GRACE-FO and Swarm Integrated Data Analysis Reveals Ionospheric Disturbances on the Accelerometer Measurements

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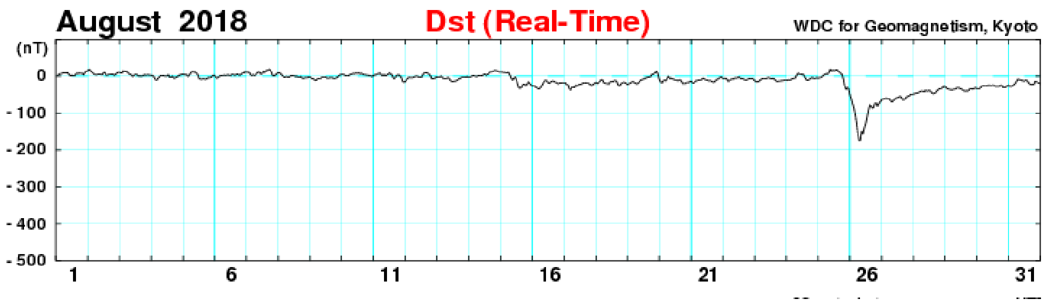
Motivation

- An unexpectedly strong development of a geomagnetic storm occurred on **August 25-26, 2018**.

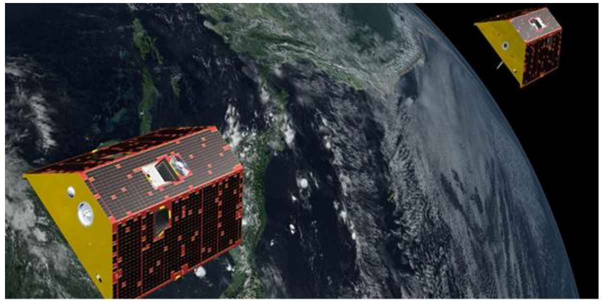
- Disturbance Storm index
  Dst peak = -171 nT.



Dst index for August 2018
Source: WDC for Geomagnetism, Kyoto

- During this storm, two satellite missions, GRACE-FO and Swarm, of a **similar near-polar orbit and altitude** cross the Earth.

Swarm constellation
Source: ESA



GRACE-FO constellation
Source: NASA

How does this geomagnetic storm affect the measurements of these two missions?

Characteristics of the missions

GRACE-FO

2 identical satellites, GRACE C followed by D and vice versa

Spacecraft separation ~ 220 km

Altitude of 500 km

89^o Inclination

Gravity field models

Swarm

3 identical satellites, Swarm A and Swarm C fly side by side at an altitude of 470km

Spacecraft separation of A and C $\sim 1.4^o$ in longitude

Swarm B orbits the Earth at 520km

Inclination (A,C) 87.3^o and (B) 88.3^o

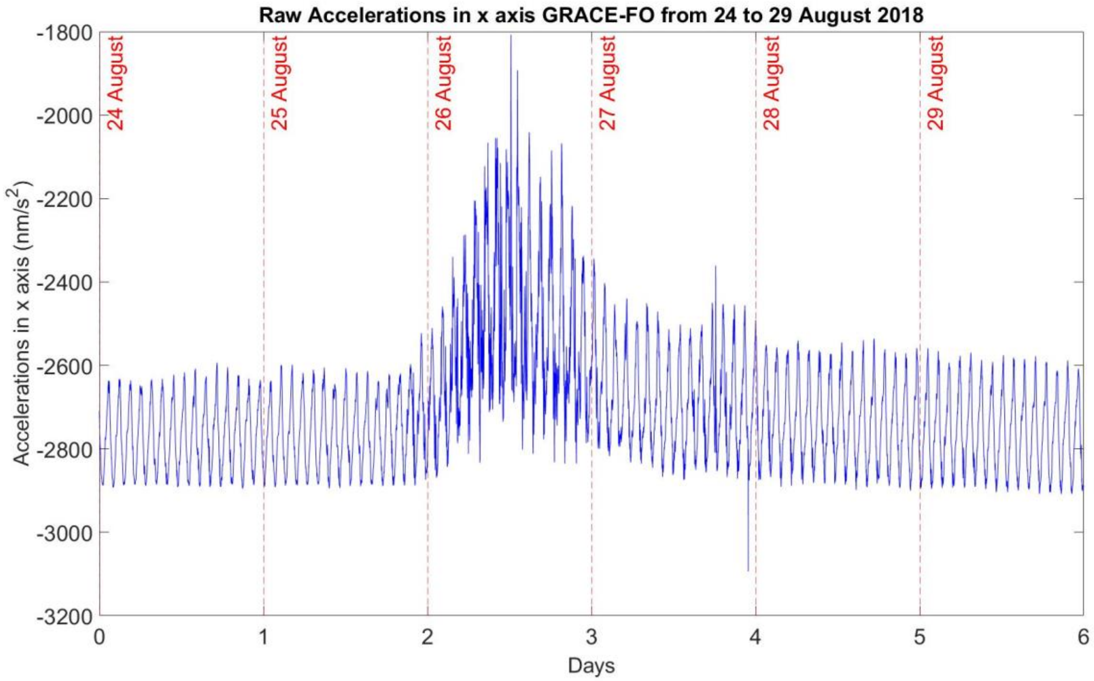
Magnetic field models

- Instrumentation of GRACE-FO : MWI, LRI, ACC, SCA, TriG receiver
- Instrumentation of Swarm : ASM, VFM, STR, EFI, GPSR, LRR, ACC

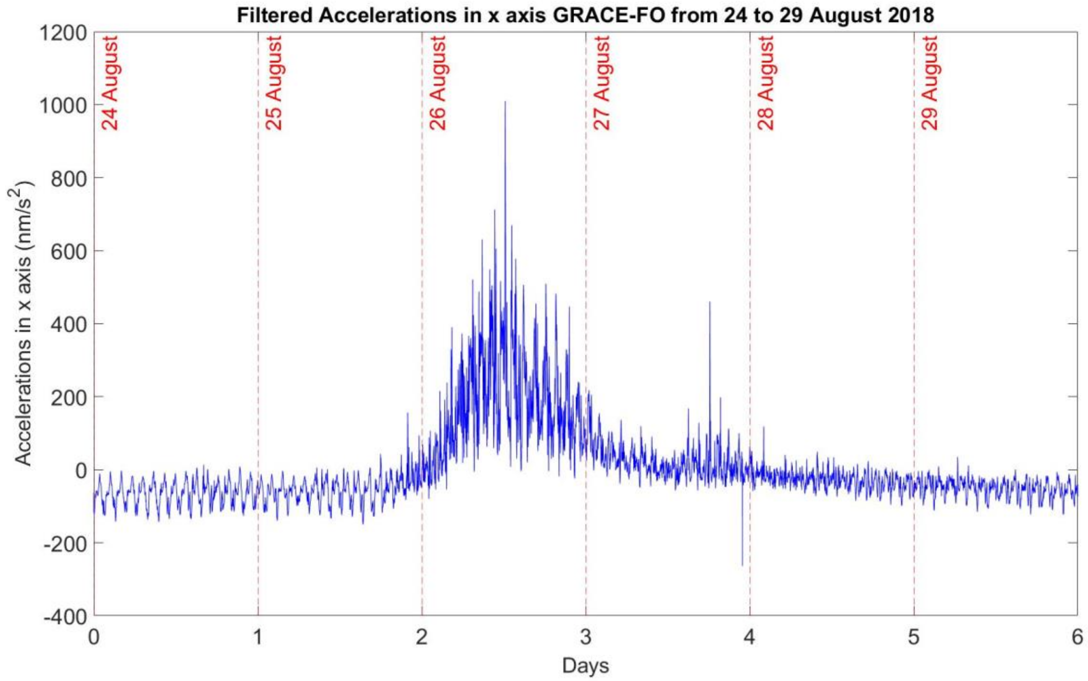
GRACE-FO C Accelerometer

The ultra sensitive accelerometer of GRACE-FO measures the total **non-gravitational acceleration**.

The x axis (along track) is highly disturbed during the storm.



Raw measurements of non-gravitational accelerations of GRACE-FO **C** (Level 1B)



Residual series of non-gravitational accelerations of GRACE-FO **C** (Level 1B). The orbital **period** and **semi-period** have been removed and a low pass filter has been applied (cut-off frequency 80mHz).

What causes the disturbances on the accelerometer?

Non-gravitational accelerations: solar radiation pressure, drag and friction forces, interaction with solar wind, geometric effects.

The magnetic disturbances affect the **accelerometers** in an unknown way.

↓

To understand these effects we combine measurements of the **magnetic field** and the **radial current densities**

↓

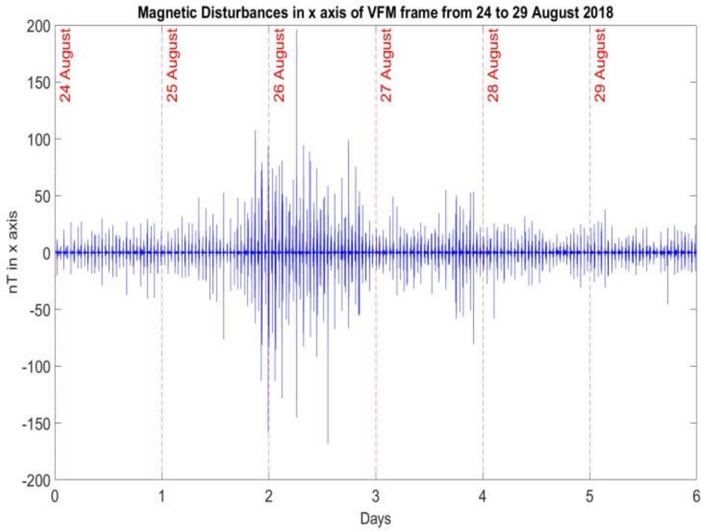
Use of the measurements provided by **Swarm** constellation along the track of the satellites
(this is of great importance due to the height dependency of the ionosphere)

↓

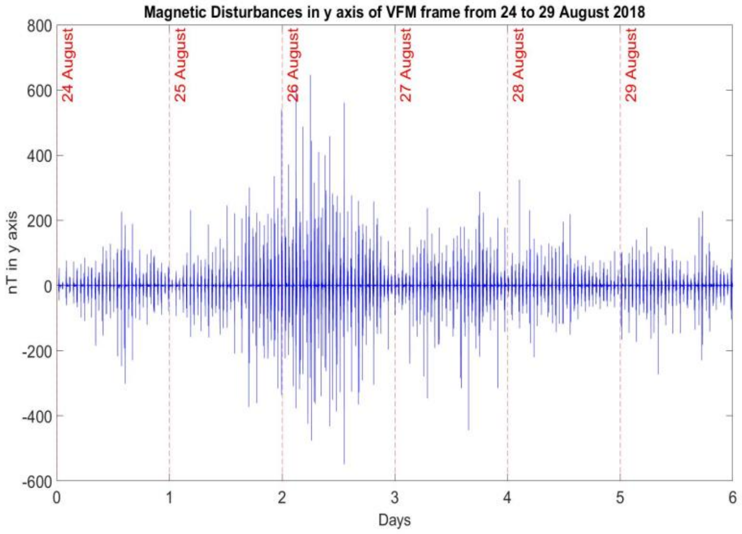
It has been shown that **ionospheric dynamics affect Low Earth Orbit satellites**. (*Ince, Pagiatakis*, 2017)
Calculation of the **force** that acts opposed to the magnetic pressure coming from the ionosphere could enhance our understanding on these effects

Swarm A : Magnetic Disturbances B field (nT)

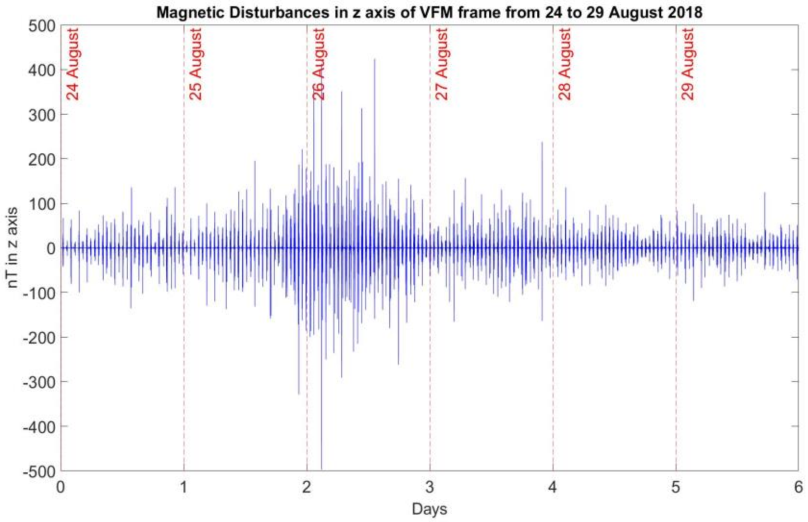
Residual time series of Vector Field Magnetometer (VFM) measurements have been used in the time interval: August 24 to August 29. (Level 1B)



Disturbances in Bx vector of VFM frame



Disturbances in By vector of VFM frame

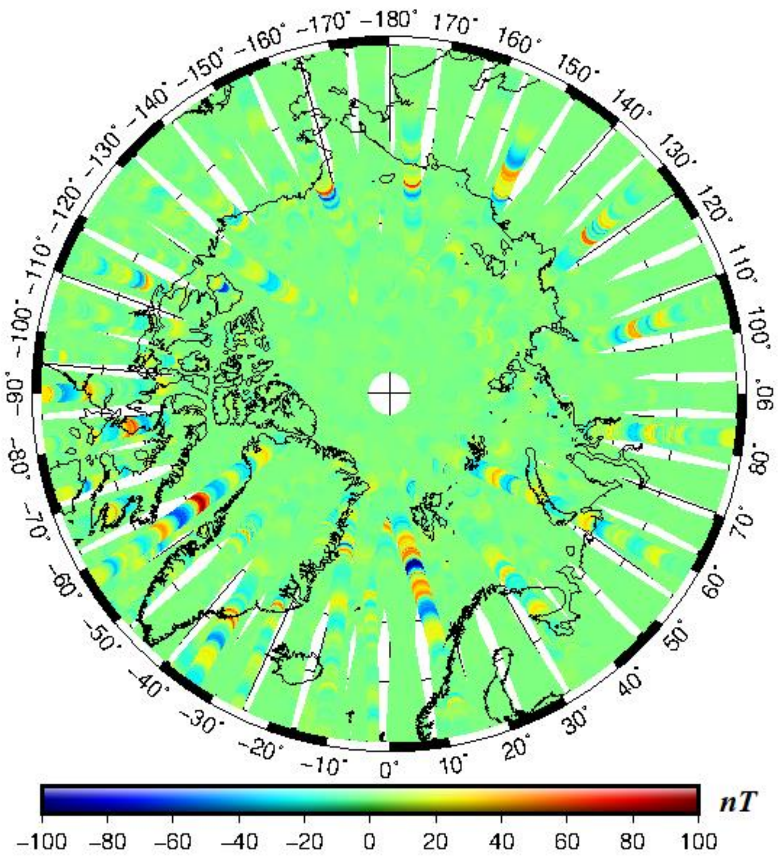


Disturbances in Bz vector of VFM frame

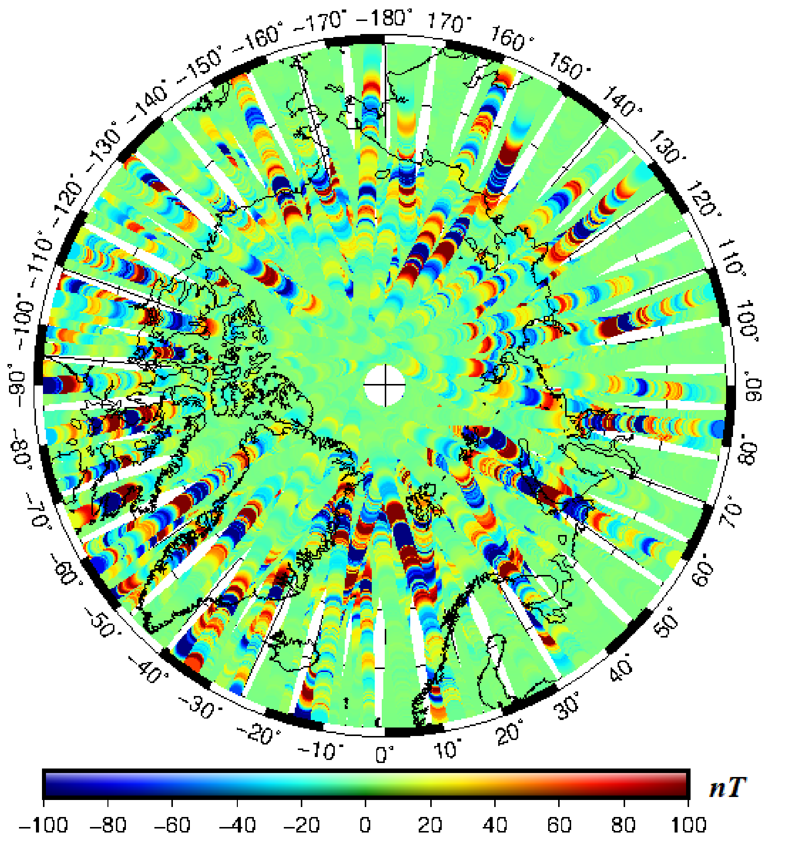
- The main magnetic field has been extracted.
- It is assumed that the magnetic field signals connected to the currents **do not evolve over 20s**.
  (low pass filter with a cut-off frequency 50mHz)
- **Magnetic Disturbances in By vector are stronger.**

Swarm A : Magnetic Disturbances B field (nT)

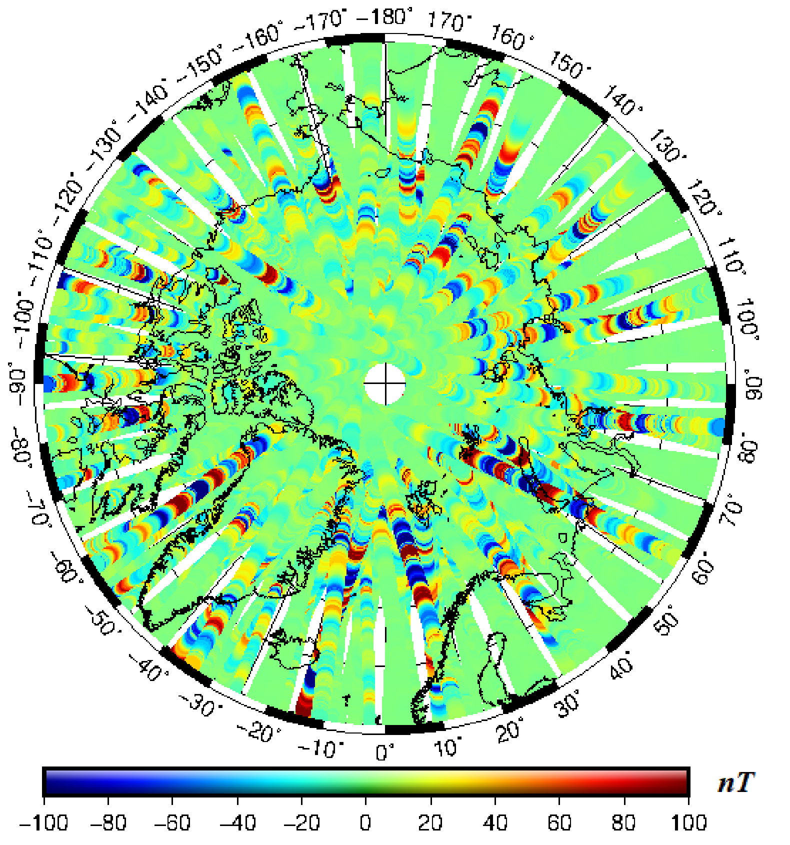
Polar plots for Magnetic Disturbances in North Pole, latitudes 50º to 87º



Disturbances in Bx vector (nT) of VFM frame
Swarm A



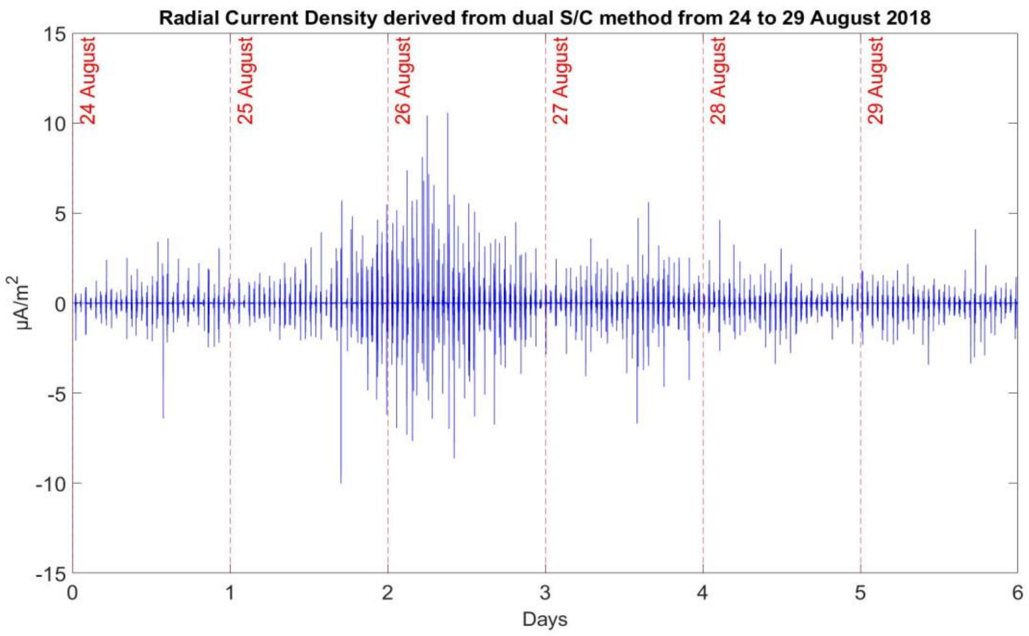
Disturbances in By vector (nT) of VFM frame
Swarm A



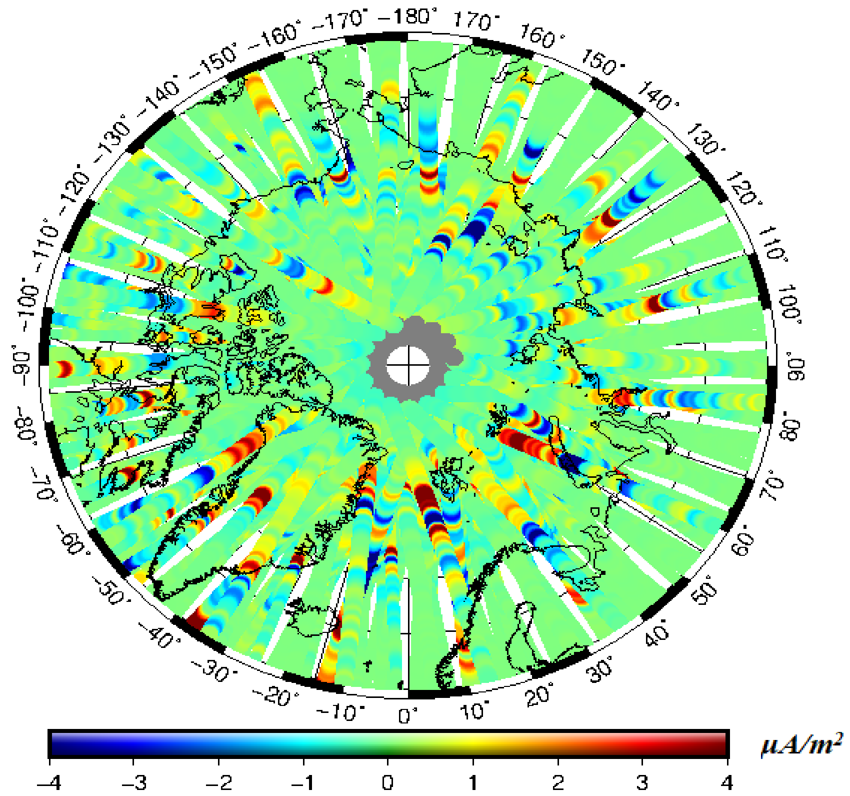
Disturbances in Bz vector (nT) of VFM frame
Swarm A

Swarm A and C: Radial Current Density J ($\mu A/m^2$)

In highly conducting space plasmas, currents produce magnetic fields that modify the existing magnetic field.



Radial Current Density values



Polar plot for Radial Current density, latitudes 50° to 86° (Level 2: non available data above 86°)

Typical values in the auroral zone for radial current density for quiet days is of order 2 $\mu A/m^2$. ***During the storm these values reach* 10 $\mu A/m^2$.**

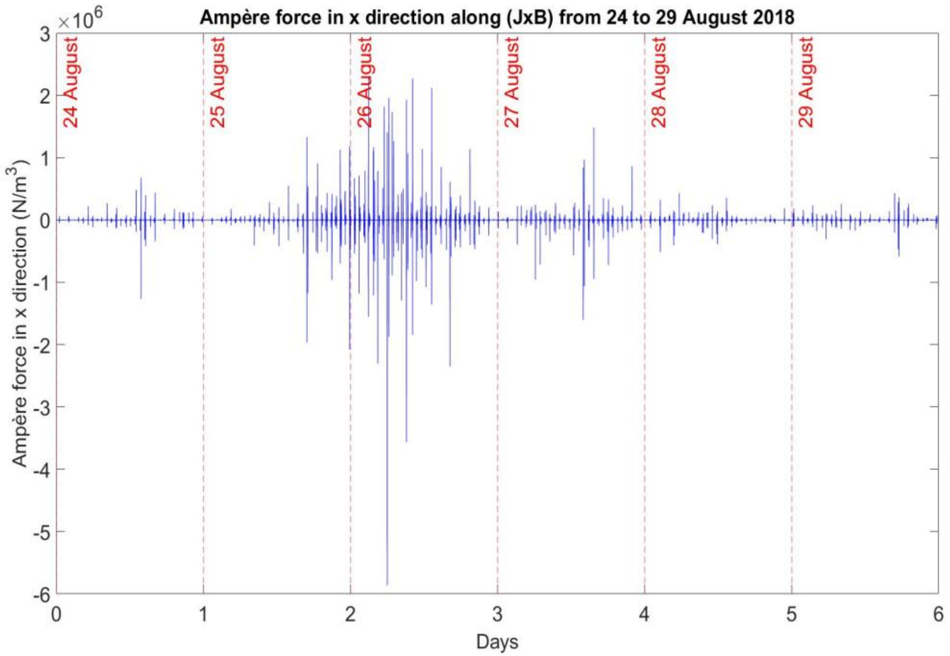
Ampère's force density J x B (N/m^3)

Maxwell's Equations

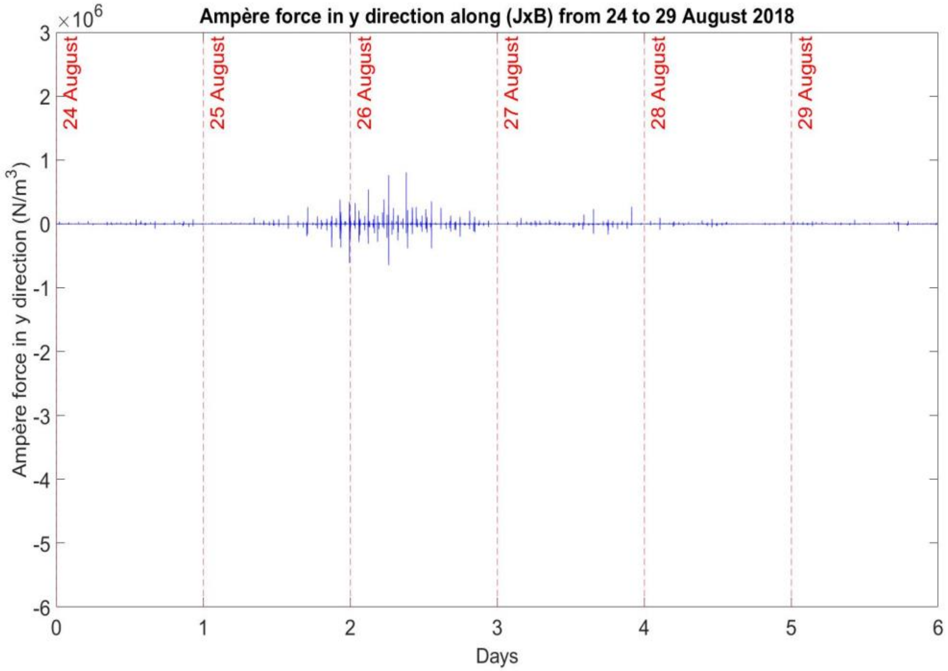
- $\nabla \times B = \mu_0 \mathbf{J}$ ⟶ This equation is used to derive the radial current density from Level 2 data of Swarm
- $\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t}$ ⟶ Electric monopole exists in space where there is a point charge or a source
- $\nabla \cdot \mathbf{B} = 0$ ⟶ The Earth's magnetic field is dipole. There is no net flow across any closed surface
- $\nabla \cdot \mathbf{E} = \frac{\rho_c}{\varepsilon_0}$ ⟶ We neglect the displacement current so that $\nabla \cdot \mathbf{E} = 0$

- Poynting Flux: $S = \frac{1}{\mu_0}(E \times B)$ ⟶ Represents the rate at which energy flows through a surface.
- Ampère's force : $\mathrm{F} = \boldsymbol{J} \times \boldsymbol{B}$ ⟶ Current flows in the magnetosphere and the magnetopause apply stresses to the ionosphere. **This force sets in motion the charged particles and accelerates them.** As a response to this force, ionospheric plasma collides with the neutral particles setting them in motion thus, creating neutral winds in the upper atmosphere.

Ampère's force density J x B (N/m^3)



Ampère's force F_x values before, during and after the storm **along the x-y plane of Swarm**

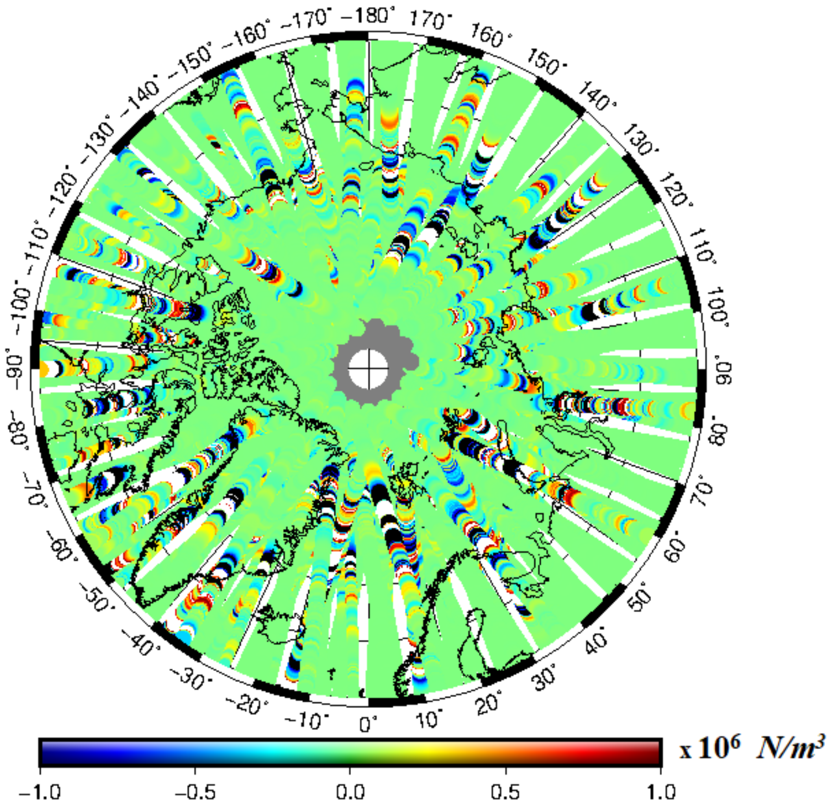


Ampère's force F_y values before, during and after the storm **along the x-y plane of Swarm**

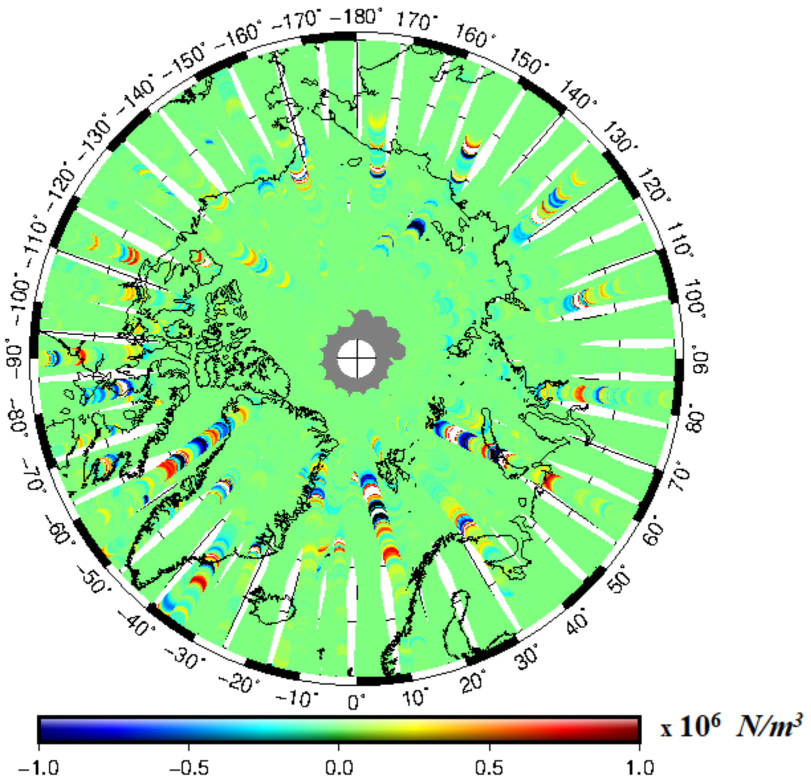
- **Geometrically**, $J \times B$ is perpendicular to both J and B.
- Maximum value of $\boldsymbol{F_x}$ **on the x-y plane** $\sim 2.2 \times 10^6\ N/m^3$.
- Maximum value of $\boldsymbol{F_y}$ **on the x-y plane** $\sim 0.7 \times 10^6\ N/m^3$.
- For the preliminary analysis, **the force has been calculated along track of Swarm A**.
- Positive x values indicate a vector pointing in the same direction of flight.

Ampère's force density J x B (N/m^3)

Polar plots for **Ampère's force density J x B** in North Pole, latitudes 50° to 86°



F_x



F_y

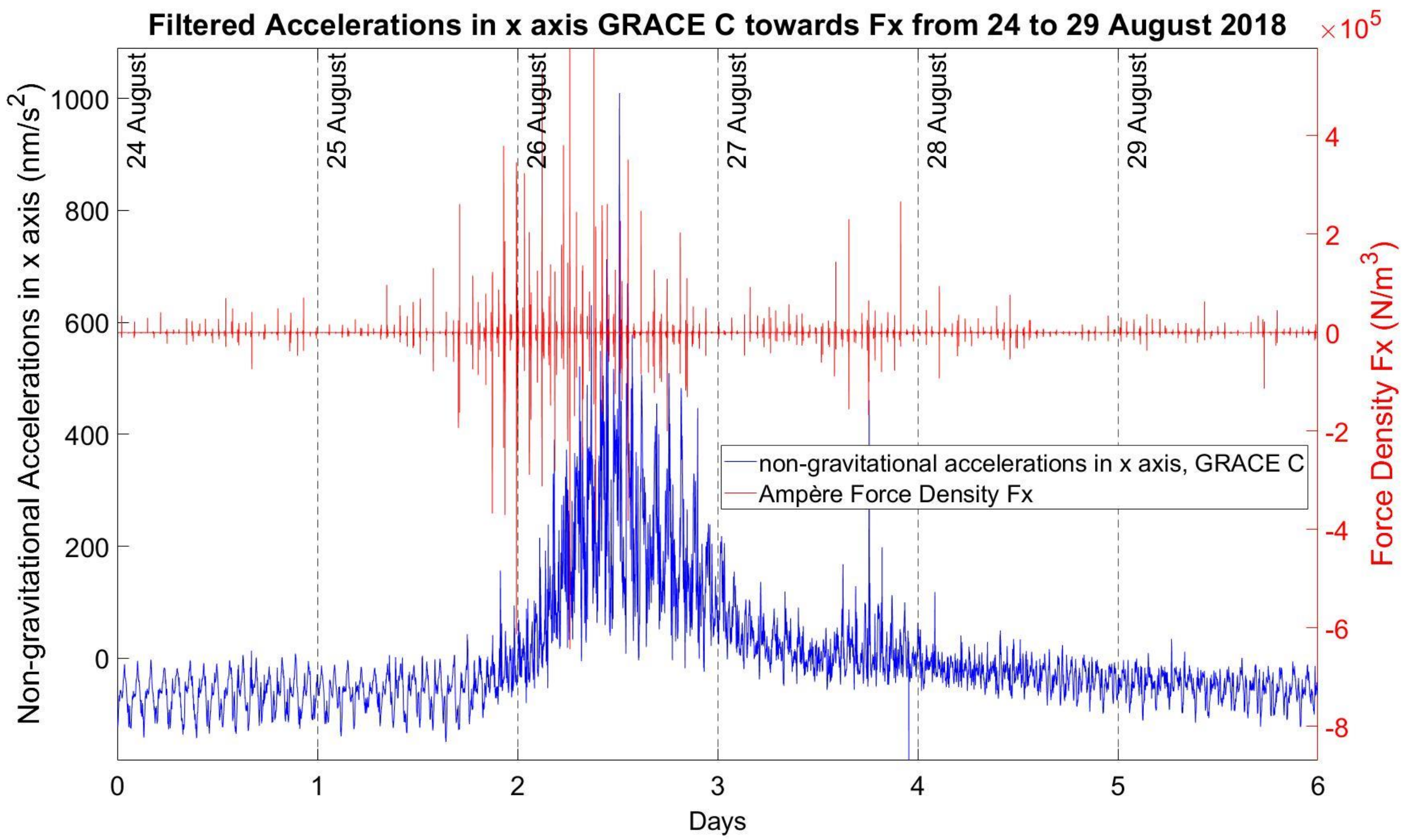
Ampère's force is an indication of the energy transfer in the ionosphere.

It **establishes an equilibrium** between the ionosphere and the magnetosphere.

Its highest values are found **above 60°**.

Calculation of F_x and F_y vectors indicates that this force acts on the **horizontal** plane.

GRACE C accelerometer and Ampère's force density



Non- gravitational accelerations towards **Ampère's force density F_x**

GRACE C measurements from the accelerometer show that the disturbances are **time lagged** towards Ampère's force density $\mathrm{F_x}$. This could be due to many reasons. A further analysis is needed to investigate them.

The $\mathrm{F_x}$ disturbances in the beginning of the storm start around 2000 UTC, while the disturbances in the accelerometer of GRACE C around 2300 UTC.

Conclusions

- From the above analysis, **magnetic, electric field** and **non-gravitational accelerations** measurements are depicted before, during and after the storm. These measurements present a similar spatial behaviour in the perturbations caused by the storm.

- **An analysis on Swarm C accelerometer shows a similar behavior** as GRACE-FO accelerometer. Understanding how this **common instrument** is affected in both missions could be helpful to enhance our knowledge about satellite's response to the ionospheric perturbations.

- The most disturbed axis in accelerometers during the storm, is the **x axis**, pointing along the track of the satellites.

- For the first time, **Ampère's force J x B is calculated** using measurements of Swarm A and Swarm C along the track. **The larger this force, the larger the vertical current**. This force accelerates the neutral particles in the upper atmosphere.

- A **further** analysis should be done on **how this force** acts on both constellations, especially on the their accelerometers.