Radiation Belt Environmental Indicators for the Safety of Space Assets

SafeSpace Newsletter

Issue 4, Months 19-24

Dear Reader,

The fourth semester of the SafeSpace project has been very productive.

"SafeSpace: Radiation Belt Environmental Indicators for the Safety of Space Assets" is a EU-funded research project launched two years ago, in January 2020, aiming 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). The program is a 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 variety of the partners ensure the efficient and optimized transfer from science to application.

Although working in pandemic conditions for, already 24 months, all our tasks run as scheduled, reaching programmed milestones and corresponding deliverables, and we are proud to share with you our latest progress in all the Work Packages (WPs).

Project Progress and Outcomes

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

The main tasks of this Work Package, which consist of the building, testing and validating the modelling pipeline prototype are now coming to an end. All interfaces have been defined and permit to propagate and forecast solar perturbations all the way from the solar surface to near Earth. All components of the pipeline are now essentially operational. The outcomes from the latest activities are reported below.

Running Helio1D: the combined Multi-VP - 1D MHD modelling pipeline

This task has reached its main milestone with the completion of the propagation pipeline of interplanetary disturbances, forecasting Corotating Interaction Regions (CIRs) properties and arrival near Earth. The automated "Helio1D" pipeline couples the Multi-VP and the 1D MHD models together. We have benchmarked the pipeline using several years of data from Multi-VP covering the solar cycles 23 and 24. The long time-series outputs produce large-scale variations (i.e., on the order of a few months up to a year) that are similar to the observations, indicating the correct physical properties of the background solar wind comprising CIRs. Using the advance technique called Fast Dynamic Time Warping, we continuously map features of CIRs in the predicted time series to the observations. This allows us to calibrate the Helio1D outputs and improve the quality of the predicted solar wind. As previously reported (e.g., in the newsletter #2), the initial 1D MHD model suffers from an over-compression effect. We have now performed a post-calibration, which alleviates the strong compression at the CIRs. Finally, we have implemented an ensemble forecasting into the pipeline using 21 points over a regular grid centred on the sub-Earth point with a maximum of 15 degrees offset in both longitude and latitude. An example forecast output is shown in Figure 1 for data from March to April, 2018. We also compare the quality of the prediction of the background solar wind using the EUHFORIA model using the same input data. The Helio1D outputs have now been delivered for use in task "Forecasting solar wind energy input to the magnetosphere" (page 5), where the geomagnetic indices are predicted using the neural network model.

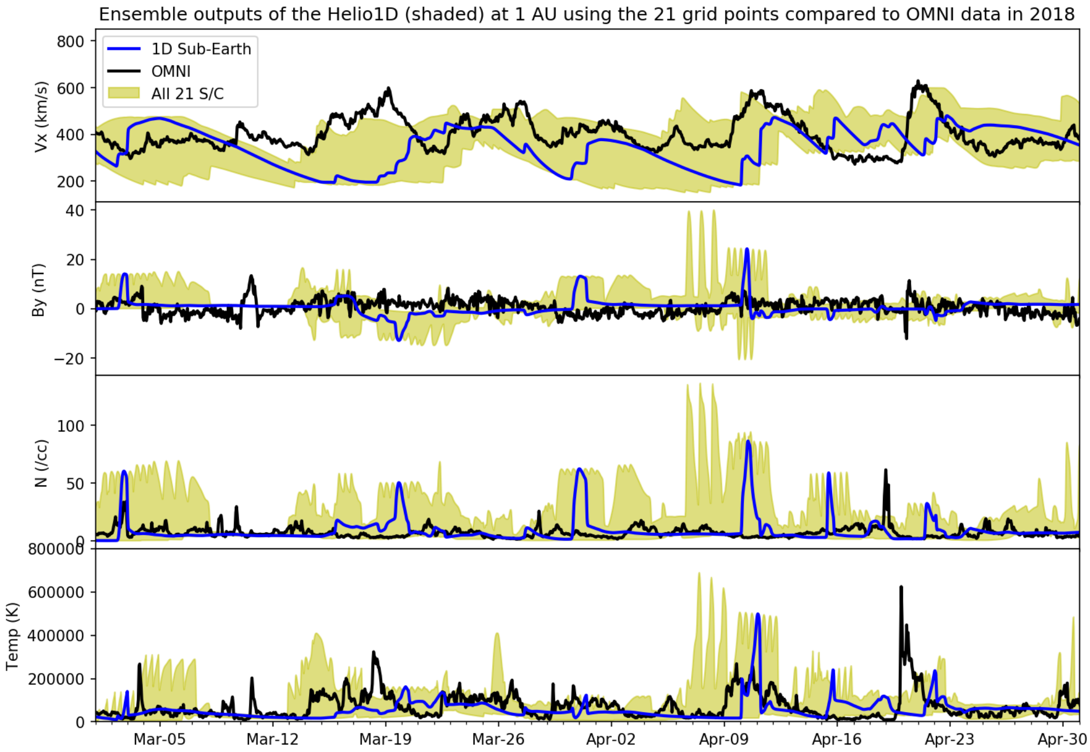


Figure 1. *Helio1D ensemble time series outputs using the 21 virtual spacecraft compared to the OMNI data for March to April, 2018 for solar wind bulk velocity (Vx), tangential magnetic field (By), ion number density (N), and ion bulk temperature (T), respectively. The ensemble Helio1D outputs are shaded in green and the output at the sub-Earth point is shown in blue. The OMNI data is in black.*

Multi-VP - EUHFORIA comparison to Helio1D and CME modelling

During the past six months, our work with regards to this chapter has focused on two final tasks. The first task consisted in the comparison of the newly coupled Multi-VP + EUHFORIA modelling pipeline with OMNI observations and with the 1D MHD (HELIO1D) predictions, using WSO magnetograms. The time interval of interest was the first semester of 2018. For a proper evaluation of the model's performance, we used both traditional metrics and skill scores (based on error functions such as the mean square error, root mean square error, etc.), but also the newly implemented Dynamic Time Warping (DTW) technique. Results show that, while the Multi-VP + EUHFORIA pipeline is well in place and robust, for this interval it is not very successful in reproducing the observations, showing a need for future improvements in terms of magnetogram selection as inputs, physics modelling enhancements, further calibrations, etc. Such work will be continued as SafeSpace proceeds.

The second task concerns the finalization of the coronal mass ejection (CME) ensemble study and error quantification. After the selection of a geo-effective CME event that influenced Earth in July 2012, we performed a study of 729 ensemble members by perturbing six out of ten input CME parameters (velocity, magnetic flux, temperature, density, tilt angle, CME radius) of the spheromak model based on a reasonable error input. Our main results are summarized as follows:

- *The time of the shock arrival is very sensitive to the initial speed and temperature.*
- *The overall prediction of the CME speed strongly depends on the initial density. The higher the input density, the higher the momentum of the structure.*
- *The overall performance of the total magnetic field strength and Bz component predictions are mainly affected by the input density, a fact that needs to be further investigated. The input flux also significantly affects the total magnetic field.*

Results concerning the variability of the forecast as a function of input parameters for the first twelve runs out of 729 are presented in Figure 2 for illustration. The graphs provide a good idea of the variability that occurs when we perturb only a single parameter at a time. The red colour corresponds to the default EUHFORIA run for which we used the best observationally constrained speromak parameters based on Scolini et al., 2019. Green and orange colours show what happens if we only perturb the input CME density by increasing it 5 and 17.5 times compared to the default value. Magenta and grey show the perturbation of the input magnetic flux when considering a value which is 50% and 25% less than the default one. The same for the CME radius, velocity and tilt angle which we perturbed by taking an error of 1.61 Rs, 200 km/s and 20 deg, respectively (light green, brown, blue-grey, pink, blue and cornflower-blue colours). Finally, we also perturbed the input temperature by assuming a value which is 5 times larger (lime) and 5 times smaller (light-blue) than the default value, respectively.

We further conducted a CME ensemble study by simulating the July 2012 CME with its default input properties, but further placing 21 virtual spacecraft on a regular grid (as for the Helio1D outputs previously discussed) around the sub-Earth point. This allows us to quantify errors on the directionality of the CME structure upon its arrival at Earth.

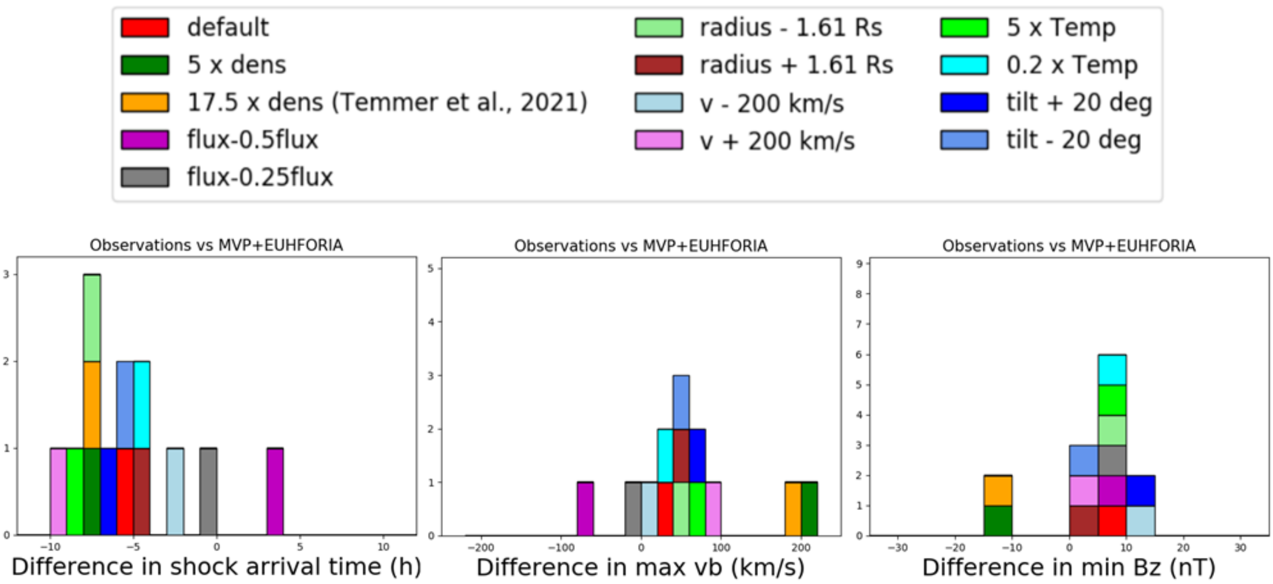


Figure 2. *Difference in shock arrival time (left panel), difference in maximum velocity (middle panel), and difference in minimum Bz value (right panel) between the modelled data and observations for the first twelve EUHFORIA ensemble runs. The y-axis shows the number of runs that corresponds to each x-value. For the description of colors, please see main text.*

Forecasting solar wind energy input to the magnetosphere

This task aims to provide deep-learning models for the geomagnetic indices required in the next work package by the magnetospheric 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.

The models, based on recurrent neural network architecture, are trained to reproduce the Kp dynamics from the solar wind parameters forecasted by heliophysics models. Three different models were trained, with various input magnetic field parameters (Bz, Btotal and By). By comparing the precision of the different models on in-situ solar wind measurements, we have shown that the three models have significant skill to reproduce Kp, compared to a climatological baseline. However, the model driven by the Bz magnetic field component significantly outperforms all other models, and in particular during CME events where the performance of the other models drops.

For the propagation of the solar wind and CIR forecasting, the models driven by the total magnetic field and the By component were found to give appropriate Kp restitution, given the large uncertainties in the solar wind conditions near Earth. For the propagation of CMEs and the forecast of their impact on Earth, the Bz-driven model is certainly required, as the other models have shown poor performance. We have shown overall good ensemble estimations of Kp using 21 virtual spacecraft positions and the standard spheromak configuration on a sample CME event (Figure 3). Although the model does not reproduce accurately the recovery phase of the storm, the forecasted peak intensity distribution is relatively narrow around the observed value. We believe this ensemble forecast would be appropriate for driving the geomagnetic models in the next WP.

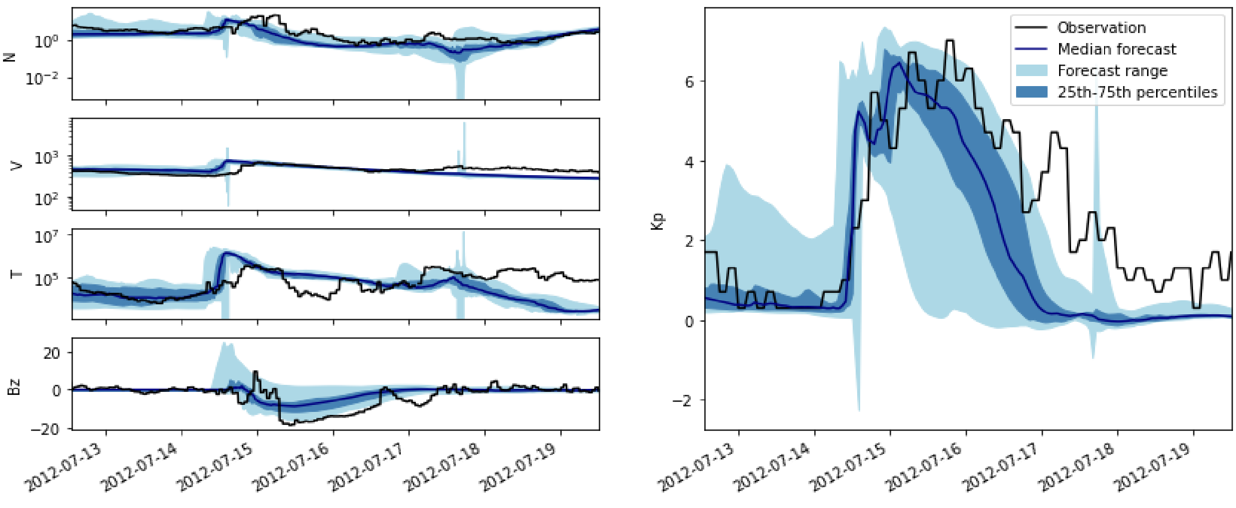


Figure 3. *EUHFORIA solar wind parameters forecast during the July 2012 CME event (left), and corresponding Kp index prediction (right).*

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

The Work Package 3 of SafeSpace has progressed in building connections between different components of an inner magnetospheric model. With well-defined interfaces between these components we were able to prepare links between physical and empirical models of different aspects influencing the inner magnetospheric dynamics. These models also rely on well-defined interfaces to the solar wind models, providing us with inputs, which describe a time varying external forcing. In preparation for the processing pipeline we set up a computational chain based on servers in Athens, Toulouse and Prague. This chain now runs in a test regime. Its components are described below.

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 improvements of the plasmaspheric model have been achieved, with in particular a new set of equations for the plasmatrough density (before, equations from Carpenter and Anderson [1992] were used). 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.

This new version of the model has been implemented on this website: https://safespace.ufa.cas.cz. The implementation and maintenance of the model in the processing chain and its interfacing through a dedicated website is under the responsibility of the IAP (Institute of Atmospheric Physics) team. The website is run within the IAP node of the SafeSpace processing chain, as a part of the webpage of the SafeSpace WP3 – Internal magnetospheric dynamics. This achievement is the deliverable D3.1 - Plasma density model on a dedicated website - 31 October 2021 - IAP.

Note that a paper explaining in details those improvements has been recently published in JGR - Space Physics: Botek, E., Pierrard, V., and Darrouzet, F. (2021). Assessment of the Earth's cold plasmatrough modeling by using Van Allen Probes/EMFISIS and Arase/PWE electron density data. Journal of Geophysical Research: Space Physics, 126, e2021JA029737. https://doi.org/10.1029/2021JA029737.

Figure 4: *Example of dynamically changing results of regular daily runs of the density model using a NOAA three-day magnetic activity forecast with a single ensemble on https://safespace.ufa.cas.cz/density_model/.*

Radial diffusion coefficients database and model

The goal of this task is to build a prototype of an operational model of diffusion coefficients (mean, median and percentiles values to address uncertainties in radiation belt dynamics) as a function of solar wind parameters.

To that end, a radial diffusion coefficients (D_{LL}) database has been built using magnetic and electric field measurements from THEMIS A, D and E satellites spanning a 9 year time period (2011–2019) during Solar cycle 24 (figure 5 illustrates the work logic for the creation of the database). All the scientific products (power spectral density of the Pc4-5 waves and the radial diffusion coefficients) are publicly available on the servers of the National and Kapodistrian University of Athens at https://synergasia.uoa.gr/modules/document/?course=PHYS120.

Note that a paper explaining in details those improvements has been recently submitted in Annales Geophysicae: Katsavrias et al. (2021), The "SafeSpace" Radial Diffusion Coefficients Database: Dependencies and application to simulations, Annales Geophisicae, https://doi.org/10.5194/angeo-2021-56

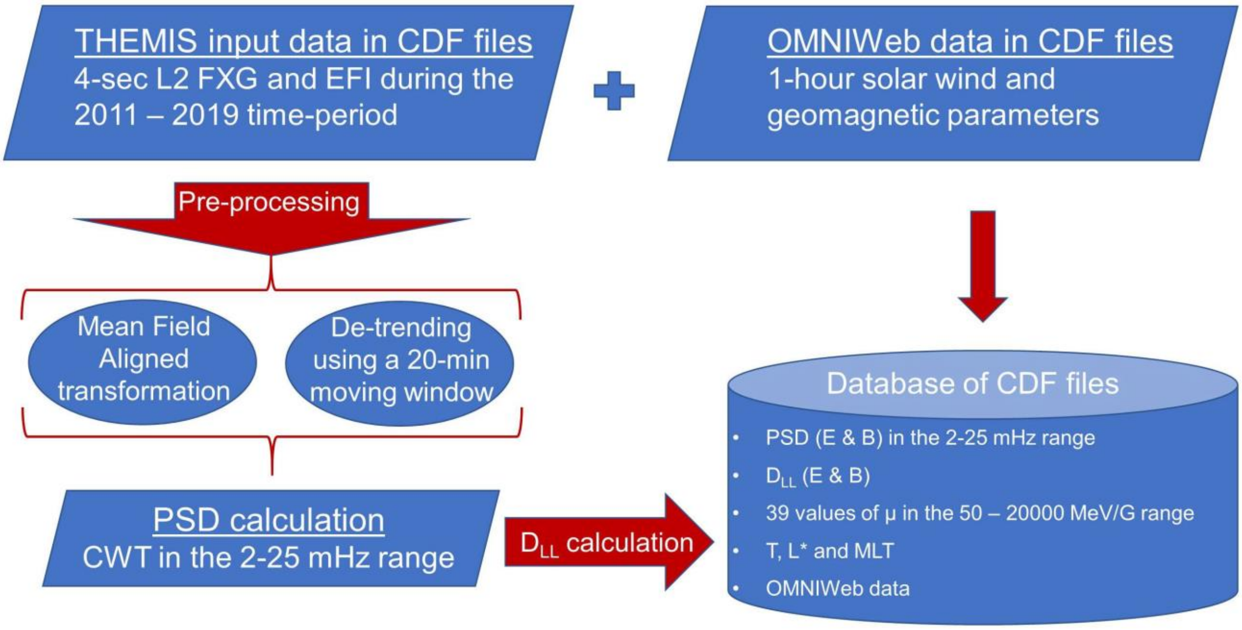


Figure 5: *Work logic towards the creation of the SafeSpace radial diffusion coefficients database.*

The aforementioned database has been used to build a machine learning based model for the prediction of the radial diffusion coefficients in the 3 – 7 L range. The model uses solely solar wind parameters (Vsw, Psw and IMF) and can predict separately the magnetic and electric component of the D_{LL} as well as the total D_{LL}. As shown in figure 6 the model can successfully predict the radial diffusion coefficients with higher scores compared to the existing semi-empirical models used in radiation belt simulations.*

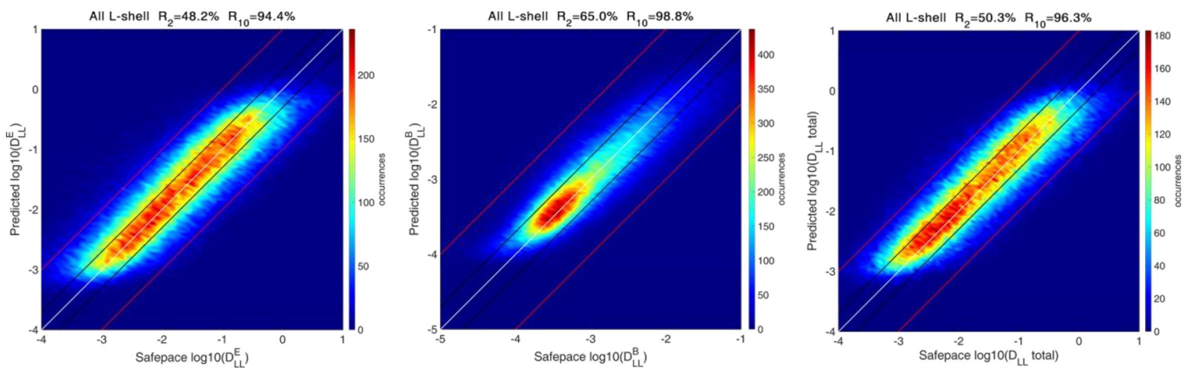


Figure 6: *Cross-plots of the predicted over the calculated D^E_{LL} (left), D^B_{LL} (middle) and total D_{LL} (right). The R2 and R10 metrics correspond to the percentage of points that fall into a factor of 2 and 10, respectively.*

Electron radiation flux map

The goal of this task is to compute the wave-particle interaction diffusion coefficients according to the time dependent plasma densities and wave properties deduced in "Cold plasma density map". Next, all *the new diffusion coefficients defined is the previous two sub-work packages are implemented into the Salammbô code to improve the energetic electron dynamics in the Earth radiation belts.*

Currently, the impact of the newly radial diffusion coefficients computed in "Radial diffusion coefficients database and model" have been investigated during past magnetic storms. It turns out an improvement of the electron dynamics in the few hundreds keV energy range. The wave-particle interaction (WAPI) code has been improved to make it a lot faster. Because the goal now is to recalculate the full matrix of coefficients every hours to account for plasma densities change in response to magnetic activity it has to be faster than real time. A new strategy to compute the coefficients has been set up where the calculations are now about a hundred times faster than it was before the project. Finally, the CPU time required by the Salammbô code to solve the diffusion equation has been largely improved. An acceleration factor of about 10 has been reached.

All these improvements, allows us to use this radiation belt model to produce real time nowcast and forecast of electron radiation belts.

Data assimilation

To improve the radiation belt nowcast, a data assimilation code is being used. It consists of in an ensemble Kalman filter, where 200 Salammbô codes are ran in parallel and are corrected with in-situ data. First of all, the Salammbô data assimilation tool has been implemented as a module of the PDAF library (Parallel Data Assimilation Framework). It has several advantages, first the overall tool is very modular, next, any change in the Salammbô code (from WP3.3) is straightforward to include and finally different Kalman filters can be tested.

Currently, this code is under testing phase on HPC to evaluate the performances and double check its ability to provide nowcast and forecast of the radiation belts faster than real type. This tool will be implemented in the Safe Space prototype to deduce further radiation belt activity indices.

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

This work package is devoted to the definition and to the settings of the SafeSpace services. It will focus on energetic electron radiation belts, which potentially leads to internal spacecraft charging events. In a first step, user needs are expressed by one major European space industry, Thales Alenia Space. Next any data produced throughout the project are traced and the data management plan collect all the corresponding details. A third sub-work package is devoted to the chaining of all the tools involved in the prototyping activity (from the outputs of WP2 to the energetic electron phase space density production). Then, radiation belt activity indices will be derived and will be made available to any end-user on a dedicated website. Finally, from those results, support web pages will be dedicated to the Galileo constellation, which is located in the heart of the electron belt.

Service/products definition

Service product definition has been investigated among several potential end-users. All requirements (even beyond the scope of SafeSpace) are collected in a table where required parameters are linked to expected impact on space systems.

Data management plan (DMP)

All the data produced along the project are captured and described in a Data Management Plan (DMP) following the FAIR (Findable, Accessible, Interoperable, Reusable) philosophy. To implement the DMP, the freely OPIDOR web tool has been used as a guide. [OPIDOR stands for Optimiser le Partage et l'Interopérabilité des Données de la Recherche (Optimising the sharing and interoperability of data from reseach activities) and is a web tool developed by French CNRS]. All partners could then describe their data on a common base. A first release of the DMP was done in July 2020 and an updated one was made available in October 2021.

Prototyping radiation belt nowcast and forecast

This task is devoted to chaining the radiation belt data assimilation tool with the outputs from WP2. It is currently in progress. First in-situ data retrieval has been set up. Two partners are providing input data to this WP. The data are made available on a dedicated web site and new data file are added in the database on a daily bases. Then in-situ data are pre-processed and are stored all together in a single daily file that can be ingested straightaway by the data assimilation tool.

Radiation belt activity indices and warnings

Because the electron fluxes can be somewhat different from location to location, long term databases have been used to investigates on daily energetic electron flux values at GEO and MEO (navigation orbits). This analysis will be extended to LEO orbit as well in the next weeks. Clearly, one single activity index cannot cover accurately all orbits and dedicated ones have to be set. From statistical analysis, it is then possible to define thresholds above which it is possible to raise an alarm. It has been decided to define three level of risk, "quiet", "moderate" and "active" where "active" level should be raised no more than 2% of time and "moderate" level no more than 20%. A mockup for the web site where the activity indices will be made available very soon. Iterations between service provision actors and end-users are expected before the end of the project.

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

This Work Package is devoted to the exploitation and 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. The Detailed plan for the exploitation, dissemination and communication of project activities and results is constantly adapting to the pandemic conditions in order for the project to receive maximum outside exposure through several channels and activities. The past six months activities are described hereafter.*

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

The past six months have been very productive publication-wise. SafeSpace refereed publications are provided on the [project website.]() Oral and poster presentations presented in international conferences during the last 6 months may be found on the website as well.

The SafeSpace team has disseminated the Project results in scientific publications, as well as through presentations in Conferences and Workshops. Since the start of the Programme, there have been 9 publications in open access scientific journals, and 36 oral and poster presentations in Conferences, Seminars and Workshops worldwide. You can view all available material below.

Scientific Publications

2022 — Space Weather

Radiation Belt Model Including Semi-Annual Variation and Solar Driving (Sentinel)

Christos Katsavrias, Sigiava Aminalragia-Giamini, Constantinos Papadimitriou, Ioannis A. Daglis, Ingmar Sandberg and Piers Jiggens (2022). Radiation Belt Model Including Semi-Annual Variation and Solar Driving (Sentinel). *Space Weather*, 20, e2021SW002936.
https://doi.org/10.1029/2021SW002936 – View Published PDF

2021 — Space Weather

Harmonization of RBSP and ARASE energetic electron measurements utilizing ESA radiation monitor data

Ingmar Sandberg, Piers Jiggens, Hugh D. Evans, Constantinos Papadimitriou, Sigiava Aminalragia-Giamini, Christos Katsavrias, Alexander J. Boyd, Thomas Paul O'Brien, Nana Higashio, Takefumi Mitani, Iku Shinohara, Yoshizumi Miyoshi, Daniel N. Baker and Ioannis A. Daglis (2021). Harmonization of RBSP and Arase energetic electron measurements utilizing ESA radiation monitor data. *Space Weather*, 19, e2020SW002692.
https://doi.org/10.1029/2020SW002692 – View Published PDF

JGR Space Physics

Assessment of the Earth's Cold Plasmatrough Modeling by Using Van Allen Probes/EMFISIS and Arase/PWE Electron Density Data

Botek, E., Pierrard, V., & Darrouzet, F. (2021). Assessment of the Earth's cold plasmatrough modeling by using Van Allen Probes/EMFISIS and Arase/PWE electron density data. *Journal of Geophysical Research: Space Physics*, 126, e2021JA029737.
https://orfeo.belnet.be/handle/internal/9675 – View PDF

JGR Space Physics

Observations and simulations of dropout events and flux decays in October 2013: Comparing MEO equatorial with LEO polar orbit

Pierrard, V., Ripoll, J.-F., Cunningham, G., Botek, E., Santolik, O., Thaller, S., et al. (2021). Observations and simulations of dropout events and flux decays in October 2013: Comparing MEO equatorial with LEO polar orbit. *Journal of Geophysical Research: Space Physics*, 126, e2020JA028850.
https://doi.org/10.1029/2020JA028850 – View Published PDF

frontiers in Astronomy and Space Sciences

Improving Predictions of the 3D Dynamic Model of the Plasmasphere

Pierrard V., Botek E. and Darrouzet F. (2021). Improving Predictions of the 3D Dynamic Model of the

Organization of dedicated splinter sessions and of a targeted workshop.

With COVID-19 pandemic restrictions being partially lifted up during summer time, the SafeSpace consortium decided to meet in-person for the first time since the kick off meeting which took place in the very beginning of the project, again after 18 months, observing all necessary safety measures. The meeting was held in Milos Island Greece, 19-20 July 2021 in "Georgios Eliopoulos" Conference Center.

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

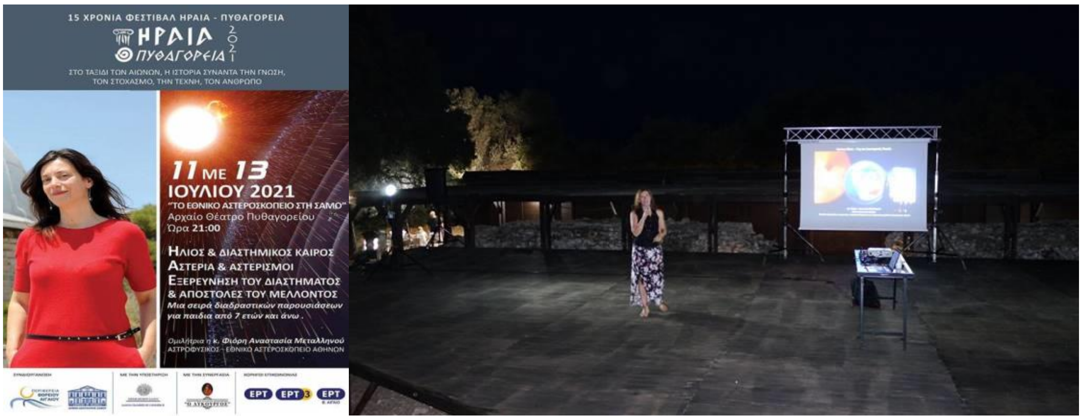
The group photo of all the participants in the SafeSpace: Sun to Belts Workshop, 21-23 July 2021, Milos, Greece

Public engagement

The team has been gently recovering from the Covid-19 pandemic reduced face to face activities, and is slowly adapting to the new border conditions imposed by the pandemic.

Three face-to-face public outreach activities were organized during the past semester, one in Milos Island on 23rd of July, and two in Samos Island (11th of July, 17th of August). All public outreach talks were given outdoors to ensure maximum safety for the speakers and participants amidst covid-19 pandemic.

- *The first public Talk, titled **"Space Weather"** was given by Fiori – Anastasia Metallinou at the Ancient Theatre of Pythagorio, Samos, on July the 11th.*



- *The second public talk **"Sounds of Space"** was addressed to adults and children and was given by both Prof. Ioannis Daglis, Professor of Space Physics at National and Kapodistrian University of Athens, SafeSpace Project Coordinator, and Dr. Fiori – Anastasia Metallinou on July the 23rd in the courtyard of the Ecclesiastical Museum of Milos, in the center of Adamas, in Milos Island, Greece.*

- *The third talk, with the title* ***"Space Sonatas"*** *was given by Prof. Ioannis Daglis, Professor of Space Physics at National and Kapodistrian University of Athens, SafeSpace Project Coordinator, on August the 17th. The talk was given during the Iraia-Pythagoria Festival, at the Town Hall Square of Samos island, Greece.*

  Samos island is the birth place of Pythagoras, a greek philosopher, mathematician, and founder of the Pythagorean brotherhood that, although religious in nature, formulated principles that influenced the thought of Plato and Aristotle and contributed to the development of mathematics and Western rational philosophy.


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

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SUBMIT

Project Leaflet

SAFESPACE

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

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COORDINATION

National and Kapodistrian University of Athens – NKUA

Prof. Dr. Ioannis A. Daglis,
Department of Physics,
Panepistimiopoli Zografou,
15784, Athens, Greece

HELLENIC REPUBLIC
National and Kapodistrian University of Athens
EST. 1837

PARTNERS

NKUA (Greece)
ONERA (France)
KULeuven (Belgium)
IAP (Czechia)
IASB (Belgium)
TAS-E (Spain)
CNRS (France)
SPARC (Greece)

SafeSpace

CONTACT & SOCIAL MEDIA

SafeSpace

SafeSpace

safespacecoordination@gmail.com
iadaglis@phys.uoa.gr
emitsaku@phys.uoa.gr