Radiation Belt Environmental Indicators for the Safety of Space Assets

SafeSpace Newsletter

Issue 3, Months 13-18

Dear Reader,

This is already the third SafeSpace Newsletter, marking the half-way milestone (months 13-18) of the SafeSpace project.

The "SafeSpace: Radiation Belt Environmental Indicators for the Safety of Space Assets" project was launched in January 2020 with a duration of 36 months. This comprehensive EU-funded project aims at advancing space weather nowcasting and forecasting capabilities and, consequently, at contributing to the safety of space assets through the transition of powerful tools from research to operations (R2O). To ensure an efficient and optimized transfer from science to application, we have foreseen close collaboration between academia (National and Kapodistrian University of Athens - NKUA, Office National d'Etudes et de Recherches Aérospatiales – ONERA, Katholieke Universiteit Leuven – KUL, Institute of Atmospheric Physics Ustav Fyziky Atmosfery AV CR, v.v.i. – IAP, Centre National de la Recherche Scientifique - CNRS, Institut royal d'Aéronomie Spatiale de Belgique Royal Belgian Institute for Space Aeronomy – IASB-BIRA), a major European space industry (Thales Alenia Space – España- TAS) and a space-oriented SME (Space Applications & Research Consultancy Sandberg & Co Private Company - SPARC). The SafeSpace Consortium shall improve radiation belt modelling through the incorporation into an existing physical model of processes and parameters that are of major importance to radiation belt dynamics. In order to set up a prototype of a new space weather service dedicated to Earth-orbiting satellites, end users' requirements related to ionizing particles in space will be defined by TAS – in consultation with other end users.

This was the third semester that the SafeSpace Consortium has been working mostly remotely, due to the COVID-19 pandemic. Teleconference meetings kept being held regularly (at least once per month) for all (technical and administrative) aspects of the project. In this time of unprecedented working conditions, we have managed to keep to the schedule of the project's work plan, including its work *packages (WPs), deliverables and milestones but we are looking forward to our very first in-person meeting in Milos Island, next month (details follow), since the kick off meeting that was held in January 2020.*

Project Progress and Outcomes

Propagating geoeffective solar wind structures to Earth (WP2 - CNRS, KULeuven, ONERA, IAP)

The Work Package 2 of SafeSpace is now in the final phase of building, testing and validating the modelling pipeline prototype. All components of the pipeline are essentially already operational, with all interfaces well defined, and permit to propagate and forecast solar perturbations all the way from the solar surface to near Earth. We have performed long term modelling works for validation, as well as several case studies on active solar periods to test the pipeline on specific geomagnetic storms. The output from this task consists in ensemble time series (with error estimates) used for modelling the radiation belts in the other WPs. Developments over the past months are described hereafter.

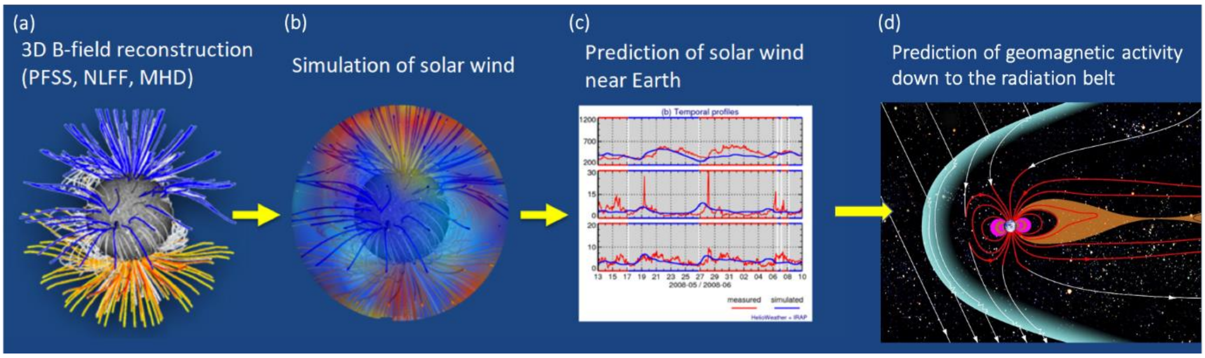


Figure 1. Data pipeline of the coupled Multi-VP (WP2.1), 1-D and 3-D MHD (WP2.2 and WP2.3), and geomagnetic indices forecasting (WP2.4). (a) The reconstruction of the 3-D solar corona using different techniques (e.g., the Potential Source Field Surface (PFSS), with magnetogram as input). (b) Multi-VP simulation of the solar wind emergence near Sun. (c) Prediction of the solar wind near Earth using the 1-D or 3-D MHD propagation. (d) Forecast of geomagnetic indices using Neural Networks with inputs from the solar wind MHD modelling.

Running the solar wind formation model (Multi-VP)

The goal of this task is to use and tune a set of models capable of providing daily forecasts of Earth-directed solar wind flows at their region of formation and acceleration. The modelling of solar wind emergence was built around the solar wind model Multi-VP, which uses solar magnetogram sources from different observatories as input, and provides maps and time-series of the solar wind at about 0.1 astronomical unit (AU), ready to be propagated to Earth (via the subsequent layers of models in the pipeline). The development and implementation of WP2.1 ended in December 2020, and we have moved since to exploiting it in order to produce a richer and more statistically significant set of solar wind meant to drive the Heliospheric magnetohydrodynamic (MHD) models Helio1D (WP2.2) and EUHFORIA (WP2.3) on a more diverse range of physical states. Ultimately, the outcome of this joint work will be used to calibrate Multi-VP itself, to improve the quality of its forecasts, and to better constrain the uncertainties associated to them.

We have prepared a long time series of Multi-VP solar wind runs that fully covers an interval of 15 years (more than a solar cycle). This series was based on Wilcox (WSO) solar magnetic field maps, which is the longest-lasting source of continuous (and coherent) magnetogram data available. These runs are being fed into Helio1D (task WP2.2) in the form of an ensemble of input time-series at ~0.14 AU (covering a latitude-longitude interval around the sub-L1 point). These Multi-VP runs are fully three-dimensional, and are being used to drive EUHFORIA for testing and validations on a long-term basis.

In parallel, we are preparing an additional sequence of solar wind runs based on ADAPT magnetograms that are more appropriate to the main goal of this project (forecasting the solar wind state at a daily cadence), but which only covers more recent epochs. We decided on a set of individual events to drive the background solar wind through which modelled coronal mass ejections (CMEs) will be propagated in EUHFORIA, and also on a time sequence covering a period between 6 months to 1 year of calm (CME-free) solar wind.

One-dimensional MHD modelling of solar wind propagation to Earth

This task connects the solar wind forecasting from near-Sun (using Multi-VP inputs) to Earth by propagating the solar wind solutions through interplanetary space from 0.14 AU to 1 AU using a 1-D MHD modelling approach. The purpose is to forecast solar wind streams, and in particular geoeffective corotating interaction regions (CIRs), that will then be used to drive the neural network model for the prediction of near-Earth geospace conditions (cf. Figure 1 and 3). In the past 6 months, we have implemented an automated interface between the two models (Multi-VP and the 1D MHD model) called the "Helio1D" pipeline. This pipeline is a prototype to perform automatic daily forecast of the solar wind at Earth using daily solar wind forecast data from the Multi-VP model. Since January 2021, the Helio1D pipeline has been scheduled to run daily and provides solar wind forecast with a lead time of 2 - 4 days (Figure 2). At the moment, we are working on improving the quality of the solar wind forecast via further benchmarking and optimization of the Multi-VP and 1-D MHD model parameters using past data. We *also aim to implement a post-calibration and ensemble forecasting of the Helio1D pipeline in the near future to provide an optimum daily solar wind forecast.*

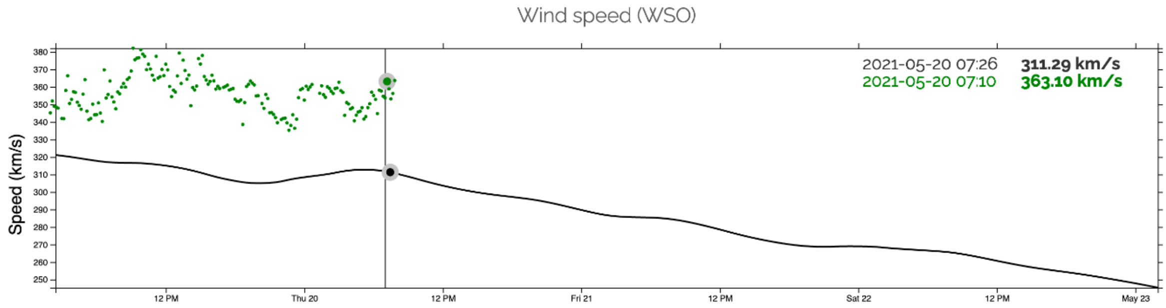


Figure 2. Example of daily solar wind speed forecasting on 20 May 2021 from the Helio1D pipeline (shown as a black solid line) compared to observations at L1 from ACE spacecraft (shown as green dots). This daily Helio1D output shows 1-day history, current day nowcasting, and 3 days of forecasting.

Implementing and validating Multi-VP - EUHFORIA coupling

During the past six months, this task's efforts were focused on two tasks: first, the continuation of the work regarding the validation of the Multi-VP model in EUHFORIA by using more statistics (not just few individual high-speed stream cases) and second, the preparation of the CME ensemble study for evaluating the uncertainties in the pipeline from Sun to Earth. For the first task, we chose a continuous interval of 6 months (January – June 2018) during a period of low solar activity and we compared the performance of the coupled Multi-VP - EUHFORIA forecast with actual solar wind observations (bulk speed, density, temperature, magnetic field etc) at 1 AU. A number of metrics are currently being applied to quantify the performance. For the second task, we selected a clear CME event (12 July 2012) that has already been modelled with the default set-up of EUHFORIA (WSA coronal model + EUHFORIA), considering a specific set of initial CME parameters (initial velocity, magnetic flux, density, temperature etc). For the goals of this task, we plan to model this CME by using (a) the solar wind from the Multi-VP coronal model and (b) perturb the initial CME parameters to conduct an uncertainty study. The first task of obtaining a realistic solar wind at Earth for the dates of interest (July 2012) was a complex procedure since it was a time of a solar polarity reversal and it was not easy for the model to capture the ongoing magnetic changes on the Sun. After a number of trials, we have obtained more realistic solar wind but the procedure is still ongoing in order to augment the modelling fidelity.

Forecasting geomagnetic indices using Deep-Learning

The goal of this task is to provide deep-learning models for the geomagnetic indices required in WP3 for the magnetosphere models, driven by the L1 solar wind parameters forecasted in WP2. We have focused our developments on modelling the Kp index, which is used by most of the models in WP3.

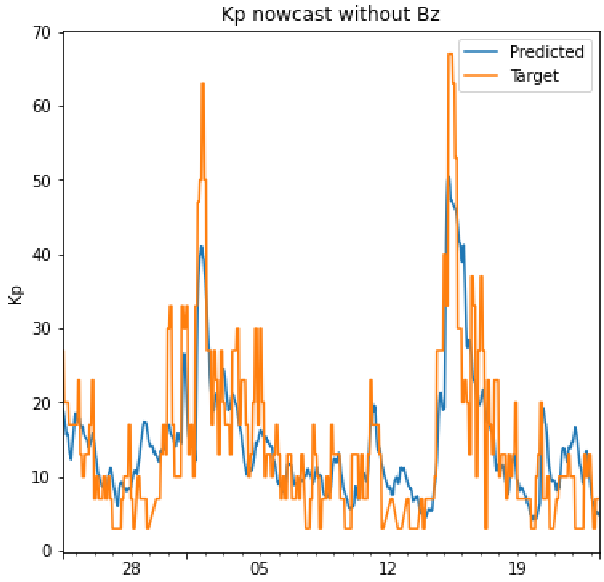


Figure 3. Example of Kp ensemble estimation over a month using Helio1D MHD solar wind parameter estimations as input to the neural network model. In red the observed Kp value, in blue the interquartile range of the estimated distribution.

One of the main challenges for this task is the lack of accurate southward magnetic field component Bz estimation in the forecast of the WP2 solar wind models. This parameter is known to be important in driving geomagnetic activity. We have trained and validated several recurrent neural networks on the OMNI2 database, both with and without Bz as input parameter. While we find that the lack of Bz information decreases the model accuracy (global RMSE increased by 35%), in particular during CME-induced geomagnetic storms (where the RMSE is increased by 70%), the models without Bz still perform somewhat accurately during CIR-induced magnetic storms (the RMSE stays below 1). Further analysis on the impact of the model errors on the radiation belt state estimation are planned using the Salammbô model. We have also developed a tool-chain that allows us to easily run our model on data provided by other tasks and producing appropriate output file format for Inner magnetosphere dynamics Package.

Having a good statistical coverage of severe space storms is important for training our models. For this reason, we use the period 2002-2012 for model training and 1995-2001 for the testing. This large training period allows a good statistical representation of all types of events. It is typical, for models focusing on large events, to over-sample such events in the training set. However, for now we have decided not to do this, as our model should also (and arguably more importantly) perform appropriately during quiet times and for moderate events.

Inner magnetosphere dynamics (WP3 – BIRA-IASB, IAP, NKUA)

The Work Package 3 of SafeSpace has progressed according to the predefined plan. The cold plasma density map is almost completed. The work on radial diffusion coefficients continued by collecting the DLL database and by analysing the possible driving mechanisms. The work on energy and pitch angle diffusion coefficients also substantially progressed. The frequency spectra have been defined as well as the form of data exchanges in CDF files. Electron radiation flux map will be generated by the Salammbô code, which has been substantially improved.

Cold plasma density map.

The goal of this task is to build cold plasma density maps in the plasmasphere and plasmatrough as a function of geomagnetic activity and location, from a physics-based 3D dynamic model (SPM, SWIFF Plasmasphere Model) improved and completed with satellite data (Cluster and Van Allen Probes / RBSP).

The plasmaspheric model has been improved in several ways. First, it can read input files (in CDF format) from the neural network and provides output files in the same format as needed by the Salammbô model. Second, a dynamic interpolation procedure was implemented to provide enough plasmapause points that cover all MLT hours. Third, its plasmatrough part has been improved.

In order to do that, density data obtained by the model have been compared with the satellite density datasets built during the first part of the project (milestone MS2, 30 September 2020, cold plasma density dataset completed), with Cluster/WHISPER and RBSP/EMFISIS data.

Concerning Cluster, no improvement of the model at high latitude has been found necessary (if time permitted, we will later check and compare the model with new Cluster sub-dataset derived from a new method to derive the density: a neural network method recently developed in Orléans, France [Gilet et al., 2021]).

Concerning RBSP, the comparison has been done with all EMFISIS data (2012-2019) resampled every 30 minutes, in 4 MLT ranges (0-6, 6-12, 12-18, 18-24) and for 2 ranges of Kp (below and above 3). It showed a plasmapause as a fine boundary in the model (no points between 2 branches of the plasmasphere region and the plasmatrough region) and not in the observational data. The plasmatrough model densities were located more frequently lower than the data.

RBSP/EMFISIS density data have been fitted with density from the model, and new equations for the plasmatrough density (before, equations from Carpenter and Anderson [1992] were used) have been defined and are now used in the model (see Figure). This new version of the model has been successfully compared with EMFISIS data for specific events and also with data from the Japanese ARASE mission.

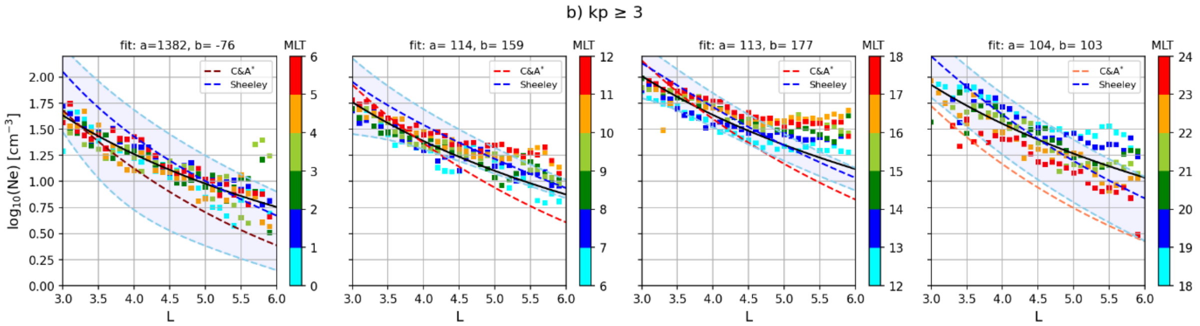


Figure 4. Electron density < 100 cm-3 measured by EMFISIS from 2012 to 2019 in the range L = 3 – 6 RE and fitted by new equations for different MLT sectors and for $\mathrm{Kp} \geq 3$*. Dashed red lines display the fits given by previous equations while solid black lines represent the new fit. Dashed blue lines delimit the regions covered by the equations of Sheeley et al. (2001) for the plasmatrough.*

Impact of plasma density and waves on diffusion coefficients.

During the past six months, our efforts were focused on two tasks: the calculation of event-specific ultra-low frequency (ULF) based radial diffusion coefficients (DLL) using magnetic and electric field measurements from THEMIS constellation and the parameterization of these calculated DLL with various parameter schemes which possibly drive the diffusion coefficients' evolution during geospace disturbances. To that end we have created a DLL database as a function of MLT, L and μ, as well as solar wind speed, density, pressure, interplanetary magnetic field and several geomagnetic indices and universal coupling functions. The database spans the 2010 – 2020 time period (a full Solar cycle).*

The calculation of the DLL is based on the approach by Fei et al. [2006] (contribution of the parallel and the azimuthal components of the magnetic and electric field, respectively), while wavelet analysis has been used in order to infer the power spectral density of the Pc4 and Pc5 waves in the 2-25 mHz frequency range.

The first statistics performed on the database have revealed several features which may be important towards the creation of a nowcasting/forecasting model for the radial diffusion coefficients. These features include MLT dependence, which is different between the electric and the magnetic field component, μ dependence, which is more important for sub-relativistic electrons, and correlation with specific solar wind and geomagnetic parameters (see also Figure 4).

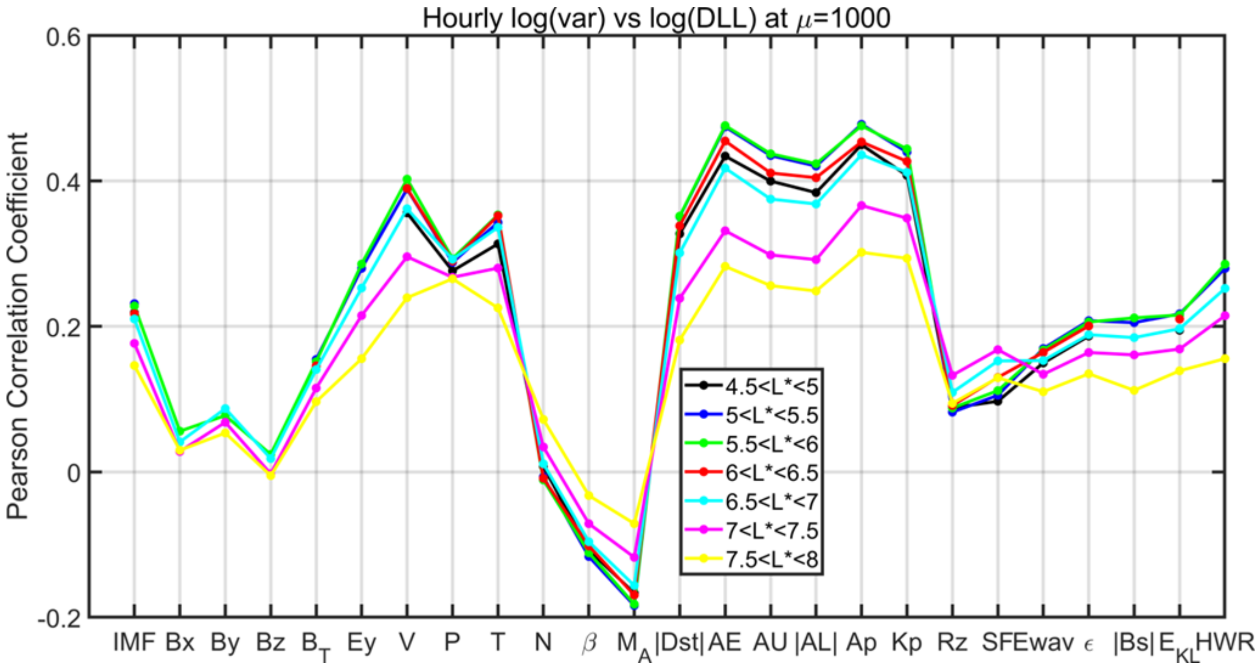


Figure 5. Pearson correlation coefficients between DLL and several solar wind parameters, geomagnetic indices and universal coupling functions.

One of the main challenges for this task is to find the appropriate schemes which drive the DLL (and its components) as well as the choice and training of the appropriate Machine Learning technique. Future work also includes cross-correlation analysis and investigation of possible cumulative effects of the solar wind drivers and/or geomagnetic indices and coupling functions.

Work on definition of the energy and pitch angle diffusion coefficients also continued by development of the very low frequency (VLF) models. The diffusion coefficients will be obtained by the Wave Particle Interaction (WAPI) code based on B2 obtained in separate models for different frequency bands. As a baseline we will use the following bands: plasmaspheric hiss, lower band chorus, and upper band chorus. The addition of the lightning whistler model is under investigation and a paper on this subject entitled “Multi-point Observation of Hiss Emerging from Lightning Whistlers” by Santolík, Kolmašová, Pickett, and Gurnett has been submitted to JGR with an acknowledgment of support from SafeSpace.

The definition of the models has been concluded by a detailed description of the common data format (CDF) files (on the confluence server) and by generation of the power spectral density model for each band. The model is defined by 16 parameters of the power spectral density in each band: table of 8 frequencies normalized by the equatorial electron cyclotron frequency, together with 8 corresponding power spectral density values. The power spectral densities are normalized to a unity integral with respect to frequency.

Electron radiation flux map

This task aims at improving the existing Salammbô electron radiation belt model, according to the new definition of interplanetary drivers as well as inner magnetosphere parameters and physical processes. This objective requires working on several aspects of the code related to:

- *The boundary condition, by introducing a realistic time dependent coupling to solar wind and inner magnetosphere interactions.*
- *The newly improved physical interaction models, provided by the previous task (*Impact of plasma density and waves to diffusion coefficients)*, that has to be implemented in the code.*
- *The numerical resolution, to ensure the code's convergence and stability under various solar wind conditions, and through different study cases.*

The latter task was treated at the beginning of the SafeSpace project and Salammbô has undergone a major overhaul of its coding strategy. Using high performance computer (HPC) and coding optimization, the computing time was divided by a factor of 10. Thus, with a more refined space grid and a shorter time step, numerically accurate results are now accessible.

The newly optimized code was then tested on the study cases selected for the project: Saint Patrick's 2015 CME induced storm and the Christmas 2013 storm. The simulations were focused on measuring the effect of different radial diffusion models provided by WP3.2, which is the main process driving the inward and outward transport of electrons inside the radiation belts. In particular, the radial diffusion model was updated, through several increments, from a unified analytical model to a storm-based energy dependent model. These simulations also confirmed the importance of the balance between global (radial diffusion) and local (wave-particle interactions) in the electron radiation belt dynamics.

Improving the estimation of wave-particle interactions represents also a major part of the work conducted between WP3.2 and WP3.3, through the recast of the WAPI code. In fact, estimating local diffusion coefficient terms is a heavy computational task that currently takes a tremendous amount of time, which is inadequate with the operability needs of the new forecast tool. With the new version of the WAPI code, currently in development, diffusion coefficients are directly interpolated from a density dependent table and efficiently averaged on the drift shell, granting a reduction of computation time of at least one order of magnitude.

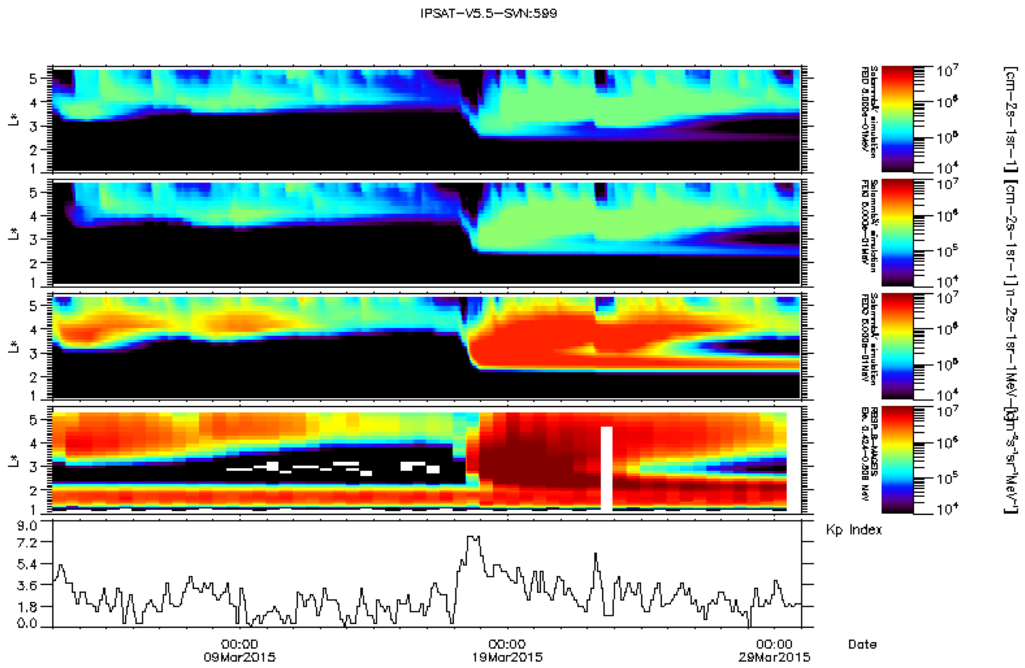


Figure 6. From the top to the bottom, Salammbô simulated unidirectional differential fluxes (cm^(-2) s^(-1) sr^(-1) MeV^(-1)) of 500 keV electrons during the St Patrick's 2015 storm using the to-be-improved analytical model of radial diffusion, RBSP-B measurements of 500 keV electrons during the same period, Kp index evolution.

Space Safety Service (WP4 - ONERA, TAS-E, CNRS, SPARC, NKUA, IAP, IASB)

Service/products definition

The objective of the Space Safety prototype service is to provide products and parameters which would match the users' requirements in terms of: exploitability of the data; correlation of the prototype service output with satellite malfunctions; quantification of the environment; time lining of the events.

This task assesses the variety of uses and needs for satellites and global navigation satellite systems. The uses and needs for space weather information are assessed across two user groups with distinct requirements for space weather products: engineers and operators. The main difference is in the degree of detailed provided to the final user. In some cases it is required all the available information. In contrast, other cases could request a simplification or partial information.

We have contacted different operators: TASinF, Galileo, SES, Hisdesat, DLR and OHB and held feedback from TASinF, Galileo, SES and Hisdesat, concerning satellite drag, solar panel degradation, internal and surface charging, and SEE.

Since Space weather requirements and investigations of environment conditions are of great interest to the space industry we are in close contact with them to recognize the needs and acknowledge the spacecraft specific requirements in terms of radiation and other space weather conditions.

Here are some key SafeSpace features, which could be useful for satellite systems:

- *The possibility for the user to define their thresholds inside a model or a warning system, such as respect the proton hazards, define a lower threshold related with the increased sensor noise - flux and an upper one related with a solar array degradation – 24 hour influence.*
- *Knowledge of the time the environment will be safe again.*
- *A warning system with three threshold level as predefined. In addition, several thresholds that can be enabled/disabled individually.*
- *Development of different systems of alarms depending on the used system or program. Also, it can be considered a distinction per user or frequency.*
- *Possible separate indicators per orbit.*

The team is in contact with the industry, and takes consideration of all their comments so the end product will be an optimal and accurate application for most satellite system needs.

Exploitation, dissemination, and communication (WP6 - NKUA, ONERA, KU LEUVEN, IAP, BIRA-IASB, TAS-E, CNRS, SPARC)

The Work Package (WP) 6 of SafeSpace is devoted to the exploitation and the dissemination of results to the scientific community, the space industry and spacecraft operators, and furthermore the deployment of a range of communication tools, techniques and activities appropriate for different public audiences. Developments over the past months are described hereafter.

Exploitation, dissemination & communication plan

The exploitation, dissemination and communication team has worked an outreach activities plan harmonized with the pandemic conditions.

Web presence

As always, you may find this newsletter along with several information regarding project details, description, goals, participants, news and additional useful facts on our user-friendly SafeSpace website, which is regularly updated with new information

Scientific dissemination of results

SafeSpace refereed publications and presentations in international conferences are provided on the [project website.]

Publications

2021 — Astronomy & Astrophysics

Implementing the MULTI-VP coronal model in EUHFORIA: Test case results and comparisons with the WSA coronal model

E. Samara, R. F. Pinto, J. Magdalenić, N. Wijsen, V. Jerčić, C. Scolini, I. C. Jebaraj, L. Rodriguez and S. Poedts (2021). Implementing the MULTI-VP coronal model in EUHFORIA: Test case results and comparisons with the WSA coronal model, A&A, 648, A35. https://doi.org/10.1051/0004-6361/202039325

2020 — JGR Space Physics

Electron Dropout Events and Flux Enhancements Associated With Geomagnetic Storms Observed by PROBA-V/Energetic Particle Telescope From 2013 to 2019

Pierrard, V., Botek, E., Ripoll, J.-F., & Cunningham, G. (2020). Electron dropout events and flux enhancements associated with geomagnetic storms observed by PROBA-V/Energetic Particle Telescope from 2013 to 2019. *Journal of Geophysical Research: Space Physics*, 125, e2020JA028487. https://doi.org/10.1029/2020JA028487

Presentations

2021 — LASP

Understanding and Forecasting the Sun-to-belts Connection

Ioannis A. Daglis, LASP Seminars, University of Colorado, May 6, 2021.

EGU General Assembly 2021

Improving nowcasting and forecasting of the Sun-to-Belts space weather chain through the H2020 SafeSpace project

Daglis, I. A., Bourdarie, S., Cueto Rodriguez, J., Darrouzet, F., Lavraud, B., Poedts, S., Sandberg, I., and Santolik, O. and the SafeSpace Team: Improving nowcasting and forecasting of the Sun-to-Belts space weather chain through the H2020 SafeSpace project, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-13466, https://doi.org/10.5194/egusphere-egu21-13466, 2021.

Perspective paper published in special issue by Frontiers on cold plasma population: Pierrard V., Botek E. and Darrouzet F. (2021), Improving Predictions of the 3D Dynamic Model of the Plasmasphere, Front. Astron. Space Sci., 8:681401, doi:10.3389/fspas.2021.681401.

Organisation of dedicated splinter sessions and of a targeted workshop.

With COVID-19 pandemic restrictions being partially lifted up, the SafeSpace consortium decided to meet in-person for the first time since the kick off meeting 18 months ago, again next month, observing all necessary safety measures. The meeting will be held in Milos Island Greece, 19-20 July in "Georgios Eliopoulos" Conference Center.

Right after that, a targeted workshop titled "Sun to Belts Workshop: nowcasting, forecasting, hindcasting" with more extended audience will take place 21-23 July 2021, at the same venue.

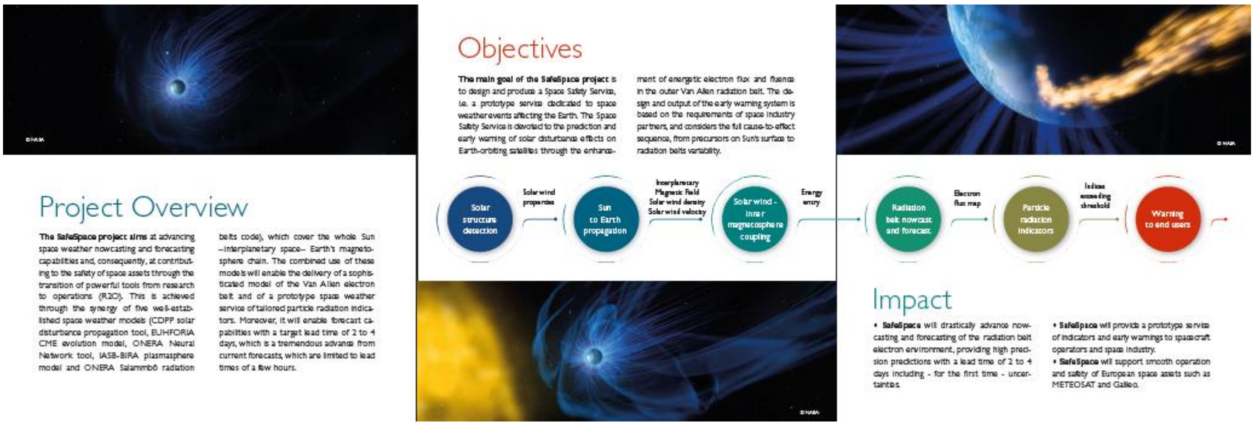
Public engagement

While most of dissemination and exploitation actions (website, newsletter etc.) are moderately affected, Communication and outreach are strongly affected by the pandemic.

The "Open Science" program of the Czech Academy of Sciences aiming at high-school students interested in science or in a series of public lectures "Science to go" and "Don't be scared by science" aiming mainly at small towns in Czechia was severely affected.

These face-to-face activities were not allowed in 2020 and 2021. Nevertheless, the team participated in online events organized by the Academy of Sciences: a) in the frame of the project "Science at home" we recorded videos for kids and students, and b) in the frame of the project "Invite a scientist to your online classroom" we gave numerous online talks for kids (10-15 years). We plan to return to the face-to-face public talks whenever it is possible.

SafeSpace Electronic Newsletter past issues and the SafeSpace Leaflet are available on the project's website. Everyone who would like to receive our semi-annual newsletter is able to subscribe at any time.



Project Overview

The SafeSpace project aims at advancing space weather nowcasting and forecasting capabilities and, consequently, at contributing to the safety of space assets through the transition of powerful tools from research to operations (R2O). This is achieved through the synergy of five well-established space weather models (CDPP solar disturbance propagation tool, EUHFORIA CME evolution model, ONERA Neural Network tool, IASB-BIRA plasmasphere model and ONERA Salammbô radiation belts code), which cover the whole Sun –interplanetary space– Earth's magnetosphere chain. The combined use of these models will enable the delivery of a sophisticated model of the Van Allen electron belt and of a prototype space weather service of tailored particle radiation indicators. Moreover, it will enable forecast capabilities with a target lead time of 2 to 4 days, which is a tremendous advance from current forecasts, which are limited to lead times of a few hours.

Objectives

The main goal of the SafeSpace project is to design and produce a Space Safety Service, i.e. a prototype service dedicated to space weather events affecting the Earth. 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. The design and output of the early warning system 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 belts variability.

Impact

- **SafeSpace** will drastically advance nowcasting and forecasting of the radiation belt electron environment, providing high precision predictions with a lead time of 2 to 4 days including - for the first time - uncertainties.
- **SafeSpace** will provide a prototype service of indicators and early warnings to spacecraft operators and space industry.
- **SafeSpace** will support smooth operation and safety of European space assets such as METEOSAT and Galileo.

Newsletters

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SUBMIT

Project Leaflet

SAFESPACE

"Radiation Belt Environmental Indicators for the Safety of Space Assets"

This project has recieved funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 870437.

European Commission

Horizon 2020 European Union Funding for Research & Innovation

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