Orbital decay of low Earth orbiting satellites during geomagnetic storms

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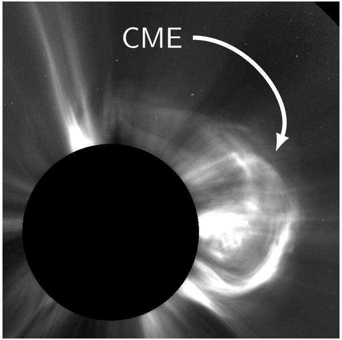
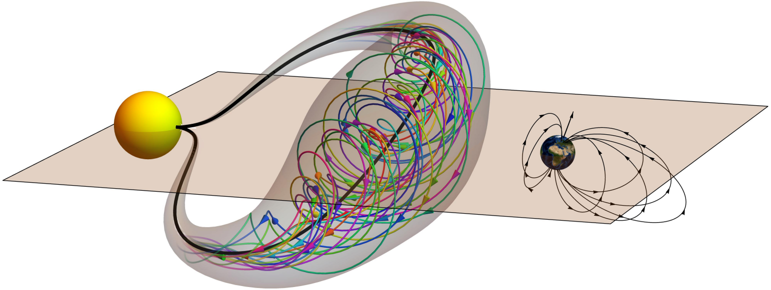
Coronal Mass Ejections

- explosive event
- ejected plasma
- magnetic cloud characteristics
- can cause **geomagnetic storms** $\rightarrow$ thermosphere heats up



helioviewer.org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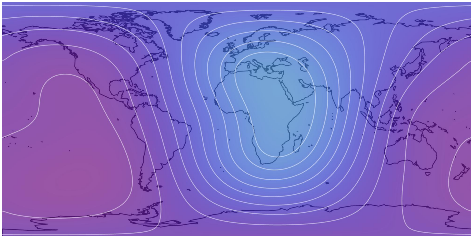
Geomagnetic Storms

Expansion of upper atmosphere
→ higher air density at low Earth orbit (**LEO**) altitude

2024-05-10 12:00 UTC



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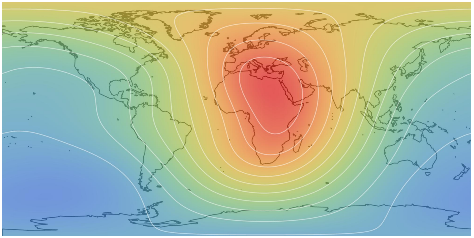
2024-05-11 12:00 UTC



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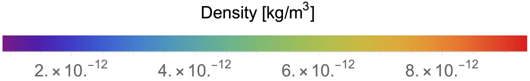


DTM2013: neutral densities at 500 km altitude

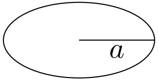
Y. Gschwind

V.-M. Mercea

Procedure

Analyse GPS data from LEO satellites → Estimate reduced-dynamic orbits with Bernese GNSS Software

Model all gravitational forces → Estimate reduced-dynamic orbits with Bernese GNSS Software



Time series for orbital elements (a, $e, i, \Omega, \omega, u_0$)

Time series for piecewise-constant accelerations (**PCAs**)

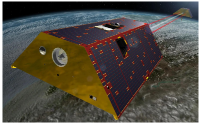
Optional: accelerometer data

Fit model approach

Gaussian approach

Orbital decay: $\sim$ slope of semi-major axis a

GRACE-FO



gracefo.jpl.nasa.gov

Swarm

earth.esa.int

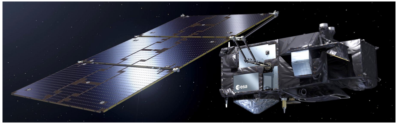
Sentinel-1

sentiwiki.copernicus.eu

Sentinel-2

sentiwiki.copernicus.eu

Sentinel-3



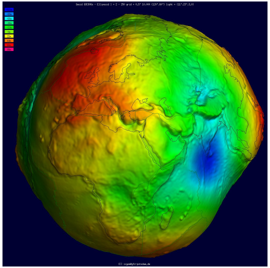
sentiwiki.copernicus.eu

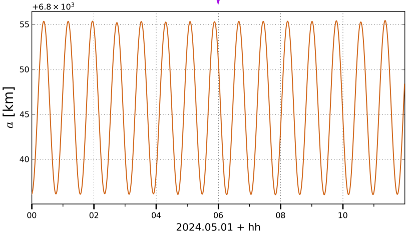
Orbit Perturbations

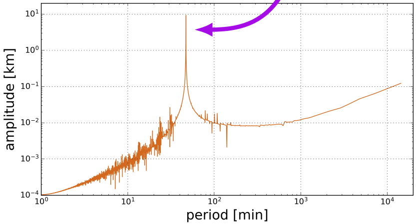
Other perturbations besides air drag:

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

icgem.gfz-potsdam.de







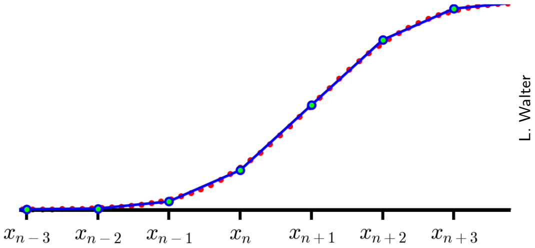
Fit Model Approach

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

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

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

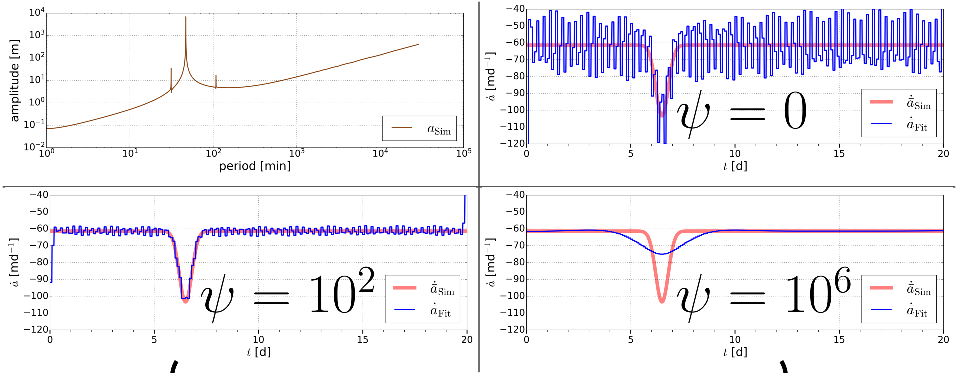
- Piecewise linear representation
  $\rightarrow$ 10 subintervals per day



- 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: $\boldsymbol{N} \rightarrow \boldsymbol{N} + \psi \cdot \boldsymbol{N}_{\text{constr}}, \qquad \boldsymbol{N}_{\text{constr}} = \boldsymbol{C}^{\mathsf{T}} \cdot \boldsymbol{C}$
  $\rightarrow$ Control constraining with ψ

Fit Model Approach - Simulation

- 3 periods simulated, 1 modelled
- $-61\,\mathrm{md}^{-1}$ drift
- geomagnetic storm $\rightarrow$ Gauss error function
- Experiment with ψ

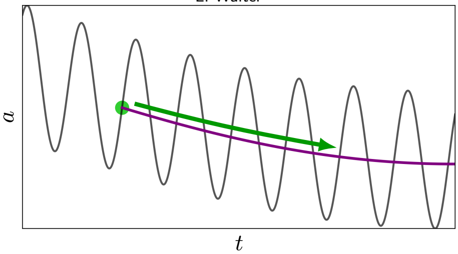


$\rightarrow$ use $\psi_1 = 10^3$, $\psi_2 = 10^4$, $\psi_3 = 10^5$

Gaussian Approach

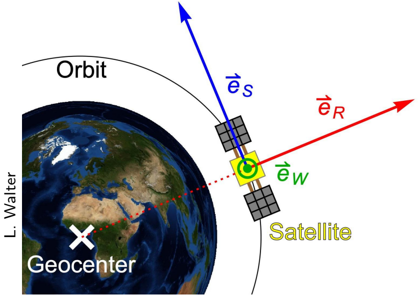
Integrate Gauss's perturbation equation

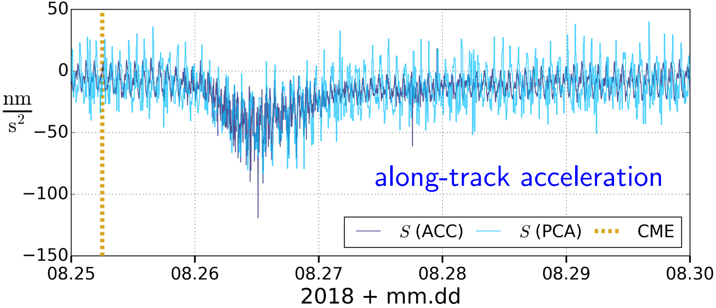
$$\dot{a} = 2\sqrt{\frac{a^3}{\gamma(1-e^2)}}\left\{e\sin(u-\omega)R+\left[1+e\cos(u-\omega)\right]S\right\}$$



Smooth obtained orbital slope

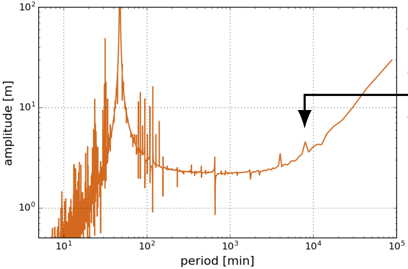
Accelerations: **PCAs** or accelerometer (**ACC**) data



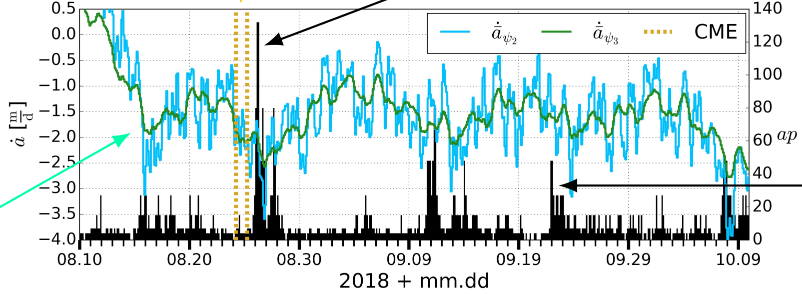


GRACE-FO-1 in 2018: Fit Model Approach

Altitude:
489 km - 508 km

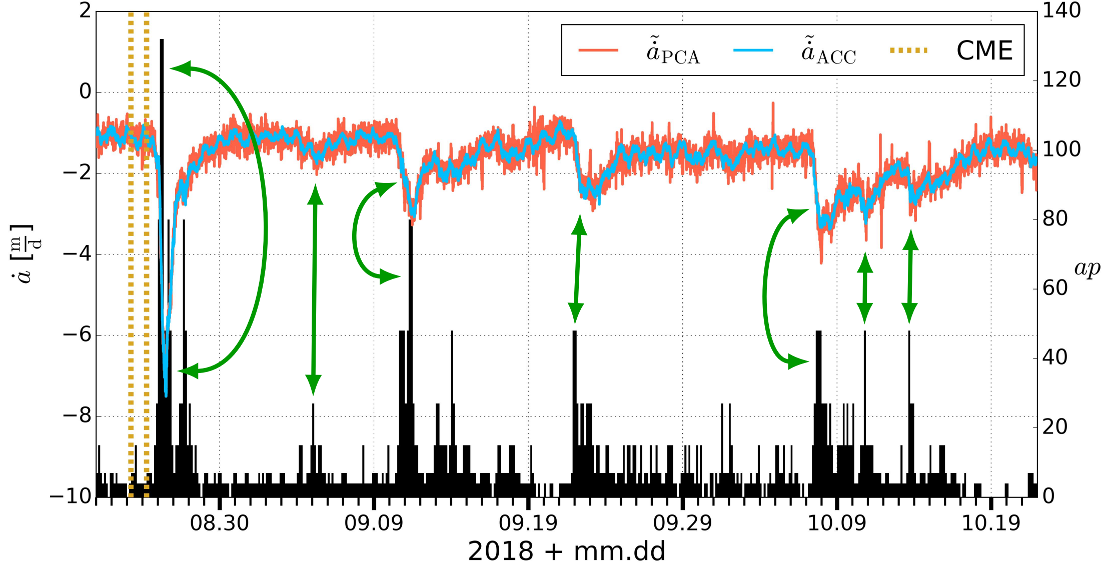


- correlation with geomagnetic activity?
- low orbital decay problematic
- disturbing period $p_2 \approx 5.55\,\mathrm{d}$ modelled



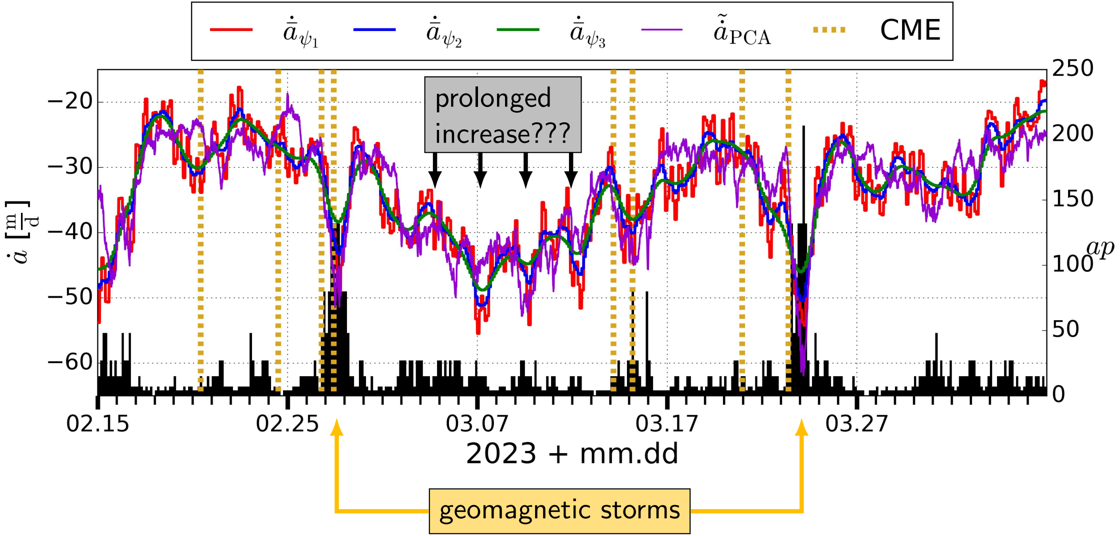
GRACE-FO-1 in 2018: Gaussian Approach

Altitude:
489 km - 508 km



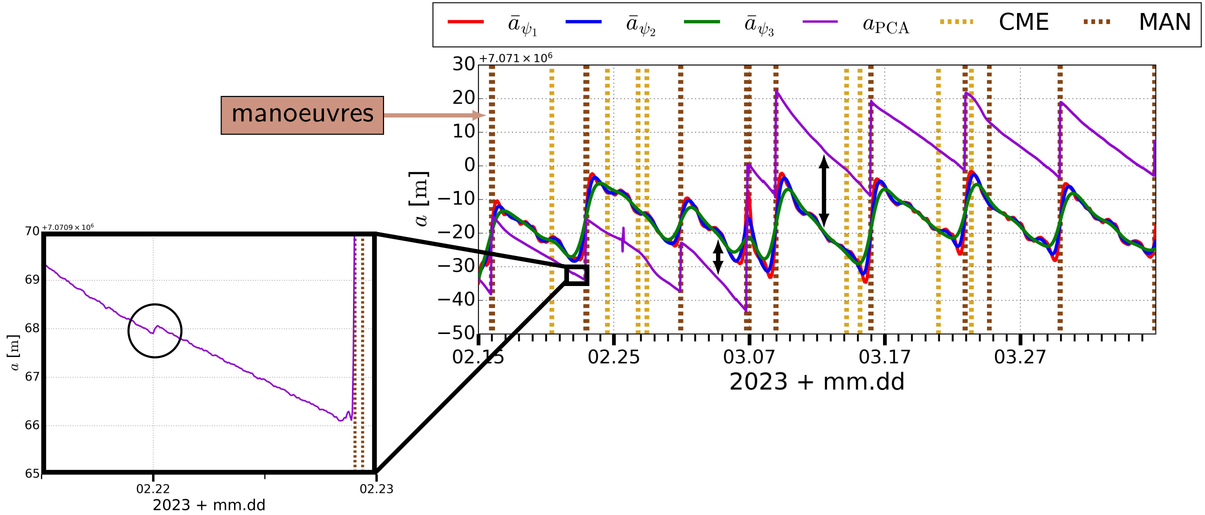
GRACE-FO-1 in 2023

Altitude: $483\,\mathrm{km}$ - $504\,\mathrm{km}$



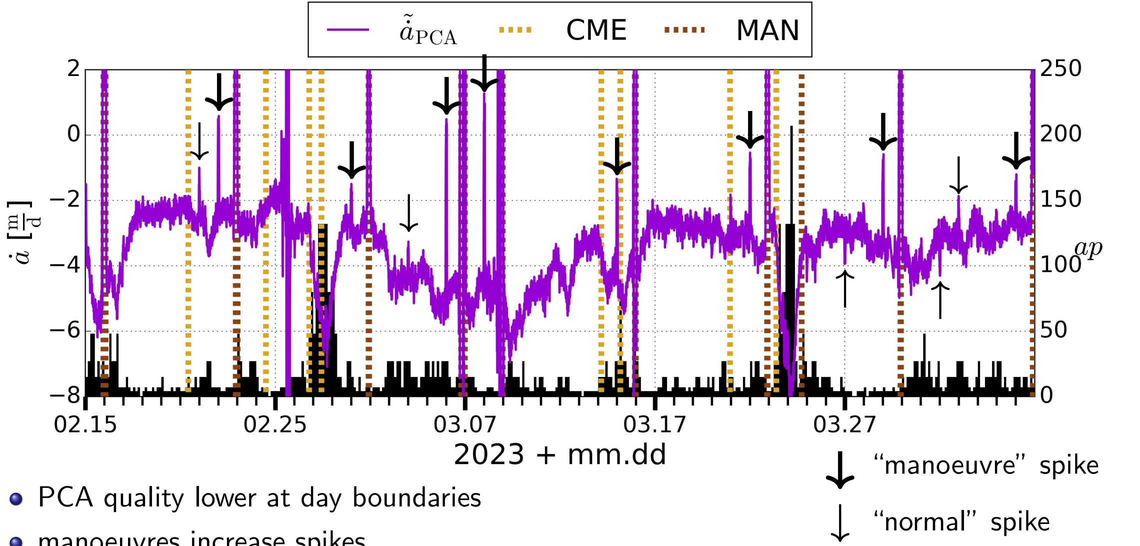
SENTINEL-1A in 2023

Altitude: $691\,\mathrm{km}$ - $709\,\mathrm{km}$



SENTINEL-1A in 2023

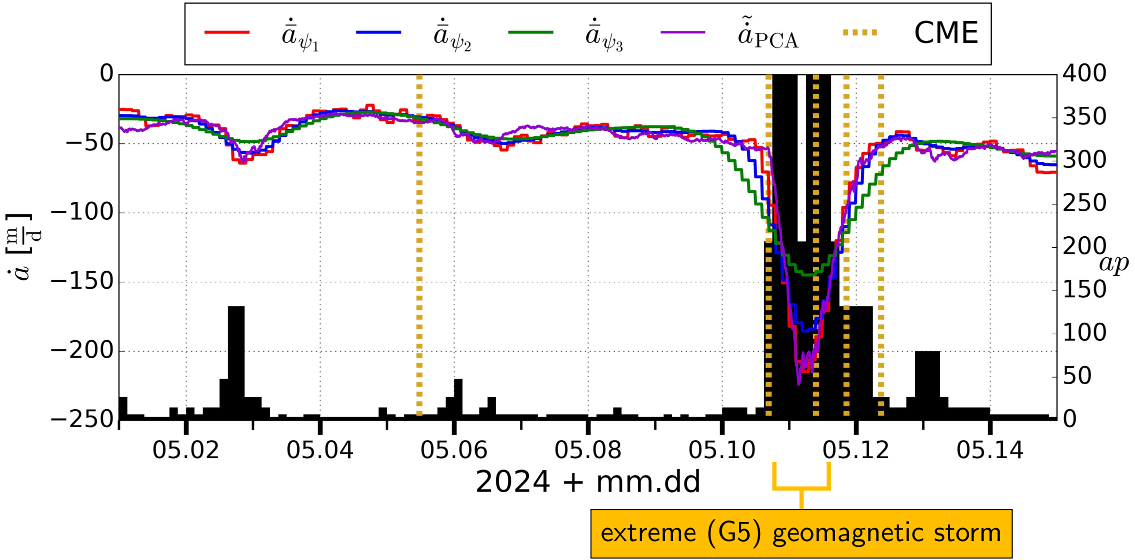
Altitude: $691\,\mathrm{km}$ - $709\,\mathrm{km}$



- PCA quality lower at day boundaries
- manoeuvres increase spikes

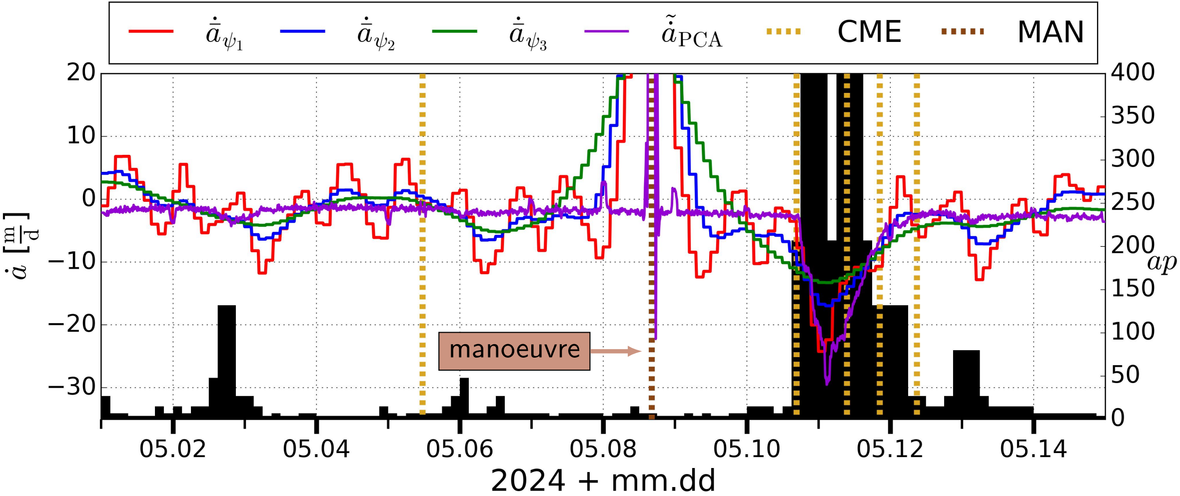
Swarm-A in 2024

Altitude: $464\,$km - $484\,$km



SENTINEL-2A in 2024

Altitude: 784 km - 802 km



Conclusion

Fit model approach

- problematic: low orbital decay, frequent manoeuvres and not modelled long periods
- strong constraining $\rightarrow$ underestimation of orbital decay during geomagnetic storm

Gaussian approach

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

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

Thank you for your attention!