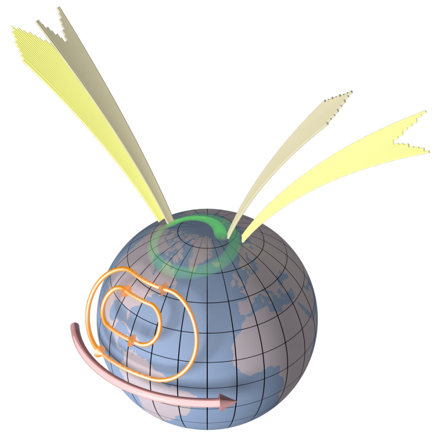

Magnetospheric field-aligned currents: Their signatures in the ionosphere

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GFZ - German Research Centre for Geosciences, Potsdam

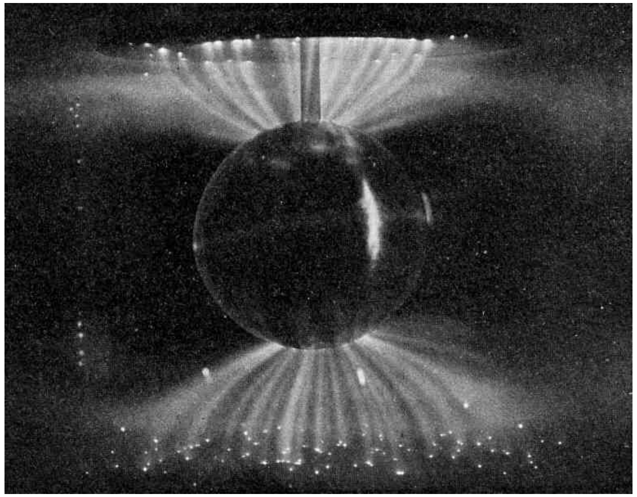
Magnetosphere Online Seminar Series
13 July 2020

Outline

- Historical background
- General characteristics of FACs
- Scale dependence of FACs
- Measurement techniques for FACs
- Storm features of FACs
- Characteristics of small-scale FACs

Here I focus on my view of FACs from the ionospheric end.

The early visions

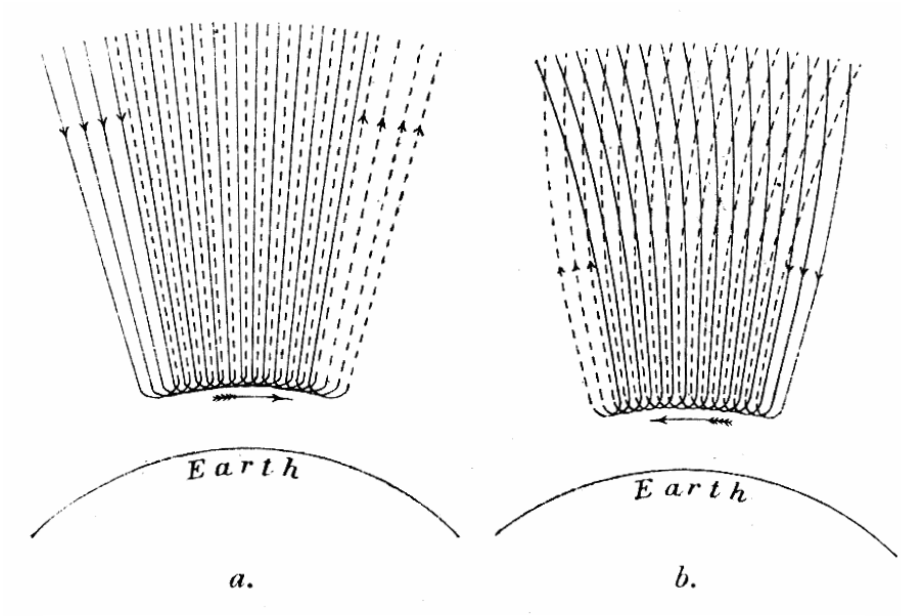


Birkeland's Terrella experiments, 1895

First suggestions for auroral field-aligned currents came from Kristian Birkeland.

In his famous Terrella experiments he was shooting cathode rays onto a magnetised sphere. Currents were guided by magnetic field lines towards the sphere.

As a reference to his early pioneering work the auroral FACs are also termed "Birkeland currents"



The systems of field-aligned currents as suggested by Birkeland (1908).

Note the horizontal currents below the FAC systems, which he already then predicted, representing our electrojets on the dawn and dusk sides.

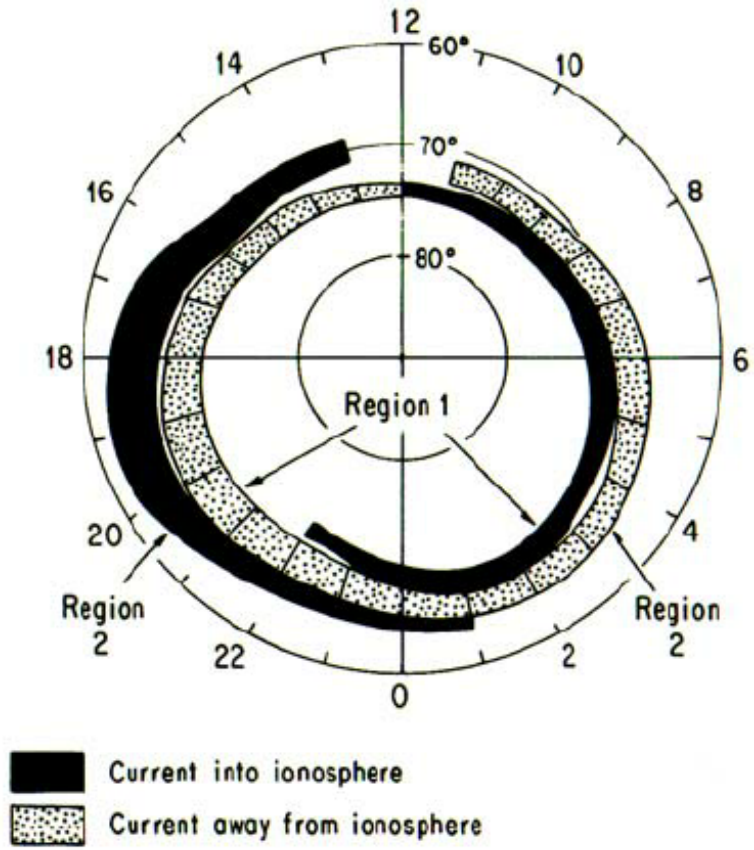
Initially there was a heated debate:

Chapman and Co. denied the existence of FACs. But Alfvén and his group strongly favoured the idea of Birkeland concerning the auroral FACs.

It required spaceborne magnetic field measurements for uniquely identifying FACs. These became available during the 1960's.

One of the sensations at the 1975 Fall AGU was the talk by Tom Potemra presenting the famous local time vs. latitude pattern of FACs.

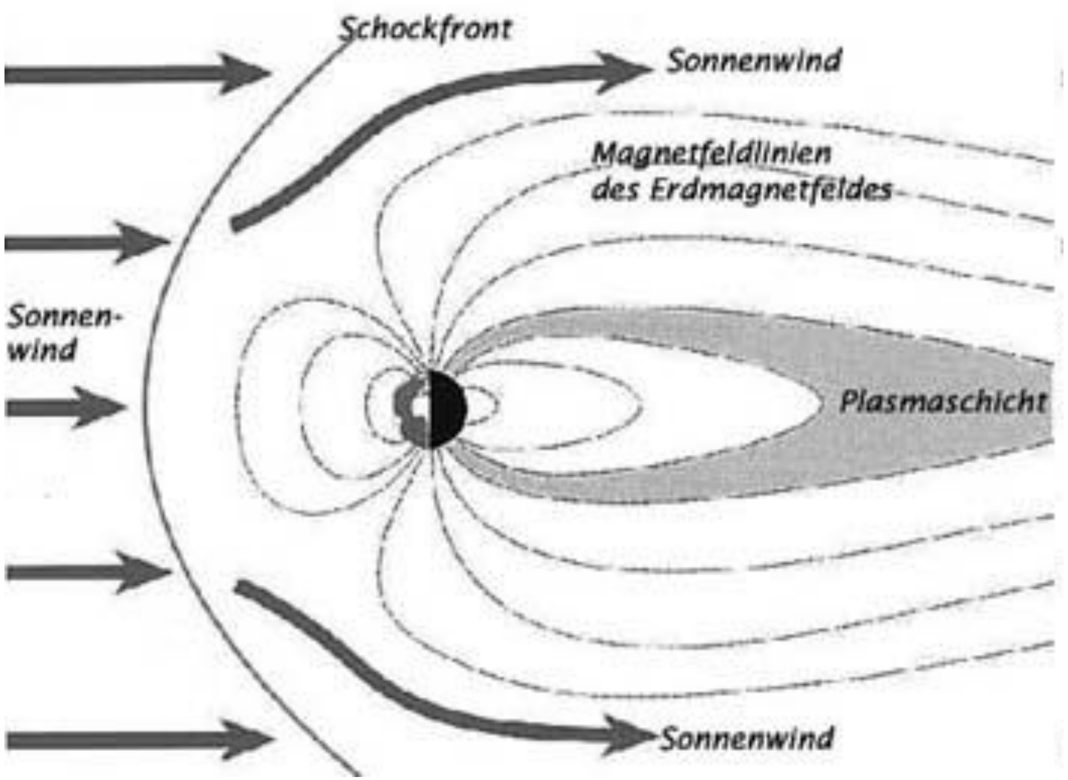
It was my first AGU meeting.



Iijima and Potemra (1976)

General role of field-aligned currents

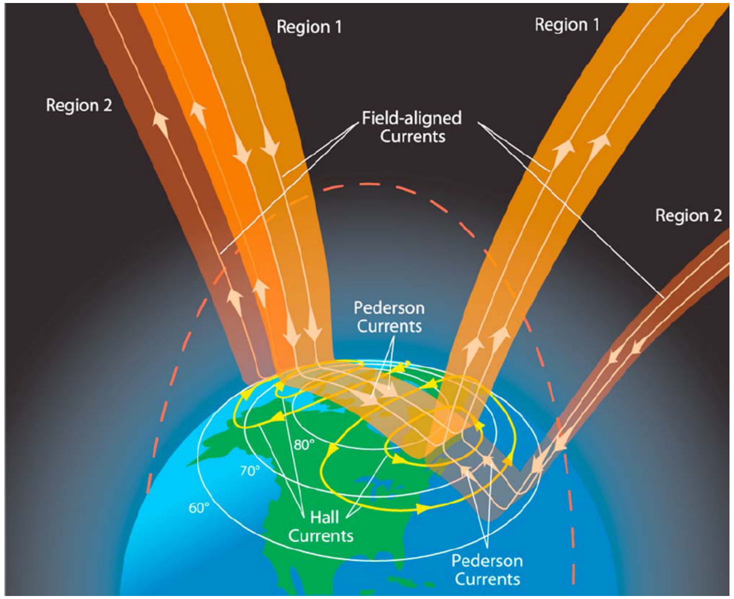
- Field-aligned currents (FAC) play an important role in space plasma physics since they connect largely separated regions electrically, and they transfer energy and momentum almost lossless.
- The conductivity along magnetic field lines is almost perfect. Therefore, field lines can be regarded as equipotential lines (under DC conditions).
  Any potential difference in the magnetosphere is mapped into the ionosphere, drives currents there and dissipates energy.
- FACs cause toroidal magnetic fields that do not contribute to the total field strength.



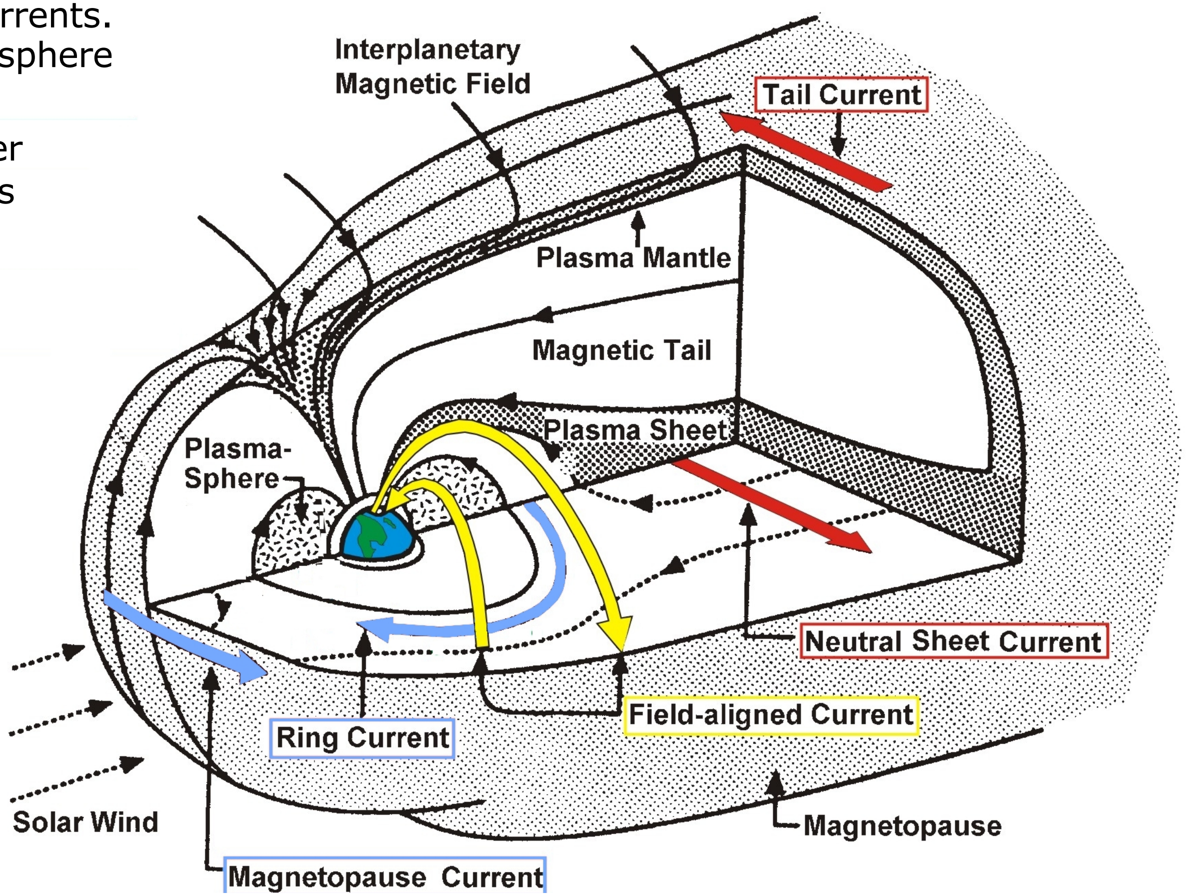
Magnetospheric FACs

In the magnetosphere exist a number of different currents. FACs are the connecting elements between magnetosphere and ionosphere.

High-latitude Region 1 (R1) FACs connect to the outer magnetosphere and lower latitude Region2 (R2) FACs connect to the outer edge of the ring current.



Le et al. (2010)



FAC drivers

In MHD limits currents can be derived from the momentum equation.

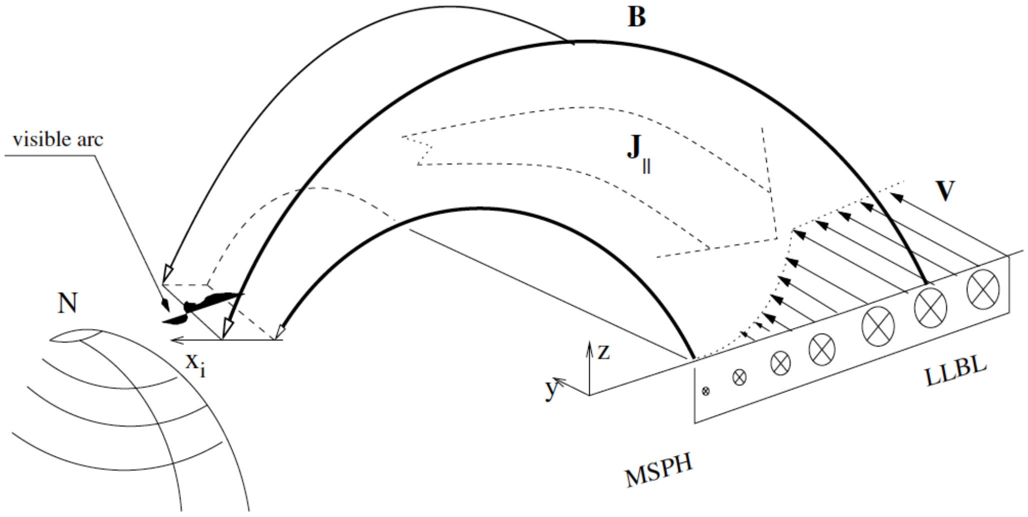
$$\vec{j}_{perp} = \frac{1}{B^2}\left[\nabla P + \rho\left(\frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v}\right)\right]\times \vec{B}$$

In the outer magnetosphere the second term, plasma inertia and shear flow, is more important.

In the inner magnetosphere, near ring current, the plasma pressure gradient is the dominating current driver, e.g. for R2 FACs.

For current continuity, the divergence of perpendicular current is feeding FACs.

$$\frac{j_{//}}{B} = -\int \frac{\nabla\cdot\vec{j}_{perp}}{B} ds_{//}$$



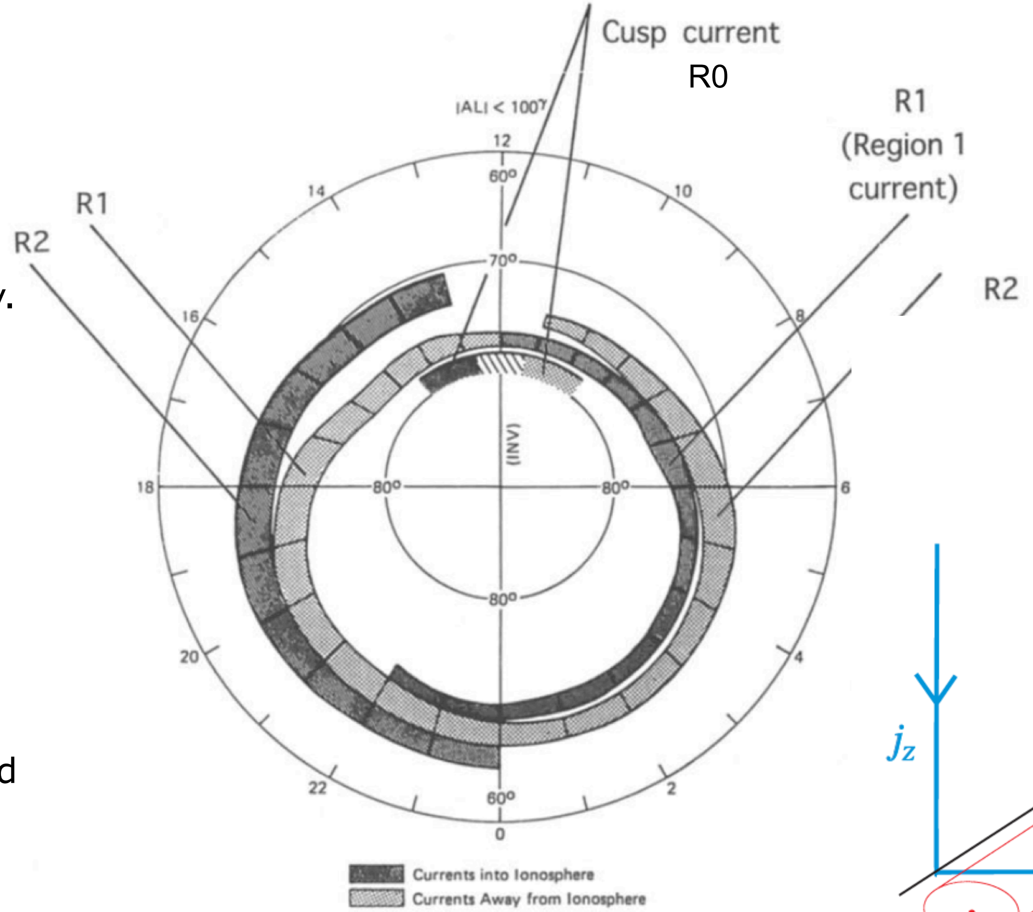
Flow shear in the low-latitude boundary layer (LLBL) is mainly responsible for R1 FACs.

Johnson and Wing (2015)

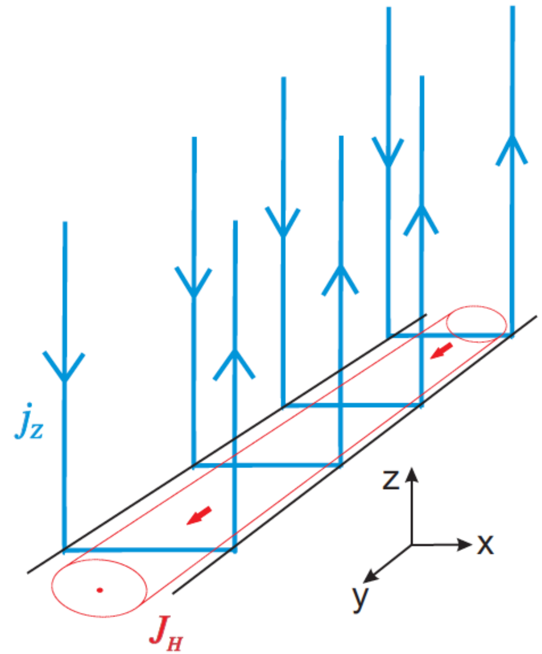
Over the years more reliable magnetic field data from dedicated satellites became available (recently CHAMP and Swarm). This increased our understanding of FAC properties greatly.

Beneath the loop of downward and upward FACs strong Hall currents are flowing, the anti-sunward electrojets (as predicted by Birkeland).

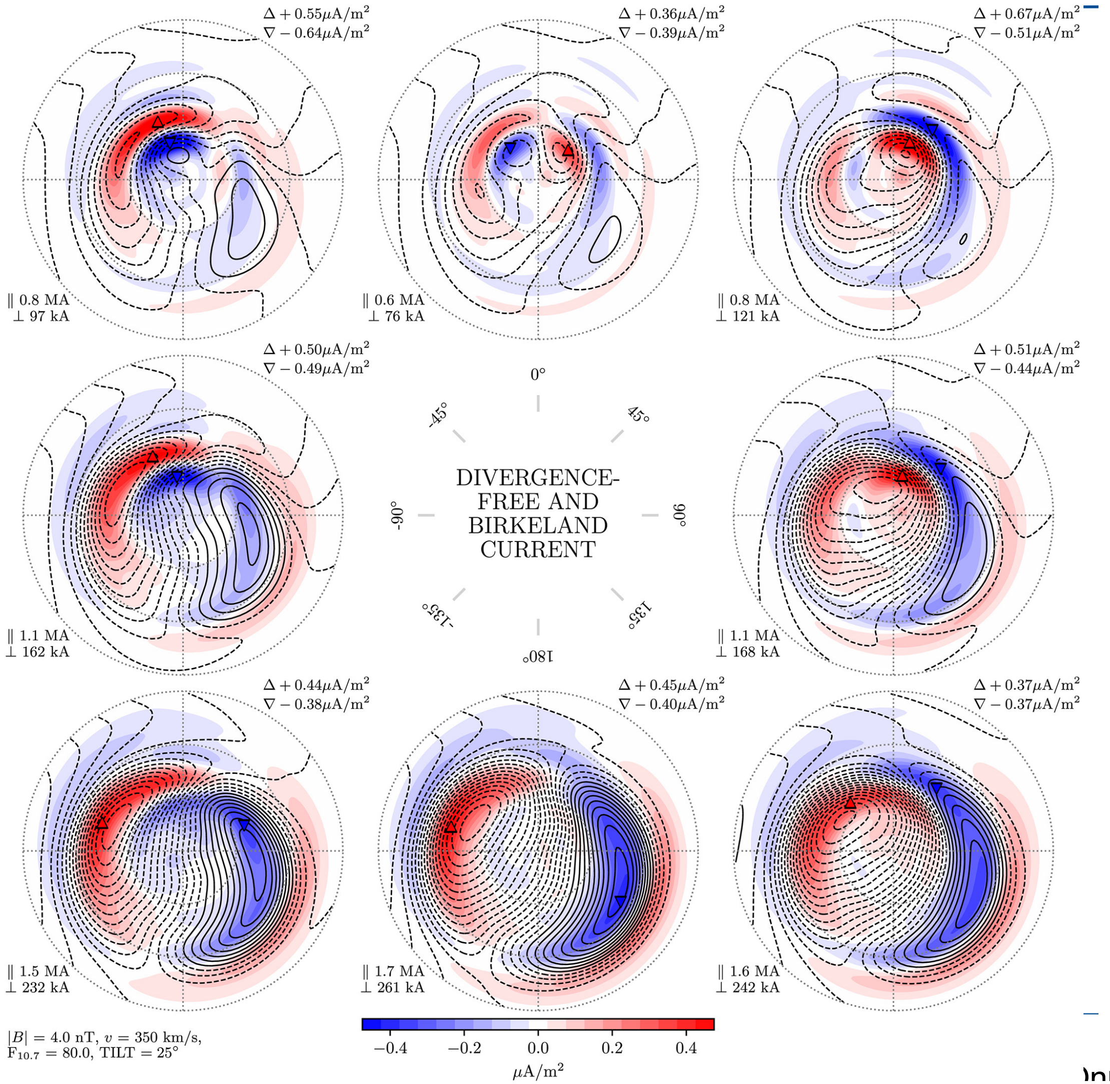
The configuration and the size of the two FAC belts around the poles is strongly controlled by the intensity and orientation of the interplanetary magnetic field (IMF). During northward IMF cusp currents become prominent. This dependence qualifies the solar wind as the main driver of the FACs.



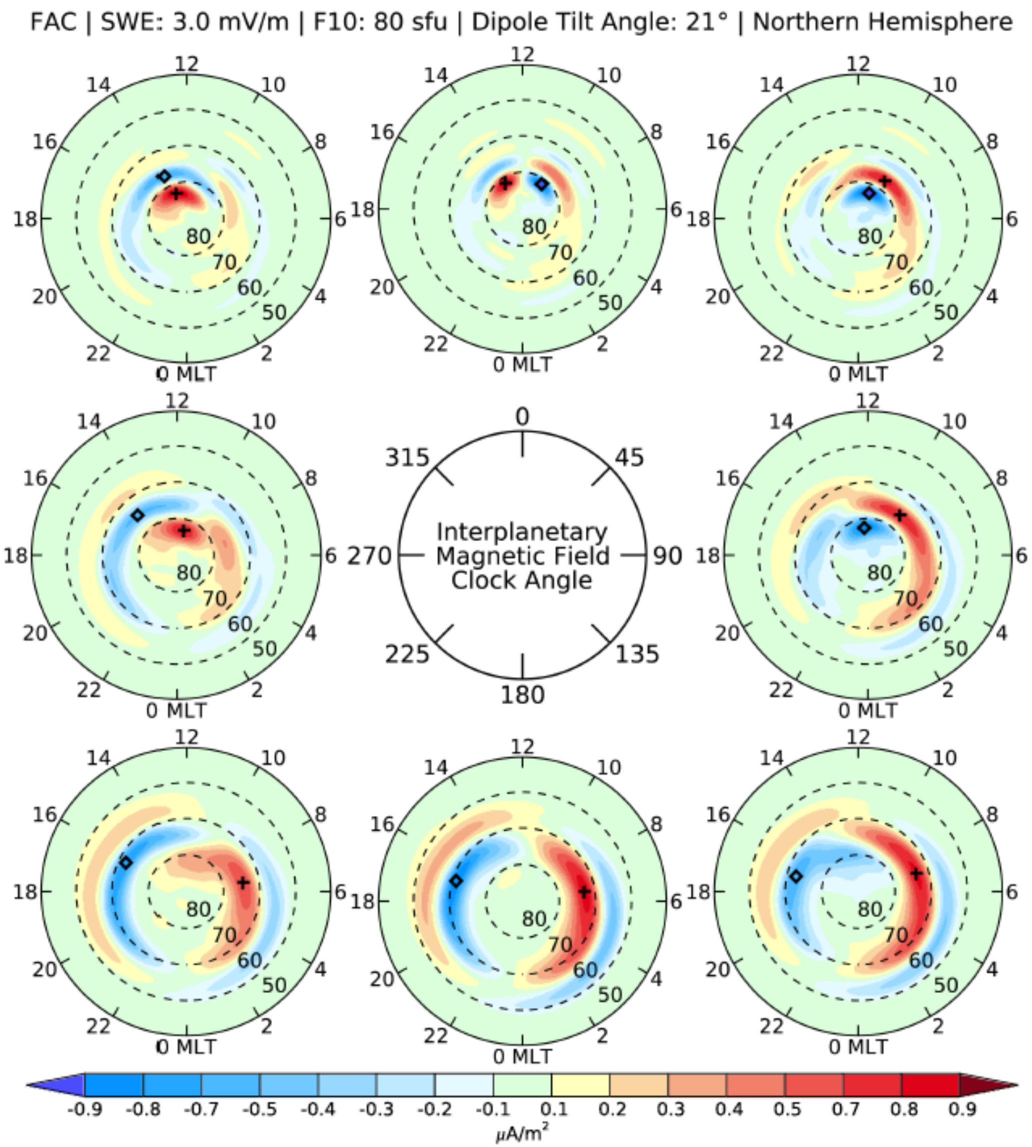
Iijima (2000)



Statistical FAC patterns sorted by IMF

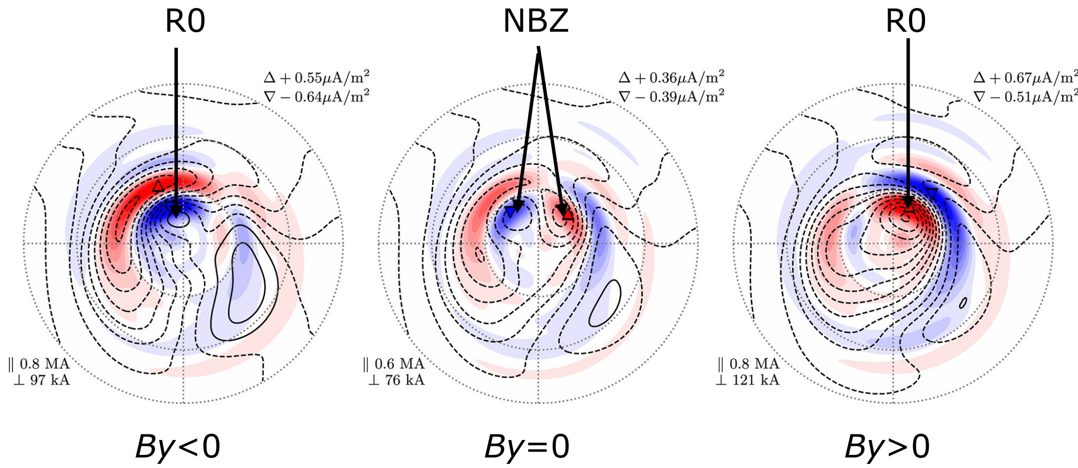


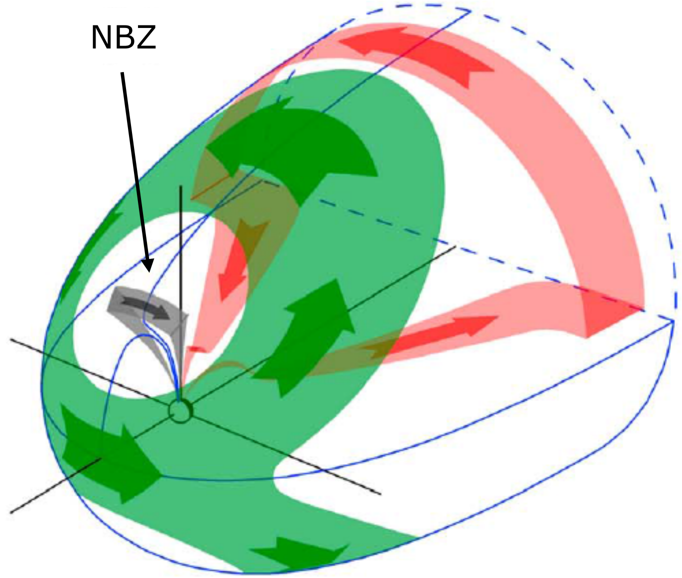
Laundahl et al. [2018]



Edwards, Weimer et al. [2020]

Polar cusp currents for northward IMF





For due northward IMF the NBZ FACs are driven by reconnection poleward of the cusp.

In case IMF *By* is significant, reconnection occurs at the lopes on dawn or dusk flank, and R0 FACs appear. The polarity and location of R0 depends on the sign of IMF *By*.

The polarity of the FACs in the cusp region is opposite in the southern hemisphere, different from that of R1, R2 FACs.

Ganushkina et al. (2018, Rev. Geophys.)

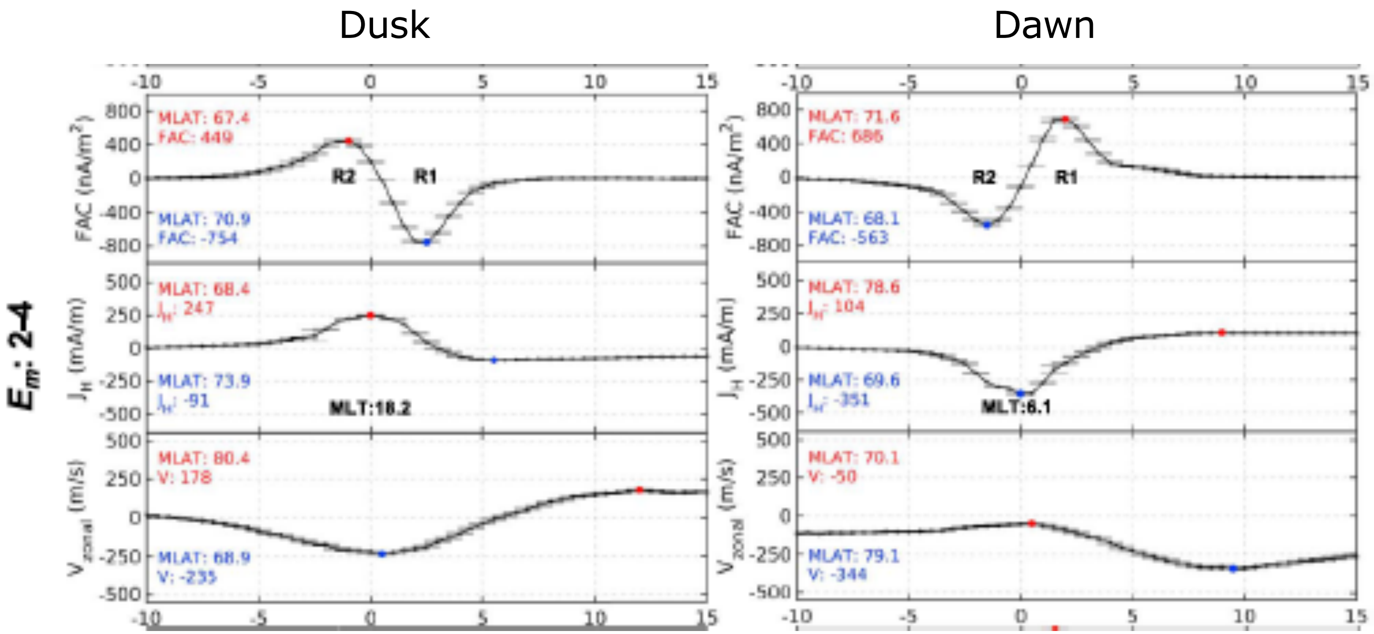
Limitations of statistical FAC patterns

Statistical FAC patterns sorted by IMF and tilt angle provide a lot of information about characteristic properties of the FAC systems in the ionosphere.

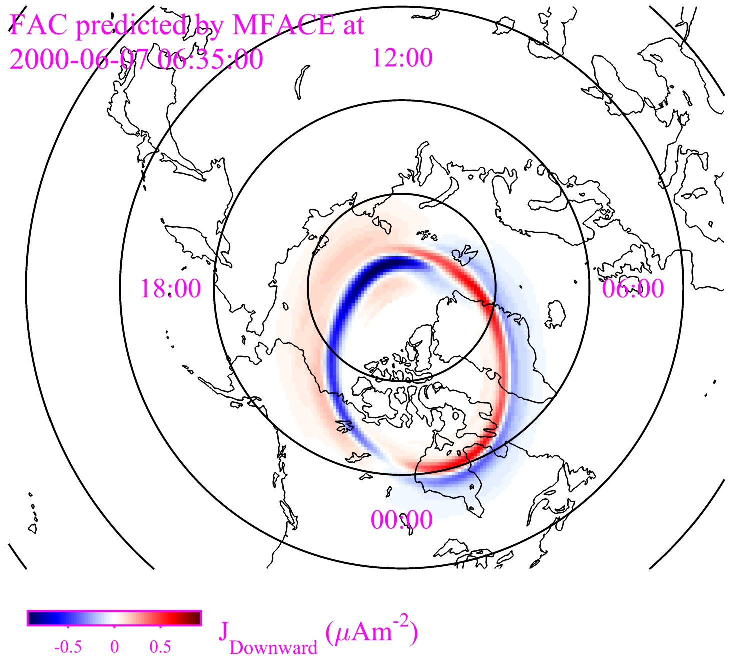
The limitations concern mainly those parts of FACs that are not closely controlled by the IMF orientation. These are for example:

- ❖ The latitudes where the FACs reach the ionosphere.
  → Peak values are distributed over a broader range;
  average shapes are flattened and broadened.
- ❖ The intensity of the R2 FAC density.
  → Unrealistic values may result. E.g. the model by Edwards et al. (2020) predicts stronger R2 on the duskside than on the dawnside, opposite to general experience.
- ❖ A void of FAC values in the region around midnight.
  The occurrence of substorms is only indirectly controlled by the IMF orientation. Therefore FAC patterns average out.

Pairs of FACs in the ionosphere are accompanied by anti-sunward electrojets. These can be used for identifying the latitude of the FACs. By superposing FAC latitude profiles with respect to the electrojet peak the smearing is avoided. Resulting statistical FAC patterns reveal more realistic (larger) amplitudes and narrower current structures.



Huang, Lühr et al. [2017]



He, Vogt, Lühr et al. [2012]

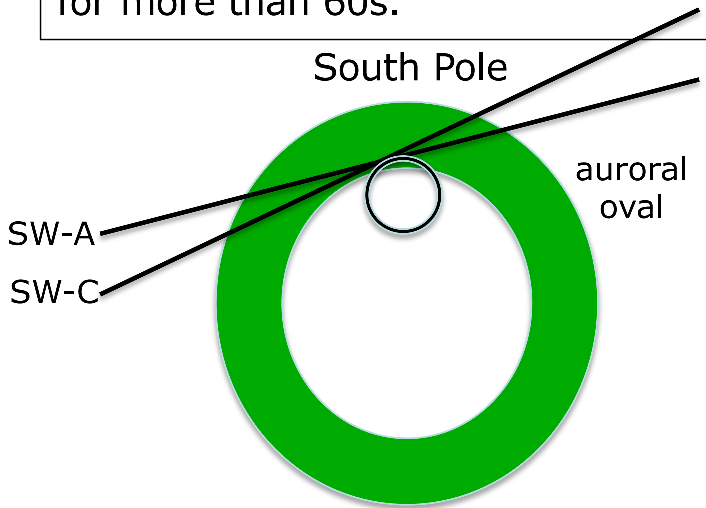
Scale analysis of FACs derived from Swarm constellation

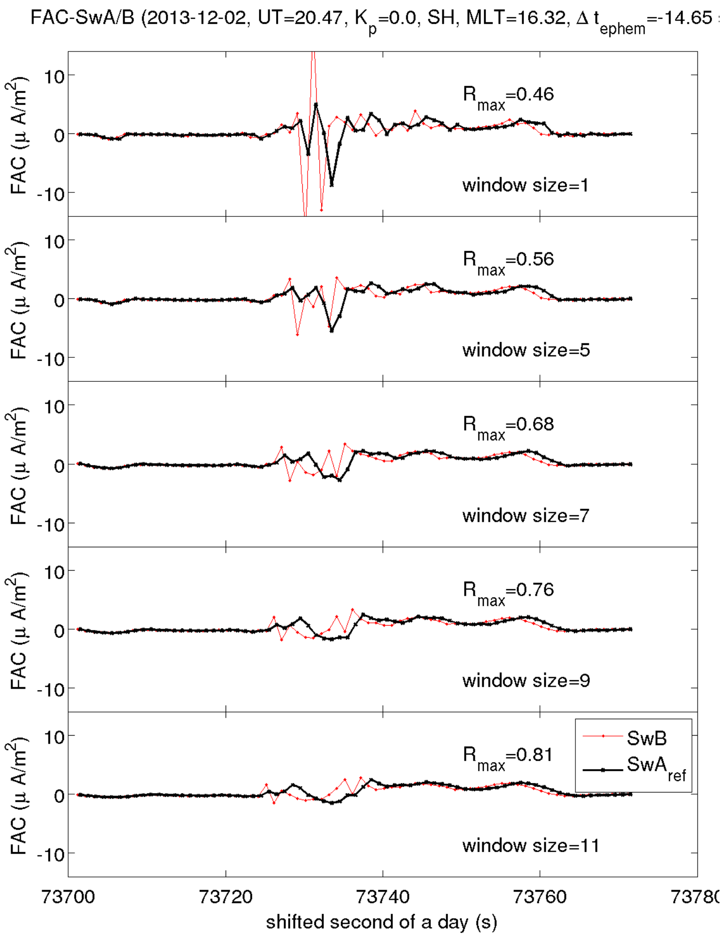
FAC come at a range of spatial scales.

For analysis, FACs are taken at same location (orbital cross-over) but sampled at different times.

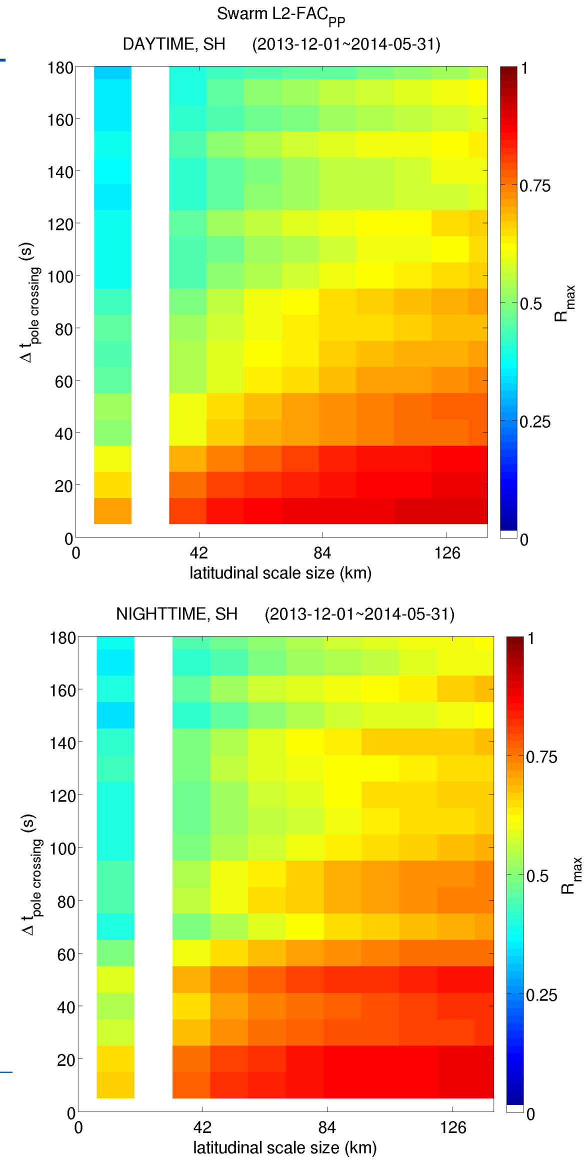
Small and large-scale FACs exhibit different behaviour. Small-scale FACs (~10km) vary on time scales of the order of 10s.

Large-scale FACs (>100km) are stable for more than 60s.





Lühr et al. (2015, GRL)



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Quasi-static and dynamic FACs

By comparing E- and B-field variations of DE-2 data Ishii et al. (1992) determined the temporal characteristics of FACs.

By evaluating $\Delta By / \mu_0 Ex$ they found that the value approached the local Alfvén velocity for high-pass filtered data with periods <4 sec (corresp. <30 km scale). This is an indication of kinetic Alfvén waves.

For longer periods (larger horiz. scales) the B/E ratio reflects the ionospheric Pedersen conductance. This indicates quasi-static FAC structures.

The scale characteristics derived from DE-2 have well been confirmed by the Swarm constellation measurements.

The AC features have to be taken into account when estimating small-scale FACs from B-field data.

ISHII ET AL.: RELATION BETWEEN MAGNETIC AND ELECTRIC NOISES (1992)

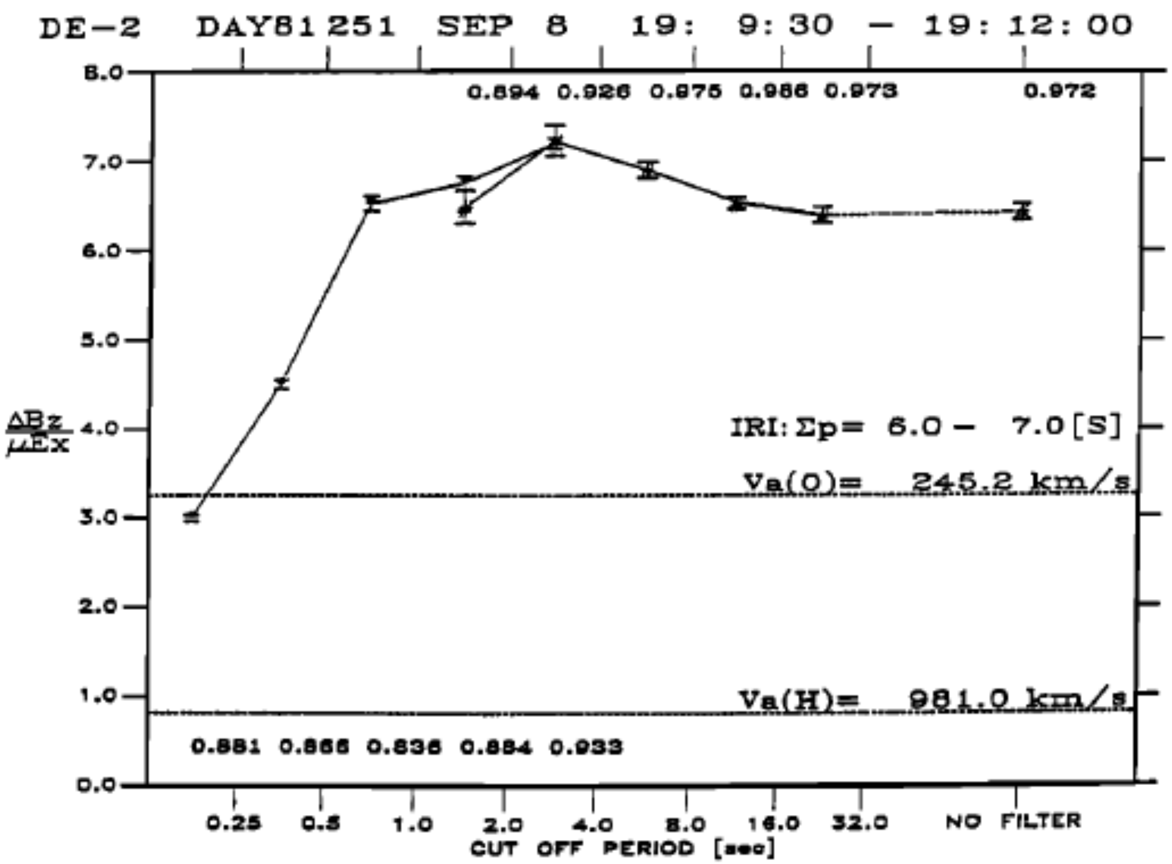


Fig. 3. The relation between the ratio $\Delta B_z/\mu_0 E_x$ and the filter cutoff period. The ratio decreases with decreasing cutoff period.

Estimating FACs from a single satellite

Current estimates from spacecraft magnetic field measurements are commonly based on Ampère's law. For the vertical component one can write

$$j_Z = \frac{1}{\mu_0}\left(\frac{dB_y}{dx} - \frac{dB_x}{dy}\right)$$

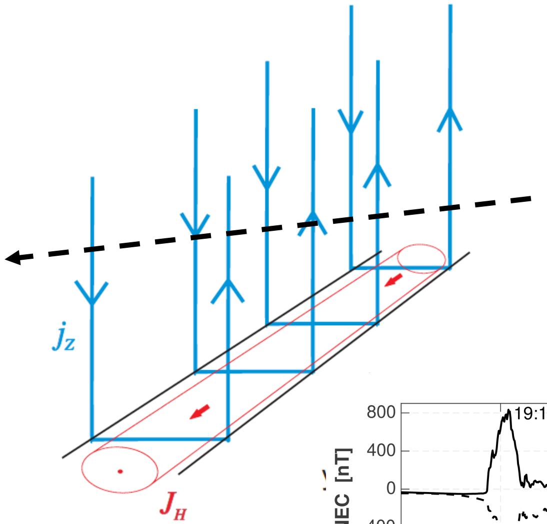
From satellite data we only obtain along-track field variations.
The equation has to be simplified.

$$j_Z = \frac{1}{\mu_0}\left(\frac{\Delta B_y}{\Delta t\ v_x}\right)$$

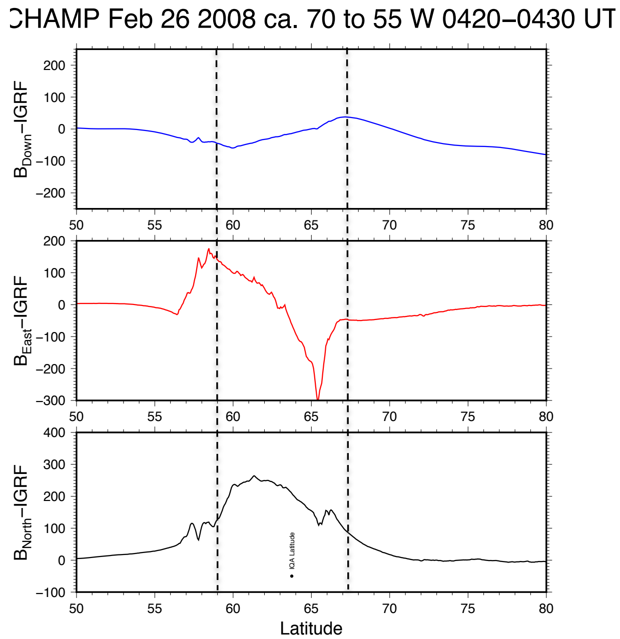
where v_x is the velocity component in flight direction, ΔB_y is the perpendicular field variations and Δt the time step.
Field variations along the track are assumed to be caused by spatial features, and ΔB_x variations have to be negligible.

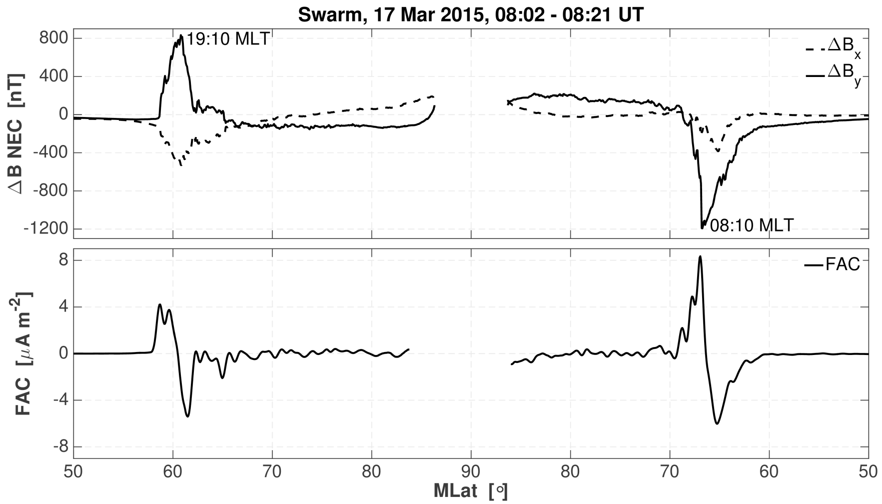
Assumptions:
(1) The FAC is stationary for the time of passage. -->suppr. Alfvén waves
(2) FACs are organised in plane sheets.
(3) The orientation of the sheet with respect to the flight direction has to be taken into account.

Estimating FACs from a single satellite



A common approach for determining the angle between orbit track and current sheet is using the minimum variance analysis applied to the Bx and By components.

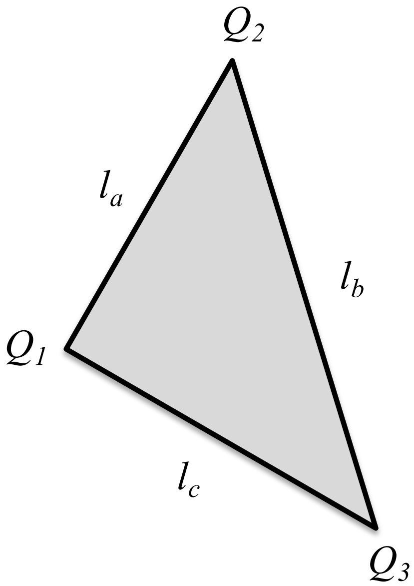




Finding the FAC sheet orientation from data of low-Earth orbiting satellites is often compromises by the magnetic effect of the auroral electrojet PEJ.
Here a case of westward PEJ over Canada.
PEJ signatures: bipolare variation of Bz and positive bay of Bx, poor correlation with By.

In case, simultaneous magnetic field observations from multiple points are available, Ampère's integral law can be applied for current density estimate.

$$\mathbf{j} = \frac{1}{\mu_0 A} \oint B\, d\ell \qquad (4)$$



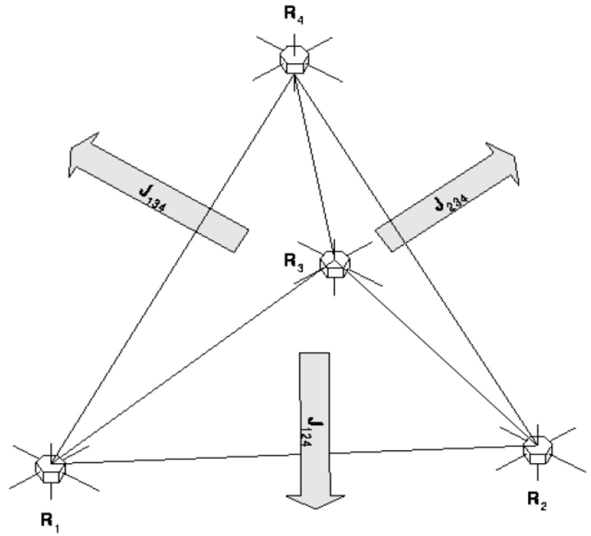
Data from at least three points are needed to calculate a ring integral. In case of four satellites in tetrahedron configuration (e.g. Cluster, MMS) four current components can be estimated, providing the full 3D current vector.

Assumptions:

(1) Transverse scale of current is larger than size of measurement triangle (else spatial aliasing)

(2) Measurements are simultaneous (within fractions of sec)

(3) Magnetic fields vary only linearly between the measurement points at the corners.



Cluster curlometer concept
Dunlop et al. (1988)

In the case of Cluster assumptions are frequently violated because of large spacecraft separations.

MMS is performing much better in this respect.

Swarm dual-spacecraft estimate of vertical currents

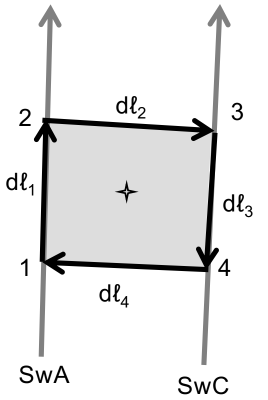
B-field data from the side-by-side flying Swarm A & C are used

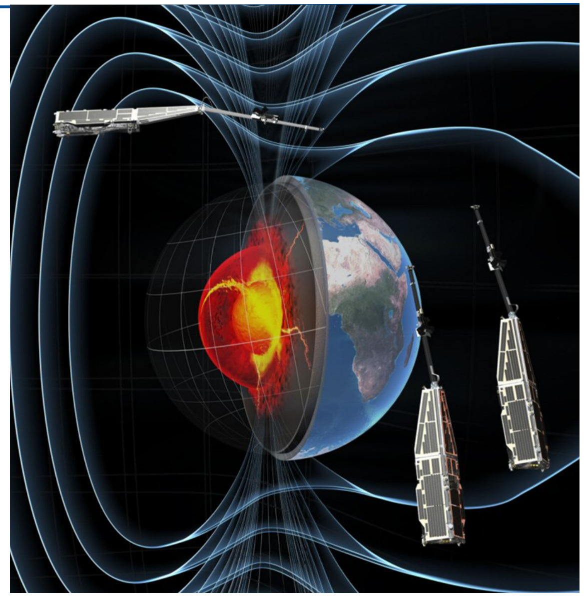
$$\mathbf{j} = \frac{1}{\mu_0 A} \oint \mathbf{B}\, d\ell$$

Applying Ampère's integral law in discrete form

$$j_z = \frac{1}{2\mu_0 \cdot A}\Big[\left(Bx_{t_1} + Bx_{t_2}\right) d\ell_1 + \left(By_{t_2} + By_{t_3}\right) d\ell_2 - \left(Bx_{t_3} + Bx_{t_4}\right) d\ell_3 - \left(By_{t_4} + By_{t_1}\right) d\ell_{4_1} \Big]$$

Integration area: $A = 0.25\left(d\ell_1 + d\ell_3\right)\left(d\ell_2 + d\ell_4\right)$





Along-track component, B_X, is derived from two subsequent measurements

$dt=5sec \rightarrow dl_{1,3}=38km$

By from cross-track separation, 1.4° in longitude (50 km @ 70).

Vertical current, j_Z, is projected on the field direction to get FAC.

<u>Assumptions:</u>

(1) Horizontal scales of FAC larger than the quad size

(2) Stationarity of FAC over the 5 s time-shift

(3) B-field changes only linearly between measurements at quad points.

For satisfying (1) and (2) data are filtered (low-pass, 20 s)

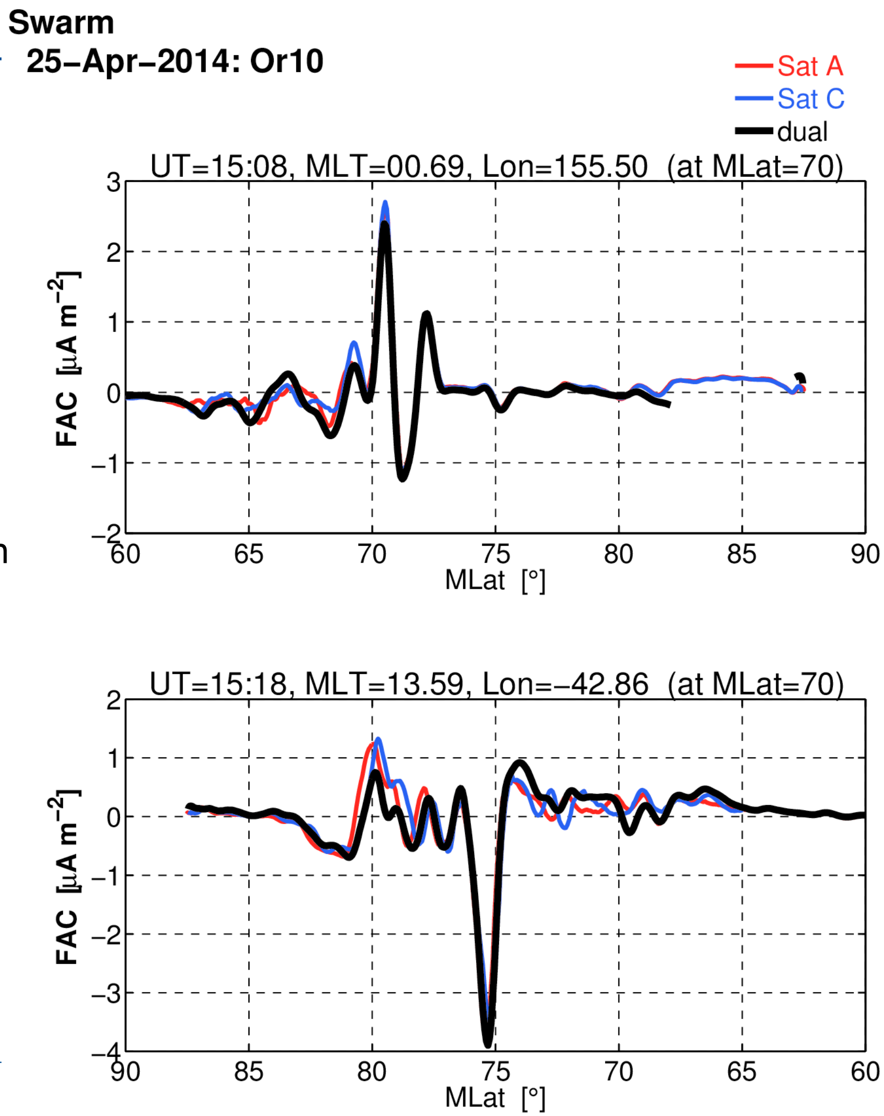
Ritter et al., 2013

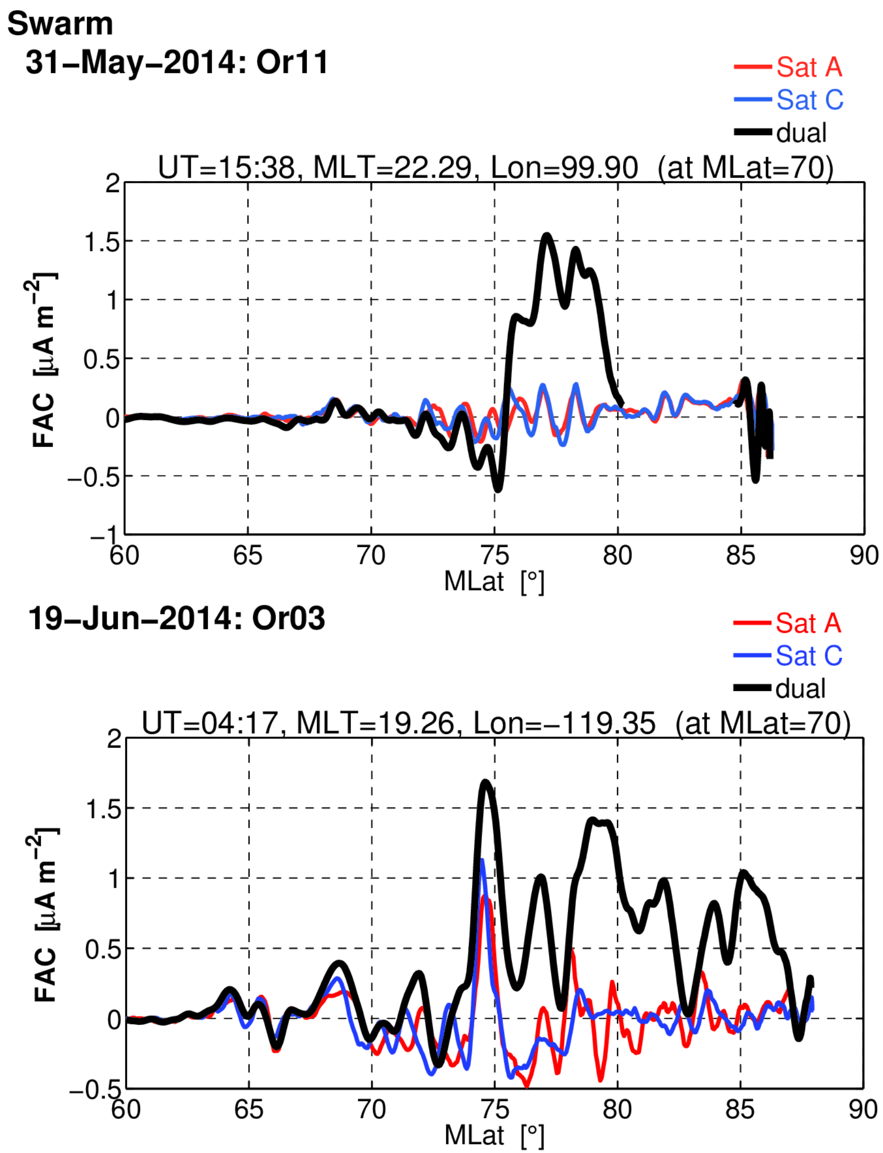
Examples

Comparison between single and dual-satellite FAC estimates.

Commonly, and particularly within the auroral oval, both results match well.

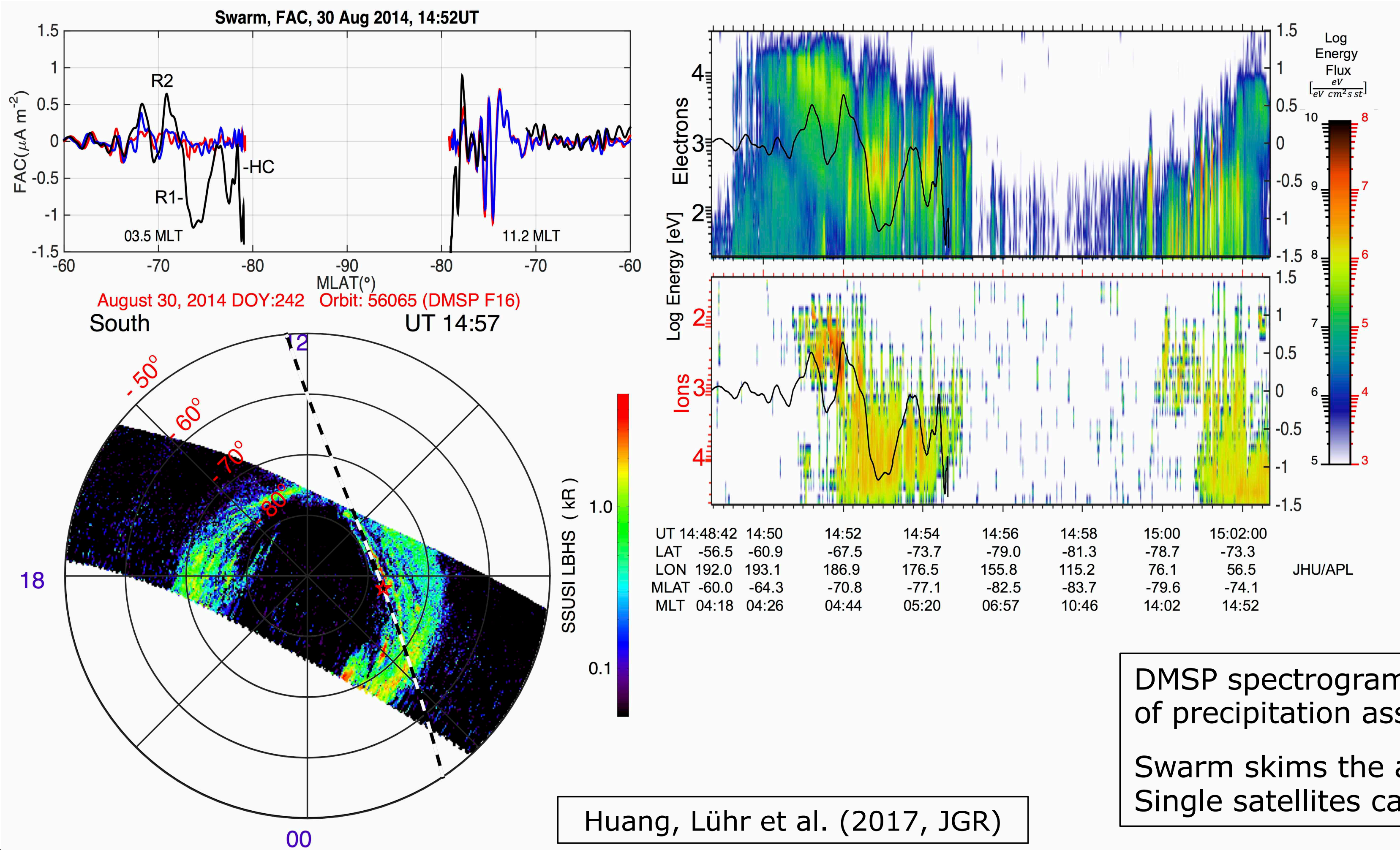
Occasionally, there are significant differences, particularly at higher latitudes, in the polar cap.





GFZ
Helmholtz-Zentrum
POTSDAM

Swarm / DMSP comparison for checking the differences

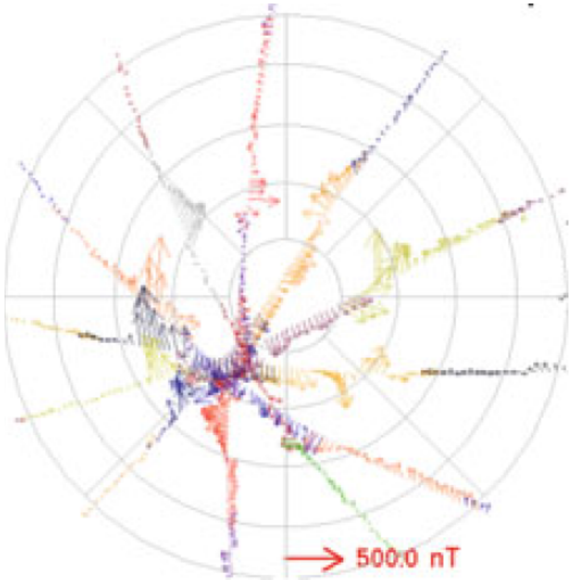


Huang, Lühr et al. (2017, JGR)

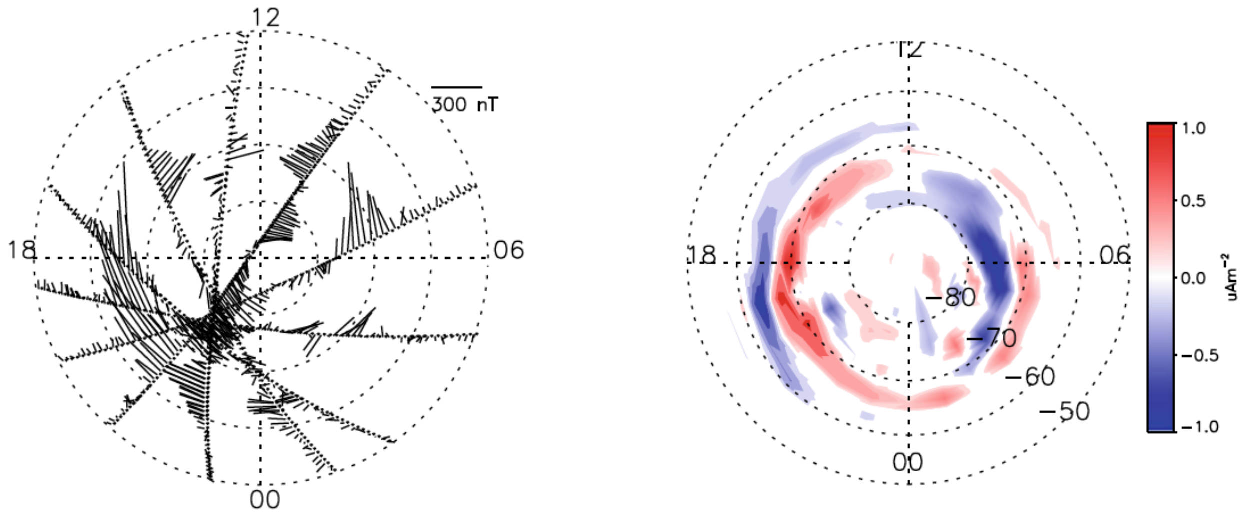
DMSP spectrograms show clear signs of precipitation associated with FACs.

Swarm skims the auroral oval.
Single satellites cannot resolve FACs.

AMPERE project, 60 Iridium spacecraft in 6 orbital planes, 10 min datasets considered



Iridium for 2348–2358 UT, 4 April 2010



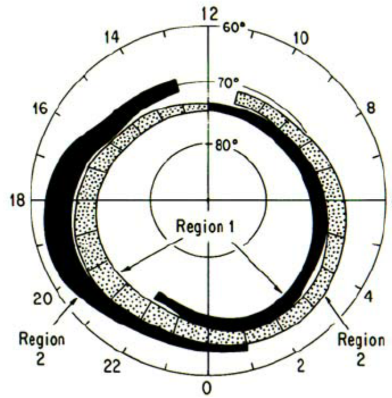
AMPERE provides the advantage of a global FAC distribution every 10 min.

Magnetic field readings are smoothed by a spherical harmonic cap analysis and then $\boldsymbol{j} = curl\, \boldsymbol{B} / \mu_0$ is determined.

The assumptions for multi-spacecraft FAC estimates are violated:

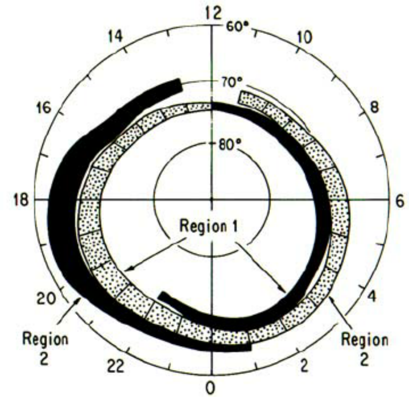
(1) Separations of spacecraft are too large, (2) Measurements are not simultaneously

But reasonable results are still obtained.

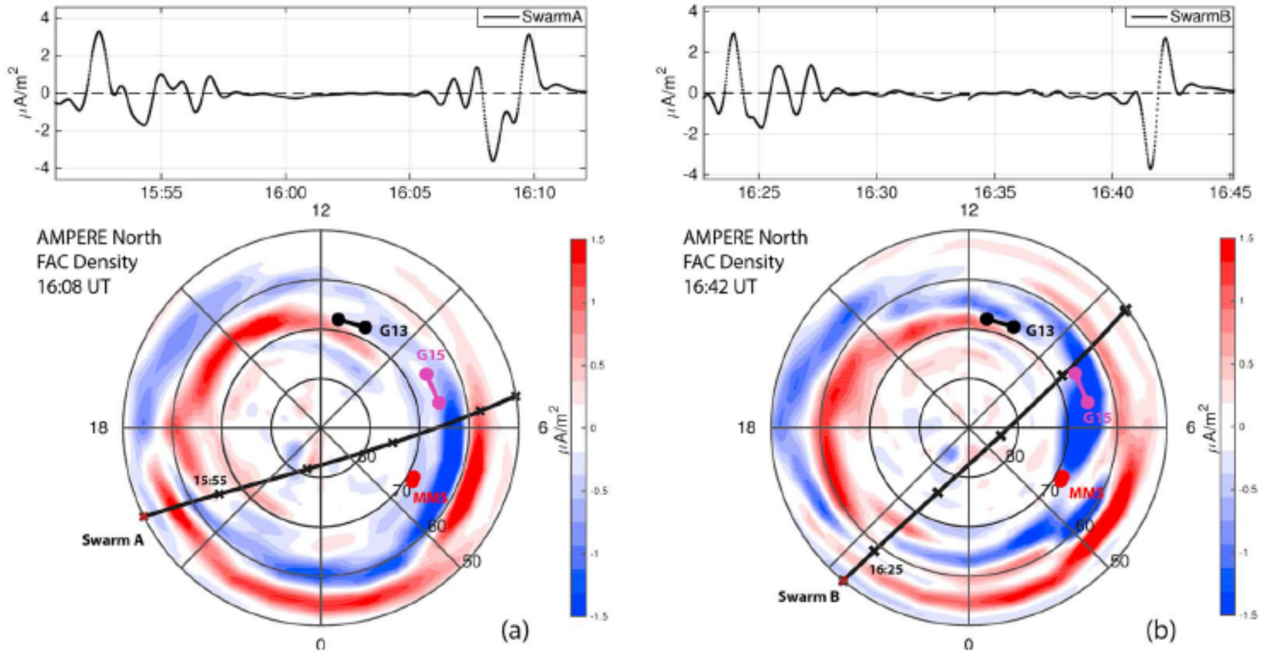


FAC distribution from AMPERE

The persistent pattern of FAC distribution dominates the AMPERE results, irrespective of measurement limitations.
Therefore, AMPERE patterns represent a rescaling of the Iijima & Potemra pattern every 10 min, tracking IMF and activity variations. Details are smoothed out.



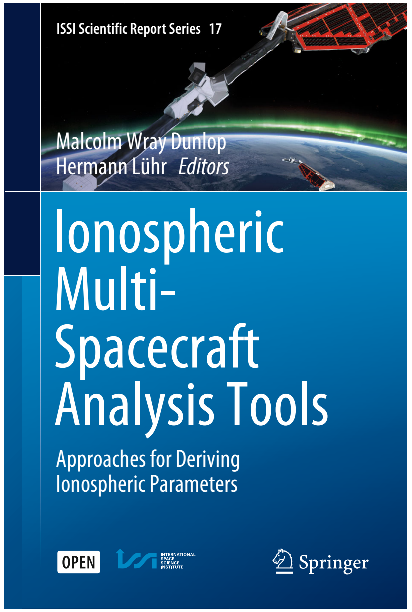
St. Patrick's Day storm, 17 March 2015



A direct comparison with reliable FACs from Swarm reveals qualitative agreement of FAC sheet locations. Amplitudes, however, are under estimated by about a factor of 2, probably due to smoothing.

Le, Lühr et al. (2016, GRL)

Recent publication

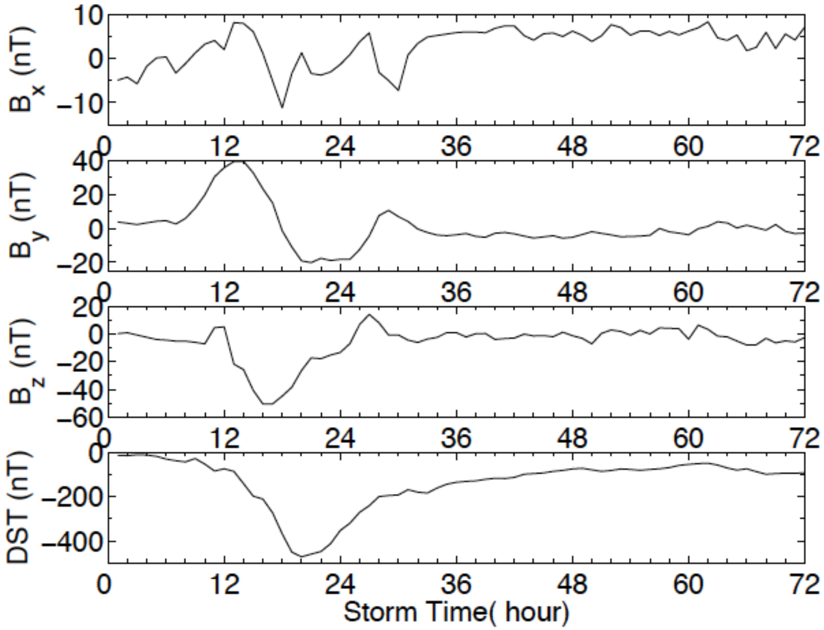


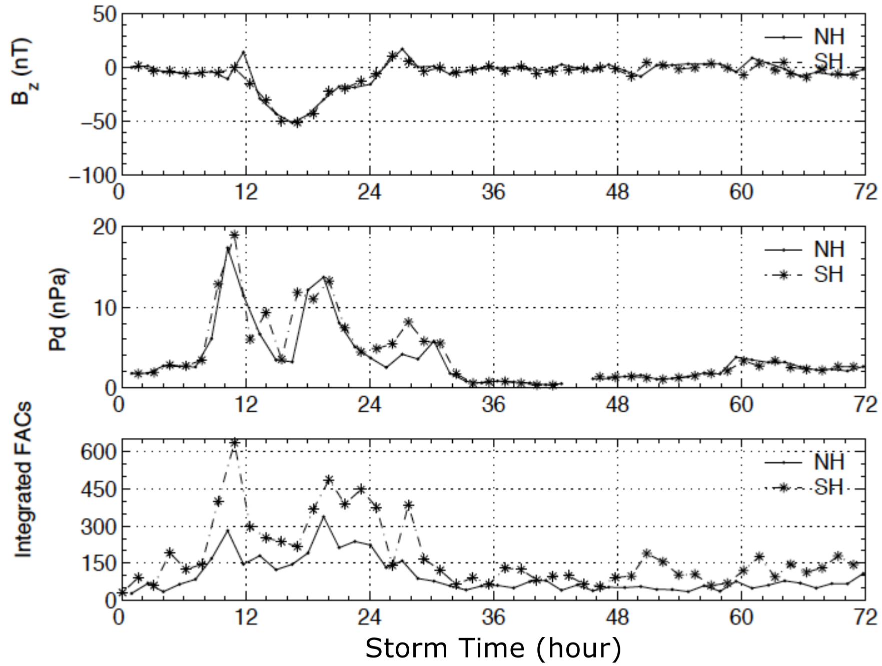
More details about FAC estimation techniques can be found in a recent book resulting from an ISSI Workshop.

Ionospheric Multi-Spacecraft Analysis Tools
M. Dunlop and H. Lühr (Eds.) (2020)

Open Access, freely available at:
https://link.springer.com/book/10.1007/978-3-030-26732-2

FACs during magnetic storms, example 20-22 Nov. 2003





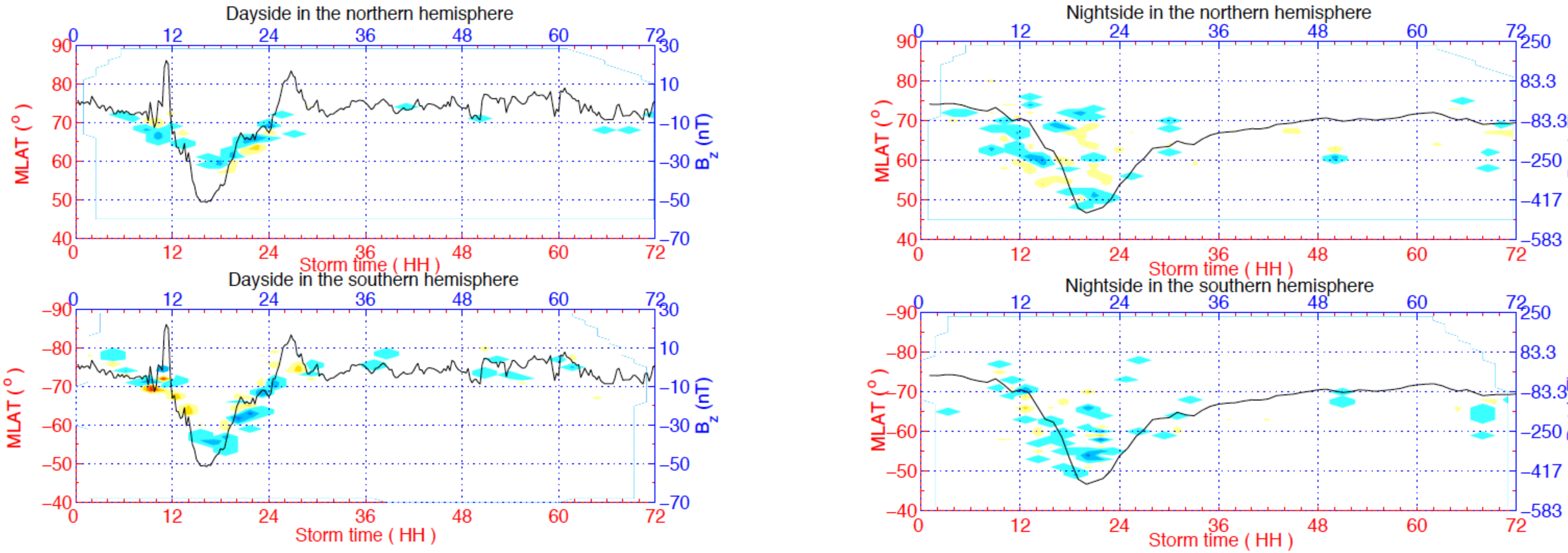
This super storm is characterised by the passage of a solar magnetic flux-rope:
→ out of phase variation of IMF By and Bz components.

There is no simple relationship between the solar wind input to the magnetosphere and the FAC intensity.

Rather, integrated FACs on the dayside follow more closely the variation of solar wind dynamic pressure.

FAC intensities are clearly larger in the southern, summer hemisphere.

Latitude variation during 20-22 Nov. 2003 storm



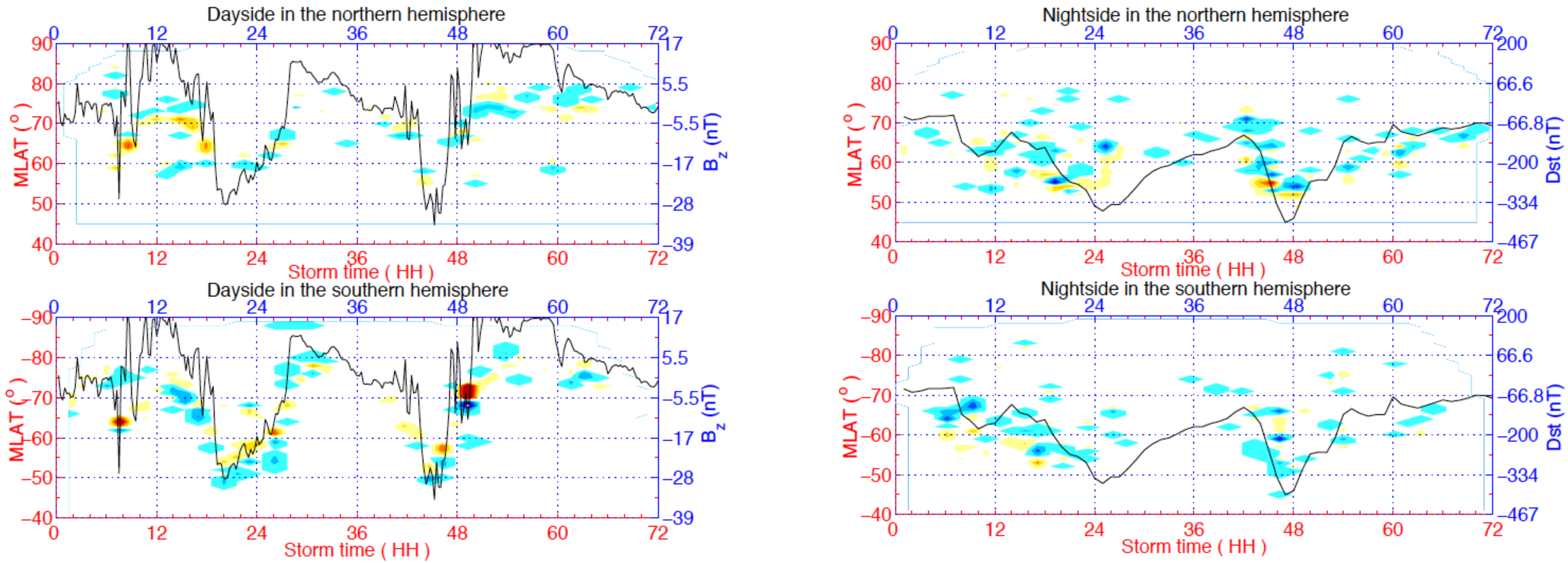
On the dayside the equatorward expansion of the FAC peak locations can be scaled quite well by the amplitude of IMF *Bz.*

At certain latitudes a saturation seems to occur.

On the nightside the FAC peak latitudes are better tracked by the evolution of the Dst value.

Variations appear delayed by about one hour with respect to the dayside.

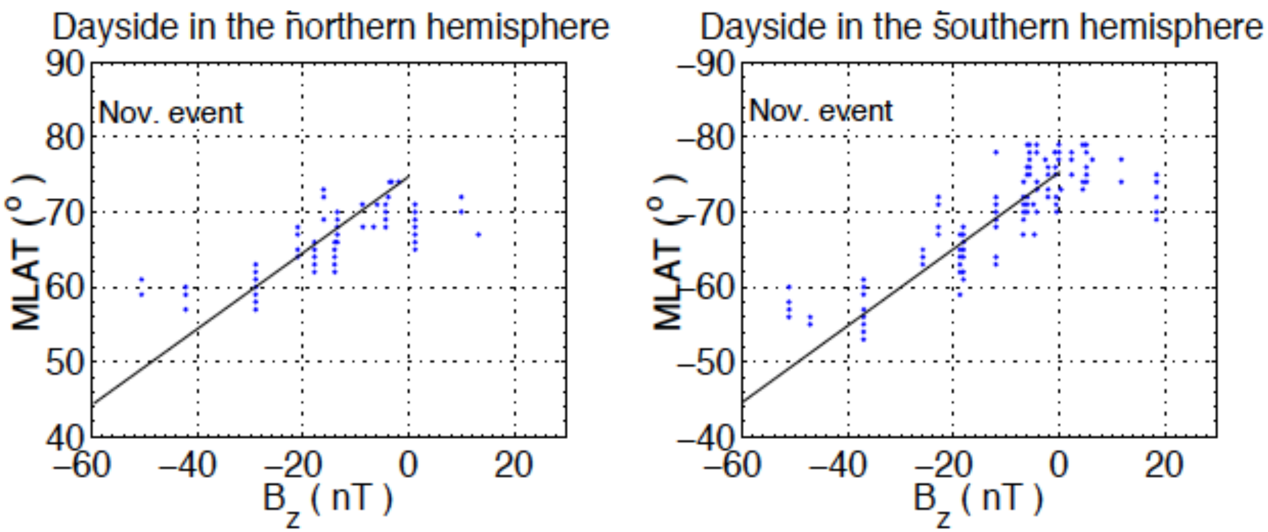
Latitude variation during 29-31 Oct. 2003 storm



The before mentioned latitudinal variations of FAC peaks are also valid during this storm, although its evolution is more structured.

Wang, Lühr et al. (2006, AnGeo)

Dayside latitude variation: 20-22 Nov. 2003 storm



Wang, Lühr et al. (2006, AnGeo)

There appears to be a linear relation between FAC peak latitudes and the southward IMF amplitude.

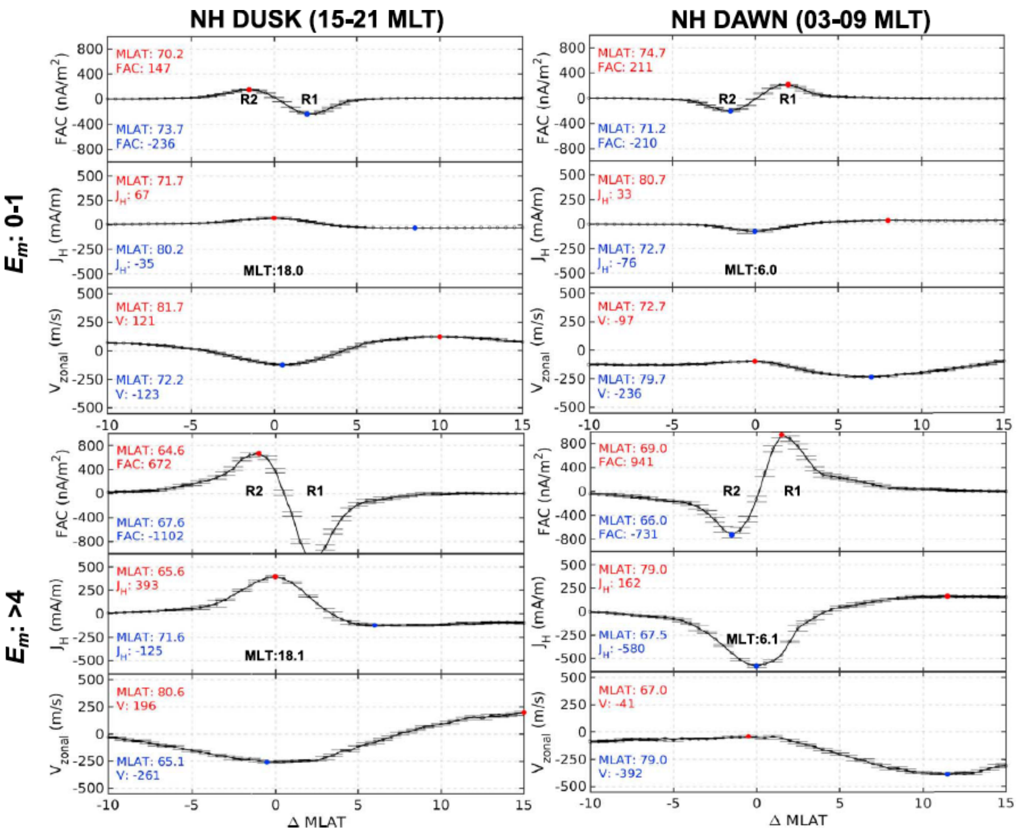
The regression slope is the same in both hemispheres, and it fits also other storms reasonably well.

It probably reflects the peeling off of field lines on the dayside.

The saturation at certain latitudes is clearly seen. Interestingly, it occurs at higher latitudes in the winter hemisphere.
This is a well documented effect, which is, however, more related to the dipole tilt angel than to the illumination of the ionosphere.

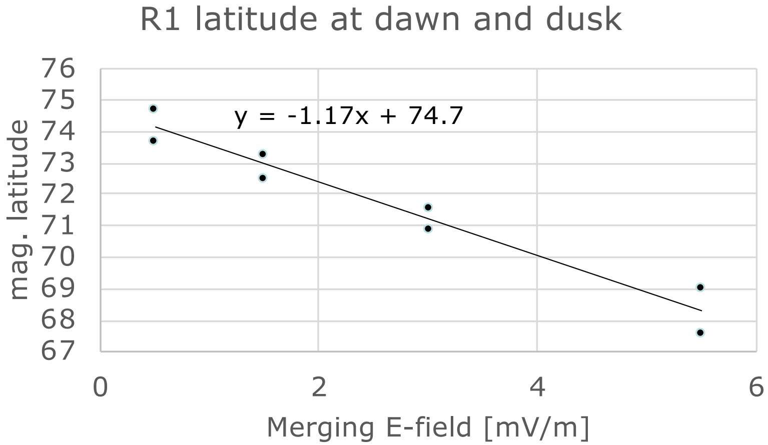
The saturation latitude depends also on the prevailing solar wind dynamic pressure.

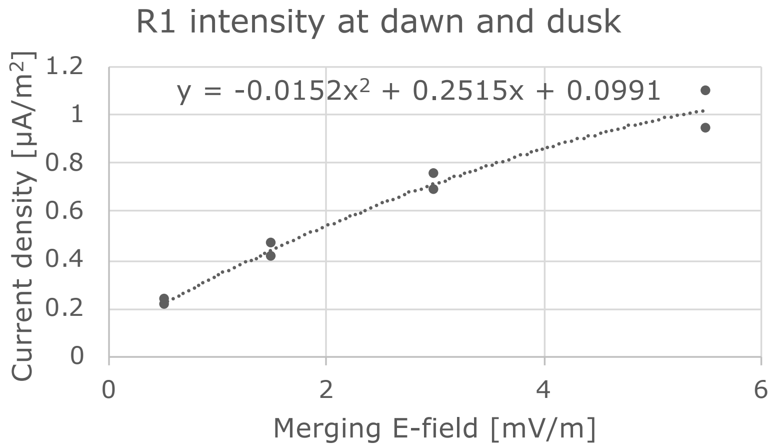
Average dawn / dusk FAC variations with increasing activity



At the flanks the FAC latitude varies linearly with the solar wind input, merging E-field.

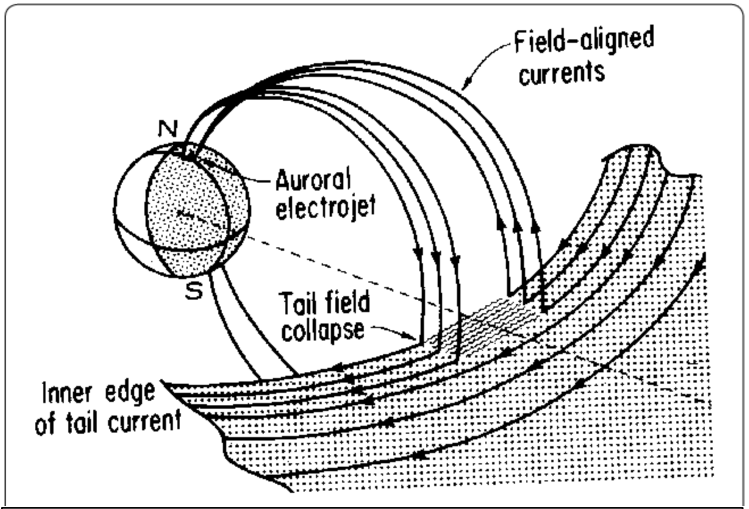
The FAC intensity rises, as expected, with solar wind input, but seems to reach a saturation at a certain level.





Huang , Lühr et al. (2017, JGR)

Substorm current systems



Clauer and McPherron (1974)

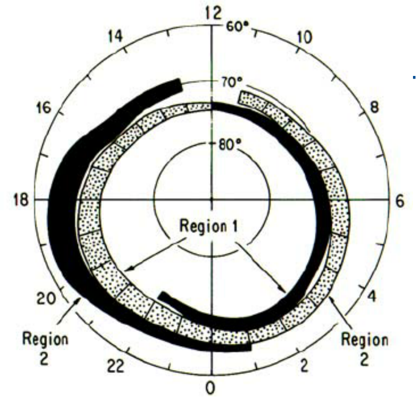
During substorms complex current systems evolve on the night side.

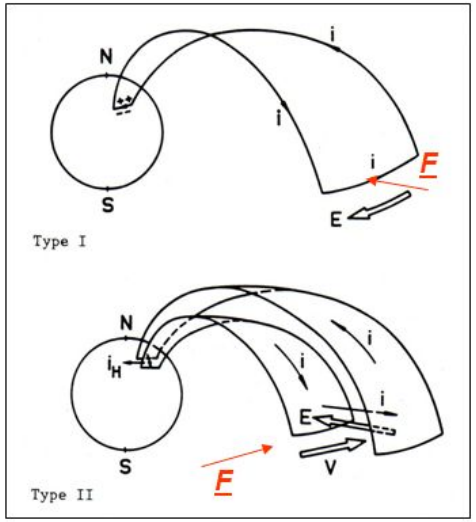
The onset is explained by a collapse of part of the neutral sheet current in the tail. The classical picture is that these disrupted tail currents are rerouted through the auroral ionosphere, termed substorm current wedge.

Already Boström had suggested, before the availability of supporting satellite data, two types of field aligned current systems that could explain the strong westward auroral electrojet accompanying a substorm.

Type I: Electrojet is Pedersen current

Type II: Electrojet is Hall current





[Boström 1964]

Substorm current systems

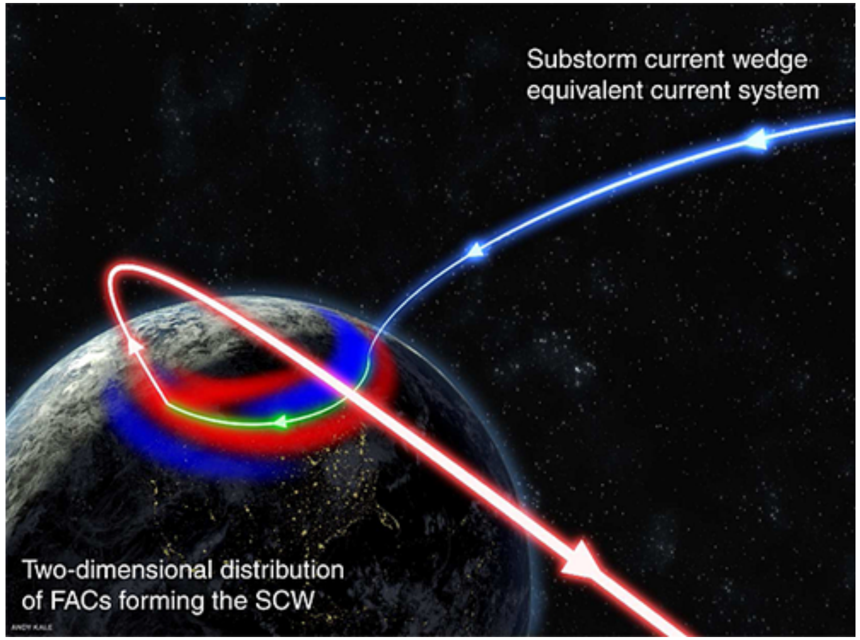
Nowadays we know, both types of Boström FAC systems are active.

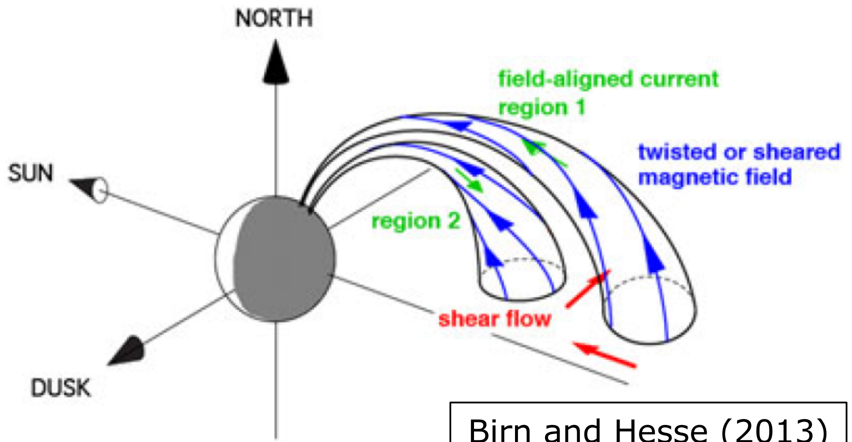
At substorm onset plasma is accelerated Earthward, which is deflected in the inner magnetosphere to the flanks. The resulting shear flow sets up pairs of R1 and R2 FACs (Type II).

As a consequence, a westward electrojet stars to flow. However, measurements show that the substorm electrojet is too strong for the E-field caused by R1/2 FACs.

There seems to form in addition a highly conductive Cowling channel that supports the strong currents of the current wedge (Type I).

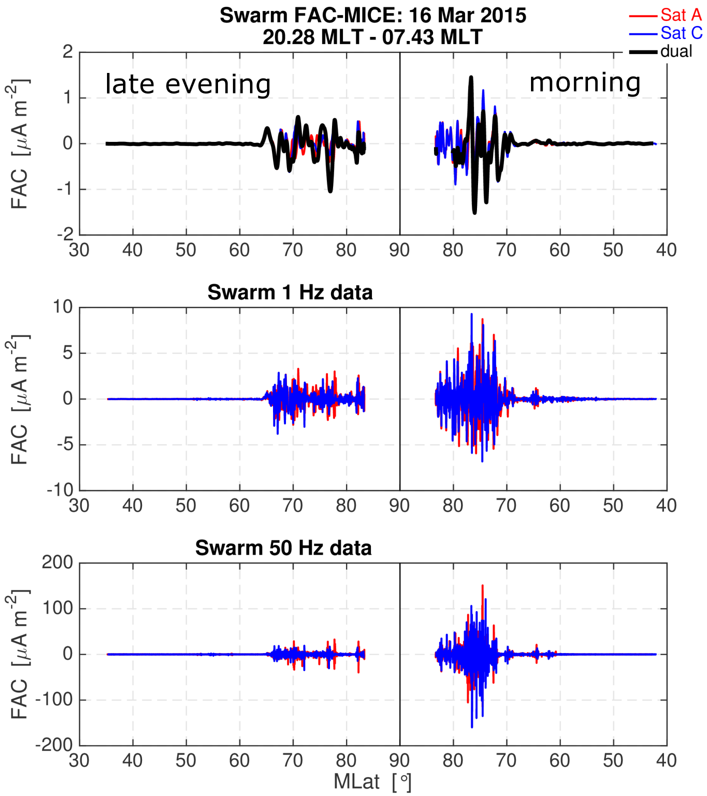
The details of all the currents involved in the evolution of a substorm are still a matter of ongoing research.





Birn and Hesse (2013)

Characteristics of small-scale FACs



Scales

>150 km

10 - 150 km

1 - 10 km

FACs come at very different scales. The smaller the horizontal scale, the larger the amplitude.

In the case of small-scale FACs, they are normally not organised in sheet-like structures and not stationary.

Small-scale FAC are important for the auroral electrodynamics, but they are difficult to be characterise from B-field data alone (wave character).

Tom Potemra once asked, is there a smallest FAC scale?

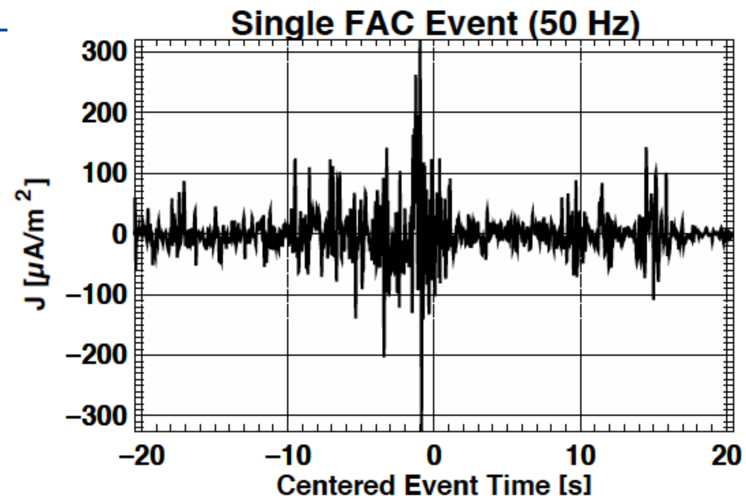
We looked into that issue with the high-resolution CHAMP magnetic field data at 50 Hz sample rate.

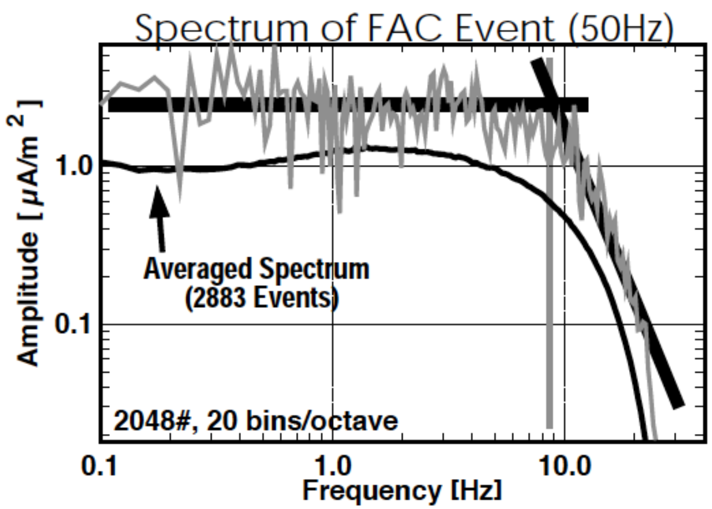
When calculating the spectrum of a prominent small-scale FAC event, a flat, almost white spectrum results over a large frequency range. This resembles a delta-function.

But at about 8 Hz the spectrum rolls off exponentially. This is expected when the individual peaks have a finite width. 8 Hz correspond to a 1 km scale when considering the spacecraft velocity of 7.6 km/s.

A similar spectral shape results when calculating the average small-scale FAC spectra from many events.

This indicates that FACs reach their largest amplitudes at sizes of about 1 km. This result is supported by theoretical considerations, e.g. Lotko & Zhang (2018). The finite conductivity in the F-region damps off smaller scales.





Rother et al. (2007, AnGeo)

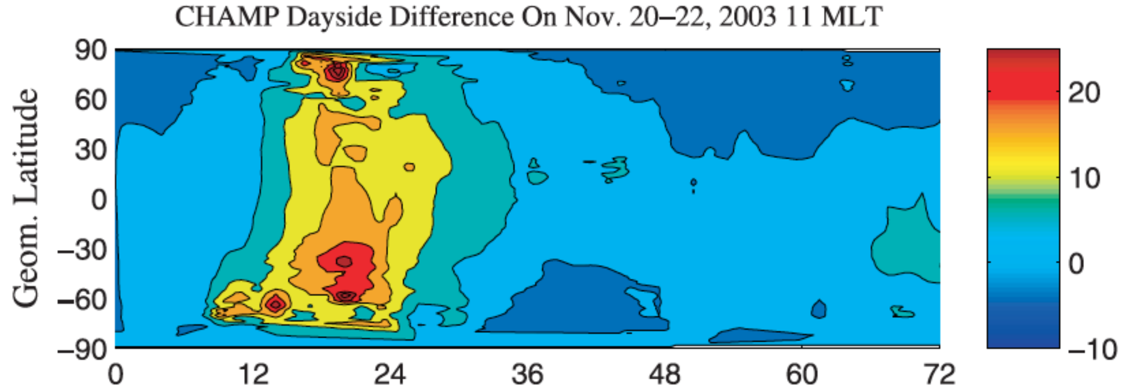
FACs are an important mechanism for transferring energy into the upper atmosphere. The energy dissipated by currents in the ionosphere is absorbed by the thermosphere, enhancing its temperature.

Thus, the thermosphere acts as a kind of ”black body” accumulating all the incoming energy.

An enhancement of atmospheric density is a good indicator for a temperature enhancement caused by energy input.

CHAMP was the first to measure systematically the thermospheric density distribution.

Air density anomaly

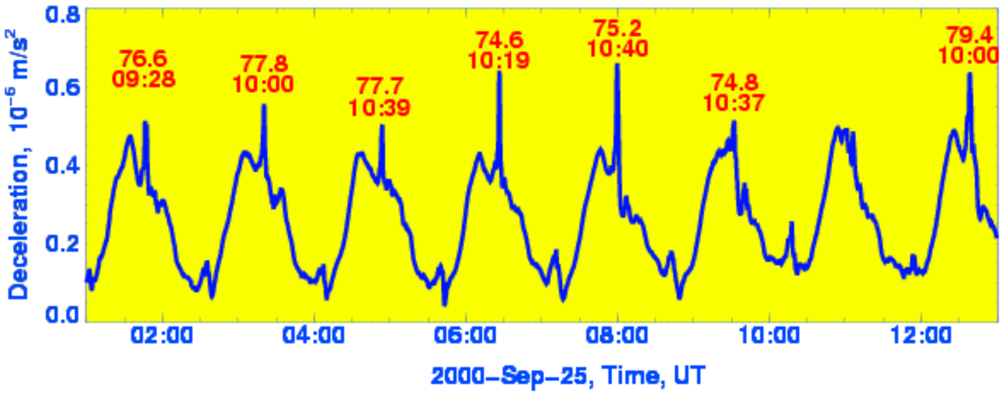


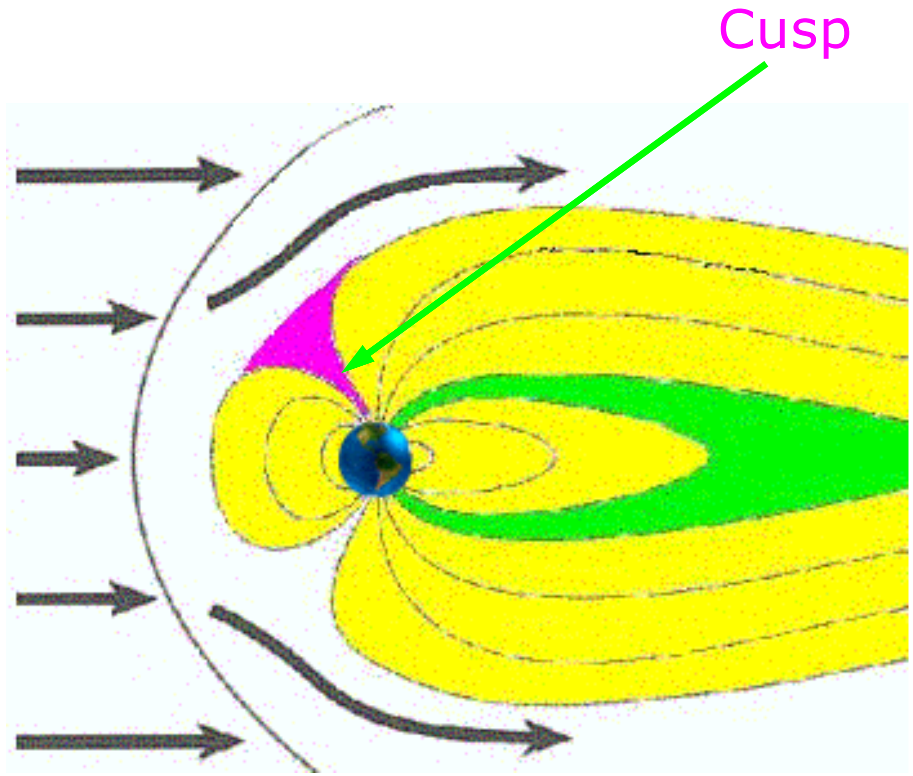
During a magnetic storm FACs are heating the upper atmosphere at auroral latitudes. The bulge of enhanced air density expands from both poles equatorward at a speed of about 600 m/s.

After about 12 hours pre-storm conditions are restored.

Liu and Lühr (2005, GRL)

CHAMP air drag peaks at cusp



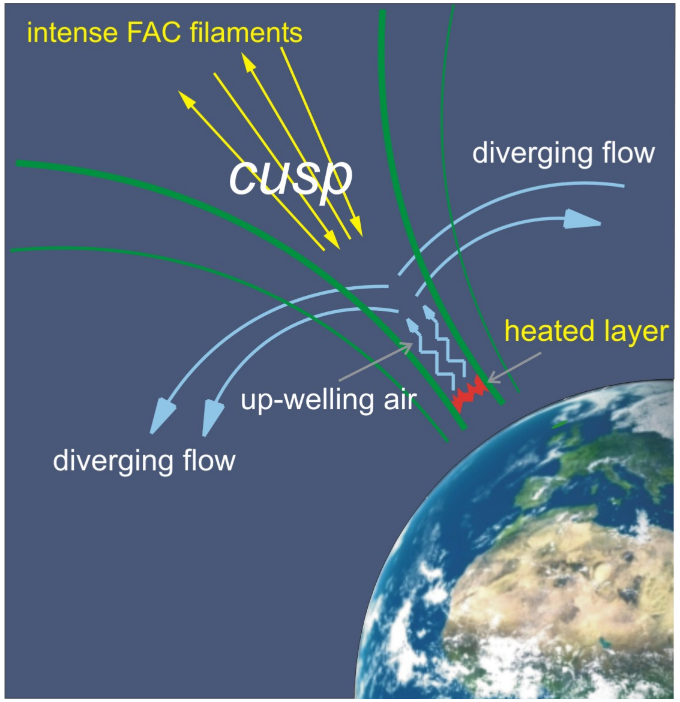


CHAMP orbits experience regularly local enhancements of air drag at the dayside high latitude.

These peaks appear at common magnetic latitudes and local times, coinciding with the cusp location.

(Lühr et al., GRL, 2004)

CHAMP air density peaks and small-scale FACs



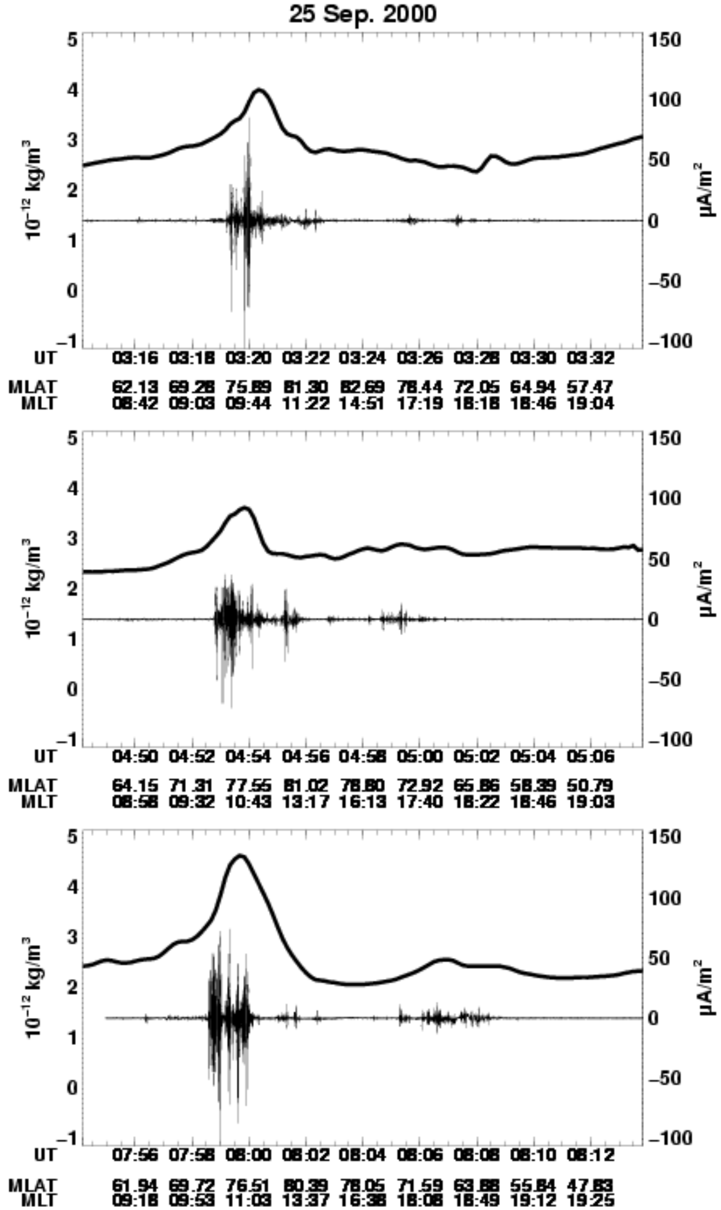
Local density anomalies are commonly accompanied by small-scale FACs with very large amplitudes.

When averaging B-field data the contributions of small-scale FACs are removed.

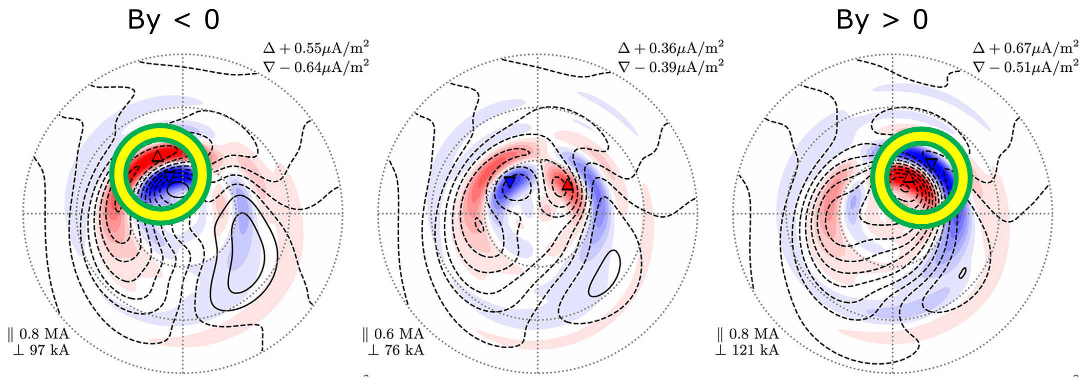
Local dissipation rates depend on large- AND small-scale FACs. The latter can become dominating.

$$\vec{j}\cdot\vec{E}(h)=\left(j_{\parallel DC}+j_{AC}\right)_{\perp}^{2}/\sigma_{P}$$

(Lühr et al., GRL 2004)



Small-scale FAC heating and air upwelling



Major air upwellings occur at the interfaces of the R1 and R0 FACs. Depending on the sign of IMF By they appear before or after local noon.

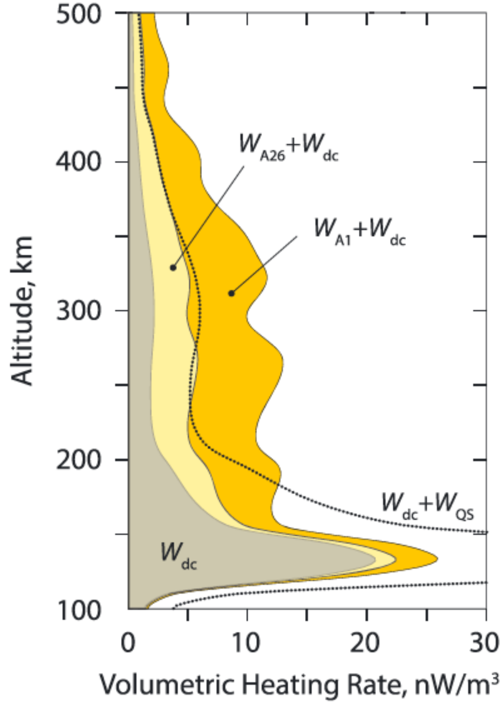
In this cusp region small-scale FACs are particularly intense.

These are also the locations where the largest fluxes of ion out-flow occur.

Lotko and Zhang treated in their model small-scale FACs as Alfvénic. The dissipation of these waves is highest where the Pedersen conductance matches the wave impedance. This occurs at F-region altitudes.

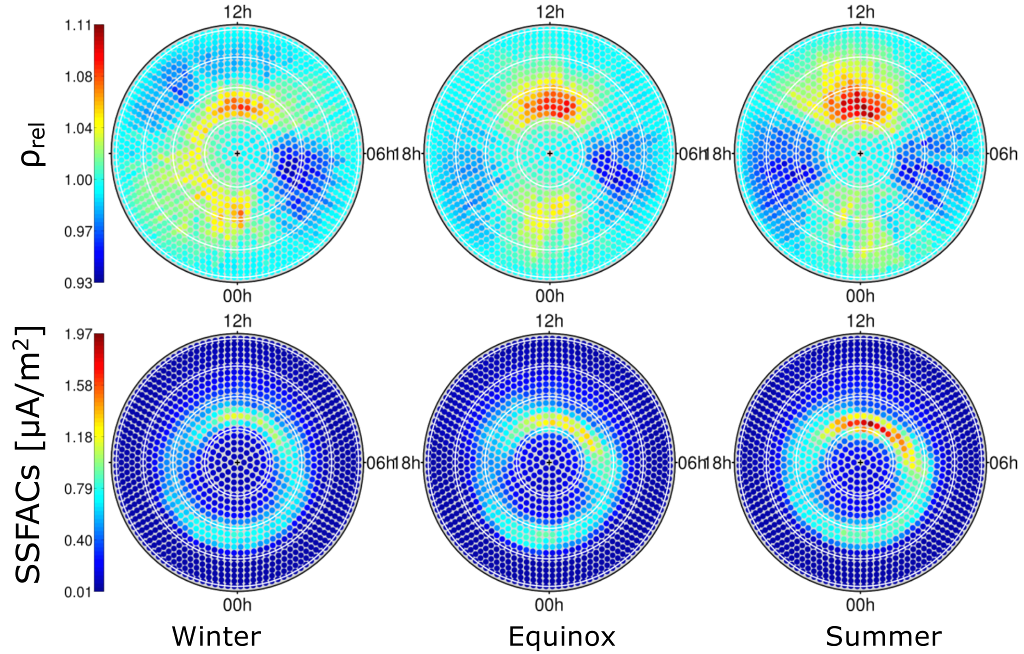
Conversely, large-scale FACs deposit their energy in the E-region.

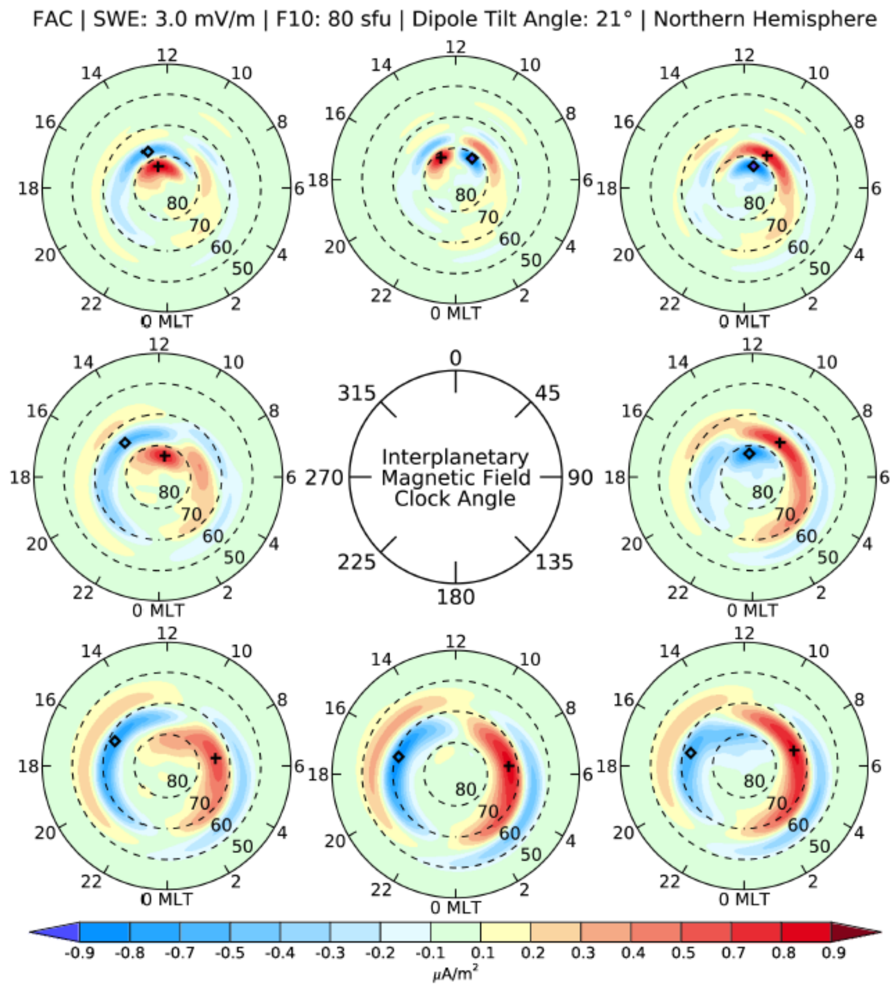
Because of the much lower air density at the F-region, the resulting temperature enhancement, due to small-scale FACs, is higher there, resulting air upwelling.



Lotko and Zhang, (2018)

Effect of FACs on thermospheric density





Air density anomalies observed by CHAMP occur predominantly around the cusp region, but also on the nightside. These locations coincide with regions of enhanced small-scale FACs.

At the flanks air density is partly even depleted, e.g. dawnside, although here strongest large-scale FACs are observed.

Small-scale FACs, Resumé

Small-scale FACs are difficult to measure. For their proper interpretation the E- and B-field have to be known simultaneously (wave character).

For the heating of the upper atmosphere small-scale FACs play an important role. Resulting air density anomalies affect satellite orbits.

Large-scale FACs are more important for the transfer of momentum. They control quite closely the plasma convection patterns.

Summary

- Field-aligned currents (FAC) play an important role in magnetised plasma since they connect largely separated regions electrically, and they transfer energy and momentum almost lossless.
- FACs in the auroral zone are on average well organised in local time. They form a double ring of R1 and R2 currents around the poles.
- During enhanced magnetic activity (storms) the FAC belts expand to lower latitudes; on the dayside locations are largely controlled by the amplitude of southward IMF, on the nightside they follow the evolution of Dst.
- Small-scale FACs make important contributions to the heating of the upper atmosphere. They are particularly intense in the cusp region and also prominent on the nightside during substorms. Their role in the auroral electrodynamics should attain more attention.

Outstanding issues

A better characterisation of the Alfvénic small-scale FACs. This should include reliable measurements of both the E- and B-fields and an extended physical interpretation aided by modelling efforts.

Outline

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