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# Comparison of ionospheric drift and magnetic deflections on the ground

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ABSTRACT

Resolute Bay, Canada, with an almost vertical geomagnetic field and the associated simplicity of ionospheric current system, is an optimal location to determine the relationship between the ionospheric electric field and the magnetic deflections on the ground. Considering uniform current sheets in a plane geometry, the magnetic deflection direction on the ground is expected to be (1) the same as the ionospheric electric field direction for the Hall current only or (2) lag the electric field direction 0-to-90° in the clockwise sense looking down when the Pedersen current is included. However, our analysis of Resolute incoherent scatter radar and magnetometer data shows that the magnetic deflection angle is leading in a range 30–70° depending on the magnetic local time. Additional magnetometers at Thule and Cambridge Bay observatories were used to investigate the effect of auroral zone currents, however, a simple deconvolution using these stations did not change the results significantly. Furthermore, inclusion of the neutral winds only slightly changed the offset angle. We conclude that a sunward magnetic contribution on the order of 50 nT caused by magnetospheric currents is needed to explain the offset.



## 1. Introduction

In a plane geometry with hypothetical uniform current sheets in the ionospheric $E$ region and no field-aligned currents (FAC), the magnetic deflection on the ground can be obtained by applying the Biot–Savart law to four separate currents: the electron Pedersen current $J_{Pe}$, the electron Hall current $J_{He}$, the ion Pedersen current $J_{Pi}$, and the ion Hall current $J_{Hi}$ (Kelley, 2009). Meanwhile, an incoherent scatter radar (ISR) can measure three of the currents: $J_{Pi}$, $J_{Hi}$, and $J_{He}$, but not the $J_{Pe}$ (incoherent scatter theory, Dougherty and Farley, 1960). The ion current is given by the product ($n_e v_i q_i$) of electron density $n_e$, ion velocity $v_i$, and the ion charge $q_i$, where $N_e$ and $v_i$ are determined by the shape and Doppler shift of the incoherent scatter spectrum. The electron current ($n_e v_e q_e$) is given mainly by the Hall current $J_{He}$ which is the EXB drift of the electrons. An ISR estimates $J_{He}$ by mapping to the $E$ region the electric field $\mathbf{E}$ inferred from the $F$ region EXB ion drift velocity. In most geophysical conditions, $J_{Pe}$ in the $E$ region is a very small fraction ($\sim\nu_e/\omega_e$) of $J_{He}$. Hence, in the simplistic geometry of uniform current sheets, we expect a correspondence between the radar measurements and the magnetic deflections on the ground.

However, in the case of strong convection electric fields, Farley–Buneman turbulence is excited (Farley, 1963; Buneman, 1963) and a significant wave-driven electron Pedersen current $J_{Pe}{}^{wd}$ is anticipated (Oppenheim, 1996, 1997). This wave driven current is associated with wave heating of electrons in the $E$ region (Schlegel and St.-Maurice, 1981; St.-Maurice et al., 1981; Bahcivan, 2007) and determination of the magnitude of $J_{Pe}{}^{wd}$ is critical for quantifying total Joule heating rates in the ionosphere. Since the magnetometers on the ground are subject to all the four currents and an ISR can measure three of them, except $J_{Pe}{}^{wd}$, a radar–magnetometer comparison can provide information about $J_{Pe}$. Fig. 1 illustrates this concept. The angular shift between radar estimates of ground magnetic deflections (based on all currents except $J_{Pe}{}^{wd}$) and actual magnetometer measurements is a measure of $J_{Pe}{}^{wd}$.

In the above plane geometry with uniform current sheets but including FACs, the Fukushima theorem (Fukushima, 1976) says that the magnetic deflections from FACs cancel those from the Pedersen currents. Therefore, the magnetic deflection on the ground will be caused only by the Hall currents. In which case, the direction of the electric field measured by an ISR should precisely match the direction of the magnetic deflection on the ground. Note that Fukushima's theorem holds in any planar or spheric geometry as long as the FACs are perpendicular to the ground, and the ionospheric conductance is spatially uniform. However, these conditions are not met quite simply because the magnetic field lines are not vertical, the FACs do not extend to infinity, and the horizontal currents are not uniform (either due to spatially varying electric field pattern or plasma density gradients).

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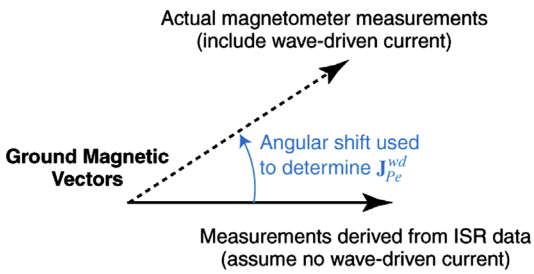


**Fig. 1.** Experimental concept. Wave-driven electron Pedersen currents (Oppenheim, 1996, 1997) would induce an angular shift between radar estimates of ground magnetic deflections and actual magnetometer measurements.

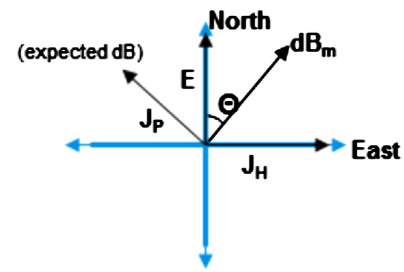


**Fig. 2.** An illustration depicting the angle convention used for a northward pointing ionospheric electric field **E** and the magnetic field ($dB$) measured on the ground. The representative measured magnetic field is denoted by $dB_m$.

With regard to the Fukushima theorem, it is beyond the scope of this paper to discuss the cancelation of the magnetic deflections caused by FACs and Pedersen currents for a realistic ionospheric and magnetospheric current geometry. The focus of this paper is to present a set of radar and magnetometer measurements that enable us to evaluate whether the magnetic deflections on the ground are due to Hall currents alone, as assumed in some models of equivalent ionospheric currents (Popov et al., 2001). We conclude that this is definitely not the case.

This radar–magnetometer comparison study was most suitable for the Resolute/polar cap region for the following reasons: (1) Resolute incoherent scatter radar-North (RISR-N) measurements show that the polar cap electric field is often strong enabling the determination of ionospheric flow with high fractional precision and high angular resolution (Bahcivan et al., 2010); (2) the electric field has a mostly uniform pattern, eliminating spatial-temporal ambiguities in radar measurements; (3) ion vertical velocity, due to being located in the polar cap region, is negligible compared to that of the horizontal component, implying the confinements of currents to the horizontal. Altogether, we have a simple geometry to interpret the magnetometer measurements.

This paper is organized as follows. We first describe the geometry used to compare radar and magnetometer data and show the diurnal variations of the averaged directions for the magnetic deflections and electric fields. We then run the Tsyganenko model (Tsyganenko and Stern, 1996) to estimate the effect of magnetospheric currents. Finally, we conclude with a summary of findings.

## 2. Observations and discussion

The coordinate system used for comparison between ISR and magnetometer data is shown in Fig. 2. In a planar geometry and looking down, a northward electric field drives an eastward Hall current, which in turn produces a northward magnetic field deflection. Any Pedersen current driven by the same electric field will cause a westward magnetic deflection. Therefore, the magnetic deflection for a northward electric field is expected to be in the fourth quadrant (270–360°), lagging the electric field by 0–90° in the clockwise sense.

Fig. 3 shows the averaged diurnal variations of the electric field (red circles) from RISR and horizontal magnetic deflection directions (blue circles) from the Resolute Bay magnetometer. The electric field data from the radar is an average of several 4–7 day experiments conducted throughout a year. The magnetometer data in blue circles represents the average of an entire year of data. The blue dots show that data spread. Surprisingly, we see that the magnetometer angle leads by 30–70°. If the Fukushima theorem applied or if the ground magnetic deflections were indeed due exclusively to Hall currents, the electric field and

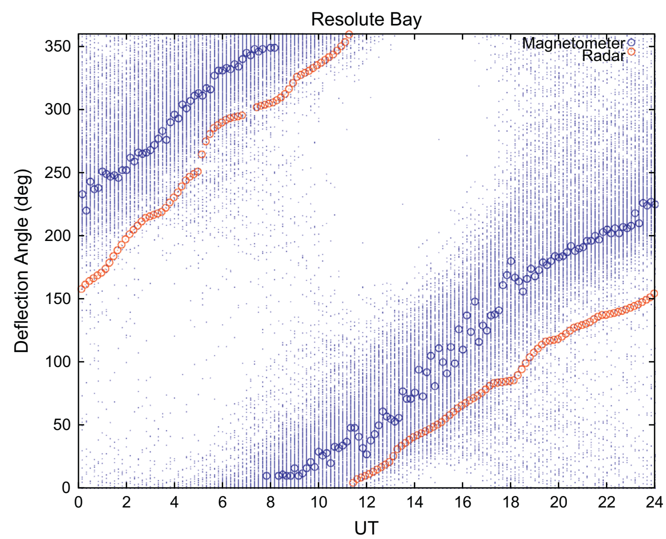


**Fig. 3.** Horizontal magnetic deflection angles from a yearly average of the Resolute magnetometer data binned by UT hour (blue circles) and the data spread (blue dots). Shown in red circles is the horizontal electric field angles also from an average of several 4–7 day experiments throughout a year binned by UT hours. The magnetometer deflection angle is consistently leading by ~30–70°. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

magnetic deflections should have pointed in the same direction (see Fig. 2) and the red and blue circles should have overlapped. In the magnetic geometry of above Resolute Bay, we expect negligible FACs. If there was indeed an electron Pedersen current flowing, we expected the magnetic deflection angle to lag the electric field angle. However, we observe the opposite, the magnetic deflection is in the first quadrant. Note that the $X$ and $Y$ DC offsets subtracted from the magnetometer data were calculated by fitting low order polynomials (parabola) to the total $X$ and $Y$ measurements over 2 years preceding the current data set of 4/30–5/4, 2011 and evaluating polynomial at the time of the data set.

To determine the cause for the radar–magnetometer offset, we first investigated if the Resolute Bay magnetometer is being affected by an instrumental bias or by a nearby man-made magnetic source. To do so, we compared yearly averages of Resolute Bay magnetic field measurements binned by the UT hours to the measurements from nearby magnetometer stations, Cambridge Bay and Thule. Table 1 lists the magnetic locations of the three stations (first two columns) as well as their relative geographic longitudes (third column). Fig. 4 shows the comparison of data from these stations by UT hour. The sharp vertical transitions around 6–9 UT are due to angular wrapping and provide a convenient assessment of the relative phase delays. We find that the diurnal phase of these nearby measurements are

**Table 1**
The magnetic locations of the three magnetometer stations used in this study (first two columns), their relative geographic longitudes (third column), and the relative angular delays estimated from the $2\pi$ transitions between 6 and 9 UT in Fig. 4.

| Station | Mag. lat. | Mag. long. | Geo. long. (relative) | Phase delay (relative) |
|---|---|---|---|---|
| Thule | 87.3°N | 13.6°W | 0.0 | 0.0 |
| Resolute Bay | 82.8°N | 53.9°W | 25.5 | 24.4° |
| Cambridge Bay | 76.3°N | 55.3°W | 35.7 | 35.0° |

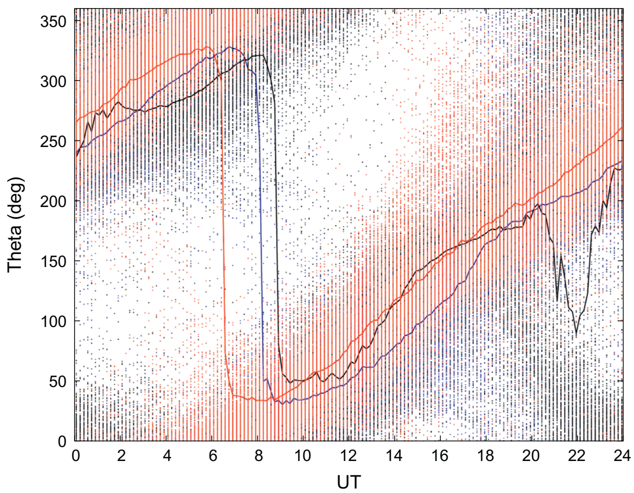


**Fig. 4.** Scatter (dots) and yearly averages (lines) of magnetometer deflection angles measured from Cambridge Bay (black), Resolute Bay (blue) and Thule (red). The yearly averages are obtained by binning an entire year of data by UT hour bins. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

very well ($\pm 1^\circ$) separated by their geographic longitudinal offsets (the estimated relative phase delays are given in the fourth column of Table 1). This agreement is in particular remarkable considering that the Cambridge Bay magnetometer is located at the edge of the auroral zone and it would be affected by auroral zone currents more than the other two stations. Note that The Cambridge magnetometer data points (dots) bifurcate around 19 UT (12 MLT) due to its location near the edge of the polar cap and auroral region, and because of averaging of both summer and winter cycles.

Considering that the magnetic field measurements at a magnetometer station are subject to currents far away including the strong auroral zone currents, we used the magnetic field data from the above mentioned stations to deconvolve the magnetic field at Resolute. First, we constructed a simple planar equivalent current system covering an area with three adjacent regions corresponding to each of the three magnetometers' local area. We parametrized each region with a pair of northward and eastward currents; therefore, a total of six parameters defined the model. We than looked for the set of six parameters that fit the horizontal magnetometer measurements in the least squares sense. The best-fit solution pair for each region was taken as the deconvolved equivalent current system.

We applied this method to 15-h of data shown in Fig. 5. The black line is the original magnetic field direction and the pink line is the deconvolved field direction. Given the small amount of correction to the original field direction, we conclude that the radar–magnetometer angle offset seen at Resolute Bay magnetometer deflections was not influenced by non-uniformity of ionospheric currents including auroral zone currents.

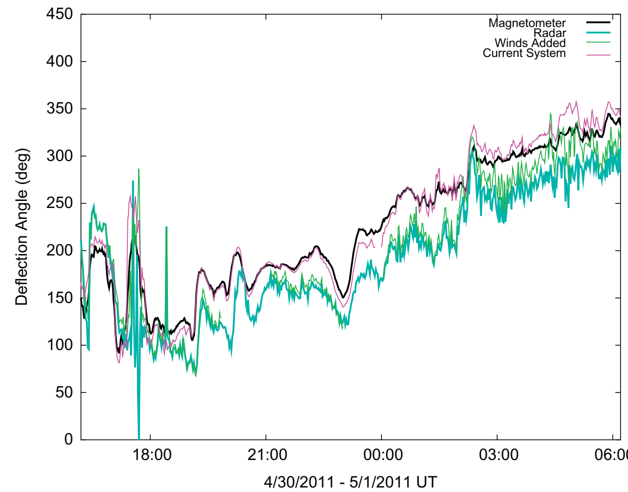


**Fig. 5.** Direction of the magnetometer horizontal component original (black line) and after the deconvolution (pink). The original radar electric field direction (blue line) and the direction for the sum of the original electric field and the wind-driven electric field (green line). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

**Table 2**
Tsyganenko model run to calculate magnetic field contribution at Resolute Bay from various magnetospheric currents.

| Current source | Sunward component at Resolute (nT) |
|---|---|
| Dipole shielding | −2 to −5 |
| Tail field | 5–11 |
| Birkeland field | 53–72 |
| Ring current | 2–7 |
| Total | 64–76 |

Next, we considered external (magnetospheric) sources that may cause the radar–magnetometer offset. The fact that the magnetic deflection angle is always leading the ionospheric electric field angle requires that there exists a sun-synchronous magnetic offset, that is, a sunward magnetic field deflection on the order of ~50 nT at all MLTs. As the source of the external magnetic field, we considered the effects of dipole shielding, tail field, Birkeland field, and ring current field. The Tsyganenko model (Tsyganenko and Stern, 1996) estimates of the contribution of these external current sources is shown in Table 2. Among these sources, only the Birkeland field has the same sign and the order of magnitude to generate the sunward field. However, note that, Tsyganenko model's Birkeland currents close through the center of the Earth, as opposed to horizontally through the ionosphere. A partial cancellation of the Birkeland field by the field generated by the transpolar horizontal Pedersen current is expected.

We finally considered the effects of neutral winds. In the polar cap, neutral winds (which are known to reach several 100 m/s and mostly anti-sunward, Wu et al., 2008) can drive a dusk-to-dawn ion Pedersen current in the *E* region. This current will generate a sunward magnetic field deflection. We used averaged wind measurements as a function of MLT (from Wu et al., 2008) to determine the wind contribution to the electric field. As shown by the green line in Fig. 5, the neutral wind driven electric field only slightly decreased the radar–magnetometer angle difference.

Two related studies are those of Baker and Kamide (1985) and Murison et al. (1985) who compared ionospheric electric fields inferred from Scandinavian Twin Auroral Radar Experiment drift data and from ground magnetic field measurements. By using a model of ionospheric conductivity and boundary conditions, the authors attempted a calculation of ionospheric electric fields and currents using an equivalent current function obtained from an array of magnetometers. Although Baker and Kamide (1985) reported that the electric fields estimated from the magnetometers and the STARE drift data generally agreed to within 20%, the results were far from precise due to the contribution of field-aligned currents and the limited accuracy of STARE drift measurements, in particular due to the saturation velocity of plasma waves for plasma drifts exceeding the ion acoustic speed (Bahcivan et al., 2005).

Although induced currents in the ground significantly affect the measured magnetic fields on the surface, in particular during rapid (~1 h) oscillations associated with substorms, in a region where the geomagnetic field is nearly vertical, the effect of currents induced in the ground is only a shift of the wavevector of the electromagnetic wave between the horizontal and the vertical directions, not in azimuth (see the derivation in Tanskanen et al., 2001). Therefore, although the induced ground currents will affect the combined magnitude of the $X$ and $Y$ components of the magnetic field, the azimuthal direction will not be affected.

## 3. Conclusion

The widely used assumption in the high latitudes that the horizontal magnetic deflections on the ground are caused by ionospheric Hall currents does not seem to hold well in the data set analyzed here. We find that the horizontal magnetic deflection angle measured by the Resolute Bay magnetometer was ahead of the electric field angle measured by the Resolute incoherent scatter radar by 30–70° depending on the MLT. The difference was the smallest (largest) around the morning (evening) sector. Some of the angle offset is accounted for by including neutral winds, however, only slightly ($<10^\circ$). What is needed is a sun-synchronous magnetic field contribution on the order of ~50 nT in the sunward direction, possibly caused by magnetospheric currents. We ran the Tsyganenko model for a range of solar wind parameters and evaluated the magnetic field contribution by exclusively turning on different components of the model including the fields from Birkeland, dipole shielding, tail, and the Ring current. Among these, only the Birkeland current resulted in a magnetic contribution with the right sign and magnitude, 53–72 nT in the sunward direction. However, the Tsyganenko model for the Birkeland currents uses a current system that does not close through the ionosphere, but rather through the center of Earth in a wedge shape. Hence, it is not clear if the Birkeland currents are responsible for the radar-magnetometer offset we measured here. We will continue our study with a modification of the Tsyganenko model that closes the currents through the ionosphere to determine if the Birkeland currents are indeed the source of anti-sunward field needed to explain the radar electric field and magnetometer deflection angle difference.

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