

Model Calculations of Currents and Magnetic Fields Along a Magsat Trajectory

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Recent models have made it possible to obtain distributions of ionospheric and field-aligned currents at high latitudes from surface magnetic observations. The surface geomagnetic field variations at high latitudes are closely associated with interplanetary medium parameters. As a result, a model has been developed that estimates high-latitude current distributions directly from the interplanetary magnetic field and solar wind values. Ionospheric and field-aligned current distributions computed with this technique are compared to the distributions computed directly from the Magsat magnetic field observations by *Zanetti et al.* [1983]. There are small variations in the two results, which are apparently due to the different resolutions of the two techniques. However, the current distributions computed from the different techniques are similar.

INTRODUCTION

Magnetic field variations at the earth's surface are caused by several current sources situated in the earth's ionosphere and magnetosphere. The identification of these sources is one of the principal goals of geomagnetic studies. However, the magnetic field observations on the earth's surface alone cannot determine uniquely the distribution of the associated three-dimensional current system. In order to make this determination, additional information on the spatial current distribution is needed.

By using the ground observations, so-called "equivalent currents" are usually determined using the potential theory applied to a spherical shell concentric with the earth. However, the surface magnetic fields are due to a more complicated three-dimensional current system that includes ionospheric and field-aligned currents. For this reason, it has been assumed that it is necessary to measure magnetic fields above the ionosphere in order to uniquely determine the associated current systems.

Considerable progress has been made in inferring three-dimensional current systems by combining electric and magnetic field measurements from satellites with radar observations. However, it was still not possible to determine the three-dimensional current distribution in the entire high-latitude region instantaneously. Ground-based magnetic data have recently been used to deduce instantaneous distributions of field-aligned currents. For the case of uniform ionospheric conductivity, the Laplacian of the current function is proportional to the field-aligned current density [Kern, 1966]. This relationship can be used for the determination of field-aligned current distributions at high latitudes during summer, when the ionospheric conductivity is sufficiently uniform [Levitin et al., 1981]. More complicated computer codes have been proposed by *Mishin et al.* [1980], *Faermark* [1980], and *Kamide et al.* [1981] for the determination of the distribution of ionospheric and field-aligned currents using nonuniform ionospheric conductivity models. However, there are constraints pertaining to the spatial distribution of current that are inherent in these models. That is why it is not surprising that the following opinion has been put forth [Potemra, 1983]: "It was not possible (before the satellite era)

to unambiguously identify current systems that are field-aligned (Alfvén, 1939, 1940) and those that are completely contained in the ionosphere (Vestine and Chapman, 1938) only from the study of surface magnetic field measurements (see also Fukushima, 1969, 1976)."

Zanetti et al. [1983] have indicated the difficulties involved in the determination of ionospheric and field-aligned current distributions from ground-based magnetometer data. They determined ionospheric and field-aligned current distributions from Magsat vector magnetometer data using a method based on the Fourier transform technique.

The purpose of this brief report is to compare the distribution of ionospheric and field-aligned currents during a Magsat pass obtained by *Zanetti et al.* [1983] with the distribution calculated with the help of the *Afonina et al.* [1983b] model, which is based on surface magnetic field variations and interplanetary magnetic field (IMF) conditions. The magnetic field variation expected along the Magsat satellite trajectory is calculated from the deduced three-dimensional current system model and is compared to the actual data.

METHOD

The method of calculating ionospheric electric fields and three-dimensional current systems, including ionospheric and field-aligned currents, used here was originally proposed by *Gurevich et al.* [1976]. The associated computer code was developed by *Faermark* [1980] and *Kamide et al.* [1981] for the case of nonuniform ionospheric conductivity.

Electric fields, E , and currents, I , in the ionosphere are determined from the relation

$$\vec{E} = -\nabla\phi \quad I = \hat{\Sigma}E = -\hat{\Sigma}\nabla\phi = I_t + I_p$$

where ϕ is the potential of the electric field, $\hat{\Sigma}$ is the height-integrated ionospheric conductivity tensor, I is the total height-integrated ionospheric current, $I_t = \mathbf{n}_r \times \text{grad } \psi = \text{Curl } \psi$ (two-dimensional curl) is the toroidal current, $I_p = \nabla F$ is the potential current, ψ is a current function uniquely related to the horizontal magnetic field variation on the earth's surface, and \mathbf{n}_r is the unit radial vector. It is assumed that the electric field is static, that the dynamo effects of ionospheric winds can be neglected, and that the geomagnetic field lines are equipotential at ionospheric heights. The ionosphere is regarded as a two-dimensional spherical current sheet with height-integrated Peder-

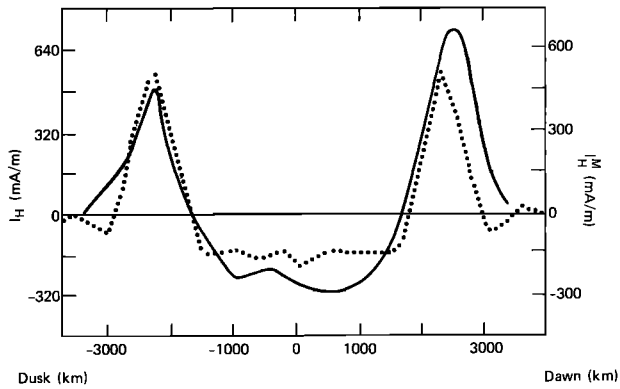


Fig. 1a Height-integrated Hall current density distribution, I_H , in the ionosphere (the dotted line and the left-hand scale) along the Magsat trajectory on December 21, 1979 [Zanetti *et al.*, 1983]. The values of I_H^M computed from the model of Afonina *et al.* [1983a] are shown as the solid line (the right-hand scale). The distances in kilometers along the trajectory are measured from the noon-midnight meridian.

sen (Σ_P) and Hall (Σ_H) conductivities. The Hall current is determined in the ionosphere from the following:

$$I_H = \Sigma_H \mathbf{E} \times \mathbf{n}_r$$

Geomagnetic field lines are taken to be radial, and the field-aligned current is determined from

$$j_{\parallel} = \text{div } I$$

The electrostatic potential, ϕ , of the electric field above the ionosphere is determined by solving

$$\text{Curl } (-\Sigma \nabla \phi) = \text{Curl } \text{Curl } \psi$$

In spherical coordinates, Θ, λ (where is Θ colatitude and λ is longitude), the equation has the form

$$-\frac{1}{r} \left[(r \Sigma_H \phi_{\Theta})_{\Theta} + \frac{1}{r} (\Sigma_H \phi_{\lambda})_{\lambda} \right] + \frac{1}{r} [(\Sigma_P \phi_{\lambda})_{\Theta} - (\Sigma_P \phi_{\Theta})_{\lambda}] = \frac{1}{r} (r \psi_{\Theta})_{\Theta} + \frac{1}{r^2} \psi_{\lambda\lambda}$$

where $r = \sin \Theta$. Algorithms for solving the equation for non-uniform ionospheric conductivity with a given current function, ψ , have been described by Faermark [1980] and Kamide *et al.* [1981]. The boundary conditions were taken to be $\phi = 0$ at $\Theta = 34^\circ$ [Faermark, 1980], or $\phi = 0$ at the pole and $\partial\phi/\partial\Theta = 0$ at the equator [Kamide *et al.*, 1981].

In the model of Afonina *et al.* [(1983b), the height-integrated ionospheric conductivity tensor is specified on a grid with a 1° step in latitude and a 15° step in longitude (1 hour of local geomagnetic time). The current function was calculated for different classes of geomagnetic field variations on the earth's surface. Each class of variation was controlled by a specific IMF component (B_y and B_z) and by the solar wind velocity and density at $B_z = B_y = 0$. Methods for determining these variations by a regression analysis and the resultant equivalent current systems are described by Levitin *et al.* [1982]. For the calculation of ϕ from a given current function, it is assumed that the magnetic contributions of the ring current, magnetopause currents, and tail currents to the equivalent current function can be neglected. The total integral Hall and Pedersen conductivities are the sum of the conductivities resulting from both ionization by solar wave radiation and corpuscular precipitation. The

corresponding conductivity values have been taken from the papers of Mehta [1979] and Wallis and Budzinski [1981].

Therefore, the distribution of ionospheric and field-aligned currents can be estimated from ground-based magnetic field variation data by assuming realistic high-latitude conductivity distributions. During the summer, the distributions of these currents are not very sensitive to the assumed corpuscular conductivity model associated with corpuscular precipitation.

RESULTS

The results of the calculation of ionospheric and field-aligned currents with two very different methods [Zanetti *et al.*, 1983; Afonina *et al.*, 1983a,b] will be compared to interpret the Magsat data. We examine here the Magsat pass of December 21, 1979, over the summer southern hemisphere. In the summer season, the ionospheric conductivity distribution is more uniform as a consequence of the stabilizing effect of solar radiation. Therefore, the actual ionospheric and field-aligned current distributions for specific cases should be closer to the average distributions described by the Afonina *et al.* [1983a,b] model than in any other season. Moreover, during this particular orbit, Magsat traversed the eastward and westward electrojets in the early evening and late morning sectors, where the electrojets are caused by strong convection electric field, and not by high ionospheric conductivity [Kamide and Vickrey, 1983]. The convection electrojets are located in these time sectors in contrast to the substorm electrojet, which is located in its midnight sector (Y. Kamide, personal communication, 1984). The convection electrojets are more closely connected with the voltage source in the magnetosphere controlled by interplanetary medium parameters than is the substorm electrojet. The solar wind density and velocity and IMF components are relatively stable during this time.

Figure 1a shows the distribution of ionospheric Hall currents, I_H (the dotted line and the left scale), along the Magsat trajectory on December 21, 1979, determined by Zanetti *et al.* [1983]. Also shown are the results of calculating the Hall current, I_H^M , from the electric field model of Afonina *et al.* [1983a] (the solid line and the right scale), and using the ionospheric conductivity model of Wallis and Budzinski [1981] for $K_p > 3$ and the IMF components $B_z = -4.3$ nT and $B_y = 0.6$ nT [King, 1983]. The similarity between I_H and I_H^M is evident.

The magnetic variations computed from the model used here have fit observed values with rms (root-mean-square) differ-

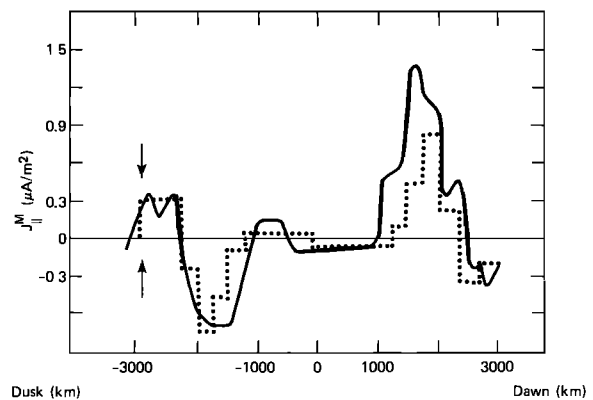


Fig. 1b The values of field-aligned current density, J_{\parallel} , along the Magsat trajectory (Zanetti *et al.* [1983], dotted line) and J_{\parallel}^M from the model (Afonina *et al.* [1983b], the solid line).

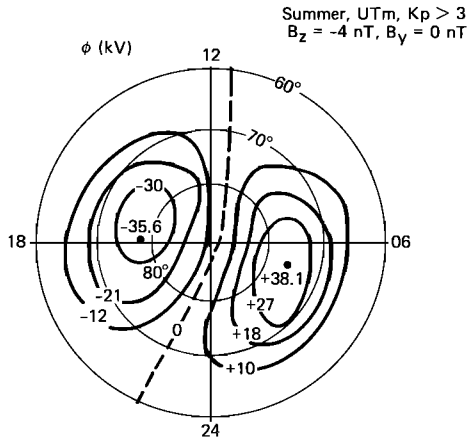


Fig. 2a

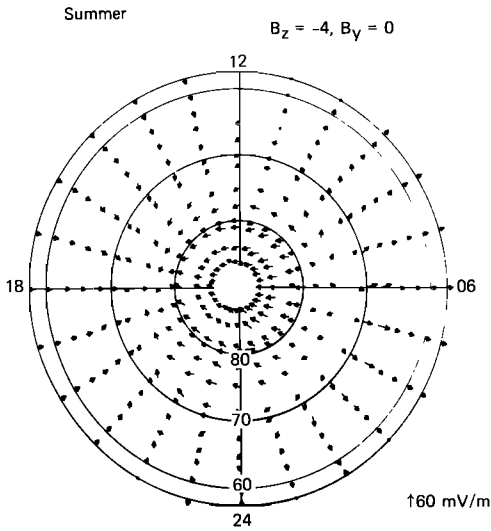


Fig. 2b

Fig. 2 The space-time patterns of the model values of (a) electrostatic potential ϕ and (b) electric field, E , in summer with $B_z = -4$ nT and $B_y = 0$. The model of Wallis and Budzinski [1981] for height-integrated ionospheric conductivity for $Kp < 3$ was used. The coordinates are corrected geomagnetic latitude and MLT.

ences of about 30 nT in the polar cap, and 50 nT in the auroral zone. The values of I_H and I_H^M compared in this study and shown in Figure 1a agree within these limits.

Figure 1b shows the field-aligned current densities, J_1 , along the same Magsat trajectory (the dotted line) according to Zanetti et al. [1983], and J_1^M computed with the model of Afonina et al. [1983b] (the solid line). The arrows indicate the J_1 flow direction. The density of J_1 is obtained from the magnetic field variation, ΔB_y , along the Magsat trajectory from the relationship [Zanetti et al., 1983]

$$J_1 = 0.796 \frac{\partial(\Delta B_y)}{\partial x}$$

where ΔB_y is in nT, x is in km, and J_1 is in $\mu A/m^2$.

Considering the complicated field-aligned current space distribution, one can find a similarity between J_1 and J_1^M . The slight differences between J_1 and J_1^M in Figure 1b may be the consequence of two very different methods of calculating field-aligned currents from different data input and of instantaneous

density deviations from the average value described by the model.

The differences of the curves for J_1 and J_1^M in Figure 1b can also be caused by the proximity of the ground measurements to the ionosphere. The short-wavelength disturbance features fall off exponentially, thus changing drastically with respect to the height difference of the ionosphere and Magsat altitudes. It is also interesting to speculate about possible relationships between the irregularity of the J_1^M curve in Figure 1b and the altitude difference.

It appears that both methods for calculating ionospheric and field-aligned currents give similar results. However, the method of ground-based geomagnetic measurements associated with various interplanetary situations makes it possible to obtain instantaneous fields and current distributions not only along a given trajectory but also in the entire high-latitude region ($\Theta < 34^\circ$).

Figures 2 and 3 show the distribution of electrostatic potential, ϕ_M , of electric field, E ; and of field-aligned current, J_1 ,

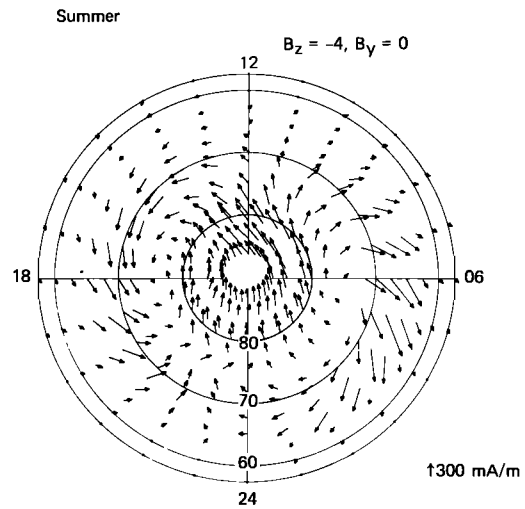


Fig. 3a

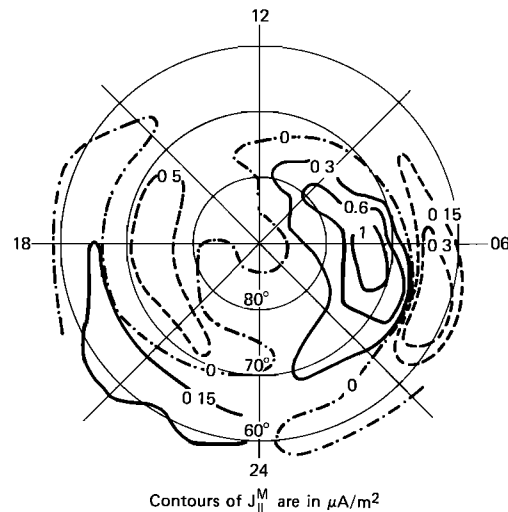


Fig. 3b

Fig. 3 The space-time pattern of the model values of (a) the total integral ionospheric current, J_\perp^M , and (b) field-aligned current, J_1^M , in summer with $B_z = -4$ nT and $B_y = 0$.

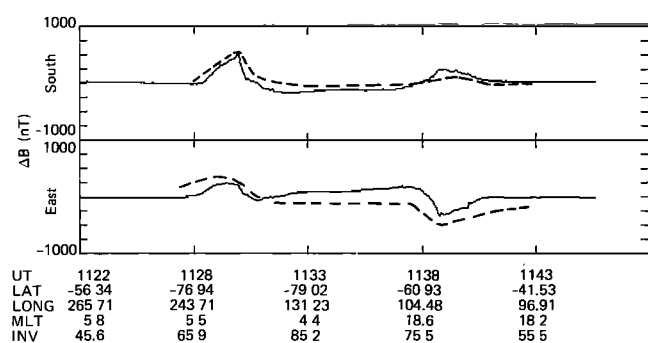


Fig. 4 The Magsat magnetometer data (southward and eastward components of geomagnetic field variation in geographic coordinates) on December 21, 1979, with the Magsat April 1981 model subtracted (the solid line) according to Zanetti *et al.* [1983]. The dashed line is the magnetogram calculated from the three-dimensional current system model [Dremuhina *et al.*, 1983] with IMF $B_z = -4.3$ nT and $B_y = 0.6$ nT. The data are plotted versus invariant latitude and magnetic local time (MLT).

and total ionospheric currents, $J_1^M = J_i + J_p$, in the summer under the interplanetary situation during the Magsat pass on December 21, 1979. The relevant models of field-aligned and ionospheric currents, and electric field and its potential, on a grid with steps of 1° of geomagnetic latitude ($\Theta < 34^\circ$) and 1 hour of MLT, are stored at the World Data Center B2 (WDC-B2). These are available as functions of the IMF intensity and orientation, for three seasons and for various ionospheric conductivity models. Copies of the models may be obtained on magnetic tape.

The present methods for determining electric fields and currents from surface geomagnetic field variations imply that the ionospheric currents are responsible for such variations. Therefore, these methods can accurately reproduce the fields and currents at high latitudes, and with somewhat less accuracy at medium and low latitudes [Kamide *et al.*, 1982; Wolf and Kamide, 1983]. This circumstance arises from the important contribution of the fields of extra-ionospheric origin to the geomagnetic field variations on the earth's surface.

We now compare the magnetic field measurements from Magsat and the field associated with our three-dimensional current system model. Figure 4 shows the geographic north-south and east-west components of magnetic fields measured by the Magsat magnetogram made on December 21, 1979, from Zanetti *et al.* [1983] (the solid line) and the magnetic field disturbance calculated from the model of Dremuhina *et al.* [1983] (the dashed line) using the method described by Kisabeth [1979]. The ionospheric current distribution was determined for the condition of $B_z = -4.3$ nT, $B_y = 0.6$ nT from the model of Afonina *et al.* [1983a]. The field-aligned currents flowing along the dipole magnetic force lines connected to the ionospheric current were taken as the boundary condition. The calculations were made on a grid with steps of 2° of latitude and 1 hour of MLT, for $\Theta < 31^\circ$ and a 400-km altitude. The model magnetogram compares very well to the observed field variations. The differences in the values of the eastward component in the polar cap are probably due to an improper choice of the baseline. Zanetti *et al.* [1982] indicate that the baseline is very sensitive to the choice of the main geomagnetic field model. An approximately 250-nT variation of the eastward component probably does not exist in the polar caps during relatively weak substorms. If the solid line in the lower panel of Figure 4 is displaced to

be coincident with the dashed line in the polar cap, the agreement of the two curves improves in the auroral zone where the field variations are largest. The field model calculations used to generate the curves in Figure 4 may be used to correct the Magsat baseline.

CONCLUSION

The present models of ionospheric and field-aligned currents based on surface geomagnetic field variations make it possible to obtain space-time distributions of ionospheric and field-aligned currents at high latitudes. The surface geomagnetic field variations at high latitudes are closely related to the parameters of the interplanetary medium. As a result, models that are based on the IMF intensity and direction and on the solar wind parameters may be used to estimate the distribution of these currents.

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REFERENCES

- Afonina, R. G., B. A. Belov, V. Yu. Gaidukov, L. A. Dremuhina, A. E. Levitin, D. S. Faermark, Y. I. Feldstein, Yu. Z. Demidova, and M. Yu. Markova, The model of large-scale electric field in the high-latitude ionosphere inferred from the geomagnetic data, in *Geomagnetic Variations, Electric Fields and Currents*, edited by A. E. Levitin, p. 3, Izmiran, Moscow, 1983a.
- Afonina, R. G., B. A. Belov, V. Yu. Gaidukov, L. A. Dremuhina, A. E. Levitin, D. S. Faermark, Y. I. Feldstein, Yu. Z. Demidova, and M. Yu. Markova, The model of large-scale field-aligned currents in the high-latitude ionosphere inferred from the geomagnetic data, in *Geomagnetic Variations, Electric Fields and Currents*, edited by A. E. Levitin, p. 39, Izmiran, Moscow, 1983b.
- Alfvén, H., Theory of magnetic storms, 1, *K. Sven. Vetenskapsakad Handl.*, 3 (3), 18, 1939.
- Alfvén, H., A theory of magnetic storms and of the aurorae, II, III, *K. Sven. Vetenskapsakad Handl.*, 3 (9), 18, 1940.
- Dremuhina, L. A., B. A. Belov, A. E. Levitin, and Y. I. Feldstein, Magnetic disturbances of the three-dimensional current system in the high-latitude on the altitude 800 km, in *Geomagnetic Variations, Electric Fields and Currents*, edited by A. E. Levitin, p. 52, Izmiran, Moscow, 1983.
- Faermark, D. S. Method of electric and magnetic field calculation in high-latitude ionosphere, in *Solar Wind and Magnetosphere Investigation*, edited by A. E. Levitin, p. 122, Izmiran, Moscow, 1980.
- Fukushima, N., Equivalence in ground geomagnetic effect of Chapman-Vestine's and Birkeland-Alfvén's electric current systems for polar magnetic storms, *Rep. Ionos. Space Res. Jpn.*, 23, 219, 1969.
- Fukushima, N., Generalized theorem for no ground magnetic effect of vertical current connected with Pedersen currents in the uniform-conductivity ionosphere, *Rep. Ionos. Space Res. Jpn.*, 30, 35, 1976.
- Gurevich, A. V., A. L. Krylov, and E. E. Tsedilina, Electric fields in the earth's magnetosphere and ionosphere, *Space Sci. Rev.*, 19, 59, 1976.
- Kamide, Y., and J. F. Vickrey, Relative contribution of ionospheric conductivity and electric field to the auroral electrojets, *J. Geophys. Res.*, 88, 7989, 1983.
- Kamide, Y., A. D. Richmond, and S. Matsushita, Estimation of ionospheric electric fields, ionospheric currents and field-aligned currents from ground magnetic records, *J. Geophys. Res.*, 86, 801, 1981.
- Kamide, Y., R. A. Wolf, R. W. Spiro, and A. D. Richmond, Inferring electric fields and currents from ground-magnetometer data—A test with theoretically derived inputs (abstract), *Eos, Trans. AGU*, 63, 420, 1982.
- Kern, J. W., Analysis of polar magnetic storms, *J. Geomagn. Geoelectr.*, 18, 125, 1966.
- King, J. H., Interplanetary data book, supplement 2, 1978–1982, *Rep. NSSDC 83-01*, Goddard Space Flight Center, Greenbelt, Md., 1983.
- Kisabeth, J. L., On calculating magnetic and vector potential fields due to large-scale magnetospheric current systems and induced currents

- in an infinitely conducting earth, in *Quantitative Modeling of Magnetospheric Processes*, *Geophys. Monogr. Ser.*, Vol. 21, edited by W. P. Olson, p. 473, AGU, Washington, D. C., 1979.
- Levitin, A. E., R. G. Afonina, B. A. Belov, and Y. I. Feldstein, Geomagnetic variation and field-aligned currents at northern high-latitudes, and their relations to the solar wind parameters, *Philos. Trans. R. Soc. London, Ser. A*, **304**, 253, 1982.
- Mehta, N. C., Ionospheric electrodynamics and its coupling to the magnetosphere, Ph.D. thesis, Univ. of Calif., San Diego, 1979.
- Mishin, V. M., A. D. Bazarzhapov, and G. D. Shpynev, Electric fields and currents in the earth's magnetosphere, in *Dynamics of the Magnetosphere*, edited by S.-I. Akasofu, p. 249, D. Reidel, Hingham, Mass., 1980.
- Potemra, T. A., Birkeland currents: Present understanding and some remaining questions, in *High-Latitude Space Plasma Physics*, edited by B. Hultqvist and T. Hagfors, p. 335, Plenum, New York, 1983.
- Vestine, E. H., and S. Chapman, The electric current system of geomagnetic disturbance, *J. Geophys. Res.*, **43**, 351, 1938.
- Wallis, D. D., and E. E. Budzinski, Empirical models of height integrated conductivities, *J. Geophys. Res.*, **86**, 125, 1981.
- Wolf, R. A., and Y. Kamide, Inferring electric fields and currents from ground magnetometer data: A test with theoretically derived inputs, *J. Geophys. Res.*, **88**, 8129, 1983.
- Zanetti, L. J., T. A. Potemra, and M. Sugiura, Evaluation of high latitude disturbances with Magsat (the importance of the Magsat geomagnetic field model), *Geophys. Res. Lett.*, **9**, 365, 1982.
- Zanetti, L. J., W. Baumjohann, and T. A. Potemra, Ionospheric and Birkeland current distributions inferred from the Magsat magnetometer data, *J. Geophys. Res.*, **88**, 4875, 1983.
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