# Improving our understanding of the ionosphere by using Swarm mission as a constellation

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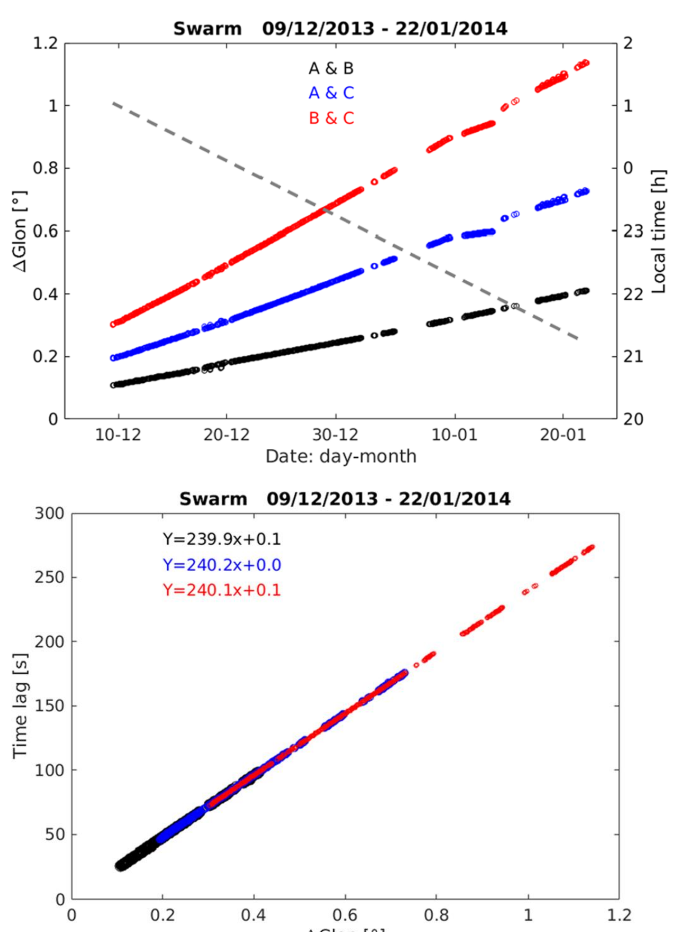
ESA' Swarm mission, consisting of three satellites, provides unique opportunities to improve our understanding of the ionospheric structures that cannot be achieved by single-satellite missions. In this study, we provide an overview of our recent work focusing on the ionospheric structures, based on observations of Swarm from the constellation perspective.

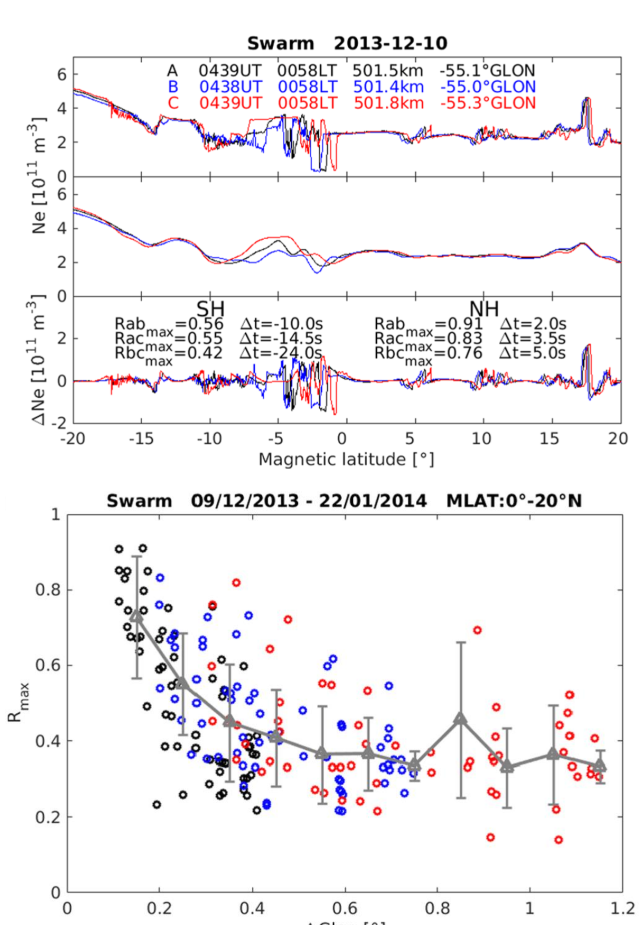
## I: String of pearls formation

During the initial mission phase, when three satellites fly in a configuration as a string of pearls, is very useful to investigate the small-scale structures of equatorial plasma irregularities (EPIs) as well as the small-scale field-aligned currents (FACs) at auroral latitudes:

### Constellation formation

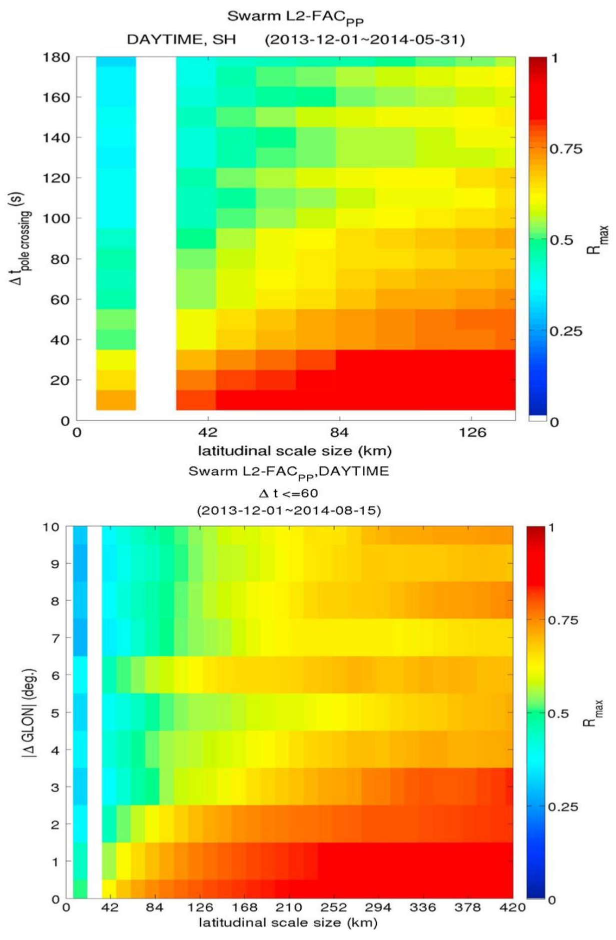


### Small-scale EPIs



[Xiong et al., 2016a]

### Small-scale FACs



[Lühr et al., 2014]

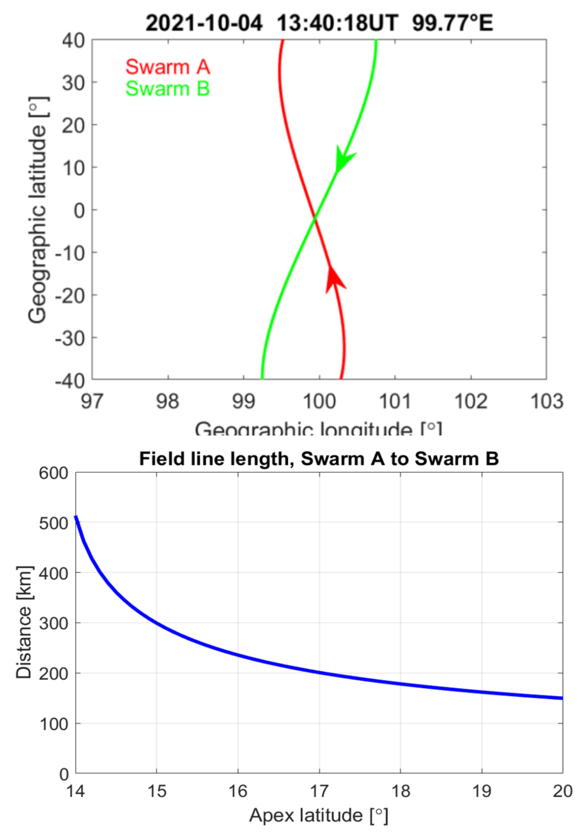
Cross-correlation has been performed of the plasma density and FACs between Swarm three satellites, we found:

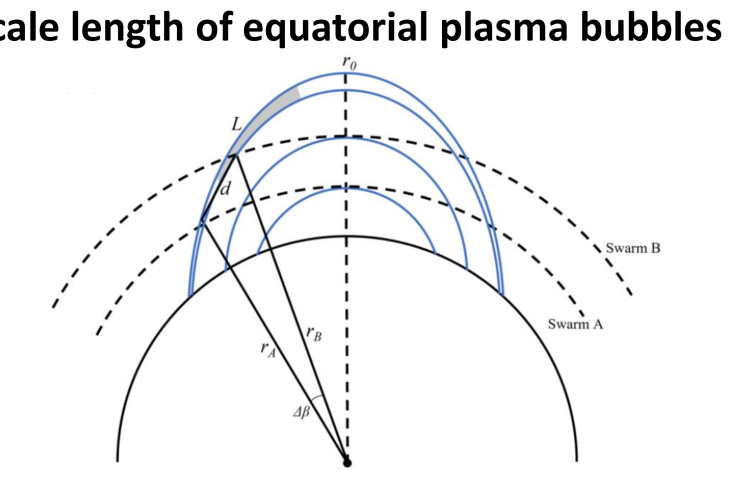
- When the longitudinal separation between Swarm satellites larger than 0.4°, no significant correlation was found any more. This result suggests that EPI structures include plasma density scale sizes less than 44 km in the zonal direction.
- A persistent period of small-scale FACs of order 10 s, while large-scale FACs can be regarded stationary for more than 60 s. Large-scale FACs are different on dayside and nightside. On the nightside the longitudinal extension is on average 4 times the latitudinal width, while on the dayside, particularly in the cusp region, latitudinal and longitudinal scales are comparable.

## III: Counter-rotation formation

The counter-rotation period between Swarm A/C and B, provides also good opportunity to investigate the field-aligned scale length of post-sunset equatorial plasma bubbles (EPBs), as well as the propagation of upstream waves at ionospheric altitude.

### Scale length of equatorial plasma bubbles





| | Apex latitude of fluxtube | | | | |
|---|---|---|---|---|---|
| | 18° | 17° | 16° | 15° | 14° |
| Swarm A | 2 | 2 | 4 | 5 | 5 |
| Swarm B | 0 | 0 | 1 | 5 | 5 |
| Swarm A + B | 4 | 5 | 8 | 7 | 11 |
| Sum | 6 | 7 | 13 | 17 | 21 |
| $p$ | 0.67 | 0.71 | 0.62 | 0.41 | 0.52 |
| $a$ | 3.0 | 3.45 | 2.6 | 1.7 | 2.1 |
| $d$ (km) | 170 | 190 | 223 | 283 | 485 |
| $L$ (km) | 510 | 655 | 579 | 481 | 1018 |

$$d^2 = r_A^2 + r_B^2 - 2\, r_A r_B \cos(\Delta \beta)$$

$$\cos^2(\beta_A) = \frac{r_A}{r_{\mathrm{Ion}}} \cos^2(\beta_{\mathrm{Ion}})$$

$$\cos^2(\beta_B) = \frac{r_B}{r_{\mathrm{Ion}}} \cos^2(\beta_{\mathrm{Ion}})$$

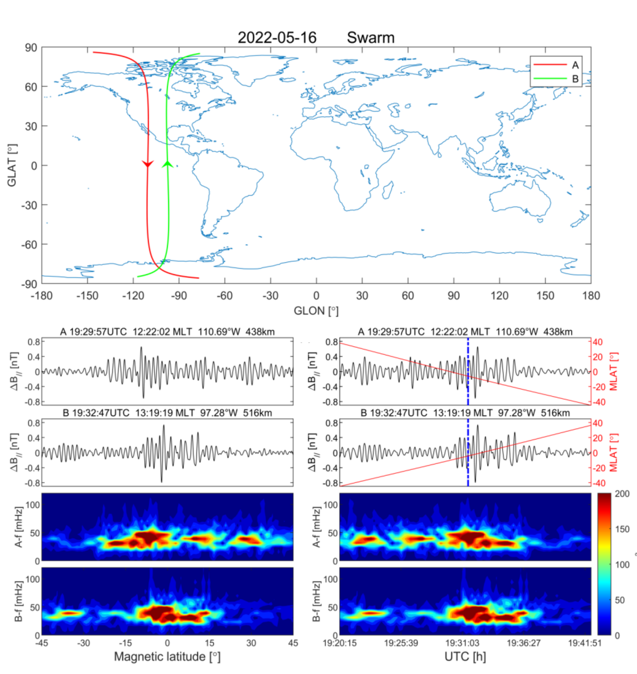
$$p = \frac{N_{\mathrm{double}}}{N_{\mathrm{single}} + N_{\mathrm{double}}} = \frac{(a-1)}{a}$$

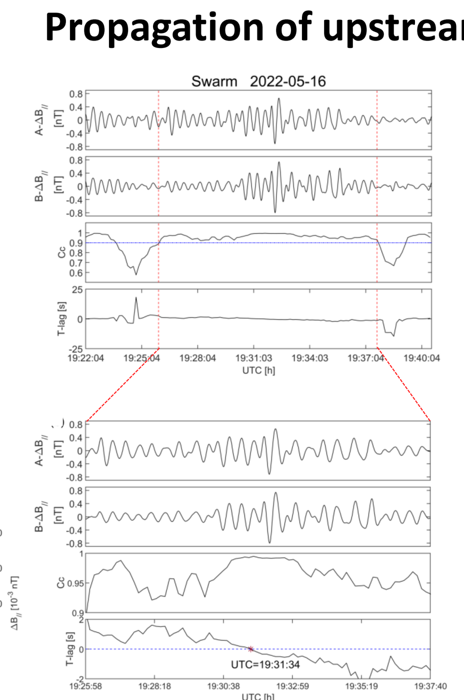
$$a = \left(1 - \frac{N_{\mathrm{double}}}{N_{\mathrm{single}} + N_{\mathrm{double}}}\right)^{-1}$$

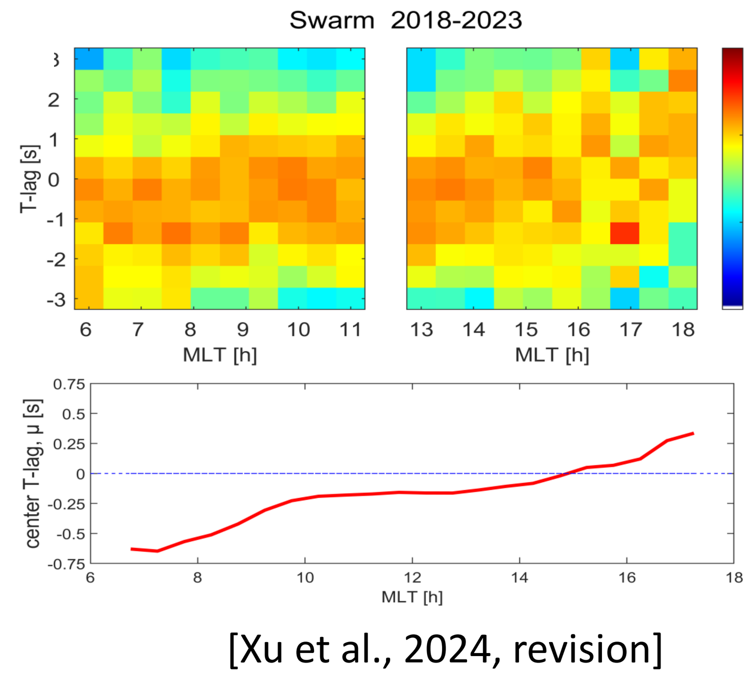
$$a = \frac{L}{d}$$

[Xiong and Lühr, 2023]

### Propagation of upstream waves





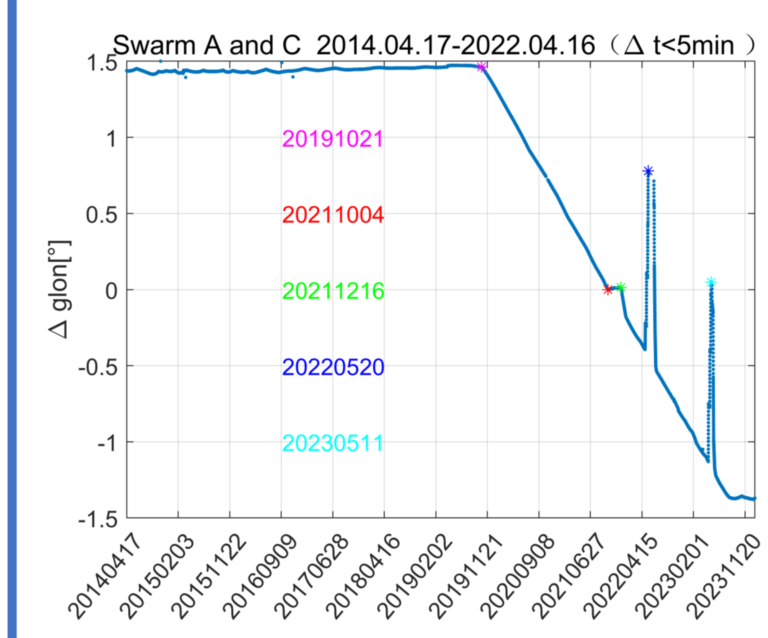


[Xu et al., 2024, revision]

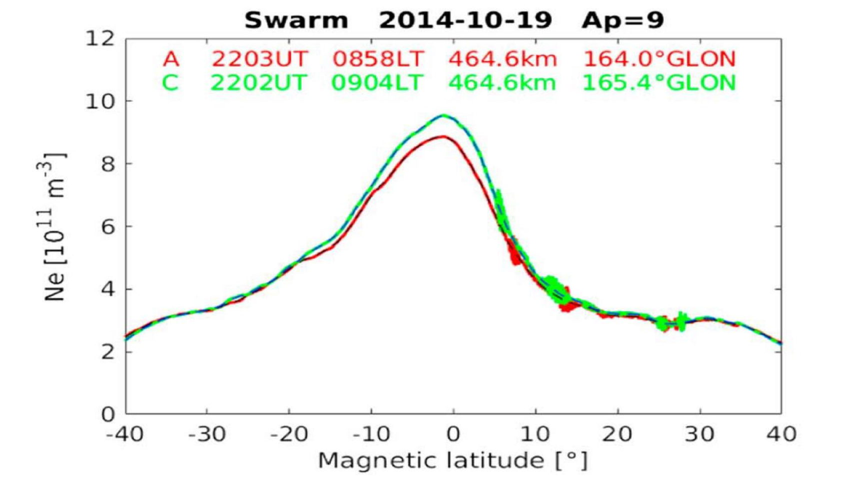
## II: Side-by-side flying formation

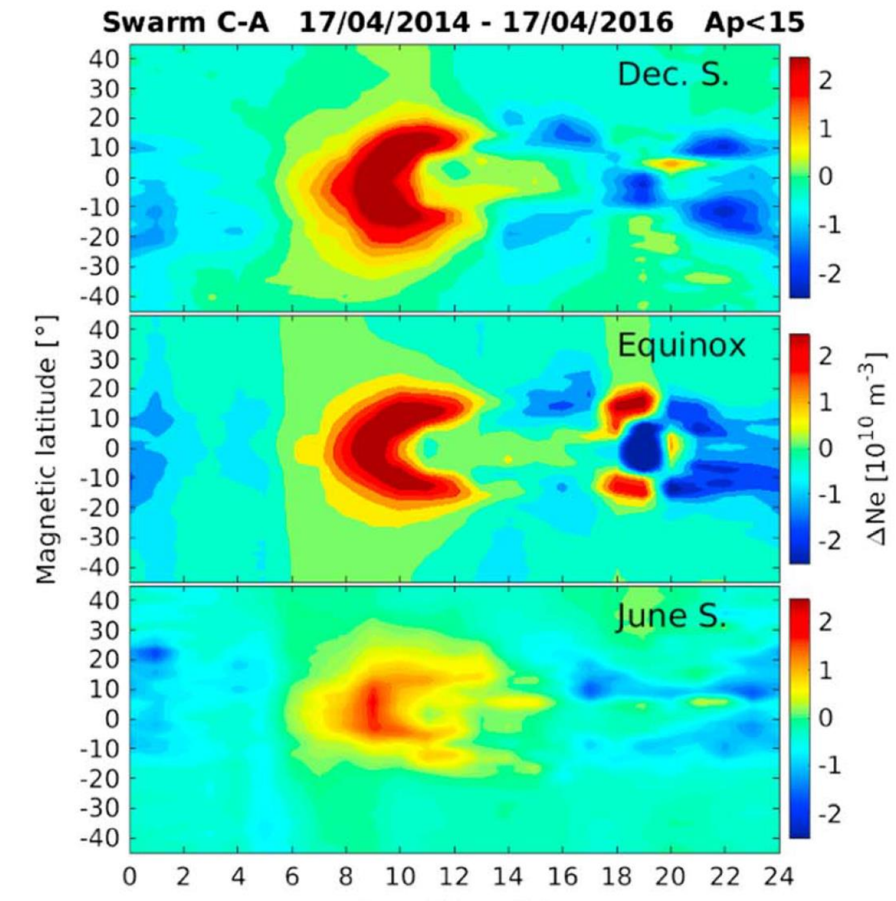
The lower-pair flying Swarm A and C, with a longitudinal separation of 1.4°, can well reflect the longitudinal (or local time) gradient of large-scale ionospheric structures, e.g., the equatorial ionization anomaly (EIA), equatorial electrojet (EEJ). In addition, the constellation provides an unique opportunity to check the assumptions and reliability of field-aligned currents calculation based on the single- and dual-satellite approaches.

### Constellation formation



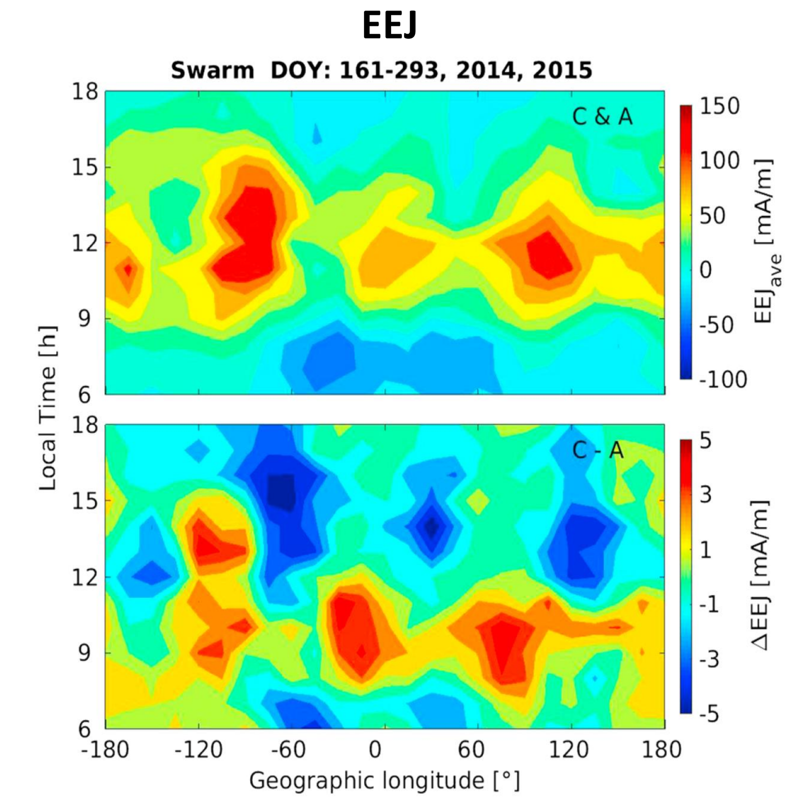
### EIA





[Xiong et al., 2016b]

### EEJ

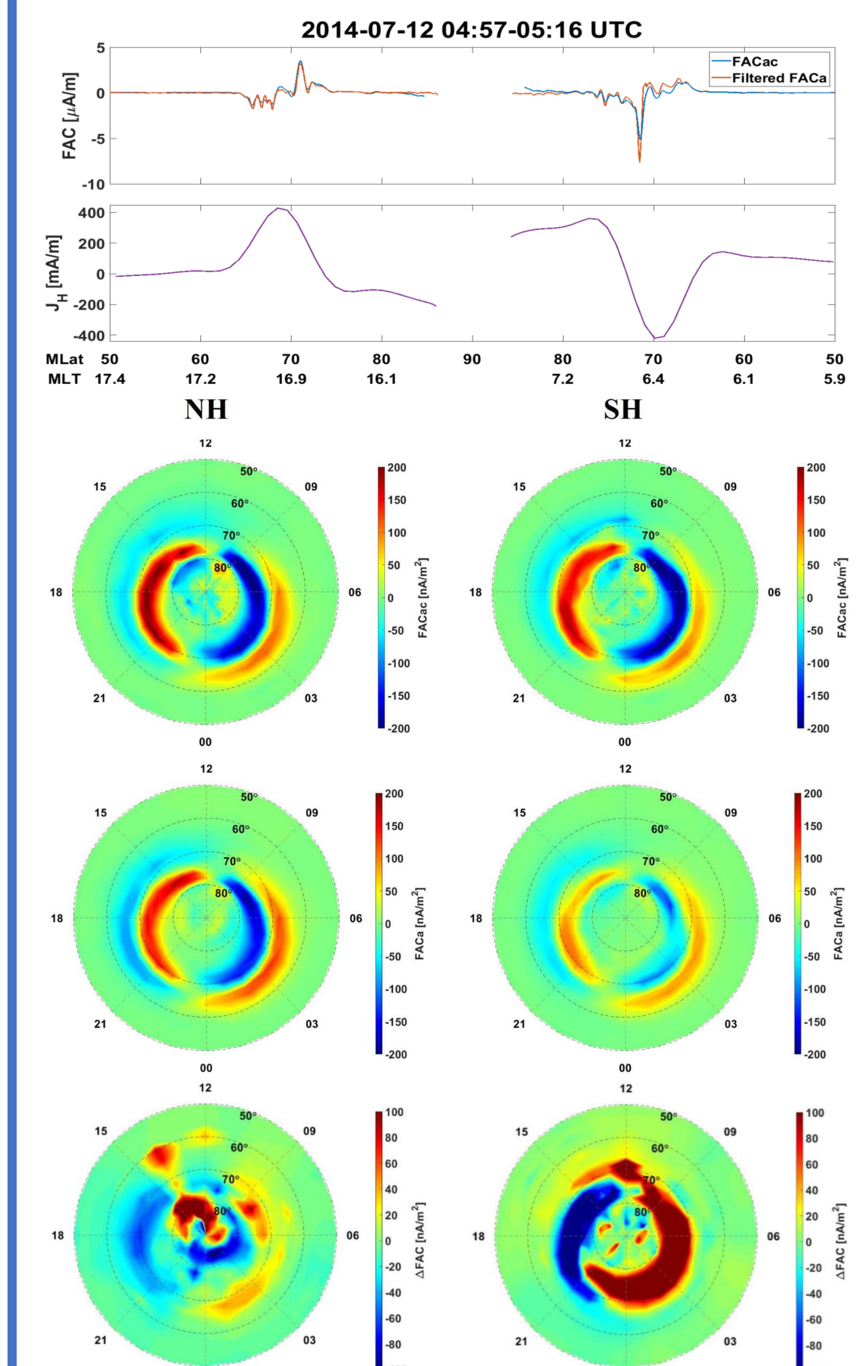


[Zhou et al., 2016]

By checking the systematic dependence of gradient between Swarm A and C, we found:

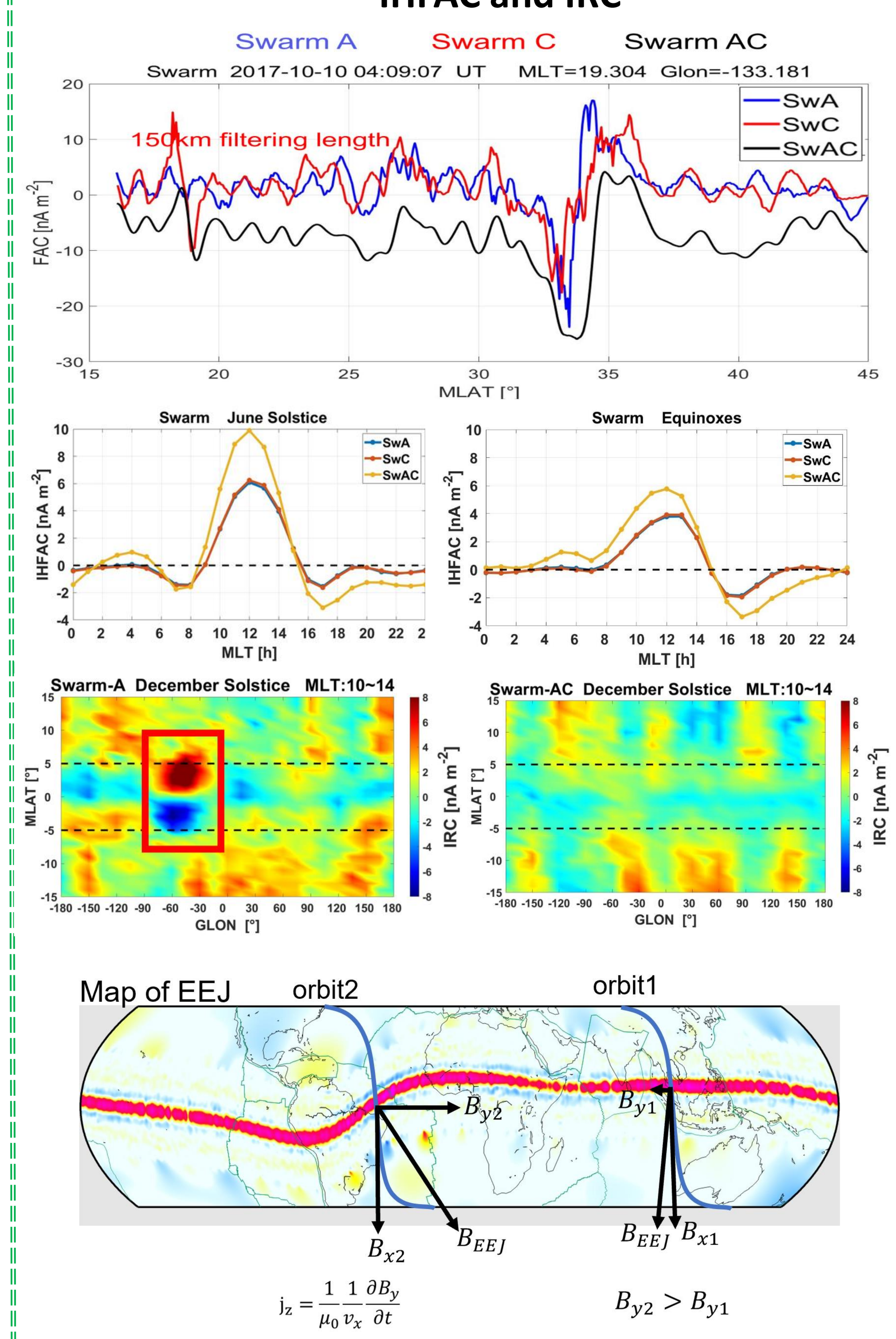
- At equinox months a fast decrease of the F region electron density is seen at the EIA trough region during the prereversal enhancement, while an increase is found meanwhile at crest regions. Afterward, a fast decrease of the EIA crest electron density occurs between 19:00 and 23:00 LT, with seasonal dependence.
- The ΔEEJ, which can be considered as a high-pass filtered result of EEJ, although having much smaller values than the EEJ, exhibits clearly the local time gradient of the EEJ diurnal variation. This kind of high-pass filtering makes the tidal signatures in ΔEEJ more prominent.

### Auroral FACs



[Xiong et al., 2023]

### IHFAC and IRC



[Wang et al., 2022; 2023]

- FACs calculated from Swarm dual-satellite are not affected by the far-field currents, e.g., the horizontal polar electrojet (PEJ). Our results reveal that the conventionally used FACs calculated with single-satellite approach underestimate the FACs' intensity.
- IHFAC derived from both approaches agree qualitatively, but the amplitudes of single-spacecraft results reach only about 70% of those from the dual-satellite.
- the radial current from single-satellite approach is contaminated by EEJ at American sectors due to large magnetic declination in this region.

## References:

1. Xiong et al. (2016a), doi.org/10.1186/s40623-016-0502-5;
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3. Xiong et al. (2016b), doi:10.1002/2016JA023034;
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