

Event study of high-energy electron precipitation by comparison of Ørsted data and ground-based observations

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Abstract. The Ørsted geomagnetic satellite in its polar orbit opens up an excellent prospect of making correlative studies with high-latitude ground stations of various types. Here is presented an event study of high-energy electron precipitation during an Ørsted pass over Greenland on January 5, 2000, at 0200 UT (midnight MLT). The ground-based data from the incoherent scatter radar and the imaging riometer in Søndre Strømfjord indicate a hard spectrum of the precipitating electrons. The measurements of the Ørsted charged-particle detector confirm this. The Ørsted vector magnetometer detects at least five occurrences of field-aligned currents during the Greenland passage. The upward currents correspond to peaks in precipitating electron flux. The ionospheric Pedersen and Hall currents inferred from the field-aligned currents are quite weak and cannot account for the large bays seen in the ground magnetometer data. The simple picture of infinite current sheets closed by Pedersen currents in the ionosphere breaks down in this case.

Observations

On January 5, 2000, the Ørsted geomagnetic satellite passes over Greenland at 0200 UT (approximately midnight MLT) during substorm conditions. The trajectory shown in Figure 1 has been projected to ground level along geomagnetic field lines. The locations of the Greenland magnetometer stations and the field-of-view of the imaging riometer (see the appendix) in Søndre Strømfjord are indicated.

Imaging riometer data

The imaging riometer in Søndre Strømfjord registers a sharp increase in absorption shortly before 0100 UT on January 5, 2000. The activity maximizes around 0130 UT, and a spike is seen at 0200 UT when Ørsted passes overhead. In Figure 2 a time series of images of this last brightening is shown. The activity is confined in latitude, but it is likely to extend in longitude beyond the riometer field-of-view. The position of Ørsted projected along magnetic field lines to 90 km altitude is indicated. It is seen that from approximately 02:00:10 to 02:00:40 Ørsted flies through the field-of-view just north of the auroral arc-like absorption structure.

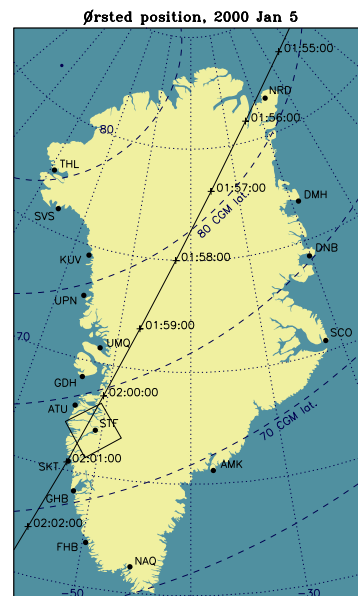


Figure 1. Footprint of Ørsted position on January 5, 2000. The Greenland ground magnetometer stations are indicated with dots. The big square at STF (Søndre Strømfjord) indicates the approximate field-of-view of the imaging riometer (200 km × 200 km).

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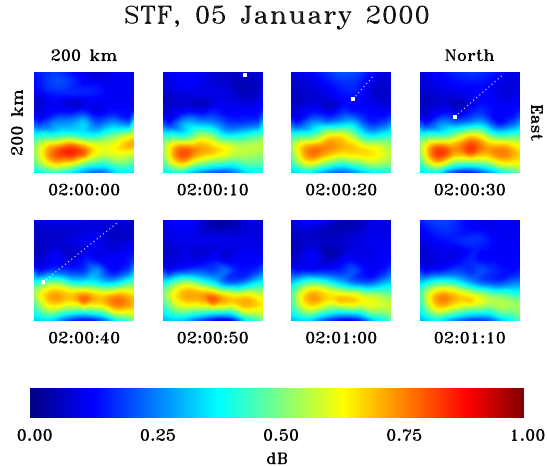


Figure 2. Radio wave absorption as detected by the imaging riometer in Søndre Strømfjord while the Ørsted satellite passes the field-of-view. The position of Ørsted mapped to 90 km altitude, where absorption events are most likely to occur, is indicated by white squares.

Magnetometer data

Figure 3 shows data (main field subtracted) from the Ørsted vector magnetometer during the pass over Greenland. Five periods of field-aligned currents are indicated and denoted A-E.

During the passage of the riometer field-of-view Ørsted for the most part detects no deflection of the magnetic field. Immediately after exiting the riometer field-of-view starts an increase in the eastward component lasting 16 seconds (period E). This upward field-aligned current can be interpreted as Ørsted flying through the extension of the auroral arc seen by the riometer.

Since the magnetic measurements are made only along one spatial direction (along the satellite orbit) the infinite current sheet approximation is used here to calculate currents from $\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$. The vertical \mathbf{B} -component is assumed have negligible variations. With only horizontal magnetic variations the currents must flow along magnetic field-lines. If e.g. x is northward, y is eastward and \mathbf{B}_x is constant then $\mathbf{j}_{\parallel} = \frac{1}{\mu_0} \frac{\partial \mathbf{B}_y}{\partial x}$. The variation of \mathbf{B}_x is minimized here by introducing an angle of 23° between the direction of the assumed infinite current sheets and geomagnetic east. This procedure works for intervals A, D and E. For B and C, however, it is not possible to rotate the horizontal coordinate system to obtain a non-varying component. The approximation of infinite current sheets can't be used. At these times Ørsted is probably flying through filamentary field-aligned currents.

If, for lack of a better approach, infinite current sheets are assumed for periods B and C, currents of $I_B = 99$ mA/m (downward) and $I_C = 80$ mA/m (up-

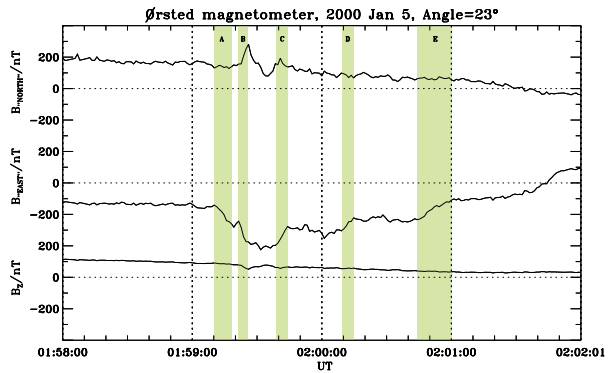


Figure 3. Ørsted vector magnetometer data, main field model subtracted. Five periods of field-aligned currents are indicated by coloured regions and denoted A-E. The horizontal \mathbf{B} -components have been rotated 23° counter-clockwise with respect to geomagnetic coordinates, as this enables use of the best possible infinite current sheet approximation for three periods of field-aligned currents (A, D and E), see text.

ward) can be calculated. In the following these will be assumed to cancel each other.

The currents calculated for the three periods A, D and E for infinite current sheets are: $I_A = 99$ mA/m (downward), $I_D = 40$ mA/m (upward) and $I_E = 109$ mA/m (upward). It is seen that these can only be closed with ionospheric Pedersen currents if an additional Pedersen current (either poleward or equatorward) of 50 mA/m is fed to the system. With this assumption the Pedersen current between sheets D and E would be either 60 mA/m or 109 mA/m. In the rest of this order-of-magnitude estimate the latter will be assumed.

The region between sheets D and E is sampled by the ground magnetometer and the incoherent scatter radar in Søndre Strømfjord. From the radar measurements the ratio of Hall to Pedersen current is known to be 1, and thus the induced westward Hall current would be of order 109 mA/m. The effect on the ground of an infinite Hall current of this size would be $B_\infty = \frac{1}{2} \mu_0 I_H = 68$ nT. Since the overhead Hall current is westward this would be seen as a negative deflection in the northward component of the magnetic field at STF. However, in the northward component of the ground magnetometer data, see Figure 4, the negative deflection is much larger. The simple picture of infinite current sheets closed by Pedersen currents in the ionosphere breaks down in this case. This is maybe not too surprising for a substorm-type case close to magnetic local midnight.

Data from the Ørsted charged-particle detector

The charged-particle detector on Ørsted has six modules for detecting high-energy electrons, protons and α -particles. Two are designed to detect mainly electrons:

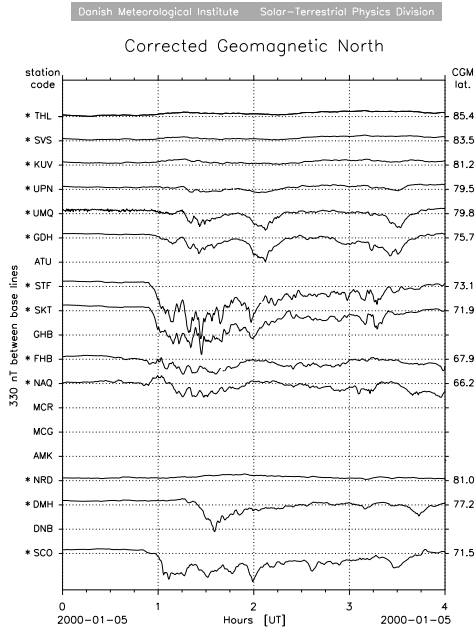


Figure 4. Northward horizontal component of the ground magnetometer data from the Greenland chain. A disturbance is starting shortly before 0100 UT. After this a strong westward electrojet is seen for at least an hour. As Ørsted passes STF and SKT at 0200-0201 UT a strong negative deflection is recovering.

one is facing upward along the boom of the satellite and the other in a direction perpendicular to this. At high latitudes this corresponds to the former looking up along magnetic field lines, i.e. sampling precipitating electrons, while the latter looks in a horizontal direction and thus samples trapped electrons. The lowest energy bin registers electrons with energies above 47 keV.

Around 0200 UT on January 5, 2000, the charged-particle detector sees a signal of high-energy precipitating electrons, see Figure 5. The intensity profiles between 0159 and 0203 UT appears to have a generally smooth variation with superimposed local reductions and enhancements. The coloured regions mark the same time intervals as in Figure 3. The last two correspond to upward currents and both fits nicely with local increases in precipitating electron flux. Field-aligned currents are for the main part carried by soft electrons (energies of a few eV to a few hundred eV), so only in cases of a very hard electron spectrum would a signature in the charged-particle detector be accompanying a field-aligned current detection.

The crossing into the radiation belt just after 0203 UT is seen as a very sharp increase at all energies (indicating hard radiation). The sharp boundary shows a compressed radiation belt, an effect of the dipolarization of the magnetic field during the substorm. The peak in precipitation right at the edge is possibly due to Fermi acceleration at the contracting field lines.

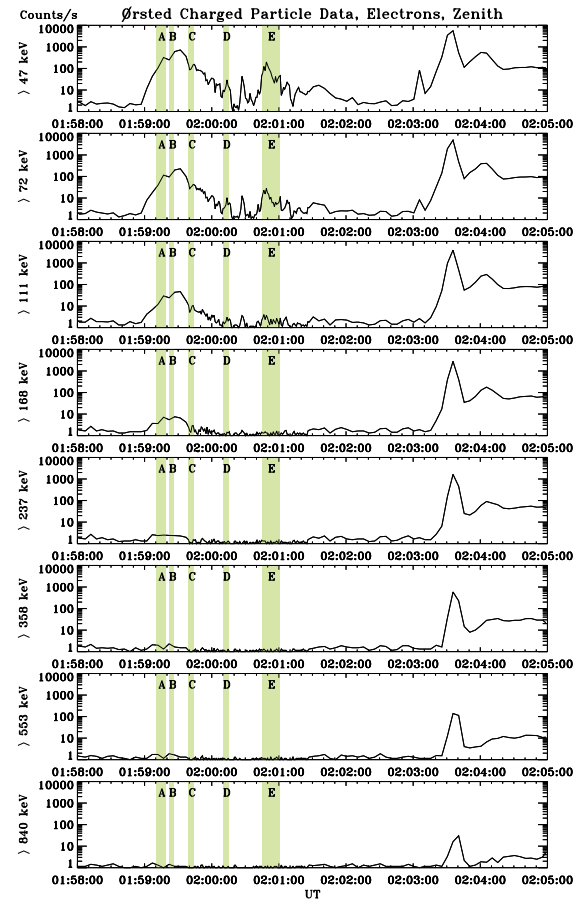


Figure 5. Data from the Ørsted charged-particle detector on January 5, 2000. The data is from the electron detector module facing along the direction of the satellite boom, i.e. approximately vertically at this high latitude. This module registers high-energy electrons: the lowest energy bin (top panel) contains electrons with energies above 47 keV. The five periods indicated by the coloured regions are the same as those indicating field-aligned currents in Figure 3. The feature seen starting around 0203 UT is due to Ørsted entering the radiation belt.

Incoherent scatter radar data

The incoherent scatter radar in Søndre Strømfjord was operating at the time of the Ørsted pass. The radar measured an increased electron density at 130 km altitude around 0200 UT, see Figure 6. This is consistent with the detection by the Ørsted charged-particle detector of a high-energy tail of the precipitating electron distribution. At higher altitude (data not shown) there is a depletion of electrons at this time .

Comparing the radar data with the imaging riometer data from 0030-0230 UT (see Figure 7), where the activity is pronounced, a very good correlation is seen. At 0100 UT the riometer at Søndre Strømfjord registers a sharp increase in absorption. The activity maximizes around 1:30 and a spike is seen at 2:00. This matches

very well with the electron density measured by the incoherent scatter radar. This also correlates well with the development seen in the Greenland magnetometer chain.

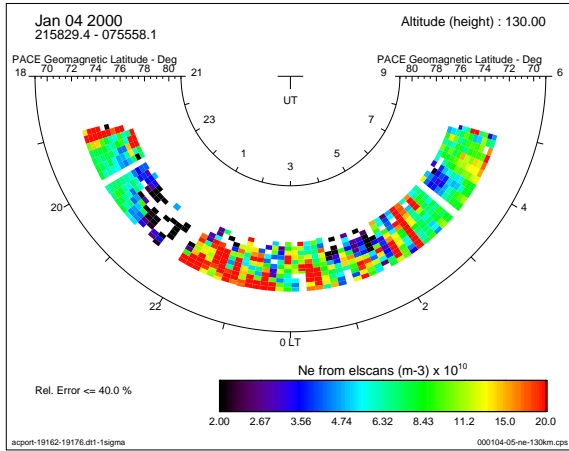


Figure 6. Electron density measurements from the incoherent scatter radar in Søndre Strømfjord, January 4-5, 2000.

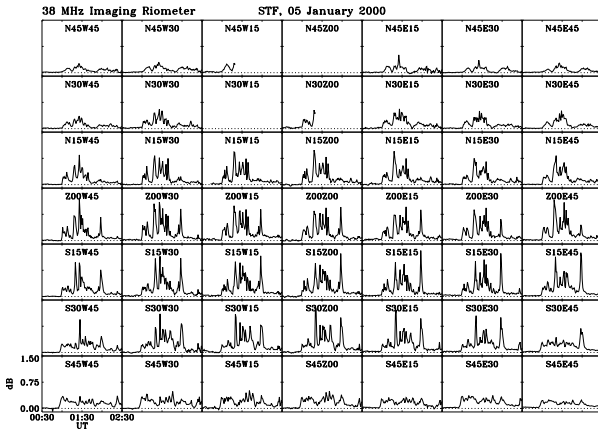


Figure 7. Individual STF recordings of the radio wave absorption in the 49 beams of the imaging riometer in Søndre Strømfjord for a two-hour period from 0030 to 0230 UT on January 5, 2000. The absorption enhancement seen in many beams at 0200 UT (when Ørsted passes overhead) is represented in more detail in Figure 2.

From the radar measurements the electric field is deduced (data not shown). Strong electric fields are seen, but around 0200 UT they show a lot of small scale structure indicating a complex configuration of currents, consistent with the Ørsted magnetic measurements' indication of filamentary field-aligned currents just north of Søndre Strømfjord.

Summary

On January 5, 2000, Ørsted passes over Greenland during a substorm. At 0200 UT the imaging riometer in Søndre Strømfjord sees an auroral arc-like absorption structure and Ørsted passes just north of this, probably crossing the feature just out of the field-of-view of the riometer, as indicated by the detection of an upward field-aligned current.

The Ørsted charged-particle detector registers precipitating electrons at energies of ~ 50 -300 keV at 0159-0202 UT with an intensity decrease just poleward of the absorption arc during the crossing of the riometer field-of-view. Upward field-aligned currents are coincident with increased high-energy electron flux.

The Søndre Strømfjord incoherent scatter radar detects an enhanced electron density which correlates well with the time and intensity development seen in the riometer data.

The field-aligned current detected by Ørsted over STF is too weak to explain the deflection seen at the ground magnetometer. The ionospheric current pattern is quite complex at this time and other sources than uniform field-aligned current sheets must be invoked to close the ionospheric currents. In the electric field deduced from ISR measurements (data not shown) there are strong small-scale features supporting the breakdown of the simple picture. Since it is a substorm case close to midnight MLT this break-down is maybe not so surprising, and it is very likely that the infinite current sheet approximation will work fine at other times.

Appendix: What is a riometer?

A riometer measures relative ionospheric opacity, hence the acronym rio. From the galaxy there is a smoothly varying background of radio wave emission. When the radio waves pass through the Earth's atmosphere there is an absorption of the signal, $A \propto \int_s \nu_{en} n_e ds$, where ν_{en} is the electron-neutral collision frequency, n_e is the electron density and s denotes the path through the ionosphere.

In the case of the imaging riometer the radio wave absorption is measured by an array of antennas, giving measurements from typically 7×7 directions. At the ionospheric height of 90 km where the absorption is most likely to take place this corresponds to a field-of-view of 200×200 km.

The data are normalized with respect to quiet day level. The absorption seen is due to enhanced electron density, typically caused by precipitating electrons of energies above 10 keV.

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