Reanalysis of radiation belt electrons relying on a Kalman filter, four spacecraft, and a diffusion model

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Space weather and its effects

What is space weather?

- The Sun is responsible for disturbances in our space environment.

[Source: Baker, 2002]
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Space weather and its effects

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- The Sun ejects clouds of ionized gas towards the Earth.
- Some effects: aurorae, communication disruptions, radiation hazards to orbiting astronauts and spacecraft, and induced currents in power lines.

[Baker, 2002].
Radiation belts: two zone structure

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Radiation belts: two zone structure

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- **Inner belt**: fairly stable.
- **Outer belt**: can change in timescale of an hour.
- **Slot region**: gap of lower fluxes.
- Particles with energies from $\sim 100$ keV up to tens of MeV.
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- The outer belt **overlaps many satellite orbits!**
Radiation belts and data assimilation

How can data assimilation be applied in radiation belt modeling?

Data assimilation can help with:

- **Understanding** the fundamental physics underlying the radiation belts dynamics.

Increased dependence on the technology in space causes surge in space weather interest.
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▶ **Predicting** radiation in space and the response of radiation belts to geomagnetic disturbances.
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How can the dynamics in the radiation belts be modeled?

The evolution of relativistic electrons in the radiation belts is modeled by the **Fokker-Planck equation**, in terms of the radial distance $L$, relativistic momentum $p$, and pitch angle $\alpha$ as follows:

$$\frac{\partial f}{\partial t} = L^* \frac{2}{\partial L^*} \left|_{\mu,J} \frac{1}{L^*} D_{L^*L^*} \frac{\partial f}{\partial L^*} \right|_{\mu,J} + \frac{1}{p^2} \frac{\partial}{\partial p} \left|_{\alpha,L^*} p^2 \left( D_{pp} \frac{\partial}{\partial p} \left|_{\alpha,L^*} f + D_{p\alpha} \frac{\partial}{\partial \alpha_0} \left|_{p,L^*} f \right) \right) + \frac{1}{T(\alpha)\sin(2\alpha)} \frac{\partial}{\partial \alpha} \left|_{p,L^*} T(\alpha)\sin(2\alpha) \left( D_{\alpha\alpha} \frac{\partial}{\partial \alpha} \left|_{p,L^*} f + D_{\alpha p} \frac{\partial}{\partial p} \left|_{\alpha,L^*} f \right) \right) - \frac{f}{\tau} \right)$$

- $\mu$, $J$, and $L^*$ are the particle adiabatic invariants.
- $D_{L^*L^*}$, $D_{pp}$, $D_{\alpha\alpha}$, $D_{p\alpha}$, and $D_{\alpha p}$ are diffusion rates, and describe the effect of **wave-particle interactions**.
- Pitch angle ($\alpha$): angle between the particle's velocity vector and the local magnetic field.
- This equation accounts for **radial**, **energy**, **pitch-angle**, and **mixed pitch angle - energy** diffusion.
Radiation belts and data assimilation

An example of 1D reanalysis (Shprits et al., 2012)

\[
\frac{\partial f}{\partial t} = L^*^2 \frac{\partial}{\partial L^*} \left| \begin{array}{c} 1 \\ L^*^2 D L^* L^* \frac{\partial f}{\partial L^*} \\ \end{array} \right|_{\mu, J}
\]

- Top: Reanalysis.
- Middle: CRRES observations.
- Bottom: Geomagnetic activity index.

PSD is given in units of \(\log_{10}(c/cm/\text{MeV})^3 \times 10^6\)
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▶ Perform reanalysis in terms of the three dimensions (\(L\): radial distance, \(\alpha\): pitch angle, and \(E\): energy) using data from multiple spacecraft.
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▶ Incorporate the following loss processes into the data assimilation code:
  1. mixed pitch angle - energy diffusion,
  2. scattering by Electromagnetic Ion Cyclotron (EMIC) waves, and
  3. losses to the interplanetary medium.
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- Assess their effect on radiation belt modeling via the **innovation vector**.
Methodology

Model framework: VERB code

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\left. \frac{1}{T(\alpha)\sin(2\alpha)} \frac{\partial}{\partial \alpha} \right|_{p,L^*} T(\alpha)\sin(2\alpha) \left. \left( D_{\alpha\alpha} \frac{\partial}{\partial \alpha} \right) f + D_{\alpha p} \frac{\partial}{\partial p} \right|_{\alpha,L^*} f \right) - \frac{f}{\tau}
\]

The VERB (Versatile Electron Radiation Belt) code (Subbotin and Shprits, 2009) solves it numerically, by accounting for radial, energy, pitch-angle, and mixed pitch angle - energy diffusion.

Spacecraft observations

- NASA’s Radiation Belt Storm Probes (RBSP), highly elliptical orbit.
- NOAA’s Geostationary Operational Environmental Satellites (GOES), geostationary orbit.
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Reconstructing the evolution of the Van Allen belts

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4. ... + losses to the interplanetary medium.
Reconstructing the evolution of the Van Allen belts

Radial profiles of electron PSD

Electron PSD for $\mu = 50$ MeV/G and $K = 0.8 \text{ G}^{0.5} \text{Re}$:

- (i) spacecraft data,
- (ii) 3D + mixed diffusion + scattering by EMIC waves + magnetopause shadowing reanalysis,
- and evolution of
- (iii) solar wind dynamic pressure and speed,
- and (iv) geomagnetic $Kp$ index.

Reconstructing the evolution of the Van Allen belts

Innovation vector: “all the new information in the observation vector”

- How much **additional information** from the data will modify the forecast in order to produce an optimal estimate of the state of the system.
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- **Positive** innovation $\rightarrow$ model underestimates data $\rightarrow$ observations add PSD $\rightarrow$ missing source of electrons in the model.

- **Negative** innovation $\rightarrow$ model overestimates data $\rightarrow$ observations remove PSD $\rightarrow$ missing loss of electrons in the model.
Innovation vector: 3D + mixed diffusion

- Mixed diffusion removes the **overestimation** of PSD, particularly at low pitch angles.
- Left column: 3D diffusion.
- Right column: 3D + mixed diffusion.

Innovation vector as a function of $L^*$ and $Kp$ for electron PSD for the indicated pairs of $\mu$ and $K$. 

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**SFB 1294 Data Assimilation**
Innovation vector: 3D + mixed diffusion + EMIC scattering

- EMIC scattering reduces the electron PSD overestimation, especially at energies greater than 2 MeV.
- Left column: 3D + mixed diffusion.
- Right column: 3D + mixed diffusion + scattering by EMIC waves.

Innovation vector as a function of $L^*$ and $K_p$ for electron PSD for the indicated pairs of $\mu$ and $K$. 
Innovation vector: 3D + mixed diffusion + EMIC scattering + magnetopause losses

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Innovation vector as a function of $L^*$ and $Kp$ for electron PSD for the indicated pairs of $\mu$ and $K$. 

![Graphs showing innovation vector changes](image-url)
Innovation vector: 3D + mixed diffusion + EMIC scattering + magnetopause losses

Innovation vector as a function of $L^*$ and $K_p$ for electron PSD for the indicated pair of $\mu$ and $K$.

- **Underestimation** at high radial distances and low energies due to absence of magnetospheric convection in the model.

- Convection brings particles from the tail region to the inner magnetosphere and can energize electrons by hundreds of keV ('seed population' for radiation belts).

Schematic representation of magnetospheric convection-dominated region in the tail and diffusion-dominated region close to the Earth [Subbotin et al., 2011].
Reconstructing the evolution of the Van Allen belts

Real-time Radiation Belt Forecast

Summary and future work

We have:

- applied a **standard Kalman filter** to multiple satellites to reconstruct the global state of the space environment,

We plan to:

- validate our DA performance by comparison with independent datasets, and
- compile a database of spacecraft anomalies and determine failures related to increases in radiation.
Summary and future work

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