Magnetospheric “Penetration” of IMF $B_y$ Viewed Through the Lens of an Empirical RBF Modeling

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Abstract

The spiral structure of the interplanetary magnetic field (IMF) is known to induce intramagnetospheric azimuthal magnetic field $B_y$, which strongly correlates with the IMF $B_y$. We reconstruct this effect for the first time in 3-D, using a large set of data taken in the near/inner magnetosphere and a flexible magnetic field model based on expansions in radial basis functions (RBF). The RBF model serves here as a magnifying glass with tunable resolution, focused on the specific region of interest. In this study, we used it to explore the IMF-induced $B_y$ both on a global scale (i.e., for the entire range of local times) and in the night sector only, to better visualize details in the region with the strongest “penetration” magnitude. The induced $B_y$ was found to maximize on the nightside at distances $R \sim 10–12 R_E$, where it concentrates around the solar-magnetic equator and bifurcates into a pair of peaks located in predawn and postdusk sectors. The $B_y$ “penetration” is associated with the IMF-induced asymmetry of field-aligned currents at the plasma sheet boundary. Even on a statistical level, the peak values of the induced $B_y$ can substantially exceed the external IMF $B_y$. The effect is significantly stronger under southward IMF $B_z$ conditions and grows with increasing geodipole tilt angle.

1. Introduction

Positive correlation between the azimuthal components of the interplanetary and intramagnetospheric magnetic fields has been reported since the early 1980s, confirmed by spacecraft observations in the tail (Fairfield, 1979) and at geostationary orbit (Cowley & Hughes, 1983). Initially, only a rather small fraction of the IMF $B_y$ (∼10–30%) was found to “penetrate” into the magnetosphere (Cowley, 1981; Cowley & Hughes, 1983; Fairfield, 1979; Kaymaz et al., 1994), though larger percentages were also reported inside the tail plasma sheet: up to ~50% by Lui (1983) and ~60% by Sergeev (1987).

Although the quoted term “penetration” has been widely used, especially in the early papers, the actual physics is more involved, and different models were proposed in the past (e.g., Cowley, 1981; Khurana et al., 1996; Moses et al., 1985). In particular, it has been debated whether the induced $B_y$ on closed field lines results from the magnetotail reconnection (Cowley, 1981) or if it is due to the asymmetric open flux loading and cross-tail shear flows (Khurana et al., 1996). The latter viewpoint has been bolstered recently by Tenfjord et al. (2015, 2018), who used MHD simulations to demonstrate that the dayside reconnection in the presence of IMF $B_y$ gives rise to an asymmetry of the flux loading, which results in asymmetric plasma flows and an induced $B_y$ on closed field lines at all local times, in no relation to the nightside reconnection.

With regard to the spatial distribution of the induced $B_y$, the most comprehensive statistics for the midtail region ($-31 \leq X_{GSM} \leq -10 R_E$) was presented by Petrukovich (2009, 2011) and Petrukovich and Lukin (2018) on the basis of Geotail data. At closer distances, the $B_y$ studies have either been limited to MHD simulations (Tenfjord et al., 2015, 2018) or made on the basis of only synchronous data (Cowley & Hughes, 1983; Tenfjord et al., 2017, 2018; Wing et al., 1995).

In this paper, we present first results of a global empirical 3-D reconstruction of the “penetrated” $B_y$ distribution. The analysis covers all local times in the interval of radial distances from 5 to 16 $R_E$ and a sufficiently wide sector of the solar-magnetic (SM) latitude, encompassing the closed field line domain. In addition, we present results of a local modeling study, exclusively focused on only the nighttime sector. The work is based on a large archive of Geotail, Polar, Cluster, Themis, and Van Allen Probes data obtained between 1995 and 2016 and on a recently developed method of the magnetic field modeling using radial basis functions (RBF) (Andreeva & Tsyganenko, 2016, referred henceforth as AT16; Tsyganenko & Andreeva, 2016, 2017, and references therein).
The paper consists of six sections. Section 2 outlines the mathematical formulation of the modeling method. Section 3 is split into two subsections, separately describing the data subsets and RBF grids used in the construction of the global and local model variants. Section 4 in the same fashion presents the modeling results obtained in both cases. Section 5 contains a discussion, focused, in particular, on the electric currents underlying the \( B_y \) penetration and on the geodipole tilt effects. Section 6 summarizes the paper. For interested readers, the paper is provided with a supporting information file that includes step-by-step derivation of the model field components.

2. Method

The essence of the approach, described in detail in the above-cited earlier papers and in the supporting information file, is to first split the external part of the magnetospheric magnetic field (i.e., with the Earth’s contribution subtracted) into a sum of toroidal and poloidal parts

\[
B_x(r) = \nabla \times (\Psi_t \ r) + \nabla \times (\Psi_p \ r) = \nabla \Psi_t \times r + \nabla \times (\nabla \Psi_p \times r) \tag{1}
\]

and represent the generating potentials \( \Psi_t(r) \) and \( \Psi_p(r) \) as linear combinations of RBFs \( \chi_i(r) \)

\[
\Psi_t(r) = \sum_{i=1}^{N} a_i \chi_i(|r - R_i|) \quad \Psi_p(r) = \sum_{i=1}^{N} b_i \chi_i(|r - R_i|) \tag{2}
\]

each of which depends only on the scalar distance \( |r - R_i| \) between the observation point \( r \) and the corresponding node \( R_i \). The nodes are regularly distributed within the modeling domain at \( N \) fixed locations, such that the model’s validity region and resolution are defined by the spatial extent and density of the node grid. The coefficients \( a_i \) and \( b_i \) are free model parameters quantifying contributions to the total field from each node; their values are calculated by fitting the model (1)–(2) to spacecraft data. There exists a wide choice of the RBFs (e.g., Gershenfeld, 2003, chapter 12.3); in this study we employed a set of Gaussian functions \( \chi(r) = \exp(-r^2/D^2) \). The scaling parameter \( D \) defines the radial falloff rate of individual RBF terms; larger values of \( D \) correspond to wider spatial extent and tighter overlap between the neighboring RBF sources and, hence, result in smoother distributions of the model field. However, as the \( D \) parameter grows too large, the interpolation matrix becomes increasingly ill-conditioned (e.g., Fornberg et al., 2011), which is manifested in unlimited growth of individual source amplitudes. Based on these considerations, we adopted a value \( D = 10 R_E \), commensurate with the characteristic dimension of the modeling region. This specific choice provided a smooth distribution of the model field, free of unphysical bumps associated with the discrete nature of the grid, and, at the same time, resulted in relatively low amplitudes of individual RBF terms, on the order of the average model field magnitude.

The general representation (1)–(2) does not imply any preconceived symmetry/antisymmetry of the magnetic field with respect to seasonal and diurnal oscillations of the Earth’s dipole tilt angle \( \psi \). In an ideal case with unlimited amount of spatially dense and uniform observations, the actual geometry of the magnetosphere would automatically emerge from the data fitting. In reality, due to nonuniformity of data distribution in the \([x, y, z, \psi]\) space, leaving the model in the above general form would inevitably result in unphysical asymmetries. To avoid them, certain symmetry assumptions should be made. In this study, we separate the expansions (2) into two groups, of which the first one corresponds to the principal part of the magnetospheric field, unrelated to the IMF \( B_y \) effects, while the second group represents the IMF-induced \( B_y \). As detailed below, the two groups have opposite types of north-south symmetry with respect to the simultaneous change of sign

\[
z \rightarrow -z, \quad \psi \rightarrow -\psi. \tag{3}
\]

The principal part has the common type of mirror symmetry with respect to (3), according to which both \( B_x \) and \( B_y \) are odd, while \( B_z \) is even (e.g., Mead & Fairfield, 1975). By contrast, the induced cross-magnetospheric \( B_y \) has the opposite symmetry, such that the “penetrated” \( B_y \) and \( B_z \) are even and \( B_y \) is odd with respect to (3).

As was shown earlier (AT16; Tsyganenko & Andreeva, 2016), both types of symmetry can be easily accommodated in the RBF approach by combining the functions \( \chi_i \) entering in (2) in pairs with opposite parities with respect to \( z \) coordinate (e for “even” and o for “odd”):

\[
\chi_i^{(e)} = \chi_i(|r - R_i^1|) + \chi_i(|r - R_i^1|) = \chi_i^e + \chi_i^o. \tag{4}
\]
where $\mathbf{R}_i^+ = X_i \mathbf{e}_x + Y_i \mathbf{e}_y + Z_i \mathbf{e}_z$ and $\mathbf{R}_i^- = X_i \mathbf{e}_x + Y_i \mathbf{e}_y - Z_i \mathbf{e}_z$ are radius vectors of the grid nodes located symmetrically on the opposite sides of the SM equatorial plane.

As also shown in the above-cited papers, the principal part of the model field (i.e., the one unrelated to the IMF-induced $B_y$) satisfies the required symmetry properties, if the toroidal and poloidal potentials $\Psi_t$ and $\Psi_p$ are, respectively, even and odd with respect to (3). For the component representing the IMF-induced $B_y$, the opposite parities should be assigned. This is achieved by representing the model potentials (2) in the following final form:

$$\Psi_t = \sum_{i=1}^{N} \left[ (a_i^{(0)} + a_i^{(1)} \psi^2) x_i^{(0)} + a_i^{(2)} \psi x_i^{(4)} \right] B_i^{\text{IMF}} \sum_{i=1}^{N} \left[ a_i^{(3)} x_i^{(0)} + a_i^{(4)} \psi x_i^{(0)} \right].$$  (6)

$$\Psi_p = \sum_{i=1}^{N} \left[ (b_i^{(0)} + b_i^{(1)} \psi^2) x_i^{(0)} + b_i^{(2)} \psi x_i^{(0)} \right] B_i^{\text{IMF}} \sum_{i=1}^{N} \left[ b_i^{(3)} x_i^{(0)} + b_i^{(4)} \psi x_i^{(0)} \right].$$  (7)

Here the principal field component, represented by the first sums in (6)–(7), includes terms up to second degree in the tilt angle $\psi$. Its form is similar to equations (7)–(8) in AT16, with the only difference that, instead of binomials in $\cos \psi$ and $\sin \psi$, it contains more flexible quadratic trinomials in $\psi$. The IMF $B_y$-related part of the model field, represented by the second sums in the right-hand side of (6)–(7), is linear both in $\psi$ and $B_i^{\text{IMF}}$. Here the first terms in brackets provide a symmetric (in $\psi$) “penetrated” $B_y$, while the second terms describe an antisymmetric part of $B_y$ due to the tilt-related deflection of the current sheet from the SM equator, which becomes significant at distances $r \gtrsim 10 R_E$. The final equations for the components of the model field $B_y$ are obtained by substituting (6)–(7) in (1). Their derivation is entirely straightforward, but the final equations are somewhat cumbersome, for which reason we do not reproduce them here and relegate the interested readers to the supporting information, which contains all the essential algebra.

The main advantage of the above formulation is the possibility to extract the IMF $B_y$ effects from the total external field by separately representing the IMF-induced $B_y$ by the second sums in (6)–(7) and thus distinguish it from the relatively large regular $B_y$, caused by the tailward flaring of the field lines and their twisting due to the Region 1/2 Birkeland currents. Results of applying this procedure are described below in section 4.

3. Data and RBF Grids

Spacecraft data used in this work were selected from a “grand” collection of 5-min average magnetic field vectors, compiled from observations by five magnetospheric missions (Geotail, Polar, Cluster, Themis, and Van Allen Probes) during 1995–2016. A detailed account of contributing experiments, general data preparation procedures, and related references can be found in our previous publications (e.g., Tsyganenko & Andreeva, 2017, section 3, and Andreeva & Tsyganenko, 2018, section 4, and references therein). To save page space and avoid repetitive descriptions, we omit those details and refer the reader to the above sources.

The subject of this study is the IMF $B_y$ effects in the low-latitude magnetosphere permeated by closed magnetic field lines, extending to the magnetopause on the dayside and to the inner magnetotail (down to $X_{\text{GSM}} \sim -15 R_E$) on the nightside. The modeling was carried out in two variants, conventionally termed below as “global” and “local.” The global variant covers the entire $360^\circ$ range of the longitude, while the local one focuses on only the nightside sector but spans a wider range of the SM latitude. The following sections 3.1 and 3.2 describe in more detail the data subsets and RBF grids used in each case.

3.1. Data/Grid in the Global Model

In this case, the modeling covers all local times, but in order to keep the problem computationally feasible, most part of the high-latitude open flux region is excluded from the analysis. To that end, both the data and the RBF grid are restricted to the inside of the domain, bounded by two symmetric funnel-like surfaces, separating the tail lobes from the low-latitude magnetosphere and defined in spherical SM coordinates $(r, \theta, \phi)$ as

$$\theta(r, \phi) = \arcsin \left[ \frac{\sqrt{r}}{(r^2 + \sin^{-2}\theta_0(\phi) - 1)^{1/2v}} \right].$$  (8)
Figure 1. Distribution of spacecraft data (blue specks) and RBF grid nodes (red circular dots) in the noon-midnight XZ (left) and equatorial XY (right) GSM projections. In the left diagram, the TA15 model field lines are also shown for the untilted geodipole orientation. Heavy green and red field lines denote those with the foot point latitudes 78\degree and 68\degree, respectively. For visual clarity, only near-meridional and near-equatorial RBF nodes are shown in the corresponding panels.

where \( \theta_s(\phi) = \theta_{oo} + \Delta \theta_{oo} \sin^2(\phi/2) \) is the colatitude of the funnel’s base at the ionospheric altitude, varying with the longitude \( \phi \) from \( \theta_s(0) = \theta_{oo} = 10\degree \) at noon to \( \theta_s(\pi) = \theta_{oo} + \Delta \theta_{oo} = 15\degree \) at midnight. The above analytical form (8) was previously introduced to define the shape of the northern and southern layers of Region 1 field-aligned currents (e.g., Tsyganenko, 2014, equation (26), and references therein). Its unique property is that at low altitudes the surface (8) is close to dipolar L-shells, while at large distances it extends radially outward and asymptotically flattens out parallel to the equatorial plane. The parameter \( \nu \) quantifies the flaring rate of the surface, so that larger values of \( \nu \) result in a faster transition from the dipole-like to nearly planar shapes at large distances. Here, for the purposes of optimal data and grid node confluence, we set \( \nu = 3 \).

The other restriction was to confine both the data and the RBF nodes inside an average magnetopause derived from the model by Lin et al. (2010) and also to keep them within the radial distance interval \( 5 \leq r \leq 16 \, R_E \). The inner and outer limits on \( r \) were dictated by the following. First, due to specifics of the numerical method (previous section) the model validity region is confined within the volume occupied by the grid nodes. With the angular resolution of the grid \( \sim 6-7\degree \) (hence, the internode distance \( \Delta Z \sim 1 \, R_E \) at \( R \sim 10 \, R_E \) needed to properly resolve the inner tail current), setting the distance limits too wide apart would result in too large a number of the nodes and, hence, in computationally infeasible codes. Second, the satellite data density sharply drops down at distances \( \sim 12 \, R_E \) (apogees of Themis spacecraft; see Figure 1 below). Third, the plasma sheet magnetic field beyond those distances becomes more irregular, chaotic, and turbulent, which makes the modeling in that region less reliable. Finally, the tilt-related deviation of the tail current sheet from the SM equatorial plane becomes significant and steadily grows beyond \( r \geq 10 \, R_E \), which also takes its toll. Taken together, these factors motivated us to restrict the radial span of the data and the RBF grid by the above limits.

In this study, we limited the analysis to only quiet and moderately disturbed conditions. To that end, besides imposing the spatial limitations, the data were also filtered with respect to the state of interplanetary medium. The interplanetary data were downloaded from the OMNI webpage (https://omniweb.gsfc.nasa.gov/form/omni&urluscore;min.html) in the form of 5-min average values of principal solar wind parameters and IMF components, time shifted to a standard location of the bow shock subsolar point. To exclude strongly disturbed or unusually quiet intervals, the following limits were applied to the solar wind speed, dynamic pressure, and IMF components: \( 250 \leq V \leq 450 \, \text{km/s}, 1.5 \leq P_{dyn} \leq 2.5 \, \text{nPa}, \text{IMF } |B_{x,y,z}| \leq 10 \, \text{nT} \). To minimize the effect of sporadic short-lived reversals of IMF \( B_z \), the selection procedure used longer IMF averages, calculated over 30-min trailing intervals, preceding the time moment of a given record. Additional restrictions were also set on the Sym-H index: \(-30 \leq \text{Sym-H} \leq 20 \, \text{nT} \).

As a final result of the data selection, a file containing 556,089 five-minute average records was created and then split into two smaller files, corresponding to northward and southward IMF \( B_z \) conditions and
and the total number of unknown coefficients in (6)–(7) equal to 2,190 in meridional (left) and equatorial (right) projections. To better visualize the boundaries of the modeling region, Figure 2 illustrates the spatial distribution of both data points (blue specks) and the RBF grid nodes (circles) used in the local variant of this study. In the left panel, the data points are rotated about the $Z_{SM}$ axis onto midnight meridian plane, and only midnight RBF nodes are shown to avoid overlapping. In the right panel, the data points are rotated about $Y_{SM}$ axis into SM equatorial plane, and only near-equatorial nodes are shown.

containing 282,839 and 273,250 records, respectively. For the sake of brevity, they will be referred to below, respectively, as Subsets 1 and 2, with the following statistical characteristics. For Subset 1, IMF $\langle |B_z| \rangle = 2.45$, $\langle |B_x| \rangle = 2.77$, $\langle |B_y| \rangle = 2.13$ nT, solar wind $\langle V \rangle = 366$ km/s, $\langle P_{dyn} \rangle = 2.21$ nPa. For the subset 2: IMF $\langle |B_z| \rangle = 2.59$, $\langle |B_x| \rangle = 2.76$, $\langle |B_y| \rangle = 2.00$ nT, $\langle V \rangle = 366$ km/s, and $\langle P_{dyn} \rangle = 2.22$ nPa.

The RBF grid was assumed in the previously used form (AT16), based on Kurihara’s (1965) scheme of the node placement on a family of nine concentric nested spheres, with the radii of the innermost and outermost spheres equal, respectively, to 6.00 and 15.24 $R_E$. The latitude resolution of the grid was set at 6.5°, which provided a spatial resolution at the inner and outer boundaries of the modeling region equal to 0.68 and 1.73 $R_E$, respectively. From thus generated spherical set of nodes, only those were then selected that fell inside the above described spatial domain. This resulted in the total number of nodes in the final RBF grid $N = 2,190$, and the total number of unknown coefficients in (6)–(7) equal to $2,190 \times 10 = 21,900$.

Figure 1 illustrates the spatial distribution of data points and RBF nodes in the global variant of the modeling, based on the above described selection criteria. To avoid overly dense data clouding in the figure, only every 15th data point was plotted. To better visualize the coverage in the context of the magnetospheric geometry, the magnetic field lines are also plotted in the left panel, calculated on the basis of the TA15 model (Tsyganenko & Andreeva, 2015) for quiet conditions and zero dipole tilt angle. For the reader’s orientation, the dayside and nightside field lines with foot point latitudes 78° and 68° are highlighted with green and red, respectively.

### 3.2. Data/Grid in the Local Model

In the local variant, the data subsets and the RBF nodes were confined to only a limited nightside longitude sector $|\phi_{SM} - 180°| \leq 60°$. At the same time, a significantly wider latitude span $|\lambda_{SM}| \leq 40°$ was adopted, with the aim to better explore the nightside effects of the dipole tilt on the IMF-induced $B_z$ field. Radially, the lower and upper limits on the data geocentric distance were again set equal to 5.0 and 16 $R_E$. The inner and outer radii of the RBF grid were assumed here equal to 5.5 and 14.0 $R_E$, and the latitude resolution was again set at 6.5°, which resulted in 774 grid nodes and the total number of unknown model coefficients equal to 7,740. With the same data selection criteria as in the global variant, two smaller subsets were again created, containing in this case 97,289 and 96,356 five-minute average records for northward and southward IMF $B_z$ conditions, and designated below as Subsets 3 and 4, respectively. Their corresponding statistical characteristics are as follows: for Subset 3, IMF $\langle |B_z| \rangle = 2.50$, $\langle |B_x| \rangle = 2.80$, $\langle |B_y| \rangle = 2.13$ nT, solar wind $\langle V \rangle = 371$ km/s, $\langle P_{dyn} \rangle = 2.22$ nPa. For the subset 4: IMF $\langle |B_z| \rangle = 2.65$, $\langle |B_x| \rangle = 2.78$, $\langle |B_y| \rangle = 2.06$ nT, $\langle V \rangle = 370$ km/s, and $\langle P_{dyn} \rangle = 2.24$ nPa.

Figure 2 illustrates the spatial distribution of both data points (blue specks) and the RBF grid nodes (circles) in meridional (left) and equatorial (right) projections. To better visualize the boundaries of the modeling domain, the data were rotated, respectively, around the $Z_{SM}$ and $Y_{SM}$ axes, so that ordinates in the plots correspond, respectively, to the data point distances $(X_{SM}^2 + Y_{SM}^2)^{1/2}$ from the $Z_{SM}$ axis and $(X_{SM}^2 + Z_{SM}^2)^{1/2}$ from the $Y_{SM}$ axis. The azimuthally extended streaks and circular bands in the data density correspond to
Figure 3. Equatorial distributions of the “penetrated” model $B_y$, induced by IMF $B_y = +5$ nT under northward (left) and southward (right) IMF $B_z$ conditions. The distributions are confined within the domain covered by data and RBF grid, limited by the model magnetopause on the dayside and by the radial distance $r = 16$ $R_E$ on the nightside.

the mission apogees, of which the most distinct one is seen in the innermost dense ring of Van Allen Probes data points.

4. Results

In both global and local cases, the numerical method was qualitatively the same, based on the least squares calculation of the coefficients $\{a_i^{(k)}, b_i^{(k)}\} (k = 0, \ldots, 4; i = 1, \ldots, N)$ entering in the expansions (6)–(7) over a set of $N$ grid nodes. Computationally, this was implemented as a two-step procedure: (1) using a Message Passing Interface based code, construct a $10N \times 10N$ matrix of a system of normal equations and a corresponding $10N$-element right-hand side vector, and then (2) solve the system by means of a Singular Value Decomposition algorithm (Press et al., 1992). The following sections 4.1 and 4.2 separately present the results for the global and local variants, respectively.

4.1. Global Modeling Results

Each of the two data subsets (1 and 2) corresponding to positive and negative IMF $B_z$ was used as input file in the model fitting, which resulted in two output sets of the coefficients $\{a_i^{(k)}, b_i^{(k)}\}$ entering in (6)–(7). Statistically, the obtained fitting results are characterized by the following metrics.

In the case of northward IMF $B_z$ (subset 1), the observed root mean square (r.m.s.) external field magnitude is equal to $|B_{\text{obs}}| = 20.18$ nT, while the residual $|B_{\text{obs}} - B_{\text{mod}}| = 8.11$ nT, that is, 40.2% of the former, which is a typical figure of merit in the empirical modeling (e.g., Tsyganenko & Andreeva, 2016, section 5). It is also instructive to evaluate in this way the relative r.m.s. weight of the IMF $B_y$-related part of the model field represented by the second sums in the right-hand side of (6)–(7). The r.m.s. model field equals here $|B_{\text{mod}}| = 18.57$ nT, whereas its IMF $B_y$-related part amounted to 1.69 nT ($\sim 9.1\%$).

In the case of southward IMF $B_z$ (Subset 2) the field magnitudes are higher (as expected): $|B_{\text{obs}}| = 23.36$ nT and $|B_{\text{obs}} - B_{\text{mod}}| = 10.31$ nT (44.1%). The r.m.s. model field equals here $|B_{\text{mod}}| = 21.43$ nT, whereas its share associated with the IMF-induced $B_y$ rises in this case to 5.18 nT, that is, as large as 24.2% of $|B_{\text{mod}}|$. The most plausible explanation for such a dramatic difference with the above results for northward IMF is twofold. The first possible reason is the dominance of substorm data in Subset 2, often taken during intervals of flux rope formation, emergence of field-aligned currents, and guide fields, strongly correlated with IMF $B_y$ (e.g., Hesse & Kivelson, 1998). The second very important factor is the contribution from the dayside Region 1 currents, whose intensification under southward IMF conditions, combined with their IMF $B_y$-induced overlapping in the noon sector results in large azimuthal fields, strongly correlated with the IMF $B_y$ (e.g., Tsyganenko & Andreeva, 2018, and references therein). As shown below, this is confirmed by the results of reconstructing spatial patterns of the “penetrated” $B_y$. 
Figure 3 shows equatorial distributions of the IMF-induced model $B_y$ under positive (left) and negative IMF $B_z$ conditions for zero dipole tilt. In this test example we set IMF $B_y = +5$ nT; it should also be noted in passing that, due to the assumed linear dependence of the model field on the IMF $B_y$ (equations (6)–(7)), reversing the IMF $B_y$ orientation does not affect the shape of the internal equatorial $B_y$ distribution nor its absolute magnitude but only reverses its polarity. Several interesting features can be seen in the plots. First, the induced $B_y$ is not limited to only the nightside but extends throughout the entire equatorial magnetosphere. The effect is clearly seen even in the noon area, where the penetration coefficient can reach nearly 0.4 (right panel). As far as we know, the IMF $B_y$ effects in the near-equatorial dayside region were studied only on the basis of geostationary measurements (Tenfjord et al., 2017, 2018; Wing et al., 1995) and our obtained penetration coefficients 0.2–0.4 agree with those previous results. Second, the largest induced $B_y$ clearly concentrates on the nightside in the form of a relatively narrow and intense dawn-dusk oriented ridge, which bifurcates into a pair of premidnight and postmidnight peaks. Incidentally, a similar bifurcation with much stronger “penetrated” $B_y$ near the tail flanks was found by Kaymaz et al. (1994) on the basis of IMP-8 data, though at much larger radial distances $r \sim 30$ $R_E$ than in the present study. Third, the penetration is dawn-dusk asymmetric, with a somewhat wider extent on the dawnside, especially in the case of northward IMF $B_z$. The cause of the effect is not clear; it may be of either internal (such as the convection asymmetry, e.g., Spence & Kivelson, 1993; Sitnov et al., 2017) or external (IMF spiral structure) origin, or both. Finally, the overall intensity of the IMF $B_y$ penetration is significantly higher under the southward IMF. Note in this regard that a qualitatively similar result was found by Tenfjord et al. (2017, 2018) and Cao et al. (2014). Petrukovich and Lukin (2018) also reported a stronger penetration during southward IMF $B_z$ at $r \leq 25$ $R_E$.

The relative magnitude of the penetrated $B_y$ obtained in the present study is probably the largest ever: as one sees in the right diagram in Figure 3, in the peak areas the induced $B_y$ not only reaches 100% of the IMF $B_y$ but also can be even higher. It is also important to emphasize that the data in our subsets represent a mixture of many different magnetospheric states and the above diagrams represent just average statistical $B_y$ distributions. This means that in real individual events, the actual induced $B_y$ may be significantly larger than the average values predicted by this model.

Figure 4 displays the noon-midnight meridional distribution of the induced $B_y$ for the same two cases of opposite IMF $B_z$ polarities. On the nightside, the penetration efficiency peaks within a relatively narrow vicinity of the equatorial plane at $X \sim -10$ $R_E$. Although the induced $B_y$ appears to completely vanish toward the outer boundaries of the modeled region, this is most likely a fringe effect due to the absence of grid nodes and the relative sparsity of data in that areas, evident in Figure 1.

In the daytime sector, the penetration coefficient does not exceed 0.4 at low latitudes but dramatically increases toward the polar cusps. In the case of southward IMF $B_z$ (right panel), the induced model $B_y$ actually rises to $\sim 10$ nT at $X = 6$ and $Z = 10$, that is, twice the IMF $B_y = 5$ nT (the color scale saturates at 5 nT and cannot reproduce larger values). This is a well-known effect due to the latitudinal splitting and longitudinal overlapping of Region 1 field-aligned currents, observed both in the AMPERE data and in the MHD simulations (Korth et al., 2011), and also reproduced in a recent empirical modeling study (Tsyganenko & Andreeva, 2018).
4.2. Local Modeling Results

As already noted in section 3.2, the purpose of the separate modeling on the nightside was to explore in more detail the dipole tilt angle dependence of the induced $B_y$, particularly in the context of the tail current seasonal and diurnal bending/warping. In the above described global variant, the midnight latitudinal extent of the RBF grid at $r \geq 10$ $R_E$ was limited within $\pm 30^\circ$ sector, while the tilt-related angular deflection of the tail current from the SM equator can also reach comparable values, which could result in unwanted fringe effects in the obtained $B_y$ distributions. Another motivating factor behind the separate local modeling was to check the overall consistency between the results obtained using RBF grids and data subsets with different spatial coverage.

Based on the data subsets 3 and 4 and the local RBF grid, described in section 3.2, two sets of local model coefficients were generated by means of the fitting codes, similar to those used for the global variant. In this case, the modeling resulted in the following metric characteristics. For Subset 3 (northward IMF $B_z$), the r.m.s. observed field $||B_{obs}|| = 24.0$ nT, and the residual $||B_{obs} - B_{mod}|| = 9.9$ nT. The r.m.s. model field magnitude was found equal to $||B_{mod}|| = 21.9$ nT, and its IMF $B_y$-related part amounted to only 0.27nT ($1.2\%$ of $||B_{mod}||$). This is much less than in the corresponding global variant; a natural explanation is the absence of the contribution to $B_y$ from the dayside Birkeland currents in the nightside modeling, as well as the general weakness of the nightside Region 1 field-aligned currents under northward IMF conditions.

In the opposite case of southward IMF $B_z$ (subset 4), all the corresponding figures are higher: $||B_{obs}|| = 29.8$ nT, $||B_{obs} - B_{mod}|| = 12.4$ nT, $||B_{mod}|| = 27.0$ nT, and its IMF $B_y$-related part equals 3.0nT, that is, $11\%$ of $||B_{mod}||$.

To better visualize the field line geometry in the region of interest, two magnetic configurations have also been reconstructed, based on the local model coefficients derived from Subsets 3 and 4. The result is shown in Figure 5, whose left/right panels display meridional field line projections for zero dipole tilt and northward/southward IMF, respectively. The blue shading indicates the area covered by data and RBF grid nodes, corresponding to the model’s region of validity.

As expected, under the southward IMF conditions the nightside field is more stretched; also, in both cases the field lines with ionospheric footpoint latitudes $|\lambda_i| \leq 68 - 69^\circ$ are closed through the equatorial plane.

Figure 6 shows the equatorial (top panel) local distribution of the model $B_y$, induced on the nightside under positive IMF $B_z$ conditions and at zero dipole tilt. Aside from minor differences, it looks quite similar to that shown in the left panel of Figure 3 for the global variant, discussed in the preceding section. The cross-tail distribution in the bottom panel corresponds to $X = -9$ $R_E$ (shown by white dashed line in the top diagram); it reveals a relatively thin region with a strong IMF-induced $B_y$, extending all the way from dawn to dusk and confined to a narrow near-equatorial layer. Heavy red dashed lines indicate the crossing of the $X = -9$ $R_E$
Figure 6. Distributions of penetrated model $B_y$, induced by IMF $B_y = +5$ nT under northward IMF $B_z$ conditions: (top) in the SM equatorial plane and (bottom) in the cross-tail section at $X_{GSM} = -9$ RE (indicated by horizontal white dashed line in the top panel). The red dashed line near the edges of bottom panel shows the outer boundary of the RBF grid.

Figure 7. Same as in Figure 6, but for southward IMF $B_z$ conditions.

In the next Figure 7, a similar plot is shown for negative IMF $B_z$ conditions and for the same input value of IMF $B_y = +5$ nT. Again, the upper diagram is close to that for the corresponding global variant in the right panel of Figure 3, with a similar double-peaked distribution, which is now more symmetric and significantly more intense in comparison with that for positive IMF $B_z$. Likewise, the bottom panel again demonstrates the concentration of the penetration effect near the equatorial plane.

The origin of relatively small areas of negative $B_y$ near the borders of the modeling region is not quite clear. They may well be due to a fringe effect at the border of the RBF grid, combined with sparsity of the data points. This conjecture is partially supported by a similar feature found in the case of tilted Earth’s dipole, as discussed below.

### 5. Discussion

In view of the confinement of the penetrated $B_y$ inside the relatively narrow near-equatorial zone, evident in Figures 6–7, a natural question arises as to the configuration of associated electric currents. To that end, we calculated a distribution of the current component $J_\rho$, normal to the surface of a cylinder $\rho = 9$ RE coaxial with the Z axis.

The result is shown in Figure 8, which reveals four separate areas of current, flowing earthward/tailward in the north/south hemispace, with a distinct gap around midnight and slightly more intense and wider $|J_\rho|$ distribution in the postmidnight sector. The currents maximize in the range $z \approx \pm (4–8)$ RE, which, in view of the magnetic configurations shown in Figure 5, suggests that they flow on open field lines that envelop the plasma sheet boundary layer. It should be kept in mind that the currents shown in Figure 8 correspond to only the IMF $B_y$-associated part of the total field, represented by the second sums in (6)–(7). Added to the main part of the system, they destroy the original dawn-dusk symmetry of the configuration; in the present example with positive IMF $B_y$, their net effect is to increase the Region 1 field-aligned currents in the north-dusk/south-dawn sectors and decrease them in the north-dawn/south-dusk sectors. Such a redistribution of currents results in a buildup of positive $B_y$ inside the plasma sheet.

One more noteworthy comment should be made. The above described model contains the Earth’s dipole tilt angle as a parameter, which prompts an interesting question about its influence on the penetration magnitude and spatial distribution. Figure 9 shows cross-tail distributions of the induced $B_y$ in the same plane $X_{GSM} = -9$ RE as in Figures 6 and 7, for both orientations of the IMF $B_z$ and the dipole tilt angle $\Psi = 25^\circ$. As intuitively expected, the positive dipole tilt results in an overall northward shift of the penetrated $B_y$ distribution, in the same manner and of roughly the same magnitude as the tilt-related shift of the tail current. The deformed cross-tail $B_y$ pattern retains its main features present in the untilted configuration, such as the double-peaked structure and the dawn-dusk asymmetry (especially in the case of northward IMF). In addition, the overall intensity of the effect is notably stronger in the tilted case. To our knowledge, the only study of the dipole tilt impact on the induced $B_y$ was made by Petrukovich (2009, 2011), but the tilt effect was described in that model via a separate term, completely unrelated to the IMF $B_y$. 
Figure 8. Distribution of the $\rho$ component of volume density of electric current across a cylindrical surface $\rho = (x^2 + y^2)^{1/2} = 9 \, R_E$ coaxial with the $Z_{GSM}$ axis, viewed from the tail along $X_{GSM}$ axis. The abscissa $S$ measures the distance along the surface from the midnight meridian plane (where $S > 0$ or $S < 0$ corresponds to dusk or dawn sectors, respectively). The current was calculated as curl of the “penetrated” part of model B for negative IMF $B_z$ conditions, and the resultant cylindrical map is unrolled onto the picture plane. The diagram corresponds to IMF $B_y = +5 \, nT$.

Another thing that immediately attracts attention is a rather extended blue-colored area in the bottom of each diagram with negative polarity of the induced $B_y$. In principle, there is no reason to reject its reality from the outset; note, however, that those regions in both cases lie outside the RBF grid boundary (red dashed line). Based on that, we interpret those features as most likely an artifact caused by the absence of the grid nodes in that area.

6. Summary

Based on the flexible RBF representation of the geomagnetic field and large multimission set of in situ magnetometer data, the effect of IMF azimuthal component “penetration” has been for the first time reconstructed in three dimensions. It is shown that, even on a statistical level with a crude selection of data, the effect is quite significant, especially under southward IMF conditions. The IMF-induced magnetospheric $B_y$ is separated from the overall background field by splitting the model field into components with different symmetry properties. It is shown that the effect (i) concentrates within a relatively narrow layer centered

Figure 9. Distribution of the IMF-induced $B_y$ in the cross-tail plane $X_{GSM} = -9 \, R_E$ for positive (left) and negative (right) IMF $B_z$, and tilted Earth’s dipole with $\Psi = 25^\circ$. The diagram corresponds to IMF $B_y = +5 \, nT$. The red dashed hyperbolic contour below the equatorial plane delineates the southern boundary of the RBF grid.
about the SM equator, (ii) increases toward dawn and dusk flanks, (iii) maximizes at radial distances in the range 10−12 R_E, and (iv) is significantly stronger under southward IMF conditions and for tilted orientation of the Earth’s dipole. The penetration effect is due to the IMF-induced asymmetry of field-aligned currents flowing in the plasma sheet boundary layer.

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