SODA - a service to forecast space weather effects on LEO satellites

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Space weather

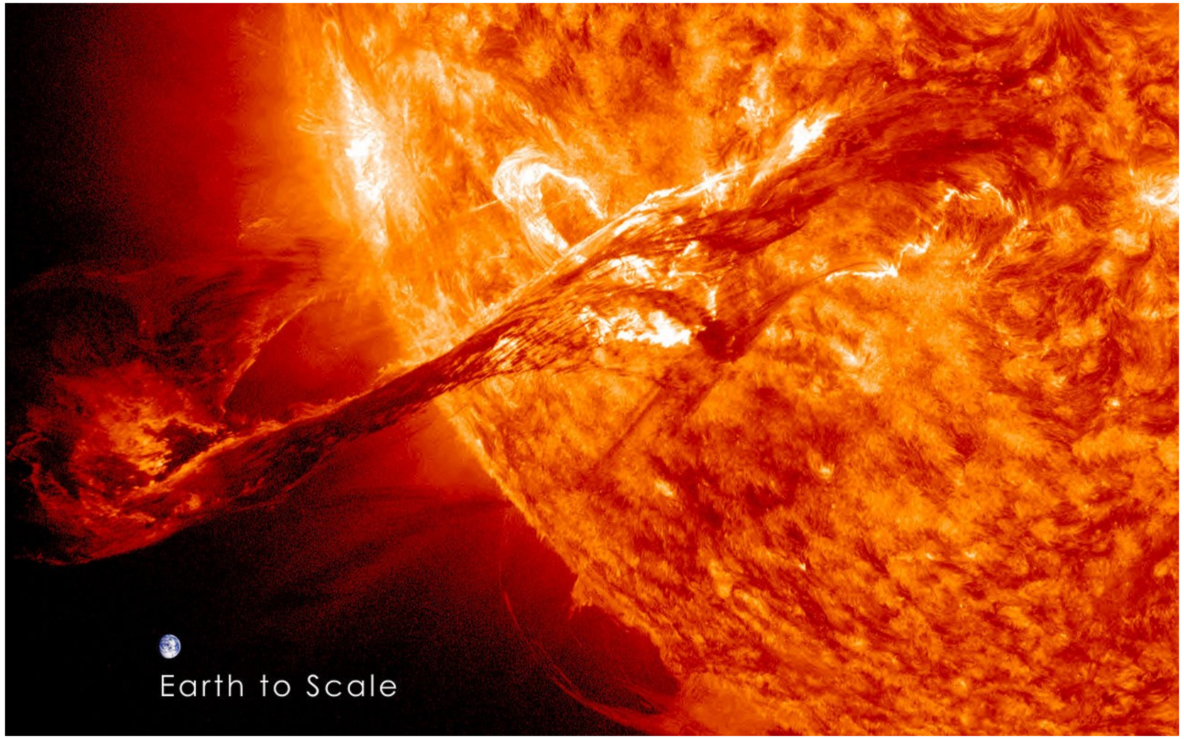
The term “Space Weather” deals with the dynamic conditions in the Earth’s outer space environment including the physical processes on the Sun, in the solar wind, the magnetosphere and in the upper atmosphere.

The strongest disturbances of the space environment are primarily caused by coronal mass ejections (CMEs). Their interaction with the Earth’s magnetic field has the potential to trigger geomagnetic storms and subsequently influence the Earth’s atmosphere.

Space weather

Quick facts:

- CMEs are huge clouds of magnetized plasma
  … up to 1 billion tons of solar material
- CME velocity 300 – 2000 km/s
- Transit time 1 – 5 days
- Interaction with Earth's magnetic field, capable to trigger geomagnetic storms
- Consequences:
  Blackouts (power supply), satellite loss, communication failure, satellite navigation, …



Space weather

SpaceX says a geomagnetic storm just doomed 40 Starlink internet satellites

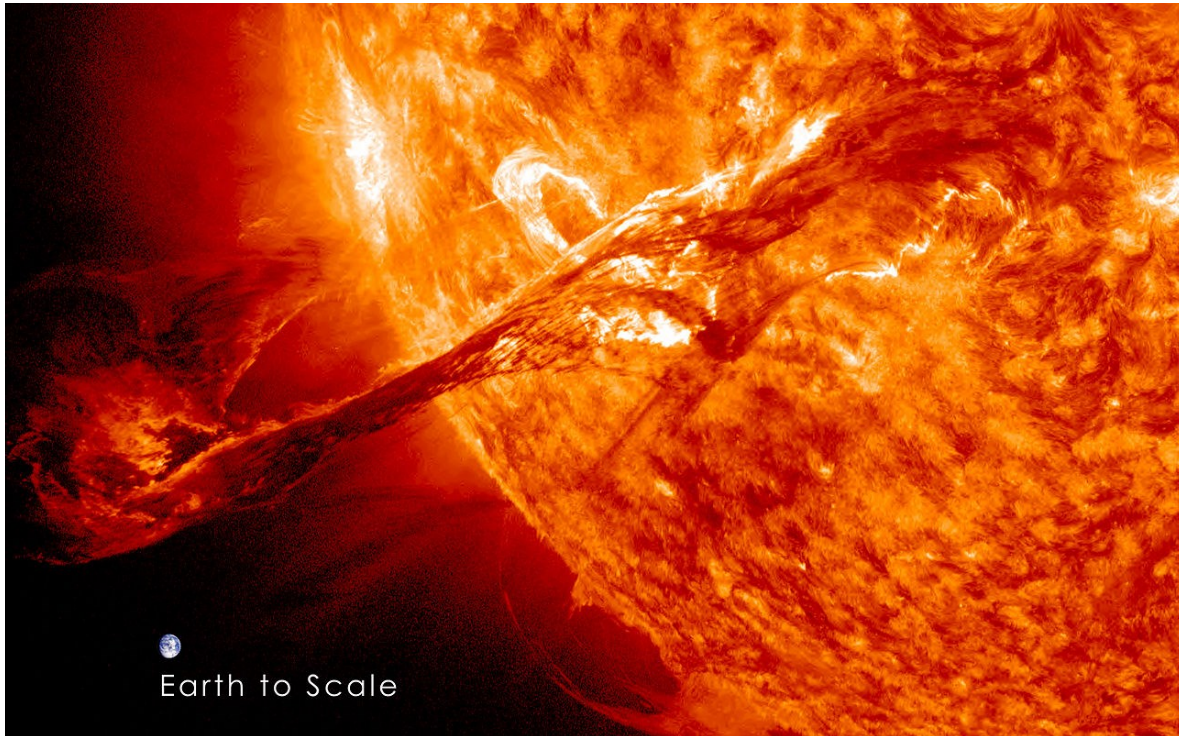
By Tariq Malik published 1 day ago

The satellites launched on Feb. 3, only to be hit by the storm a day later.

A SpaceX Falcon 9 rocket launches 49 Starlink internet satellites into orbit from Pad 39A of NASA's Kennedy Space Center in Cape Canaveral, Florida on Feb. 3, 2022. (Image credit: SpaceX)

SpaceX is in the process of losing up to 40 brand-new Starlink internet satellites due to a geomagnetic storm that struck just a day after the fleet's launch last week.

A SpaceX Falcon 9 rocket launched 49 Starlink satellites on Thursday (Feb. 3)



Space Weather Events

Carrington Event (1859):

- Most intense geomagnetic storm in recorded history.
- Telegraph systems all over Europe and North America failed and pylons threw sparks
- Auroras were seen around the world (Caribbean, China, Rome, Mexico, …)
- Modern estimates of Dst: -850 nT

March 1989:

- Collapse of the entire Hydro-Quebec power grid in Canada, 9h blackout for 6 Mio. people
- Damage to a transformer at a nuclear power plant in New Jersey
- Economic loss of about 6 billion USD [Bolduc 2002, Erinmez et al. 2002]
- Dst index: -589nT

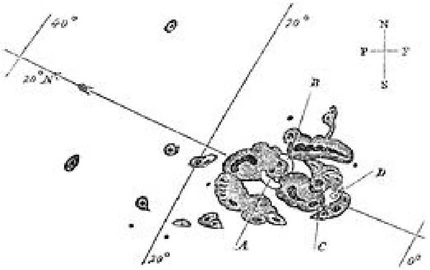
October 2003 ("Halloween event"):

- Transformer damages in Malmö (90-min. blackout)
- Anomalies in the signalization systems of railway networks in Russia [Eroshenko et al. 2010]
- 10% of satellites recorded anomalies, 1 satellite was lost (Midori-2), 10 satellites lost operational service for more than one day [Webb and Allen 2004]
- Dst index: -383nT

July 2012:

- Carrington type event
- NOT Earth directed CME (9 days aside), cost estimates $0.5-2.7 trillion USD [Lloyd 2013] if Earth directed

Definition of storm intensity (Oliveira et al. 2019)		
Storm intensity	**Category**	**Dst-index**
Minor	G1 (Kp=5)	Dst ≥ -50 nT
Moderate	G2 (Kp=6)	-100 ≤ Dst < -50nT
Strong	G3 (Kp=7)	-150 ≤ Dst < -100nT
Severe	G4 (Kp=8, 9-)	-250 ≤ Dst < -150nT
Extreme	G5 (Kp=9o)	Dst < -250 nT



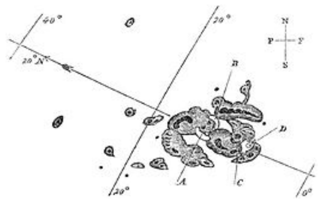
Sunspots of 1 September 1859, as sketched by Richard Carrington.

Permanent damage to the Salem New Jersey Nuclear Plant GSU Transformer (@ NASA)

Space Weather Events

Carrington Event (1859):

- Most intense geomagnetic storm in recorded history.
- Telegraph systems all over Europe and North America failed and pylons threw sparks
- Auroras were seen around the world ()
- Modern estimates of Dst range from -800 nT to a staggering -1750 nT



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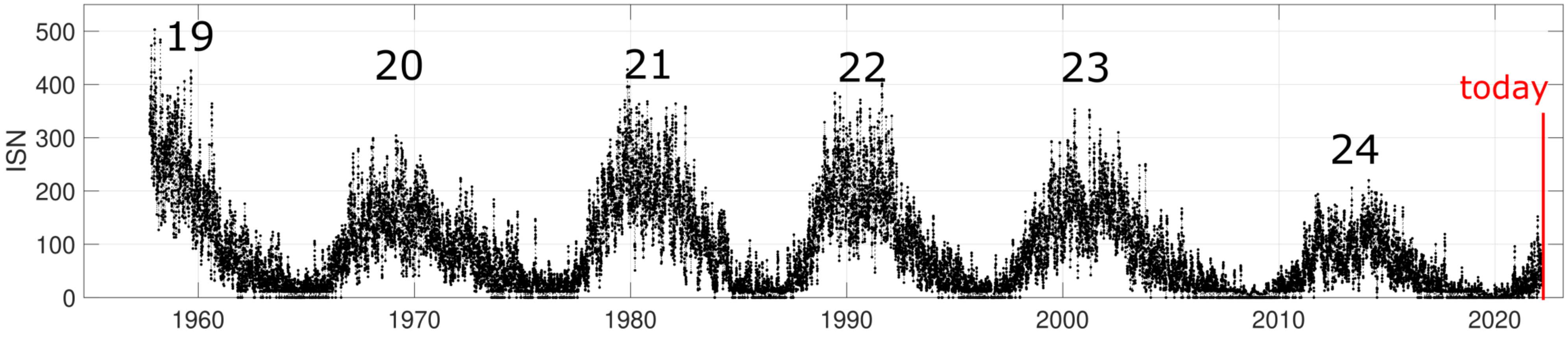


ESA – Saftey and Security

ESA established in 2009 the Space Situational Awareness Program to watch for objects and natural phenomena that could harm satellites in orbit or infrastructure such as power grids on ground. As of 2019 developed segments are part of

Planetary Defense Office:

"Detecting natural objects such as asteroids that can potentially impact Earth and cause damage."

Space Debris Office:

"Watching for active and inactive satellites, discarded launch stages and fragmentation debris orbiting Earth."

Space Weather Office:

Provide owners and operators of critical spaceborne and ground-based infrastructure timely and accurate information to enable mitigation of the adverse impacts of space weather.

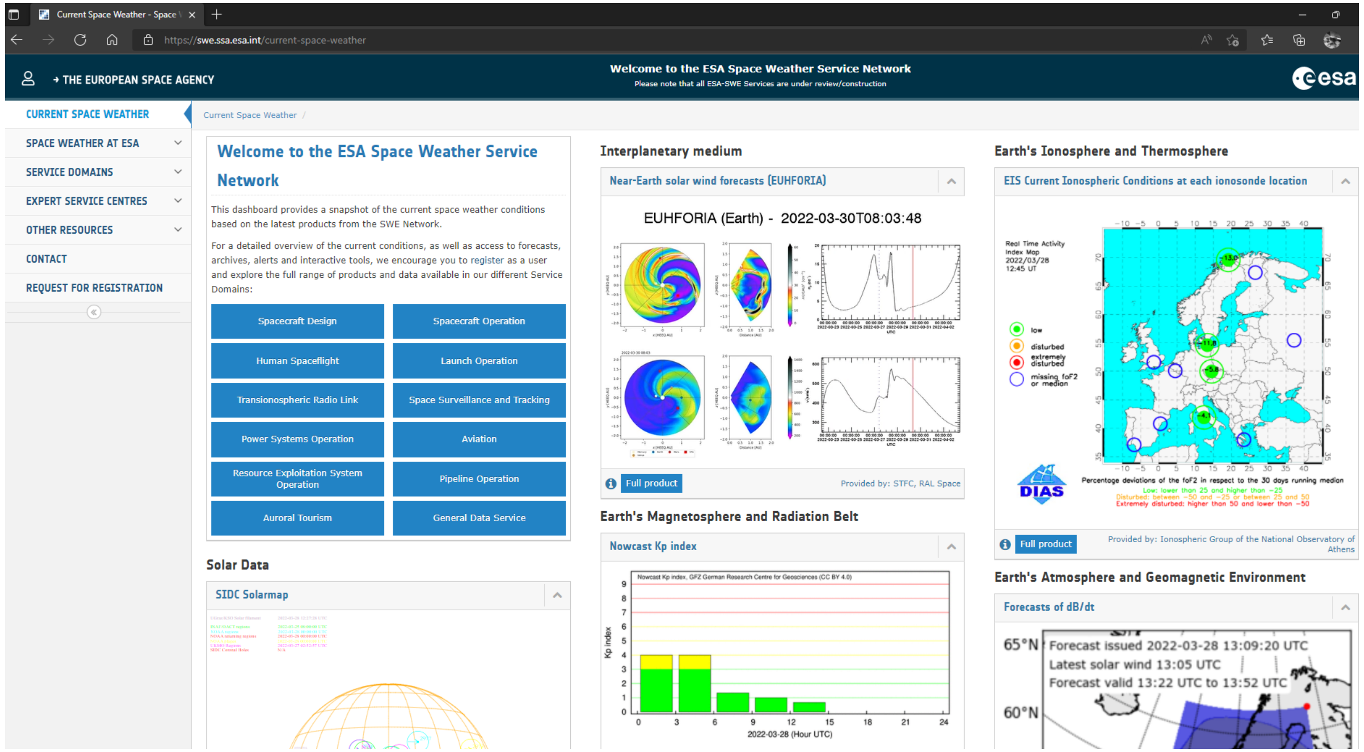
Space Weather Service Network (SWESNET) https://swe.ssa.esa.int/ssa-space-weather-activities

Five Expert Service Centres (ESCs), which build on existing expertise and link a network of approximately 40 Expert Groups

- Solar Weather
- Space Radiation
- Ionospheric Weather
- Geomagnetic Conditions
- Heliospheric Weather

Project SODA

- SODA is carried out within the Space Weather Service Network (SWESNET) program
- SODA tool is developed within the FFG national project (2020-2022) SWEETS
  - We currently run a validation campaign to approve our product
  - For the next portal release (planned in autumn 2022), SODA will become part of the Ionospheric Expert Service Center (I-ESC)



- All services from the ESCs can be found under the portal: https://swe.ssa.esa.int/expert-centres

Project SODA

SODA (Co-I)

Service for orbit decay analysis
Duration: 01.02.2021 – 01.09.2023
Funded by: European Space Agency (ESA)
Cooperation: University Graz, Institute of Physics

SWEETS (PI)

Forecasting space weather effects on low Earth orbiting satellites
Duration: 01.07.2020 – 31.07.2022
Funded by: Austrian Research Promotion Agency (FFG)
Cooperation: University Graz, Institute of Physics

AIM

Development of **a short-term forecasting model, to predict the expected impact of solar events**, like coronal mass ejections (CMEs), on satellites at different altitudes between 300-800 km

Combined evaluation of solar wind plasma and magnetic field data, combined with thermospheric neutral density estimates from various satellites

Forecasting space weather effects on LEO satellites

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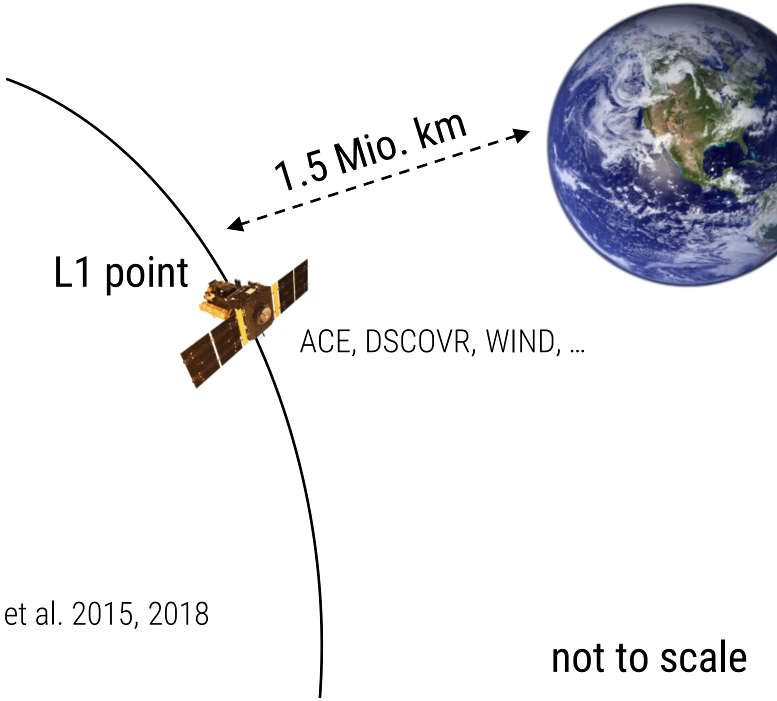
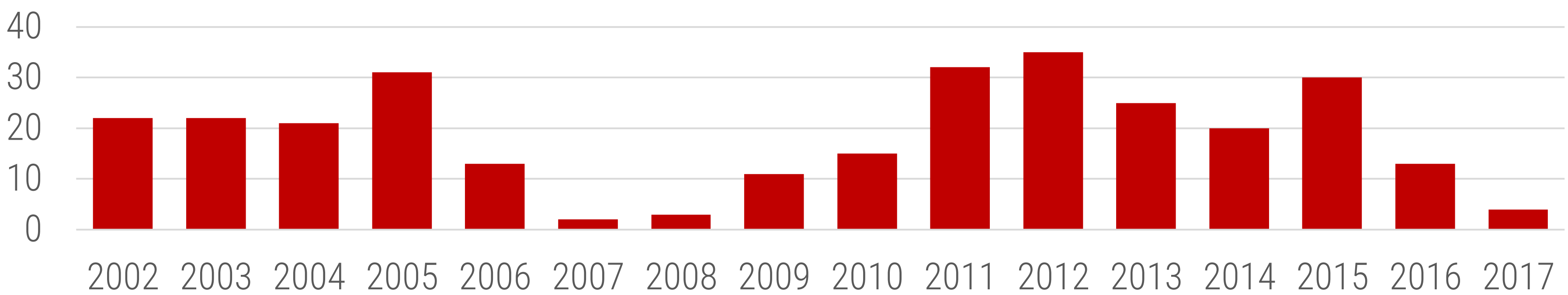


Krauss et al. 2015, 2018

Analyzed 299 CME events: 12.04.2002 - 27.05.2017



Forecasting space weather effects on LEO satellites

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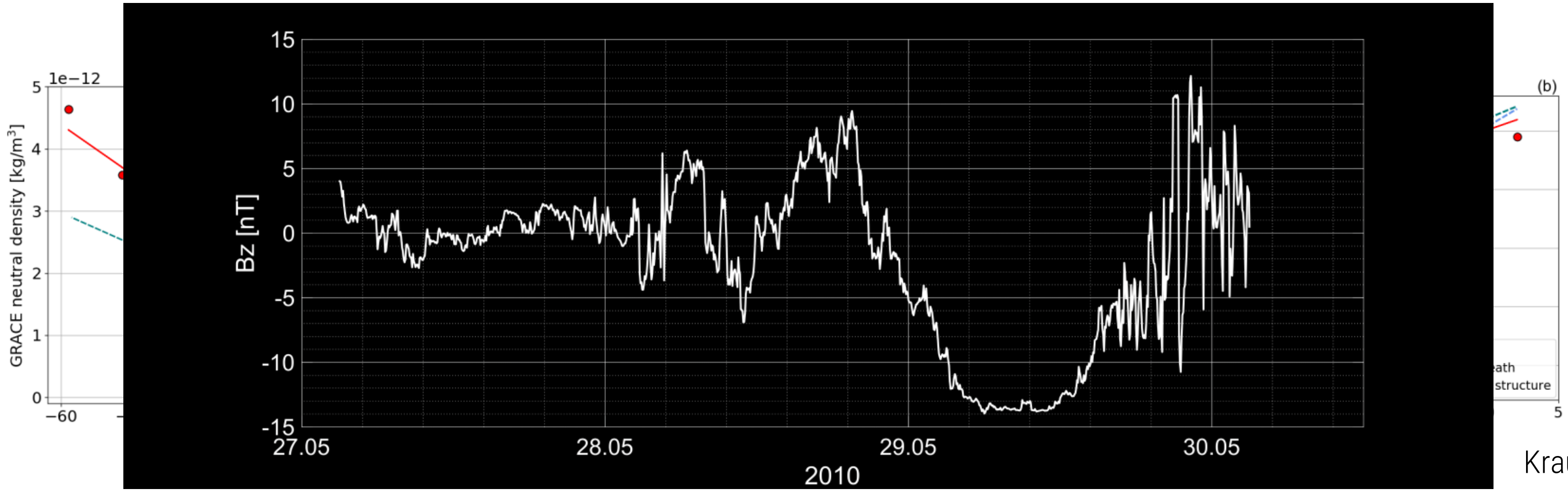

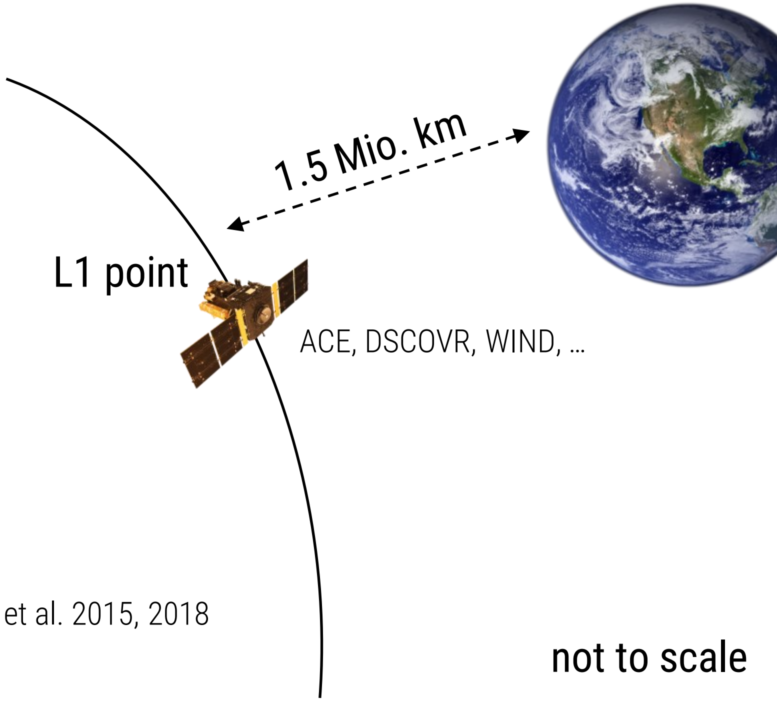

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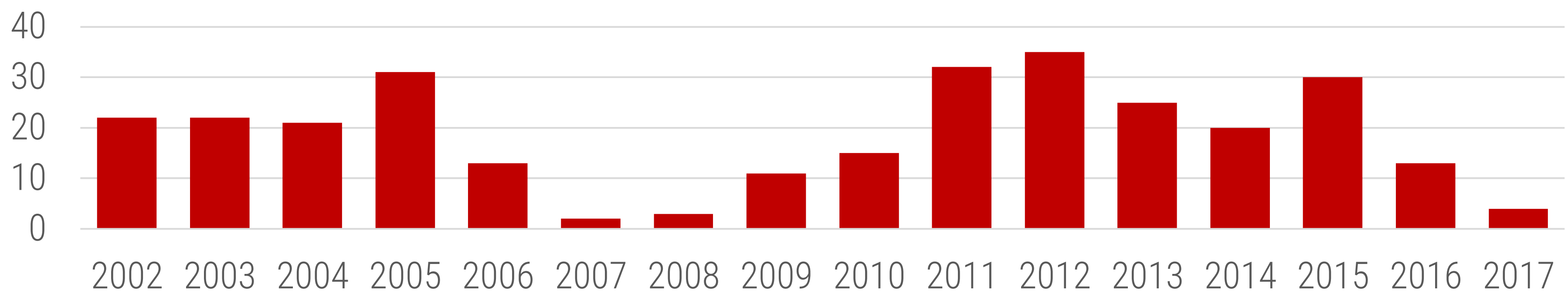

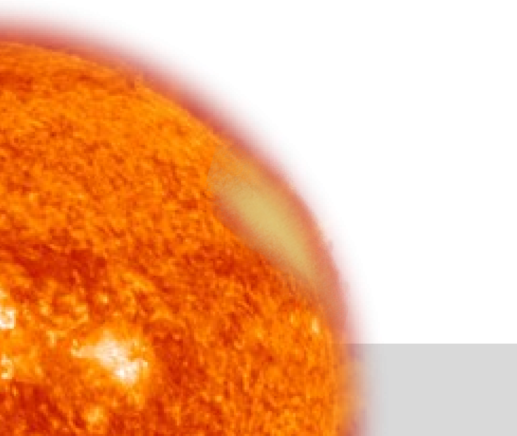

how to
estimate neutral mass densities

Neutral density estimation

Doornbos (2012), Krauss (2013)

Relation between acceleration due to drag and neutral mass density

$$\vec{a}_d = \sum_i -\frac{1}{2}\rho\frac{A_i}{m}C_F v_r^2 \frac{\vec{v}_r}{\|\vec{v}_r\|}$$

- $\vec{a}_d$: acceleration due to atmospheric drag
- ρ: neutral mass density
- m: satellite mass
- A_i: satellite area
- C_F: drag & lift coefficient
- $\vec{v}_r$: satellite velocity (w.r.t co-rotating atmosphere)

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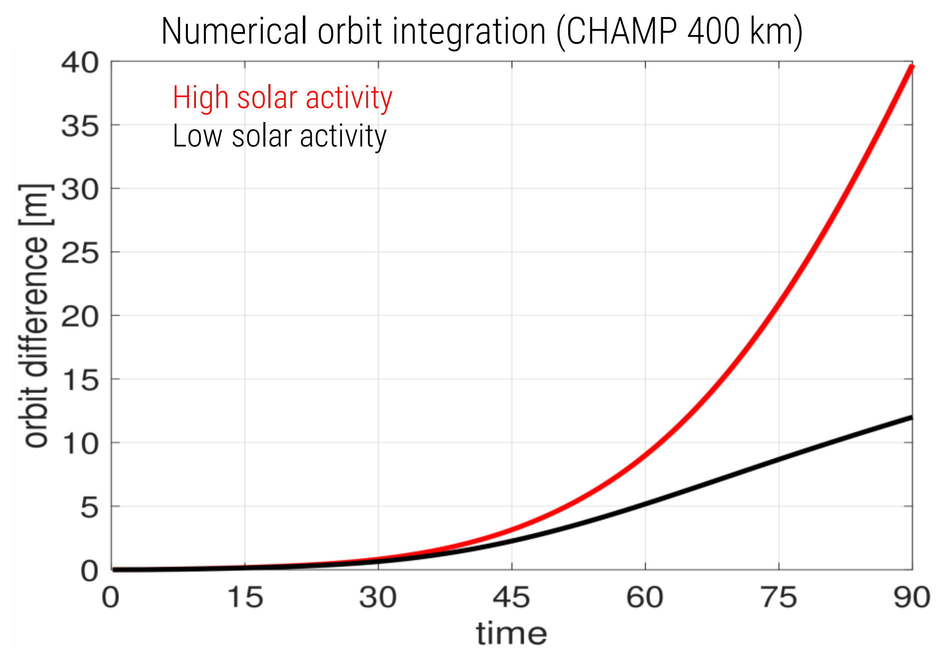
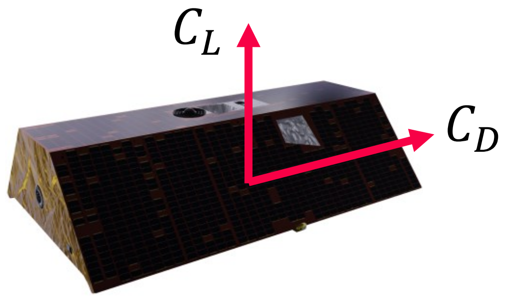


constant vs. variable drag coefficient



- Highly, variable quantity
- Physical properties of the satellite surface

  Satellite macro model including reflectivity information
- Assumptions on the flow regime

  Free molecular flow, random thermal motion
- Depends partially on atmospheric state (T, m_m)

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acceleration due to atmospheric drag

neutral mass density

satellite mass

satellite area

drag & lift coefficient (highly variable quantity)

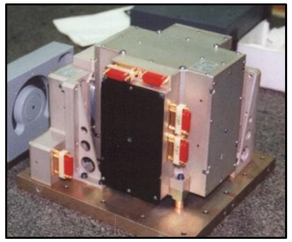
satellite velocity (w.r.t co-rotating atmosphere)

Approach 1: On-board accelerometer (CHAMP, GRACE, GRACE-FO)

Instrument is located at the center of mass and measures all non-gravitational accelerations acting on the satellite and attitude control operation.

- Atmospheric drag
- Spacecraft thermal re-radiation (SRR)
- Solar radiation pressure (SRP)
- Earth radiation pressure (ERP)

Temporal resolution for science use (Level-1B): 1 second



source GFZ Potsdam

Approach 2: Kinematic orbit information (Satellites equipped with GNSS receivers)

Neutral density estimation

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Approach 1: On-board accelerometer (CHAMP, GRACE, GRACE-FO)

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Accelerometer measurements → Accelerometer calibration → undesired non-grav. accelerations → (Atmospheric drag force, $\rho = f(a_d, m, C_F, A, v)$) → Thermospheric mass density

SRP, ERP, SRR → undesired non-grav. accelerations

Klinger and Mayer-Gürr (2016)

Vielberg and Kusche (2020)
Krauss et al. 2020

Kinematic approach

Relation between acceleration due to drag and neutral mass density

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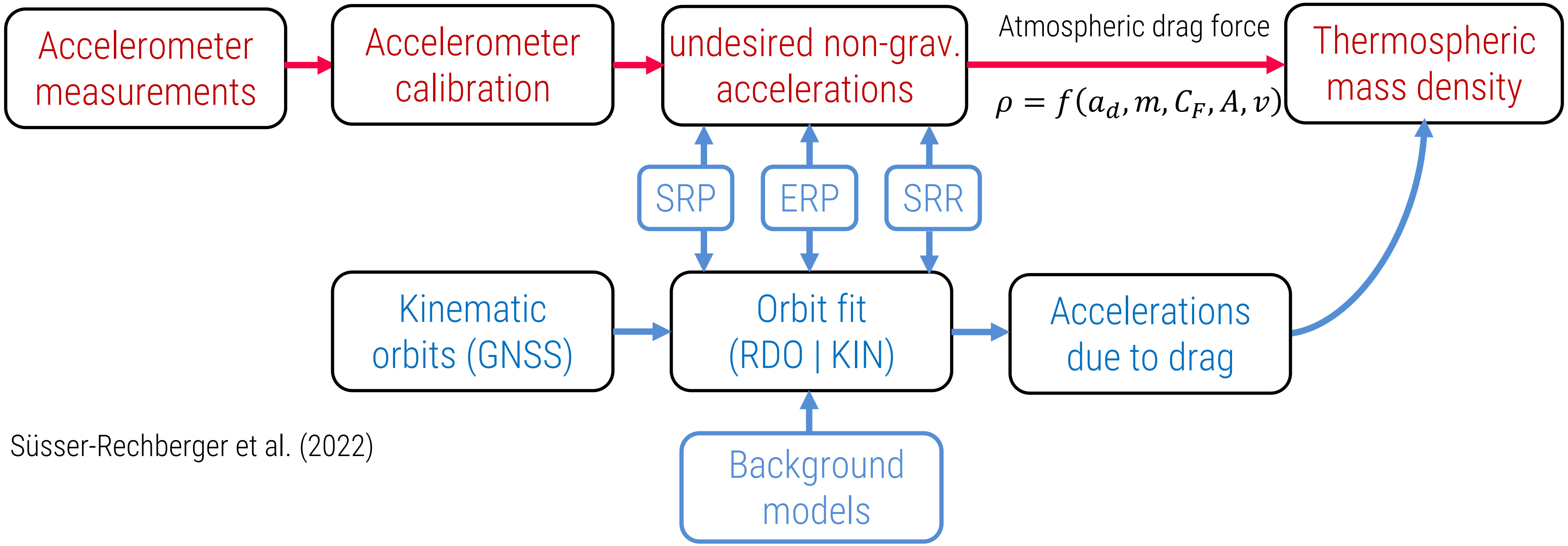

Süsser-Rechberger et al. (2022)

Neutral density estimation

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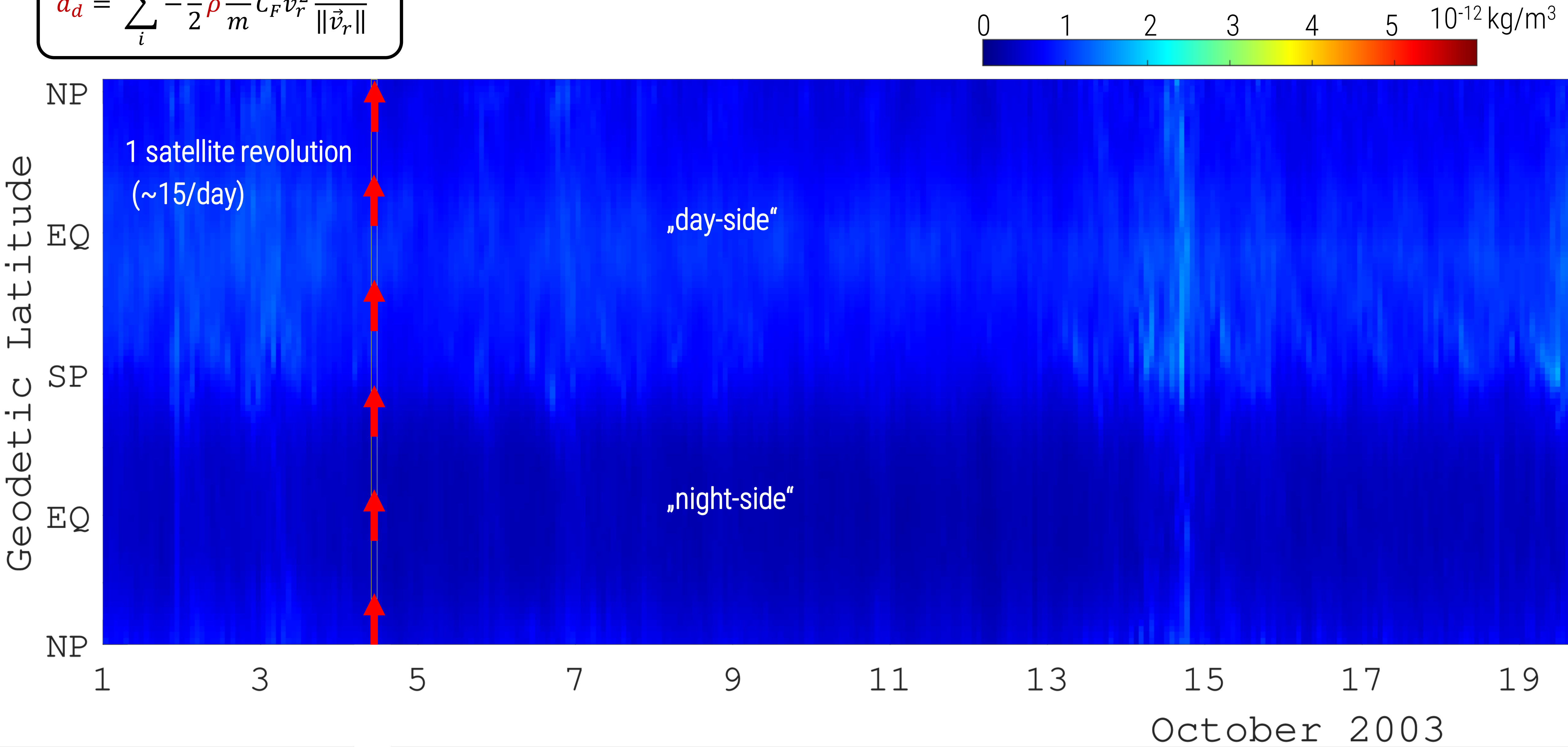

Neutral density estimation

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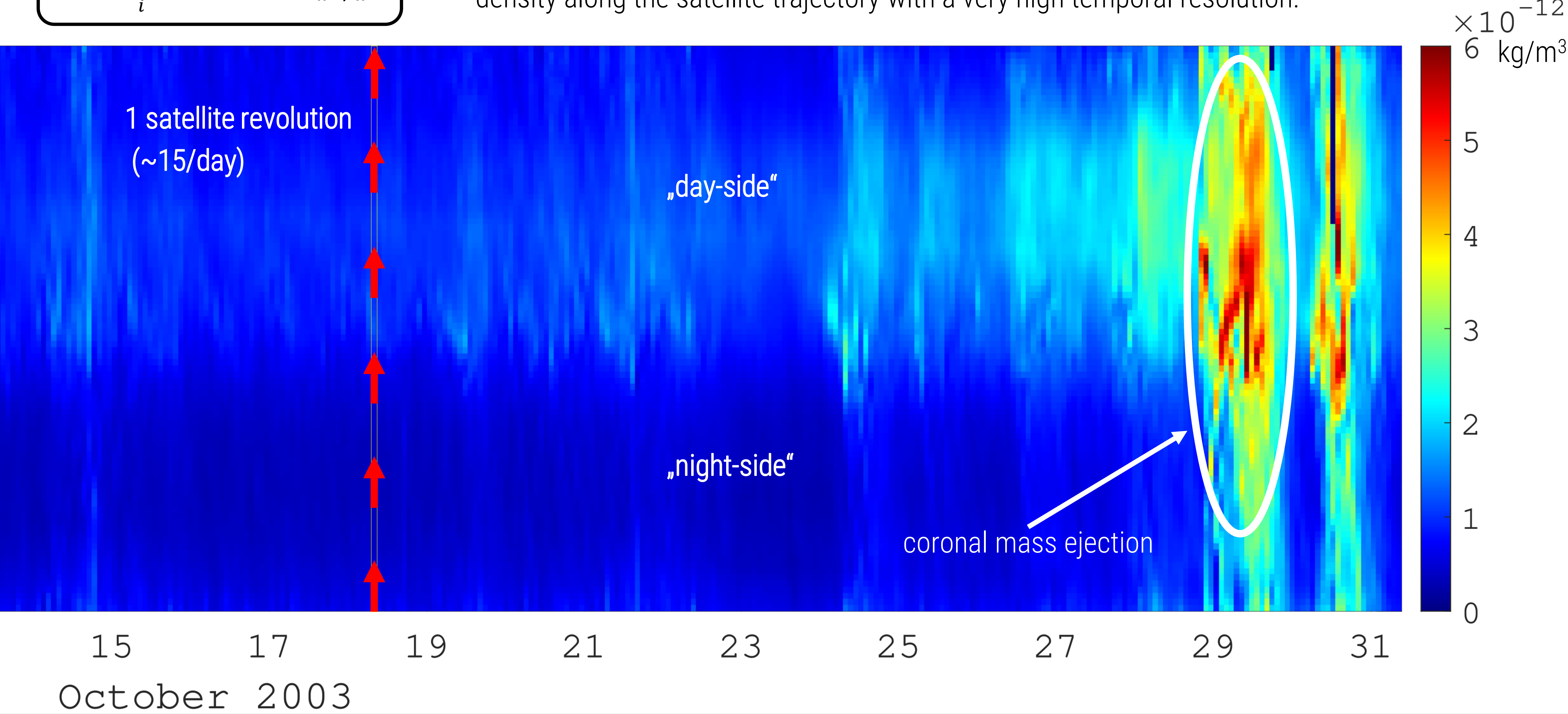
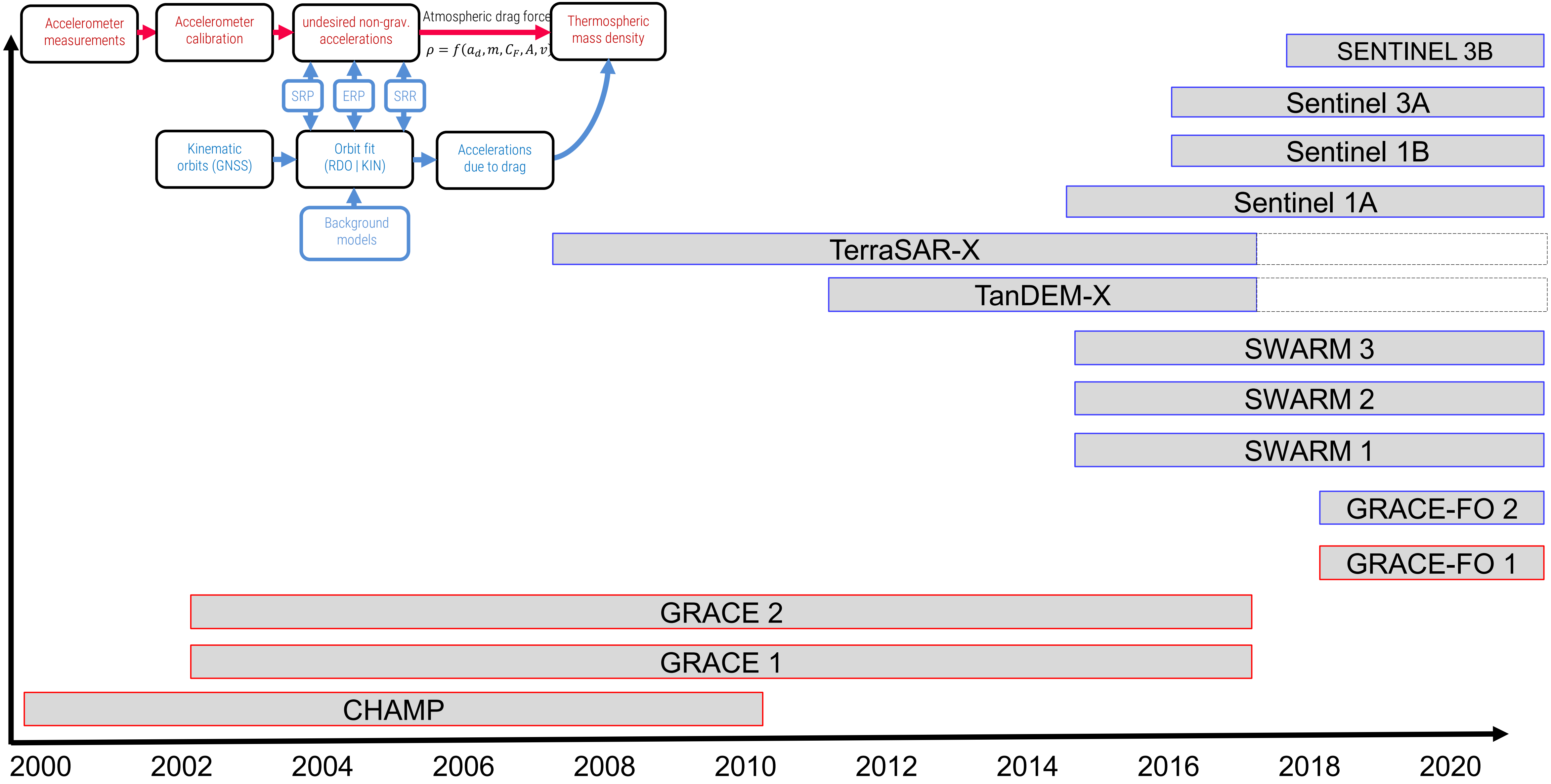
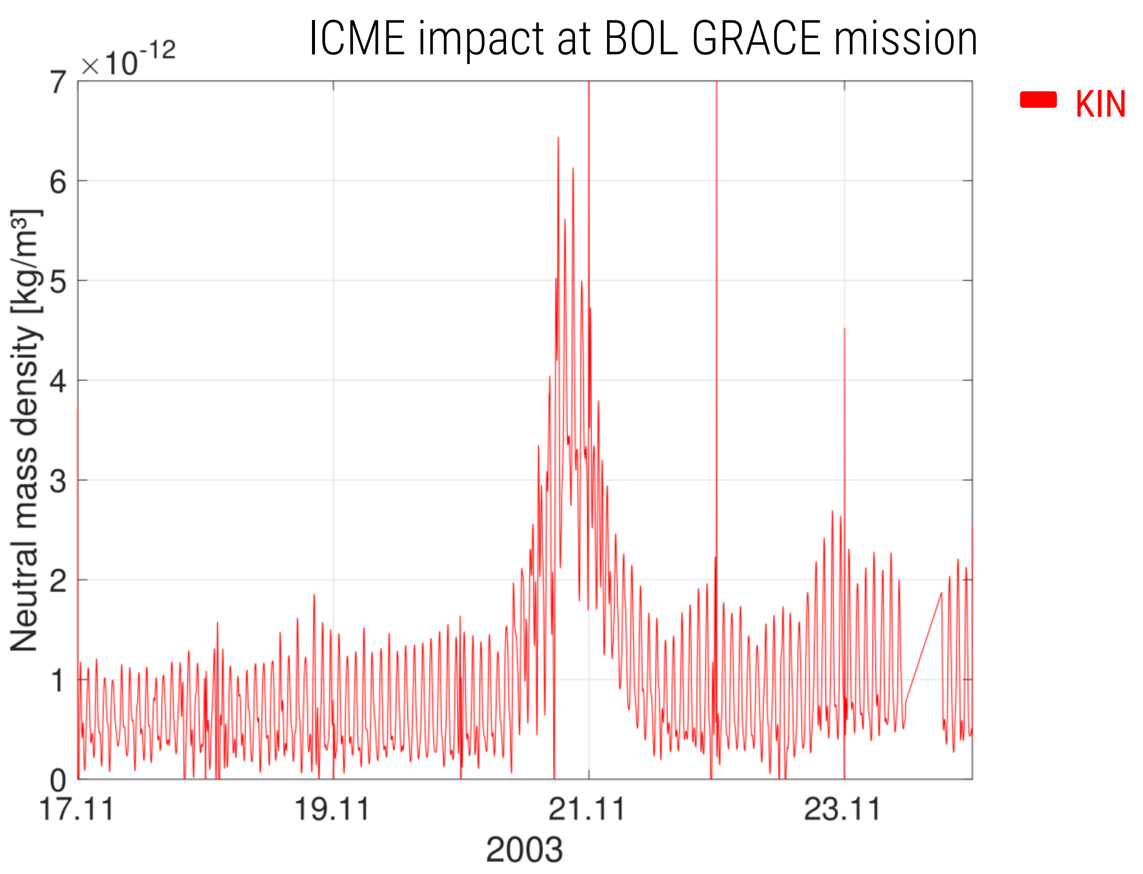
Based on accelerometer measurements we can monitor the neutral mass density along the satellite trajectory with a very high temporal resolution.

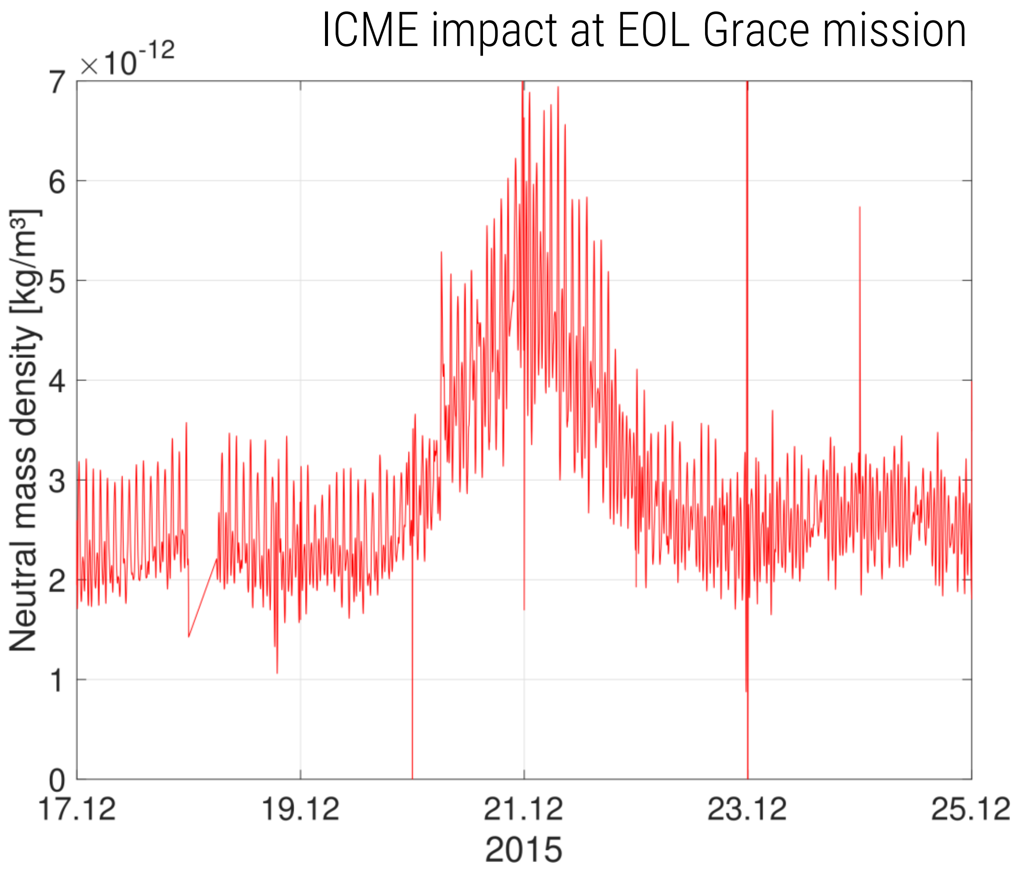


Currently processed satellites



Acc. vs. kin. approach





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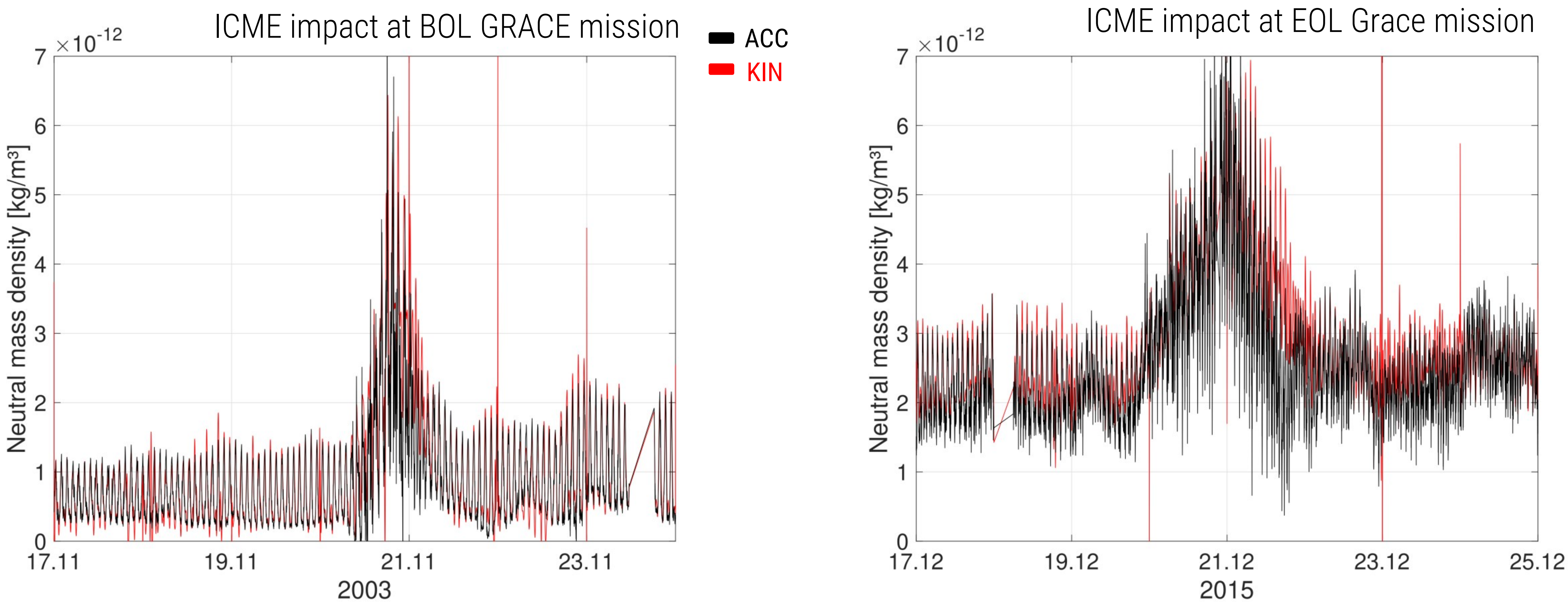
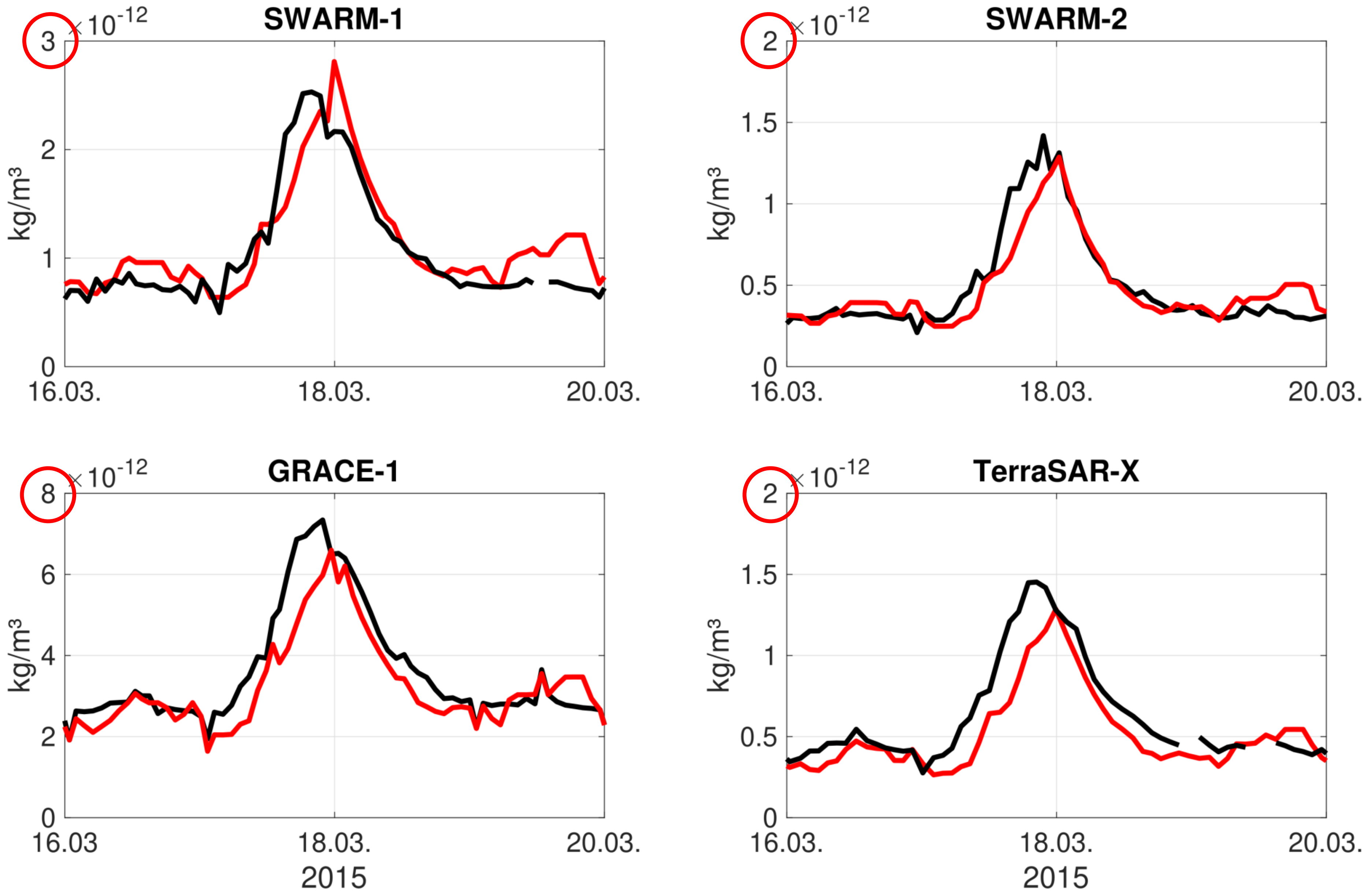


Side note: multi-mission analysis

Mean density per revolution
Satellite observation
Model (JB2008)

470 km

520 km



420 km

525 km

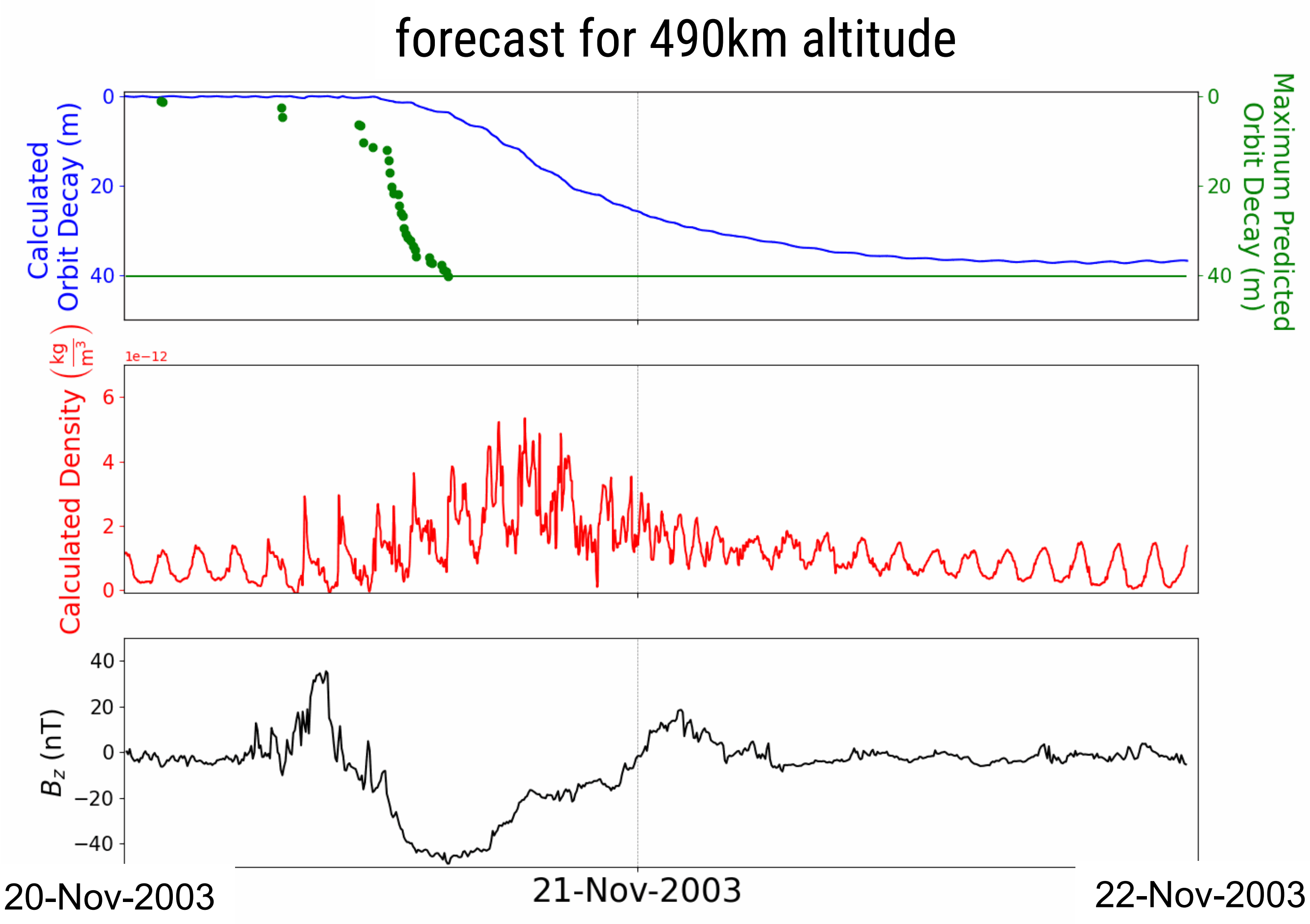
SODA: Service for orbit decay analysis

Aim:
Development of **a short-term forecasting model, to predict the expected impact of solar events**, like coronal mass ejections (CMEs), on satellites.

Storm-induced satellite orbit decay

$$\frac{da}{dt} = -\Delta\rho \frac{C_F A}{m} \sqrt{GM\bar{a}} \cdot \psi(e)$$

- $\Delta\rho$: density increase
- $\frac{C_F A}{m}$: ballistic coefficient
- GM: gravity parameter
- $\bar{a}$: mean semi-major axis
- $\psi(e)$: eccentricity function



Krauss et al. (2020)

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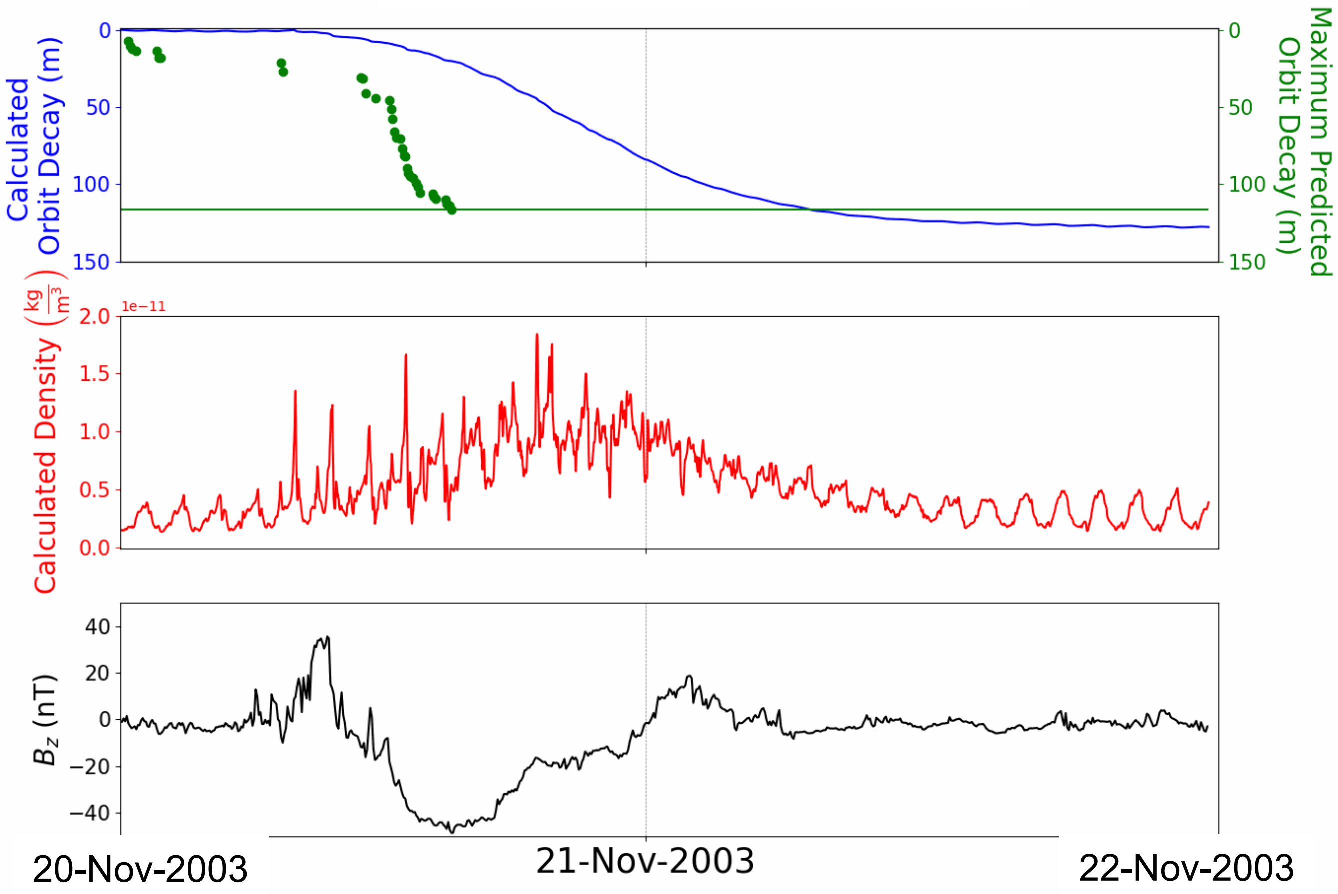
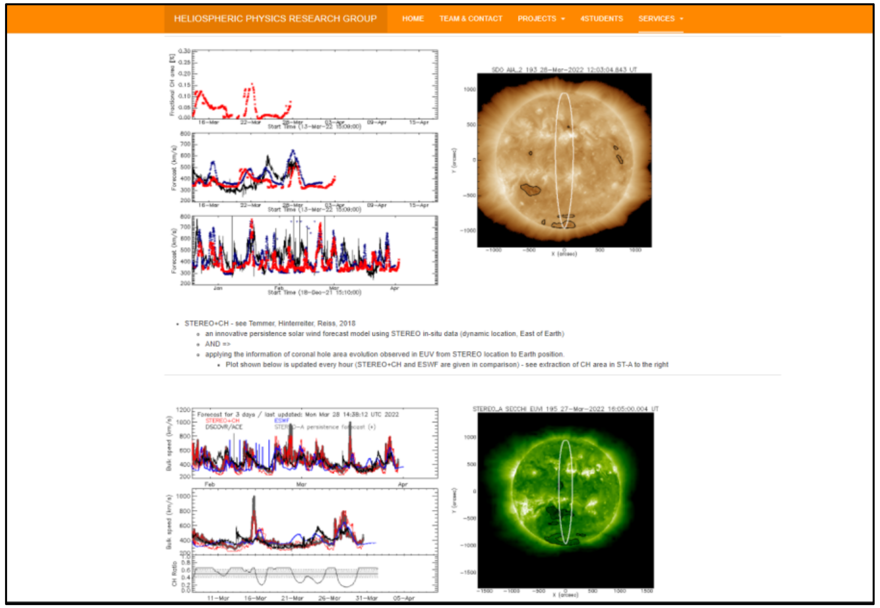
Krauss et al. (2020)

forecast for 400km altitude

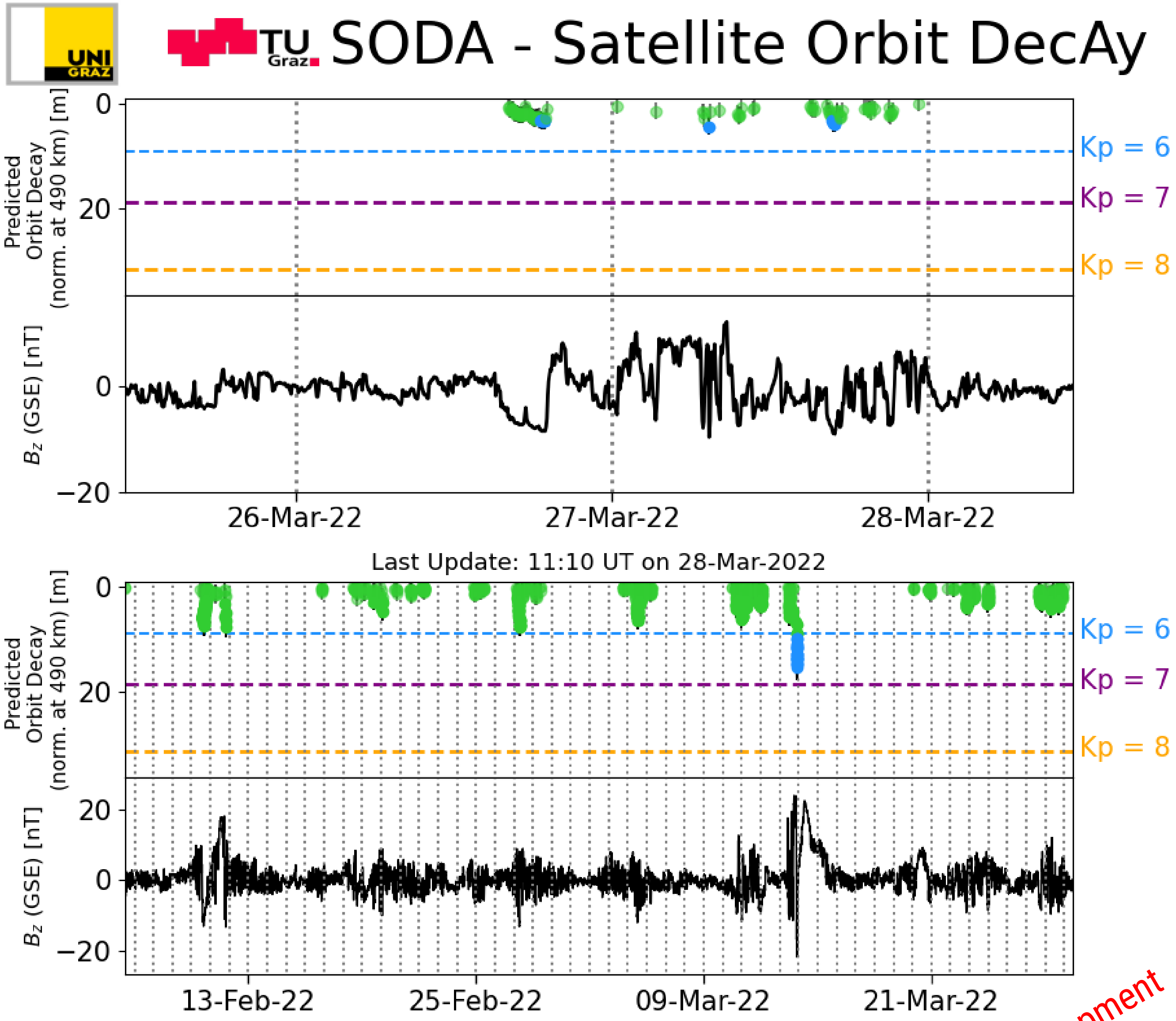


Service for orbit decay analysis:

Heliospheric Research Group (University of Graz)



https://swe.uni-graz.at/index.php/services/esa-space-safety-services



under development

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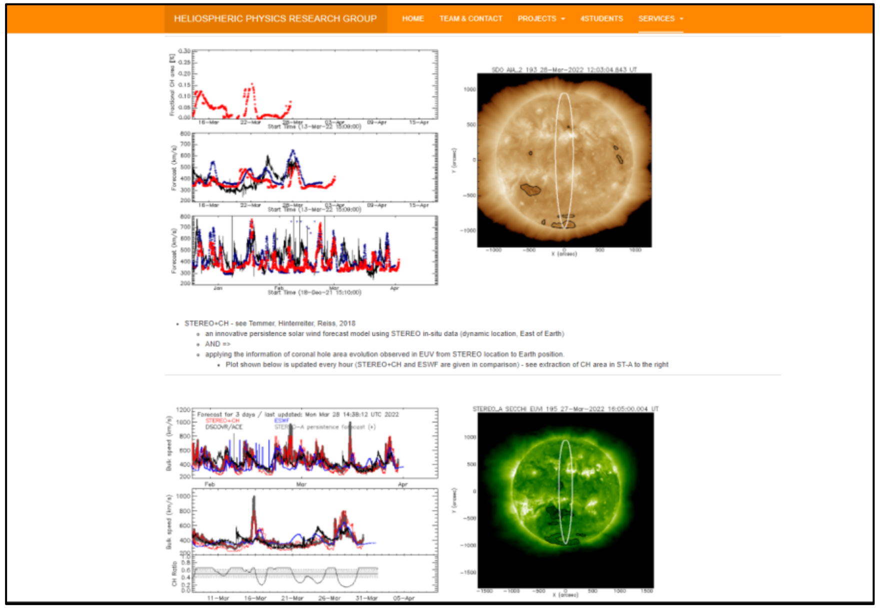

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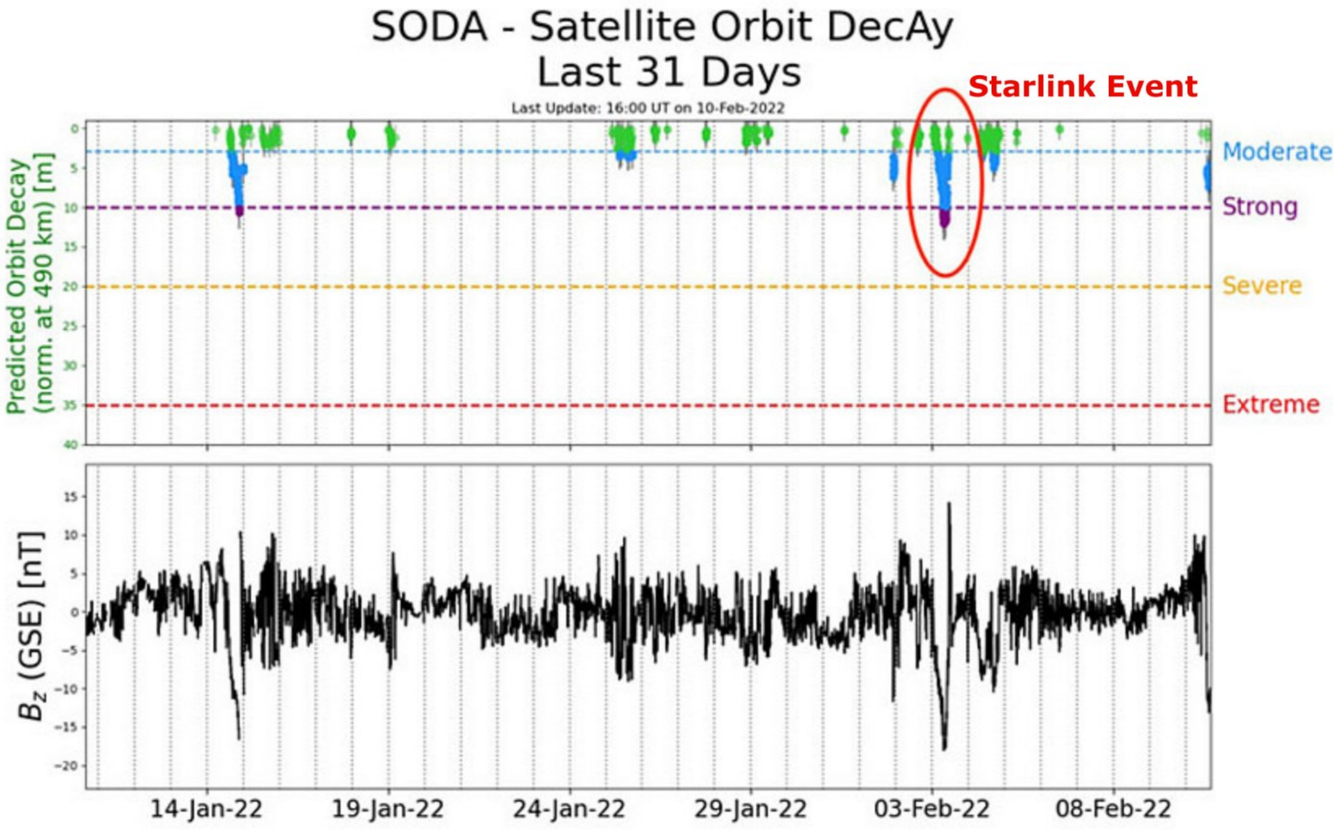

Thank you for your attention