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The Prototype SafeSpace Service of Advanced Prediction of the Outer Van Allen Belt Dynamics

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Abstract

The European SafeSpace project has been implementing a synergistical approach to improve space weather forecasting capabilities from the current lead times of a few hours to 2-4 days. We have combined the solar wind acceleration model MULTI-VP with the heliospheric propagation models Helio1D and EUHFORIA to compute the evolution of the solar wind from the surface of the Sun to the Earth orbit. The forecasted solar wind conditions are then fed into the ONERA Geoeffectiveness Neural Network, to forecast the level of geomagnetic activity with the Kp index as the chosen proxy. The Kp index is used as the input parameter for the IASB plasmasphere model and for the Salammbô radiation belts code. The plasma density is used to estimate VLF wave amplitude and then VLF diffusion coefficients, while the predicted solar wind parameters are used to estimate the ULF diffusion coefficients. Plasmaspheric density and VLF/ULF diffusion coefficients are used by the Salammbô radiation belts code to deliver a detailed flux map of energetic electrons. Finally, particle radiation indicators are also provided as a prototype space weather service of use to spacecraft operators and space industry, accessible at http://www.safespace-service.eu. The performance of the prototype service has been evaluated in collaboration with space industry stakeholders. The work leading to this paper has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 870437 for the SafeSpace (Radiation Belt Environmental Indicators for the Safety of Space Assets) project.

Keywords: Space Weather, Forecast, Van Allen Belts, Electron Acceleration, Trapped Particles, Particle Radiation

Acronyms/Abbreviations

EUHFORIA: EUropean Heliospheric FORecasting Information Asset
EMERALD: Electric and Magnetic Electron RAdiaL Diffusion
CME: Coronal Mass Ejections
VLF: Very Low Frequency
LEO: Low Earth Orbit
MEO: Medium Earth Orbit
GEO: Geostationary Orbit
GNSS: Global Navigation Satellite Systems

1. Introduction

The main goal of the SafeSpace project is to design and produce a Space Safety Service, i.e., a prototype service dedicated to adverse space weather events impacting near-Earth space and threatening space-borne assets. The Space Safety Service is devoted to the prediction and early warning of solar disturbance effects on Earth-orbiting satellites through the enhancement of energetic electron flux and fluence in the outer Van Allen radiation belt. Effective mitigation of the detrimental effects of such events is possible with reliable warnings and could result in cost avoidance of several billion dollars globally per decade. The design and output of the early warning system of

SafeSpace is based on the requirements of space industry partners and considers the full cause-to-effect sequence, from precursors on Sun's surface to radiation belt variability. This is achieved through the synergistic use of several well-established models (CNRS solar disturbance propagation tool, KULeuven EUHFORIA CME evolution model, ONERA Neural Network tool, IASB plasmasphere model, IAP VLF waves model, NKUA EMERALD radial diffusion coefficients model, and ONERA Salammbô radiation belts code) that cover different regions of the complete Sun – interplanetary space – magnetosphere chain of space weather. The coupling of these distinct and complementary models enables a holistic approach of radiation belt forecasting, incorporating the study of plasma and energy flow from the Sun to the near-Earth environment, the transfer into the magnetosphere, and the effects on cold plasma density and electromagnetic wave properties, driving radiation belt dynamics. The ultimate result of the project will be a sophisticated model of the electron radiation belt and a space weather service prototype of tailored radiation belt environmental indicators, which will provide forecasts with lead times of 2-4 days. A typical run to produce a daily forecast requires roughly 9 hours of CPU on CNRS and ONERA computers. Specifically, from the detection of precursors of solar disturbances on the solar surface to the propagation of solar wind properties from the Sun through interplanetary space to L1 requires 4 hours CPU on CNRS computers; a typical EUHFORIA run for the heliosphere requires 2h 30 min CPU on KULeuven computers (running on ~220 cores) next, estimating the energy transfer from L1 to the inner magnetosphere and forecasting the resulting radiation belt properties requires 5 hours CPU on ONERA computers. This estimation involves results of inner magnetosphere dynamics models (IASB plasmasphere model and IAP VLF waves model) running for 50 minutes of CPU time on IAP server.

2. Aims and main objectives of SafeSpace

The SafeSpace project [1] has aimed at:

- Improving Van Allen radiation belt modelling by incorporating seven well-established space weather models
- Contributing to the safety of space assets by advancing space weather nowcasting and forecasting capabilities
- Prototyping a space weather warning service by defining tailored particle radiation indicators

The major interconnected objectives of the SafeSpace project, leading to the achievement of its goals, have been the following:

- To map solar disturbances (both real and idealized events) at the Sun and propagate them in interplanetary space all the way from the Sun to the Earth, including uncertainties in the propagation.
- To subsequently map the obtained interplanetary space conditions into geospace through the use of a neural network coupling tool which estimates geomagnetic indices from interplanetary parameters.
- To produce a detailed map of plasma density in the inner magnetosphere parameterized by geomagnetic activity levels - obtained through the mapping of solar and interplanetary conditions into geospace.
- To accurately define - to the highest degree possible - plasma density and wave diffusion coefficients, including their uncertainties, in order to improve the performance of the Salammbô model of the electron radiation belt.
- To predict a time-dependent state of the energetic electrons trapped in the outer radiation belts including the median plus percentiles giving a metric on the confidence of a prediction.
- To produce information on physical quantities such as radiation belt fluxes (median and percentiles) along specific spacecraft orbits; emphasis will be given to heavily used orbits like GEO, GNSS (MEO) and operational satellite constellations like O3b in the slot region, where the space radiation environment is poorly defined so far.
- To define, in collaboration with space industry, particle radiation activity indices that are useful to spacecraft operations (situational awareness, scheduling of operations, testing, maintenance and post-event analysis).
- To design and establish a prototype service of such indicators and early warnings and provide them to spacecraft operators and industries for evaluation.
- To use the service evaluation feedback for improvements of its functionality.

3. Work performed

Here we provide an overview of the work performed, leading to the implementation of the protype service.

3.1 Solar and interplanetary drivers of geospace conditions

The initial part of the pipeline is devoted to extensive modelling of space weather events (CMEs and CIRs) all the way from the Sun's surface to Earth's magnetosphere. It focuses on determining the occurrence and propagation of the solar wind perturbations susceptible of affecting the terrestrial magnetosphere and on quantifying the predictability of key space weather driving parameters at Earth. Through the use of neural networks, it is in the process of providing quantification of when, where and how much energy is fed from the solar wind into the inner magnetosphere via the prediction of magnetic activity indices (like Kp). Finally, the work also consists in defining the requirements for enhancements to future space weather modelling tools.

In more detail, we have implemented solar wind acceleration model MULTI-VP, the first of SafeSpace Sun – interplanetary space – Earth's magnetosphere chain of models in SafeSpace. The goal was to build a system capable of delivering daily forecasts of the Earth-bound solar wind flows based on solar surface observations and physical principles. In order to do so, we have embedded MULTI-VP within a modeling pipeline that we have implemented at CNRS. The pipeline is composed of three main layers. The first one handles heterogeneous input data (magnetograms from different observatories, ground and space based, in different formats), and provides a regular and uniform set of inputs for the solar wind computations. The second one is MULTI-VP itself, which calculates the physical properties of the solar wind from the surface of the Sun up to ~0.15 AU. The third layer translates these computations into inputs used to drive heliospheric propagation models (SW1D and EUHFORIA), that compute the evolution of the solar wind to Earth.

We first built a monolithic pipeline, on which all the layers are directly and tightly coupled one after the other. Upon testing, we concluded that the pipeline would benefit from a modular approach, on which each main layer follows its own data/model update cycle, polls into a common database, checks for the consistency of the inputs it requires, and acts accordingly. This approach has proved to be much more dependable: development/maintenance of the pipeline became much easier, and the operation became much more robust (with respect, e.g., to data gaps or delays from input sources; the pipeline has now been running non-stop for several months). After verifying the system's performance, and in agreement with the rest of the consortium, we settled into a setup that runs daily with a forecast lead time of 2 days at 0.1 – 0.14 AU (extendable to up to 6 days at Earth).

Calibration of the outputs at intermediate altitudes is complex due to the scarcity of measurements. We benefited nevertheless from the new solar missions Parker Solar Probe and Solar Orbiter, and prepared the system to be re-calibrated in the future. Continued long-term calibration is, on the other hand, possible via the coupling to heliospheric models (that connect to near-Earth spacecraft). We therefore proceeded with several combined tests that let us define the optimal sets of input magnetogram data and refine some physical parameters of MULTI-VP.

We tested the model propagation using two years of solar wind data generated from the MULTI-VP model. The output from the 1-D MHD model showed promising results. We have benchmarked the model output versus the real observation to quantify uncertainties such as time-lags and magnitudes. We have also performed ensemble modelling where the forecast is performed for multiple targets around the Earth point to cover the spatial and temporal uncertainties. Due to some limitations of the code and the quality of the inputs, we found features in the forecasted data that need improvement (over-compressions). To address this issue, we are implementing a post-calibration of the model output. Various techniques for the data calibration have been tested such as polynomial fitting and high-order fitting using supervised machine learning tools. This approach significantly improves the results of our model, which will eventually improve the quality of other downstream models and the overall space weather service of SafeSpace.

3.2 Inner magnetosphere dynamics

We further conducted extensive modelling of space weather events in the inner magnetosphere and carried out research to improve existing radiation belt models. We focused on modelling of inner magnetosphere drivers (including full distribution, median and percentiles) for a space weather service dedicated to the Earth radiation belts which is to say: parameterization of cold plasma density (today, the main limiting factor to evaluate accurate wave-particle diffusion coefficients) by solar/IMF parameters from WP2 through predicted geomagnetic activity indices (note that electromagnetic waves intensity and propagation angle from previous EU-FP7 projects, such as SPACECAST and MAARBLE is used and is augmented by wave observations at LEO from the recent European Swarm mission); prototype of an operational model of diffusion coefficients (mean, median and percentiles values to address uncertainties in radiation belt dynamics). So, this work package conducts the improvement of both the existing Salammbô electron radiation belt model and the data assimilation tool according to new definition of interplanetary drivers as well as inner magnetosphere ones. In the purpose of a space weather service that would provide forecast capabilities, special care was given to quantify the benefits gained thanks to these improvements to produce high fidelity nowcasts of the state of the radiation belts.

This part of the pipeline included work on the:
- Cold plasma density map
- Impact of plasma density and waves on diffusion coefficients
- Electron radiation belt flux map
- Data assimilation

3.3 Space Safety Service definition and design

Considerable effort was devoted to the definition and to the settings of the Safe Space service. The service focuses on energetic electron radiation belts, which potentially lead to internal spacecraft charging events. In a first step, user needs were collected and expressed by a major European space industry, Thales Alenia Space. Next any data/software produced or improved throughout the project are traced and the data management plan collect all the corresponding details. Special care was devoted to the chaining of all the tools involved in the prototyping activity. Then, radiation belt activity indices have been derived and are made available to any end-user on a dedicated web site. Finally, from those results, support web pages are dedicated to the Galileo constellation, which is located in the heart of the electron belt.

4. The prototype SafeSpace service

The prototype SafeSpace service is available at http://www.safespace-service.eu. The service provides forecasts of the Kp index and of the electron radiation belt activity indices.

The electron radiation belt activity indices are the keystone of the SafeSpace safety service. They are meant to indicate how severe the electron space environment is at a given time and will serve for post-event anomaly analysis or prevent some anomalies on-board spacecraft. After consultation and feedback from the space industry, these indices were based on daily averaged electron fluxes defined on three standard orbits: LEO, MEO (GNSS) and GEO. They are dedicated to the quantification of the internal charging risk for each of the three orbits. Besides, they serve in a three-color warning system, associated to three levels of risk: "quiet", "moderate" if the daily averaged flux is among the 20% strongest historical fluxes values and "active" if the daily averaged flux is among the 2% strongest historical fluxes values. The historical flux values are built from long-term measurements over the three studied orbits to be as representative possible of the full range of the electron radiation belt dynamics. The safety warning system associated to the pipeline was tested over the St-Patrick 2015 storm. It was able to accurately nowcast the indices as observed on the MEO and GEO orbit, with a slight overestimation during the return to equilibrium phase of storm. They reflect a precise physical description of the dynamics by the pipeline and the assimilated data on the studied orbits. The LEO orbit index however is underestimated due to the coarse refinement of the solving grid near the loss cone. Forecast results of the storm that occurred March 17, 2015, are also good but introduce high uncertainties due to the absence of assimilated data.

The SafeSpace service is open access and available for free use to anyone. Registration is optional. However, registered users may modify the thresholds of the forecasted fluences, either as a percentage of the CDF or the absolute values.

Additionally, a dedicated server for the retrieving, the processing, and the hosting of near-real time Environmental Monitoring Units (EMU) measurements from the units on-board Galileo satellite 0207 and 0215 has set up. The service retrieves Level 1 Version 1 measurements from the Galileo EMU data science repository, derives updated flux products (i.e., Level 1 Version 2 flux measurements) and the magnetic coordinates of the GSAT orbits. The database is updated in real time provided the availability of updated datasets in the EU Galileo EMU database. The L2 database, which is hosted at SPARC, is accessed by ONERA on a daily basis for the provision of dedicated inputs to the Salammbô runs in relation to the electron flux environment along GNSS orbit.

Furthermore, a dedicated website (https://galileo.safespace.sparc.space) has been created to provide dedicated services related to the EU Galileo navigation satellites. The website provides:

- High level quality of electron flux measurements made by the EMU on-board GSAT215 (nowcast)
- Forecasted electron flux series along the GSAT215 orbit based on the outputs of the SafeSpace Salambo runs (forecast)

The near-real-time plots in the https://galileo.safespace.sparc.space website allow a direct comparison between past, nowcasted and forecasted electron flux series along Galileo orbits.

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