

SODA – A tool to predict storm-induced orbit decays for low Earth-orbiting satellites

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Abstract—Due to the rapidly increasing technological progress in the last decades, the issue of space weather and its influences on our everyday life has more and more importance. Today, satellite-based navigation plays a key role in aviation, logistic, and transportation systems. With the strong rise of the current solar cycle 25 the number and intensity of solar eruptions increases. The forecasting tool SODA (Satellite Orbit DecAy) is based on an interdisciplinary analysis of space geodetic observations and solar wind in-situ measurements. It allows the prediction of the impact of in-situ measured interplanetary coronal mass ejections (ICMEs) on the altitude of low Earth-orbiting satellites at 490 km with a lead time of about 20 h, which is defined as the time difference between measuring the minimum B_z component and the orbit decay reaching its maximum. Additionally, it classifies the severeness of the expected geomagnetic storm in the form of the Space Weather G-scale from the National Oceanic and Atmospheric Administration (NOAA). For the establishment and validation of SODA, we examined 360 ICME events over a period of 21 years. Appropriated variations in the thermospheric neutral mass density, were derived mainly from measurements of the Gravity Recovery and Climate Experiment (GRACE) satellite mission. Related changes in the interplanetary magnetic field component B_z were investigated from real-time measurements using data from spacecraft located at the Lagrange point L1. The analysis of the ICME-induced orbit decays and the interplanetary magnetic field showed a strong correlation as well as a time delay between the ICME and the associated thermospheric response. The derived results are implemented in the forecasting tool SODA, which is integrated into the Space Safety Program (Ionospheric Weather Expert Service Center; I.161) of the European Space Agency (ESA).

Keywords: Forecasting / Orbit decay / Geomagnetic storms / CME / ESA Space Safety Programme

1 Introduction

Our Sun is an active star and variations in solar activity have a direct impact on Earth's magnetic field and its different atmospheric layers (so-called space weather), starting from changes in the strength of solar wind coupling processes with the magnetosphere down to neutral density variations in the thermosphere. As the activity level increases, more and more energy is deposited into the Earth's atmosphere causing it to heat up and expand (Knipp et al., 2004; Forbes, 2007). This leads to a higher neutral density in the Earth's upper atmosphere, the thermosphere, and as a result, the natural satellite orbit decay for low Earth orbiting (LEO) satellites increases due to a higher drag force acting on these satellites (e.g., Sutton et al., 2005; Bruinsma et al., 2006; Doombos, 2012; Emmert, 2015).

Due to the long history of sunspot records, there is a very good knowledge about the Sun's activity level changing over a period of about 11 years. Against predictions from previous studies, recent investigations expect the maximum to be higher compared to cycle 24 and to occur already mid-2024 to early 2025 (McIntosh et al., 2023; Zhu et al., 2023; Nagovitsyn and Ivanov, 2023). As a consequence, the impacts on the upper Earth's atmosphere are expected to be more severe compared to the preceding solar cycle (Bruinsma et al., 2021; Oliveira et al., 2021). A daily updated comparison of observed and predicted sunspot numbers is shown in Figure 1.

Accompanying the strong rise of the current solar cycle also the number of space weather affecting phenomena, such as solar flares and interplanetary coronal mass ejections (ICMEs), increases (see e.g., review by Temmer, 2021). When carrying a strong southward directed magnetic field component (B_z), ICMEs have the capability to trigger geomagnetic storms,

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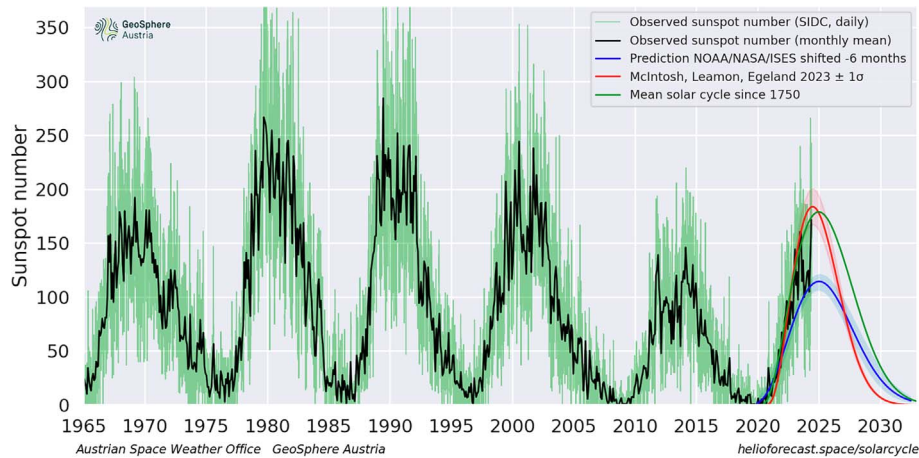


Figure 1. Sunspot numbers observed from 1975 to 2023 and comparison to two sunspot number predictions for solar cycle 25. The first prediction was made by the NOAA/NASA/ISES panel in 2019 (blue curve) and the second is based on the timing of the so-called terminator event (McIntosh et al., 2023) in the revised version from early 2023 (red curve). An average solar cycle is shown for reference (green curve). Source: helioforecast.space/solarcycle, accessed on June, 4 in 2024.

which may damage technical infrastructure on Earth (see review by e.g., Pulkkinen, 2007) as well as disrupt satellites in space, when flying in very low orbits as recently experienced with the so-called “Starlink event” (Dang et al., 2022; Fang et al., 2022; Kataoka et al., 2022). ICMEs, therefore, can be responsible for interferences of navigation and telecommunication services (Hapgood et al., 2021), may lead to an increase in radiation doses in air traffic, increase in the natural decay of satellite orbits (Krauss et al., 2020), and can even cause severe damage to power equipment and lead to complete shutdowns of power transmission lines as it was the case in Quebec 1989 (Bolduc, 2002; Boteler, 2019). Hence, the deterioration of these modern and familiar services becomes immediately apparent to anybody. As a result, space agencies like ESA and NASA initiated programs and working groups (e.g., ESA’s Space Safety Program, NASA’s Heliophysics Division for Space Weather) dealing with this topic. The objective is to support the independent utilization of and access to, space through the provision of timely and accurate information and data regarding the space environment-, particularly regarding hazards to infrastructure in orbit and on the ground. A recent ESA study¹ estimated that the potential socio-economic impact in Europe today from a single extreme space weather event could be about €15 billion.

In the following, we describe the development and functionality of the forecasting service called SODA (Satellite Orbit DecAy). SODA has been included in the ESA Space Safety Program in the Expert Service Center “Ionospheric Weather” (I.161) since the portal release 3.7.0. on July 11, 2023. Based on real-time measurements of the interplanetary magnetic field component B_z , SODA predicts the impact of an ICME event on LEO satellites at 490 km with an area-to-mass ratio of a GRACE type satellite in terms of the storm-induced orbit decay (Chen et al., 2012; Oliveira and Zesta, 2019; Krauss et al., 2018, 2020). The average lead time of the forecast is derived from

about 20 h. Furthermore, it has the capability to classify the severeness of the expected geomagnetic storm in the form of the Space Weather G-scale from the National Oceanic and Atmospheric Administration (NOAA). In the upcoming Section 2, we will describe the datasets that we used to establish SODA, discuss how we selected the ICME events, and outline the determination of satellite orbit decays based on neutral mass densities. In Section 3, we will discuss the findings from the correlation analysis of the various datasets and present the forecasting tool SODA and its validation. In the concluding outlook Section 4, we will recap the current state of SODA and go into more detail about future updates of the forecasting tool.

2 Data and methods

As an overview, Figure 2 shows a standard illustration of typically observed ICME structures and related in-situ measurements (left panel from Zurbuchen and Richardson, 2006; right panel from Temmer and Bothmer, 2022). ICMEs can be identified by shocks and associated turbulent sheath regions, as well as by their strong magnetic field structures. The latter appear smoother than the interplanetary magnetic field and show rotation signatures (to the strong and smoothly rotating magnetic field structure of the ICME we refer to as ‘magnetic ejecta’). These features are used for the ICME selection process and for the calculation of the magnetic field variations, especially the minimum value of the B_z within the ICME.

As could be already shown in Krauss et al. (2015, 2018), the strongest effects on the neutral density in the thermosphere stems from a strong negative B_z component in the magnetic field structure of an ICME. The increase in neutral density is mostly related to the magnetic ejecta, which presumably represents a flux rope, as detected by the smooth and rotating magnetic field vector components in the interplanetary magnetic field. The basis of the SODA tool is therefore the statistical relation between the thermospheric density increase and the magnetic field variations during ICME occurrences as derived from in-situ measurements, such as the Advanced Composition

¹ https://www.esa.int/Space_Safety/Space_weather_and_its_hazards.

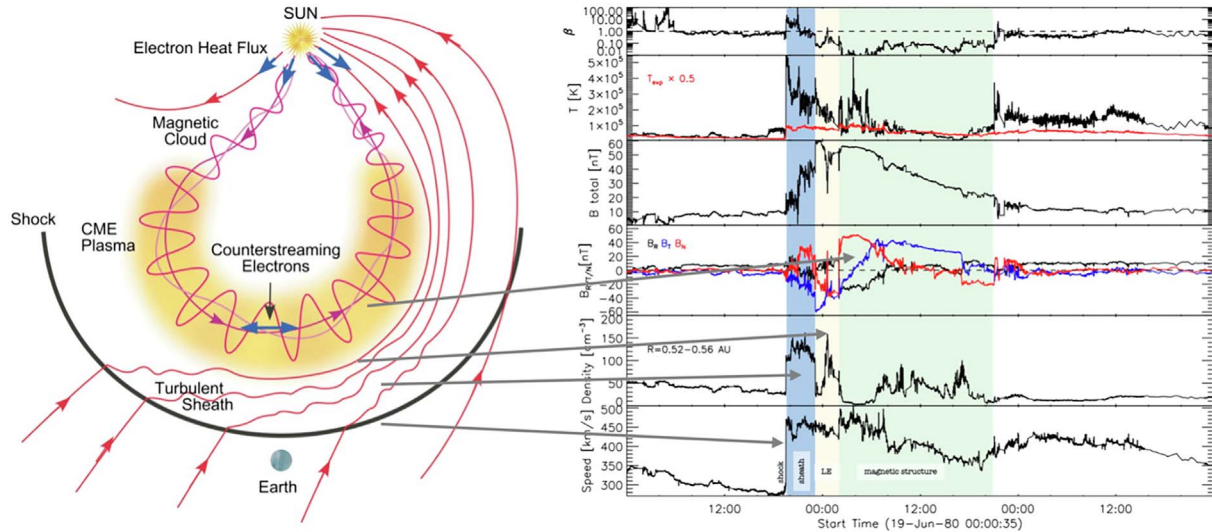


Figure 2. From in-situ measurements distinct structures can be identified such as shock-sheath (blue), leading-edge (yellow), and magnetic ejecta (green). The magnetic ejecta with its strong and smoothly rotating magnetic field is most directly related to the orbit decay of satellites. The Figure is adapted from Zurbuchen and Richardson (2006) and Temmer and Bothmer (2022).

Explorer (ACE; Stone et al., 1998) and Deep Space Climate Observatory (DSCOVR; Burt and Smith, 2012) spacecraft.

For the estimation of the neutral mass densities, we mainly rely on observations from the Gravity Recovery and Climate Experiment (GRACE) satellite mission (Tapley et al., 2004). As input data we used the Level-1B data products for the accelerometer measurements (ACC1B), spacecraft attitude (SCA1B) and orbits (GNV1B) with a resampled temporal resolution of 5 s. The final orbit decays are processed based on 60 s density solutions. As a consequence, for the statistical analysis i.e. relating interplanetary magnetic field and neutral density variations in the Earth's thermosphere, we examine ICMEs which that occurred during the GRACE mission duration from 2002 to 2017 (299 events). Events that emerged afterwards are used to validate the SODA tool (61 events). To accomplish this task we additionally analyzed data from the satellite missions GRACE Follow-On (GRACE-FO Kornfeld et al., 2019) and Swarm (Olsen et al., 2013).

2.1 Solar event selection

For the definition of the specific ICME period, we used the ICME occurrence times listed in the catalog² thoroughly maintained by Richardson and Cane (R&C; Richardson and Cane, 2013). Within the R&C catalogue various information (e.g., mean and maximum velocity, the existence of a magnetic ejecta), about a specific ICME are listed. Also included are the time stamps of the disturbance start (shock) as well as the start and end time of the magnetic ejecta based on plasma and magnetic field observations. For our analysis, we used these provided timestamps to assign the minimum value of the ICME magnetic field component B_z and to calculate the orbit decay, which is based on the neutral density estimates, to each single event. For our main investigation period (2002–2017), there are in total 299 ICMEs listed by R&C. By checking the quality

of the ICME data as well as the thermospheric density profiles, during the analysis it became evident that not all of these events are reasonable suitable for the analysis and further establishment of SODA. The shortcomings and number of events that needed to be discarded from the analysis include:

- Low event strength, i.e. no significant density increase could be observed (83 events).
- Occurrence of data gaps at any point during the ICME (23 events).
- Insufficient time between successive ICME events to reliably distinguish their individual effects (35 events).
- Density did not recede to the background intensity prior to the event (45 events).

The last point is problematic, because a continuing further enhanced density after the event makes a meaningful detection of the orbit decay and its end time unreliable. Regarding the ICME events that occurred within a short period of time (interacting ICMEs), we decided to combine some of these events into one single event. The prerequisite was that the events occurred within 6 h. As a result, we introduce ten new events, which are tagged as “combined” events. From the total number of 299 ICME events, we finally selected a subset of 116 events for a thorough analysis and the subsequent development of the SODA tool. The complete data-set created within this study is made publicly available (Krauss et al., 2023). Besides temporal information about the respective ICME event, it further comprises knowledge about various geomagnetic and solar activity indices as well as the observed minima of the interplanetary B_z component and observed orbit decays derived from different satellite missions (including meta-information about the event).

2.2 Orbit decay from thermospheric density estimation

The SODA tool makes use of the relation between the thermospheric density increase $\Delta\rho$ and variations in the

² <https://izw1.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm>.

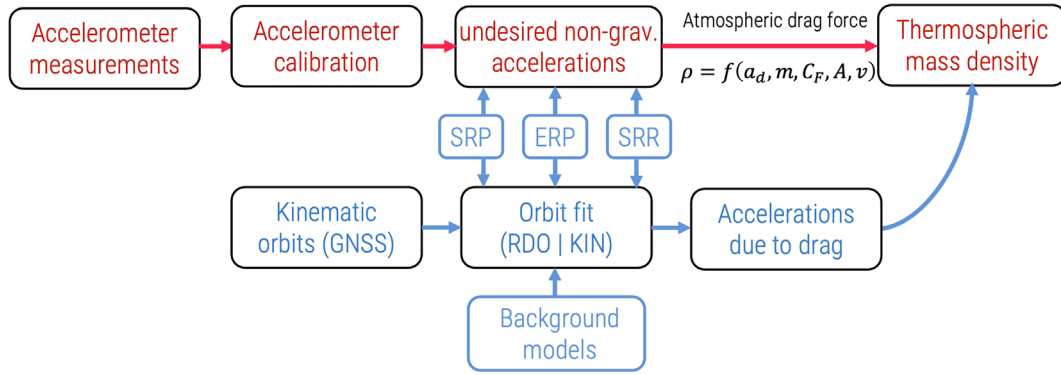


Figure 3. Processing chain for the estimation of neutral densities from satellite observations. In red the procedure based on accelerometer measurements is outlined and in blue the kinematic orbit approach is illustrated. The abbreviations stand for: Solar radiation pressure (SRP), Earth radiation pressure (ERP), Spacecraft re-radiation (SRR), Reduced dynamic orbit (RDO), Kinematic orbit (KIN), and Global Navigation Satellite Systems (GNSS).

interplanetary magnetic field component B_z of an ICME. To estimate the neutral mass density, we apply two different approaches. The first is based on accelerometer measurements onboard a satellite (Bruinsma et al., 2006; Sutton, 2008; Doornbos, 2012; Emmert, 2015) and is used in case of processing the satellite missions CHAMP (Reigber et al., 2002), GRACE and GRACE-FO. To extend the number of applicable satellites (e.g., Swarm) we additionally calculated mass densities based on kinematic orbit information (Suesser-Rechberger et al., 2022) using Global Navigation Satellite Systems (GNSS) measurements. The suitability of this second approach has already been demonstrated by other research groups (e.g., van den IJssel et al., 2020; Callejon Cantero, 2023). In Figure 3, the processing chain for both applied approaches is depicted. In either case, we have to reduce the total non-gravitational accelerations on the satellites by undesired forces like solar radiation pressure, Earth radiation pressure, and thermal re-radiation of the satellite. For the establishment of the first SODA release, we used the models described in Krauss et al. (2020).

As revealed by Figure 3, applying the second approach implies one preceding step: a fit of the dynamic orbit to the kinematic observations. For this step, the atmospheric drag is determined from the kinematic orbit positions by means of a least-square adjustment. This involves setting up the equation of motion with all conservative and non-conservative forces acting on the satellite. Thereby, the atmospheric drag force is excluded since it has to be determined during the adjustment. The dynamic orbit model is obtained by integrating the equation of motion twice. This model is then fitted to the kinematic positions and the due to aerodynamic acceleration is estimated.

Afterwards, regardless of the approach, the neutral mass density ρ can be estimated based on the equation for aerodynamic drag acceleration (Anderson, 2017) a_d and following Doornbos (2012), written! as:

$$\rho = \frac{2m}{A_{ref} v_r^2} \frac{a_{a,x}}{C_{a,x}}. \quad (1)$$

In equation (1) the respective x-components of the aerodynamic acceleration a_a and the dimensionless force coefficient C_a which represents the sum of the drag and lift coefficient for each single

satellite plate that is subject to the flow are used. The satellite mass is indicated by m and A_{ref} is the reference area of the entire spacecraft. The magnitude of satellite velocity relative to the co-rotating atmosphere is denoted by v_r . Thermospheric wind circulations are incorporated by applying the horizontal wind model HWM14 (Drob et al., 2015). Specific information about the satellite geometry and the thermo-optical properties are taken from the individual satellite mission documents (Bruinsma and Biancale, 2003; Bettadpur, 2012; Siemes, 2019; Hackel et al., 2017; Fernandez, 2019). New findings by Siemes et al. (2023) and Hładczuk et al. (2024) regarding deficiencies within the GRACE-FO satellite model (size and reflectivity properties) in the official documents (GRACE-FO, Wen et al., 2019) are currently under investigation and will be incorporated in the next release of SODA for events after the launch in May 2018.

Due to the slightly elliptic orbit, the satellites altitude changes during one orbital revolution. Thus, the neutral mass densities were normalized to average altitudes of 490 km following Bruinsma and Biancale (2003) and using the empirical thermosphere model Jacchia-Bowman 2008 (Bowman et al., 2008). On this basis, it is possible to determine comparable storm-induced satellite orbit decays over a longer time span. As outlined by Krauss et al. (2020), the orbit decay itself can be represented by the temporal change of the mean semi-major orbit axis $\bar{a}$ and written as:

$$\Delta a = - \frac{C_{a,x} A_{ref}}{m} \sqrt{GM \bar{a}} \cdot \psi(e) \int (\rho - \rho_b) dt. \quad (2)$$

Here ρ denotes the storm induced density variations, which represents the difference between the observed density value ρ and ρ_b the background density of the Earth thermosphere (Krauss et al., 2018). We specify the latter as the mean density for two consecutive satellite revolutions prior to the ICME arrival time (see R&C disturbance time). Further included are the Earth's gravitational parameter GM as well as the mean semi-major axis $\bar{a}$ estimated over the period of the ICME event and an eccentricity function $\psi(e)$, which can be considered to be approximately 1 for satellites currently under consideration.

Exemplary, Figure 4 depicts for an ICME event in November 2003 the evolution of the neutral density, the

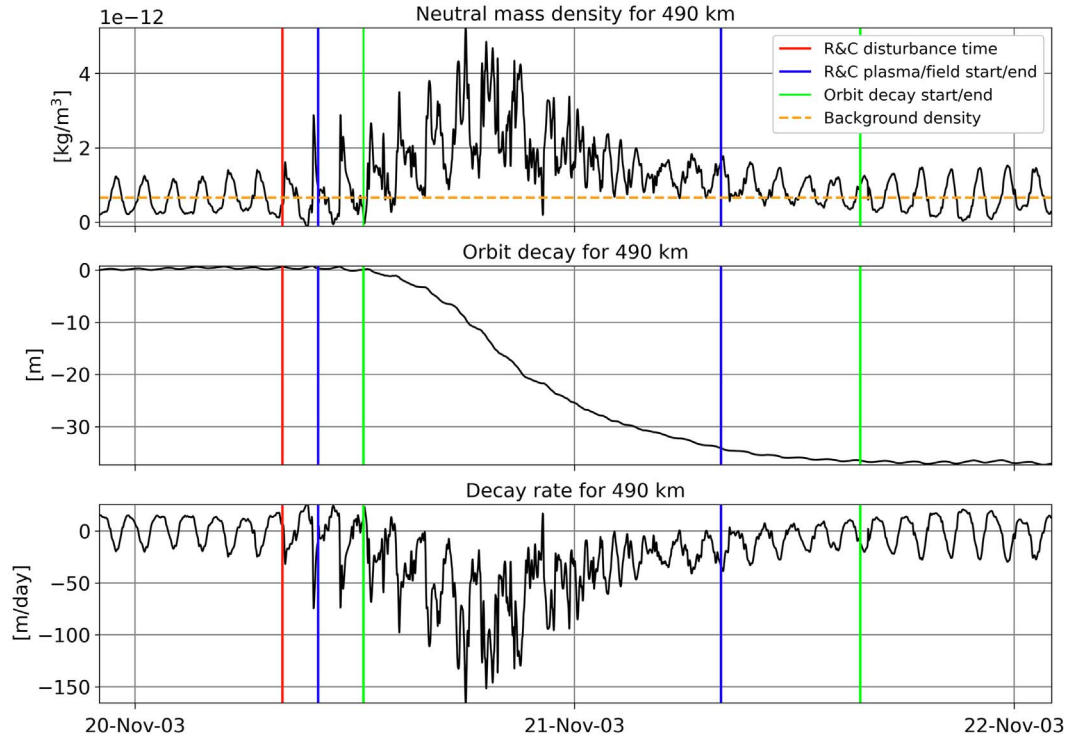


Figure 4. Impact of an ICME in November 2003 on the GRACE-A satellite (normalized to 490 km). The top panel shows the neutral density evolution, middle panel the resulting orbit decay (OD), and bottom panel the OD rate (black lines). Additionally illustrated are the calculated background density (orange line), the disturbance time (red line), and the ICME plasma/field start and end times (blue line) taken from the R&C catalog and the start and end times of the orbit decay (green lines).

triggered storm-induced orbit decay, and the associated orbit decay rate for the GRACE-A satellite at a normalized altitude of 490 km. The latter is used to define the end of the orbit decay, which we define to be the time when the orbit decay rate declines to the pre-event state. A more in-depth description can be found in [Chen et al. \(2014\)](#), [Oliveira and Zesta \(2019\)](#), [Krauss et al. \(2020\)](#) and [Li and Lei \(2021\)](#).

3 Results

3.1 Correlation analysis

For the development of SODA, a combined analysis of the interplanetary magnetic field component B_z and the thermospheric density increase in the form of storm-induced satellite orbit decays was performed. The existence of a utilizable relation between the minimum B_z component in ICMEs and the maximum orbit decay has been shown by [Krauss et al. \(2018\)](#). Applying the identified ICME times we performed an automatic minimum B_z detection and compared that to the calculated orbit decay. In that respect, we note that due to the occurrence of high variations in the interplanetary magnetic field, the automatic detection of the minimum B_z value had to be revised manually in only two out of 116 cases. We, therefore, conclude that this approach leads to a reliable automatic detection of the minimum B_z component and robust performance of SODA in the operational mode. [Figure 5](#) shows the findings of the regression analysis between the storm-induced orbit decay and the minimum value of the ICME B_z component. We derive from the

analysis a linear relation with $y = -0.55x - 0.76$ with a Pearson correlation coefficient of -0.78 . For SODA, we use the results from the derived linear relation to forecast the orbit decay.

Real-time measurements of the B_z component are available from the ACE or DSCOVR spacecraft located at the Lagrange Point L1, 1.5×10^6 km upstream of Earth. With the ICME passing L1, the minimum B_z value is automatically extracted. Our real-time processing automatically extracts the minimum B_z value, from which the orbit decay is subsequently calculated. As the ICME needs on average approximately 30–45 min, depending on its propagation speed, from L1 to reach the Earth, there is some time for advance warning. Moreover, as already shown in [Figure 4](#), the maximum orbit decay is not reached instantaneously as the ICME hits Earth due to the storm cycle development ([Kamide et al., 1998](#)). Hence, we gain additional lead time for the prediction, which we in general defined as the time difference between measuring the minimum B_z component and the orbit decay reaching its maximum. In this context, the left panels in [Figure 6](#) show in detail the profile and temporal relations between the density increase in the upper Earth's atmosphere, the storm-induced orbit decay, and the variations of the interplanetary magnetic field component B_z for the largest ICME event during the solar cycle 23 on November 20, 2003 ([Liu and Lühr, 2005](#)).

By analyzing the temporal behavior of the B_z component together with the storm-induced orbit decays for all 116 ICME events, we derive the time delay for each single event, as given presented in [Figure 6](#) in the form of a histogram plot. On

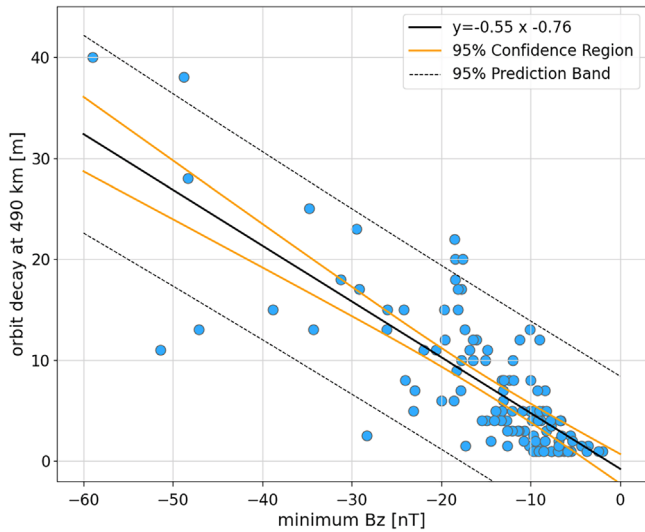


Figure 5. Scatter plot of the minimum B_z component measured by the Advanced Composition Explorer with the storm-induced orbit decay at 490 km comprising the 116 ICME events used for the SODA establishment. Indicated with black dashed lines is the 95% prediction band and with solid orange lines the 95% confidence interval.

average, a time difference of around 20 h is obtained, which we use as a definition of the average lead time for the SODA service.

To obtain a standardized measure for the expected severity of the geomagnetic storm and the associated orbit decay, we additionally conducted a joint analysis with the geomagnetic index a_p . Figure 7 shows the correlation between the estimated orbit decay at 490 km and the maximum value of the geomagnetic index a_p for the 116 analyzed ICMEs. From this analysis, we derive a linear relation with $y = -0.07x + 1.24$ with a Pearson correlation coefficient of -0.79 . As a result, the severity of the expected ICME impact can be classified using the NOAA geomagnetic storm scale (G1–G5)³, which follows the geomagnetic index k_p , which is closely connected to the analyzed a_p index (Menvielle et al., 2011).

3.2 Visualization of the SODA tool

The graphical presentation of the forecasting tool SODA, as it is integrated into the ESA Space Safety Program (Ionospheric Weather Expert Service Center; I.161), is visualized in Figure 8. The illustration of the interdisciplinary observation analysis is divided into an upper and lower part. In both cases, observations of the interplanetary magnetic field component B_z (ACE, DSCOVR) and the storm-induced satellite orbit decay forecast for 490 km are visualized. For a more convenient overview of past solar events, the upper two panels depict the history of the parameters over the last 50 days. Thus, the user can review past events very easily. In contrast, the lower panels show the evolution over the last four days for a closer examination. In both cases, the red vertical line represents the current time (present) and the gray shaded area highlights the lead time of the 20-h forecast period.

Based on the statistical analysis of the training data (116 ICMEs) with and the geomagnetic index a_p , the level of the ICME impact on the Earth's atmosphere is divided into different classes. When SODA predicts an orbit decay, a coloured dot appears in the forecast area. The dot, which is color-coded according to the level of the impact and divides and illustrates geomagnetic storms as follows: minor (G1) in green, moderate (G2) in blue, strong (G3) in violet, severe (G4) in orange and extreme (G5) in red. Regardless of the current state always the complete intensity range is displayed. To improve the readability, we visualize only orbit decays which that correspond at least to a G1 class storm. For interested users in the complete data range, ESA's SODA service also offers an archive where the data are stored without any restrictions.

3.3 Validation of forecasting

For the validation of the operational SODA forecasts, we use ICME events which that occurred after 2017 and were thus not part of the establishment of used to train SODA. For maximum independence in the neutral density estimates based on GRACE-FO, we used external data provided by the Delft University of Technology.⁴ Table 1 presents the results for ten of the biggest events during 2018–2023. For each of the ICME events, we list the geomagnetic index Dst (Sugiura, 1964; Sugiura et al., 1991), the detected minimum of the B_z component, the prediction value of the orbit decay predicted by SODA, as well as our reference value – the observed orbit decay based on external density data. Additionally, also a classification of the triggered geomagnetic storm is presented.

The results reveal, that SODA is capable to predict the impact of ICMEs on the Earth's upper atmosphere and, at the same time, the storm-induced orbit decays in a variety of cases. Most events have an accuracy in the low meter range. However, there are also events where the prediction quality is lower. In the following, we will discuss three examples. The first event occurred on May 12, 2021, for which SODA predicted a significantly higher orbit decay than observed in the post-processing (10.8 m vs. 4.4 m). In contrast to the orbit decay, the predicted geomagnetic storm intensity (G3) by the registered value of the $k_p = 7$ index. A detailed description of this specific event was elaborated provided by Piersanti et al. (2022). We suspect that cooling effects (Mlynckzak et al., 2014; Knipp et al., 2017; Bag et al., 2023) have occurred, which subsequently reduced the increase of the neutral mass density during this specific event. In Oliveira and Zesta (2019) the authors have quantified such density uncertainties due to NO cooling effects and shown that they are more pronounced during the recovery phase of storms. A more detailed investigation in this direction is currently being carried out.

The second event we highlight is the most prominent example on our validation list. It is related to the ICME events at the beginning of February 2022, which can be associated with the loss of 38 Starlink satellites. Though a series of two ICMEs arrived on Earth on February 1 and 3, 2022, they were not particularly strong with minimum B_z values of more than -20 nT. However, the external energy injection into the thermosphere might have generated a sufficiently high enhancement in the neutral density in the LEO environment to support the

³ <https://www.swpc.noaa.gov/noaa-scales-explanation>.

⁴ <http://thermosphere.tudelft.nl>.

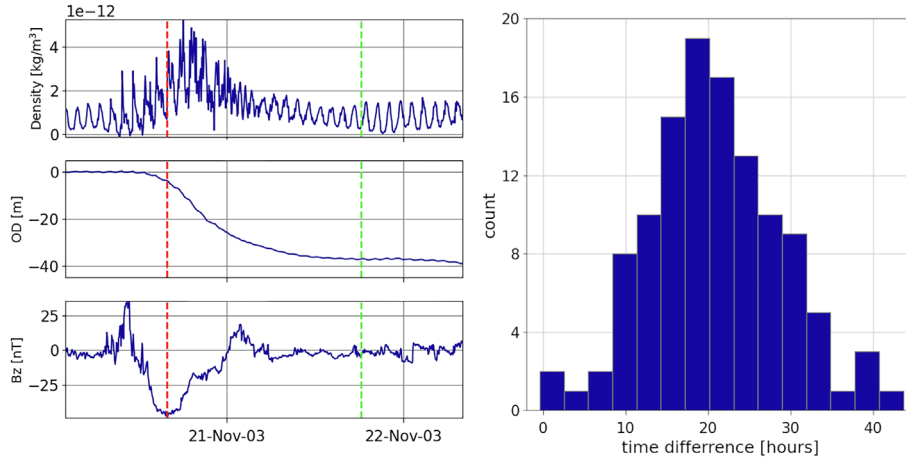


Figure 6. (Left) From top to bottom the panels show the evolution of the neutral density, the orbit decay, and the observed B_z component for an ICME event on November 20, 2003. In each panel, the red dashed line corresponds to the detection time of the minimum B_z and the green dashed line to the detected end time of the orbit decay. (Right) Histogram showing the time difference between the minimum of the B_z component detected at L1 (from real-time in-situ measurements) and the orbit decay reaching its maximum for all 116 ICME events.

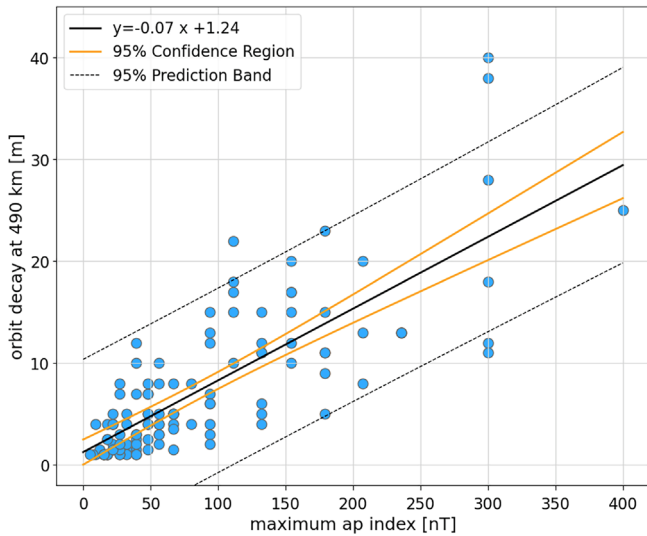


Figure 7. Orbit decay as a function of the geomagnetic index a_p used to deviate the severeness level of the storm indices orbit decay. Indicated with black dashed lines is the 95% prediction band and with solid orange lines the 95% confidence interval.

de-orbiting of these satellites (Fang et al., 2022). To take this ICME interaction process into account, the value depicted in Table 1 and marked with * refers to a combined post-processed solution of the two ICMEs. The combined solution (8.9 m) is close to the observed one (11.0 m), while analyzing the events separately would lead to orbit decays of about 3 m and 7 m, respectively. This indicates that events that occur sequentially in a short period of time need special attention for a reliable forecast. For this particular event, we would like to stress that SODA estimated only a moderate drop stemming from the ICMEs, for a satellite in a 490 km orbit. However, the Starlink satellites were in much lower (~ 210 km) and thus more dangerous orbit heights, even for a weak/moderate geomagnetic storm.

While the ICMEs contributed to the orbit drop of the satellites, it may not necessarily have been the primary cause of the loss of the Starlink satellites (Baruah et al., 2024).

The third event we would like to discuss in more detail occurred on July 07 (09:00 UT) in 2022. For this ICME, it became apparent that the predicted value of SODA was too low. This could be related to the fact that this event was the first out of a series of three incoming ICMEs, with two further events arriving at Earth on July 8 (02:00 UT) and July 9 (12:00 UT). According to the R&C catalog, the start of the second event was earlier than the end of the first event, and the minimum B_z values for the three events were measured with -18 nT, -10 nT, and -6 nT, respectively. Thus, the forecast may have deteriorated because especially the second ICME superposes the first event of the superposition of the first and second ICMEs. Together, this shows that forecasting becomes increasingly difficult when events overlap in time. For improving the forecast of such complex events, more detailed investigations are required to better understand the relation between the minimum B_z and neutral density.

4 Outlook

One aspect we are currently focusing on is complex magnetic ejecta events. As shown in Section 3.3, forecasts of SODA perform very well for the majority of the ICME events. However, one weakness in the current version becomes apparent when multiple field compression regions within an event occur. Especially, during high solar activity phases, the interactions between ICMEs may happen on a frequent basis (Lugaz et al., 2017). In this process, shocks of one ICME may penetrate the magnetic field of another ICME, propagating ahead and compressing a different region of that ICME's magnetic field (e.g., Lugaz et al., 2015; Scolini et al., 2020). By investigating consecutively arriving ICMEs, it could be shown that the combination of two events occurring within a time window of less than 6 h (“combined” events) was beneficial for the

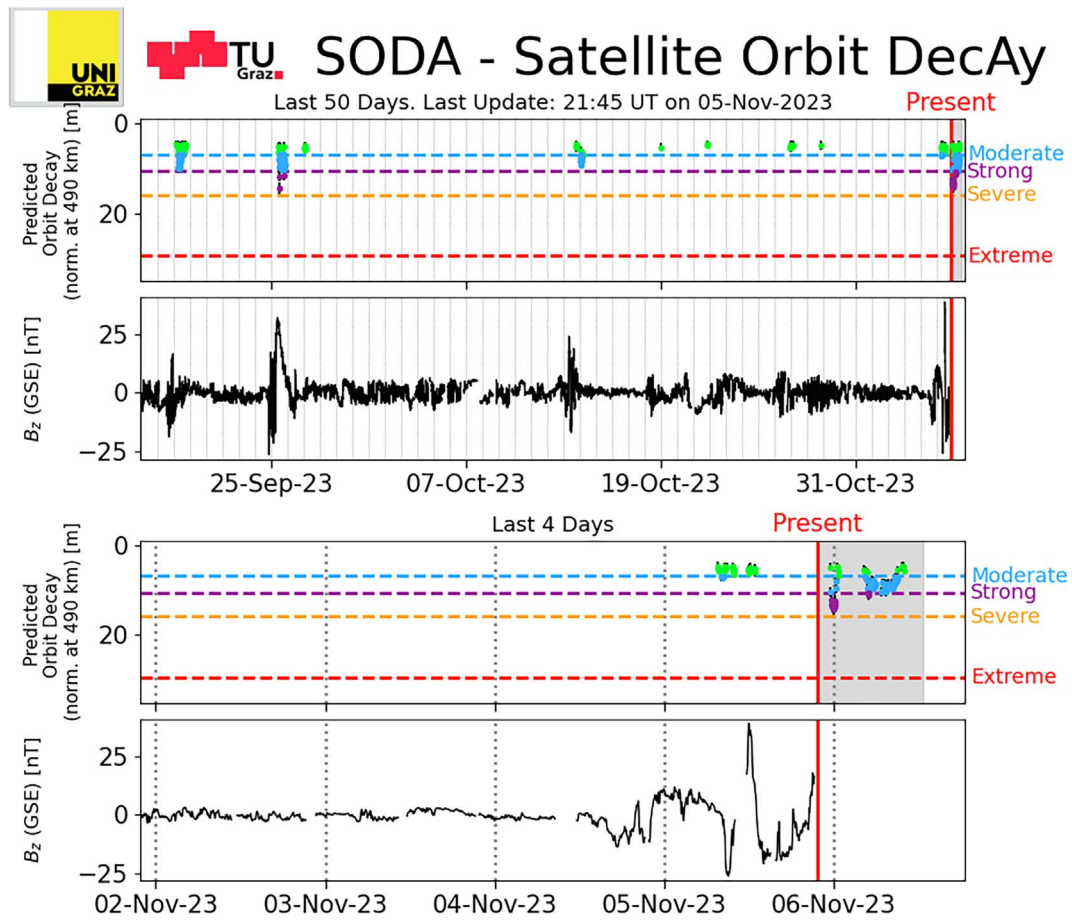


Figure 8. Illustration of the SODA tool, integrated into ESA's Space Safety Programme, during late September and early November 2023. Highlighted is the prediction of a G-class storm for November 6, 2023 which triggered stable auroral red, arcs which were even visible over central Europe.

Table 1. Overview of a selection of ICME events that were used for validation purposes. For each event, we list the geomagnetic index Dst , the detected min B_z component, the prediction value of SODA, the observed orbit decay using external density data, and finally the solution based on the predicted solar and geomagnetic indices. Remarks: (i) * refers to a combined observed solution of the ICMEs on February 1 and 3 in 2022. (ii) for the indicated event in April 2023, we used our own density estimates since no external data were available.

Date	Dst index	min. B_z	G-class	SODA	Observed
Aug. 25, 2018	−175 nT	−15.50 nT	G3	7.8 m	6.5 m
May 12, 2021	−61 nT	−21.05 nT	G3	10.8 m	4.0 m
Aug. 27, 2021	−82 nT	−14.94 nT	G2	7.5 m	4.0 m
Nov. 03, 2021	−105 nT	−16.11 nT	G3	8.1 m	9.0 m
Feb. 01, 2022	−66 nT	−17.58 nT	G2	8.9 m	3.0 m
Feb. 03, 2022	−61 nT	−9.97 nT	G2	4.7 m	7.0 m
Feb. 01-03, 2022*	−66 nT	−17.58 nT	G2	8.9 m	11.0 m
Apr. 14, 2022	−81 nT	−13.02 nT	G2	6.4 m	6.5 m
Jul. 07, 2022	−81 nT	−17.53 nT	G2	8.9 m	15.0 m
Jul. 18, 2022	−61 nT	−11.37 nT	G1	5.5 m	5.5 m
Apr. 23, 2023	−212 nT	−31.22 nT	G4	16.4 m	15.0 m

determination of the orbit decay. However, overlaps within larger time windows could not be successfully predicted (see July 07, 2022 event described in Section 3.3). On the other hand, we found that when there are more than two events in a series of incoming ICMEs, only the first two have a significant effect on the orbit decay (see Master thesis by Kroisz, 2023). With this

in mind, further research and in-depth analysis of such events is required to expand the existing ICME database and improve the predictions on the effects of magnetically complex ICMEs on LEO satellites. In this regard, it is planned to incorporate more parameters (e.g., solar wind speed) in the prediction process.

Another objective is the unification and combination of different available ICME catalog. For the first SODA release, we solely investigated ICME events mentioned in the R&C catalogue. Even though this list has a long comprehensive history, there are still events missing, which are cited in other sources (Nieves-Chinchilla et al., 2018; Larrodera and Cid, 2020; Möstl et al., 2020). Based on a careful unification, the samples of solar events could be increased (see Larrodera and Temmer, 2024).

Finally, to increase the stability of the forecast, for the next SODA release the database used for the next SODA release will be extended by the events which were currently used only for validation purposes. In this context, new findings regarding radiation pressure modeling (Wöske et al., 2019; Siemes et al., 2023; Hładczuk et al., 2024) and the treatment of magnetic field data (Oliveira, 2023) will be incorporated, and two additional altitude layers (400 km and 450 km) will be introduced for the forecast.

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