CCAR

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

## GEM Mini-Workshop
## Modeling Challenges in the Auroral Region
### Sunday Dec. 13, 2015

# Improving conductivity modeling for the satellite and assimilation age

Ryan McGranaghan

*Colorado Center for Astrodynamics Research*

*University of Colorado at Boulder*

**Collaborators**: Delores Knipp (advisor), Tomoko Matsuo, Stan Solomon, Ellen Cousins, Rob Redmon, Xiaohua Fang, Humberto Godinez, Steven Morley, Liam Kilcommons

Acknowledgement:
Research supported by NSF Graduate Research Fellowship

# Talk outline



**Introduction:**

Where is conductivity modeling currently?

**Part I:**

Overcoming simplifying assumptions and optimally estimating full high-latitude distributions

- ➔New modeling capabilities
- ➔Better upper atmospheric data assimilation

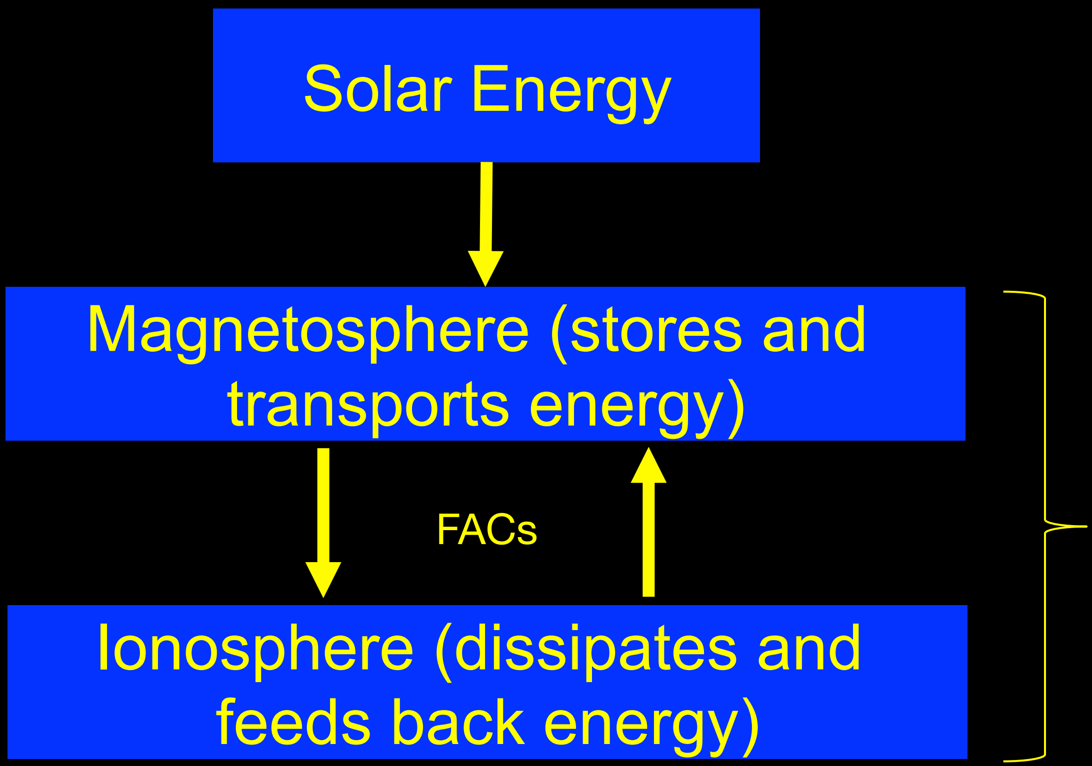
**Part II:**

Discussion pieces: Future of this work? What is needed/GEM-CEDAR plans?

# Where is conductivity modeling currently?

Colorado Center for Astrodynamics Research
University of Colorado
Boulder, Colorado






$$\mathbf{J} = \tilde{\sigma} \cdot \mathbf{E}$$

Electromagnetics governed by conductivity

# Where is conductivity modeling currently?



Maxwellian energy particle precipitation assumption

and

Robinson formulas (*Robinson et al.*, [1987])

$$\Sigma_P = \frac{40E}{16 + E^2} \Phi_E^{1/2}$$

$$\frac{\Sigma_H}{\Sigma_P} = 0.45(E)^{0.85}$$

# Part I

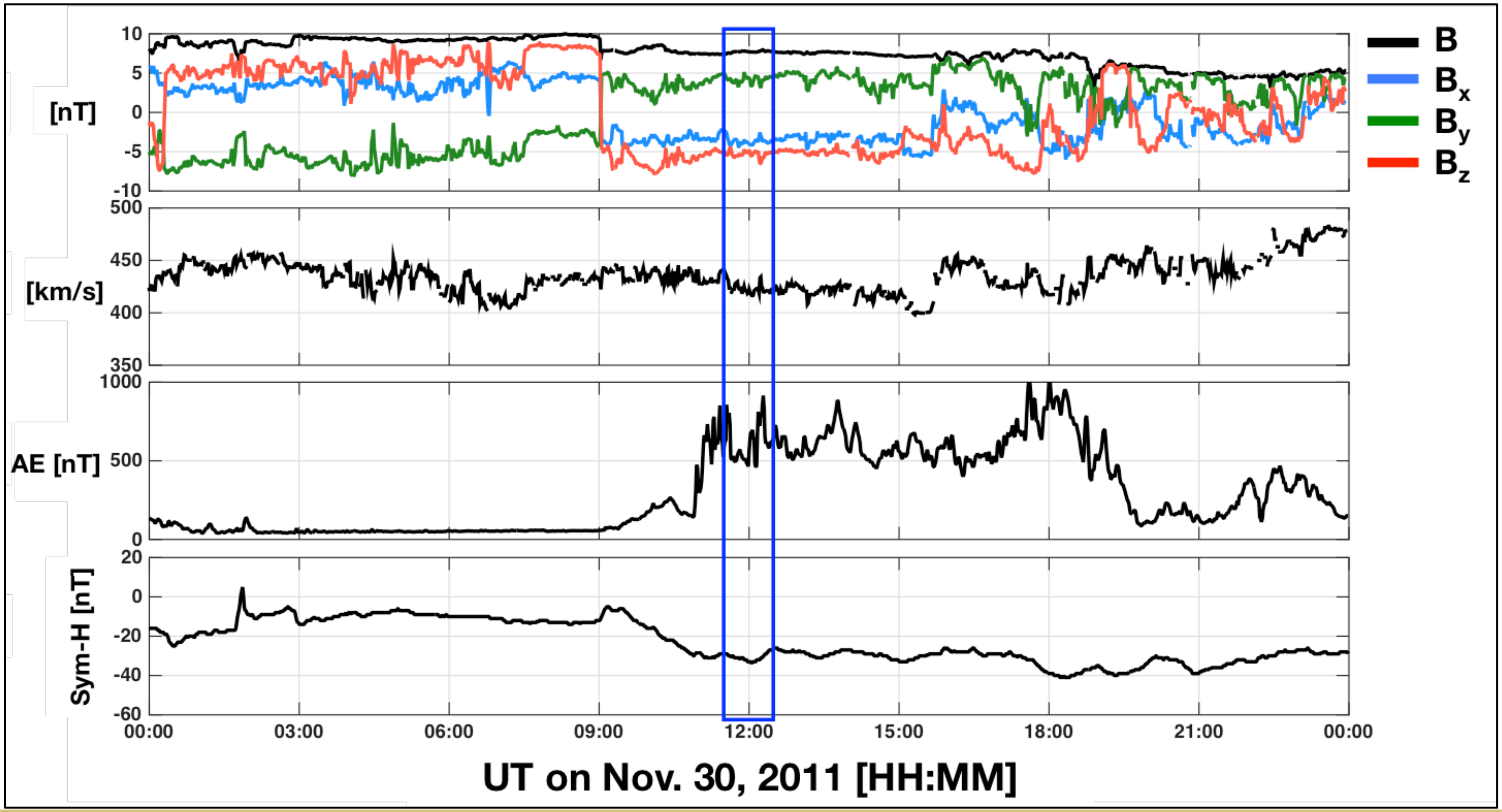
## Optimally estimating full high-latitude distributions of ionospheric conductivity

McGranaghan, R. et al. (2015), Optimal interpolation analysis of high-latitude ionospheric Hall and Pedersen conductivities. J. Geophys. Res. Space Physics, [Manuscript in Prep].

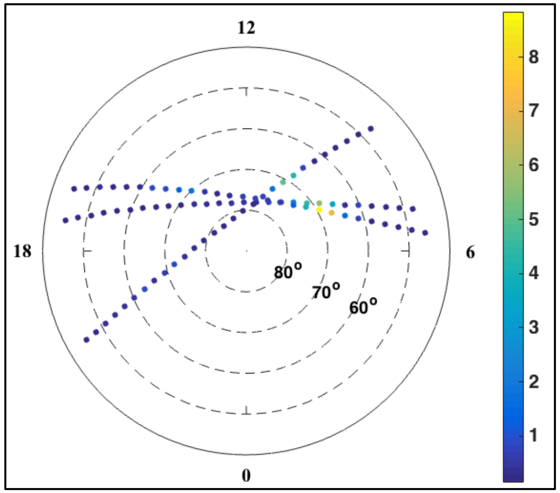
Cousins, E. D. P., T. Matsuo, and A. D. Richmond (2015), Mapping high-latitude ionospheric electrodynamics with SuperDARN and AMPERE, J. Geophys. Res. Space Physics, 120, doi:10.1002/2014JA020463.

# Reconstruction via optimal interpolation (OI) technique

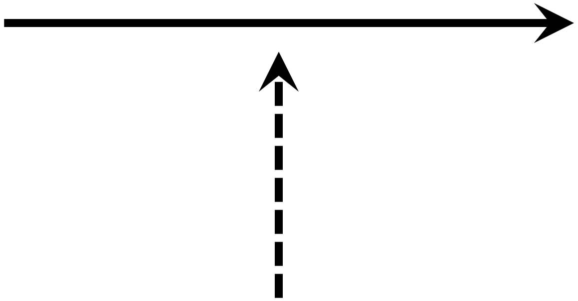
- *Matsuo et al.*, [2005] and *Cousins et al.*, [2013] (electric potential)
- Demonstration of this method for November 30, 2011

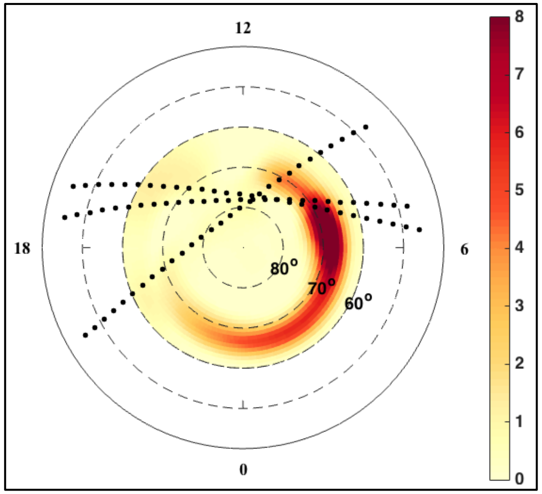


# Optimal interpolation (OI) technique




Minimize observation-model difference in least squares sense






**Required input:**

- Background model (mean pattern estimated from EOFs)
- EOF-based model error covariance
- Observation uncertainty information

**Optional:**

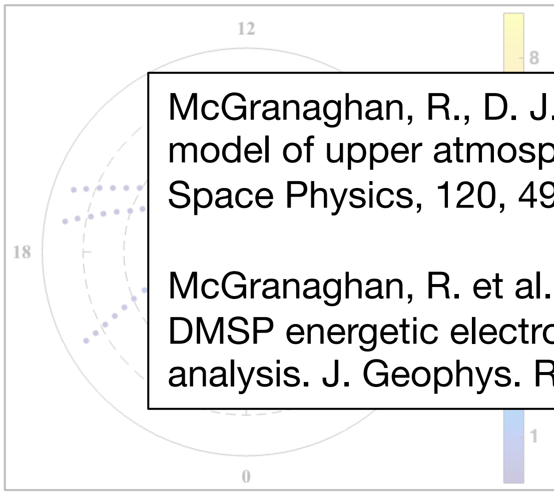
- Localization

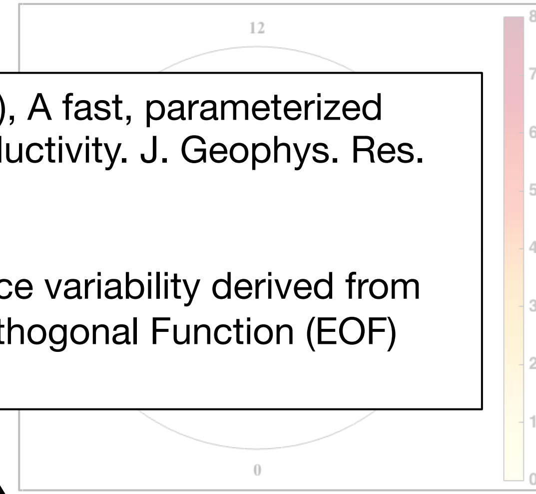
CCAR

# Optimal interpolation (OI) technique

**Colorado Center for Astrodynamics Research**
University of Colorado
Boulder, Colorado






McGranaghan, R., D. J. Knipp, S. C. Solomon, and X. Fang (2015), A fast, parameterized model of upper atmospheric ionization rates, chemistry, and conductivity. J. Geophys. Res. Space Physics, 120, 4936–4949. doi:10.1002/2015JA021146.

McGranaghan, R. et al. (2015), Modes of high-latitude conductance variability derived from DMSP energetic electron precipitation observations: Empirical Orthogonal Function (EOF) analysis. J. Geophys. Res. Space Physics, [Accepted].

**Required input:**
- Background model (mean pattern estimated from EOFs)
- EOF-based model error covariance
- Observation uncertainty information

**Optional:**
- Localization

# Qualitative metric – OI conductance model captures discrete precipitation

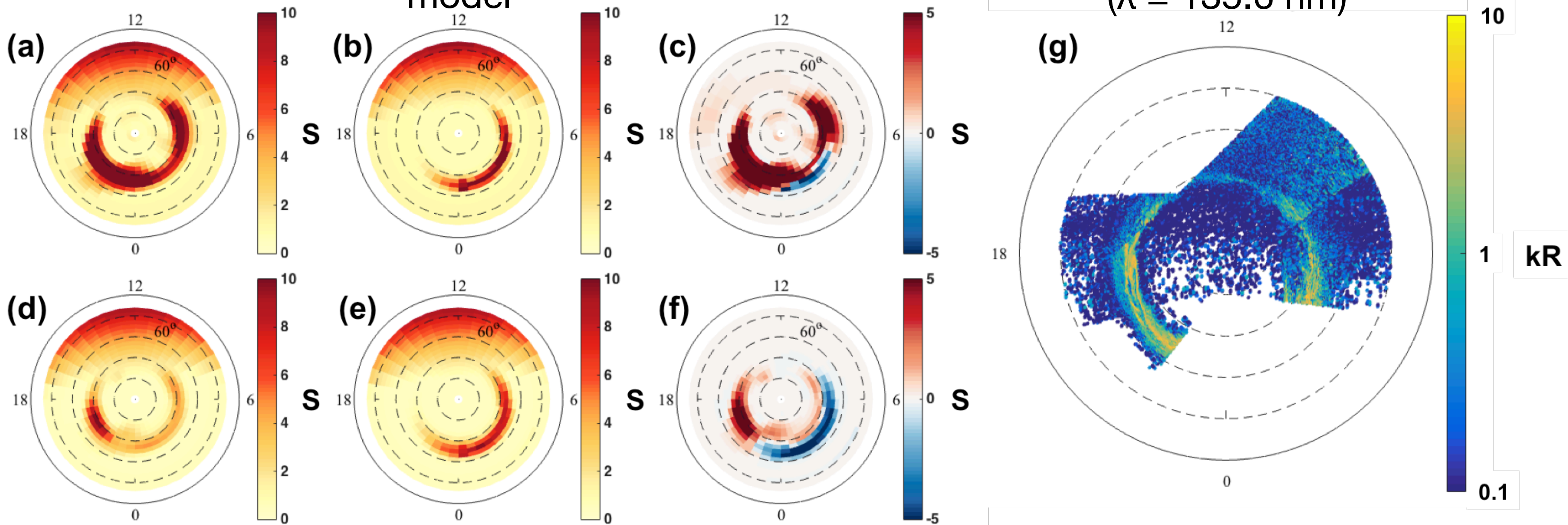
Colorado Center for Astrodynamics Research
University of Colorado
Boulder, Colorado



OI conductance model | Cousins et al. [2015] model | Difference ($\Sigma_{OI} - \Sigma_{C2015}$) | SSUSI auroral emission ($\lambda$ = 135.6 nm)

Hall [S]

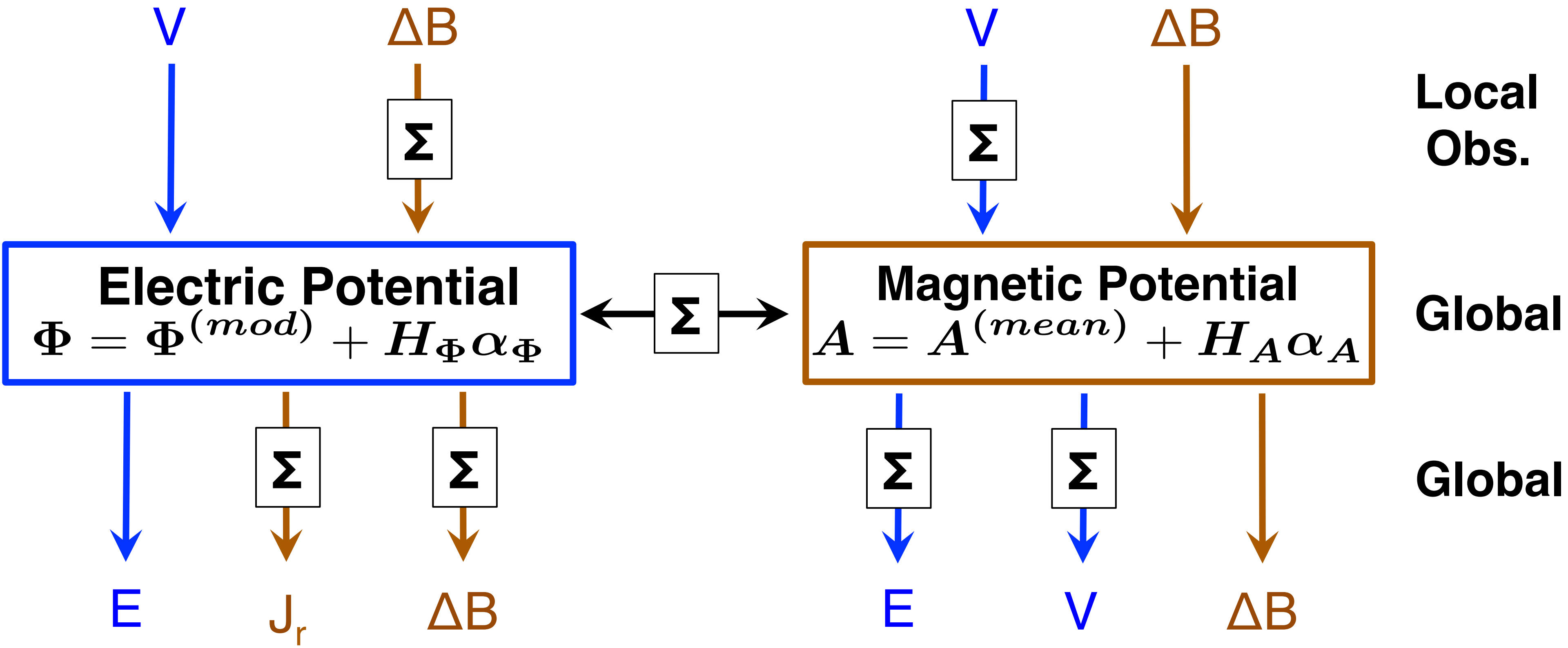
Ped. [S]

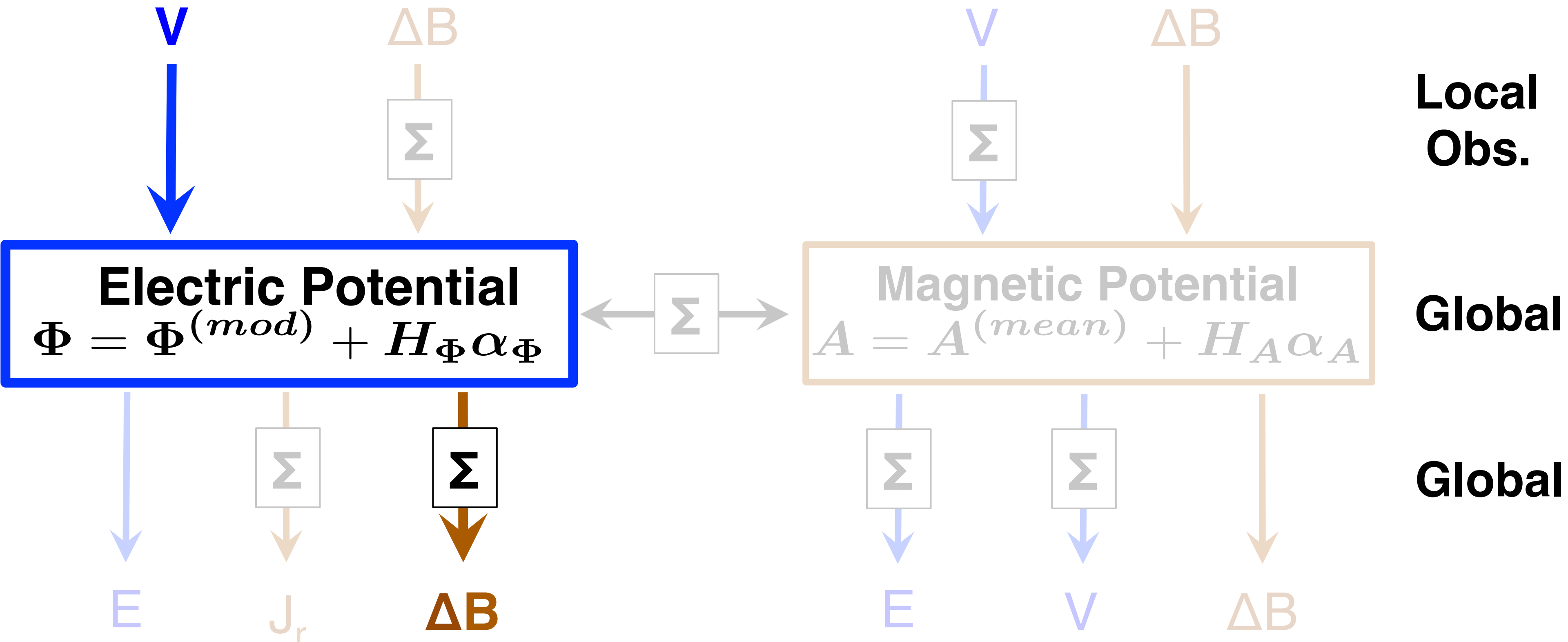



UT Time: 1200

UT Time: 1135-1225

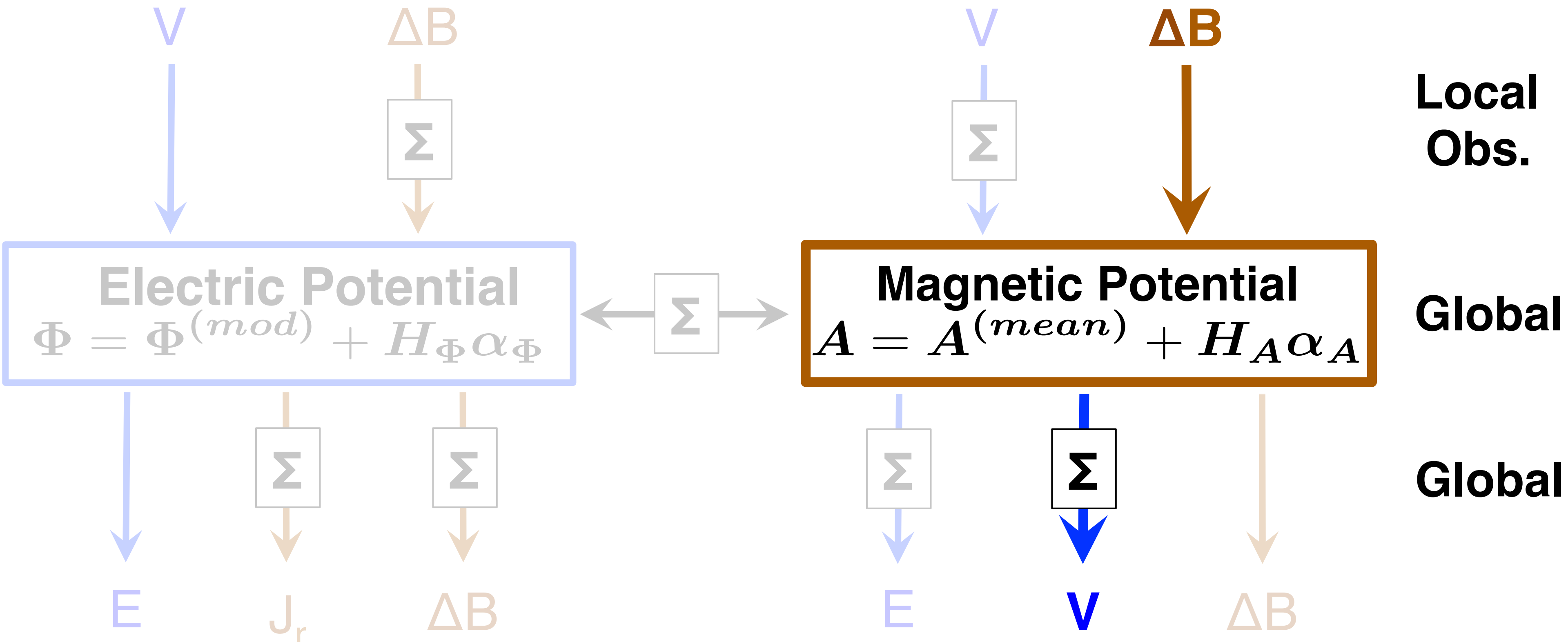
# How can we quantitatively test the conductance models?


V
ΔB
Σ
V
ΔB
Σ
Local Obs.
Electric Potential
$\Phi = \Phi^{(mod)} + H_\Phi \alpha_\Phi$
Σ
Magnetic Potential
$A = A^{(mean)} + H_A \alpha_A$
Global
Σ
Σ
Σ
Σ
Global
E
$J_r$
ΔB
E
V
ΔB



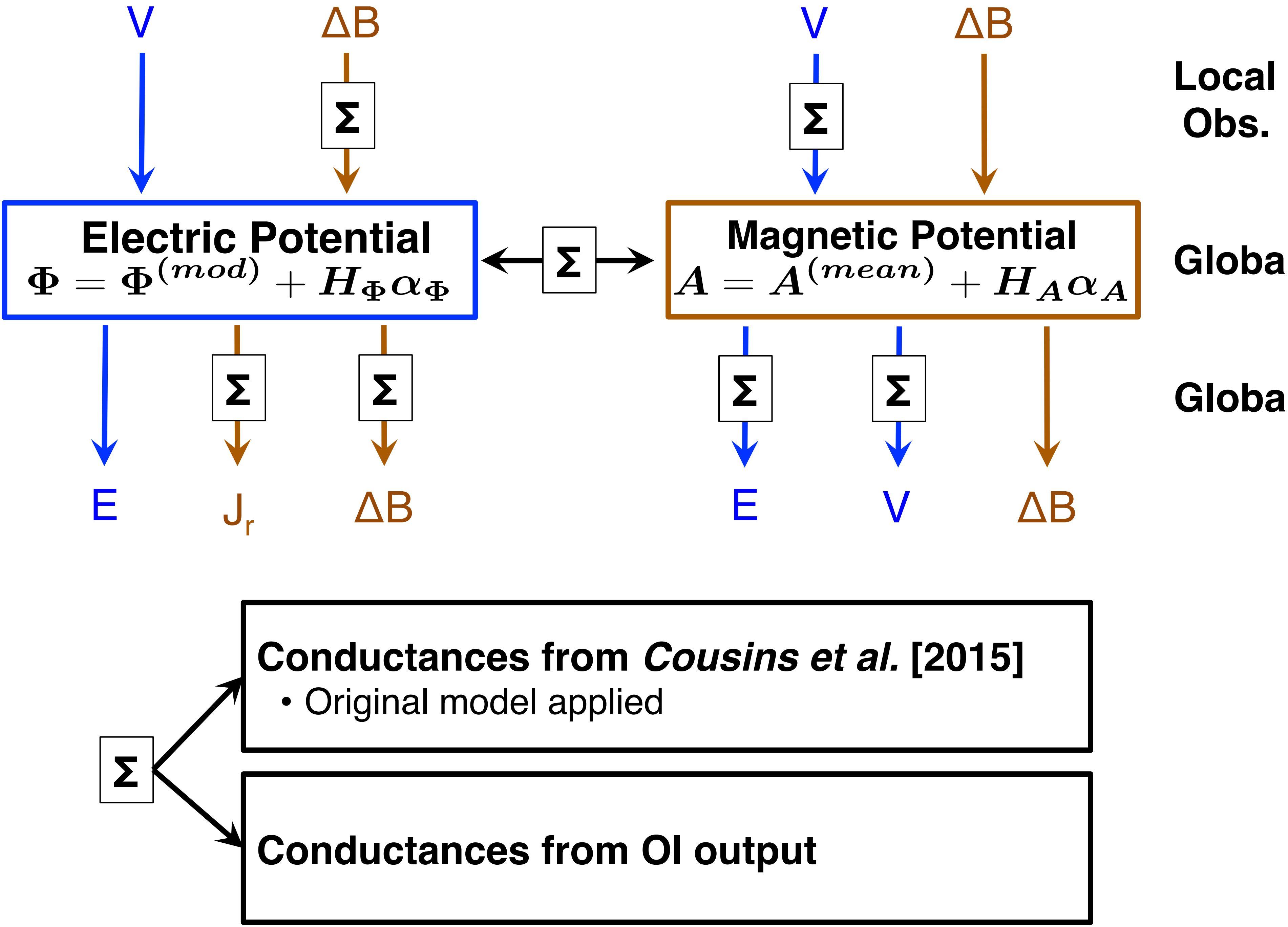

**#1: SuperDARN to predict AMPERE**

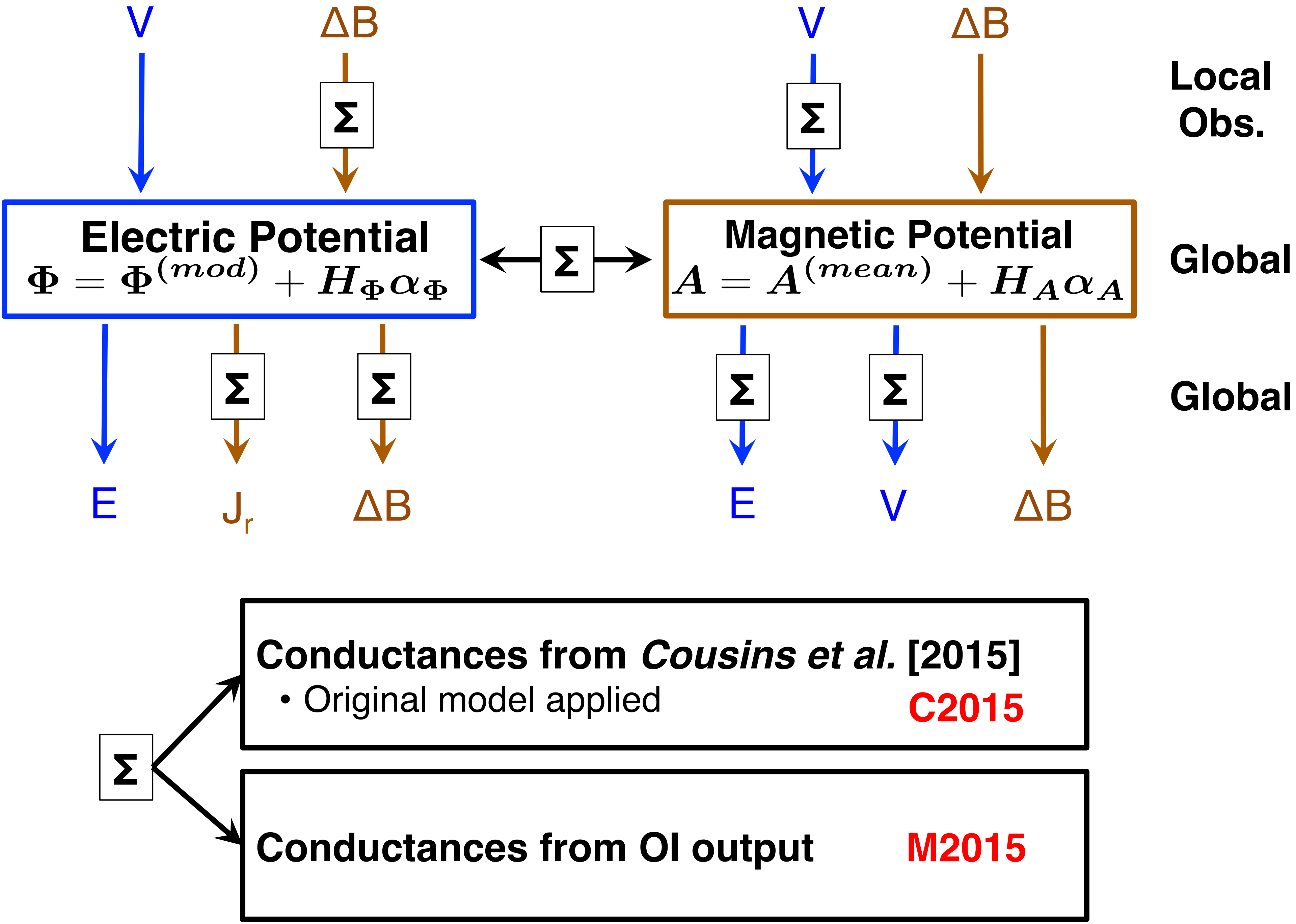
V → ΔB




**#2: AMPERE to predict SuperDARN**

ΔB → V


V
ΔB
V
ΔB
Local Obs.
Σ
Electric Potential
$\Phi = \Phi^{(mod)} + H_\Phi \alpha_\Phi$
Magnetic Potential
$A = A^{(mean)} + H_A \alpha_A$
Global
Global
E
$J_r$
ΔB
E
V
ΔB
Conductances from *Cousins et al.* [2015]
• Original model applied
Conductances from OI output



V
ΔB
V
ΔB
Local Obs.
Σ
Electric Potential
$\Phi = \Phi^{(mod)} + H_\Phi \alpha_\Phi$
Magnetic Potential
$A = A^{(mean)} + H_A \alpha_A$
Global
Global
E
$J_r$
ΔB
E
V
ΔB
Conductances from *Cousins et al.* [2015]
• Original model applied
C2015
Conductances from OI output
M2015

# Testing conductance models



| | Median Absolute Deviations [nT or m/s] | |
|---|---|---|
| **Conductance Model** (night-side value) | **C2015** $\Sigma_P>0.4$; $\Sigma_H>0.8$ | **M2015** $\Sigma_P>0.4$; $\Sigma_H>0.8$ |
| $\Delta B \rightarrow V$ | 684.20 | 392.51 |
| $V \rightarrow \Delta B$ | 36.88 | 37.03 |

# Testing conductance models



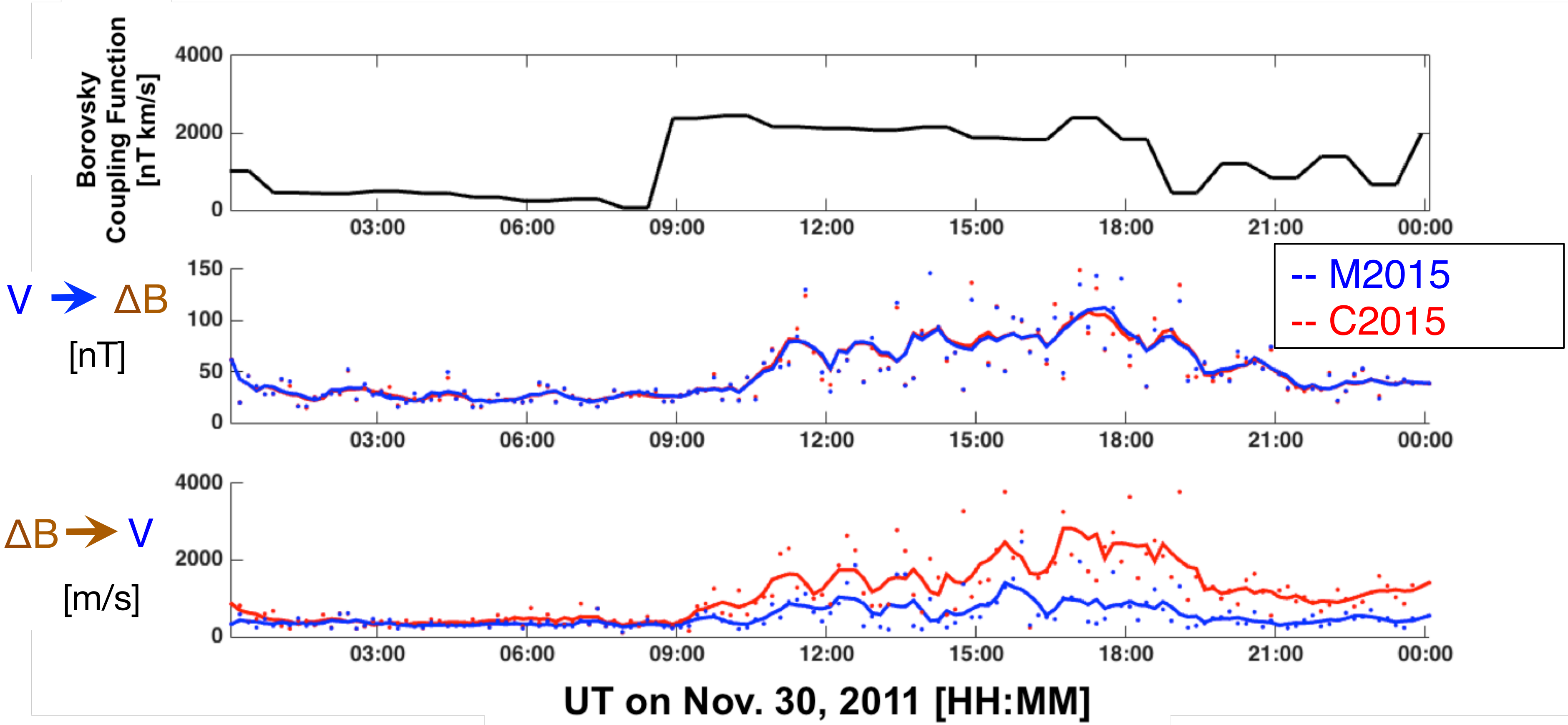
| | Median Absolute Deviations [nT or m/s] | |
|---|---|---|
| **Conductance Model** (night-side value) | **C2015** $\Sigma_P$>0.4; $\Sigma_H$>0.8 | **M2015** $\Sigma_P$>0.4; $\Sigma_H$>0.8 |
| ΔB ➔ V | 684.20 | 392.51 |
| V ➔ ΔB | 36.88 | 37.03 |

OI produces nearly 50% improvement in SuperDARN observation prediction

➔ capable of producing more meaningful electrodynamic fields

# MADs throughout November 30





# Part II
## Future and Discussion

# Future work in conductivity modeling



Improving OI conductance distributions

- Using SSUSI data to create better covariance
- Additional data

3D conductivities

How do we go to finer scales?

**Poster SA31C-2357**
**Wednesday morning 8-12:**
Energy Budget of Ionosphere-Thermosphere during Geomagnetic Storms: Current Understanding and Perspectives of Forecasting Posters

# Positioning improvement for future needs



Big picture questions:

- Can we calibrate magnetospheric and upper atmospheric models to reflect small-scale behavior?
- What are the effects of small- and mesoscale ionospheric dynamics for regulation of entire ground-MIT system?

# Positioning improvement for future needs



Big picture questions:

- Can we calibrate magnetospheric and upper atmospheric models to reflect small-scale behavior?
- What are the effects of small- and mesoscale ionospheric dynamics for regulation of entire ground-MIT system?

**➔ Merging global and local physics**

# Concluding remarks

## Part I

Model of ionospheric conductivity using particle precipitation data and GLOW model; parameterized version freely available

OI procedure to reconstruct complete high-latitude distributions in three dimensions

Showed these distributions can accurately describe conductance enhancements due to discrete precipitation

**Poster SA31C-2357**
**Wednesday morning 8-12:**
Energy Budget of Ionosphere-Thermosphere during Geomagnetic Storms: Current Understanding and Perspectives of Forecasting Posters

## Part II

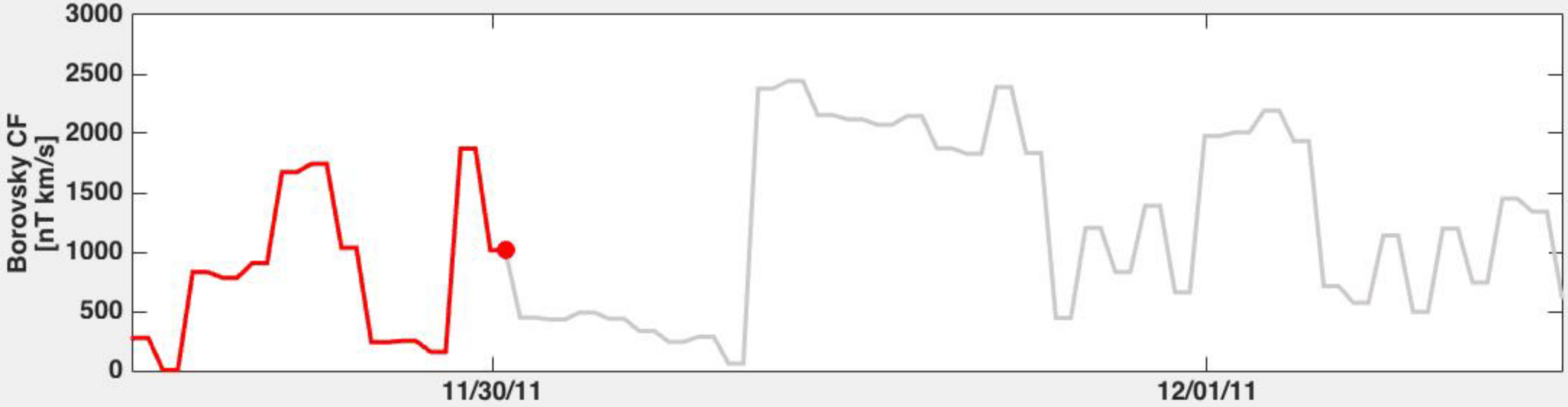
How do we address scale feedback in auroral region?

**Email: Ryan.McGranaghan@colorado.edu**

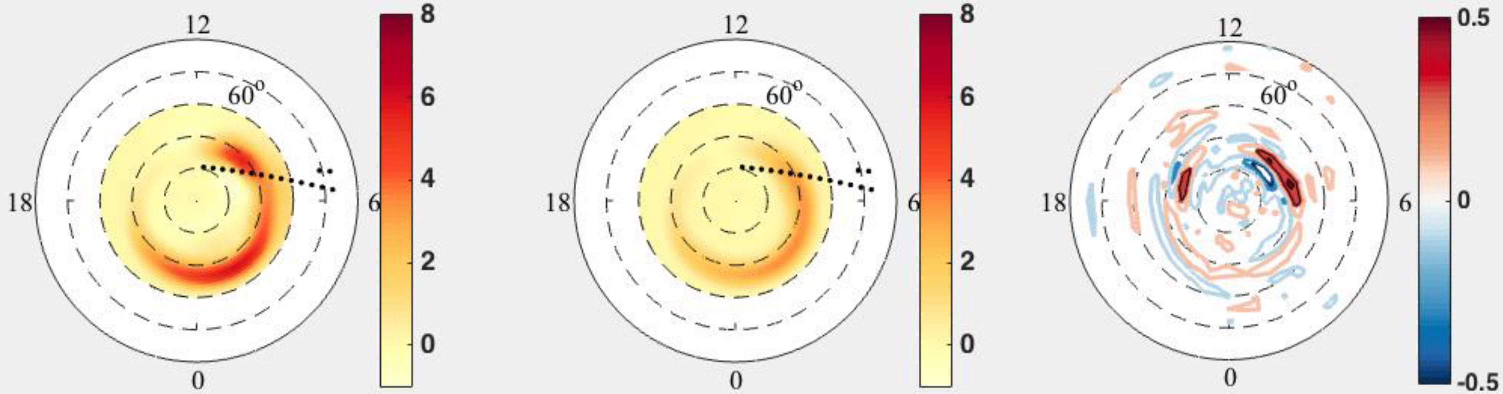
# Backup Slides

# OI reconstruction for Nov. 30, 2011





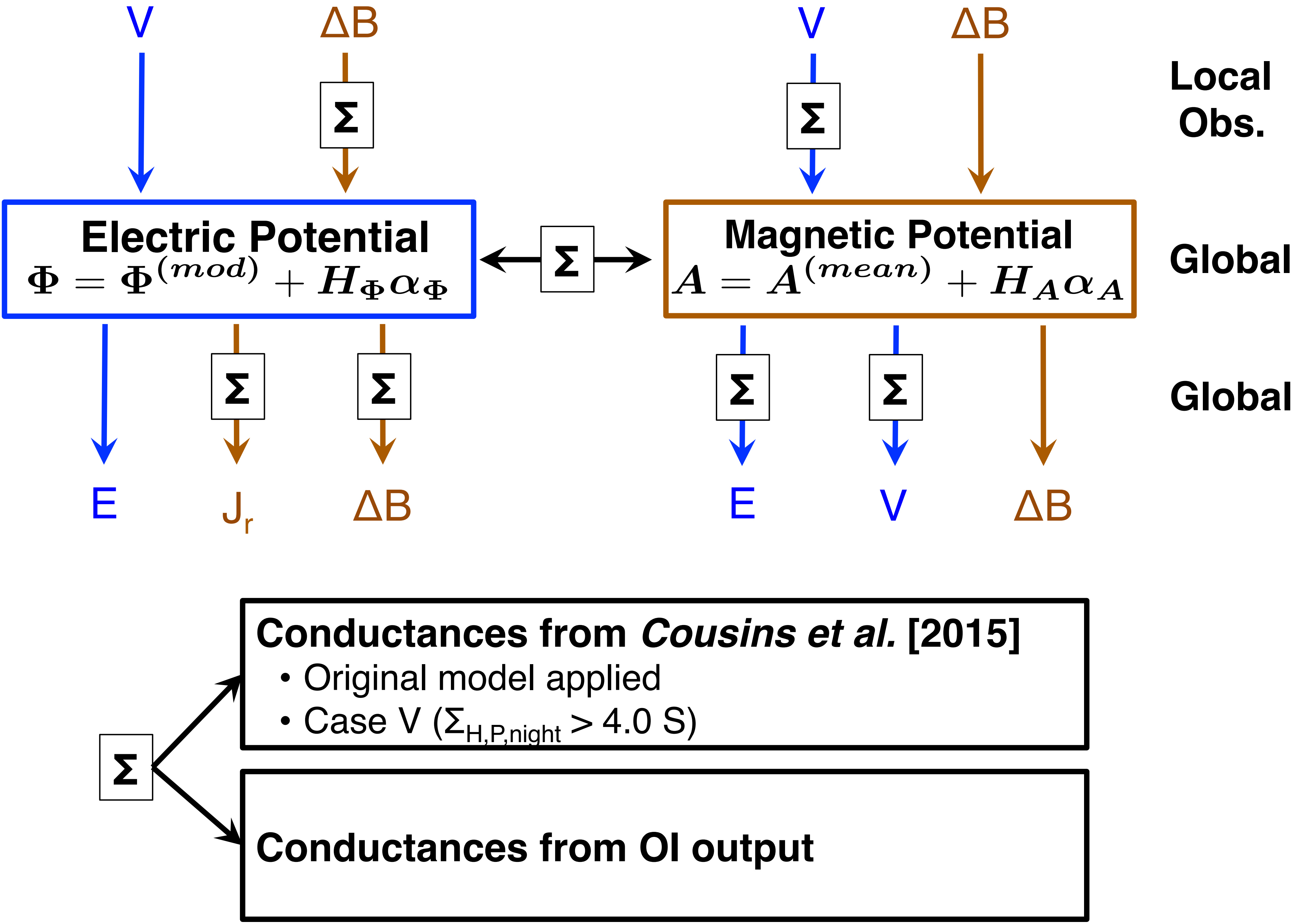

Time (UT day:hr) =
334:0.00
to
334:1.00

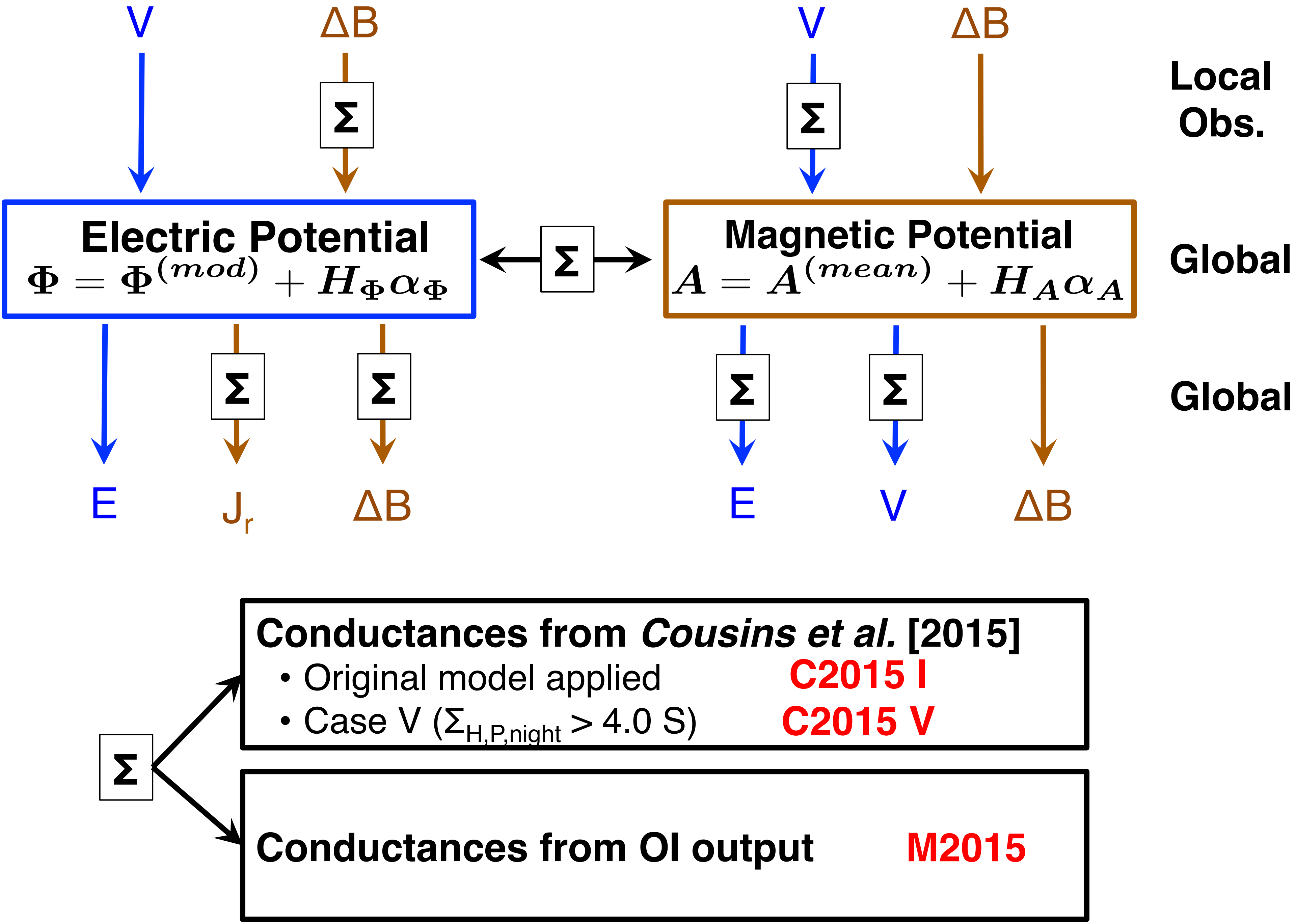



Hall [S]

Pedersen [S]

AMPERE Radial Current Density [$\mu A/m^2$]


V
ΔB
V
ΔB
Local Obs.
Σ
Σ
Electric Potential
$\Phi = \Phi^{(mod)} + H_\Phi \alpha_\Phi$
Σ
Magnetic Potential
$A = A^{(mean)} + H_A \alpha_A$
Global
Σ
Σ
Σ
Σ
Global
E
$J_r$
ΔB
E
V
ΔB
Conductances from *Cousins et al.* [2015]
• Original model applied
• Case V ($\Sigma_{H,P,night}$ > 4.0 S)
Σ
Conductances from OI output



V
ΔB
V
ΔB
Local Obs.
Σ
Σ
Electric Potential
$\Phi = \Phi^{(mod)} + H_\Phi \alpha_\Phi$
Σ
Magnetic Potential
$A = A^{(mean)} + H_A \alpha_A$
Global
Σ
Σ
Σ
Σ
Global
E
$J_r$
ΔB
E
V
ΔB
Conductances from *Cousins et al.* [2015]
• Original model applied C2015 I
• Case V ($\Sigma_{H,P,night}$ > 4.0 S) C2015 V
Σ
Conductances from OI output M2015

# Testing conductance models

Colorado Center for Astrodynamics Research
University of Colorado
Boulder, Colorado



| | Median Absolute Deviations [nT or m/s] | | | |
|---|---|---|---|---|
| **Conductance Model** (night-side value) | **C2015 I** $\Sigma_P>0.4$; $\Sigma_H>0.8$ | **C2015 V** $\Sigma_{P,H}>4$ | **M2015** $\Sigma_P>0.4$; $\Sigma_H>0.8$ | **M2015** $\Sigma_{P,H}>4$ |
| $\Delta$B ➔ V | 684.20 | 149.77 | 392.51 | 145.69 |
| V ➔ $\Delta$B | 36.88 | 39.03 | 37.03 | 38.99 |

# Testing conductance models

Colorado Center for Astrodynamics Research
University of Colorado
Boulder, Colorado



| | Median Absolute Deviations [nT or m/s] | | | |
|---|---|---|---|---|
| **Conductance Model** (night-side value) | **C2015 I** $\Sigma_P$>0.4; $\Sigma_H$>0.8 | **C2015 V** $\Sigma_{P,H}$>4 | **M2015** $\Sigma_P$>0.4; $\Sigma_H$>0.8 | **M2015** $\Sigma_{P,H}$>4 |
| ΔB ➔ V | 684.20 | 149.77 | 392.51 | 145.69 |
| V ➔ ΔB | 36.88 | 39.03 | 37.03 | 38.99 |

With reasonably accurate background night-side conductances, OI produces nearly 50% improvement in SuperDARN observation prediction

# Testing conductance models



| | Median Absolute Deviations [nT or m/s] | | | |
|---|---|---|---|---|
| **Conductance Model** (night-side value) | **C2015 I** $\Sigma_P$>0.4; $\Sigma_H$>0.8 | **C2015 V** $\Sigma_{P,H}$>4 | **M2015** $\Sigma_P$>0.4; $\Sigma_H$>0.8 | **M2015** $\Sigma_{P,H}$>4 |
| ΔB → V | 684.20 | 149.77 | 392.51 | 145.69 |
| V → ΔB | 36.88 | 39.03 | 37.03 | 38.99 |

With artificially-inflated background conductances, OI produces same level of predicted accuracy as conductance model that produced best results in *Cousins et al.*, [2015]

# Testing conductance models



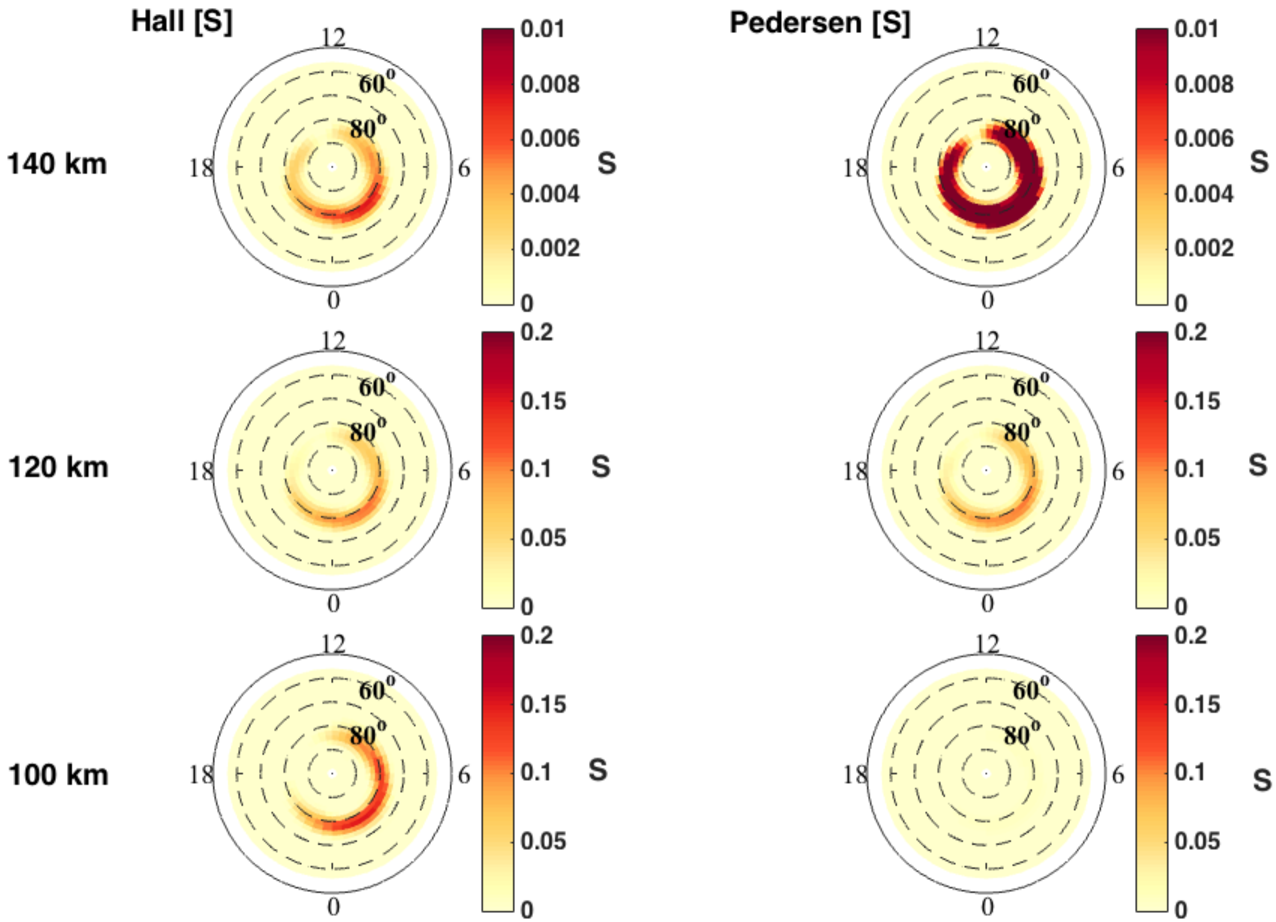
| | **Median Absolute Deviations [nT or m/s]** | | | |
|---|---|---|---|---|
| **Conductance Model** (night-side value) | **C2015 I** $\Sigma_P>0.4$; $\Sigma_H>0.8$ | **C2015 V** $\Sigma_{P,H}>4$ | **M2015** $\Sigma_P>0.4$; $\Sigma_H>0.8$ | **M2015** $\Sigma_{P,H}>4$ |
| ΔB ➔ V | 684.20 | 149.77 | 392.51 | 145.69 |
| V ➔ ΔB | 36.88 | 39.03 | 37.03 | 38.99 |

OI results produce better predictions without artificially inflating background conductances ➔ capable of producing more meaningful electrodynamic fields

# Fully three-dimensional analyses



UT Time: 1200

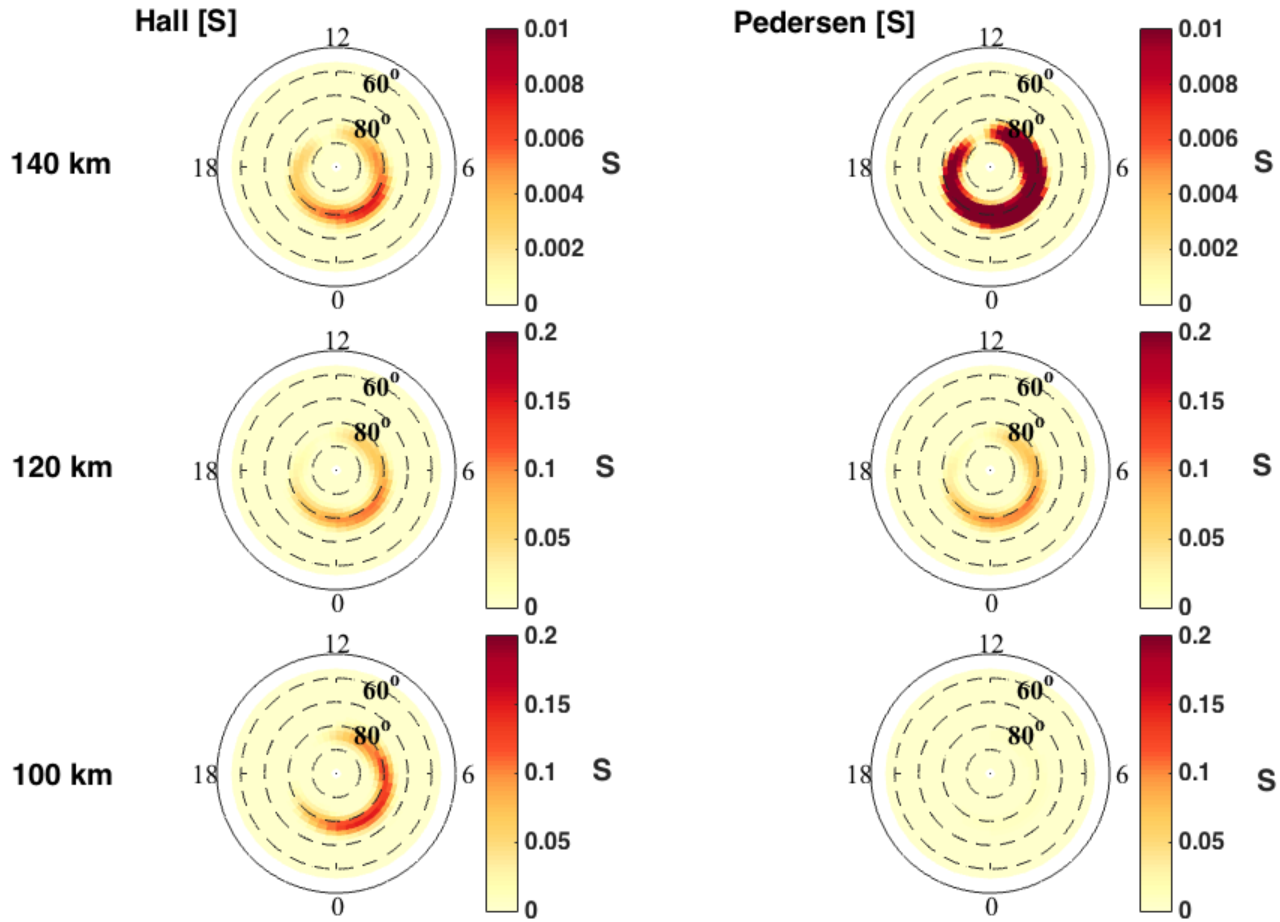


# Fully three-dimensional analyses

Colorado Center for Astrodynamics Research
University of Colorado
Boulder, Colorado

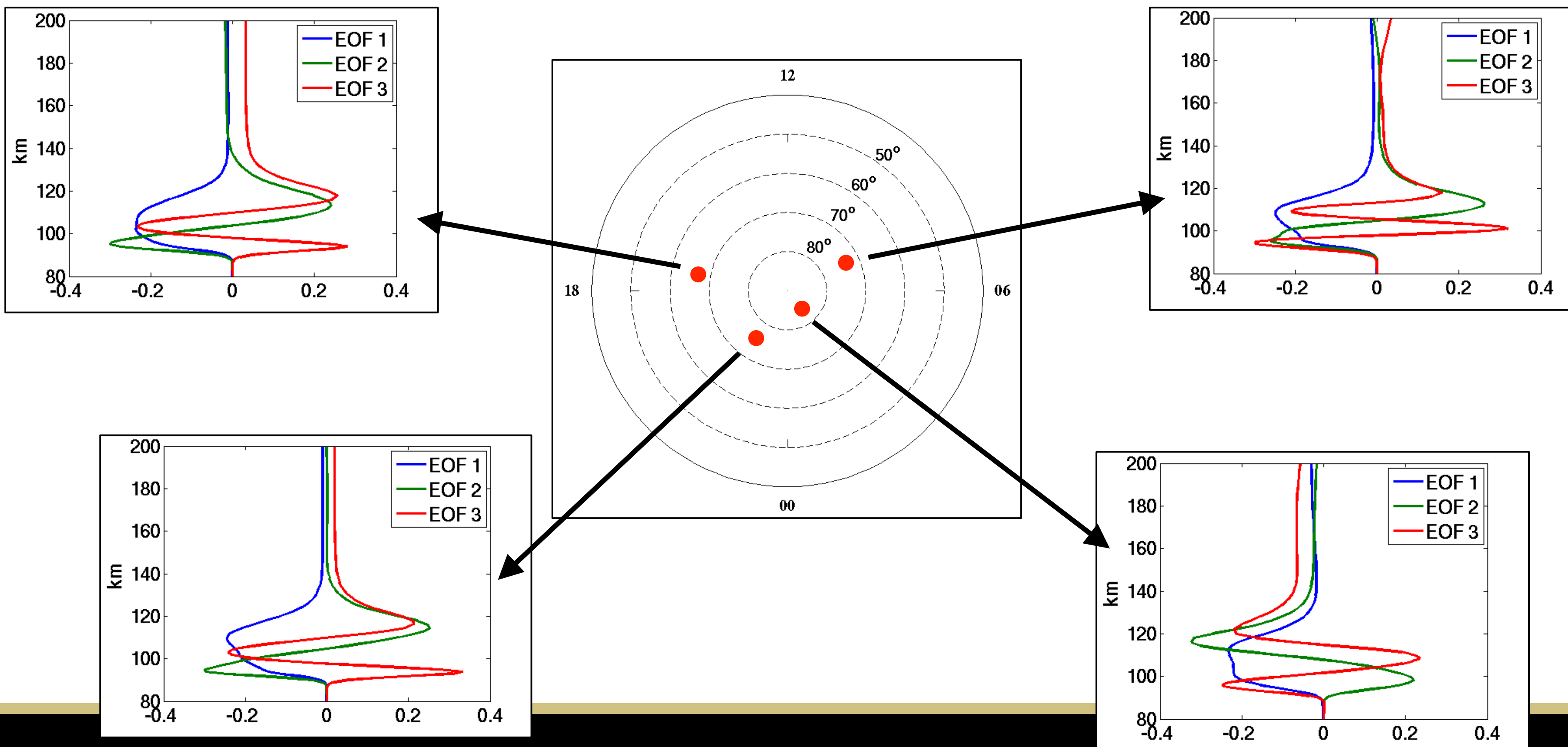


UT Time: 1200



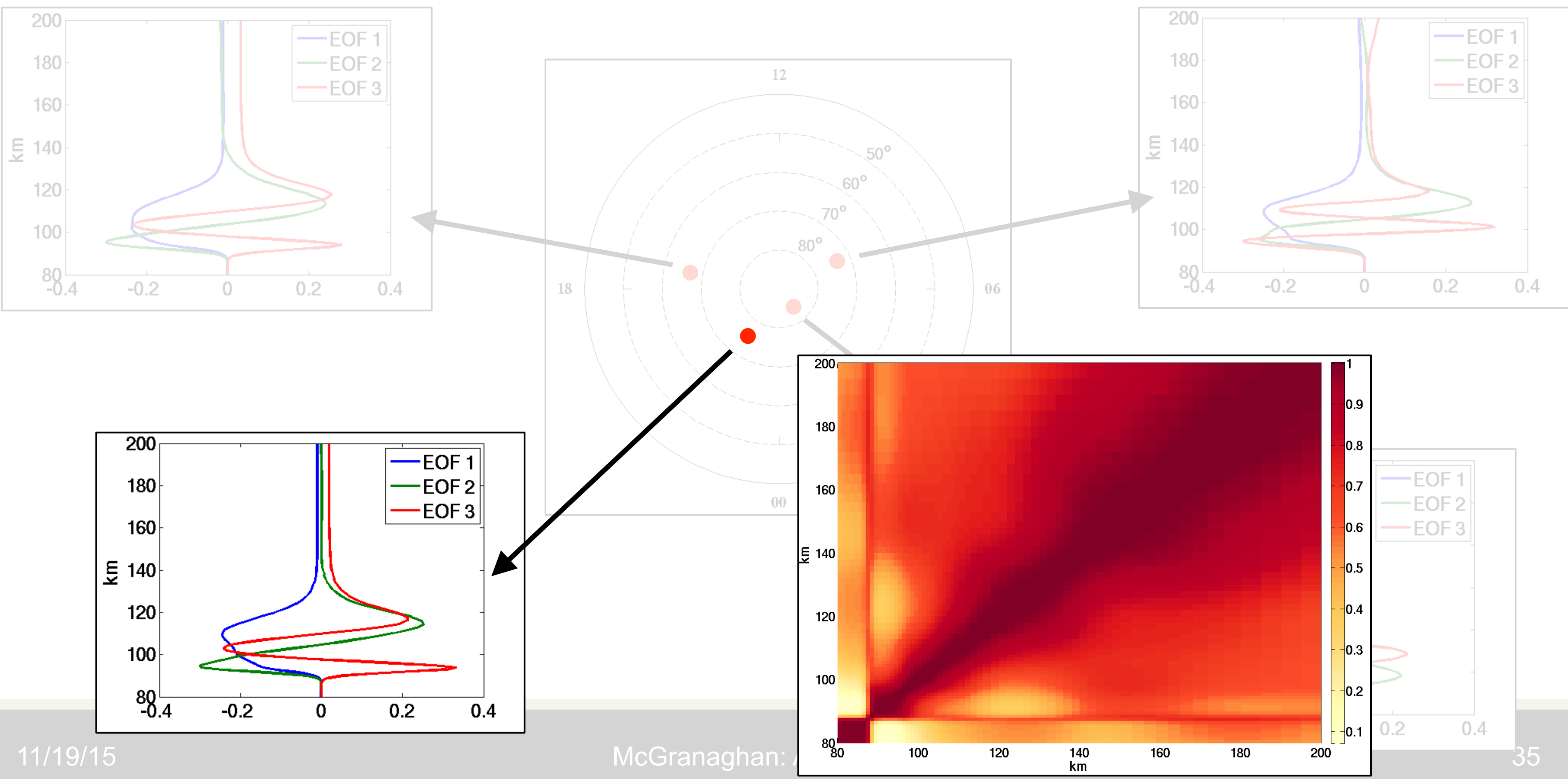

Will be important to address difference in **Σ** and **σ** in terms of model sensitivity

Can perform EOF analysis in vertical direction as a function of geomagnetic location



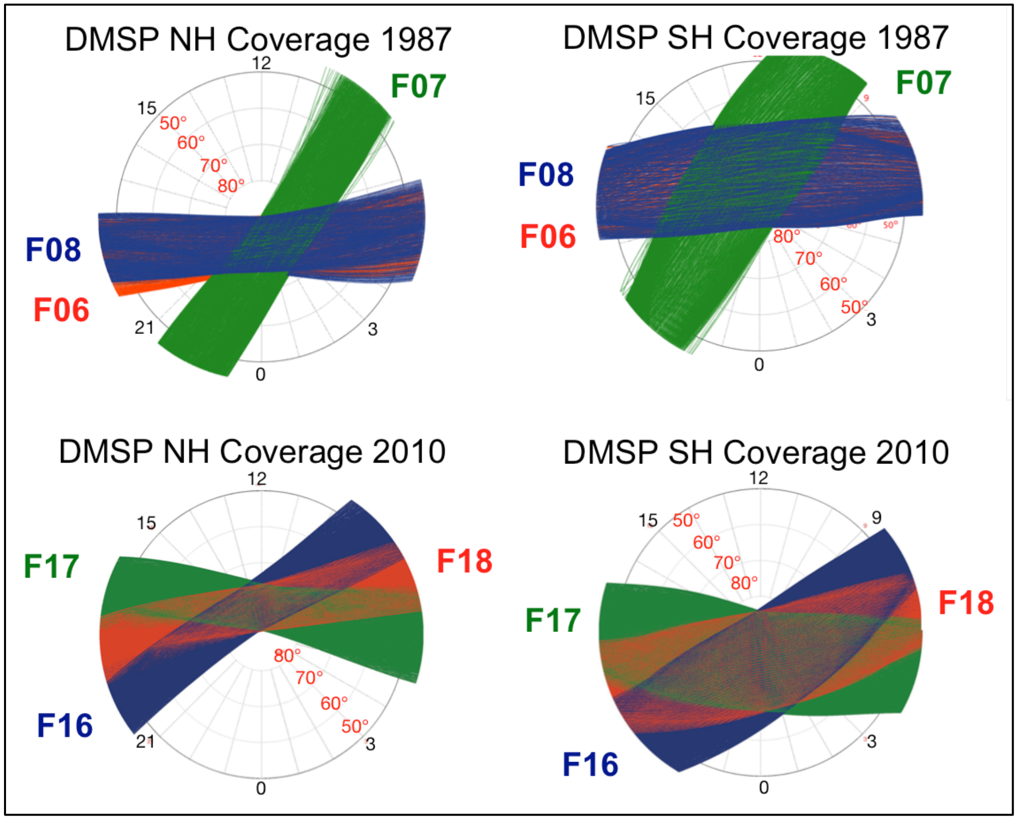
# Fully three-dimensional analyses

Can perform EOF analysis in vertical direction as a function of geomagnetic location

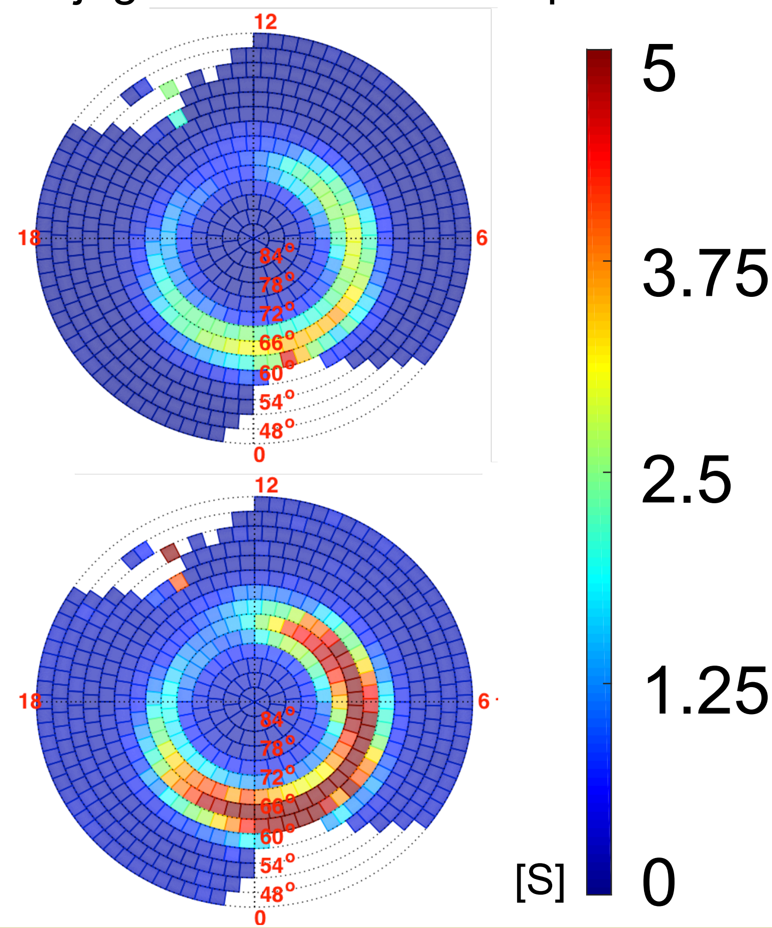


# Results: DMSP Conductance EOFs

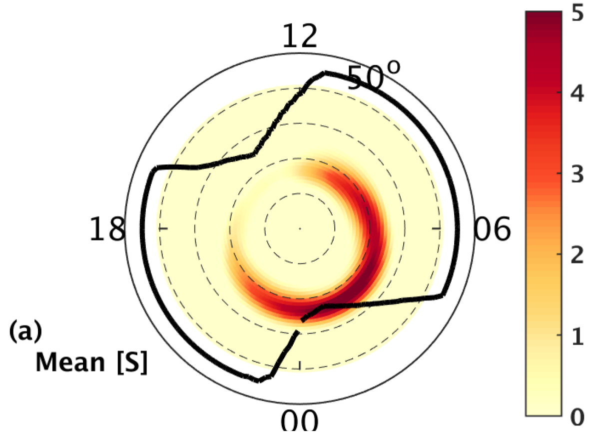
Observations (6 satellite years):
- F6 -F8 (1987)
- F16-F18 (2010)



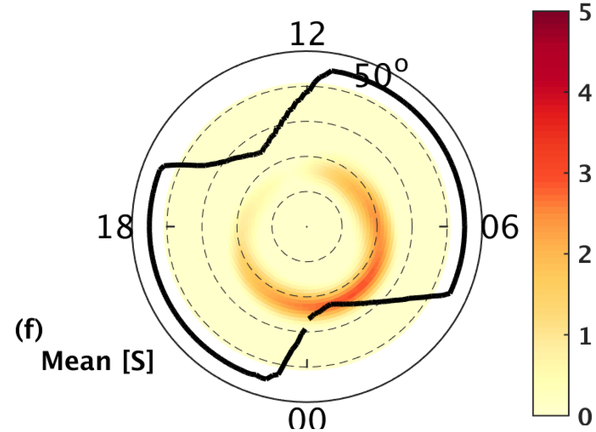

Pedersen (top) and Hall (bottom) binned observation means: Northern and conjugate southern hemispheres



Hall

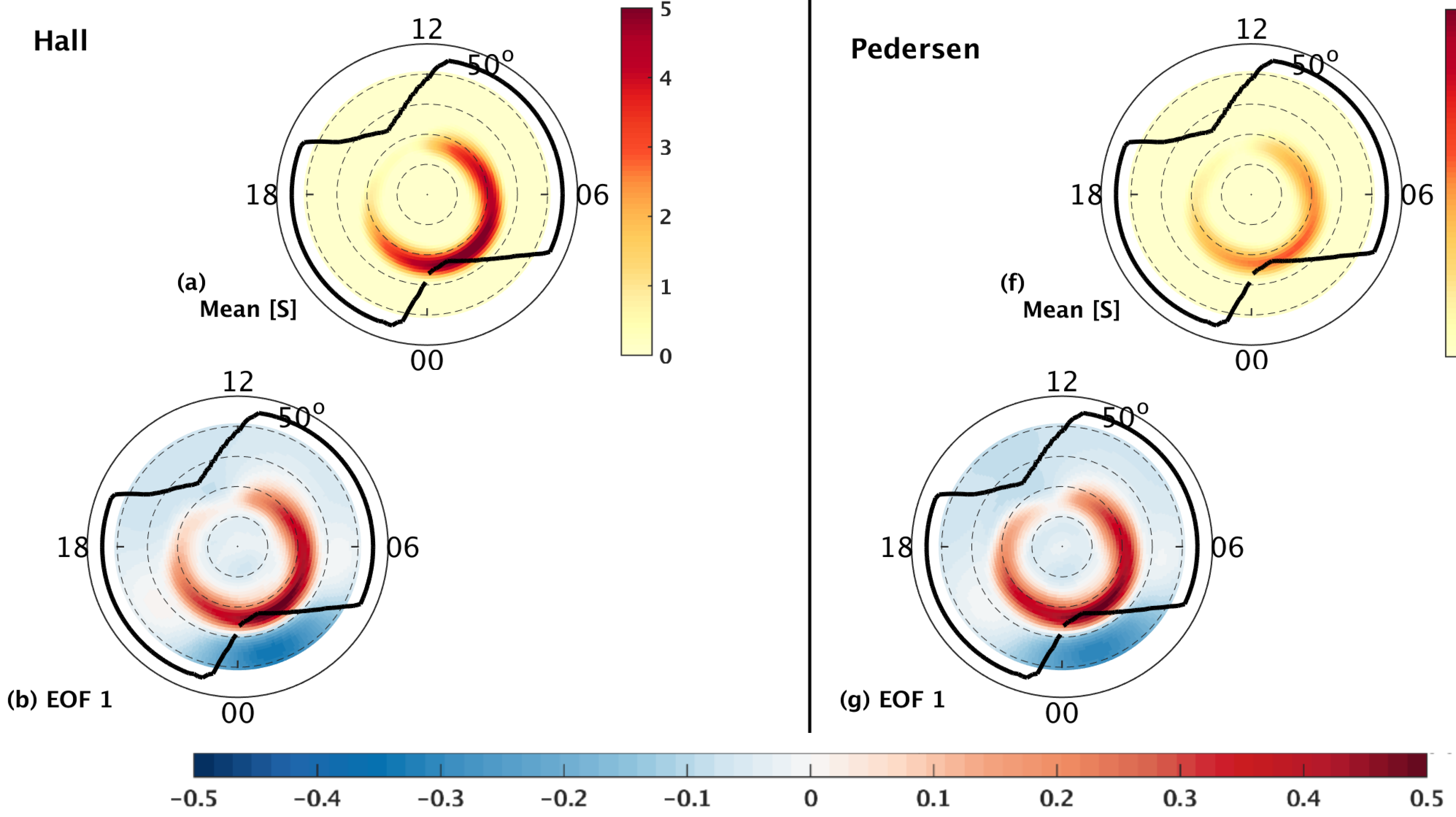



Pedersen



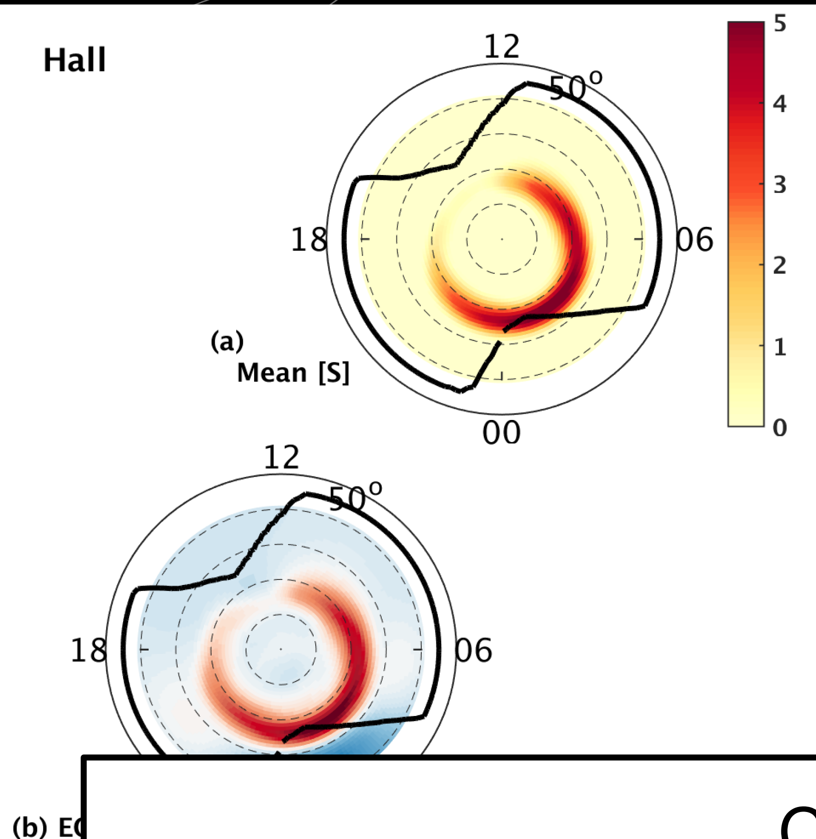

# Mean patterns:

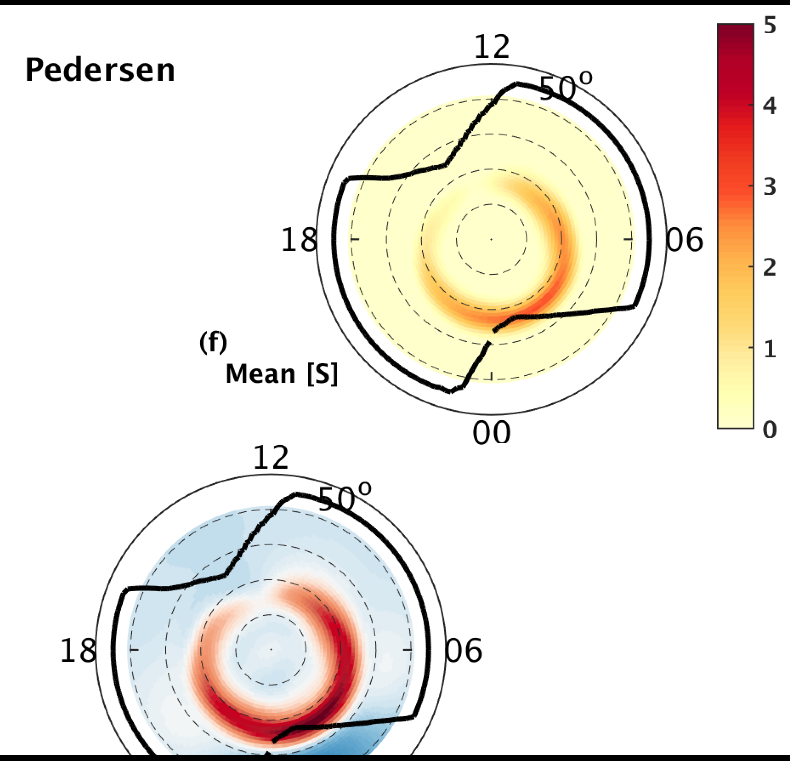
- **Must calculate a mean to remove from observations, then we can look at the modes of variability in residual-space**
- **Means show typical quiet-time aurora characterized by diffuse precipitation [*Winningham et al.,* 1975; *Hardy et* al., 1985; Newell *et al.*, 2009]**




# EOF1:

- **Strengthening/weakening of large-scale, quasi-permanent conductances**



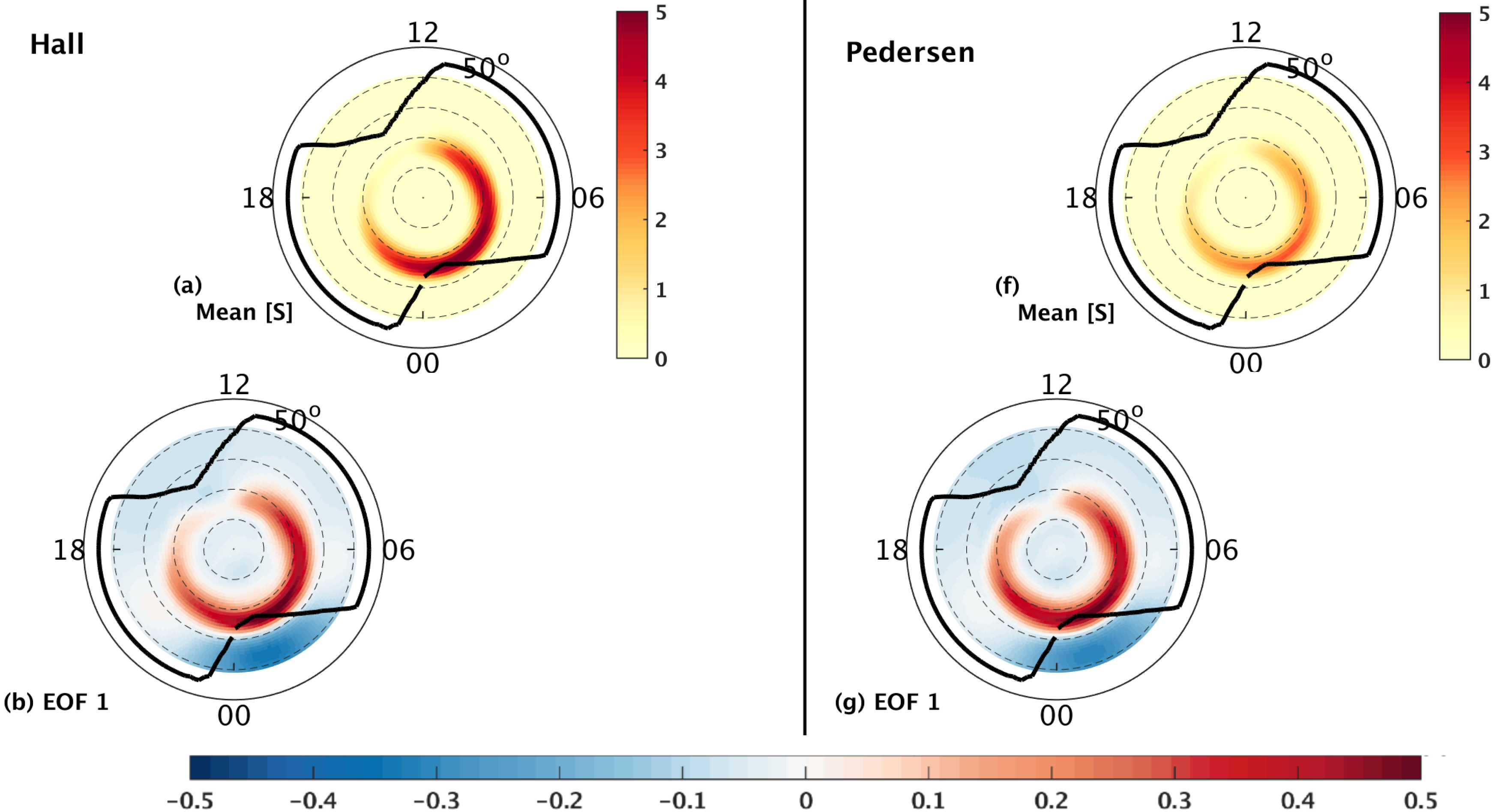




Coefficients are time series

$$\Sigma' = \Sigma - \bar{\Sigma}$$

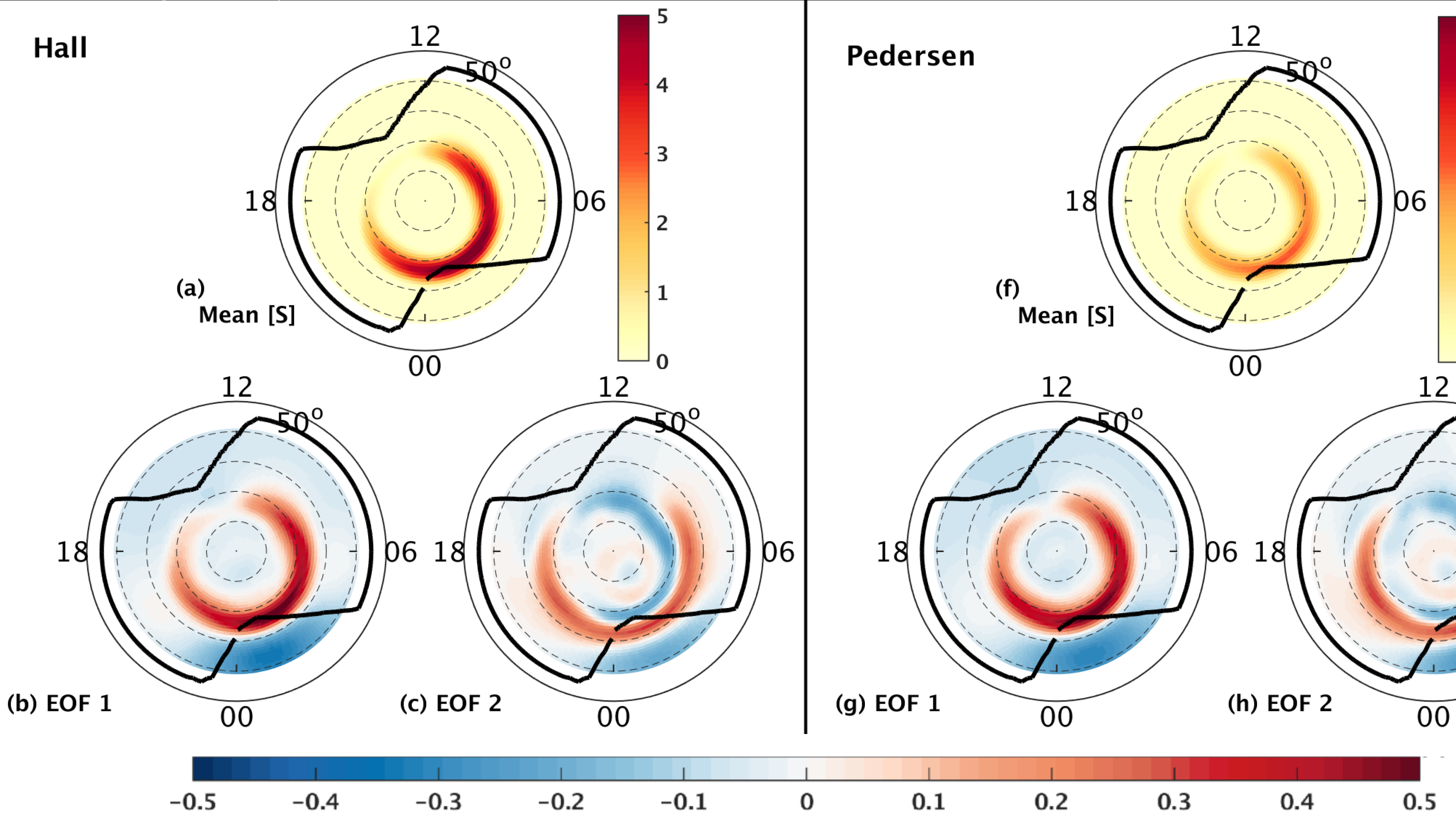
$$\Sigma'(\mathbf{r},t) = \alpha^{(1)}(t)\cdot\mathcal{EOF}^{(1)}(\mathbf{r}) + \dots$$
$$\alpha^{(v)}(t)\cdot\mathcal{EOF}^{(v)}(\mathbf{r}) + \mathbf{e}'(\mathbf{r},t)$$

Basis functions are time-invariant spatial fields



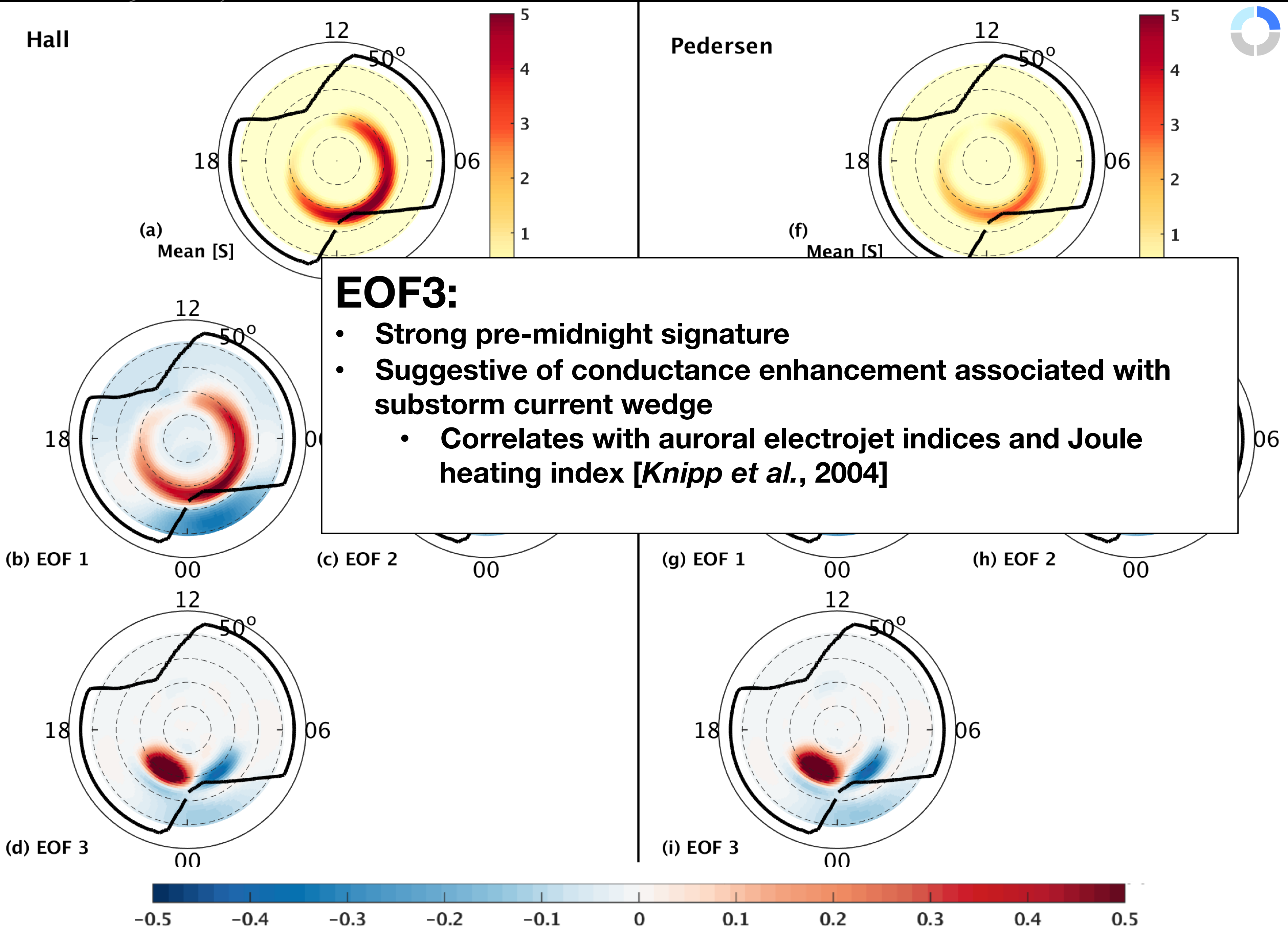

# EOF1:

- Strengthening/weakening of large-scale, quasi-permanent conductances
- Strong correlations with auroral EJ, PC, and Kp indices



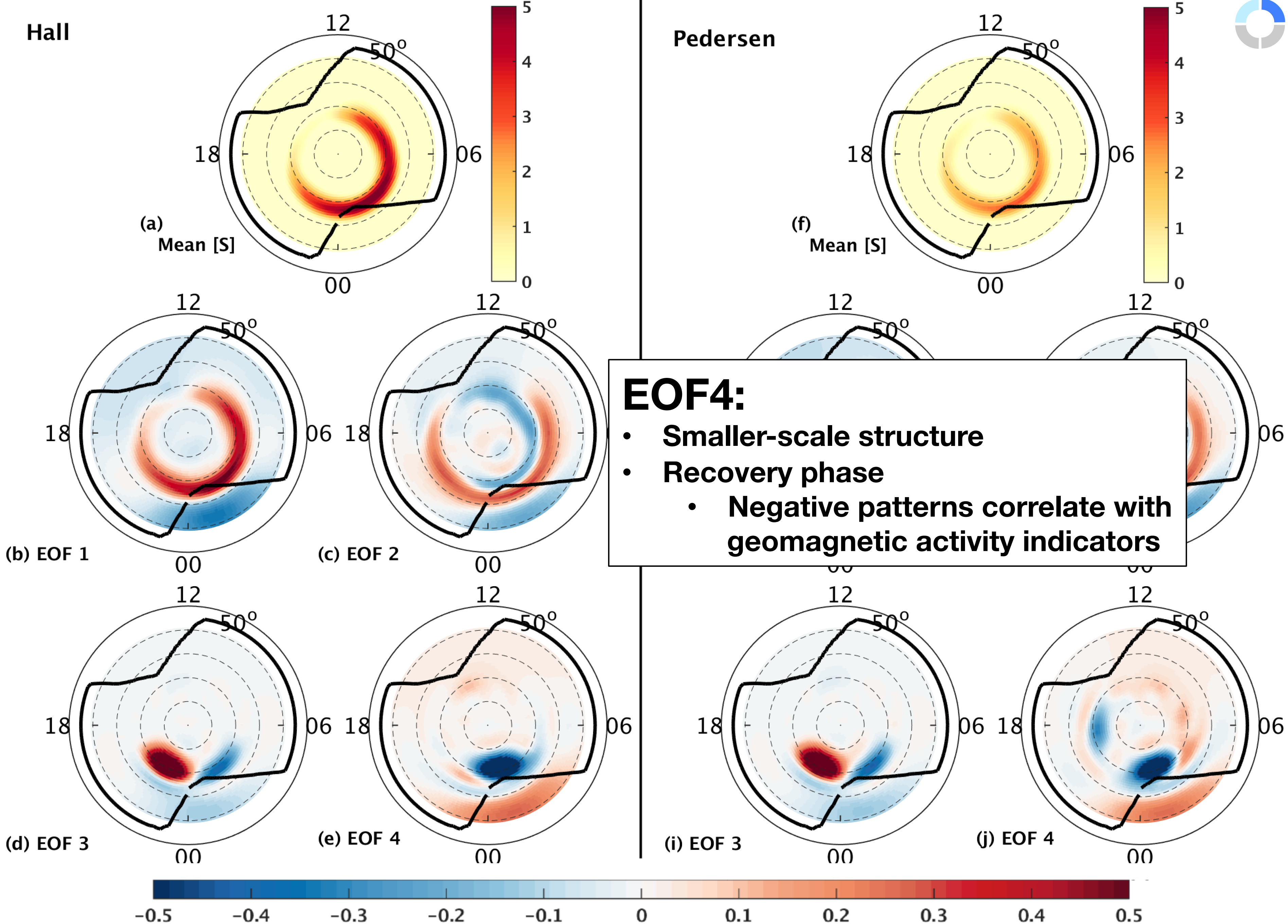

# EOF2:

- **Auroral zone broadening brought on by geomagnetic activity (large-scale magnetospheric convection [*Kamide and Kokubun*, 1996])**
  - **Strongest correlations with AE, AL, AU**
  - **Also correlated with Newell Coupling Function (CF) [*Newell et al.*, 2007] and Borovsky CF [*Borovsky et al.*,2013]**




# EOF3:

- **Strong pre-midnight signature**
- **Suggestive of conductance enhancement associated with substorm current wedge**
  - **Correlates with auroral electrojet indices and Joule heating index [*Knipp et al.*, 2004]**

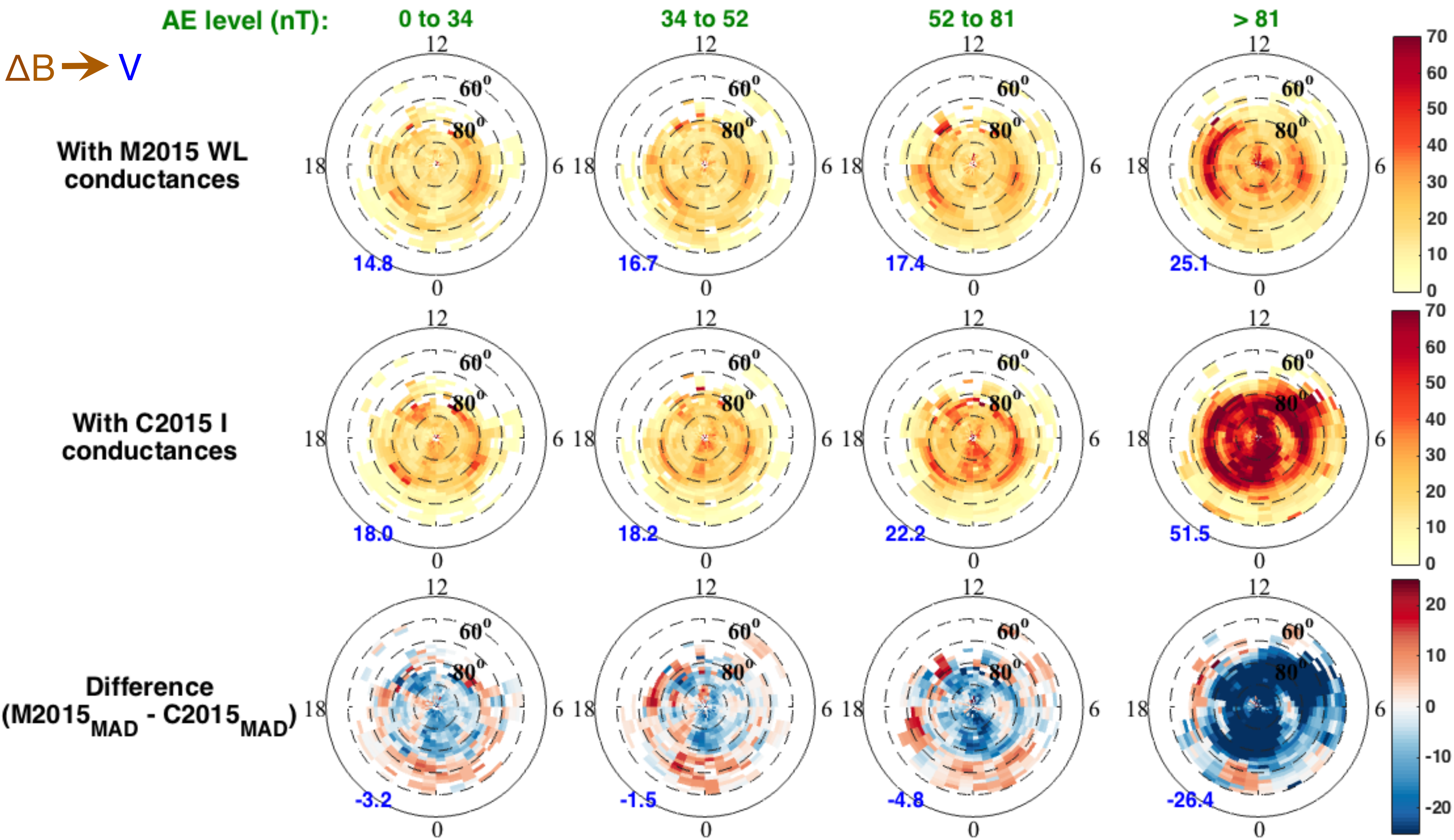



# EOF4:

- Smaller-scale structure
- Recovery phase
    - Negative patterns correlate with geomagnetic activity indicators

# Improvement over Nov. 26 – Dec. 2 period

Colorado Center for Astrodynamics Research
University of Colorado
Boulder, Colorado



# How can we improve this further? Additional observations

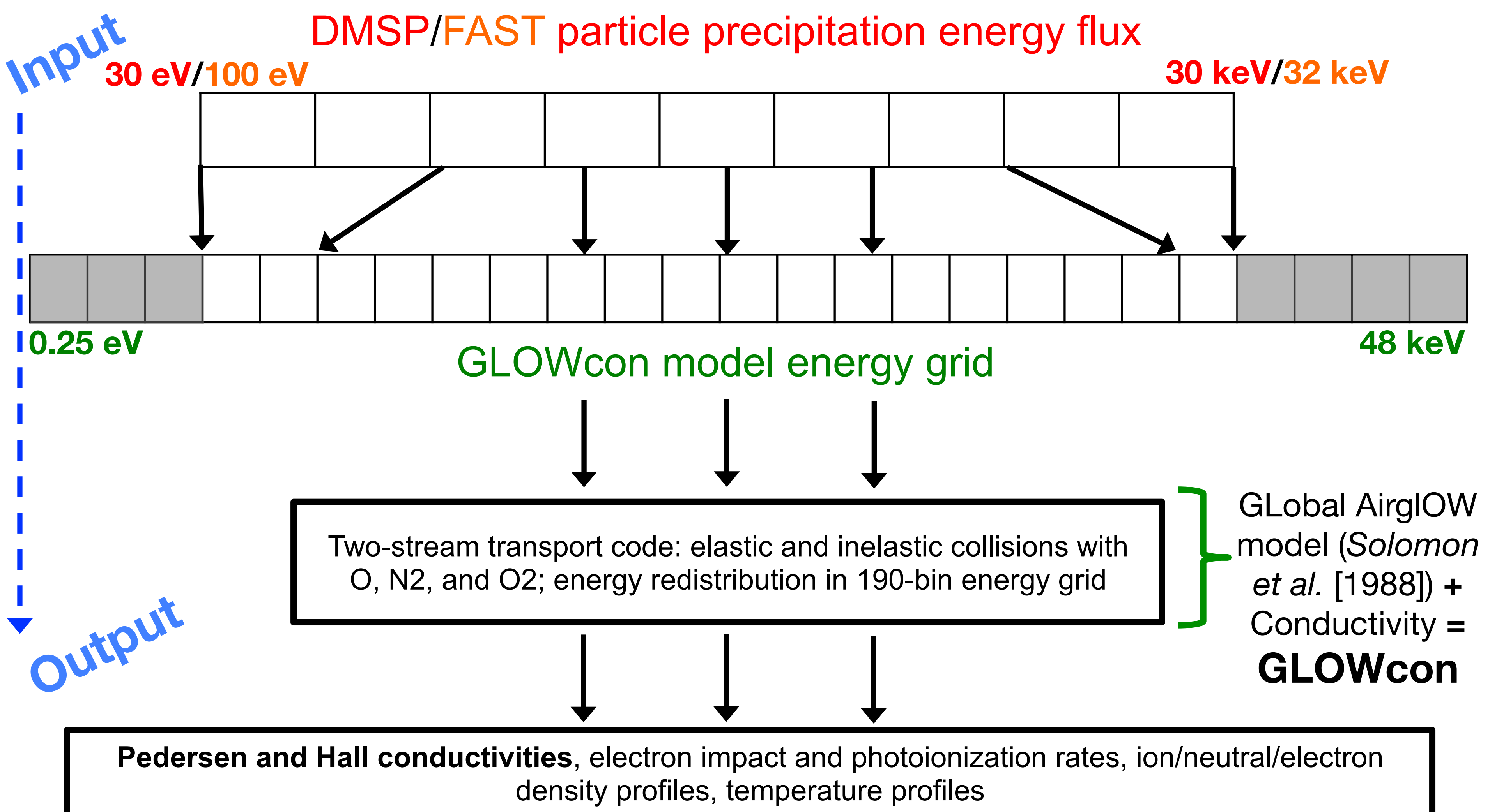
| | Median Absolute Deviations [nT or m/s] | | | | | |
|---|---|---|---|---|---|---|
| **Conductance Model** (night-side value) | **C2015 I** $\Sigma_P$>0.4; $\Sigma_H$>0.8 | **C2015 V** $\Sigma_{P,H}$>4 | **M2015 SL** $\Sigma_P$>0.4; $\Sigma_H$>0.8 | **M2015 WL** $\Sigma_P$>0.4; $\Sigma_H$>0.8 | **M2015 WL** $\Sigma_{P,H}$>4 | **M2015 WL + SSUSI** $\Sigma_P$>0.4; $\Sigma_H$>0.8 |
| ΔB → V | 684.20 | 149.77 | 382.69 | 392.51 | 145.69 | 359.14 |
| V → ΔB | 36.88 | 39.03 | 37.03 | 37.03 | 38.99 | 37.84 |

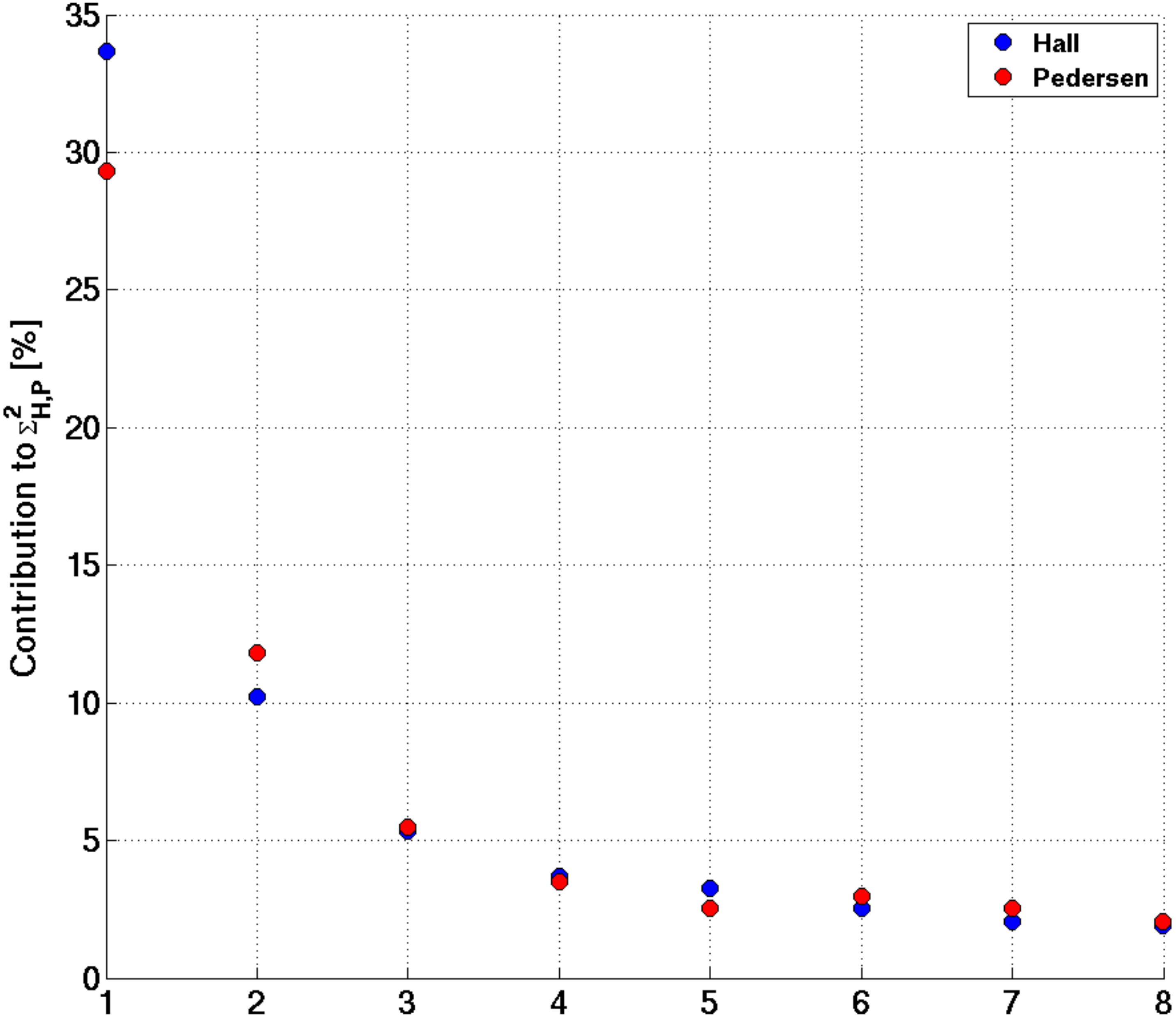
Evidence that additional data can help reduce differences further

- Already using SSUSI
- Exciting opportunity to use COSMIC, ISR, SuperMAG

# Solving lack of observation: Calculating conductivity






Hall
Pedersen
Contribution to $\Sigma^2_{H,P}$ [%]
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8

| Properties of the first four Hall EOFs | | | | |
|---|---|---|---|---|
| EOF | 1 | 2 | 3 | 4 |
| Mode | Strengthening/Weakening | Auroral zone broadening | Substorm current wedge | Recovery/small-scale features |
| Contribution to $\Sigma_H^2$ | 33.67 | 10.2 | 5.33 | 3.72 |
| Top Correlation | AE/PC: 0.6 | AE: 0.72 | SME/SMU: 0.17 | SME: 0.21 |
| 2nd Correlation | AL: -0.57 | AL: -0.69 | AL/SML: -0.15 | SML: -0.20 |
| 3rd Correlation | SME/Kp: 0.57 | AU: 0.66 | AE/JHP: 0.14 | SMR: -0.19 |

| Properties of the first four Pedersen EOFs | | | | |
|---|---|---|---|---|
| EOF | 1 | 2 | 3 | 4 |
| Mode | Strengthening/Weakening | Auroral zone broadening | Substorm current wedge | Recovery/small-scale features |
| Contribution to $\Sigma_P^2$ | 29.3 | 11.8 | 5.51 | 3.49 |
| Top Correlation | PC: 0.56 | AE: 0.78 | SMU: 0.16 | Kp: 0.22 |
| 2nd Correlation | Kp: 0.54 | AL: -0.74 | SME: 0.14 | AU/dst: 0.21/-0.21 |
| 3rd Correlation | AE: 0.54 | AU: 0.73 | SML/Newell & JHP: -0.11/0.11 | $P_{SW}$: 0.20 |

# EOF extensions

## 3-Dimensional study

- 3-D observations running now; 200k EOFs for each altitude next
- What will the visualization look like?
- Future? Multi-frequency tomographic techniques to study 3-D ionosphere (Olaf Amm work between 2010-2013)

## Introducing new observations

- FAST – EOFs
- COSMIC – show movie of COSMIC-DMSP coincidence
- ISR
- Future: SWARM, COSMIC 2, GOLD, ICON

# EOF-based covariance procedure

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

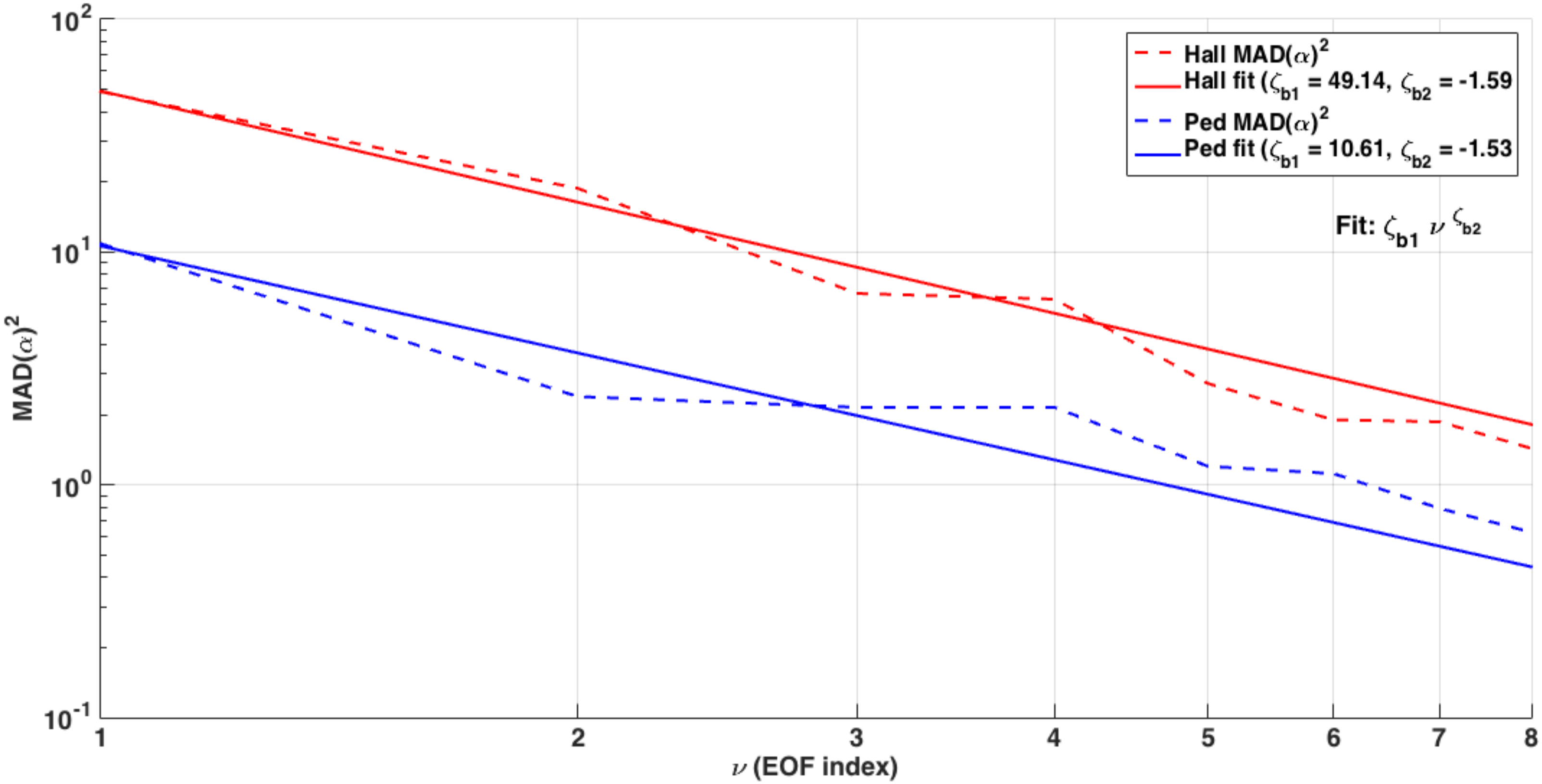
$$\mathbf{x} \sim MN\left[\mathbf{x}_b, \mathbf{P}_b\right]$$

$$\mathbf{P}_b \equiv \mathrm{E}\left[\left(\mathbf{x}_b - \mathbf{x}\right)\left(\mathbf{x}_b - \mathbf{x}\right)^{\mathrm{T}}\right]$$

$$\mathbf{P}_b \approx \mathbf{P}_b\left(\zeta_{b1}, \zeta_{b2}\right) = \zeta_{b1}\nu^{\zeta_{b2}}$$

# EOF-based covariance procedure

$$\mathbf{P}_b \approx \mathbf{P}_b\left(\zeta_{b1}, \zeta_{b2}\right) = \zeta_{b1}\nu^{\zeta_{b2}}$$



# SSUSI covariance augmentation procedure

Colorado Center for Astrodynamics Research
University of Colorado
Boulder, Colorado

SSUSI emission observations

↘

SSUSI characteristic energy and electron energy flux data products from LBHS and LBHL bands

↘

Maxwellian assumption + GLOWcon yields conductivities (pseudo-observations)

↘

Many OI realizations from subsets of complete pseudo-observations with EOF-based background covariance → Non-stationary sample covariance

# SSUSI covariance augmentation procedure

SSUSI emission observations

↘

SSUSI characteristic energy and electron energy flux data products from LBHS and LBHL bands

↘

Maxwellian assumption + GLOWcon yields conductivities (pseudo-observations)

↘

Many OI realizations from subsets of complete pseudo-observations with EOF-based background covariance → **Non-stationary sample covariance**

Applied to SSJ observations with no precipitation spectrum assumption to produce OI conductance fields as function of time

# Optimal interpolation method of data assimilation

- Optimally combine information from **observations** and a **background model**, taking into account **error properties** of both
- **Background model**: EOF-based mean
- **Observations**: DMSP particle precipitation data
- **Error properties**:
  - For background model: Estimated from EOFs
  - For DMSP particle precipitation data: Poisson statistics for individual spectra

$$\vec{x}_a = \vec{x}_b + K\left(\vec{y} - H\vec{x}_b\right)$$

$$K = P_b H^{\mathrm{T}}\left(H P_b H^{\mathrm{T}} + R\right)$$

$\vec{x}_a -$ Analysis field

$\vec{x}_b -$ Background model

$K -$ Kalman gain

$\vec{y} -$ Observations

$H -$ Forward operator

$P_b -$ Background model error covariance

$R -$ Observational error covariance

# Relationship among electrodynamic variables (assuming purely toroidal magnetic perturbation values)

$$\delta\vec{B} = \nabla \times (\hat{r}A_r), \tag{6}$$

$$\mu_0 J_r = \hat{r} \cdot \nabla \times \delta\vec{B} = -\nabla^2 A_r, \tag{7}$$

$$J_r = \nabla \cdot \vec{I}, \tag{8}$$

$$\vec{I} = \Sigma \cdot \vec{E}, \tag{9}$$

$$\vec{E} = -\nabla\Phi, \tag{10}$$

$$\vec{v} = \frac{\vec{E} \times \vec{B}}{B^2}, \text{ and} \tag{11}$$

$$\nabla^2 A_r/\mu_0 = \Sigma_P \nabla^2\Phi + \nabla\Phi \cdot \nabla\Sigma_P \pm \hat{r} \cdot (\nabla\Sigma_H \times \nabla\Phi), \tag{12}$$

where $\mu_0$ is the permeability of free space, $\hat{r}$ is a unit radial vector, $J_r$ is the radial current density above the ionosphere (which is assumed to be equivalent to FAC density), $\vec{I}$ is the height-integrated horizontal current density flowing in the ionospheric layer, $\vec{E}$ is the horizontal electric field in the ionosphere, $\Sigma$ is the conductance in the ionosphere and is a tensor, $\vec{B}$ is the geomagnetic field (given by the International Geomagnetic Reference Field (IGRF)), and $\Sigma_P$ and $\Sigma_H$ are the Pedersen and Hall conductances, respectively. The + and − signs in equation (12) are for the Northern and Southern Hemispheres, respectively.

# Cousins et al. [2015] conductance model comparison

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

**Table 1.** Conductance Model Evaluation[a]

| Conductance | I | II | III | IV | V | VI | VII | VIII |
|---|---|---|---|---|---|---|---|---|
| Model | FAC Adjustment | E Adjustment | $\Sigma > 0.4$ | $\Sigma > 2$ | $\Sigma > 4$ | $\Sigma > 6$ | OVATION-SM | No Aurora |
| $V \rightarrow \delta B$ | 33.3 | 38.6 | 33.2 | 33.5 | 34.7 | 36.7 | 34.6 | 34.7 |
| $\delta B \rightarrow V$ | 501 | 723 | 512 | 175 | 147 | 142 | 146 | 147 |

[a] Median absolute errors are given for using SuperDARN data to predict AMPERE data ($V \rightarrow \delta B$), in nT, and vice versa ($\delta B \rightarrow V$), in m/s, with estimated uncertainty values of ~0.2 nT and ~1 m/s, respectively.