HISTORY AND RECENT PROGRESS OF ASSIMILATIVE MAPPING OF IONOSPHERIC ELECTRODYNAMICS

All I know about AMIE I learned from Dr. Arthur D Richmond

Tomoko Matsuo
Anne and HJ Smead Aerospace Engineering Sciences Department
University of Colorado Boulder
With contributions from
Ellen Cousins, Ryan Mcgranagahan, Liam Kilcommon, Delores Knipp, Gang Lu, Barbara Emery, Aaron Ridley, Doug Nychka
AMIE early days

1980' NCAR/HAO's CEDAR database was set up to store and distribute large amounts of data from many different instruments and models
1988 Richmond and Kamide [1988]
1989 CEDAR Prize Lecture, titled AMIE, by Art Richmond

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 93, NO. A6, PAGES 5741–5759, JUNE 1, 1988

MAPPING ELECTRODYNAMIC FEATURES OF THE HIGH-LATITUDE IONOSPHERE FROM LOCALIZED OBSERVATIONS: TECHNIQUE

A. D. Richmond
High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado

Y. Kamide
Kyoto Sangyo University, Japan
Vision for the future observing

Richmond and Kamide: Ionospheric Electrodynamic Mapping Technique

IONOSPHERIC ELECTRODYNAMICS MAPPING

\[
\Phi = \sum_i a_i 
\]

- Statistical Model
- Radar
- Satellite
- Radar
- Satellite Magnetometer
- Ground Magnetometer
- Data
- Fitted Distributions
- Fitted Coefficients
- Basis Functions
- Conductances
- Data
- I.S. Radar
- Particle Fluxes
- Magnetic Variations
- Photometric Images
- Statistical Model
- \( \Phi_i \)
- \( \vec{E}_i \)
- \( \vec{B}_i \)
- \( \Sigma_H \)
- \( \Sigma_P \)
Vision for the future observing

Richmond and Kamide: Ionospheric Electrodynamic Mapping Technique

IONOSPHERIC ELECTRODYNAMICS MAPPING

\[
\Phi = \sum_i a_i ^{\Phi_i} \cdot \sum_p \Sigma_p \cdot \Sigma_H \cdot \Sigma_E \cdot \Sigma_J \cdot \Sigma \cdot \Phi
\]
AMIE’s estimation problem

Inverse Problem

[States]

\[ x_0, x_1, x_2, \cdots, x_t \]

[Observations]

\[ H \]

[Observations]

[Inverte Problem]

[Inverse Problem]

\[ X \]\n
\[ Y \]

[Kamide, Richmond and Matsushita, 1981]
AMIE’s estimation problem

Bayesian Inference (DA) Problem

Bayes’ rule

\[
[x|y] \propto [y|x][x]
\]

with assumptions of Gaussian errors for \([y|x]\) & \([x]\), \([x|y]\) is Gaussian with

\[
x_a = x_b + K(y - Hx_b)
\]

\[
C_a = (I - KH)C_b
\]

[Richmond and Kamide, 1988]
AMIE solves for coefficients of polar-cap vector spherical harmonic basis functions

\[ \Phi = \sum_i x_i \Psi_i \]

\( \Psi \) : Polar-cap SH

\( x \) : coefficients

[Richmond and Kamide, 1988]
AMIE solves for coefficients of polar-cap vector spherical harmonic basis

\[ \Phi = \sum_i \mathcal{X}_i \]

\[ \begin{align*}
\Psi_i & \\
-\nabla \Psi_i & \\
-\sum_P \nabla \Psi_i - \sum_H \mathbf{b} \times \nabla \Psi_i & \\
\nabla \cdot (\sum_P \nabla \Psi_i + \sum_H \mathbf{b} \times \nabla \Psi_i) & \\
\Delta \mathbf{B}_i &
\end{align*} \]
AMIE example for January

Background

1987 JAN 10 11:10+/-003 12
Bx,y = -3.9, -10.2
Bz = -8.2
MH I 10
HPI = 19

Electric Potential
81 kV

Observations

1987 JAN 10 11:10+/-003 12

 OBS MAGNETIC VARIATIONS (ROTATED 80°)

Foster empirical model
Energy Flux (NH) with contours of Electric Potential

Contour increment is 10.0 kV
Min pot. = -52.13 kV
Max pot. = 107.28 kV

data averaged over ± 3 mins
Recent AMIE progress – background error covariance

Covariance model with Empirical Orthogonal Functions (EOFs)

\[ C_b \approx \mathbf{Q} \mathbf{\Gamma} \mathbf{Q}^T \]  

[Matsuo et al., 2002, 2005]

EOFs estimated from SuperDARN data

[Cousins et al., 2013a]
SuperDARN Map Potential

SuperDARN Assimilative Mapping

SAM Analysis Errors

Figure 5. Mapped potential distributions for three selected times, organized and plotted in the same format as Figure 2. Results from the Map Potential procedure are shown in the left column (panels a, d, and g). Results from the SAM procedure are shown in both the center column (panels b, e, and h) and the right column (panels c, f, and i), with errors in the mapped potential added as background coloring in the right column.

SAM available at http://vt.superdarn.org/

[Cousins et al., 2013b]
Recent AMIE progress – solve for magnetic potentials in addition to electrostatic potential

Toroidal and poloidal decomposition

\[ \Delta \vec{B} = \nabla \times \vec{r} A^t + \nabla \times \nabla \times \vec{r} A^p \]

Analysis of toroidal fields observed by satellite magnetometer

\[ \Delta \vec{B} = \sum_i x_i \nabla \times \vec{r} \Psi_i \]

\[ J_{||} = \frac{1}{\mu_0} \sum_i x_i \nabla^2 \Psi_i \]

EOF-based background error covariance estimated from Iridium/AMPERE data

\[ C_b \approx QQ^T \]

[Matuo et al., 2015] [Cousins et al., 2015a]
AMIE analysis errors

AMIE next

AMPERE product

[Matsuo et al., 2015]
Recent AMIE progress – Assimilative mapping of conductance update

DMSP F15-F18/SSUSI auroral emission 135.6 nm

1205 – 1215 UT

[Mcgranaghan et al., JGR, 2016a]
Recent AMIE progress – Dual optimization of electrostatic and toroidal magnetic potential

\[ \mathbf{J}_\parallel = \nabla \cdot \left( \sum p \mathbf{E} + \sum h \mathbf{b} \times \mathbf{E} \right) \]

[Coatin et al., 2015b]
Figure 5. Distributions of electrostatic potential and FAC density, with uncertainties, and of Poynting flux for 0050–0100 UT, 29 November, 2011, following the format of Figure 4.

[Cousins et al., JGR, 2015b]
Recent AMIE progress – New assimilative mapping of conductance improves agreement of AMPERE and SuperDARN observations
Recent AMIE progress as AMIE NextGen

Figure 7. Distributions of electrostatic potential, FAC density, and Poynting flux for 1500–1510 UT, 29 November 2011, following the format in Figure 3. Results are shown for (a–c) the Northern Hemisphere and (d–f) the Southern Hemisphere.

Results from both hemispheres from an example snapshot (29 November, 1500 UT) are shown in Figure 7, following the format in Figure 3. The IMF is $B_Y$ dominated at this time, and both the convection pattern and the dayside FAC distribution have different morphologies in the two hemispheres, as expected [e.g., Feldstein et al., 1984; Heppner and Maynard, 1987]. The electrostatic potential and FAC density values are larger in the South than in the North, and the Poynting flux is significantly enhanced in the South, especially in the polar regions.

Figure 8. Distributions of electrostatic potential, FAC density, and Poynting flux for 0900–0910 UT, 29 November 2011, following the format in Figure 7.

[Cousins et al., 2013b, 2015b; Matsuo et al., 2015; Mcgranaghan et al., 2016a]
AMIE NextGen and beyond - extending capabilities for the assimilative mapping of ionospheric electrodynamics to exploit new geospace instrumentation capacity

① New prior covariance models derived from SuperDARN and AMPERE data to better account for the prior model uncertainty.
② Optimization problem now solved in terms of both magnetic potential and electrostatic potential to take advantage of the global monitoring of multiple electrodynamics variables (e.g., SuperDARN, AMPERE, and SuperMag).
③ Improved conductance specification from DMSP data to facilitate a self-consistent inference of electrodynamics variables.
④ Towards 3D mapping enabled by 3D conductivity mapping.
⑤ Towards non-Gaussian stochastic parameterization of subgrid scale high-latitude ionospheric electrodynamics processes.
⑥ Open shared source Python version of AMIE and AMIE Nextgen - AMIEPy

References: Richmond and Kamide, JGR, 1988; Richmond, JGG, 1995; Matsuo et al., GRL., 2002; Matsuo et al., JGR, 2005; Cousins et al., JGR 2013a, 2013b, 2015a, 2015b; Matsuo et al., JGR, 2015; Mcgranaghan et al., JGR, 2015, 2016; Mcgranaghan et al., GRL, 2016; Fan et al., JASA, 2017, AAS, 2017.