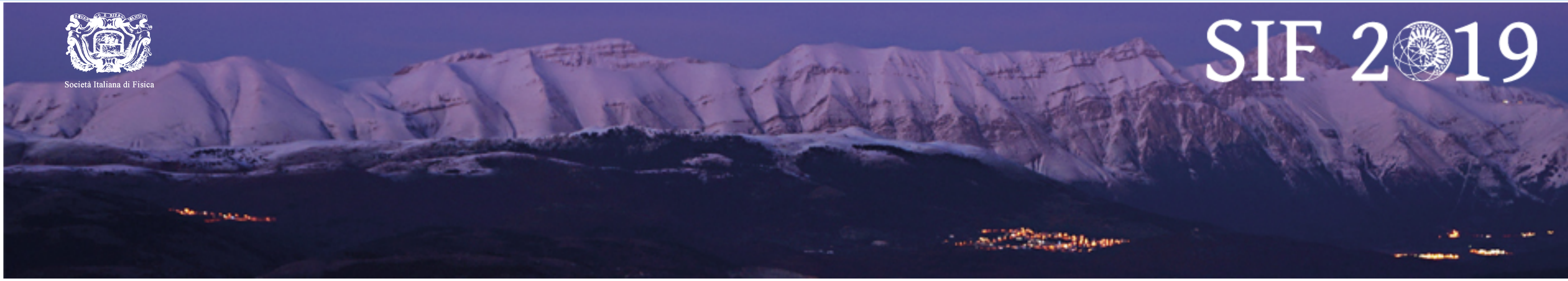

Spatio-temporal small-scale features of force-free field-aligned currents in space plasmas

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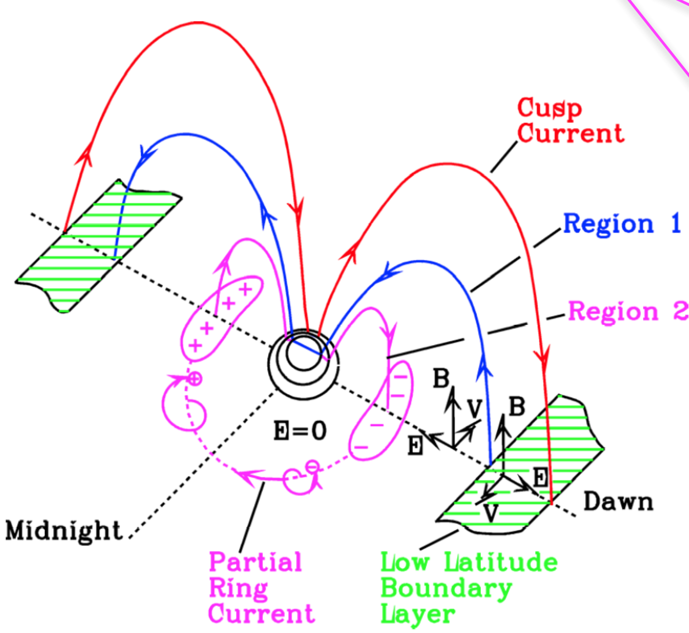
Introduction

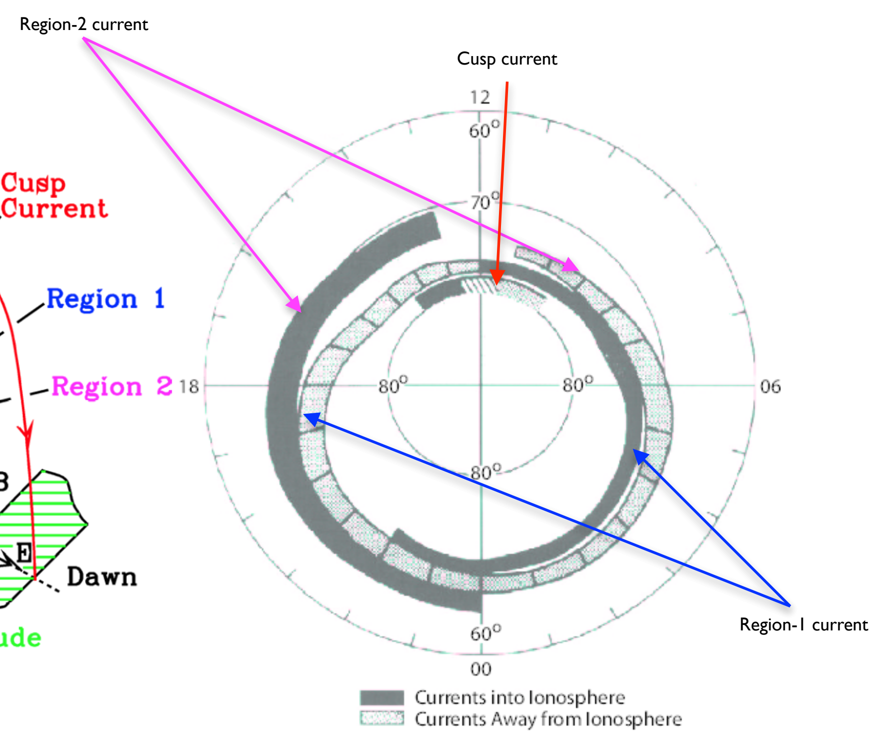
Field-Aligned-Currents (FACs) play a very important role in several processes taking place in the circumterrestrial environment (magnetosphere, ionosphere,..)

FACs were originally postulated by Birkeland (*Birkeland*,1908) and detected for the first time sixty years later by spacecraft observations of localized magnetic fluctuations (*Zmuda et al.*, 1966; *Cummings and Dessler*, 1967).

In the polar ionosphere, the *pattern of FACs* consists of *two current belts* (*Region-1* and *Region-2*) that flow upward and downward along the magnetic field lines according to latitude and magnetic local time.



from R. McPherron, AGU FM 2005



from Iijima and Potemra, 1976

FACs play a crucial role in *energy and momentum transfer among different circumterrestrial regions*: the solar wind the magnetosphere the ionosphere and thermosphere.

The knowledge of their structure is of *uppermost importance to understand how energy deposition processes*.

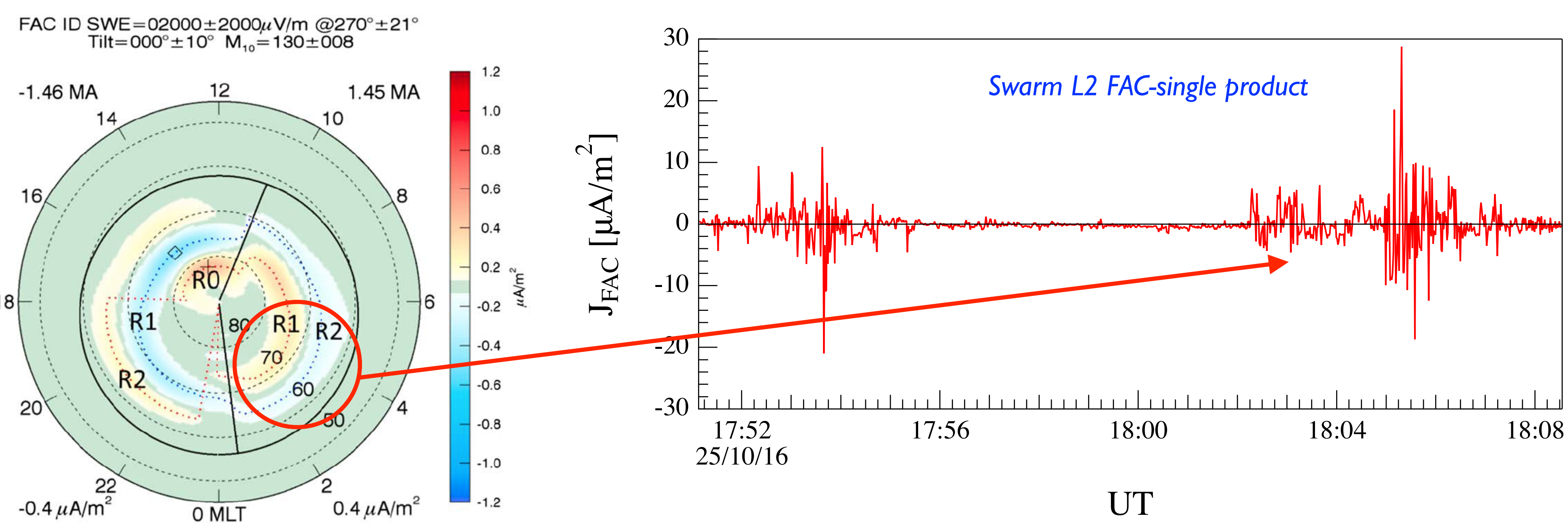
Introduction

Although significant progresses have been achieved, some scientific questions still need to be answered.

An interesting point is the *characterization of the FAC structure on small-spatial scales* and their link with *turbulence phenomena*.

Surveys (*Neubert and Christiansen*, 2003) have shown that *small-scale FACs* can be found throughout the *auroral oval and the pre-noon cusp region*.

These currents (typical *widths* of a *few hundred meters*) are very intense reaching *several hundreds μA/m²* (*Lühr et al.*, 1994; *Stasiewicz and Potemra*, 1998).



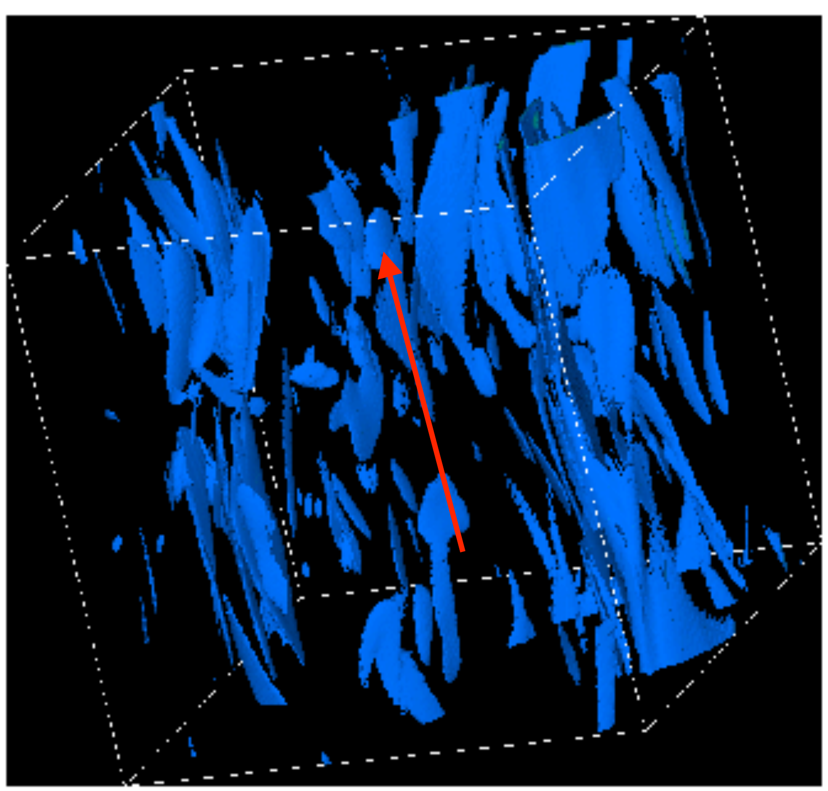
from Edwards et al., JGR, 2017

Theoretical framework

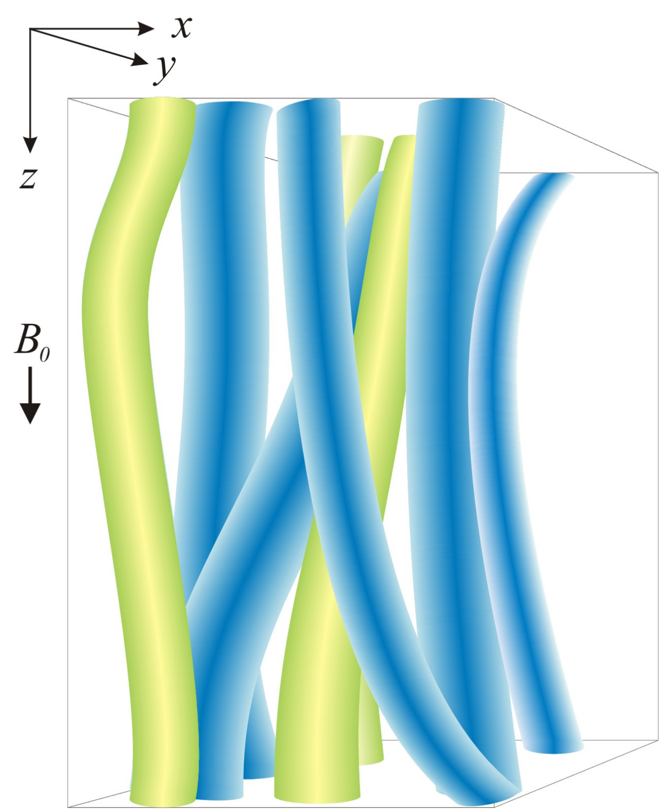
Small-scale FACs are *randomly oriented* due to their *possible filamentary structure* and their origin might be linked with the occurrence of *turbulence*.

Turbulence, indeed, plays a crucial role in generating *multiscale coherent structures in the form of flux tubes.*

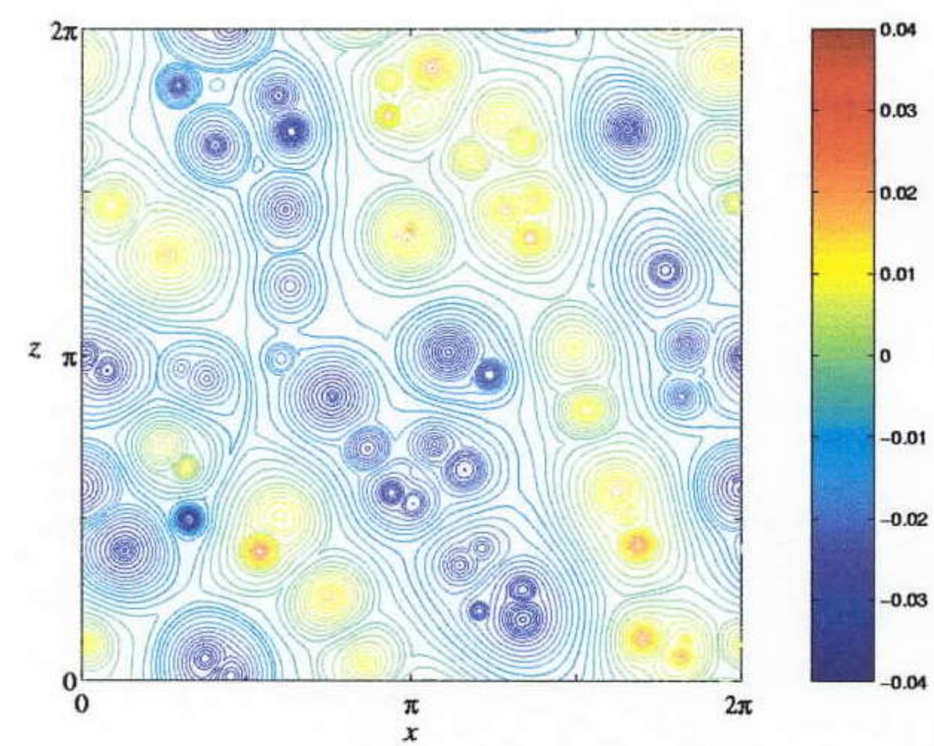
$B \neq 0 \Rightarrow$ ribbons



from Biskamp & Nuller, 2000



from Wu and Chang, GRL, 2000



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$$\mathbf{B} = \mathbf{e}_z \times \nabla\psi + B_0\mathbf{e}_z \;\rightarrow\; \mathbf{B} = (\delta B_x, \delta B_y, B_0)$$

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$$\mathbf{J} \times \mathbf{B} \sim 0$$

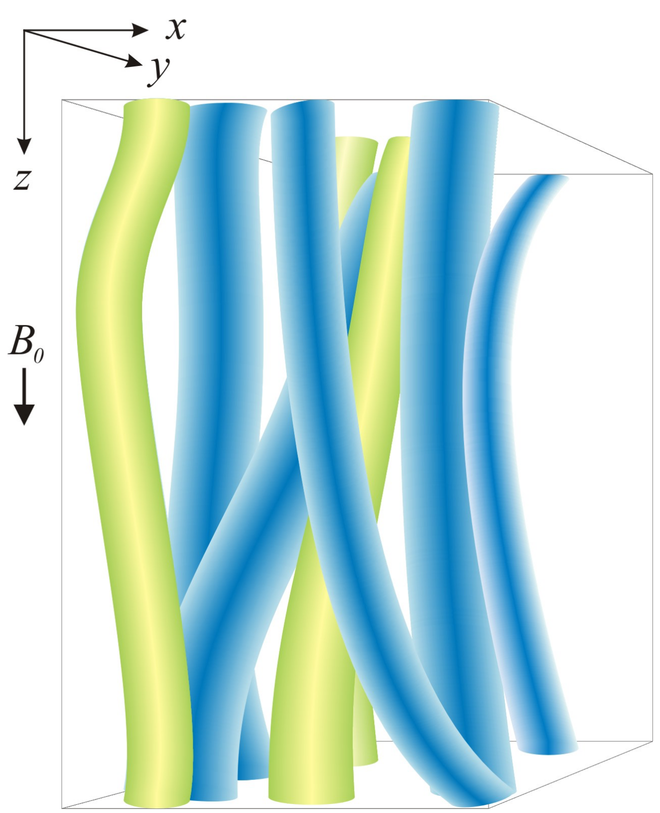
$$\nabla \cdot \mathbf{J} \sim 0$$

$$\mathbf{B} \cdot \nabla J_z = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$B_0 \frac{\partial J_z}{\partial z} = -\left(\delta B_x \frac{\partial}{\partial x} + \delta B_y \frac{\partial}{\partial y}\right) J_z + \ldots.$$

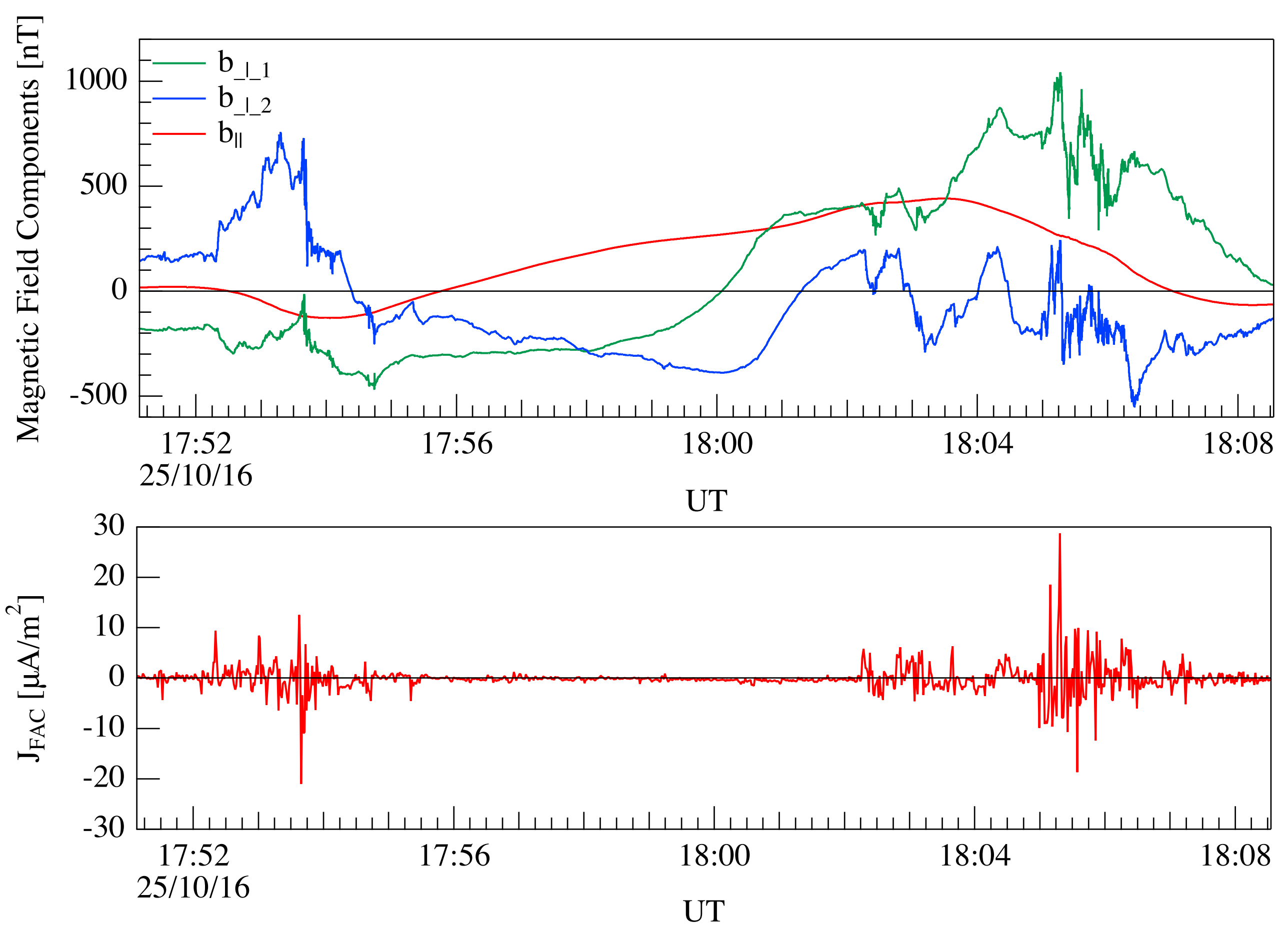
$$(\delta B_x, \delta B_y) = \left(\frac{\partial \psi}{\partial y}, -\frac{\partial \psi}{\partial x}\right)$$



Data description

This study is based on *in-situ* observations of FACs via magnetic field measurements by *ESA-Swarm satellites*, *Swarm A* and *C*.

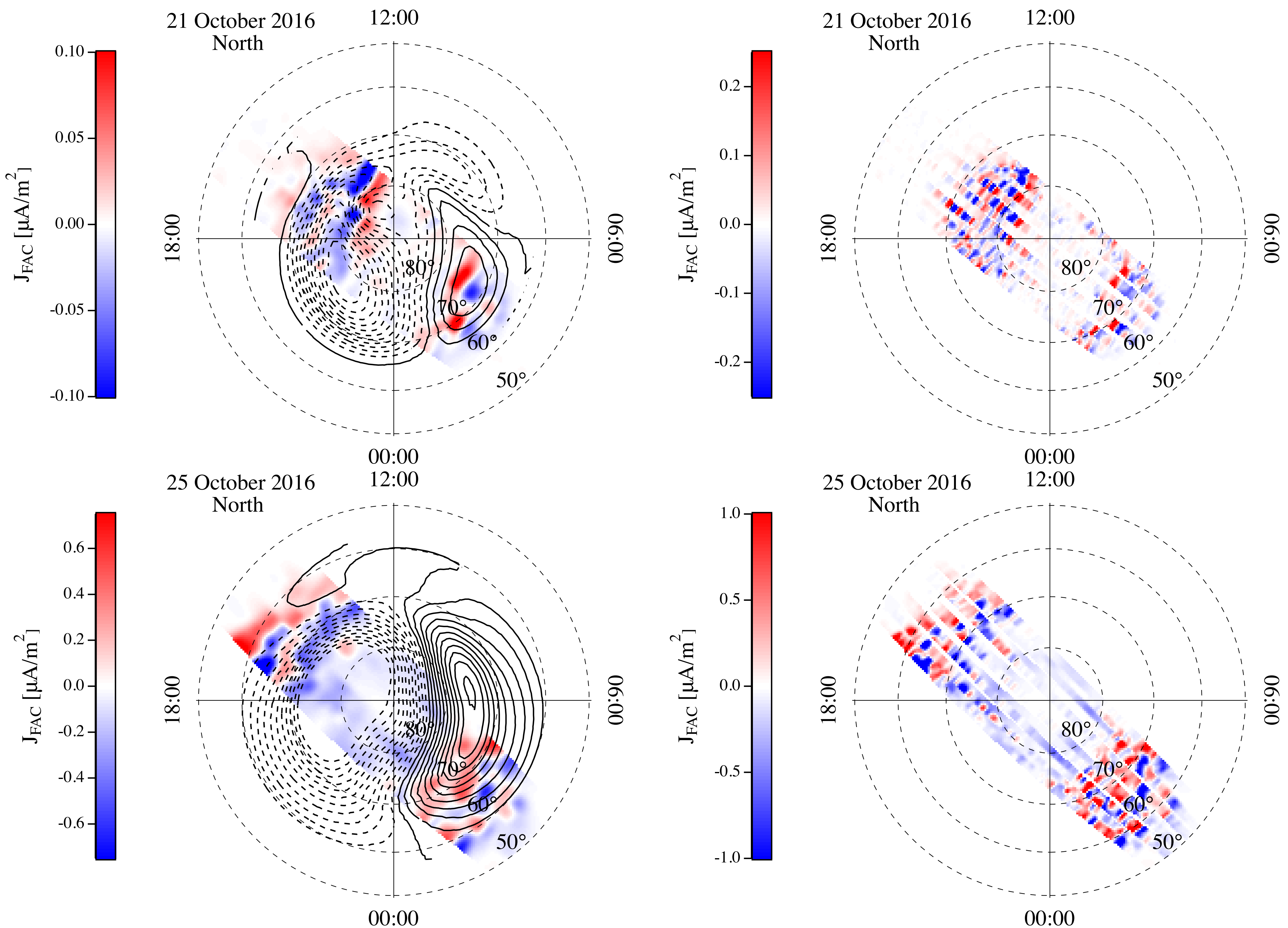
We selected two days characterized by a different geomagnetic activity level: *October 21*, and *October 25, 2016*, during which the average *AE-index value* is *160 nT* and *660 nT,* respectively.



FAC density data, used in this analysis, are the *Swarm Level-2 (L2-FAC) single-spacecraft product* (*Ritter et al.*, 2013), calculated from the spatial gradients of the magnetic field observed along the direction defined by the spacecraft orbit track (*ftp://swarm-diss.eo.esa.int; FACATMS_2F file type*).

Temporal resolution is 1 s.

Data description



Analysis Method: Sign-Singularity Measure

The properties of many physical processes can be described by *multifractal probability measures*. In contrast with *positive measures*, a *signed measure* can be useful to describe and to characterize *random fields which oscillate in sign*.

Ott et al. (1992) introduced a *scaling exponent* κ (the *cancellation exponent*) to characterize the *sign-singularity* of a signed measure.

Let $f(t)$ be a signal with zero mean, over a finite interval T. Consider a partition of size ε covering the interval T. On each subset T_i it is possible to define a *signed measure*, $\mu_\varepsilon(T_i)$,

$$\mu_\epsilon(T_i) = \int_{T_i} f(t)dt$$

By introducing a *partition function* $\chi(\varepsilon)$

$$\chi(\epsilon) = \sum_i \mid \mu_\epsilon(T_i) \mid$$

the *cancellation exponent* κ can be defined as

$$\kappa = -\lim_{\epsilon \to 0} \frac{\ln \chi(\epsilon)}{\ln \epsilon}$$

Analysis Method: Sign-Singularity Measure

For a *positive measure κ = 0*, being trivially *χ*(*ε*) = *const* ∀ ε. Conversely, for *non-positive sign-singular measures κ > 0* at least on scales larger than a cuttoff below which the measure is regular and smooth with a well defined sign.

For 1D signals the *cancellation exponent κ* is generally in the *range* [0,1], with *κ*=1/2 for *Brownian motions* and *Markovian stochastic* signals, and *κ*=1 for *nondifferentiable signals* (*Bertozzi and Chhabra*, 1994; *Vainshtein et al.*, 1994).

As clearly shown in some specific study of both *fluid and MHD turbulence* (*Bertozzi and Chhabra*, 1994; *Vainshstein et al.*, 1994; *Carbone and Bruno*, 1996) the value of the *cancellation exponent* can be linked to other *scaling features*: the *structure functions*.

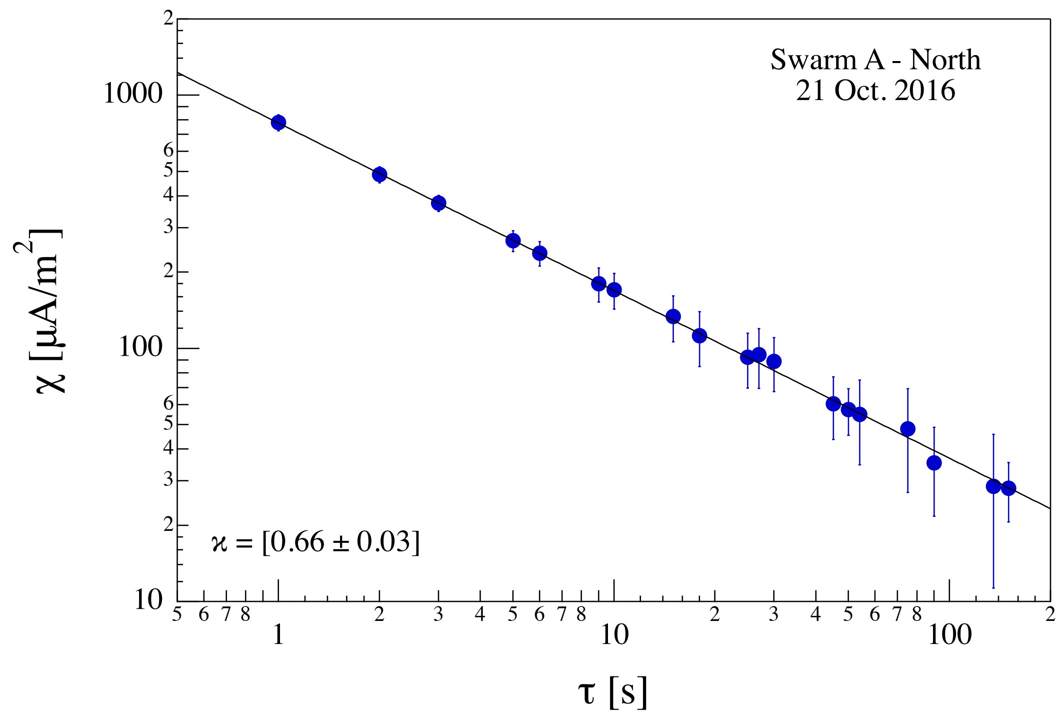
For instance, for the Kolmogorov scaling (*Frisch*, 1995) the *first order structure function* of the fluid velocity at the *scale ε* is related to the *partition function χ*(*ε*) by the expression,

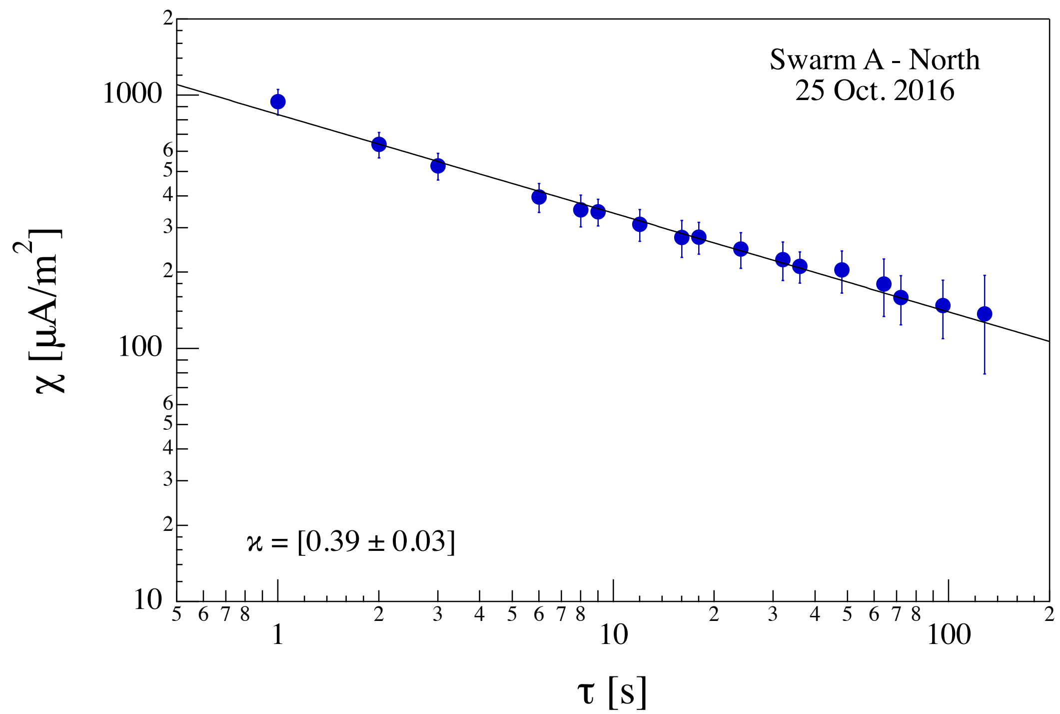
$$\langle | \, v_{||}(r+\epsilon) - v_{||}(r) \, | \rangle \sim \epsilon \chi(\epsilon)$$

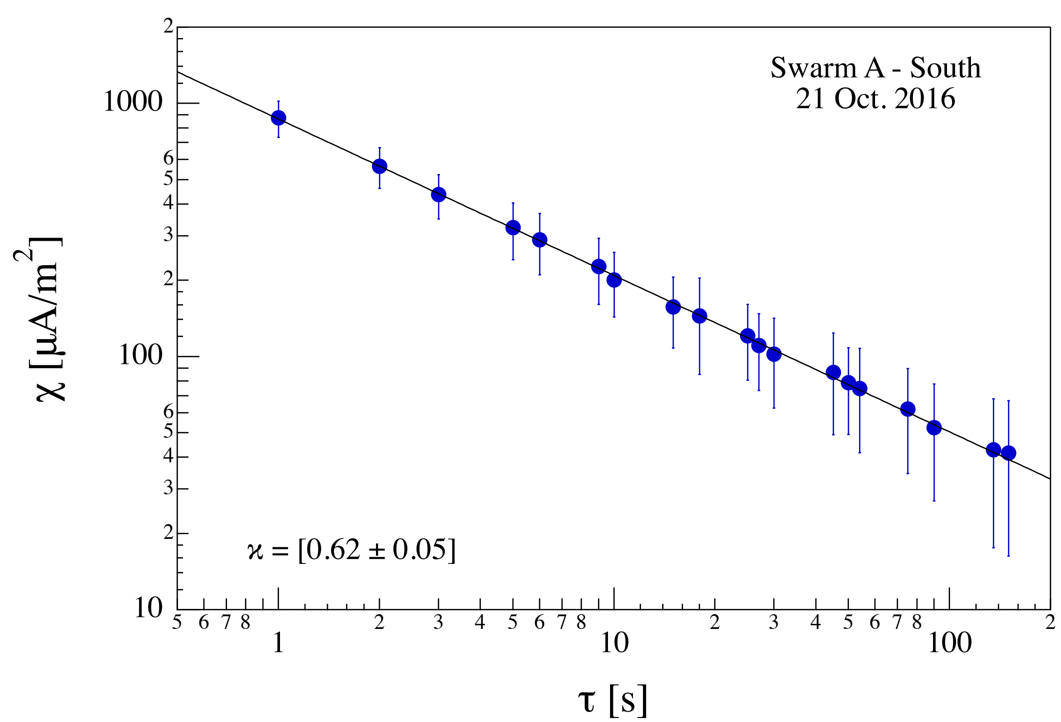
$$\kappa = 1 - \gamma(1)$$

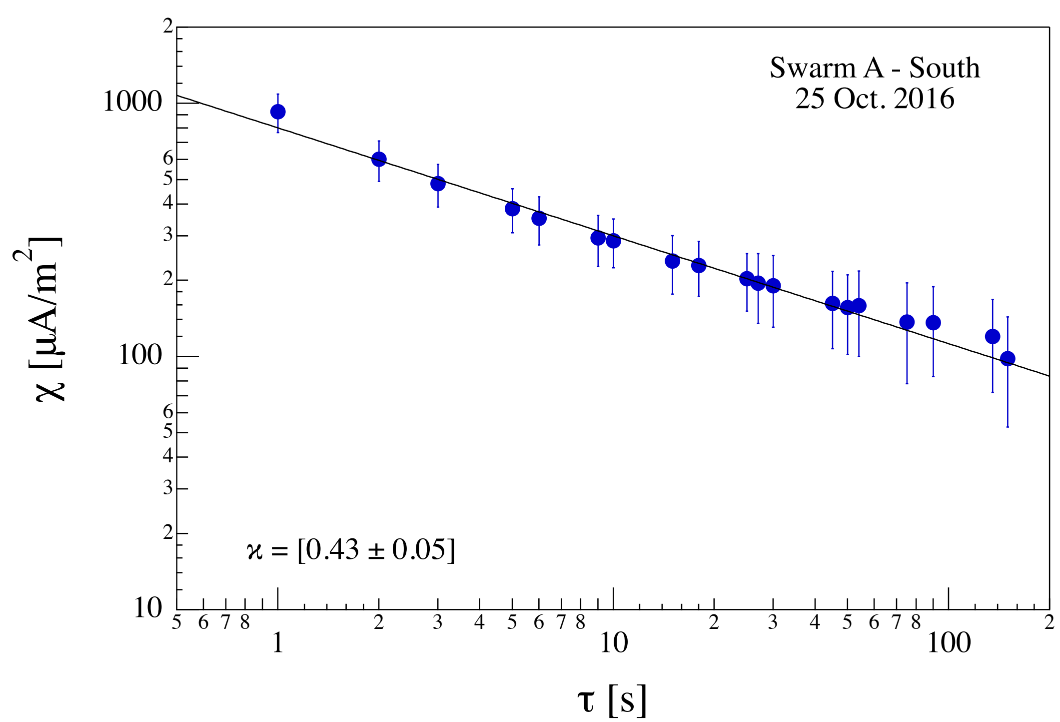
Results

$$\mu_\tau(\Omega_i) = \sum_{t_k \in \Omega_i} j_{FAC}(t_k) \quad \rightarrow \quad \chi(\tau) = \sum_i \mid \mu_\tau(\Omega_i) \mid$$









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Cancellation Exponent κ

21 Oct 2016	Swarm A	Swarm C
North	0.66 ± 0.03	0.67 ± 0.03
South	0.62 ± 0.05	0.62 ± 0.05

25 Oct 2016	Swarm A	Swarm C
North	0.39 ± 0.03	0.38 ± 0.03
South	0.43 ± 0.05	0.43 ± 0.05

Conclusions

The results of our analysis returns:

- the FAC fluctuations show *non-trivial sign-singularity*;
- the observed *scaling features are non-trivial* and *depend on the geomagnetic disturbance level*: the *cancellation exponent κ decreases for increasing geomagnetic activity* (AE-index);

$$\langle AE - index \rangle = 160\ nT \quad \longrightarrow \quad \langle \kappa \rangle = [0.64 \pm 0.04] \quad (\gamma(1) = 0.36)$$

$$\langle AE - index \rangle = 660\ nT \quad \longrightarrow \quad \langle \kappa \rangle = [0.41 \pm 0.04] \quad (\gamma(1) = 0.59)$$

$intermittency$

- the cancellation exponent values point toward an *intermittent turbulent* character of the observed current fluctuations.

These preliminary results support the *filamentary nature (strong inhomogeneity) of the FACs* in the polar ionosphere. However, more work is necessary to put all the emerging scenario in a theoretical framework.

Acknowledgements

The results presented rely on data collected by the three satellites of the Swarm constellation. We thank the European Space Agency that supports the Swarm mission.

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INTENS Team:

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