ELECTRODYNAMIC PARAMETERS OF THE AURORAL OVAL FROM COMBINED SPACECRAFT AND GROUND MEASUREMENTS

Martin Connors(1)

(1)*Athabasca University, 1 University Drive, Athabasca AB, T9S 3A3 Canada, Email:martinc@athabascau.ca*

ABSTRACT/RESUME

Spacecraft traversing the auroral oval respond primarily to the field-aligned currents at its poleward and equatorward borders that are part of a solenoidal current system. If electric and magnetic field measurements are done, it is possible to determine the integrated Pedersen conductivity of the auroral oval. On the ground, however, one detects primarily the magnetic effects of the Hall currents associated with the auroral oval electric field. If the Hall current can be determined, along with the electric field, one can obtain the Hall conductivity. Inversion of magnetic perturbations in the meridian traversed by the spacecraft can give the Hall current. The Automated Forward Modelling (AFM) method permits this to be done effectively. The method is described with an example based on FAST over the Churchill meridian in Canada. Studying temporal and spatial variations needs multiple instrumented meridians and spacecraft. Efforts to increase the number of instrumented meridians in Canada are described.

1. MAGNETIC AND ELECTRIC PERTURBATIONS IN THE AURORAL OVAL

The basic nature of the current systems in the auroral oval has been well established for about 50 years. Much of the electrodynamics is controlled by electric fields associated with magnetospheric convection. These point generally equatorward in the morning sector and poleward in the evening sector. The anisotropic ionosphere responds to these imposed electric fields with Pedersen currents, following the **E** field projection, and Hall currents, perpendicular to **E** and **B** (which is essentially vertical). Closure of the current systems is by field-aligned currents (FAC), which are generally local to close the Pedersen currents, and may be distant to close the Hall currents, which are often of large longitudinal extent. The closed north-south system associated with Pedersen currents is essentially solenoidal and produces little perturbation outside of the three-dimensional system bounded by current sheets. Notably, on the ground the perturbations due to the Pedersen system are small. In addition, a satellite outside of the auroral zone detects little effect from this system. However, when it traverses the bounding currents, large offsets from baseline levels are seen. The Hall system has in some ways the converse magnetic effect. Its perturbations are readily detected on the ground, which is only roughly 100 km below the relatively nonsolenoidal Hall ionospheric currents. Since Hall flow is often largely east-west, the main effects detected on the ground are in the X (geographic northward) component and the Z (vertically downward) components. Since satellites generally pass several hundred (often 700) or more kilometers above the ionosphere, the Hall current effects at satellite altitude are usually not pronounced. For completeness it should be noted that the direct detection of the FAC whose locally unbalanced parts are associated with the Hall system is possible: their magnetic effects at low latitude are referred to as “low-latitude bays” and observed mainly in the X and Y (eastward) components. During active times the usual configuration is to have downward FAC east of midnight, an ionospheric westward Hall current traversing the midnight or late evening sector, and upward FAC to the west. This delineates the “substorm current wedge” associated with substorm onset, which will not be discussed further here.

Although other techniques (notably radars) can be used to determine ionospheric parameters, the discussion here will focus on in-situ direct measurement of auroral zone **E** fields and the relation to currents through conductivity. A current dataset of interest is that of nearly ten years from the FAST satellite [1]. The Canadian e-POP project [2] should provide relevant measurements in the next couple of years. After that, and relevant here, the Canadian Electric Field Instrument on Swarm will mean that **E** and **B** field measurements will be available. The satellite measurements alone can be used to determine the Pedersen current and the relation of **E** to **B** allows determination of the integrated Pedersen conductivity of the ionosphere. To determine the Hall conductivity, however, requires that the Hall current be determined, and as indicated above, ground measurements respond to the Hall current more than do most satellites. We must therefore consider how to combine ground and satellite data to obtain all of the electrodynamic parameters of the auroral ionosphere by direct measurement.

2. AUTOMATED FORWARD MODELLING (AFM)

Interpretation of ground magnetic data is difficult, even if the data come from the same magnetic meridian. Examples of magnetic data from many locations are common in the literature, or one may examine the solid lines in Fig. 1. These show perturbations from the CANOPUS stations of the Canadian Churchill meridian on June 3, 1997. The data were carefully baselined by using quiet days throughout 1997. Only the X and Z components are used in single meridian modeling, so the Y component is not shown. It is clear that an auroral event (onset) with accompanying currents took place very close to 6 UT on this day. The perturbations seem maximal near FCC (Fort Churchill), so that the centre of the onset must have been near there. This is borne out by the change in sign of the Z component. Negative X perturbations arise from westward ionospheric currents over the station; the placement of the station with respect to the current determines the sign of Z. For a westward current, Z is positive as observed north of the electrojet, and negative south of it. The near-zero Z perturbations at FCC, along with the +Z perturbations north of it, and the –Z perturbations south of it, support the conclusion that the currents were centred near this station. We can note the duration of the event and that there was some precursory activity. Importantly, this is about *all* that a skilled interpreter can deduce from what is in fact a fairly complete dataset for the meridian.

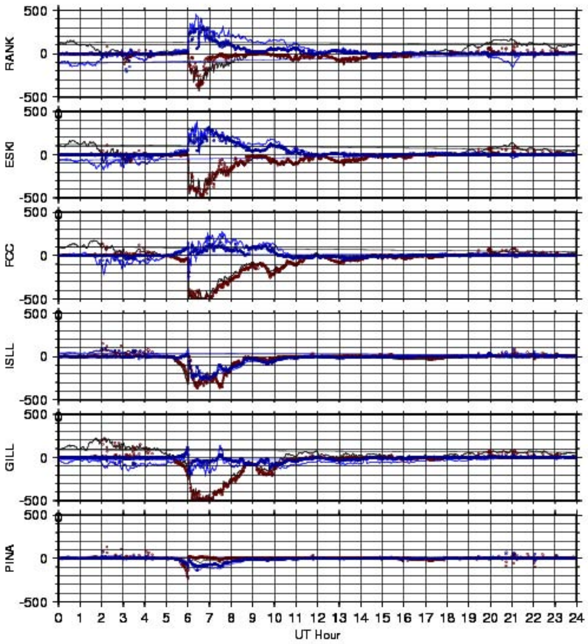

Figure 1. Magnetic X and Z component perturbations in the Canadian Churchill meridian on June 3 1997. Lines represent data, black for the X component, blue for the Z component. Red dots correspond to X model output once parameters were optimally adjusted, and blue dots to Z model results.

To go further, a quantitative method of inversion of the magnetic data is needed. Approaches based on potential functions are possible [3]. The technique used here, Automated Forward Modelling, proposes a forward model of current systems which could give rise to the magnetic perturbations observed. The parameters in that model are varied in such a way that the deviation between the observed magnetic fields and those predicted by the model are reduced. In the ideal case, the parameters can be chosen to correspond to simple physical parameters associated with the current system. A forward model can be made using the Biot-Savart law in combination with Earth induction, by specifying where currents flow in space and the ionosphere [4][5]. Adjustment of the parameters specifying the current system can be done until the match to the input data is optimal. In principle, arbitrarily complex current systems may be described in three dimensions in near-Earth space and their parameters determined. In practice, available magnetic data is sparse and well-determined solutions can be difficult to obtain.

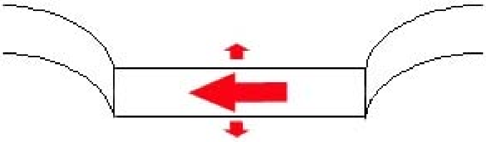

Figure 2. By varying the current (large horizontal arrow) and latitudinal boundaries (small vertical arrows) an optimal match of model results and data can be made and these physical parameters determined. Field-aligned currents may be included (as shown at ends of ionospheric current flow region).

The optimum situation can be found when data from meridian chains is available, since in many cases a simple model involving an electrojet flowing across the meridian chain is physically realistic, and in this case there is a good ratio of data available to number of parameters to be determined. From meridian chain data a forward modeling procedure can give the current across the meridian and the latitudes between which it flowed. In this way the many data points specifying the magnetic perturbations along a meridian can be reduced to three simple parameters, which have an easily understood physical significance. For efficient processing of large amounts of magnetic data, the matching process can be automated. In the Automated Forward Modeling (AFM) procedure this is done using the Levenberg-Marquardt algorithm [6]. A schematic of the variables involved and the way in which they are varied is shown in Fig. 2. Detailed descriptions of the AFM procedure are given elsewhere [7][8].

Fig. 3 shows the results of applying a fully automated (i.e. no special starting conditions used) version of AFM to the dataset of Fig. 1, for the period of interest near the time of substorm onset. This allows a clear identification of the slightly disturbed period before onset as having typical growth phase behaviour of equatorward motion of the electrojet boundaries. In addition, it may be seen that the current across the meridian smoothly strengthened during the growth phase, which has been identified between two vertical lines. The onset is seen to have taken place well poleward of the region of growth phase currents. Following onset, the poleward border of the electrojet moved rapidly poleward, a well established behaviour, and the current continued to rise. The unusual activation of a region well poleward of the growth phase region could be confirmed in this case by inspection of POLAR spacecraft images. What is important to note here is that the inversion made obvious what the stacked magnetograms did not: the growth phase currents and the unusual onset location. In addition, the three parameters needed to describe the electrojet are available as physical quantities in numerical form.

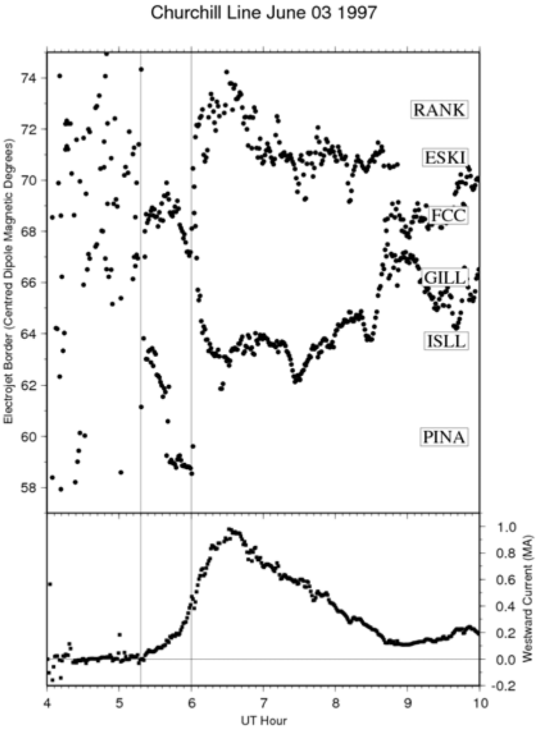

Figure 3. ModellingGrowth phase and onset of a substorm on June 3 1997. Upper panel shows the electrojet north and south boundaries as it traversed the Churchill meridian. Bottom panel shows total current across the meridian. The growth phase is clear. Subsequent substorm onset is somewhat unusual in being well poleward of the region of growth phase currents.

Further examination of Fig. 1 shows the degree to which the AFM modeling has succeeded in representing the data from the six magnetic stations by three simple parameters. The X (generally lower) component data is shown by a solid line, while the X resulting from the model is shown by discrete points. At times from 2 UT to 13 UT the two agree very well. Some care has to be taken in interpreting this agreement when the perturbations are near zero. At such times the geometric parameters may not be well determined simply since there is basically no current upon which to base an inversion. Generally, when this happens there will be large scatter in the electrojet border parameters as may be seen in Fig. 3 before the growth phase began. For the period of interest between 5:15 and 10 UT both the match to X data and the lack of scatter suggest an excellent model fit. The Z component is also plotted in Fig. 1 (generally as the upper trace). Here the fit is generally very good but not quite as excellent as that for X. This is attributed to the more rapid variation in Z when a station is near a current source in the ionosphere. Z can reflect structure in the electrojet which is not present in the simple model and thus is harder to match than is X.

3. ELECTRODYNAMIC PARAMETERS OF THE AURORAL ZONE

We have now seen how AFM may be used to determine what amount to Hall currents in the ionosphere. We now consider determination of **E** and **B** from spacecraft overflight and their use to determine conductivity. Fig. 4 illustrates the magnetic perturbations detected as the FAST spacecraft overflew the Churchill meridian on February 22, 1997. The primary perturbation is eastward, but some equatorward component is also seen due to the spacecraft trajectory not being perpendicular to the current system. The changes in eastward B at the equatorward and poleward boundaries are due, in turn, to traversing downward and upward FAC.

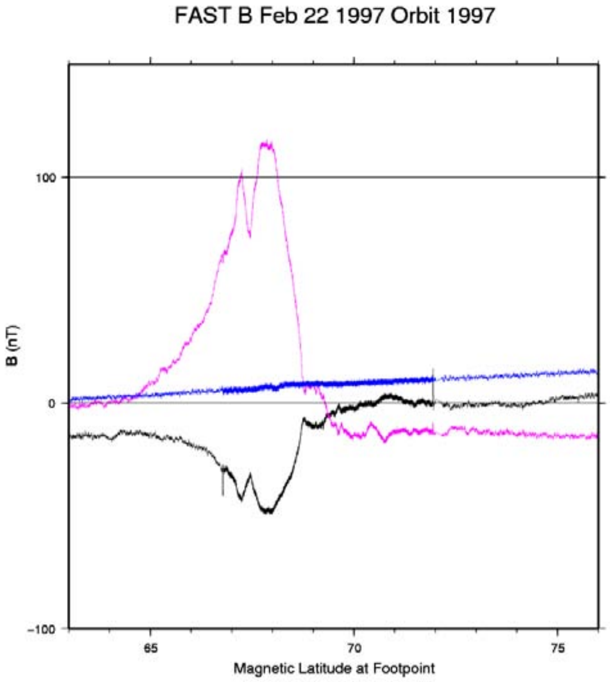

Figure 4. FAST traversal of the northern auroral oval on February 22 1997, very near the Churchill meridian. The pink (upper) trace is the eastward B component, the black (lower) trace the equatorward B component, and the blue (middle) trace the vertical component.

The DC **E** field instrument of FAST also detected perturbations associated with the auroral oval on this pass. These are shown, with the **B** fields, in Fig. 5.

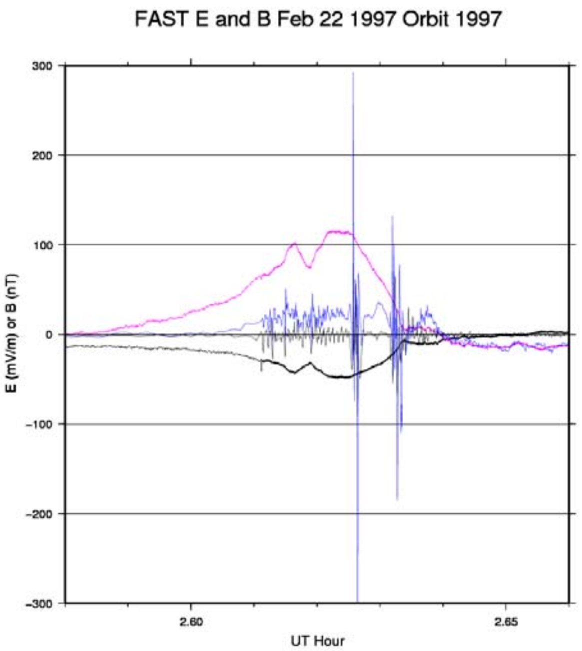

*Figure 5. Electric fields added to plot of FAST passage. The poleward component (blue; generally above 0) and eastward component (thin black trace near origin) are shown. Large perturbations of **E** near inflection points of **B** are likely due to wave activity.*

With some minimal assumptions it can be shown [9] that the Pedersen conductivity is

$$\Sigma_P = \frac{\Delta B_y}{1.256E} \qquad (1)$$

where the units for **B** are nT and for **E**, mV/m. Using the values from the graph (average E 25 mV/m), one obtains Σ_P=3.5 mho. This is a fairly typical value [10].

The AFM method gives the (Hall) current I_H across the meridian and in addition the electrojet boundaries. From these the electrojet width W may be determined by subtraction. Then the Hall conductivity may be computed, using E from the spacecraft, as

$$\Sigma_H = \frac{I_H}{EW} \qquad (2)$$

with quantities in SI units. We now combine the FAST and ground data to determine the Hall conductivity for this overflight.

Fig. 6 shows the results of inversion plotted over optical data from the Churchill meridian station of Gillam. The optical data consists of meridian scans of the 557.7 nm emission characteristic of aurora, stacked to a keogram.

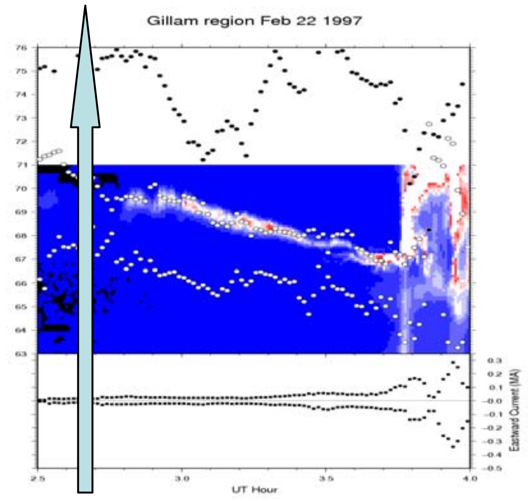

Figure 6. Top panel: Inversion results for February 22 1997 plotted as points in upper panel for a two electrojet model, over a keogram of optical emission over Gillam. Bottom panel: current strength across the meridian. With the initial conditions used, the results are meaningful only during growth phase, i.e. until roughly 3.8 UT. An arrow marks the time of FAST passage through the early growth phase currents.

The inversion (a single eastward electrojet is more appropriate; this gives nearly the same results as shown) gives an eastward electrojet width of 440 km and total current of 0.04 MA. With the known E as before, this leads to Σ_H=4 mho, comparable to Σ_P determined above. This result is also not unexpected [10] but represents a direct measurement using basic quantities **E** and **B** only.

We have shown how basic electrodynamic parameters can be determined using a satellite and a magnetometer chain. In principle **E** could also be measured from a radar, and the Hall conductivity determined with Eq. (2). However, we proceed to consider the practicality of using a satellite to get an in-situ **E** value to carry out the exact procedure described above.

4. SATELLITE-GROUND CONJUNCTIONS

The basic problem with carrying out the determination of parameters through time or indeed at all, using a satellite and ground meridian, is that conjunctions are rare. In addition, sequential conjunctions take place at different longitudes so that, since there really are only three dense auroral zone meridian chains in the world (Alaska, Churchill and IMAGE in Scandinavia; Greenland in times of low magnetic activity), orbit-to-orbit use is not possible.

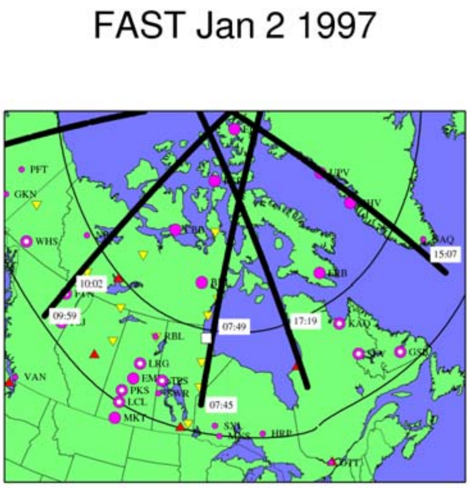

Figure 7. FAST overflights of Canada, Greenland, and Alaska on Januray 2 1997. UT at various places along the orbit paths is indicated.

Fig. 7 shows FAST passages over North America and Greenland on a typical day. A northbound pass starting at 7:45 UT went over the Churchill meridian, whose magnetometers (and other CANOPUS magnetometers) are marked by inverted yellow triangles (Churchill is shown as a white square as it also has an NRCan federal government magnetometer). Purple or purple and white symbols are STEP magnetometers, many of which are no longer operative. The CANOPUS magnetometers are located mainly in western Canada. Federal NRCan magnetometers are more widely distributed (red triangles) but do not form chains. The 15:07 pass goes over Greenland but the magnetic latitude (shown by traces at 60º and 70º) at the southern end of that chain is too high to allow effective use for AFM inversion in active conditions. Thus the 7:45 UT pass, well situated as this is near midnight local time for the Churchill meridian, is the single useful conjunction on this day.

Obviously more continuous coverage would be possible if there were more satellites equipped with **E** and **B** field detectors. However, from known plans for launches of low-altitude satellites, this does not seem a likely solution.

5. EXPANSION OF GROUND FACILITIES IN CANADA

The most effective way to increase the number of ground-satellite conjunctions is to increase the number of ground stations and deploy them strategically, which basically means in meridian chains. The most useful country in which to do this is Canada. Existing facilities are already relatively good although sparsely spread over the vast country. Canada has the largest landmass under the auroral zone, roughly delineated by the curved lines in Fig. 8. Some expansion is already funded. CANOPUS is now known as CARISMA and more magnetometers will be deployed in western Canada. The Churchill meridian is being extended southward in cooperation with American efforts. There is a THEMIS ground-based array which will include magnetometers throughout Canada (and some in Alaska; magnetometers also form part of the outreach effort in the northern USA). In general the THEMIS instruments will be placed to optimize optical coverage and not necessarily to form meridians. Athabasca University has placed instruments in southern and central Alberta which allow a chain to be formed there if combined with CARISMA and NRCan instruments. From all these known efforts, then, only one new chain spanning the auroral oval arises.

6. STEP FORWARD

The most obvious way to have good coverage is to take advantage of existing instruments. The STEP project of the University of Tokyo, led by Dr. Kanji Hayashi, emplaced an impressive array of fluxgate and induction coil magnetometers in Canada starting in the 1980s. The project now has little or no funding. Some magnetometers have been kept operative with volunteer effort including that of Dr. Hayashi. An evaluation has been done of the status of instruments in Canada and a proposal developed to implement chains at minimal cost through use of existing instruments, most of which need only upgrades to computer and communications infrastructure. This proposal is called STEP Forward.

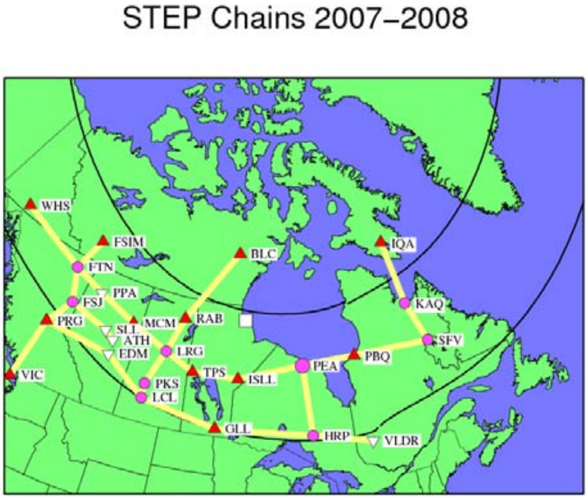

Figure 8. Possible alignments of ground instruments in the STEP Forward proposal. The proposed site at Peawanuck (PEA) is coloured the same as STEP sites but would be a new installation.

The following chains would be created if the full project is funded, with existing NRCan sites in bold, CARISMA sites in italics, and THEMIS (where known) or AU sites underlined. The sites are shown by abbreviation on the map of Fig. 8.

STEP Forward Proposed Chains:

1) Eastern Meridian Chain: **Iqaluit** – Kuujjuaq – Schefferville
2) Hudson Bay Gap mini-meridian Chain: Peawanuck – Hornepayne
3) Saskatchewan Meridian Chain: **Baker Lake** – *Rabbit Lake* – La Ronge – Park Site – Lucky Lake
4) British Columbia Meridian Chain: *Fort Simpson* – Fort Nelson – Fort St. John – Prince George
5) Latitude 64 Longitudinal Chain: Whitehorse – Fort Nelson – Paddle Prairie - *Fort McMurray* – La Ronge – The Pas* – *Island Lake* – Peawanuck – **Poste de la Baleine** – Schefferville* (*=slightly off chain)
6) Latitude 62 mini-chain: Fort St. John – Slave Lake – Athabasca
7) Subauroral 59 Chain: Prince George – Edmonton/Red Deer – Lucky Lake – **Glenlea(Brandon)** – Hornepayne – Val d'Or

When the existence of the Alberta chain (partly made up of sites ATH and EDMO on the map) is taken into account, the addition of 3 meridian chains, plus a mini-chain at Hudson Bay, gives a large increase in the number of meridians available for conjunctions.

Another possibility arising from multiple chains is that if more than one suitably equipped satellite is in orbit at a given time, then the chances of simultaneous conjunctions, one satellite each over a ground chain, are greatly enhanced. Certain Swarm configurations could also give well-timed passes for studying time evolution of conductivity parameters.

7. SUMMARY

The Automated Forward Modelling (AFM) technique allows inversion of magnetic data into simple physical parameters. This is especially effective when applied to magnetic meridian data.

AFM can be combined with satellite **E** field data, such as that which will be available from Swarm, to determine the integrated Hall conductivity of the ionosphere. The **B** field data from the satellite itself can allow determination of the Pedersen conductivity as has been already well established.

These techniques are all the more effective if significantly more ground data is available. There are already projects underway which will increase the amount of ground data from Canada to support satellite missions. Methods to yet further increase that amount of data, notably from meridian chains, and at minimal cost, have been described.

ACKNOWLEDGEMENTS

The Canadian Space Agency funded the CANOPUS array whose magnetic and optical data was used here. C. Carlson of U.C. Berkeley provided FAST data through CDAWeb and the FAST website. Kanji Hayashi has continued efforts which leave a viable amount of the STEP network in place to be a basis for expansion as described above. Baselining and June 3 1997 magnetic inversions using the meridmrq code were done by Jason Ponto. Bob Strangeway has provided useful insight into use of FAST data. This work was funded by Canada Research Chairs and NSERC.

REFERENCES

1. Elphic R. C. et al., *Geophys. Res. Lett.,* Vol. 25, 2033-2036, 1998.
2. Yau A. W., James H. G., and Liu W. W., *Adv. Sp. Res.*, in press, 2006.
3. Amm O. and Viljanen A.,*Earth Planets Space*, Vol. 51, 431–440, 1999.
4. Kisabeth J. L. and Rostoker G., Geophys. J. R. astr. Soc., Vol. 49, 655-683, 1977.
5. Kisabeth J. L., in *Quantitative Modeling of Magnetospheric Processes*, edited by W. P. Olson, American Geophysical Union, Washington, pp. 473-498, 1979.
6. Press W. H. et al., *Numerical Recipes in C, Second Edition*, Cambridge University Press, Cambridge, 1992.
7. Connors M., Auroral Current Systems Studied Using Automated Forward Modelling, Ph.D. Thesis, Department of Physics, University of Alberta, 410 pp., 1998.
8. Connors M. and Rostoker G., in Sixth International Conference on Substorms (ISBN 0-9711740-3-2), R. Winglee, ed., University of Washington Press, Seattle, 490-495, 2002.
9. Smiddy M. et al., *J. Geophys. Res.*, Vol. 85, 6811-6818, 1980.
10. Reiff P. H., in *Magnetospheric Currents*, T. A. Potemra, Ed., American Geophysical Union, Washington, pp. 180-191, 1984