COMBINING MULTI-POINT SPACECRAFT AND TWO-DIMENSIONAL GROUND-BASED OBSERVATIONS: THEORY AND EXAMPLE OF AN IMF B_Y-RELATED CUSP CURRENT SYSTEM

O. Amm[1], K. Kauristie[1], T.I. Pulkkinen[1], M.J. Engebretson[2], R.A. Greenwald[3], H. Lühr[4], T. Moretto[5]

[1]Finnish Meteorological Institute, Geophysical Research Division, P.O. Box 503, FIN-00101 Helsinki, Finland
(Phone: +358 9 1929-4689; FAX: +358 9 1929-4603; Email: Olaf.Amm@fmi.fi, Kirsti.Kauristie@fmi.fi, Tuija.Pulkkinen@fmi.fi)
[2]Augsburg College, 2211 Riverside Avenue, Minneapolis, MN 55454, USA
[3]Applied Physics Laboratory, Johns Hopkins University, Johns Hopkins Road, Laurel, Maryland 20723-6099, USA
[4]Geoforschungszentrum Potsdam, Telegrafenberg, D-14473 Potsdam, Germany
[5]Danish Space Research Institute, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark

ABSTRACT

Ground-based support is crucial even for a multi-spacecraft mission in the magnetosphere to obtain information on the medium and global scale plasma environment the satellites are located in. Such support can be provided by networks of magnetometers, radars, all-sky cameras, and other ground-based instruments. We give an overview of methods for obtaining two-dimensional, instantaneous distributions of macroscopic ionospheric electrodynamic parameters, starting from different measured input data sets of both satellite and ground-based data. Detailed explanation is given for the method of characteristics which uses ground magnetometer and coherent scatter radar data as an input, and for the newly developed "elementary current method" that can be used if the field-aligned current (FAC) distribution mapped to the ionosphere has additionally been masured by satellites. An application example for the method of characteristics is given for which the detailed FAC configuration of an IMF B_Y-related cusp current system is derived.

1. INTRODUCTION

During and after the International Magnetospheric Study (IMS, 1976-1979), several methods have been developed to obtain spatial, instantaneous distributions of the macroscopic electrodynamic parameters of the ionosphere from ground-based measurements (e.g., Akasofu *et al.*, 1980; Kamide *et al.*, 1982; see the review of Untiedt and Baumjohann, 1993, for methods used with data from Scandinavia). Mostly, the ground magnetic field disturbance measured by magnetometers is the main input quantity to these methods, supported by ionospheric electric field data measured by radars, and optical data, if available. Since no spatial, instantaneous measurements from satellites, e.g., of the FAC distribution, were available, satellite data were mainly used for comparison with the ionospheric results obtained (e.g., Sulzbacher *et al.*, 1982), or as statistically derived distributions using many different satellite pathes (e.g., Rich and Kamide, 1983). Under favourable geometrical circumstances, the four Cluster II satellites now offer the possibility to infer such FAC distributions mapped to the ionosphere, thus giving opportunity to enhance the analysis methods with this input quantity.
In this paper, we will shortly review some of the existing methods, with a focus on the method of characteristics (Inhester *et al.*, 1992; Amm, 1995, 1998). Furthermore, improved methods using the FAC distribution as an input are discussed, and the "elementary current method" (ECM) that utilizes this input together with ground magnetic and ionospheric electric field data is presented.

2. OVERVIEW OF METHODS TO INFER SPATIAL IONOSPHERIC ELECTRODYNAMICS

Table 1 shows basic properties of selected methods to infer the macroscopic ionospheric electrodynamic parameters from ground-based and/or satellite data. The full parameter set that is intended to be measured or calculated consists of the ionospheric electric field $\vec{E}$ or electric potential Φ_E, the Hall and Pedersen conductances Σ_H and Σ_P, the horizontal ionospheric sheet current density $\vec{J}$, and the field-aligned currents (FACs) $j_\parallel$.
First we note that from measurements of the ground magnetic field disturbance $\vec{B}_G$ alone, we can only derive equivalent ionospheric currents $\vec{J}_{eq,Ion}$ from an upward field continuation procedure, but not the true currents $\vec{J}$. Since $\vec{J}_{eq,Ion}$ is divergence-free, no conclusions regarding the FACs can be drawn from it, unless uniform ionospheric conductances are assumed (cf. Untiedt and Baumjohann, 1993).
When a model of the ionospheric conductances is added, Φ_E can be calculated by solving a second order partial differential equation. This approach is known as the KRM method (Kamide *et al.*, 1981). While the KRM method has successfully been applied to global scale studies, for regional analyses the unknown boundary conditions cause substantial uncertainty in the results (Murison *et al.*, 1985).
The AMIE procedure (Richmond and Kamide, 1988) is one of the most commonly used methods for deriving ionospheric electrodynamics. In contrast to KRM and all other methods mentioned in this paper, AMIE is an optimisation method, i.e., the wanted electrodynamic parameters are optimised such that they are as consistent with all available measurements as possible, using a least square approach. This gives AMIE the flexibility to utilize many different data sets, and not every input data set has to cover the full analysis region, as it is required for forward methods that base on solution of algebraic or differential equations. On the other hand, AMIE uses assumptions on both ionospheric conductances usually taken from statistically-based models and other statistical "a priori" information which reduces its ability to adequately represent single events. Moreover, it is not

Proc. Cluster-II Workshop on Multiscale/Multipoint Plasma Measurements, London, 22-24 September 1999, ESA SP-449, February 2000

easy to estimate the uncertainty of the results in regions where the density of actually measured data is sparse. Until now, AMIE is only available for global-scale analyses.

Other modeling approaches of the three-dimensional ionospheric current system on global and regional scales, although usually technically not as advanced, belong to the same category as the AMIE method. During the IMS period, the "trial and error method" was frequently used in regional scale studies (e.g., Baumjohann *et al.*, 1981; Opgenoorth *et al.*, 1983). Models of the desired electrodynamic quantities are improved on a heuristical basis until a sufficient agreement between the measurements and their values predicted from the model is achieved.

The method of characteristics (Inhester *et al.*, 1992; Amm, 1995, 1998) uses measurements of $\vec{B}_G$ and $\vec{E}$ to derive the full set of electrodynamic parameters. Unlike the previous techniques, it needs an estimate of the distribution of the Hall to Pedersen conductance ratio $\alpha = \Sigma_H/\Sigma_P$ only. Lester *et al.* (1996) have shown that this ratio, in contrast to Σ_H and Σ_P themselves, shows a relatively stable relation to the ground magnetic disturbance level and is therefore more easily assessible. In addition, Amm (1995) found that the results of the method are robust with respect to the estimate of α as well as to boundary conditions. The method is described in more detail in the next section.

Finally, we mention some methods to calculate the ionospheric electrodynamic parameter set when spatial, quasi-instantaneous distributions of FACs ($j_\parallel$) are measured by a fleet of satellites like Cluster II. However, it should be stated that even with several satellites, it is not always possible to obtain this input parameter. To fulfill the quasi-instantaneous condition, the ionospheric footpoints of the satellite need to move sufficiently fast over the analysis region. Depending on the size of that region, for Cluster II this condition may be satisfied near the perigee of the orbit (4 Earth radii), but is unlikely to be satisfied near the apogee (19.6 Earth radii). Additionally, the satellites' footpoints must not be aligned in the direction of the footpoints' movement, but spatially distributed. Finally, some uncertainty in the FAC estimation may be introduced by the field line mapping procedure, and by possible field-aligned potential drops.

If only $j_\parallel$ is known, the full electrodynamic parameter set can be obtained by assuming a model for Σ_H and Σ_P, and integrating a second-order partial differential equation for Φ_E (the same technique as used, e.g., by Rich and Kamide, 1983). Like with the KRM method, this approach works well for global analysis regions, but unknown boundary conditions are a major problem when trying to apply it to regional studies. Since, as pointed out above, quasi-instantaneous $j_\parallel$ distributions are not available on a global scale, this approach is of minor significance for the Cluster II analysis.

Additional knowledge of the $\vec{B}_G$ distribution does not overcome the necessity to assume Σ_H and Σ_P to calculate the full parameter set, but it resolves the boundary value problem. $\vec{J}$ can be calculated from $j_\parallel$ and $\vec{B}_G$ without further assumptions, in the same way as described for the "elementary current method" (see below). The multitude of possible Σ_H and Σ_P models needed to obtain $\vec{E}$ can, however, be restricted by the assertion that $\vec{E}$ is curl-free.

Finally, the "elementary current method" utilizes $j_\parallel$ and $\vec{B}_G$ to calculate $\vec{J}$ without any integration needed, by expanding $\vec{J}$ into curl-free and divergence-free spherical elementary current systems (SECS; see Amm, 1997). With $\vec{J}$ and measurements of $\vec{E}$, the conductances can immediately be calculated. None of the input distributions has to be assumed. This method is presented in more detail in section 4.

3. METHOD OF CHARACTERISTICS

Using measurements of $\vec{B}_G$ and $\vec{E}$, and an assumption of α, the basic ionospheric electrodynamic equations can be combined to solve a first-order partial differential equation for Σ_H. The main idea of the method of characteristics is to solve this 2D equation along its 1D

Table 1. Overview of selected methods to derive macroscopic ionospheric electrodynamic parameters from ground-based and satellite data

Input	Assumptions	Output	Name of method	Remarks
$\vec{B}_G$	-	$\vec{J}_{eq,Ion}$	field continuation	forward method no true currents, no FACs
$\vec{B}_G$	Σ_H, Σ_P	$\vec{E}$ (Φ_E), $\vec{J}$, $j_\parallel$	KRM	forward method boundary conditions critical if non-global
$\vec{B}_G$, {$\vec{E}$ (Φ_E), satellite data}	Σ_H, Σ_P	{$\vec{E}$ (Φ_E)}, $\vec{J}$, $j_\parallel$	AMIE, "three-dimensional modeling"	optimisation method (least square or "trial and error"); data need not to cover whole analysis area
$\vec{B}_G$, $\vec{E}$	$\alpha = \Sigma_H/\Sigma_P$	Σ_H, Σ_P, $\vec{J}$, $j_\parallel$	method of characteristics	forward method α assessible from ASC or $\vec{B}_G$
$j_\parallel$	Σ_H, Σ_P	$\vec{E}$ (Φ_E), $\vec{J}$	-	forward method boundary conditions critical if non-global
$\vec{B}_G$, $j_\parallel$	Σ_H, Σ_P	$\vec{E}$ (Φ_E), $\vec{J}$	-	forward method
$\vec{B}_G$, $\vec{E}$, $j_\parallel$	-	Σ_H, Σ_P, $\vec{J}$	elementary current method	forward method

characteristics $\vec r(\ell)$, i.e., to split up the 2D problem into many independent 1D ones. Along each characteristic with the geometric path lenght ℓ a first-order ordinary differential equation has to be solved that can be integrated to obtain

$$\Sigma_H(\vec r(\ell)) = \Sigma_H(\vec r_0)\, e^{-I(0,\ell)} + \int_0^{\ell} \frac{D(\vec r(\ell'))}{|\vec V(\vec r(\ell'))|}\, e^{-I(\ell',\ell)}\, d\ell' \qquad (1)$$

with

$$I(\ell',\ell) = \int_{\ell'}^{\ell} \frac{C(\vec r(\ell''))}{|\vec V(\vec r(\ell''))|}\, d\ell'' \qquad (2)$$

where the parameters $\vec V = \vec E - \alpha^{-1}\,\vec E\times\hat r$, $C = \nabla_h\cdot\vec V$, and $D = -[\nabla\times\vec J_{eq,Ion}]_r$ are known from the input. Here, r denotes the radial outward direction, $\hat r$ is the unit vector in that direction, and the subscript h means the horizontal part of a vector operator. Since the direction of integration is chosen along each characteristic such that $I(0,\ell)$ is positive, the influence of the unknown boundary value $\Sigma_H(\vec r_0)$ typically decreases rapidly. Moreover, since the characteristics diverge in direction of integration, boundary values usually have to be given on a small part of the total boundary (at most on 50% of it). By selecting physically resonable upper and lower values for $\Sigma_H(\vec r_0)$, error estimates for the solution of Σ_H are obtained for the different parts of the analysis area. For more details see Amm (1998).

4. ELEMENTARY CURRENT METHOD

From measurements of $\vec B_G$ and $j_\parallel$, and after applying upward field continuation to calculate $\vec J_{eq,Ion}$ from $\vec B_G$, by virtue of

$$\nabla_h\cdot\vec J = j_\parallel \qquad (3)$$

and

$$\nabla_h\times\vec J = \nabla_h\times\vec J_{eq,Ion} \qquad (4)$$

we know the curl and divergence of $\vec J$. While this knowledge could be used to integrate $\vec J$, it is much easier to solve (3) and (4) without the need of any integration by composing $\vec J$ of curl-free and divergence-free spherical elementary current systems (SECS). As shown by Amm (1997), any current system $\vec J$ can uniquely be decomposed as integrals over SECS as

$$\vec J(\vec r) = \iint_{\text{Ionosph.}} \left(\frac{[\nabla_h\times\vec J(\vec r')]_r}{4\pi R_I}\cot(\tilde\vartheta/2)\,\underline{e}_{\tilde\varphi} + \frac{\nabla_h\cdot\vec J(\vec r')}{4\pi R_I}\cot(\tilde\vartheta/2)\,\underline{e}_{\tilde\vartheta} \right) d^2r' \qquad (5)$$

In (5), $\tilde\vartheta$ and $\tilde\varphi$ are spherical coordinates with respect to the center ("pole") of each elementary system, and $\underline{e}_{\tilde\vartheta}$ and $\underline{e}_{\tilde\varphi}$ the unit vectors in these directions. During the integration, the vector inside the brackets has to be transformed into the coordinate system of $\vec r$ and $\vec r'$ (usually geographic or geomagnetic). Hence with (5), $\vec J$ can directly be composed from its curls and divergences. However, parts of $\vec J$ that contain neither divergences nor curls inside the analysis area will not be represented.

Figure 1. Ionospheric electric potential derived by SuperDARN, and by 90 degrees clockwise rotated ground magnetic disturbance vectors; the CGM coordinate system is used; circle: area of cusp currents studied in detail.

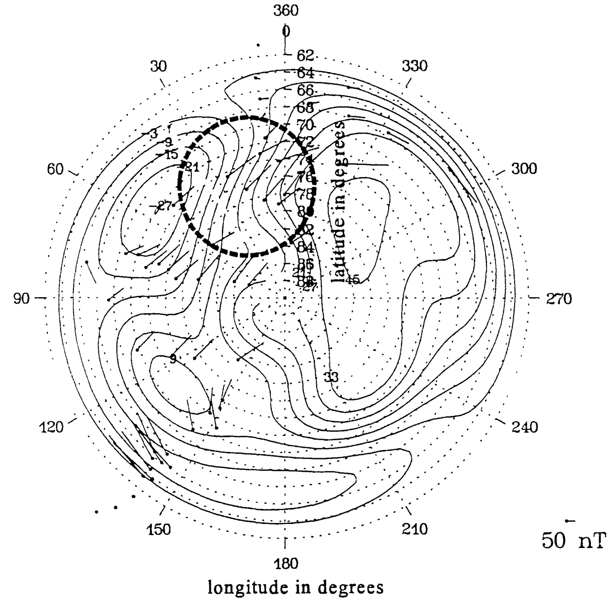
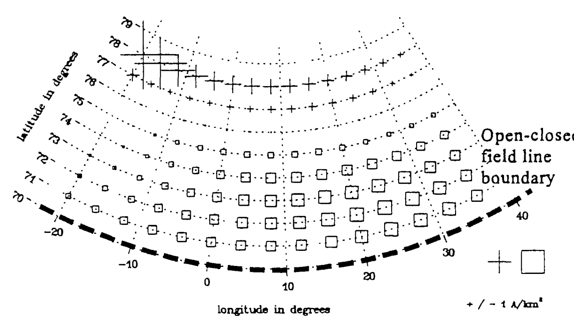


Figure 2. Resulting FAC distribution from the method of characteristics (crosses: downward; squares: upward); the open/closed field-line boundary was derived from DMSP F10 and SuperDARN spectral width data.



Therefore, it is important that the analysis area includes the essential FAC systems that cause the horizontal currents. For more details on SECS, see Amm (1997). Once $\vec J$ is known, with the measurement of $\vec E$ the conductances are straightforwardly derived from Ohm's law to

$$\Sigma_H = \frac{(\vec J\times\vec E)_r}{|\vec E|^2} \quad ; \quad \Sigma_P = \frac{\vec J\cdot\vec E}{|\vec E|^2} \qquad (6)$$

5. APPLICATION EXAMPLE FOR METHOD OF CHARACTERISTICS

Very briefly, we demonstrate the application of the method of characteristics on an IMF B_Y-related cusp current event on November 13, 1996, at 1900 UT. Details of this event study can be found in Amm *et al.* (1999). The input data, Φ_E derived from SuperDARN measurements, and magnetometer measurements from many different sources (IMAGE, Greenland, MACCS, CANOPUS arrays, and Canadian Geological Survey stations) are shown in Fig. 1. The magnetic disturbance has been rotated by 90 degrees clockwise. We concentrate on the circled area on the dayside, where about 20 min. after an IMF B_Y transition from positive to negative an "enhanced convection event" in the cusp is seen by the radar, visible in Fig. 1 by the narrow potential iso contour lines. The magnetic disturbance in this region shows the signature of a DPY current system (Friis-Christensen and Wilhjelm, 1975). From the analysis with the method of characteristics in the interesting subarea where the spatial data coverage is good, we obtain a FAC distribution of two latitudinally aligned sheets: The poleward one consists of downward and the equatorward of upward FAC (Fig. 2). This is the first time that these cusp current FACs can unambigously be determined for an instantaneous single event study, both in their location and their magnitude. The equatorward FAC sheet merges at its equatorward edge with the afternoon region 1 currents. Using DMSP F10 satellite data, as well as the spectral width of the backscatter received by SuperDARN, the open/closed field line boundary is located at 70 degrees of latitude. Therefore, both cusp FAC sheets clearly lie on open field lines. This result solved a long-standing controverse between the theories of Lee *et al.* (1985) and Clauer and Banks (1986) on the origin of such cusp current systems.

REFERENCES

Akasofu, S.-I., J. Kisabeth, B.-H. Ahn, and G.J. Romick, The S_q^p magnetic variation, equivalent current, and field-aligned current distribution obtained from the IMS Alaska meridian chain of magnetometers, *J. Geophys. Res., 85*, 2085, 1980.

Amm, O., Direct determination of the local ionospheric Hall conductance distribution from two-dimensional electric and magnetic field data: Application of the method using models of typical ionospheric electrodynamic situations, *J. Geophys. Res., 100*, 24173, 1995.

Amm, O., Ionospheric elementary current systems in spherical coordinates and their application, *J. Geomag. Geoelectr., 49*, 947, 1997.

Amm, O., Method of characteristics in spherical geometry applied to a Harang discontinuity situation, *Ann. Geophys., 16*, 413, 1998.

Amm, O., M.J. Engebretson, R.A. Greenwald, H. Lühr, and T. Moretto, Direct determination of IMF BY-related cusp current systems, using SuperDARN radar and multiple ground magnetometer data - a link to theory on cusp current origin, *J. Geophys. Res., 104*, 17187, 1999.

Baumjohann, W., Pellinen, R.J., Opgenoorth, H.J., and Nielsen, E., Joint two-dimensional observations of ground magnetic and ionospheric electric fields associated with local auroral break-ups, *Planet. Space Sci., 29*, 431, 1981.

Clauer, C.R., and P.M. Banks, Relationship of the interplanetary electric field to the high-latitude ionospheric electric field and currents: Observations and model simulation, *J. Geophys. Res., 91*, 6959, 1986.

Friis-Christensen, E., and J. Wilhjelm, Polar cap currents for different directions of the interplanetary magnetic field in the Y-Z plane, *J. Geophys. Res., 80*, 1248, 1975.

Inhester, B., J. Untiedt, M. Segatz, and M. Kürschner, Direct determination of the local ionospheric Hall conductance distribution from two-dimensional electric and magnetic field data, *J. Geophys. Res., 97*, 4073, 1992.

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., B.-H. Ahn, S.-I. Akasofu, W. Baumjohann, E. Friis-Christensen, H.W. Kroehl, H. Maurer, A.D. Richmond, G. Rostoker, R.W. Spiro, J.K. Walker, and A.N. Zaitzev, Global distribution of ionospheric and field-aligned currents during substorms as determined from six IMS meridian chains of magnetometers: Initial results, *J. Geophys. Res., 87*, 8228, 1982.

Lee, L.C., J.R. Kan, and S.-I. Akasofu, On the origin of the cusp field-aligned currents, *J. Geophys., 57*, 217, 1985.

Lester, M., J.A. Davies, and T.S. Virdi, High-latitude Hall and Pedersen conductances during substorm activity in the SUNDIAL-ATLAS campaign, *J. Geophys. Res., 101*, 26719, 1996.

Murison, M., A.D. Richmond, and S. Matsushita, Estimation of ionospheric electric fields and currents from a regional magnetometer array, *J. Geophys. Res., 90*, 3525, 1985.

Opgenoorth, H.J., R.J. Pellinen, W. Baumjohann, E. Nielsen, G. Marklund, and L. Eliasson, Three-dimensional current flow and particle precipitation in a westward traveling surge (observed during the Barium-GEOS rocket experiment), *J. Geophys. Res., 88*, 3138, 1983.

Rich, F.J., and Y. Kamide, Convection electric fields and ionospheric currents derived from model field-aligned currents at high latitudes, *J. Geophys. Res., 88*, 271, 1983.

Richmond, A.D., and Y. Kamide, Mapping electrodynamic features of the high-latitude ionosphere from localized observations: Technique, *J. Geophys. Res., 93*, 5741, 1988.

Sulzbacher, H., W. Baumjohann, T.A. Potemra, E. Nielsen, and G. Gustafsson, Observations of ionospheric and field-aligned currents in the late afternoon sector with Triad and the Scandinavian Magnetometer Array, *J. Geophys., 51*, 55, 1982.

Untiedt, J., and W. Baumjohann, Studies of polar current systems using the IMS Scandinavian magnetometer array, *Space Sci. Rev., 63*, 245, 1993.