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

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EGU, Sharing Geosciences Online, May 2020
Motivation

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

• Disturbance Storm index $\text{Dst}$ peak = -171 nT.

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

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° 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 ~1.4° in longitude

Swarm B orbits the Earth at 520km

Inclination (A,C) 87.3° and (B) 88.3°

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)

- 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.

Disturbances in Bx vector of VFM frame
Disturbances in By vector of VFM frame
Disturbances in Bz vector of VFM frame
Swarm A: Magnetic Disturbances B field (nT)

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

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 $10 \, \mu A/m^2$.*

Polar plot for Radial Current density, latitudes $50^\circ$ to $86^\circ$ (Level 2: non available data above $86^\circ$)
Ampère's force density \( J \times B \ (N/m^3) \)

Maxwell’s Equations

- \( \nabla \times B = \mu_0 J \) \quad \( \rightarrow \) \quad This equation is used to derive the radial current density from Level 2 data of Swarm

- \( \nabla \times E = \frac{\partial B}{\partial t} \) \quad \( \rightarrow \) \quad Electric monopole exists in space where there is a point charge or a source

- \( \nabla \cdot B = 0 \) \quad \( \rightarrow \) \quad The Earth’s magnetic field is dipole. There is no net flow across any closed surface

- \( \nabla \cdot E = \frac{\rho_c}{\varepsilon_0} \) \quad \( \rightarrow \) \quad We neglect the displacement current so that \( \nabla \cdot E = 0 \)

- Poynting Flux: \( S = \frac{1}{\mu_0} (E \times B) \) \quad \( \rightarrow \) \quad Represents the rate at which energy flows through a surface.

- Ampère's force: \( F = J \times B \) \quad \( \rightarrow \) \quad 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 $J \times B \ (N/m^3)$

- Geometrically, $J \times B$ is perpendicular to both $J$ and $B$.
- Maximum value of $F_x$ on the $x$-$y$ plane $\sim 2.2 \times 10^6 \ N/m^3$.
- Maximum value of $F_y$ 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 $J \times B \ (N/m^3)$

Polar plots for Ampère's force density $J \times B$ in North Pole, latitudes 50° to 86°

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

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

The $F_x$ 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 $J \times B$ 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.