

A Swarm-only model of the magnetosphere to degree and order 3

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Abstract – In this study, we utilise satellite measurements to investigate variations in the magnetosphere. Using 8- to 12-h time windows, we map the time-varying night-side magnetospheric fields up to degree and order 3, capturing lateral offsets from a simple tilted dipole model. We determine the field over the night-side hemisphere during geomagnetic storms and examine how azimuthal symmetry is disrupted at storm maxima and re-established during the storm recovery phase, as exemplified by the St. Patrick's Day storm in 2015. For this event, we demonstrate substantial variations in magnetospheric field intensity throughout the storm, followed by a gradual recovery to background levels over several days. Analysing over a decade of data, we investigate long-term seasonal and solar cycle-related variations alongside the impact of intense geomagnetic storms. We observe that the alignment of the Earth's dipole with the Sun-Earth line plays a key role in shaping the latitudinal geometry of the magnetospheric field. Furthermore, we find that, during quiet conditions, the night-side magnetosphere is characterised by a dipolar field with $q_1^0 \approx 8$ nT. On average, geomagnetic storms induce a tilt of the inducing dipole towards dawn and an enhancement of the equatorial ring current near dusk.

Keywords: Swarm satellite / Magnetosphere / Degree/order 3 / Ring current / Space weather climate

1 Introduction

The Swarm mission, launched in November 2013, consists of three identical satellites in near-polar orbits, dedicated to measuring the Earth's magnetic field with very high accuracy. Two satellites orbit at a lower altitude in close proximity, while the third orbits at a higher altitude, producing a steady drift both in the local time at the orbits' ascending nodes and in the separation between the orbits' ascending nodes. This unique configuration allows for a wide range of new models to be developed for the various sources of the magnetic field, from the core to the magnetosphere (e.g. Olsen and Stolle, 2017). In this study, we develop an algorithm to construct a Model of the Magnetosphere (MMA) for the night-side, using data from Swarm satellites. On the night side, the ionospheric fields are relatively weak and lack the complex dynamics observed on the day side, allowing empirical models to represent these fields accurately. This, in turn, enables a more reliable representation of the MMA, where the ionospheric influence can be removed effectively. The use of only Swarm satellites allows us to use a complete, high-quality database with a span of more than 10 years. The development and validation of this algorithm will also enable the future integration of additional data sources (such as platform magnetometers), as

well as offer users a degree of customisation in producing night-side magnetospheric models using the VirEs virtual environment (Smith et al., 2022). One of the drawbacks of our Swarm-only model is its limited local time coverage, which greatly restricts the resolution of the model's meridional features. We expect that climatological analysis helps mitigate these issues, by using data from varying orbital configurations throughout the whole mission.

The magnetic field measured at spacecraft altitudes results from a combination of various sources. The strongest component comes from the geodynamo. Earth's outer core consists of metallic liquid that flows slowly, generating a self-sustained magnetic field. In addition, there is a broad array of natural magnetic field sources that influence the geomagnetic field across a wide range of frequencies (Constable and Constable, 2023). When the electrically-charged solar wind reaches Earth, its interaction with the main field creates a shock wave centred at the subsolar point. The majority of the plasma flows around Earth, but the Earth's magnetic field lines undergo deformation, resulting in what is known as the magnetosphere. This has an asymmetric shape due to compression on the sun-facing direction by flow towards Earth and extension on the night side.

Various other current systems exist within Earth's geomagnetic environment, shaped by the interaction between the interplanetary magnetic field and the core field. The magnetosphere is asymmetric with respect

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to the day-night plane, resulting in daily variations (Ganushkina et al., 2018). The geomagnetic field also exhibits seasonal variations due to the inclination of the Earth's rotation axis relative to the ecliptic plane. Additionally, it undergoes decadal variations correlated with the solar cycle; i.e., the Sun's activity follows an approximately 11- and 22-year cycle, and this variation is observed on Earth.

Space weather thus refers to variations in the external field (to Earth's surface) on the scale of days to weeks, driven by solar wind conditions. In contrast, space climate encompasses variations driven by solar wind conditions over longer time scales, such as months to years. These variations are governed by the Earth-Sun system's geometry, which results in an annual periodicity. Additionally, geomagnetic activity is influenced by the solar cycle, as solar maxima increase the likelihood of enhanced geomagnetic activity due to a greater number of coronal mass ejections (CMEs).

Earth's magnetic environment contains a network of interconnected currents, including the ring current (RC), a large-scale toroidal current in the equatorial plane extending from roughly 3 to 8 Earth radii (Chapman and Ferraro, 1941). During geomagnetically quiet times, the ring current is mostly symmetric around Earth, with some day-to-night structure (e.g., Ganushkina et al., 2018). This simplicity allows the RC to be effectively modelled as a dipole magnetic source. However, studies of the ring current have found not only day-night asymmetries within the ring current, but also dusk-dawn asymmetries (e.g., Ohtani, 2021), some of which are prevalent during geomagnetic storms.

During periods of disturbance, plasma is injected and transported from the night-side plasma sheet to the inner magnetosphere. This process creates a highly asymmetric plasma pressure distribution in the inner magnetosphere, which is reflected in the spatial asymmetry of the ring current in the dawn-dusk direction (Ganushkina et al., 2018).

A complex system of currents links the polar regions to the equatorially distributed plasma and forms part of the partial westward ring current. Shore et al. (2017) identify the main modes governing the behaviour observed during geomagnetically active periods. Their analysis revealed that the DP1 and DP2 current systems (the substorm and eastward auroral electrojets) account for a significant portion of the variations detected on the ground. The latter contributes to the development of the storm-time ring current in the inner magnetosphere, indicating that the high-latitude ionosphere interacts with the ring current region through magnetic field lines.

During geomagnetic storms, particles are transported from the magnetotail through the inner magnetosphere to the day-side magnetopause. This process leads to a surge in the partial ring current, which intensifies predominantly on the night-side and develops additional non-dipolar structures (e.g., Ohtani, 2021; Ganushkina et al., 2018; Moore, 2007; Lockwood et al., 2020). In extreme cases, natural variations in the external magnetic field at

Earth's surface may reach up to 10% of the internal field strength and can induce large ground-level electric fields, which may affect human technology and infrastructure (Pulkkinen et al., 2005; Svalgaard and Hansen, 2013).

One commonly used measure of geomagnetic disturbance is known as the Dst index (e.g. Nose et al., 2015), which is computed using the horizontal component of the magnetic field measured at four mid-latitude ground observatories. After removing secular, seasonal, and daily variations, a latitude-weighted average across all local times is computed, yielding a measure of variations in the strength of the horizontal magnetic field at the equator. Negative values of this index correlate with a stronger ring current in the magnetosphere, making it a reliable indicator of geomagnetic storm intensity. Measurements equivalent to the Dst index but with minute-resolution data are also available, such as SYM-H.

The SYM-H index is used to describe axisymmetric geomagnetic disturbances at mid-latitudes in the horizontal component (H) (e.g. Imajo et al., 2022; Bower et al., 2025). The Dst index uses ground observatory data, recorded with high precision and available in real time. However, definitive values differ from preliminary as jumps in measurement baselines can affect the calculated indices, sometimes rendering them unreliable for characterising the geomagnetic field.

In recent decades, improved coverage has been achieved by spacecraft measurements (e.g., Reigber et al., 2002; Olsen et al., 2003; Friis-Christensen et al., 2008). Unlike observatory-based measurements, polar-orbiting satellite observations offer almost complete geographic coverage. Due to their position, particularly their altitude, magnetic measurements taken in space exhibit different sensitivities to various sources of magnetic fields compared to ground-based observatories. For instance, satellites in low Earth orbit are closer to magnetospheric currents, but they are also positioned above ionospheric current systems. Therefore, it is necessary to develop algorithms that can separate these sources to effectively combine satellite and observatory data during joint analysis.

Efforts to investigate the magnetospheric field using satellite data have been undertaken in previous studies. For instance, Maus and Lühr (2005) and Lühr and Maus (2010) utilised data from Ørsted and CHAMP to construct a model of the quiet-time magnetosphere. Their findings indicate that variations in the magnetospheric field are primarily governed by two contributions: (1) a set of coefficients in Solar Magnetic (SM) coordinates, parameterised by the E_{st} and I_{st} indices; and (2) a set of coefficients in Geocentric Solar Magnetic (GSM) coordinates, parameterised by the B_y component of the Interplanetary Magnetic Field (IMF), which lies perpendicular to the Earth-Sun line within the ecliptic plane. The authors attribute the SM contribution to the influence of the equatorial ring current, RC, and the Chapman-Ferraro currents. The GSM component is predominantly driven by tail currents.

Various models of the magnetospheric fields from spacecraft measurements are available, including a comprehensive model built from satellite and ground observatories measurements (Sabaka et al., 2020), as well as a dedicated fast-track Swarm-only model produced daily (Hamilton, 2013). More recently, Fillion et al. (2023) developed a model of the near-Earth magnetic field from inner magnetospheric currents. Their study presents a 25-year model (1997–2022) of hourly variations in the near-Earth inner magnetospheric field, validated against the RC index (Olsen et al., 2014). The model captures local-time asymmetries and performs best at degree 2 for moderate to high geomagnetic activity. Ou et al. (2024) developed a magnetospheric model incorporating data from the Macao Science Satellite-1 (MSS-1A) and Swarm missions. Their findings confirm that the dawn-dusk asymmetry, previously observed during geomagnetic storms, persists during both geomagnetically quiet periods and the storm recovery phase. They propose that local time asymmetry is a key factor in the evolution of the ring current, significantly affecting plasma injection and decay processes within the magnetosphere.

Additionally, there are magnetospheric models based on the analysis of observatory and spacecraft measurements (e.g. Finlay et al., 2020). There are also a variety of empirical models of how the magnetosphere responds to given solar wind conditions, some global (e.g. Tsyganenko 2002a, 2002b; Tsyganenko and Sitnov 2005), some focused on specific phenomena or regions (e.g. Antonova and Stepanova, 2021). In order to understand the behaviour of the ring current, we need a global model that includes the night-side magnetospheric currents.

Tsyganenko (2002a) built a global semi-empirical model that uses solar wind conditions from in-situ measurements, and a field deformation technique accounting for various asymmetries observed in the ring current. This model has been adapted to other planets (e.g., Korth et al., 2015; Tsyganenko and Andreeva, 2014) by adding or excluding several features as needed. This model can account for a ring current that is asymmetric both in local time and latitude (Tsyganenko and Sitnov, 2007). Modelling the detailed magnetospheric environment is challenging due to its complexity and non-linear dynamics, and there are still many issues to be addressed (e.g., Borovsky, 2022). For example, Castillo et al. (2017) studied how well the Tsyganenko and Sitnov (2005) reproduced the transient magnetospheric signal measured at four mid-latitude stations in the Northern Hemisphere. They found that with this empirical approach, the East-West component is more accurate than the North-South component, especially on geomagnetically active days, where the symmetric and partial ring currents dominate the variability and magnitude of the field at the Earth’s surface. Even under the best conditions, remaining discrepancies—particularly in North-South direction—arise, likely from the geometry and variation in the field-aligned currents.

Magnetic measurements on a spacecraft in low Earth orbit are primarily influenced by the core, crustal magnetisation, ionosphere, and magnetic fields created by

magnetospheric currents. Depending on the relative position between the source of the magnetic field and the measuring spacecraft, we can define them to have an internal or external origin. At Earth’s surface, the rapidly varying internal component is driven by currents induced by the external component. Consequently, changes in the external magnetic potential must always precede the response of the internal magnetic field. The conductivity distribution governs the surface induction response. A frequency-dependent response coefficient can be constructed to separate the inducing and induced components of a measured field. This coefficient is determined by the mantle’s electrical conductivity. Based on this principle, an approach can be developed that relies on the inversion of electromagnetic transfer functions, organised as the Q-response matrix. This matrix links the external (inducing) and internal (induced) coefficients in a spherical harmonic expansion of the time-dependent magnetic field originating from the magnetosphere (Olsen, 1999; Grayver et al., 2021).

In this paper, we employ a technique that enables magnetic field solution for both the zonal and meridional components of the magnetospheric field (see Grayver et al., 2021). We provide a brief description of the methodology used, along with the data and models applied to calculate the residuals we processed (see Sect. 2). Additionally, we compare our results with previously published magnetospheric models during the St. Patrick’s Storm in March 2015 (e.g. Kader et al., 2022).

Using our inversion technique, we analyse the temporal and spatial behaviour of the magnetosphere based on Swarm spacecraft measurements from launch (November 2013) to the present. Our focus is on the night-side magnetosphere, where we observe seasonal variations during geomagnetically quiet periods (see Sect. 3.5). We acknowledge that correctly resolving degree and order 3 features is not always possible given the configuration of the satellites during the mission, so the study is also curiosity driven in order to examine the limitations. This is obvious in storm scenarios with very rapid field changes.

In Section 3.6, we examine the solar cycle variability of the MMA. Furthermore, we investigate local-time and latitudinal variations during geomagnetic storms by developing a model that integrates Swarm and MSS-1A spacecraft data. This combined model demonstrates significant improvements due to enhanced local time coverage during the ‘Gannon’ geomagnetic storm (10–11 May 2024) in Section 3.7. Finally, we evaluate the validity of our new model, highlight its advantages, and discuss future developments and improvements to the algorithm in Section 4.

2 Methodology

We use the spacecraft measurements in geocentric coordinates (GEOC) and models of the core, crustal, and ionospheric fields (these models will be discussed below)

to produce a residual where we expect the signal of magnetospheric origin is present. There are two parts to this signal: the primary field that comes from the magnetosphere (inducing), and a secondary signal generated by the magnetospheric field inducing currents in the Earth's mantle (induced). From the frame of reference of the spacecraft, the inducing field is external, and the induced field is internal.

In order to separate external and internal sources from the satellite measured magnetic fields, we use the Q-matrices (Olsen, 1999). The residuals that correspond to the magnetospheric field can be expressed in the frequency domain, $\mathbf{B}(\mathbf{r}, \omega)$, where $\mathbf{r} = (r, \theta, \phi)$, and ω refers to the signal frequency from a Fourier transform applied to the signal time series. Assuming the magnetic field is potential, i.e., there are no currents at satellite altitude, one can write

$$\mathbf{B}(\mathbf{r}, \omega) = -\nabla V^e(\mathbf{r}, \omega) - \nabla V^i(\mathbf{r}, \omega), \quad (1)$$

where each of the potentials may be expanded in spherical harmonics as

$$V^e(\mathbf{r}, \omega) = a \sum_{n=1}^N \sum_{m=-n}^n \epsilon_n^m(\omega) \left(\frac{r}{a}\right)^n P_n^m(\cos \theta) e^{im\phi}, \quad (2)$$

and

$$V^i(\mathbf{r}, \omega) = a \sum_{n=1}^N \sum_{m=-n}^n \iota_n^m(\omega) \left(\frac{a}{r}\right)^{n+1} P_n^m(\cos \theta) e^{im\phi}, \quad (3)$$

where a is Earth's radius, P_n^m is the Legendre polynomial degree n and order m , ϵ_n^m and ι_n^m are the external and internal coefficients, respectively.

The internal field arises from the induction of the external part on the conducting crust, sea, and mantle. The relationship between the inducing and induced fields depends on the electrical conductivity σ . We can use the Fourier domain representation and we write the conductivity as a function of frequency, $\sigma(\omega)$. Each external coefficient ϵ_n^m induces the internal coefficient ι_n^m .

Assuming that horizontal variations in crustal and upper mantle conductivity are small (i.e., $\partial\sigma/\partial x, \partial\sigma/\partial y \ll \sigma/p$ with p as the skin depth), it is possible to estimate the amplitude and phase response to an electromagnetic impulse such as

$$\iota_n^m(\omega, \sigma) = Q_n(\omega, \sigma) \epsilon_n^m(\omega), \quad (4)$$

where $Q_n(\omega, \sigma)$ is the Q-matrix transfer function.

The ratio of induced to inducing field can be measured and it depends exclusively on the Earth's conductivity depth profile, $\sigma(r)$. From Grayver et al. (2021), it is possible to write the external coefficients by minimising the difference between the observed horizontal field, $B_{\alpha i}$, and the modelled horizontal fields $B_{n\alpha}^m(\mathbf{r}_i, t, \sigma)$, where α denotes the horizontal field components θ and ϕ . Here, $\mathbf{r}_i$ and t represent the position and time of the i th measured

vector $B_{\alpha i}$.

$$B_{n\theta}^m(\mathbf{r}_i, t, \sigma) = \sum_{j=0}^{N_t} -I_{Q_n}(j, \sigma) \left(\frac{a}{r_i}\right)^{n+2} \frac{dP_n^m(\cos \theta)}{d\theta} \Big|_{\theta=\theta_i} \times [q_n^m(t - j\Delta t) \cos(m\phi_i) + s_n^m(t - j\Delta t) \sin(m\phi_i)] \quad (5)$$

$$B_{n\phi}^m(\mathbf{r}_i, t, \sigma) = \sum_{j=0}^{N_t} I_{Q_n}(j, \sigma) \left(\frac{a}{r_i}\right)^{n+2} \frac{m}{\sin \theta_i} P_n^m(\cos \theta_i) \times [q_n^m(t - j\Delta t) \sin(m\phi_i) - s_n^m(t - j\Delta t) \cos(m\phi_i)] \quad (6)$$

where $N_t = \frac{T}{\Delta t}$ represents the total time span of the samples T divided by the time interval window Δt . The function $I_{Q_n}(j, \sigma) = \int_{j\Delta t - \Delta t/2}^{j\Delta t + \Delta t/2} Q_n(t, \sigma) dt$ is the time-domain representation of the Q-matrix transfer functions, q_n^m and s_n^m are the Gauss coefficients for the external field (see Grayver et al., 2021).

This solution assumes that magnetic field sources (i.e., the magnetospheric field sources) remain constant over the time interval Δt . However, for a rapidly varying magnetospheric configuration, this approximation provides only a time-averaged source field. To ensure sufficient geographical coverage, we use long-period (6 h–12 h) cadences for Δt . This approximation is reasonably well justified even in an active geomagnetic environment because the long-timescale asymmetry in the configuration of the ring current is expected.

We have implemented this algorithm using two of the Swarm satellites, enabling simultaneous coverage of two local times for most of the observation period. We use data from Swarm Alpha (A) and Bravo (B). Since Swarm B orbits at a higher altitude, it drifts through local time at a different rate compared to the lower pair (A/C). During certain periods, such as immediately after launch and in 2021, the satellites were in approximately the same local time, limiting the measurement of higher-order terms.

We start with Level 1b data from the Swarm satellites A and B in the NEC frame. We subsample the data at a 15-second cadence. To apply the above decomposition, it is essential to remove all non-magnetospheric fields. We use standard Swarm-derived models for the core, crustal, and ionospheric fields to compute the residuals required for our Model of the Magnetosphere (MMA). During the preparation of this study, we tested various model combinations. Our analysis shows that the choice of ionospheric model introduces only minor differences in the resulting magnetospheric models. The results presented in this paper are based on the dedicated models from the Swarm Level 2 products (e.g. Beggan et al., 2013). Following Hamilton (2013), we use the core and crustal models from the dedicated core model: MCO_SHA.2D (Rother et al., 2013) for the core and MLI_SHA.2D (Thébault et al., 2013) for the lithosphere; in combination with the ionospheric model CM4 (for a more recent version, CM6, see Sabaka et al., 2020).

For performance assessment and comparison, we also cross-checked the results with models available from the VirES for Swarm service, such as the CHAOS Core (Finlay et al., 2020) and CHAOS Static (Olsen et al., 2006) models, as well as the ionospheric dedicated model MIO_SHA_2D (Chulliat et al., 2013). We find minor differences in the results depending on the integration time used for the ionospheric models. A 12-h cadence yields identical MMA model results, while 8-h and 6-h cadences show deviations of up to 10 nT during geomagnetically active periods.

Using the core, crust, and ionospheric models, we subtract their estimates from the Swarm data to compute residuals which we assume contain primarily the magnetospheric contribution. We select only night-side data, i.e., measurements between 18:00 and 06:00 local time. High geomagnetic latitudes are excluded, and only measurements below $|\phi| > 60^\circ$ dipole latitude are considered. After computing the residuals, the algorithm fits data within a time window Δt , assuming that the sources remain constant and stationary. This allows for the separation of internal and external components, where the external component corresponds to the magnetosphere model.

This algorithm finds the best-fit coefficients for a spherical harmonic representation of the Gauss coefficients to degree and order 3 for inducing and induced fields, assuming the sources are stationary. The MMA model consists of time series of the inducing spherical harmonic coefficients, which give a 2D representation of the external fields at spacecraft altitude as measured by the Swarm satellites.

It is important to note that, due to the data selection we chose, i.e., night-time data only, our solution does not have any input information to resolve the coefficients q_l^{2p+1} (i.e., when the order $m = 2p + 1$ is odd) in SM coordinates. These values are, as expected, close to zero, but we have not used this as a constraint in the MMA solution.

3 Results

In this section, we demonstrate how the MMA performs by comparing it with previous models based on satellite data (Sect. 3.2) and ground observatory data (Sect. 3.4). We use the MMA to observe the evolution of the night-side magnetosphere during the March 2015 (St. Patrick's Day) storm (Sect. 3.3). We also include results of the climatological evolution of the night-side magnetosphere in Sections 3.5 and 3.6.

3.1 Evaluation of the model using satellite residuals

Using the algorithm presented in the previous section, we are able to reproduce the magnetic field measured by the Swarm satellites.

Based on the time interval used to define the model, we calculate the modelled field at the interpolated satellite positions, resulting in the horizontal field evaluated with a Δt cadence. To compare with the magnetospheric residual, we resample the measured field to match the model's time cadence (see Fig. 1).

Comparing the measured and modelled horizontal components, we see a number of outliers in the model. These outliers do not always coincide with poor fits to the data, i.e., with low values of R^2 , shown in the colour map in Figure 1. The measure for quality of the linear fit used is the coefficient of determination

$$R^2 = 1 - \frac{\sum_i (y_i - f_i)^2}{\sum_i (y_i - \bar{y})^2} \quad (7)$$

where y_i is the i -th measured value, $\bar{y}$ is the mean observed value over the interval Δt , and f_i is the predicted value at i (e.g. B in equations (5) and (6)). Colour values close to 1 (yellow) indicate a good linear fit to the time interval chosen for the model (8h in this case) and values close to zero (dark purple) indicate that the fit is not good and the data variation within the time window is large.

To ensure an independent comparison with the model predictions, we make use of magnetic field measurements from the MSS-1A mission, whose data are not involved in the model construction. We compared the model predictions at the MSS-1A satellite locations from January to September 2025. To derive the observed MMA at the MSS-1A positions, we applied the same filtering and smoothing procedures used for the Swarm data in Figure 1, interpolating both the satellite locations and the magnetic field measurements accordingly. The resulting residuals represent the differences between the measured and modelled MMA signals at MSS-1A throughout most of 2025. The distribution of these model-measurement differences is shown in Figure 2.

The distribution of these residuals shows that the best-resolved component overall is B_ϕ , i.e. the east-west component, with a standard deviation of approximately 10 nT. Conversely, B_r displays the largest deviation at approximately 40 nT. This behaviour is expected, as the radial component is not explicitly accounted for in our model; instead, the solution assumes it to arise from the divergence-free potential field. We do not observe major differences between the various values of $l_{\max}$.

3.2 Comparison with Previous Satellite-Based Magnetospheric Models

Using a method similar to that described in Section 2, Olsen (2021) computed a model of the magnetospheric field for the period 1 March to 30 April 2015. Their study utilised data from the Swarm A and B satellites, supplemented by measurements from platform magnetometers on CryoSat-2 and GRACE (A and B). During this period, the local time coverage provided by Swarm A and B alone was limited because their orbital planes were separated

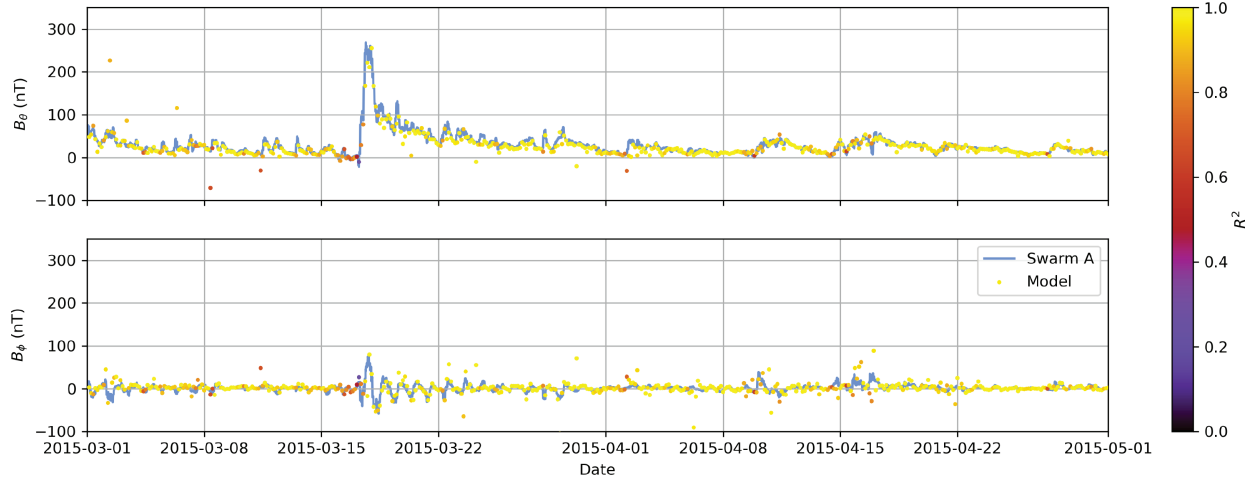


Figure 1. Plots of the time series of the residual magnetospheric field measured by Swarm A during the St Patrick storm 2015. The light blue line shows the satellite interpolated measurements at the modelled time, and the colour dots show the model evaluated at the interpolated satellite positions. The colours indicate the coefficient of determination, R^2 , for the model linear regression fit to the Gauss coefficients. Colour values close to 1 (yellow) indicate a good linear fit to the time interval chosen for the model (8 h in this case) and values close to zero (dark purple) indicate that the fit is not good and the data variation within the time window is large.

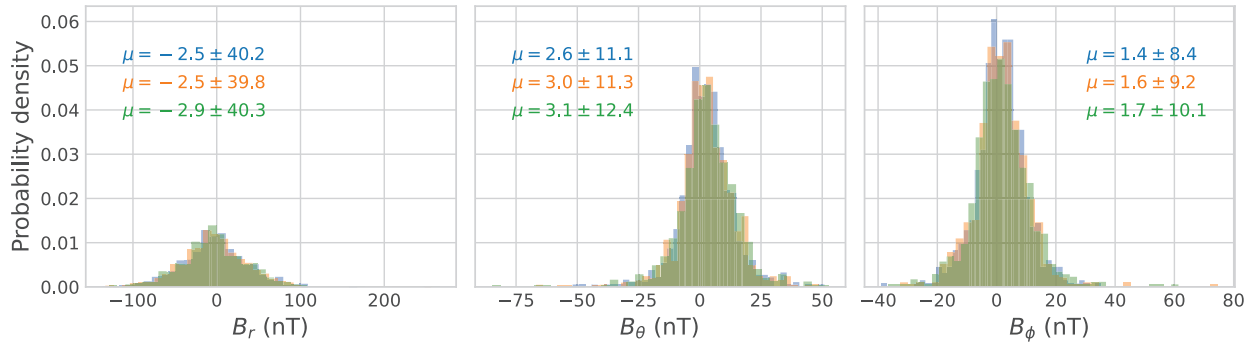


Figure 2. Histograms showing the distribution of the residuals (modelled minus measured MMA) for 8-h cadence models with maximum spherical harmonic degrees $l_{\max} = 1$ (blue), $l_{\max} = 2$ (orange), and $l_{\max} = 3$ (green). Each panel includes the mean (μ) and standard deviation of the corresponding distribution. The comparison is based on a model derived from Swarm A and B data and measurements from MSS-1A. The east-west component is the best resolved across all three models, whereas the radial component exhibits a broader spread. Overall, the integrated results show no significant differences between the three models for MSS-1A data collected from January to October 2025.

by only 20° in March 2015. The results of the external field decomposition in spherical harmonics are shown in Figure 3, which presents Olsen’s model coefficients to degree and order 2 (coloured lines), the fast-track Swarm model (MMA_SHA_2F, grey) of Hamilton (2013), and our new MMA up to degree and order 3 (black).

The dipole component (q_1^0) shows good agreement with the solution by Olsen (2021). The integration time for our model (black) in Figure 3 is 8 hours, while the fast-track model (grey) and Olsen’s model (coloured lines) use a 1.5-h sampling. As a result, finer-scale features captured in the higher time-cadence models are naturally smoothed in our solution. The storm maximum value of q_1^0 differs between the models presented here. These differences are influenced by the method of calculation of the residuals but mainly the chosen time interval Δt of 8 hours.

The new MMA model exhibits variations in the higher order harmonics that are not present in Olsen’s solution. This is due to differences in local time coverage. The Olsen model benefits from multiple satellites which provided a more homogeneous local time sampling, whereas our model relies on data from only two local time sectors. The local time separation of Swarm A and B was 1.5 h (about 20°) in early 2015.

3.3 Asymmetry during 17 March 2015 storm

We can examine the spatial evolution of the external field during storm periods. Figure 4 presents three snapshots of the external magnetic field, showing the magnitude of the horizontal component, i.e. $B_H = \sqrt{B_\theta^2 + B_\phi^2}$ (blue to yellow) at spacecraft altitude. These fields are drawn in

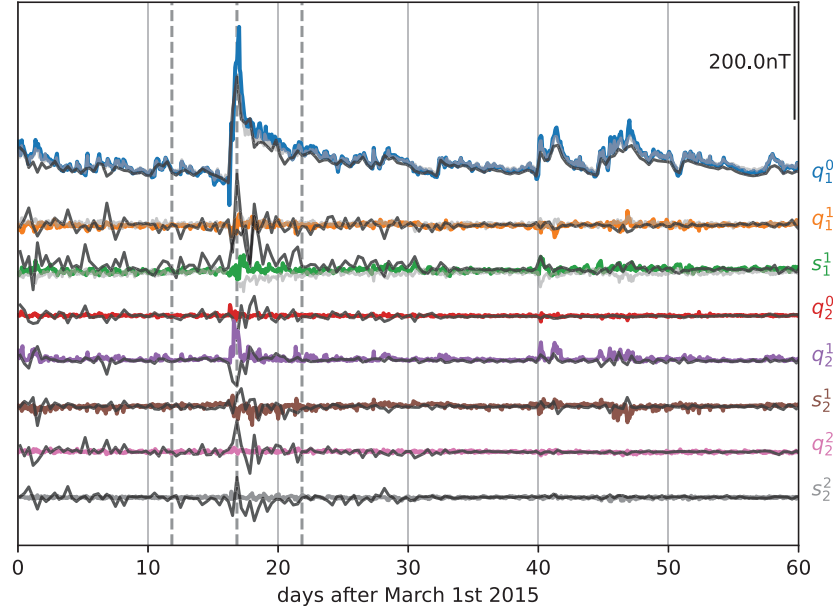


Figure 3. Time series of external field spherical harmonic coefficients during March to April 2015, in geocentric coordinates. Results from Olsen (2021) are shown as coloured lines; the daily fast-track magnetospheric model from Swarm-only data, MMA_SHA_2F (grey), q_1^0 , q_1^1 , and s_1^1 ; and the model from this study, MMA (black). The vertical dashed lines indicate the times corresponding to the snapshots in Figure 4.

solar magnetic coordinates, with midnight at the centre of each map. The shaded regions mark the day-side, where no satellite data are included, but the spherical harmonic model will nevertheless produce a value. The boundaries of this region correspond to dusk (18:00 local time) on the left and dawn (06:00 local time) on the right.

The left panel depicts the pre-storm quiet time background field where the external field on the night-side resembles a tilted dipole. At storm maximum (middle panel), the external field intensifies significantly, exhibiting a strong non-axisymmetric component. The maximum horizontal component shifts toward dusk and south of the geomagnetic equator. Finally, during the storm recovery phase (right panel), the external field weakens but remains enhanced toward dusk.

3.4 Comparison with ground observatory models

To evaluate the magnetospheric model using ground observatory data, we compare it with the Vector Magnetic Disturbance (VMD) index (Thomson and Lesur, 2007) (Fig. 5). The VMD index is derived from night-time data collected from observatories situated at magnetic latitudes below 50° , ensuring compatibility with the coverage of our magnetospheric model.

Thomson and Lesur (2007) constructed the VMD index by processing 1-minute averaged geomagnetic data obtained from INTERMAGNET observatories time-series. This index is designed to monitor rapid fluctuations in the strength and direction of large-scale external magnetic fields. It comprises two three-dimensional vector time series that cover three-month intervals throughout

the year, with data from observatories situated between 50° and -50° magnetic latitudes, under specific local time and zenith angle conditions. The mathematical framework used to analyse the observed data incorporates constants representing linear time variations that account for slowly changing core fields, and rapid fluctuations attributed to the large-scale external field and its corresponding induced effects. The estimation process for the VMD index consists of three main steps: first, determining observatory offsets and linear trends; second, modelling rapid variations; and finally, separating external signals from internal ones.

We find good agreement between the degree $l = 1$ component of the MMA solution and the negative VMD index during the St. Patrick's geomagnetic storm (17 March 2015), see Figure 5, right panels. For the VMD calculation, observatory offsets are determined such that the quiet-time mean VMD value is zero. However, for the MMA model, we explicitly include the quiet-time ring current. This methodological difference accounts for the offset observed in Figure 5 between the VMD index (lines) and MMA model (dots), seen also as a non-zero intercept on the right side correlation plots. See also the discussion on offsets with the Dst index in Grayver et al. (2021). As expected, the coefficient q_1^1 , which is poorly resolved due to the data selection, shows no correlation with the VMD counterpart (shown in green).

3.5 Seasonal quiet time magnetosphere

The model is most effective in capturing features of the magnetosphere that persist over several days rather

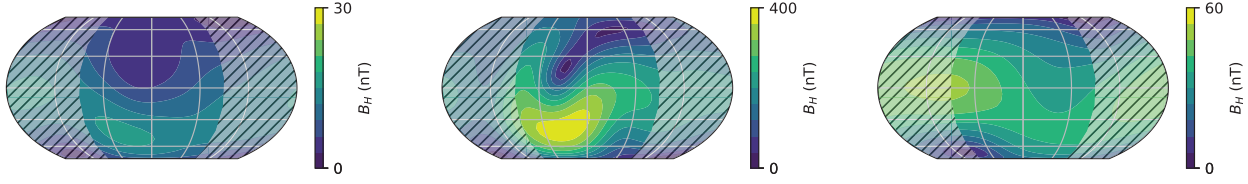


Figure 4. Snapshots of the external field calculated from Swarm satellite measurements during the St. Patrick's storm, March 2015. The figures show the magnitude of the horizontal component $B_H = \sqrt{B_\theta^2 + B_\phi^2}$ of the external field. Each map is in solar magnetic coordinates, with midnight at the centre. The shaded region represents the day-side.

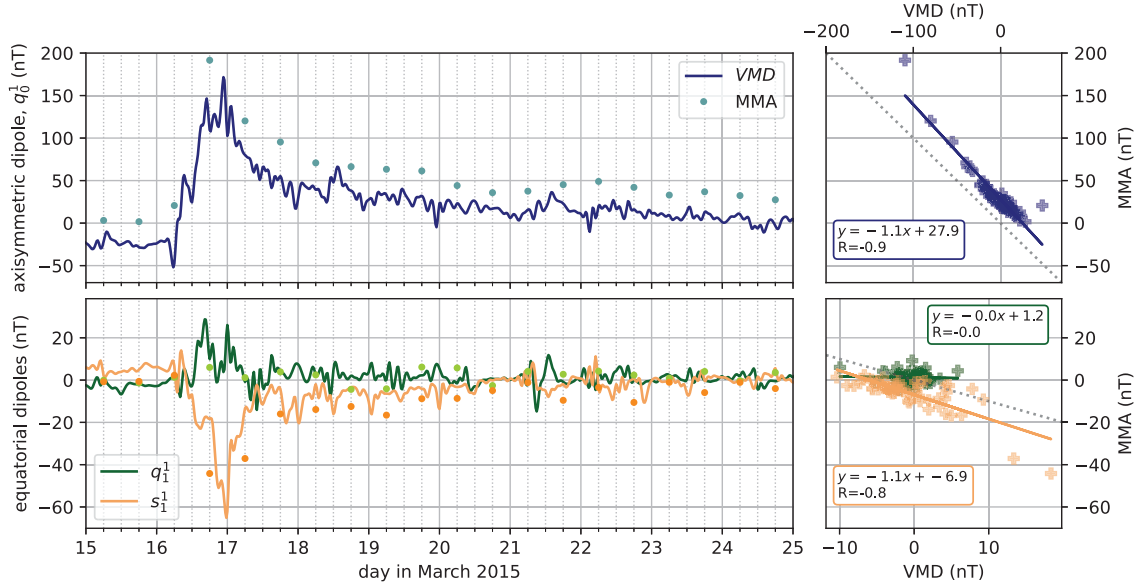


Figure 5. (Left) Time series of the dipolar components of our MMA model (points) with a 12-h cadence and the Vector Magnetic Disturbance (VMD) index Thomson and Lesur (2007) (lines). The top left panel shows the axisymmetric dipole, q_1^0 , from the MMA (blue points) alongside the symmetric part of the negative VMD index (blue line). The bottom left panel displays the equatorial dipoles q_1^1 (green) and s_1^1 (orange) from the same MMA solution (points), compared with the negative VMD index (lines). (Right) Correlation plots of MMA vs. VMD. Text boxes with the best fit line and corresponding Pearson correlation coefficient R value, using the same colours as the left panels. Dotted grey line shows a line with slope -1 .

than rapid fluctuations during magnetic storms. We analysed the external field during geomagnetically quiet periods by computing the mean external field for each month over the 10-year duration of the Swarm mission as shown in Figure 6. The lower panel presents the 10-year average of the axisymmetric dipole during quiet days, where $\langle q_1^0 \rangle_{\text{day}} < 10$ nT. Two vertical solid grey lines indicate the time of the equinoxes. We observe increased activity near the equinoxes, particularly in April and September, and lower activity during the solstices. This seasonal pattern is consistent with previous observations (e.g., Russell and McPherron, 1973).

The top panel of Figure 6 displays maps of the horizontal component of the magnetospheric field at spacecraft altitude in solar magnetic coordinates, with midnight at the centre. The maps correspond to March, June, September, and December, representing equinoxes (left) and solstices (right). The external field remains predominantly dipolar and is strongly influenced by the ring current. The dipole appears tilted during June and December, when

the Earth's northern pole is oriented toward and away from the Sun, respectively.

This seasonal behaviour results from the change in inclination of the geomagnetic dipole relative to the Sun-Earth line (e.g., Hoshi et al., 2018; Eggington et al., 2020). The combined effect of Earth's internal dipole tilt and inclination of the rotational axis causes Earth's magnetic field to align with the Earth-Sun line during solstices (June and December) and to be perpendicular to it during equinoxes (March and September) (Lockwood et al., 2020). Additionally, we observe an enhancement of the field in the dusk equatorial region.

3.6 Variation over a solar cycle

From the 10 years of model evaluation, we can observe how the magnetospheric field varies with the solar cycle. Figure 7 presents the monthly means of the axisymmetric dipole (q_1^0) for the whole dataset (blue) and during quiet periods (orange), where days with $\langle q_1^0 \rangle_{\text{day}} < 10$ nT are

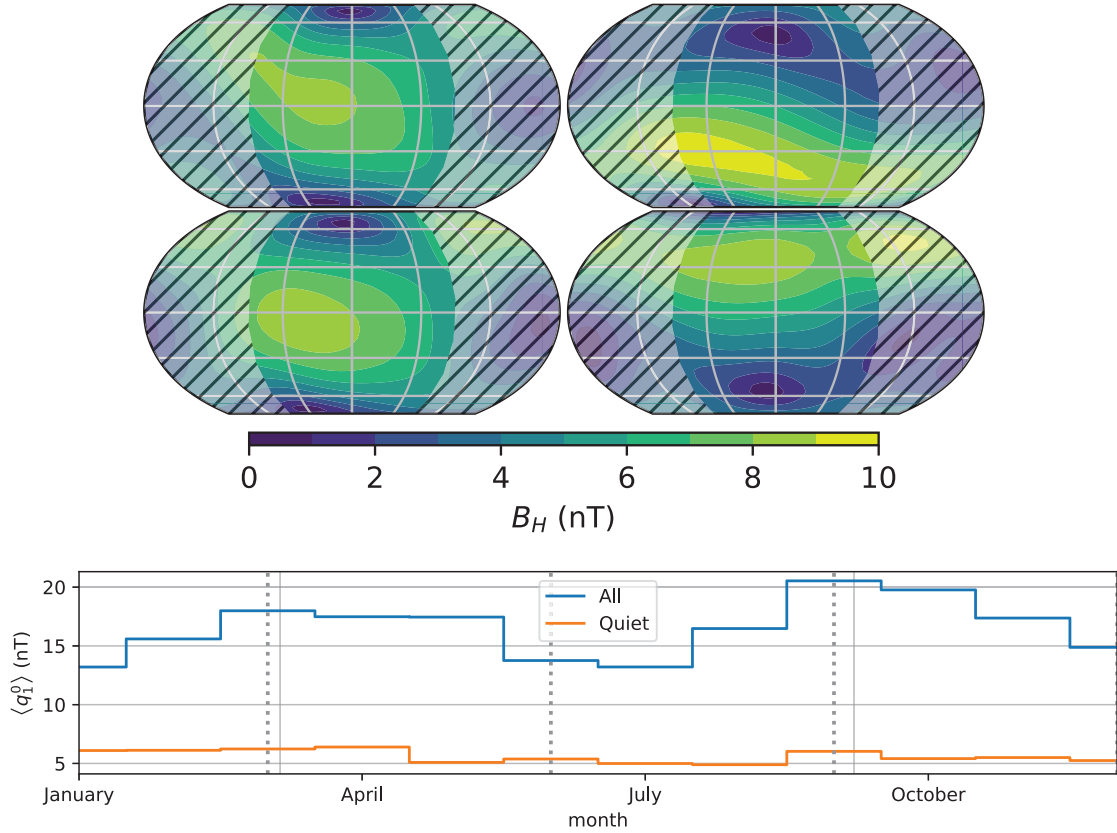


Figure 6. Maps showing the magnitude of the horizontal magnetospheric field at satellite altitude. Each map represents a monthly averaged field based on geomagnetically quiet periods over the 10-year Swarm mission dataset. The panels display averages for March (upper left) and June (upper right), September (lower left) and December (lower right). The bottom panel shows the average monthly amplitude of $\langle q_1^0 \rangle$ for all data over 10 years (blue) and for selected quiet time only (orange). Dashed grey vertical lines correspond to the times of the snapshots above. Solid grey vertical lines mark the equinoxes.

classified as geomagnetically quiet periods. We show the sunspot number (green dots) and the 13-month averaged sunspot number (green line) from [SILSO World Data Center \(2013–2025\)](#).

The models indicate a background constant value of the ring current of $q_1^0 \sim 8$ nT. This axisymmetric ring current is enhanced during storm periods, with both the intensity and frequency of activity increasing during solar maximum. This value is consistent with the ~ 10 nT offset seen in the axisymmetric dipole, shown in blue in [Figure 5](#), between the MMA and the VMD index.

Alternatively, we can identify active periods within this dataset. Active days are selected based on the criterion $\langle q_1^0 \rangle_{\text{day}} > 50$ nT, corresponding to periods of geomagnetic storms. [Figure 8](#) presents the monthly means of these active-day data for three Gauss coefficients: q_1^0 , s_1^1 , and s_2^1 , in SM coordinates. Additionally, we include the Kernel Density Estimate, which highlights the highest occurrence of these coefficients during geomagnetic activity. Since these are monthly means, active months typically include multiple storms within the same period. Despite the large variability, positive values of q_1^0 are consistent with observations of depressions in the horizontal components at ground-based observatories, a feature also captured by the Dst index. Negative values of s_1^1 , on the

order of 10 nT, indicate an enhancement in the equatorial horizontal component, while non-zero values of s_2^1 suggest a dusk–dawn asymmetry.

Using the same dataset of active days, we transformed the data into solar magnetic coordinates. We determined the modal value of the inducing coefficients, rounded to two decimal places, and reconstructed the radial and horizontal fields corresponding to the most common inducing field, as shown in [Figure 9](#). The typical configuration of the magnetospheric field during a geomagnetic storm is a dipolar field tilted towards dawn, with an enhanced RC near the dusk terminator. This configuration is expected to characterise the magnetosphere during the storm recovery phase, as this phase has the longest duration.

3.7 Addition of MSS–1A night-side coverage

To improve local time coverage, we combine data from Swarm and MSS–1A. The MSS–1A spacecraft was launched on 21 May 2023 and has provided high-quality magnetic measurements since 2 November 2023. Unlike the Swarm constellation, MSS–1A has an orbital inclination of 41° (e.g., [Zhang, 2023](#)).

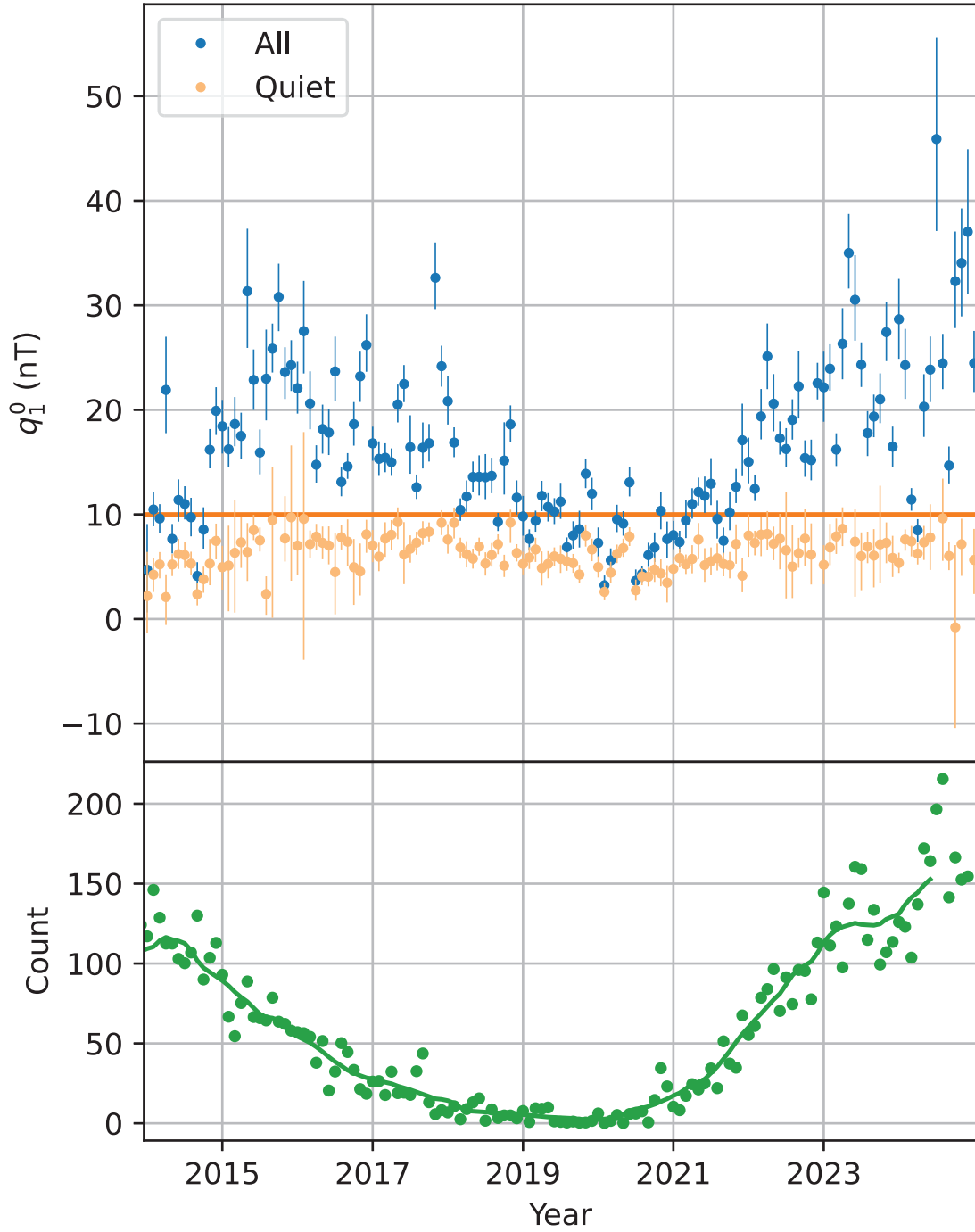


Figure 7. Monthly mean values of q_1^0 in GEOC coordinates, for all data (blue) and for quiet days (orange). We use $\langle q_1^0 \rangle_{\text{day}} < 10$ nT as the threshold for quiet days, represented by the horizontal orange line in the q_1^0 plot. The bottom panel shows the sunspot number (green circles) and the smoothed sunspot number (green line) from [SILSO World Data Center \(2013–2025\)](#).

We analyse the magnetospheric model results using a combination of Swarm and MSS-1A data, comparing MMA models at various integration times. Longer integration periods of 12, 8, and 6 hours produce comparable results for the axisymmetric dipole (Fig. 10). However, a 3-h Δt cannot resolve an accurate model using Swarm data alone. This time resolution requires an improved local time coverage, only possible by incorporating MSS-1A data. This limitation likely extends to higher harmonics,

though the number of available models for comparison is limited.

4 Discussion

We constructed a new model of the night-side magnetosphere using Swarm-only data, enhancing our understanding of magnetospheric dynamics during both quiet

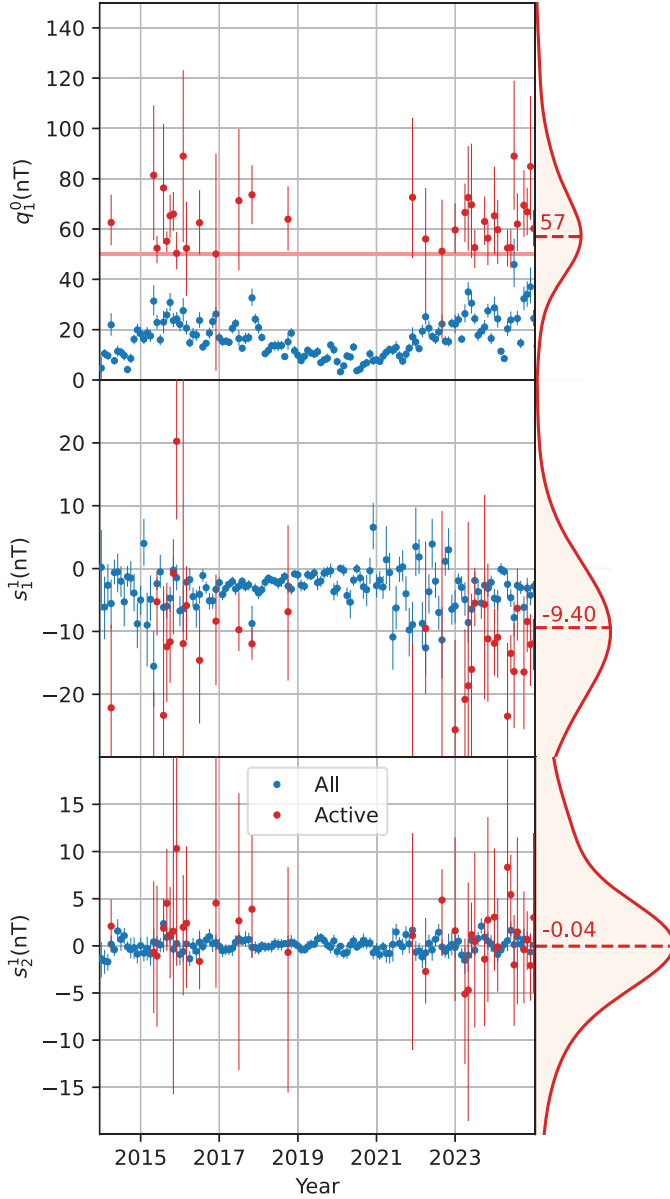


Figure 8. Monthly mean values of q_1^0 , s_1^1 and s_2^1 in SM coordinates for all data (blue) and for Active days (red). We use $\langle q_1^0 \rangle_{\text{day}} > 50$ nT as the threshold for active days, represented by the horizontal red line in the q_1^0 plot. On the right side, using the same y-axis values, we show the Kernel Density Estimation (KDE) to find the most likely values for these three coefficients, shown in red. The highest occurrence value is shown with a horizontal dashed line and its value is given in red above the line.

and storm conditions. The model captures the magnetospheric field up to degree and order 3, with local time resolution constrained by the orbital configuration of the satellites, which changes during the mission due to precession. While challenges arise due to the limited local time coverage, particularly in defining meridional coefficients, the MMA remains comparable to previous models such as that of [Hamilton \(2013\)](#) and [Olsen \(2021\)](#), while extending the time series to the full operational period of

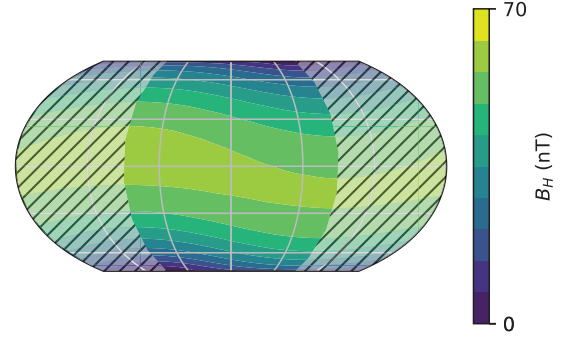


Figure 9. Solar magnetic maps of the night-side were generated using the highest occurrence Gauss coefficients for active periods, as indicated by the red circles in [Figure 8](#). The resulting configuration for active periods reveals an enhancement in the dusk region and a slightly tilted ring current (RC), which is displaced northward at the dusk terminator and southward at the dawn terminator.

the Swarm mission. However, the degree 3 and to a lesser extent degree 2 coefficients are often cross-correlated due to the generally limited local time coverage across much of the mission.

With the MMA, we can determine the geometrical configuration of the night-side magnetosphere during geomagnetic storms, enabling the direct observation of storm variability at different local times (e.g., [Pinzon-Cortes et al., 2025](#); [Lockwood et al., 2019](#)). Even though we do not recommend using an integration time Δt of less than 6 hours for Swarm-only data, large geomagnetic storms can still be captured with the q_1^0 , and their impact could potentially be analysed in near real time using MMA with Swarm FAST data, and perhaps complementary missions to improve the local time coverage.

The seasonal variation of the quiet-time ring current has been derived, showing consistency with observations of the seasonal shifts in the magnetospheric neutral point (e.g. [Eggington et al., 2020](#)). As expected, the ring current plane shifts southward and northward along the Earth-Sun line during June and December, respectively (see [Fig. 6](#)). We observe an enhancement of the seasonal ring current due to geometric alignment, which allows for more efficient energy transfer from the solar wind into the magnetosphere during equinoxes.

Over a 10-year period, the background quiet-time ring current remains largely stable, as indicated by the orange points in [Figure 7](#). However, during periods of heightened solar activity, characterised by an increased sunspot number (shown in green), the ring current intensifies in response to enhanced energy transfer from the interplanetary magnetic field to the magnetosphere (blue points).

Analysing the configuration of active days during the Swarm mission, we find that during geomagnetic storms, the magnetosphere is predominantly characterised by a dipolar field tilted towards the dawn terminator, with a stronger ring current near the dusk terminator ([Fig. 9](#)).

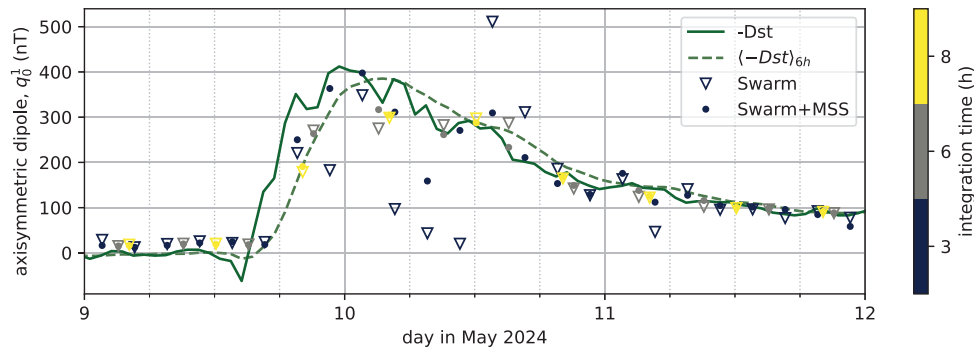


Figure 10. Time series of q_1^0 for May 2024. Colours indicate integration time: blue (3 h), grey (6 h), and yellow (8 h). Open triangles represent results using only Swarm data, while dots show results from the combined Swarm and MSS-1A dataset. In green, we also include the negative Dst index with the dashed green line representing a 6-h moving average of the -Dst index.

Integrating low-inclination orbital data from MSS-1A significantly improves local time coverage, greatly enhancing the inversion process for producing the MMA (Fig. 10). In the future, we anticipate further improvements with the launch of the NanoMagSat constellation (Brown et al., 2023) and additional MSS satellites.

With this model, we can provide a space-based Dst proxy by calculating q_1^0 , with a 6-h cadence using the new FAST data from Swarm, adding to current now-cast capabilities other measurements (e.g. Orr et al., 2024). This decomposition allows for near real-time monitoring of geomagnetic storms and the tracking of asymmetries developing on the night-side during storm evolution.

5 Conclusions

A new model of the magnetosphere has been developed, based on over ten years of Swarm data from November 2013 to January 2025. The model captures the variation of the magnetosphere to degree and order 3 using night-side only measurements.

We describe the development of the model and illustrate the application to understanding of storm times, quiet periods and seasonal to solar-cycle changes in the magnetosphere. We find the steady ring current (dipole) holds steady at around 8 nT while the majority of the variation over the solar cycle relates to short periods of intense storms.

For the first time, this model offers a high-resolution representation of the nighttime magnetosphere. It can be used to compute residuals that exclude magnetospheric effects or be integrated with other measurements to improve our understanding of Earth's magnetic field variations.

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Conflicts of interest

The authors declare no Conflict of Interest.

Data availability statement

All figures contain data from the Swarm mission courtesy of ESA. The data are publicly available at <http://swarm-diss.eo.esa.int>. We also extend our gratitude to the China National Space Administration (CNSA) and the Macao Special Administrative Region Government for providing data from the MSS-1A satellite mission (<https://mss.must.edu.mo/index.html>).

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