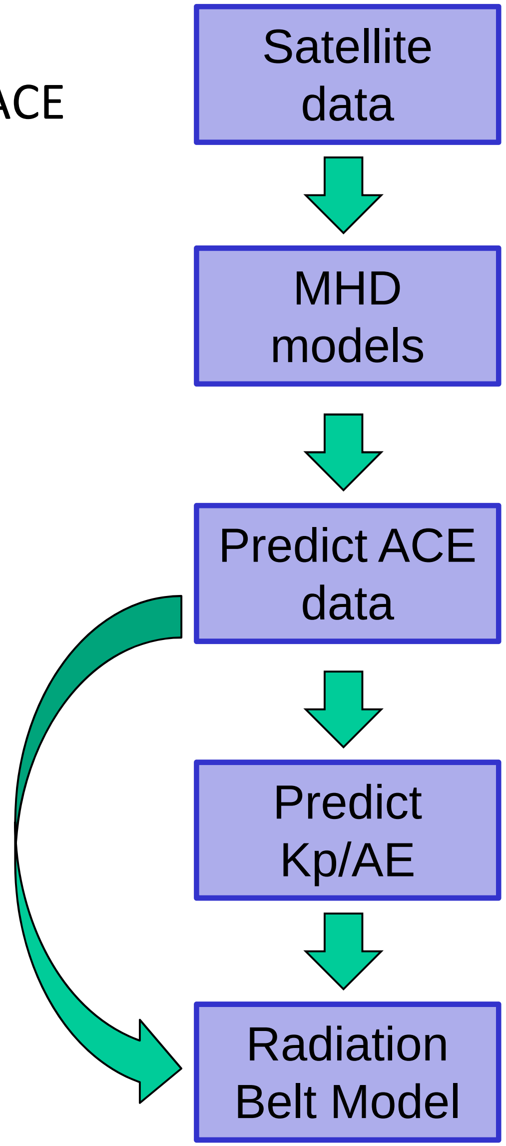
Possible projects

- Complete sun to Earth
  - Could extend forecasting time IF you could predict ACE
  - Can't use ENLIL – need IMF Bz



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SPACECAST risk index

Based on the 24 hour electron fluence (F) for >2MeV electrons

The Satellite risk index is set according to

High	$F > 5\times10^{8}$	electrons $cm^{-2}\ sr^{-1}$
Medium	$5\times10^{7} < F < 5\times10^{8}$	electrons $cm^{-2}\ sr^{-1}$
Low	$F < 5\times10^{7}$	electrons $cm^{-2}\ sr^{-1}$

Electron fluence: >2MeV electron flux integrated over 24 hours ($cm^{-2}\ sr^{-1}$)

Threshold values above which internal charging occurred on satellites at geosynchronous orbit [*Wrenn et al., 2002*].

Wrenn, G. L., D. J. Rodgers, and K. A. Ryden (2002), A solar cycle of spacecraft anomalies due to internal charging, *Ann Geophys*., *20*, 953–956.

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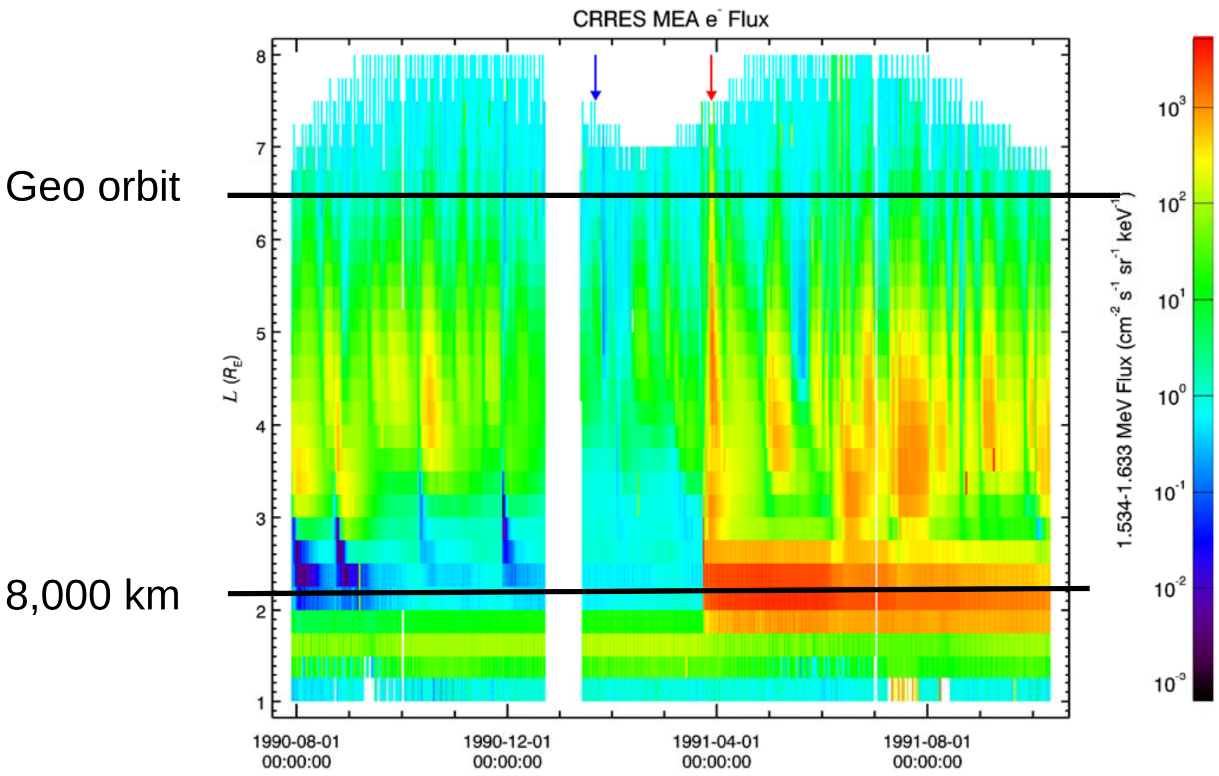
SPACECAST

All Electric Propulsion Satellites

- Launch to orbit ~ 100 – 180 days
- Needs full assessment of variable radiation environment
- SPACESTORM will cover the whole outer belt – electron flux, fluence, charging



- 1.5 MeV electrons flux from CRRES
- Much higher charging environment after March 1991
- Charging depends on materials
- Note 8,000 km for O3b satellites

- Heynderickx [2014]

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