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Towards Solar Maximum: Increasing Space Weather Activity and ESA's Low Earth Orbit Spacecraft Operations

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Abstract

Spacecraft in-orbit are subject to a range of effects resulting from changing space weather conditions. Depending on their orbit, these may include single event effects in electronics, surface or internal charging effects and increased thermospheric drag resulting from solar and/or geomagnetic activity. Space weather activity follows the 11 year Solar Cycle. At the present time, activity is increasing as we move towards the next solar maximum, currently predicted to take place in 2025. Over the course of 2021-2022 ESA's mission operators had to face a number of small to significant anomalies initially attributed to space weather effects. A few examples will be discussed in this paper and compared with data and products characterising the space weather conditions at the time to analyse the potential cause. Example events observed by the Swarm mission include SEUs detected in instrumentation i.e. bit flips in science or housekeeping data leading to actions such as instrument power cycling or reboots and in one case a coarse pointing transition leading to the switch-off of all instruments.

A particular effect of the Solar Cycle, not in terms of a direct effect on instruments and equipment in orbit, is the contribution to satellite orbital decay due to increased drag. For satellites in LEO this is particularly evident, especially for Swarm, if we compare the annual orbital decay (~2.5 km per year) with what was experienced in the first phases of the Solar cycle (~20 km per year). The forecasts of the solar activity of Solar Cycle 25 were carefully analysed in order to choose the size of the orbit raise of the two low-orbiting satellites, Swarm-A and Swarm-C, such as to design a set of manoeuvres to sufficiently raise their orbits and avoiding re-entry in 2025. On the very low flying Aeolus mission with an operational altitude of 320 km the impact of sudden changes in atmospheric drag is immediate and has led to rapid deterioration of orbit predictions and major impact on science return. Adjustments to the operational scheme had to be done to counteract the increasing effects of the solar cycle. Due to the increased fuel consumption at this orbit the space weather is also a life limiting factor for the less than 4 years old mission and will play a significant role in the end-of-life operations foreseen in 2023.

As part of ESA's Space Safety Programme, ESA's Space Weather Service Network provides targeted pre-operational space weather services for a range of end users including spacecraft operators. The services provide access to data and tools to monitor and forecast potentially hazardous conditions, and also support operators in post-event analysis. This for example allows the missions, such as Swarm and Aeolus, to correlate anomalous behaviour on electronics with space weather conditions. In some other cases, routine activities such as payload calibrations of instruments sensitive to periods of enhanced geomagnetic activity could be delayed if forecasts of geomagnetic storms are received with sufficient advance warning time.

This paper presents the influence of space weather on Swarm and Aeolus mission operations over the early stages of Solar Cycle 25, discusses effects observed and actions taken. This is presented along with data and products from the ESA Space Weather Service Network illustrating space weather conditions at the time. The paper then further discusses space weather data availability, needs and utilisation in an operational context and also presents the outlook for operations in view of the coming Solar Maximum

Keywords: space weather, thermospheric drag, solar activity

Acronyms/Abbreviations

ANeMoS: Athens Neutron Monitor Station
ASM: Absolute Scalar Magnetometer
CACTus: Computer Aided CME Tracking Software
CCD: Charge-coupled device
CD: Drag coefficient
CLS: Collecte Localisation Satellites
CME: Coronal Mass Ejection
DTM: Drag Temperature Model
DWD: Deutsche Wetter Dienst
ECMWF: European Centre for Medium-Range Weather Forecasts
EFI: Electric Field Instrument
ESA European Space Agency
ESOC: European Space Operations Centre
EUV: Extreme Ultraviolet Radiation
G1/G2/G3/G4 Geomagnetic Storm: Minor/Moderate/Strong/Severe Geomagnetic Activity
GEO: Geostationary Orbit
GOES: Geostationary Operational Environmental Satellite
GLE: Ground Level Enhancement
GPS: Global Positioning System
JAM: Japan Meteorological Agency
LEO: Low Earth Orbit
LIDAR: Light Detection and Ranging
NCMRWF: National Centre for Medium Range Weather Forecasting
OCM: Orbit control manoeuvre
RAAN: Right Ascension of the Ascending Node
SEU: Single Event Upset
SWE: Space Weather
VFM: Vector Field Magnetometer

1. Introduction

Space weather can impact spacecraft operations in a variety of ways, through interaction of charged particles with the spacecraft platform or components, enhanced thermospheric drag and/or impacts on communication systems relying on signal propagation through the ionosphere.

Space weather activity is known to vary with the solar cycle of approximately 11 years duration. During periods of high solar activity close to the solar maximum, increased activity results in increased frequency of solar flares, energetic particle events and geomagnetic storms, all of which may impact mission operations. At the present time, as we approach the maximum of Solar Cycle 25, activity is increasing [1]. With Solar Maximum predicted to take place in 2025, trends in increasing activity observed in the past 1-2 years can be expected to continue in the coming period leading to increased impacts on spacecraft operations. It should also be noted that, while this solar cycle does not yet show signs of being unusually strong, the rapid growth in on-orbit population in some orbits results in the need for increasingly accurate orbital predictions in order to support a growing need for collision avoidance services.

For satellites in Low Earth Orbit, thermospheric drag provides an important contribution to the forces acting on the spacecraft leading to orbital decay and associated along-track dispersions. The local temperature, composition and resulting densities are strongly driven by space weather effects from solar Extreme Ultraviolet Radiation (EUV) and from Coronal Mass Ejections (CMEs) leading to geomagnetic storms. The recent loss of 38 Starlink satellites during a series of moderate geomagnetic storms [2] further highlights the need for accurate atmospheric density prediction and information exchange between satellite operators and the space weather community. Figure 1 provides an illustration of the variation of atmospheric density with altitude and solar activity based on the NRLMSISE-00 model currently in use by the ESA flight dynamics team [3].

Empirical density models such as NRLMSISE-00 utilised in an operational context rely on the correlation of space weather proxies such as F10.7 and Ap with an observation database of past density, composition and temperature variations. Uncertainties are introduced due to both correlation of the space weather proxies with the datasets underlying the models which may be incomplete and through the correlation between the space weather proxies and density variations as these proxies aim to parametrise complex space weather conditions based on particular ground based measurements and do not directly provide atmospheric density information [4]. F10.7 is one of the most widely used indices of solar activity providing a daily measurement of solar emission at radio wavelengths [5]. Ap is a ground-based geomagnetic index giving a global indication of geomagnetic activity with daily cadence [6]. Taking into account these limitations, recently developed semi-empirical models utilise more recently developed space weather indices such as F30 and Hp60 with promising results. At this time these models are currently utilised primarily for research purposes and testing in an operational context see e.g. DTM-2020 [7], and ATMDEN which provides an implementation of DTM-2013 combined with nowcast and forecast indices to provide up to 27 day forecast of thermospheric density in the range 120-1500km via the ESA SWE Service Portal (https://swe.ssa.esa.int/atmden-federated).

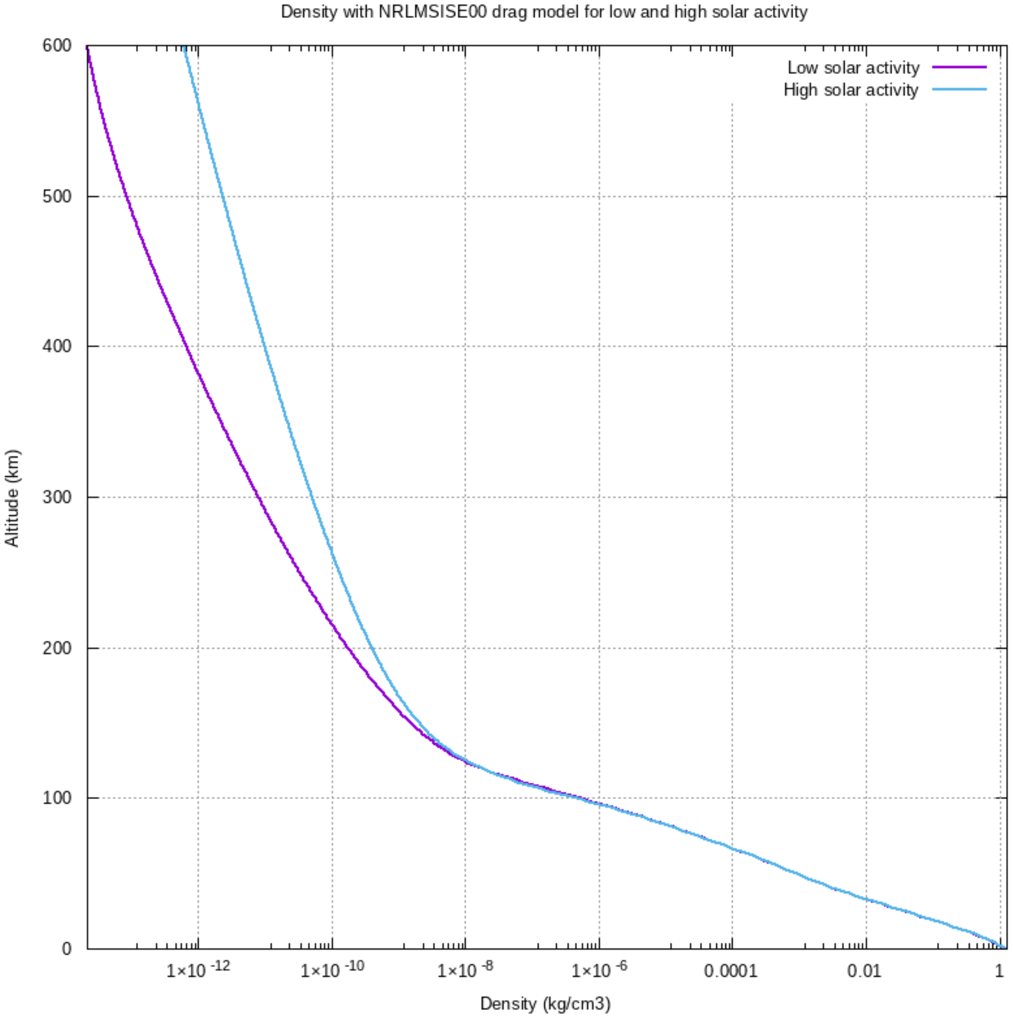


Figure 1: Atmosphere model NRLMSISE-00 illustrating atmospheric density variation with altitude and solar activity

For LEO missions such as ESA's Swarm mission, precise orbit determination may be achieved through use of onboard dual-frequency GPS receivers and onboard reflectors for e.g. laser ranging [8]. However, predicting the orbital evolution of a given mission will need to rely on thermospheric modelling taking into account forecast space weather proxies, introducing a further source of uncertainty.

2. Matching Space Weather Service Capabilities to Spacecraft Operation Needs

This section briefly outlines the characteristics of Swarm and Aeolus missions along with tools and products available via ESA's Space Weather Service Network's services for spacecraft operators.

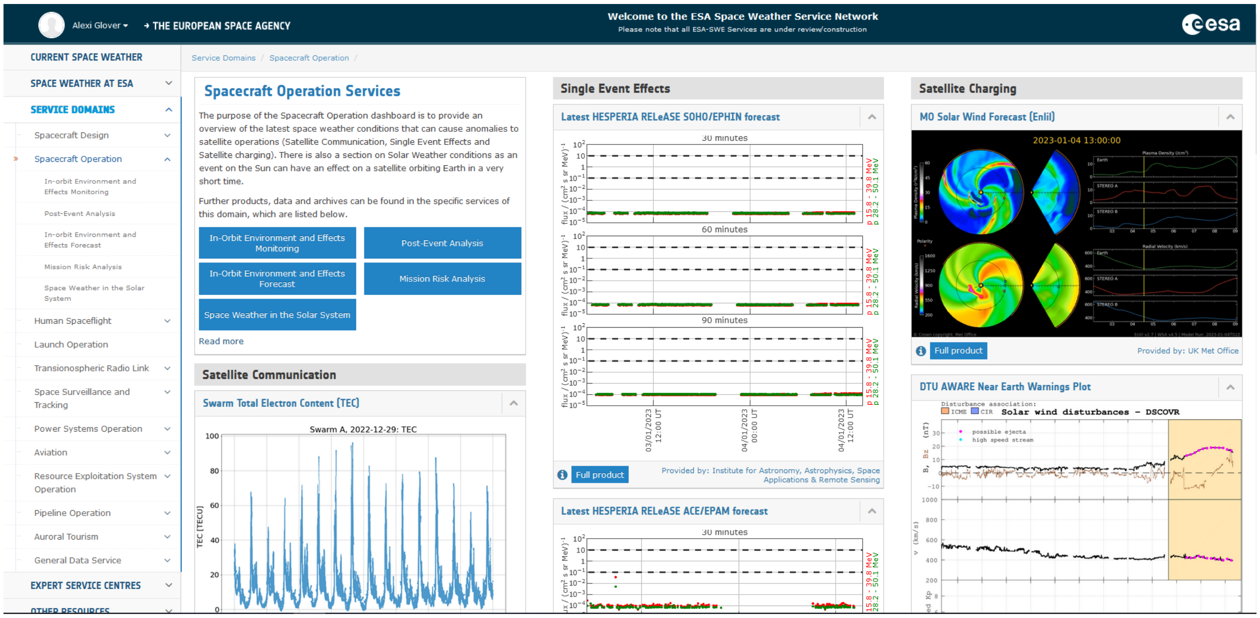
2.1 ESA Space Weather Services for Spacecraft Operators

Forming part of ESA's Space Safety Programme, the ESA Space Weather Service Network focuses on the development and provision of actionable information to a diverse range of end users in domains ranging from satellite operation, navigation, the aviation sector through to power distribution network operators. Via a centralised web portal (https://swe.ssa.esa.int), the Network currently provides access to almost 300 individual service elements. These individual elements are provided by a network of over 50 participating entities from across Europe and structured into user driven services in consultation with end user communities.

Within the Spacecraft Operation service domain, the following services are provided:

- In-orbit environment and effects monitoring
- Post-event analysis
- In-orbit Environment and Effects Forecast
- Mission Risk Analysis
- Space Weather in the Solar System

Each service is comprised of a range of products and tools, combined with end user support available both online and via the dedicated space weather helpdesk. An overall dashboard provides a first entry point to the Spacecraft Operation service domain, highlighting capabilities available within the individual services (https://swe.ssa.esa.int/sco_dashboard). Figure 2 provides a snapshot of the Spacecraft Operations dashboard. Example products include archive data and tools supporting post-event analysis, latest data and alerting supporting timely notification of ongoing events and forecast information supporting prediction of on-orbit conditions. The services address the radiation environment, geomagnetic disturbances, space weather impacts on thermospheric density and space weather impacts on communication systems which rely on ionospheric propagation. The full service catalogue can be retrieved via the following link: https://swe.ssa.esa.int



The purpose of the Spacecraft Operation dashboard is to provide an overview of the latest space weather conditions that can cause anomalies to satellite operations (Satellite Communication, Single Event Effects and Satellite charging). There is also a section on Solar Weather conditions as an event on the Sun can have an effect on a satellite orbiting Earth in a very short time.

Further products, data and archives can be found in the specific services of this domain, which are listed below.

Figure 2: ESA SWE Service Portal's Spacecraft Operations Dashboard

At the present time ESA's space weather services are available on a pre-operational basis. This means that products and services can be accessed via the centralised service portal (https://swe.ssa.esa.int) at any time. The services are supported by a helpdesk and second line expert support network which is available during European office hours. Registration is free and open to all users.

While the SWE Service Network services are available to all users, ESA mission operators naturally form a high priority user group for the Service Network and tailored service campaigns are regularly organised with the mission teams in order to both demonstrate and test the services and to ensure that the services under development are effectively targeted towards user needs. To date, tailored campaigns have been organised together with ESA missions including Mars Express, BepiColombo and Gaia. The work described in later sections of this paper also highlights cases where space weather services may provide valuable insight into the effects of space weather on regular operations.

2.2 Swarm

ESA's Swarm mission consists of three spacecraft launched on 22 November 2013 into a near-polar (87.5° inclination) orbit with initial altitude of about 500 km. From January 2014 onward the three spacecraft were moved apart, achieving their final constellation on 17 April 2014.

Swarm, as a magnetic and plasma mission is creating a highly detailed survey of the Earth's geomagnetic field, its temporal and spatial evolutions as well as the Electric field in the atmosphere, carrying a suite of four instruments per satellite. The magnetic instruments, a Vector Field Magnetometer (VFM) and an Absolute Scalar Magnetometer (ASM), measure the magnetic field components and the absolute magnetic field, the ASM having an additional mode, called "Burst Mode", producing data at 250 Hz. The other two instruments are the Electric Field Instrument (EFI), providing indirect Electric Field measurements through a Thermal Ion Imager and two Langmuir Probes, and an Accelerometer.

The constellation is built by Swarm-A and Swarm-C, called "lower pair" satellites, that are separated by a small Right Ascension of the Ascending Node, their along-track separation is kept between four and ten seconds. Swarm-B instead, was put at a higher altitude.

The initial orbit of the lower pair was targeted to an altitude of 470 km and an inclination of 87.35°. It was maintained until October 2019 as a side-by-side constellation separated in RAAN by around 1.4° +/- 0.2°. It was then decided to perform a series of out-of-plane constellation manoeuvres deemed at aligning the lower pair orbital planes in order to obtain the same orbital plane of Swarm-B in September/October 2021 (Swarm-A and Swarm-C counter-rotating but coplanar with Swarm-B). The Delta-RAAN of the lower pair crossed therefore zero at the beginning of October 2021. The other spacecraft (Swarm B) was placed in a higher orbit (altitude ca. 516 km), with an inclination higher than the lower pair by 0.4° at 87.75°. Its orbital plane is evolving different, due to different effect of the orbit perturbations.

The different angular evolution of the orbital planes was exploited during the so-called "counter-rotating orbital scenario" from 15/07/2021 to 15/01/2022, where also the lower pair along-track separation was fine-tuned to provide different configurations for science: a 4 seconds separation phase has been established on 15/06/2021, the target separation of only two seconds was kept from 23/09/2021 until 05/10/2021, until the beginning of the variable separation phase, which was concluded on 13/01/2022, when the routine constellation separation threshold was re-established.

Although not provided in real-time, Swarm data provides valuable information on space weather conditions and as such, several products based on data from the Swarm mission are already included in the Space Weather Service Network, as shown in Figure 3 below:

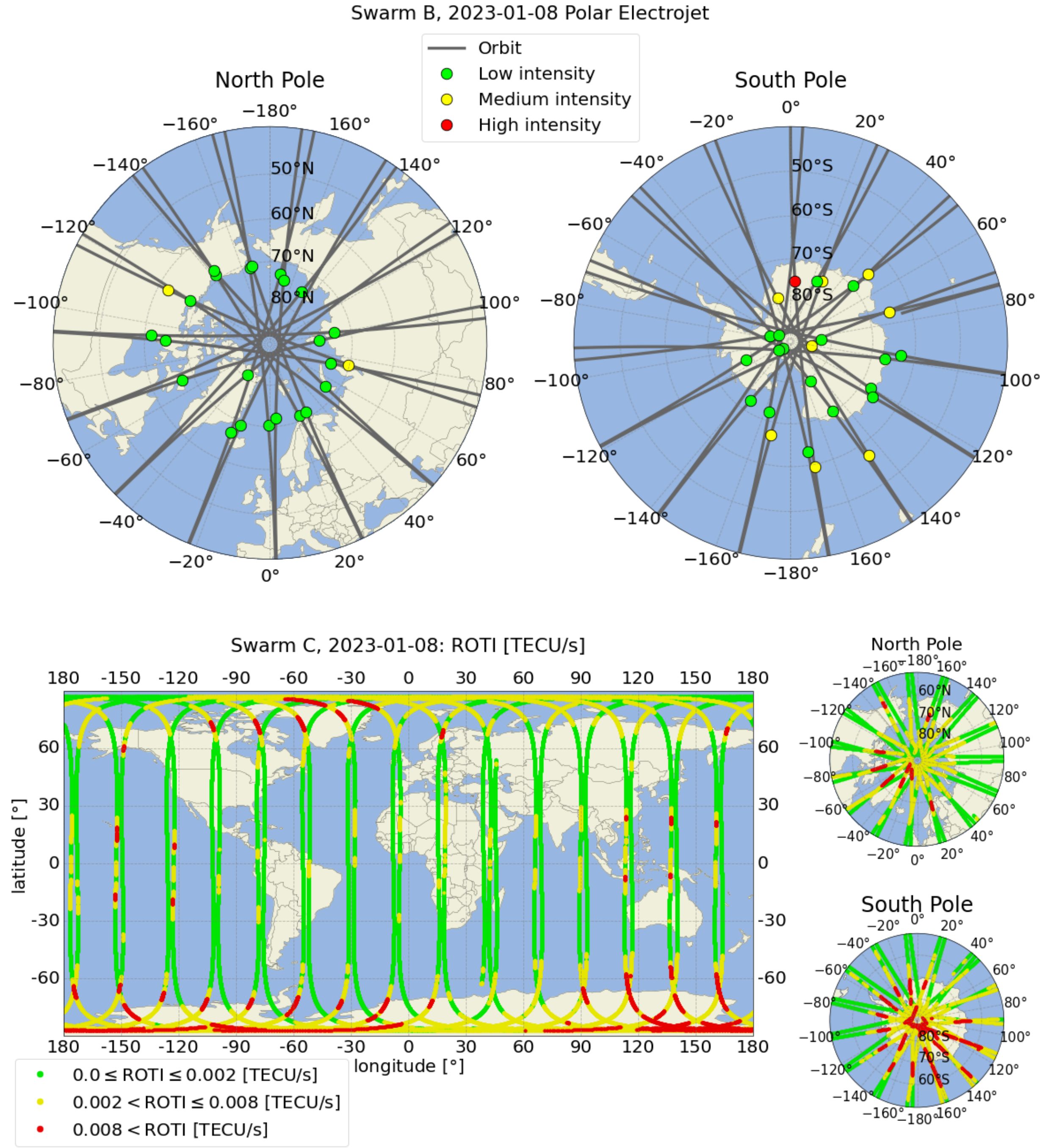


Figure 3: Example products based on Swarm data forming part of ESA's Space Weather Service Network providing information on geomagnetic activity and ionospheric conditions.

2.3 Aeolus

Aeolus is the European Space Agency's 5th Earth Explorer (EE) mission in the context of the Living Planet programme and was launched on 22 August 2018. It is the first earth observation satellite equipped with a Doppler Wind LIght Detection And Ranging (LIDAR) instrument: a sophisticated, high performance direct-detection laser emitting light pulses in the UV spectral wavelength of 355 nm. This laser provides global wind speed profiles from the troposphere and lower stratosphere (0 – 30km) through the measurement of the residual Doppler shift of the backscattered laser signals from the atmospheric layers consisting of aerosols, clouds and molecules.

The scientific mission objectives are to improve weather forecasts by filling the gap of much-needed wind profiles on a global scale in near-real time and to improve the understanding of atmospheric dynamics. In addition, Aeolus' Explorer objectives are to demonstrate the space-based Doppler Wind Lidar (DWL) technology and to help pave the way for future wind LIDAR missions. Aeolus wind data is by now operationally assimilated at different meteorological centres such as the European Centre for Medium-Range Weather Forecasts (ECMWF), the Deutsche Wetter Dienst (DWD), Météo France, the UK MET office, and the Indian NCMRWF and the Japanese JMA. In line with its mission objectives, Aeolus is contributing to several research streams led by worldwide scientists, see [9] and references therein.

The satellite flies in a polar (97° inclination, 7-day repeat cycle), sun-synchronous orbit at a low operational altitude of 320 km. In the context of Space Weather, Aeolus is an example for the immediate operational impact of (sudden) variations in the air density in the thermosphere due to solar and geomagnetic activity. A few examples will be provided here below on how the space weather has impacted spacecraft operations.

3. Space Weather Impacts on Swarm and Aeolus

For a given space mission, three key timeframes/scenarios can be identified with which to consider space weather impacts on spacecraft operation:

- Analysis over the mission lifetime
- Preparation for specific or routine events e.g. re-entry or station keeping maneuvers
- Sporadic effects

This corresponds to:

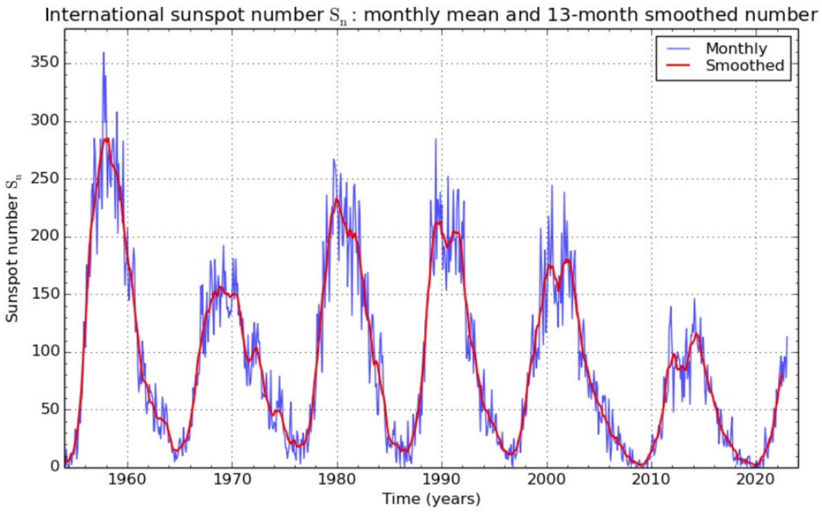
- Retrospective analysis of a given event or period
- Prediction/forecast
- Alerting/notification and support for rapid post event analysis

The following subsections provide a series of case studies illustrating the impact of space weather on Swarm and Aeolus during the rise phase of Solar Cycle 25 to date in combination with space weather information utilised by the mission and available via the SWE Service Network.

3.1 Space Weather Influence over the Mission lifetime

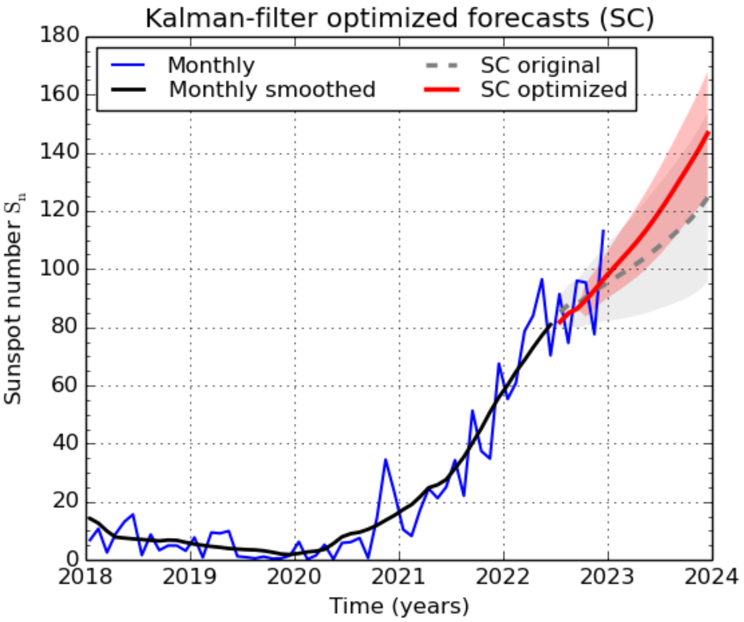
This section focuses on the influence of space weather on satellite drag as space weather activity increases towards the predicted peak of Solar Cycle 25.

Solar activity is modulated by the solar cycle, driven by the Sun's underlying magnetic field. The current Solar Cycle 25 started in December 2019. The cycle evolution is illustrated by the International Sunspot Number, which accounts for the number of sunspots and groups on the visible solar disk. We show a plot of this index below covering several solar cycles where it can be seen that the previous Solar Cycle 24 was small in comparison to the several preceding cycles (Figure 4). At the ESA SWE Service Portal, two products provide the computed (nowcast) sunspot number and a prediction for the current year respectively. These are provided by ROB/SIDC, as shown in Figure 5 below.



SILSO graphics (http://sidc.be/silso) Royal Observatory of Belgium 2023 January 4

Figure 4: International sunspot number from Solar Cycle 19 until the current Solar Cycle 25



SILSO graphics (http://sidc.be/silso) Royal Observatory of Belgium 2023 January 4

Figure 5: forecast of the international sunspot number for the current year.

Solar ultraviolet emission also varies with the solar cycle. The ultraviolet radiation strongly impacts the Earth's atmosphere. A proxy of the ultraviolet radiation is the F10.7 index (meaning radio wavelengths of 10.7 cm or 2.8 GHz), observed daily and calibrated in form of an index. We show a plot of the daily F10.7 index for the current Solar Cycle 25 starting towards the end of 2019. Data is retrieved from the ESA SWE Service Portal using the SGIArv database of indices relevant for thermospheric density calculation (Figure 6). The rise phase of Solar Cycle 25 can clearly be seen with a significant increase in January 2023 at the time of writing.

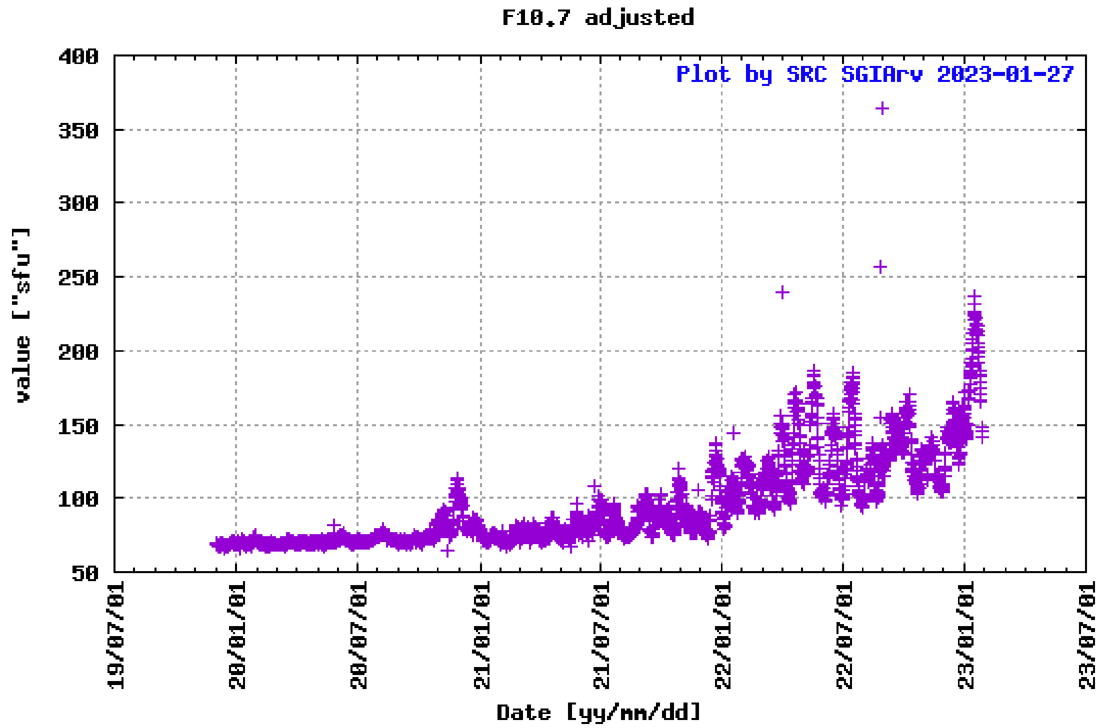


Figure 6: F10.7 adjusted solar radio flux index, plot generated using the SGIArv database interface available via the ESA SWE Service Portal.

Other solar features, such as coronal mass ejections which may trigger geomagnetic storms on arrival at Earth show a daily occurrence which also follows roughly the trend of the sunspot number, plus in the solar cycle declining phase a significant daily occurrence rate may continue to be observed. Figure 7 shows CMEs detected using the automated CACTus tool used with coronagraph data from SOHO and STEREO missions during several solar cycles.

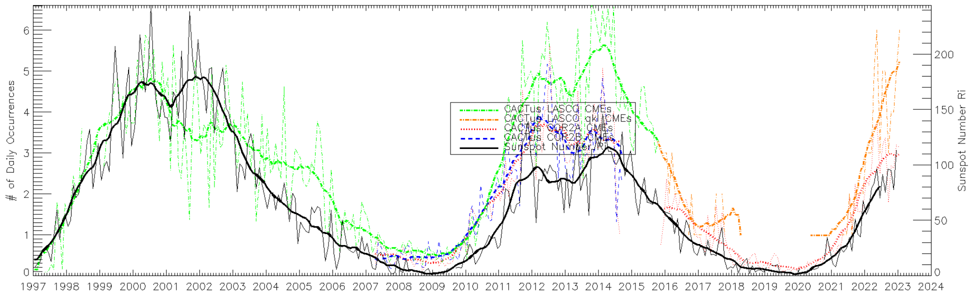


Figure 7: Plot from the CME catalogue CACTus showing Solar Cycle 23, 24 and the current Solar Cycle 25. https://www.sidc.be/cactus/. CACTus is incorporated into the SWE Service Portal as product S.111.

Impact of a CME arrival at Earth, depends on the interaction of these features with the Earth's magnetosphere. The level of disturbance resulting from this interaction can be characterised by a variety of geomagnetic indices The ESA SWE Service Portal provides access to a diverse range of geomagnetic indices with different spatial coverages (global, local) and different time resolutions (e.g. daily, 3 hours, 30 minutes etc.). Indices such as Kp and Ap are available from 1932. The portal retains archives of these data, for example through the product *Kp and Ap index* *archive* provided by, among others, GFZ, and SGIArv mentioned above. These archived data are used in Figure 8 to show the daily Ap index (blue solid line) recorded during Solar Cycles 23, 24, 25 together with the Sunspot Number (orange solid line in the background).

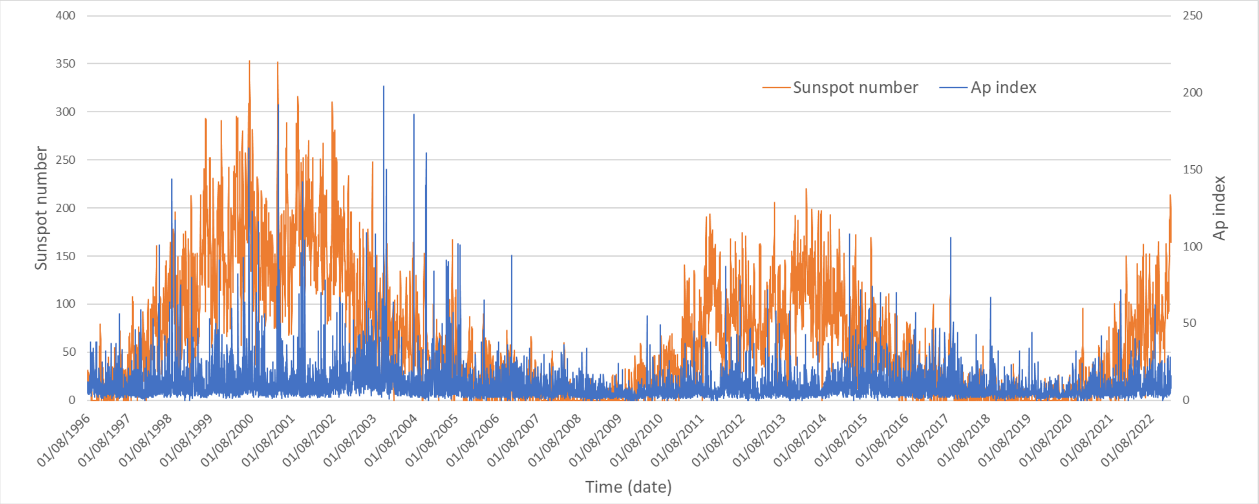


Figure8 Plot of the International Sunspot Number and daily Ap index (ESA SWE product Kp and Ap index archive provided by GFZ) from solar cycle 23 onwards.

From the figure above it is possible to recognise that the magnitude of geomagnetic activity grows along with the solar activity within the solar cycle with geomagnetic perturbations appearing more frequent and stronger in the descending phase of each cycle, following the trend of the daily CME occurrences.

3.1.1. Aeolus mission lifetime:

A way to find correlations to space weather changes over the mission lifetime is by looking at:

- the hitherto fuel consumption,
- the evolution of the drag coefficient,
- the amount/frequency and magnitude of necessary Orbit Control Manoeuvres (OCM) to counteract orbital drifts which are particularly driven by sudden changes in the atmospheric density (drag variations) at lower operational altitudes

The bookkeeping of the remaining fuel onboard Aeolus shows an increase in the average fuel consumption which became more distinct from mid-2021, indicating higher fuel usage per OCM to keep the satellite within its ground track limits. This was attributed to the increase in solar activity which had to be compensated by higher thrusting, delta-v, during the OCMs. This can be seen in the below graph which shows the remaining fuel evolution vs. the fuel required per OCM.

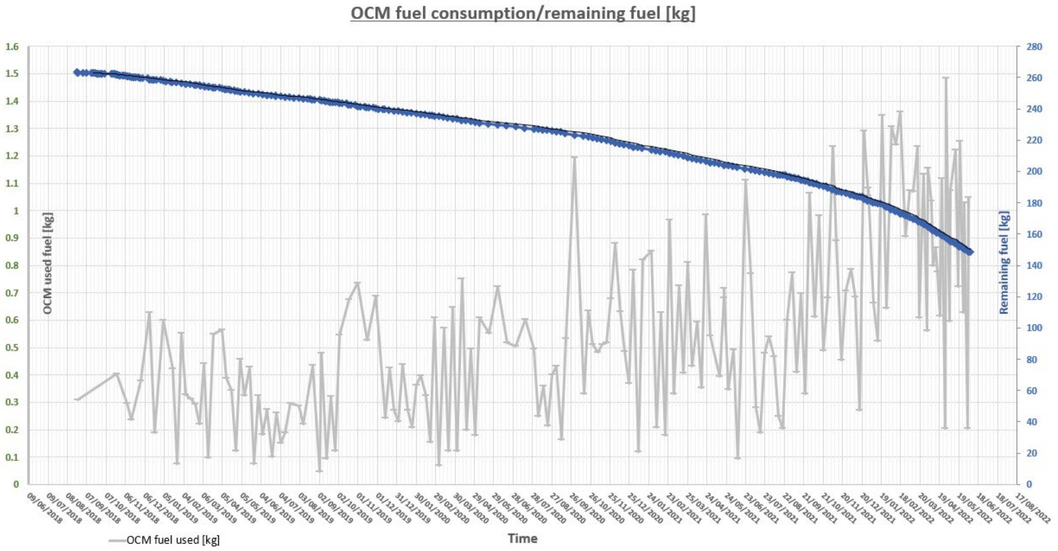


Figure 9: Aeolus remaining fuel vs. fuel used per OCM. The denser OCM lines starting from 2022 are due to the operational implementation of 2 OCMs per week.

Since the stronger and sudden variation in solar activity has led to numerous events where the satellite exited its ground track control band limits, and therefore jeopardizing the science measurement and acquisition of the satellite by ground (i.e. need to replan an ongoing operations week), it was decided to change the routine operations scheme from a single OCM per week to two OCMs. This allowed the mission operations to continue with almost no ground track control band exits despite higher solar activity (while keeping a maximum thrust limit per OCM imposed by the mission) and provided a mean to adjust to higher variations, i.e. sudden changes in solar activity when compared to the predicted one for the operations week[*].

An example of the ground track control pre- and post-in-flight operations scheme adjustment is shown in Figure 10 below, together with an example where the ground track was exceeded by more than 10 km due to sudden changes in the solar activity (Figure 10c). The effect of the resulting variability in the air density in the upper layers of the atmosphere (thermosphere) is higher drag when solar activity is high and lower drag when it calms down again. At higher drag levels the satellite will sink and fly lower, hence faster as seen from ground (relation between speed vs. orbital radius). This causes an East-ward drift of the orbit (or equator crossing position) and leads to a potential ground track deviation outside the allowed limits.

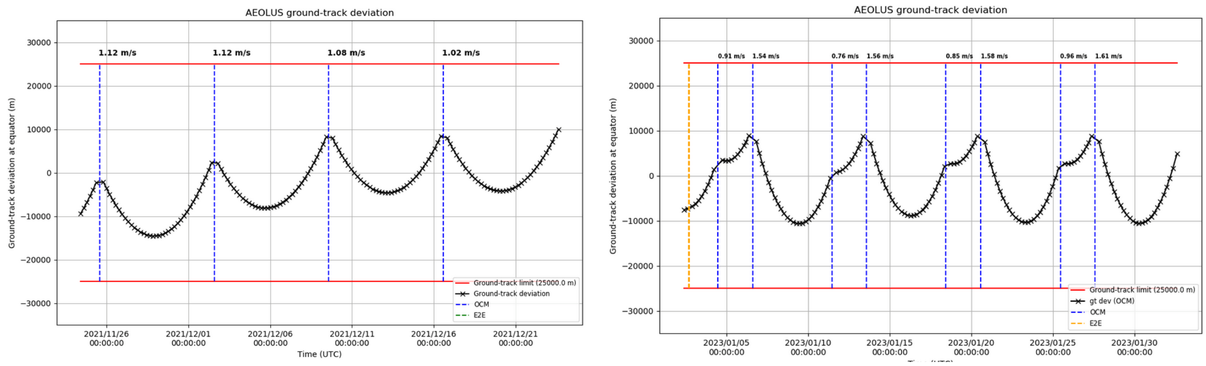


Figure 10a,b: Aeolus ground track deviation plot before (left) and after (right) implementing 2 OCMs per week

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[*] Note that satellite operations are typically planned about one week ahead using Flight Dynamics orbit predictions which assume certain space weather conditions, such as drag and solar activity.

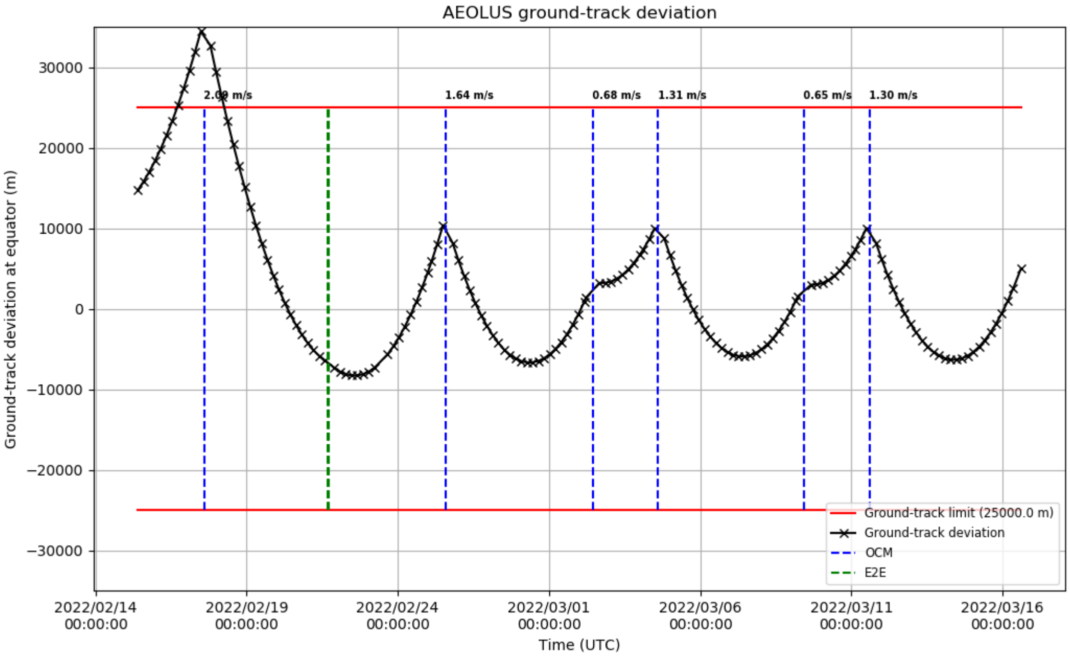
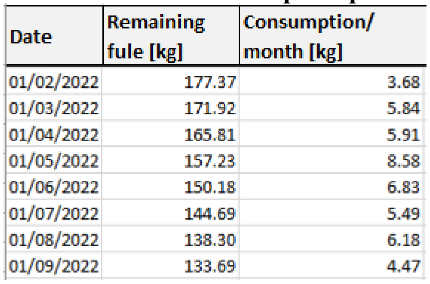


Figure 10c: An example of a ground-track limit violation, just prior to transitioning to two OCMs per week.
The highly variable fuel consumption per month also poses challenges to the prediction of future fuel consumption and therefore remaining mission lifetime. One can see in the table below the fluctuations in the monthly fuel consumption.

Table 1: Aeolus fuel consumption per month



Date	Remaining fule [kg]	Consumption/ month [kg]
01/02/2022	177.37	3.68
01/03/2022	171.92	5.84
01/04/2022	165.81	5.91
01/05/2022	157.23	8.58
01/06/2022	150.18	6.83
01/07/2022	144.69	5.49
01/08/2022	138.30	6.18
01/09/2022	133.69	4.47

To complete the picture, the historical data of the drag coefficient as estimated by ESA Flight Dynamics for the Aeolus mission along with the historical F10.7 index is provided here below.

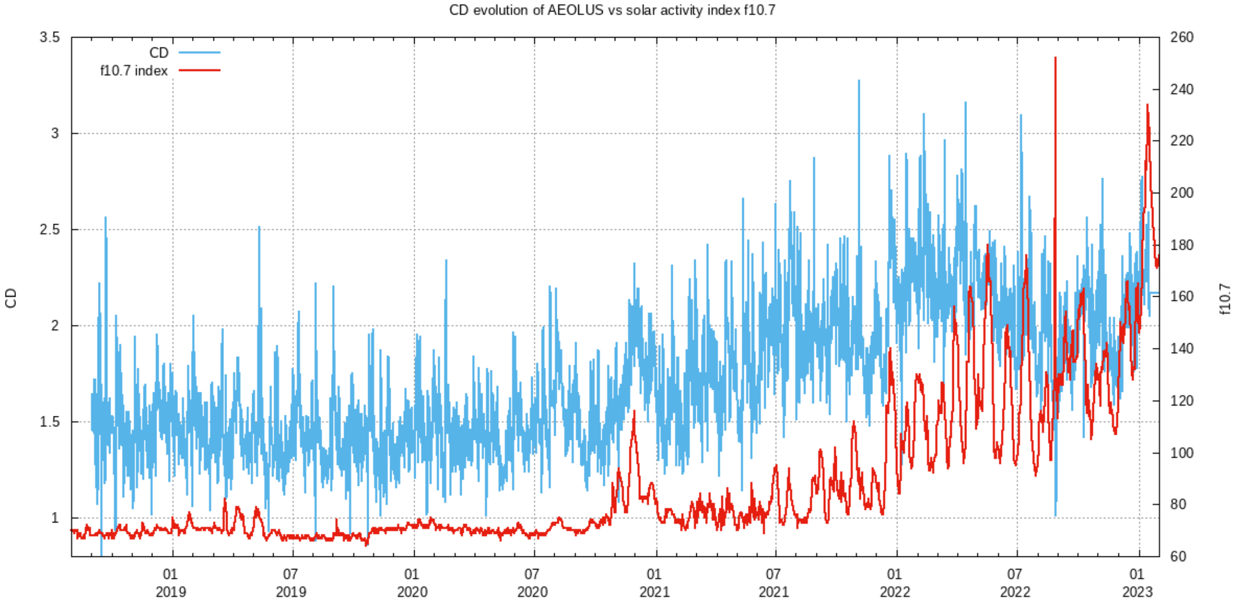


Figure 11: Drag coefficient evolution, CD, as used by Flight Dynamics for Aeolus since launch plotted alongside the solar F10.7 index. An increase in both is visible starting about mid 2021.

3.1.2 Swarm Mission lifetime.

The Swarm mission was originally planned to be a four year mission; however, due to the excellent status of the platform and the instruments, in particular the magnetic “core” instruments, the mission have been extended twice after the nominal phase, and it is currently still in the routine extended phase, until at least the entire 2025. One of the reasons for these extensions has been the relevant fuel reserves, ensuring not only many years of lifetime in terms of Attitude and orbit control, but also a fundamental opportunity and need to keep the mission flying.

The challenge, for the lower pair of the Swarm satellites, was to survive the effects of the Solar Cycle 25, that since the ramp-up at the end of 2021 started to cause a greater orbital decay than during solar minimum – from an average of 2.5 km/year to more than 20 km/year and then increasing parabolically. These effects, if not counteracted with a substantial orbit raise, would mean a re-entry from orbit some time in 2024-2025, depending on the solar maximum.

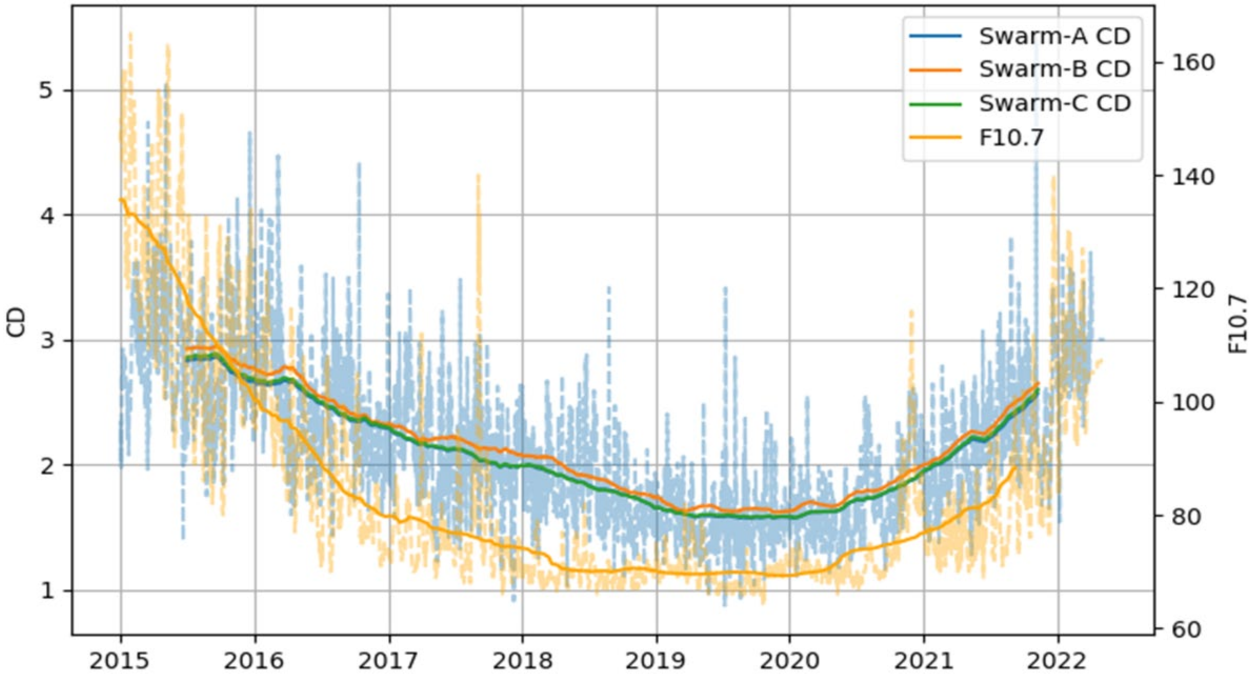


Figure 12: Swarm daily drag scale factor (CD) for all 3 spacecraft plotted alongside F10.7.

It is with the objective to fully survive the Solar Cycle and get to an average altitude of ~350 km in 2030 that a major orbit raising campaign was carried out by the Swarm mission in 2022 with the aim to continue science operations until 2030, not only for Swarm-B, but also for Swarm-A and C, subject to this major operational milestone. Considering the ramp-up of the Solar cycle, in May 2022 a first step of the manoeuvring campaign allowed to raise the orbits of Swarm-A and Swarm-C semi-major axis around 45km, the final target was decided based on the latest information on the current Solar cycle. Further phases of the orbit raise will be planned for the next months/years. This step-wise approach will allow a better tuning of the target altitude, depending on the Solar cycle's strength and also to better identifying the altitude the satellite will fly during the next solar minimum. Also Swarm-B orbit will be raised at a later stage in order to ensure a consistent altitude separation with respect to the lower pair.

The approach followed for this campaign is detailed in [10].

3.2 Preparation for Specific Events and/or Campaigns

This section provides examples where space weather information may provide key input in preparing for specific events and/or campaigns.

3.2.1 Preparation for Aeolus Re-entry Campaign

The Aeolus mission team is currently preparing for a re-entry campaign foreseen in 2023 (still TBC). In essence the mission is looking into actively reducing the satellite altitude in a short time frame by performing a series of anti-flight manoeuvres to decrease the perigee to a certain height and to target a specific subsequent re-entry corridor in the south Atlantic Ocean. Although this campaign requires fuel to be reserved, it will reduce the global casualty risk by an order of magnitude.

One of the main challenges here are the atmospheric variability and uncertainties during the deorbit phase, especially towards the final stage of the re-entry campaign. Modelling the aerodynamic drag for example is a crucial element in defining the re-entry scenario and the dispersion of surviving elements of the satellite on ground. This is on top influenced by variations in atmospheric density resulting from unforeseen changes in the solar activity and underlying atmospheric models (including the errors). As this campaign aims at "pushing" the satellite down to a predefined perigee altitude with a final boost from where it will re-enter within a few revolutions, the atmospheric variations encountered until this last boost are of significance.

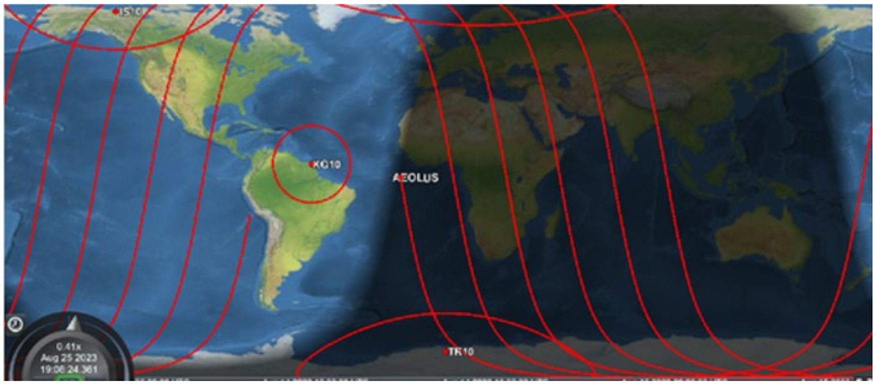


Figure 13: Aeolus mission South Atlantic re-entry target point

3.3 Sporadic effects, alerting and rapid post event analysis

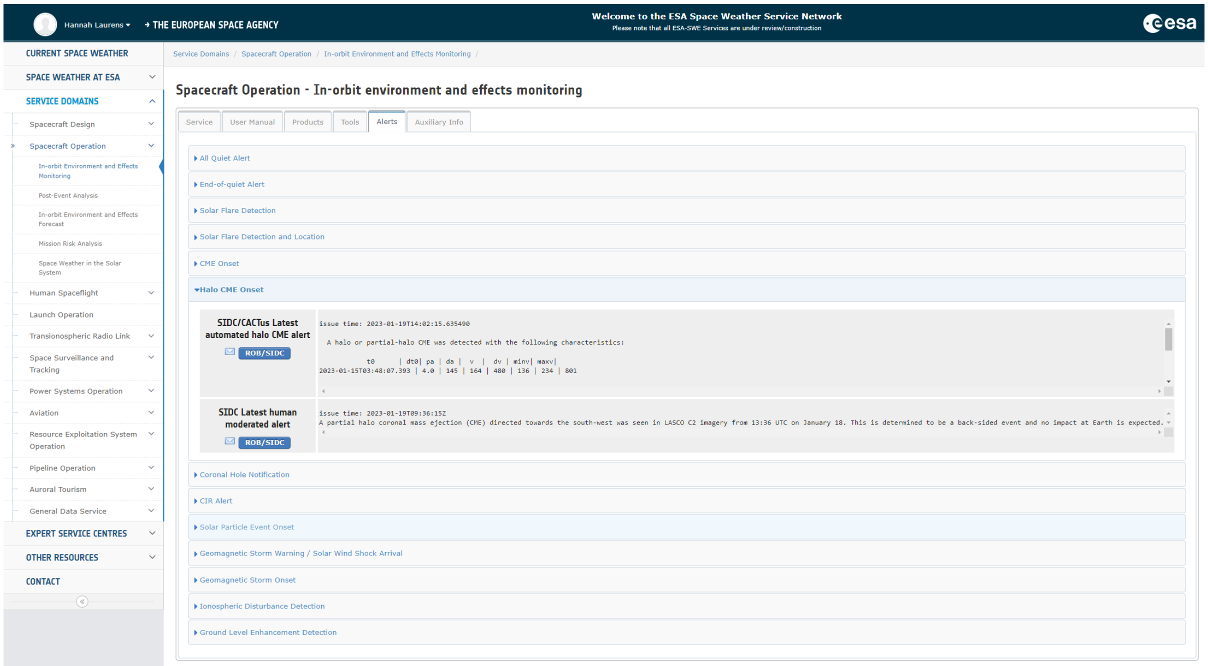
This section discusses notification and alerting on specific conditions that may lead to increased drag or other timely effects in low Earth orbit.

To assess the impact of space weather for both observed sporadic effects on a spacecraft or in advance of an imminent planned manoeuvre, spacecraft operators need an awareness of active, or soon to be active space weather conditions. This awareness may be achieved through alerting and notifications to users that conditions of interest are currently (or expected to be) taking place. Through the ESA Space Weather Service Network's diverse range of products, a selection of these may be classified as 'Alerts' and disseminated to the user either via a clear notification on the ESA SWE Service Portal product page or in some cases through a subscription allowing notifications to be received to an email address. Through the Spacecraft Operation Domain dashboard, a number of representative alerting products are provided for the domain. One example is H.106b (DTU AWARE Near-Earth Warnings Plot) visible on the bottom right of Figure 2 above. Here, detections and arrivals of solar wind disturbances with a potential to create geomagnetic storms are clearly identifiable by coloured blocks allowing a user to associate a period of time with a possible disturbance.

The Spacecraft Operation dashboard provides a first entry point to the domain as a whole. In addition the data and information is further organised into dedicated services as described in section 2.1. Within each service a list of all relevant alerts is provided, where applicable via a dedicated 'Alert Tab' within the service page. Figure 14 shows an example for the Spacecraft Operations – In-orbit environment and effects monitoring service.

In the context of the Spacecraft Operation Domain the following services provide alerts:
- In-orbit environment and effects monitoring
- In-orbit environment and effects forecast
- Space Weather in the Solar System

Available alerts are categorised according to the specific conditions being reported on and, where applicable, a preview of the latest available alert is shown. From a LEO mission operator perspective, alerts pertaining to potential drag effects arising from increased thermospheric density could be of high importance. In this case operators could look for related alerts such geomagnetic storm onsets and active solar conditions. Some alerts available via the SWE Service Network provide information on multiple space weather phenomena such as H.106a Near-Earth Space Weather Notifications (Figure 15) which comprises numerous detailed sections with associated forecaster commentary e.g., Technical Forecast Overview as well as Geomagnetic and Radiation Storm summary over the past twenty-four hours and forecast for the next four days. In addition, others focus on specific phenomena such as S.107d KSO Solar Flare Alerts providing detections of solar flares from Halpha images acquired at Kanzelhöhe Observatory. Each service is provided with guidance to help users determine which products, including alerts, are most relevant for their needs and the SWE Service helpdesk is available to provide support where requested.



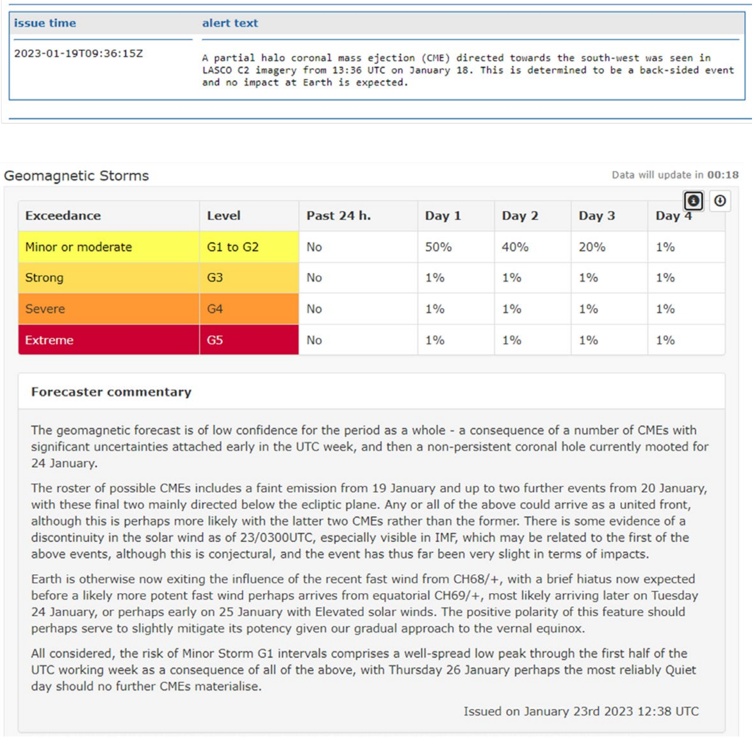
```
issue time: 2023-01-19T14:02:15.635490

  A halo or partial-halo CME was detected with the following characteristics:

           t0      | dt0| pa | da |  v  |  dv | minv| maxv|
2023-01-15T03:48:07.393 | 4.0 | 145 | 164 | 480 | 136 | 234 | 801
```

```
issue time: 2023-01-19T09:36:15Z
A partial halo coronal mass ejection (CME) directed towards the south-west was seen in LASCO C2 imagery from 13:36 UTC on January 18. This is determined to be a back-sided event and no impact at Earth is expected.
```

Figure 14: ESA SWE Service Portal's Spacecraft Operations - In-orbit environment and effects monitoring service page highlighting the available alerts.



issue time	alert text
2023-01-19T09:36:15Z	A partial halo coronal mass ejection (CME) directed towards the south-west was seen in LASCO C2 imagery from 13:36 UTC on January 18. This is determined to be a back-sided event and no impact at Earth is expected.

Geomagnetic Storms

Data will update in **00:18**

Exceedance	Level	Past 24 h.	Day 1	Day 2	Day 3	Day 4
Minor or moderate	G1 to G2	No	50%	40%	20%	1%
Strong	G3	No	1%	1%	1%	1%
Severe	G4	No	1%	1%	1%	1%
Extreme	G5	No	1%	1%	1%	1%

Forecaster commentary

The geomagnetic forecast is of low confidence for the period as a whole - a consequence of a number of CMEs with significant uncertainties attached early in the UTC week, and then a non-persistent coronal hole currently mooted for 24 January.

The roster of possible CMEs includes a faint emission from 19 January and up to two further events from 20 January, with these final two mainly directed below the ecliptic plane. Any or all of the above could arrive as a united front, although this is perhaps more likely with the latter two CMEs rather than the former. There is some evidence of a discontinuity in the solar wind as of 23/0300UTC, especially visible in IMF, which may be related to the first of the above events, although this is conjectural, and the event has thus far been very slight in terms of impacts.

Earth is otherwise now exiting the influence of the recent fast wind from CH68/+, with a brief hiatus now expected before a likely more potent fast wind perhaps arrives from equatorial CH69/+, most likely arriving later on Tuesday 24 January, or perhaps early on 25 January with Elevated solar winds. The positive polarity of this feature should perhaps serve to slightly mitigate its potency given our gradual approach to the vernal equinox.

All considered, the risk of Minor Storm G1 intervals comprises a well-spread low peak through the first half of the UTC working week as a consequence of all of the above, with Thursday 26 January perhaps the most reliably Quiet day should no further CMEs materialise.

Issued on January 23rd 2023 12:38 UTC

Figure 15: Example alerting products reporting on a variety of space weather phenomena for both [top] forecaster moderated current active space weather conditions based on select thresholds and [bottom] activity for the past 24 hours and 4 days forecast with commentary.

3.3.1 Products Used by Aeolus in Regular Operations

The Aeolus flight control team primarily utilise orbit products provided by the ESA flight dynamics team which include the daily orbit drift between predicted and actual, which can be derived from the time offset between the orbit predictions used for a planning cycle (typically about one week in the future, assuming certain space weather conditions, e.g. drag coefficient/solar activity) and the reconstituted orbit and shorter term predictions based on newly acquired in-flight data. The alerting is done via active and daily monitoring of the time offset.

Space Weather warnings on potential geomagnetic storms are also received by the flight control team With Impacts being observed for geomagnetic storms of G2 (Kp=6) and above.

3.3.2 Products Used by Swarm in Regular Operations

One of the SW products routinely used by the Swarm operations team is the Kp index as proxy of the geomagnetic activity. The index is used in the context of an operational activity of Swarm: the CCD gain maps calibration of the Electric Field Instrument. In particular, this is used as an alert, because higher values of the Kp index – above 5 – are fundamentally influencing the plasma environment and hence causing the calibration to have a potential bias. Because of this, the operational procedures in place and agreed with the EFI Principal Investigator (University of Calgary) enforce to hold off performing such activities if, the day before the commanding the Kp index is forecast to be high.

One Gain map calibration over two consecutive orbits (one per CCD sensor) was planned in March, 2022 (for all Swarm satellites), the activity was planned and organised by ESOC, but the check of the space weather conditions in the form of the Kp index showed an upcoming geomagnetic storm within the timeframe of the calibrations (30/04/2022 and 01/05/2022). In particular up to G3 storm conditions were forecast. This was escalated to the EFI Principle Investigator, but it was exceptionally decided to let the calibration continue and evaluate a posteriori the effect of the storm on the CCD maps then calculated by the algorithm. This was the first time this forecast was actively used during an operational activity.

In practice only minor geomagnetic disturbances were recorded with Kp not reaching the threshold for a G1 event (Kp=5).

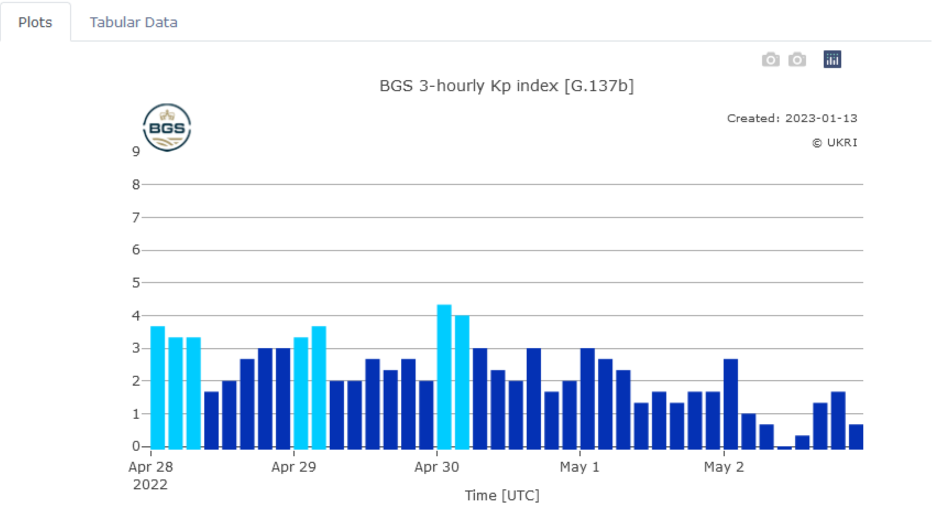


Figure 16: Kp for the period surrounding the planned EFI calibration activities as shown in product G.137b, BGS 3-hourly Kp index.

3.3.3 28th October – 4th November 2021, X1 flare and Related Activity: Case Study

The Swarm team reported a number of SEUs which might be attributed to space weather impacts, including one which caused satellite AOCS fallback to coarse pointing mode on 1st November 2021. For a given time period, the SWE Service Portal provides a range of tools and products which can be queried in order to understand what activity was taking place and whether this could have been the cause of a particular event. The following provides an example workflow for this type of analysis noting that the period of 28th October – 4th November corresponded to a period of enhanced space weather activity.

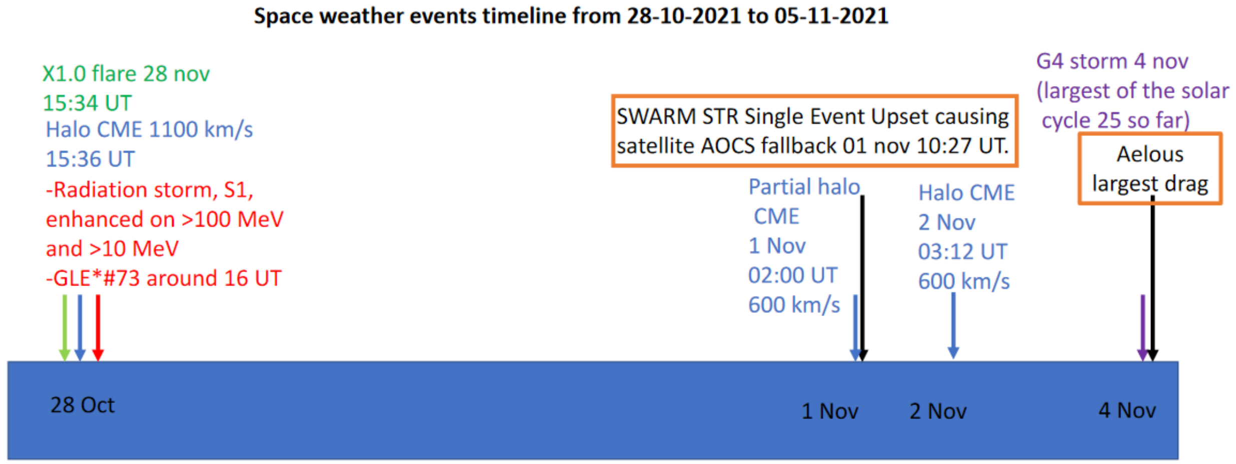


Figure 17: Timeline of events surrounding the Swarm SEU on 1st November 2021, highlighting key space weather phenomena taking place within this period of enhanced activity.

For these post event analyses, we may query the data around one week before the anomalies to safely assess the Sun-Earth system features and potential effects that may happen. Therefore we decided to choose a period from 27 October 2021 until 5 Nov 2021, utilising some of the products offering alerts, mentioned on Section [3.3].

Starting on the date of 28 October 2021, the first alert was reported by the S.112a SIDC Solar GOES-flare alert product, triggered by an X1-class flare, peaking 15:34 UT. The next alert was S.112b SIDC/CACTus Automated halo CME alert, releasing an alert on a halo CME (Earth directed) at 15:36 UT, with an average speed of 1100 km/s, displayed in Figure 18. Soon before 16:00 UT, R.102 GLE Alert++ service from the Athens Neutron Monitor Station (ANeMoS) released an alert on a ground-level enhancement (GLE), corresponding to the GLE#73 [11]. H.106a Near-Earth space weather notifications were also visible, reporting an S1 proton event onset based on the levels of > 10 MeV proton flux measured in GEO orbit.

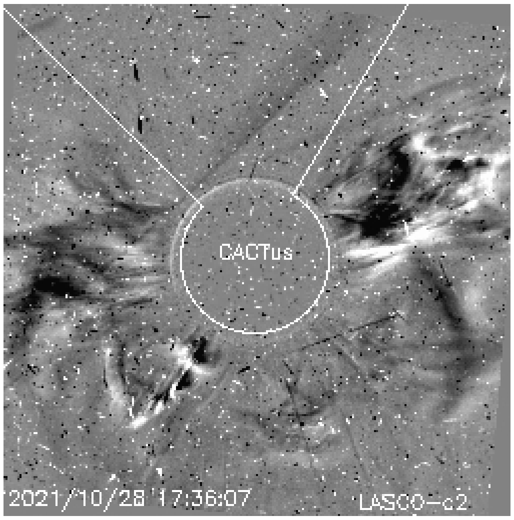


Figure 18: snapshot of the Coronal Mass Ejection from 28-10-2021 and the high energy proton traces observed in the SOHO/LASCO C2 coronagraph detector.

On the 1 November 2021, the product S.112b SIDC/CACTus Automated halo CME alert released another alert on a partial halo CME with an onset time of 02:00 UT, and an average speed of around 600 km/s. Another automated alert from CACTus concerning the Earth-directed CME indicated this was ejected with an average speed on 600km/s at 03:12 UT, associated with an M1.5 class flare peaking at 01:45 UT. The >10MeV proton flux at GEO remained slightly enhanced but below the event threshold. An increase, possibly related to the CME could be noticed and was reported in product S.110 the SIDC daily space weather bulletin. The anomaly reported by the Swarm mission occurred on 10:27 UT on 1st November. The above discussion demonstrates that space weather conditions were active during this period, although the level of >10MeV proton flux was at this time below the individual proton event threshold and levels normally associated with a high probability of triggering SEUs.

Figure 11 above shows the drag coefficient evolution, CD, as used by Flight Dynamics for Aeolus since launch plotted alongside the solar F10.7 index. Within this plot it can be seen that the largest value of the drag coefficient for the mission to date was recorded on 4 November 2021. This corresponds to the largest geomagnetic storm so far of the Solar Cycle 25, where Kp reached up to 8-, corresponding to a G4 geomagnetic storm, as shown by the product G.137b from BGS and illustrated in Figure 19 below.

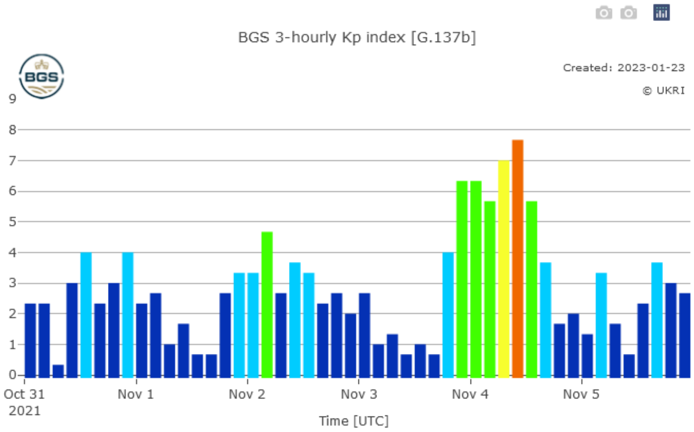


Figure: 19: Severe geomagnetic storm detected on 4th November 2021, as shown by G.137b BGS 3-hourly Kp index.

5. Results & discussion

This paper aims to highlight some of the increasing impacts of space weather on low Earth orbiting spacecraft as we approach Solar Maximum along with some of the tools and products available via the ESA Space Weather Service Network portal which are made available in order to help operators and flight dynamics teams characterise and predict the state of the environment and its potential impacts on their activities. While both increasing drag effects and a number of important SEUs have been reported, the focus has been placed on the increased atmospheric drag observed together with some individual case studies demonstrating timely impacts and a potential analysis methodology using the SWE Service Portal.

Both Swarm and Aeolus clearly experience the increasing effects of atmospheric drag since the start of the current solar cycle with both missions taking direct action to mitigate these effects, Swarm having carried out a series of complex orbit raising manoeuvres in 2022 and Aeolus having changed the frequency with which the orbit is adjusted to compensate for drag at the end of 2021. Furthermore, at the time of writing this paper in January 2023 a period of enhanced solar activity is leading to further impact on mission operations.

Operators and flight dynamics teams rely on atmospheric drag forecasts that incorporate a number of uncertainties. These derive from both the models and the indices frequently used to characterise the space weather conditions. In the case of Aeolus, accuracy of atmospheric drag forecasts will play a crucial role in the final months of the mission in preparation for re-entry.

Considering the operational scenarios described in the earlier sections of this paper, accurate F10.7 nowcast and forecast products are clearly of high importance for the ESA space operation teams. Within the SWE Service portal, the product S.109a 10.7cm Solar radio flux (F10.7) forecast provided by ROB/SIDC already offers a short-term 3-day forecast. In addition, a new product offering a 3-day forecast of F10.7 and F30 indices developed by the University of Graz using a complementary technique [12] will be available in summer 2023 providing an opportunity for further testing and development.

In terms of medium-term forecasting, a new product currently in preparation for integration into the SWE Service Portal and provided by CLS will provide a nowcast and up to 30 day forecast of F10.7 & F30 solar radio flux indices, based on models using neural networks [13].

Longer term prediction of continuous monthly solar activity indices, remains a challenge. However, recent work carried out by Petrova et al [12] show promising results for 24 month forecasts of F10.7 and F30 which compare well to the SOLMAG model in use by ESA [14,15] and will be the subject of further analysis later this year.

While considerable work is ongoing in the space weather community at the moment to develop improved models and to test new techniques for forecasting conditions likely to lead to increased drag, substantial testing and validation is required before these can be implemented operationally. Furthermore, in adopting a new or updated model or index, data availability may also be a concern where this is provided by a single source. As part of its Space Safety Programme, ESA is developing a new telescope capable of providing reliable and continuous measurements of F10.7 and F30. The new facility is being deployed at a site in Poland and is set to start operation in 2023, providing a complementary source of these two crucial datasets.

Reducing the uncertainties associated with orbital propagation overall helps reduce the need for collision avoidance manoeuvres in increasingly populated orbits and as such supports improved situational awareness.

6. Conclusions

The increasing space weather activity associated with Solar Cycle 25 can already be observed in ESA's low Earth orbit mission operations. With activity set to increase in the coming years, a proactive approach to manage these effects is adopted by the mission operations teams.

In parallel a substantial amount of space weather information is available to mission operations teams providing timely information on space weather conditions, forecasts and alerting. While thermospheric models and indices in use for operational purposes include a number of uncertainties, new models in development and new facilities promise to provide significant improvement in the coming years. Furthermore, scenarios such as the Aeolus re-entry campaign may also provide opportunities to test the performance of new models and space weather indices forecast techniques in parallel to established operational approaches. Close cooperation between operators and space weather service developers and providers is essential in order to ensure that new developments target the information that's most needed, helping to improve our situational awareness and ensure continued reliable operations during periods of active space weather.

Acknowledgements

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We therefore acknowledge all the institutions providing products shown in this paper: Solar Influences Data analysis Centre (SIDC) at the Royal Observatory of Belgium (ROB), Kanzelhöhe Observatory for Solar and Environmental Research (KSO), British Geological Survey (BGS), GFZ German Research Centre for Geosciences, Technical University of Denmark (DTU), Athens Neutron Monitor Station of National and Kapodistrian University of Athens (NKUA), UK Met Office (UKMO), Space Research Centre Polish Academy of Sciences, and The ESA Space Safety Programme. We also acknowledge the use of a diagram from CACTus produced by ROB/SIDC.

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