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Next generation magnetic field measurements from low-earth orbit satellites enable enhanced space weather operations

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Large-scale current systems in the ionosphere and the magnetosphere are intimately controlled by the solar wind-magnetosphere interaction and the magnetosphere-ionosphere coupling. During space weather events, these currents reconfigure and intensify significantly in response to enhanced solar wind-magnetosphere interaction, facilitating explosive energy input from the magnetosphere into the ionosphere-thermosphere system and inducing electric current surges in electric power systems on the ground. Therefore, measurements of magnetic manifestations associated with the dynamic changes of the current systems are crucial for specifying the energy input into the ionosphere-thermosphere system, understanding energy dissipation mechanisms, and predicting the severity of their space weather impacts. We investigate the potential uses of high-quality magnetic field data for space weather operations and propose real-time data products from next generation constellation missions that enable improved space weather forecasting and mitigation.

KEYWORDS

magnetic field measurements, ionospheric currents, magnetospheric currents, field-aligned currents, ring current, magnetic storm, space weather operations

1 Introduction

The magnetic field in the ionosphere is dominated by the earth's main magnetic field associated with the internal electric current maintained through the convective geodynamo (Glatzmaiers and Roberts, 1995). External current systems in the ionosphere and the magnetosphere are the main sources of dynamic variations of the magnetic field. Unlike the internal magnetic field that changes very slowly on time scales of years and longer, the external currents are very dynamic, varying on much shorter time scales (from seconds to days) and spatial scales. They are intimately controlled by the solar wind-magnetosphere interaction and the magnetosphere-ionosphere coupling.

In the region up to ~1,000 km from the earth's surface, the external currents that generate the largest magnetic field perturbations include ionospheric currents in the high latitude regions (field-aligned currents and horizontal currents) and major magnetospheric currents (the ring current, the magnetopause current, and the tail current). During space weather events, the current systems reconfigure and intensify significantly in response to increased solar wind-magnetosphere interaction. Enhanced field-aligned currents (FACs) that couple the magnetosphere and the ionosphere facilitate explosive electromagnetic energy input into the ionosphere-thermosphere system. The resulting space weather effects can potentially impact human activities and technology in near-Earth space and on the ground. The magnetic field perturbations associated with the rapid temporal and/or spatial variations of the current systems are also the main cause of geomagnetically induced currents (GICs).

Magnetic field measurements in the ionosphere are crucial to determine the spatial and temporal variations of the external current systems, necessary for specifying the solar wind energy inputs, understanding energy dissipation mechanisms, and predicting the severity of the space weather impacts. However, space weather operational models in use currently could not take advantage of any real-time *in-situ* magnetic field measurements from LEO satellites, mainly because high-quality datasets of magnetic field perturbations are not readily available. Therefore, next generation magnetic field measurements from future missions, such as the planned Geospace Dynamic Constellation (GDC, Jaynes et al., 2019), a strategic mission in NASA's Living with a Star program, can be instrumental in enabling improved real-time space weather specification and forecasting. Herein, we propose potential uses of real-time magnetic field data products for improved space weather operations.

2 Potential uses of real-time magnetic field data from LEO satellites

Space weather operational models in use currently do not ingest and utilize any real-time *in-situ* magnetic field measurements from LEO satellites. However, high-quality measurements of magnetic field perturbations in the ionosphere provide opportunities to enhance and extend space weather models and will enable improved real-time space weather forecasting and response.

2.1 Real-time space weather model validation

NOAA Space Weather Prediction Center (SWPC) is using the Geospace suite from the University of Michigan's Space Weather Modeling Framework (SWMF, Tóth et al., 2005; Gombosi et al., 2021) to track a satellite's orbit (actual or predicted) and calculates the predicted *in situ* parameters, such as plasma density, velocity, electric field, and magnetic field perturbations ($\delta\mathbf{B}$). Currently, SWMF only provides such satellite orbit tracking in the magnetosphere and specifies $\delta\mathbf{B}$ on the ground to predict Geomagnetically Induced Currents (GICs). Calculation of $\delta\mathbf{B}$ along the LEO satellite trajectory has not been implemented between the lower boundary of the ionosphere and 1.5 R_E altitude (2.5 R_E from earth's center, the inner boundary of the magnetosphere magnetohydrodynamic model). Recently, SWPC's Whole-Atmosphere-Model + Ionosphere-Plasmasphere-Electrodynamics (WAM-IPE) model (e.g., Fang et al., 2018) transitioned into operations, providing a 2-day forecast of the ionosphere and thermosphere conditions every 6 h. WAM-IPE does not calculate magnetic perturbations in the ionosphere or on the ground at this point. Both the SWMF and WAM-IPE models are driven by real-time IMF and solar wind data from L1, and do not ingest any real-time *in-situ* magnetic field data from LEO or geosynchronous satellites within their model domains. Predictive capability (up to about 45 min) comes from ballistic propagation time between L1 and earth or the upstream model boundary (32 R_E for SWMF Geospace suite).

Predicted FAC $\delta\mathbf{B}$ along the polar orbiting LEO satellite may be compared to the measurements of magnetic field perturbations for real-time model validation to assess a model's ability to predict FAC position and intensity in real time during space weather events. Specifications of $\delta\mathbf{B}$ at ionospheric altitudes are necessary in any future RT-coupled geospace model because adaptations to the $\delta\mathbf{B}$ calculation in the ionosphere will be needed (e.g., Egbert et al., 2021).

2.2 Real-time specification of ionospheric electrodynamics

Ionospheric models specifying the ambient ionospheric conditions can be used to assess the conditions that favor the occurrence of ionospheric irregularities and scintillations. Certain favorable ambient ionosphere conditions need to occur, together with certain electrodynamic and thermospheric conditions, may drive the formation of ionospheric irregularities. The Department of Defense (DoD) uses the Utah State University Global Assimilation of Ionospheric Measurements (USU-GAIM) model (Schunk et al., 2004) to specify ambient ionosphere conditions, such as three-dimensional (3D) electron density (including peak electron density, NmF2, and peak value altitude, hmF2), ion density, total electron content (TEC), and critical radio frequency. The DoD is also working on the implementation of a Global Assimilation of Ionospheric Measurements Full-Physics (GAIM-FP) model, which uses a more sophisticated Ensemble Kalman filter technique together with a physics-based ionosphere-plasmasphere model including D-region physics (Scherliess et al., 2017). Currently, the GAIM models do not use any real-time *in situ* magnetic field observations; however, the real-time magnetic field data can potentially be incorporated into GAIM-FP to help constrain the high-latitude electromagnetic forcing that is central in assimilating ionospheric plasma density distributions.

Furthermore, future development of operational ionospheric models can incorporate real-time high-latitude electrodynamic patterns to improve the magnetospheric forcing and therefore the ambient ionosphere conditions. The Assimilative Mapping of Ionospheric Electrodynamics (AMIE) can provide this specific high latitude forcing in near-real time using magnetic field measurements from a constellation of polar orbiting LEO satellites, such as GDC, together with other real-time space and ground-based observations when available. AMIE is a widely used data assimilation algorithm specifically designed to obtain snapshots of ionospheric electrodynamic fields by synthesizing simultaneous observations from various ground- and space-based instruments (e.g., ion drift/electric field, magnetic field, particle precipitation) (Richmond and Kamide, 1988; Richmond, 1992). When constrained with adequate data, AMIE provides a more realistic specification of high latitude forcing than those from empirical models. Lu. (2017) extensively discussed the effects of different data inputs on the AMIE outputs and demonstrated that global electric potential and FACs can be contained by the magnetic field measurements from a pair of satellites on different orbital planes, that together cover a broad polar region.

AMIE can assimilate real-time magnetic field data $\delta\mathbf{B}$, or its temporal $[d(\delta\mathbf{B})/dt]$ or along-track spatial $[d(\delta\mathbf{B})/dx]$ modulations over polar cap passes from 2 or more widely spaced satellites to provide real-time specifications of ionospheric electrodynamics. AMIE can update the real-time global electric potential pattern in the southern and northern high latitude regions at least 2 times every satellite orbit (~90 min) with multiple satellites widely spaced in longitude. Since AMIE assimilates magnetic field data for the entire polar cap pass (~15 min) to update each specification, the latency is expected to be ~20 min from data acquisition.

2.3 Real-time satellite-based proxy for the *Dst* index

DoD forecasts neutral density as part of its operation to produce the North American Aerospace Defense (NORAD) satellite catalog in support of the command and control of space forces. The US Space Force 18th Space Defense Squadron (18 SDS) runs the High Accuracy Satellite Drag Model (HASDM) to predict thermospheric density up to the next 72 h (Storz et al., 2005). HASDM incorporates the Jacchia-Bowman 2008 (JB 2008) Empirical Thermospheric Density Model (Bowman et al., 2008) as a background density model. As demonstrated in Bowman et al. (2008), the estimate of storm-time atmospheric drag effects on LEO space objects can be greatly improved using the *Dst* index as a driver for the JB2008 model. JB2008 uses Dst during geomagnetic storms if the minimum Dst < -75 nT. Currently, forecasted Dst is used in JB2008 based on solar wind kinetic energy and location observables (Tobiska et al., 2013). This Dst forecast could be augmented using near-RT space based magnetic observations.

Predicting atmospheric drag for collision avoidance is a serious and ongoing concern for all space-faring nations, which underscores the importance of a real-time proxy for the *Dst* index. Several studies have demonstrated the feasibility of using space-based magnetic field measurements from LEO satellites to extract a RT proxy for the provisional *Dst* index. Le and Russell (1998) showed that δB (the difference between the measured and model field strength) over the magnetic pole is a good proxy for the *Dst* index near the perigee of the Polar spacecraft (~5,000 km altitude). Burke et al. (2011) showed that a provisional *Dst* can be extracted from δB_Z (the perturbation in the magnetic northward component) at the magnetic equator from the DMSP satellite at ~840 km. Le et al. (2011) demonstrated the feasibility of extracting a timely proxy for the provisional *Dst* index using δB_Z from the low-inclination C/NOFS satellite (~400–867 km). Most recently, Papadimitriou et al. (2021) presented three major geomagnetic indices, *Dst*, ap (or Kp) and, AE, based on Swarm data with high degree of accuracy using post-processed science grade magnetic field data. Cianchini et al. (2022) applied deep learning technique to estimate the *Dst* index quickly directly from Swarm magnetic field data.

The earth's internal magnetic field and the magnetic field generated by the ring current are aligned with the earth's magnetic axis at the magnetic equator and magnetic pole, where δB_Z and δB are essentially the same. But using δB for the *Dst* proxy is more advantageous in real time because it is not affected by data-model directional misalignment due to potential errors in real-time attitude data. The error in the attitude data has little effect on the field strength, $B = \sqrt{(B_X^2+B_Y^2+B_Z^2)}$, in contrast to the magnetic field components.

For a polar orbiting LEO satellite, the magnetic field measurements can be used to extract the real-time proxy for *Dst* at least twice per orbit near the magnetic poles (every ~45 min). Due to local time asymmetry of the ring current, especially during storms, δB or δB_Z data at the magnetic equator should be averaged over a wide range of local times from multiple spacecraft to obtain a better proxy for *Dst*. Thus, the real-time proxy for the *Dst* index is available at a ~45 min cadence from the measurements at the magnetic poles from a single polar orbiting satellite, and more frequently from multiple satellites when the measurements at the magnetic equator are added. For an equatorial satellite, magnetic measurements from a single satellite can specify the ring current's temporal evolution, quantify its local time asymmetry and extract a timely proxy for the provisional Dst index at high cadence, as demonstrated in Le et al. (2011) using C/NOFS data.

2.4 Real-time monitoring of equatorward FAC boundaries

Recent work by Lukianova (2020) has demonstrated that the equatorward boundary of large-scale FACs derived from the Swarm satellite constellation may contain "early warning" information about storm time energy deposition. Though energy is entering into the magnetosphere-ionosphere system during the initial phase, *Dst* is often positive or weakly negative due to magnetopause compression and enhancement of magnetopause current. When using *Dst* as a proxy for energy input, this initial energy is often not captured. Lukianova (2020) shows that the FAC equatorward boundary moves to lower latitude in the initial phase, and thus could provide a timely indicator of energy build-up prior to the storm main phase. Along the orbit of a polar orbiting satellite, the time rate of change of the magnetic field perturbation, d(δ**B**)/dt, or the along-track spatial gradient, d(δ**B**)/dx, can be used to identify the instantaneous FAC boundaries, as it would exhibit a sudden change across such boundaries. The d(δ**B**)/dt or d(δ**B**)/dx data can be used in real-time to monitor the FAC boundaries and when the equatorward FAC boundary moves to lower latitude (by comparing with the previous boundary crossing) to provide an early warning of a magnetic storm before it can be detected in the Dst index. A polar orbiting satellite crosses the equatorward boundary of the FAC region every ~20–25 min (4 times per orbit), at a cadence adequate for monitoring storm evolution.

2.5 Real-time spectral powers supporting USGS mapping of geomagnetic disturbances

USGS is responsible for developing capabilities for real-time mapping of geomagnetic-field disturbances and magnetic-storm-induced geoelectric fields, which is of particular importance for evaluating the vulnerability of electric-power-grid systems (Love et al., 2020). Signals of ultra-low-frequency (ULF, $f < 1$ Hz) geomagnetic pulsations are often considered as a source of noise in some geophysical analysis techniques, such as aeromagnetic surveys and transient electromagnetics. USGS is exploring the feasibility of developing near real-time space weather products such as pulsation maps to monitor these geomagnetic pulsations, as a part of the Geomagnetic Hazard Map project at the USGS Geomagnetism Program (Xu et al., 2013). Due to the limitation of the spatial resolution of USGS ground stations, the satellite magnetic field spectral power in ULF frequency bands can be used in real time to aid the interpretation of these maps and flag reliability of geomagnetic measurements during conjunctions between the USGS magnetometers and the satellite.

3 Real-time magnetic field data products

We summarize the real-time magnetic field data products from LEO satellites that support and improve space weather operations based on the discussion in Section 2. The vector magnetic field measurements **B** and the predicted magnetic field $\mathbf{B}_m$ from a model of the earth's internal magnetic field, such as the International Geomagnetic Reference Field (IGRF) and CHAOS—a model of the earth's magnetic field derived from CHAMP, Ørsted, and SAC-C magnetic satellite data (Olsen et al., 2006), will be used to calculate the real-time magnetic field data products. The primary real-time magnetic field data products can be made available for the entire orbit at the same cadence as the original measurements.

- Vector magnetic field perturbations $\delta\mathbf{B} = \mathbf{B}\text{-}\mathbf{B}_m$
- Perturbation in magnetic field strength $\delta B = |\mathbf{B}|\text{-}|\mathbf{B}_m|$

In addition, the following real-time data products can be derived at reduced cadences or in the regions where appropriate.

- Time rate of change d(δ**B**)/dt or along-track spatial gradient d(δ**B**)/dx
- AMIE global patterns of ionospheric electrodynamics constrained by measurements of δ**B**, or d(δ**B**)/dt, or d(δ**B**)/dx, over the polar cap
- Proxy for the *Dst* index derived from δB or δBz near the magnetic pole and the magnetic equator
- Equatorward boundary of FACs derived from d(δ**B**)/dt or d(δ**B**)/dx variations
- Magnetic spectral powers, both transverse and compressional, in ULF frequency bands (from 1 mHz up to 1 Hz)

4 Summary

Separating magnetic field perturbations of the external currents from the total fields measured by LEO satellites has always been very challenging. Therefore, real-time data processing is feasible only if high-quality magnetic field measurements are available so that data calibrations can be minimized and streamlined for timely data reductions. It requires accurate measurements by high-performance magnetometers that are extremely stable and highly linear in a strong background field (up to ~50,000 nT), made from magnetically clean satellites carrying star trackers that deliver accurate attitude knowledge. The planned GDC mission in NASA's Living with a Star program offers the best opportunity to make inroads in using *in situ* magnetic field measurements in real time for enhanced space weather operations.

The external currents driven by the solar wind-magnetosphere-ionosphere interaction are very dynamic and change in various spatiotemporal scales that are much smaller than those of the earth's internal sources. Future constellation mission such as GDC would provide simultaneous magnetic field measurements at different latitudes and local times with a global coverage. These measurements would not only result in a global specification of the external currents under different solar wind forcing, but also present unprecedented opportunities for contributing to improved space weather operations. We have assessed the current state of operational space weather models with respect to the potential use of real-time magnetic field data. We conclude that real-time magnetic field data products from LEO satellites can enhance and extend space weather models and enable improved real-time space weather forecasting and response.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

GL was responsible for the organization of this article and contributed to all sections. All the co-authors contributed to all sections.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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