Using Ground-Based Observations to Explore the Plasmasphere

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Outline

- Field Line Resonance modeling
- Comparison with the FLIP model
- Data Assimilation
- DGCPM
- One event: July 15, 2012
- Conclusion

Field Line Resonance

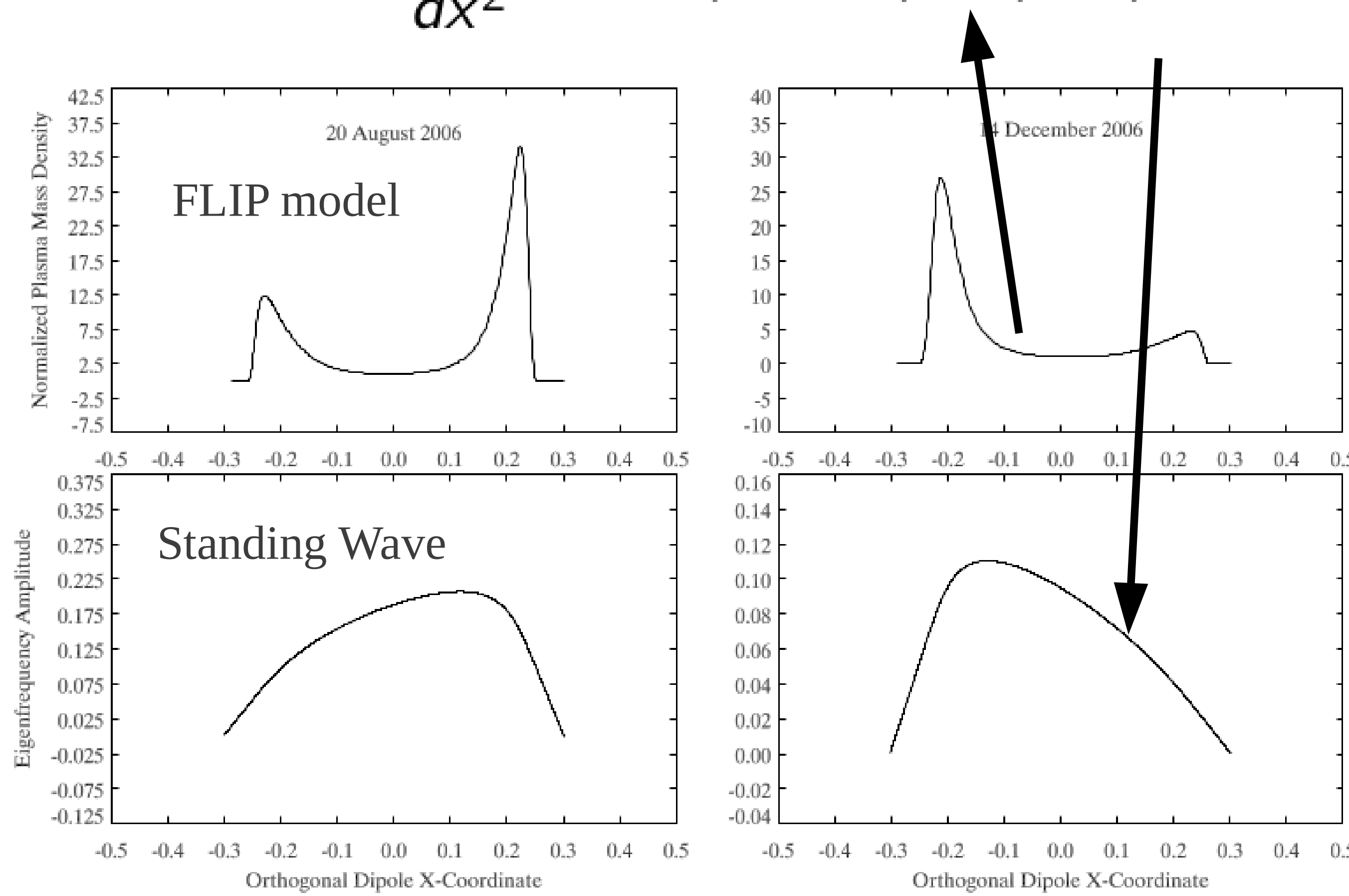
$$\frac{\partial^2 \mathbf{E}}{\partial t^2} = \mathbf{c}_A \times \mathbf{c}_A \times \nabla \times \nabla \times \mathbf{E} \longrightarrow \frac{d^2 T_n}{dx^2} + \Omega_\nu^2 (1 - x^2)^6 N(x, L) T_n = 0$$

$$c_{A_0}^2 = \frac{B_0^2}{\mu_0 \rho_e}$$

Resonance frequency (eigen value) accompanies each standing wave shape (eigen mode).

We expect the slope at the end points to be related to the amplitude of the oscillation observed by a ground magnetometer.

Schulz (1996) model bettter in the outer plasmasphere, but less well for L<3.



Phil Richards' FLIP models field-aligned transport with multiple species based on an ionospheric model boundary

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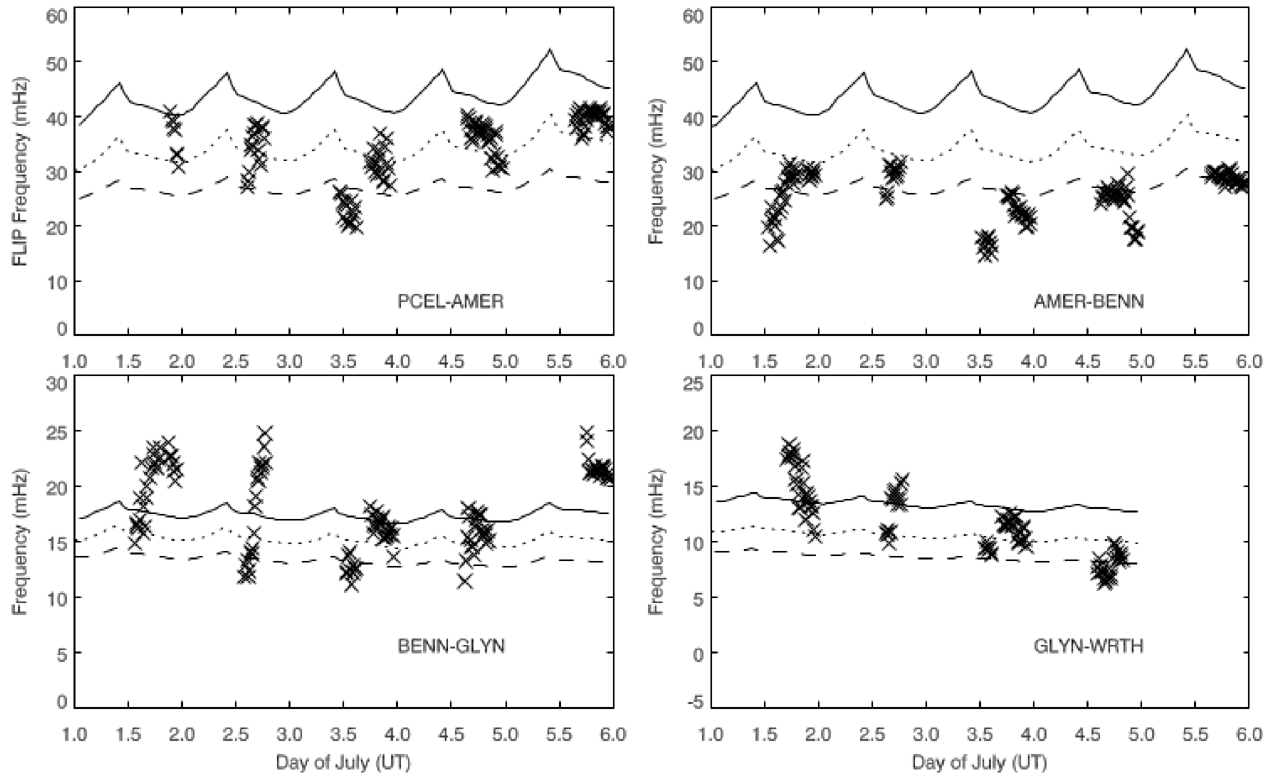
Comparison With Quiet Time Observations

Fundamental mode frequencies derived from solving standing wave equation in the FLIP density distribution compared with FLR frequencies derived from SAMBA station pairs.

This is a quiet interval in July 2006.

Agreement is good, but depending on the accuracy of the observations there are still variations which are not modeled by FLIP.



Top left:	Bottom Left:	Top Right:	Bottom Right:
PCEL-AMER	BENN-WRTH	AMER-BENN	WRTH-GLYN
1.99 - solid	2.61 - solid	2.28 - solid	2.86 - solid
2.135 - dotted	2.735 - dotted	2.445 - dotted	3.13 - dotted
2.28 - dashed	2.86 - dashed	2.61 - dashed	3.40 - dashed

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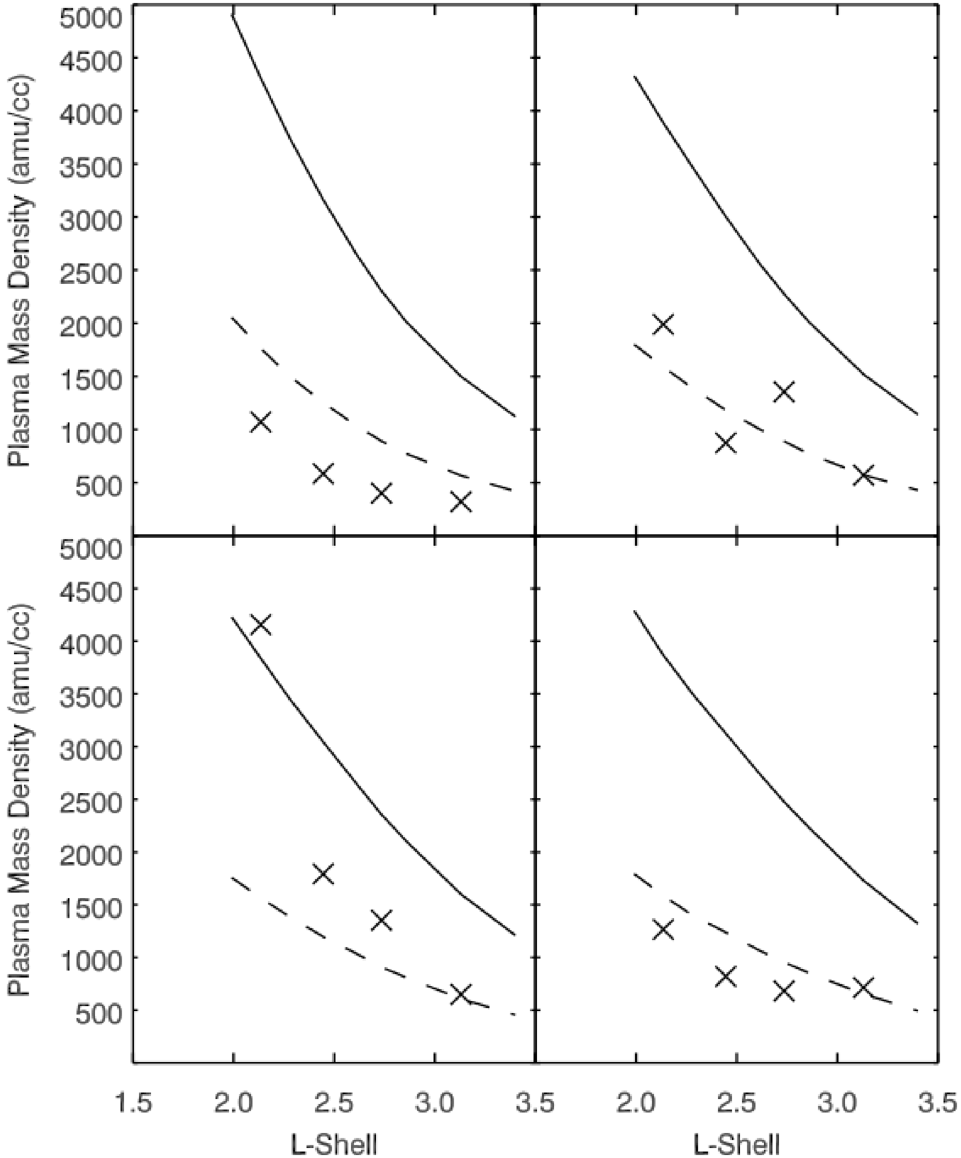
Comparison With Quiet Time Observations (2)

- To Schulz or not to Schulz...

Densities derived using the Schulz (1996) approach can be off by a factor of several. The difference is greatest in the inner region of the plasmasphere.

Nevertheless, the frequencies derived from the numerical solver agree with observations.



Solid line: FLIP produced densities

Dashed line: FLIP derived frequencies inverted via Schulz formula

X symbols: Magnetometer frequencies inverted via Schulz formula

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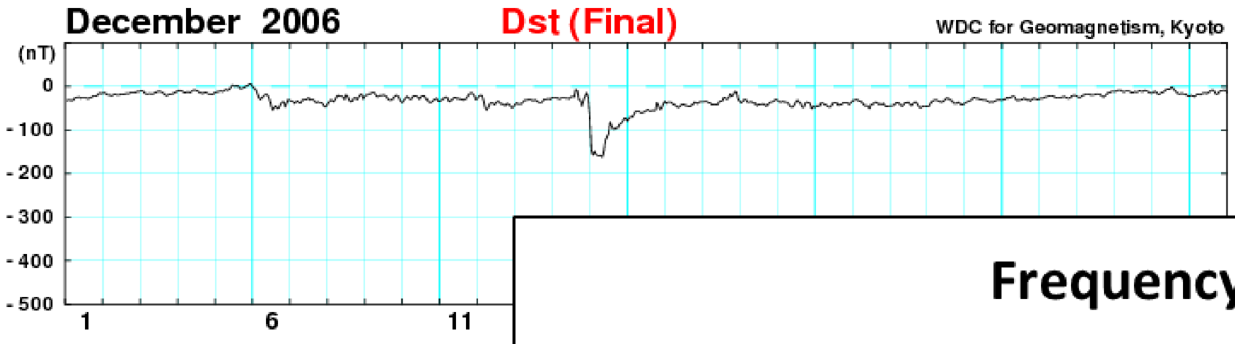
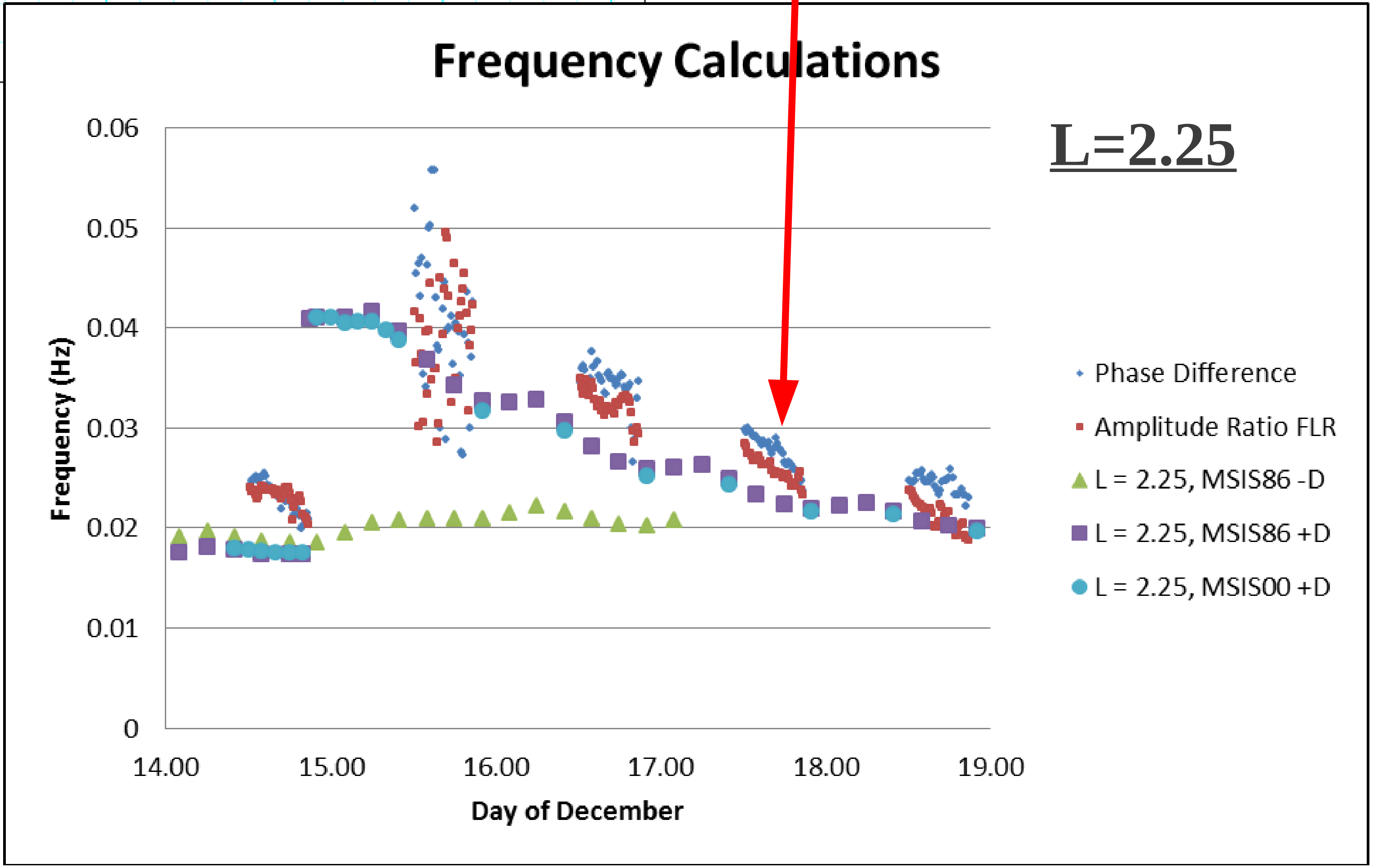
Comparison With Active Time Observations



Refilling seen in data and model



SAMBA magnetometer array data compared with the FLIP field line transport model for a large storm

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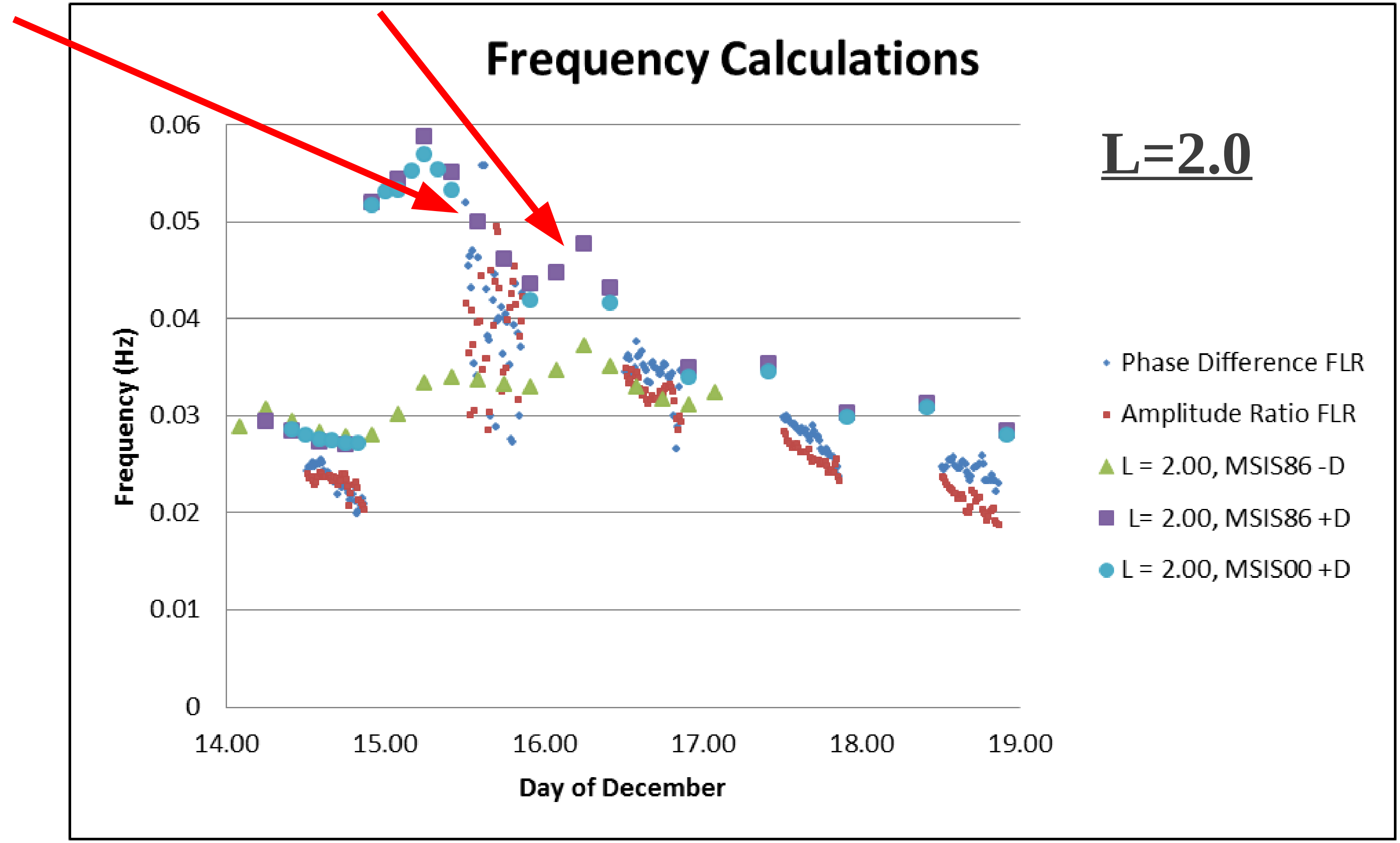
Comparison With Active Time Observations (2)

- Same event
- Both refilling and emptying seen in model

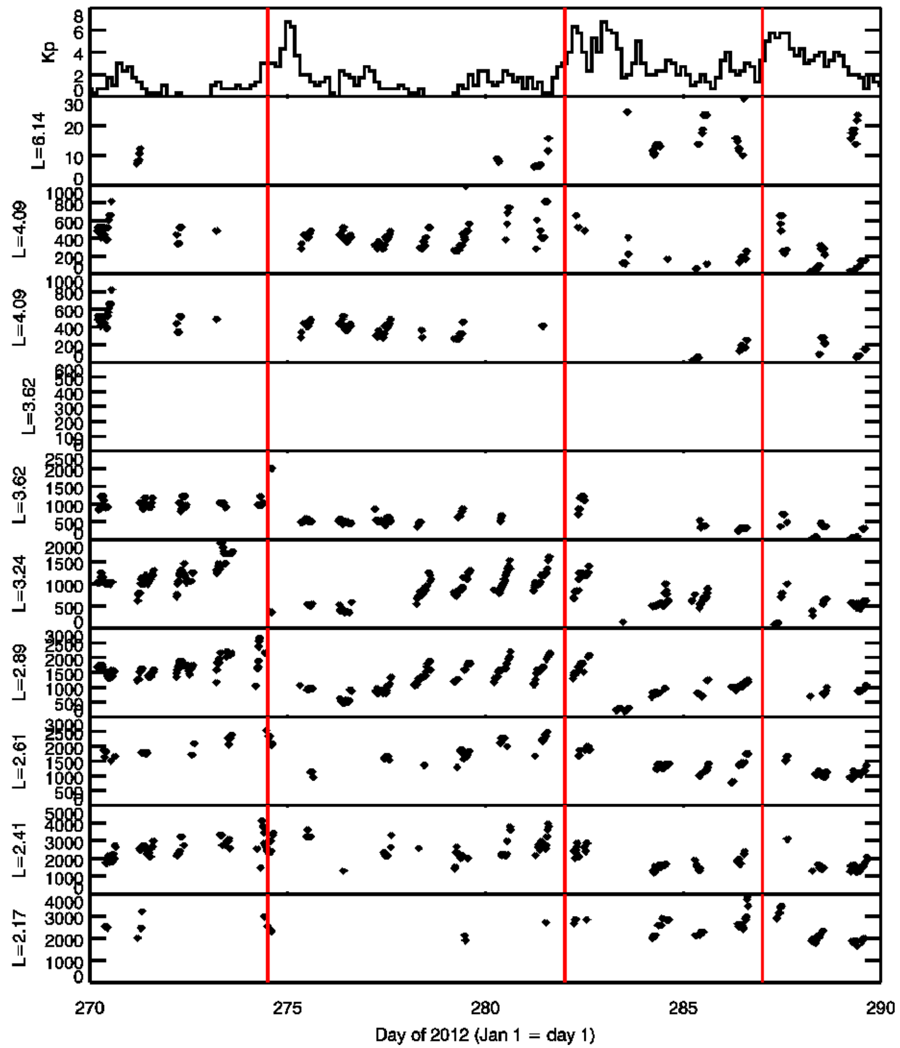


Data Assimilation

- Model
  - Plasmasphere model which is not perfect
  - If run open-loop it should reproduce qualitatively correct dynamics
- Observations
  - Satellite or ground-based observations of density at different points
  - More accurate than the model, but sparse in time and space
- Data assimilation combines the two
  - A (hopefully) more accurate state of the system – plasma density everywhere even where there are no observations
  - Run the model forward in time
  - Perturb the model in the direction of the observations (explained shortly)
  - Perturb more or less, depending on trust in model versus data – for example based on uncertainty on observations

Ground-Based Observations of the Plasmasphere

- Sparse observations
- FLR only present on the dayside
- Upward slope is refilling during the dayside pass of the field line
- Depletion associated with larger Kp, enhanced convection.
- Sometimes a delay between larger Kp and depletion
- Enhanced convection can easily erode the plasmasphere inside L=3 (inside L=2 also sometimes)
- Perhaps we don't call these deep erosions plasmapause but they are gradients which are important for controlling waves



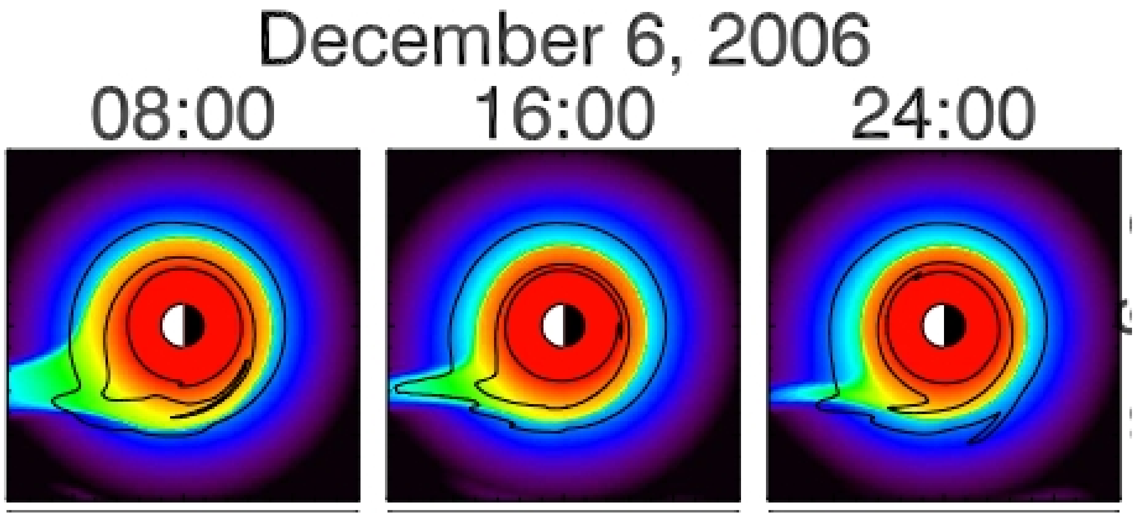
Dynamic Global Core Plasma Model

- 2D single species model of the plasmasphere (e.g. Ober et al. [1997])

$$\vec{B}(\vec{r}) \qquad \vec{E}(\vec{r})$$

$$F_n = -\frac{NB_i}{\tau}$$

$$F_d = \frac{n_{\text{sat}} - n}{n_{\text{sat}}} F_{\max}$$

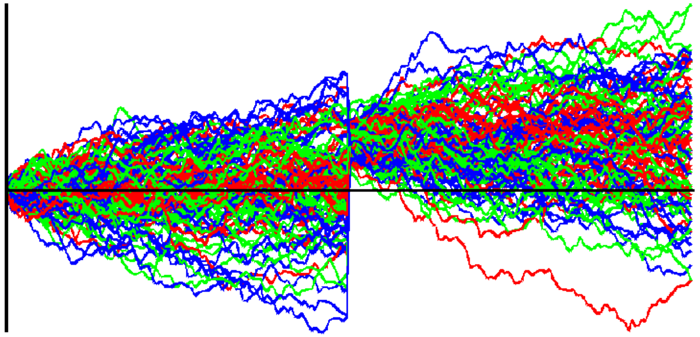


$$\frac{D_\perp N}{Dt} = \frac{F_N + F_S}{B_i}$$

- We implement data assimilation by finding the electric field evolution which results in best agreement between observations and model

Ensemble Kalman Filter

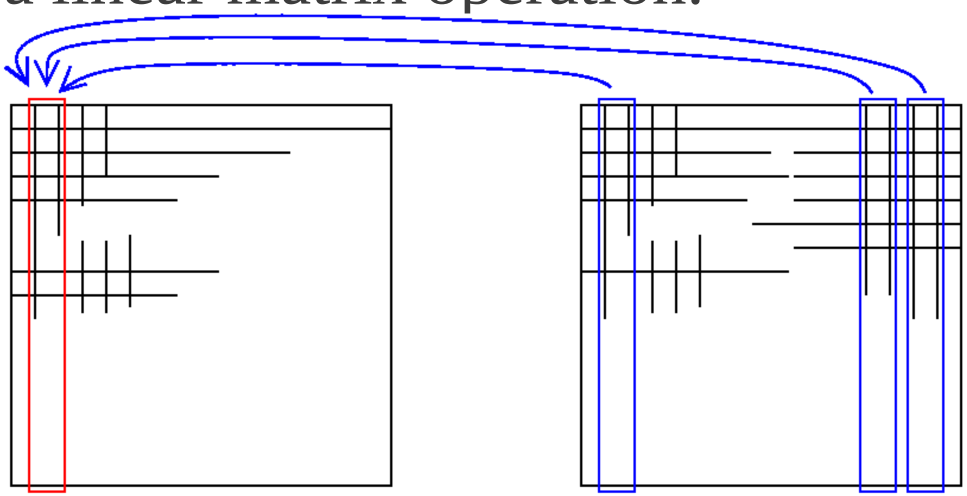
- Start with an ensemble of model
- Perturb each on in a different direction such that the ensemble realistically represents the paths the model could take without prior knowledge.



- When observations become available transform the ensemble to reflect reduced, posterior uncertainty (process is called "Analysis"). For the EnKF it is a linear matrix operation.
- Breaks physical consistency, but hopefully not by too much!

$$\overline{\overline{\psi}}_a = \overline{\overline{\psi}}_f \overline{\overline{X}}$$

$$\overline{\psi}_{ai} = \sum_j x_{ji} \overline{\psi}_{fj}$$

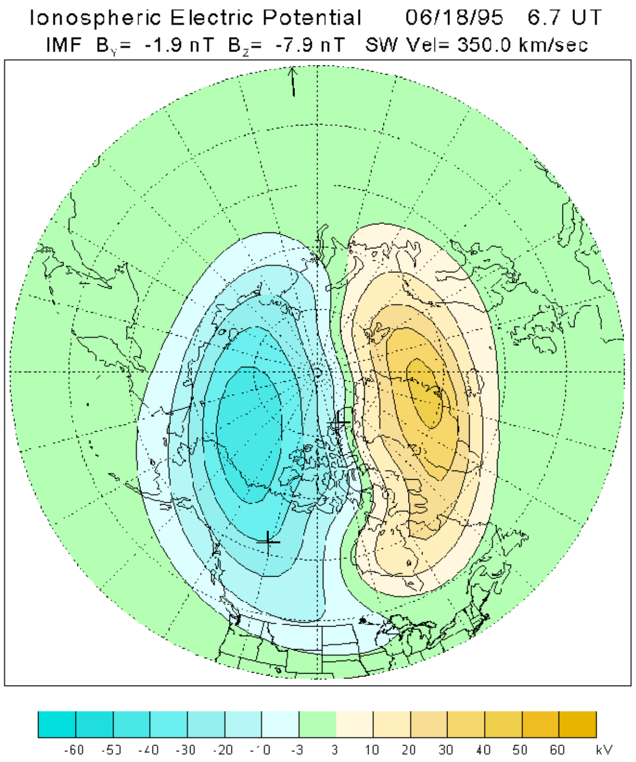


Ensemble Kalman Filter
Electric Field Model

- The perturbation we use is to vary the electric field, because it is a primary driver of the dynamics, and it is poorly constrained.

- Enlarge the state vector:

$$\psi = \begin{pmatrix} q \\ \psi_N \\ \vdots \\ \psi_0 \end{pmatrix}$$



- Red noise:

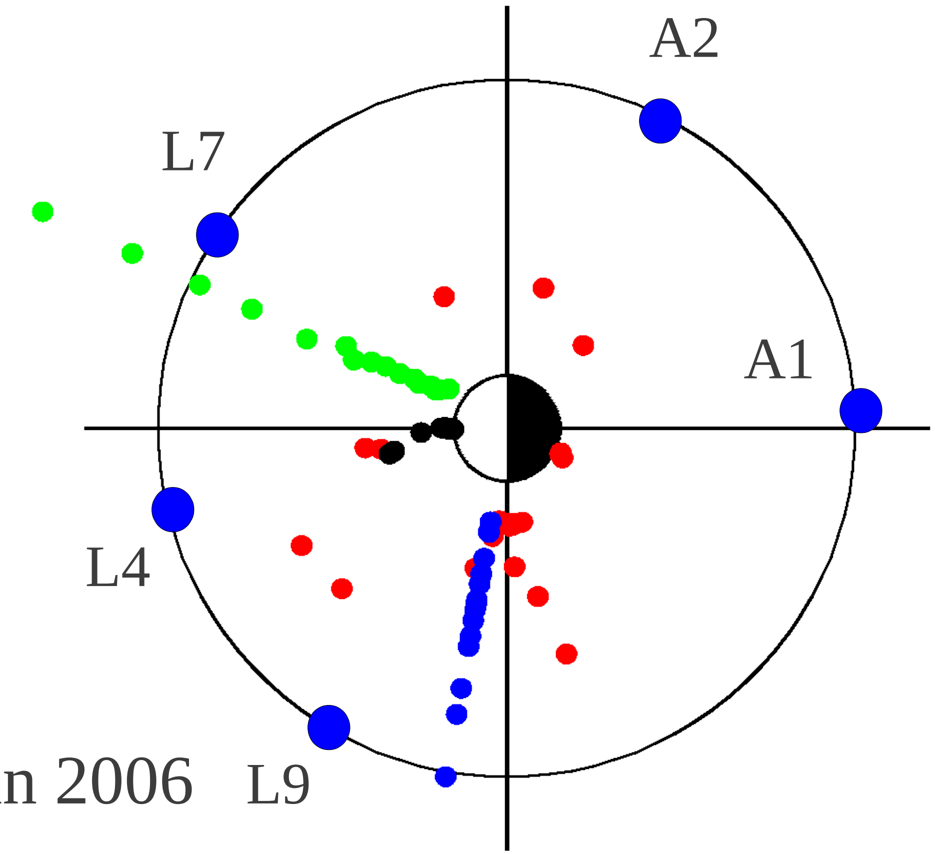
$$q_{k+1} = \alpha q_k + \sqrt{1-\alpha^2}\, w$$

- Used in some versions of Weimer E-field models

$$\Phi(\theta,\phi) = \sum_{l=0}^{4} \sum_{m=0}^{min(l,3)} (A_{lm}\cos m\phi + B_{lm}\sin m\phi) P_l^m(\cos\theta),$$

Data Sources

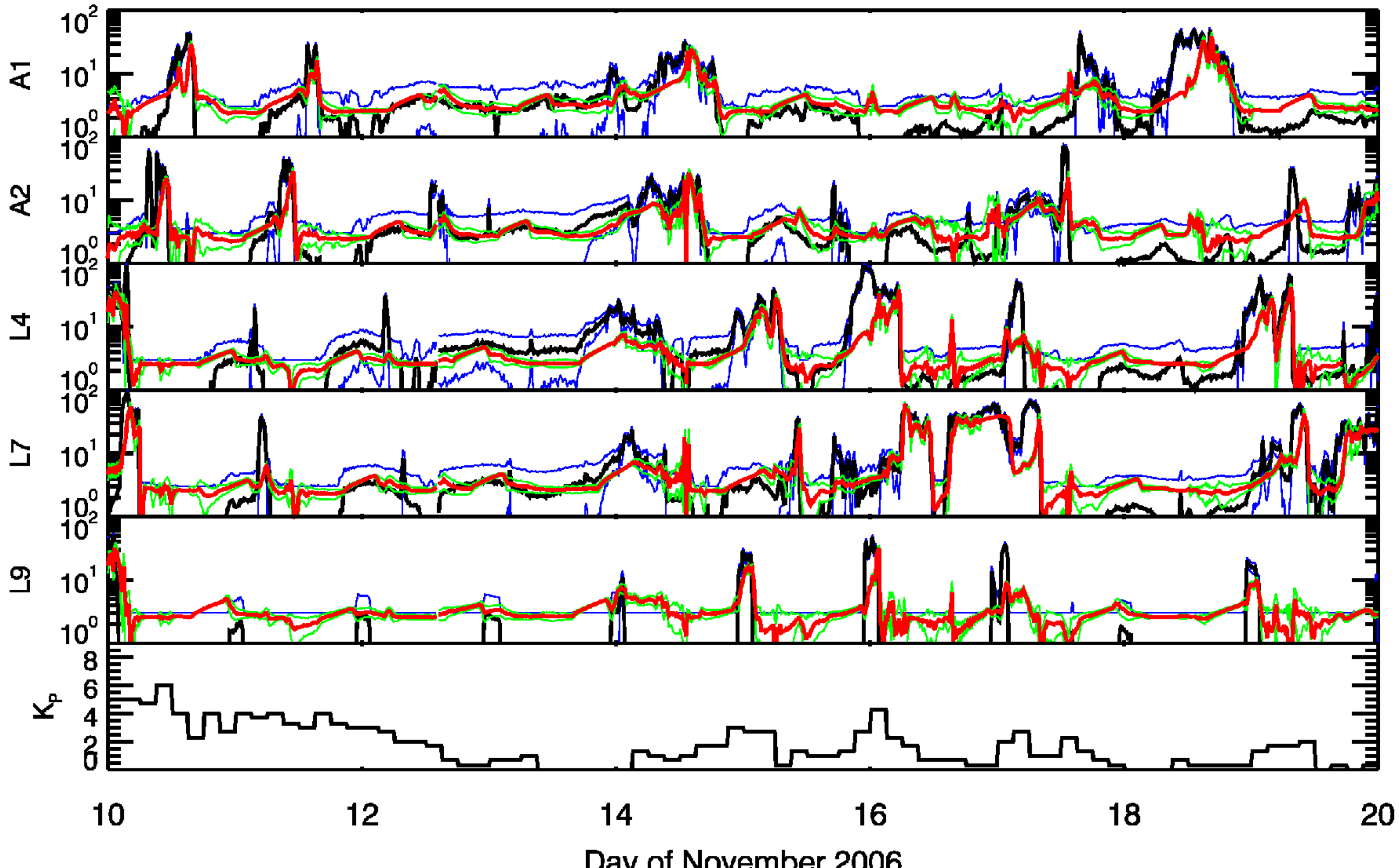
- PLASMON project (FP-7 funded): expand VLF and magnetometer networks and process data for ingestion into data assimilative plasmasphere model
- Red: VLF stations
- Blue: EMMA magnetometer array (Central Europe)
- Black: SAMBA magnetometer array (South America west coast)
- Green: McMac magnetometer array (North America central)
- Large blue: LANL geo satellites in 2006



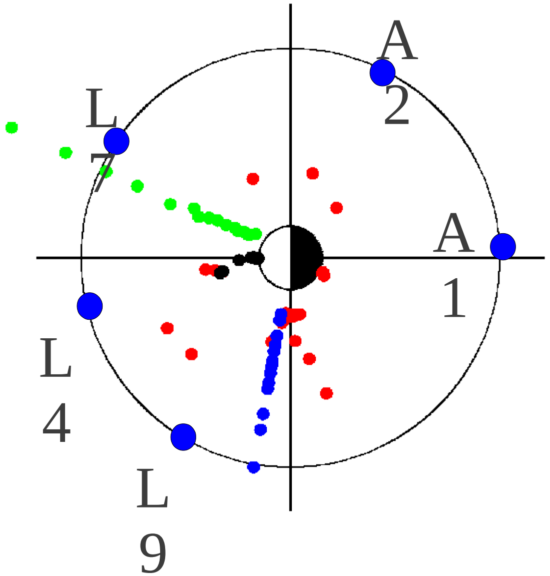
(asia/pacific sector magnetometers would be helpful)

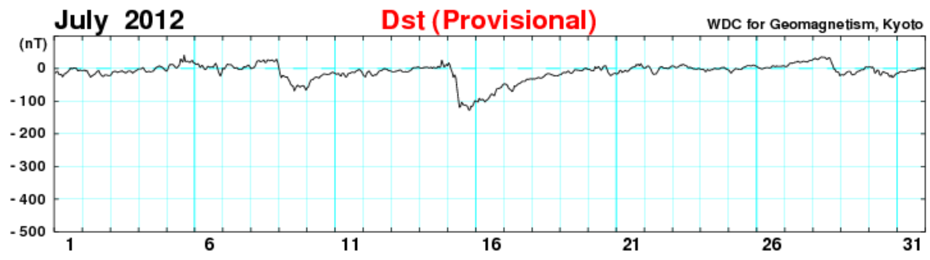
Data Assimilation with LANL In-situ Observations

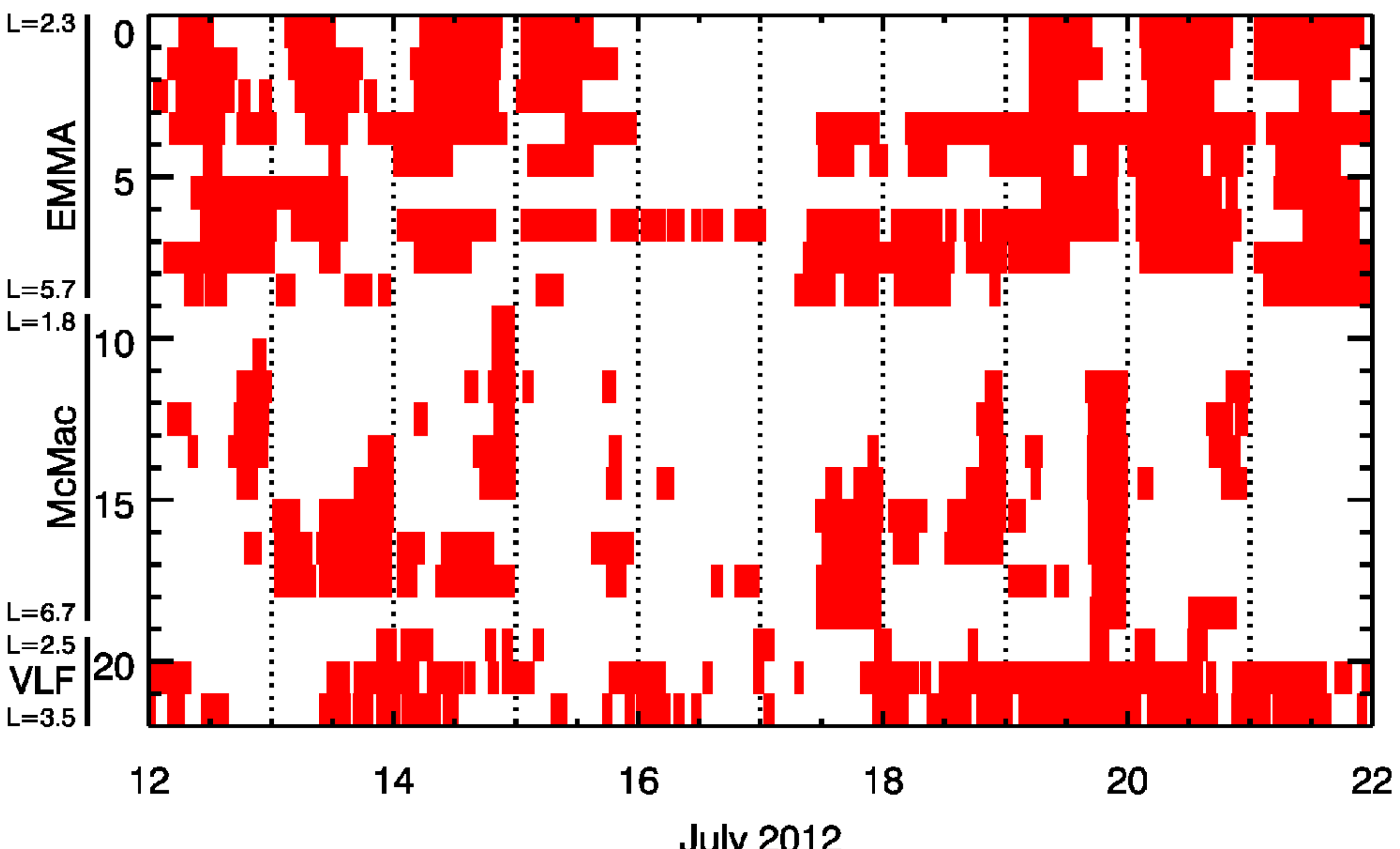
Black/blue: data and its uncertainty   Red/green: assimilation output and uncertainty



Storm July 15, 2012





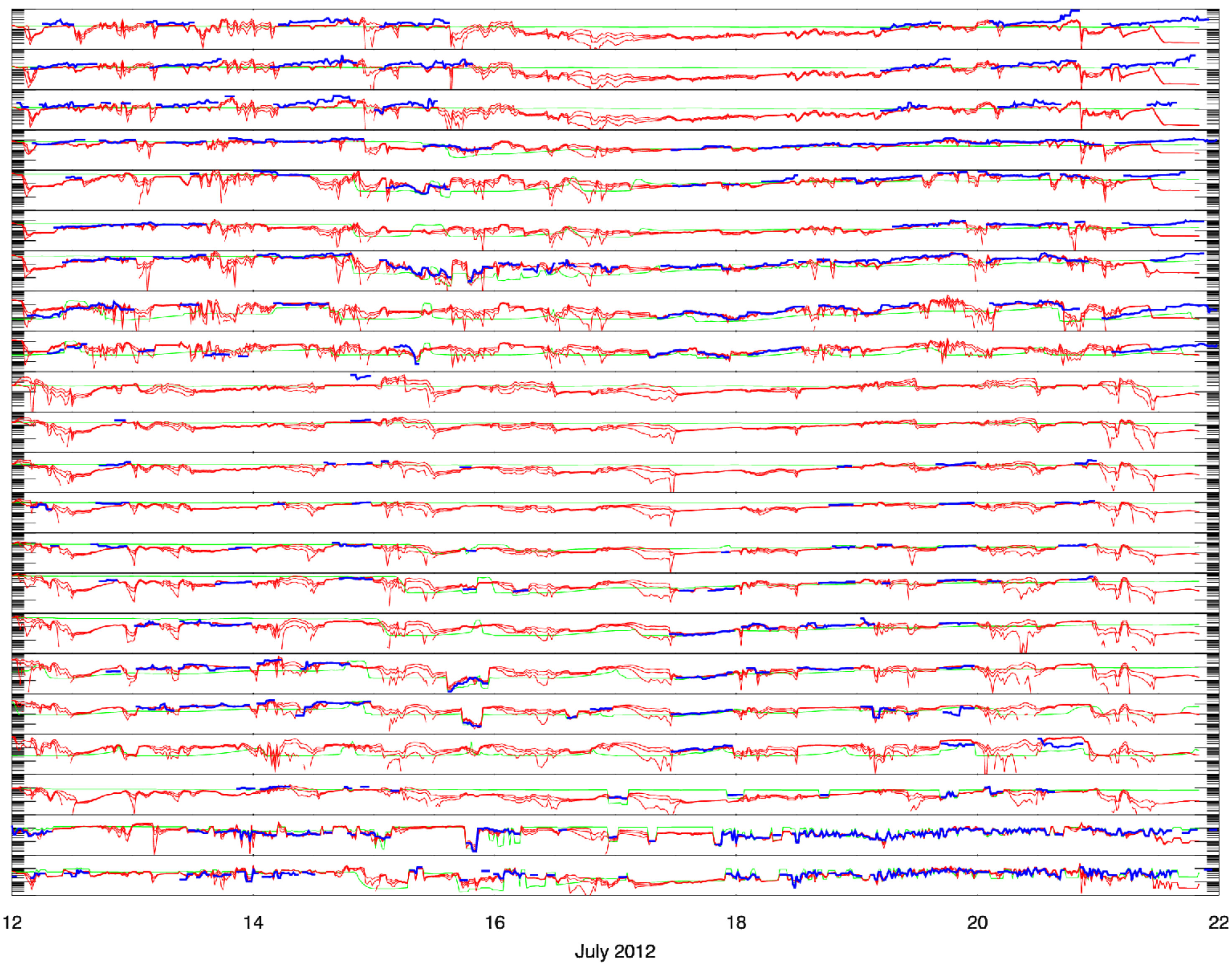


9 EMMA pairs
10 McMac pairs
3 VLF stations

Large gaps, very little coverage at outer L-shells

Assimilation Result

Too many panels, unreadable, so let's zoom in on a few areas of interest.



Green: reference model run from Kp

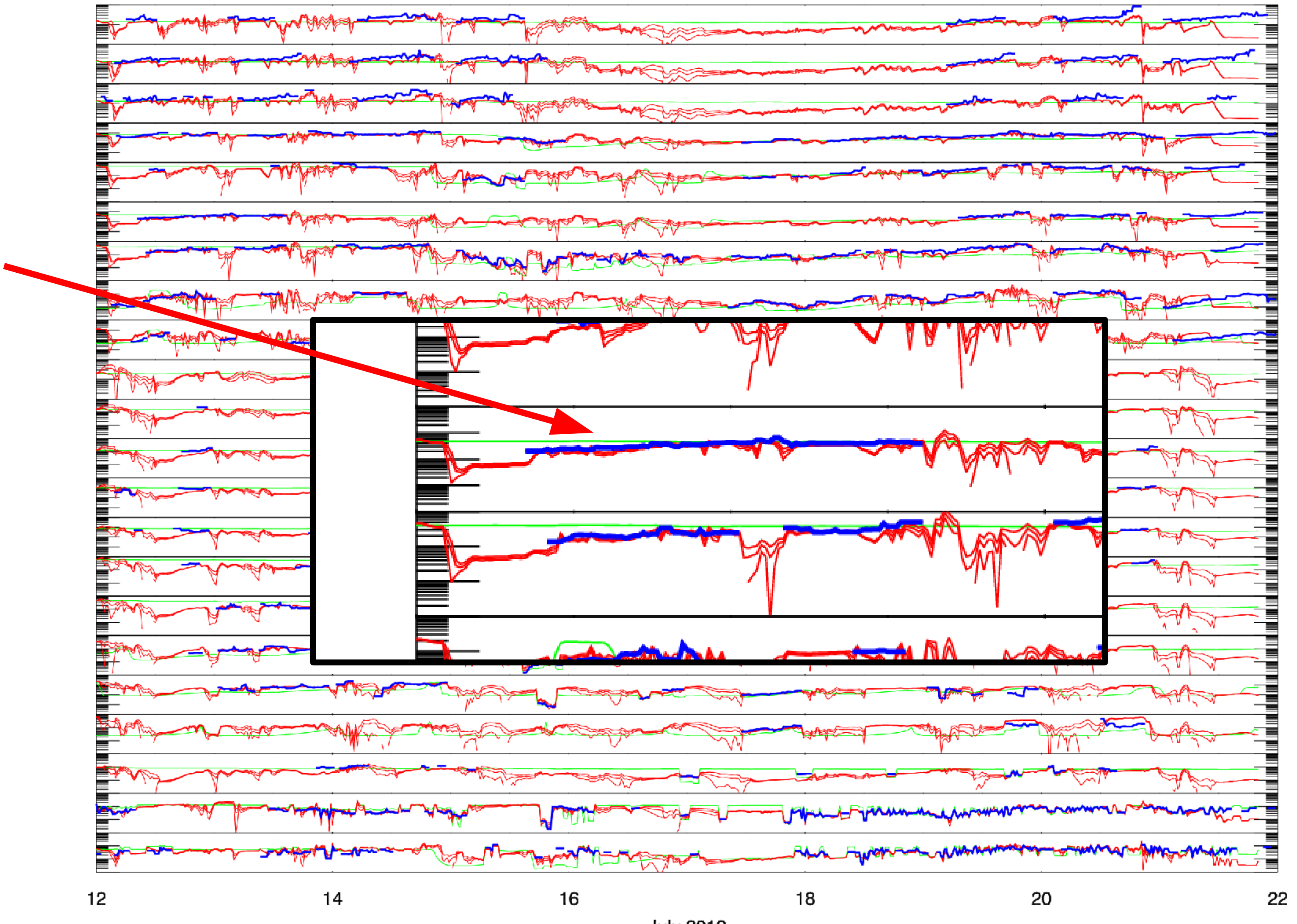
Red: assimilation result and uncertainty (three curves)

Blue: input data

Blue overlapping red is good.

Assimilation Result

Observations show refilling in progress after depletion in previous storm. Assimilation reproduces this recovery.

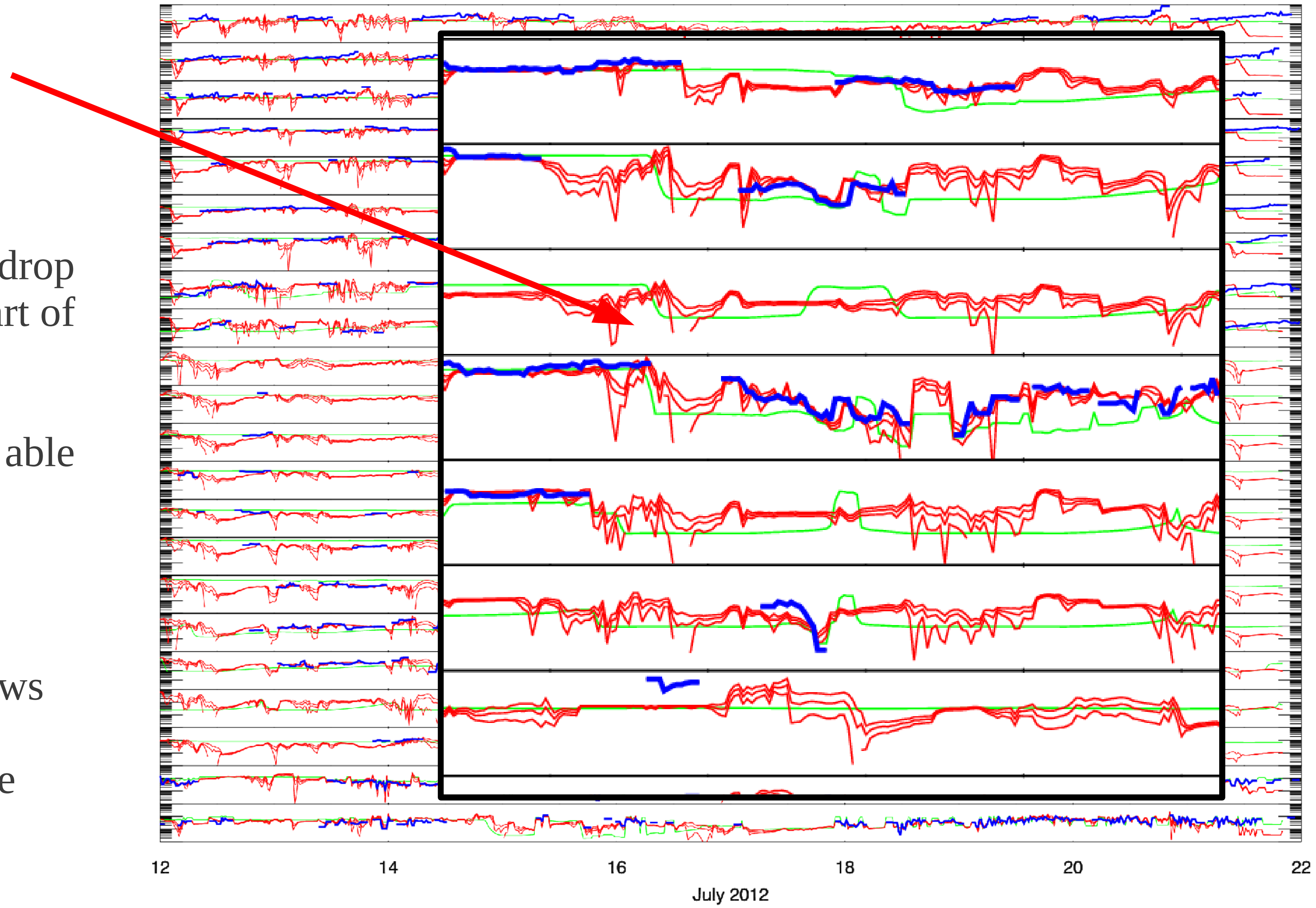


Assimilation Result

Both open loop model and data agree on sharp drop in density at start of storm.

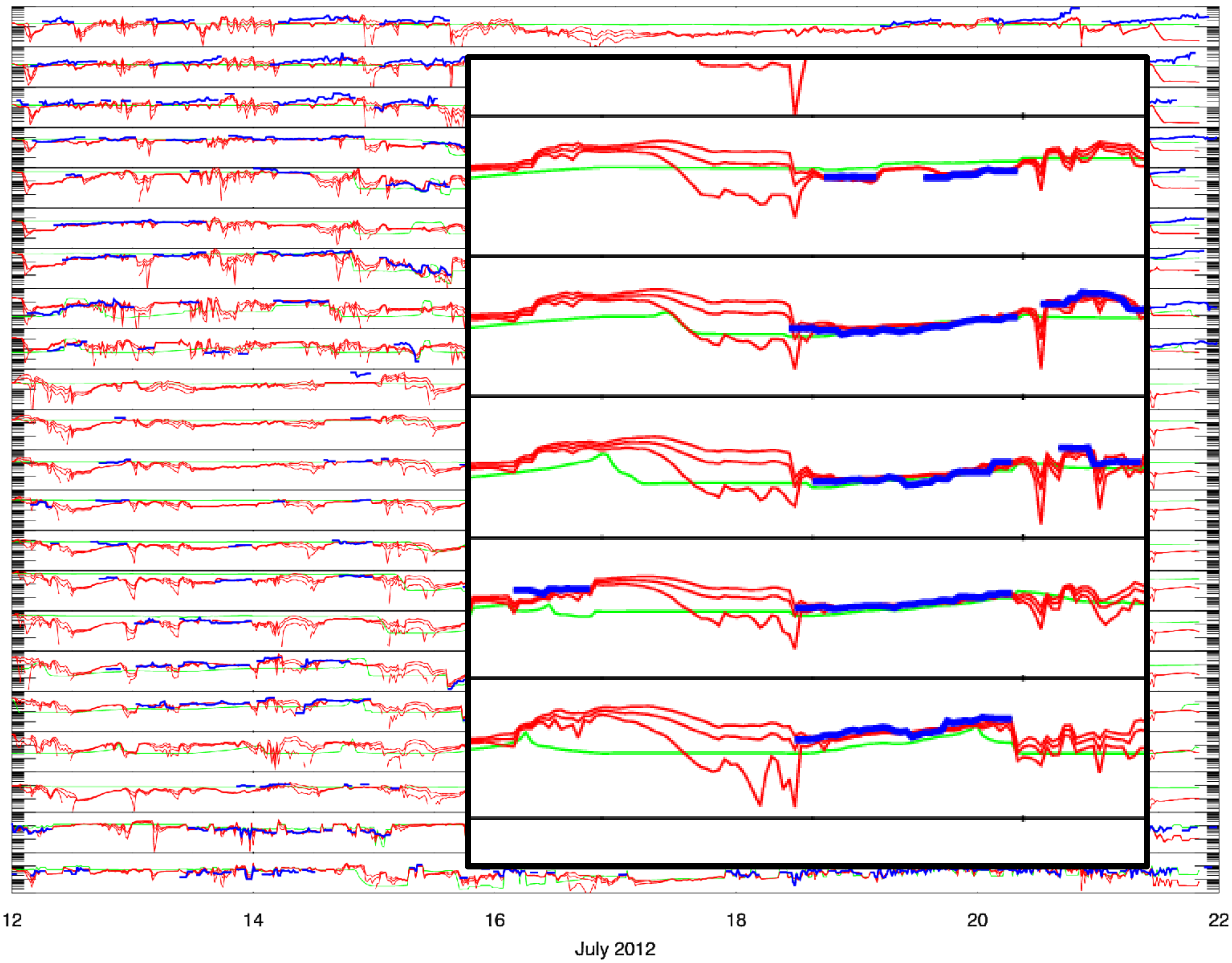
Assimilation is able to reproduce observations.

Assimilation uncertainty grows when no observations are available.

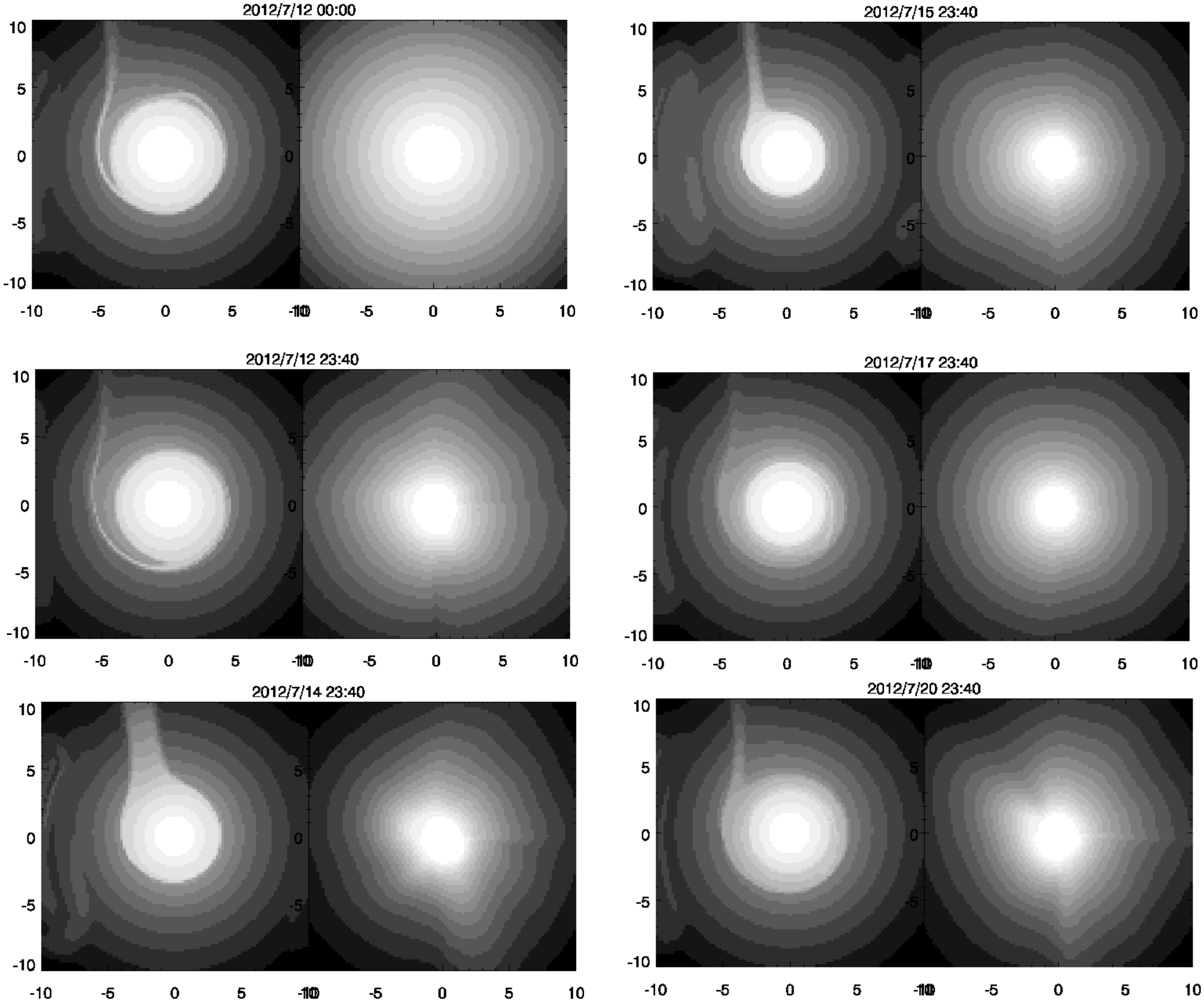


Assimilation Result

Assimilation uncertainty grows when no data are available, shrinks when data become available.



Plasma Density Distribution



Right image is reference simulation, left is assimilation.

Sun is up

The assimilation does not produce as sharp a plasmapause as the reference simulation.

Future and Related

- Better empirical or analytical modeling to match the observations.
- Improve data assimilation and infrastructure to obtain and ingest large diverse data set.
- Explore the full wave equation ($\frac{\partial^2 \mathbf{E}}{\partial t^2} = \mathbf{c}_A \times \mathbf{c}_A \times \nabla \times \nabla \times \mathbf{E}$) at low altitude, and to understand driven oscillations and inter-hemispheric differences in noise spectrum.
- Much more data needed, including outside the plasmasphere.
- Instrumentation:
  - Sensor Networks
  - Magnetometer
  - VLF receiver
  - NMTSat CubeSat

Conclusions

- Ground-based FLR are a excellent souce of information about the plasmasphere dynamics.
- Large-scale agreement with FLIP, small-scale differences
- Data assimilation is one good approach to combining the sparse observations – but we need more data still.
- Inversion requires care – power law does not work (well enough?) in the inner plasmasphere.