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Storm-time Ion Drifts Estimation via a New Augmented Data Assimilation Algorithm

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ITIT-11

Motivation

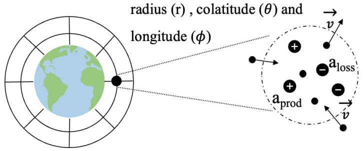
- **During the geomagnetic storm[1]**
  - The earth's ionosphere is highly impacted by the enhanced plasma flow ejected from the sun
  - Weather models' capabilities of predict ionospheric behaviors are limited

Objective

- **Improve storm-time ion velocity estimation via a data assimilation tool: Estimating Model Parameters from Ionospheric Reverse Engineering(EMPIRE) algorithm**
  - Augment ion velocity measurements

Background – EMPIRE algorithm

- **EMPIRE algorithm: Reduce the gap between background model estimations and measurements [2]**
  - Analyze the ionospheric drivers with a **4D global grid map** governed by the **ion continuity equation**
    - **4D global grid map**



jth grid point given by magnetic radius (r) , colatitude (θ) and longitude (ϕ)

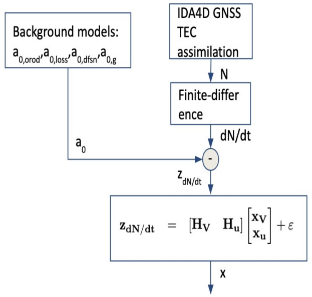
Fig. 1 Global grid map and representation of plasma flow in a volume.

- **Ion continuity equation**

$$\frac{\partial \mathbf{N}}{\partial \mathbf{t}} - \underbrace{(a_{0,prod} + a_{0,loss} + a_{0,dfsn} + a_{0,g})}_{\mathbf{a_0}} = \mathbf{a_u} + \mathbf{a_{exb}}$$

  - Measurements: 4D Total Electron Content(TEC) density rate[∂**N**/∂**t**]
  - Background components[$\mathbf{a_0}$]: Production rate[$a_{0,prod}$], loss rate[$a_{0,loss}$], Diffusive rate[$a_{0,dfsn}$], Gravitation effect[$a_{0,g}$]
  - Drivers to be estimated:
    - Neutral wind[$\mathbf{a_u}$]: Parallel to the earth's magnetic field
    - Ion drifts[$\mathbf{a_{exb}}$]: Perpendicular to the earth's magnetic field

- **Algorithm flowchart[3]**



$$\mathbf{z}_{dN/dt} = \begin{bmatrix}\mathbf{H_V} & \mathbf{H_u}\end{bmatrix}\begin{bmatrix}\mathbf{x_V}\\ \mathbf{x_u}\end{bmatrix} + \varepsilon$$

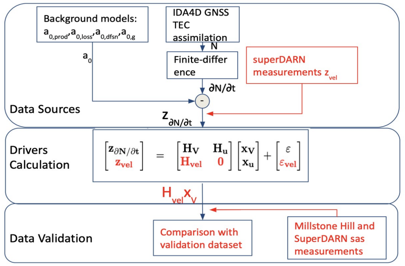
Fig. 2 Flowchart of EMPIRE algorithm in the original setup. The 0 subscription indicates the background model value.∂**N**/∂**t** is the total electron content density rate. $\mathbf{H_v}$ is the mapping matrix that maps electrical potential driver $\mathbf{x_v}$ to ion drifts. $\mathbf{H_u}$ is the mapping matrix that maps natural wind driver $\mathbf{x_u}$ to neutral winds. $\boldsymbol{\varepsilon}$ is the total of measurement and representation errors.

Acknowledgment

This project is funded by NSF travel support

Method – New Augmentation

- **Augment from Super Dual Auroral Radar Network(superDARN) radar sites[4]**
  - The high latitude radar system
  - Ingest the measured line of sight (LOS) ion velocity[$\mathbf{z_{vel}}$]
  - Formulate the mapping function[$\mathbf{H_{vel}}$] to project electron potential driver [$\mathbf{x_v}$] onto the observation space of LOS ion velocity
- **Validate the results at 450 km altitude with ion velocity measured by**
  - Incoherent Scattered Radar at Millstone Hill, at geographic location 41° N 72°W
  - Coherent Scatter Radar from superDARN at Saskatoon(SAS), at geographic location 61° N 101 °W
- **New methodology flowchart**



$$\begin{bmatrix}\mathbf{z}_{\partial N/\partial t}\\ \mathbf{z_{vel}}\end{bmatrix} = \begin{bmatrix}\mathbf{H_V} & \mathbf{H_u}\\ \mathbf{H_{vel}} & \mathbf{0}\end{bmatrix}\begin{bmatrix}\mathbf{x_V}\\ \mathbf{x_u}\end{bmatrix} + \begin{bmatrix}\varepsilon\\ \varepsilon_{\mathbf{vel}}\end{bmatrix}$$

Fig. 3 New augmentation of EMPIRE algorithm. The red text indicates the difference from the original setup written in the black text from Fig.2. $\mathbf{z_{vel}}$ is the LOS ion velocity measurements. $\mathbf{H_{vel}}$ is the formulated mapping function that maps the electrical potential state vector $\mathbf{x_v}$ onto the LOS ion velocity observation space. $\boldsymbol{\varepsilon_{vel}}$ is the errors of measurement and representation.

Data Inputs

- **Ionospheric Data Assimilation 4-Dimensional (IDA4D) coupled with SAMI3 model vertical Total Electron Content(TEC) map**

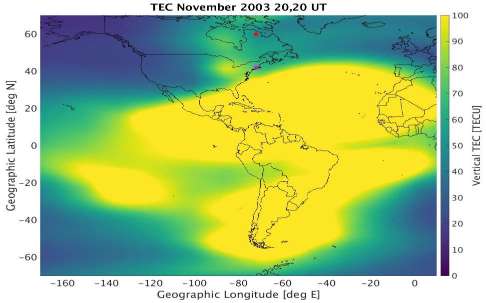


Fig. 4 Representation of IDA4D TEC map from 18UT on November 20th to 24UT on November 21st 2003 storm event. Red star is the SuperDARN SAS site location and magenta star is the Millstone Hill radar location.

- **Ion drifts measured from SuperDARN SAS site**

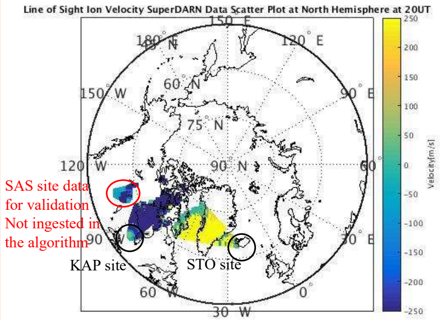


Fig. 5 Plot of the Northern hemisphere with Ingested superDARN site data coverage in 5-min time interval at 20UT on November 20th 2003 storm event. Data from two radar sites is ingested to the algorithm: KAP located at Kapuskasing, geographic location at 49° N 82°W. STO is located at Stokkseyri, geographic location at 64° N 21°W

Results

- **EMPIRE results of ion velocity validating with Millstone Hill radar measurements**

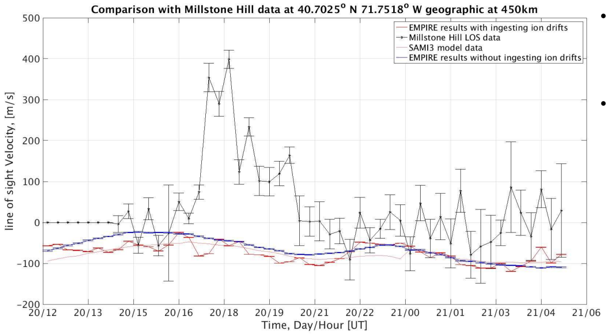


Fig. 6 EMPIRE in the previous setup and new augmentation on November 20th, 2003 storm.

- During the time period 11:30 LT to 16:00 LT, both EMPIRE results didn't show the uplift ion motion
- The EMPIRE error bars appear too small

Table 1 Root mean square error(RMSE) comparison with two experimental setups.

	Root mean square error [m/s]
Primary setup	147.71
New setup	155.68

- **EMPIRE results of ion velocity validating with SuperDARN SAS site radar measurements**

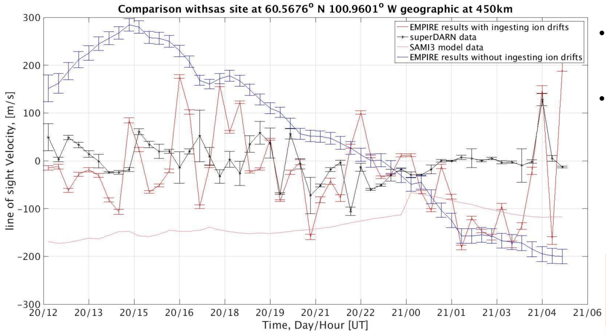


Fig. 7 EMPIRE in the previous setup and new augmentation on November 20th, 2003 storm.

- The new augmentation yields a smaller root mean square error comparing the original setup
- The new augmentation captures the trend of ion motion better than the original setup

Table 2 Root mean square error(RMSE) comparison with two experimental setups.

	Root mean square error [m/s]
Primary setup	166.29
New setup	98.09

Conclusions and Future Work

- At high latitude, the new augmentation ingesting superDARN performs better in estimating ion velocity, than the previous experiment setup from table 2.
- The new augmentation result is influenced by the data ingestion locations by comparing table 1 and table2.
- Adjust the model and measurement error covariance to improve performance.

Reference

[1] Datta-Barua, S., A. J. Mannucci, T. Walter, and P. Enge (2008), Altitudinal variation of midlatitude localized TEC enhancement from ground- and space-based measurements, Space Weather, 6, S10D06, doi:10.1029/2008SW000396.

[2] S. Datta-Barua, G. Bust, G. Crowley, N. Curtis, and A. Reynolds, "Estimating model parameters from ionospheric reverse engineering (empire) of the November 2004 geomagnetic storm," in AGU Fall Meeting Abstracts, vol. 2008, 2008, pp. SA11A–1493.

[3] D. S. Miladinovich, S. Datta-Barua, A. L. Rubio, S. Zhang, and G. S. Bust, Assimilation of gnss measurements for estimation of high-latitude convection processes, Space Weather, 18(2020).

[4] Chartier, Alex T., & Wiker, Jordan R. (2022). SuperDARN data in netCDF format (2011-Mar) (1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.6534253