How can we investigate global Magnetosphere-Ionosphere coupling?

J. Gjerloev, S. Ohtani, R. Barnes, C. Waters, T. Motoba, C. Olson

The Johns Hopkins University Applied Physics Laboratory
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CS
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JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

AMPERE

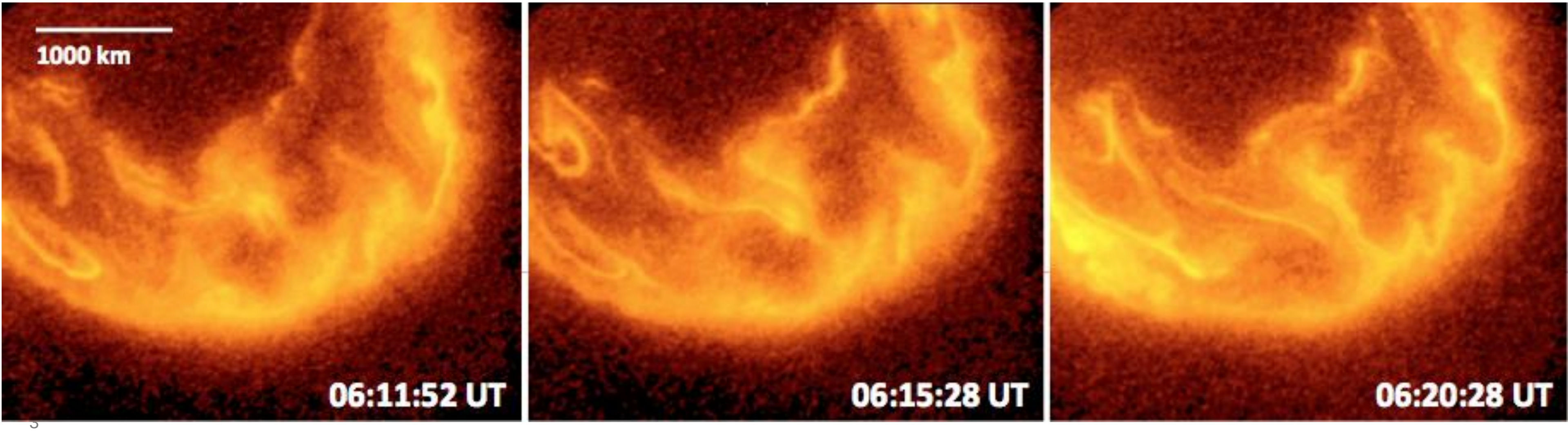
SuperMAG
International - Ground Magnetometer - Collaboration

Outline

1. How do we derive global solutions from sparse data coverage?

2. What are the limitations of the global solutions?
   - Derived parameters
   - Processes/phenomena

3. The holy grail of M-I physics: Global, continuous and complete electrodynamic solutions.



Outline

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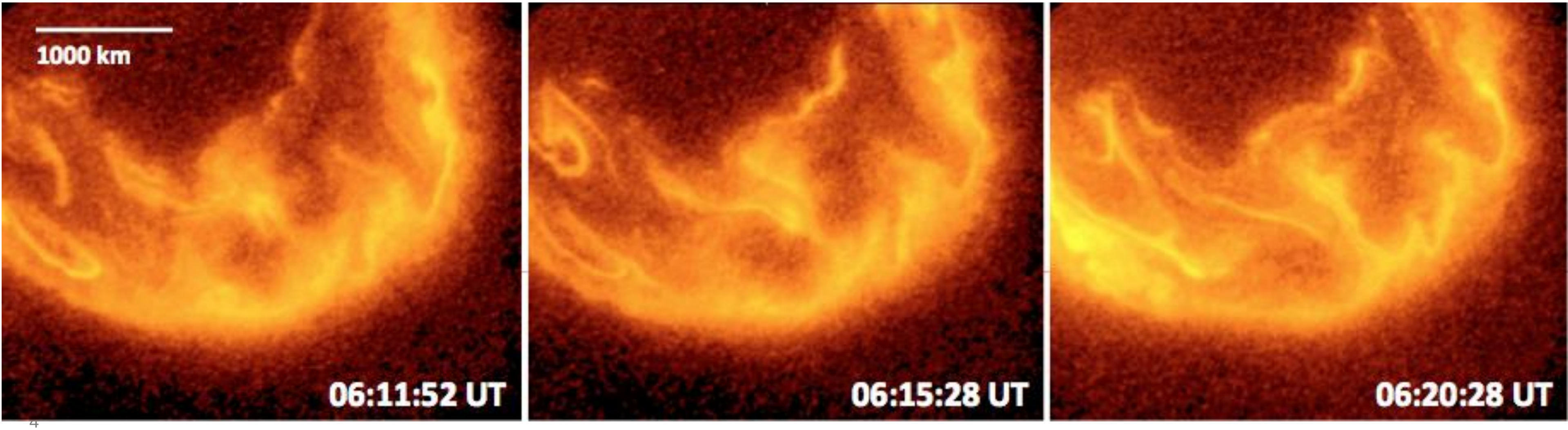
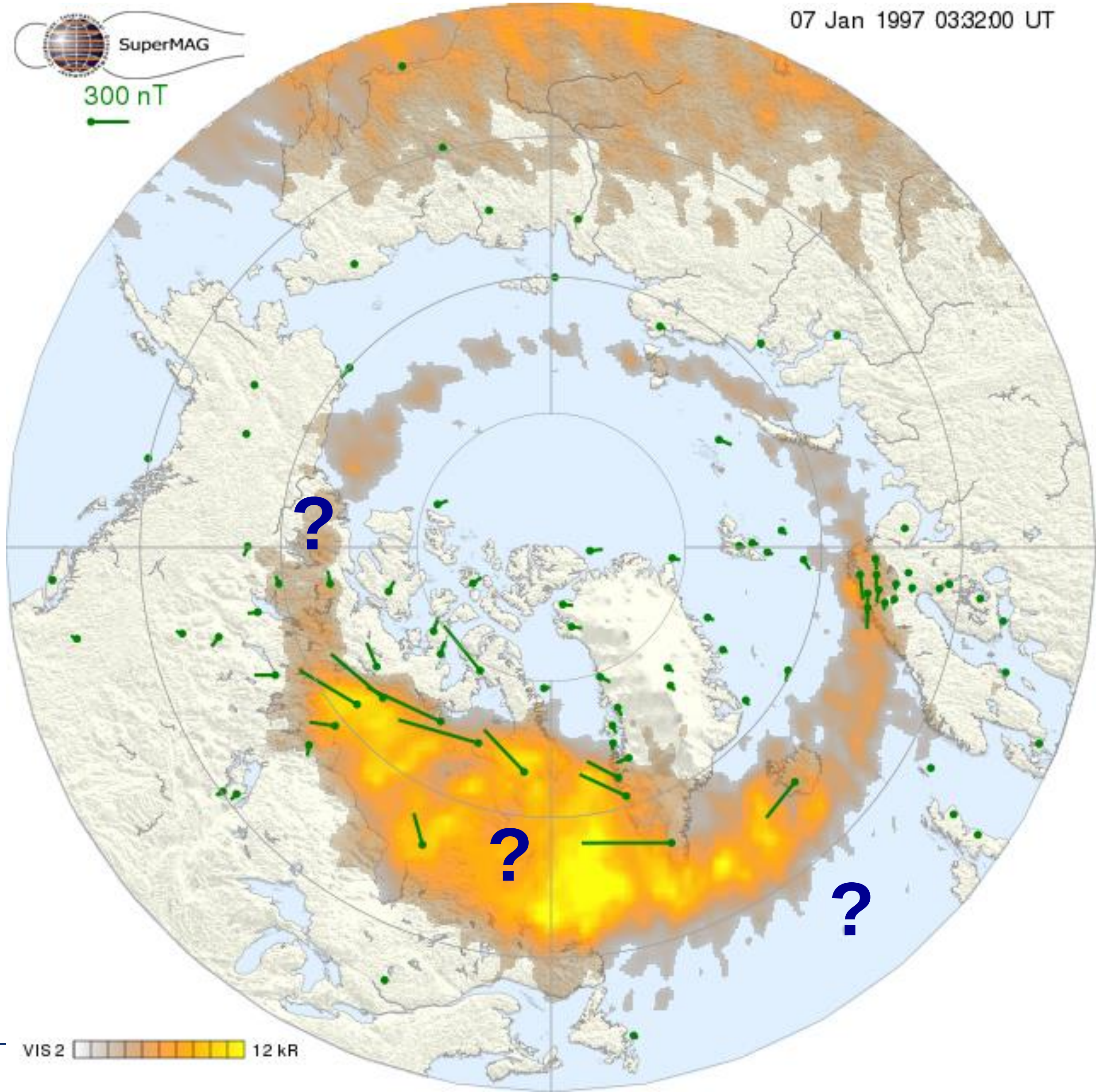


Deriving global solutions: What is the problem?

Challenges:
- **Spatial coverage**
- **Temporal resolution**

Deriving global solutions: What is the problem?

SuperMAG



Challenges:
- **Spatial coverage**
- **Temporal resolution**

Deriving global solutions: Three approaches

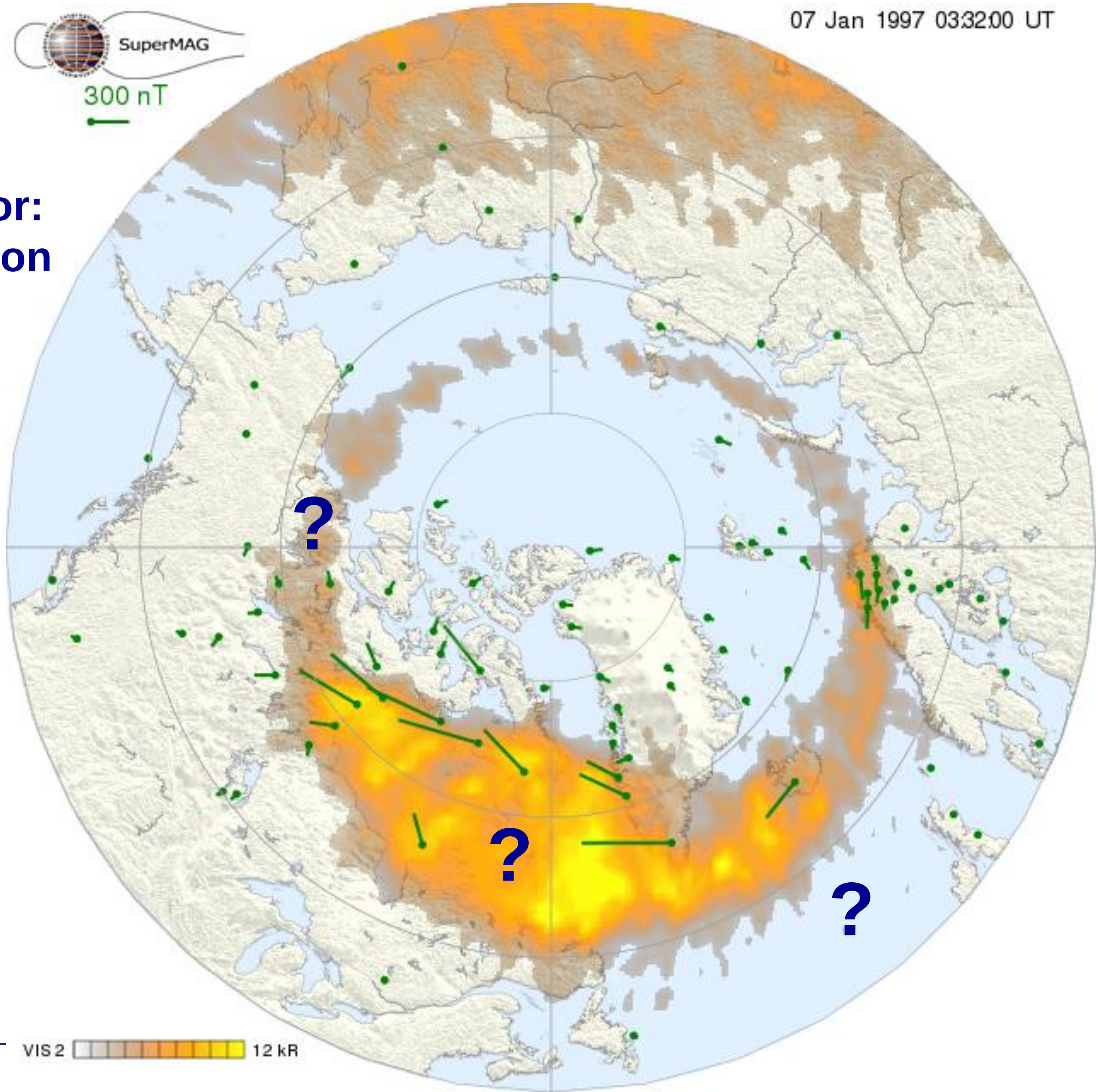
Approach 1: No assumed knowledge of system behavior:

1) Simple spatial interpolation

Approach 2: Assuming knowledge of the system behavior

2) External driver

3) State descriptors



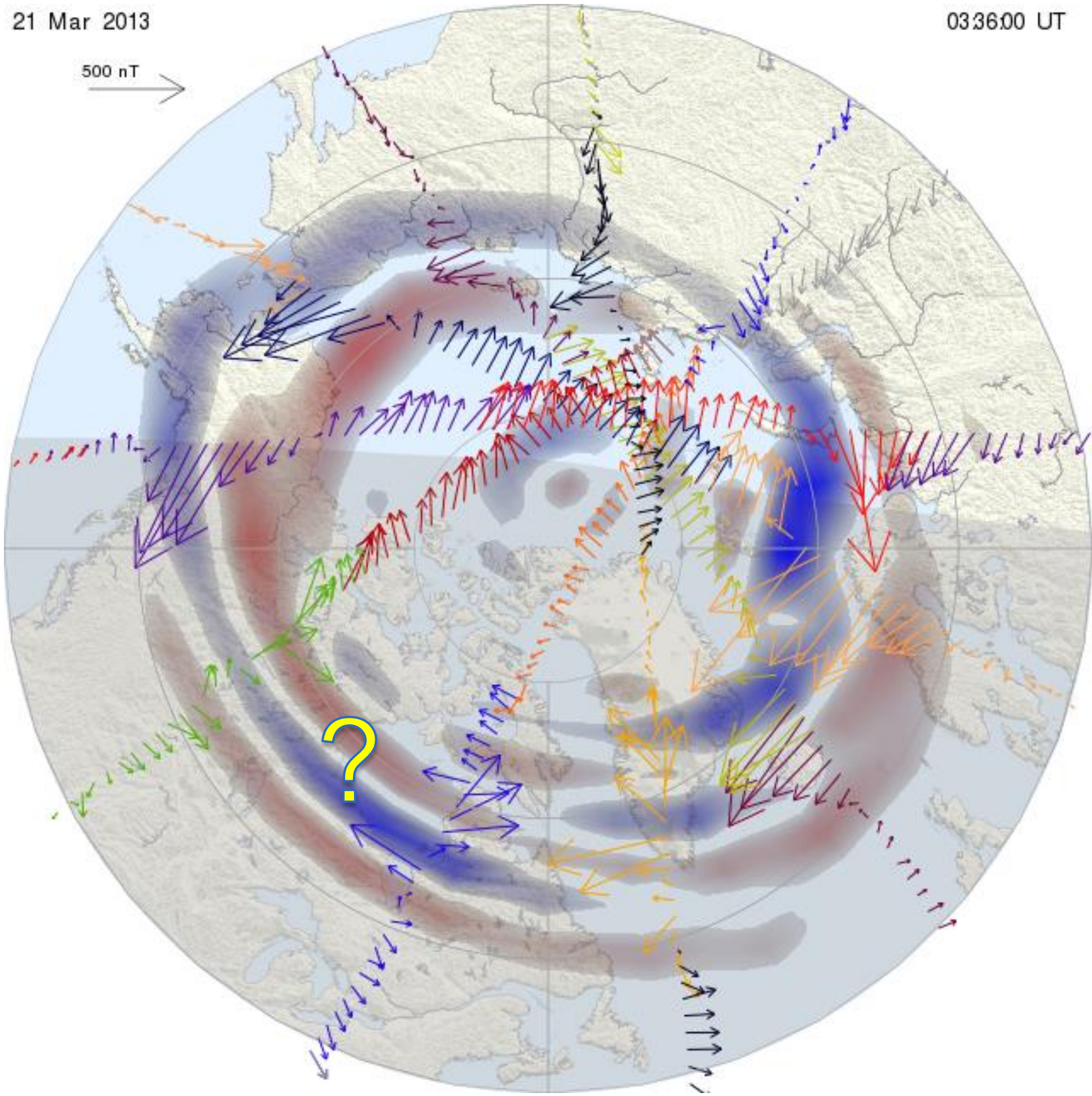
Approach 1: No assumed knowledge of system behavior
Simple Spatial Interpolation

Approach 1: No assumed knowledge of system behavior:
1) Simple spatial interpolation

Question: Are the scale sizes of the features larger than the spatial data gaps?

Answer: No/yes/maybe.

Depend on:
- **science objective**
- **parameter**



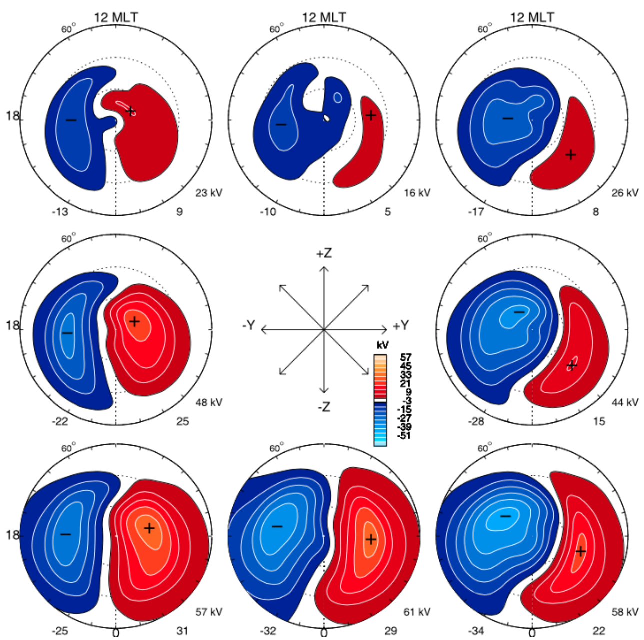
Approach 2: Assuming knowledge of the system behavior
External Drivers

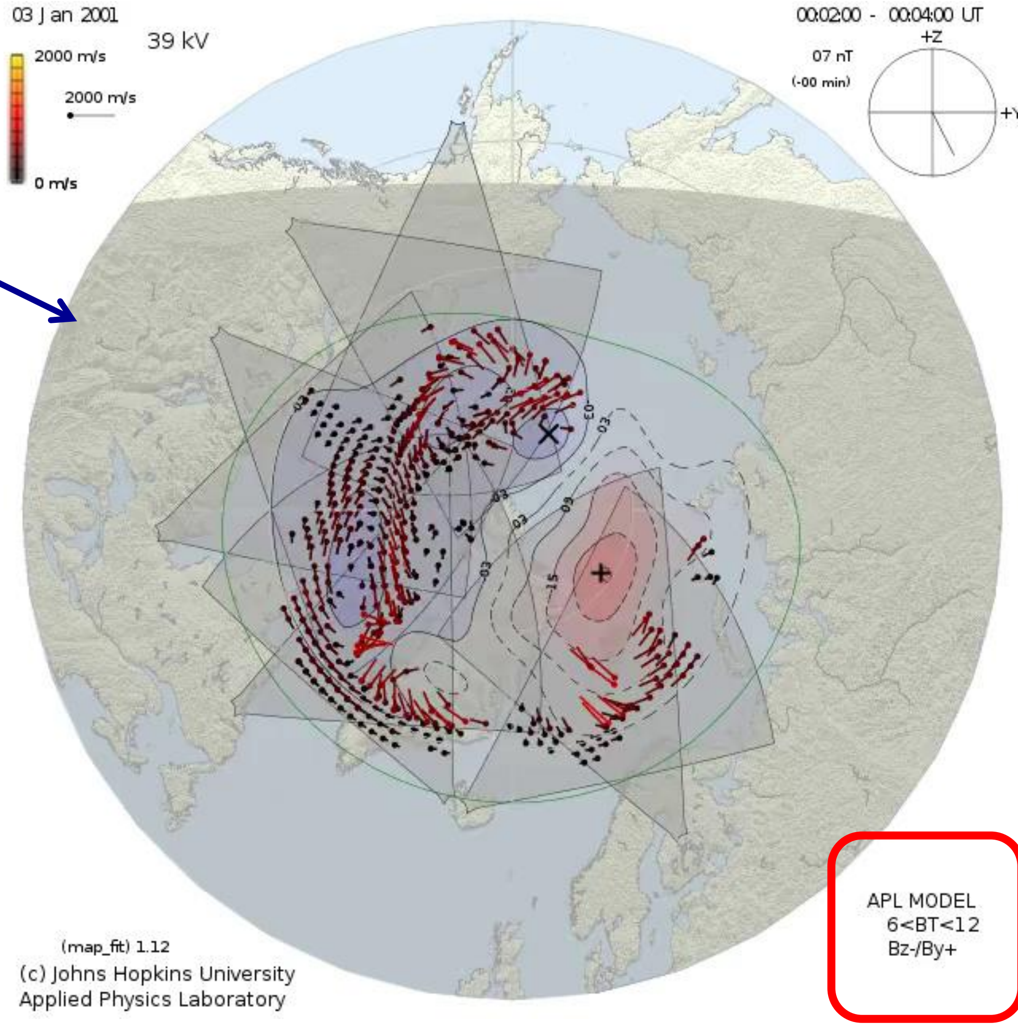
Sparse Observations → Spherical harmonics fitting (weighted)

Fill-in data → Spherical harmonics fitting (weighted)

Spherical harmonics fitting (weighted) →

Fill-in data are provided by discrete bins of solar wind driver:

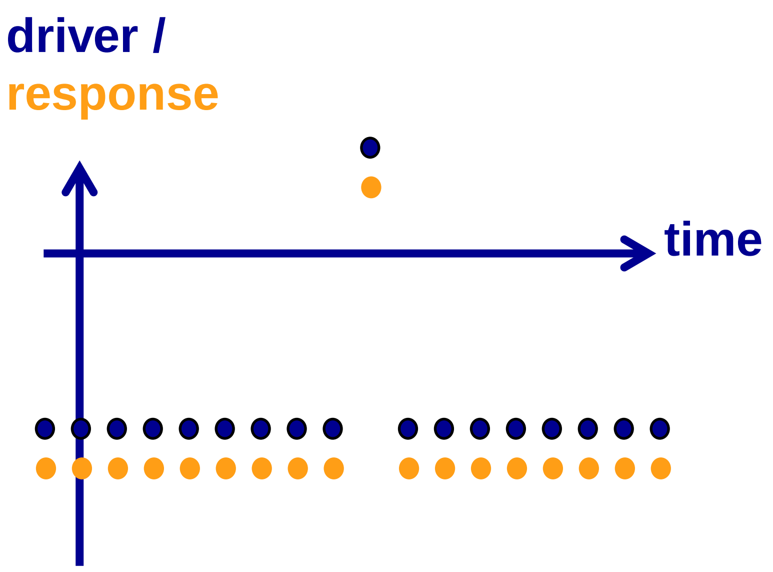


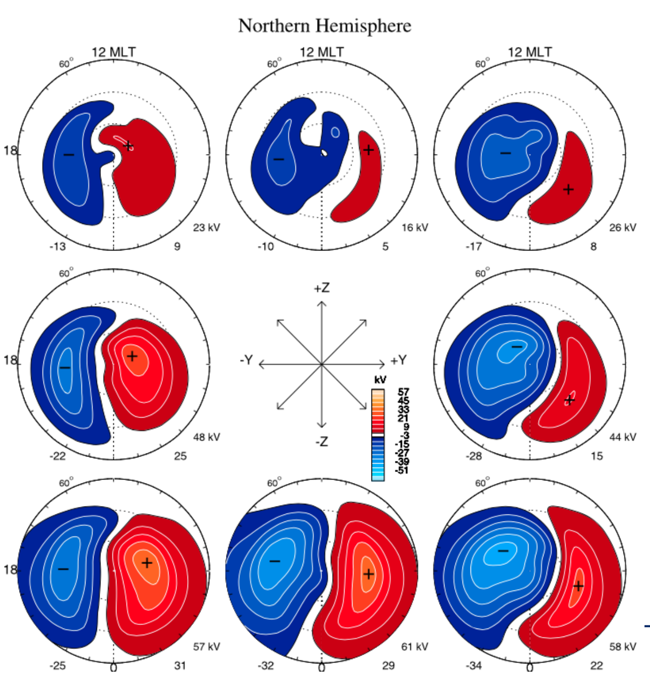


Pettigrew et al. (2010)

Approach 2: Assuming knowledge of the system behavior
External Drivers

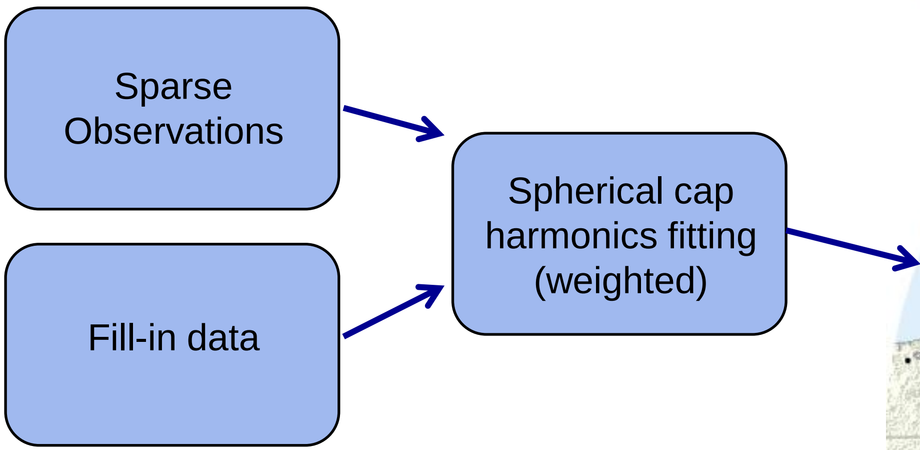
Inherent complexities
- **Delay (causality)**
- **M-I low pass filtering**
- **SW-M-I history**
- **M-I internal processes**
- **Predictability / system info**

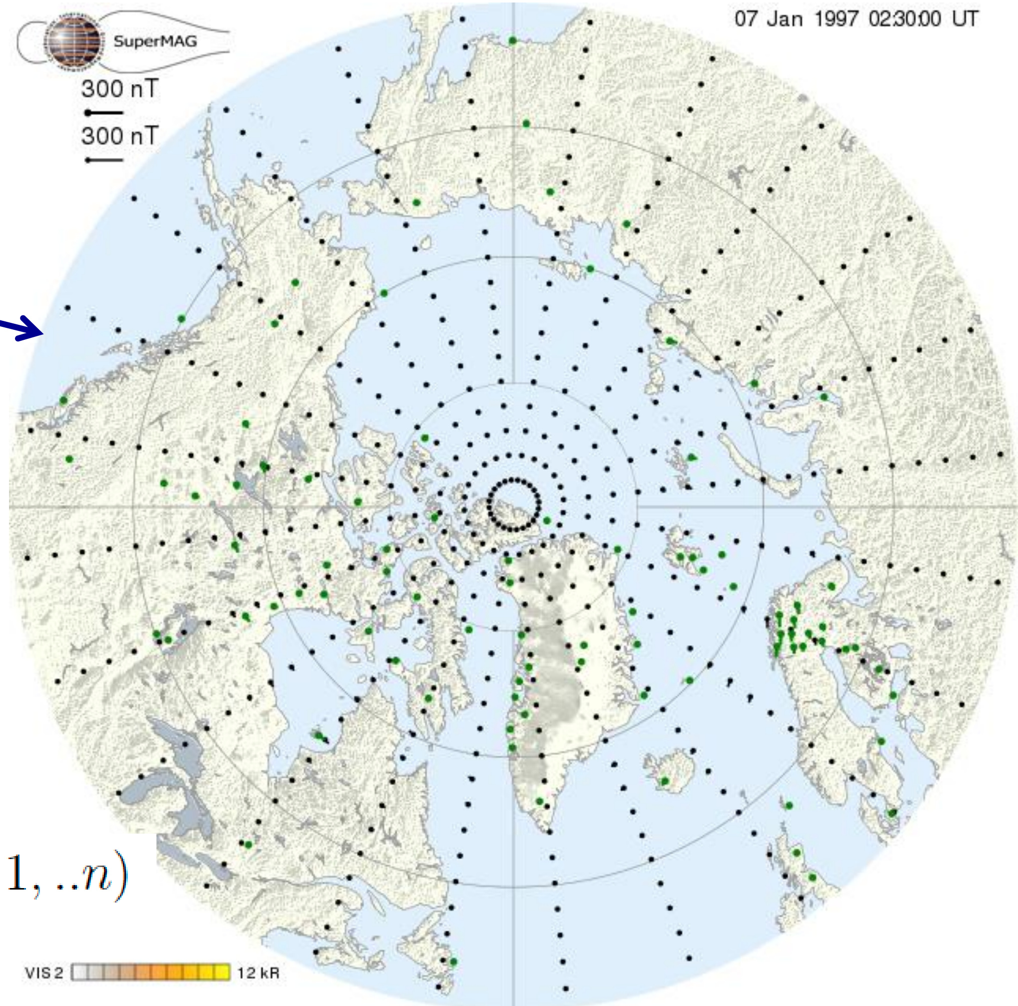




Pettigrew et al. (2010)

Approach 2: Assuming knowledge of the system behavior State Descriptors





Fill-in data are provided by a multi-linear regression model:

$$y_i = \beta_0 + \beta_1 x_{1i} + ... + \beta_k x_{ki} + \epsilon_i \quad (i = 1, ..n)$$

where β_k are the regression coefficients, x_{ki} are SuperMAG indices, and ε_i is the model errors.

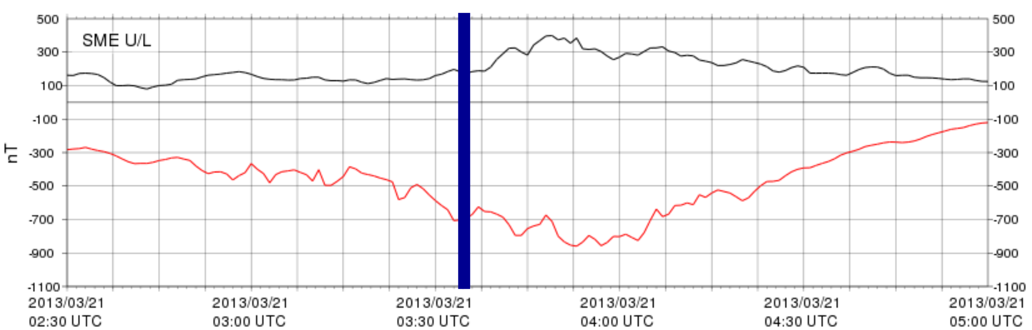
Waters, Gjerloev, Dupont, Barnes, JGR, 2015

Approach 2: Assuming knowledge of the system behavior
State Descriptors

Inherent complexities

- **Can a scalar describe a 2D or 3D system?**
- **What does the index even mean?**
- **Does it have appropriate temporal resolution?**
- **Does it have appropriate spatial resolution?**

Rostoker **[1972] concluded that in order to avoid the obvious pitfalls for the AE index it should be used only in statistical studies rather than individual events.**



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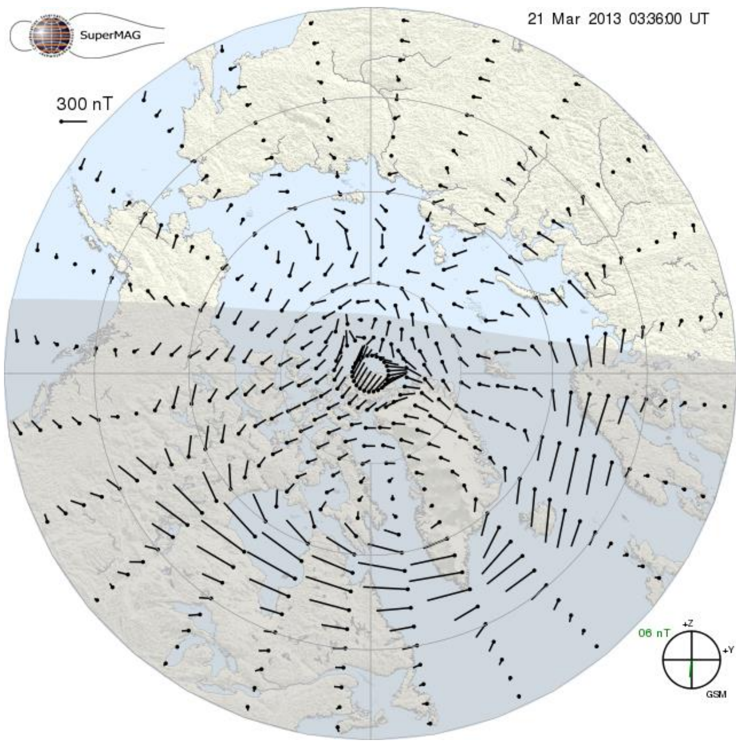
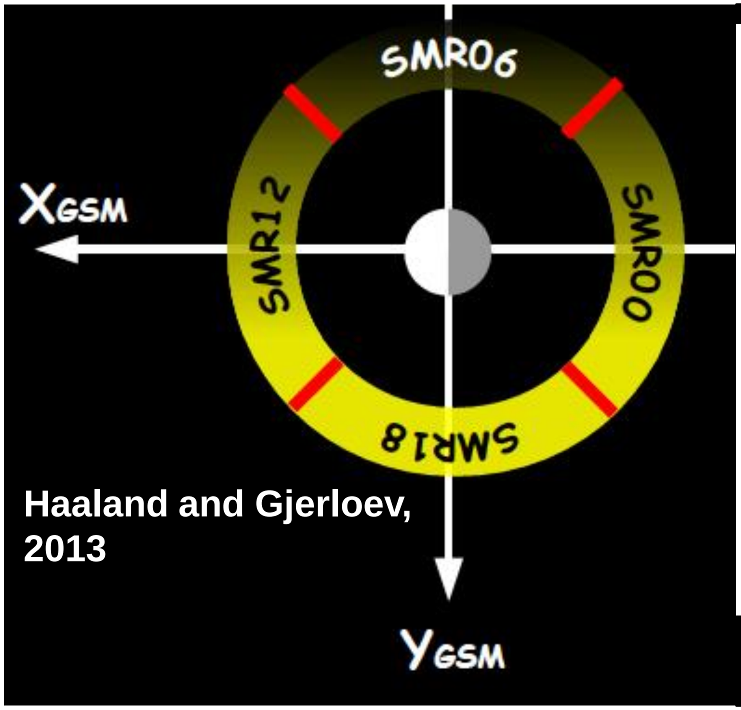
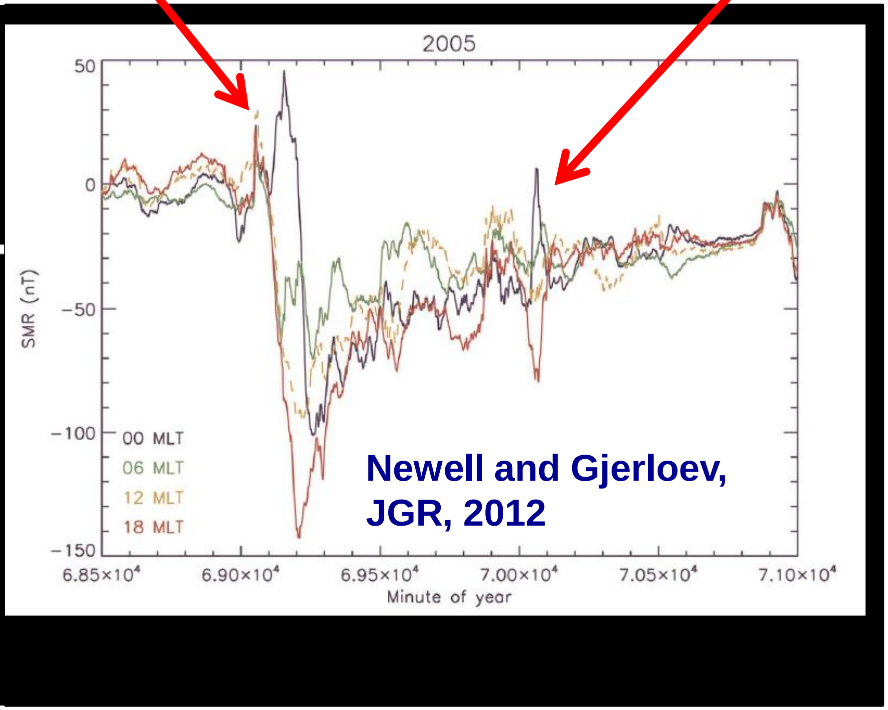


Approach 2: Assuming knowledge of the system behavior
State Descriptors

$$\bar{B}_{measured}(\bar{r},t) = \bar{B}_{main}(\bar{r}) + \bar{B}_{noise}(t)$$

$$+ \bar{B}_{Sq}(\bar{r},t) + \bar{B}_{EEJ}(\bar{r},t) + \bar{B}_{RC}(\bar{r},t) + \bar{B}_{CT}(\bar{r},t) + \bar{B}_{MP}(\bar{r},t) + \bar{B}_{AEJ}(\bar{r},t) + \bar{B}_{GI}(\bar{r},t) + \bar{B}_{FAC}(\bar{r},t) \ldots$$





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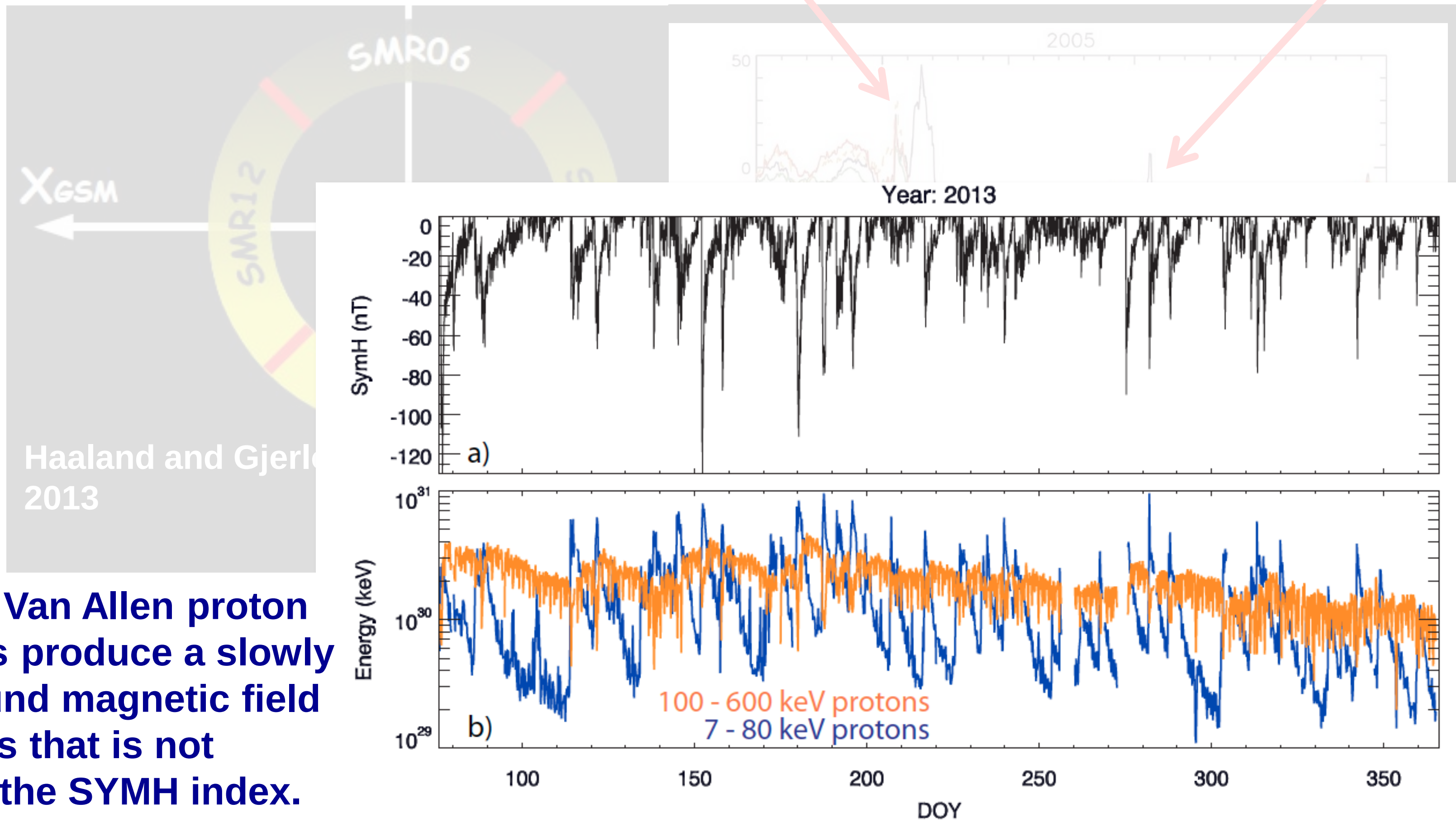

High energy Van Allen proton observations produce a slowly varying ground magnetic field perturbations that is not captured by the SYMH index.

Gkioulidou et al., GRL, 2015

Approach 2: Assuming knowledge of the system behavior State Descriptors

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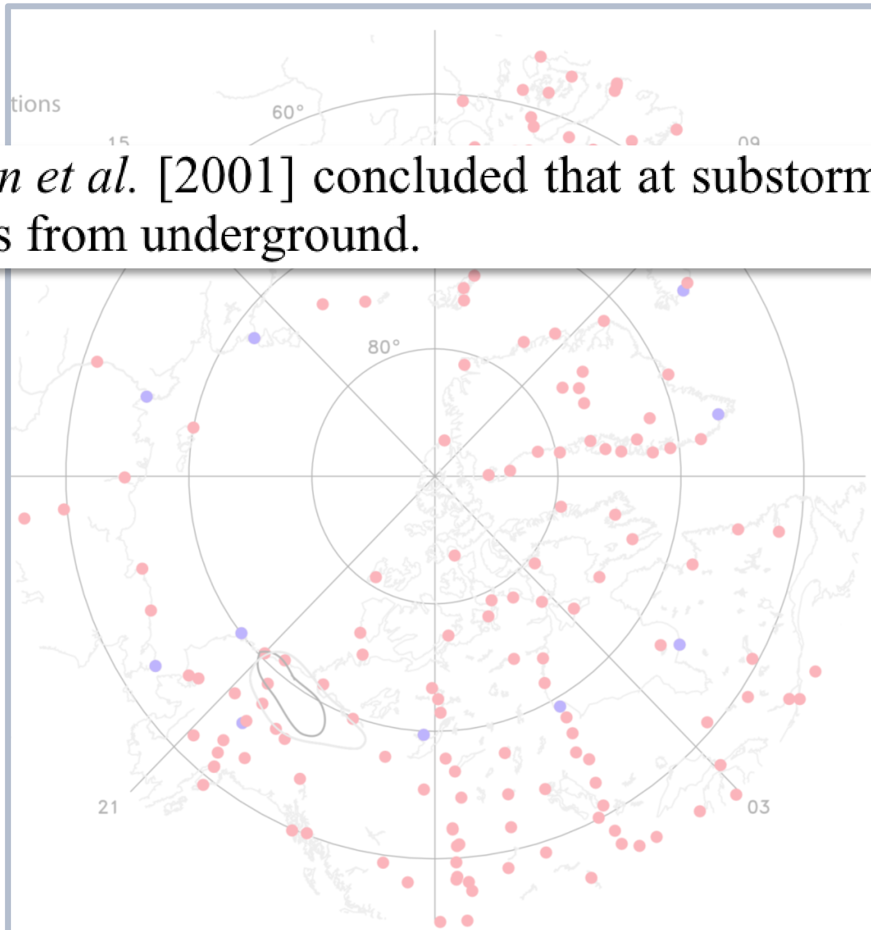
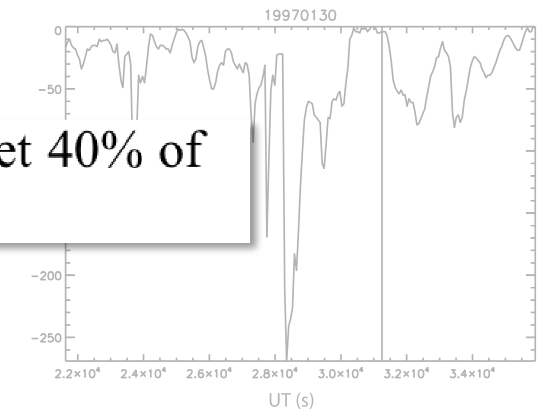
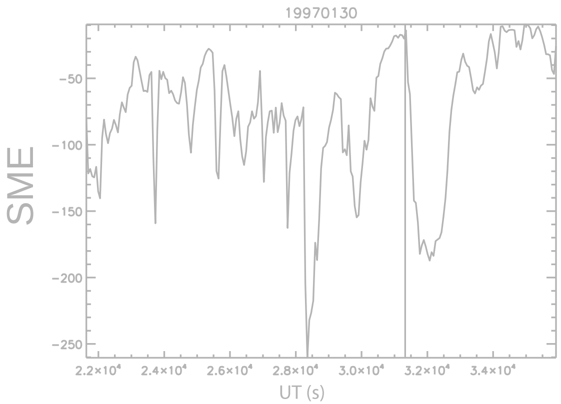


Tanskanen et al. [2001] concluded that at substorm onset 40% of AL comes from underground.





Newell and Gjerloev, JGR, 2011 a,b

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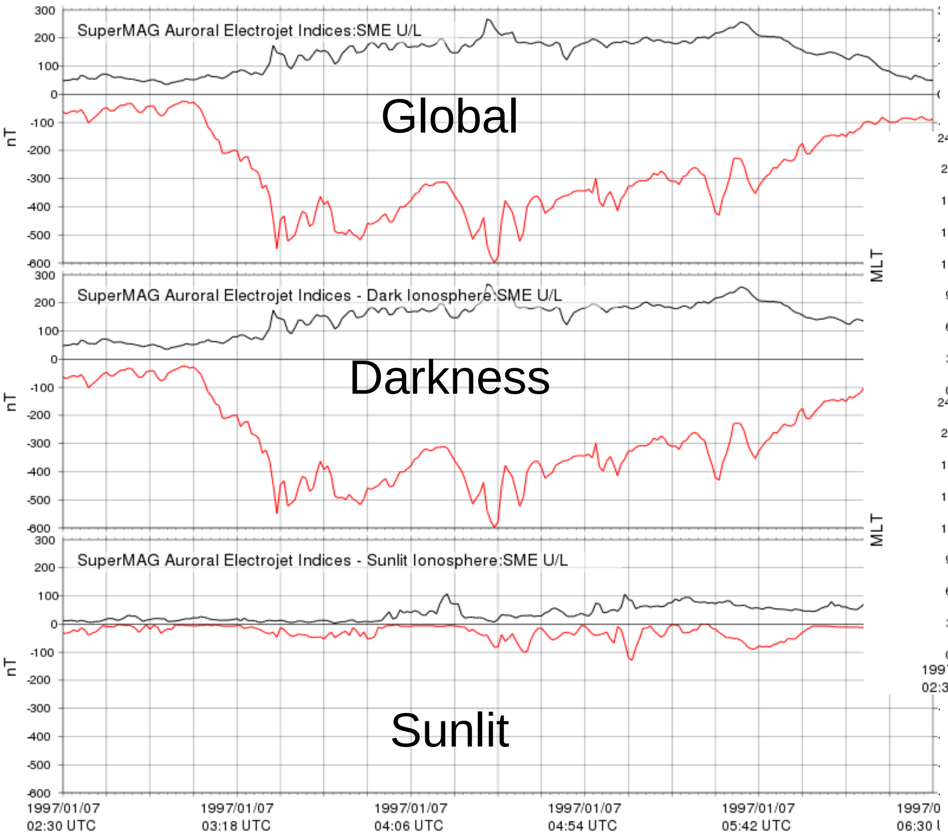
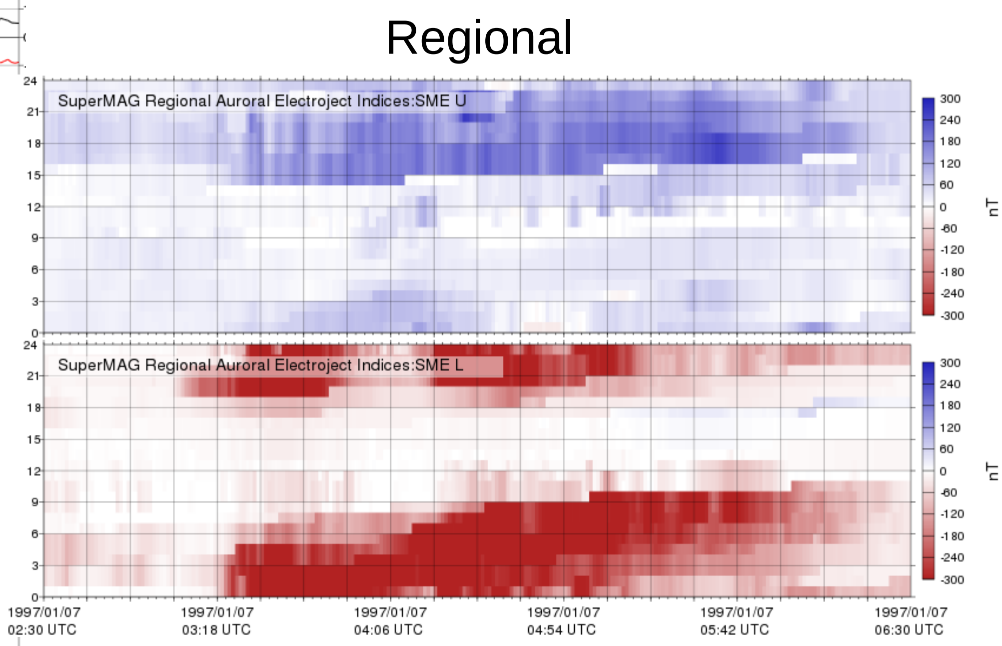
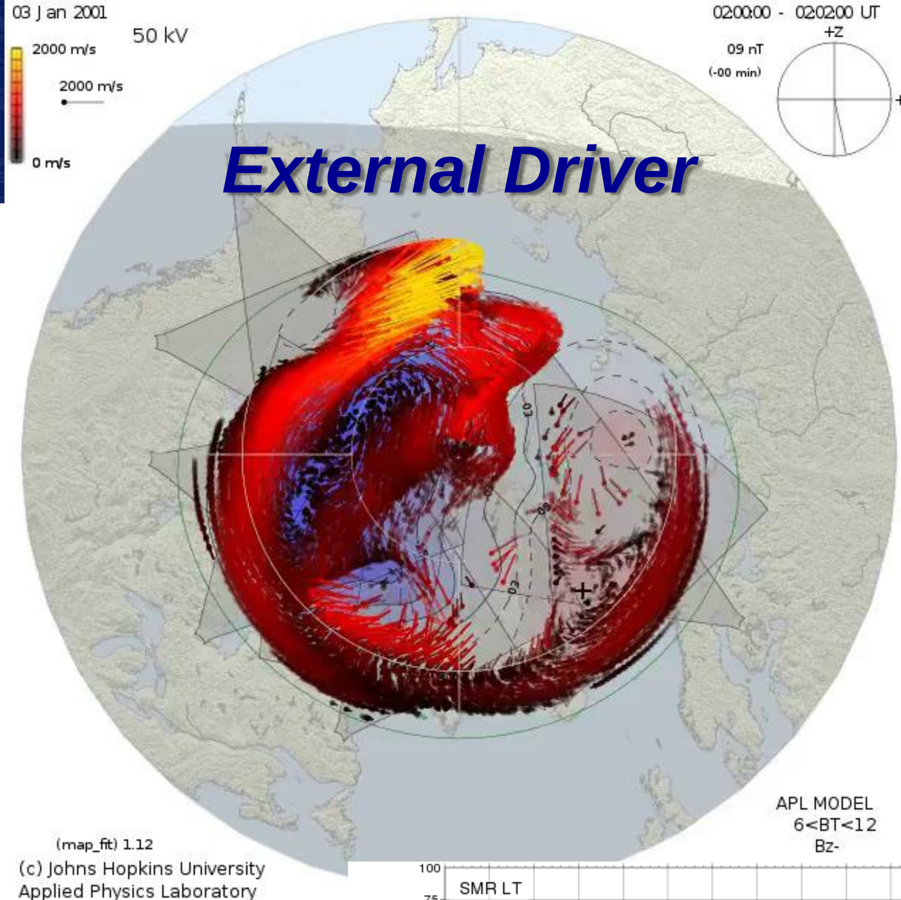
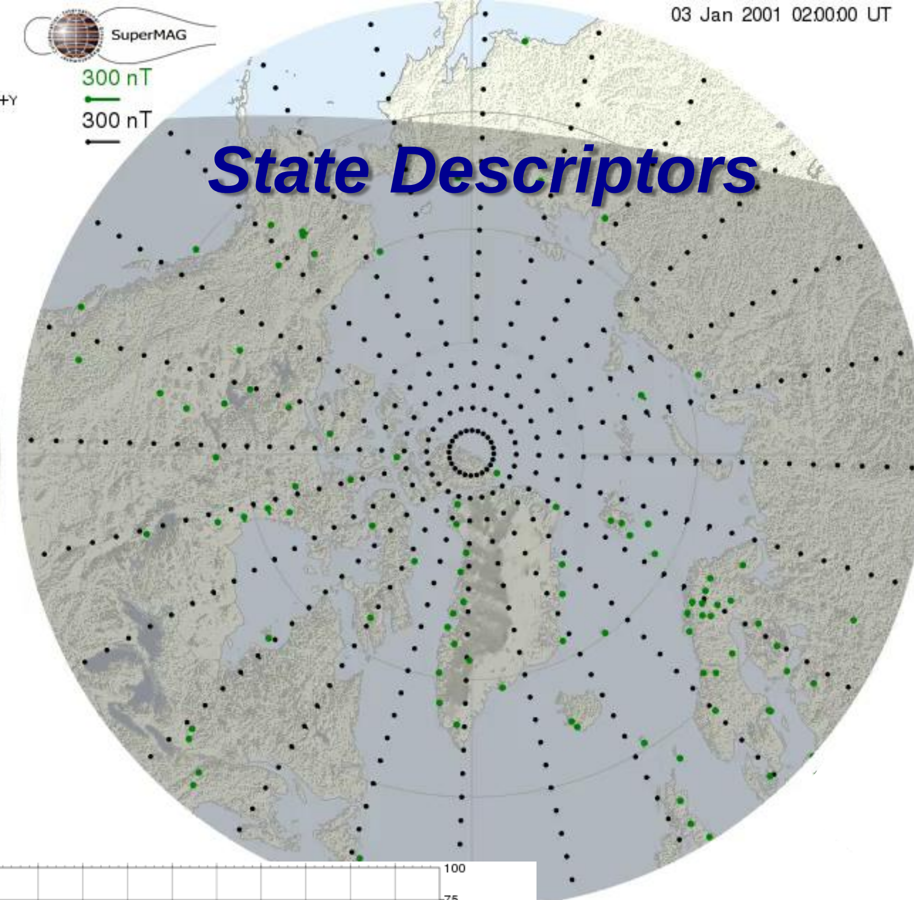


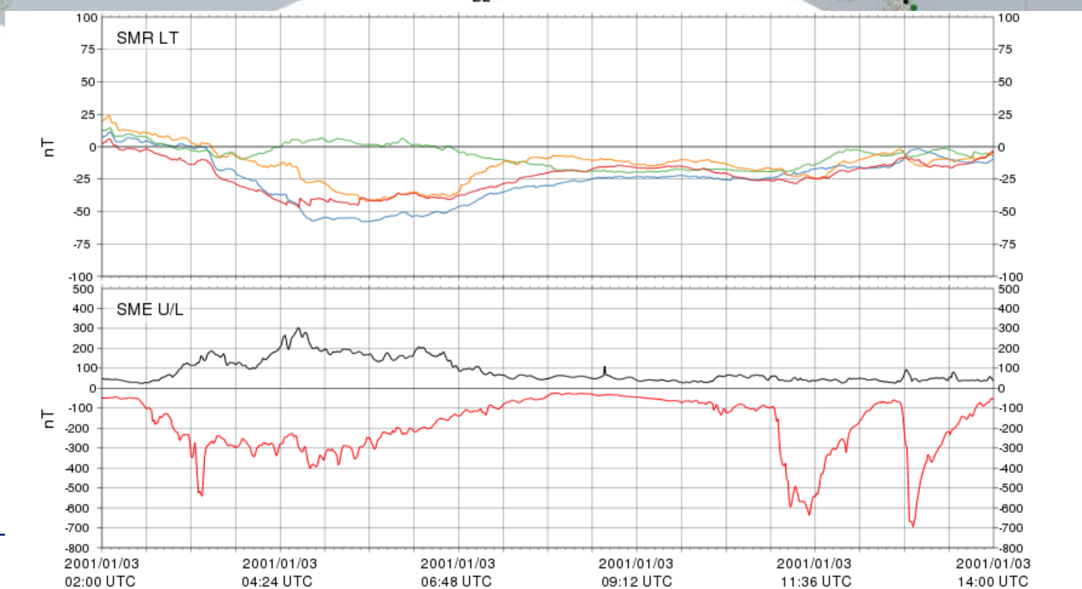


External Driver



State Descriptors





Deriving global distributions: What have we learned?

Conclusions:

- **Simple spatial interpolation:**
  - assume scale sizes are larger than spatial data gaps
- **External driver:**
  - assume causality
- **State descriptors:**
  - assume these adequately describe the system state
- **It is unclear to what extend pretty smooth distributions provide insight into system behavior.**

Recommendations:

- **More emphasis should be put on validation of results/models.**
- **We must remember which underlying physical processes are excluded/ignored by the large-scale solutions.**
- **New models should include/acknowledge the dynamics of the system.**
- **Models should increasingly allow the user to control settings.**

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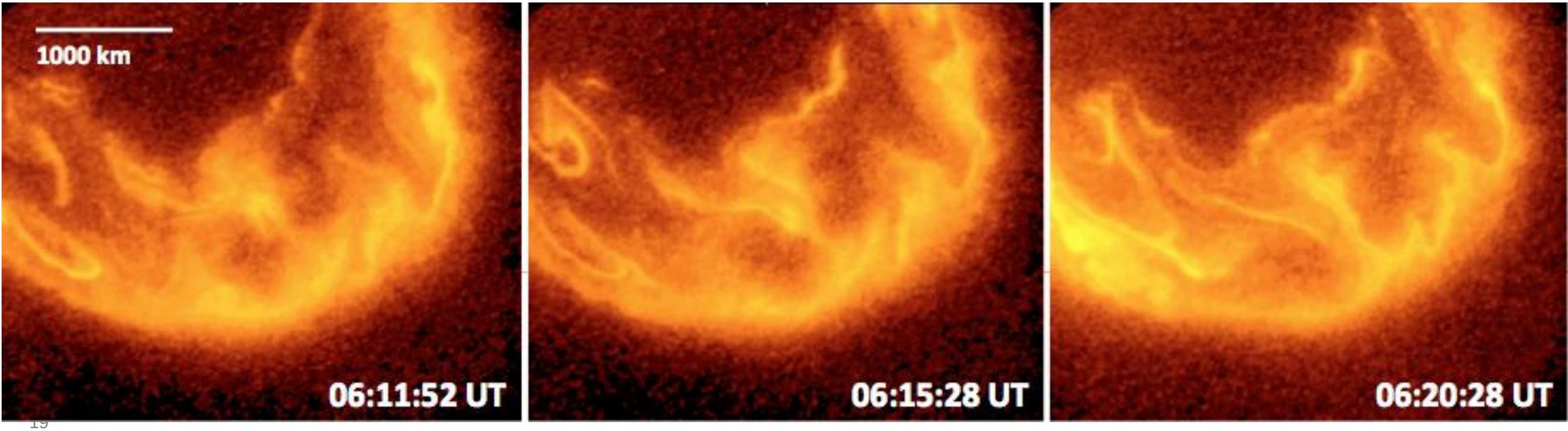
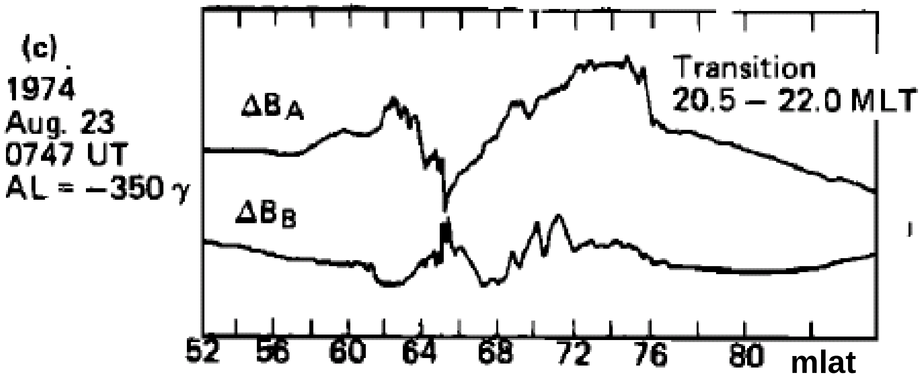
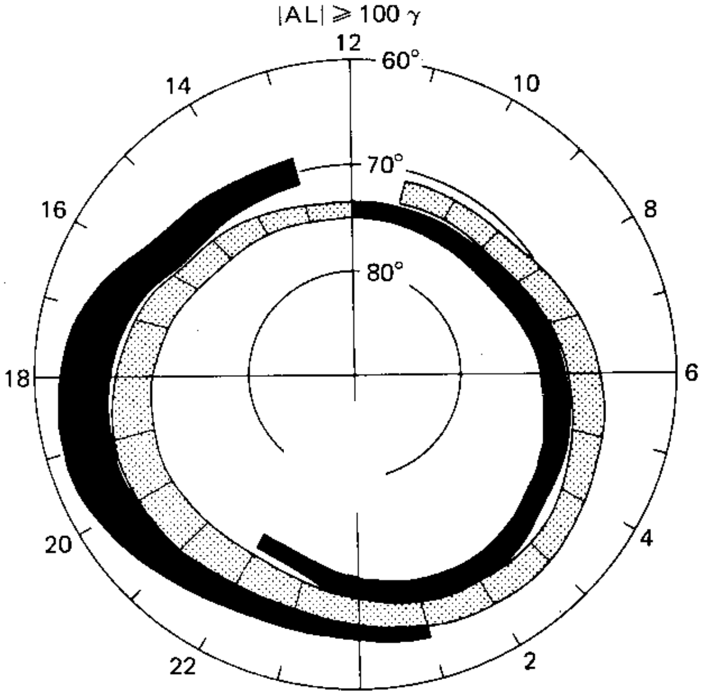


Global Birkeland Current Distribution: Inherent Assumptions

Reality



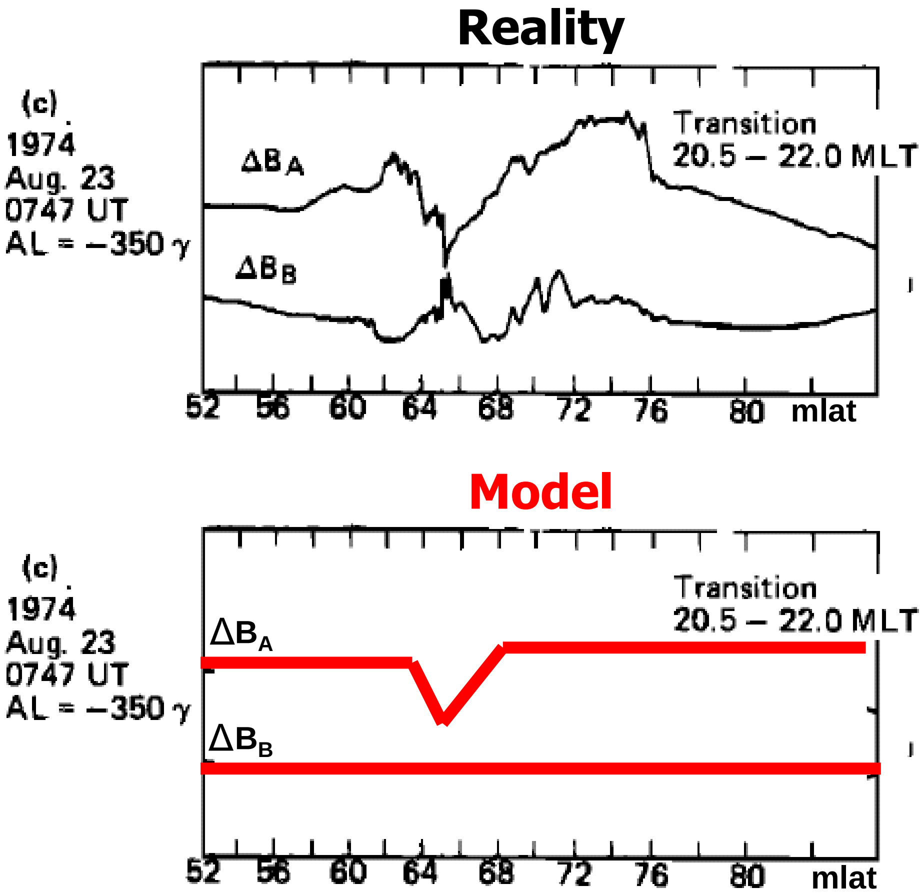


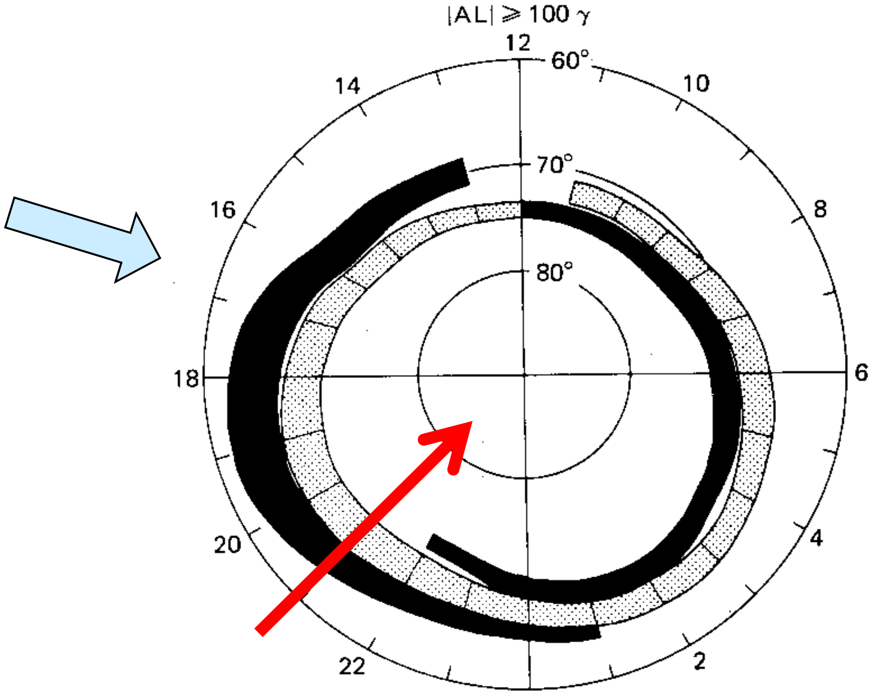
Iijima and Potemra, 1978

Inherent assumption:

- **Currents with scale sizes smaller than the R1-R2 currents are insignificant;**

Global Birkeland Current Distribution: Inherent Assumptions





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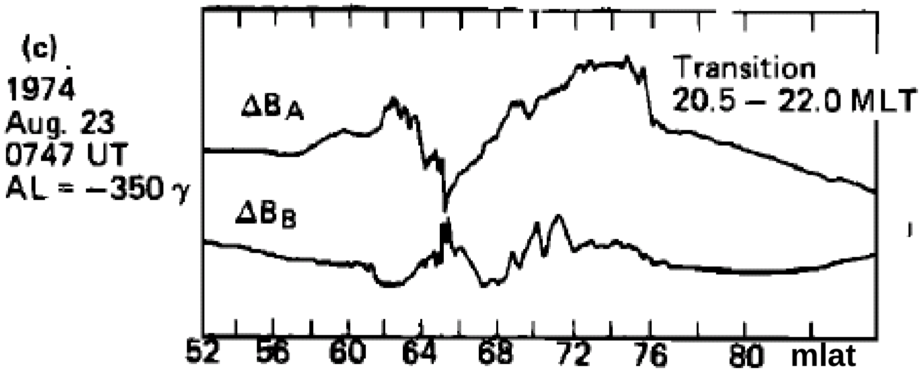
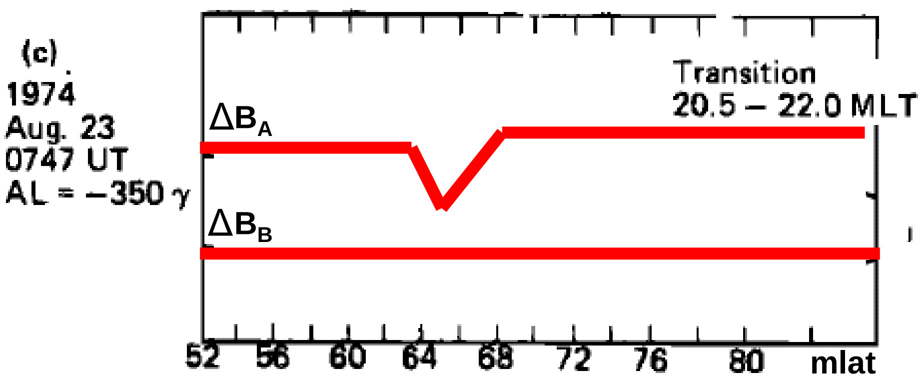
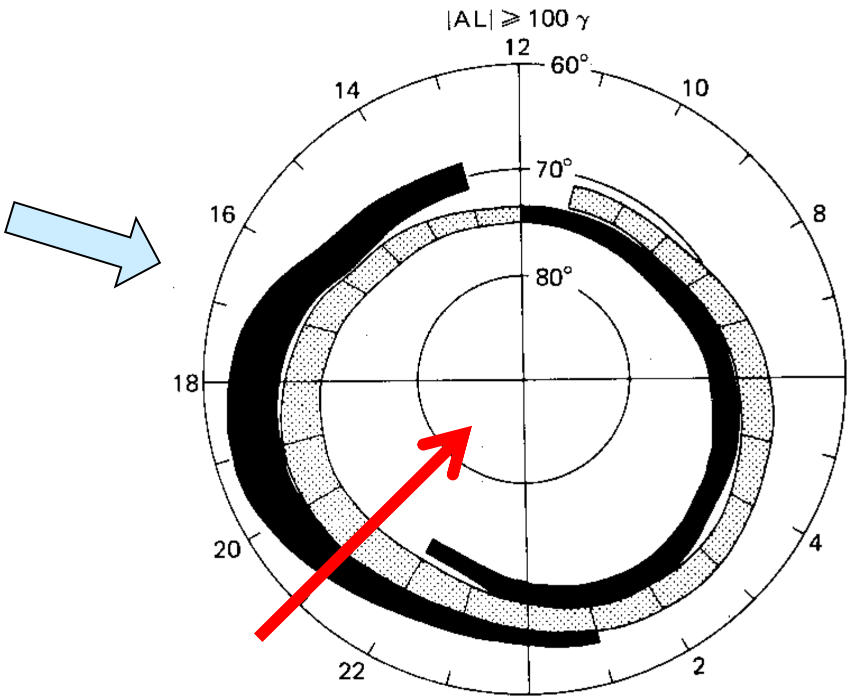
Global Birkeland Current Distribution: Inherent Assumptions

Reality



Model





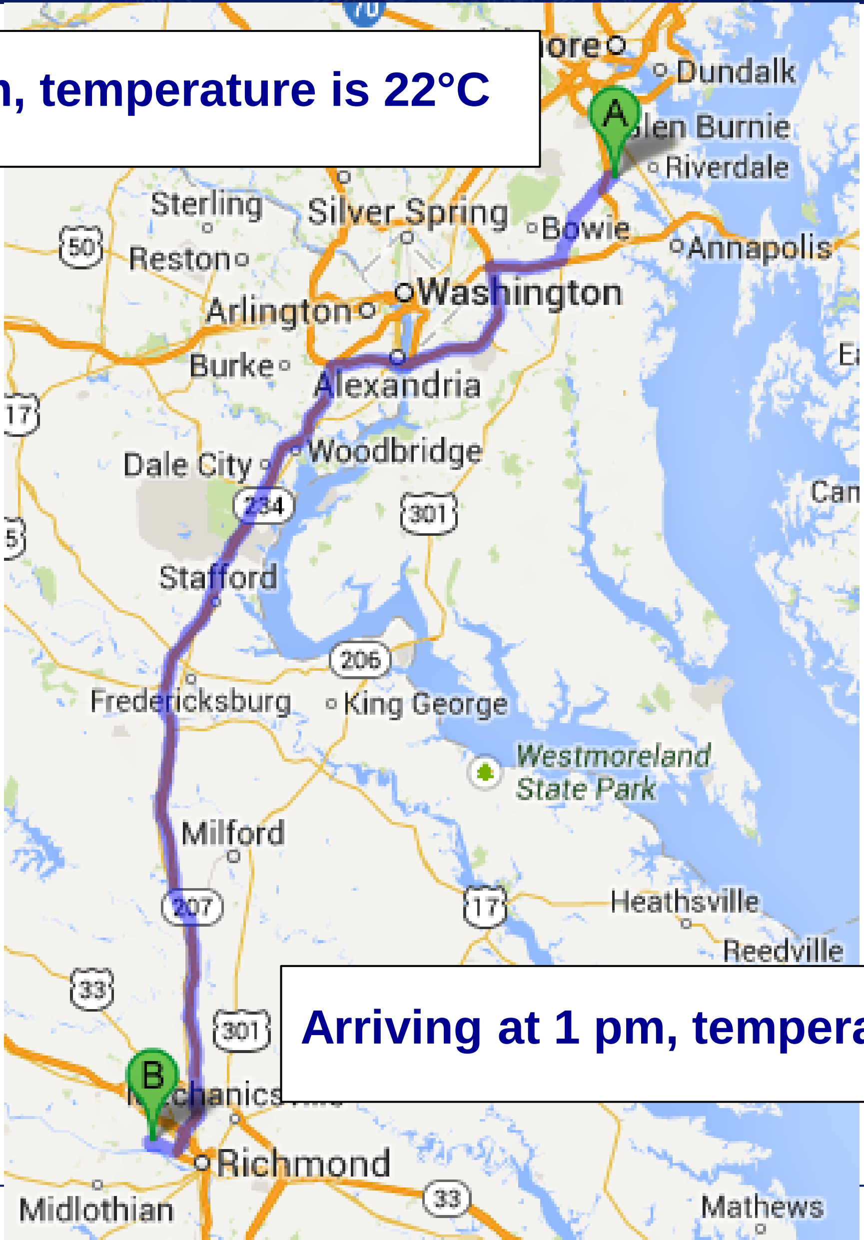
Iijima and Potemra, 1978

Inherent assumption:

- **Currents with scale sizes smaller than the R1-R2 currents are insignificant;**
- **The observed magnetic field perturbations are due to static currents.**

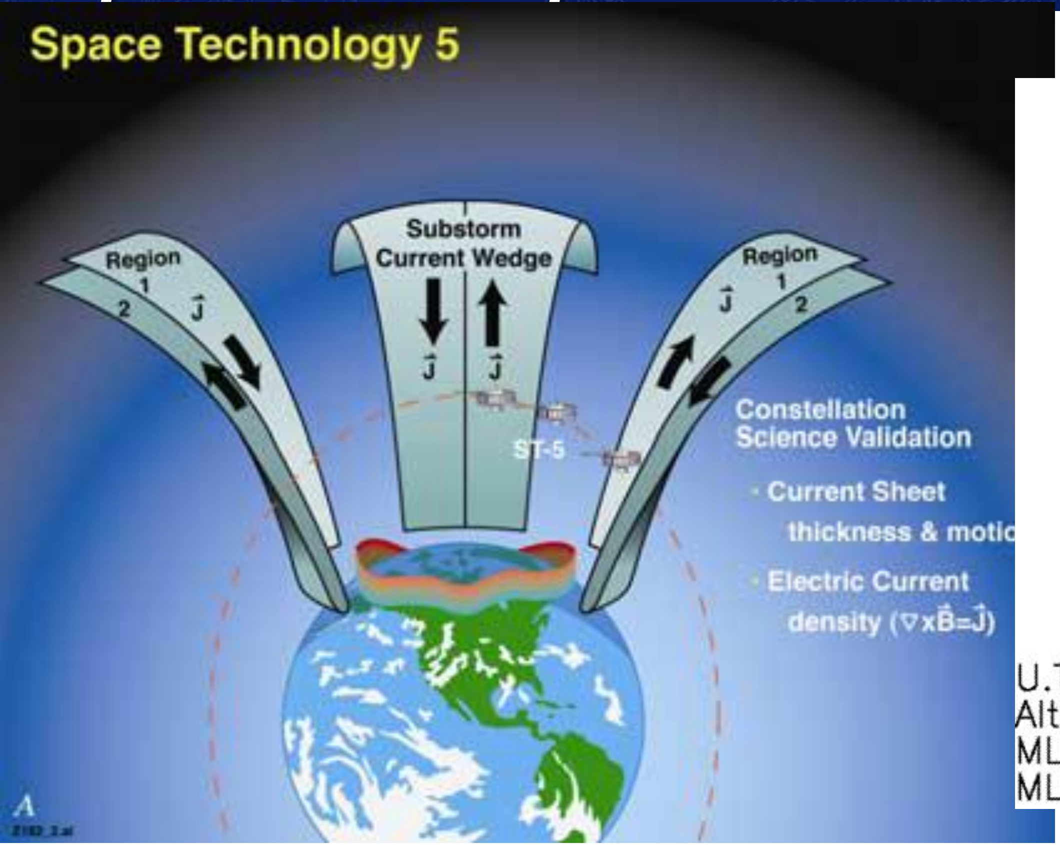
Observational Challenge: Mixing Space and Time

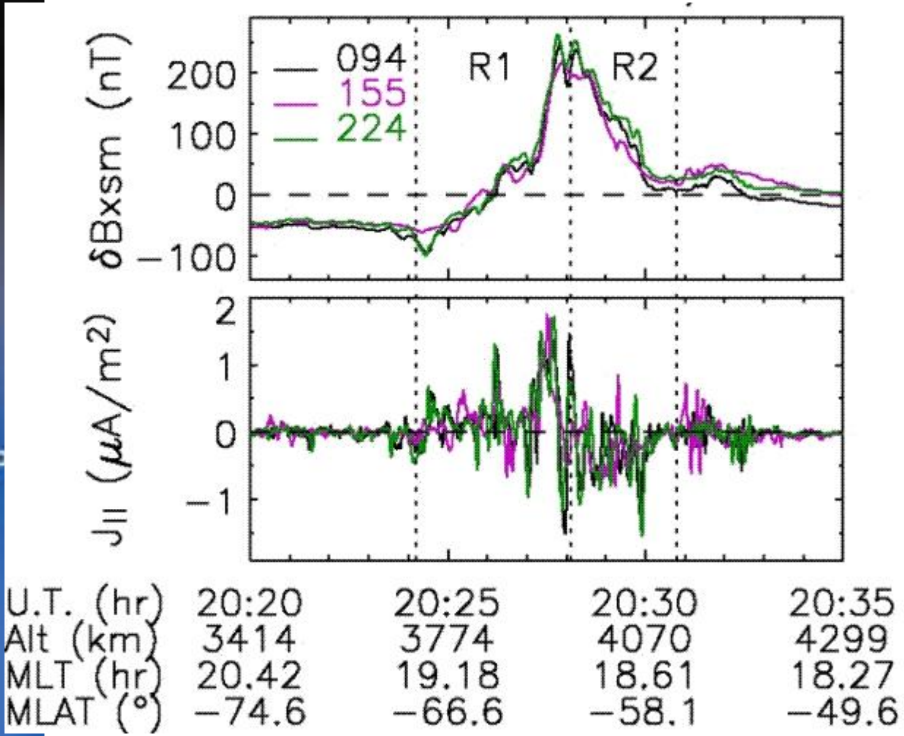
Leaving at 9 am, temperature is 22°C



Arriving at 1 pm, temperature is 31°C

ST 5 Mission: Multi point measurements enabling separation of space and time





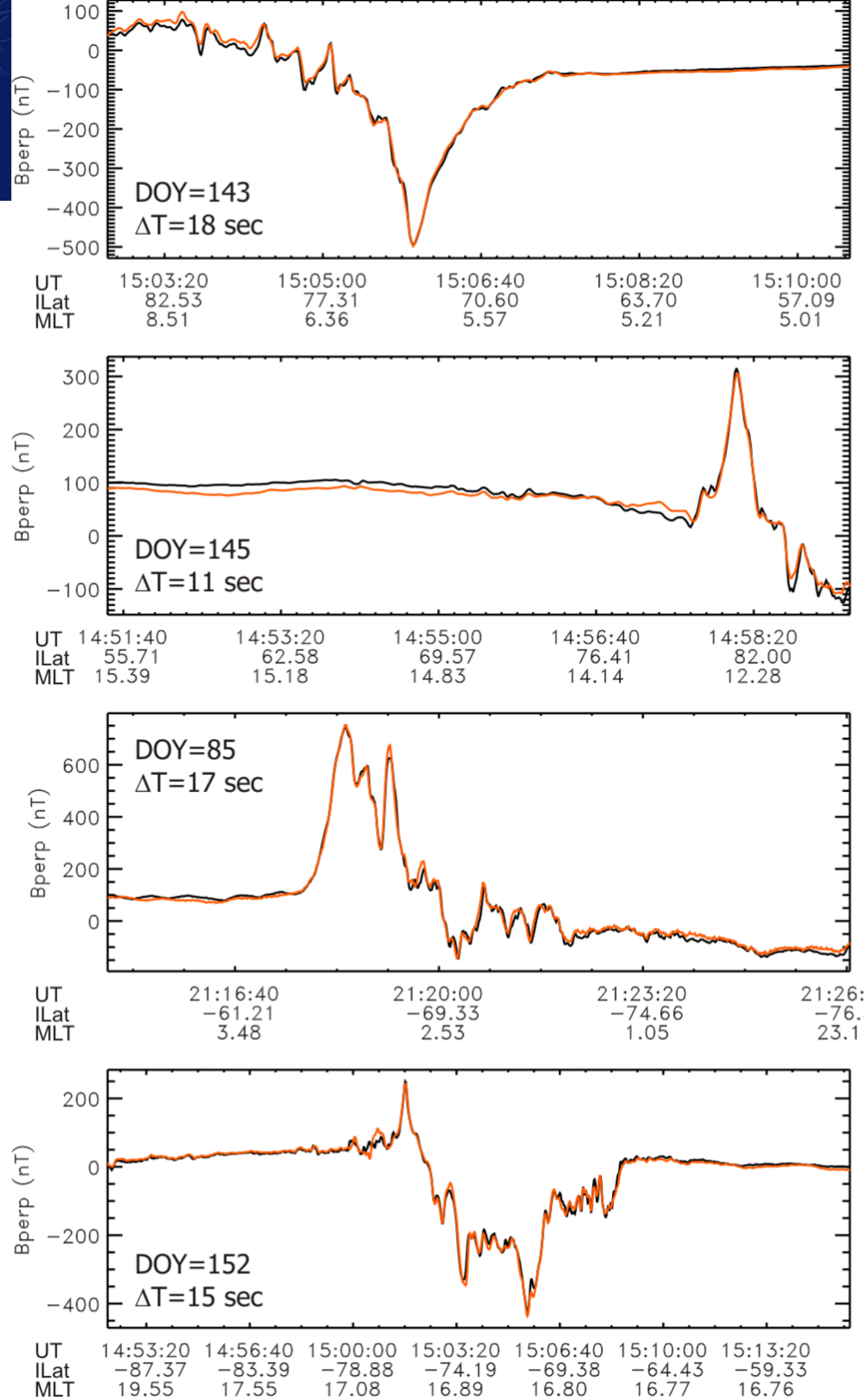
Slavin et al., 2008

Observations appear to indicate:

- **The FAC density is highly structured;**
- **The FAC density changes significantly over the 1-6 min separation of the ST 5 satellites.**

Typical Events:
Δt~15 sec

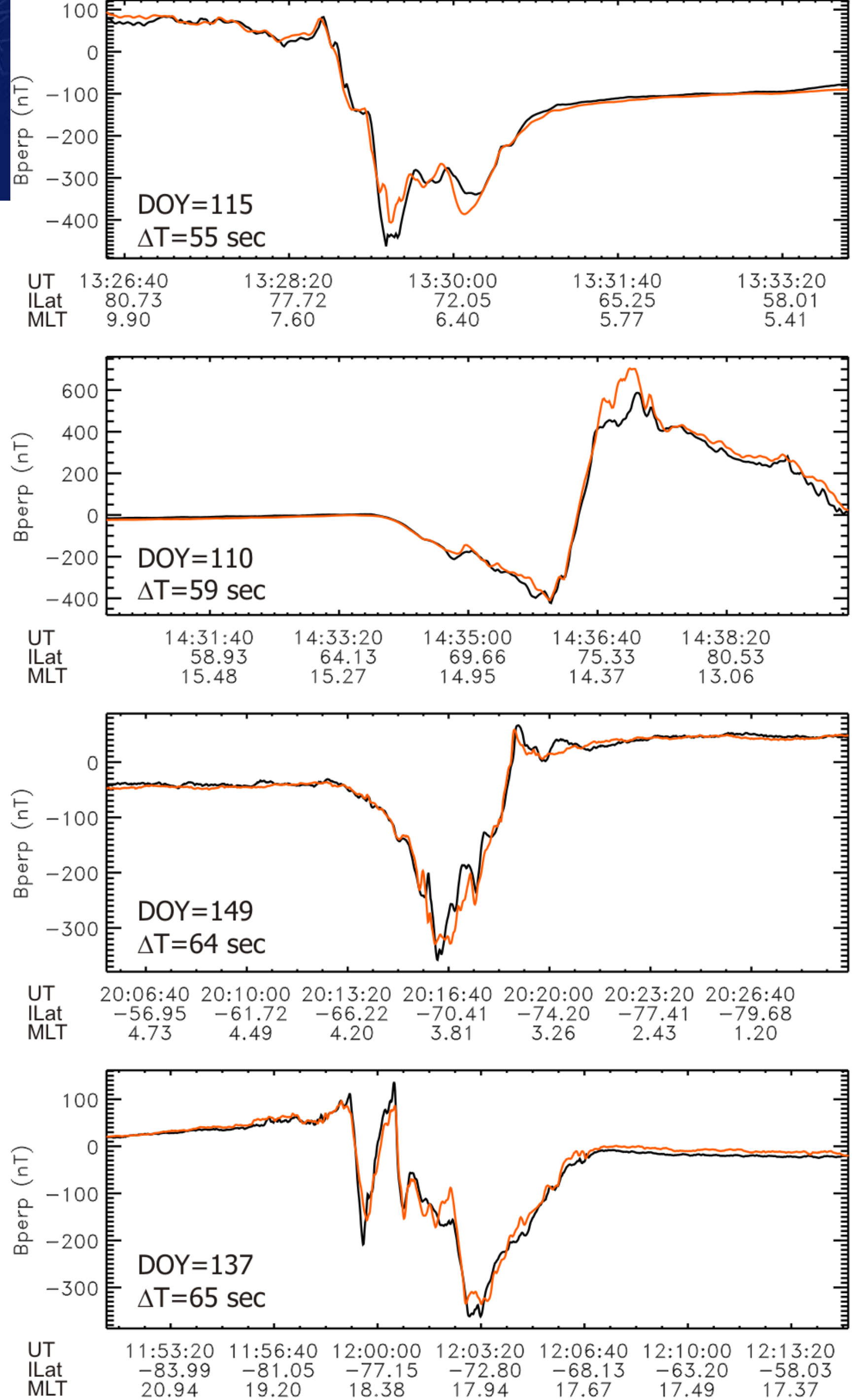
Current filaments with scale sizes larger than ~50 km change on time scales longer than ~15 sec.



Gjerloev et al. [2011]

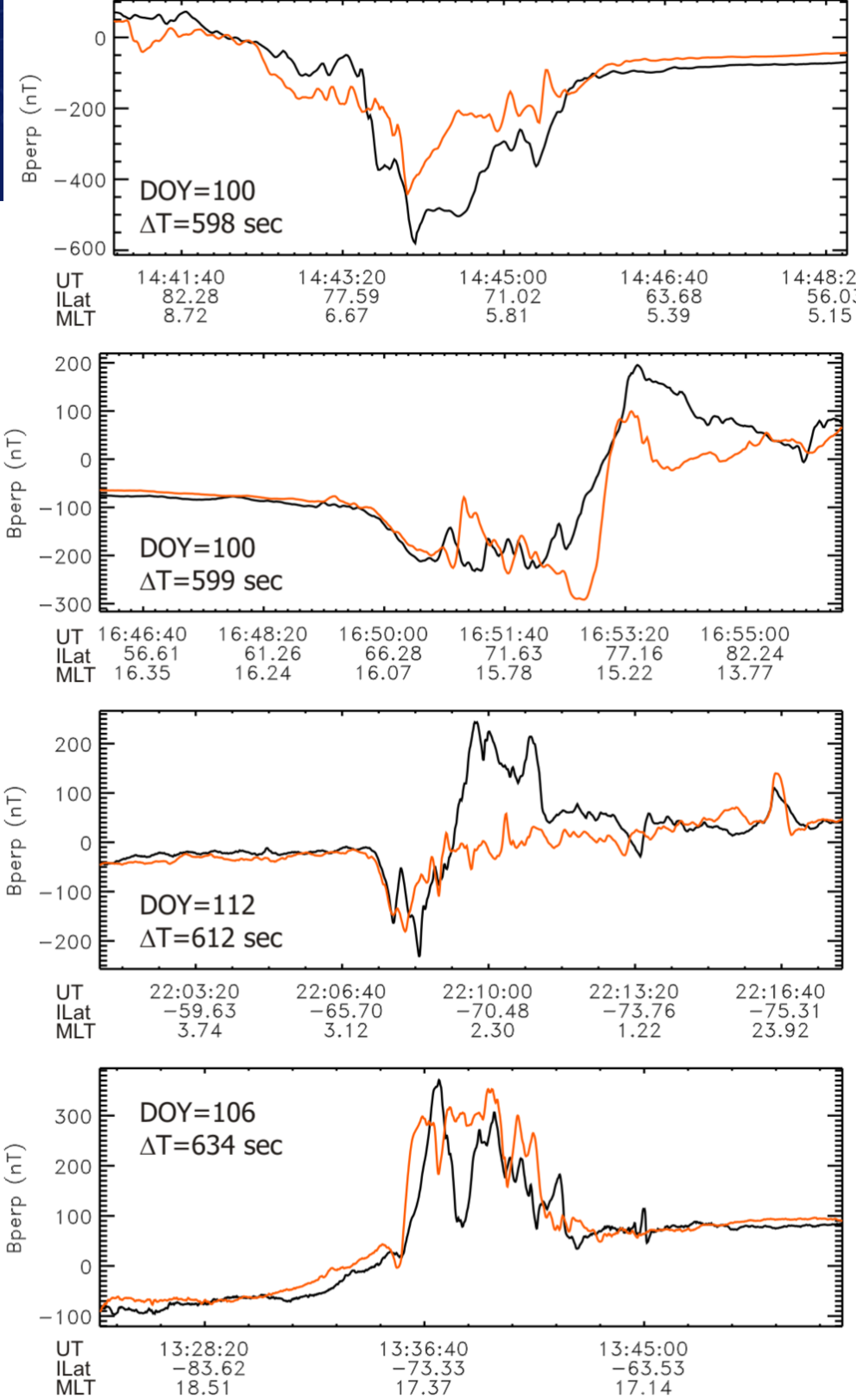
Typical Events: Δt~60 sec

Current filaments with scale sizes larger than ~200 km change on time scales longer than ~60 sec.



Gjerloev et al. [2011]

Typical Events: Δt~600 sec

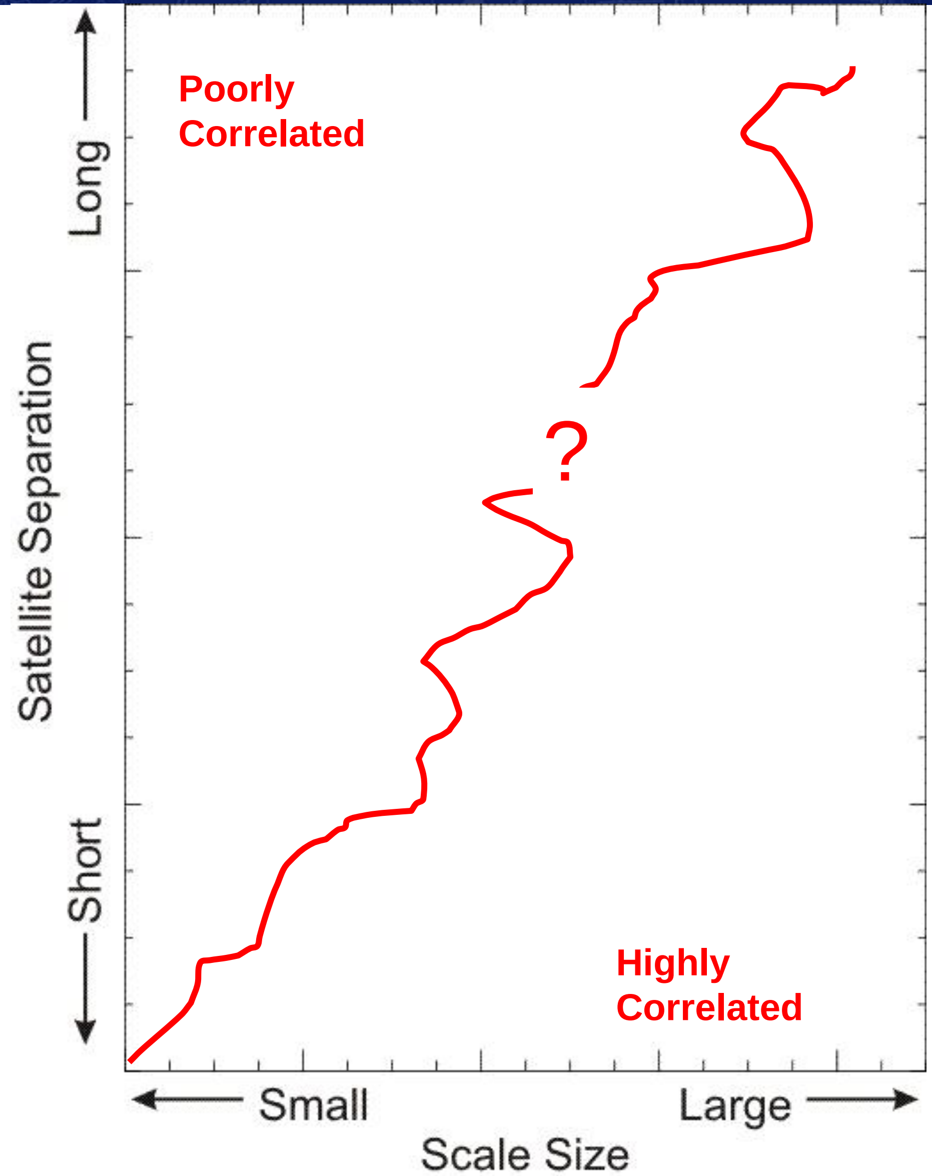


On time scales of ~600 sec we find significant changes to the entire FAC system at all scale sizes.

Gjerloev et al. [2011]

Scale Size and Variability of Birkeland Currents
Anticipated result

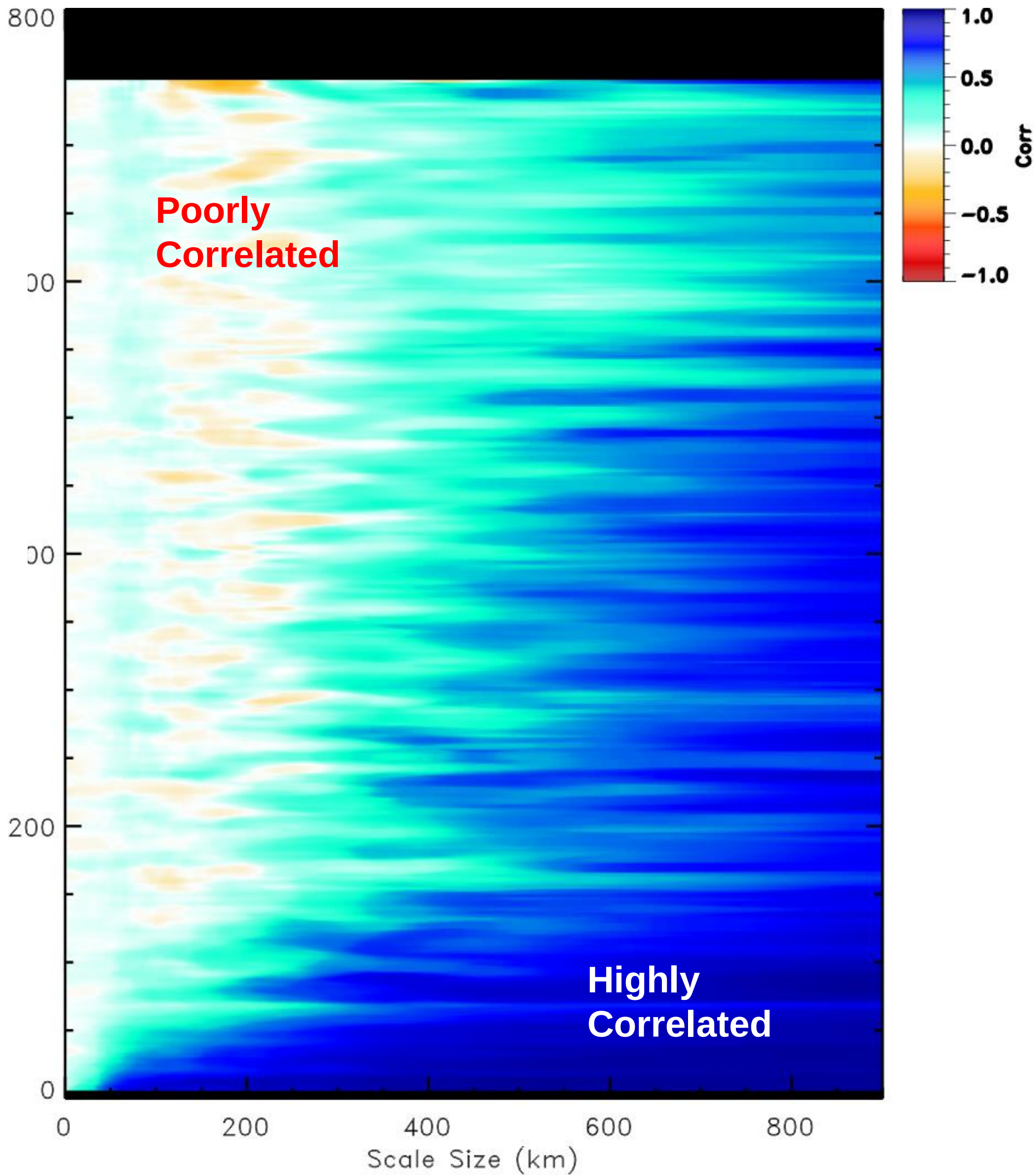
Is it reasonable to assume that the magnetosphere-ionosphere system is repeatable?



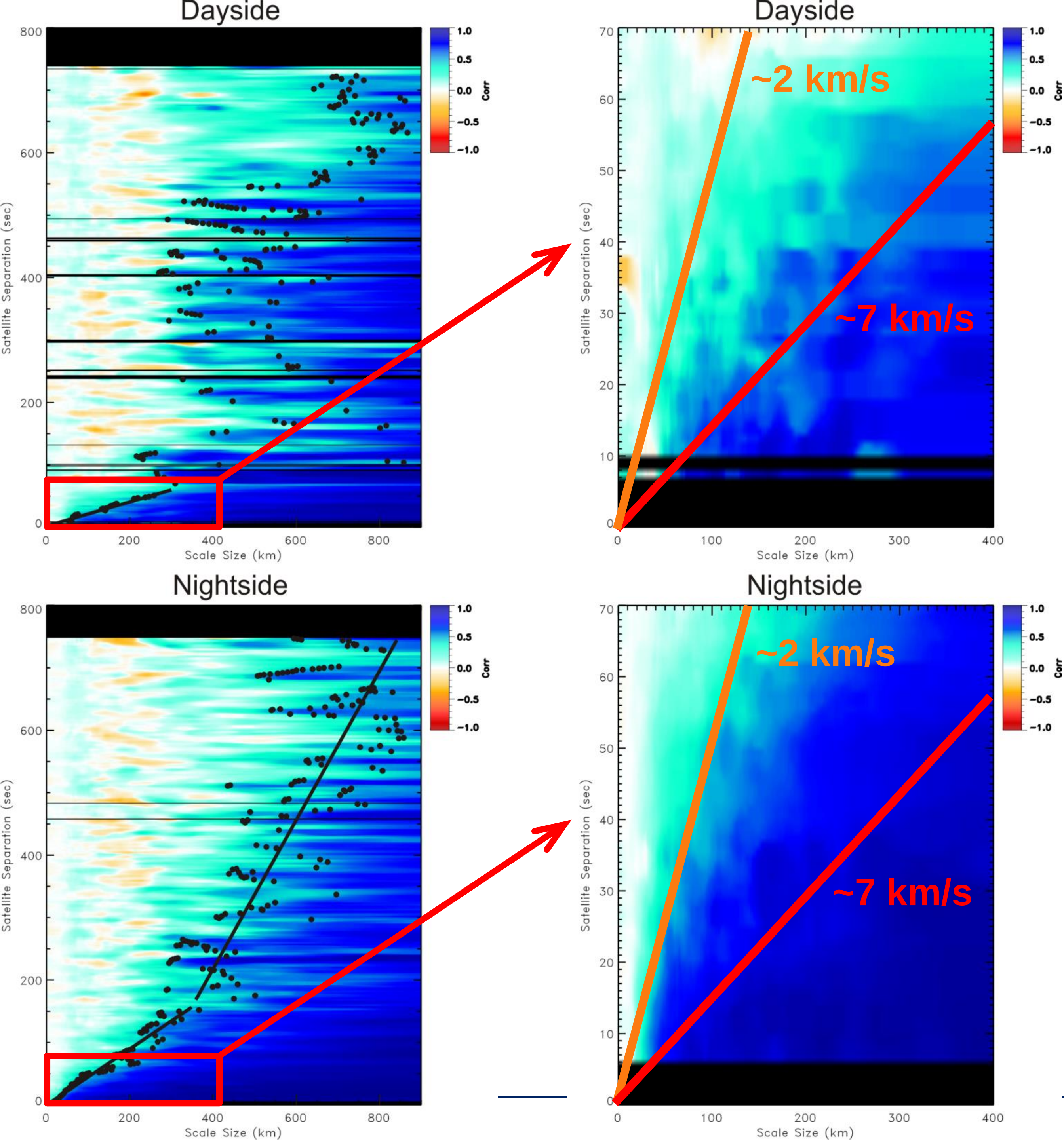
Scale Size and Variability of Birkeland Currents
Actual result

Is it reasonable to assume that the magnetosphere-ionosphere system is repeatable?

Surprisingly the answer is yes.



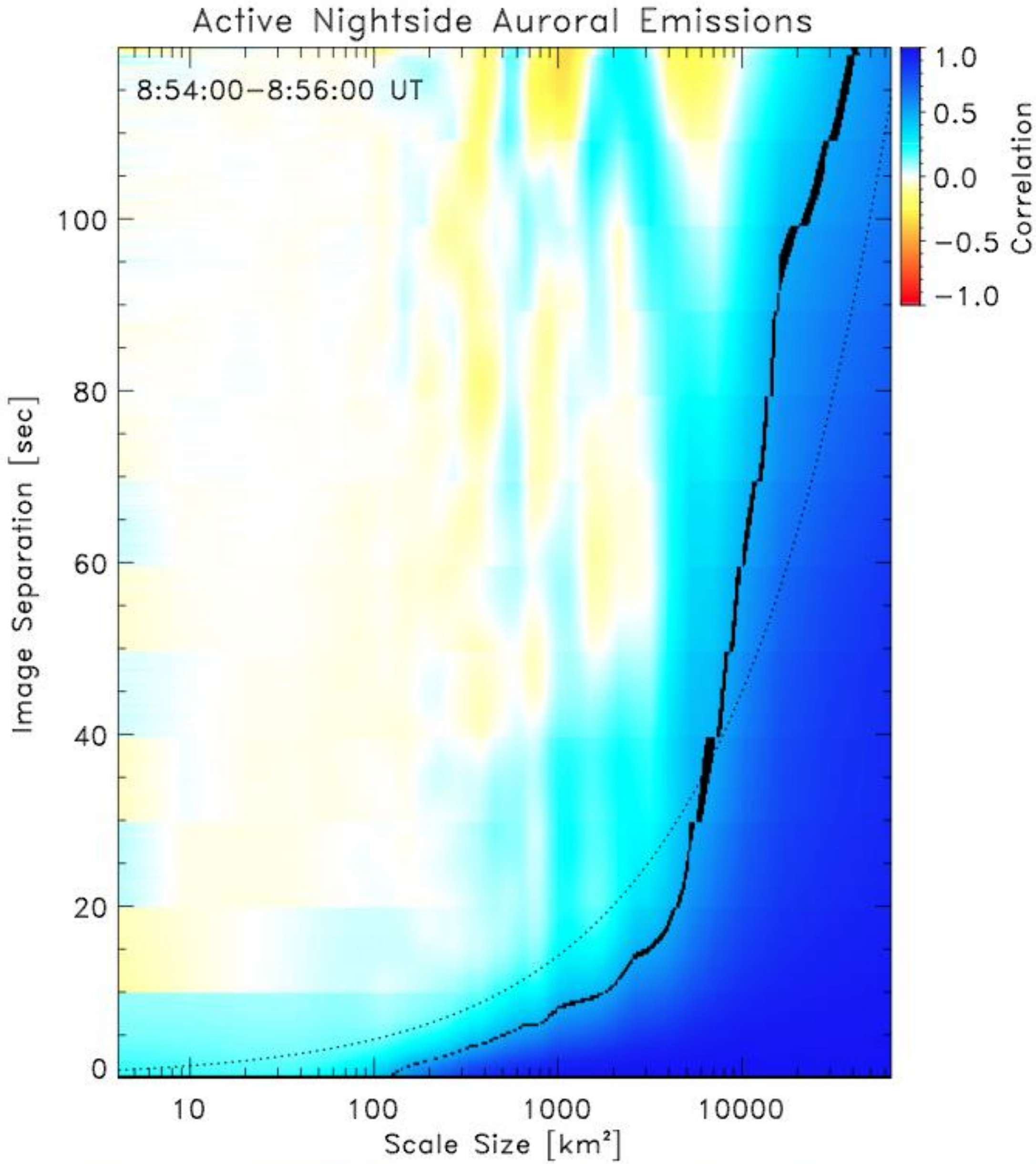
Gjerloev et al. [2011]



A satellite pass is marginally in the high correlation region on the dayside.

A sounding rocket is typically in the poor correlation region.

Scale Size and Variability of Green Light Emissions

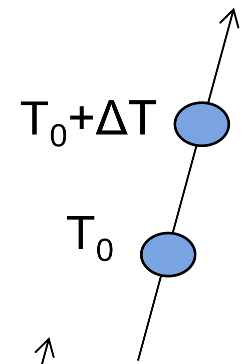


Humberset et al. [2016]

Calculating FAC's using Swarm

Single satellite (classical)

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \quad \Rightarrow \quad J_z = \left[\partial B_y/\partial x - \partial B_x/\partial y\right]/\mu_0$$

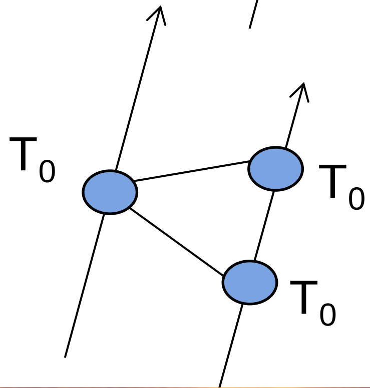


Assumptions:

- Static over the time it takes to traverse current sheet
- Simplistic current configuration (e.g. infinite sheet)

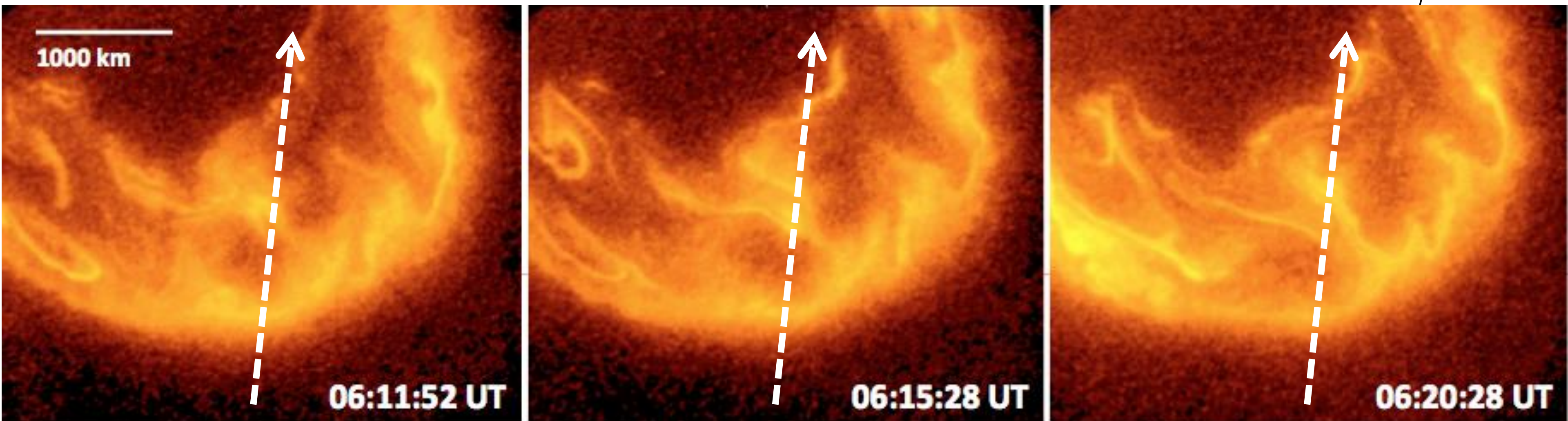
Three satellites (curlometer technique)

$$j = \frac{1}{\mu_0 A}\oint \boldsymbol{B}\cdot d\ell \quad \Rightarrow \quad J_z \approx \frac{1}{\mu_0}\left(\frac{\mathbf{r}_{13}\cdot\Delta\mathbf{B}_{12} - \mathbf{r}_{12}\cdot\Delta\mathbf{B}_{13}}{\left|\mathbf{r}_{13}\times\mathbf{r}_{12}\right|}\right)$$

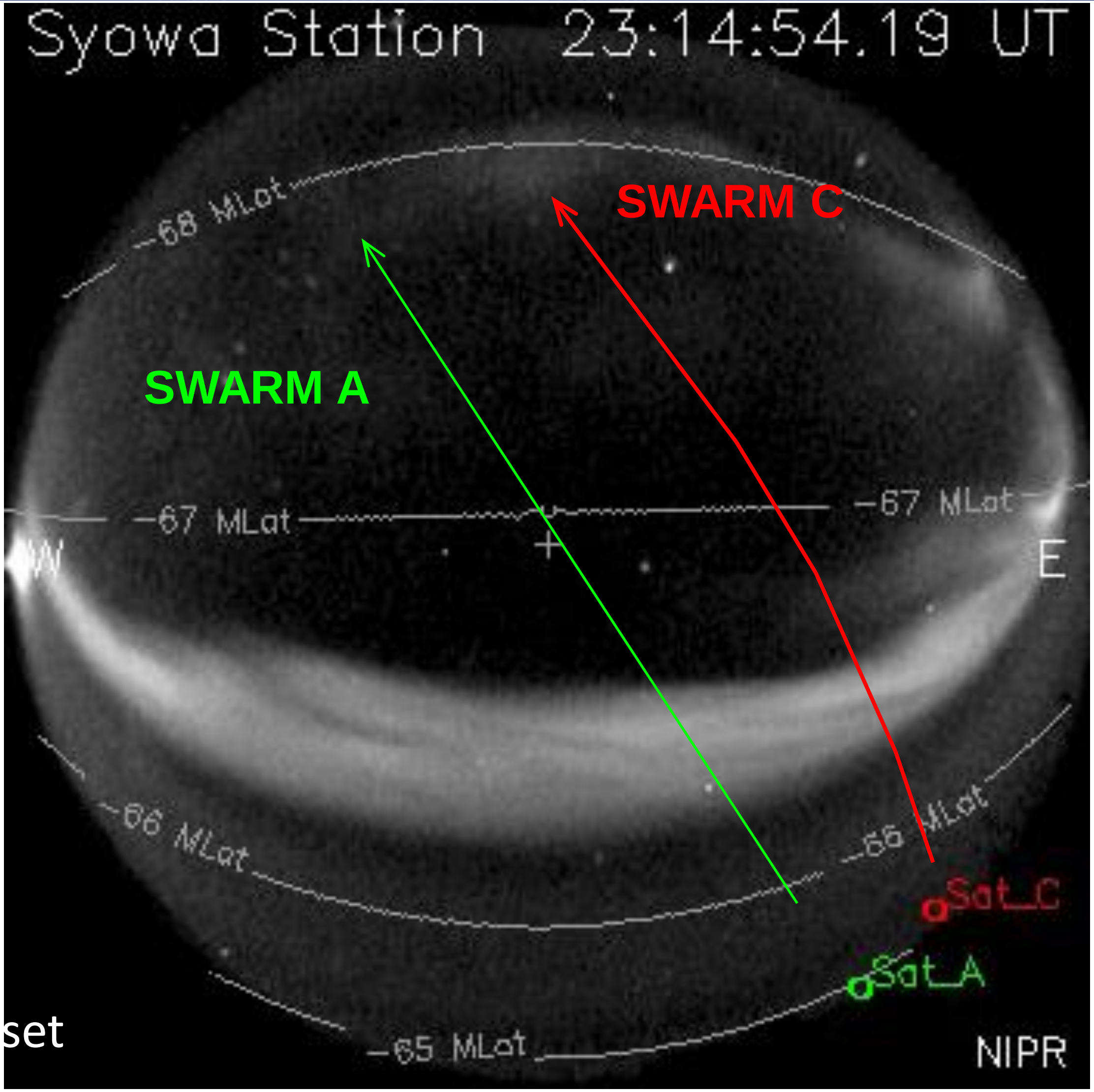


Assumption:

- Constant current over area

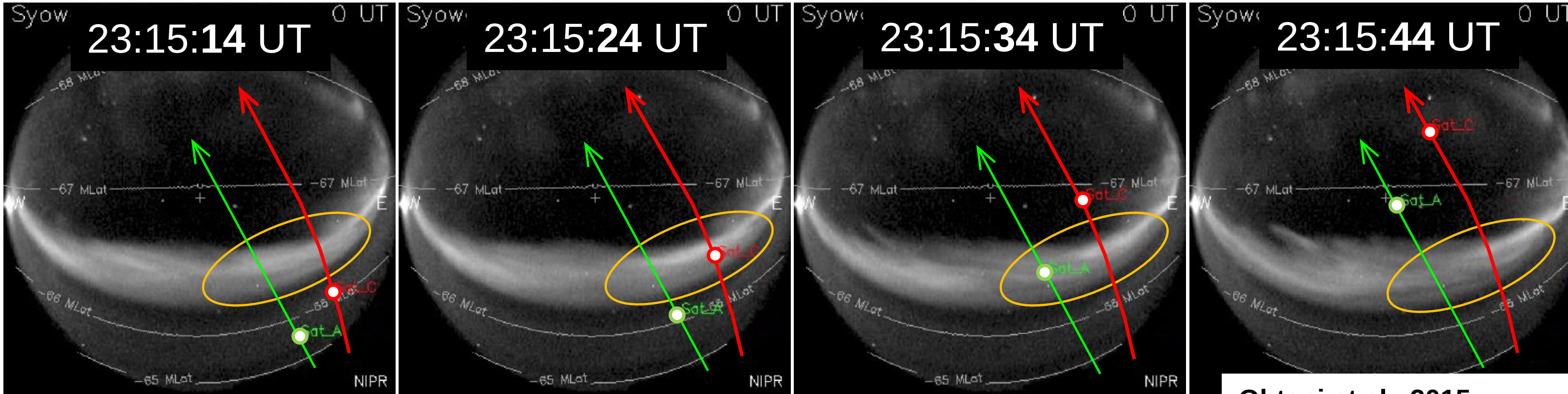


Calculating Birkeland Currents using ESA Swarm Example on 1 September 2014



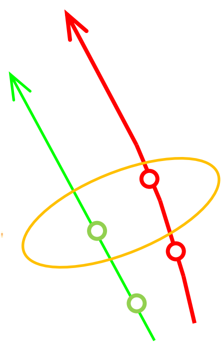
Special thanks to Tetsuo Motoba(STEL, Nagoya U) and Natl. Inst. Polar Res. (Japan)

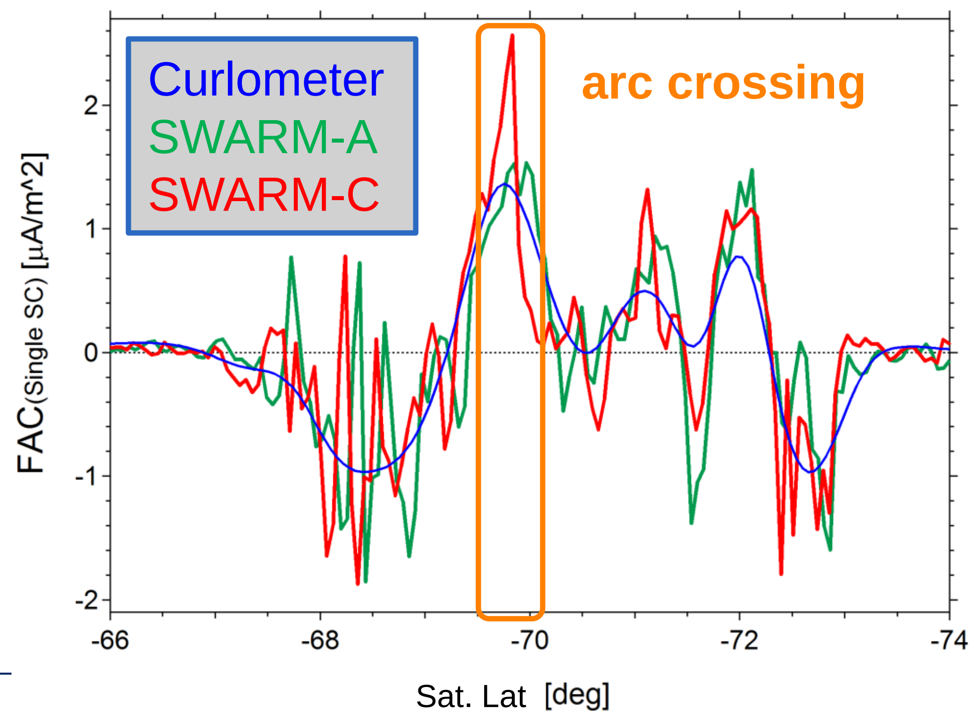
Calculating Birkeland Currents using ESA Swarm Example on 1 September 2014



Ohtani et al., 2015

$$j = \frac{1}{\mu_0 A} \oint \boldsymbol{B} \cdot d\boldsymbol{\ell}$$





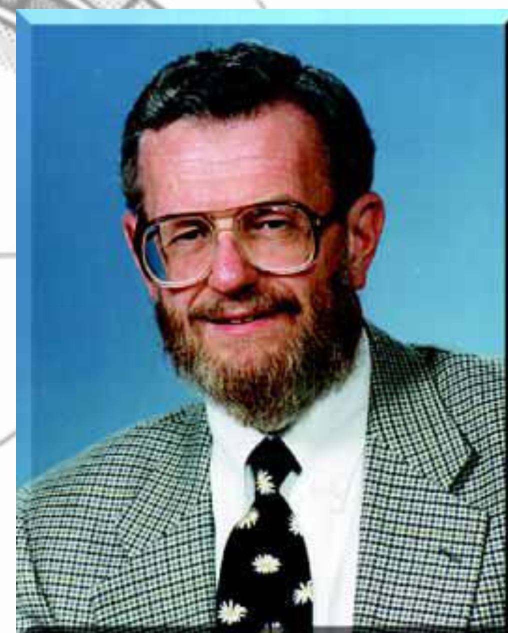
Even for best case scenario (stable arcs) Birkeland currents:

- **are not static**
- **are not infinite sheets**
- **are not uniform over 50 km**

Special Session at the 2016 Fall AGU Meeting
(San Francisco; 12-16 December 2016; Abstract Submission : 15 June - 3 August 2016)

Birkeland Currents:
Achievements since Iijima and Potemra [1976], and Challenges in Years to Come

Takeshi Iijima (1938–)



Thomas A. Potemra (1938–1998)

Conveners:

Aoi Nakamizo,[1] Natalia Ganushkina,[2] Hermann J. Opgenoorth,[3] and Lawrence J. Zanetti,[4,5]

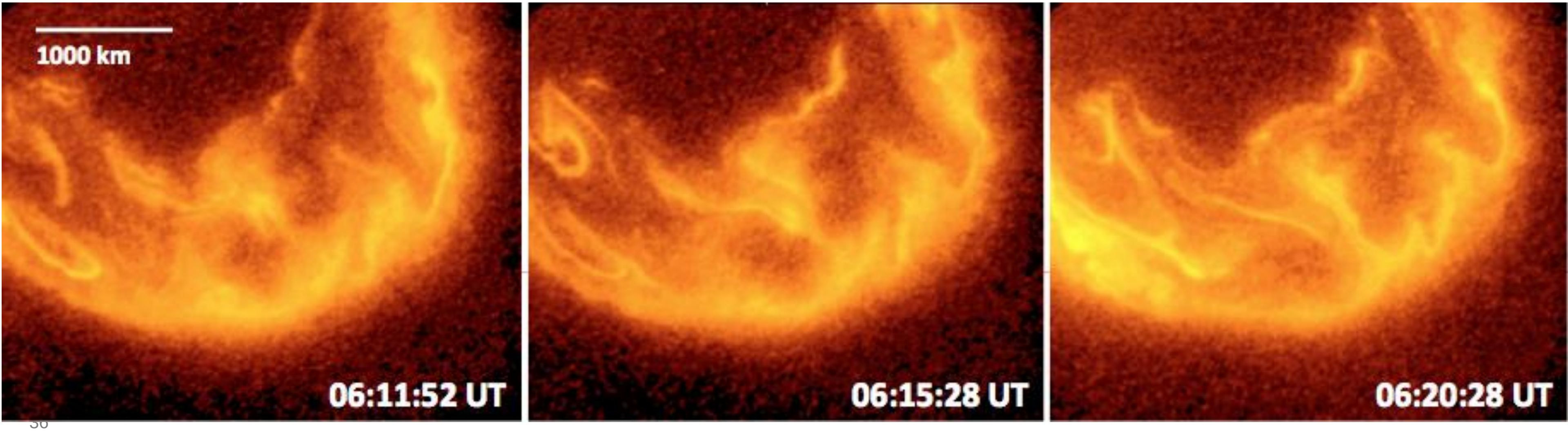
1: NICT (Japan); 2: FMI (Finland)/Univ. Michigan (USA); 3: IRF (Sweden); 4: NOAA (USA); 5: JHU/APL (USA)

Outline

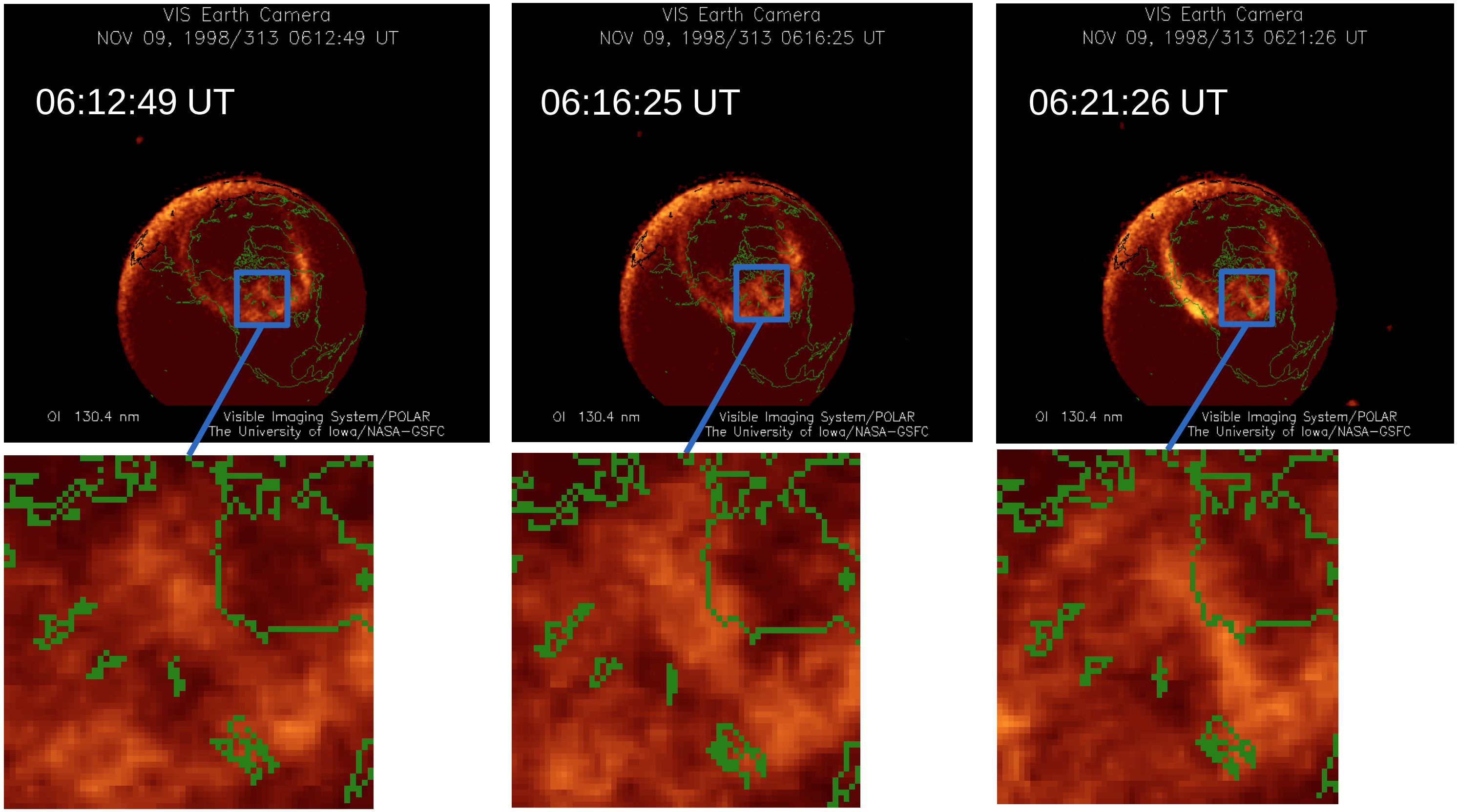
1. How do we derive global solutions from sparse data coverage?

2. What are the limitations of the global solutions?
   - Derived parameters
   - Processes/phenomena

3. The holy grail of M-I physics: Global, continuous and complete electrodynamic solutions.



North-South Structures



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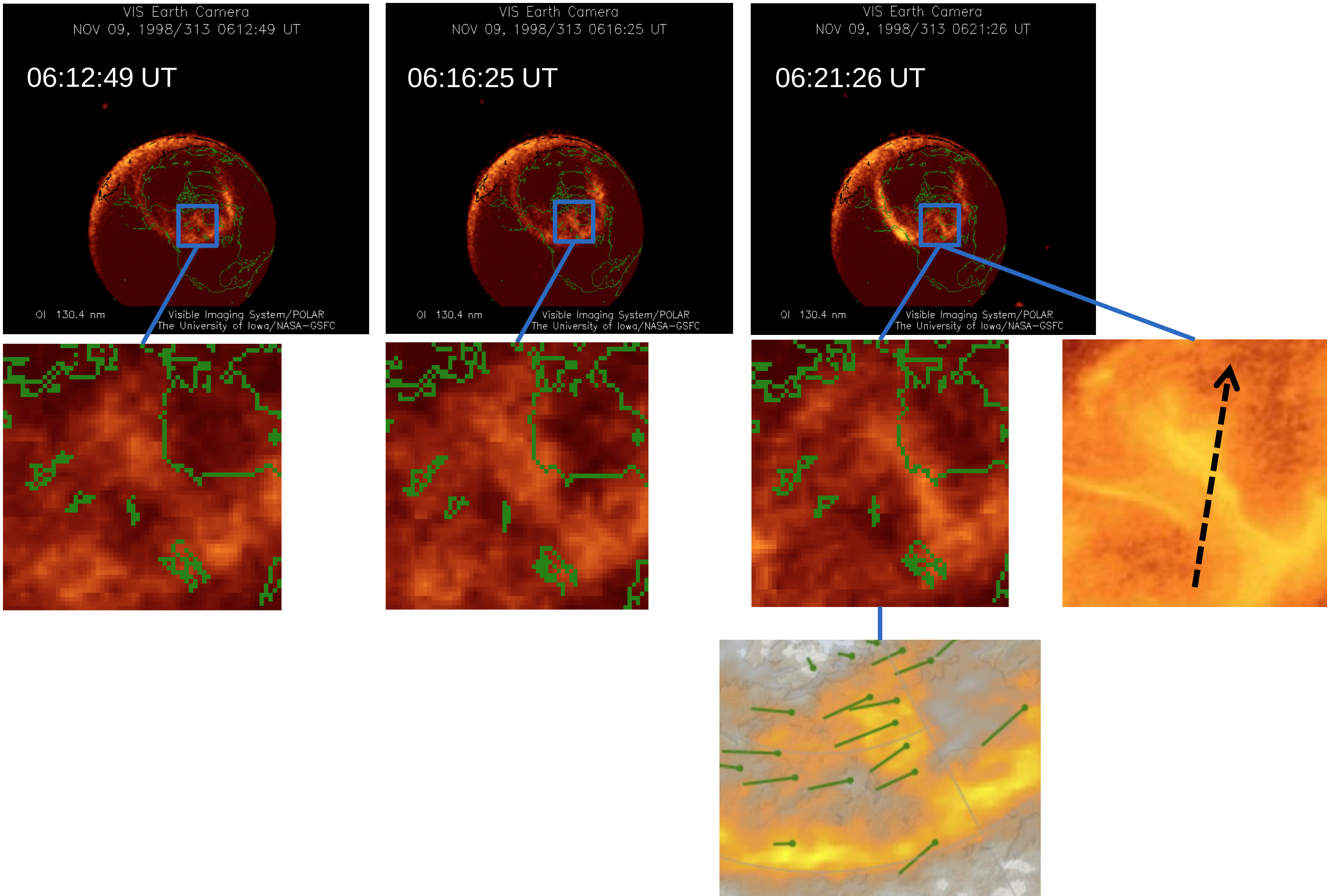
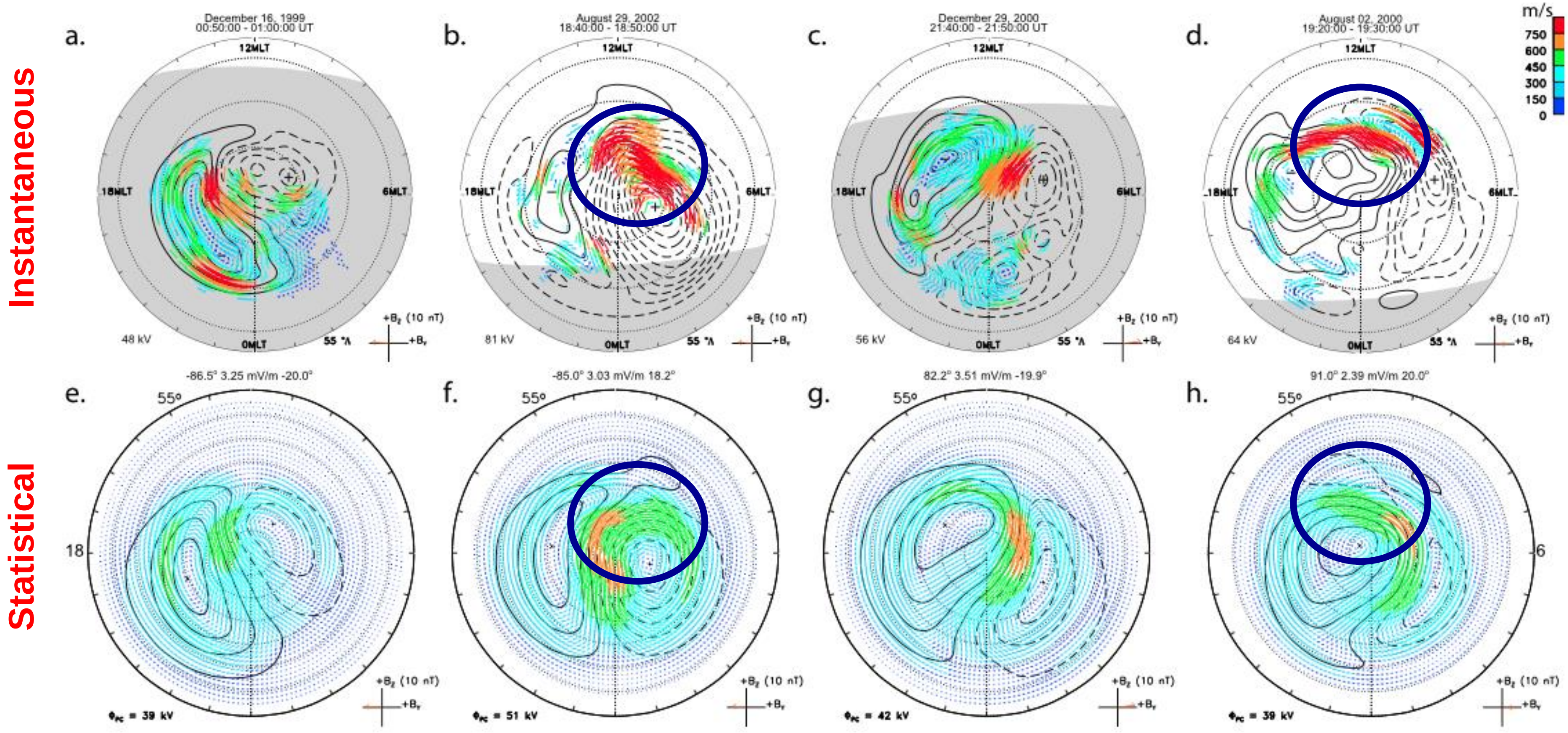


Limitations of statistical models



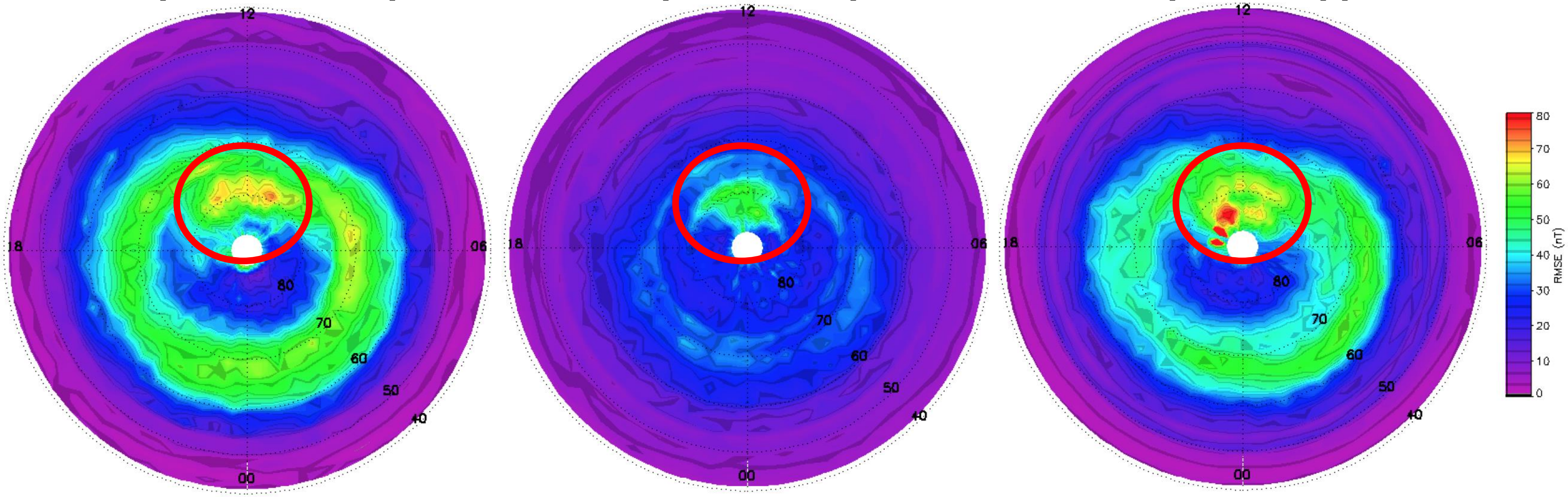
Cousins, E. D. P. and S. G. Shepherd (2010)

To what extend does pretty smooth average solutions provide the system information we seek?

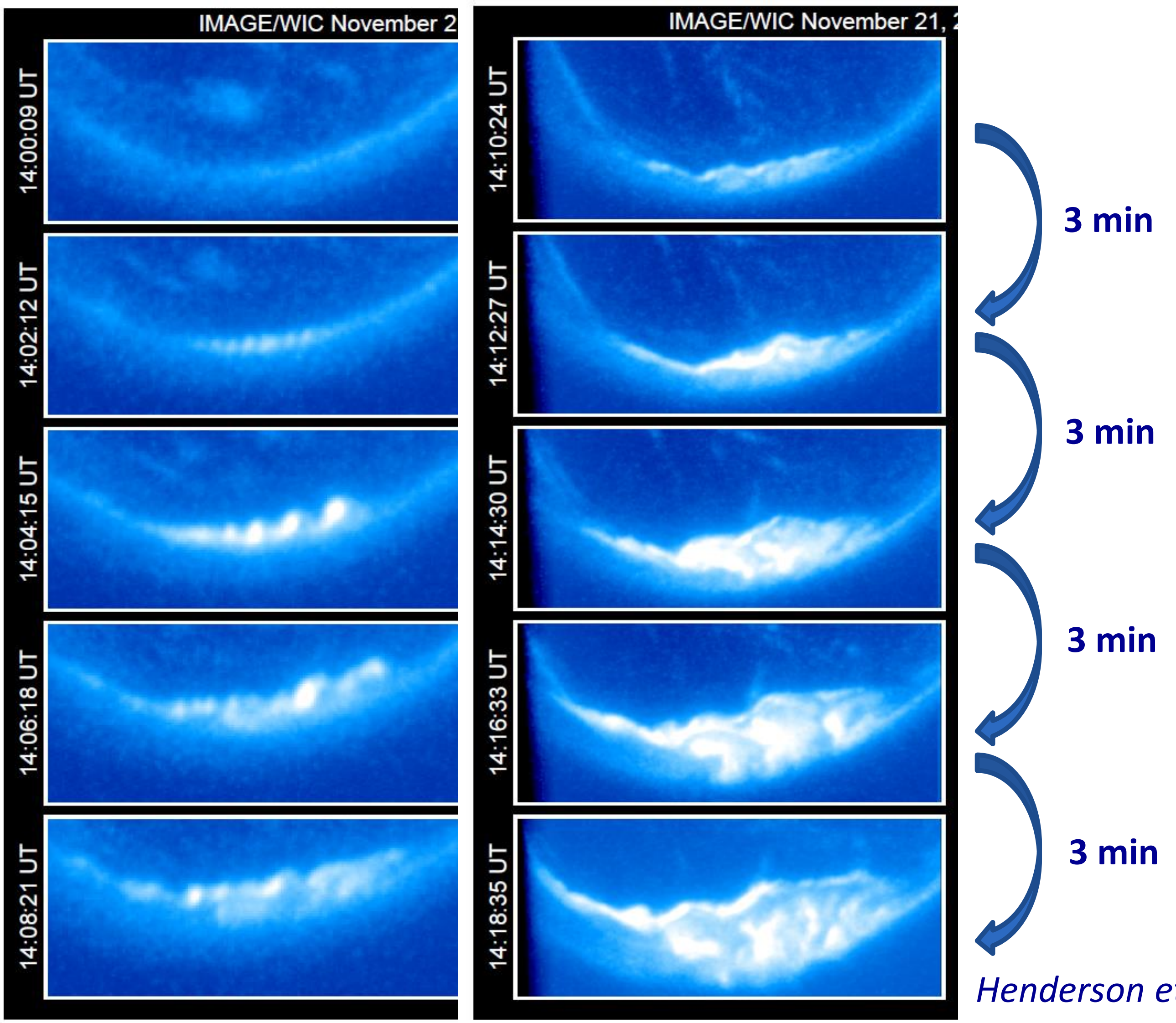
Limitations of statistical models

Waters, Gjerloev, Dupont, Barnes, JGR, 2015

N (north-south) **E (east-west)** **Z (down-up)**



Special Session at the 2016 Fall AGU Meeting
(San Francisco; 12-16 December 2016; Abstract Submission : 15 June - 3 August 2016



Henderson et al. [2009]

***SM003.* Advancing our Understanding of the Dynamic Magnetosphere-Ionosphere System Using Auroral Imaging**

Conveners:
J. Gjerloev, R. Floberhagen, S. Zou, D. Knudsen

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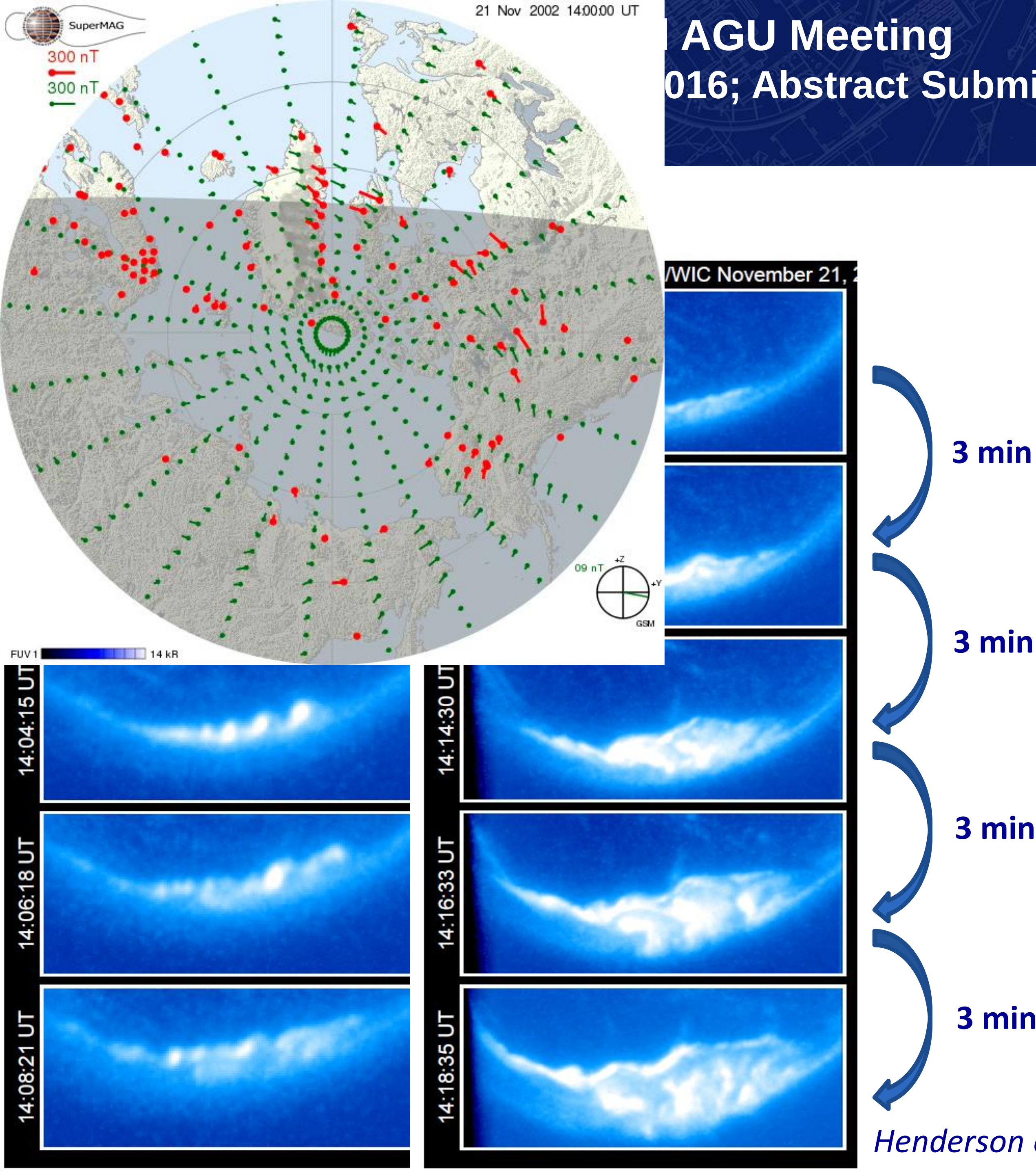

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Henderson et al. [2009]

Limitations of global distributions: What have we learned?

Conclusions:

- **Derived quantities from measurements is based on assumptions that often are violated.**
- **SuperMAG-SuperDARN-AMPERE spatiotemporal resolution limit the processes and phenomena that can be addressed.**

Recommendations:

- **Users should keep assumptions and limitations in mind before making conclusions. Providers should be open about these complexities and provide quality flags (when possible).**
- **Relationship between large-scale and meso-scale processes should be emphasized (e.g. feeding and drainage of the auroral electrojet system).**

Outline

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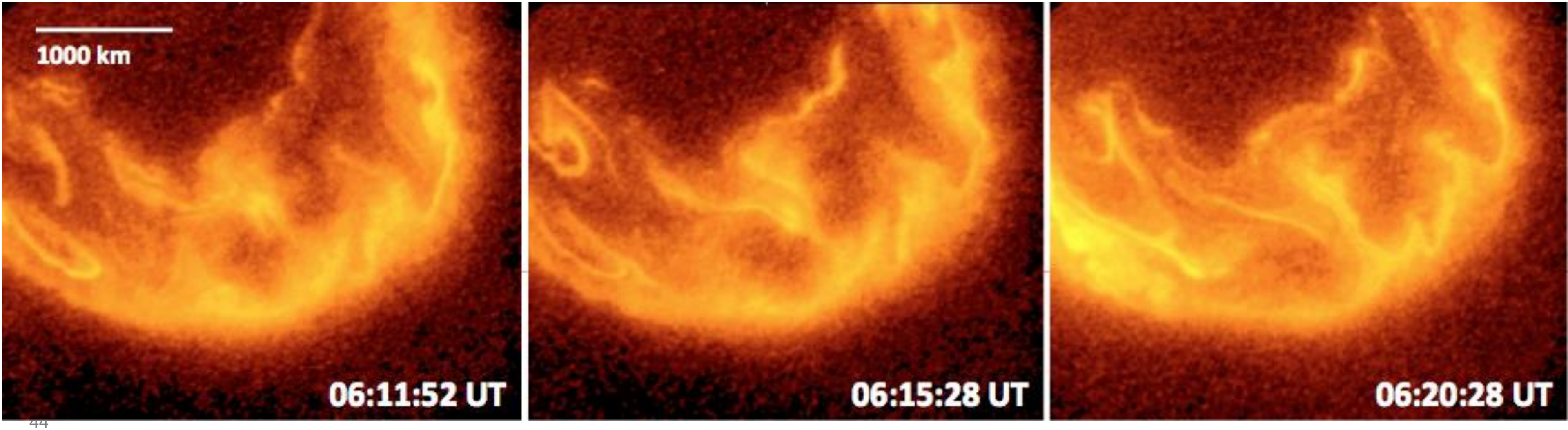
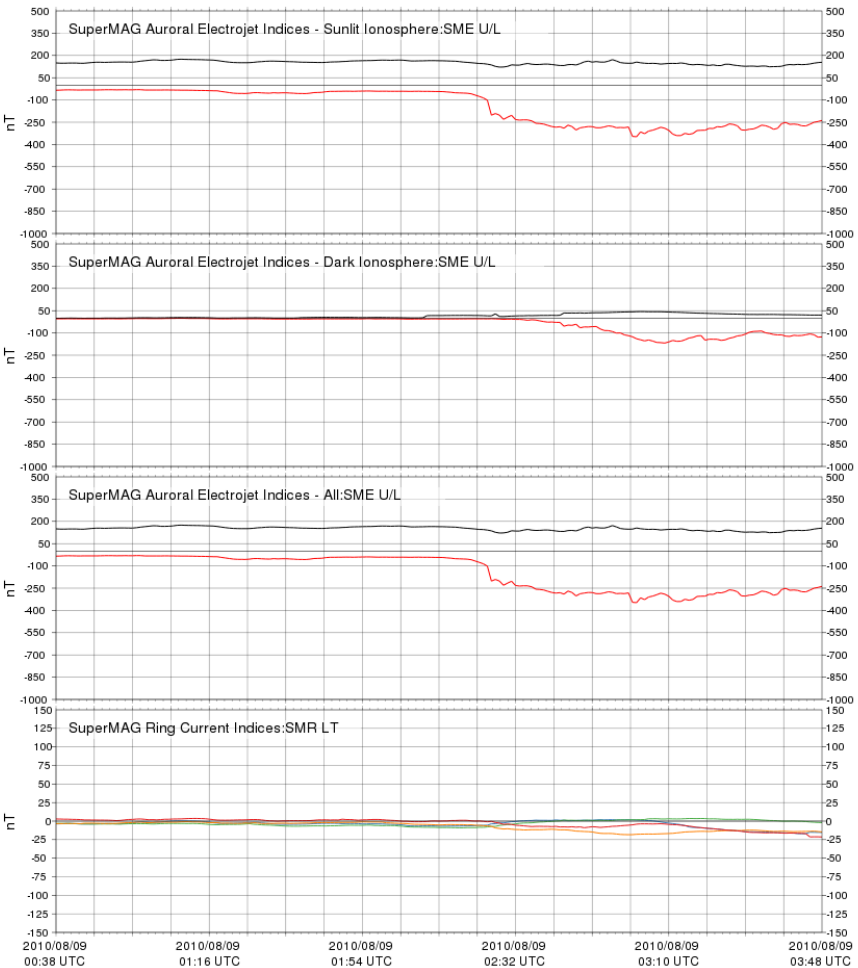
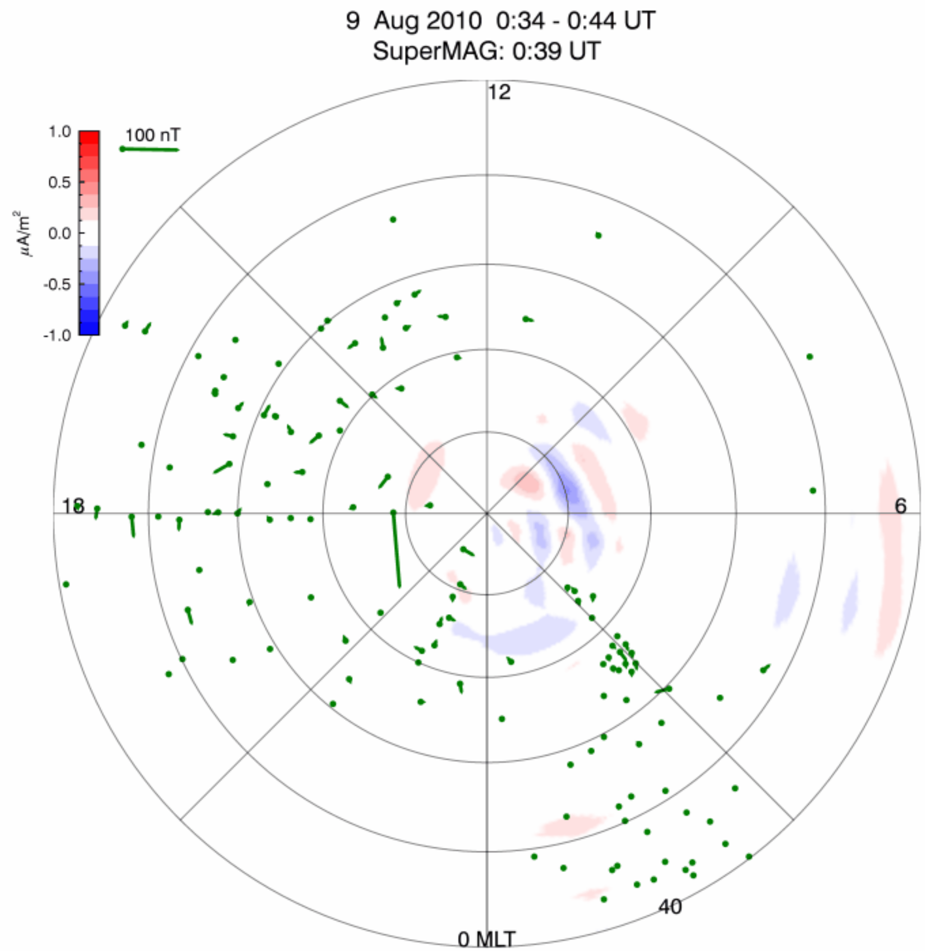


AMPERE-SuperMAG

AMPERE-SuperMAG substorm.
- Non-storm conditions.

Special thanks to Cameron Olson (JHU/APL, Augsburg College)





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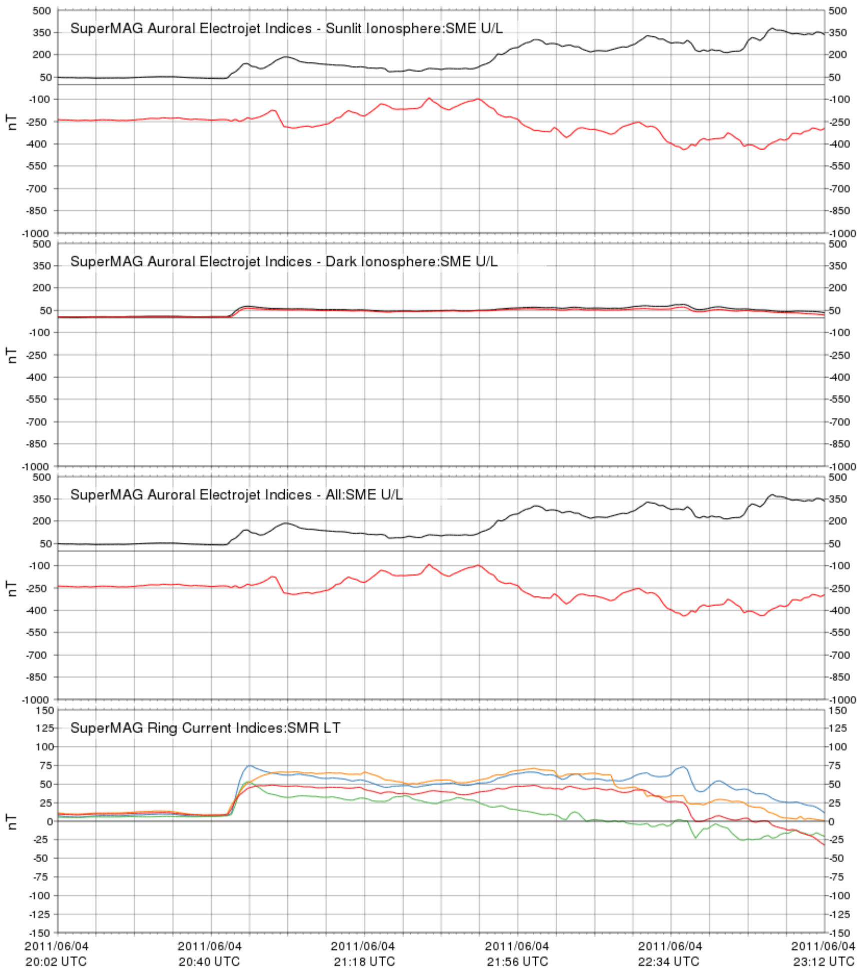
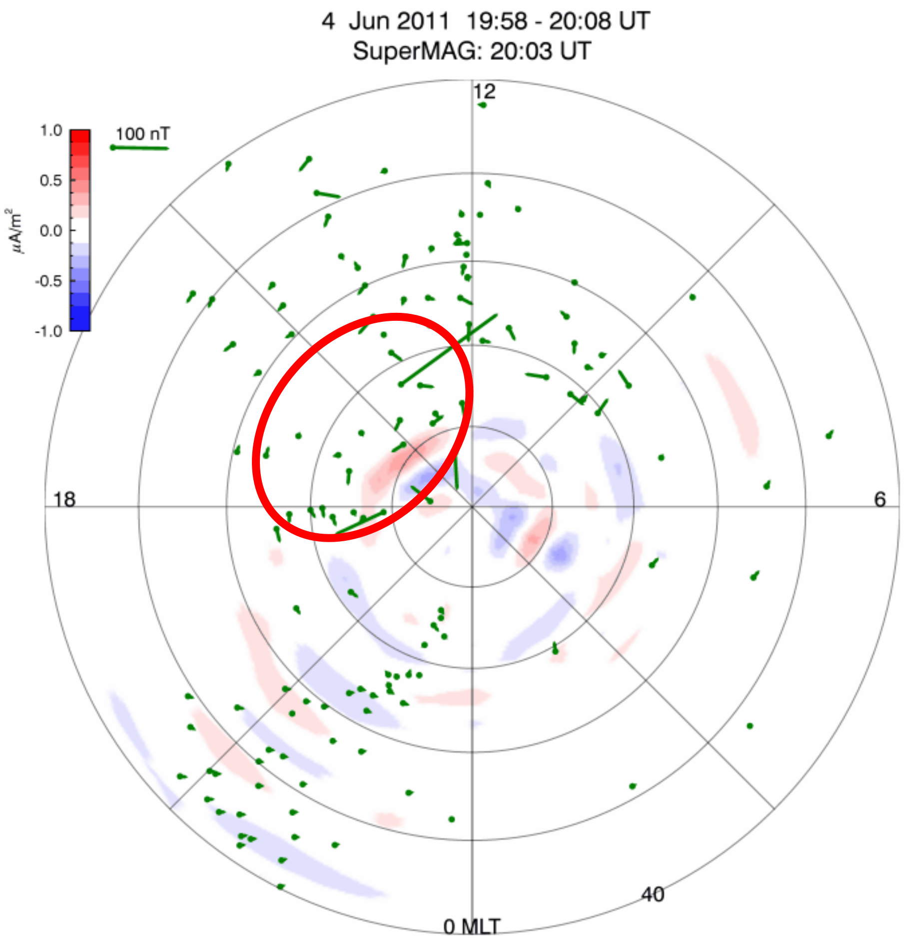
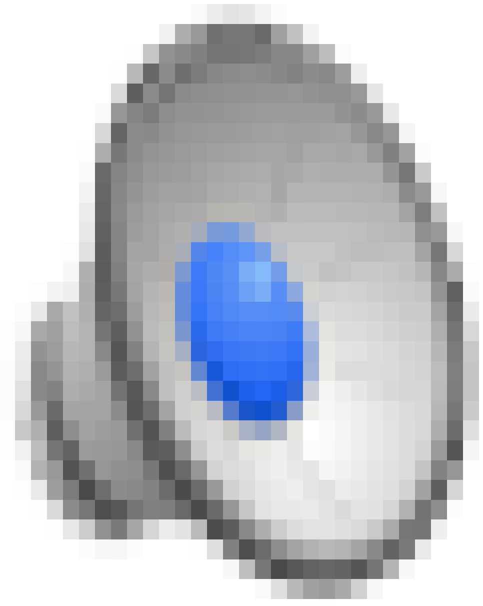




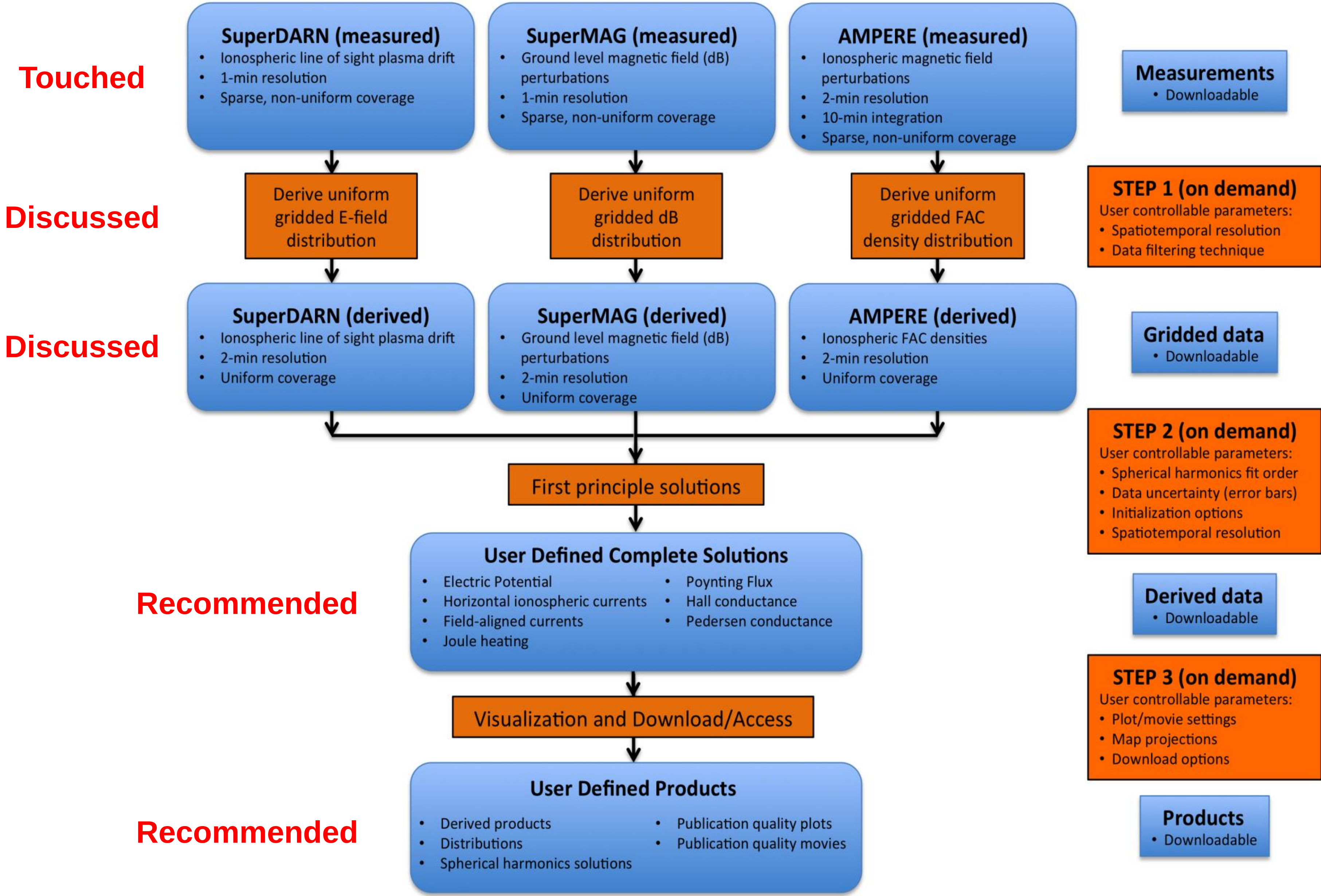
Magnetosphere-Ionosphere-Atmosphere-Coupling Project (MIAC)

Challenges:

- Difference in temporal resolution of datasets
- Non uniform spatial coverage
- Measurement uncertainties and errors
- Technique of deriving parameters from measurements



Magnetosphere-Ionosphere-Atmosphere-Coupling Project (MIAC)



Global, continuous and complete solutions: What have we learned?

Conclusions:

- **SuperMAG-SuperDARN-AMPERE allow complete-continuous-global first-principle solutions but:**
  - **- measurements have inherent limitations**
  - **- parameters derived from measurements use fundamental assumptions**
  - **- difference in temporal resolution**
  - **- difference in spatial coverage**

  The solutions will not (generally) allow studies of small to meso-scale processes.

Recommendations:

- **Comprehensive objective validation of solutions is essential.**

Outline

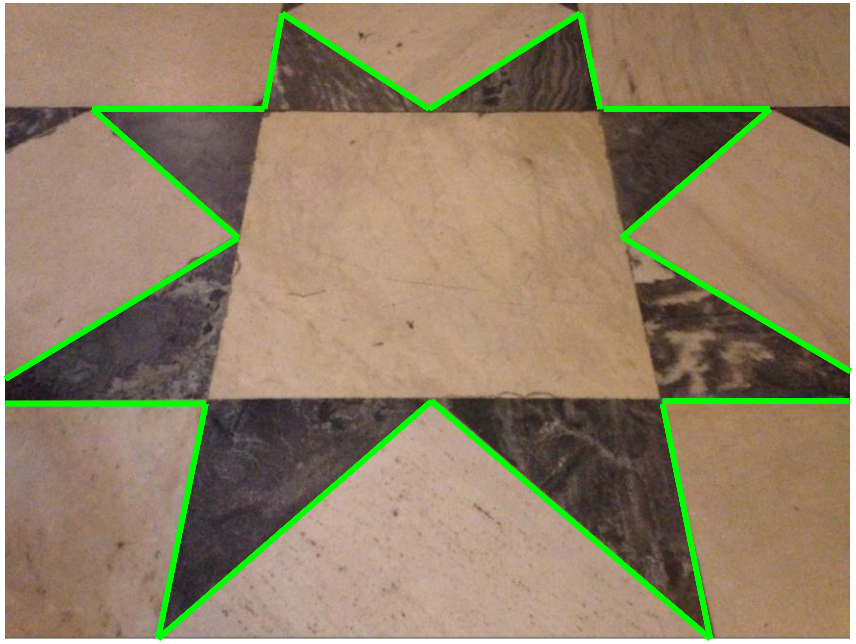
1. **How do we derive global solutions from sparse data coverage?**

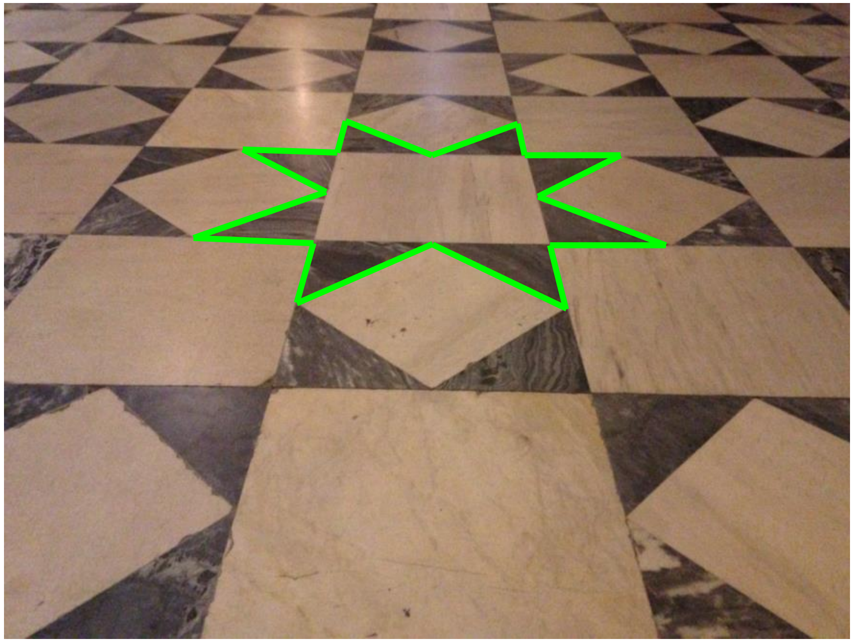
2. **What are the limitations of the global solutions?**
   - **Derived parameters**
   - **Processes/phenomena**

3. **The holy grail of M-I physics: Global, continuous and complete electrodynamic solutions.**

4. **Bonus slide.** ☺

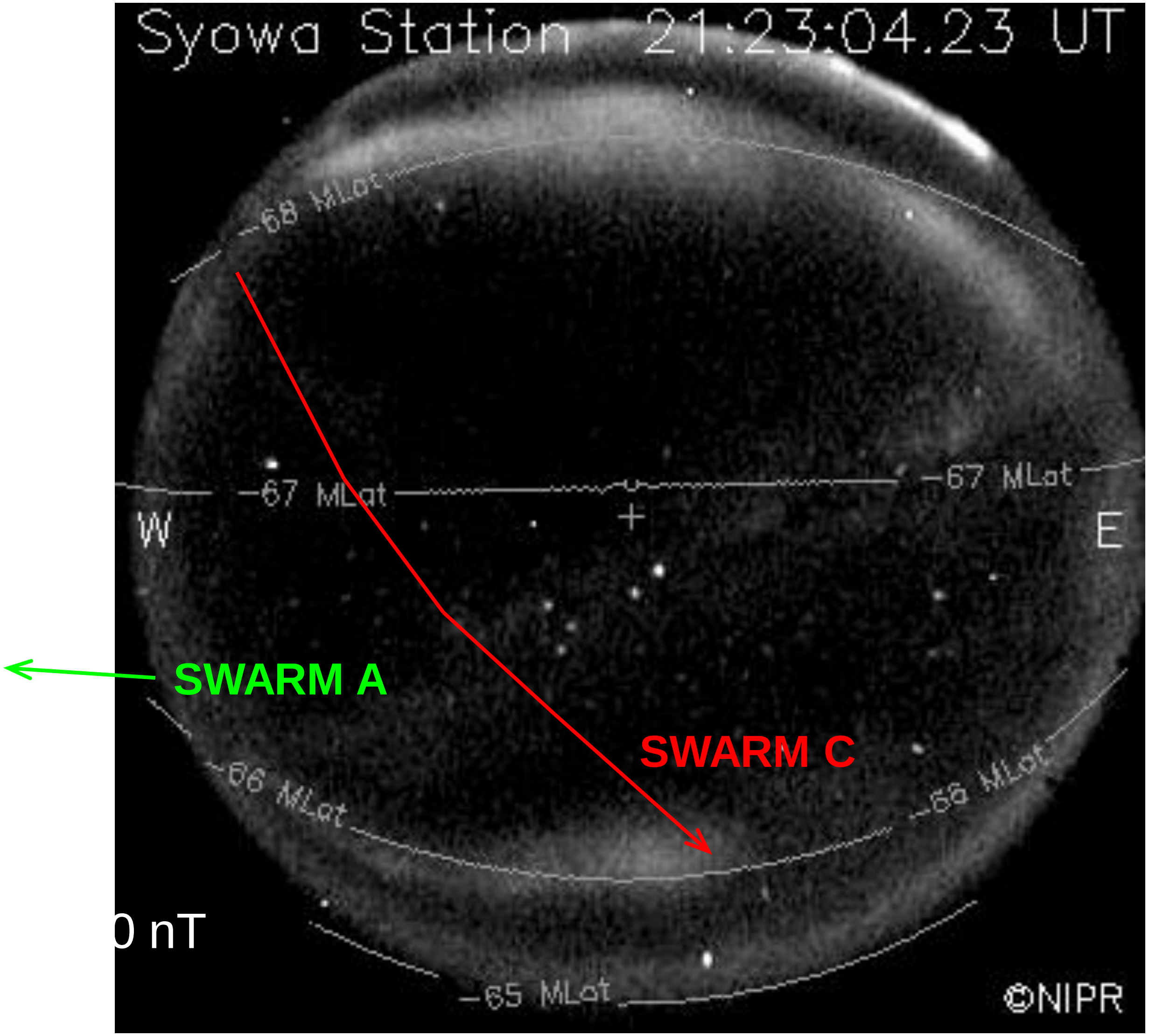
Drawing Conclusions From Local/Sparse Observations





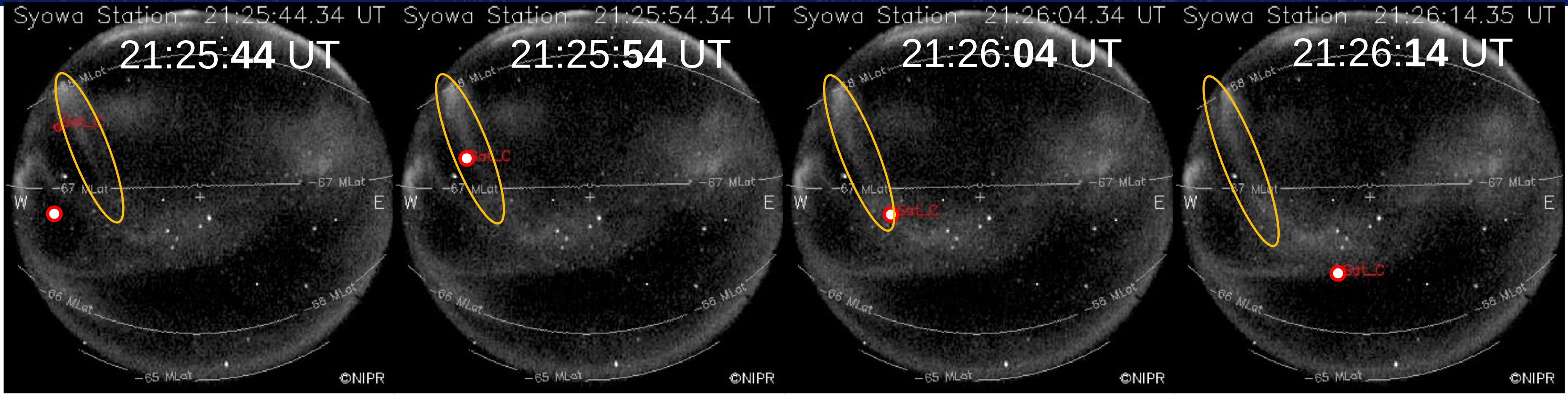
Backup

Calculating Birkeland Currents using ESA Swarm Example on 3 May 2014



Special thanks to Tetsuo Motoba(STEL, Nagoya U) and Natl. Inst. Polar Res. (Japan)

Calculating Birkeland Currents using ESA Swarm Example on 3 May 2014



SWARM-C(MLT: 22:20)

Curlometer and single-SC results differs because FACs are structured along the SWARM orbit.