Data Assimilation, and Forecasting the near-Earth Radiation Environment

Adam C. Kellerman\textsuperscript{1}, Y. Y. Shprits\textsuperscript{1,3}, T. Podladchikova\textsuperscript{4}, A. Drozdov\textsuperscript{1}, H. Zhu\textsuperscript{5}, D. Kondrashov\textsuperscript{2}

1. Department of Earth, Planetary, and Space Sciences, UCLA
2. Department of Atmospheric and Ocean Sciences, UCLA
3. GFZ German Research Centre for Geosciences, University of Potsdam, Germany
4. Skolkovo Institute of Technology, Skolkovo, Russia
5. University of Texas, Dallas
Presentation Outline

1. VERB
2. GOES/Van Allen Probe data
3. Data Assimilation
4. Data Assimilative Forecasting with VERB
5. A long-term reanalysis dataset
The **VERB code** models the global state and evolution of the Earth’s radiation belt electrons.

What’s special about this code?

1. We operate in an invariant coordinate system, where radiation particles ‘live’
2. The code is fast, and can be run on a personal computer due to its advanced, and accurate, numerical architecture
Observations (data)

GOES 13 and 15:
   MagED and EPEAD: 10’s of keV to ~2 MeV

Van Allen Probe A & B:
   MagEIS: 10’s of keV to MeV

Coverage at GEO and through GTO
Solar Wind/Geomagnetic Indices

SWPC: 3-day forecast Kp index:

The greatest observed 3 hr Kp over the past 24 hours was 8 (NOAA Scale G4).
The greatest expected 3 hr Kp for Sep 08-Sep 10 2017 is 8 (NOAA Scale G4).

Rationale: G1-G4 (Minor-Severe) geomagnetic storm levels are expected on day one (08 Sep) and G1-G3 (Minor-Strong) storm levels on day two due to the combined influence of the 04 Sep and 06 Sep CMEs.

SWPC: Ace data:
Data Assimilation

Individually, data and models may not accurately specify the environment.

- Model: Global estimate with some error and bias
- Data: Sparse observation with some error and bias
If we combine the model and data, we may obtain an estimate closer to the truth.

Global coverage with a smaller overall error and bias.
Real-time Van Allen Probe data

Real time GOES 13 and 15 data

Real time and forecast Kp (SWPC)

Real time ACE solar wind (SWPC)

Data Assimilation

Forecast radiation belt state

Nowcast radiation belt state
Global Radiation Belt Forecast
Data assimilation allows to account for hysteresis (bias) effects

Data are sparse, often missing, or have processing errors. There are many gaps

Reanalysis allows for reconstruction of the radiation belt fluxes, even when data are missing

Here we highlight the importance of GOES data for our forecast framework

Forecast solar wind data are limited

In order to test and validate model performance, a study of forecast performance using final data is required

http://rbm.epss.ucla.edu/realtime-forecast/
We have a 4-year dataset of radiation belt-electron reanalysis currently 2012-2016 Will be extended back to 1995

Such a dataset can be useful for specifying the environment around a given spacecraft

Averaging over time, energy, and space can be accomplished for 100 keV to multi-MeV electrons
1. Implemented a robust and fast data-assimilation method for VERB 2.0

2. Real-time radiation belt nowcasts and forecasts using data assimilation - running every 2 hours, begun in 2015 – SWPC & APL

3. A long-term dataset of globally reconstructed fluxes is available from 2012-2016. This will be extended back to 1995, and forward as more data are available

4. Forecast validation has been complete – a more accurate and advanced model will be released in the near future
Space Weather Effects

Radiation is hazardous to satellite electronics & humans in space.

Over 3,000 satellites; Supporting $25B/yr industry;
Replacement cost: over $75B; GPS industry ~ $1 trillion

Electric-orbit raising ~6 month transition through the belts

Space radiation impacts polar flights (~7,000) (cost ~$0.1 M per flight) examples: NY -Tokyo; LA - Moscow; disruption of power grids, produces blackouts (up to $100M in losses)

A Carrington type storm (1859) may cause $0.6-2.6 trillion in damage.
Particle Motion

Bounce period for a particle on an equipotential field line. The integrable singularity at the mirror points poses a problem.

We can use a change of variables

\[
1 - \frac{B}{B_m} = \cos^2 \alpha_{eq} \sin^2 \psi,
\]

Orlova and Shprits, [2011]

\[
\frac{ds}{dB} = \frac{ds}{d\psi} \left( \frac{dB}{d\psi} \right) d\psi
\]

\[
\tau_B = -\frac{4}{v} \cos \alpha_{eq} B_m \int_0^\pi \frac{ds}{dB} \cos \psi d\psi.
\]

In this way, we can compute the bounce time using standard numerical approaches at all points along the bounce orbit

\[
J = \int p_\parallel ds = m \int v \mu ds
\]

\[
K = \frac{J}{2\sqrt{2mM}} = I \sqrt{B_m}
\]

\[
I = \int_{s_m}^{s_m} \left[ 1 - \frac{B(s)}{B_m} \right]^{\frac{1}{2}} ds
\]

We use MPI-FORTRAN routines to trace particles at high precision in a realistic time-dependent magnetic field model, and compute I, \( \tau \), and the \( \delta I/\delta r \)
How do we compute the bounce-averaged gradient and curvature drift velocity?

Related to the second invariant $J = 2pI$

We compute $I$ numerically in a realistic magnetic field model, in order to match our predetermined grid in $K$.

We obtain $I$ for the reference field line, as well as $B_m$, alpha, and the gradient of $I$.

The location of the mirror point allows us to compute a time-dependent and MLT-dependent loss cone.

Last, we also compute the $E \times B$ drift using a Volland-Stern $E$-field.
Adiabatic invariants are conserved for electron energies of 100’s of keV to several MeV, which form the electron radiation belts.

Electron radiation belts typically consist of an inner and an outer belt

‘Slot’ region caused by scattering of particles, principally plasmaspheric hiss [Lyons and Thorne, 1973; Abel and Thorne, 1998]

The inner region is very stable and particles have a very long lifetime ~ years

The outer region is much more dynamic and is a topic of ongoing study
\[ PE = 1 - \frac{\sum_{i=1}^{N} (m_i - p_i)^2}{\sum_{i=1}^{N} (m_i - \langle m_i \rangle)^2}. \]

\[ FS = \frac{PE_{Model}}{PE_{Persist}} = \frac{\sum_{i=1}^{N} (m_i - \langle m_i \rangle)^2 - \sum_{i=1}^{N} (m_i - p_i)^2}{\sum_{i=1}^{N} (m_i - \langle m_i \rangle)^2 - \sum_{i=1}^{N} (m_i - m_{i-1})^2}. \]

\[ SS = \frac{PE_{Model} - PE_{Persist}}{1 - PE_{Persist}} = \frac{\sum_{i=1}^{N} (m_i - m_{i-1})^2 - \sum_{i=1}^{N} (m_i - p_i)^2}{\sum_{i=1}^{N} (m_i - m_{i-1})^2}. \]

\[ SS = \frac{PE_{Persist} (FS - 1)}{1 - PE_{Persist}}. \]
CASE STUDIES

CRRES

Reanalysis from CRRES era
In this study, we use the VERB code 2.0 with the following settings, to simulate radiation belt dynamics.

\[
\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L} \left[ \frac{1}{2} D_{LL} \frac{\partial f}{\partial L} \right] _{\mu,j} L^2 D_{LL} \frac{\partial f}{\partial L} _{\mu,j} \frac{\partial}{\partial \mu} + \frac{1}{p^2} \frac{\partial}{\partial p} \left[ \frac{p^2 D_{pp}}{\mu^2} \frac{\partial f}{\partial p} \right]_{\mu,j} + \frac{1}{T(\alpha_0) \sin(2\alpha_0)} \frac{\partial}{\partial \alpha_0} T(\alpha_0)
\]

Diffusion coefficients: \( D_{pp} \) and \( D_{aa} \)

(field-aligned, Gaussian wave power spectrum for night and day chorus, and plasmaspheric hiss)

\[
D_{LL} = 10^{0.056K_p - 9.325} L^{10}.
\]

[Brautigam and Albert, 2000]

Wave Parameters:

\[
\begin{array}{|c|c|c|c|c|c|c|}
\hline
\text{Wave type} & B_n (\mu T) & \lambda_{\text{max},n} & \text{Ratio of plasma to gyrofrequency} & \text{MLT} & \text{Wave spectral properties} \\
\hline
\text{Chorus day} & 10^{0.75+0.043} & 35 & N_0 = 124 \cdot \left(\frac{3}{L}\right)^4, n & 25 & \omega_n/\Omega_e = 0.2, \\
& & & \omega_p = \sqrt{4\pi N_0 e^2/m} & & \delta\omega/\Omega_e = 0.1, \\
& & & f_n = \frac{2\pi}{T} & & \omega_{sc}/\Omega_e = 0.3, \\
& & & & & \omega_{sc}/\Omega_e = 0.1 \\
\hline
\text{Chorus night} & 50 & 15 & N_0 = 124 \cdot \left(\frac{3}{L}\right)^4, n & 25 & \omega_n/\Omega_e = 0.35, \\
& & & \omega_p = \sqrt{4\pi N_0 e^2/m} & & \delta\omega/\Omega_e = 0.15, \\
& & & f_n = \frac{2\pi}{T} & & \omega_{sc}/\Omega_e = 0.65, \\
& & & & & \omega_{sc}/\Omega_e = 0.05 \\
\hline
\text{Hiss inside} & 30 & 40 & N_0 = 10^{0.3145+3.9043}, 60 & 60 & \omega_n = 3587 \text{rad/sec}, \\
& & & \omega_p = \sqrt{4\pi N_0 e^2/m} & & \delta\omega/\Omega_e = 1297 \text{rad/sec}, \\
& & & f_n = \frac{2\pi}{T} & & \omega_{sc} = 12566 \text{rad/sec}, \\
& & & & & \omega_{05} = 628, \text{rad/sec} \\
\hline
\end{array}
\]

Table 2.1: Wave parameters used for computing pitch angle and energy diffusion coefficients

(a)[Sheeley et al., 2001] (b)[Carpenter and Anderson, 1992] (c)[Meredith et al., 2006]
Boundary conditions are as indicated to right, except for outer boundary. We use $L = 6$ and update outer boundary PSD from reanalysis from previous time step.

Wave Parameters:

- Subbotin and Shprits, 2009

We use a simplified single grid. $(L, \mu, \alpha)$, which is correct within wave parameterization error $\sim 30\%$, provided the grid is large enough, time step is small enough, and we use a logarithmic energy grid.

[Subbotin and Shprits, 2009]
Radiation Belt Forecast Framework

http://rbm.epss.ucla.edu/realtime-forecast/

- Real-time Van Allen Probes
- Real time GOES 13 and 15
- Real time and forecast Kp
- Real time ACE solar wind

L* and PSD (T89)

Nowcast PSD

VERB

Kalman Filter

Forecast radiation belt state

Data
Model
Process
Product

Nowcast radiation belt state
Recent example of radiation belt forecast fluxes at 1 MeV

The forecast runs every 2 hours automatically, and the most recent forecast figure is shown at the following web address

http://rbm.epss.ucla.edu/realt ime-forecast/
Forecast Performance

*Kellerman et al., [2016], Space Weather – in preparation*
The B-field model is important!
Hui Zhu - Friday 4pm – GEM, QARBM
Diffusion Coefficients
Kalman Filter

X: State vector, PSD \((c/(\text{cm.MeV}))^3\)
M: Model matrix (VERB code)
P: State error covariance matrix
Q: Model covariance matrix.
y: PSD measurements
K: Kalman Gain
R: Measurement error

Forecast Step:

\[
X_f = M_t X_{t-1}
\]
\[
P_f = M_t P_{t-1} M_t^T + Q_t
\]

Update Step:

\[
X_a = X_f + K_t (y_t - X_f)
\]
\[
K_t = P_f (P_f + R_t)^{-1}
\]
\[
P_a = (I - K_t) P_f
\]
We set out to minimize:

\[ \Delta PSD_{21} = 2(c_f \times PSD_2 - PSD_1)/(c_f \times PSD_2 + PSD_1) \]

PSD at fixed \( L^* \), \( \mu \), and \( K \).

\( PSD_1 \) is the reference or gold standard
\( c_f \) is a calibration coefficient

\[ \Delta L^* \leq 0.1R_E \quad \Delta t \leq 5 \text{ min} \]

Find \( c_f \) that minimizes the mean \( \Delta PSD \) for each fixed invariant pair

Use the weighted mean of \( c_f \) for all \( L^* \) and \( K \) conjunctions to correct each energy channel, and estimate the bias. The width of the distribution gives an estimate of the error between the two spacecraft.
Observational error and bias
In this study, we focus on two enhancements in electron flux observed during the same storm.
We include 5 Spacecraft:

CRRES - HAEO
Akebono - LEO
GPSns18 - MEO
GEO1989 - GEO
GEO1990 - GEO
The Third Radiation Belt

CRRES was located pre-midnight at 23.5 MLT and near L* = 4 during this period

a) Flux increases across all energies early on March 26

b) Adiabatic above ~0.4 MeV, and non-adiabatic below.

c) Evidence of dipolarization in Bz

Evidence of a particle injection.
We usually consider $L^*$ vs time figures of PSD at fixed $\mu$ and $K$.

Peaks in PSD at a particular $L^*$ represent either local acceleration or variable boundary effects. [Selesnick and Blake, 2000]

In 3D reanalysis we reconstruct the PSD globally, over a complete grid of $L^*$, $\mu$, and $K$.

In order to investigate PSD evolution over various $\mu$ in $L^*$, one can plot a set of snapshot figures, each for a fixed $K$ and time.
Each panel represents a snapshot, indicated by the blue dashed lines in panel (k)

1) Rapid loss during the main phase

2) The appearance of a third radiation belt

3) Growing peaks in PSD to form a fourth belt

The growing peaks in PSD indicate that the fourth belt was created by local acceleration.

Kellerman et al., [2014], JGR
There are 4 mechanisms that resulted in the observed four-zone structure:

1. Prompt injection
2. Secondary injection
3. Losses/outward radial diffusion
4. Local acceleration
Van Allen Probe and GOES data, now including losses to the magnetopause based on the last-closed-drift shell (LCDS)

Invariant coordinates are based on T89, T04s and TS07D-1A

The LCDS is currently based on T04s


LCDS work with Steve Morley and Jay Albert (LANL/AFRL)

TS07D model work with Grant Stephens and Misha Sitnov (APL)

Integration into IRBEM with Paul O’Brien (Aerospace) and Sebastian Bourdarie (ONERA)
1D Data Assimilation

First application to our 1D-radial diffusion model

\[
\frac{\partial f}{\partial t} = I^2 \frac{\partial}{\partial L} \frac{1}{\mu J L^2} \frac{\partial f}{\partial L} f \tau
\]

Hourly averaged CRRES observations

\[\mu = 700 \text{ MeV } G^{-1}, \ K = 0.11 \ G^{0.5} \ R_E\]

Radial Diffusion Model

[Shprits et al., 2007]
1D Data Assimilation

First application to our 1D-radial diffusion model

\[
\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L} \left|_{\mu,J} \right. \frac{1}{L} \frac{\partial f}{\partial L} \left|_{\mu,J} \right.
\]

-\( f/\tau \)
Persistent peaks in PSD and positive innovation indicate that in addition to the radial diffusion there is another acceleration mechanism present in the inner magnetosphere.

Negative innovation at the outer L-shells may indicate an additional loss mechanism.

\[ X_a = X_f + K_t (y_t - X_f) \]

[Shprits et al., 2007]
2D Data Assimilation

\[ X_t^f = M_{t-1} X_{t-1} \]

\[ X_t^f = M_{t-1\alpha} M_{t-1E} X_{t-1} \]