Science & Technology Facilities Council

Multi-scale magnetospheric and ground currents from Swarm, Cluster and MMS

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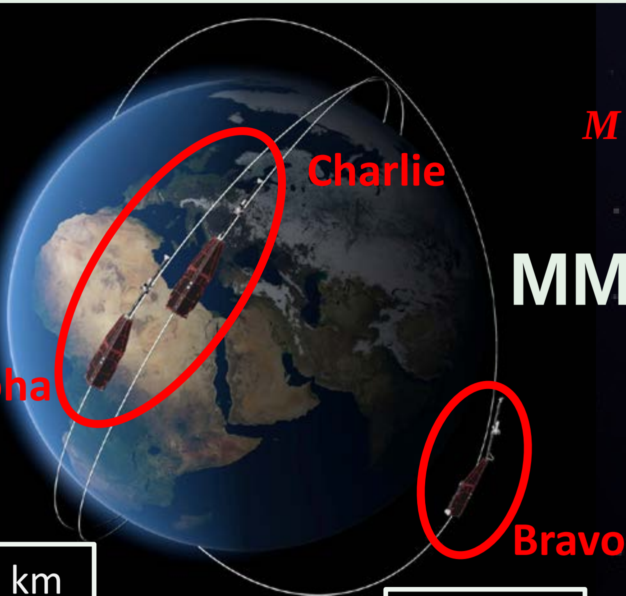
MMS - Cluster - Swarm - SuperMAG



~460 km

~510 km

A-C pair ~150 km.

B relative drifting LT.

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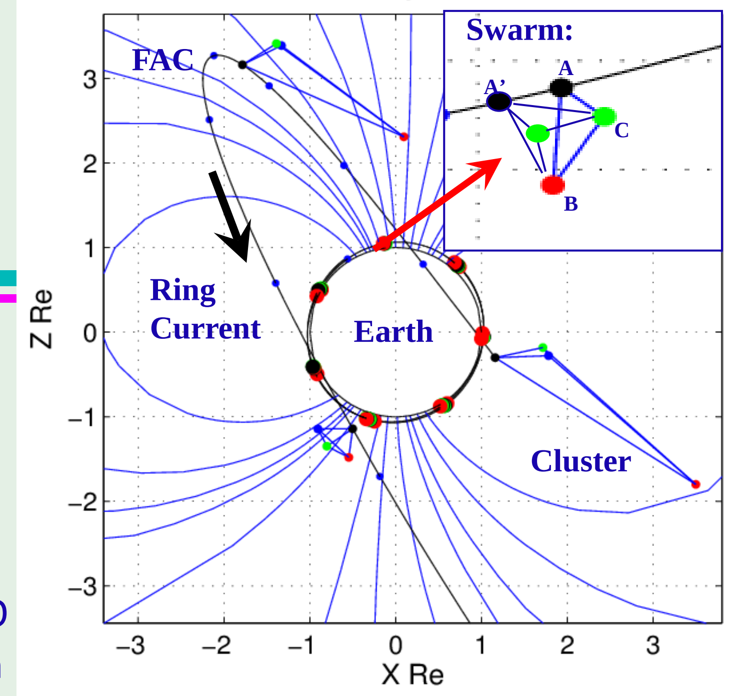
esa

Earlier coordinated event studies:

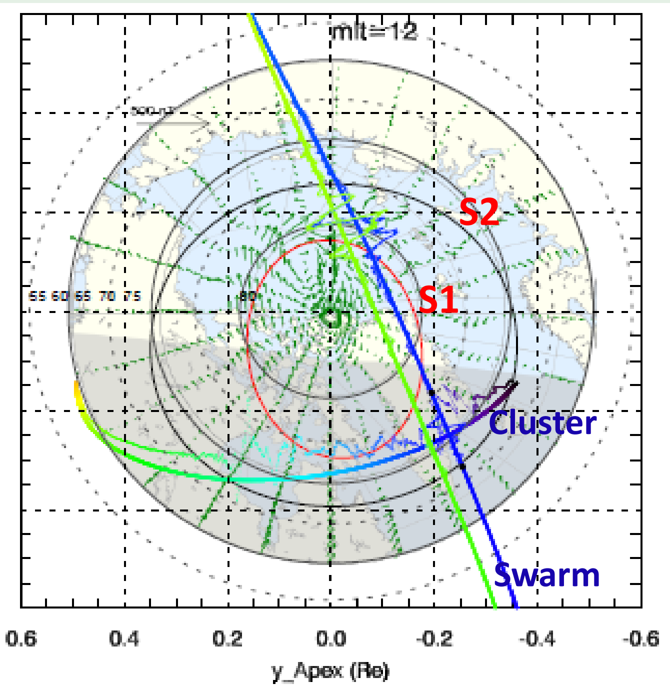
Example of FAC scaling: configurations (right, enlarged) and magnetic tracks below show conjunction of 7 spacecraft.

Dunlop, et al. (2019), ISSI, DOI:10.1007/978-3-030-26732-2_5



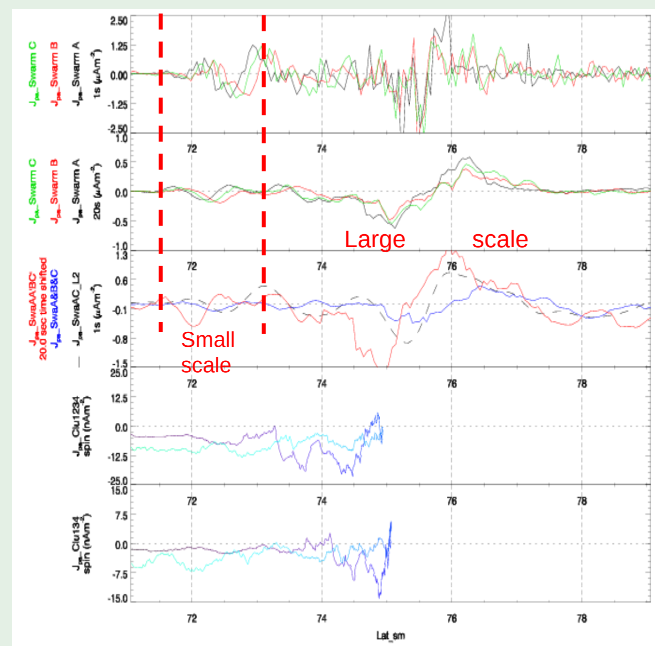
Scaled Cluster FACs show similar signatures to those for AMPERE model currents (mapped along orbit track)

Dunlop, et al. (2015), Geophys. Res. Letts., doi:10.1002/2015GL063738



Demonstrated common signatures can occur at LEO and MEO altitudes through adaptive use of multi-spacecraft analysis (curlometer technique: allows direct measure of field-aligned currents (FACs) at high and low orbits)

Right: Current estimates at Swarm and Cluster.



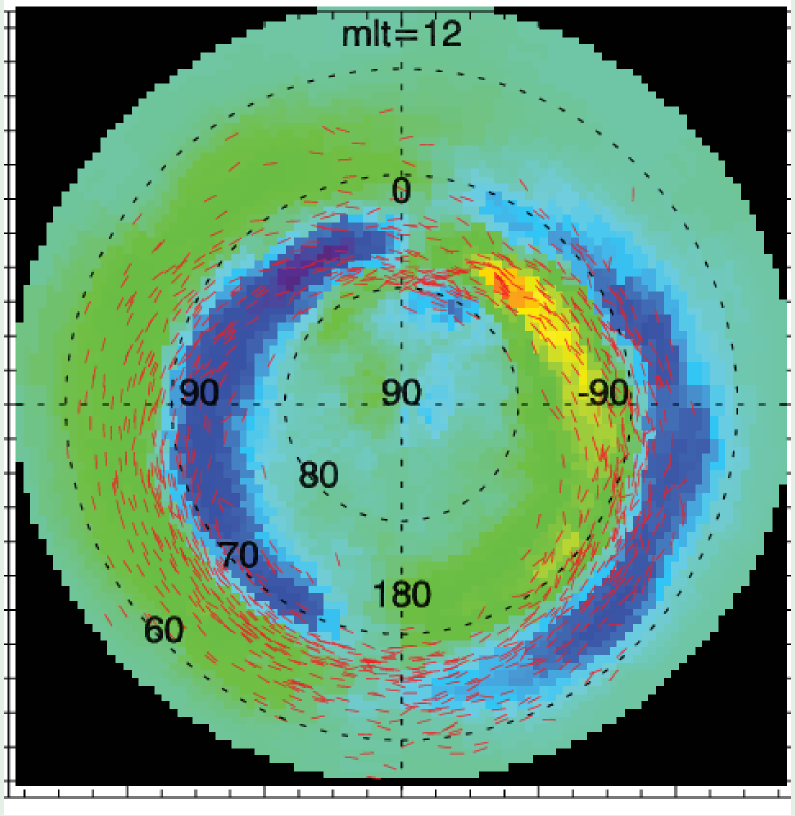
Swarm currents echoed in 4-spacecraft Cluster data: **coherent structures exist at vastly different altitudes**

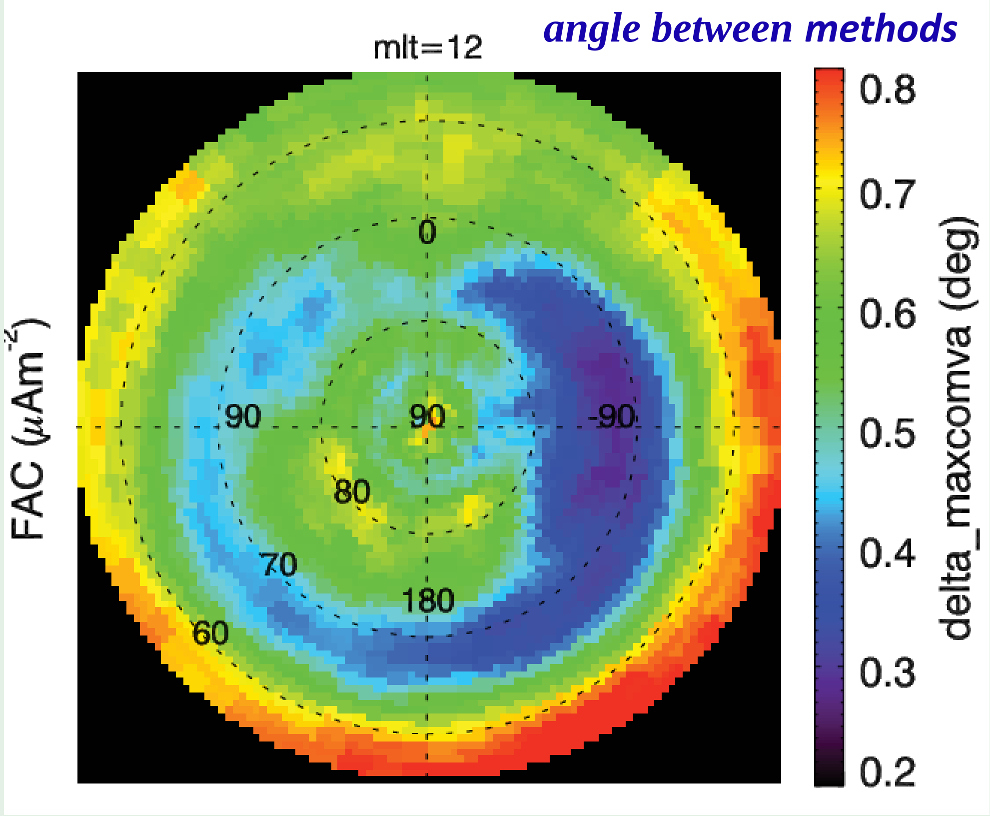
ESA Highlight:
http://sci.esa.int/cluster/56098-seven-esa-satellites-team-up-to-explore-earths-magnetic-field/

Swarm FAC cross-correlation study: current sheet alignments

- **Orientations from connecting line** between sliding interval mid-points on A-C orbits (at positions of maximum correlation) *[Yang, Dunlop, et al., J. Geophys. Res. 2018]*
- Highest (large-scale) ordering on dusk-side R2; higher variability in R1 (quiet time climatology)

- Expect **smaller-scale variations** for high (storm) activity: prevailing conditions also pass by pass.
- Correlation values as a function of MLT can also be obtained
- Comparison of current sheet orientations to **maximum variance directions** (MVAB)

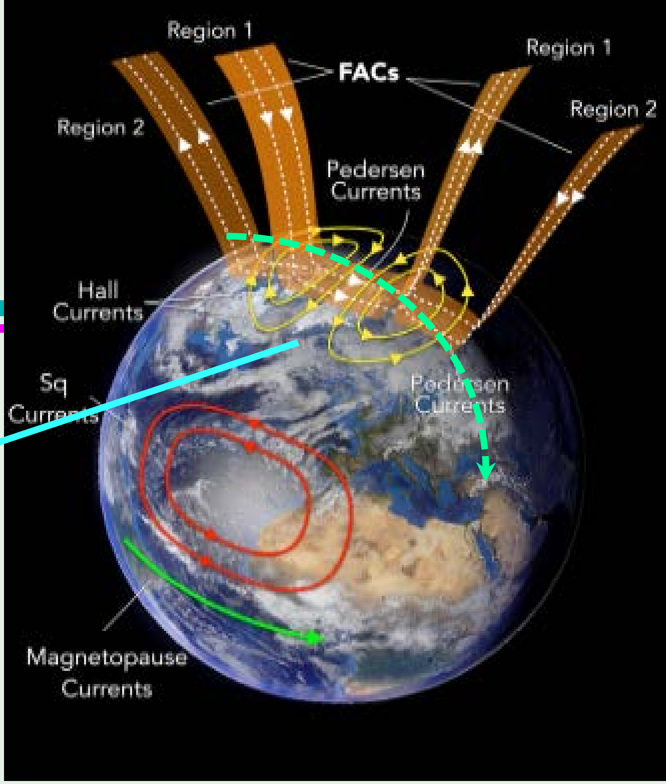




Maps can be aligned w.r.t. auroral boundaries from max FAC intensity gradient (Xiong et al.) – see later.

Determination of auroral boundaries:

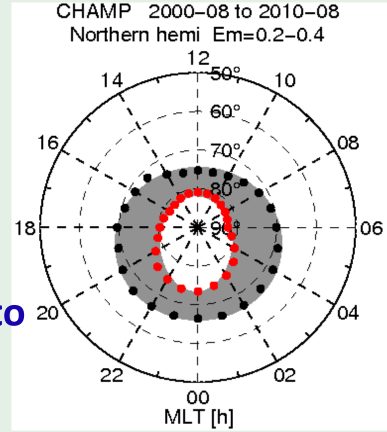
Based on positions of maximum-gradient of FAC intensity: defined as S1 and S2 for Region 1 and Region 2 zones (after *Xiong et al., 2014a,b*)



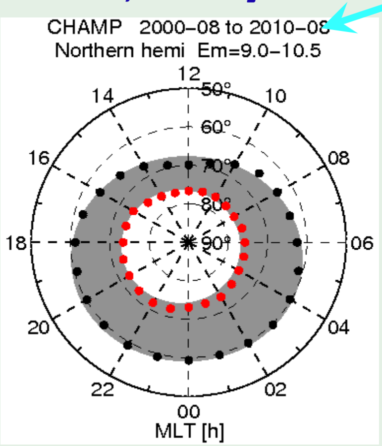
Semi-empirical boundaries: elliptical shape parametrized by solar wind merging electric field (E_m) *[Newell et al, 2007]*

Elliptical fit:
(x_0, y_0); φ_0
$Semi_x$; $Semi_y$

$$E_m' = \frac{1}{3000} V_{SW}^{\frac{4}{3}} \left(\sqrt{B_y^2 + B_z^2} \right)^{\frac{2}{3}} \sin^{\frac{8}{3}} \left(\frac{\theta}{2} \right)$$



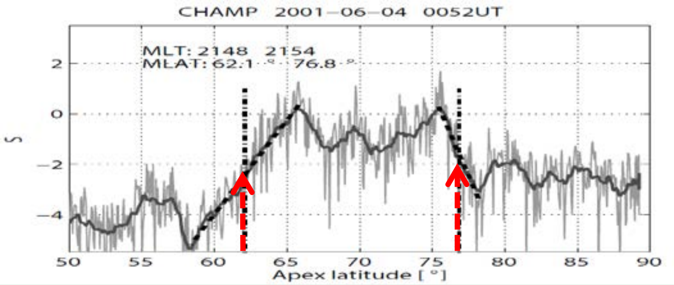
Low Activity

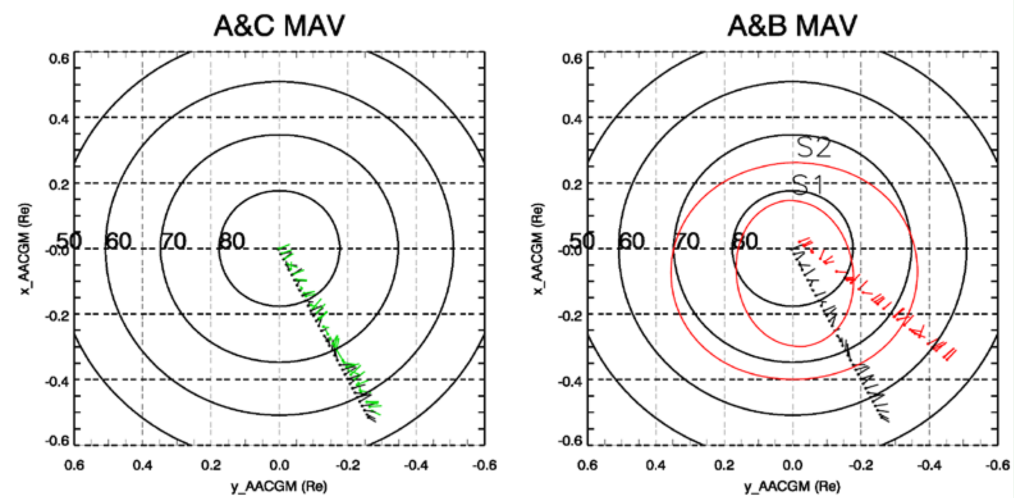


High activity

Model can be compared to actual positions of S1, S2 pass by pass along orbit

Possibility of NRT values based on *Em* and corresponding Swarm FAC's





Combine with **current sheet orientations**; plot relative to (sub-) **auroral S1/S2** boundaries (with choice of time filtering)

Coordinated events (Cluster-Swarm-SuperMAG): GICs

Mapped positions of Cluster and Swarm onto locations of SuperMAG stations

Provide a close conjunction (in location and timing)

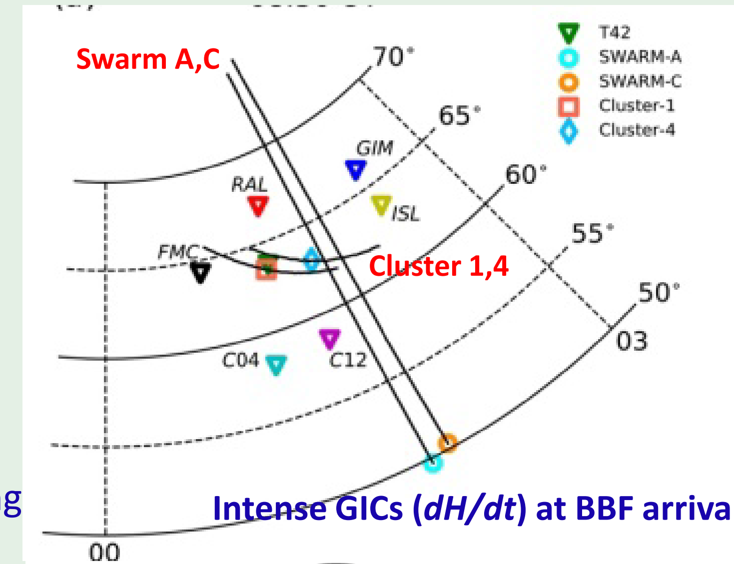
[*Wei et al. 2021, Geophys. Res. Letts, doi:10.1029/2020GL091781*]

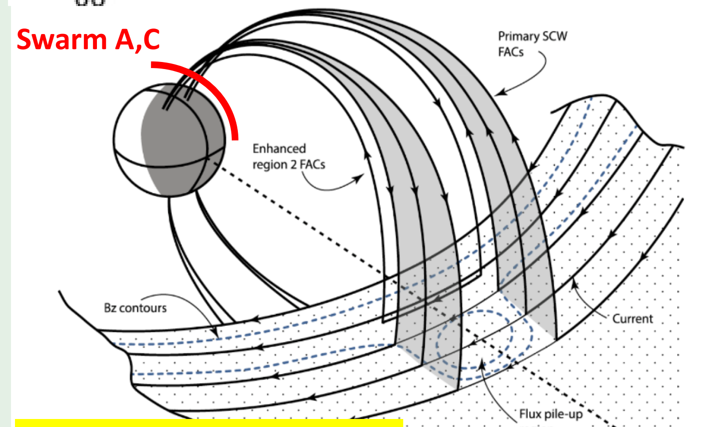
Cluster (L~6) sees arrival of a sub-storm driven BBF which drives electric currents (also seen at Swarm) into the ionosphere

- Cluster and Swarm both see the onset of a similar up/down structure of field aligned currents, consistent with a (modified) sub-storm current wedge structure – *Kepko et al 2015*

Intense (associated) dH/dt variations seen by surrounding ground stations, driven through the FAC system

- SuperMAG ground stations see onset of GICs (*dH/dt*) developing across Swarm/Cluster footprints where signal is largest
- Suggests the presence of a field-aligned current sheet in the centre of the group of stations
- We expect the induced ground response is indirect via Hall and Pederson currents driven by the FAC- electrojet system
- *SFAC (ΔB)- AE&PEJ(SECS, line currents) – ΔH&dH/dt*





Kepko et al., SSR 2015

ESA Highlight:

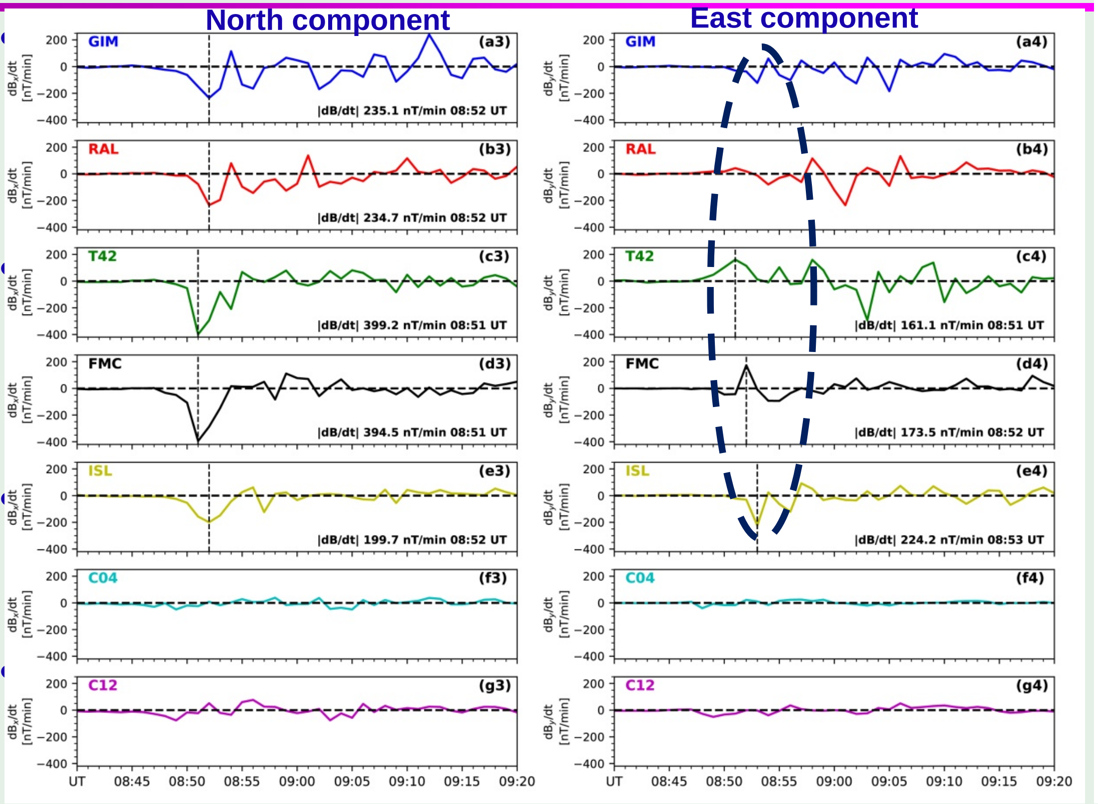
https://www.esa.int/Applications/Observing_the_Earth/Swarm/Swarm_and_Cluster_get_to_the_bottom_of_geomagnetic_storms

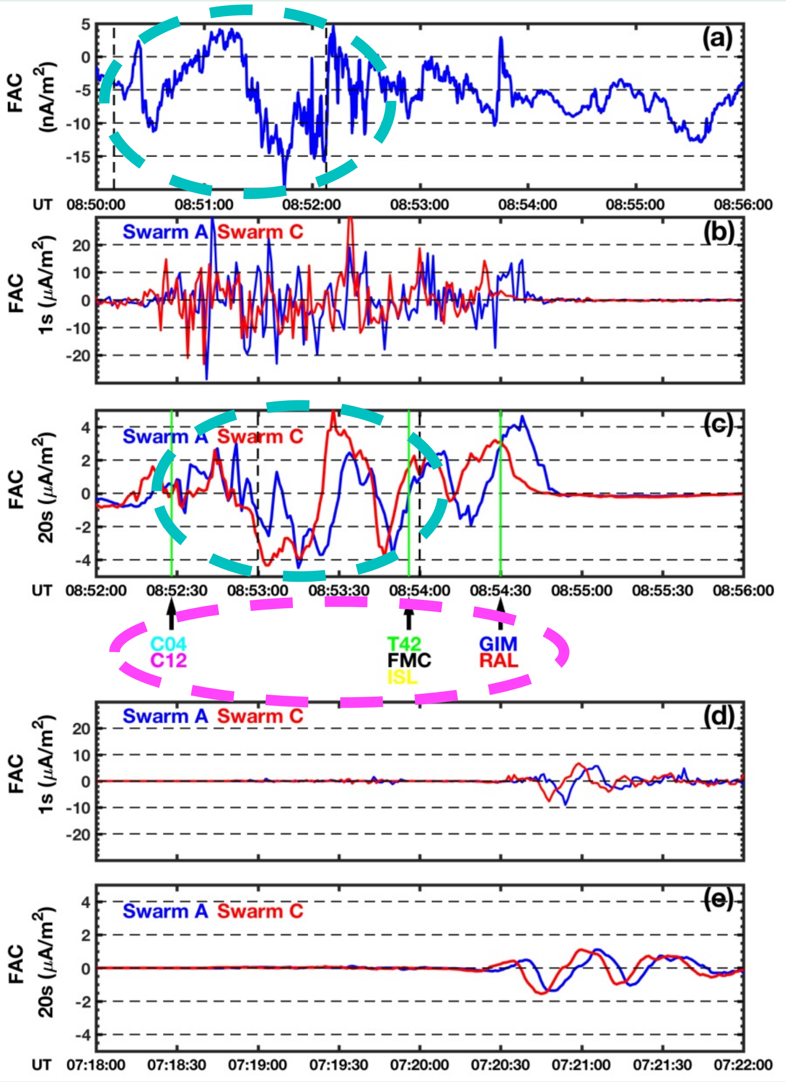
[Also consistent with the *Engebetsen et al.* interpretation of magnetic connections and recent analysis by *Nishimura et al.*]

FACs in the magnetosphere and ionosphere:

upward-downward-upward FACs at Cluster and Swarm, following the arrival of the BBF

Corresponding ground signatures: largest near Cluster



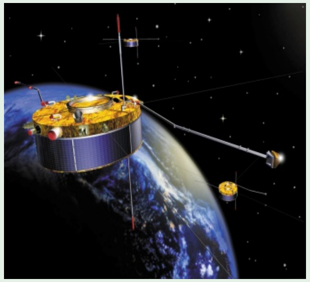


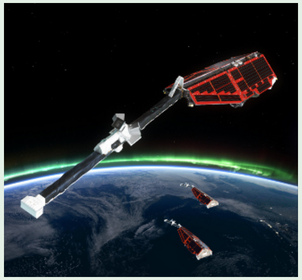
- **The Eastward component reverses across footprint locations** (e.g. from one side to the other of Swarm tracks)
- The orientation of the current sheet plays an important role in the evolution of the geomagnetic perturbation

Implication: FAC system is carried by the BBFs (e.g. at C4) and produces negative and positive eastward perturbations between GIM/ISL and T42/RAL/FMC ground stations

Extended coverage:

Core space observations: 2-Cluster, 2-Swarm, Seven SuperMAG ground stations





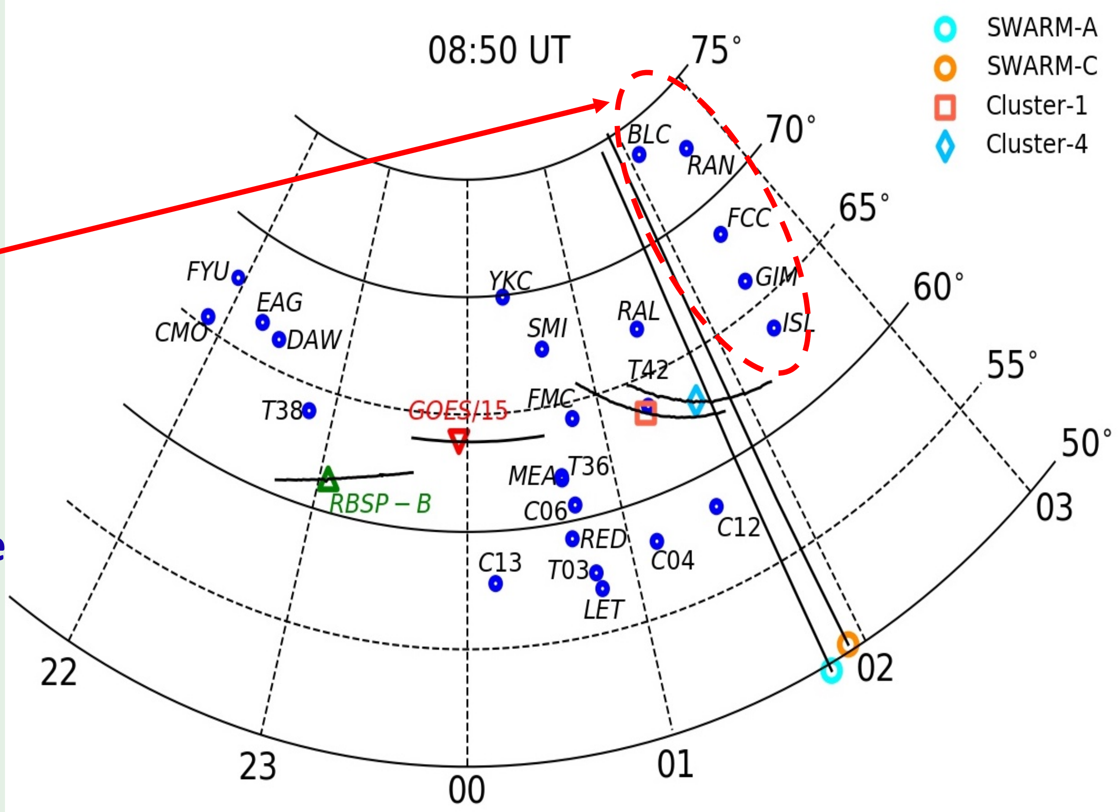
Additional spacecraft ground tracks are superimposed on a wide array of ground stations

Added locations: 24 ground stations; RBSP-B; GOES-15

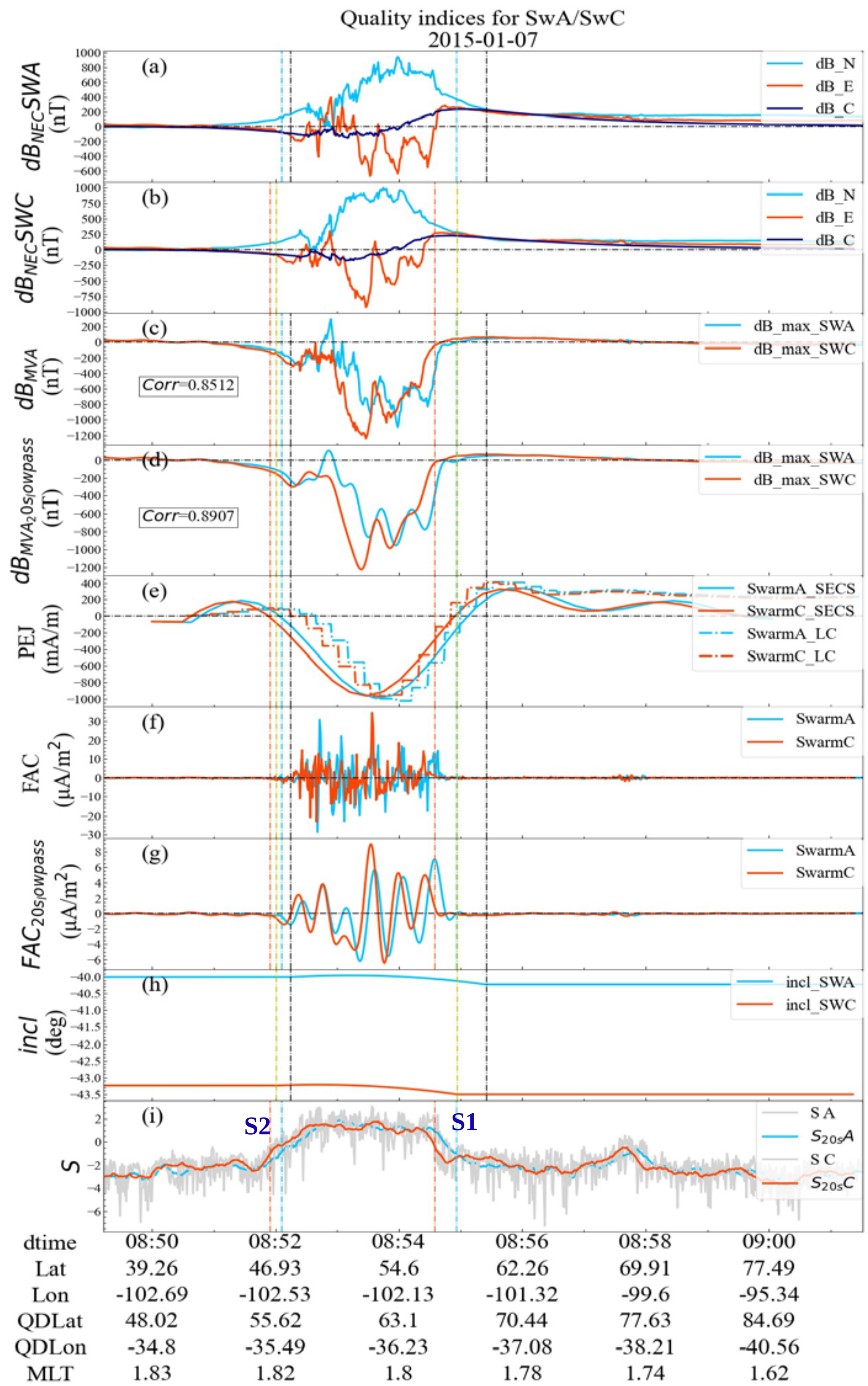
RBSP and GOES-15 also record arrival of dipolarisation fronts (BBF arrival @ L~6-7)

The wider array confirms the most intense ground *dH/dt* occurs near the MLAT of the Swarm/Cluster crossing carrying the FAC

Can select both latitude and local time chains from the added (GMAG) stations to probe structure of the current wedge (e.g. group around dashed oval)

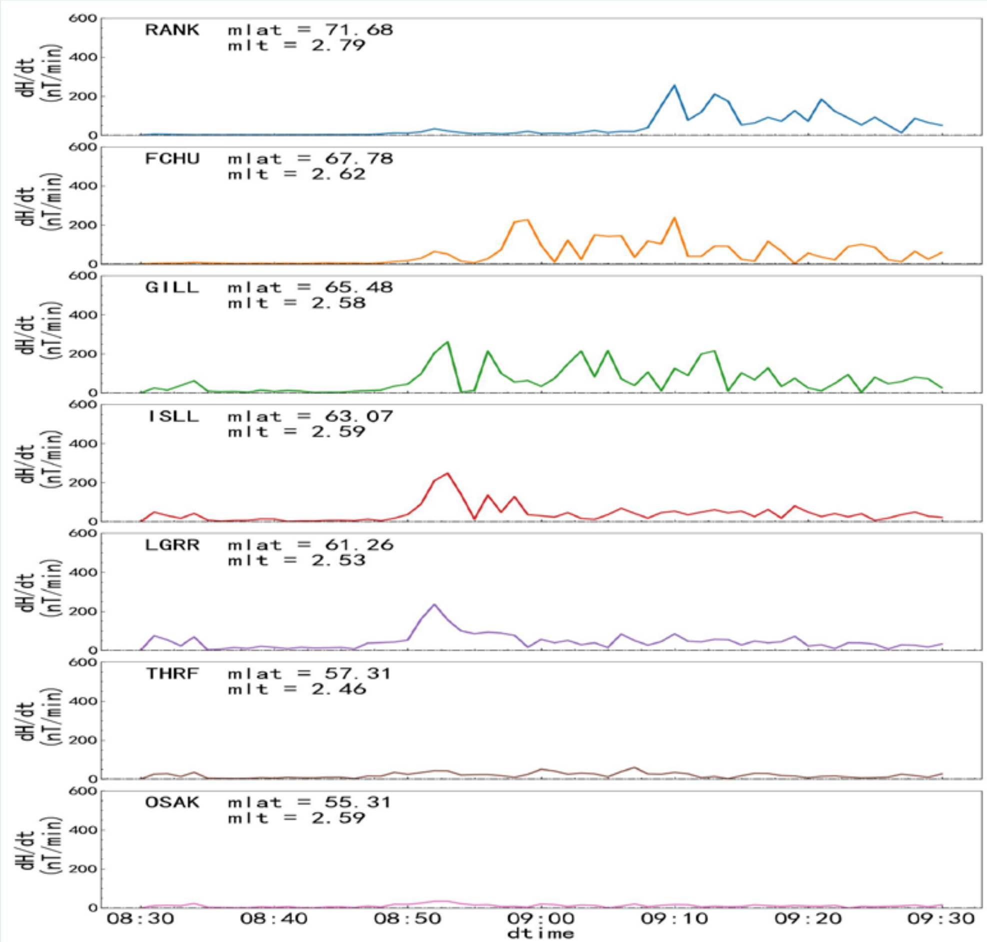


- **The *dH/dt* pattern, is localised to the FAC sheet**
- **Signatures correspond to the BBF arrival/location rather than global sub-storm development**



- Adding PEJ estimates shows peak in the centre of the FAC signatures
- S1/S2 boundaries (A,C) show that after Swarm exits through R1, the *dH/dt* peak becomes delayed (at higher latitudes)

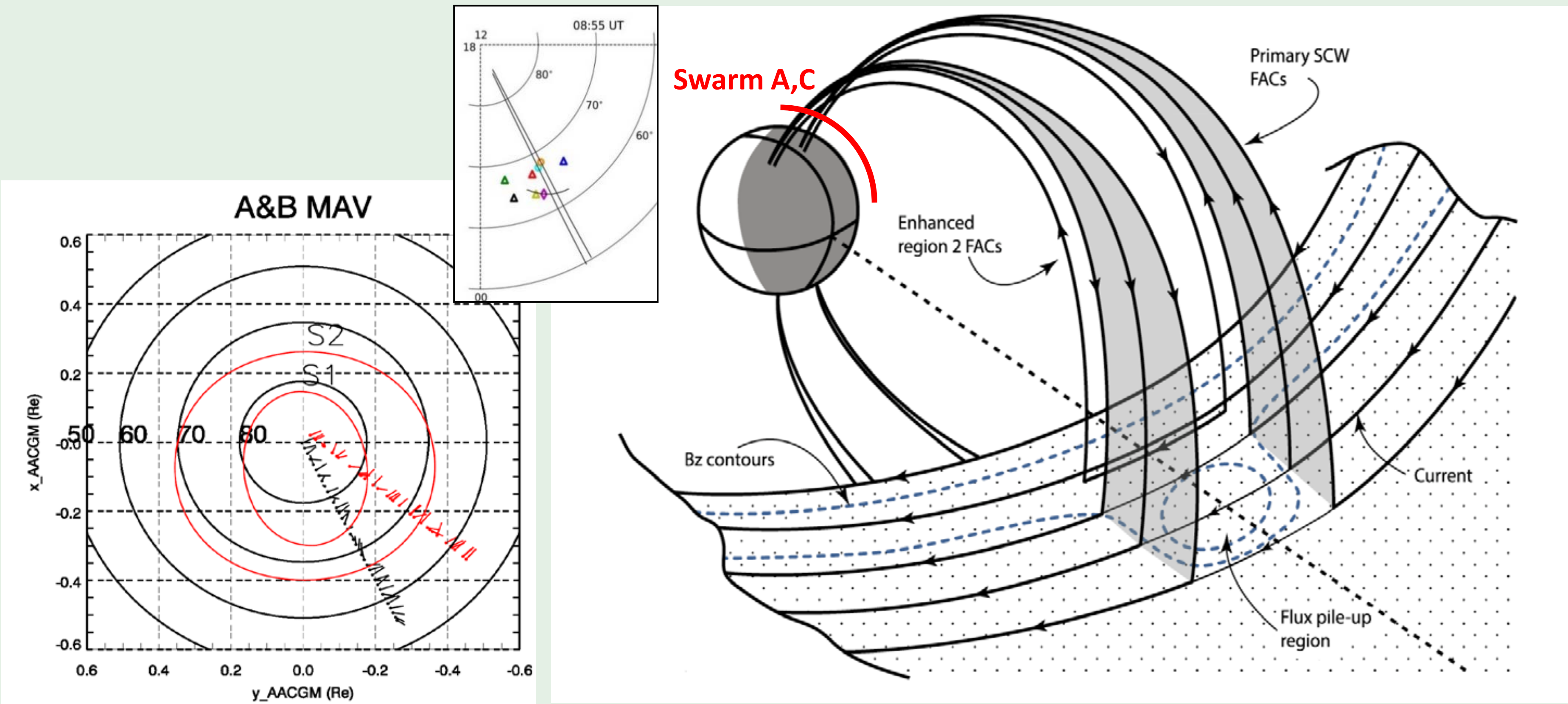
- Both the PEJ and GMAG chain appear to be consistent with the implied form of the modified SCW



Kepko et al., SSR 2015

Basic interpretation: Schematic picture of SCW

- Large-scale R1 sense FACs system during a sub-storm expansion phase
- Recently **updated to include a R2 sense FAC system; Earthward of the R1 FAC system**



Swarm current sheets (from cross-correlations) well matched to auroral S1 and S2 boundaries:

- Expect modifications during expansion
- Deviation of current sheets at S2 as Swarm flies across Cluster and through ground stations

Storm driven cusp signatures:

Simultaneous mesoscale polar cusp field-aligned currents showing vertical scaling and corresponding geomagnetic disturbance

Multiple pairs of opposite FACs in the cusp region are dominant currents system at the dayside during storm time which may caused by unsteady magnetic reconnection at the magnetopause

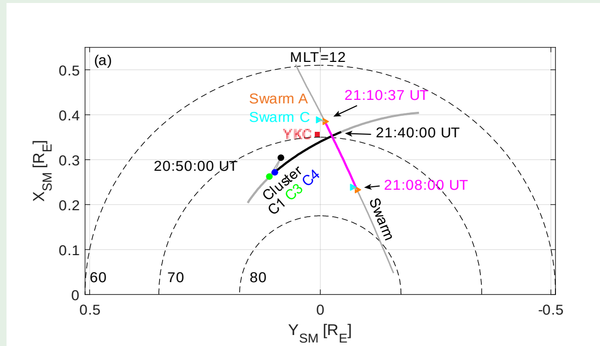
Multi-spacecraft Cluster and Swarm measurements reveal matched magnetic perturbations and FACs (two pairs of -+-+) at different altitudes simultaneously

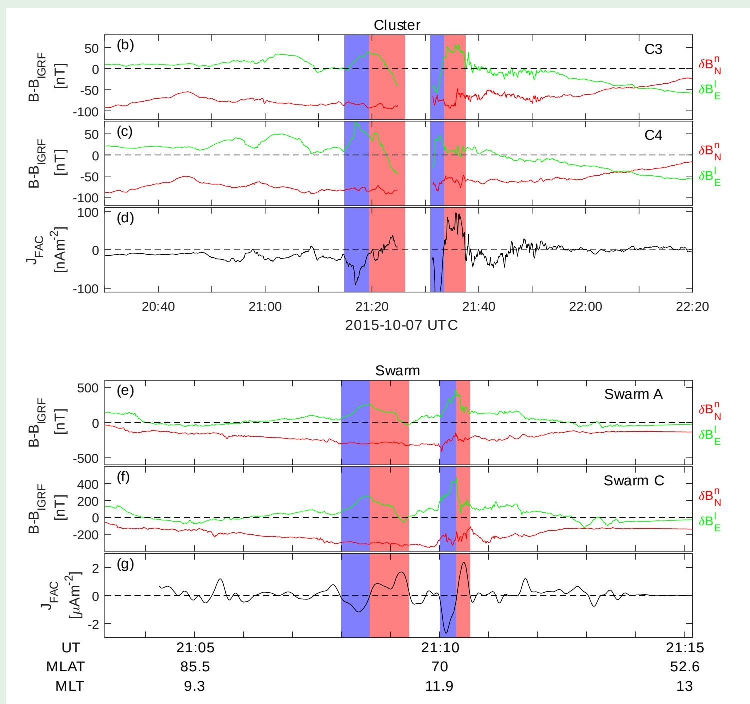
Direct evidence for detailed dayside FACs coupling between magnetosphere, ionosphere and ground

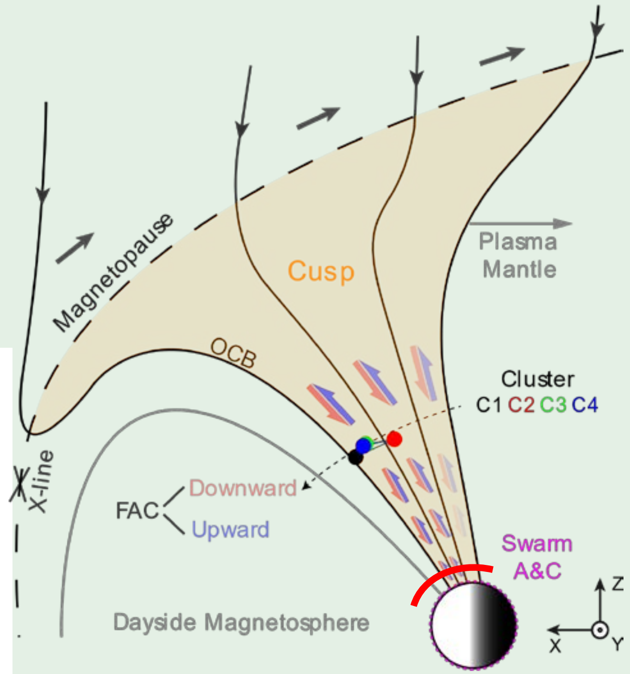
Note: Both dB and FAC show good agreement between Cluster and Swarm

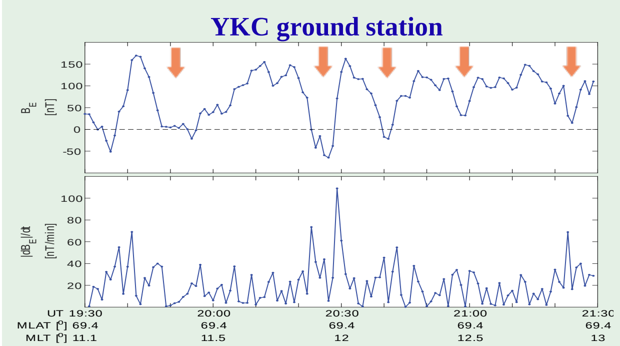
Nearest SuperMAG ground station shows corresponding disturbances

[Dong, X-C., et al. (2022), *Geophys, Res. Letts.*, doi: 10.1029/2022GL102460]









Ring current morphology from MMS observations:

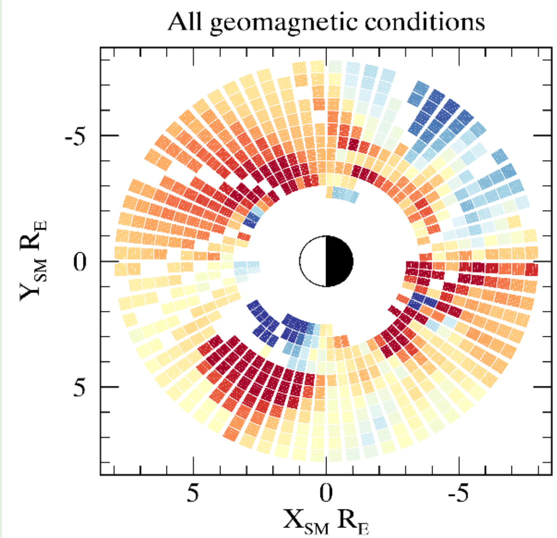
In situ estimates of MMS RC density and local FACs show both large and small-scale structures

Shows local time asymmetry in both the inner (eastward) and outer (westward) ring currents
[*Tan et al. (2023) J. Geophys. Res., doi: 10.1029/2023JA031372; Carter, et al., doi: 10.26464/epp2023055*]

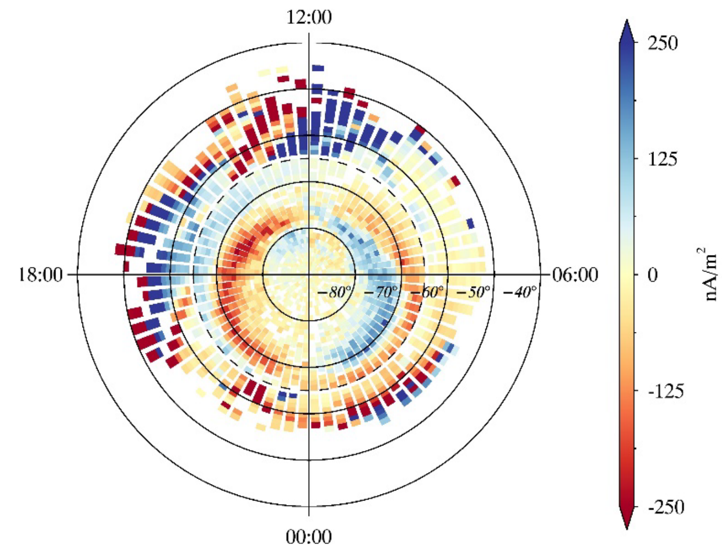
Right: adjacent FACs at MMS mapped to the LEO auroral and sub-auroral regions compare well with Swarm FACs

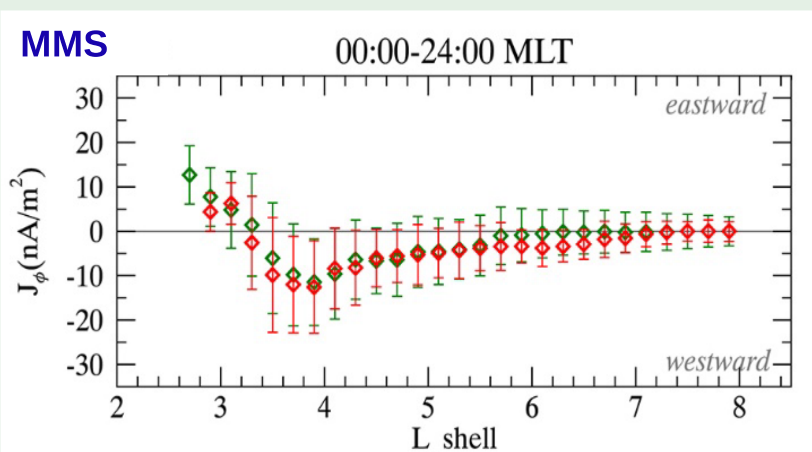
Parallel currents adjacent to the RC show statistical connectivity to FAC’s near ionosphere

[RC behaviour and the operation of R2 FACs can be investigated directly]



Jpara (MMS) and FAC (Swarm)

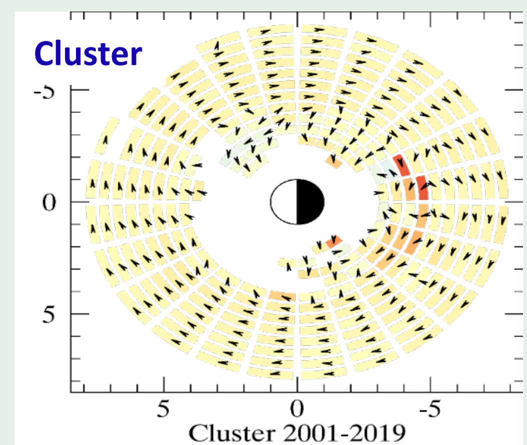




MMS: Broad radial profiles in Jphi agree with previous THEMIS results:

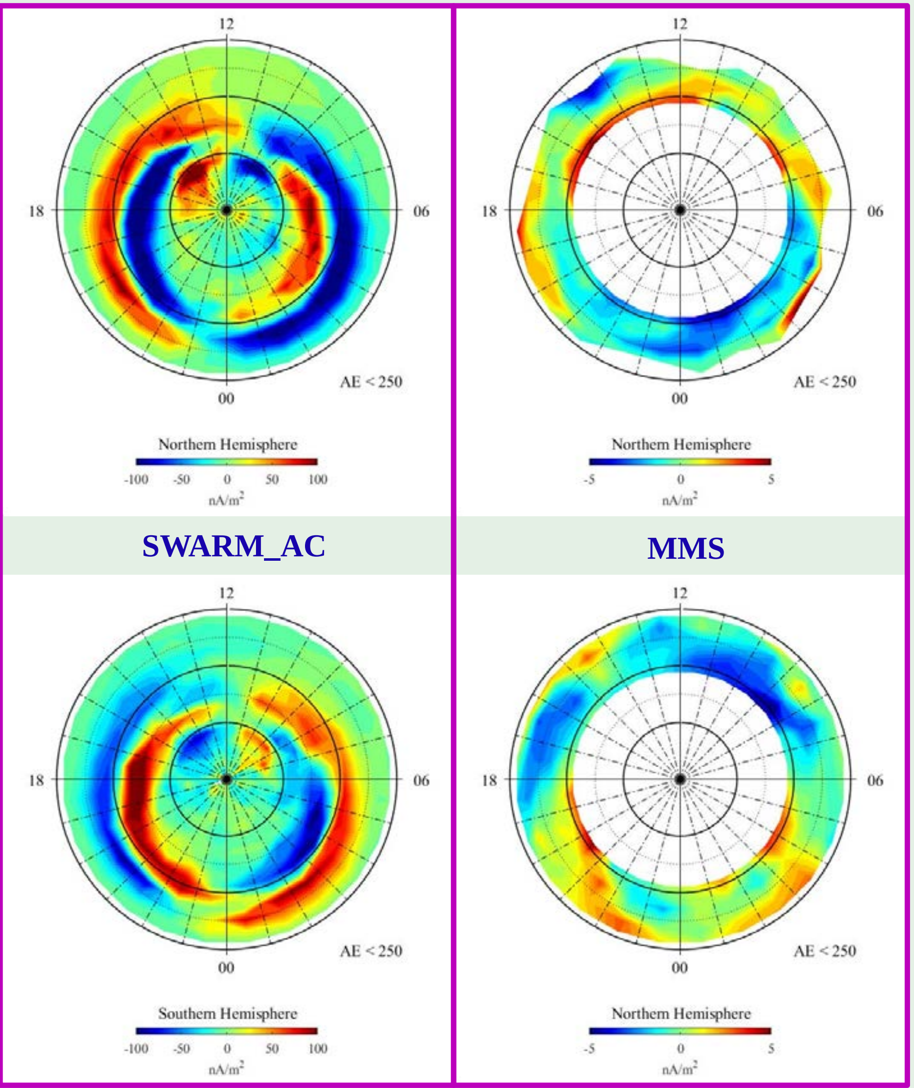
Cluster: long term average shows ‘classic’ RC form

Corresponding MMS period shows consistent trends



Ring current morphology from MMS observations II:

Details of comparison of $\boldsymbol{J}_{//}$ from MMS (adjacent to the RC) and FACs at Swarm (A,C average)

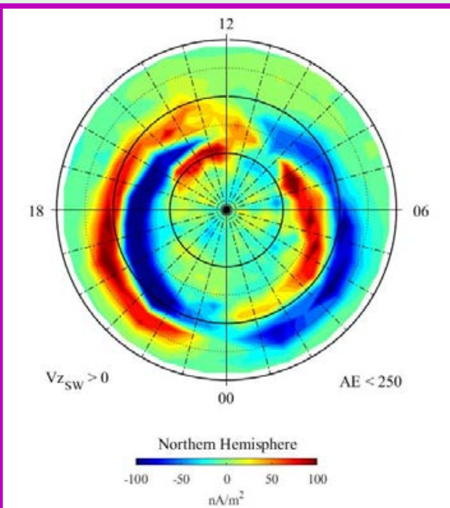


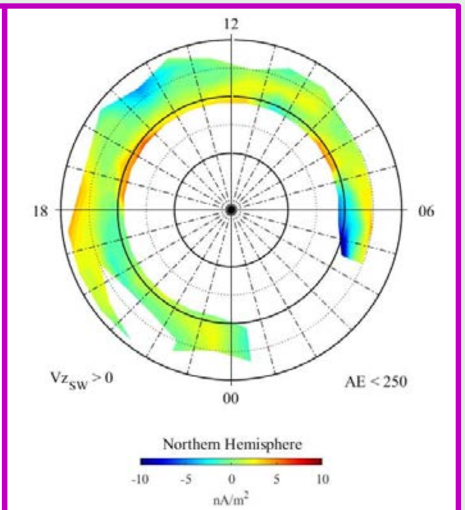
Separated maps for Swarm/MMS parallel currents

- Average MMS currents during substorm quiet periods match reasonably well R1/R2 Swarm FAC region
  (MMS range: ~65-70° SM)
- Best for northern hemisphere
- Key differences pre-noon and pre-midnight (south)
- MMS current magnitudes do not scale well to LEO:
  - simple assumption of converging field-lines not valid
  - sensitive to effective latitude of foot-points

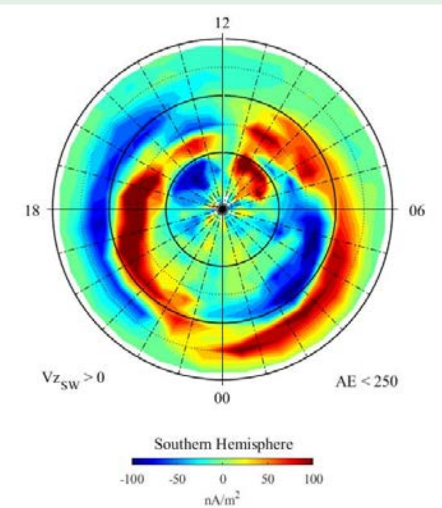
Effect of the Z component (SM) of the upstream solar wind velocity:

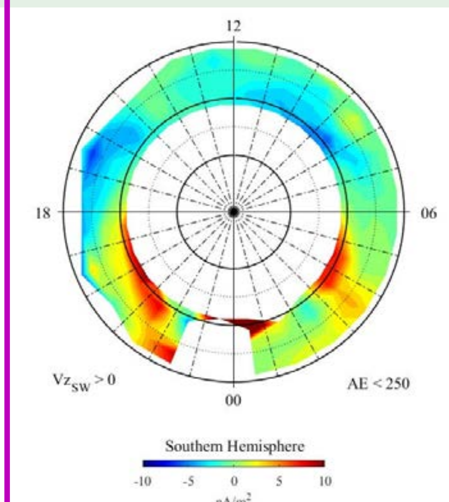
- Positive/negative Vz appears to enhance R2 FACs in the northern/southern polar regions respectively
- Most apparent from MMS currents

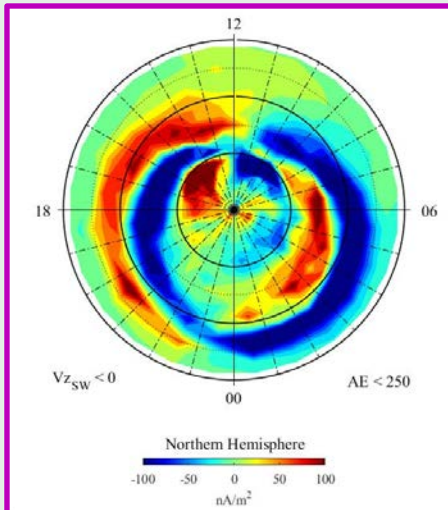


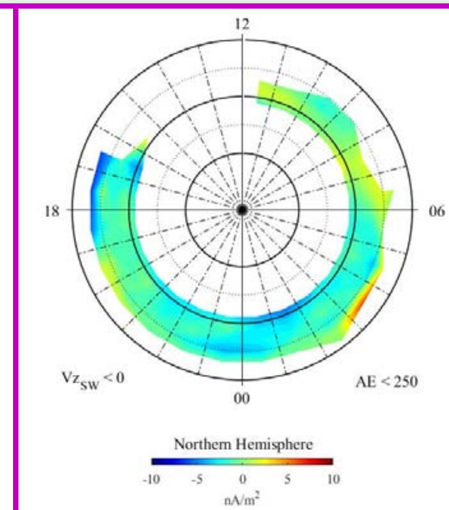


SWARM_AC **MMS**

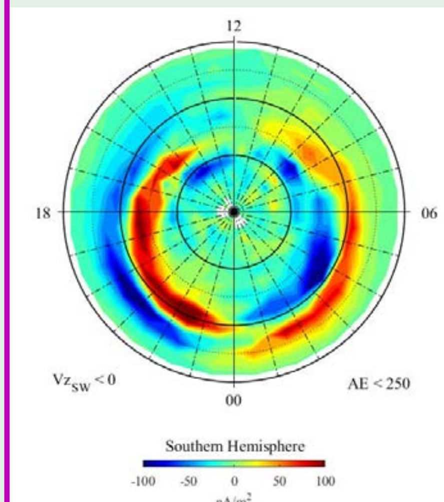


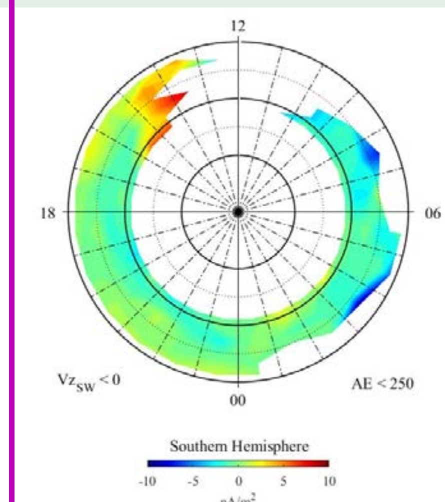






SWARM_AC **MMS**





Summary:

- Basic Curlometer can be adapted to the SWARM, THEMIS and MMS missions

    Applies in a wide range of current systems and transient structures

- Close Swarm configurations can access 3-D currents: perpendicular components
- Combined Cluster-Swarm signatures track similar (scaled) FACs
- Conjunctions of Swarm & Cluster over superMAG locations show corresponding currents:

    -substorm driven FACs and corresponding GICs at nightside locations (SCW)

    -storm driven cusp signatures at different heights, with ground signatures

- Ring current morphology and connection of adjacent FACs (MMS-Swarm):

    -Detailed asymmetry in MLT and east/west currents (with radial profile)

    -Parallel currents adjacent to the RC map to FACs seen at Swarm low altitudes