Beyond AMPERE-NEXT: Envisioning the Next System of Global High-Latitude Electrodynamics

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Authors: Sarah Vines[1*], Brian Anderson[1], Colin L. Waters[2], Robert C. Allen[1], Astrid Maute[3], Bharat Kunduri[4], Larry Paxton[1], Robert J. Strangeway[5], Dong Lin[3], Shin Ohtani[1], Robert Robinson[6,7], Guan Le[7], Qingyu Zhu[3], Steve Milan8[,9], Doğacan Ozturk[10], Haje Korth[1], Karl Laundal[11], Alex Chartier[1], Kyle Murphy[12], Tomoko Matsuo[13], Thomas Sotirelis[1], Delores Knipp[13], Sam Califf[14,15], Rafael Luiz Araujo de Mesquita[1], Hyunju Connor[7], James Clemmons[16], Gang Lu[3]

Affiliations: [1]Johns Hopkins University Applied Physics Laboratory; [2]University of Newcastle; [3]High Altitude Observatory/National Center for Atmospheric Research; [4]Virginia Tech; [5]University of California - Los Angeles; [6]The Catholic University of America; [7]NASA Goddard Space Flight Center; [8]University of Leicester; [9]Birkeland Centre for Space Science, University of Bergen; [10]University of Alaska - Fairbanks; [11]University of Bergen; [12]Independent Contractor; [13]University of Colorado - Boulder; [14]Cooperative Institute for Research in Environmental Sciences; [15]National Centers for Environmental Information; [16]University of New Hampshire

Synopsis:

The Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) is a unique program that has been providing important observations of the high-latitude magnetosphere-ionosphere-thermosphere-mesosphere (M-ITM) coupling region since 2010. There is no equivalent prior, currently in operation, or planned heliophysics mission, and AMPERE has been incredibly valuable for fundamental M-ITM coupling science through direct, continuous observations of global field-aligned current systems, coordination with other spacecraft and ground-based assets, and with ingestion into and comparison with empirical models and physics-based simulations of the polar cap and ionosphere at lower altitudes. The scope of the AMPERE dataset is also cross-cutting, with potential critical contributions to Earth system science and applications in space weather operations and space domain awareness. Enabling uninterrupted continuation and delivery of AMPERE data throughout the next decade is vital for further advancement in our understanding the complex dynamics and interplay between the magnetosphere and ionosphere. The next several years are a critical time to ensure the continuation of this dataset by building upon our partnership with Iridium Communications LLC, as well as by fostering other industry partnerships to include additional magnetometers capable of producing AMPERE measurements from new and future constellations to produce multi-scale observations. This coming decade also presents an exciting opportunity to expand upon the demonstrated infrastructure of AMPERE through adding key measurements that provide more complete specification of M-ITM electrodynamics in a global configuration necessary for full-system understanding.

Insights into High-Latitude Electrodynamics with AMPERE Field-Aligned Currents

Low-Earth orbiting (LEO) satellites with high inclinations pass through the Birkeland currents, the global field-aligned current (FAC) system at high latitudes connecting magnetospheric current systems to the ionosphere [*1, 2, 3*]. Magnetic perturbations from these FACs are present primarily between sheets of current. Above the ionosphere, the high-latitude currents are radial, and can be described by horizontal perturbations [e.g., *4, 5*], but these currents generate small signals, only 0.1 to 1% of Earth's magnetic field, even during active geomagnetic conditions.

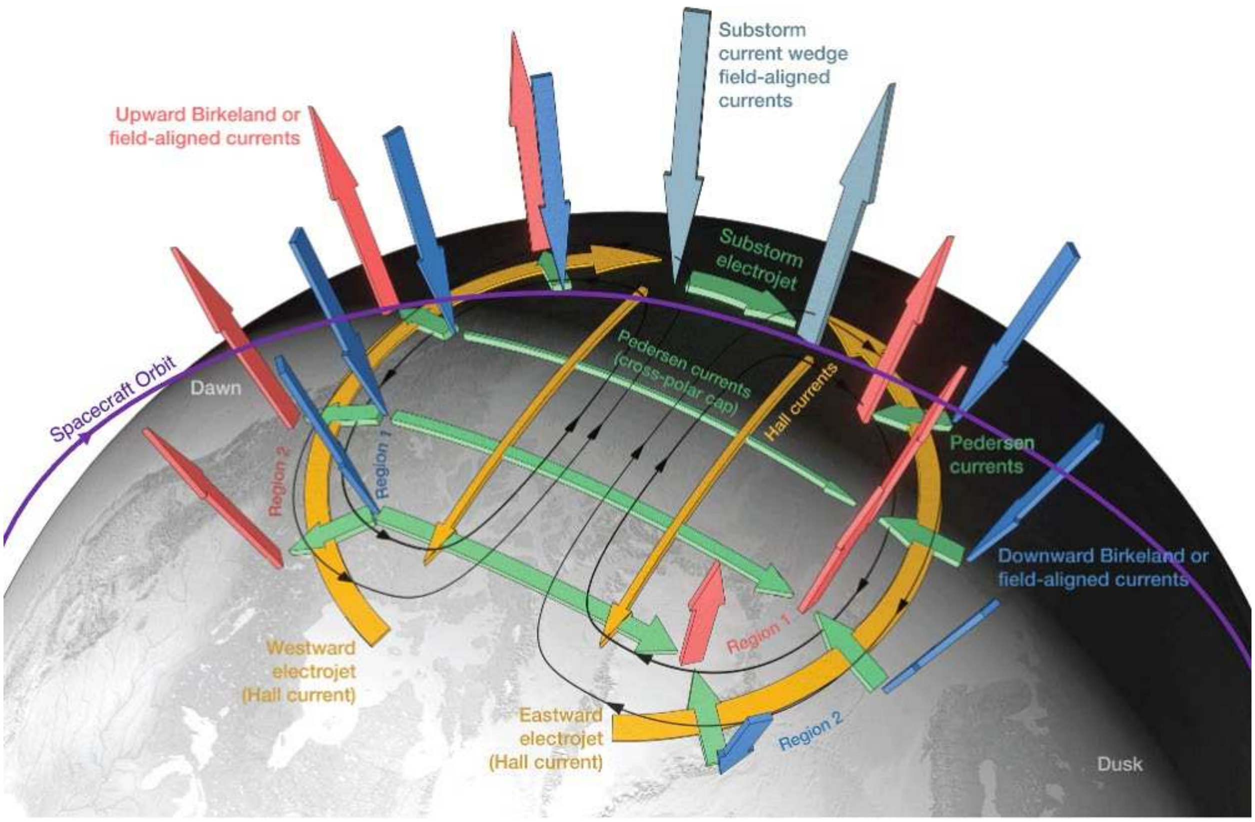

Figure 1. Overview of current systems in the high-latitude ionosphere, depicting the closure of Birkeland currents. High-inclination spacecraft in LEO directly sample the magnetic perturbations due to these current systems (from [6]). Crucial to understanding M-ITM coupling, AMPERE uses Iridium spacecraft to sample horizontal perturbations due to field-aligned currents at high-latitudes.

The Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) program has been employing the ~70 LEO satellites of the Iridium Communications Network to provide the heliophysics community nearly continuous, global observations of a critical parameter of M-I coupling – FACs in the polar cap region – for over a decade (see, e.g., [*7*] for highlights of this research). AMPERE data is comprised of global magnetic field (**B**) measurements from the Iridium Communications Network satellite constellation via the telemetry stream from the body-mounted avionics magnetometers [*8, 9, 10*]. These 66 satellites are polar orbiting at 780 km, spread approximately evenly in 6 local time planes with a resample cadence of ~9 minutes. Importantly, because continuous global coverage is a key driving requirement for the Iridium constellation, AMPERE data provides instantaneous observations of both hemispheres spanning all levels of geomagnetic activity, rather than requiring statistical analysis for local time coverage or multiple passes at different times that may not capture all of the temporal variation of FAC development.

From each Iridium spacecraft, magnetic field data are gathered and processed to produce horizontal magnetic field perturbations, $\delta\mathbf{B}$. These are fitted to a regular grid through spherical cap harmonic analysis (SCHA), where linear interpolation is used to estimate the $\delta\mathbf{B}$ values between tracks. With Ampere's Law, the system of SCHA basis functions is used to obtain radial FACs, J_r [*4, 11*]. These data products are further distilled to integrated total currents in both the northern and southern hemispheres, and used in conjunction with assumptions and/or models of the underlying ionospheric conductivities to produce polar cap potential patterns. Evolution of the magnetic field perturbations, FAC distributions, and potential hemispheric differences in current development can be tracked over the course of a geomagnetic storm, as well as indicate the onset of substorms.

Along with revealing details of magnetospheric dynamics and solar wind-magnetosphere interactions through current closure in the polar cap region [e.g., *12, 13, 14, 15*] and impacts of high-latitude driving on the ionosphere-thermosphere-mesosphere (ITM) system [e.g., *16*], AMPERE has demonstrated utility for machine learning algorithms [*17*] and data assimilation [e.g., *18, 19, 20*], and shown promise for Earth main field studies and models [e.g., *10, 21*]. AMPERE will also provide key contextual observations of the large-scale FAC development and response at high-latitudes for the upcoming EZIE and GDC missions. The coordination of these missions with AMPERE provides opportunities for enhanced science return of all three assets, enabling detailed analysis of multi-scale current systems and an understanding of the energy input via FACs and an insight into associated particle precipitation and Poynting flux into the ITM system.

Through its critical contributions for M-ITM coupling, along with science-enabling capabilities for other missions and datasets, AMPERE has established itself as a vital dataset that should be continued throughout the next decade to at minimum the guaranteed lifetime of Iridium NEXT, at least through 2030. Plans for the follow-on to Iridium NEXT are beginning, and so the next few years of this Decadal timespan are critical for ensuring its continuation and expansion for the benefit of the science community.

The Evolution of AMPERE

The genesis of AMPERE remains a useful template for future commercial-agency partnerships. AMPERE first started with a feasibility study in the 1990's, upon recognition that every Iridium Communications Network satellite carried a magnetometer. Early studies using Iridium magnetometers required very large current signatures and several hour windows for data collection [*22*], but demonstrated the utility of this new constellation for research of M-I coupling. Further development enabled Iridium to return data streams at 10 – 100x the original rate, becoming the

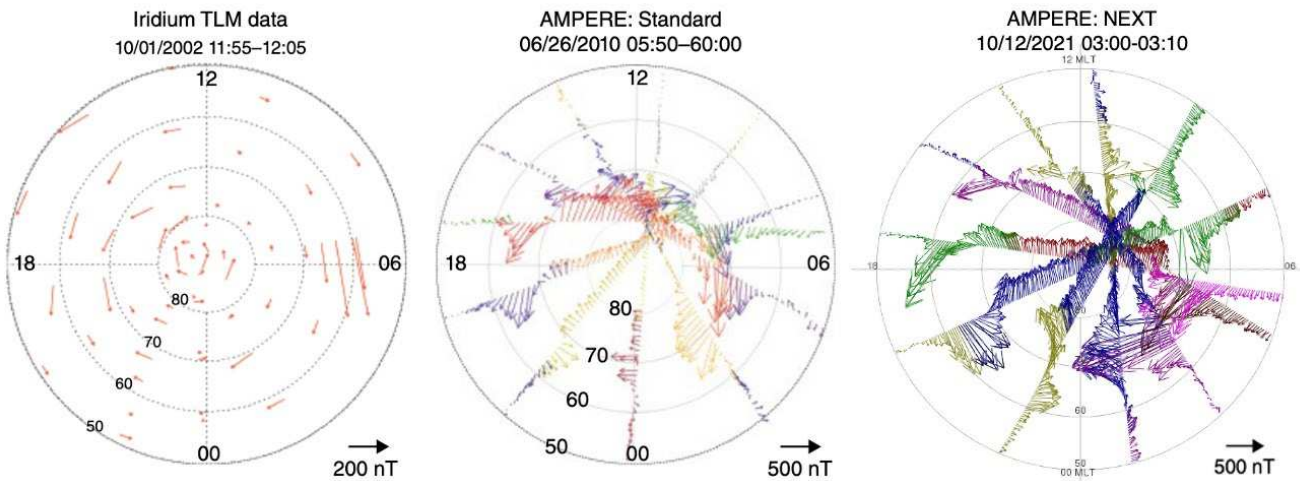

Figure 2. From the initial demonstration of the Iridium engineering "TLM" data, to AMPERE Block-1 data, to the current AMPERE-NEXT data, the AMPERE program has been evolving with the community and requires continued agency investment for future M-ITM science investigations and potential applications in space weather and Earth science (from [7] and https://ampere.jhuapl.edu).

first AMPERE dataset released to the community in 2012 under the NSF AMPERE-1 and AMPERE-2 programs (2008-2020).

Along with statistical determination of characteristics and development of FACs, AMPERE Block-1 data allowed for global observations of the Birkeland currents during geomagnetic storms and substorms on timescales down to 10's of minutes for the first time [*7*], has been vital for quantifying electrodynamic parameters in conjunction with other satellite and ground-based measurements [e.g., *23, 24, 25, 26*], and has been used for model inputs and validation [e.g.*, 27, 28, 28*]. Importantly, this era of AMPERE data has provided uninterrupted global coverage of the high-latitude FACs over the span of a solar cycle, now enabling large-scale statistical analysis and climatological studies, and machine learning and assimilative studies requiring large, curated datasets.

Iridium began launching its NEXT satellites to replace the Block-1 constellation in 2017. All 8 launches and deployments were successful, with 75 satellites successfully commissioned and in place in early 2019. AMPERE has continued with the launch and operation of the Iridium NEXT satellites under the NSF AMPERE-3 program (2020-2025). With improvements in the NEXT satellite avionics systems, AMPERE data now has up to 10x higher attitude accuracy, ~2 times lower error in $\delta\mathbf{B}$, and over twice the sampling cadence per spacecraft than data from the Block-1 constellation. The time period of transition from Block-1 to NEXT satellites (Sept 2017 – Feb 2019) also allows for additional scale sizes to be investigated using multiple satellites in close conjunctions during the constellation formation and decommission, which provides additional insight into mesoscale structuring and sub-structuring of the large-scale Birkeland current and related lower-latitude systems.

Key to the progression of AMPERE from the Iridium Block-1 to NEXT satellites was the planned inclusion of the AMPERE data stream for Iridium NEXT, which was enabled by on-going support from NSF during the AMPERE-2 program. Through the combination of established relationships giving rise to early planning and the prospect of continued agency support was the AMPERE-NEXT program able to be realized as a feature of the Iridium NEXT constellation. ***As was learned during the envisioning of AMPERE-NEXT, planning for what the future of AMPERE will hold must start now, and we must be striving to continue and expand upon AMPERE purposefully. This begins with a commitment to continue the AMPERE program through the end of the Iridium NEXT constellation and with support for beginning the processes of defining what will come after AMPERE-NEXT.***

Towards Future AMPERE Measurements

Expansion into Space Weather Applications:

With global and continuous coverage of the magnetospheric coupling in the polar cap region via FACs, AMPERE data and its derived products are ripe for use in space weather applications. More exploration is needed for production of appropriate end-user products, and efforts are beginning to be formulated to establish feasibility for more real-time products and indices, including ingestion of AMPERE data into models useful for space weather applications [e.g., *30*]. ***Robust investment in ground-processing infrastructure and operations support is required to enable AMPERE to become a valued resource for now-casting and system-state determination.*** The addition of AMPERE to space weather applications would dramatically improve the resources given to space weather operators and forecasters by proving a near-real time view of the global FAC system.

Mesoscale Global Coverage:

A critical advantage of the AMPERE and AMPERE-NEXT datasets is the simultaneous, interhemispheric coverage of the polar cap regions. To further understand the complexities of FACs at these latitudes, we a need to be able to spatially resolve current structures down to mesoscales [e.g., *31, 32, 33*] with these global measurements. Along with the continuation of global FAC observations currently provided by AMPERE-NEXT, more satellites at similar altitudes resulting in longitudinal resolutions of <1-hour local time, likely requiring additional high inclination constellations, would allow for discernment of mesoscale current structures. ***This requires expanding the AMPERE program to incorporate additional constellation data streams with data from Iridium NEXT and future Iridium satellites.***

Complete Measurements for M-I Electrodynamics:

Another key target is global specification of a more complete parameter set describing high-latitude electrodynamics. Specifically, simultaneous global measurements that provide ion flows, electric fields, Poynting flux, and properties of precipitating ions and electrons are needed in concert with the $\delta\mathbf{B}$ measurements obtained currently by AMPERE-NEXT. ***A post-AMPERE-NEXT should include opportunities on the satellites generating the AMPERE data stream for hosted payloads consisting of smaller, low-cost sensors that provide a more complete picture of the electrodynamics.***

In particular, targeted sensors on an expanded AMPERE platform include:

- Drift meter, electrostatic analyzer-based sensor, or related instrument to measure bulk ion velocities
- Low-cost particle detectors to measure ion and electron precipitation (1's – 100 keV)
- Magnetometer sensors with better configurations and/or capabilities for magnetic noise corrections to enable resolution of smaller perturbation signatures
- Electric field probes where feasible

These observations would allow for continuous specification of electric currents, plasma flows, energy flux, and precipitating particle fluxes and energies to resolve the system electrodynamics across global to mesoscales. The inclusion of ion velocity and particle precipitation observations with the AMPERE data stream on a platform like the Iridium constellation, in particular, would provide a major advance in our current observational capabilities. Additionally, concentration of even more tightly spaced observations would relate electrodynamics from small to global scales.

Supporting Needs for the Next Generation of AMPERE

Such increases in data quality, quantity, and type requires continued innovation in models, tools, and techniques for data ingestion, assimilation, analysis, and visualization. Techniques for regional/mesoscale to small-scale inversions, ingestion of multiple mission data, and incorporation of AMPERE data for driving empirical and physics-based models are underway [e.g., *4, 16, 18, 20, 29, 34*], but need continued development and expansion for different applications in the realms of M-ITM coupling, ITM physics, space weather, and Earth science.

The next generation of AMPERE, and generally any platform of globally distributed measurements of FACs and related electrodynamics observables, also requires continued engagement and innovation in our partnerships with the commercial sector to provide viable opportunities for constellation observations of scientific quality. The funding mechanisms for such a partnership, or variations on these kinds of partnerships, need to be expanded to allow for options of data stream purchases and fees, and generally a more long-term sustenance of such a data stream. Long-term funding enables these types of collaborations with industry to be fruitful, similar to how the existing relationship and funding through AMPERE-2 allowed for the discussions to ensure the Iridium NEXT spacecraft would be able to continue and improve upon previous AMPERE data streams.

Expanding on these capabilities will enable a more fundamental understanding of the dynamic and highly coupled processes of the high-latitude M-ITM system. Planning for such an expansion must happen early within this Decadal time frame, prior to key decision points for our community and our industrial partners. ***This will require an asserted effort by agencies to not only guarantee the continuity of the AMPERE program, but also to provide resources and expanded opportunities and mechanisms for data buys, potential rideshare contributions, and/or constellation-based observing platforms to advance M-ITM science and applications.***

References

1. Iijima, T., and T. A. Potemra (1976), The amplitude distribution of field-aligned currents at northern high latitudes observed by Triad, *J. Geophys. Res.*, *81*(13), 2165–2174, doi: 10.1029/JA081i013p02165.
2. Iijima, T., and T. A. Potemra (1976), Field-aligned currents in the dayside cusp observed by Triad, *J. Geophys. Res.*, *81*(34), 5971-5979, doi:10.1029/JA081i034p05971.
3. Le, G., J. A. Slavin, and R. J. Strangeway (2010), Space Technology 5 observations of the imbalance of regions 1 and 2 field-aligned currents and its implication to the cross-polar cap Pedersen currents, *J. Geophys. Res., 115,* A07202, doi:10.1029/2009JA014979.
4. Waters, C.L., B. J. Anderson, D. L. Green, H. Korth, R. J. Barnes, H. Vanhamäki (2020), Science Data Products for AMPERE, *in Ionospheric Multi-Spacecraft Analysis Tools*, *ISSI Scientific Report Series*, **17**, edited by M. Dunlop and H. Lühr, Springer, pp. 141 – 165, Cham, Switzerland, doi:10.1007/978-3-030-26732-2_7.
5. Green, D. L., C. L. Waters, B. J. Anderson, H. Korth, and R. J. Barnes (2006), Comparison of large-scale Birkeland currents determined from Iridium and SuperDARN data, *Ann. Geophys., 24*(3), 941–959, doi:10.5194/angeo-24-941-2006.
6. Palmroth, M., et al. (2021), Lower-thermosphere–ionosphere (LTI) quantities: current status of measuring techniques and models. *Ann. Geophys.*, *39,* 189-237, doi:10.5194/angeo-39-189-2021.
7. Coxon, J. C., S. E. Milan, and B. J. Anderson (2018), A Review of Birkeland Current Research using AMPERE, in *Electric Currents in Geospace and Beyond*, *Geophysical Monograph 235*, eds. A. Keiling, O. Marghitu, and M. Wheatland, American Geophysical Union, John Wiley & Sons, Inc., ISBN: 978-1-119-32449-2, doi:10.1002/9781119324522.ch16.
8. Anderson, B. J., K. Takahashi, T. Kamei, C. L. Waters, and B. A. Toth (2002), Birkeland current system key parameters derived from Iridium observations: Method and initial validation results, *J. Geophys. Res. Space Phys.*, *107*(A6), doi:10.1029/2001JA000080.
9. Anderson, B. J., H. Korth, C. L. Waters, D. L. Green, and P. Stauning (2008), Statistical Birkeland current distributions from magnetic field observations by the Iridium constellation, *Ann. Geophys.*, *26*, 671–687, doi:10.5194/angeo-26-671-2008.
10. Anderson, B. J., R. Angappan, A. Barik, S. K. Vines, S. Stanley, P. N. Bernasconi, H. Korth, and R. J. Barnes (2021), Iridium Communications Satellite Constellation Data for Study of Earth's Magnetic Field, *Geochem. Geophys. Geosyst., 22,* e2020GC009515, doi:10.1029/2020GC009515.
11. Waters, C. L., B. J. Anderson, and K. Liou (2001), Estimation of global field aligned currents using the Iridium® system magnetometer data, *Geophys. Res. Lett.*, *28*, 2165–2168, doi:10.1029/2000GL012725.
12. Imajo, S., M. Nosé, A. Matsuoka, S. Kasahara, S. Yokota, M. Teramoto, K. Keika, T. Motoba, B. J. Anderson, R. Nomura, A. Fujimoto, I. Shinohara, and Y. Miyoshi (2018), Magnetosphere-ionosphere connection of storm-time region-2 field-aligned current and ring current: Arase and AMPERE observations, *J. Geophys. Res.: Space Phys.*, *123*(4), 9545–9559, doi:10.1029/2018JA025865.
13. Keesee, A. M., N. Buzulukova, C. Mouikis, and E. E. Scime (2021), Mesoscale structures in Earth's magnetotail observed using energetic neutral atom imaging, *Geophys. Res. Lett.*, *48*(3), doi:10.1029/2020GL091467.
14. Le, G., H. Lühr, B. J. Anderson, R. J. Strangeway, C. T. Russell, H. Singer, J. A. Slavin, Y. Zhang, T. Huang, K. Bromund, P. J. Chi, G. Lu, D. Fischer, E. L. Kepko, H. K. Leinweber,

W. Magnes, R. Nakamura, F. Plaschke, J. Park, J. Rauberg, C. Stolle, and R. B. Torbert (2016), Magnetopause erosion during the 17 March 2015 magnetic storm: Combined field-aligned currents, auroral oval, and magnetopause observations, *Geophys. Res. Lett.*, *43*, 2396–2404, doi:10.1002/2016GL068257.
15. Shi, Y., D. Oliveira, D. J. Knipp, E. Zesta, T. Matsuo, and B. J. Anderson (2019), Effects of nearly frontal and highly inclined interplanetary shocks on high-latitude field-aligned currents (FACs), *Space Weather*, *17*, 1659 – 1673, doi:10.1029/2019SW002367.
16. Maute, A., A. D. Richmond, G. Lu, D. Knipp, Y. Shi, and B. J. Anderson (2021), Magnetosphere-ionosphere coupling via prescribed field-aligned current simulated by the TIEGCM, *J. Geophys. Res. Space Phys.*, *126*(1), doi:10.1029/2020JA028665.
17. Kunduri, B. S. R., M. Maimaiti, J. B. H. Baker, J. M. Ruohoniemi, B. J. Anderson, and S. K. Vines (2020), A deep learning based approach for modeling the dynamics of AMPERE Birkeland currents, *J. Geophys. Res. Space Phys., 125*(8), doi:10.1029/2020JA027908.
18. Merkin, V. G., Kondrashov, D., Ghil, M., and Anderson, B. J. (2016), Data assimilation of low-altitude magnetic perturbations into a global magnetosphere model, *Space Weather*, *14*, 165– 184, doi:10.1002/2015SW001330.
19. Wilder, F. D., G. Crowley, B. J. Anderson, and A. D. Richmond (2012), Intense dayside Joule heating during the 5 April 2010 geomagnetic storm recovery phase observed by AMIE and AMPERE, *J. Geophys. Res. Space Phys.*, *117*, doi:10.1029/2011JA017262.
20. Matsuo, T., (2020), Recent Progress on Inverse and Data Assimilation Procedure for High-Latitude Ionospheric Electrodynamics, *in Ionospheric Multi-Spacecraft Analysis Tools*, *ISSI Scientific Report Series*, **17**, edited by M. Dunlop and H. Lühr, Springer, pp. 219 – 232, Cham, Switzerland, doi:10.1007/978-3-030-26732-2_10.
21. Califf, S., P. Alken, A. Chulliat, B. Anderson, K. Rock, S. Vines, R. Barnes, and K. Liou (2022), Investigation of geomagnetic reference models based on the Iridium® constellation, *Earth Planets Space*, *74*, doi:10.1186/s40623-022-01574-w.
22. Anderson, B. J., K. Takahashi, and B. A. Toth (2000), Sensing global Birkeland currents with Iridium® engineering magnetometer data, *Geophys. Res. Lett.*, *27*, 4045–4048, doi:10.1029/2000GL000094.
23. Forsyth, C., M. Shortt, J. C. Coxon, I. J. Rae, M. P. Freeman, N. M. E. Kalmoni, C. M. Jackman, B. J. Anderson, S. E. Milan, and A. G. Burrell (2018), Seasonal and temporal variations of field-aligned currents and ground magnetic deflections during substorms, *J. Geophys. Res. Space Phys., 123*, 2696–2713, doi:10.1002/2017JA025136.
24. Cousins, E. D. P., T. Matsuo, A. D. Richmond (2015), Mapping high-latitude ionospheric electrodynamics with SuperDARN and AMPERE, *J. Geophys. Res. Space Phys.*, *120*, 5854–5870, doi:10.1002/2014JA020463.
25. Robinson, R. M., L. Zanetti, B. J. Anderson, S. K. Vines, and J. Gjoerlev (2021), Determination of auroral electrodynamic parameters from AMPERE field-aligned current measurements, *Space Weather*, *19*(4), doi:10.1029/2020SW002677.
26. Knipp, D. J., T. Matsuo, L. Kilcommons, A. Richmond, B. Anderson, H. Korth, R. Redmon, B. Mero, and N. Parrish (2014), Comparison of magnetic perturbation data from LEO satellite constellations: Statistics of DMSP and AMPERE, *Space Weather*, *12*, 2–23, doi:10.1002/2013SW000987.
27. Lu, G., I. Zakharenkova, I. Cherniak, and T. Dang (2020), Large-scale ionospheric disturbances during the 17 March 2015 storm: A model-data comparative study, *J. Geophys. Res. Space Phys., 125*(5), doi:10.1029/2019JA027726.

28. Edwards, T. R., D. R. Weimer, N. Olsen, H. Lühr, W. K. Tobiska, and B. J. Anderson (2020), A third generation field-aligned current model, *J. Geophys. Res. Space Phys.*, *125*(1), doi:10.1029/2019JA027249.
29. Wiltberger, M., V. G. Merkin, V., B. Zhang, F. Toffoletto, M. Oppenheim, W. Wang, J. G. Lyon, J. Liu, Y. Dimant, M. I. Sitnov, and G. K. Stephens (2017), Effects of electrojet turbulence on a magnetosphere-ionosphere simulation of a geomagnetic storm, *J. Geophys. Res. Space Phys., 122*, 5008–5027, doi:10.1002/2016JA023700.
30. Chartier, A. T., J. D. Huba, D. P. Sitaram, V. G. Merkin, B. J. Anderson, and S. K. Vines (2022), High-latitude electrodynamics specified in SAMI3 using AMPERE field-aligned currents, *Space Weather*, *20*, e2021SW002890, doi:10.1029/2021SW002890.
31. McGranaghan, R. M., A. J. Mannucci, and C. Forsyth (2017), A comprehensive analysis of multiscale field-aligned currents: Characteristics, controlling parameters, and relationships, *J. Geophys. Res. Space Phys., 122*, 11931–11960, doi:10.1002/2017JA024742.
32. Forsyth, C., V. A. Sergeev, M. G. Henderson, Y. Nishimura, and B. Gallardo-Lacourt (2020), Physical Processes of Meso-Scale, Dynamic Auroral Forms, *Space Sci. Rev.*, *216*, 46, doi:10.1007/s11214-020-00665-y
33. Zou, Y., et al. (2016), Localized field-aligned currents in the polar cap associated with airglow patches, *J. Geophys. Res. Space Physics*, *121*, 10172– 10189, doi:10.1002/2016JA022665.
34. Merkin, V. G., Anderson, B. J., Lyon, J. G., Korth, H., Wiltberger, M., and Motoba, T. (2013), Global evolution of Birkeland currents on 10 min timescales: MHD simulations and observations, *J. Geophys. Res. Space Physics*, *118*, 4977– 4997, doi:10.1002/jgra.50466.