Reconstruction of three-dimensional auroral ionospheric conductivities via an assimilative technique

Ryan McGranaghan\(^1\), Delores J. Knipp\(^1,2\), Tomoko Matsuo\(^3\), Ellen Cousins\(^4\), Stan Solomon\(^2\)

\(^1\)University of Colorado Boulder - Boulder, CO
\(^2\)High Altitude Observatory, National Center for Atmospheric Research - Boulder, CO
\(^3\)Cooperative Institute for Research in the Environmental Sciences - Boulder, CO
\(^4\)Weather Analytics – Bethesda, MD

Email: ryan.mcranaghan@colorado.edu

Key Findings

- New optimal interpolation technique reconstructs conductivities in two- and three-dimensions
- Improved global conductivity distributions bring SuperDARN and AMPERE data into closer agreement, especially during geomagnetically active periods
- 2D and 3D specification of conductivity reveal new understanding of the solar wind-magnetosphere-ionosphere system and allow better estimation of high-latitude conductances and application to assimilative ionospheric electrodynamics reconstruction
- Overcame Maxwellian assumption for precipitating particles

Importance of Analyzing Ionosphere in 3D: Empirical Orthogonal Functions

EOF Process
1. Directly-measured electron energy spectra from Defense Meteorological Satellite Program (DMSP) satellites F8-FB and F10-FB are used to characterize auroral ionization losses
2. Global AIRGLO (GLOW) model (Solomon et al., 1998) + conductivity (GLOW/amp) or McGranaghan et al. (2016) active 2-stream electron transport to yield conductivity profiles
3. EOFs spread sparse information into global picture by deconstructing the Hall and Pedersen residual fields into a few dominant modes of varying 2D fields to the right (McGranaghan et al., 2015b) and 3D fields below (McGranaghan et al., 2016b, in prep.)

Mean fields and EOFs time-invariant spatial field for Hall and Pedersen conductances (left) and conductivities beneath in magnetic coordinates. The low latitudes limit all polar plots in 3D and dashed lines are plotted at 10-100 nT (approximately up to 80°). The solid black curves indicate the boundaries of observational support.

Conductance models and details

- **Auroral Conductance Model**
- **Details**
  - C2015 I: Offline precipitation from Ovation Prime auroral precipitation model (Nawal et al., 2005); no discrete precipitation; Pedersen formula used to calculate relative energy flux and average energy to conductance; Background I: Same as C2015 I, but with background II
  - C2015 II: Same as C2015 I, but with background I

- **Hall Conductance Model**
- **Details**
  - M2015 I: Conductances using DMSP particle precipitation observations; EOFs based background convection; Background I: Same as C2015 I, but with background II
  - M2015 II: Same as C2015 I, but with background I

Optimal Interpolation (OI) Technique

Reconstruction of complete high-latitude conductivities via optimal interpolation (OI) follows technique developed by Richmond and Kamide (1988) (AMIE), Matsuo et al. (2009), and Cousins et al. (2013). Optimal: Optimally combine information from observations and a background model, taking into account error properties of both Background model: EOF-based mean (see next section)

Observations: DMSP particle precipitation data

Error properties:
- For background model: Estimated from EOFs
- For DMSP particle precipitation data: Poisson statistics for individual spectra

Values:
- \(\tilde{x} = \bar{x} + K (y - \bar{y})\)
- \(K = \frac{P_{HH}^{	ext{H}} (H P_{HH}^{	ext{H}} + R)^{-1} P_{HH}^{	ext{H}}}{\text{Forward operator}}\)
- \(P_{HH}^{	ext{H}} - \text{Background model error covariance}\)
- \(R - \text{Observational error covariance}\)

Optimal interpolation analysis of high-latitude ionospheric Hall and Pedersen conductivities (a) Applying an assimilative approach to complete high-latitude auroral conductance variability (b) Using EOFs spread sparse information into global picture by deconstructing the Hall and Pedersen residual fields into a few dominant modes of varying 2D fields to the right (c) Hall and Pedersen conductances and conductivities beneath in magnetic coordinates.

3D IO Conductivity

Perform the OI estimation at discrete altitudes (100-140 km @ 1200 UT shown): Background model: Altitude-specific EOF-based mean Observations: Altitude-specific conductivities from DMSP particle precipitation data

Conclusions

Ionicospheric Conductivity Empirical Orthogonal Functions: First characterization of primary modes of ionospheric Hall and Pedersen conductance variability as EOFs (McGranaghan et al., 2015b)

Extended analysis to 3D conductivities (McGranaghan et al., 2016b, in prep.)

And 2D and 3D treatment of conductivities distinctly different

Optimal Interpolation of Ionospheric Conductivities [McGranaghan et al., 2016a]

New optimal interpolation technique yields complete high-latitude conductance distributions
- Technique capable of better ionospheric conductance specification, especially during geomagnetically active periods

Yields cross agreement between AMPERE and SuperDARN data

Showed significant vertical gradients in three-dimensionality

Larger Implications:
- Overcame Maxwellian assumption for precipitating particles

Better conductivity information allows consistent assimilation of ground- and space-based data

Critical to study fully 3D ionosphere

References

McGranaghan et al. (2015a, b, 2016, [in prep.])

Acknowledgements

The Author: DMSP F8-FB/Auroral SUPERDARN/AMPERE/OMI/DMSP, Ofelia Southward, and Dani Nava for their roles in preparing and launching observational data. The University of Colorado Boulder: Tomoko Matsuo, Ellen Cousins, and Barbara Emery for their roles in preparing and launching observational data.

DMSF was partially supported by NSF Fellowship award DEB 1150480. NSF grant AGS-1003598. NASA grant NNA13BQ79G, and the NASA Fellowship at the University of California Irvine Space Weather Science C (McGranaghan et al., 2016b, in prep). Reconstructions of high-latitude ionospheric conductivity variability - use of Assimilative Mapping of Ionospheric Electrodynamics (AMIE) and for precipitating particles: Pedersen formula used to calculate relative energy flux and average energy to conductance.

Conductance model evaluation

- **Conductance model evaluation**
- **Details**
  - C2015 I: Offline precipitation from Ovation Prime auroral precipitation model (Nawal et al., 2005); no discrete precipitation; Pedersen formula used to calculate relative energy flux and average energy to conductance; Background I: Same as C2015 I, but with background II
  - C2015 II: Same as C2015 I, but with background I
  - M2015 I: Conductances using DMSP particle precipitation observations; EOFs based background convection; Background I: Same as C2015 I, but with background II
  - M2015 II: Same as C2015 I, but with background I

- **Conductance model evaluation**
- **Details**
  - C2015 I: Offline precipitation from Ovation Prime auroral precipitation model (Nawal et al., 2005); no discrete precipitation; Pedersen formula used to calculate relative energy flux and average energy to conductance; Background I: Same as C2015 I, but with background II
  - C2015 II: Same as C2015 I, but with background I
  - M2015 I: Conductances using DMSP particle precipitation observations; EOFs based background convection; Background I: Same as C2015 I, but with background II
  - M2015 II: Same as C2015 I, but with background I

Quantitative validation of M2015 I conductances capturing discrete precipitation shown in auroral imagery from DMSP Special Sensor Imaging Proton Spectrometer images. Conductance maps from Harris et al. 1999, Hall and Pedersen conductance maps for the northern hemisphere on November 30, 2011 for the time period 1330-1350 UT from the (a) M2015 model, (b) C2015 model, (c) difference (M2015 - C2015), and (d) AMPERE P10 F16-SUL, 1135-1225 UT. The difference between the two models shows significant changes in the northern hemisphere on November 30, 2011 for the time period 1330-1350 UT.

Conductance model evaluation

- **Conductance model evaluation**
- **Details**
  - C2015 I: Offline precipitation from Ovation Prime auroral precipitation model (Nawal et al., 2005); no discrete precipitation; Pedersen formula used to calculate relative energy flux and average energy to conductance; Background I: Same as C2015 I, but with background II
  - C2015 II: Same as C2015 I, but with background I
  - M2015 I: Conductances using DMSP particle precipitation observations; EOFs based background convection; Background I: Same as C2015 I, but with background II
  - M2015 II: Same as C2015 I, but with background I

Quantitative validation of M2015 I conductances capturing discrete precipitation shown in auroral imagery from DMSP Special Sensor Imaging Proton Spectrometer images. Conductance maps from Harris et al. 1999, Hall and Pedersen conductance maps for the northern hemisphere on November 30, 2011 for the time period 1330-1350 UT from the (a) M2015 model, (b) C2015 model, (c) difference (M2015 - C2015), and (d) AMPERE P10 F16-SUL, 1135-1225 UT. The difference between the two models shows significant changes in the northern hemisphere on November 30, 2011 for the time period 1330-1350 UT.