Data Assimilation for Prediction and Reanalysis of the Radiation Belts

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Radiation Belts – Two-Zone Structure

- Radiation belts – two donut-shaped regions of high radiation encompassing the Earth.
  - energies $>100$ keV
  - two-zone structure
- Inner belt: fairly stable.
- Outer belt: can change on the time scale of an hour.
Increased Interest in Ionizing Radiation

- Radiation is hazardous to satellite electronics & humans in space
- Miniaturizations of satellite electronics makes satellites more vulnerable than ever before.
- Electric orbit rising satellites spend a long time in heart of the belts.
Competition Between Acceleration and Loss

Inward radial diffusion driven by the ULF magnetic fluctuations.

Energy and pitch angle scattering due to resonance interactions with different waves.

Combined effect of losses to magnetopause and outward radial diffusion.

[Shprits et al., 2008; Review JASTP]
\[
\frac{\partial f}{\partial t} = \left. L^* \frac{\partial}{\partial L^*} \right|_{J_1, J_2} + \left. \frac{1}{L^*} D_{L^*L^*} \frac{\partial f}{\partial L^*} \right|_{J_1, J_2} + \left. \frac{1}{p^2} \frac{\partial}{\partial p} \right|_{L, \alpha_0} p^2 \left( D_{pp} \frac{\partial f}{\partial p} \right)_{L, \alpha_0} + \left. D_{p\alpha_0} \frac{\partial f}{\partial \alpha_0} \right|_{L, p} + \left. \frac{1}{T(\alpha_0) \sin(2\alpha_0)} \frac{\partial}{\partial \alpha_0} \right|_{\alpha_0, \alpha_0} T(\alpha_0) \sin(2\alpha_0) \left( D_{\alpha_0\alpha_0} \frac{\partial f}{\partial \alpha_0} \right)_{L, \alpha_0} + \left. D_{\alpha_0\alpha_0} \frac{\partial f}{\partial \alpha_0} \right|_{L, p} + \text{Sources} - \text{Losses}
\]
Boundary conditions from observations around GEO.
Radial diffusion, chorus and hiss waves are parameterized by Kp.

[Shprits et al., 2008; Kim et al., 2010]
Comparison of the Observations and the Radial Diffusion Model

Observations are sparse.

Model is continuous but may be missing essential physics.

L is approximately the distance from the Earth.

Kp is the index of geomagnetic activity.

[Shprits et al., 2007]
Data assimilation can fill in spacio-temporal gaps. Data assimilation shows building up peaks in Phase Space Density.

[Shprits et al. 2007]
Data is blended with the model according to the underlying structure of data and model errors.

Data from 5 spacecraft is assimilated and radial profile of PSD is dynamically reconstructed.
Multi-Point Observations

EQUATORIAL ORBIT
- Allows observations of the whole pitch-angle distribution including nearly equatorially mirroring particles.

LEO ORBIT
- e.g. Lomonosov, SAMPEX, NOAA. Observations of precipitating and locally trapped fluxes. Several passes per day.
Radiation Belts Assimilative Forecast

Data from different satellites is blended with a physics-based model

Real-time Radiation Belt Forecast, Jan-18-2016, 02:00 UTC
Radiation Belts Assimilative Forecast

http://rbm.epss.ucla.edu/realtime-forecast/
Drift of lower energy particles is dominated by ExB drift.
Radiation Belt particles are subject to the gradient and curvature drifts and will drift around the Earth.
Electrons – eastward,
Ions – westward.
Block Diagram Showing Data Exchange between the modules of the VERB 4D code

- Satellite data, Kp, Solar wind parameters
  - Waves Parameterization
  - Magnetic field
  - Electric field

- Initial PSD
- Boundary PSD
- Magnetopause location
- Diffusion coefficients
- Drift velocities

Fokker-Planck equation with convective terms (C++)

- Read Input
- Update coeff-s (t)
- Adiabatic transport
- Convection
- Radial diffusion
- Local diffusion

Next time step

PSD as a function of (MLT, L*, μ, K), Electron flux as a function of (MLT, L*, E, α)

Precipilation into Ionosphere
PROGRESS
PRediction Of Geospace Radiation Enviroment
and Solar wind parameterS

New EC Horizon 2020 funded project.

PARTICIPANTS

- U. Sheffield
- FMI
- U. Warwick
- GFZ/ U. of Potsdam
- U. Michigan
- SRI NASU
- CNRS -LPC2E
- IRF-L

AIMS

- Development of a European Solar Wind model
- Models for the evolution of geomagnetic indices
- Statistical Wave models of wave activity
- Development and coupling of systems methodologies with physically based models
- Tools for robust, reliable forecasts for
  - geomagnetic indices
  - particle environment of the inner magnetosphere
Summary

• Data assimilation allows us to blend observations from various instruments on various spacecraft and allows us to accurately reconstruct the state of the radiation belts.

• Data assimilation will be curtial for space weather modeling, for combining data from the upcoming missions and developing models for forecasting, now casting and specification models.

• Data assimilation will significantly improve our ability to forecast the near-Earth radiation environment.

• Future work should include code coupling with neural networks, and validation of the newly developed VERB 4D that can model the entire inner magnetosphere.
Reconstruction of the State of the Radiation Belts Using 5 Spacecraft
Thank You