Orbital decay of low Earth orbiting satellites during geomagnetic storms

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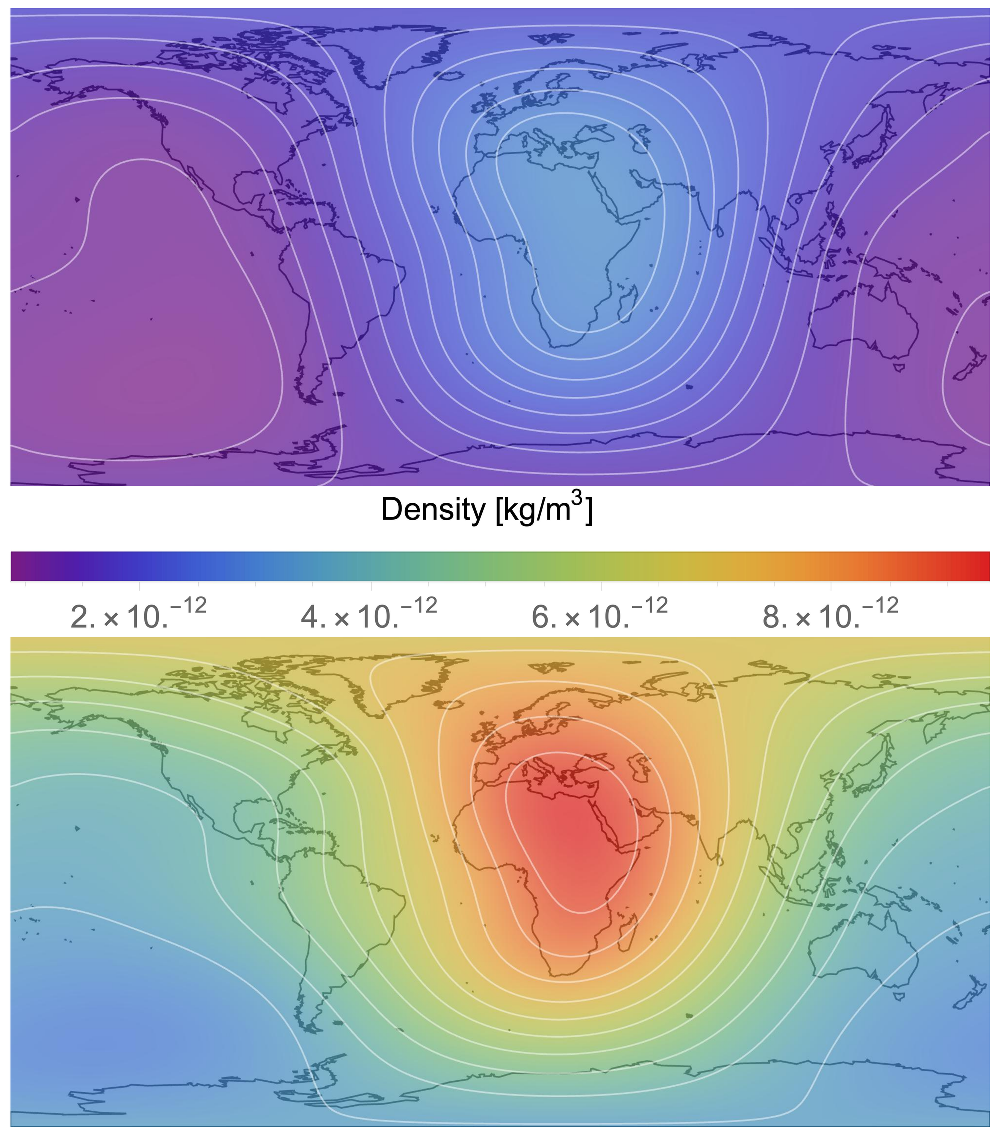
1. Introduction

Coronal mass ejections (CMEs) originate from the Sun and can cause geomagnetic storms, during which energy is injected into the atmosphere causing it to expand. Satellites in LEO will experience more air drag due to a higher air density. This leads to increased orbital decay for a LEO satellite.

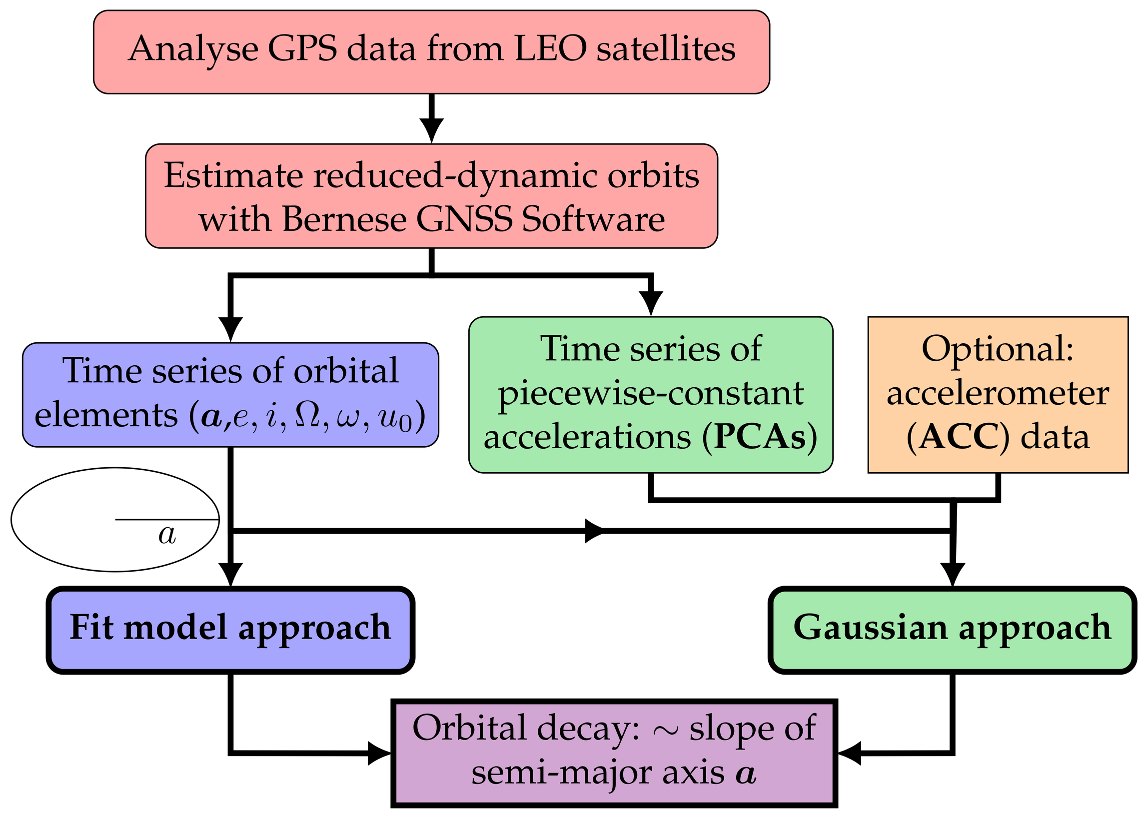
The goal of this work was to study the orbital decay of satellites in low Earth orbit (LEO). We explored two different methodologies for recovering increased orbital decay induced by space weather for five LEO satellites at different orbital altitudes.

DTM2013: neutral densities at 500 km altitude



2. Procedure

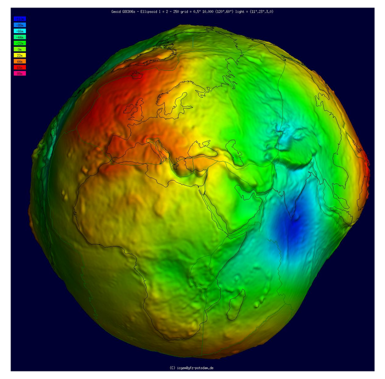
Analysed satellites: GRACE-FO-1, Swarm-A, Sentinel-1A, Sentinel-2A and Sentinel-3A. Analysed years: 2018, 2023 and 2024. Measurements from on-board GPS receivers are used to estimate reduced-dynamic orbits with the Bernese GNSS Software. Non-gravitational accelerations (due to air drag and radiation pressure) are not explicitly modelled, but estimated by means of piecewise-constant accelerations (PCAs) with a 6-minutes spacing. Osculating orbital elements are derived from the reduced-dynamic orbit solutions. In our first approach the time series of the semi-major axis a is fitted with a model consisting of a piecewise linear trend and periodic variations with amplitudes varying according to a piecewise linear model. The orbital decay is taken as the slope of the trend of the semi-major axis. The other approach is to use the PCAs or (in case of GRACE-FO) accelerometer (ACC) data to integrate Gauss's perturbation equation for the semi-major axis.



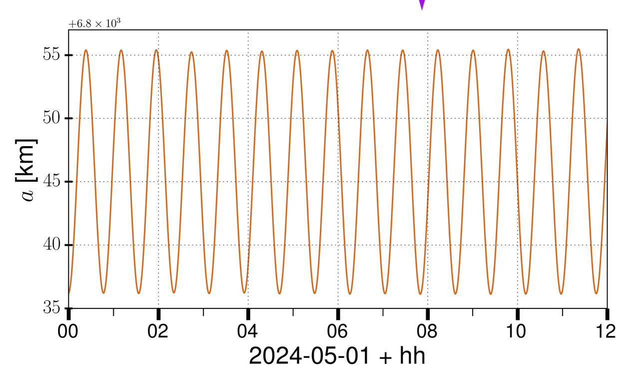
3. Challenge: orbit perturbations

Besides **air drag** there are other perturbations:

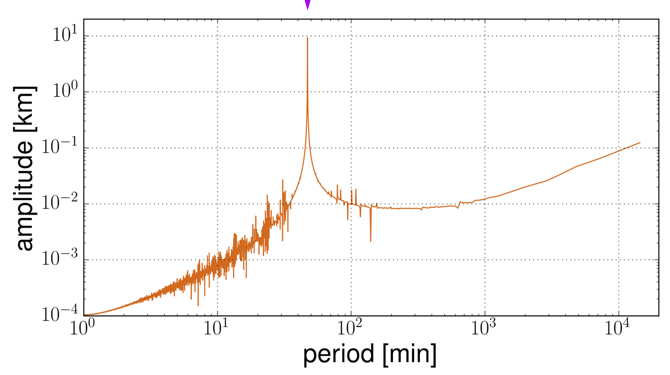
- **Gravitational field of Earth**: largest periodic perturbation due to oblateness ($C_{2,0}$)
- **Radiation pressure**: Solar, Earth, ...
- **Other celestial bodies**: Sun, Moon, tidal effects, ...



Gravitational field of Earth. Source: icgem.gfz-potsdam.de.



Semi-major axis of Swarm-A in May 2024.



Spectrum of the semi-major axis of Swarm-A in May 2024.

4. Fit model approach

Time varying trend + periodic variations: $a(t) = \bar{a}(t) + \sum_{r=1}^{R} \left(\mu_r(t) \sin(\omega_r t) + \eta_r(t) \cos(\omega_r t) \right)$

→ Orbital decay = $\frac{\mathrm{d}}{\mathrm{d}t}\bar{a}(t)$

Least squares adjustment for $\bar{a}(t)$, $\mu_r(t)$ and $\eta_r(t)$:

- Piecewise linear representation
  → 10 subintervals per day

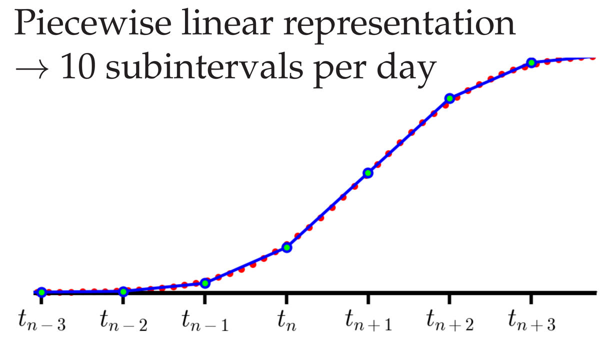
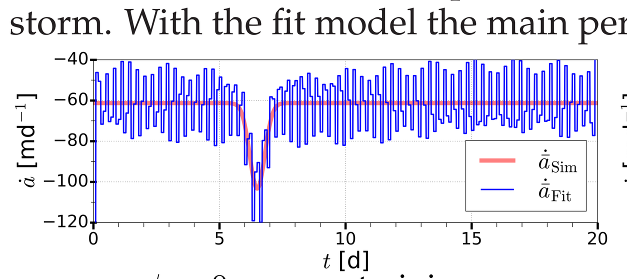


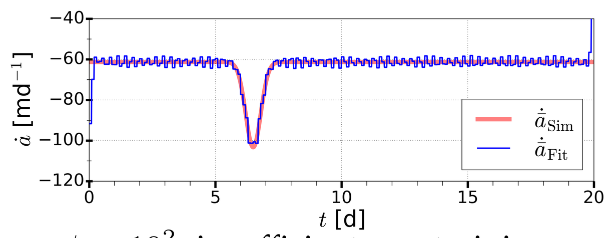
Illustration of the piecewise linear representation.

- Tikhonov regularisation:
  $(x_{n+1} - x_n) - (x_n - x_{n-1}) \approx 0, \quad \forall x \in \{\bar{a}, \mu_r, \eta_r\}$.
  In matrix notation: $\boldsymbol{C} \cdot \vec{x} = \vec{0}$
  Add to normal equation system:
  $\boldsymbol{N} \to \boldsymbol{N} + \psi \cdot \boldsymbol{N}_{\text{constr}}, \quad \boldsymbol{N}_{\text{constr}} = \boldsymbol{C}^{\mathrm{T}} \cdot \boldsymbol{C}$
  → Control constraining with ψ

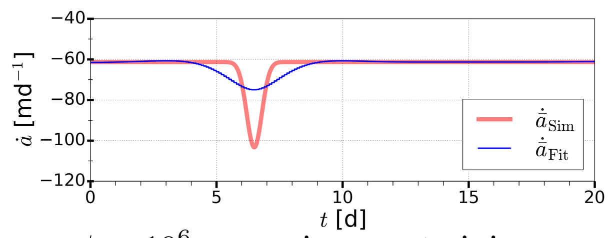
Simulation (for model validation and tuning): simulated a signal consisting of an offset, a linear term and oscillations of three different periods and amplitudes. A Gauss error function is added to simulate a geomagnetic storm. With the fit model the main period is modelled.



$\psi = 0$: no constraining.



$\psi = 10^2$: insufficient constraining.



$\psi = 10^6$: excessive constraining.

→ use in the following
$\psi_1 = 10^3, \psi_2 = 10^4, \psi_3 = 10^5$

5. Gaussian approach

Numerically integrate Gauss's perturbation equation for the semi-major axis:

$$\dot{a} = 2\sqrt{\frac{a^3}{\gamma(1-e^2)}}\left\{ e \sin(u-\omega) R + [1 + e\cos(u-\omega)] S \right\}$$

- γ - gravitational constant multiplied with mass of Earth
- e - numerical eccentricity
- ω - argument of perigee
- u - argument of latitude at time t
- R - perturbation acceleration in radial direction
- S - perturbation acceleration in along-track direction

} PCA or ACC data

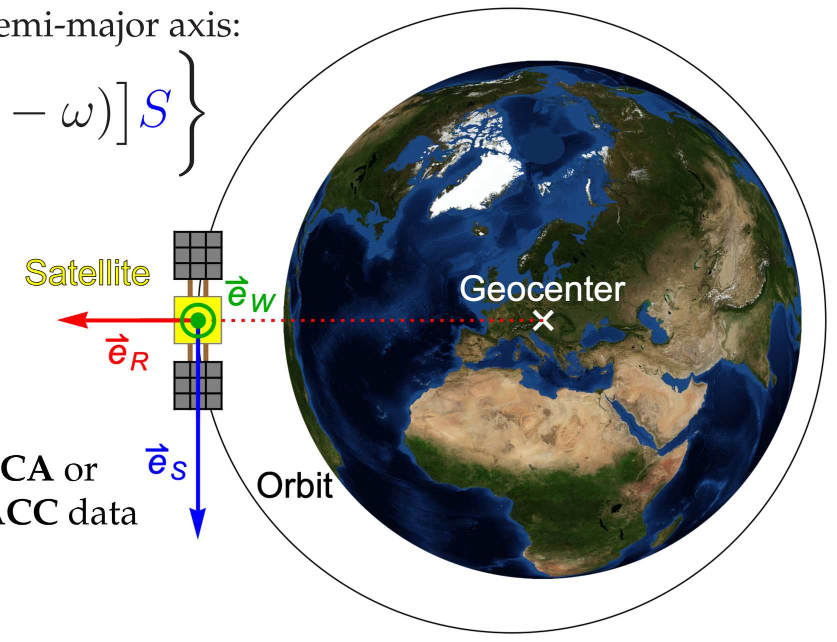


Illustration of the RSW coordinate system.

The obtained orbital decay rates can be smoothed to filter out oscillations.

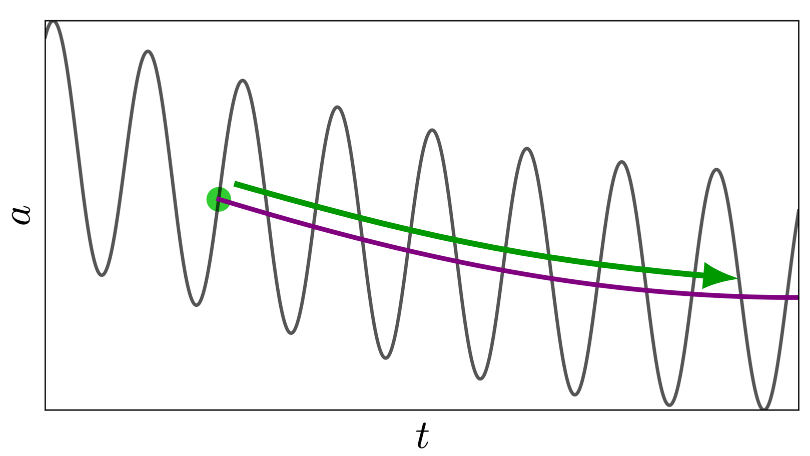
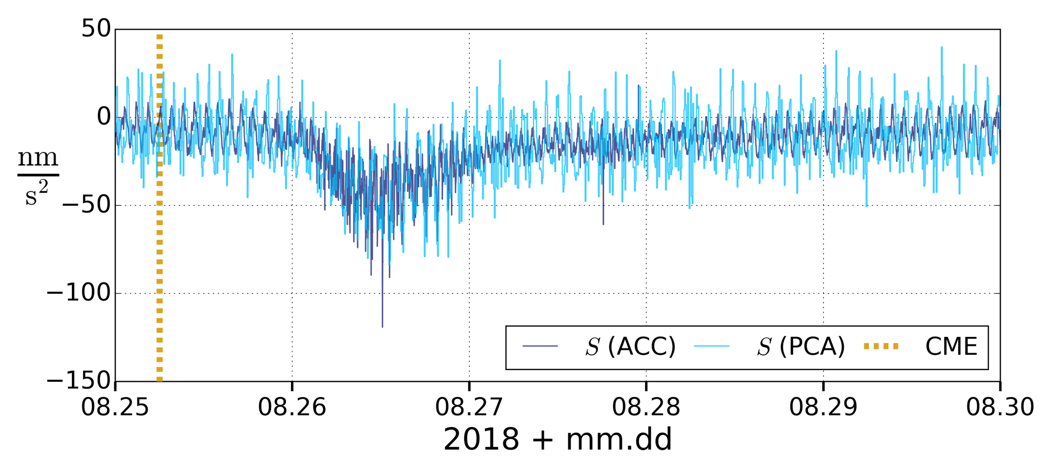


Illustration of the propagation of an orbit free of gravitational perturbations.

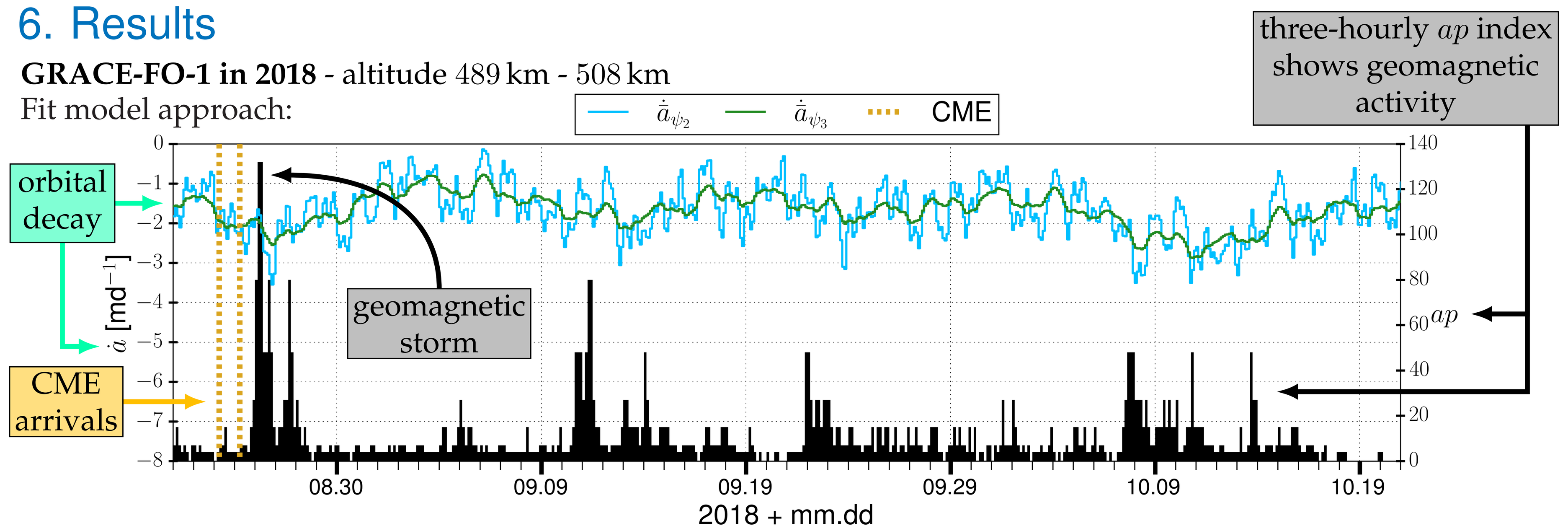


Along-track acceleration: ACC data and PCAs for GRACE-FO-1.

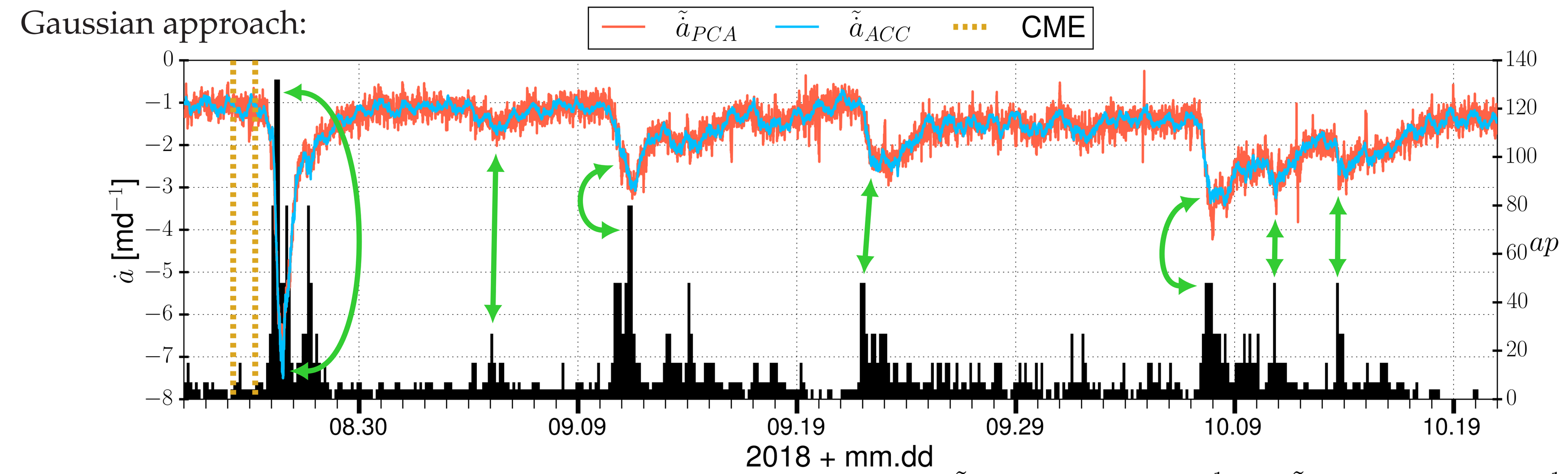
6. Results

GRACE-FO-1 in 2018 - altitude 489 km - 508 km

Fit model approach:



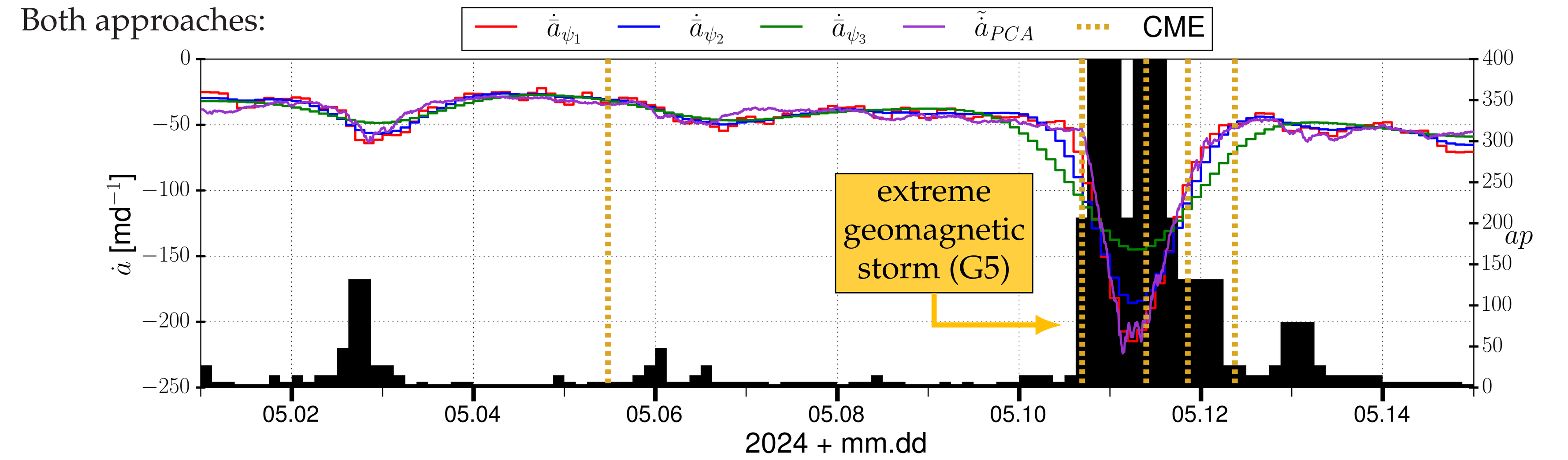
Gaussian approach:



Maximum orbital decay reached during the storm on 2018-08-26: $\tilde{a}_{PCA} = -7.35\,\text{md}^{-1}$ and $\tilde{a}_{ACC} = -7.51\,\text{md}^{-1}$.

Swarm-A in 2024 - altitude 464 km - 484 km

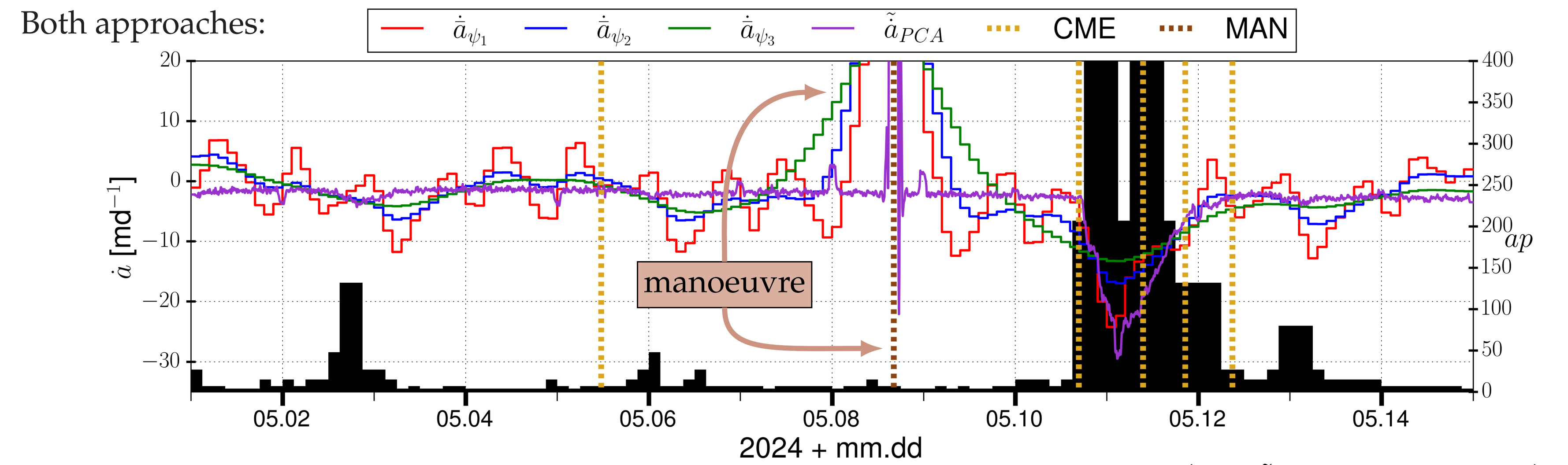
Both approaches:



Maximum orbital decay reached during the G5 storm in May 2024: $\dot{a}_{\psi_1} = -214.81\,\text{md}^{-1}$ and $\tilde{a}_{PCA} = -224.15\,\text{md}^{-1}$.

SENTINEL-2A in 2024 - altitude 784 km - 802 km

Both approaches:



Maximum orbital decay reached during the G5 storm in May 2024: $\dot{a}_{\psi_1} = -24.22\,\text{md}^{-1}$ and $\tilde{a}_{PCA} = -29.50\,\text{md}^{-1}$.

7. Conclusion

Fit model approach

- difficulties: low orbital decay rates, frequent manoeuvres and not modelled long periods
- low constraining → large variations, high constraining → underestimation during geomagnetic storm

Gaussian approach

- impact of low geomagnetic activity observable
- PCAs as alternative to ACC data, but noisier
- low quality at day boundaries, especially for manoeuvre days
- quasi-instantaneous reaction to manoeuvres but orbital changes not realistic

Intense geomagnetic storms → steep and deep drops in orbital decay.
Both methods have potential for improvement.

8. Work and code

A more extensive description of the methodology and the results can be found in Walter, L. (2024): Impact of Space Weather Events on the Orbit of Low Earth Orbiting Satellites. Bachelor Thesis, Astronomical Institute, University of Bern.

The analysis of the data was performed with Python. The thesis and the code can be found on the GitHub repository with the following QR code: