European Space Agency Space Weather System

Juha-Pekka Luntama
European Space Agency, Space Safety Programme, Space Weather Office
European Space Operations Centre (ESOC), Robert-Bosch-Str. 5, 64293 Darmstadt, Germany

Alexi Glover, Melanie Heil, Stefan Kraft
European Space Agency, Space Safety Programme, Space Weather Office
European Space Operations Centre (ESOC), Robert-Bosch-Str. 5, 64293 Darmstadt, Germany

ABSTRACT

European Space Agency's (ESA) Space Situational Awareness (SSA) Programme has been developing since 2009 the European Space Weather (SWE) System for the capability to provide operational space weather services to support protection of European space and ground based assets against adverse effects from space weather. This system is based on use of European space weather assets through a federated network consisting of thematic Expert Service Centres (ESCs) and SSA Space Weather Service Coordination Centre (SSCC). Many European space weather centres of excellence in academia, research institutes and industry are already part of the network and inclusion of additional groups in the framework of coming ESA space weather activities. This allows the system to efficiently utilise the scientific research and application prototyping that is carried out in academia and research institutes accross Europe. The results of the development activities and particularly the space weather forecasting and nowcasting tools that have been made available to the users can be found from the ESA Space Weasther Service Portal: http://swe.ssa.esa.int/.

In parallel to the development of services, models and applicaitons, ESA is developing European space weather monitoring capability for operational services. The Enhanced Space Weather Monitoring System under development utilises essentially all available methods for space weather monitoring combining space based hosted payload and SmallSat/nanosatellite missions and larger, dedicated space missions targeting solar and heliospheric observations outside Earth's magnetic field with ground based and airborne observations. The first hosted payload missions are already in operation and procurements and developments of instruments for further missions are in progress. In parallel ESA is developing a medium size dedicated space weather mission that will provide solar imaging, coronagraphy and in-situ solar wind observtions away from the Sun-Earth line. The data from all these space weather monitoring missions will be made available for operational space weather services in near real-time.

1. INTRODUCTION

The development of ESA's Space Weather System was started in 2009, when the Member States mandated ESA to start the Space Situational Awareness (SSA) Programme. Over the following 10 years ESA established through industrial contracts a network of Expert Groups that carry out the processing of space weather measurement data into space weather products. SSA Space weather Coordination Centre (SSCC), also part of the Space Weather Service Network, combines the products to services to the end users, handles the interfacing with the users and provides a user helpdesk function. The overall ESA Space Weather System includes, in addition to the Service Network, a Data System providing data dissemination, archiving and data access functions, and a measurement system providing space weather data for the services. While the system is currently in testing and validation phase providing pre-operational products and services, the architecture of the system has been designed for operational space weather service provision. The main elements of ESA's Space Weather System are presented in Fig. 1.

The objectives for the ESA Space Weather System development activities are that by 2030 Europe will have capability for tailored space weather services, early space weather warnings with actionable information, operational space weather monitoring system and resilient society. In order to achieve these objectives, ESA is carrying out industrial contracts for research, technology development and testing and validation of the space weather models, tools and applications.

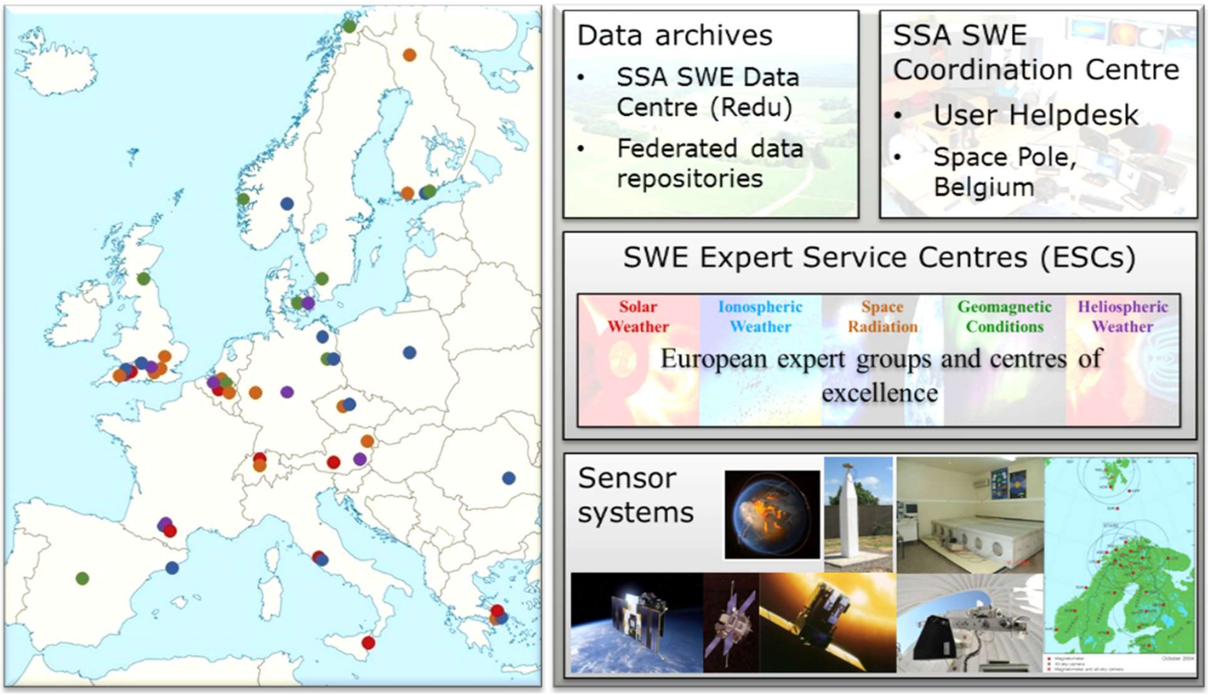

Fig. 1. Key elements of ESA's Space Weather System. The dots on the map on the left present the locations of Expert Groups participating Service Network at the end of 2019. The colors correspond to the Expert Service Centre (ESC) that the group is part of.

2. SPACE WEATHER SERVICE NETWORK

The SWE Service Network has been developed over the course of the 3 periods of the SSA Programme building firmly on the principle of federating and further developing established European expertise and assets. Prior to the SSA programme commencing, a number of national and local initiatives existed individually in the ESA Member States targeting mainly local/regional end users and/or the scientific community. In addition, an ESA GSP funded pilot project geared towards space weather service capability demonstration presented positive early results in terms of the added value which could be achieved through networking European capabilities.

Starting from a detailed assessment of the European space weather service end user community needs following the start of SSA Period 1 in 2009, the SWE Service Network developed within the SSA Programme has demonstrated that a unique, federated approach can be used to successfully deliver high quality space weather services to end users in a reliable manner.

The SWE Service Network's federated approach brings together a wide range of space weather expertise and assets from across Europe in order to develop and provide space weather services targeting user needs. In order to ensure network-wide coordination, approximately 40 participating groups are structured into five Expert Service Centres (ESCs) covering the full space weather domain, from solar activity through to geomagnetic disturbances, and the SSA Space Weather Coordination Centre. These have been the subject of a set of dedicated development activities that enabled growth both in the service content provided to end users and the maturity of the SWE service provision concept itself.

The SSA Space Weather Coordination Centre (SSCC) provides the SWE Service Helpdesk, with operators available to answer questions via email or telephone about the SWE Service Network or space weather conditions in general. The helpdesk is staffed during normal office hours with a voicemail service available at other times. The SSCC monitors the Service Network and provides the first-level user support via the Service Helpdesk. The Helpdesk is further supported by the ESCs who, upon request, provide second line expert support according to their domain of expertise and products provided.

The SSCC also leads the overall SWE Service Network's user engagement activities through providing tailored space weather bulletins for high-priority end users including ESA mission operation teams and commercial satellite operators, developing professional training courses and through in-person meetings with representatives of the user communities either at their premises or at conferences/workshops. Engagement activities cover the full range of end user communities affected by space weather from spacecraft operators through to power grid operators and feedback from users received during these activities is used to help improve the information provided via the SWE Services.

Within the SWE Service Network, an ESC consists of a Coordinating Group and a number of Expert Groups addressing a given space weather domain. The ESCs work together within the SWE Service Network to carry out the processing of space weather measurement data into products that constitute elements of end user services. The space weather domains of the five ESCs in the network are:

- Solar Weather (S-ESC),
- Heliospheric Weather (H-ESC),
- Space Radiation (R-ESC),
- Ionospheric Weather (I-ESC),
- Geomagnetic Conditions (G-ESC).

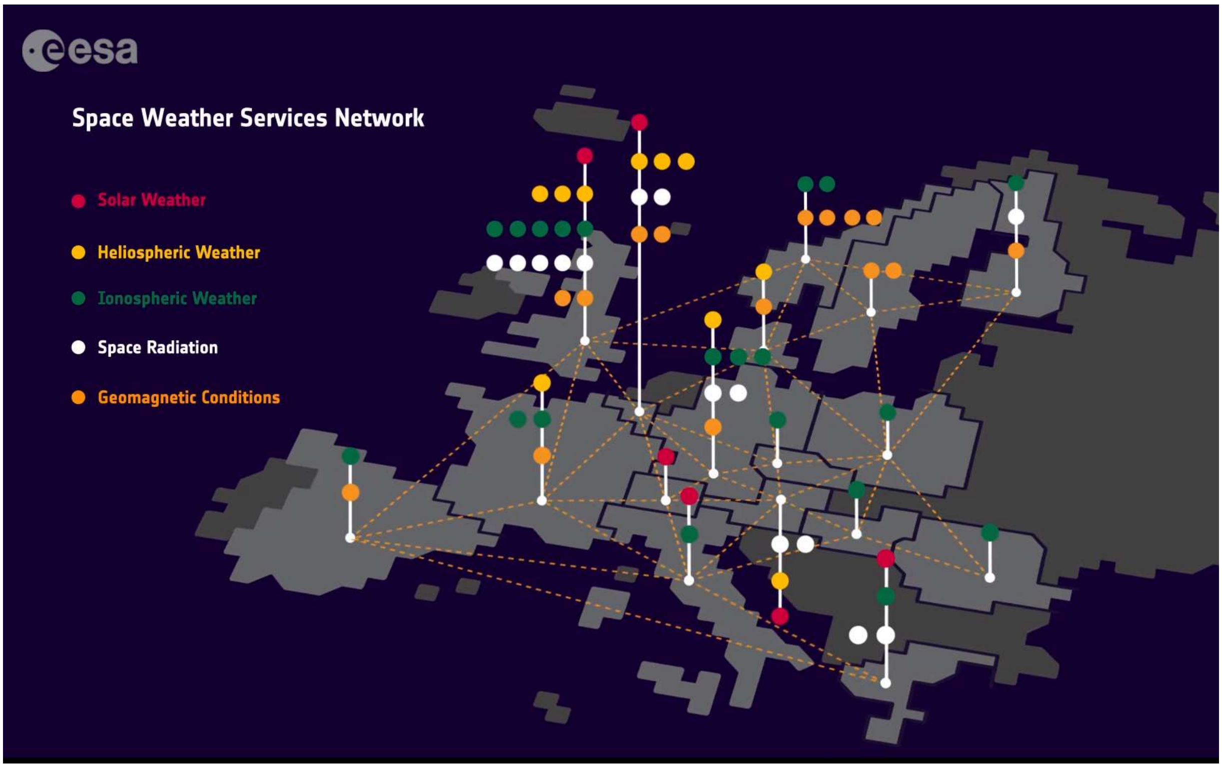

Fig. 2. A schematic presentation of ESA's Space Weather Service Network consisting of five Expert Service Centres (ESCs) with Expert Groups in all ESA Space Safety Programme (S2P) Participating States.

The Space Weather Services provided by the SWE Service Network are structured according to the following main user domains:

- Spacecraft design
- Spacecraft operation
- Human spaceflight
- Launch operation
- Transionospheric radio link
- Space Surveillance and Tracking
- Power System Operation

- Aviation
- Resource Exploitation System Operation
- Pipeline Operation
- Auroral Tourism Sector
- General data services.

Within these domains, the SWE Customer Requirements have been further structured into user driven services. A Space Weather Service is provided through a combination of derived data products, software tools, reporting and associated end user support.

For the audience of the AMOS conference the services for the Space Surveillance and Tracking user domain are particularly important. The available services for this domain include:

- Atmospheric estimates for drag calculation,
- Archive of geomagnetic and solar indices for drag calculation,
- Forecast of geomagnetic and solar indices for drag calculation,
- Nowcast of ionospheric group delay.

These services can be found from ESA's Space Weather Service Portal from address: http://swe.ssa.esa.int/space-surveillance-and-tracking. The web page for each service contains summary descriptions of the tools and assets that form the service. The asset descriptions include the names of the institutes that have carried out the scientific and technical developments. In ESA's Space Weather System the tools and assets are in most cases executed from the data system of the developing institute or company. This is part of the federated approach adopted for the system implementation. Access to the assets and tools will require registration to the system. Registration is free and available to users around the world.

As an example of the current service interface and available assets, the web page of the Atmospheric estimates for drag calculation service is presented in Fig. 3. A short summary information about the available assets is provided on the front page of the services. The tabs at the top of the page give the user access to additional information, data products and tools related to the service. The assets are accessed through the buttons at the bottom of the page. It should be noted that the Service Portal is being revised and a new portal with a new layout and enhanced user experience will be released soon.

Most assets in the Service System provide access to the products both as a graphical display and also in numerical format. The users can download the numerical data for further processing and analysis into their own computers. Open access to all data is the baseline principle of the system. In some cases, however, access to some data may be restricted to protect the intellectual property rights or commercial interests of the data owner. Application Programming Interface (API) based access has been implemented for some of the data in the system and work is in progress to extend the interface to cover all the data. ESA Space Weather System also provides a service where the users can register for the latest data to be continuously automatically sent to their home system. This service is particularly targeting third-party service providers who want to develop new services utilizing the data available through the system.

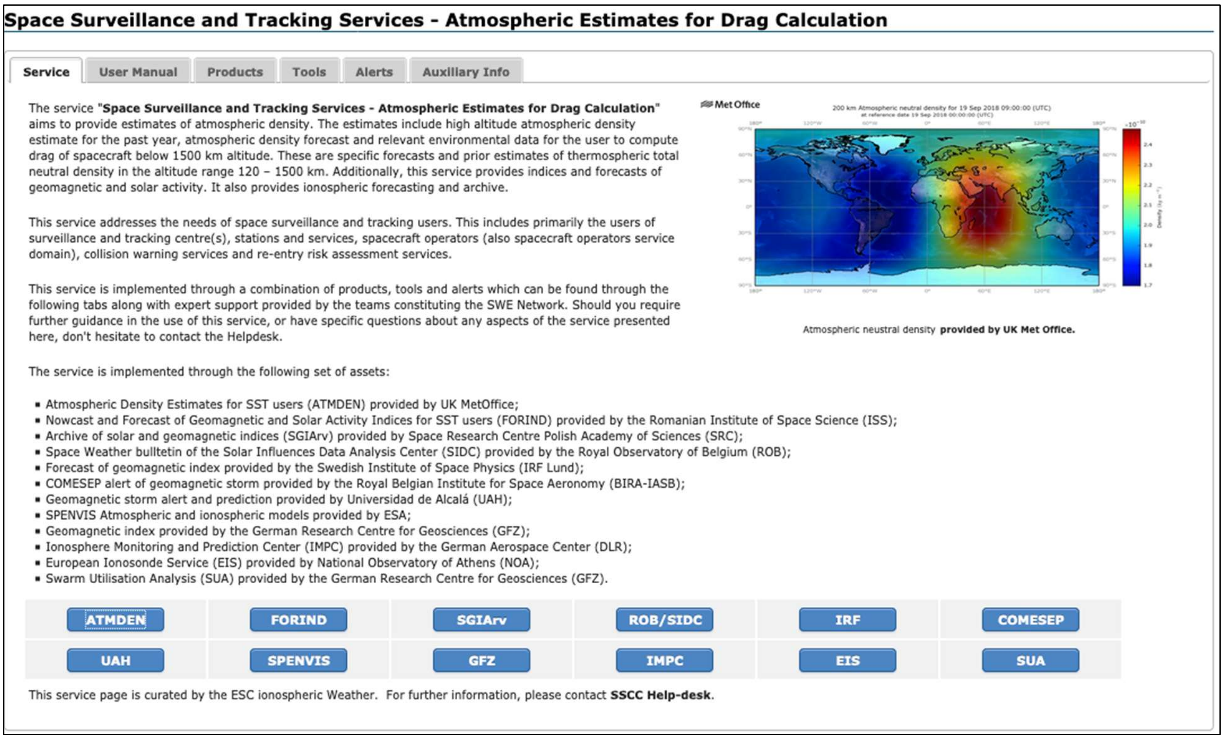

Fig. 3. Web page for Atmospheric estimates for drag calculation services in ESA's Space Weather Service Portal.

3. SPACE SEGMENT

Space weather services described earlier in this paper would not be feasible without accurate and timely measurement data from space weather instruments. Ground based instruments like for example solar telescopes, ionospheric radars, ionosondes, fiducial GNSS receivers and magnetometers provide extremely important data for space weather applications. However, because Earth is protected against solar wind and harmful wavelengths of the solar irradiation by the magnetosphere and atmosphere, space-based measurements are mandatory for a complete picture of the space weather status and for space weather forecasting.

Implementing European capability for space-based monitoring of space weather is a very important part of ESA space weather activities. The requirements for the measurements are defined in the System Requirements Document and Product Specification Document for the ESA Space Weather System. These documents are available from the on-line repository: http://swe.ssa.esa.int/documents.

An efficient, affordable and sustainable approach has been selected for the space segment development approach. The baseline plan is to implement as much monitoring capability as feasible with low cost hosted payload and SmallSat/nanosatellite missions. This part of the space segment targeting monitoring of the space environment in the vicinity of the Earth is called Distributed Space Weather Sensor System (D3S). The focus of the D3S is monitoring of the Earth's magnetic field, neutral/charged particle, plasma and micro-particle environments and auroral imaging by UV and visible light. D3S precursor missions already in orbit and demonstrating the feasibility of this concept for operational space weather monitoring include Service Oriented Spacecraft Magnetometer (SOSMAG) that is part of the Korean Space wEather Monitor (KSEM) instrument package onboard the Korean GEO-KOMPSAT-2A meteorological satellite, and the Next Generation Radiation Monitor (NGRM) that is flying onboard the European Data Relay Satellite C (EDRS-C) satellite. Very recently the scope of D3S has been expanded to cover also the space environment around the Moon with the approved proposal to implement ESA Radiation Sensor Array (ERSA) instrument package as a payload for the Lunar Gateway Power and Propulsion Element (PPE).

The other part of the space segment of ESA's Space Weather System are missions that are required to monitor solar wind outside Earth's magnetosphere and provide visibility to the solar disk and heliosphere away from the Sun-Earth line. The first mission in this category under implementation is the Lagrange mission (https://www.esa.int/Safety_Security/Lagrange_mission) with the objective to place a spacecraft providing data for operational space weather applications to an orbit around the 5th Lagrangian point (L5). From this perspective the mission will be able to provide measurement data covering solar coronagraphy, heliospheric imaging, EUV imaging of the solar disk that is not yet visible to the Earth, photospheric magnetography, X-ray flux and in-situ observations at L5 including the solar wind speed, interplanetary magnetic field and solar energetic particle flux. Lagrange mission is targeted to be launched in early 2027.

An overview of the main elements of the space segment of ESA's Space Weather System including some of the current and near-future elements of D3S is presented in Fig. 4.

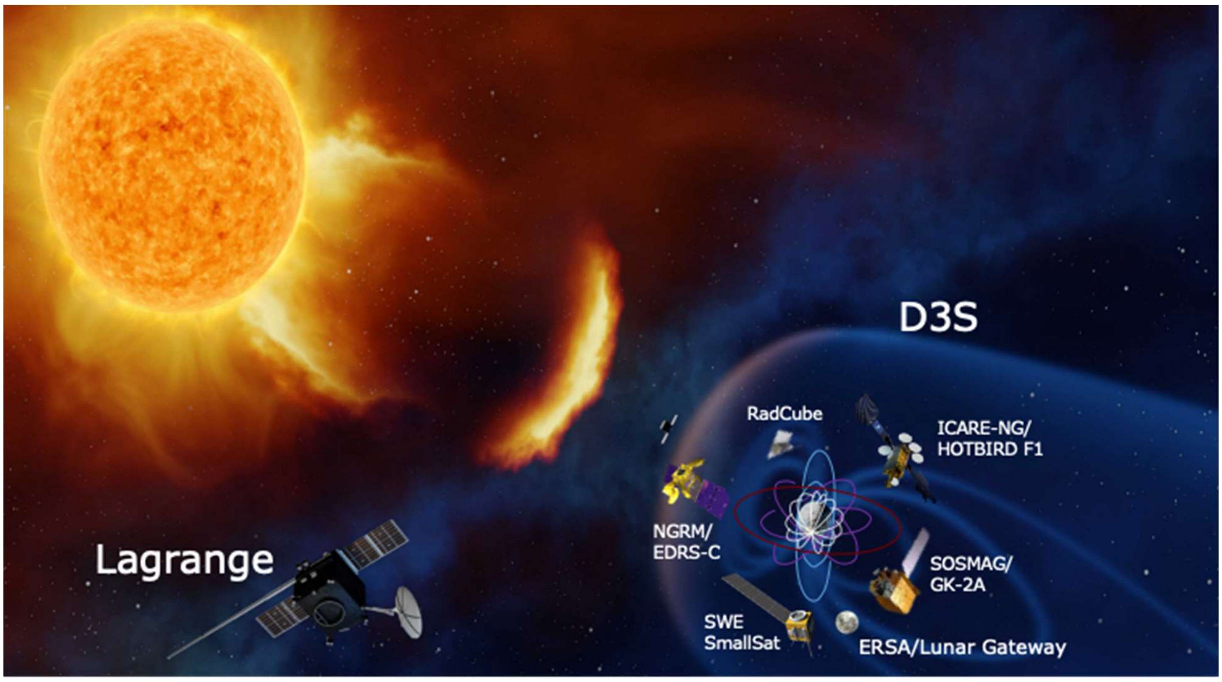

Fig. 4. Space Segment of the ESA Space Weather System with the Distributed Space weather Sensor System (D3S) and the Lagrange deep space mission in L5.

4. INTERNATIONAL COLLABORATION

International collaboration is a vital element in the development of the Space Weather System. Global monitoring of space weather from ground-based observation systems would not be feasible without international collaboration and data sharing. For space-based observations internal collaboration is equally important. One of the most critical issues is funding, because building a comprehensive space weather monitoring system that can provide data for services addressing the needs of the user domains listed earlier in this paper will be expensive and it is unlikely that any nation could afford to build such a system alone. Near real-time transmission of the measurement data down from Low Earth Orbit (LEO), Medium Earth Orbit (MEO) or from deep space missions also requires a global network of ground stations for continuous tracking of the satellite telemetry. Sharing measurement data from national and multinational missions, and collaboration in the use of ground-based assets like ground stations is step towards making space weather monitoring affordable and sustainable.

ESA is working in close collaboration with international partners for the implementation of the space segment of the Space Weather System. The SOSMAG magnetometer mission for D3S was implemented in close collaboration with Kyung Hee University (KHU) and Korean Meteorological Administration (KMA). The second D3S mission for the NGRM radiation monitor was carried out in the European Data Relay System project, that is collaboration between

European nations in the framework of ESA and European aerospace industry. For the continuation of the D3S development ESA will be looking for flight opportunities onboard European and international satellite missions for hosted payload instruments and sharing data with international partners who are flying their own space weather instruments. Coordination and sharing plans for the new measurements for D3S are coordinated for example in the framework of Coordination Group for Meteorological Satellites (CGMS).

For operational monitoring of the Sun and heliosphere ESA is also cooperating with international partners, particularly with NOAA and NASA, for implementing an enhanced monitoring system that gives better coverage of the solar disk and the space between the Sun and the Earth. This system is foreseen to facilitate substantially more accurate space weather nowcasts and forecasts that what we can achieve today. Meteorological community has been successful in coordinating weather satellite missions so that the actors owning and operating the satellites take responsibilities for an observation position. The cooperation between ESA, NOAA and NASA is the first step to achieve similar coordination and sharing responsibilities in space weather monitoring.

Fig. 5 shows a visualisation of the space weather monitoring system that ESA, NOAA and NASA are cooperating for. NOAA has expressed the intention to maintain an operational space weather observation capability on the Sun-Earth line with Space Weather Follow-On (SWFO) missions. ESA's plan to fly the Lagrange mission to L5 is adding the new observation perspective that is 60° away from the Sun-Earth line. STEREO science mission has demonstrated the value of space weather observations away from the Sun-Earth line and the collaboration between ESA, NOAA and NASA is targeting to make this advantage to be permanently available for space weather services.

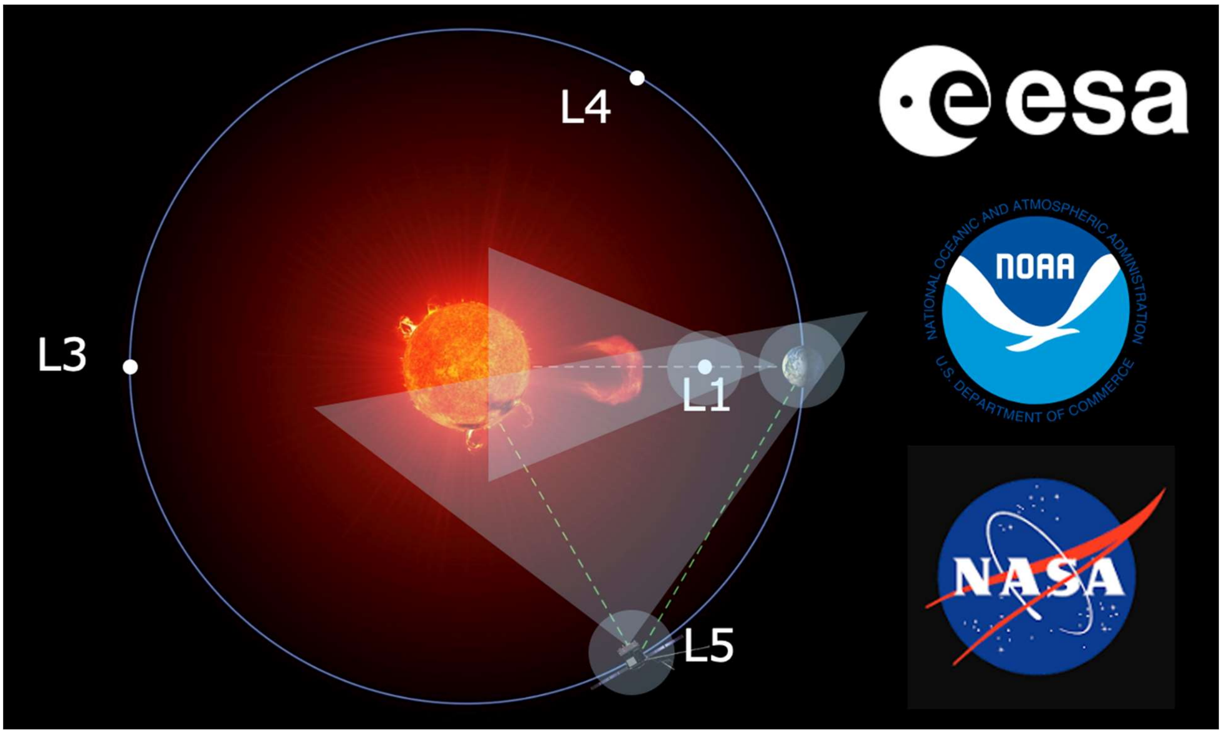

Fig. 5. Visualization of the coverage of the space weather monitoring from the Sun-Earth line and L5. This combination of observation directions gives an excellent coverage of the heliosphere between the Sun and the Earth and substantially increases the coverage of the solar disk by EUV imaging, magnetography and X-ray flux monitoring. In-situ measurements in L5 provided the added value of monitoring of the solar wind turning towards the Earth and detection of Solar Particle Events (SPEs).