Open Call for Ideas for

New data products, tools and services for Swarm

Template

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Product/Tool/Service Idea

Swarm-based models of high-latitude electrodynamics during substorms

Product/Tool/Service Description (2 pages maximum)

We suggest that a call be made for using Swarm magnetometer and cross-track ion drift measurements to produce models of high-latitude electrodynamics during magnetospheric substorms.

These models would intentionally use the same basic design as the Swarm-based Average Magnetic Field and Polar Current System (AMPS) model (Laundal et al, 2018) and the Swarm Ionospheric Polar Electrodynamics model (Hatch et al, 2024). The latter of the two, the Swipe model, is built upon both the AMPS model and the Swarm High-latitude Convection (Swarm Hi-C) model. Because of the linearity of the spherical harmonics-based potentials that are the foundation of these models, they may be extended to include the effects of the explosive outbursts associated with reconnection in the Earth's magnetotail, otherwise known as substorms. For example, at any given time the ionospheric potential can be modeled as consisting of separate and independent contributions from convection influenced by e.g. the interplanetary magnetic field (IMF) and Earth's dipole tilt, and more dynamic substorm-related convection:

$$\Phi = \Phi_{IMF} + \Phi_{substorm}. \quad (1)$$

At present, the first term (which depends on IMF, dipole tilt, etc.) is modeled by the Swarm Hi-C model, while the second "substorm" term depends on the configuration of the Earth's magnetotail. The magnetotail configuration can be parameterized by substorm epoch time and substorm onset magnetic local time (MLT). Magnetic field perturbations and current systems in the ionosphere can be decomposed in a similar fashion, as illustrated for example by Equation 1 and Appendices A and B in Laundal et al (2018).

A substorm-based model of the ionospheric potential has already been partially explored (Figure 1) and clearly indicates that substorm-related effects on the nightside are superimposed on the "background" potential pattern determined by the IMF orientation and dipole tilt, as indicated by Equation 1. At the same time, there are no existing empirical models of ionospheric currents, magnetic field perturbations, electric potentials, and related quantities (e.g., electromagnetic work/Joule heating, Poynting flux, and ionospheric conductance) as a function of substorm onset epoch time and substorm onset MLT.

A Swarm-based empirical model of high-latitude ionospheric electrodynamics during substorms would provide extremely valuable insight into substorm processes on the nightside, and fill a gap: In contrast to empirical models of ionospheric convection and/or ionospheric currents parameterized by the

interplanetary magnetic field (of which there are many; see references in Lomidze et al, 2019, and Edwards et al, 2020), there are, to our knowledge, *no empirical models of these quantities that are parameterized based on substorms*. The closest one comes in the literature are the studies of Grocott et al (2010, 2017), who used SuperDARN measurements binned by substorm epoch to investigate ionospheric convection during substorms, but did not produce or release empirical models.

Given studies such as those of Walker et al (2024) and Elhawary et al (2024) — who show that the same ground magnetic field signature can correspond to vastly different ionospheric electrodynamics during substorms, and that the substorm equivalent current system is mostly independent of dipole tilt angle and IMF B_y — the models we suggest would therefore be a natural point of reference for substorm-based studies, including studies based on NASA's upcoming Electrojet Zeeman Imaging Explorer (EZIE) mission that is focused on ionospheric field perturbations and current systems during magnetospheric substorms.

As with the AMPS and Swipe models, we suggest that the code for producing these substorm-based models—the inversion code and the model forward code/visualization tools—be open source and publicly available, with the three models (substorm-based versions of AMPS and Swipe) and visualization tools publicly released as a Python interface similar to pyAMPS (https://github.com/klaundal/pyAMPS/) and pySwipe (https://github.com/Dartspacephysiker/pyswipe). The two benefits of releasing the inversion code in addition to the visualization tools are that the inversion code can be used to upgrade these models as new Swarm data become available, and that the inversion code can be relatively easily used and adapted by anybody for use with other data sets.

In summary the expected primary outcomes are (i) tools for model inversion and visualization, including a Python interface; (ii) a peer-reviewed article describing high-latitude ionospheric electrodynamics during substorms using substorm-parameterized versions of the AMPS and Swipe models.

The expected user base for the models we suggest is the thermosphere-ionosphere research community. Many from this community have recently and clearly expressed a need for improved, observation-based estimates of the key ionosphere-thermosphere parameters that these substorm-parameterized models would provide—Joule dissipation, Poynting flux, and ionospheric conductances (Heelis and Maute, 2020; Öztürk, Garcia-Sage and Connor, 2020; Palmroth *et al.*, 2020; Richmond, 2021; Weimer and Edwards, 2021).

We estimate that a substorm-based version of AMPS+Swipe could be developed as part of a one-year project. With additional time it could be possible to include dynamic effects related to Faraday's law using, e.g., the methodology outlined by one of our postdoctoral researchers (Madelaire et al, 2024).

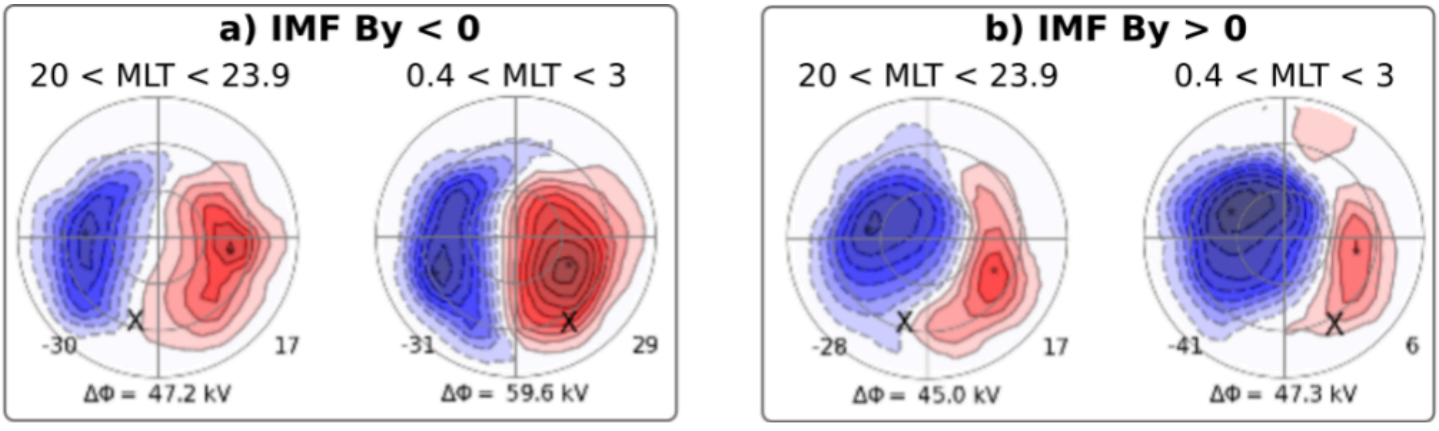


Figure 1. High-latitude ionospheric potentials during the first ten minutes after substorm onset. Potential patterns are shown for negative IMF By (panel a) and positive IMF By (panel b) configurations for early-MLT substorm onsets (20 < MLT < 23.9, left in each panel) and late-MLT substorm onsets (0.4 < MLT < 3, right in each panel), derived by Anna Kvamsdal in 2021 using curl-free Spherical Elementary Current System basis functions, a preliminary subset of Swarm Thermal Ion Imager measurements, and a substorm list based on SuperMAG measurements.

References

Edwards, T. R., Weimer, D. R., Olsen, N., Lühr, H., Tobiska, W. K., & Anderson, B. J. (2020). A Third Generation Field-Aligned Current Model. *Journal of Geophysical Research: Space Physics*, *125*(1). https://doi.org/10.1029/2019JA027249

Elhawary, R., Laundal, K. M., Reistad, J. P., & Madelaire, M. (2024). How Do Substorms Influence Hemispheric Asymmetries in Equivalent Currents? *Journal of Geophysical Research: Space Physics*, *129*(8). https://doi.org/10.1029/2024JA032507

Grocott, A., Milan, S. E., Yeoman, T. K., Sato, N., Yukimatu, A. S., & Wild, J. A. (2010). Superposed epoch analysis of the ionospheric convection evolution during substorms: IMF B_Y dependence. *Journal of Geophysical Research: Space Physics*, *115*(A5). https://doi.org/10.1029/2010JA015728

Grocott, A., Laurens, H. J., & Wild, J. A. (2017). Nightside Ionospheric Convection Asymmetries During the Early Substorm Expansion Phase: Relationship to Onset Local Time. *Geophysical Research Letters*, *44*(23), 11,696-11,705. https://doi.org/10.1002/2017GL075763

Hatch, S. M., Vanhamäki, H., Laundal, K. M., Reistad, J. P., Burchill, J. K., Lomidze, L., Knudsen, D. J., Madelaire, M., & Tesfaw, H. (2024). Does high-latitude ionospheric electrodynamics exhibit hemispheric mirror symmetry? *Annales Geophysicae*, *42*(1), 229–253. https://doi.org/10.5194/angeo-42-229-2024

Heelis, R. A. and Maute, A. (2020) 'Challenges to Understanding the Earth's Ionosphere and Thermosphere', *Journal of Geophysical Research: Space Physics*. doi: 10.1029/2019JA027497.

Laundal, K. M. *et al.* (2018) 'Solar Wind and Seasonal Influence on Ionospheric Currents From Swarm and CHAMP Measurements', *Journal of Geophysical Research: Space Physics*. John Wiley & Sons, Ltd, 123(5), pp. 4402–4429. doi: 10.1029/2018JA025387.

Lomidze, L., Burchill, J. K., Knudsen, D. J., Kouznetsov, A., & Weimer, D. R. (2019). Validity Study of the Swarm Horizontal Cross-Track Ion Drift Velocities in the High-Latitude Ionosphere. *Earth and Space Science*, *6*(3), 411–432. https://doi.org/10.1029/2018EA000546

Madelaire, M., Laundal, K., Hatch, S., Vanhamäki, H., Reistad, J., Ohma, A., Merkin, V., & Lin, D. (2024). Estimating the Ionospheric Induction Electric Field Using Ground Magnetometers. *Geophysical Research Letters*, *51*(8). https://doi.org/10.1029/2023GL105443

Öztürk, D., Garcia-Sage, K. and Connor, H. (2020) 'All Hands on Deck for Ionospheric Modeling', *Eos*, 101. doi: 10.1029/2020EO144365.

Palmroth, M. *et al.* (2020) 'Lower thermosphere - ionosphere (LTI) quantities: Current status of measuring techniques and models', *Ann. Geophys. Discuss.* Copernicus Publications, 2020, pp. 1–73. doi: 10.5194/angeo-2020-42.

Richmond, A. D. (2021) 'Joule Heating in the Thermosphere', in Wang, W., Zhang, Y.-L., and Paxton, L. J. (eds) *Space Physics and Aeronomy Vol. 4: Upper Atmosphere Dynamics and Energetics*. Washington, D.C.: American Geophysical Union. Available at: https://www.wiley.com/en-ca/Space+Physics+and+Aeronomy%2C+Volume+4%2C+Upper+Atmosphere+Dynamics+and+Energetics-p-9781119507567.

Walker, S. J., Laundal, K. M., Reistad, J. P., Hatch, S. M., Ohma, A., & Gjerloev, J. (2024). The Ionospheric Leg of the Substorm Current Wedge: Combining Iridium and Ground Magnetometers. *Journal of Geophysical Research: Space Physics*, *129*(7). https://doi.org/10.1029/2024JA032414

Weimer, D. and Edwards, T. (2021) 'Testing the electrodynamic method to derive height-integrated ionospheric conductances', *Annales Geophysicae*, 39(1), pp. 31–51. doi: 10.5194/angeo-39-31-2021