Space Situational Awareness Systems Overview

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Abstract:Modern economies use navigation, communication, Earth observation, meteorology, and many other derived applications and services to be competitive and grow. However, these capacities are based on the continued availability of an infrastructure that includes a spatial component. Achieving a better understanding of space, especially outer space, objects close to Earth, the population of spacecraft, and the ability to anticipate events related to associated risks is essential to protect critical infrastructures and human life.

We present an overview of the Space Situational Awareness (SSA) domain and introduce the SAFESPACE platform, which was implemented to provide storage and computational resources for SSA services and applications. Space weather (SWE) is relevant for critical infrastructures such as the power grids, as the impact of geomagnetic storms can be severe. We provide an example for geomagnetic storm assessment based on Dst index forecasting using ARIMA and LSTM models.

Keywords: Space Situational Awareness, Space Weather, Geomagnetic Storm, Time Series Prediction, ARIMA, LSTM.

INTRODUCTION

Systems that provide information from space have become particularly important for a wide range of applications for critical segments of the economy, including those associated with security, and their dependence on space activity can be expected to grow rapidly in the immediate future. The concept of Space Situational Awareness (SSA) refers to comprehensive knowledge and understanding of space objects in orbit, the space environment, and associated threats and risks. This should be achieved by providing timely information and knowledge, alerts on potential threats, environmental data, and the sustainable exploitation of space around the Earth.

Modern economies use navigation, communication, Earth observation, meteorology, and many other derived applications and services to be competitive and grow. However, these capacities are based on the continued availability of an infrastructure that includes a spatial component. Achieving a better understanding of space, especially outer space, objects close to Earth, the population of spacecraft, and the ability to anticipate events related to associated risks is essential to protect critical infrastructures both in space and on Earth.

It is noticeable that space is becoming accessible to many more users than in the past. Both the increased number of smaller satellites and the development plans for deploying large satellite constellations further increase the need for reliable and timely information on the population of space objects.

In response to all of these necessities, the SSA domain has been segmented into three components: Space Weather (SWE), Near-Earth Objects (NEO), and Space Surveillance and Tracking (SST).

The Space Weather segment addresses all aspects related to the conditions for monitoring the activity of the Sun and the solar wind in the Earth's magnetosphere, ionosphere, and thermosphere. All of these can affect space and terrestrial infrastructure or endanger human life or health. Reliable space meteorological services require constant monitoring of the space environment from several points of view, including advanced models and calculation tools. Equally important is the timely dissemination of real-time information, the generation of advanced warnings, and forecasts of future space weather conditions for users in industry, government, or research institutes. For instance, Europe's extensive expertise, as well as the results already obtained from existing observations and models, are used in a federative concept of providing meteorological services for space weather. This approach avoids duplication of effort and ensures that existing assets and resources continue to play a key role in Europe's SSA system. (Flohrer & Krag, 2017).

A large number of the known objects in our Solar System are asteroids or comets with dimensions between a few meters and tens of kilometers in the orbit of the Sun and whose orbital paths are close to Earth's. More than 90% of these near-Earth objects are known if the diameter is greater than 1 km. However, only 10% of the 100m objects are known, and any of them could have caused more damage than those that occurred as a result of the Tunguska or Chelyabinsk events (Miller et al., 2013).

The NEO segment expands the knowledge of the current and future position of objects in the vicinity of the Earth through active observation that includes the global tracking of asteroids by integrating and federalizing current observation capabilities. New technologies and research methods are developed, as well as efficient data and information processing networks. Moreover, the NEO segment can predict the orbits of celestial bodies and produce impact warnings by estimating the probability of such an object's impact on the Earth. Subsequently, assessments of the consequences of any possible event can be made, and methods can be developed to alter the orbit of a NEO body as well as measures to mitigate the impact with it.

The SST segment focuses on the development of specialized sensors and data processing capabilities for space objects surveilling, and implementation of applications for collision avoidance, prediction of re-entry events and event detection. Furthermore, object catalogs need to be maintained and integrated, and subsequently validated using the available data. Maintenance also includes the implementation of standardized formats for sending messages in support of basic SST activities. A new direction in developing SST activities in Europe has emerged by implementing the Space Surveillance and Monitoring Framework through EU-funded programs to include testing and validation efforts, sensor technology development, data processing, and applications. Data processing activities evolve towards a community-based approach to the development of core applications. New sensor developments are needed to complement national and institutional capacities for research, monitoring, and forecasting of risks in outer space. The development and establishment of formats for the transfer of data is very important for the evolution and progressive integration of existing systems in Europe towards an interoperable European SST system (Flohrer & Krag, 2017).

This study aims to present a general overview of the SSA domain and to describe the main objectives and requirements of the SSA systems. The rest of the part is structured as follows. Section 2 is dedicated to the analysis of the SSA systems. In Section 3, we present the SAFESPACE platform which was implemented to provide resources for the development of SSA services and applications and propose in Section 4 a case study dedicated to the Dst geomagnetic index forecasting. Finally, we conclude in Section 5.

SPACE SITUATIONAL AWARENESS SYSTEM REQUIREMENTS

In general, the functional analysis of an SSA system requires the definition of external components as well as the relationships that the system must ensure with them. Such relationships between the external components of the system will define its functional needs. First, the SSA system's external assets are represented by users who may have two different profiles: military users in the defense system and civilian users (Donath, Schildknecht, Martinot, & Del Monte, 2010). These users have a common interest centered on three areas, as suggested by the SSA definition: (a) the population of celestial bodies in the vicinity of Earth's orbit, (b) the space environment, and (c) threats.

The following aspects may be considered in relation to these situations of interest in the field of SSA:

- The population of celestial bodies in the vicinity of Earth's orbit is composed of man-made artificial objects that can be researched and tracked.
- The space environment is composed of electron fluxes, heavy-ion fluxes, proton fluxes, magnetic flux, natural particles (objects close to the Earth, meteorites), man-made artificial particles (very small particles that cannot be tracked individually).

Moreover, when investigating threats that are relevant to the space infrastructure, the following elements need to be considered as well:

- The space segment can be affected by fragmentation, collisions on orbit, interruptions of mission and/or service capabilities (due to radiation or particles from space, interference, etc.);
- Space threats to terrestrial activities may be due to space objects in orbit and their re-entry.

Military users have a particular interest in information protection and priority access to information. As space assets of defense interest need to be protected, these users are likely to require that any features related to these assets be disseminated only to authorized users and maintained conveniently.

This constraint is of particular importance for the system's future design because, although it is easy to protect certain information, some of it must be used for the essential needs of civilian users. For example, in a celestial body collision warning situation, which is essential for all users, such an event can be highly likely and can affect both defense and civilian space equipment, so both users must be warned even if civilian users are unaware of the information on the defense asset. Another example is access to information that must be a priority for crisis defense users. The SSA system's main objective is to provide information of interest to users and comply with information protection constraints. In order to obtain the information to be provided, the system will have its own assets, while other components that may already exist, such as national ones, can be used as contributing elements (external to the system). Organizations that contribute components are expected to impose certain constraints on the use of these elements. Moreover, the fact that the information requested by the user can be classified in a certain sense will impose rules of the data policy to be managed by the system.

The core element of a Spatial Situational Awareness system is thus a database of traceable objects and spatial meteorological data, which must be constantly updated. Due to the three-dimensional distribution of thousands of small objects, a worldwide network of sensors is needed to track these objects. It is possible that these can be detected several times by different sensors. This means that updating the database is a complex process, and the essential capacity and the great challenge is determined by the exact calculation of the trajectory of an object using radar data or an image provided by a telescope.

It is also necessary to be able to determine precisely whether a particular trajectory belongs to a new object or whether it can be used to update the process of tracking an already identified object (Kalden & Bodemann, 2011).

In general, an SSA system will include:

- Sensors: located on the ground and in space.
- Data centers (one per segment): to receive and correlate sensor data.
- Management system (including a dedicated data center): to perform general system control and data distribution.
- Service centers (one per segment): to deliver data products, warnings, and alerts to SSA users. The flow of SSA information is bottom-up, respectively, from sensors and scientific instruments to data centers and then to service centers, being coordinated by a management system.

In addition to the systems described above, many other technical and service capabilities are required in order to be able to produce collision risk predictions, avoid collisions, and secure space assets (Kalden & Bodemann, 2011). These issues are presented below.

- Database - As mentioned earlier, the core of an SSA system is the database of space objects and their current orbits. The data are collected, for example, on sensors on the ground and in space, monitoring stations, external sources (which require an international cooperation network). Additional tools are used to determine if a path is new, an update of an existing one, or a duplicate.
- Path generation - Software applications also need to be developed to generate trajectories using data from radar installations or optical images.
- Space weather - The risks that the space environment imposes on space assets are not only determined by objects but also by solar storms, magnetospheric fluctuations, ionospheric fluctuations, and space weather. Therefore, the database must also include this information.
- Modeling and simulation - Simulation and modeling of space objects are also necessary, as objects smaller than the detectable size can cause significant damage.
- Re-entry events - Remains of space objects that are in an orbit of the earth can re-enter the atmosphere. This can be a problem with a satellite, as some components can have an impact on the planet. In order to have early warning capabilities within SSA assets, essential information on spacecraft design is essential.
- Spacecraft data - SSA is not limited to the remains of spacecraft. Information on satellites on a mission, their capabilities, and their orbit is also of interest. This is essential for both civilian and military purposes.

SAFESPACE PLATFORM

The SAFESPACE project (http://safespace.rosa.ro) has implemented a computational platform in order to provide resources for the development of services and applications in the field of SSA. It includes a component dedicated to data management and analysis - SAFESPACE Core, and 3 specialized segments (SAFESPACE GNSS IONO, SAFESPACE GEOMAG, SAFESPACE SKY) that are implemented independently and offer functionalities covering specific areas SSA, respectively space weather (SWE), surveillance and tracking of artificial objects (SST) and celestial bodies near the Earth (NEO). The conceptual model of the SAFESPACE platform is presented in the Figure 1.

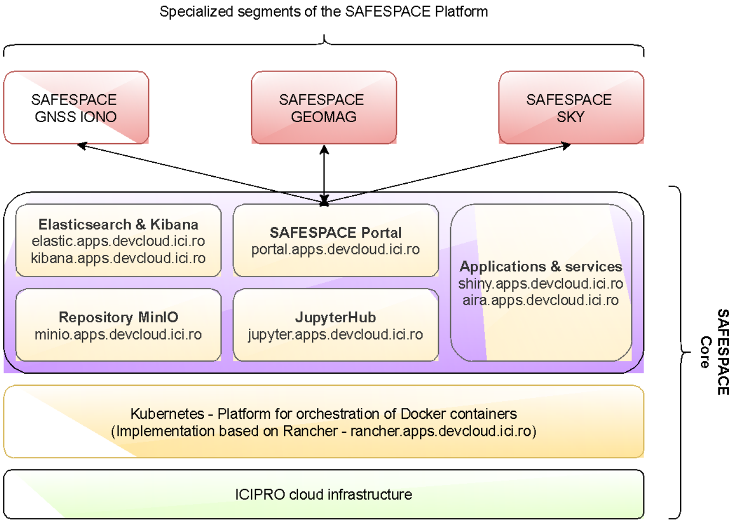


***Fig. 1:** SAFESPACE platform conceptual model*

SAFESPACE Core has the role of hosting the SAFESPACE Portal through which a user can access the services available within the platform. In addition, SAFESPACE Core implements a repository for storing data that can be provided by specialized components. Along with it, there is also a database for time series in which the variations of the geomagnetic field that are monitored by the Geomagnetic Observatory from Surlari (http://igr.ro/departamente/instalatii-de-interes-national/observatorul-national-geomagnetic-surlari/) are recorded and then can be retrieved and visualized.

SAFESPACE Core is the component that manages computational and storage resources for data processing and analysis, being implemented by using the ICIPRO cloud infrastructure (http://www.icipro.ro). This is based on the use of Docker containers that are managed using the Kubernetes resource manager.

This structure stores data that is transferred from the specialized components of the SAFESPACE platform and also provides computing resources for the execution of applications and services.

The following applications are used to store data:

- MinIO: generic files can be stored, being extremely flexible in this regard. Data transfer can be done similarly to the rsync utility. It provides a web interface for users to access both public content and a private area that requires prior authentication.
- Elasticsearch and Kibana: for recording data with geomagnetic field variations and then viewing them. The data is retrieved using the Logstash application that accesses the MinIO repository.
- JupyterHub: a solution for data analysis is also implemented within the SAFESPACE Core structure.

GEOMAGNETIC STORM FORECASTING

Using the JuytherHub instance deployed on the SAFESPACE platform, we present a study for the forecast of the Dst geomagnetic index, which is computed using data provided by low-latitude geomagnetic observatories using 1-hour average values of the horizontal component of the Earth's magnetic field.

The Dst index is used to assess the severity of geomagnetic storms and to determine the effects of the solar wind on space and terrestrial infrastructures. As it is understood that that Earth's magnetosphere is influenced by solar activity, it is important to be able to predict its effects on the geomagnetic environment. The impact of the geomagnetic storms can be extremely severe, including the disruption of GNSS applications or the induced currents in the power grid infrastructure.

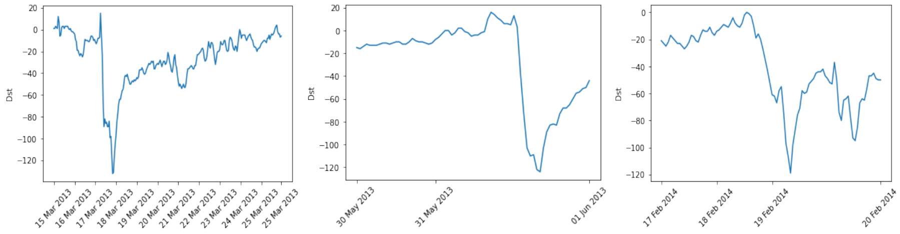


Fig. 2:*Geomagnetic storms analyzed in three periods*

For the geomagnetic storm analysis, we identified the following 3 major events: 16 March – 19 March 2013, 30 May – 2 June 2013 and 17 February – 20 February 2014 (Figure 2).

As we are interested in predicting the value of Dst index from 1 hour ahead to 6 hours ahead, we could implement a predictive model for each case (i.e. a model for 1 hour ahead prediction, a different model for 2 hours ahead prediction, and so on).

Specifically, for training the ARIMA model, we extend the period that included the first geomagnetic storm such that a total of 11 days was considered as training data. The ARIMA model was implemented with the following parameters: p=5, d=1, q=0.

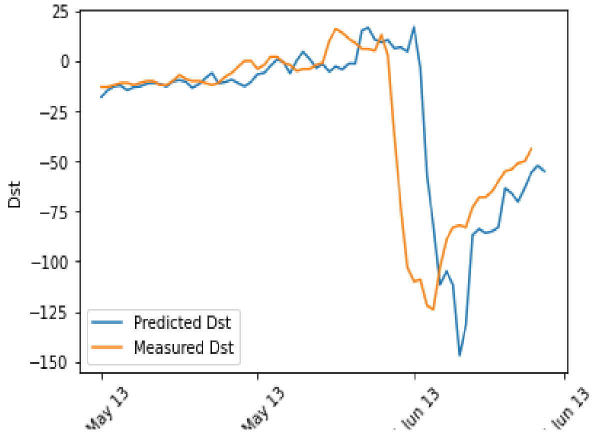


Fig. 3:*Using ARIMA model to predict the geomagnetic storm between 30 May – 2 June 2013*

For a 3 hour ahead prediction, the model was tested on the 30 May – 2 June 2013 geomagnetic storm (Figure 3) and had a Correlation Coefficient (CC) of 0.84 and Root Mean Square Error (RMSE) of 21.61.

However, more advanced Deep Learning algorithms such as Recurrent Neural Networks like LSTM have been proven to provide better results for time series forecasting (Gruet, Chandorkar, Sicard, & Camporeale, 2018; Sagheer & Kotb, 2019). In this regard, we implemented an LSTM network to model the Dst forecasting and compared the results to the ARIMA model (Figure 4). The LSTM model obtained a CC of 0.85 and an RMSE of 19.97.

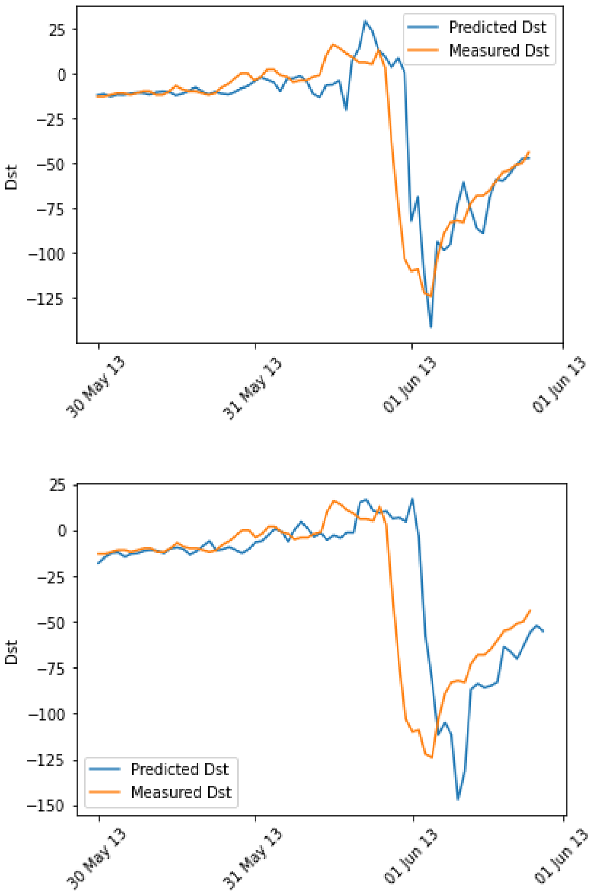
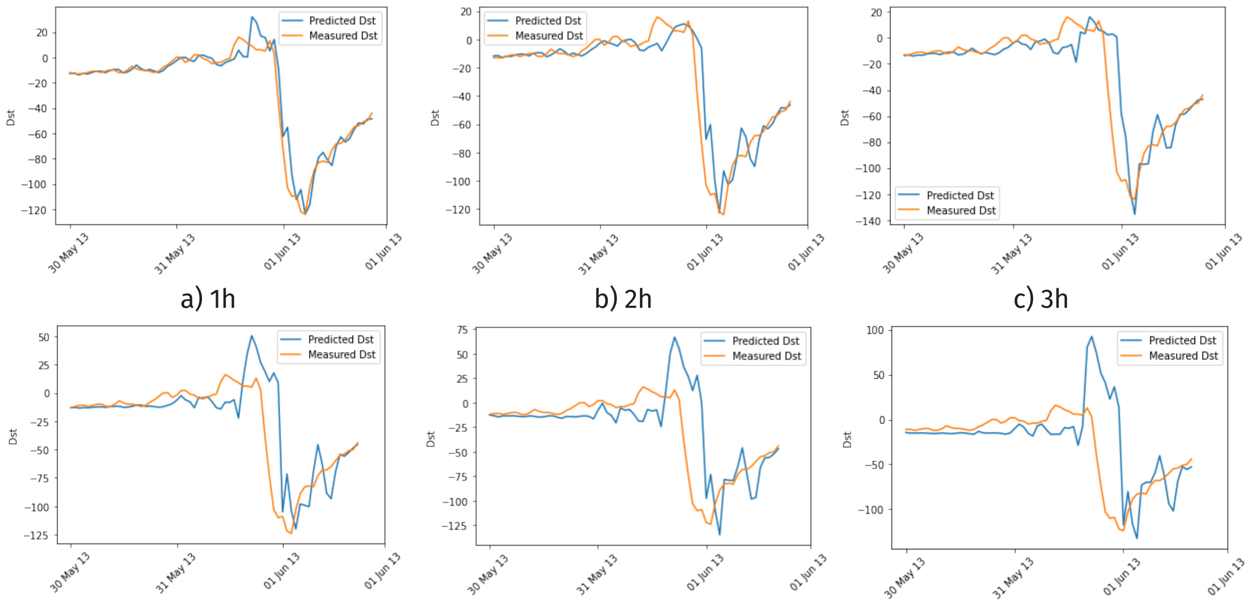


Fig. 4:*Comparison of LSTM and ARIMA models for 3 hours ahead Dst forecasting*

	1H	2H	3H	4H	5H	6H
CC	0.96	0.93	0.85	0.72	0.62	0.44
RMSE	9.62	14.11	19.97	28.41	32.31	35.58

Table 1: *Comparison of LSTM models' performance for 1 hour ahead to 6 hours ahead forecasting*



a) 1h b) 2h c) 3h

d) 4h e) 5h f) 6h

Fig. 5a-f: *1 hour to 6 hours ahead Dst forecasting using LSTM models*

Furthermore, we experimented an LSTM model for each 1 hour ahead to 6 hours ahead forecasting, and the results are shown in the Table 1 and Figure 5.

In addition, for each LSTM model we can implement a Gaussian Process (GP) in order to obtain probabilistic forecasting and calculate empirical confidence intervals.

For instance, the 3 hours ahead LSTM model can be used as a mean for a GP with an RBF kernel, as depicted in Figure 6.

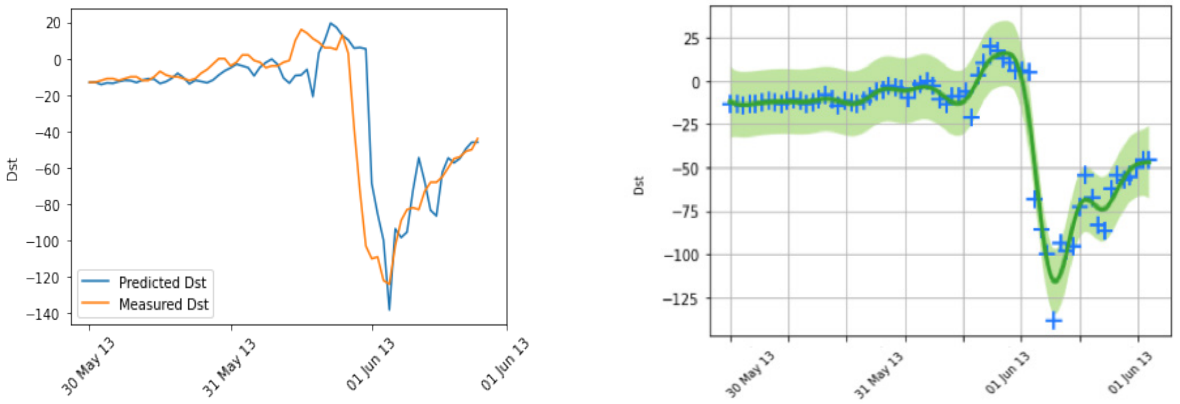


Fig. 6:*Gaussian Process (GP) based on the LSTM model*

Based on the LSTM model we can create a classifier for the geomagnetic storms. For instance, storms in which Dst has a value < -100 nT can be classified as intense, whereas for -100 < Dst < -50, we can consider moderate storms. For such a classifier we calculated the ROC curve and reliability diagram in the case of 3 hours ahead prediction in Figure 7.

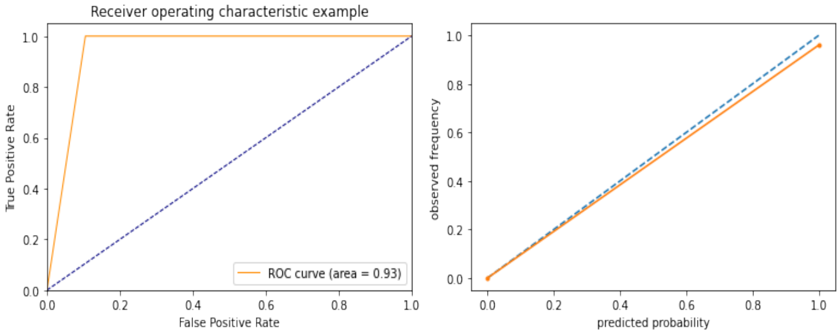


Fig. 7:*ROC curve and Reliability diagram for 3 hours ahead geomagnetic storm classifier*

The ROC curve provides useful information regarding the classifier's selection, and the reliability diagrams show how good forecast probabilities correspond to the actual frequency of the event; for instance, an event predicted with probability p is observed with the same probability.

CONCLUSIONS

Due to the difficult conditions in space, the remnants of objects, micro-meteorites or satellites in orbit, the growing number of actors in space, and the lack of means to protect or repair space assets, knowledge of the space situation is essential to reduce the risk in space operations.

The solar wind, which consists of plasma and magnetic fields expelled from the Sun, has strong variations that influence the shape and size of the magnetosphere. Phenomena such as auroras and variations in the Earth's magnetic field are manifestations of the interaction of the solar wind with the magnetosphere, observable directly from the Earth's surface. Geomagnetic disturbances with various sources are simply found under the name of geomagnetic activity, and are important because they can affect the operation of scientific, commercial, or military systems. For example, they pose a risk to electricity distribution and transmission systems, which can affect the operation of electrical transformers because the electric field induced in the Earth can produce an electric current in the earthing circuit of the transformers, with a destructive effect.

Spatial Situation Awareness (SSA) capability is essential for the security of space infrastructure and for other critical services that enable navigation, communications, broadcasting, environmental protection, earth observation, or meteorology.

We have presented a general overview of the SSA domain and described the main objectives and requirements of the SSA systems. As an exemplification of actual resources that are available for the development of services and applications in the field of SSA we have introduced the SAFESPACE platform, and we have presented a case study related to the Dst index forecasting for geomagnetic storms classification.

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