Forecasting the Earth's Radiation Belts with SPACECAST
to help Protect Satellites on Orbit

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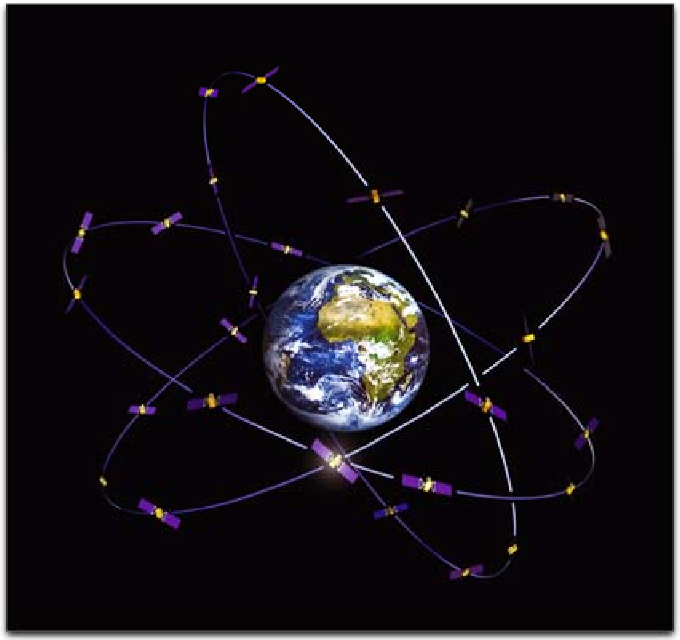
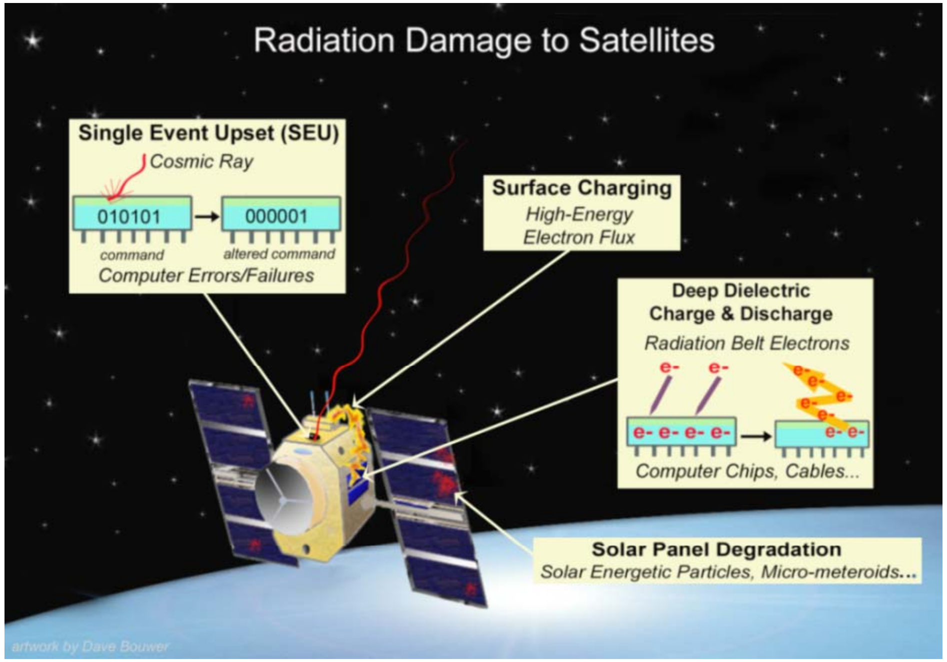
- Space is strategically important for Europe
  - Industry, GMES, Galileo,….
- Space assets are vulnerable to high energy particles
- Vulnerability increasing – new technology
- Risk changes with solar cycle
- Effects of another Carrington event?
  - Estimated $30 bn [Odenwald and Green, 2007]



Galileo - Courtesy of ESA

Radiation Damage to Satellites



- Solar energetic particles
  - Single event upsets
  - Degrades solar array power
- High energy electrons (Rad. belts)
  - Internal charging – ESD
- Low energy electrons
  - Surface charging - ESD
- Total ionizing dose
- Micrometeoroids and debris - ESD

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Satellite Anomalies – When SW Conditions Disturbed

- 20th Jan 1994
  - Intelsat 4, Anik E1 and Anik E2
  - Intelsat 4 and Anik E1 were recovered in a few hours
  - Anik E2 - Loss of service for 6 months
- 11th January 1997
  - Telstar 401 - Total loss – Insurance payout $132m
- 19th May 1998
  - Galaxy IV - Total loss – Insurance payout $165m
- 23rd Oct to 6th Nov 2003
  - 47 satellites reported malfunctions
  - Midori 2 - Total loss - US$640m – scientific satellite
- 5th Apr 2010
  - Galaxy 15 - Loss of service for 8 months - drifted around GEO – risk of collision
- 7th March 2012,
  - Sky Terra 1 and Spaceway 3 - Safe mode, loss of service for hours - days

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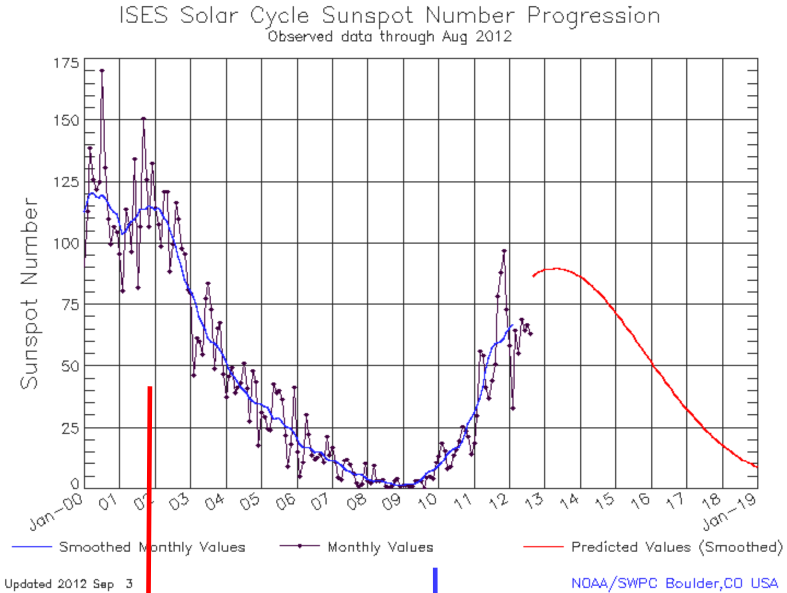
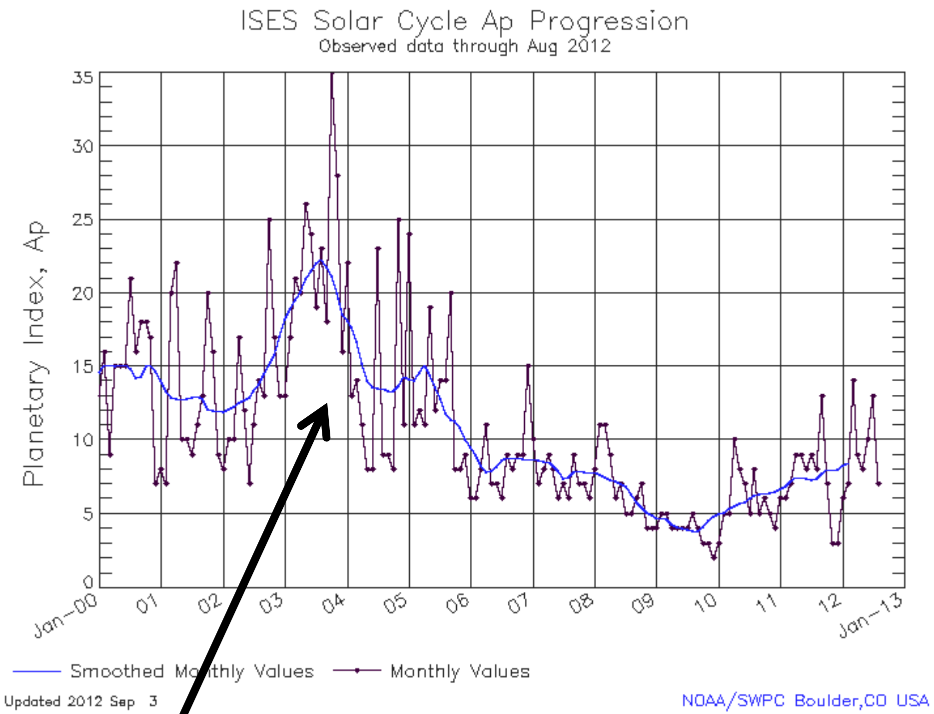
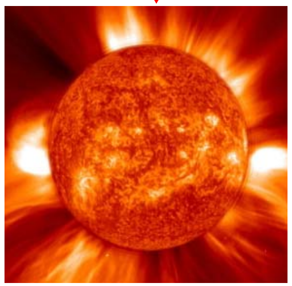
Sunspot Cycle – Geomagnetic Activity







active sun **quiet sun**

- Magnetic activity (mag storms) peaks 1-2 years after sunspot max.
- Risk is greater 1-2 years after sunspot max.

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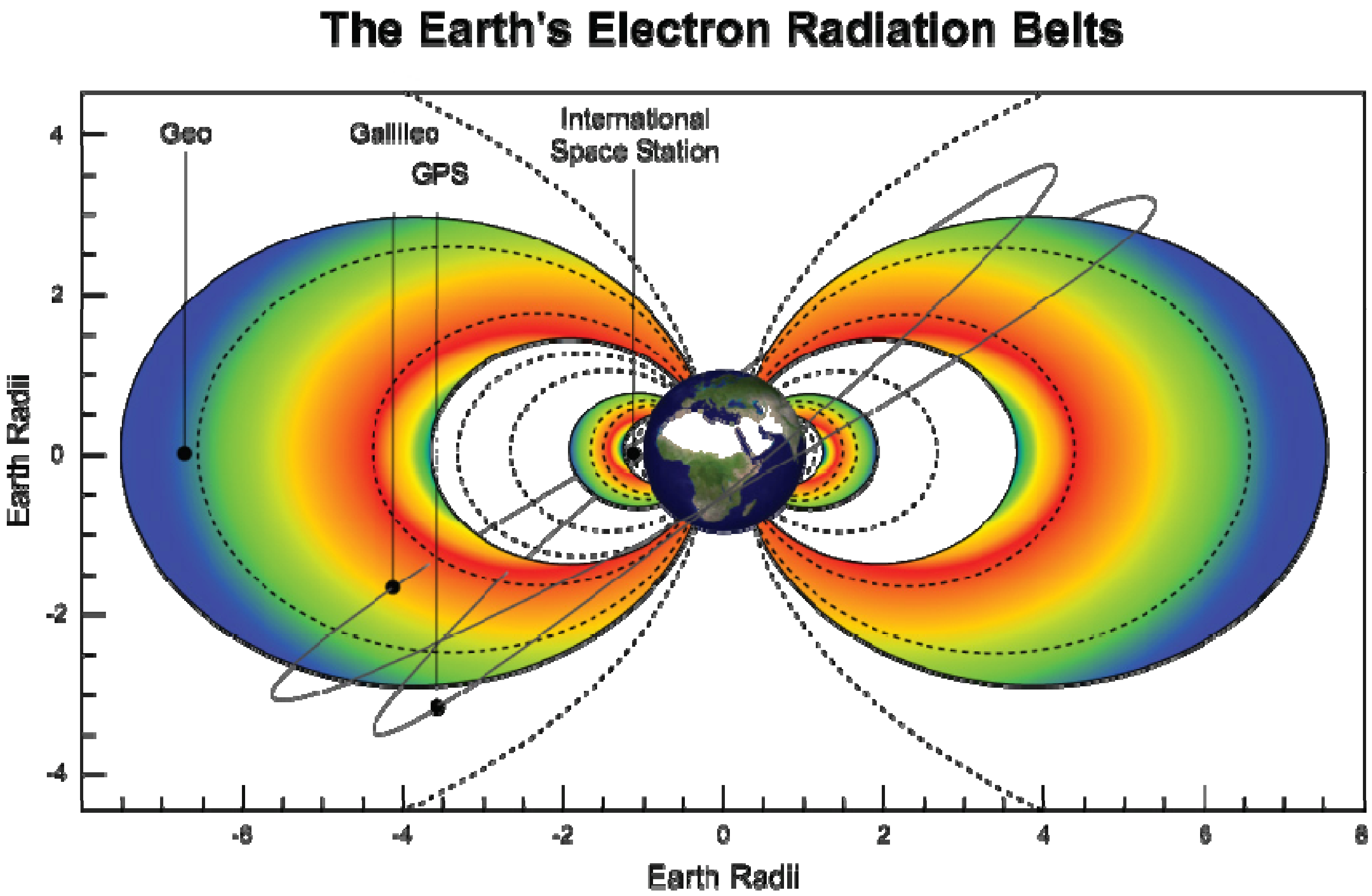
Earth’s Radiation Belts



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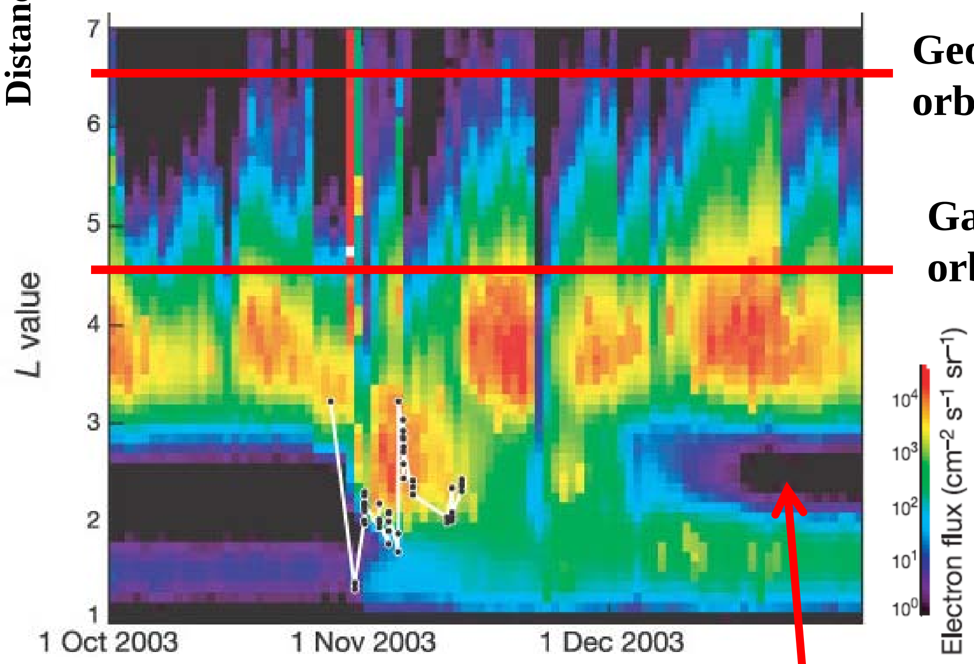
Magnetic Storms – Radiation Belts

Distance (Re)

> 2 MeV electron flux



Geostationary orbit

Galileo orbit

Baker et al. Nature [2004]

- The electron radiation belts are highly variable
- Electron flux can change by 5 orders of magnitude within 3 minutes
- Note higher radiation for GNSS/Galileo orbits
- Boeing – launch to GTO and use plasma thrusters – 1-2 months in radiation belts

Slot region
Usually benign – except during large storms

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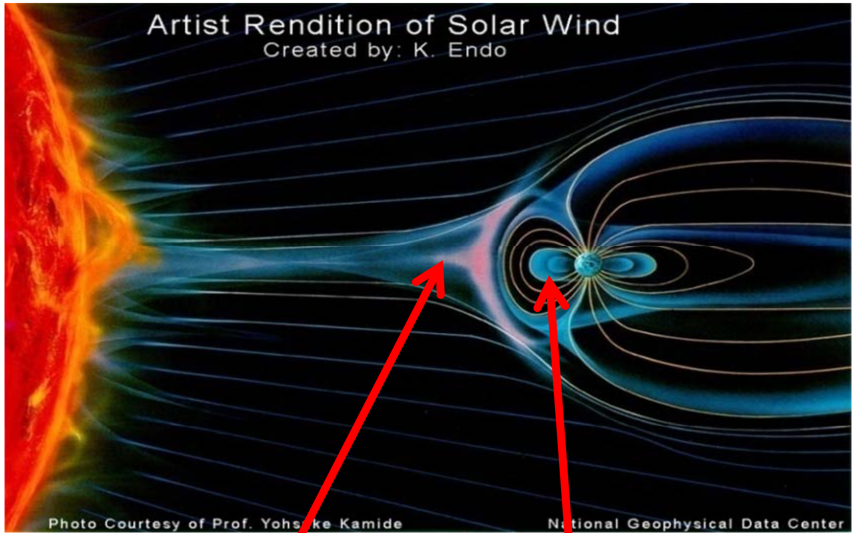
Forecasting Concept



ACE satellite

Radiation Belts

- 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
- Use a forecast of Kp index from Swedish Inst. Sp. Phys. (Lund) and BGS (UK) and data from Europe, USA and Japan
- We use physical models
  - Like weather forecasting

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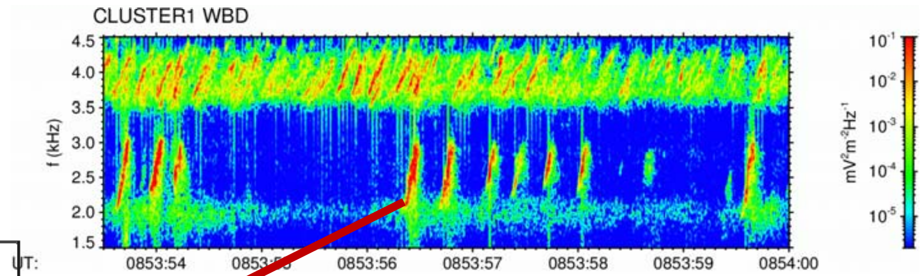
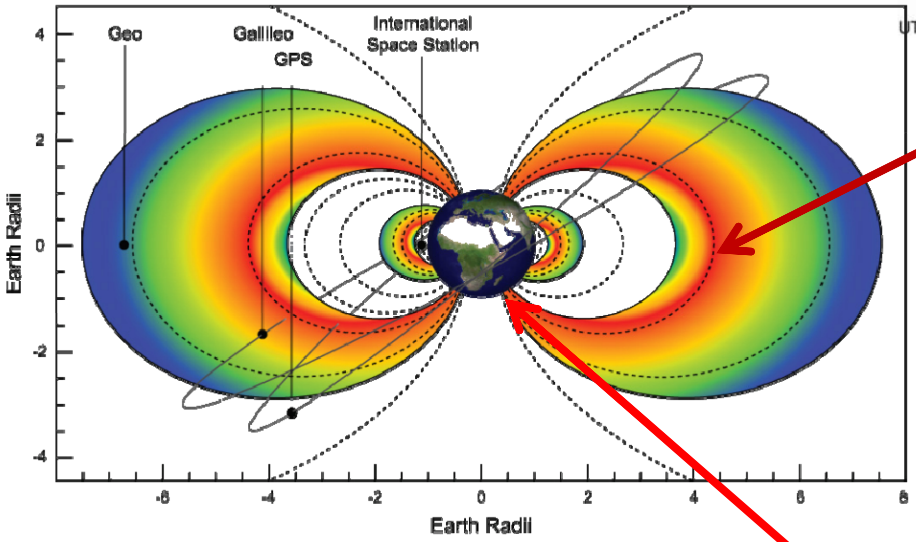
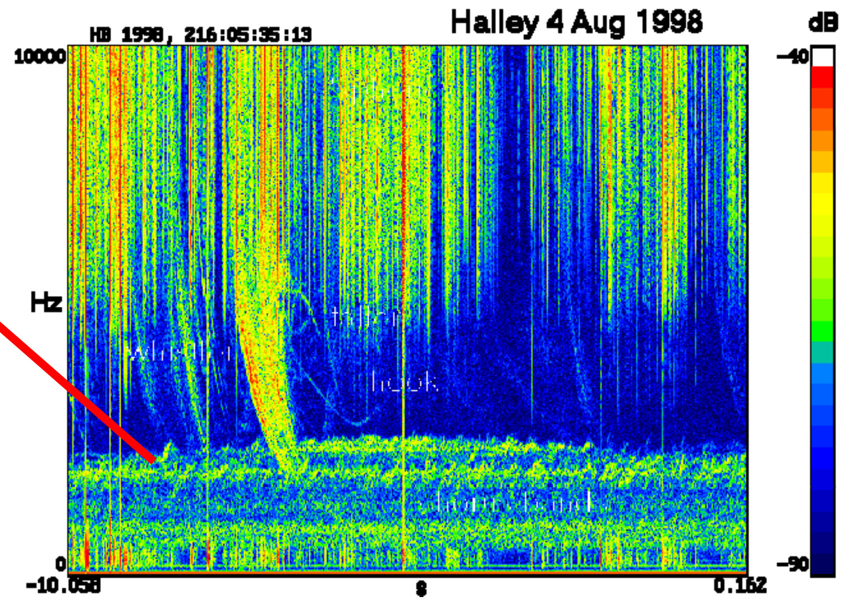
Physical Models Include Wave-Particle Interactions



Satellite observations



Antarctic observations



- Wave-particle interactions cause electron acceleration and loss
- Cause variability
- Changed ideas lasting 40 years

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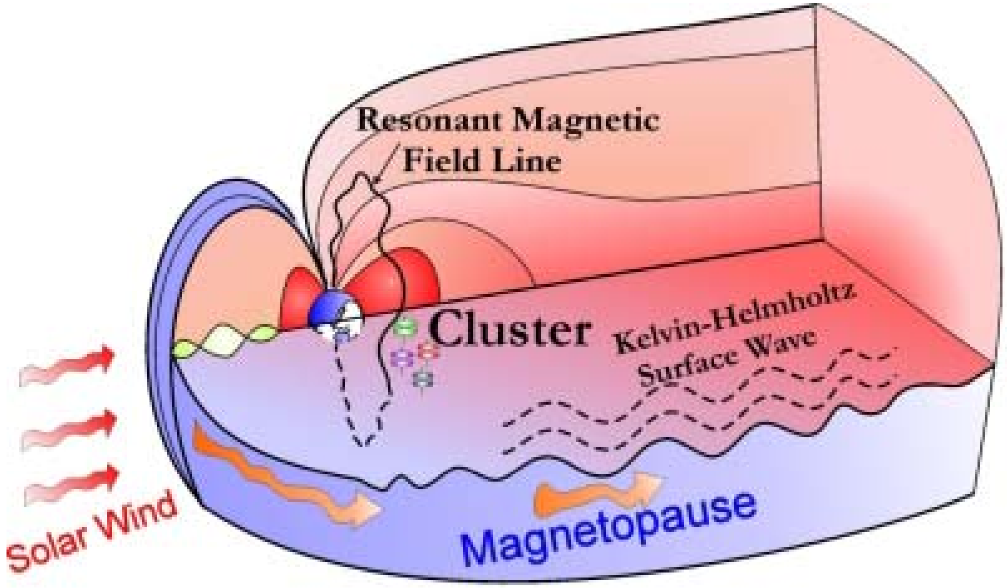
Radial Diffusion:
Transport of Electrons Across the Magnetic Field



- Fast solar wind drives ultra-low frequency (ULF) waves
  - Oscillations in the Earth's magnetic field
- ULF waves enhance electron transport across the magnetic field
  - Radial diffusion

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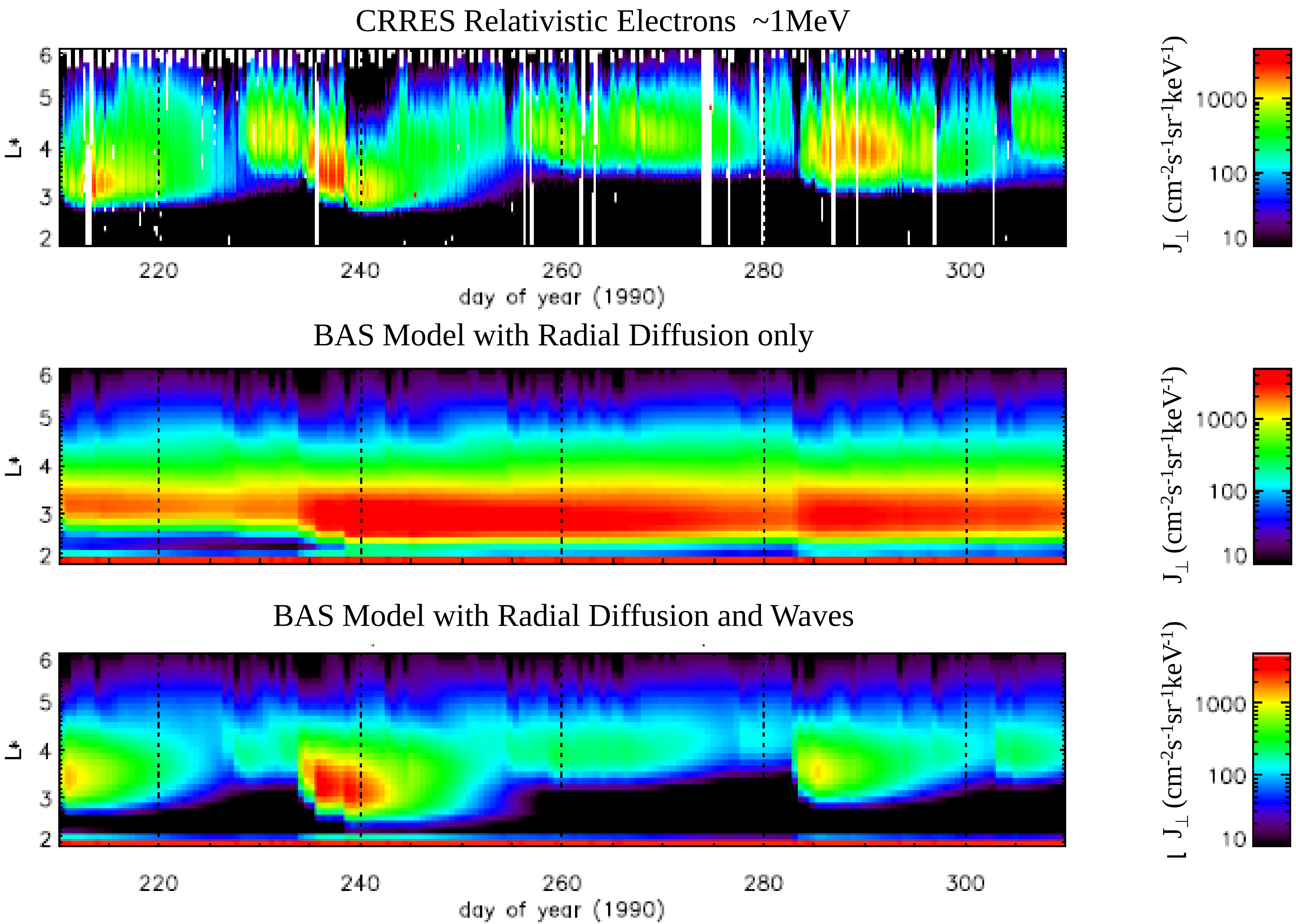
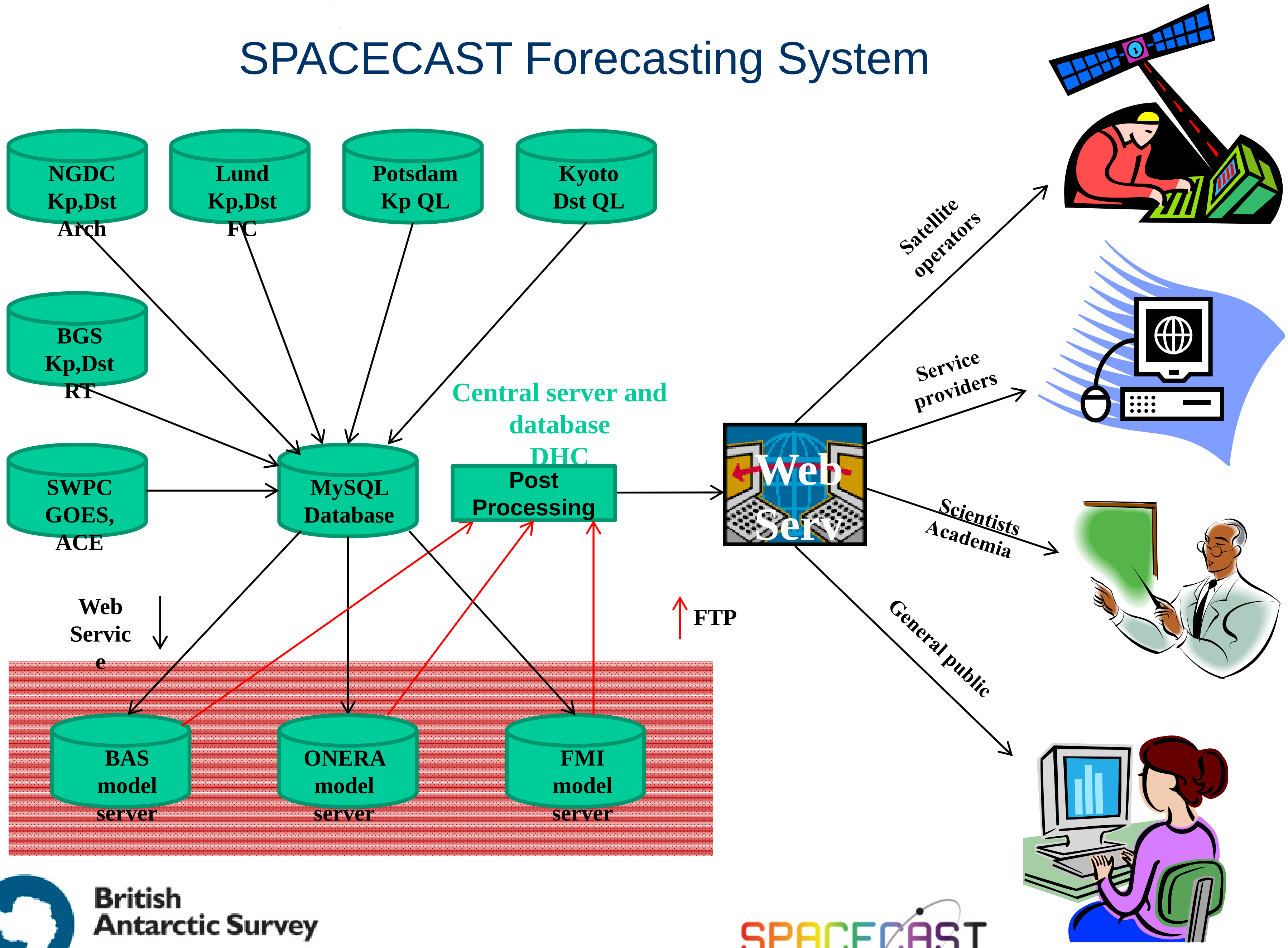
Testing the BAS Radiation Belt Model



SPACECAST Forecasting System



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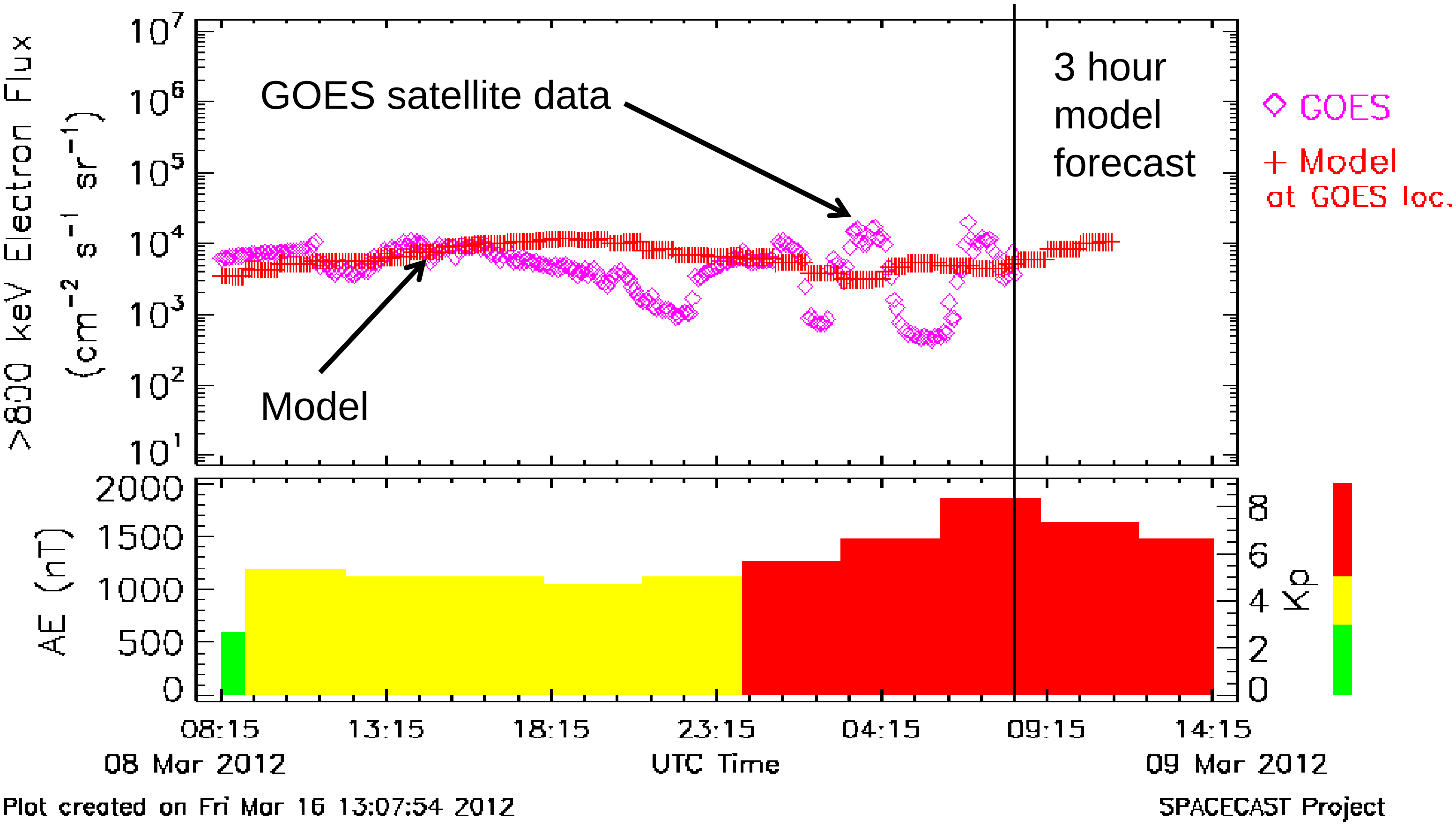
SPACECAST – Forecast >800 keV electrons



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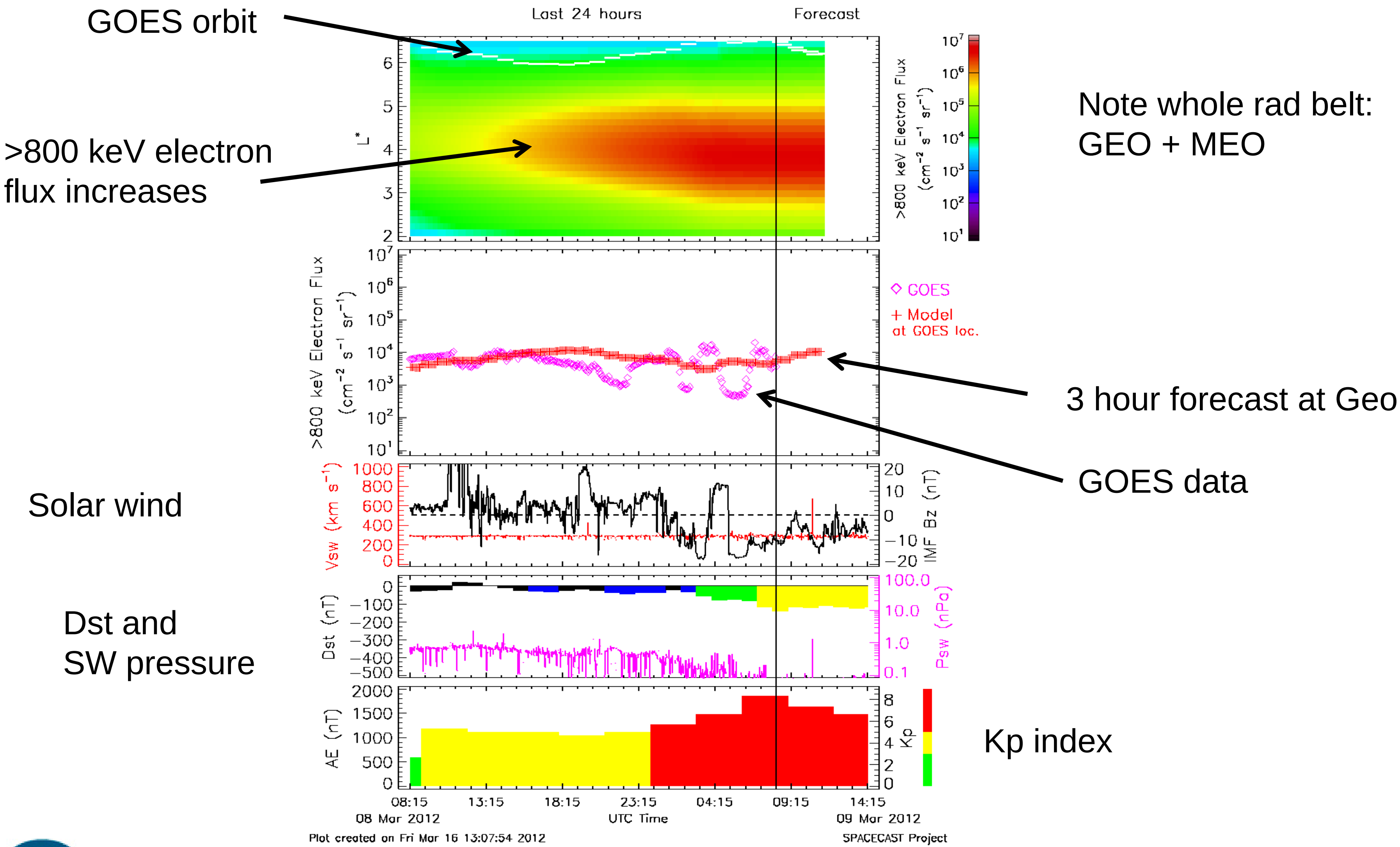

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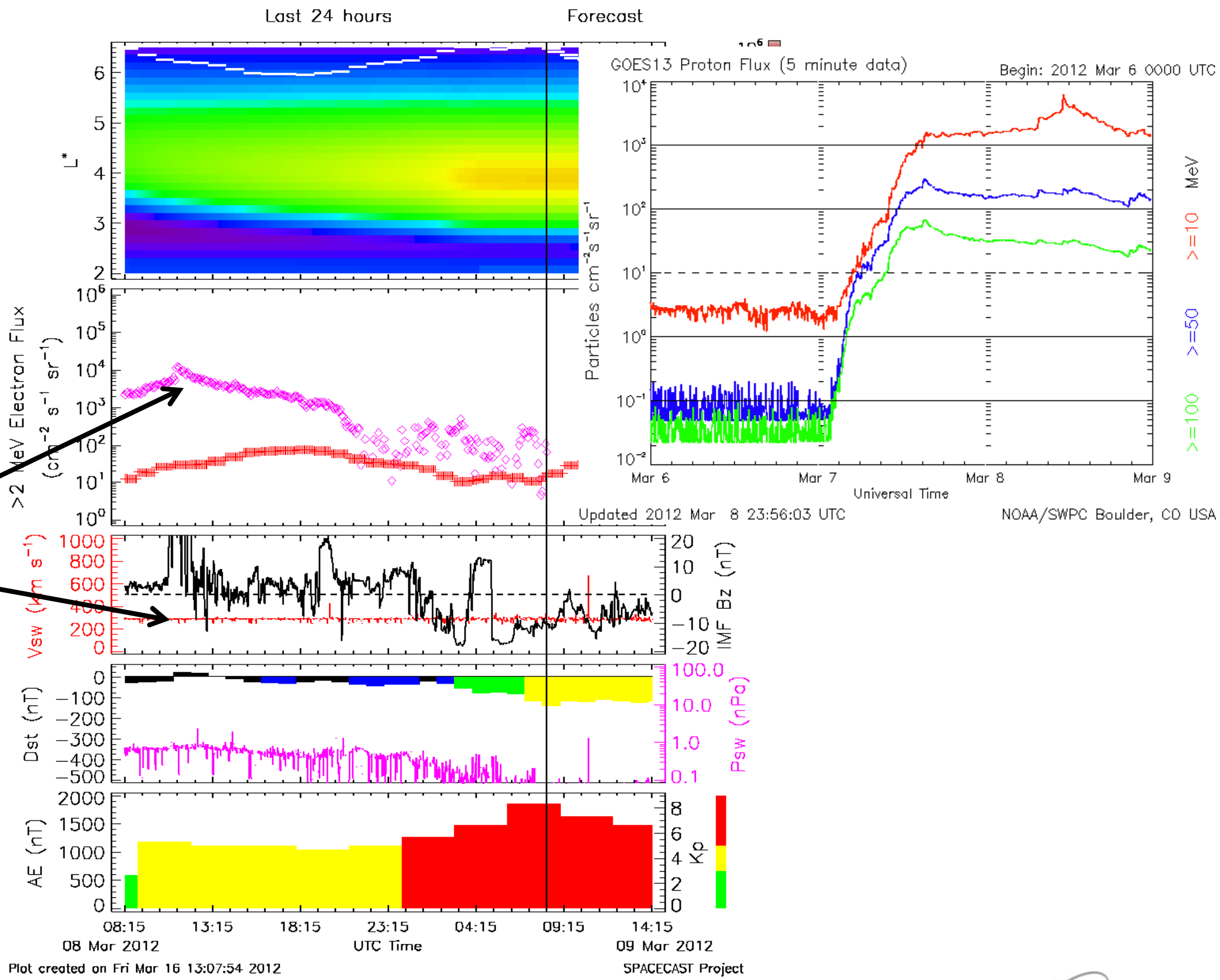
SPACECAST > 2 MeV Electrons



Satellite data affected by SW

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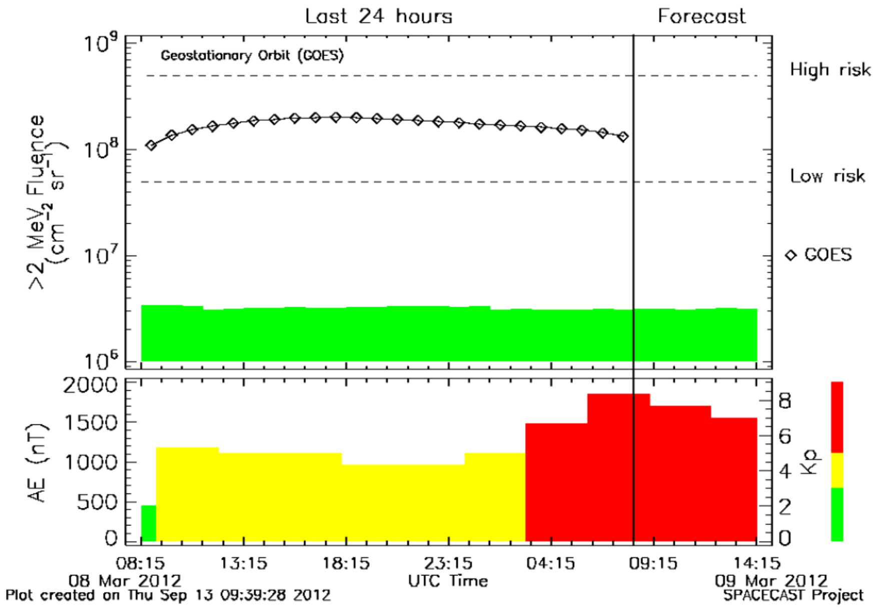
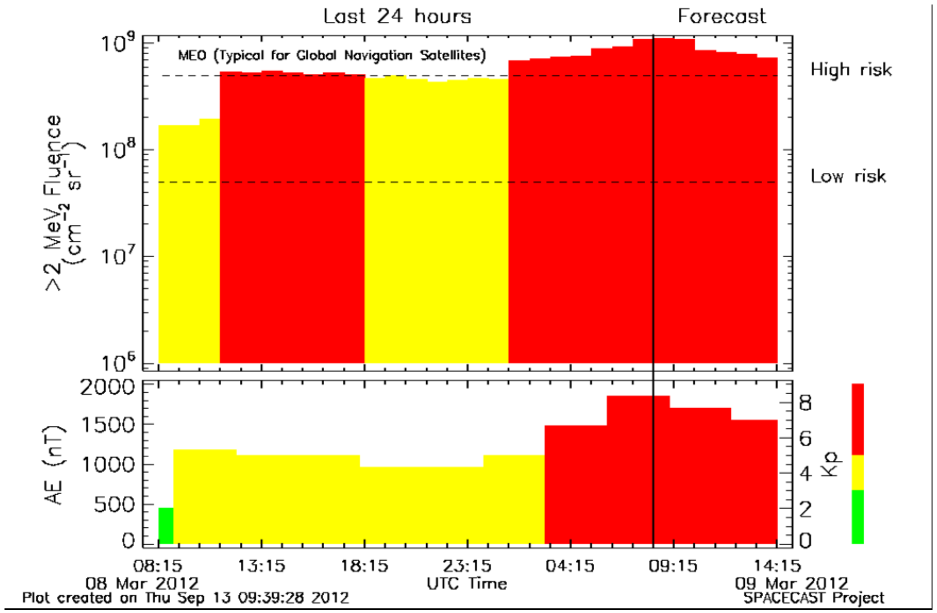
Risk of Satellite Charging - ESD

Model results converted into a risk index based on previous satellite anomalies

Geosynchronous Orbit



GNSS/Galileo Orbit



- Risk depends on satellite design
- Needs close collaboration with satellite operators and designers

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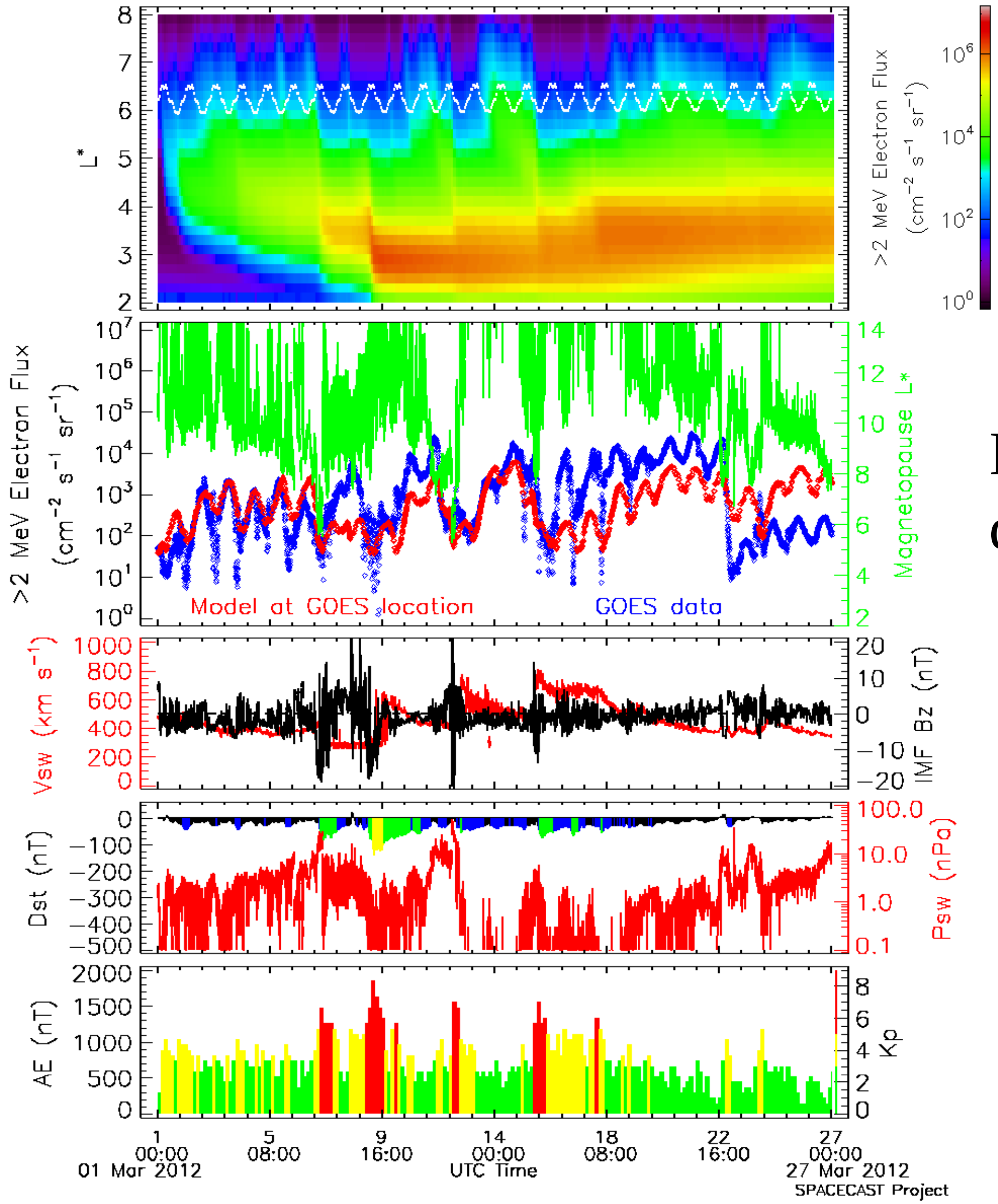
March 2012

Magnetopause
in Green



Forecast in red
data in blue

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Benefits of Physical Models

- Forecast what is likely to happen – enables mitigation
- Reconstruct what happened in the past - identify the cause of satellite anomalies
- Construct data where there are little/no observations – GNSS orbits
- Calculate extreme conditions based on physical principles
- Calculate number of particles precipitating into the atmosphere - effects on low altitude satellites, ionization and GPS signals

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Conclusions

- SPACECAST makes real time forecasts of the radiation belts for satellite operators

- Forecast for 3 hours, updated every hour, and translated into a risk index

- Unique features
  - Physical models, that include wave-particle interactions
  - Forecast for the whole radiation belts – including GNSS/Galileo orbits
  - European led – with USA and Japan

- Forecasts can be improved by
  - Coupling the solar wind/magnetopause to the radiation belts
  - Including low energy electrons – surface charging

- Options to model extreme events and orbits where there is little/no data

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