Radiation Belt Environmental Indicators for the Safety of Space Assets

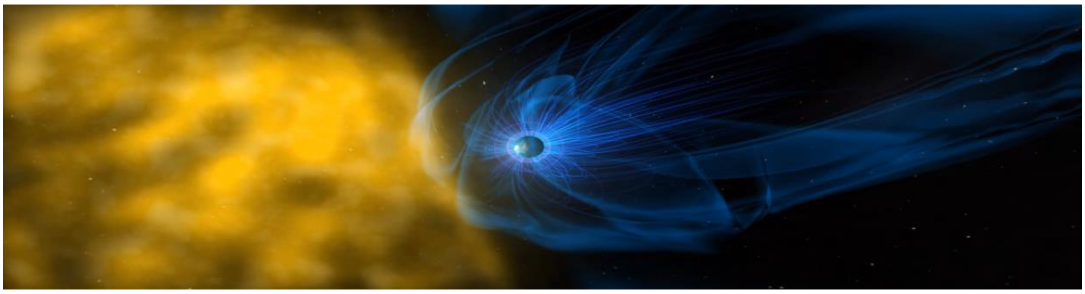
SafeSpace Newsletter

Issue 2, Months 7-12

Dear Reader,

With the following Newsletter we are happy to inform you about the second half-year period (months 7-12) 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.

Because of the Covid-19 pandemic, the SafeSpace Consortium has been working mostly remotely. Teleconference meetings have been 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.



Project Progress and Outcomes

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

The task of WP2, which is to construct a pipeline that permits to propagate and thus forecast potentially harmful solar wind perturbations all the way from the solar surface to near Earth, is now well underway. We have continued to work on several active solar periods to develop and test the forecasting pipeline. The output from this task consists in ensembling a time series (with error estimates) used for radiation belts modelling. The main recent developments are described hereafter.

Tuning the solar wind formation model (MULTI-VP)

This past semester we have focused on improving the solar wind acceleration model MULTI-VP, the first of SafeSpace's Sun – interplanetary space – Earth's magnetosphere chain of models. The goal is to build a system capable of delivering daily forecasts on the Earth-bound nascent solar wind flows from the surface of the Sun up to the high solar corona. These flows constitute the seeds of corotating interaction regions (CIRs) that develop above, in the interplanetary medium, and determine the conditions through which coronal mass ejections (CMEs) and shocks propagate. We set ourselves up to two tasks: making our pipeline smarter, more modular, and more resilient to, e.g., gaps in the observed data that we use as input, and to calibrate the model with respect to solar wind data measured in-situ by space probes. Direct calibration of the outputs at these intermediate altitudes is a complex affair due to the rarity of direct 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 with WPs 2.2 and 2.3 that let us define the optimal sets of input magnetogram data and refine some physical parameters of MULTI-VP.

Finally, we set up the data interfaces that feed MULTI-VP forecast data into the next layer of models in SafeSpace (heliospheric propagation models HELIO1D and EUHFORIA).

CIR propagation to Earth using one-dimensional MHD modelling

The 1-D magnetohydrodynamic (MHD) modelling propagates the solar wind predictions at 0.14 Astronomical Unit (AU) from the MULTI-VP model to upstream of the Earth at 1 AU. In the past 6 months, we have continued to test and validate this MULTI-VP – 1-D MHD pipeline to ensure the quality of the solar wind stream which will be input to other downstream space weather models such as the neural network forecasting of the geomagnetic indices (WP2.4). We have employed an ensemble forecasting for the pipeline such that the forecast is performed for multiple targets around the Earth (L1 point) that permit to produce spatial and temporal uncertainties (see Figure 1). We have also measured the performance of the MULTI-VP – 1-D MHD pipeline by comparing with observations. This was done using the Dynamic Time Warping (DTW) algorithm - a technique to measure similarities of two time-series via an optimal alignment (commonly used for speech recognition). Finally, we also identified limitations of the 1-D MHD model which at times results in unrealistically extreme solar wind parameters. We identified ways to better calibrate the pipeline and to provide errors from the model in the near future.

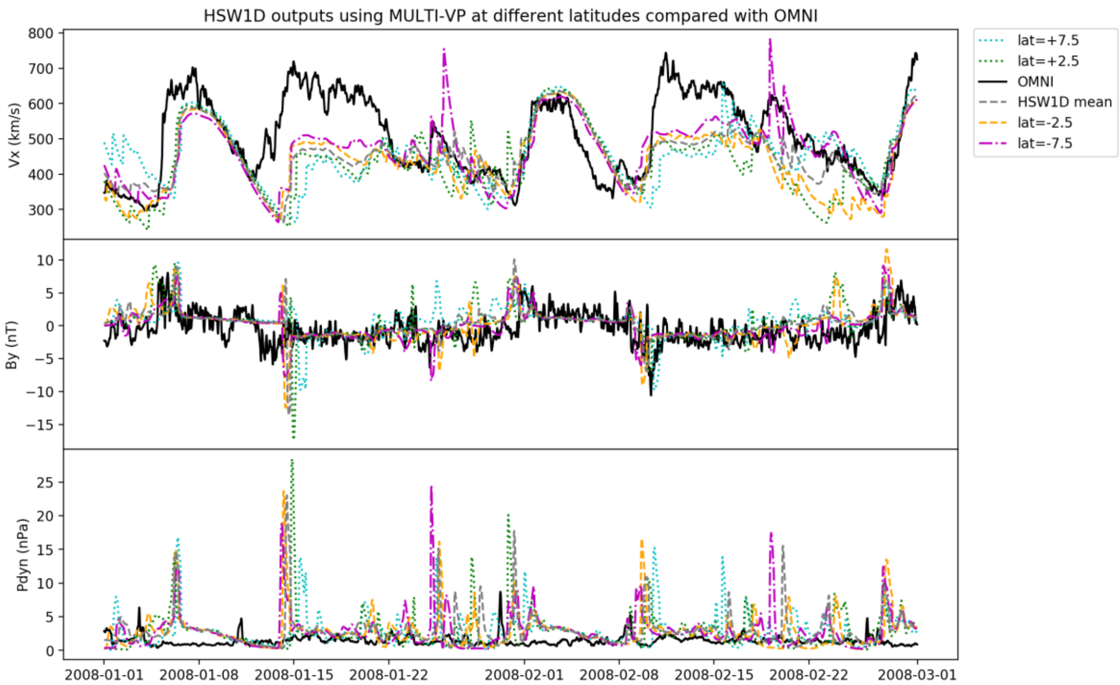


Figure 1. Example of the ensemble forecasting from the 1-D MHD model using inputs from the MULTI-VP time series at multiple targets around the Earth. The model outputs are shown in colors with labels for different latitudes above (+2.5°, +7.5°) and below (-2.5°, -7.5°) the Earth point (average in grey). The OMNI data at L1 are in black. One can see that the solar wind velocity (first panel) from the 1-D MHD model at certain latitudes, e.g., at -7.5° near 2008-02-22, is closer to the observed values than the others. A few unrealistic solar wind parameters, e.g., in the dynamic pressure (third panel), are also seen. We identified ways to correct and improve the modelling for that purpose in the near future.

Implementing the Multi-VP model in EUHFORIA: coupling and validation of the new set-up

This task's recent developments focused on optimizing the coupling between the Multi-VP coronal model (Pinto and Rouillard, Astrophysical Journal 2017) and EUHFORIA (Pomoell and Poedts, Journal of Space Weather and Space Climate 2018). Multi-VP provides the full set of physical quantities required by EUHFORIA as boundary conditions to its heliospheric domain. Nevertheless, the interfacing procedure needs to undergo an intermediate verification step to confirm the validity of the inputs and specifically to ensure that the wind is super-critical everywhere at the interface between the two models. For that purpose, flows were adjusted, where needed, by interpolation through their closest, super-critical neighbours and by conserving the mass-flux.

After the Multi-VP boundary data are properly adjusted at 0.1 AU, they are inserted into the heliospheric part of EUHFORIA and the forecast begins. In the upper panel of Figure 2 we present the 8-day solar wind forecast at Earth for a high-speed stream (HSS) on 2011-06-22. Blue time series represent the modelling output obtained by the newly coupled Multi-VP+EUHFORIA while black data correspond to observations from the WIND satellite. For comparison, we also plot the modelling output as given by the default EUHFORIA set-up (Wang-Sheeley-Arge coronal model+EUHFORIA) in the same figure. For this HSS test case, Multi-VP+EUHFORIA reproduced realistically the observed HSS, opposite to the default set-up. The bottom part of Figure 2 shows the radial solar wind velocities in the three-dimensional (3D) space. The fast solar wind structure that reached Earth is here visualized using color isosurfaces impacting the planet (shown as a small, light-blue sphere) with a range of velocities between 490-600 km/s.

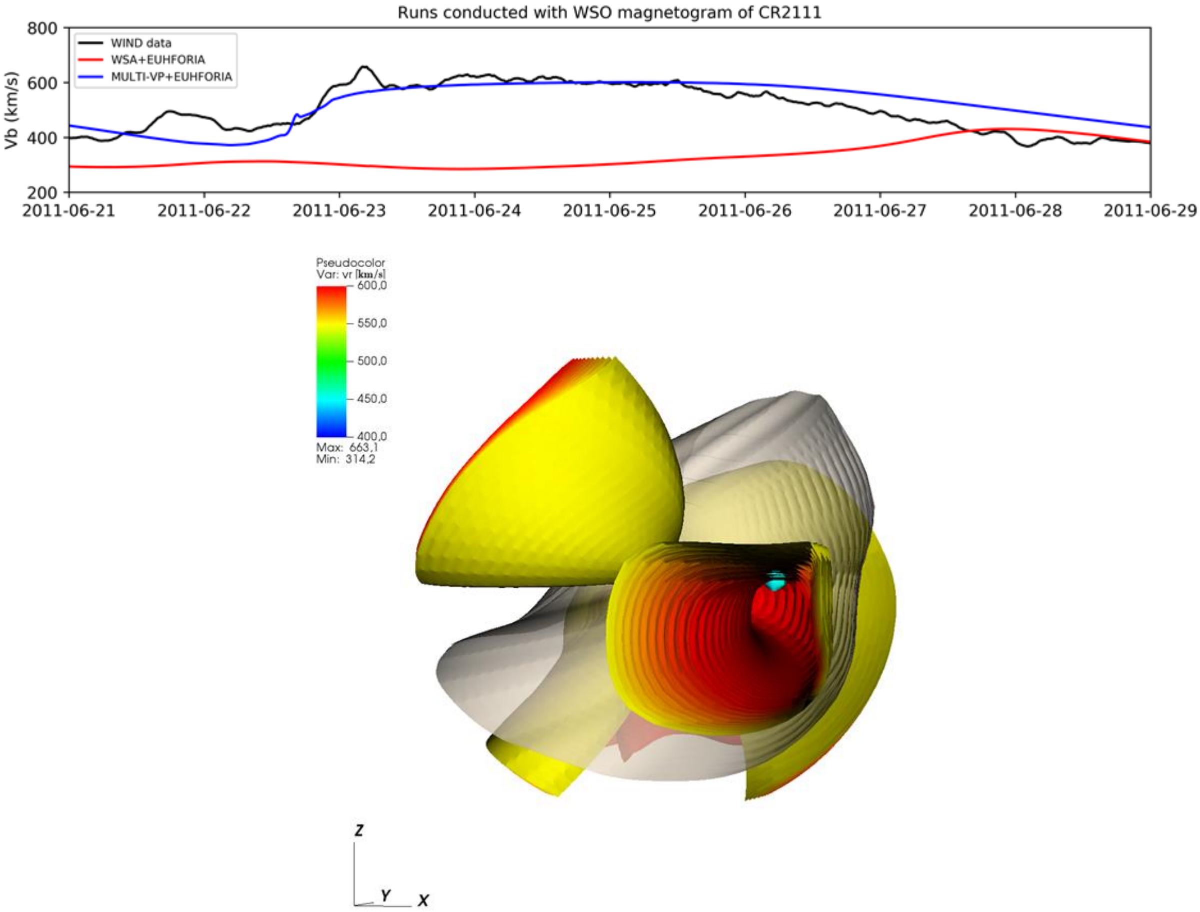


Figure 2. Top: Solar wind bulk speed at 1 AU as modelled by WSA+EUHFORIA-heliosphere (red) and MULTI-VP+EUHFORIA-heliosphere (blue) with a Wilcox Solar Observatory (WSO) magnetogram. The observed data as captured by WIND are depicted in black for the HSS that reached Earth on 2011-06-22. Bottom: Contour plot of the radial solar wind velocity in 3D space as modelled with the same WSO magnetogram (CR2111) used in Fig. 2 (top). The range of the velocities shown in the figure is between 490- 600 km/s. The HCS (B=0) is depicted in grey while the light-blue sphere represents Earth.

Solar wind energy entry into the magnetosphere

This last task of WP2 only recently started. It is devoted to developing a model that estimates geomagnetic activity indices from solar wind conditions at 1 AU using neural networks. One challenge for this task is to devise a model that only uses as inputs the solar wind parameters produced by the heliospheric propagation models, namely the density, velocity and magnetic field amplitude. In particular, the vertical component of the interplanetary magnetic field (Bz) component that is often used to drive the magnetic activity indices is not easily produced by (any) heliospheric models.

The neural networks model we are developing will ultimately estimate both planetary K-index (Kp) and Auroral Electrojet (AE) index, which are needed by the magnetospheric models. We have initially focused on the Kp estimation. For this, we have trained a Long Short-Term Memory (LSTM) neural network model on the OMNI2 dataset from 2002 to 2012, using the 2015-2020 and 1995-2001 periods as validation and test datasets, respectively. We have shown that the model uncertainties, even using the available parameters, are relatively small compared to the estimated input uncertainties. Using an ensemble *approach, we are able to estimate these input uncertainties, and thus provide a good stochastic estimation of the Kp index (Figure 3).*

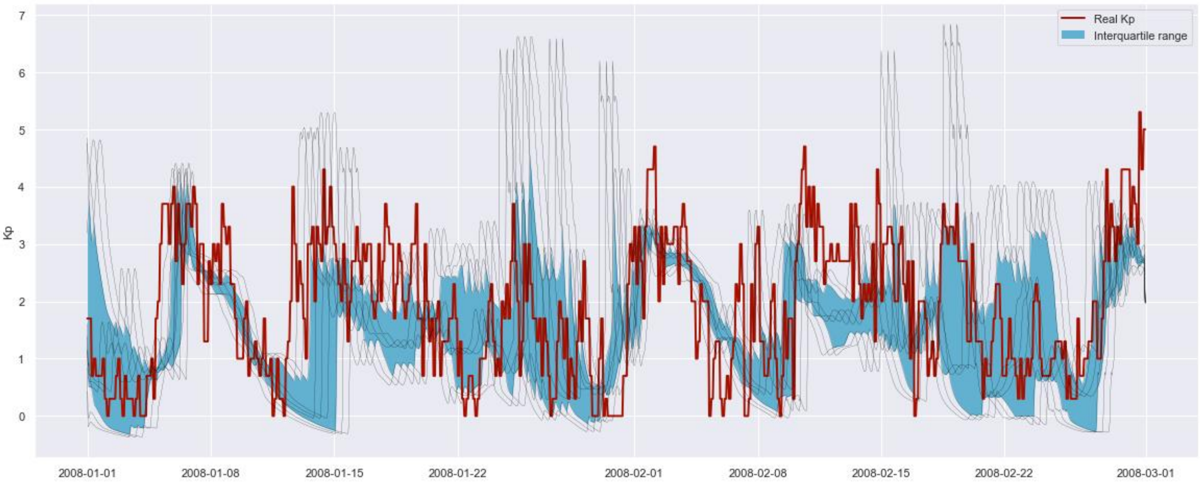


Figure 3. Example of Kp ensemble estimation using 1-D MHD Solar Wind parameters estimations as input to the LSTM network. In red the observed Kp value, in blue the interquartile range of the estimated distribution. The time interval is the same as in Figure 2.

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

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 electron density in the plasmasphere and plasmatrough is now determined in a spatio-temporal grid compatible to the input needed by the Salammbô code (WP4) and reading the input Kp indices from the neural network (WP2), together with their 24-hour history.

The comparison between the results of the plasmaspheric model and RBSP/EMFISIS density data has been started. In order to be able to improve some parts of the model, this comparison is made in particular MLT (magnetic local time) sectors and for special geomagnetic activity ranges (as determined by the Kp index). First results have been presented and discussed during regular SafeSpace meetings (see Figure 4 below).

All density data of the EMFISIS instrument onboard both Van Allen Probes / RBSP satellites have been collected and stored as well as needed orbital parameters (X_{gsm}, Y_{gsm}, Z_{gsm}, LON_{dip}, LAT_{dip}, X_{sm}, Y_{sm}, Z_{sm}, MLT, R, L, L_m_eq). Cluster density data from WHISPER instrument and similar orbital parameters have also been stored for selected events (those with very high confidence in the density data). Both datasets build then a cold plasma density dataset, which is the second milestone of the project (MS2-Cold plasma density dataset completed). It has been confirmed on time (30 September 2020).

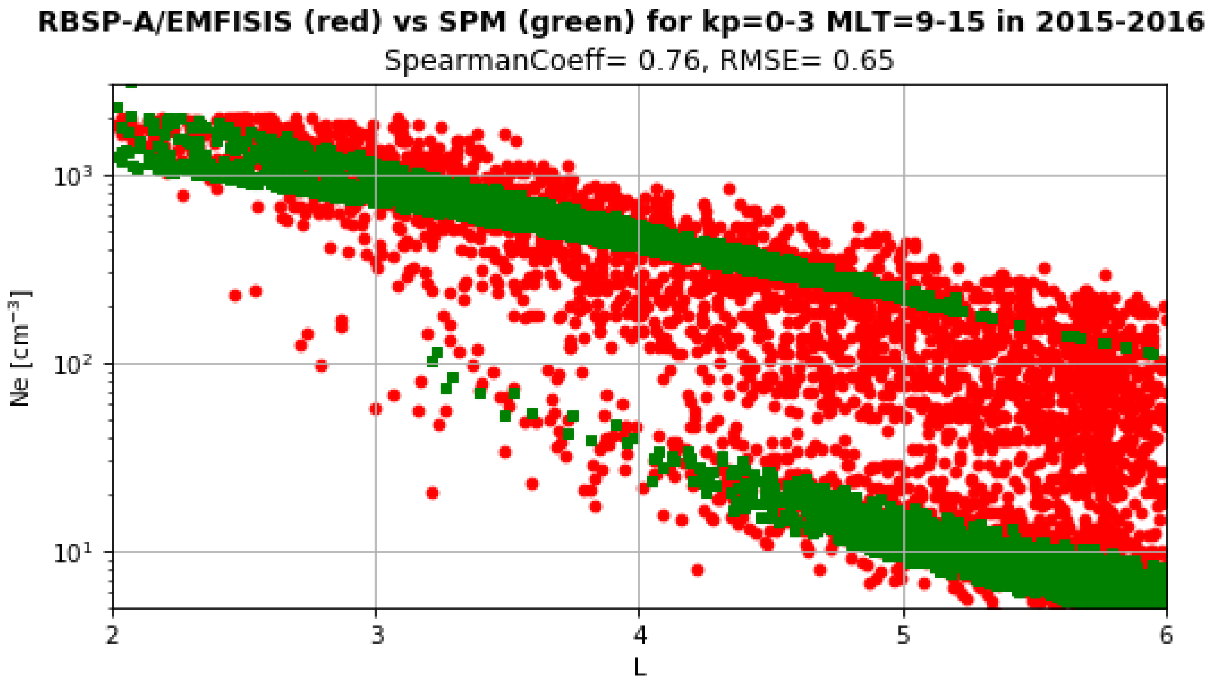


Figure 4. Electron density in the plasmasphere and in the plasmatrough plotted as a function of the McIlwain parameter L for Kp between 0 and 3 and in the MLT sector 9-15. Data from the model are plotted in green and data from RBSP-A/EMFISIS instrument in 2015-2016 in red.

Impact of plasma density and waves to diffusion coefficients.

During the past six months the consortium has worked on the calculation of the ULF based radial diffusion coefficients using magnetic and electric field measurements from THEMIS constellation. Eleven years of measurements (spanning a full solar cycle) were exploited in order to create a DLL database as a function of L and μ, as well as solar wind speed, density , pressure, interplanetary magnetic field and several geomagnetic indices. As the DLL calculations are almost complete, the consortium has also initialized the parameterization with various parameter schemes which possibly drive the diffusion coefficients' evolution during geospace disturbances.*

The consortium also continued to develop procedures for calculation of the energy and pitch angle diffusion coefficients using VLF models. The technique will be based on the ONERA WAPI code, modified to achieve high efficiency of calculations needed for operational purpose. The consortium worked on definition of the computational scheme with pre-calculated coefficients, parametrized by geomagnetic activity indices.

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

Public engagement

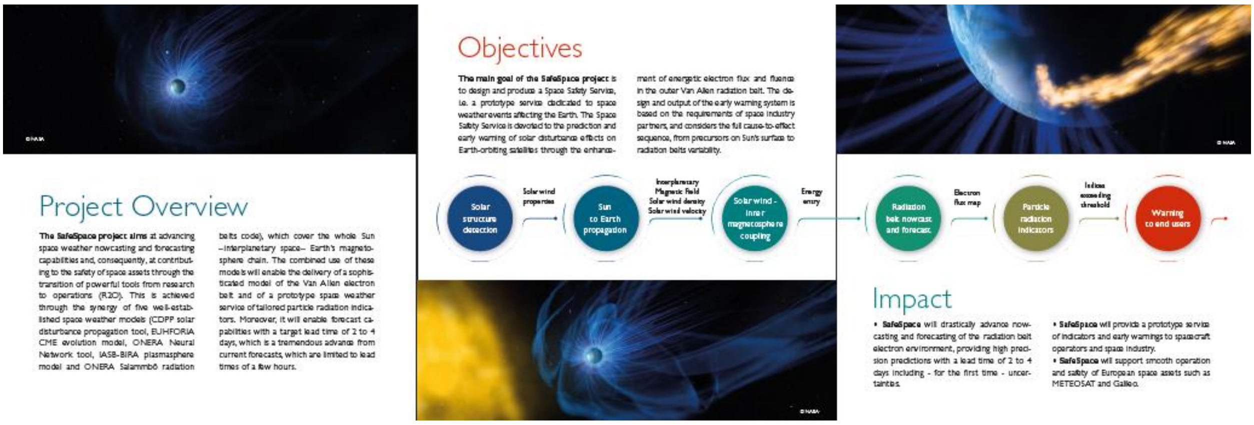
In order to ensure increased visibility of the project, SafeSpace has organized two public outreach talks, taking place outdoors to ensure maximum safety for the speakers and participants amidst covid-19 pandemic.

Both talks were given in the gardens of the Visitor Center of National Observatory of Athens located on the Hill of the Nymphs, in Athens, Greece. The site is situated across from the Parthenon and just to the north of the hill of Pnyx, where Meton built his heliotrope in the 5th century BC to perform the first astronomical observations of the classical Greek period.

- *The first public Talk, titled **"Space Sonatas"** was given by Prof. Ioannis Daglis, Professor of Space Physics at National and Kapodistrian University of Athens, SafeSpace Project Coordinator, on July the 15th.*

- *The second public Talk, titled **"Music of the Spheres and Space Physics"** was given by Prof. Ondrej Santolik, head of the Department of Space Physics at the Institute of Atmospheric Physics of the Czech Academy of Sciences and professor at the Charles University in Prague, on September 4th . The talk was filmed by the Bodossaki Cultural Foundation and may be found in Bodossaki Lectures on Demand (BLOD) platform.*

Also a leaflet containing basic information about the project aiming to inform the public has been produced. The pdf version of the leaflet is also available on-line.



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.

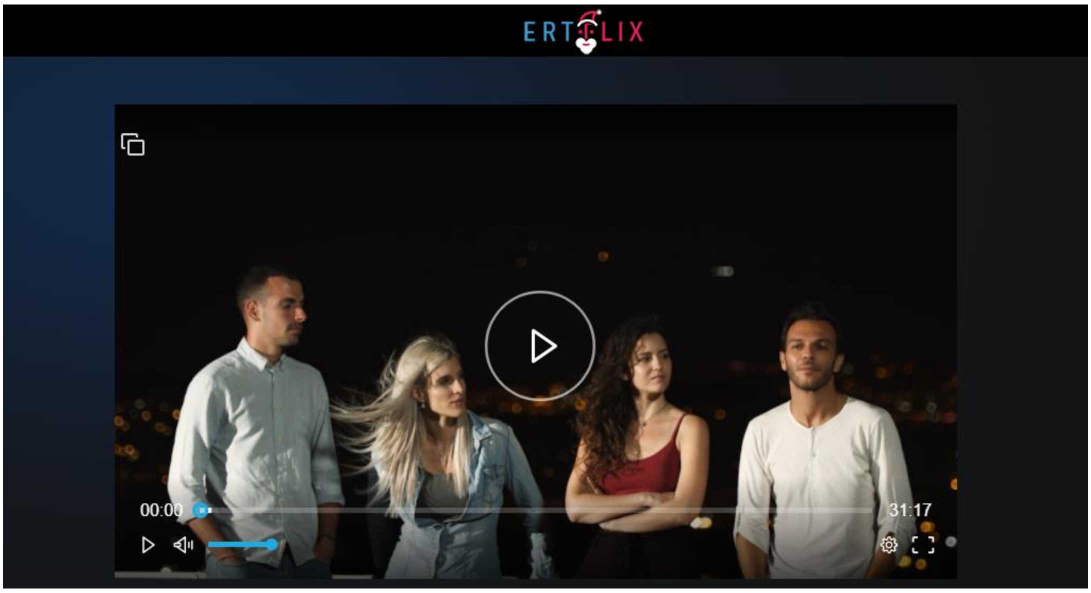
Objectives

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.

Last, but not least, the SafeSpace team participated in a documentary film broadcasted by the Greek National Television devoted on our research team. The documentary may be found on the Ertflix Platform.



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.

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.

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