SODA – a forecast service to predict storm induced satellite orbit decays

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Abstract

With the strong rise of the current solar cycle 25 also the number of solar eruptions, like solar flares, interplanetary coronal mass ejections (ICMEs), increases. These solar events have the capability to trigger geomagnetic storms, which may disrupt and damage satellites in space as well as technical infrastructure on Earth. The forecasting tool SODA (Satellite Orbit DecAy) is based on an interdisciplinary analysis of geodetic observations and solar wind in-situ measurements. It allows the prediction of the impact of CME events on the altitude of low Earth orbiting satellites with a lead time of 15 hours. To calculate the storm induced orbit decay, we analyzed 299 CME events over a period of 15 years. Appropriated variations in the thermospheric neutral mass density, were derived from measurements of the CHAMP, GRACE and SWARM satellite missions. In addition, we investigated deviations in the magnetic field component B_z measured by the ACE and the DSCOVR spacecraft at the L1 point. The analysis of the CME induced orbit decays and the interplanetary magnetic field showed a strong correlation as well as a time delay between the CME and the associated thermospheric response. This correlation is implemented in the real time forecasting tool SODA, which is integrated in the ESA Space Safety Program (Ionospheric Weather Expert Service Center; I.161).

Data

Relationship between $\vec{a}_d$ and the neutral mass density of the atmosphere ρ

Following Vallado [5] the drag acceleration acting on a satellite can be written as

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

Relationship between orbit decay (OD) - neutral density of the atmosphere ρ

As stated by Krauss et al. [2] the temporal change of the semimajor axis is given by

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

Estimates of the acceleration due to atmospheric drag are based on:

- accelerometer measurements by CHAMP, GRACE and GRACE-FO
- kinematic orbits information [3] when operating with satellite missions like Swarm, TerraSAR-X, TanDEM-X

As the ICME passes the Earth, it causes a density increase, leading the spacecraft to experience enhanced drag, and hence, losing on altitude.

The interplanetary magnetic field component B_z

The SODA tool makes use of the relation between the thermospheric density increase and the magnetic field component B_z of an ICME. Observations of the B_z component (GSE) are taken at the Lagrange point L1 from the spacecraft ACE and DSCOVR.

An example of these correspondences are illustrated in Fig.1, for an ICME event which occurred in late 2003.

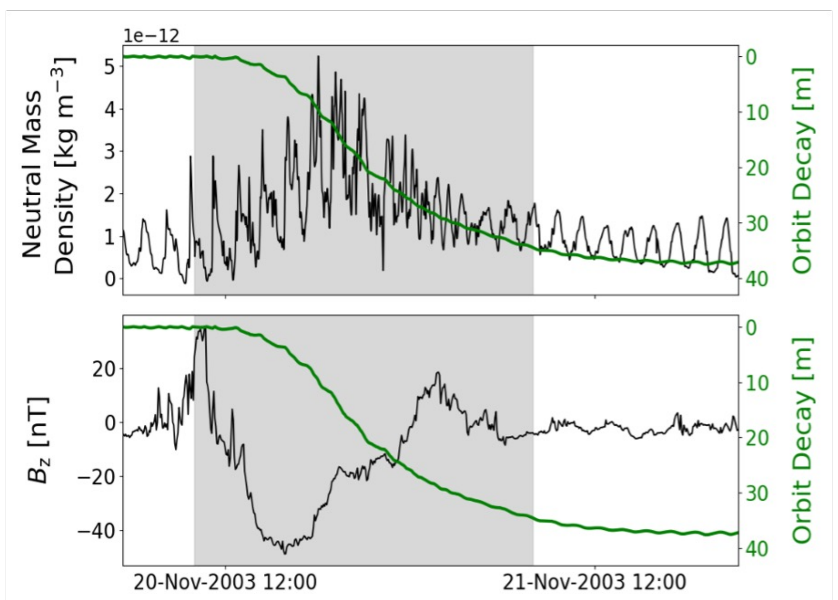


Figure 1: Green lines in both panels corresponds to the orbit decay while the gray shaded area represents the duration of the ICME (R&C list). Top: neutral mass density increasing and bottom: B_z component of the interplanetary magnetic field measured at L1 with a cadence of 4 minutes.

Coronal mass ejections - event selection

ICME catalogue by Richardson and Cane [R&C, 4]

The catalogue maintained by R&C comprises findings of ICMEs event analysis starting in 1996; including among others the arrival times of the shock-sheath region, start and end times of the magnetic structure (based on the plasma and magnetic field observations) and the minimum value of the geomagnetic disturbance storm time index (Dst). During the GRACE mission duration (2002 - 2017) the R&C catalogue list 299 ICME events, which were analysed thoroughly. However, for the establishment of the SODA forecasting tool we decided to use 120 events.

Events were not included if:

- no significant density increase was visible due to a too weak storm
- intensity of the density stayed above the pre-storm level which impeded the OD calculation
- data gaps occurred in the density estimation during certain storm periods

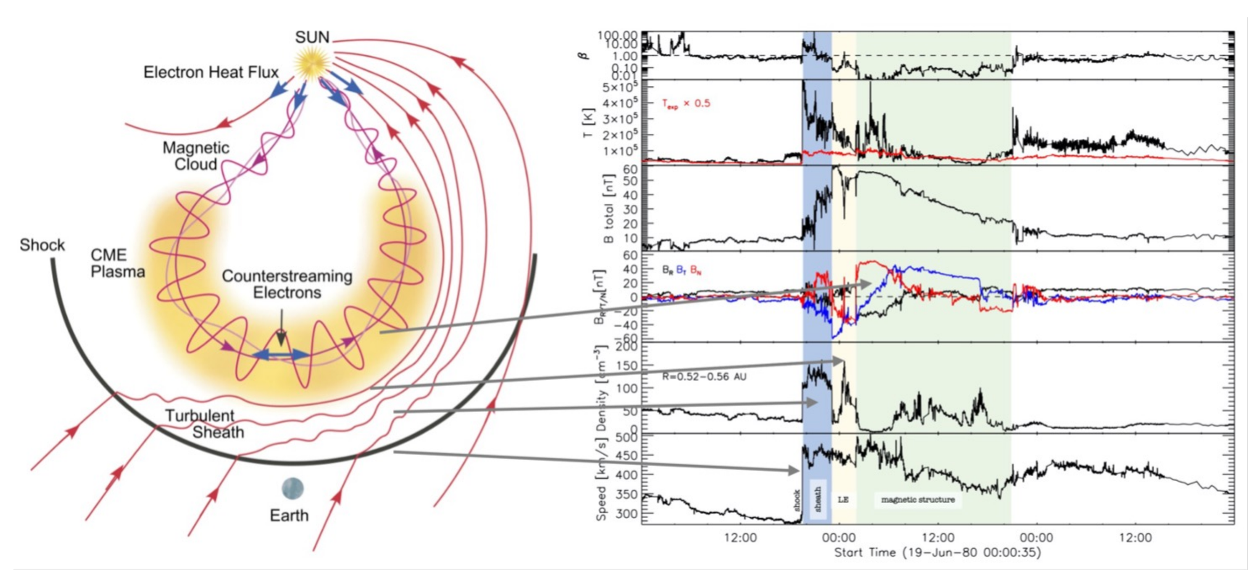


Figure 2: Distinct structures can be distinguished such as shock-sheath (blue), leading edge (yellow), and magnetic structure (green). The magnetic structure with its strong and smoothly rotating magnetic field is the structure which is most directly related to the orbit decay of satellites.

Analysis

The analysis of the 120 ICME events covers several objectives including:

- Correlation between the density increase and the deflection and shape of B_z
- Duration between the occurrence of the minimum B_z and the orbit decay
- Comparison with geomagnetic indices to allow a forecast classification (G-scale)

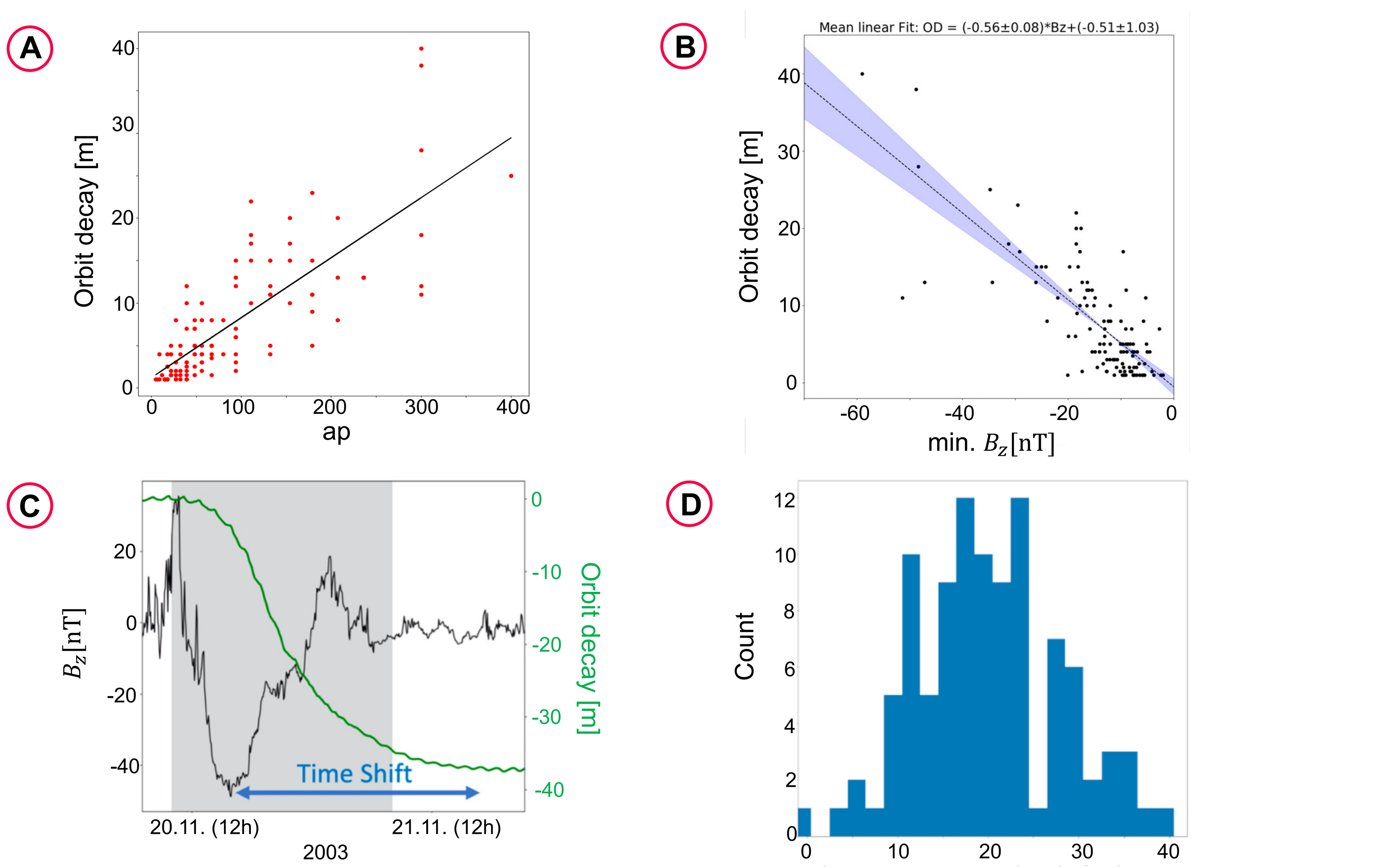


Figure 3: (A): Scatterplot of 120 ICMEs and their respective OD. (B): OD as a function of the minimum B_z. The blue shaded area corresponds to an uncertainty of one sigma (cc=0.78). (C): OD reaching its maximum after a certain time period. (D): Histogram of analyzed ICMEs and their time difference between the minimum of B_z component.

Forecasting tool SODA

The forecasting tool SODA (Satellite Orbit DecAy) allows the prediction of the impact of CME events on the altitude of low-Earth orbiting satellites.

After downloading real-time magnetic field data from DSCOVR the OD calculation is done. The visualization is made via a Python routine. Top two panels show the last 50 days, bottom two panels only the last four days. The vertical limits of all the panels are fixed for easier comparison. The red line represents the current time (Present) from which the magnetic field data stem and the gray shaded area the forecast period of 15 hours.

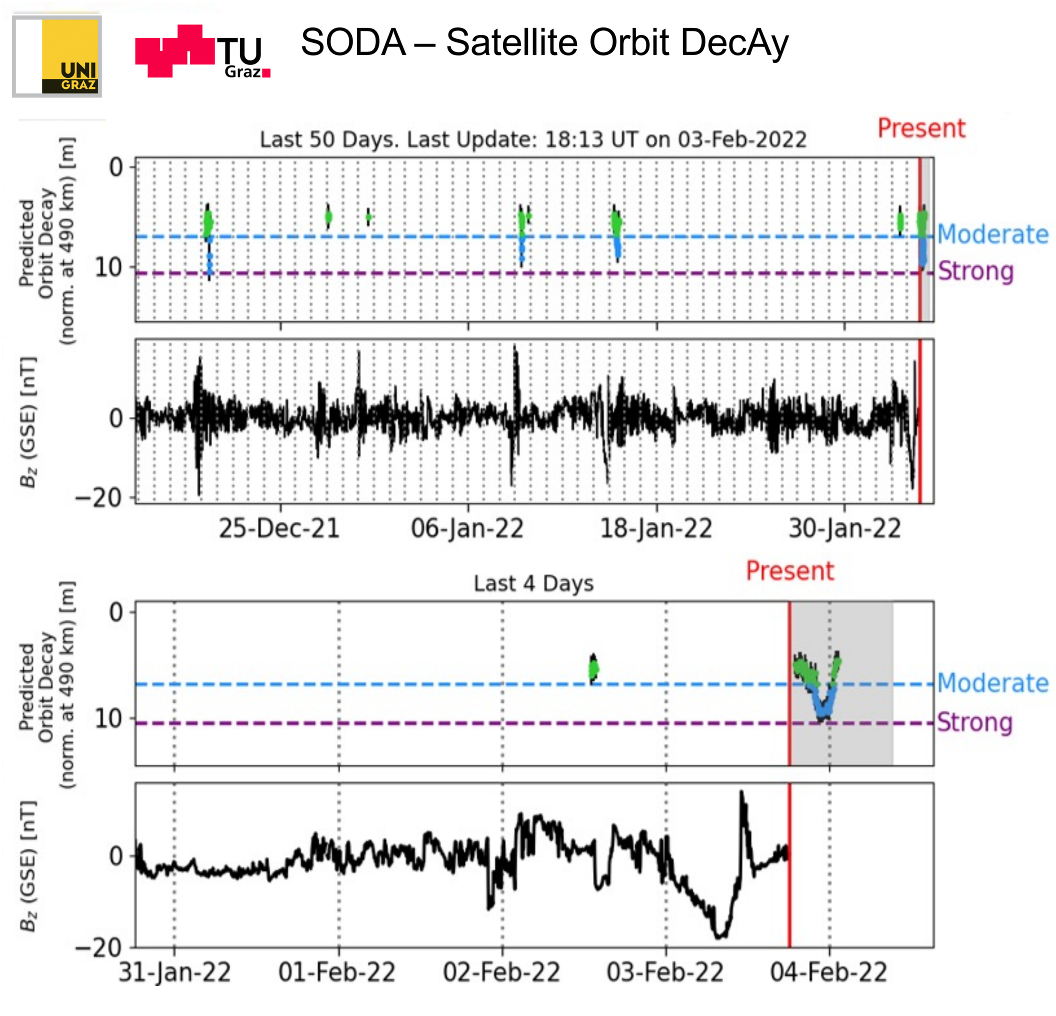
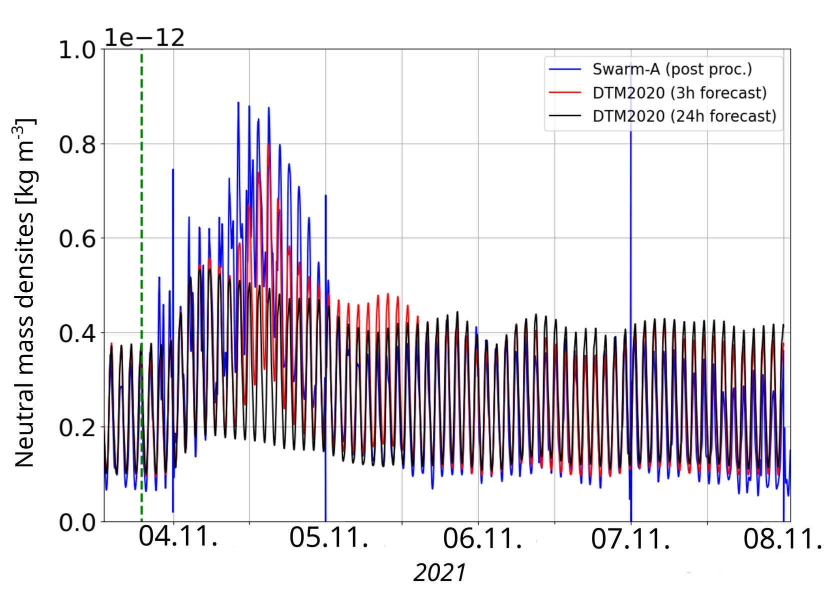


Figure 4: Forecast of OD for Starlink event in February 2022 (Visualization taken during the development phase)

Validation of SODA service:



Date (R&C)	27-08-2021	03-11-2021	02-02-2022	04-02-2022
Dst Index	-82 nT	-105 nT	-75 nT	-71 nT
Classification	G1	G3	G1	G1
DTM2020 24 h forecast	2.0 m	5.8 m	2.0 m	1.2 m
DTM2020 3 h forecast	2.9 m	9.6 m	7.3 m	1.4 m
DTM2020	5.0 m	10.1 m	7.8 m	1.8 m
SODA 15 h prediction	7.5 m	8.5 m	9.6 m	5.3 m
Validation in post processing	7.0 m	14.5 m	8.5 m	3.6 m

Figure 5: Comparison of post processed thermospheric densities using SWARM-A data, and densities from the DTM2020 model [1] by using predicted values for input indices (3h & 24h). Right: Table 1: Validation of SODA predictions.

Acknowledgments

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FWF Österreichischer Wissenschaftsfonds

FFG Promoting Innovation. esa

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