Ionosphere Monitoring and Prediction Center (IMPC)

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Abstract. Reaching the maximum of solar cycle 25 the influence of space weather is becoming increasingly critical, with phenomena like solar flares and geomagnetic storms occurring more frequently, affecting satellite technology, aerospace operations, telecommunications, and navigation systems more severely. The DLR Institute for Solar-Terrestrial Physics in Neustrelitz (DLR-SO) studies these impacts on critical infrastructures. Central to these activities is the Ionosphere Monitoring and Prediction Center (IMPC) which provides near real-time monitoring and prediction capabilities for space weather impacts, enhancing system resilience and reliability. It leverages advanced instrumentation and data processing technologies, including GNSS-based remote sensing and ionospheric modeling. IMPC instruments like the Global Ionospheric Flare Detection System (GIFDS) and eCALLISTO offer comprehensive space weather data assets. Integrated into international networks, the IMPC contributes to a global effort to understand and mitigate space weather impacts to protect and improve our technology and its operational performance during space weather events.

Keywords: Space Weather · Realtime Monitoring · Remote Sensing

1 Introduction

In an era of high-precision and increasingly autonomous Global Navigation Satellite Systems (GNSS) applications, the influence of space weather on their system performance has become an area of growing concern and active research. Space weather phenomena, such as solar flares, geomagnetic storms, and ionospheric disturbances, can significantly affect satellite technology, aerospace operations, telecommunications, navigation systems, and power grids. The DLR Institute for Solar-Terrestrial Physics (DLR-SO) in Neustrelitz is a leading institution investigating these effects on critical systems and infrastructures on the ground- and in space. Central to this research is the Ionosphere Monitoring and Prediction Center (IMPC), developed and operated by the Pre-operational Services working group in collaboration with the German Remote Sensing Data Center of DLR. As illustrated in Fig. 1, a significant strength of the IMPC is its utilization of state-of-the-art data processing technologies, enabling rapid and precise

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analysis of large ground and space based data quantities. This facilitates near real-time monitoring and response to space weather events. The IMPC's capabilities extend beyond monitoring to include a range of products and services designed to mitigate space weather impacts on contemporary technologies, crucial for sectors reliant on GNSS and RF communications. The IMPC acts as a bridge between scientific expertise and the diverse requirements of users from national and international public and private sectors, academia, and industry. Providing near real-time monitoring and predictive capabilities for space weather impacts, it is enhancing the resilience and reliability of modern technological systems.

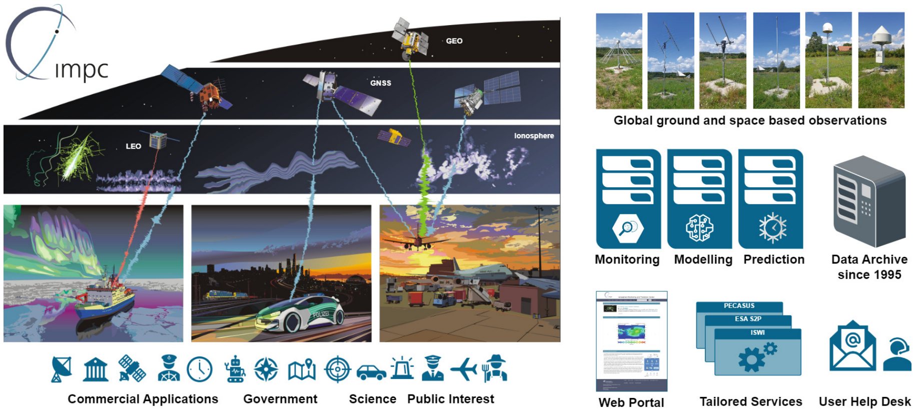

Fig. 1. Schematic overview of the core components of the IMPC to address the impact of space weather on the various end-user sectors.

2 Capabilities

2.1 IMPC Framework

The IMPC provides a scalable and robust platform for the automated processing, archiving and dissemination of ionospheric products on a 24/7 near real-time basis [1]. Each data product is currently processed, archived and delivered in approximately one minute. The developed system is highly efficient and generates thousands of products daily. The platform integrates data from real-time data streams and files and follows a three-step processing environment that transitions from development through a test zone to operational deployment. The framework is highly containerized and being developed towards open data standards, e.g. driven by the Open Geospatial Consortium (OGC), to enhance system interoperability and user-friendliness. To ensure high-quality service management in development and maintenance, the FitSM approach, a lightweight framework for effective IT service management, is applied. The IMPC User Help Desk (impc-uhd@dlr.de) is available to address technical, functional, or thematic issues and requests from registered users, project partners, and anyone interested in space weather. Additionally, the platform's services are continuously monitored by an automated system to ensure reliability and performance required by safety-critical applications.

2.2 Observational Networks, Products and Services

In order to provide services of interest to the very complex end user domain it is essential to assess the space weather situation in real time. This section provides a brief overview of selected space weather observation techniques utilized by the IMPC, showcasing its unique observational capabilities throughout different space weather domains and characteristics.

Multi-instrument Ionospheric Radio observation Array (MIRA) DLR-SO established MIRA, an antenna measurement and test field for various passive reception measurement techniques ranging from 10 kHz to 2 GHz. This easily accessible and configurable, yet undisturbed site serves two purposes: we can check antenna and measurement equipment before shipping to international partners, and it is used for long-term measurement of ionospheric and solar disturbances. MIRA also facilitates the development of various radio reception techniques and hosts multiple receivers for GNSS, Beacon, and VLF signals, as well as solar spectrometers, supporting various DLR-SO projects. The field's size allows for the installation and testing of additional receivers upon request from cooperation partners.

GNSS Realtime Data Processing System Well-established ground and space based GNSS measurements offer a unique opportunity to continuously monitor the electron density and structure of the ionosphere-plasmasphere system. IMPC processes hundreds of real-time GNSS stations in real time, providing detailed measurements for GPS, Galileo, and GLONASS and other GNSS across multiple frequencies with 1 Hz cadence. These data are pre-processed continuously to mitigate outliers, to correct cycle slips and to reconstruct the geometry of each observed GNSS connection. Afterwards the total electron content (TEC) is estimated and distributed to other near real-time processing applications, supporting various scientific tools and algorithms. Leveraging long-term expertise in ionospheric modeling [2], IMPC develops near real-time products like Total Electron Content (TEC) maps, Rate of Change of TEC index (ROTI), and normalized information on ionospheric disturbances [3] as shown in Fig. 2. Delivered with high cadence and low latency, these products significantly support internal and global research activities in space weather and related applications.

Monitoring and Modelling of Ionospheric Scintillations Especially at very high or low latitudes, small-scale ionospheric disturbances can cause severe radio scintillations of signals transmitted from global navigation satellite systems (GNSS). These plasma irregularities can significantly degrade GNSS performance, posing challenges for safety-critical applications. IMPC's capabilities to model and forecast these disturbances are important, as simply upgrading GNSS equipment is insufficient to mitigate scintillation effects. IMPC operates the Experimentation and Verification Network (EVNet) of high-rate, multi-frequency GNSS receivers across polar to equatorial regions, collecting data to analyze space weather events and study ionospheric scintillations [4, 5]. By applying data assimilation, these datasets significantly enhance IMPC's modeling capabilities based on the Global Ionospheric Scintillation Model (GISM), which includes numeric simulations with multiple phase screens (1D and 2D), utilization of the NeQuick or

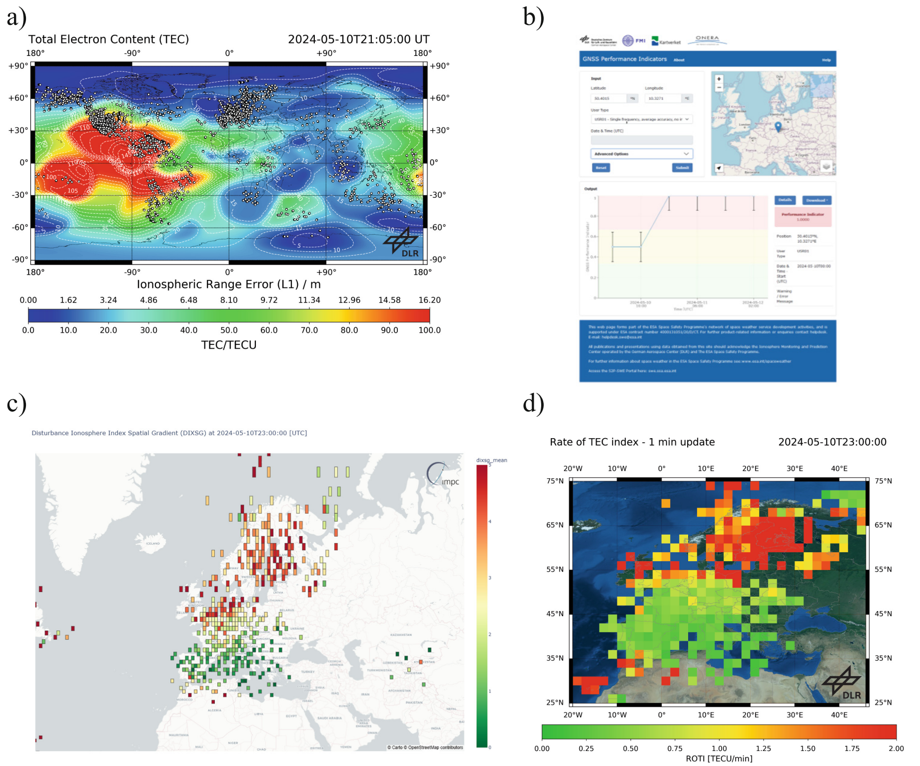

Fig. 2. Response on the severe space weather activity during 10–12 March 2024 observed by several low latency IMPC products provided by IMPC in near-real-time to the end users: TEC maps based on 1 Hz real-time GNSS observations and the Neustrelitz TEC model (NTCM) (a), the response of the GNSS performance indicators application utilized to provide simple indicators over Germany (b), real-time map of the disturbance index (DIX-SG) (c) and maps of the rate of TEC index (ROTI) with an update rate of one minute to real time (d).

Neustrelitz Electron Density Model (NEDM) models of ambient ionospheres, refractional ray bending, and synthetic scintillation time series simulation and extraction [6, 7].

CALLISTO for Solar Radio Burst Monitoring Sudden eruptions of high-energy particles and electromagnetic radiation from the Sun may disrupt GNSS and high-frequency communication systems. The global e-Callisto network, with around 70 stations worldwide, monitors these bursts as part of the ISWI activities. DLR contributes to this network and is developing and operating three types of receivers across different spectral ranges. Each CALLISTO receiver (Compound Astronomical Low frequency Low cost Instrument for Spectroscopy and Transportable Observatory) includes an antenna, preamplifier, heterodyne receiver, and computer, recording frequencies from 45 to 870 MHz, adjustable to other ranges. DLR's dual-band receivers can cover 10 to 1,600 MHz, with antennas following the Sun's position for best measurements. We are currently preparing the automatic data integration into the IMPC for further processing and interactive visualization.

Global Ionosphere Flare Detection System (GIFDS) The ISWI instrument GIFDS has been developed by DLR-SO to monitor sudden ionospheric disturbances (SIDs) in the D-layer ionosphere caused by solar flares [8]. As severe solar flares can have a strong impact on communications and navigation signals, users of such systems can be informed of potential performance degradation or malfunctioning. The major advantage is that the system is ground-based, simplifying hardware maintenance compared to x-ray detectors on satellites. Moreover, the actual influence on Earth is measured instead of the source strength in space, which suits better to ground technology. The integration into IMPC for user-friendly data provision and search are in active development, as is extending the models behind.

Reception and Processing of Solar Wind Parameters Solar wind information is crucial for evaluating and predicting solar storms and their impacts on Earth, making it extremely important for the IMPC services. DLR is the only European member of the Real Time Solar Wind (RTSW) observation network and plays a key role in the data transfer and analysis of information from NASA's Advanced Composition Explorer (ACE) and the Deep Space Climate Observatory (DSCOVR). Within the IMPC framework, the received solar wind data is analyzed in real-time to generate space weather warnings and forecasts.

GNSS Performance Indicators (GPI) The GPI application utilizes products available within the SWE Service Network (TEC, ROTI, scintillation indices, Kp index), subsequently processing them to provide the end user with an indication of positioning uncertainty caused by space weather impact at their location. The application interface was designed to allow the user to indicate a given geographic position in order to receive an estimate of the performance in positioning services they can expect based on current space weather conditions and GNSS satellites in view. These results are retrievable via a web interface designed by be easy to interpret by end users and through an API enabling machine to machine communication [9, 10].

2.3 Contribution to International Networks and Outreach

International Space Weather Initiative (ISWI) There are strong connections between ISWI and DLR-SO, and we are coordinating their actions in Germany. With CALLISTO and GIFDS, DLR-SO is constructing and further developing two acknowledged ISWI instruments. Both systems are expanding in terms of the number of stations as well as their functionality and presentation.

ESA Space Weather Service Network Since several years DLR is coordinating the Expert Service Center Ionospheric Weather (I-ESC) within the Space Weather Service Network developed in the ESA Space Safety Programme (S2P). The I-ESC provides, implements and supports the Ionospheric and upper Atmosphere Weather products and capabilities of the network, including the observation, monitoring, interpretation, modelling and forecasting of ionospheric and upper Atmosphere weather conditions. Within this activity, the IMPC plays an important role by continuously providing products of ionospheric key parameters e.g. nowcast and forecasts of TEC and ROTI maps, scintillation indices accessible via a Web Feature Service (WFS), MUF alarms for skip distances of 750 km, slab thickness, TEC gradients via TechTIDE as well as developing and operating interactive web services e.g. to provide GNSS performance indicators [11].

PECASUS – Global SWX Center for ICAO The PECASUS consortium is one of the four global centers providing space weather advisories according to ICAO regulations. These advisories are sent to airliners using the existing aeronautical fixed network for international aviation (AFS). The three other services providing advisories are the Space Weather Prediction Center of NOAA, the ACFJ consortium formed by Australia, Canada, France and Japan and the CRC consortium formed by China and Russia. DLR leads the GNSS domain (DLR, INGV, SRC, STCE, FMI) and continuously delivers near real time products e.g. maps of the total electron content and rate of change of TEC (ROTI) as well as amplitude and phase scintillation indices (S4 and σ_φ) in near real-time with five minutes cadence [12, 13].

International Space Environment Service (ISES) In April 2023, the DLR Institute for Solar-Terrestrial Physics joined ISES as a Collaborative Expert Center (CEC) [14]. This partnership aims to provide real-time forecasting and monitoring of space weather to mitigate risks to technology, critical infrastructure, and human activities. Within this frame, IMPC will facilitate international communication and coordination during periods of increased space weather activity and extreme events. Additionally, IMPC will enhance its space weather services, promoting understanding among users, researchers, the media, and the public.

PITHIA-NRF – Building European Research Infrastructure PITHIA-NRF aims to establish a European distributed network integrating research infrastructures focused on the ionosphere, thermosphere, and plasmasphere, providing access to facilities like EISCAT, LOFAR, and Ionosondes. IMPC is involved in developing the eScience Center, providing access to high-rate GNSS data and a web service for NEDM runs. The project advances upper atmosphere research by integrating satellite data and prediction models and supports technology development and standardization. Through the Trans-National Access programme, PITHIA-NRF facilitates access for external research teams to its nodes such as the IMPC activities provided through the DLR-SO node [15, 16].

3 Conclusion

In conclusion, the IMPC plays a central role in addressing the challenges posed by space weather to modern technologies. Its advanced monitoring and prediction capabilities, supported by integration into global networks, ensure stakeholders across various sectors receive accurate and timely space weather information. This enables the mitigation of space weather impacts, safeguarding critical systems and enhancing the reliability of services that underpin modern society. The joint efforts of the IMPC framework represents a significant advance in applied space weather research and its practical applications and emphasize the importance of further investment in this area.

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