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ESA's Space Weather Monitoring System

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Abstract

The European Space Agency's (ESA) Space Safety Programme aims at protecting space and ground assets against adverse effects from space. The Space Weather Segment is focussing on such effects due to the activity of our Sun. Monitoring of the Earth's and Sun's environment is an essential task for the now- and forecasting of Space Weather and the modelling of interactions between the Sun and the Earth. Due to the asymmetry and complexity of Earth's magnetosphere, the involved particle environment and its dynamics, it is necessary to capture the state of the magnetic field and the particle distribution in a sufficiently large number of sampling points around the Earth, such that it allows state-monitoring and modelling of the involved processes with sufficient accuracy and timeliness. ESA is implementing a space weather monitoring system, including the Vigil mission, monitoring the solar disk, heliosphere between Sun and Earth as well as the solar wind from the 5th Lagrange point of the Sun-Earth-System, and the establishment of a Distributed Space Weather Sensor System (D3S) to observe the effects of solar activity within Earth's vicinity. It's current configuration and planned implementation including the use of SmallSats and CubeSats will be presented.
Keywords: space safety, space weather, space segment, constellation, instrumentation

Acronyms/Abbreviations

CSA – Canadian Space Agency, D3S – Distributed Space weather Sensor System, EDRS-C – European Data Relay Satellite C, ERSA – European Radiation Sensor Array, ESA – European Space Agency, GEO – Geostationary Orbit, GNSS – Global Navigation Satellite System, Geostationary Operational Environmental Satellites – GOES, HERMES – Heliophysics Environmental and Radiation Measurement Experiment Suite, JAXA – Japanese Aerospace Exploration Agency, KMA – Korean Meteorological Administration, KSEM – Korean Space Environment Monitor, LEO – Low Earth Orbit, L1/5 – 1st/5th Lagrange point, MEO – Medium Earth Orbit, Metop-SG – Meteorological Operational Satellite Second Generation, MTG – Meteosat Third Generation, NASA – National Aeronautics and Space Administration, NGRM – New Generation Radiation Monitor, NOAA – National Oceanic and Atmospheric Administration, NRHO – Near Rectilinear Halo Orbit, PDC – Payload Data Centre, Polar Orbiting Environmental Satellites – POES, SOSMAG – Service Oriented Spacecraft Magnetometer, SREM – Standard Radiation Environment Monitor, SSA – Space Situational Awareness, SSTL – Surrey Satellite Technology Limited, SWE – Space Weather, UV – Ultra-Violet.

1. Introduction

ESA's Space Safety Programme is aiming to detect, predict and assess threats from space and their potential risk to life, property, and infrastructure. The Space Weather Office in the Space Safety Programme is addressing those risks associated to the activity of our Sun with the goal of providing owners and operators of critical spaceborne and ground-based infrastructure timely and accurate information that will enable mitigation of the adverse impacts of space weather. ESA's Space Weather Office is responsible for defining and demonstrating European space-based observation systems to enable operational space weather services.

This paper first introduces the background, namely ESA's Space Safety Programme, the Space Weather segment within and the Enhanced Space Weather Monitoring System, in section 1. Section 2 describes the objectives and design of the Distributed Space Weather Sensor System; section 3 provides the international context to ESA's undertakings and section 4 concludes this paper.

1.1 Background

The general objective of ESA's Space Safety Programme is to contribute to the protection of our planet, humanity, and assets in space and on Earth from hazards originating in Space and to contribute to Europe, by providing safety from such hazards, as a service to its society.

The Space Safety Programme has three main segments: the Debris and Clean Space Segment concerned with the numerous man-made objects in Near-Earth Space and the sustainable use of Space, the Planetary Defence Segment monitoring natural Near-Earth Objects and their probability of impacting on Earth, and the Space Weather Office detailed in the following.

Space Weather can be defined as the description of the state of the space environment. Changes in the space environment, resulting mainly from changes on the Sun, include modification of the ambient plasma, particulate radiation (electrons, protons, and ions), electromagnetic radiation (including radio, visible, UV and X-ray light), and magnetic and electric fields. In addition to the Sun, non-solar sources such as galactic cosmic rays can also be considered as altering the space environment conditions near the Earth and are thus covered by the Space Weather segment of the Space Safety programme.

The effects of space weather are observed in the degradation of spacecraft communications, performance, reliability, and lifetime. In addition, it leads to enhanced risks to human health on crewed space missions. Space weather also has numerous potential effects on ground including damage to aircraft electronics, enhanced radiation dose for air passengers and crew, damage and disruption to power distribution networks and pipelines and degradation of radio communications.

1.2 Space Weather at ESA

The Space Weather Office can be segmented into a service segment and a space segment. The service segment is concerned with the formation and management of a European Space Weather Service Network and the development and provision of space weather products to end-users. These users span from spacecraft designers and operators, human spaceflight and launch providers to GNSS users, power grid or pipeline operators as well as airlines. The space segment is concerned with the collection of the space-based space weather measurements required as input for the provided services.

1.3 Enhanced Space Weather Monitoring

ESA is planning to set up the Enhanced Space Weather Monitoring System to address the identified need for an independent European Space Weather measurement system. The space segment of this system will consist of sensors deployed in strategic locations on the Sun-Earth line, away from the Sun-Earth line, and within the planetary environments of interest. Safety of Earth is the highest priority of the Programme and thus the deployment of the measurement system will be started from locations that first of all serve space weather services protecting affected infrastructure and systems both on ground and in Earth orbit.

In order to distinguish the measurements in specific locations on and away from the Earth-Sun line, i.e. in the Sun-Earth Lagrange points L1 and L5, which are covered by dedicated missions, the terminology of the Distributed Space Weather Sensor System (D3S) is introduced, meant to address the need for distributed multi-point observations mainly in near-Earth space, see Figure 1. For observations from the 5^{th} Lagrange point the Vigil mission [1] is under development by ESA and a collaboration agreement has been signed with the US National Oceanic and Atmospheric Administration (NOAA) ensuring exchange of data for their missions to the 1^{st} Lagrange point [2]. D3S is focussing on measurements in Earth's vicinity, also covering the Lunar environment. Hosted payload instruments on board deep space science missions can be included under D3S definition.

2. The Distributed Space Weather Sensor System

D3S is ESA's system of missions for space weather state and Earth impact monitoring. Due to the asymmetry and complexity of Earth's magnetosphere, the involved particle environment and its dynamics, it is necessary to capture the state of the magnetic field and the particle distribution in a sufficiently large number of sampling points around the Earth, such that it allows state-monitoring and modelling of the involved processes with sufficient accuracy and timeliness. Therefore, D3S is implemented through a combination of different mission types to perform measurements from a large variety of orbits and local times.

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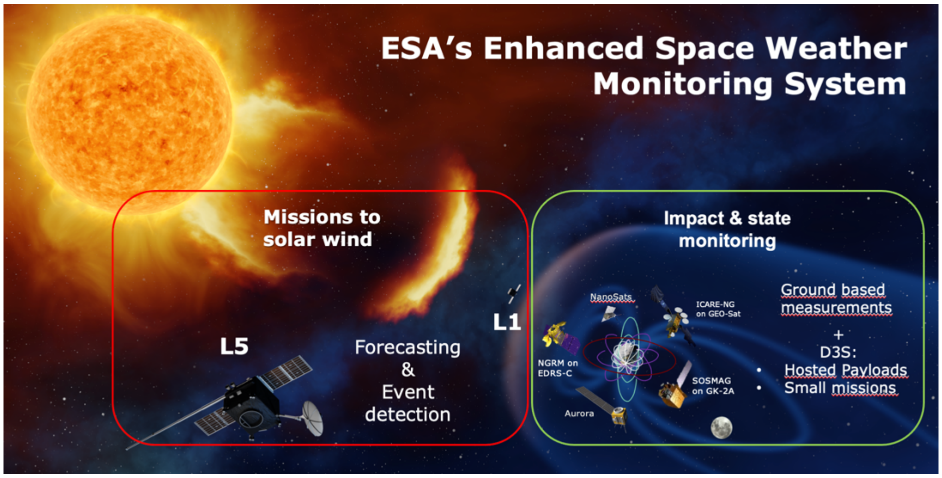

Figure 1. ESA's Enhanced Space Weather Monitoring System.

3.1 Objectives

The objective of D3S is to provide the Space Weather measurements required in Earth's vicinity to provide Space Weather services for Europe. These measurements inform on the state of the space environment and thereby enable nowcasting space weather conditions at Earth or the moon as well as the monitoring of space weather impacts.

The required measurements to monitor the state of the magnetosphere, ionosphere and thermosphere as well as the lunar environment span both in-situ monitoring, e.g. of the local magnetic fields, plasma densities and the particle environment from a large variety of locations, such as different orbital altitudes and local times, as well as remote sensing observations of the upper atmosphere [3].

3.2 Architecture

The mission architecture of D3S contains a space segment and a ground segment. The space segment combines various types of missions, ranging from hosted payload missions of individual instruments to dedicated small satellite missions collecting data on a range of phenomena. The ground segment is distributed, just like the space segment, in the sense that the operations of the D3S missions is carried out by multiple operators and ground-based measurements are collected from distributed locations. The measurement data of the different sources is eventually all processed in the ESA Space Weather Payload Data Centre (PDC). An additional goal for the D3S architecture is to benefit of international collaboration and data exchange agreements, where possible, to obtain the required data.

An implementation option for D3S missions is "Mission/Data as a Service", in which only the specifications of the measurements are provided by ESA and their implementation is fully under the responsibility of a contracted party.

3.2.1 Space Segment

The Space Segment is constituted by different mission types. In orbits and locations for which opportunity for hosted instruments on ESA led or external missions is available, hosted payload missions are deemed preferential due to the cost efficiency of such missions. Typically, such flight opportunities are more easily identified for GEO missions, due to the size of the platforms and the data timeliness requirements not inflicting an additional driving requirement to the mission operations, as GEO satellites nominally operate with real-time data exchange. Some of the measurements have a lower data timeliness requirement. Such measurements could also be obtained via hosted payload missions in LEO or MEO, if available, provided they download data at least once per orbit in LEO and several times in MEO. While hosted payloads are not mission driving and therefore may have a lower availability requirement for the mission or a non-compliance to a measurement requirement may have to be accepted, the distributed nature of the required measurements and cost effectiveness of such missions implies their exploitation, e.g. in Lunar orbit.

Hosted payload missions need to be complemented by dedicated space weather missions to achieve coverage of the D3S measurement requirements. In particular, the wide span of observations to be performed in LEO and the data timeliness requirement driving the mission architecture in this orbit make dedicated missions the optimal solution. As space weather instrumentation is typically compact and needs low resources, these missions could be performed on platforms spanning from CubeSats to micro-satellites with mass up to 100 kg.

3.2.2 Ground Segment

Similar to the sensor system, also the mission operations of D3S are distributed. Most space weather instruments are designed for autonomous and continuous operations, such that commanding of the instruments is only needed in case an anomalous behaviour is observed. This simplifies outsourcing of operations, such as for hosted payloads. For the dedicated space weather missions of D3S, mission operations can be performed by ESA or be outsourced to industry. Mission operations shall ensure the safe operations of the spacecrafts and instruments as well as reliability and availability of the system in order to provide the data according to the mission requirements.

In the Payload Data Centre the instrument data from all D3S missions comes together to be processed up to Level 1, see Figure 2. Processing to Level 2 may also be performed in the PDC for individual missions. The PDC is responsible for the full processing chain:

- obtaining the raw data, either through internal ESA links or from external operators
- processing of the raw data to established Level 0 and Level 1 data sets
- archiving the raw and processed data
- forwarding the L1 data to the Space Weather Portal for dissemination.

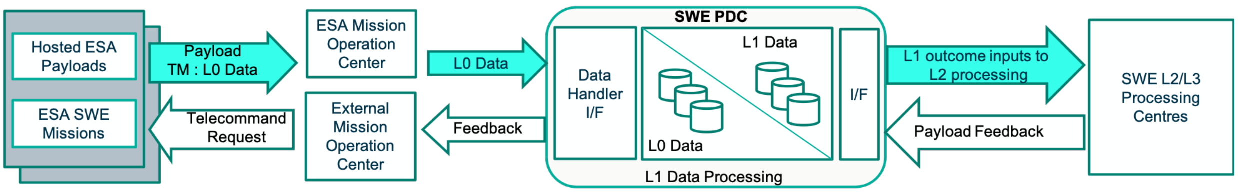

Figure 2. Space Weather Payload Data Centre Interfaces

As latency is critical for space weather data, the PDC is designed to perform efficient and robust processing in order to add as little delay as possible to the release of the data. Automated monitoring processes are put in place to ensure the availability and reliability of the provided data. Particular mission implementation options might foresee a reduced use of the functionality of the PDC, such as directly providing Level 1 data as a deliverable, in which case the PDC would only provide its archiving and dissemination function for the respective data.

3.3 Implementation

D3S is a system of systems. It will be implemented though a variety of mission types and in a stepwise approach. All measurement requirements have been analysed with regards to suitable instrumentation to collect the measurements and to mission orbits from which they should be collected. A first allocation to the mission type, i.e. hosted payload mission or dedicated satellite mission, has been performed per requirement. As the wealth of requirements cannot be addressed all at once, the respective missions are implemented stepwise. For cost-efficiency first hosted payload missions were implemented as pre-cursers of D3S. The first mission to launch with a D3S payload in 2018, namely the Service Oriented Spacecraft Magnetometer (SOSMAG), was the Korean Geo-Kompsat-2A hosting the Korean Space Environment Monitor (KSEM) of which SOSMAG is an integral part and was included in the payload in the framework of an international collaboration [4]. Shortly after, the first unit of the ESA developed New Generation Radiation Monitor (NGRM) was launched to GEO onboard the European Data Relay Satellite C (EDRS-C) [5]. Both instruments are providing their measurement data with high availability and the Level 1 data is made available through the ESA Space Weather Portal* within the latency target of 5 minutes, demonstrating the suitability of hosted payload missions for the collection of space weather data to be utilised in operational space weather applications. Several additional hosted payload missions have been launched and further missions are in preparation.

Also, two dedicated small satellite missions are currently in preparation for implementation, as described in the next sections. These missions are expected to benefit from the recent technology advances making nano-, micro- and small-satellite systems increasing efficient and capable allowing to implement the missions in a cost- and schedule-effective way. The D3S small satellite missions will be further complemented in the next years based on successful preparatory studies and the availability of funding.

3.3.1 Active and upcoming hosted payload missions

In addition to the two hosted payload missions mentioned above, SOSMAG on GEO-Kompsat-2A and NGRM on EDRS-C, two more radiation monitors called ICARE-NG [6] have already launched on the HOTBIRD™ 13F and 13G satellites in 2022. These will reach their operational GEO orbit in the spring of 2023 and the data is expected to become

* ESA's Space Weather Portal is accessible at: https://swe.ssa.esa.int

available later this year. Also Sentinel-6 and MTG-I1, as well as all further upcoming MTG and Metop-SG satellites, carry radiation monitors whose data is being processed in the PDC and will be made available through ESA's Space Weather Portal.

Hosted payload missions currently in preparation include two lunar missions to address the needs of the increased interest in lunar exploration and exploitation. One radiation monitor currently under development, called MiniRMU, has been agreed to be hosted on SSTL's Lunar Pathfinder, and the ESA developed European Radiation Sensor Array (ERSA) is a comprehensive suite of instruments for early utilisation of the Lunar Gateway, a collaboration of ESA, NASA, CSA and JAXA. ERSA includes three radiation monitors, i.e. ESA's Standard Radiation Environment Monitor (SREM), NGRM, ICARE-NG, a set of magnetometers, and dosimeters.

Additional instruments are being procured to address further measurement needs und to have an instrument pool available to be able to quickly respond to emerging flight opportunities.

Table 1 shows all active and currently planned hosted payload missions with planned launch through 2026 with instrument, hosting flight, orbit, launch date and mission lifetime.

Instrument	**Hosting flight**	**Orbit (altitude in km / longitude in º)**	**Launch Date**	**Mission Lifetime**
SOSMAG	GEO-Kompsat-2A	GEO (128º East)	2018	10 years
NGRM	EDRS-C	GEO (31º East)	2019	10 years
NGRM	Sentinel-6	LEO (1336 km)	2020	7 years
ICARE-NG	HOTBIRD 13F	GEO (13º East)	2022	10 years
ICARE-NG	HOTBIRD 13G	GEO (13º East)	2022	10 years
NGRM	MTG-I1	GEO (0º)	2022	8.5 years
NGRM	MTG-S1	GEO (0º)	2024 (planned)	8.5 years
NGRM	Metop-SG A1	LEO (830 km)	2024 (planned)	7 years
NGRM	Metop-SG B1	LEO (830 km)	2025 (planned)	7 years
NGRM	MTG-I2	GEO (0º)	2025 (planned)	8.5 years
MiniRMU	Lunar Pathfinder	Lunar (elliptical)	2025 (planned)	8 years
ERSA	Lunar Gateway	Lunar (NRHO)	2025 (planned)	5+ years

Table 1. Overview of active and upcoming hosted payload missions of D3S.

3.3.2 Aurora

The Aurora mission is addressing the measurement requirements of the upper atmosphere [7]. The main mission objective is to constantly monitor the entire auroral oval while identifying the location of on-going geomagnetic storms and sub-storms, to provide information to the locally affected users and to enable space weather nowcasting about the dynamics. The constant (24/7) monitoring of the aurora shall be achieved by observations carried out by four small satellites providing sufficient coverage of the complete auroral oval with good spatial resolution and fast transmission of the data. A suitable satellite constellation in a low polar MEO orbit (around 7000 km altitude) has been identified that is expected to fulfil the following objectives:

- Continuous observation of the aurora borealis and australis to monitor the impact of the solar wind and Coronal Mass Ejections (CME) on the terrestrial system caused by the modified flow of particles inside the Earth's magnetosphere and into the ionosphere.
- Provision of imaging data of the dayside and the nightside of the auroral oval of sufficient quality to enable the determination of the strength, dynamics, location, and extent of the auroral region. This will be enabled by measuring the far-UV and visible emission lines of the aurora.
- The observations shall be performed with sufficient spatial resolution and short enough sampling intervals to identify the location, extent, and dynamics of geomagnetic storms.
- Observations shall as a goal identify geomagnetic 'local' sub-storms and monitor their development and progression.

To meet these objectives, the Aurora satellites will carry wide field optical imagers for the observation of the Aurora [8].

As secondary objectives the following observations are planned:

- Vector components of the local magnetospheric magnetic field to support models and the interpretation of the particle propagations,
- Particle intake and outflow inside the Earth magnetosphere as a source of particle precipitation into the ionosphere at relevant energies with a focus on electron precipitation,
- Speed, density, and temperature of the plasma environment.

The mission will first fly a demonstrator satellite to prove the mission concept and instrument performances. The collected data of the demonstrator will also allow to prepare the data utilisation to make best use of the mission lifetime of the full constellation. The demonstrator mission is currently being implemented and planned to be launched in 2027.

3.3.3 Nanosatellites

The space weather nanosatellite missions are meant to be a cost- and schedule-effective way to address the D3S measurement requirements. Several studies have been performed over the last years confirming the feasibility to use these small platforms for the collection of space weather data to feed into operational applications [9]. To foster industry capability these missions may be implemented as a service providing the collected and Level 1 processed measurement data. In this case, ESA will specify requirements on the type, quality, cadence, and latency as well as availability of the measurement data to be provided. The design and implementation of a mission to collect these measurements will then be the responsibility of the awarded entities.

A first nanosatellite mission is currently being prepared for implementation that is focussing on the state of the radiation belts and the ionosphere and therefore the following measurements are requested:

- High energy proton, electron, and ion flux
- Thermal electrons’ and ions’ flux, density and temperature
- 3D electron density in the ionosphere
- Scintillation parameters (S4, Sigma_phi)
- Magnetic field (optional)
- Thermosphere neutrals density, wind velocity (optional)
- Atomic oxygen density (optional)
- Solar X-ray measurements (optional)
- Satellite potential (optional)

The data latency threshold shall be 60 minutes from the moment the measurement is recorded on board the satellite and the latency goal is 15 minutes. As the data shall be useable in operational space weather applications, a high availability and continuity will be required [10].

This satellite mission will demonstrate the suitability of the data-as-a-service approach for space weather measurements as well as the individual instrument performances from the mission orbit. The successful demonstration would be followed by the implementation of a comprehensive constellation, which is needed to fulfill the required spatial and time resolutions of the measurements.

Further nanosatellite missions addressing other D3S measurement requirements will be studied and proposed for implementation in the next years.

3. International Context

As space weather is for most parts a global phenomenon, and in particular space weather forecasting requires data from all around the globe and all local times in orbit, international collaboration is essential in addressing observational needs.

International collaboration agreements have been established with NOAA. As a first step a data sharing agreement for data from both measurements at L1/L5 as well as measurements in Earth orbits, such as performed by instruments on the Geostationary Operational Environmental Satellites (GOES) and Polar Orbiting Environmental Satellites (POES), has been put in place. This agreement ensures European access to the critical measurements from the first Lagrange point as well as aiding to fulfilling the D3S measurement requirements for GEO, namely providing magnetic field and energetic particle measurements.

In the course of the SOSMAG mission on GEO-Kompsat-2A, a data sharing agreement is in place with the Korean Meteorological Administration (KMA) on all measurements performed by the Korean Space Environment Monitor consisting of the SOSMAG magnetometer, a particle monitor and a charge monitor.

Further international collaboration and data exchange in the frame of D3S is established through the ERSA and Heliophysics Environmental and Radiation Measurement Experiment Suite (HERMES) payload missions on the Lunar Gateway. While ERSA is focussing on providing measurements of the Lunar radiation environment for space weather and human exploration science objectives, HERMES complements these with measurements of the solar wind and interplanetary magnetic field for both space weather and heliophysics science objectives.

Further international collaborations will be investigated, and implemented where possible, to the benefit of the system.

4. Conclusions

In conclusion, ESA's Space Weather Monitoring System aims to ensure the safety and sustainability of modern technology and infrastructure by providing real-time data enabling improved space weather services. Its network of satellites and ground-based observatories is advancing our understanding of space weather and its impacts. The system continues to evolve and improve, with many new space-based data sources becoming available in the coming years. ESA's hosted payload missions as well as dedicated satellites, spanning from nanosatellites in Earth orbits to Vigil at L5, will provide crucial data for space weather nowcasts, forecasts as well as the further development of space weather models.

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