

# Solar Wind Control of Field-Aligned Current Dynamics

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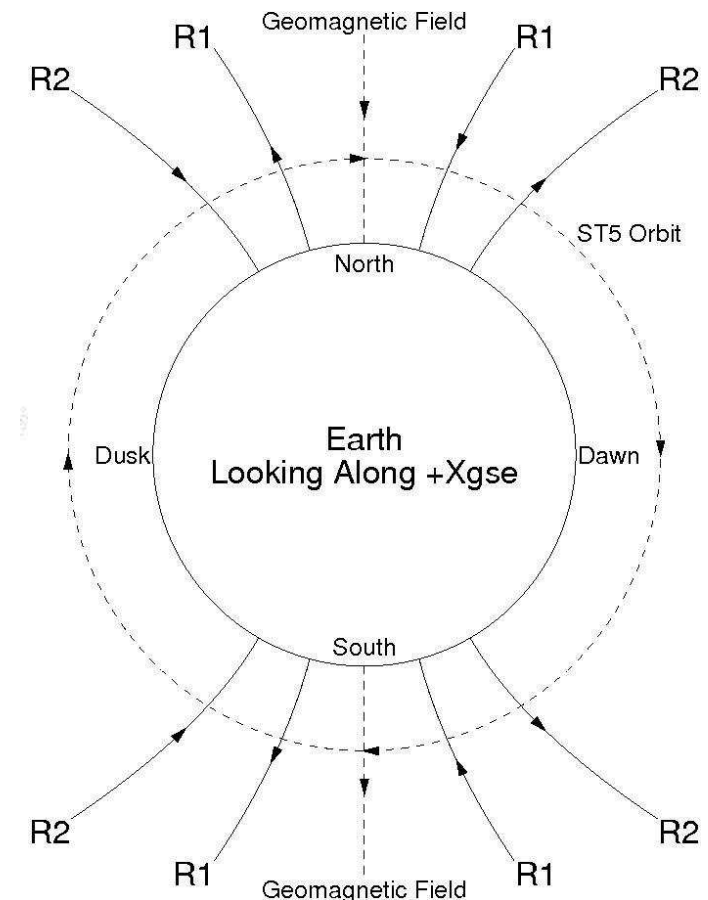
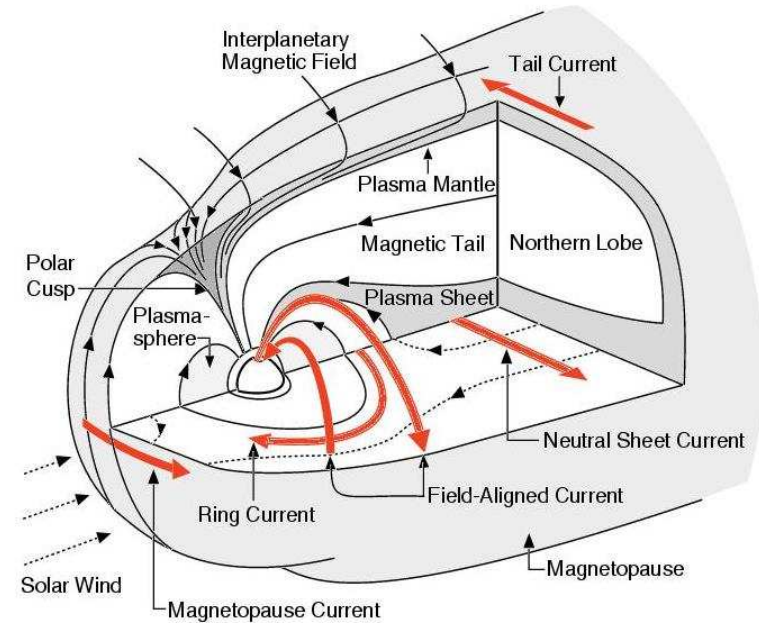
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**UMBC**  **GSFC**  **UCLA**

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# Introduction

- Field-aligned currents (FACs) are the currents flowing into and out of the ionosphere which connect to the magnetosphere. They provide an essential linkage between the solar wind-magnetosphere system and the ionosphere.
- The distribution and variability of FACs determine ionospheric Joule heating rate, and affect the density and composition of the neutral atmosphere.
- Since the detection of the first FAC signatures [**Zmuda et al., 1966**], many studies have been dedicated to the characterization of FACs [e.g., **Iijima and Potemra, 1976, 1978**].
- The motion of FACs has been found to depend on the interplanetary magnetic field (IMF) and related to geomagnetic activities [e.g., **Iijima and Potemra, 1978; Zanetti et al., 1983; Fujii et al. 1992; Anderson et al. 2002; Wang et al. 2006**].
- Although the majority of in situ FAC observations have been made from individual satellites, multi-spacecraft in situ observations have also been carried out to understand FACs [e.g., **Kelly et al., 1986; Chun and Russell, 1991; Marklund et al. 2007; Snekvik et al. 2007**].

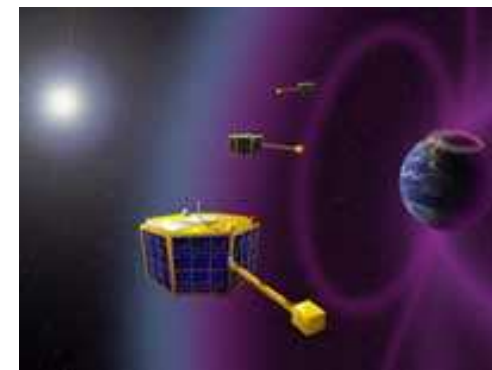
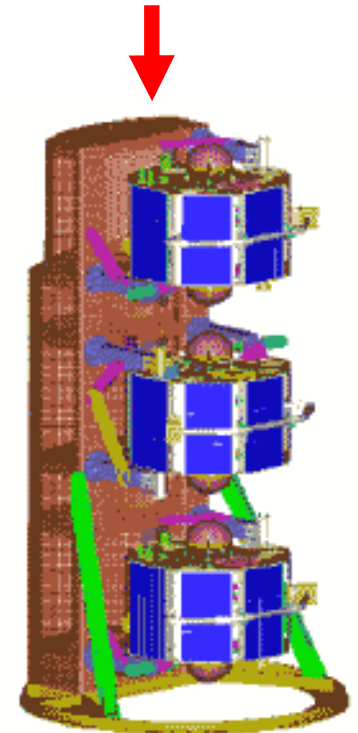
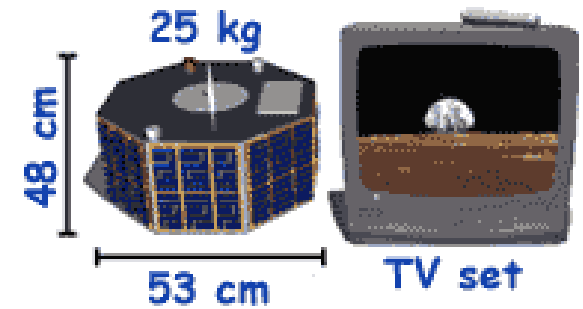


# ST-5 Mission and Orbit Profile

- **Launch:** Pegasus out of Vandenberg on March 22, 2006
- **Mission Duration:** March 22 – June 21
- **Orbit:** Sun-Synchronized Dawn-dusk Meridian Plane
- **Inclination:**  $105.6^\circ$
- **Orbit Perigee/Apogee:** 300/4500 km
- **Orbit Period:** 136 minute
- **Constellation Configuration:** String-of-Pearls
- **Spacecraft Spacing:** ~50 - 4000 km
- **Spacecraft Separation:** ~10 s – ~10 min
- **Communications:** Deep Space Network McMurdo Ground Station

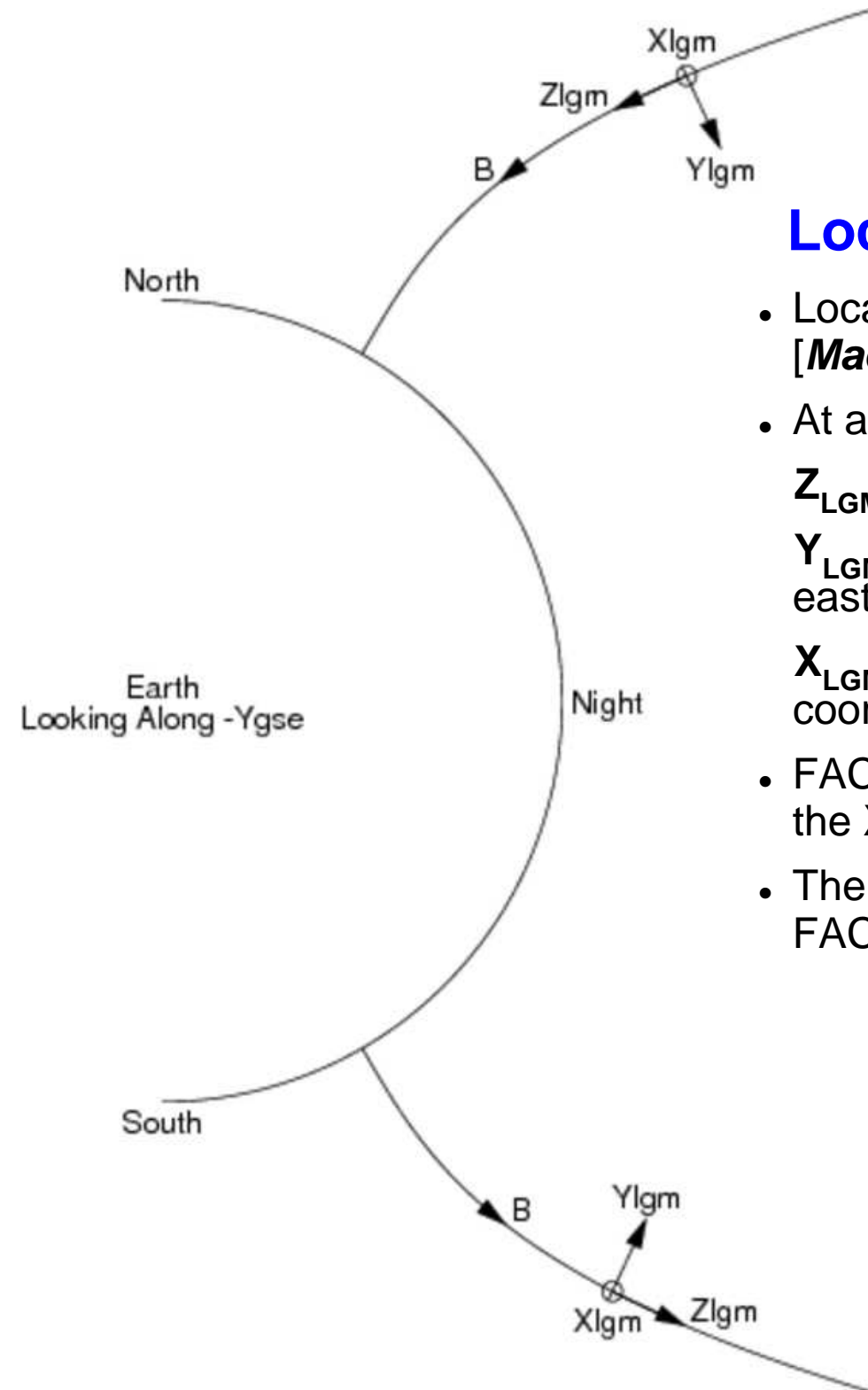
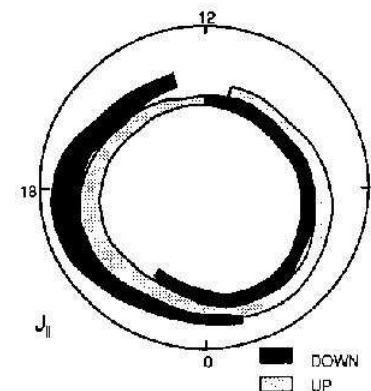
Multi-spacecraft ST-5 in situ FAC observations with large ranges of spatial and temporal separations at low-Earth orbit (LEO) provide an unprecedented opportunity to advance our understanding of FAC structure and dynamics [**Slavin et al., 2008**].

**In this study, we use the magnetic field observations during the whole ST-5 mission to study FAC sheet motion and its dependence on solar wind and geomagnetic conditions.**

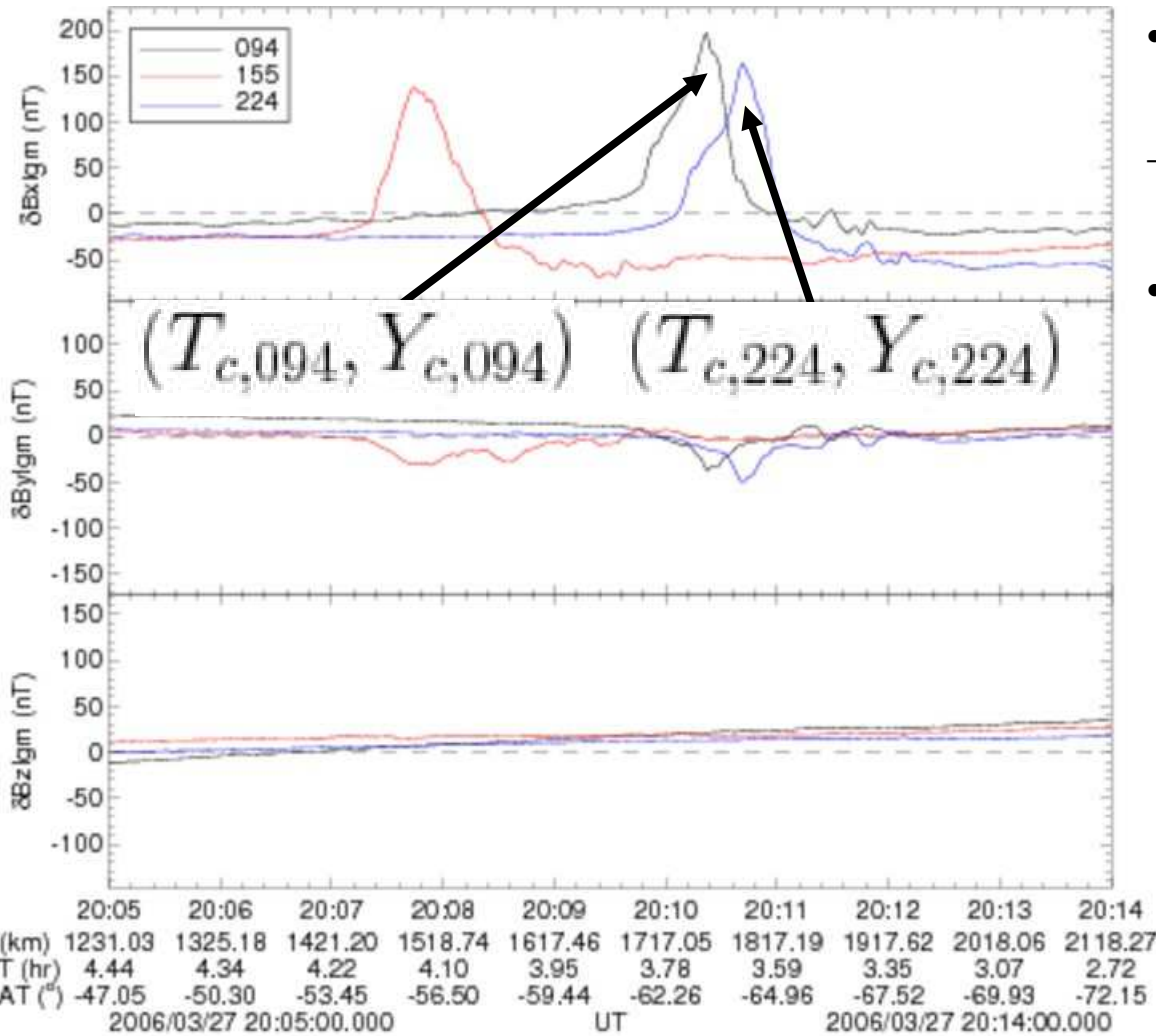


## Local Geomagnetic Coordinates (LGM)

- Local Geomagnetic Coordinates (LGM) using IGRF-10 [Macmillan and Maus, 2005].
- At a particular point in space:
  - $\mathbf{Z}_{LGM}$  is along the local magnetic field direction;
  - $\mathbf{Y}_{LGM}$  is the cross product of  $\mathbf{Z}_{LGM}$  and the geomagnetic eastward unit vector;
  - $\mathbf{X}_{LGM}$  completes the right-handed orthogonal coordinate system.
- FACs are assumed to have sheet-like structure along the  $\mathbf{X}_{LGM}$ - $\mathbf{Z}_{LGM}$  plane.
- The maximum magnetic field variations caused by FAC should be along the  $\mathbf{X}_{LGM}$  direction.



# Calculation of FAC Speed, Thickness, and Current Density



- Spin-averaged magnetic field observations of 1-s resolution are used.
- Residual magnetic field in the  $X_{LGM}$  direction is used.
- Best cross-correlation technique is used for spatial and temporal separations for each chosen pair for FAC speed calculation.

**Most other studies with single S/C:**

$$V_y^{FAC} = 0$$

**This study:**

$$V_y^{FAC} = \left( \frac{Y_{c,094} - Y_{c,224}}{T_{c,094} - T_{c,224}} \right)$$

**FAC Thickness:**

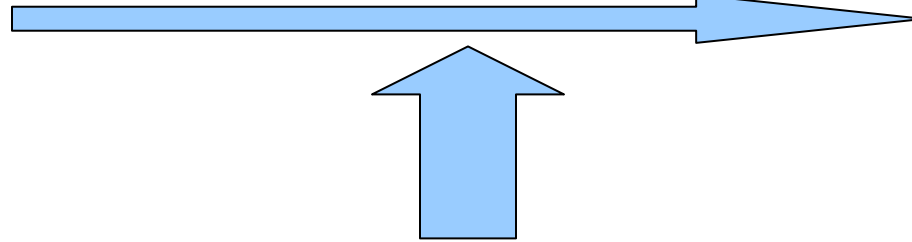
$$L = |V_y^{SC} - V_y^{FAC}| \Delta t$$

**FAC Current Density:**

$$J = -\frac{1}{\mu_0} \frac{1}{V_y^{SC} - V_y^{FAC}} \frac{\partial \delta B_{xlgm}}{\partial t}$$

## FAC Criteria

2535 FACs

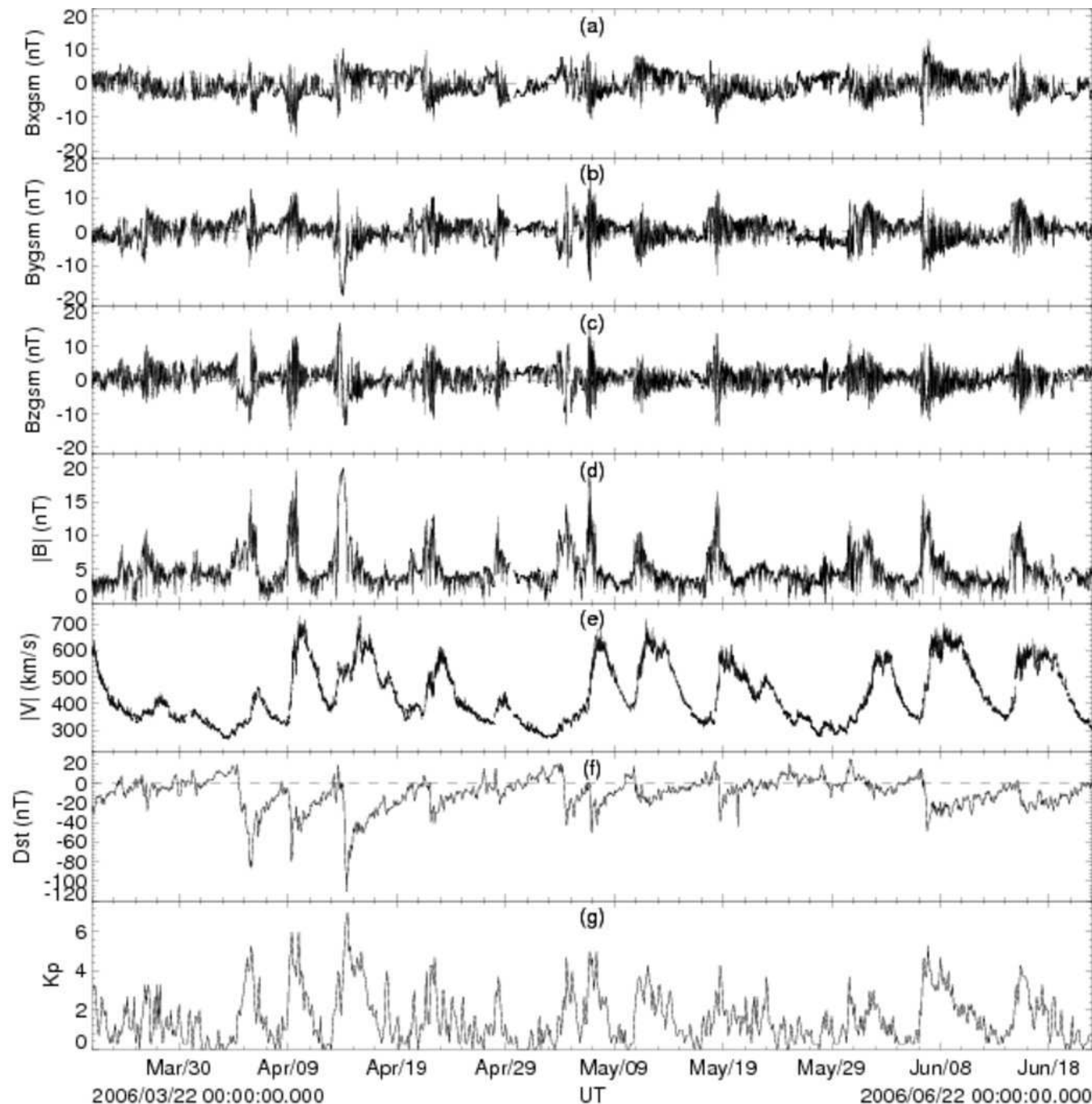


1030 FACs  
with valid speed

- 1) The angle between the FAC maximum field variation direction, corresponding to the maximum MVA eigenvalue, and the LGM x axis is less than  $30^\circ$  (72% of the initial FACs).
- 2) The ratio between the medium and the maximum MVA eigenvalues is less than 0.3 (93% of the initial FACs) to make sure that the variation along the maximum variance direction is much more significant than that in the other directions.
- 3) The maximum Euler angle between the central and the two boundary LGM transformation matrices is less than  $10^\circ$  (81% of the initial FACs) to make sure that the constant LGM transformation matrix from the center of an FAC is valid throughout the entire FAC interval.
- 4) The maximum cross-correlation coefficient between each chosen spacecraft pair is larger than 0.9 (94% of the initial FACs) to restrict our FAC database to the FACs without much change between the chosen ST-5 pairs.
- 5) The attack angle of each FAC, the angle between the current sheet normal direction and spacecraft orbit track, is less than  $60^\circ$  (82% of the initial FACs) to avoid spacecraft skimming along current sheet which makes the determination of FAC speed and current density unreliable.
- 6) Speed error is less than 0.1 km/s (87% of the initial FACs) to ensure the accuracy of FAC speed calculations.

# Solar wind and geomagnetic conditions

- The solar wind conditions from OMNI database with 1-minute resolution [**King and Papitashvili, 2005**] and geomagnetic Dst and Kp indices during the whole ST-5 mission.
- We add an extra 15-minute delay for FAC corresponding solar wind conditions to account for the response at the ionosphere to the development of the FACs from the magnetosphere [**Stauning et al., 1994; Vennerstrøm et al., 2002; Wang et al., 2006**].
- Generally mild conditions in wide ranges with several moderate magnetic storms.



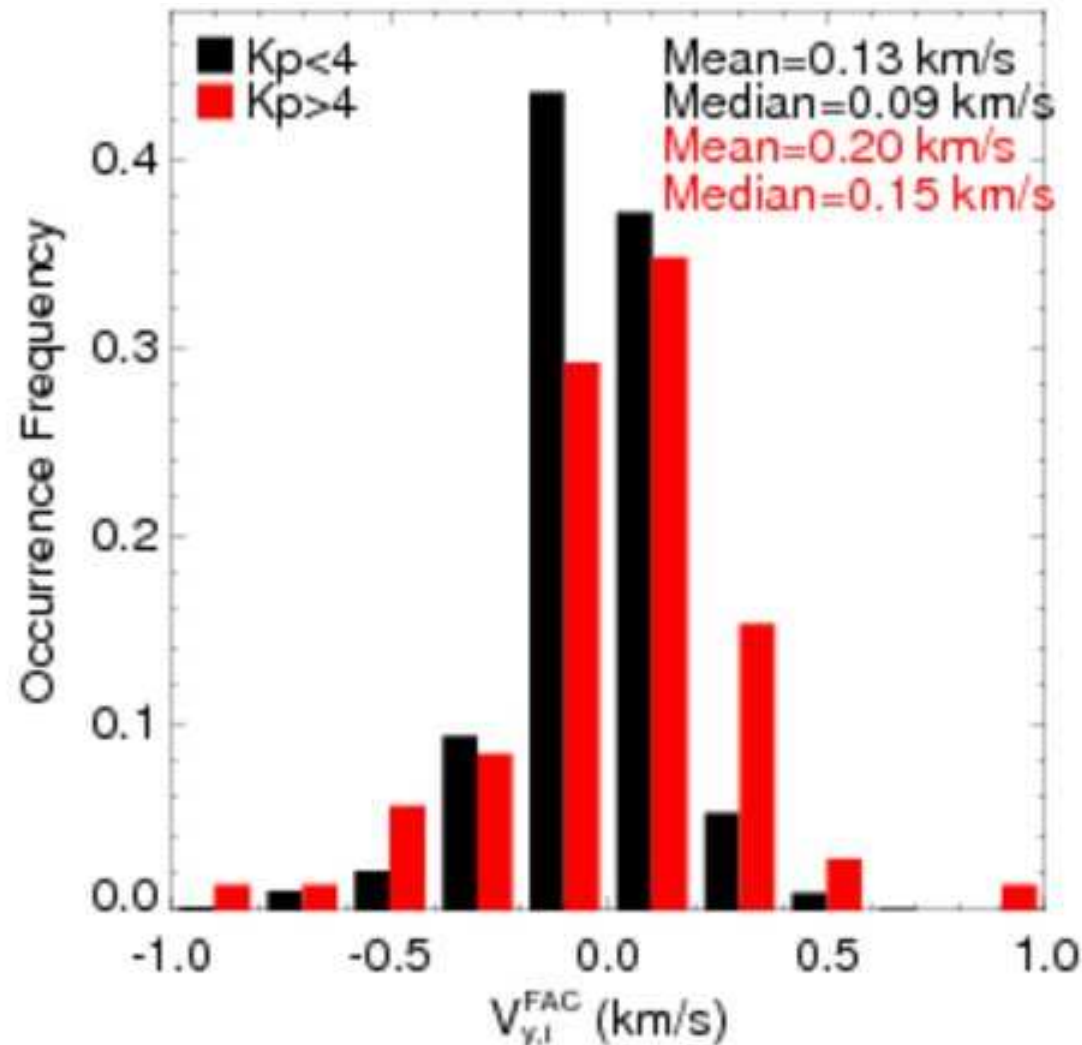
## FAC ionospheric footprint speed distribution

In order to avoid orbital bias, we map down each ST-5 FAC speed along IGRF-10 magnetic field line assuming that FAC current sheet sideways motion can be approximated as the entire current sheet structure mapped to new field lines [**Kelly et al., 1986; Chun and Russell, 1991**]:

$$V_{y,map}^{FAC} = V_{y,ST-5}^{FAC} \frac{|\mathbf{B}_{ST-5}|}{|\mathbf{B}_{map}|} \sqrt{\frac{(x_{ST-5}^{SM})^2 + (y_{ST-5}^{SM})^2}{(x_{map}^{SM})^2 + (y_{map}^{SM})^2}} \cos(\theta)$$

(Here  $\theta$  is the angle between Earth radial direction and magnetic field)

- There is a normal distribution for FAC speed between -1 and 1 km/s with the majority smaller than 0.5 km/s.
- Larger FAC speeds are more likely to be seen during higher geomagnetic activities ( $K_p > 4$ ) than during lower geomagnetic activities ( $K_p < 4$ ).
- During high geomagnetic activities, still a significant number of low FAC speeds are observed.



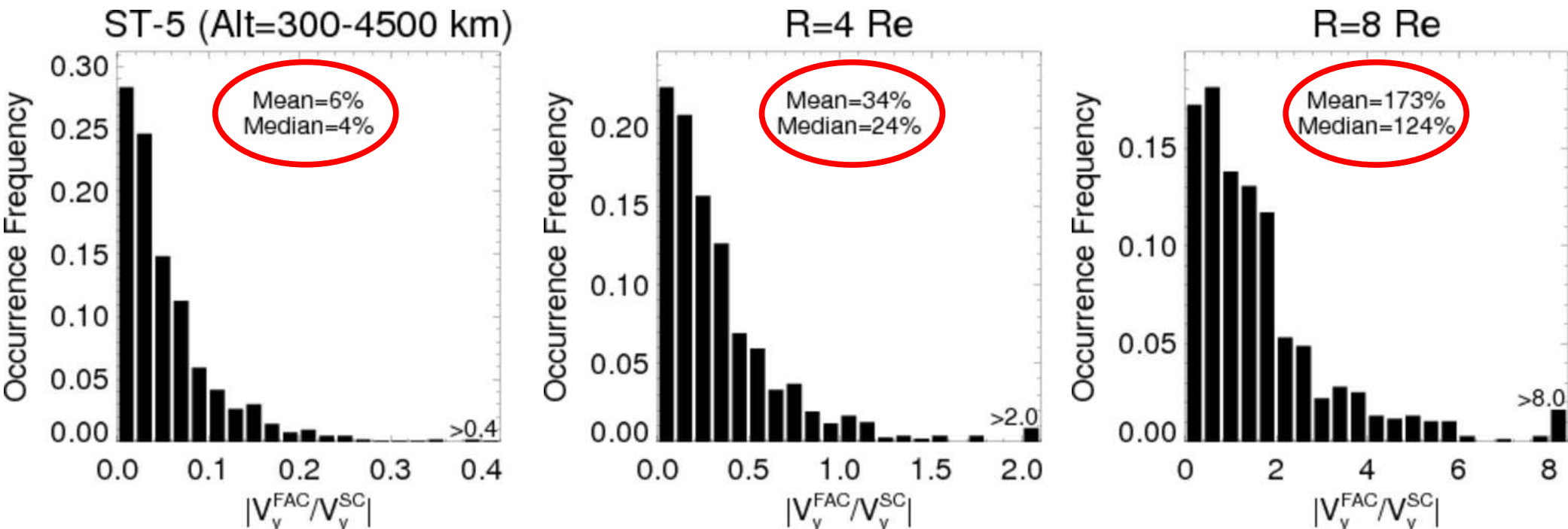


## The $V_{FAC}/V_{SC}$ at different altitudes

- The ratio between FAC speed and S/C speed is closely related to the accuracy of FAC thickness and current density calculations if stationary FAC is assumed.
- Mapping FAC speed along field line makes it possible to study the effects of FAC speed at different altitudes.
- Except at ST-5, circular spacecraft orbit perpendicular to the current sheet is assumed for the mapped cases, which is a reasonable assumption for the noon-midnight meridian plane where ST-5 orbit resides.

$V_{FAC}$  mapping along IGRF-10 field line:

$$V_{y,map}^{FAC} = V_{y,ST-5}^{FAC} \frac{|\mathbf{B}_{ST-5}|}{|\mathbf{B}_{map}|} \sqrt{\frac{(x_{ST-5}^{SM})^2 + (y_{ST-5}^{SM})^2}{(x_{map}^{SM})^2 + (y_{map}^{SM})^2}}$$



# Relative error of FAC thickness and current density if stationary FAC is assumed

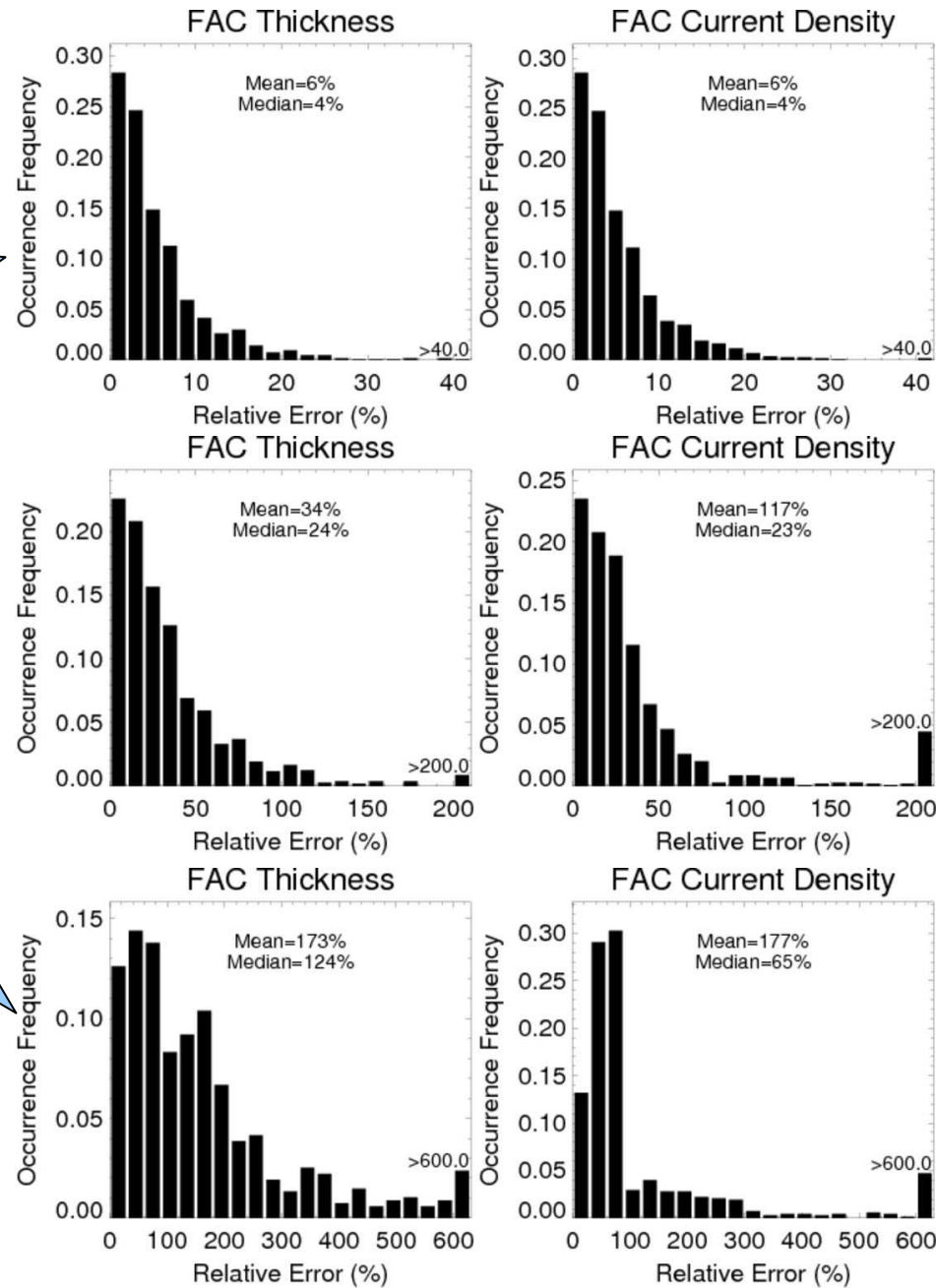
- The relative mean and median errors are **small**.
- The relative mean and median errors are **quite big**.
- The relative mean and median errors are **very significant**.

We should be **cautious** to assume stationary FAC at mid- and high-altitudes.

ST-5

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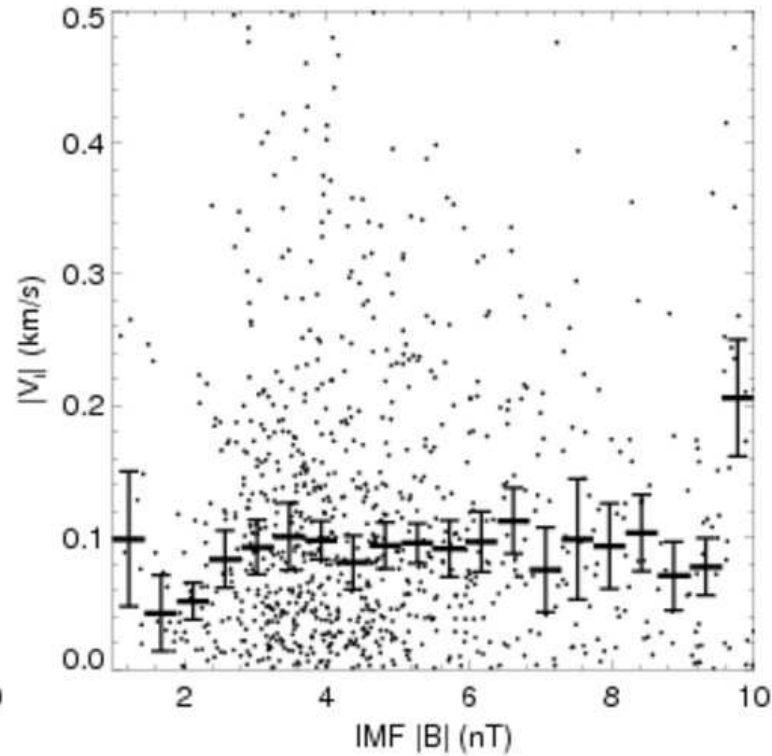
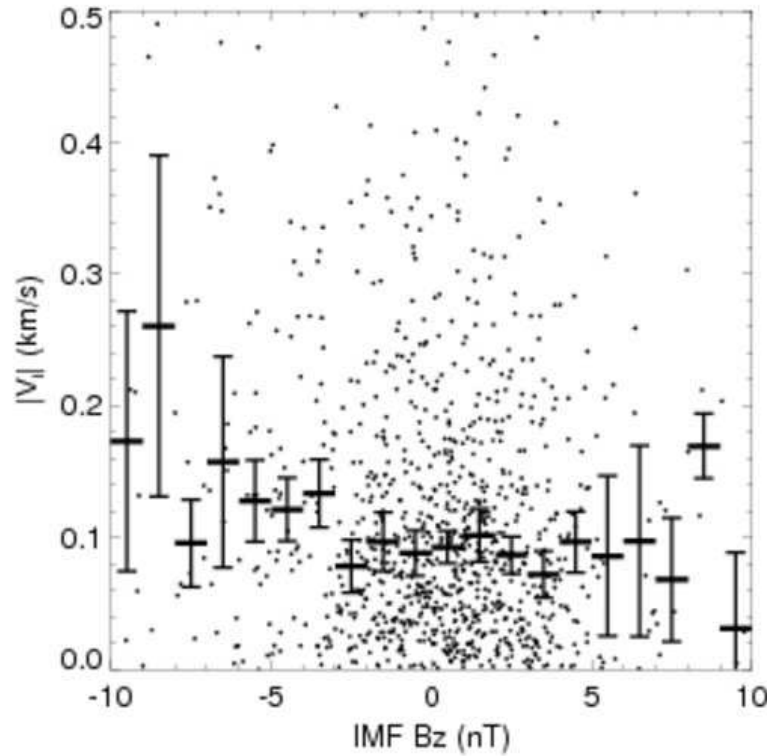
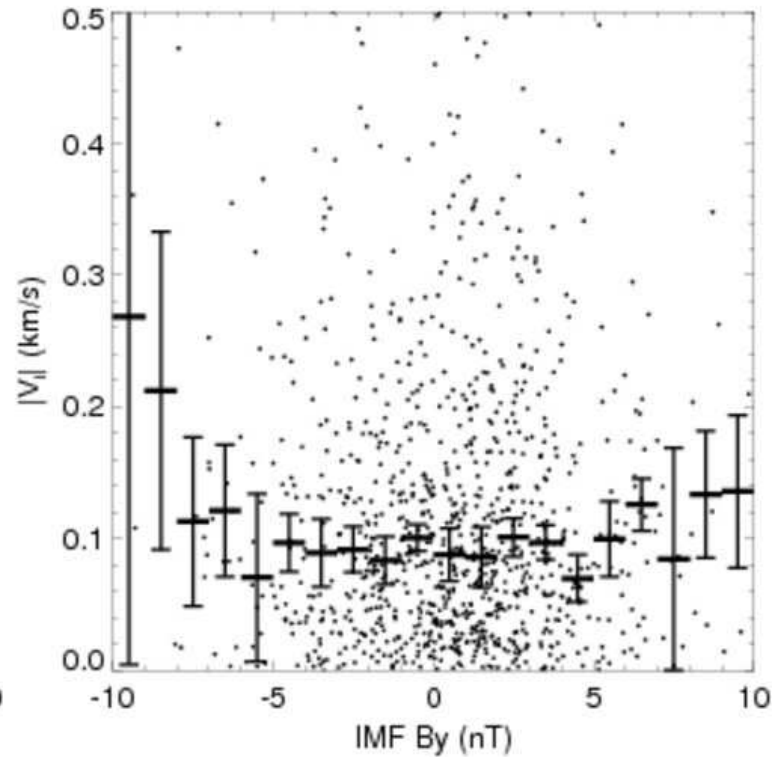
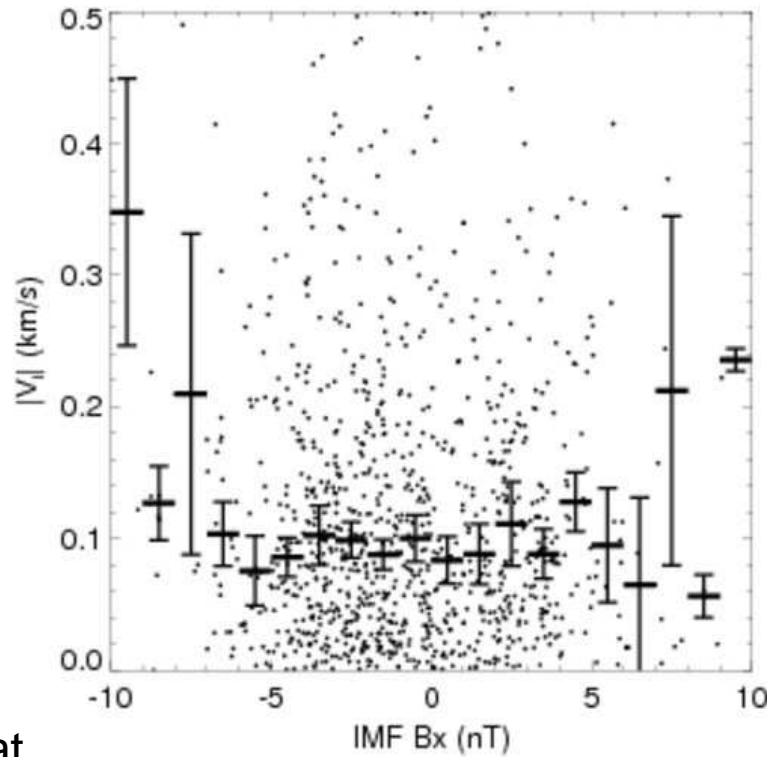
$$E_l = \left| \frac{V_y^{SC} \Delta t - (V_y^{SC} - V_y^{FAC}) \Delta t}{(V_y^{SC} - V_y^{FAC}) \Delta t} \right| = \left| \frac{\frac{V_y^{FAC}}{V_y^{SC}}}{1 - \frac{V_y^{FAC}}{V_y^{SC}}} \right|$$

$$E_j = \left| \frac{-\frac{1}{\mu_0 V_y^{SC}} \frac{\partial B_{xlgm}}{\partial t} - \left( -\frac{1}{\mu_0 V_y^{SC} - V_y^{FAC}} \frac{\partial B_{xlgm}}{\partial t} \right)}{-\frac{1}{\mu_0 V_y^{SC} - V_y^{FAC}} \frac{\partial B_{xlgm}}{\partial t}} \right| = \left| \frac{V_y^{FAC}}{V_y^{SC}} \right|$$

← Relative Errors

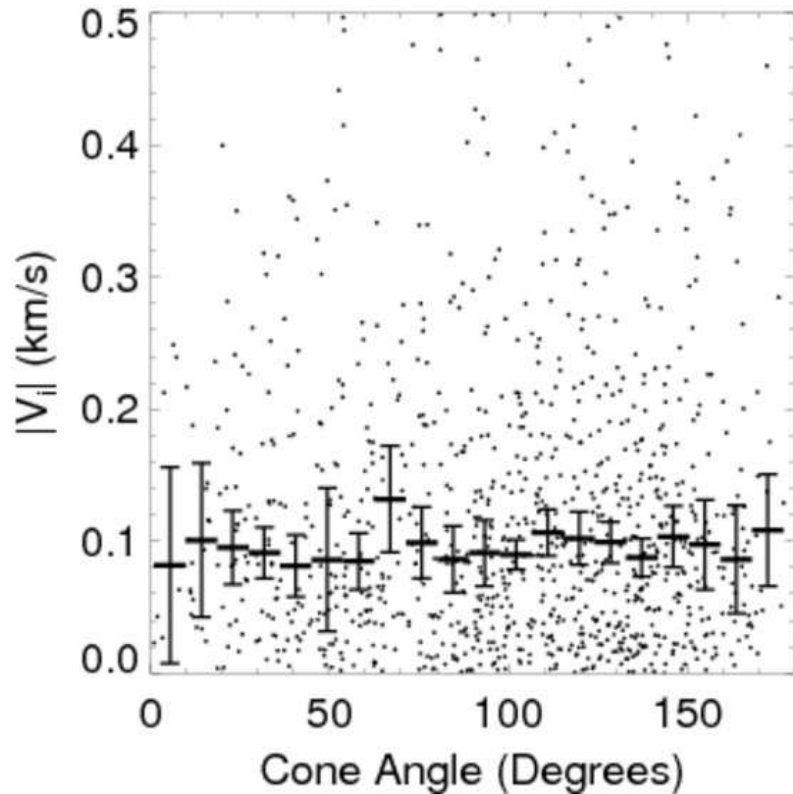
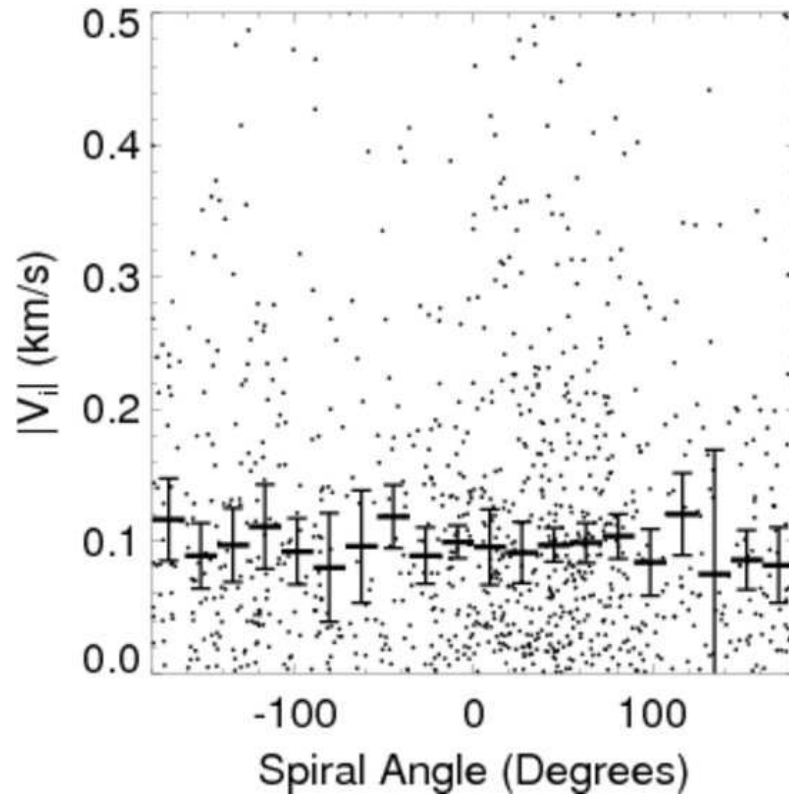
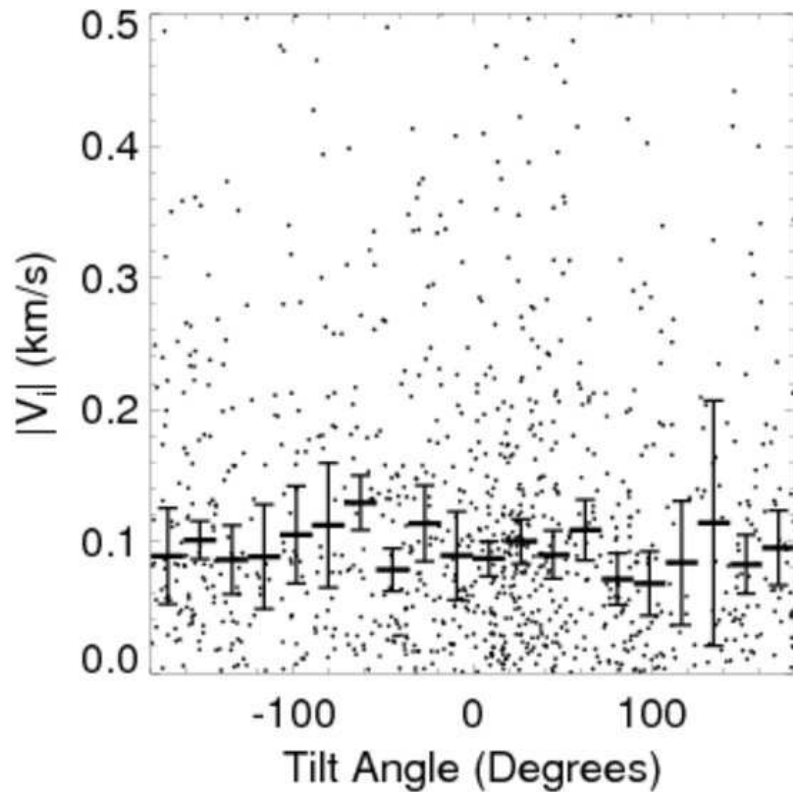
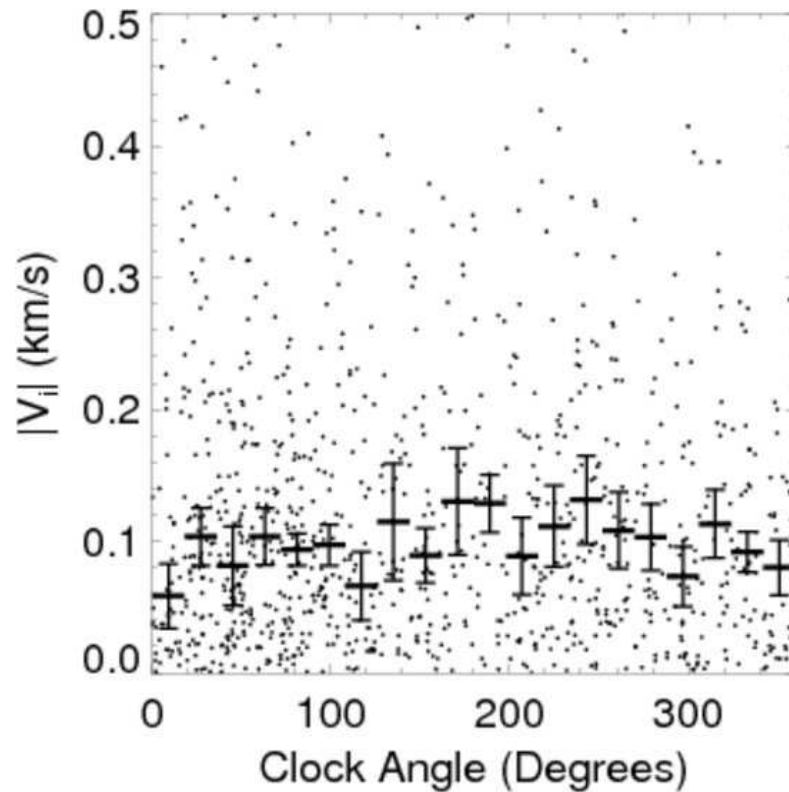
# FAC ionospheric footprint speed dependence on IMF

- The median values are shown as thick horizontal bars, and errors are the corresponding standard deviations from the medians.
- There is a little  $|V_i|$  jump at  $B_z \sim -3$  nT.
- $|V_i|$  increases between  $\sim 0.5$  and  $\sim 3.5$  nT with  $|\mathbf{B}|$  before it flattens out for higher  $|\mathbf{B}|$ .
- We see no other clear dependence of FAC ionospheric footprint speed on IMF.



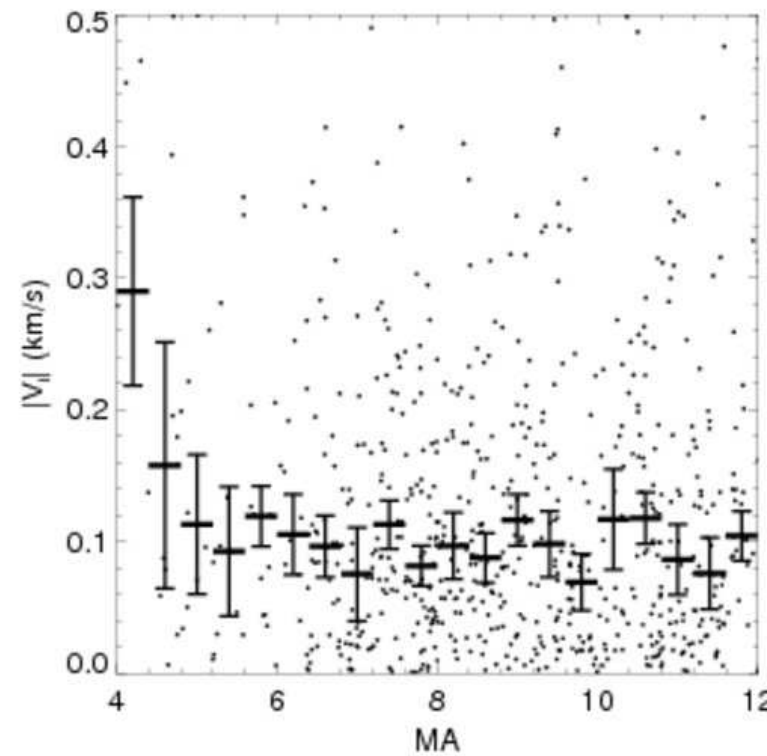
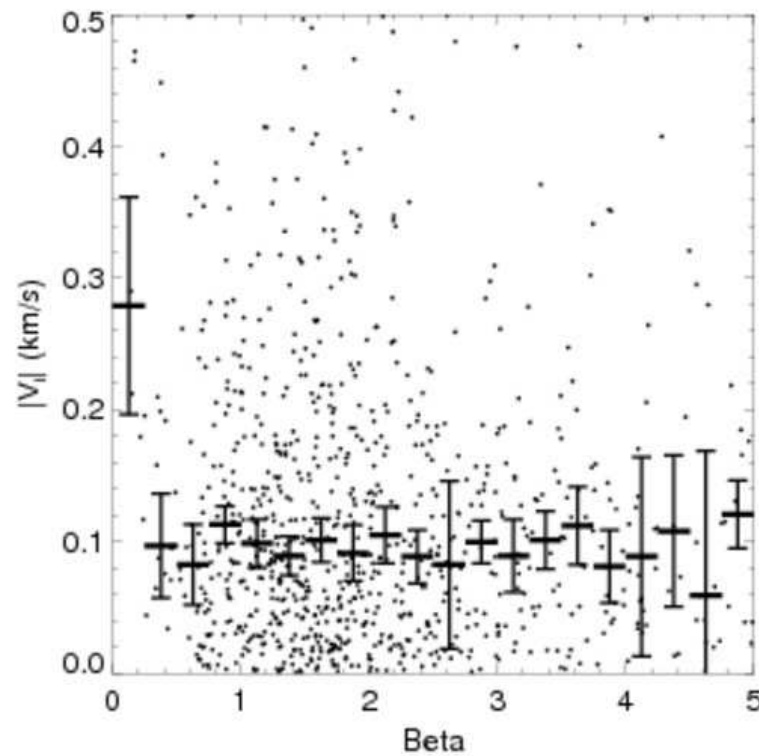
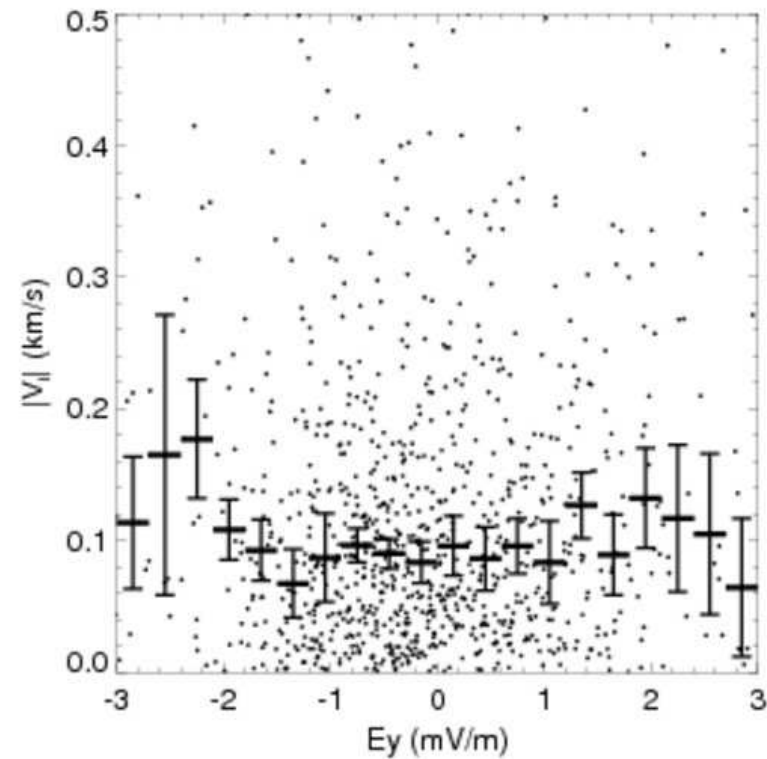
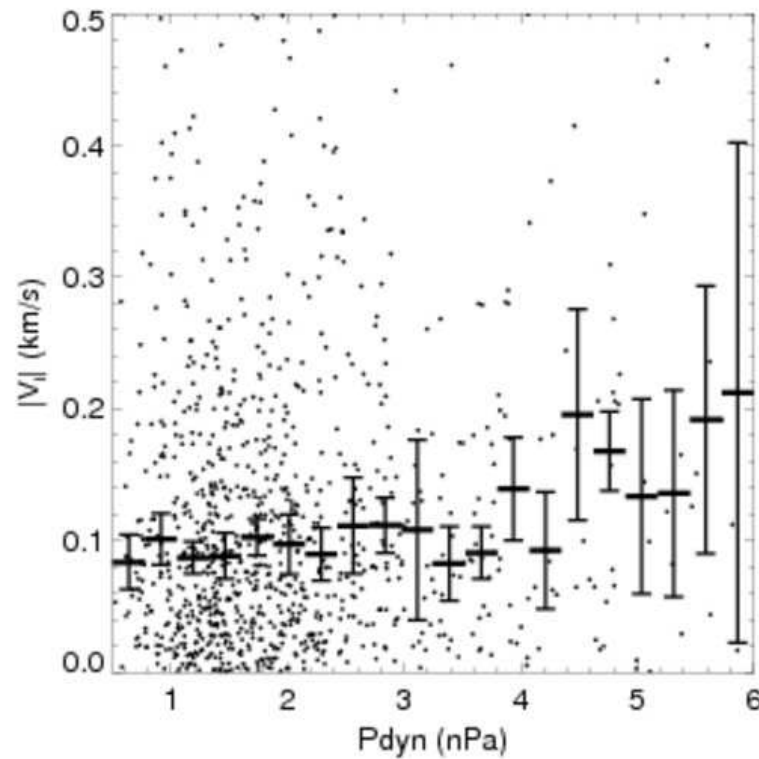
# FAC ionospheric footprint speed dependence on IMF angles

We see no clear dependence.



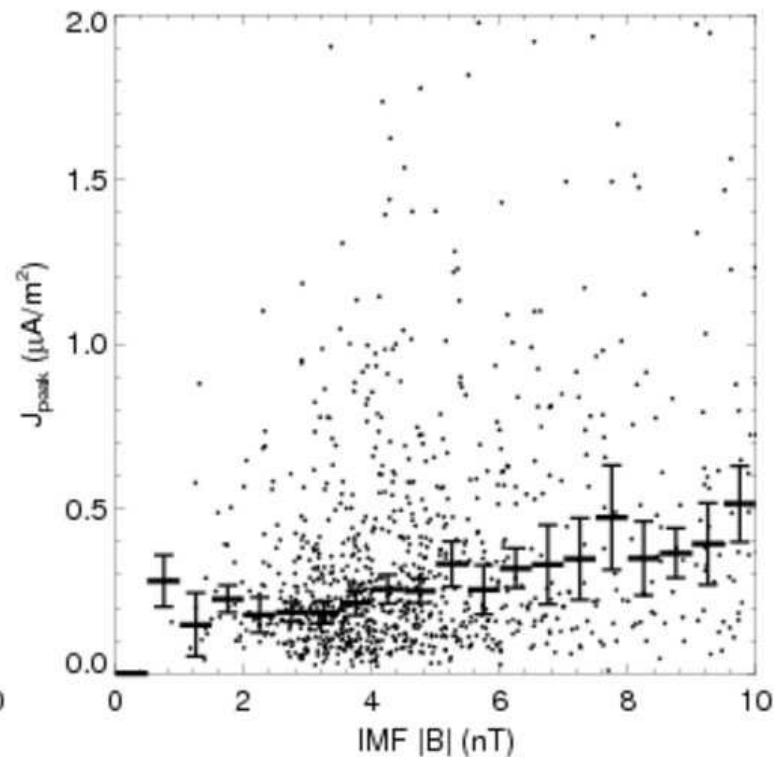
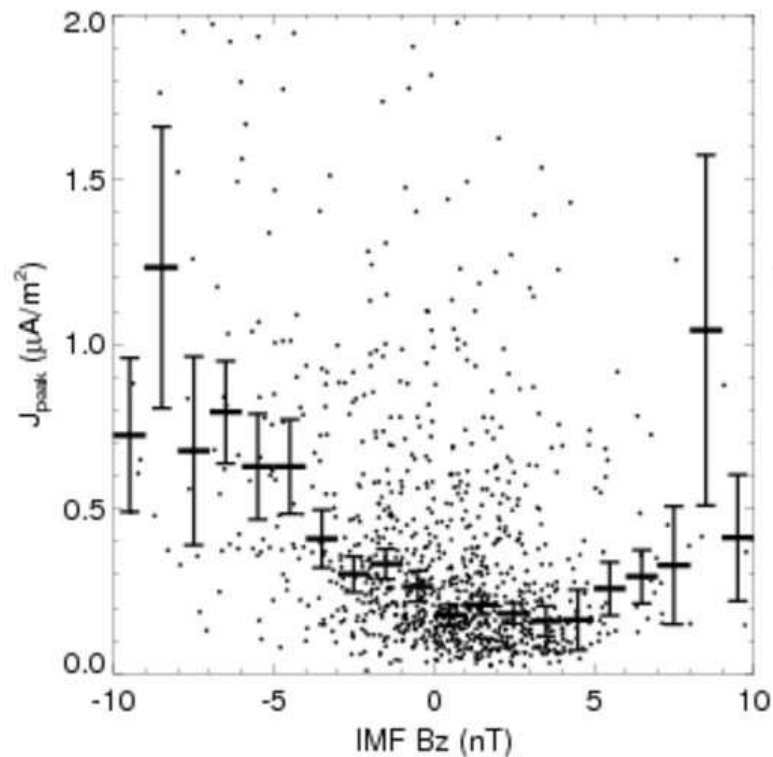
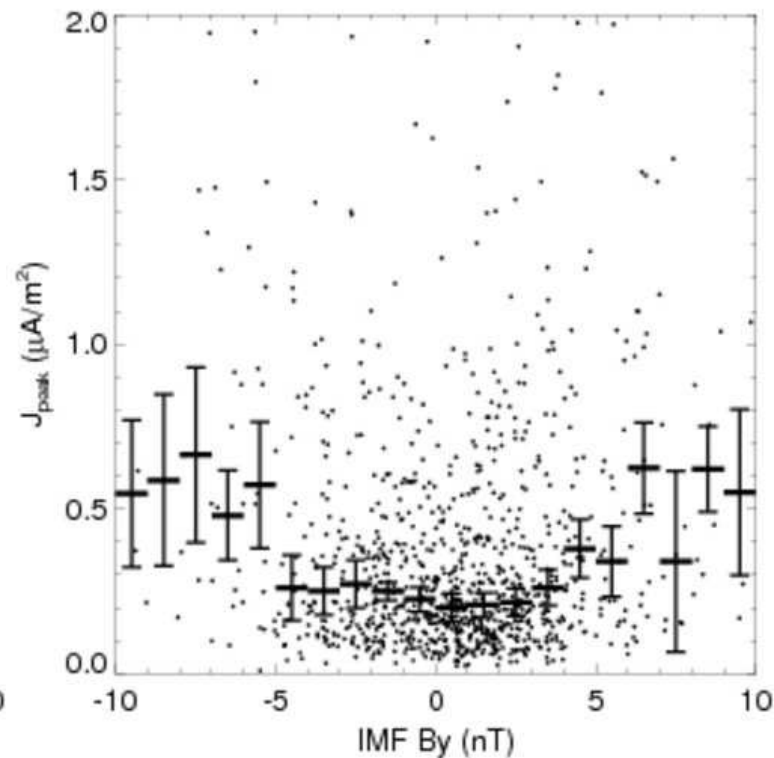
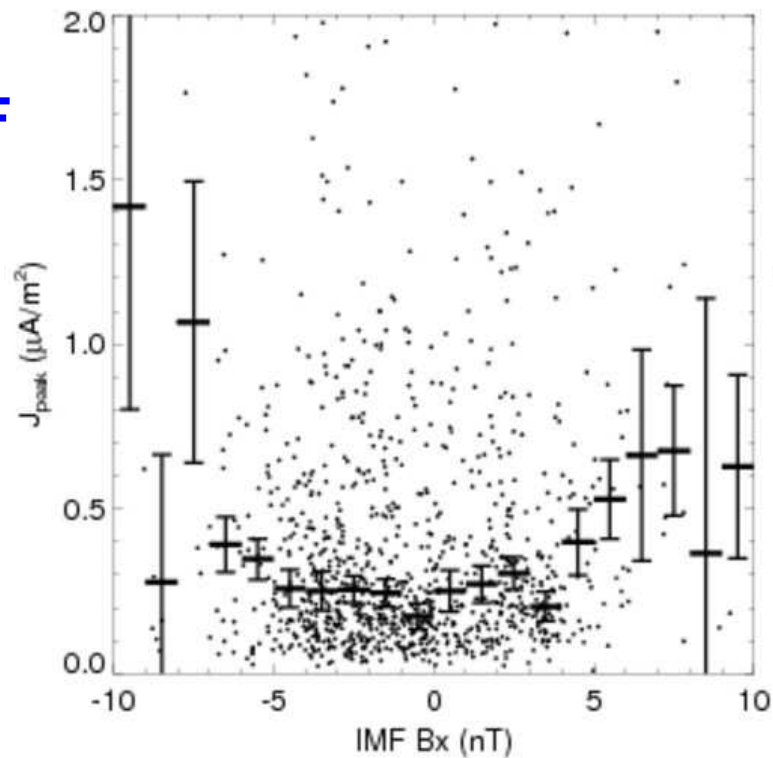
# FAC ionospheric footprint speed dependence on solar wind conditions

We see no clear dependence.



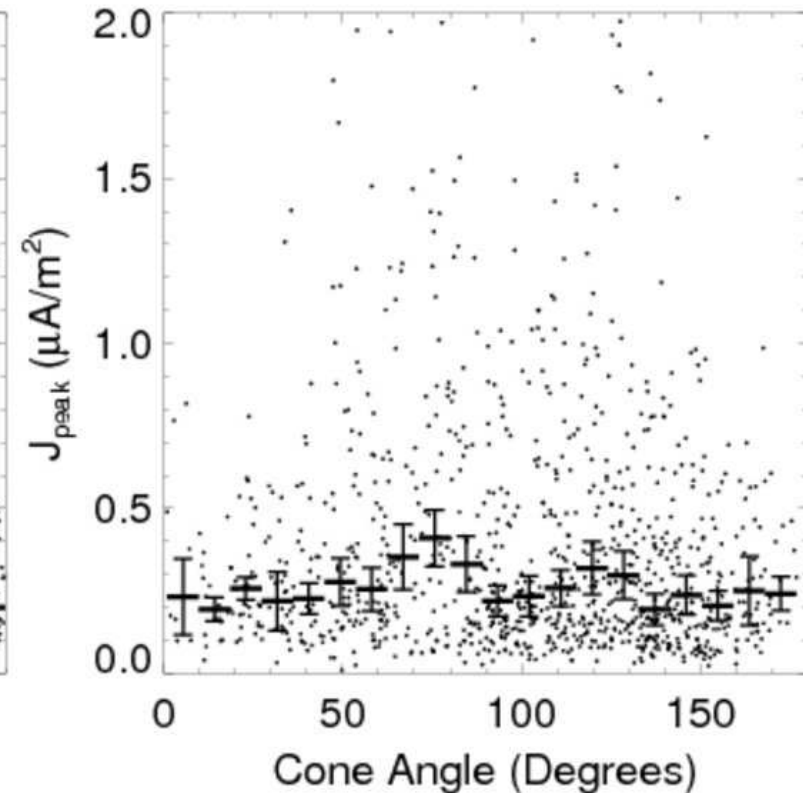
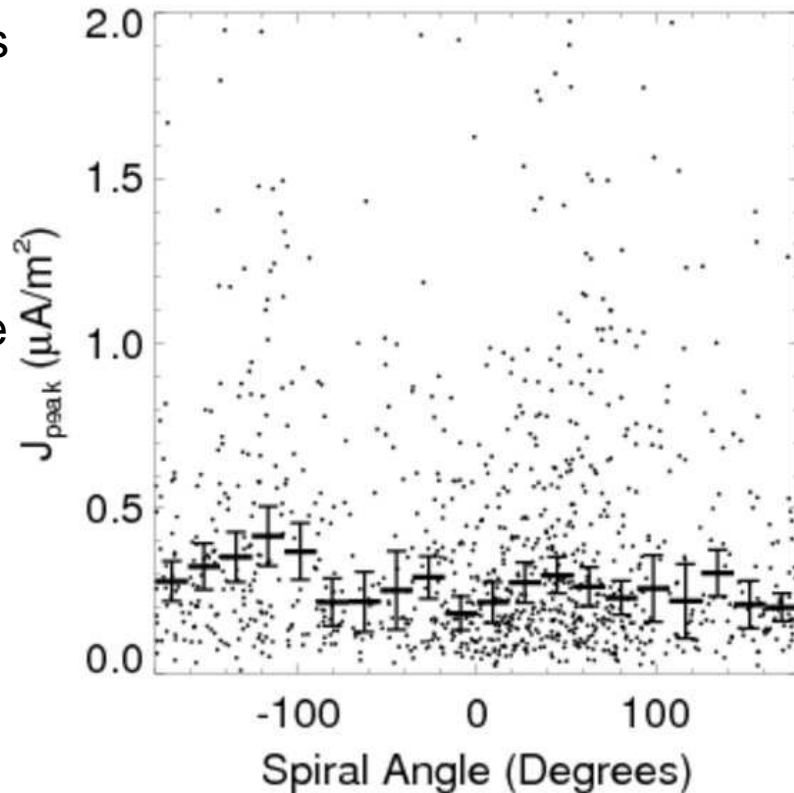
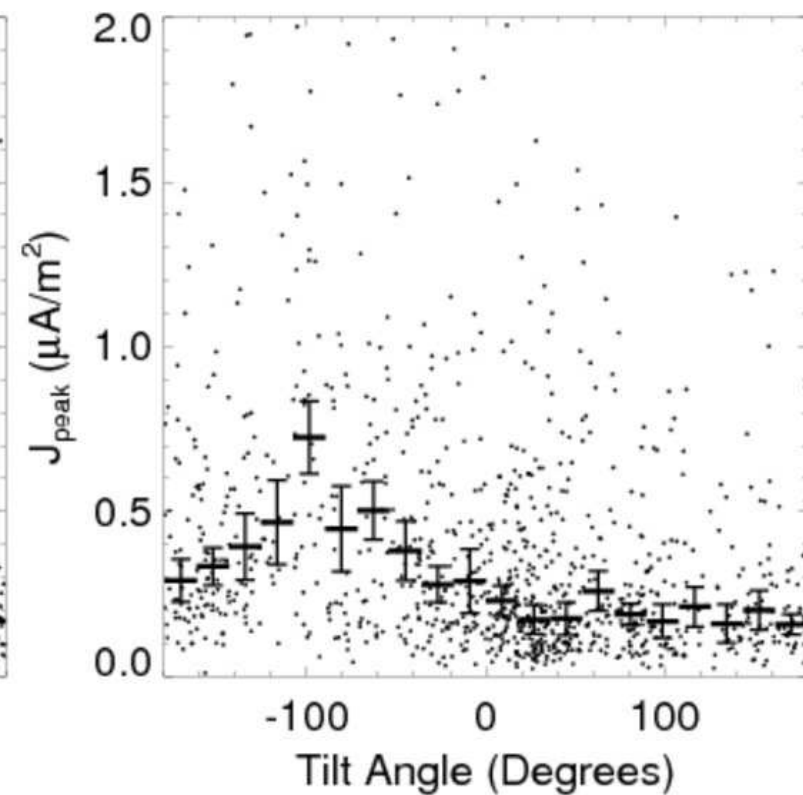
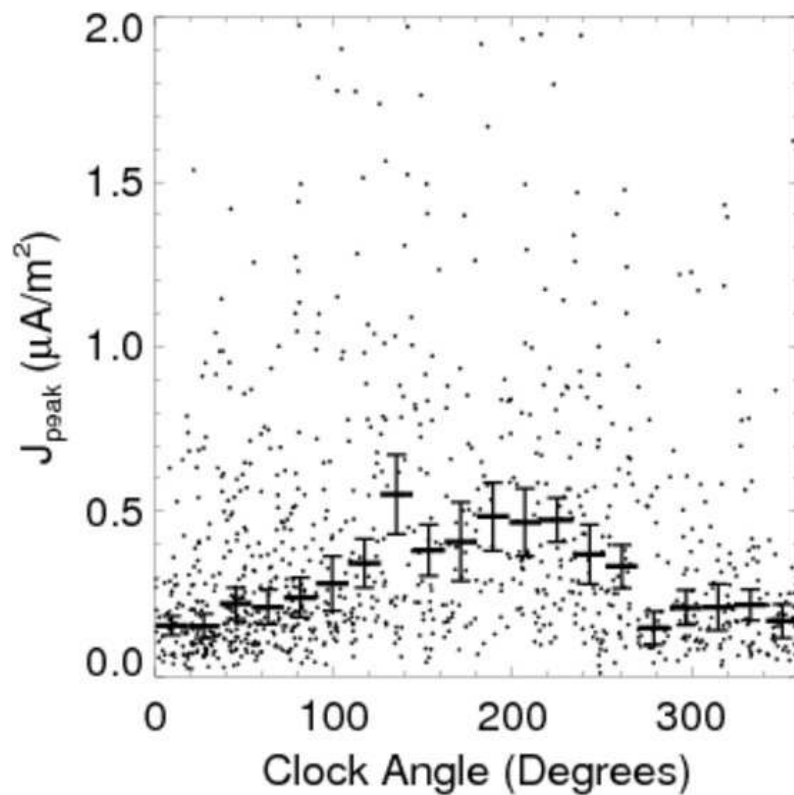
# FAC $J_{\text{peak}}$ dependence on IMF

- We see general increase of  $J_{\text{peak}}$  with increasing  $|B_x|$ ,  $|B_y|$ , and  $|\mathbf{B}|$ .
- There is clearly more significant increase of  $J_{\text{peak}}$  with decreasing  $B_z$  when it is negative. And  $J_{\text{peak}}$  increases moderately with IMF  $B_z$  when it is positive.



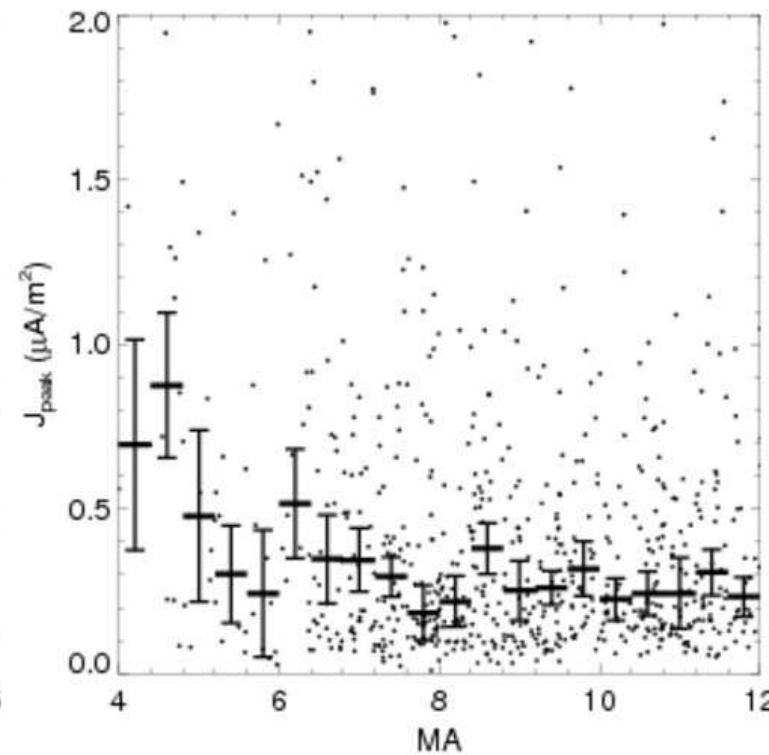
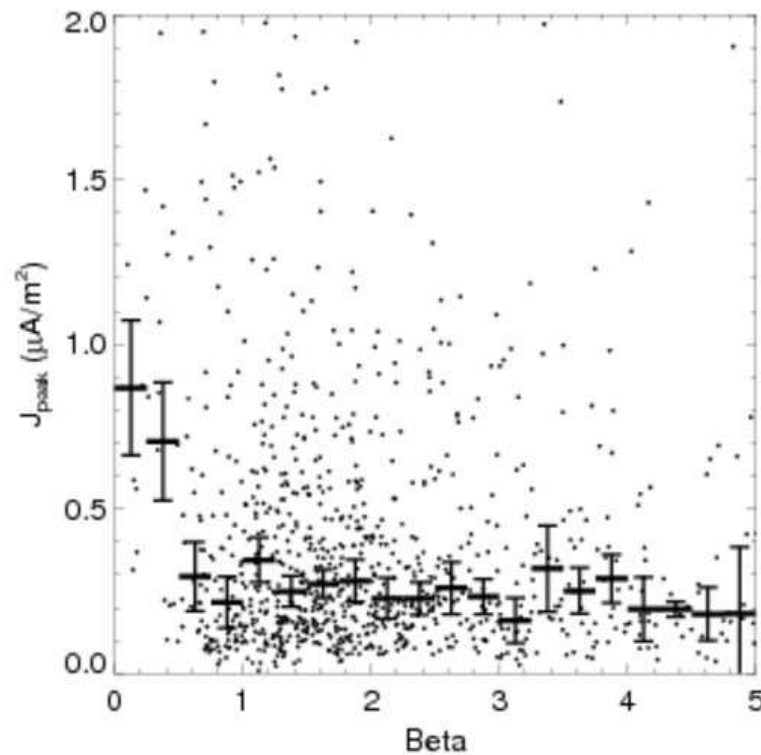
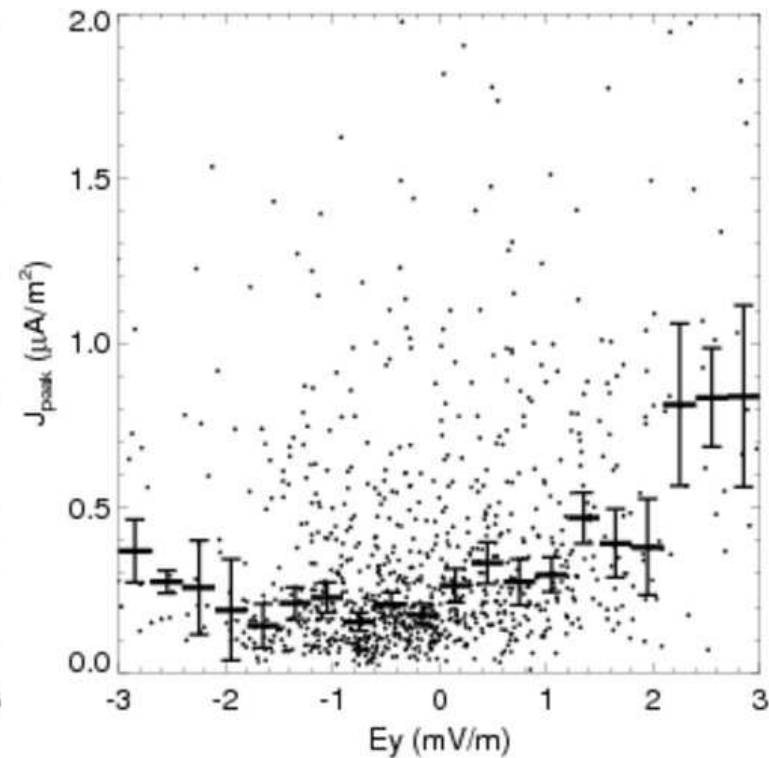
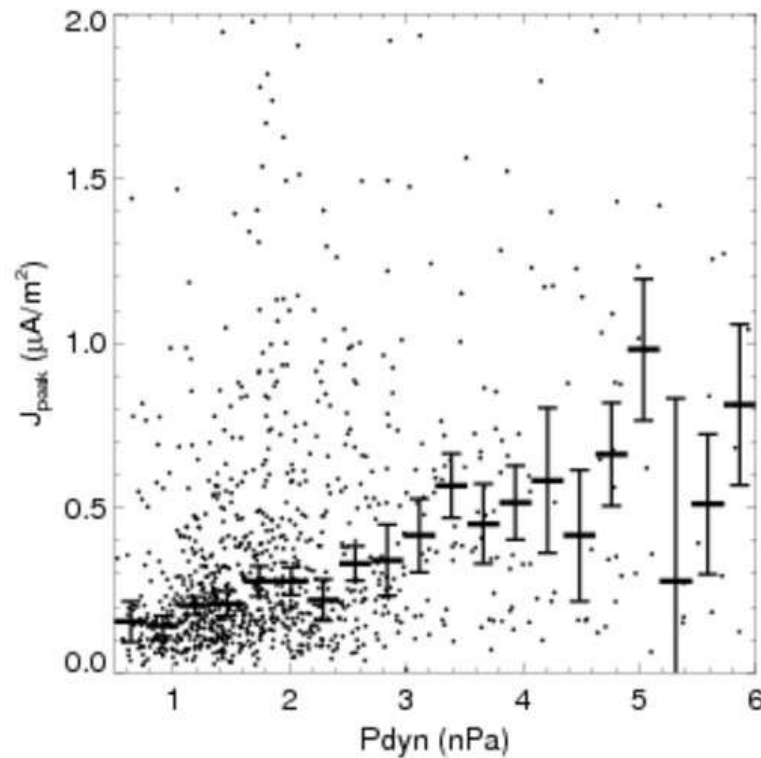
# FAC $J_{\text{peak}}$ dependence on IMF angles

- We see clear  $J_{\text{peak}}$  bump between  $90^\circ$  and  $270^\circ$  IMF clock angle (Sbz).  $J_{\text{peak}}$  is flat beyond this range (NBz).
- There is clear  $J_{\text{peak}}$  bump for negative IMF tilt angle (SBz).  $J_{\text{peak}}$  is flat when the tilt angle is positive (NBz).
- We see no clear dependence of  $J_{\text{peak}}$  on IMF spiral and cone angles.



# FAC $J_{\text{peak}}$ dependence on solar wind conditions

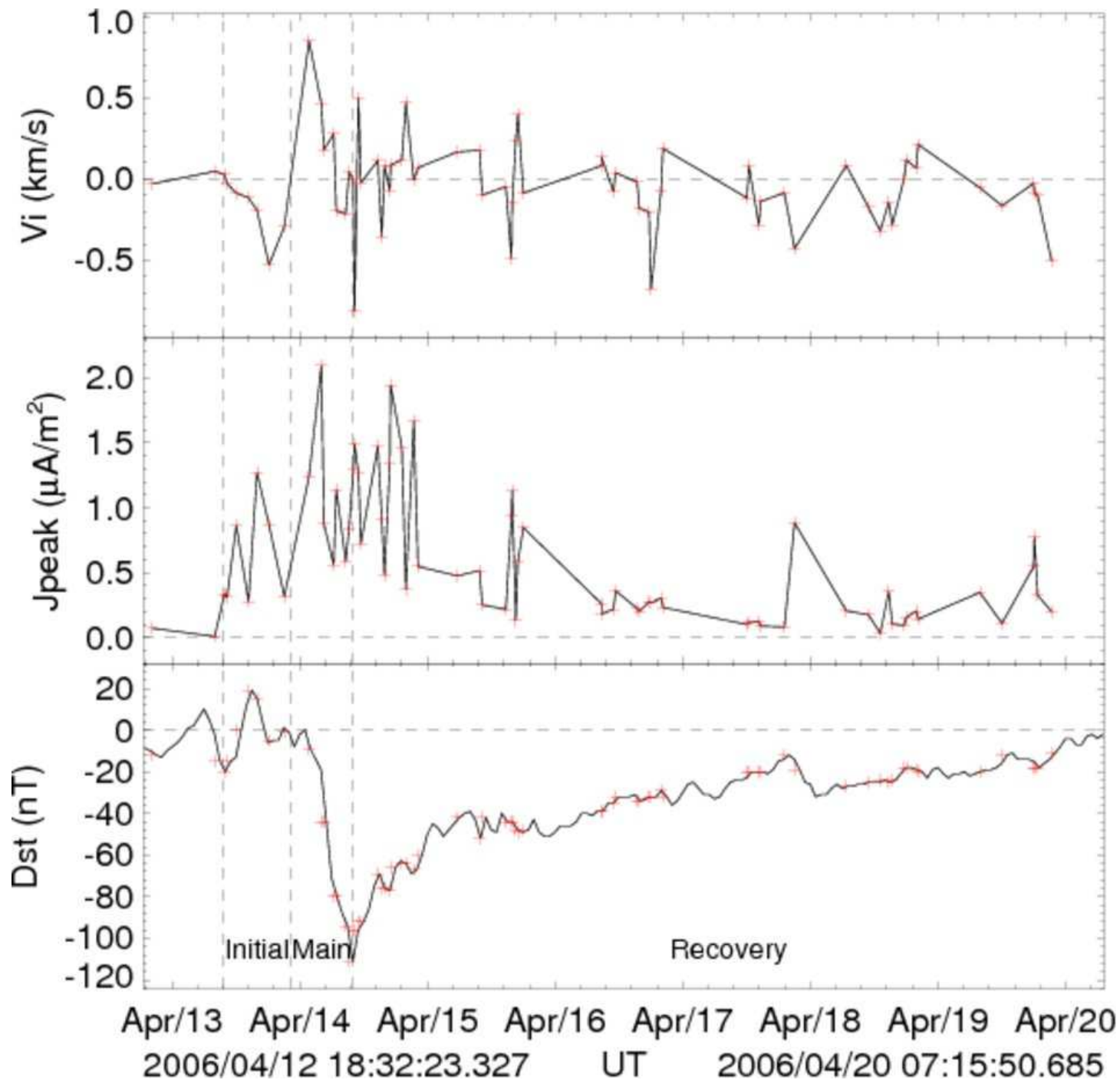
- We see clearly enhanced  $J_{\text{peak}}$  with increasing solar wind dynamic pressure.
- $J_{\text{peak}}$  is more or less flat when  $E_y$  is negative, and it increases with  $E_y$  when  $E_y$  is positive.
- We see no clear dependence of  $J_{\text{peak}}$  on solar wind Beta and  $M_A$ .





## FAC speed and peak current density during magnetic storm

- The right panels show the FAC ionospheric footprint speed and ST-5 peak current density during 12-20 April 2006 geomagnetic storm.
- During the storm initial phase, we see clear FAC poleward motion.
- During the storm main phase, we see strong FAC equatorward motion.
- During the storm recovery phase, we see FAC motion in both directions.
- There is significantly enhanced peak current density during the storm initial and main phases, as well as the earlier part of the recovery phase.



## Summary and Conclusions

- We surveyed FAC observations from the whole ST-5 mission and found **2535** FAC signatures. **1030** are used with qualifying speed calculations after six filtering criteria to ensure the quality of the statistics.
- FACs are found to move generally faster during high geomagnetic activities than low geomagnetic activities with non-negligible exceptions.
- FAC speed can become more comparable to spacecraft speed across the current sheet with increasing altitude. As a result, the errors for FAC thickness and current density calculations can be significant if stationary FACs are assumed at mid- and high-altitudes.
- We find no dependence of FAC speed on IMF and solar wind conditions. We get much stronger dependence of FAC peak current density on some IMF and solar wind conditions.
- A case study of FAC speed and peak current density during a moderate geomagnetic storm shows unique pattern of FAC motion: First poleward motion, then equatorward motion, and finally motion in both directions.