Analysis of a severe geomagnetic storm on August 26, 2018 and the related effects on the GRACE-FO mission

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Content

Estimation of ICME induced disturbances of the upper Earth atmosphere and the associated orbit decay of the low Earth orbiting satellites from the GRACE Follow-on mission (GRACE-FO)

Severe geomagnetic storm occurred on August 26, 2018

Satellites of interest: GRACE Follow-on (GRACE-FO)
Advanced Composition Explorer (ACE)

Data basis:

- Magnetic field component B_z (measured at L1 by ACE)
- Accelerometer observations from GRACE-FO

Krauss S., Behzadpour S, Temmer M. and Lhotka C. (2020): Exploring thermospheric variations triggered by severe geomagnetic storm on August 26, 2018 using GRACE Follow-On data, J. Geophys. Res., Space Physics, 10.1029/2019JA027731

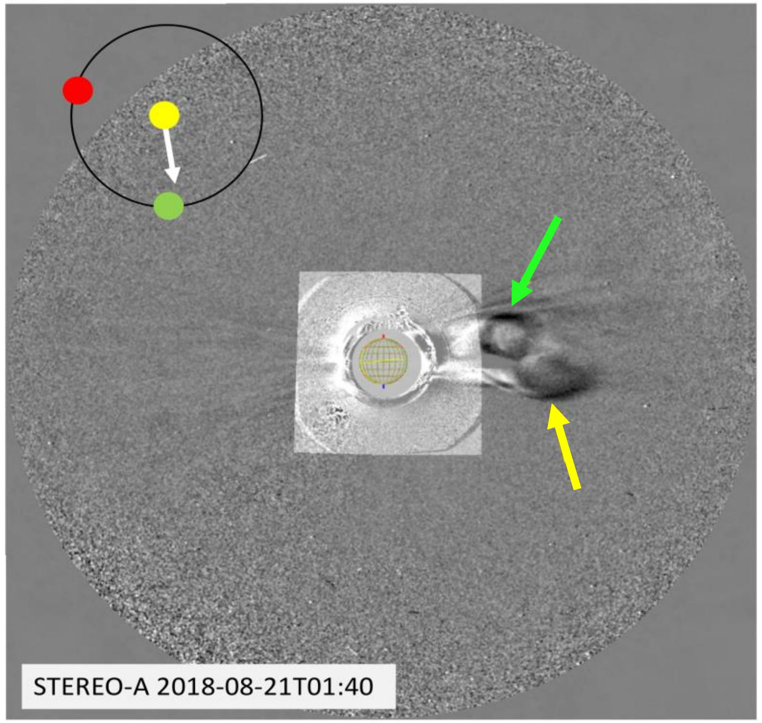
ICME event on August 21, 2018

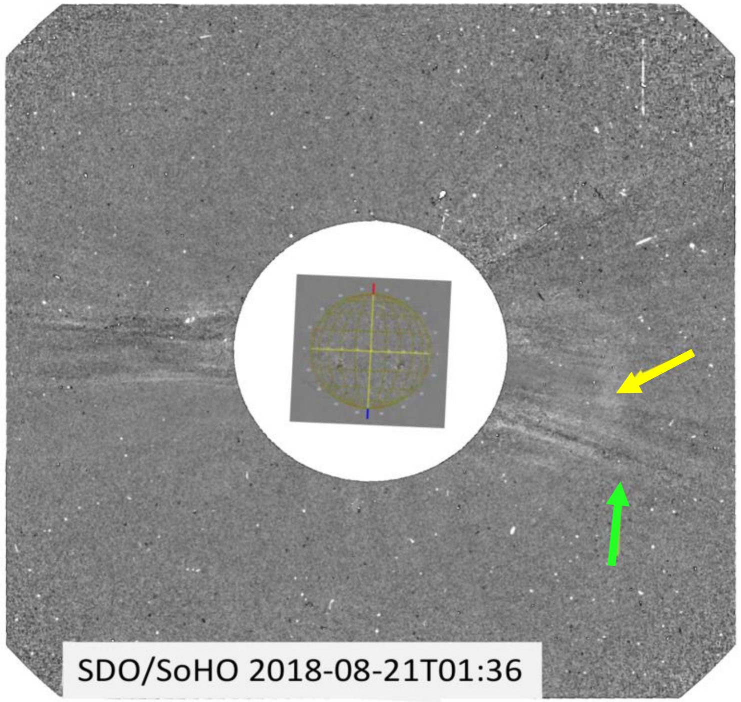
"Interplanetary coronal mass ejections (ICME) are huge clouds of magnetized plasma propagating from the solar corona into interplanetary space, which often reveal a typical three part structure" (*Illing and Hundhausen, 1985*).

This specific event had a **unexpected strong impact** on the near-Earth environment and **forecasters did not see this coming**. LASCO observations assess the CME to be only a very poor event of low density.

However, **more details** on the CME flux rope structure can be revealed from the **STEREO-A perspective**. This includes streamer structures, which now become visible as straight lines, that refer actually to open fields.

The event has being related to a **filament channel eruption**. According to Hα data, plasma material is embedded in the elongated channel that is actually becoming the CME. As can be seen from EUV, the area involved in the eruption is **surrounded by coronal holes**.





Left: In the top, the position of STEREO-A (red dot), L1 (green dot) and the Sun (yellow dot) together with the estimated ICME direction of motion (white arrow). Right: SOHO located at L1: The yellow and green arrows refer to closed and open magnetic field structures *[Composite images were prepared with JHelioviewer]*.

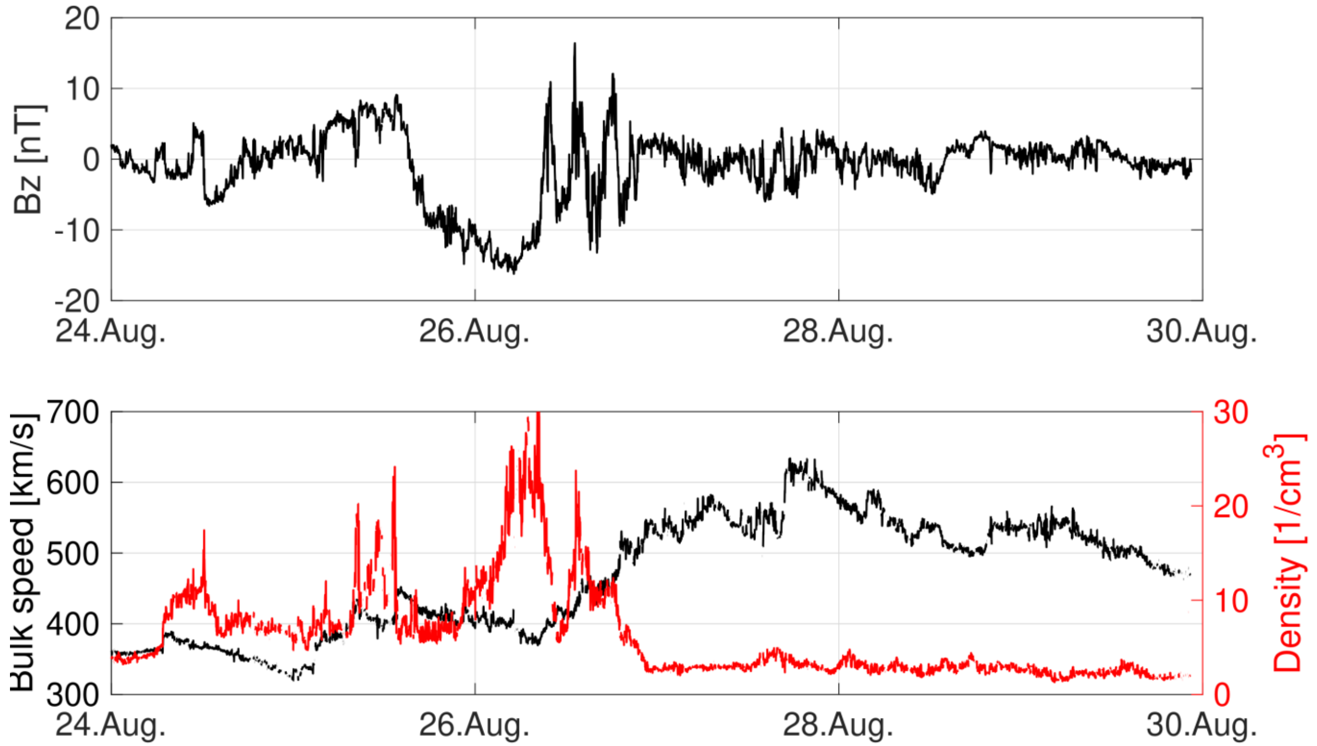
Interplanetary observations: ACE

Advanced Composition Explorer (ACE):

Analysis is based on solar wind flow speed (proton bulk speed) and in-situ measurements of the magnetic field component Bz (GSE); Level-2 data products, with a time resolution of 4 minutes *(OMNI database; King and Papitashvili, 2004)*

The profile shows a weak disturbance coming from the rather slow ICME (av. speed of ~420 km/s) and the embedded flux rope structure (min. Bz=16.32 nT) with a duration of roughly 24 hours.

The ICME signature is followed by a high speed solar wind streams (HSS) with a maximum speed of ~650 km/s. We assume that, the interaction between the weak ICME and the HSS leads to the enhanced geomagnetic effect (see also Heinemann et al. 2019)



Top: Illustration of the solar wind IMF (Bz component in GSE) during the CME event on August 26, 2018.
Bottom: Black and red curves represent the plasma speed and proton density profiles, respectively.

For more details see: Krauss et al. 2020

Near-Earth observations: GRACE Follow-On

Gravity Recovery And Climate Experiment Follow-On (GRACE-FO)

- Partnership between NASA and the German Research Centre for Geosciences (GFZ).
- Successor to the original twin-satellite GRACE mission, which orbited Earth from 2002-2017.
- Successful launch on May 22, 2018 from Vandenberg Airforce Base, California.
- Instrument of interest: SuperStar-Accelerometer

To mitigate the primary errors in the GRACE-D accelerometer data - spurious measurements of high frequency signals and bias jumps which occur commonly in all-axes accelerometer data from GRACE-C are transplanted to GRACE-D after June 21, 2018 [McCullough et al. 2019].

Thus, for the current study we solely analyse accelerometer measurements directly recorded by GRACE-C satellite.

Data availability

The first Level-1 data products were made publicly available on May 24, 2019 from the NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC) and the GFZ's Information System and Data Center (ISDC) and date back to June 2018.

Quick facts - gracefo.jpl.nasa.gov/

Spacecraft
Width: 1.94 meters
Length: 3.12 meters
Height: 0.72 meters

Mass: 600 kg
Near polar inclination of 89°
Mission altitude: 490 km

Distance between spacecraft:
220 km on average

Velocity: 7.5 km/s
Orbits per day: ~15

From the observation to the desired parameter

Get/Calibrate
Level-1b ACT1B

cf.: Kornfeld et al. 2019, Klinger et al. 2016

Remove: disturbing forces
Obtain: drag force

cf.: Wetterer et al. 2014, Fahnestock et al. 2012, Montenbruck et al. 2015, Vielberg et al. 2020

Apply:
Shadow function

cf.: Vokrouhlicky et al. 1993, Robertson et al. 2015

Estimated:
Neutral mass density

cf.: Bruinsma et al. 2006, Sutton 2008, Dornboos et al. 2009, Krauss et al. 2012

Calculate:
Satellite orbit decay

cf.: Chen et al. 2012, Krauss et al. 2015, 2020

For more details see: Krauss et al. 2020

Non-gravitational accelerations

Remove: disturbing forces to obtain drag force

Since the satellite-borne accelerometers measures the sum of all non-gravitational forces, the influence of disturbing accelerations in the observations must be reduced in advance.

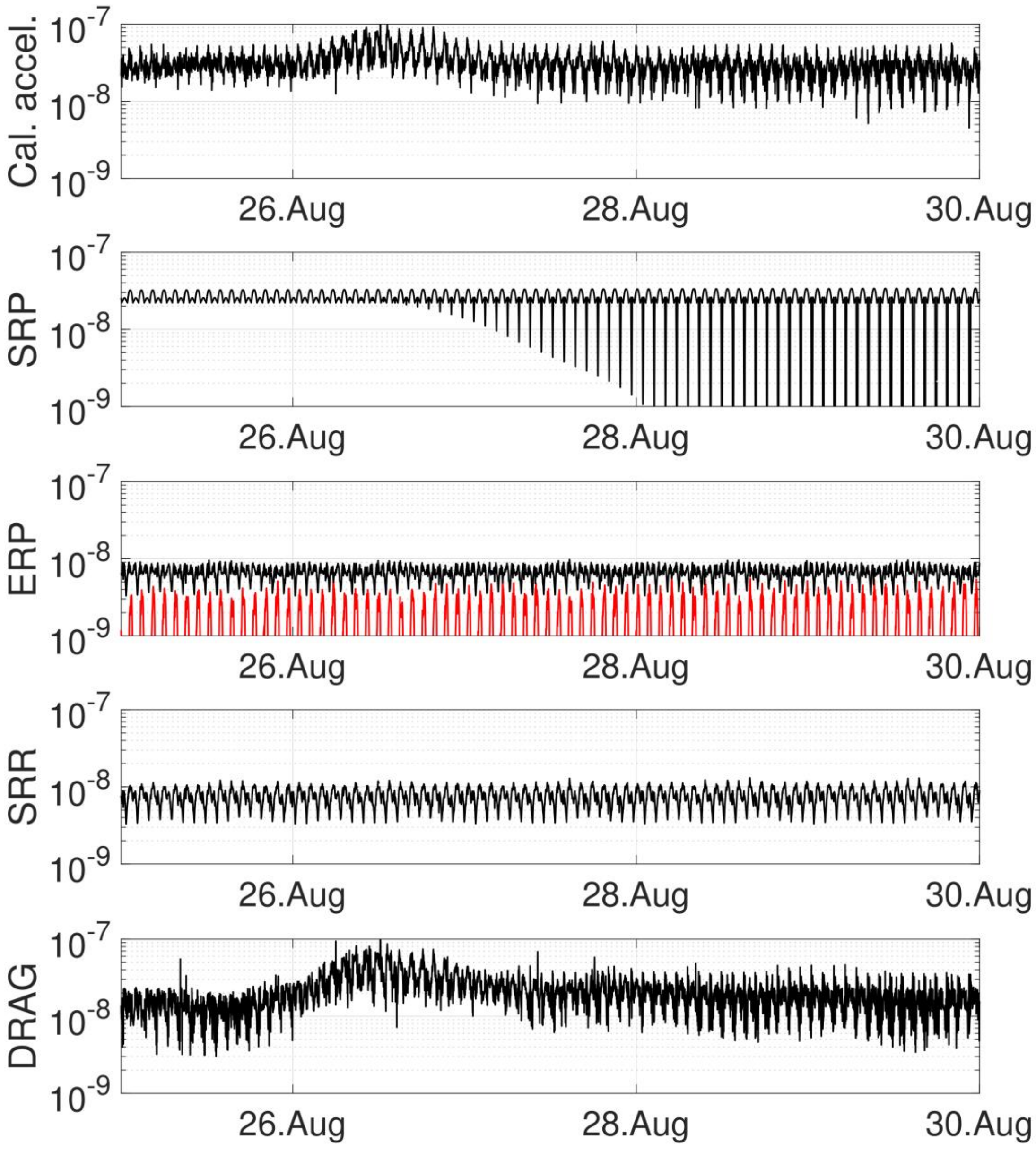
This includes:

- Solar radiation pressure (SRP)
  We use daily total solar flux values based on version-17 data from the Solar Radiation and Climate Experiment (SORCE) satellite
  see Wetterer et al. 2014

- Re-radiation of the Earth (ERP) - visible and infrared
  by using Clouds and the Earth's Radiant Energy System (CERES) outgoing radiation product
  see Vielberg and Kusche 2020

- Spacecraft re-radiation (SRR)
  see Fahnenstock et al. 2012, Montenbruck et al. 2015

processing steps



Calibrated accelerations of GRACE-C (units are ms^{-2}), accelerations due to SRP, ERP (visible (red) and infrared range (black)), SRR and the final estimated non-gravitational accelerations due to atmospheric drag.

For more details see: Krauss et al. 2020

Estimated thermospheric mass densities

Equation for aerodynamic drag:

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

a_d ... *acceleration due to drag (estimated in the previous steps)*

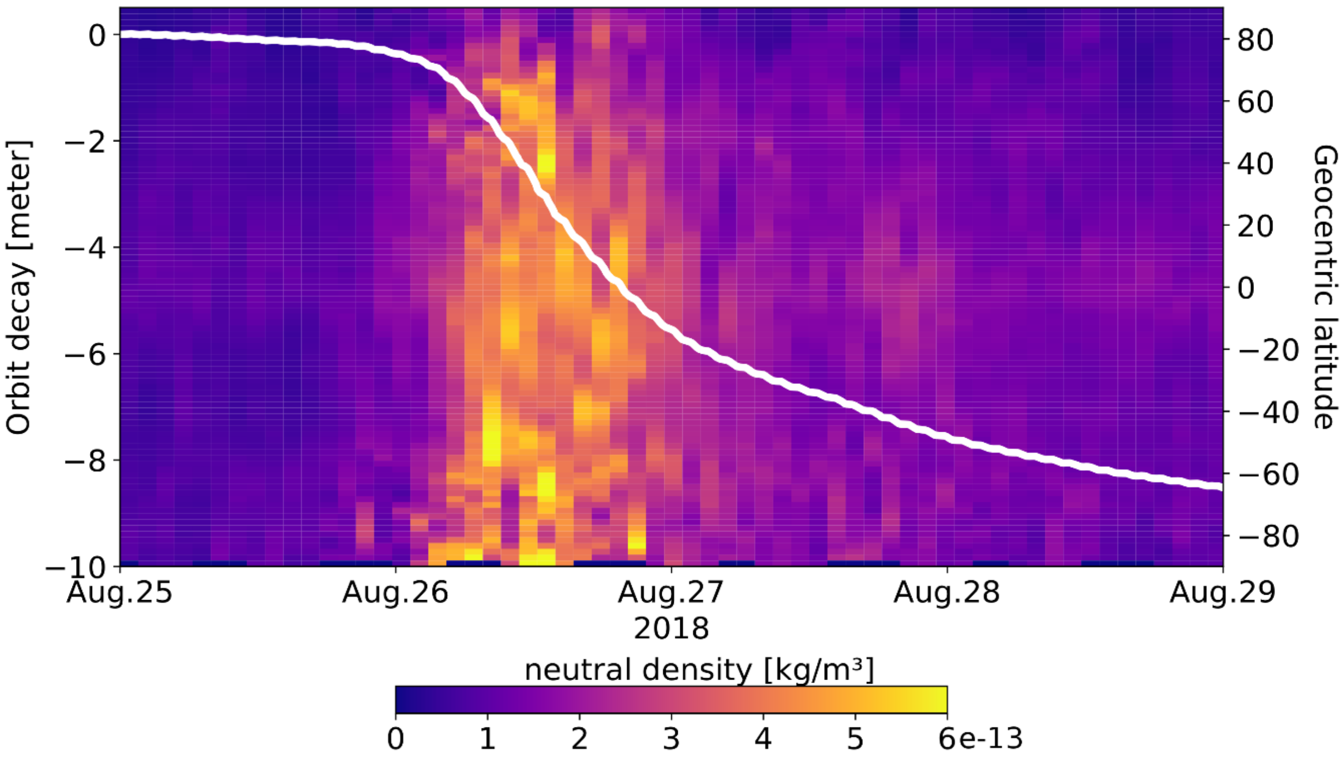
ρ ... *neutral mass density*

A_i ... *satellite plate area*

m ... *satellite mass*

$C_{F,i}$ ... *sum of variable drag and lift coefficients*

v_r ... satellite velocity relative to the co-rotating atmosphere, including the horizontal wind model (HWM14)



Estimated, normalized thermospheric neutral densities together with the storm-induced orbit decay (white line) during the perturbed period starting on Aug. 26, 2018.

For more details see: Krauss et al. 2020

Estimated thermospheric mass densities

Calculate: Satellite orbit decay

$$\frac{da}{dt} = -\Delta\rho \frac{C_F A}{m}\sqrt{GM\bar{a}} \cdot \frac{(1+2e\cos(\nu)+e^2)^{3/2}}{(1-e^2)^{3/2}} \simeq -\Delta\rho \frac{C_F A}{m}\sqrt{GM\bar{a}} \cdot \psi(e)$$

e … eccentricity, ν …. true anomaly, $\bar{a}$ … mean semi-major axis
GM … standard gravitational parameter of the Earth
Δρ … storm induced density variations (relative to background density)

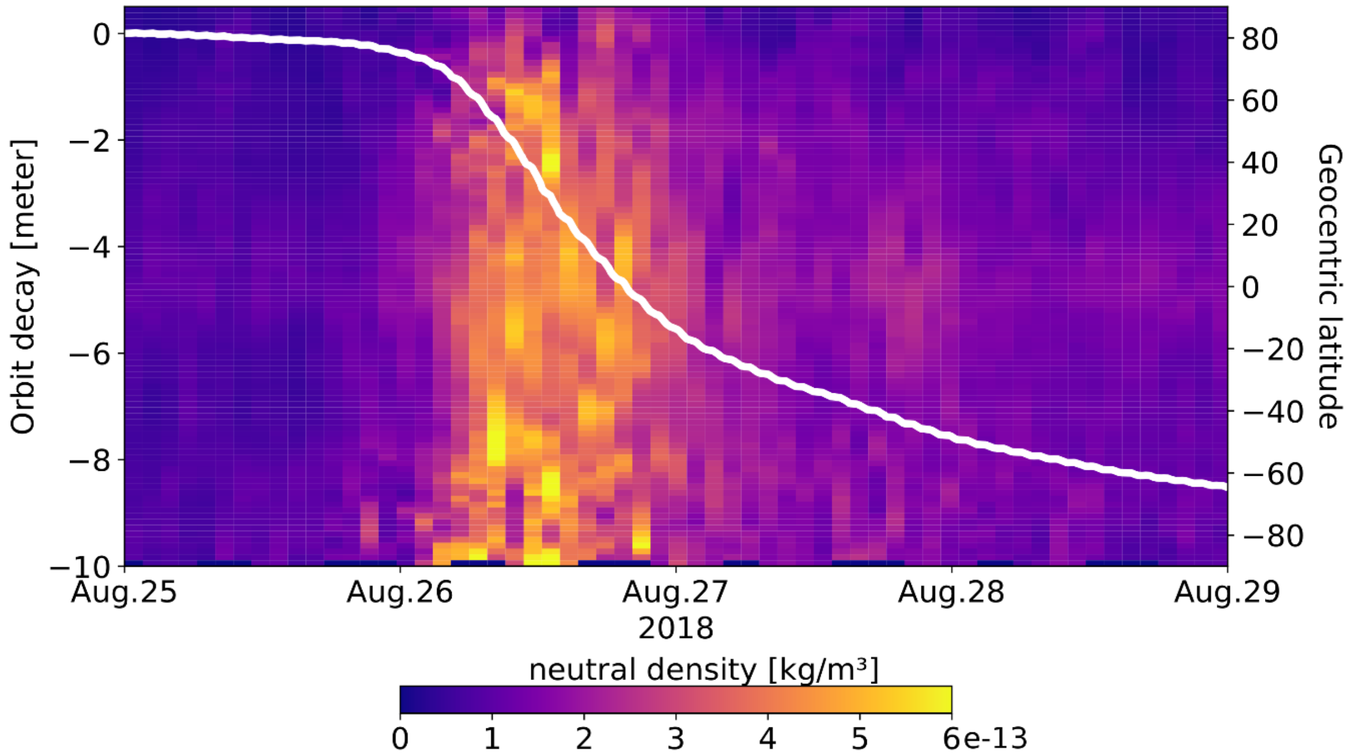
Orbit decay as the comprehensive representation of the temporal change of the semi-major axis da/dt.

With the eccentricity function

$$\psi(e) \simeq \frac{1}{2\pi}\int_0^{2\pi} \psi(M,e)dM = 1 + \frac{3e^2}{2} + \frac{21e^4}{32} + O(e^6)\ .$$

Numerical values for the mean contribution of ψ(e) over one full orbital revolution:

eccentricity	0.0	0.1	0.2	0.3	0.4	0.5
approx. ψ	1.000	1.008	1.031	1.070	1.128	1.207



Estimated, normalized thermospheric neutral densities together with the storm-induced orbit decay (white line) during the perturbed period starting on Aug. 26, 2018.

For more details see: Krauss et al. 2020

Results: Comparison with predicted values

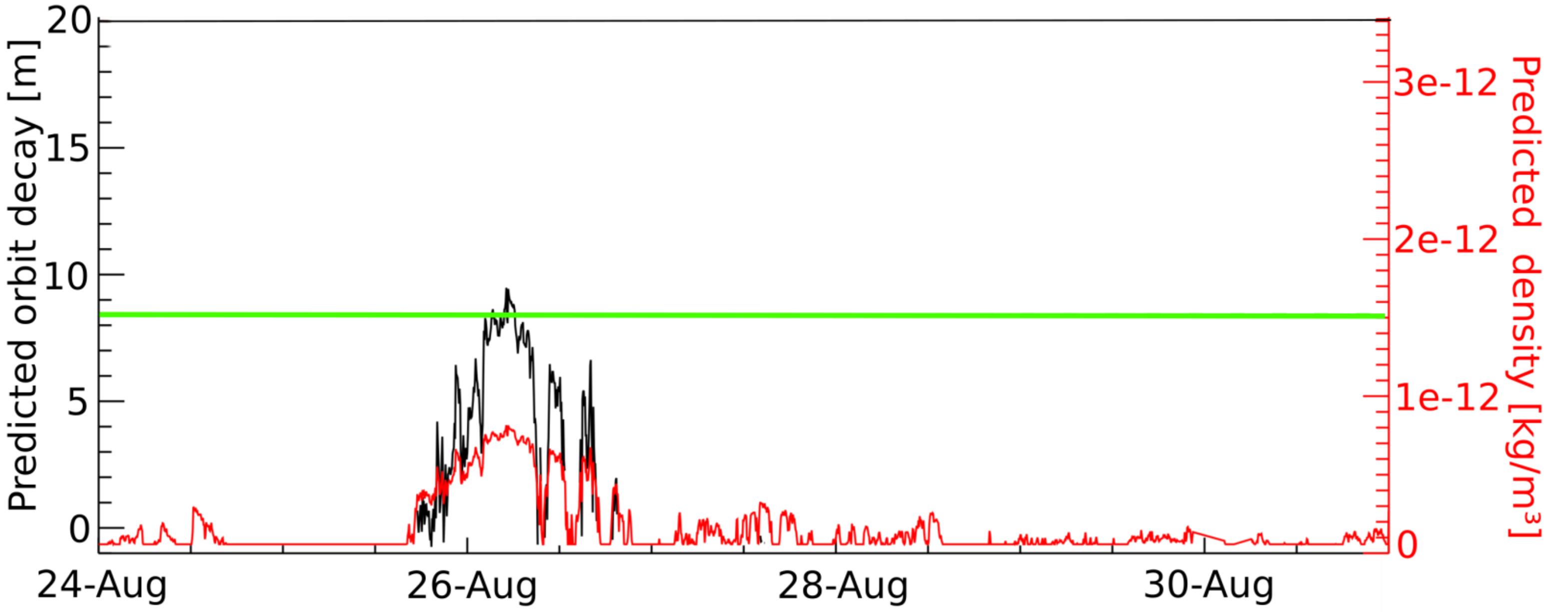
Our provisional near-real time thermospheric density forecasting tool is based on the study by Krauss et al. (2018), which deals with the estimation and analysis of orbit decay for the CHAMP and GRACE satellite triggered by nearly 400 ICME and co-rotating interaction regions.

Predictions are limited so far to a fixed altitude of 490 km and neglect the exact temporal course. However, in August 2018 GRACE-FO was at an altitude of ~515 km, thus for a direct comparison the estimated decay had to be normalized to 490 km using the Jacchia-Bowman 2008 model*.

R E S U L T

GRACE-FO orbit decay:	
Predicted value:	9.5 meters
Lead time of the forecast:	60 minutes
Post-processed value:	8.2 meters

see:
http://swe.uni-graz.at/index.php/services/nd-forecast



Predicted orbit decay (black line) and thermospheric density (red line) for a fixed altitude of 490 km. The green line indicates the post-processed maximum orbit decay for the GRACE-C satellite during the storm period in August 2018.

For more details see: Krauss et al. 2020

* credit: JB2008 data courtesy of Space Environment Technologies (SET)

Summary and outlook

What was done:

- Estimated the neutral density variations in the upper Earth’s atmosphere and the associated satellite orbit decay for the satellite mission GRACE-FO
- Study analysis the largest ICME event (August 26, 2018) since the launch of GRACE-FO

Results:

- GRACE-FO suitable to resume the analysis of accelerometer data regarding space weather induced perturbations of the Earth's thermosphere
- Predicted orbit decay (9.5 m) is in rather good agreement with the estimated value (8.2 m) - especially when taking into account the current inevitable normalization step

Next steps:

- So far, the predicted orbit decay reflects the expected maximum value and neglects the temporal course. This will be revised in a future release.
- Extend the analysis to further satellites at different altitudes (based on kinematic orbit)
- Investigate the impact of cooling mechanism in the Earth’s atmosphere

For more information

… the reader is referred to the basis of the presentation:

Krauss S., Behzadpour S, Temmer M. and Lhotka C. (2020): Exploring thermospheric variations triggered by severe geomagnetic storm on August 26, 2018 using GRACE Follow-On data, Journal of Geophysical Research, Space Physics, doi: 10.1029/2019JA027731.

and

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www.tugraz.at/institutes/ifg/home/

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