Data Assimilative Real Time Prediction of the Earth Radiation Belts

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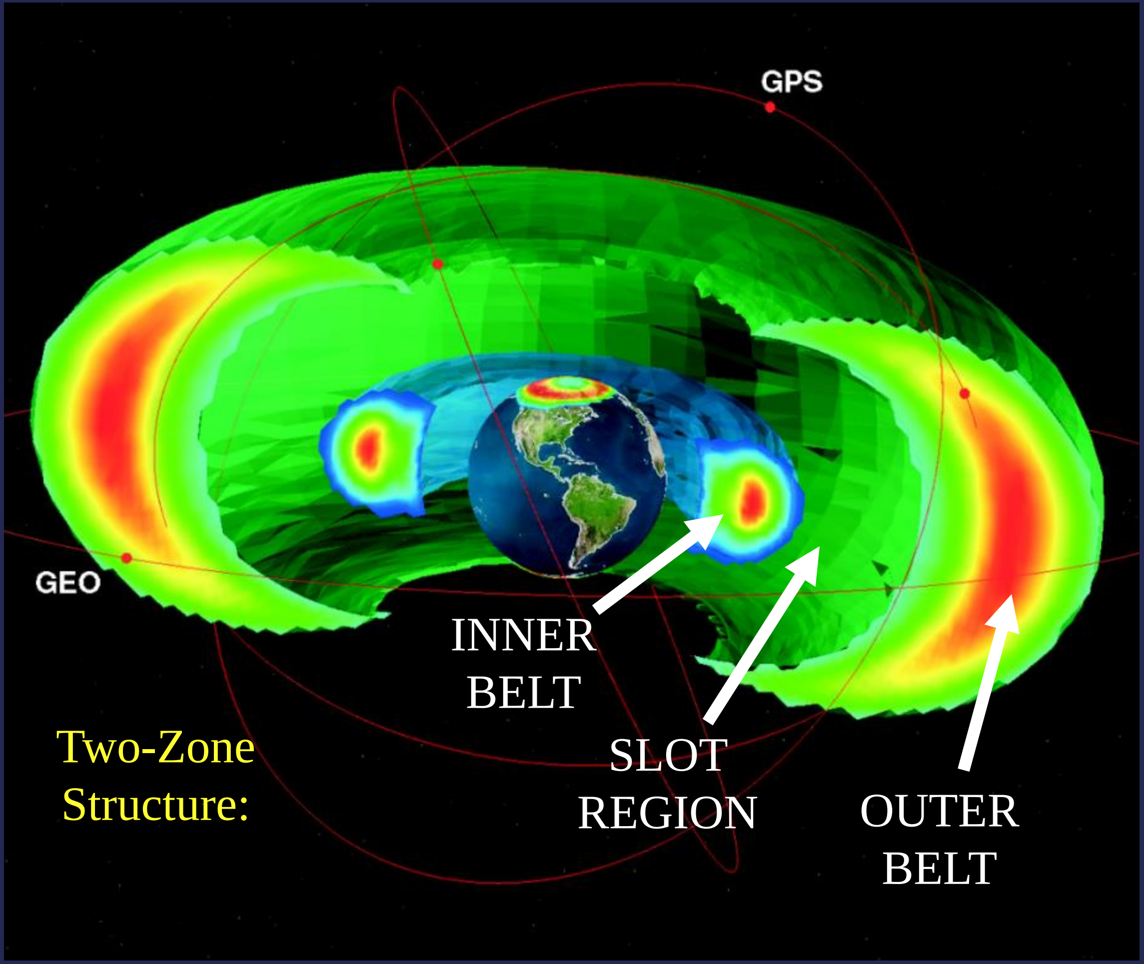
Talk Outline

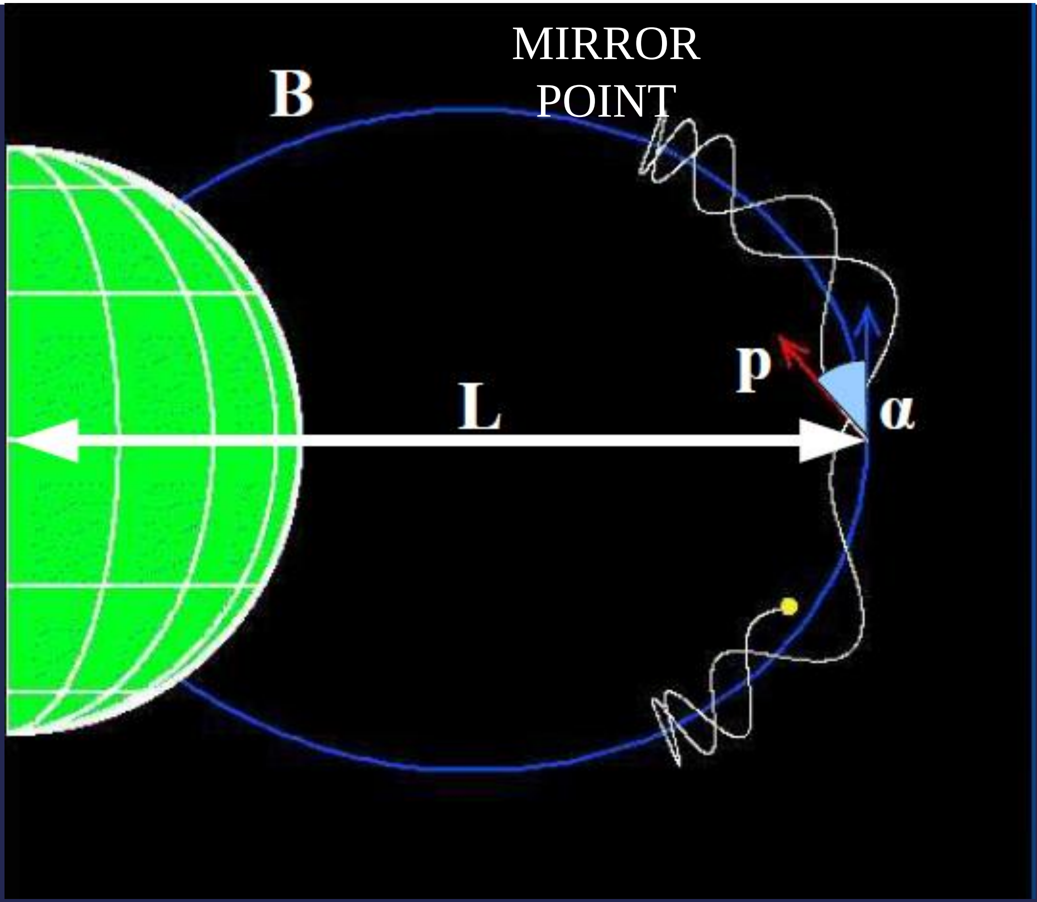
- Introduction
- 1D Data Assimilation
- VERB-3D
- Data Assimilation with VERB-3D
- Summary

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.

Bounce Motion



Pitch-angle – the angle between the magnetic field and particle's velocity.

90˚ pitch-angle particles will stay in the equatorial plane

Small pitch-angle particles will be lost to the atmosphere.

To determine the net radiation on spacecraft, fluxes should be known for all radial distances, pitch angles, and energies.

Kalman Filter

Kalman filtering uses observations containing inaccuracies (errors) and combines them with a model of RB by weighting observations and model according to their errors and producing a more precise estimate of state of RB.

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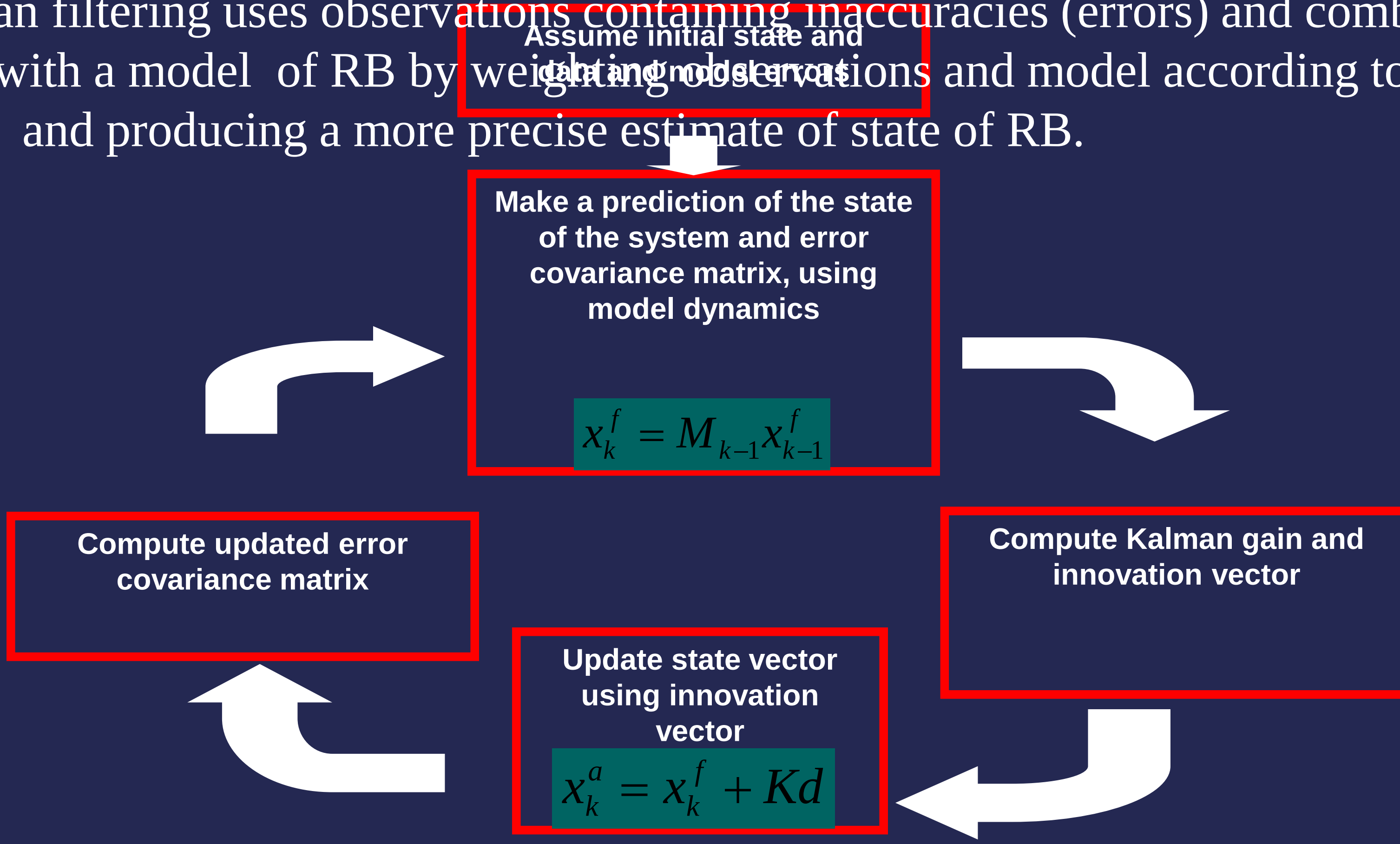
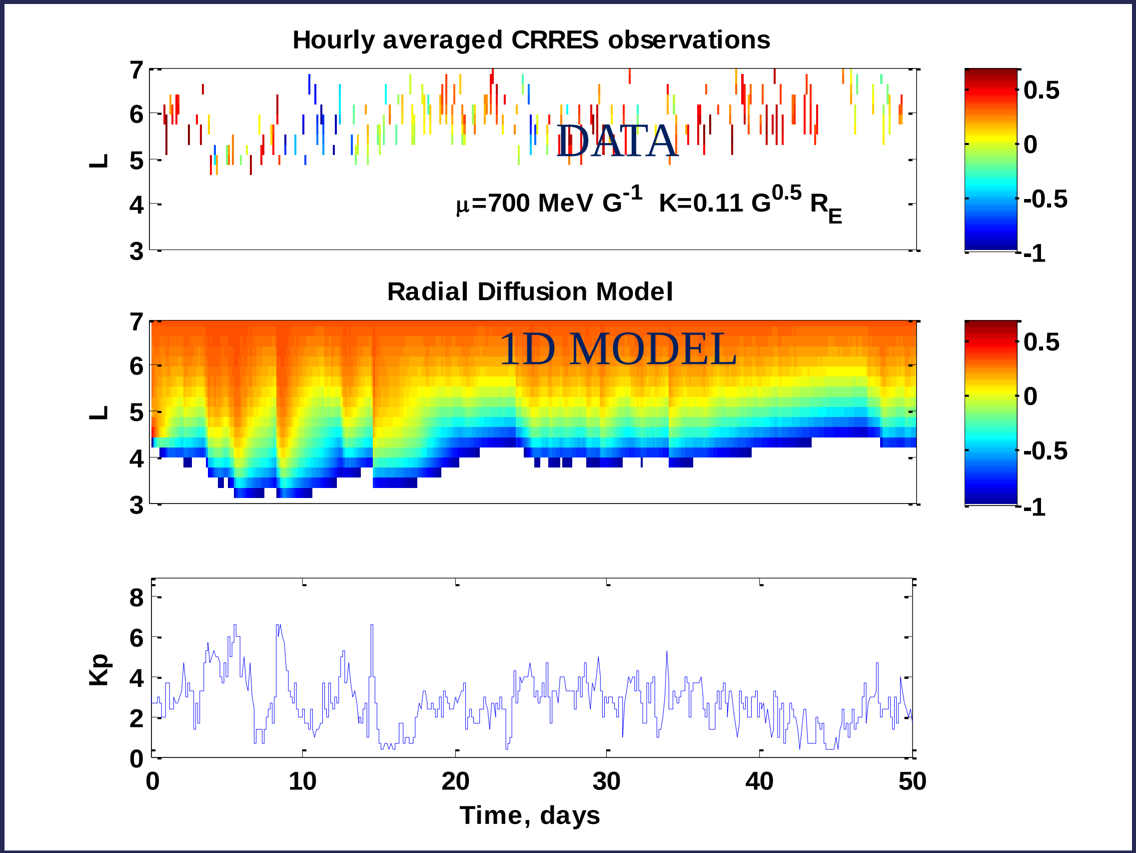


Kalman filters are used for robotic motion planning and control, trajectory optimization, signal processing, weather prediction, atmospheric and oceanic sciences and econometrics.

Comparison of the Observations and the Radial Diffusion Model



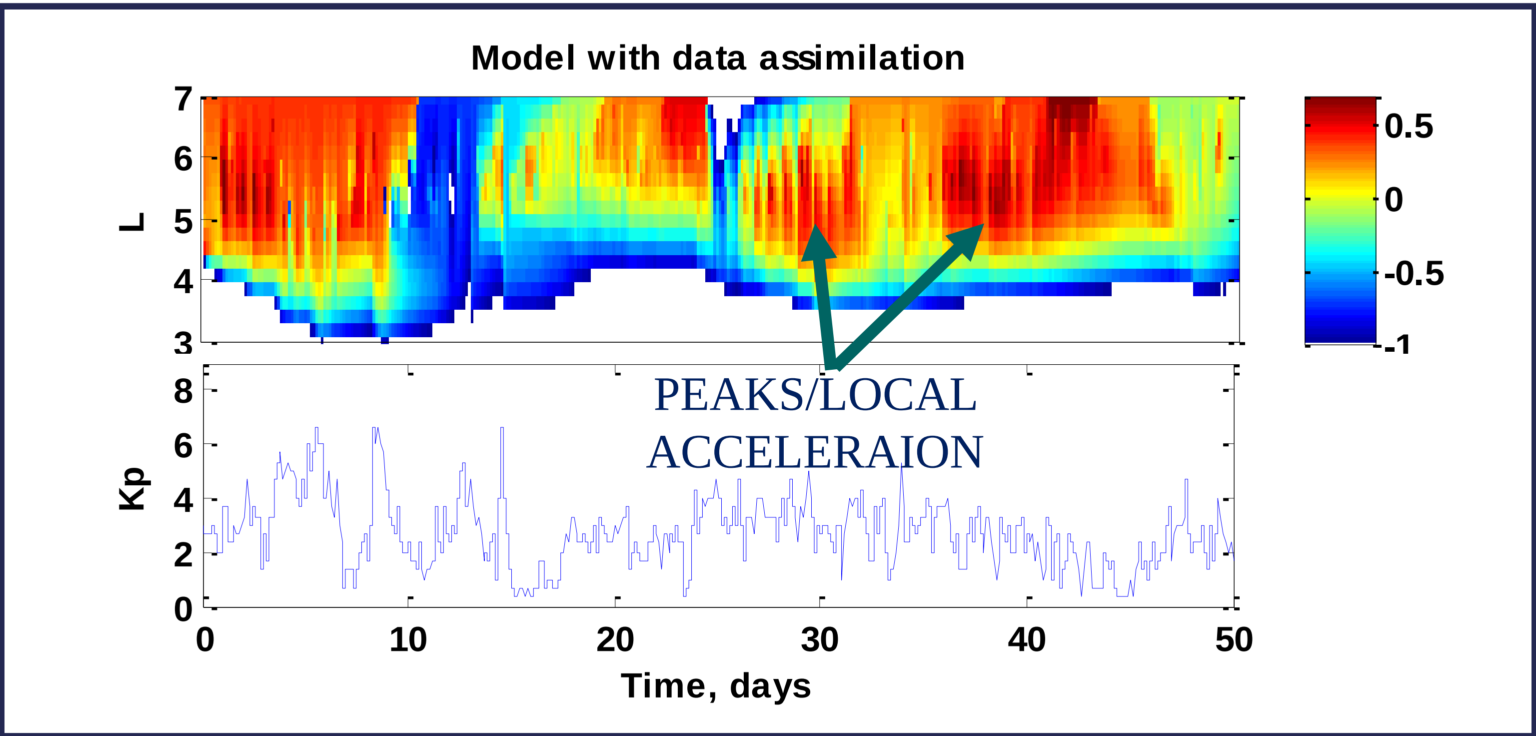
[Shprits et al., 2007]

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.

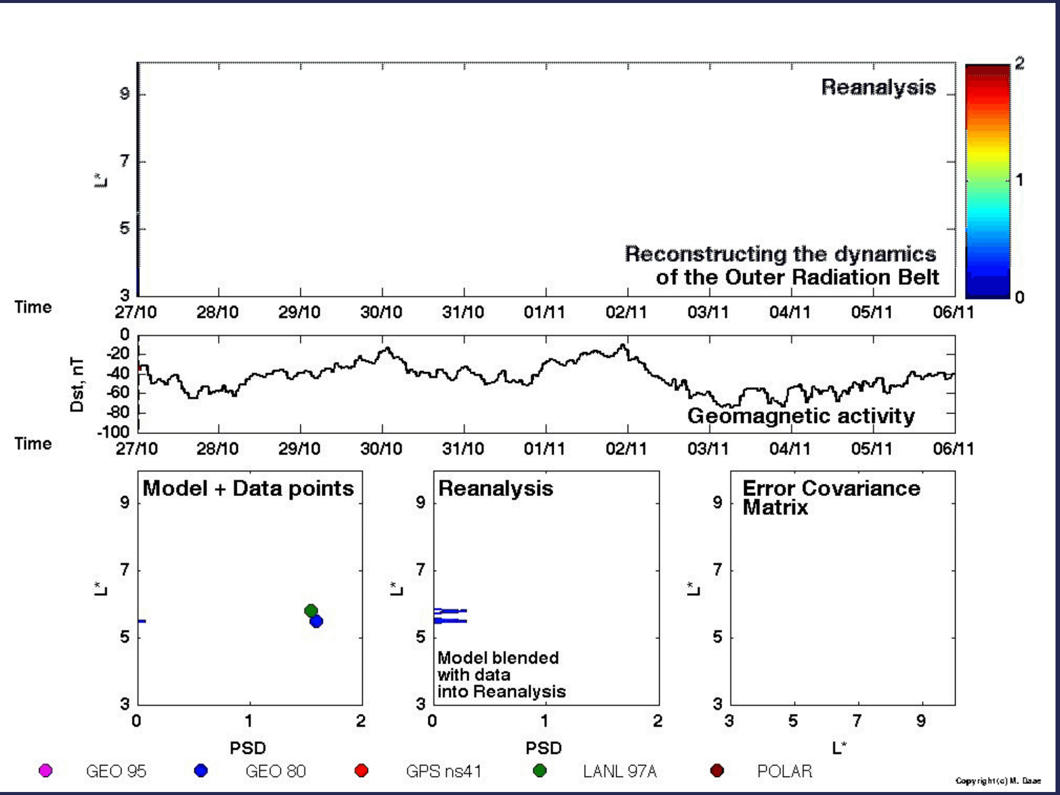
Data Assimilation/ Peaks in Phase Space Density



Data assimilation can fill in spacio-temporal gaps
Data assimilation shows building up peaks in Phase Space Density.

Shprits et al., 2007

Dynamic 1D Data Assimilation



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Data is blended with the model according to the underlying structure of data and model errors.

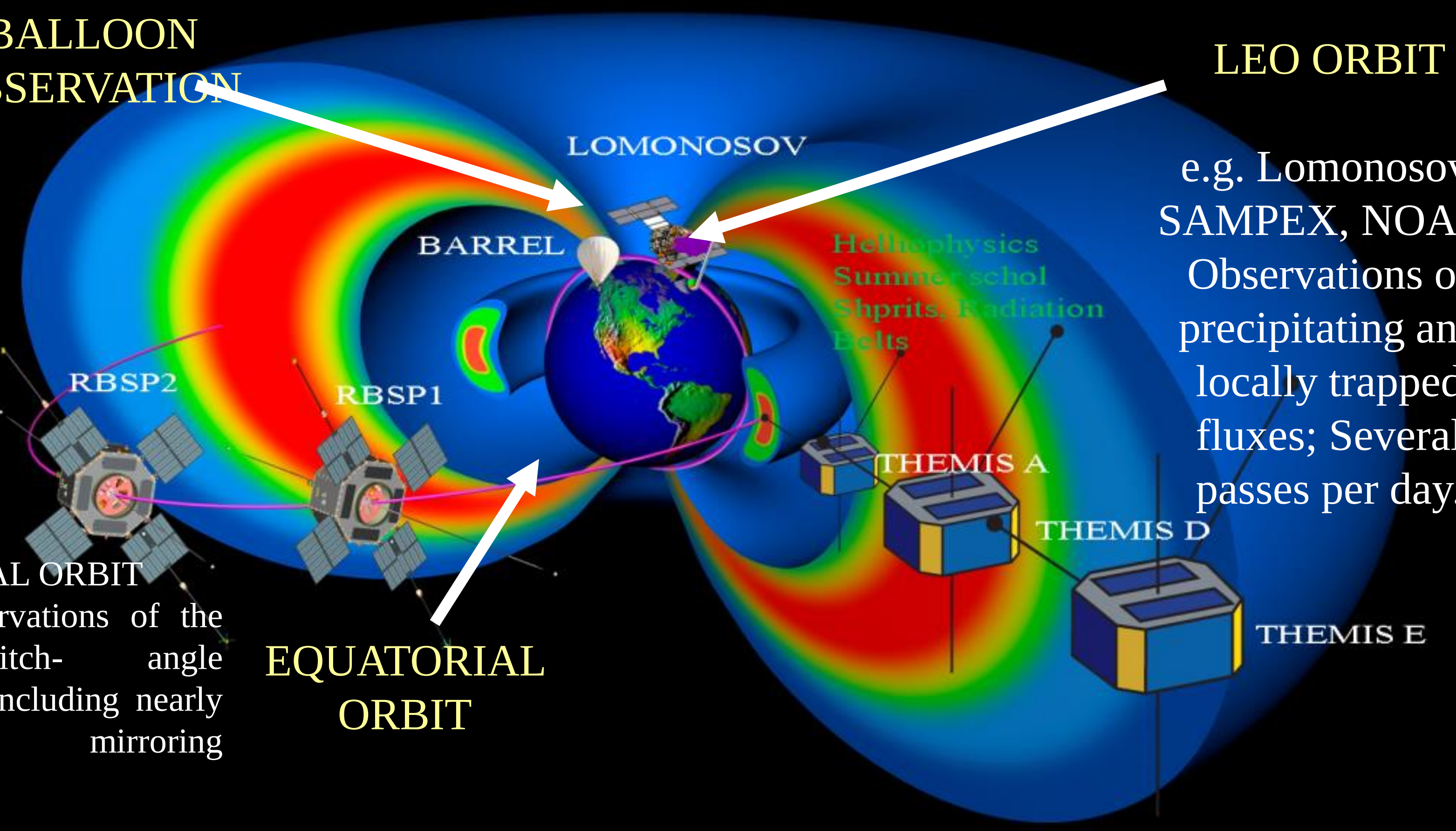
Data from 5 spacecraft are assimilated and radial profile of PSD is dynamically reconstructed.

[Shprits et al., 2012, movie produced by M. Daa]

Multi Point Observations

BALLOON OBSERVATION

LEO ORBIT



e.g. Lomonosov, SAMPEX, NOAA. Observations of precipitating and locally trapped fluxes; Several passes per day.

EQUATORIAL ORBIT

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

EQUATORIAL ORBIT

3D Fokker Planck Equation including the Mixed Diffusion Terms

Radial diffusion

$$\frac{\partial f}{\partial t} = L^{*2} \frac{\partial}{\partial L^*}\bigg|_{J_1,J_2} \frac{1}{L^{*2}} D_{L^*L^*} \frac{\partial f}{\partial L^*}\bigg|_{J_1,J_2} +$$

Energy diffusion

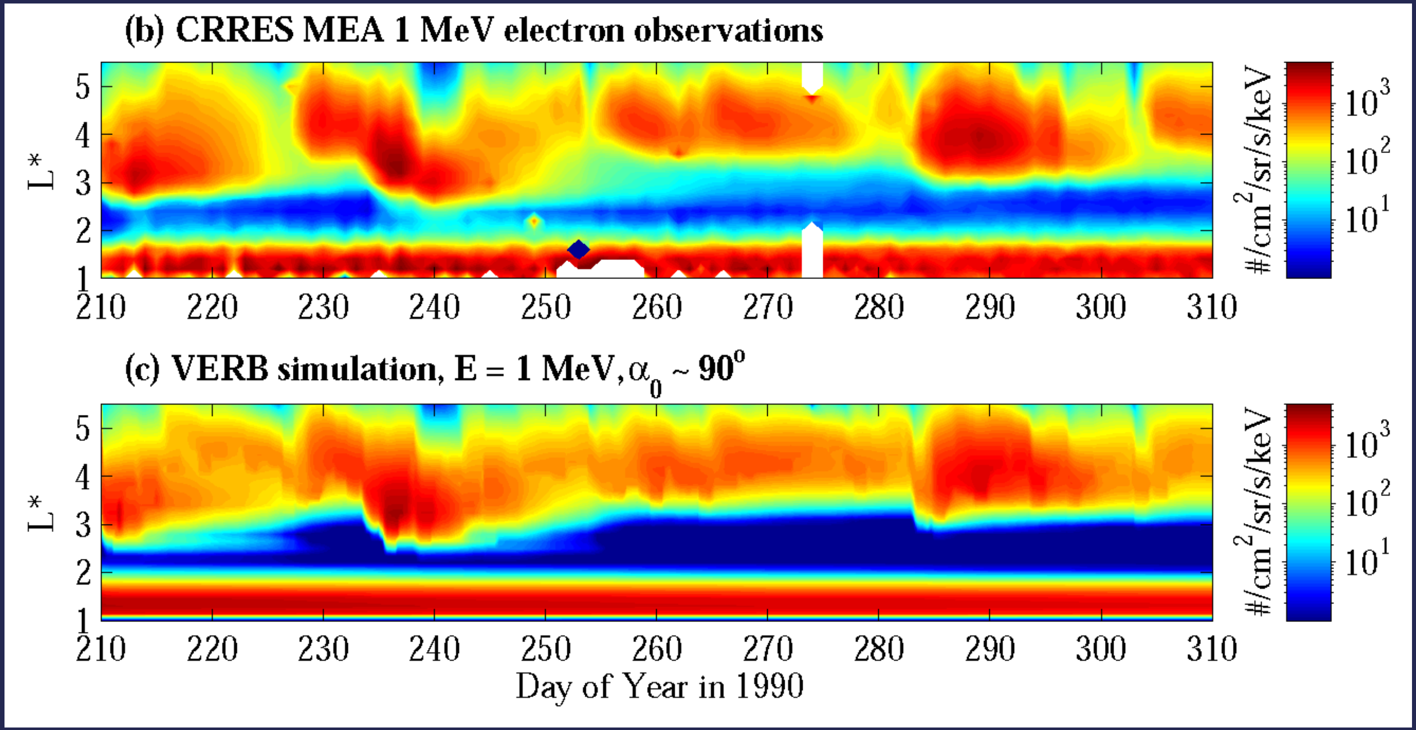
$$+ \frac{1}{p^2} \frac{\partial}{\partial p}\bigg|_{L,\alpha_0} p^2 \left(D_{pp} \frac{\partial f}{\partial p}\bigg|_{L,\alpha_0} + D_{p\alpha_0} \frac{\partial f}{\partial \alpha_0}\bigg|_{L,p} \right) +$$

Pitch-angle diffusion

$$+ \frac{1}{T(\alpha_0)\sin(2\alpha_0)} \frac{\partial}{\partial \alpha_0}\bigg|_{L,p} T(\alpha_0)\sin(2\alpha_0) \left(D_{\alpha_0 p} \frac{\partial f}{\partial p}\bigg|_{L,\alpha_0} + D_{\alpha_0\alpha_0} \frac{\partial f}{\partial \alpha_0}\bigg|_{L,p} \right) +$$

$$+ Sources - Losses$$

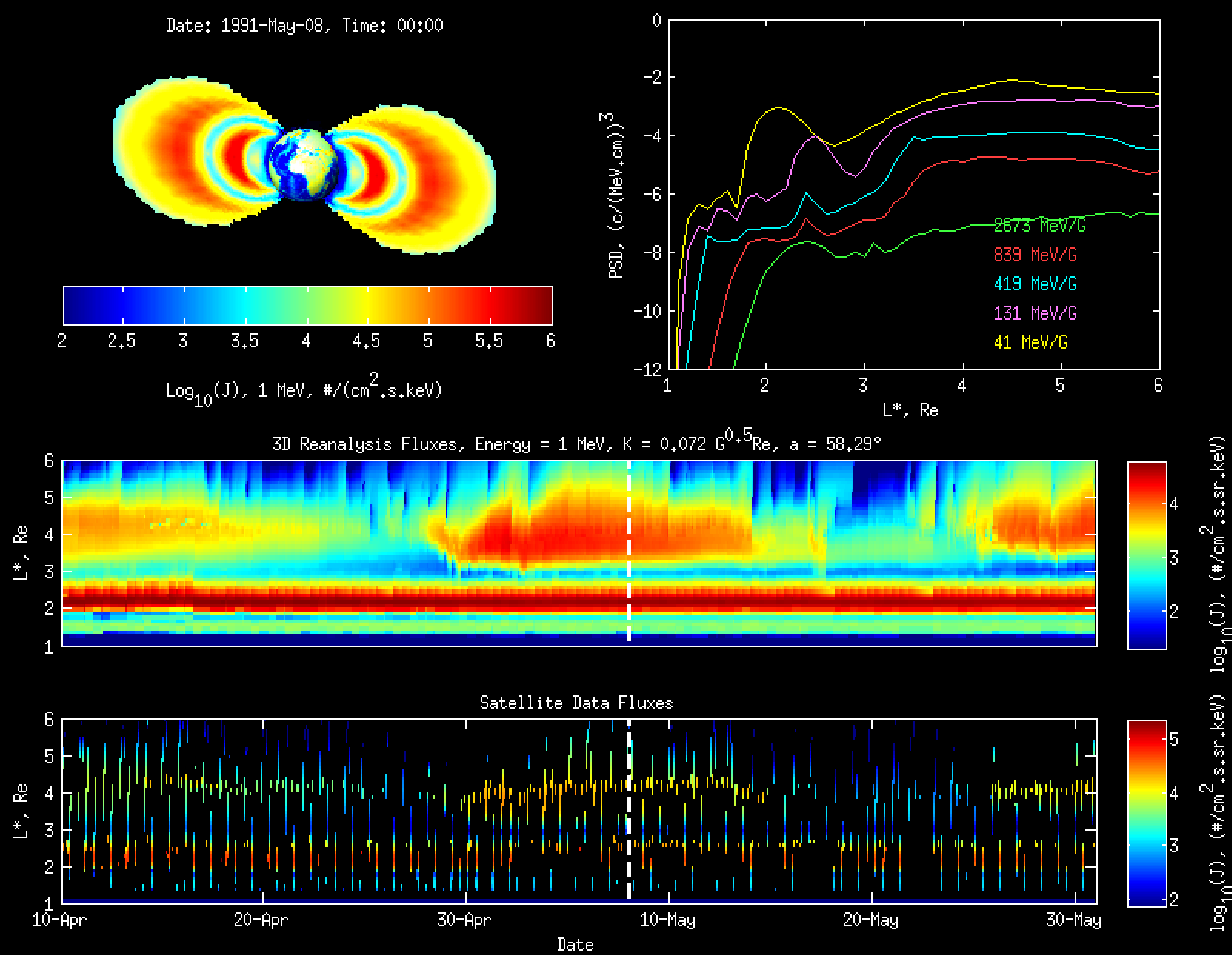
Validation of the Versatile Electron Radiation Belt (VERB) Code for Over 100 Days in 1990



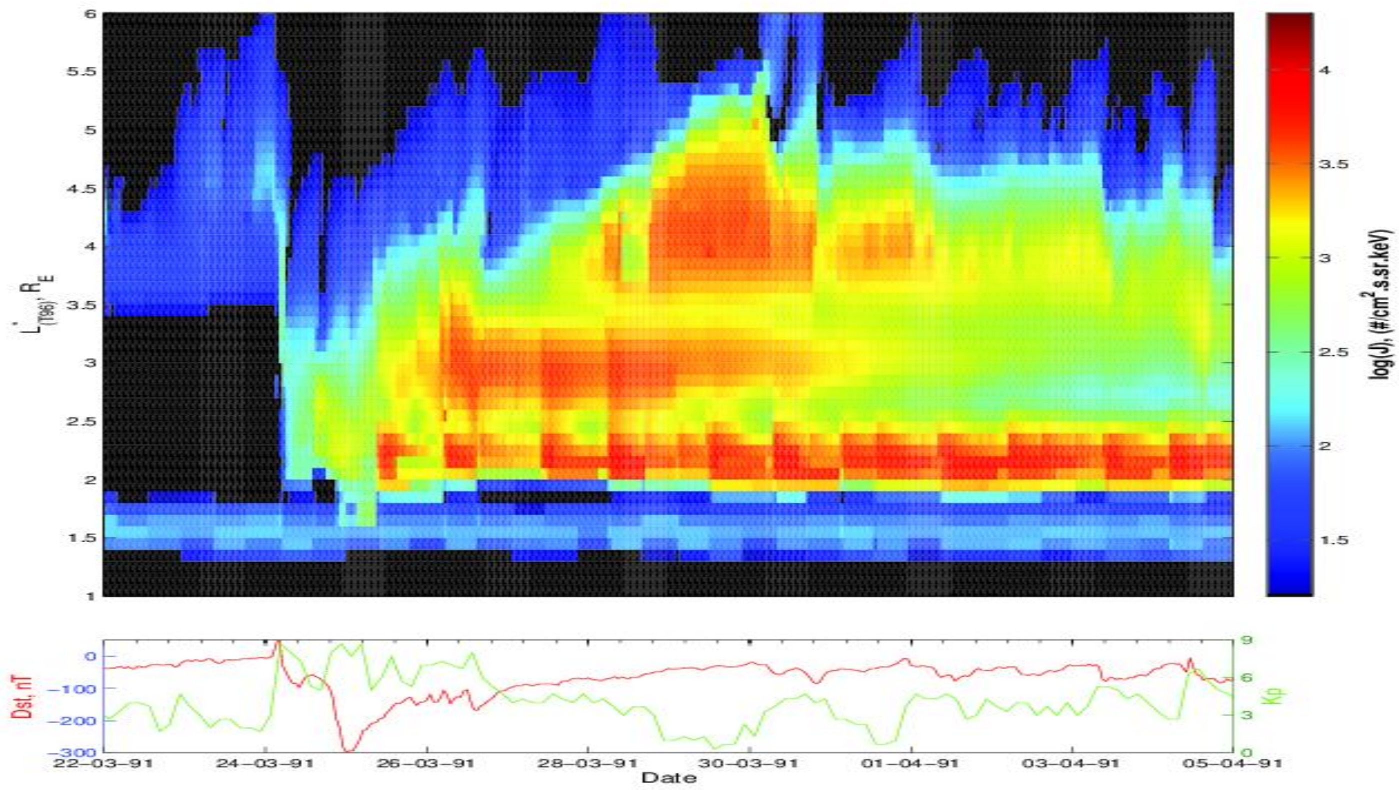
Shprits et al., 2009; Kim et al., 2010

- VERB accounts for scattering into the atmosphere, loss to the magnetopause, local acceleration by waves and predicts global evolutions in terms of pitch angle, energy and radial distance.
- VERB predicts the instantaneous location of the upper boundary of the slot region, the empty slot region, the stable inner belt, the location of the peak of fluxes and the amplitude of fluxes.

Reconstruction of the State of the Radiation Belts $J(L, E, \alpha)$ Using 5 Spacecraft



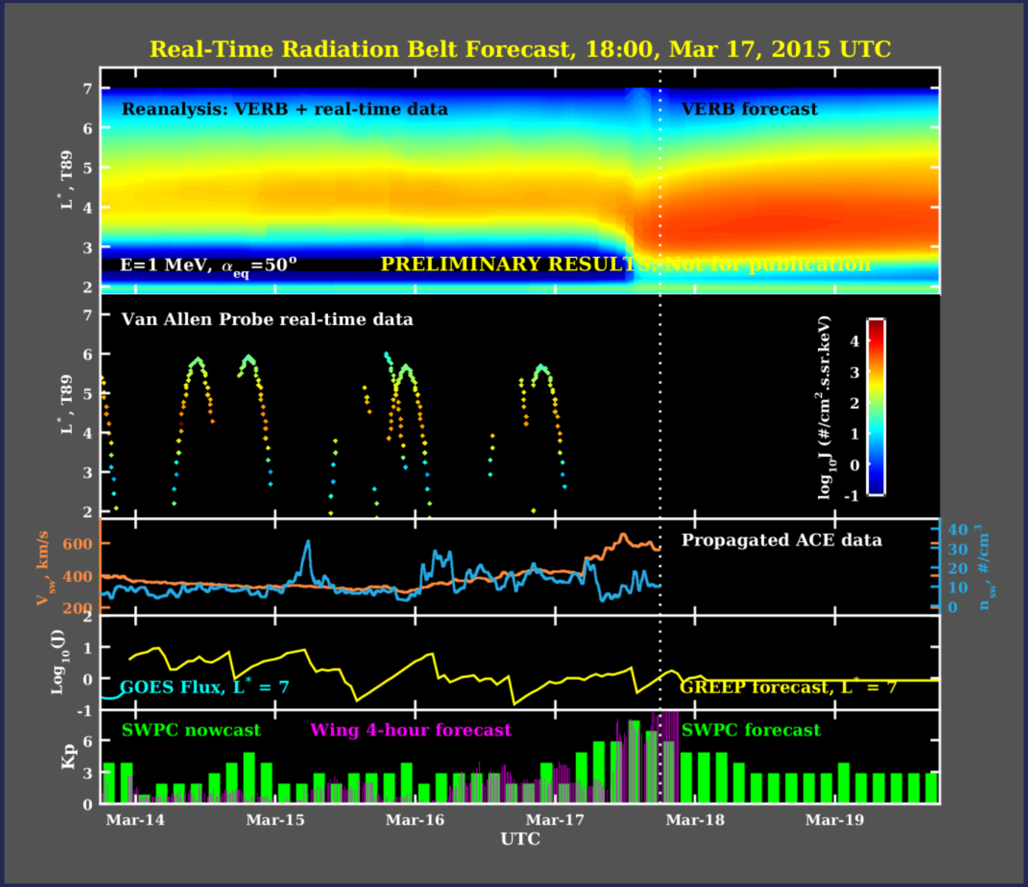
4 Zone Structure During the March 1991 Storm



Data assimilation helped reveal the 4-zone structure during the March 1991 storm.

St Patrick's Day Strom

Real-time data from GOES, Van Allen Probes, ACE

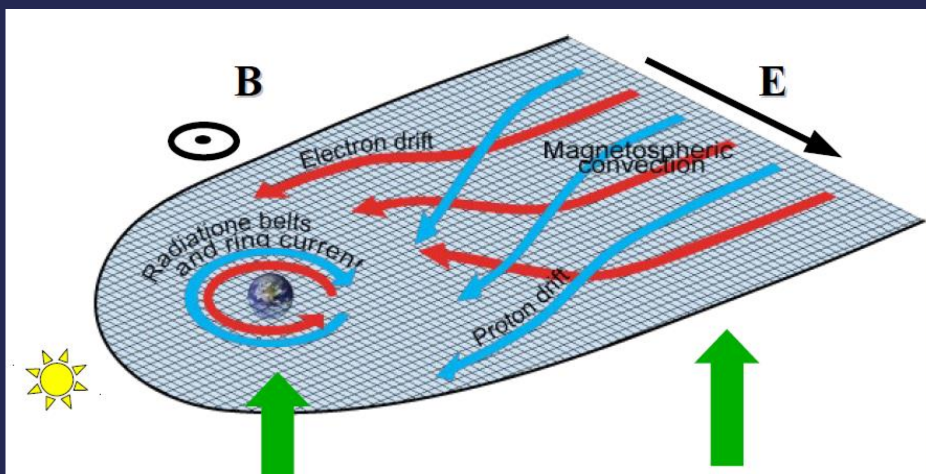


Our tools mature to the level that we can apply them for operational weather prediction.

We use ACE, GOES, Van Allen Probes real time data and GREEP predictions.

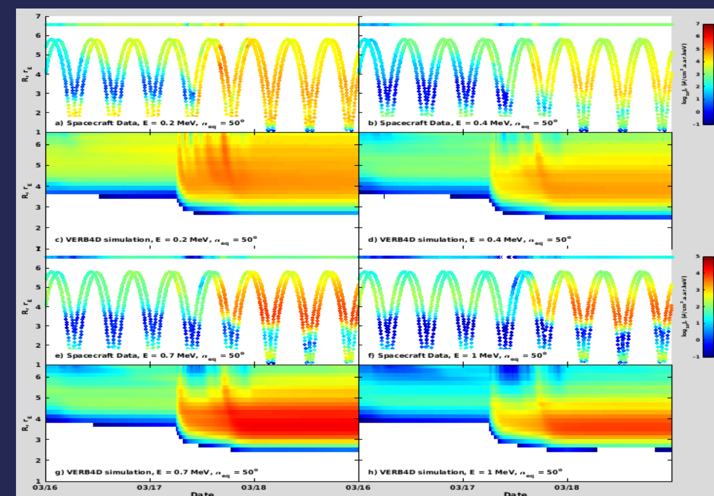
http://rbm.epss.ucla.edu/realtime-forecast/

Comparison of the VERB-4D with Van Allen Probes Observations



Stably trapped particles

Convection of the seed population of energetic electrons



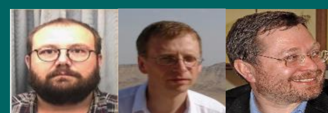
PROGRESS

PRediction Of Geospace Radiation Enviroment and Solar wind parameterS

New EC Horizon 2020 funded project currently at Grant Agreement Preparation phase.

PARTICIPANTS

U. Sheffield



FMI

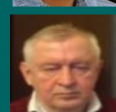
U.Warwick

UCLA

MIT/

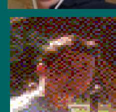
U. Michigan

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

Conclusions

- **Data assimilation allows us to blend observations from various spacecraft and allows us to reconstruct the global state of the radiation belts.**
- **Data assimilation will be crucial for developing models for forecasting, nowcasting and specification models.**
- **Future work should include code coupling (PROGRESS), 3D and 4D data assimilation using multiple spacecraft.**
- **We need to develop new data assimilation tools for space weather applications.**