

## **RB-FAN Advancing Radiation Belt Nowcasting and Forecasting through Data Assimilation and the Salammbô Model**

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### **Abstract**

In the frame of the ESA Space Safety Programme's Space Weather Service Network, the Radiation Belt Forecast And Nowcast framework (RB-FAN) has been developed to nowcast and forecast the particle populations and their dynamics within the radiation belts. Databases at ONERA and at SPARC premises, supplemented by other external databases, are combined with the Salammbô codes (electron and proton) using data assimilation methods. The objective of the RB-FAN framework is to provide end-users with dedicated products, such as quick looks for specific orbits (LEO, GNSS, GEO as well as user pre-defined) radiation levels and risks alerts and assessment (internal charging, solar cell degradation, surface charging and solar protons events). For that purpose, a global model chain has been developed. To enable a 3-day forecast, the RB-FAN framework relies on a dedicated model chain based on Virtual Space Weather Modelling Centre (VSWMC) infrastructure. Solar wind structures are propagated from the Sun using the EUHFORIA model. The output of estimated solar wind parameters and Kp values then feed the Salammbô data assimilation codes. In parallel IMPTAM model provides low energy boundary conditions for Salammbô codes too. The fluxes evolution produced by the Salammbô data assimilation codes constitute the basic outputs of the RB-FAN framework. Based on this Level-1 raw database, different products are computed for end-users and displayed as dynamical webpages, reachable on the ESA SWE portal since July 2023 (<https://swe.ssa.esa.int/onera-rb-fan-federated>, ESA-SWE account required).

The RB-FAN framework is currently being upgraded, as part of the ESA Space Safety Program. The main objective is to improve the forecast accuracy provided as well as identifying and answering to all end-users needs. This contribution aims at introducing the overall architecture of the RB-FAN framework. Focus is put on the end-user tailored products available to Space Operators through the ESA SWE Service Network and future plans. The performance assessments of this framework are also discussed to highlight the benefits and remaining challenges for this Space Weather framework.

**Keywords:** radiation belts, space weather, end-users needs, effects on s/c, forecast

### **Acronyms/Abbreviations**

CCMC	Community Coordinated Modeling Center
CIR	Corotating Interaction Region
CME	Coronal Mass Ejection
FARBES	Forecast of Actionable Radiation Belt Scenarios
HEO	Highly Elliptical Orbit
HPC	High Performance Computing
HSF	Human Space Flight
IPODE	Ionising Particle ONERA Database
NATO	North Atlantic Treaty Organization
RB-FAN	Radiation Belts Forecast And Nowcast
S2P	Space Safety Program
SAA	South Atlantic Anomaly
SCD	Spacecraft Designers
SCO	Spacecraft Operators
SSA	Space Situational Awareness
SLA	Service-Level Agreement
SWSC	Space Weather Scientific Community

## 1. Introduction

The increasing reliance on space-based technologies has elevated the critical importance of understanding and forecasting space weather. Consequently, the Sun-Earth connection is under increasing scrutiny, driven by the rapid expansion of satellite launches and space exploitation. Extreme space weather events have a global impact, affecting both ground-based and space-borne infrastructures. As society and industry become ever more dependent on space-enabled services, the risks posed by these events—including spacecraft anomalies and disruptions to navigation, communication, and power grids—are amplified. This growing recognition has spurred the need for coordinated risk assessments and improved forecasting capabilities at national and international levels [1], a concern shared by groups such as the NATO Military Space Weather group alongside considerations of space climate.

Earth's radiation belts are central to both space weather (posing a risk of anomalies to in-flight satellites) and space climatology (informing the refinement of satellite specifications). Indeed, these belts pose significant hazards to space missions, underscoring the necessity for accurate forecasting of their dynamic behavior [2], which is the primary focus of this paper. Therefore, providing accurate forecasts of Earth's radiation belts presents a significant challenge. As the final stage of the Sun-Earth chain (see Fig. 1), forecasting their dynamics necessitates two key elements: a comprehensive understanding of the entire chain, from solar activity to its impacts on the solar wind, magnetosphere, and ground level, and the identification of crucial proxies to accurately model these dynamics. As [3] aptly points out, a single event provides limited insight. The response of the radiation belts is strongly dependent on the complete Sun-Earth chain. As illustrated in Fig. 1, Coronal Mass Ejections (CMEs) and Corotating Interaction Regions (CIRs) exhibit distinct signatures in the solar wind and interact differently with the magnetosphere, leading to varying magnetic field disturbances observed on the ground. Consequently, different dynamic processes are triggered within the radiation belts. To adequately forecast these dynamics, various research directions have been explored over the past decades.

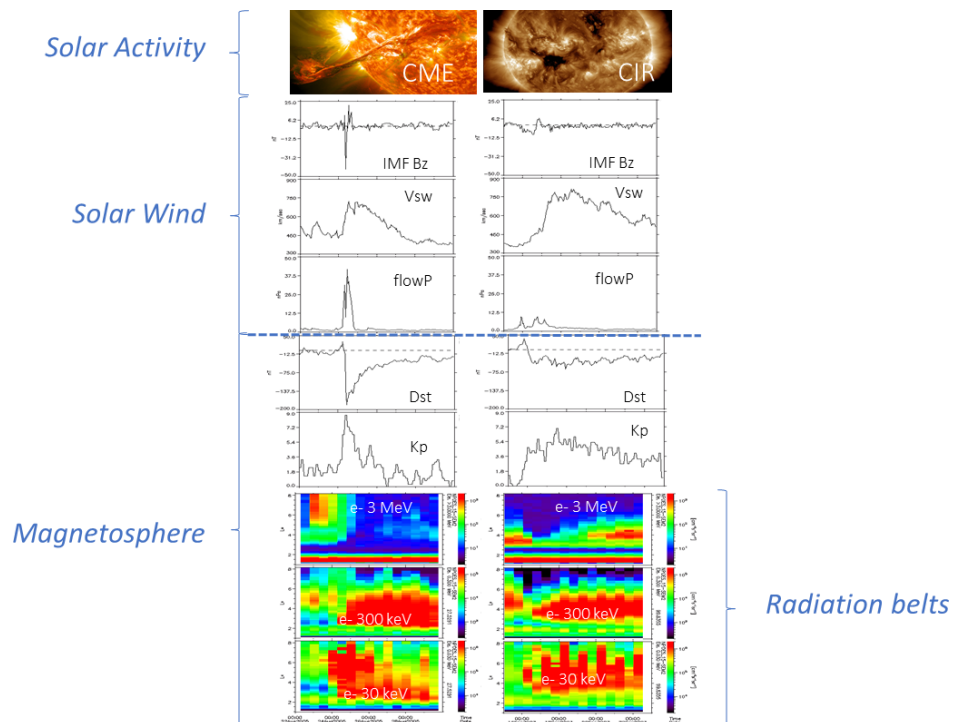


Fig. 1. Sun-Earth connection illustrated for two kind of geomagnetic storms (CME-driven storm on the left, CIR-driven storm on the right). From top to bottom, sun activity illustrations, solar wind parameters for these two events, geomagnetic indices and electron flux (radial distance from Earth versus time) measured by NOAA-POES 15 spacecraft for 3 energies.

A primary approach involves modeling the entire Sun-Earth pipeline, integrating various science-based models. This way, forecast is made on the time gains on the propagation of the solar emission to the Earth, on the order of a few days in case of CME and CIR. A prominent example is NASA's Community Coordinated Modeling Center (CCMC) [4], which allows the combination of different science-based models, using the output of one as input for another. In Europe, with support from the European Commission and ESA, various components of such a modeling chain have been developed. A significant European initiative is the VSWMC, developed at KU Leuven [5], which offers a framework for combining science-based models, whether they are federated (running at their home institution) or integrated into their High-Performance Computing (HPC) infrastructure. Initially dedicated to heliospheric physics, its scope is expanding to encompass the full spectrum of space weather needs [5]. In this context, ONERA has been a leading developer of science-based models for Earth's radiation belts for years, addressing the dynamics of both trapped electrons and protons ([6], [7], [8], [9], [10], [11]). While other groups worldwide also develop such models ([12], [13], [14], [15]), ONERA uniquely models the dynamics of both electrons and protons and possesses a large in-situ database called IPODE [16]. Nevertheless, relying solely on sequential physics-based models for forecasting implies accumulating the uncertainties inherent in each model, potentially leading to significant divergence.

Two other key research directions warrant mention. Over the last decade, supervised machine learning techniques have been increasingly explored, particularly to mitigate modeling limitations and inherent uncertainties. Notable efforts include forecasting magnetospheric disturbances based on solar imagery, such as predicting geomagnetic indices using solar composite images as inputs for neural networks ([17], [18], [19]). Furthermore, leveraging over 50 years of in-situ measurements, and even longer ground-based records, researchers are investigating historical analogs to the currently observed conditions. These investigations are central to the European-funded project FARBES (<https://www.farb.es.eu/>). By utilizing a dedicated list of radiation belt events, analog ensemble methods are employed to forecast the most probable evolution of specific drivers of an ongoing event by identifying the most similar past periods [20]. While these methods show promise, they are not yet sufficiently mature to serve as a reliable baseline for providing forecasts to spaceborne users.

For pre-operational to operational services dedicated to spaceborne users, validation, performance assessments, confidence levels, and Service Level Agreements (SLAs) are mandatory. Consequently, the aforementioned methods cannot be directly implemented. More sophisticated approaches are required, and data assimilation is a proven technique for ensuring reliability in reconstructing system dynamics by optimally combining available data with a baseline science-based model. Widely used in atmospheric weather and oceanography for decades, ONERA has been developing such methods for over 15 years now ([21], [22], [23], [24]). Programs like NASA NSF and ESA S2P (formerly SSA) provide funding to industries and laboratories to build upon these scientific foundations. In parallel efforts to serve end-users, ESA awarded ONERA, in collaboration with European institutes and companies, a grant in 2020 to develop a specific framework addressing the following challenges:

- Provide a 3-day forecast of radiation belt dynamics (electrons and protons).
- Deliver relevant end-user products on the ESA SWE Network portal.
- Assess the performance of the overall developed framework.

To this end, the Radiation Belts Forecast And Nowcast (RB-FAN) framework has been developed through this funding. This paper aims to present this new framework, available as a prototype for future operational Space Weather services on the ESA SWE Network portal (<https://swe.ssa.esa.int/onera-rb-fan-federated>) since July 2023. Section 2 details the architecture and development logic. Section 3 presents the practical implementation and key achievements. Section 4 discusses the validation of the RB-FAN framework and presents performances, especially on the May 2024 event. Finally, Section 5 raises a discussion on recommendations and ongoing efforts to further improve the RB-FAN framework.

## 2. RB-FAN Framework Architecture and development logic

To develop a relevant framework capable of providing timely key information for spaceborne users, we analysed potential use cases, leveraging ESA reference documents gathering together end-user needs. According to ESA standards, spaceborne end-users can be categorized into spacecraft designers (SCD), spacecraft operators (SCO), and human space flights (HSF). An effective Space Weather service must be sufficiently modular to address the diverse inquiries from all these groups. Our focus within the RB-FAN activity has been to limit our use-case testbed to SCD and SCO. Reaching HSF was challenging at that time, as their primary interest lies in forecasting high-energy protons from solar flares—a topic not considered within this activity (this evident gap will be revisited in Section 5). Table 1

summarizes the use cases addressed by the RB-FAN framework, categorized by the concerned end-user family. Furthermore, within the RB-FAN activity, we proposed including the space weather scientific community (SWSC) as a distinct end-user group.

Table 1. Tailored use-cases and relevant end-users families tackled by RB-FAN framework

Use-case Name	End-Users concerned
<i>Umbrella needed?</i>	SCO, SCD, SWSC
<i>SAA world maps</i>	SCO, SWSC
<i>Deep charging mitigation</i>	SCO
<i>Anomaly risks quantification</i>	SCO
<i>Post-anomalies analysis</i>	SCO, SCD
<i>Solar Cells degradation mitigation</i>	SCD
<i>System Design mitigation</i>	SCD
<i>Space Weather long term statistics</i>	SCD, SWSC
<i>Specific time periods investigation</i>	SWSC

As highlighted in Table 1, the RB-FAN framework aims to address diverse inquiries, ranging from the temporal evolution of particle flux within the radiation belts (primarily targeting expert users) to more macroscopic risks associated with specific spacecraft effects (reaching a broader user base). Given this complexity, we designed the RB-FAN framework as a decision tree. This structure initially provides a high-level, immediate assessment of risk for a given orbit and day, as illustrated in Fig. 2. Three generic orbits are offered (GEO, GNSS, and LEO), and users can define additional orbits of interest. The overall risk for these orbits is presented as three-colored flags, derived by aggregating the risks related to specific spacecraft effects, accessible by clicking on an orbit. These specific risks consider both deep charging and solar cell degradation and are also indicated by three-colored flags. To accommodate varying user needs, all these flags are user-configurable (different onboard technologies exhibit varying sensitivities to radiation effects, for instance). Finally, a detailed analysis page is also available, offering users key features of the forecasted radiation belt dynamics.

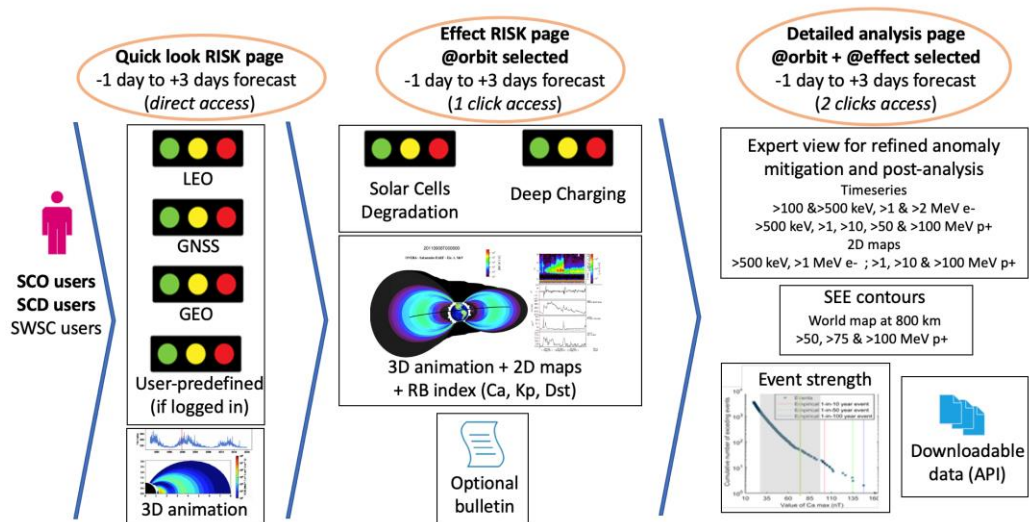


Fig. 2. Decision tree logic used in the RB-FAN framework

Behind this end-user interface, a concise workflow has been specifically designed to ensure the automatic daily update of these forecasts. The underlying logic of RB-FAN involves simulating the entire Sun-to-Earth radiation belt chain using complementary models. This interdisciplinary approach is a key strength of the RB-FAN team, which gathers expertise from various but complementary domains to optimally design this hybrid framework:

- ONERA:

- Salammbô codes and data assimilation tools for reconstructing radiation belt dynamics using near real-time datasets.
- Near real-time dataset provider.
- Expertise in end-user needs and dedicated products, including existing products developed with partners.
- Initial forecasting of key dynamic drivers through PhD research.
- BIRA-IASB:
  - R-ESC coordinators and ECSS experts.
  - PROBA-V EPT data provider with added-value (uncertainty estimation).
- KU Leuven:
  - EUFHORIA models (propagation of solar activity from the Sun to the magnetosphere).
  - VSWMC framework.
- AKochanov:
  - VSWMC infrastructure IT expert.
- SPARC:
  - European datasets providers (GSAT and HIMAWARI8).
  - SAPI interface to database.
  - Validation and performance analysis.
- FMI:
  - IMPTAM model for <100keV electron and proton dynamics in the inner magnetosphere.

Based on the VSWMC infrastructure and this complementary expertise, the following model chain (Fig. 3) has been designed to provide a daily 3-day forecast of radiation belt dynamics, serving as the foundation for the proposed end-user products.

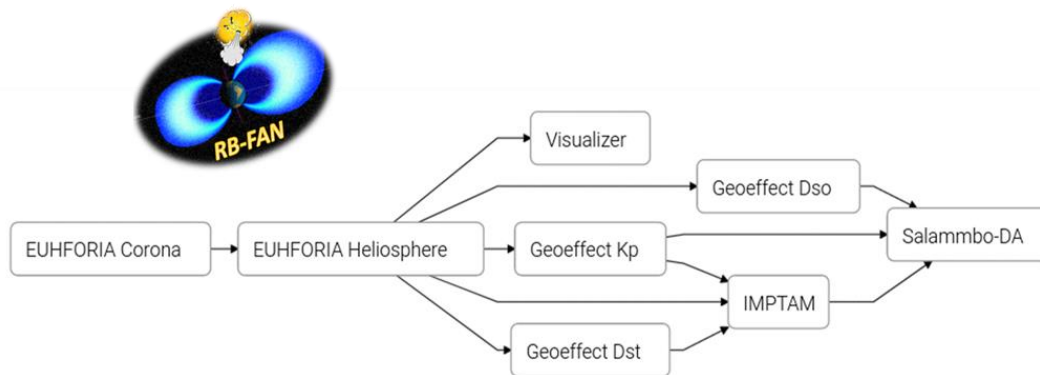


Fig. 3. RB-FAN models chaining

Finally, ONERA has also designed a runtime manager to supervise the entire workflow, from model execution to the calculation and display of products on the website. This manager has been specifically designed to handle any issues in the interfacing and retrieval of key inputs (geomagnetic indices, near real-time measurements, ...) and to provide appropriate mitigation options in case of missing data. The RB-FAN framework is therefore designed for full automation, with daily execution and the capability for re-launching during significant space weather events.

### 3. Main Achievements

After a year of comprehensive development and a validation process overseen by ESA/ESOC, complemented by a dedicated end-user test campaign, the RB-FAN activity has delivered several key achievements. The RB-FAN framework stands as one of the first integrated prototypes on the ESA SWE Network portal. Its global architecture is modular and readily adaptable, featuring a dedicated runtime manager that simplifies future upgrades. Multiple interfacing APIs for both models and data, crucial for the framework's operation and the integration of relevant forecasting inputs, have been developed. Notably, the RB-FAN framework is connected to the ONERA IPODE database, the BIRA-IASB PROBA-V/EPT database, and the SPARC database (a provider of European datasets, particularly NGRM data). The RB-FAN framework also utilizes available products from the ESA SWE Network portal, such as the nowcasted Kp index provided by the GFZ-Potsdam institute. The integration of VSWMC into the

RB-FAN framework offers significant advantages by enabling different models to interact seamlessly while running at their home institutes, thereby distributing HPC computation and mitigating failure risks.

The end-user interface has been carefully developed to ensure ease of use, as illustrated in Fig. 4. A status bar at the top of the page provides essential information about the framework, while the homepage offers an immediate overview of orbital risks. Pop-up windows are available for quick analysis of the specific effects contributing to the overall risk assessment.

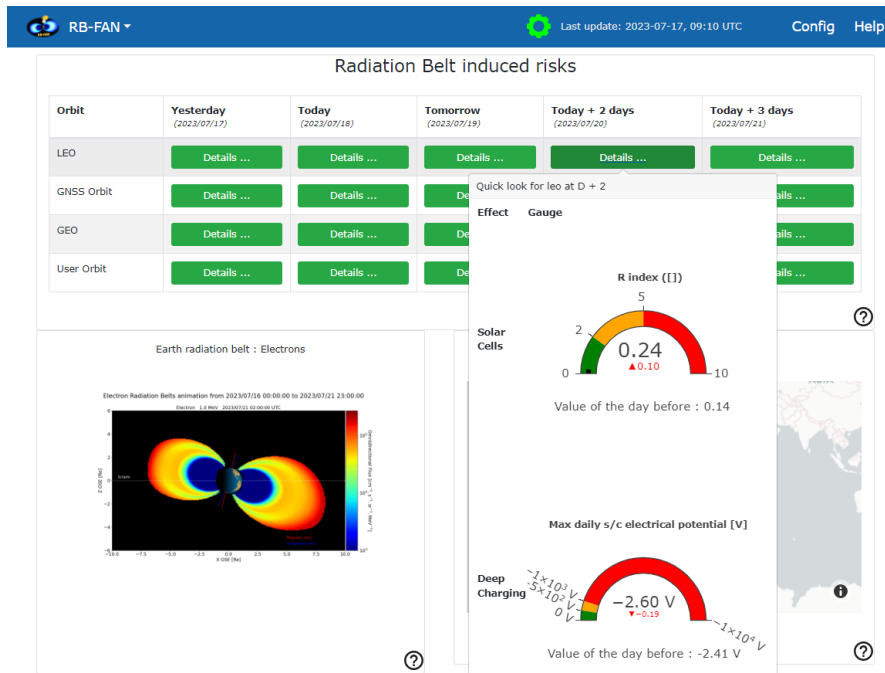


Fig. 4. RB-FAN end-user interface

Behind the displayed forecast products, a comprehensive nowcasting and forecasting chain is executed. The logic of the RB-FAN framework is detailed below, and its architecture is overviewed in Fig. 5. Databases are represented by cylinders, processes by boxes, and data transfer/calls by arrows. Elements are integrated within rectangles depicting different perimeters (VSWMC infrastructure, ONERA DMZ, ONERA internal infrastructure, ESA-SSA SWE portal). For example, Salammbô-DA (HPC) runs within the ONERA internal infrastructure. The RB-FAN Framework execution follows this sequence, managed by a dedicated crontab referred to as the RB-FAN crontab:

0. The Onset Watcher is executed every 3 hours based on the RB-FAN crontab. It attempts to connect to the GFZ-Potsdam database to retrieve nowcasts of the Kp index (G.107) and definitive values (G.108). If significantly enhanced space weather conditions are observed compared to the EUHFORIA estimation, the RM VSWMC Driver (1) is called (only if the entire RB-FAN framework is not already running).
1. The VSWMC Driver is executed daily at a fixed time based on the RB-FAN crontab. It can also be automatically triggered by the Onset Watcher (0) under specific conditions (see above) and manually for reanalysis and testing. The VSWMC Driver launches the VSWMC models chain (see Fig. 3), starting with EUHFORIA code, as well as other RB-FAN runtime manager instances to optimize parallel work.
4. The VSWMC supervisor deposits the EUHFORIA and IMPTAM results onto the ONERA SFTP Server.
5. The Salammbô Driver retrieves the EUHFORIA and IMPTAM results from the SFTP Server when available. It also retrieves datasets from IPODE, the BIRA-IASB EPT database, and the SPARC database to prepare the assimilation process for the Salammbô-DA codes. The datasets from the BIRA-IASB EPT database and the SPARC database are retrieved once daily to limit interconnections and potential issues.
6. Salammbô-DA are launched on ONERA HPC
8. The Products Driver retrieves the Salammbô-DA outputs from the internal ONERA Storage and generates the products, which are subsequently delivered to the website database.

On the end-user's side, access to the RB-FAN website is granted through the ESA SWE Service Network authentication system. A dedicated configuration database is maintained by the RB-FAN website to store end-users' specific configurations.

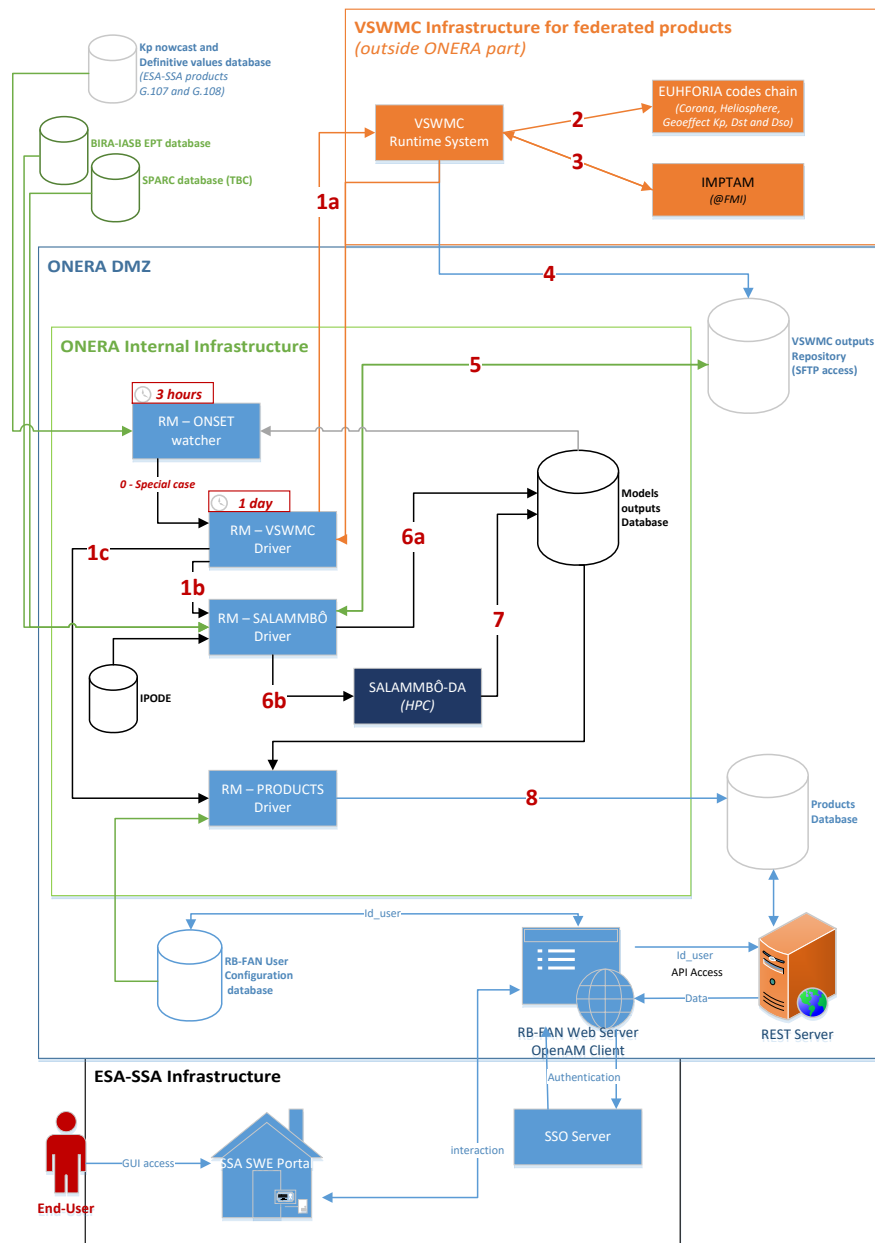


Fig. 5. Full RB-FAN framework architecture

The RB-FAN framework has been available on the ESA SWE Network portal for approximately two years (since July 2023) and has demonstrated efficient operation for over 80% of the time.

#### 4. Validation and Performance: example of May 2024 event

As the primary goal of the RB-FAN framework is to forecast the dynamics of the radiation belts, we developed a specific performance assessment method to ensure an objective evaluation of its capabilities. We will briefly detail this methodology and highlight some relevant results, followed by specific examples focusing on the May 2024 event.

Firstly, the RB-FAN framework's outputs are validated through comparison with in-situ data. The framework's predictions are compared and analyzed against historical in-situ measurements to estimate the physical accuracy of the nowcast/forecast system. Data from the Van Allen Probes mission, operating in a highly eccentric orbit (HEO), form a cornerstone of this validation activity. Specific metrics, following the methodology outlined in [25] for flux predictions, are employed to quantify the framework's performance. Regarding specific end-user products (three-colored flags), we derived skill scores based on precision-recall quantification within dedicated confusion matrices.

Subsequently, we selected two historical geomagnetic storms (one CME-driven, one CIR-driven) that occurred during the operational lifetime of the Van Allen Probes, on which the framework's performance will be assessed. These events are illustrated in Fig. 6. While focusing solely on the electron radiation belts, they exhibit distinct temporal evolutions. The CME-driven storm (March 2015) is characterized by a significant depletion at the storm's onset, followed by an intensification of flux across all energies in the slot region. The CIR-driven storm (August 2017) does not show a strong depletion but presents a substantial intensification in high-energy electron flux (often referred to as killer electrons).

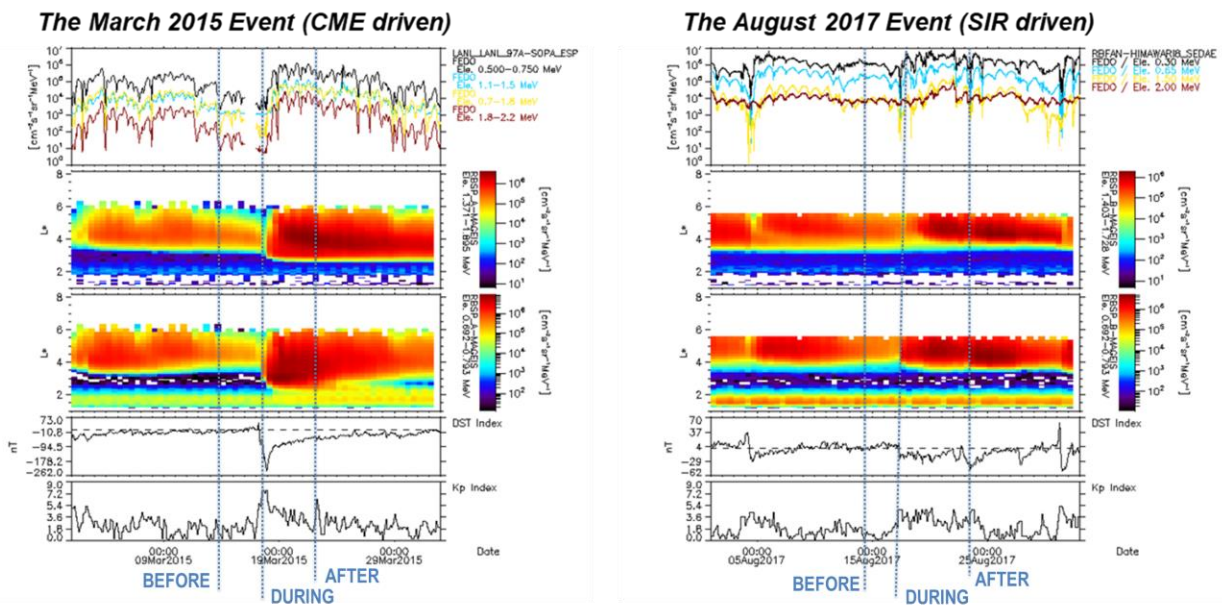


Fig. 6. Selected geomagnetic storms to assess performances of RB-FAN framework

Finally, Fig. 7 illustrates the methodology developed to ensure an objective assessment of the RB-FAN framework, with a primary focus on evaluating forecast performance. As shown in Fig. 6, three temporal snapshots are identified as "BEFORE," "DURING," and "AFTER," representing typical stages of a geomagnetic storm from which we aim to forecast the temporal evolution of the radiation belts. If the current time is "BEFORE" the storm, any energy transfer from the solar wind to the radiation belts remains a forecast with potentially high uncertainty. When positioned "DURING" the main phase of the storm, the forecast benefits from more observed key features, leading to a more confident prediction with probable medium to low uncertainty. Finally, when positioned "AFTER" the main phase, the forecast is expected to be more accurate, providing crucial information for operators such as the event's duration and the time it takes for the flux to recover to low levels (probable low uncertainty). To quantify these performances, Figure 7 shows a comparison of our forecast to two baselines: (1) a "reference simulation," which is a basic simulation of radiation belt dynamics using our physics-based code driven by the consolidated Kp index, and (2) a "Gold Standard," which is a data assimilation simulation using the best available data at that time and driven by the consolidated Kp index. Thus, while (1) represents a prediction with limited information, (2) represents our target for real-time forecasting. Comparing the RB-FAN framework to these two baselines allows us to estimate our current accuracy and identify areas for further improvement.

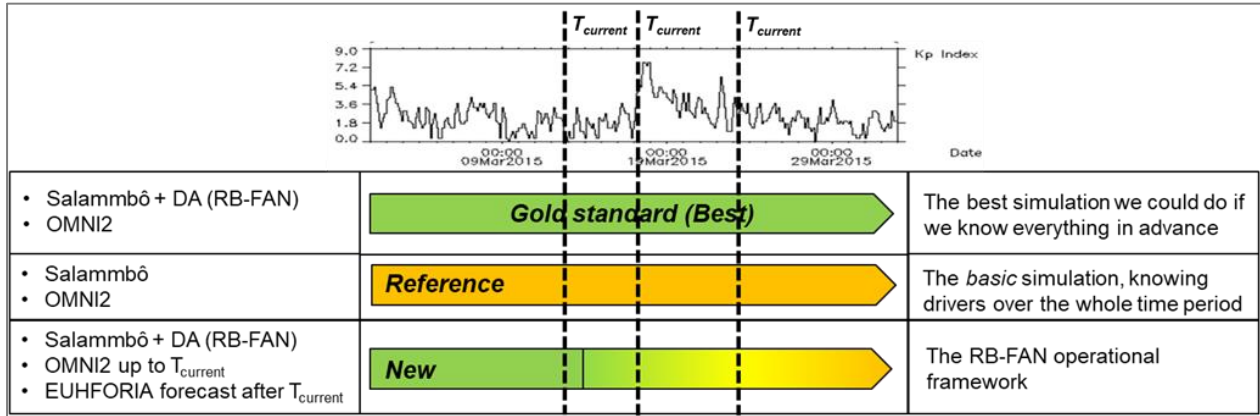


Fig. 7. Objective performances assessment methodology developed as part of RB-FAN activity

Results indicate that the RB-FAN framework can forecast particle flux with the same order of magnitude as measurements, for both protons and electrons, during both active and quiet periods (Fig. 8). This analysis highlights localized discrepancies prior to storm onsets, challenges in precisely predicting the start of events, and generally improved performance after the initial strong onset. More specifically, as previously mentioned, the forecast accuracy depends on the input accuracy. Fig. 9 illustrates the inherent limitations in forecasting the Kp index for the March 2015 event across the three temporal tests ("BEFORE," "DURING," "AFTER"). Finally, the forecast accuracy proves to be dependent on the storm type (CIR storms are better predicted than CME storms in this initial implementation) and the energy of the particles.

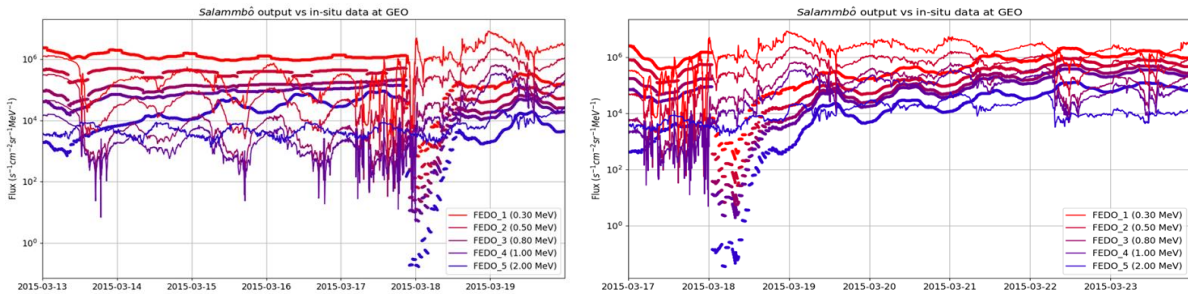


Fig. 8. Comparisons of RB-FAN flux outputs as compared to in-situ data for both geomagnetic storms (March 2015 on the left side, August 2017 on the right side)

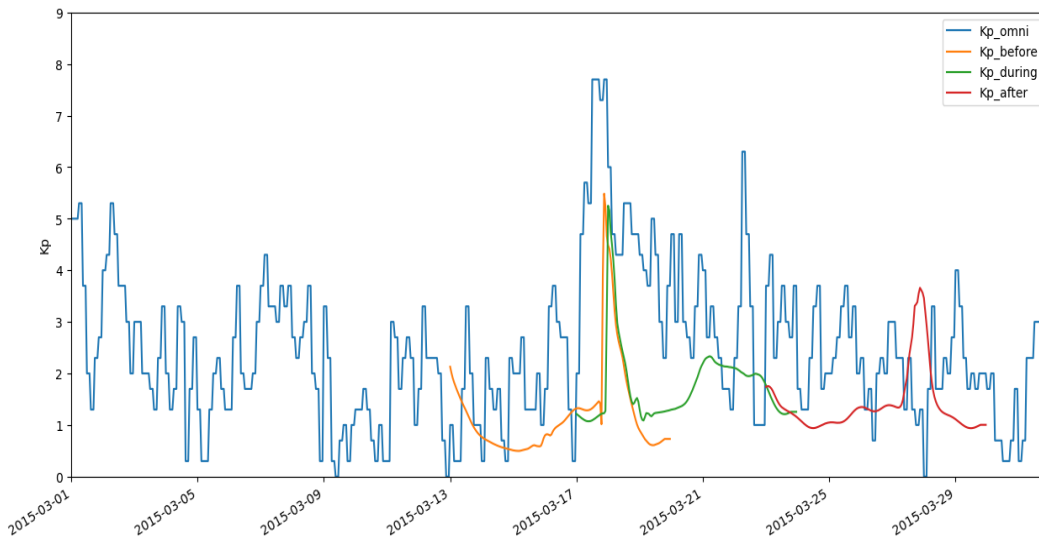


Fig. 9. RB-FAN forecasted Kp index for March 2015 event, for the three snapshots ("BEFORE," "DURING," "AFTER")

The May 2024 event has been identified as a rare occurrence, estimated to be a one-in-20-year event in terms of both solar protons reaching Earth and the magnitude of geomagnetic disturbances. However, as depicted in Fig. 10, the arrival times of solar protons were asynchronous with the geomagnetic storms, preventing the trapping of new protons. Consequently, despite this being a major CME-driven storm, no significant intensification in particle flux was observed, and few radiation-related effects on satellites were identified. Fig. 10 details the forecast table provided by the RB-FAN framework before the storm's onset. Notably, no major alerts were issued, with the exception of a yellow alert for geostationary orbit, indicating a potential increase in high-energy electrons at that altitude. The upper right panel shows that the forecasted Kp index was largely consistent with the actual values, enabling the RB-FAN framework to adequately forecast the orbital risks in advance of the event. This outcome confirms the relevance of the development efforts undertaken during this activity.

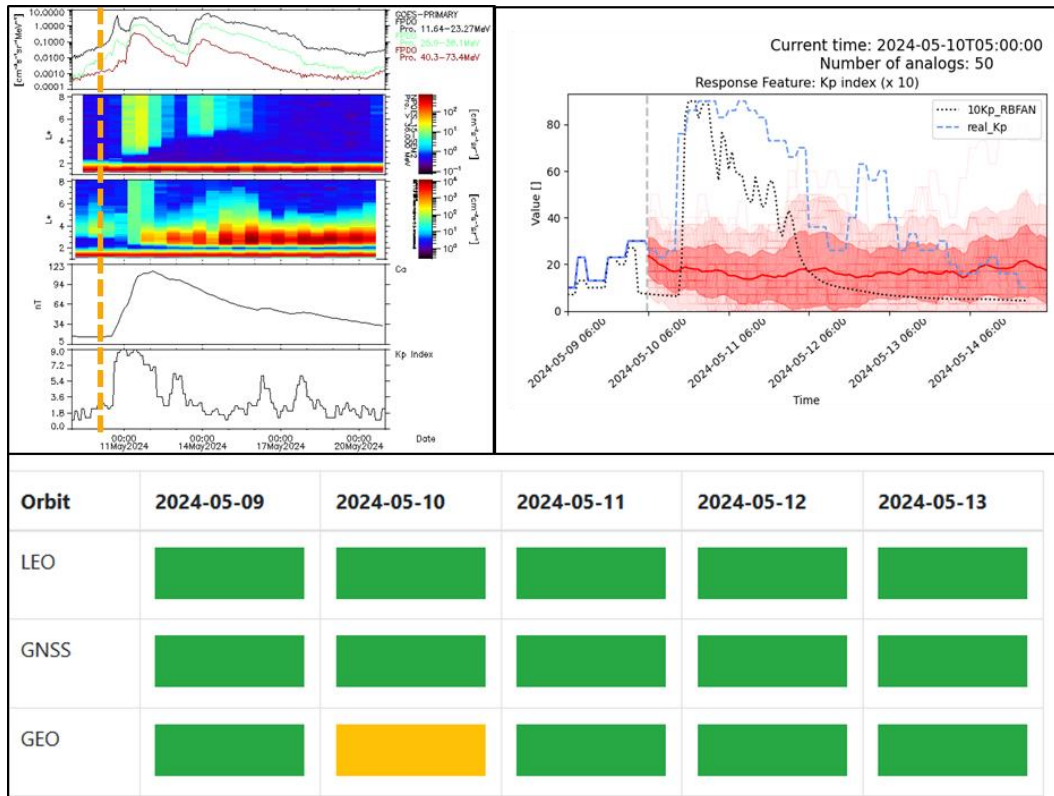


Fig. 10. May 2024 event before the onset (10<sup>th</sup> May 2024). The upper left panel presents measurements from (from top to bottom) GOES-PRIMARY data, from NOAA-POES15 for protons greater than 36MeV, from JASON3 for electrons greater than 1.6MeV, Ca index and Kp index. The upper right presents the temporal evolution of Kp index: real values are in dashed blue, forecasted values used by RB-FAN framework in dashed black, and forecasted by EU-FARBES project in red (confidence levels included). The bottom panel presents the synthetic table (RB-FAN homepage) displaying global daily alerts by orbits.

Highlighting positive results is important, but the RB-FAN framework is still under development and currently operates as a pre-operational service. As the May 2024 event unfolded, the RB-FAN forecast issued on May 13<sup>th</sup>, 2024, triggered full alerts, as shown in Fig. 11. Observing the left panel, it's evident that the forecasted Kp value used for that prediction remained constant at 6, which is unrealistic. This was due to a simple mitigation strategy implemented during this activity to handle failures in Kp index forecasting: retaining the last known value. This illustrates a current limitation of this initial RB-FAN framework implementation, which will be addressed further in Section 5. In conclusion, it's worth noting that the RB-FAN framework, operated solely by research institutes, was able to provide daily forecasts throughout the event with generally good confidence levels, with this specific day being an exception.

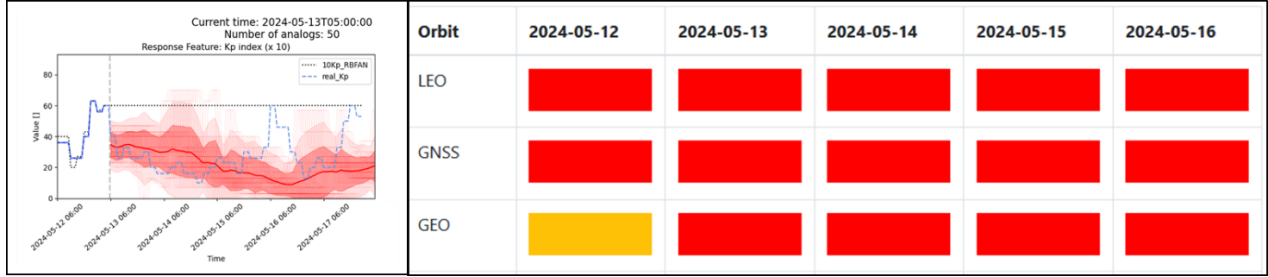


Fig. 11. Same plots as previous figure, but forecasted on the 13<sup>th</sup> May 2024.

### 5. Discussion and Future Developments

It is crucial to emphasize that the accuracy of forecasts hinges on the quality of the drivers of dynamics (such as the Kp index) and the data used for assimilation. The discrepancies observed in the Kp index forecasts generated by the EUHFORIA models during geomagnetic storms highlight a potential avenue for improvement, as does the time lag in retrieving in-situ measurements. Mitigation strategies must be defined and implemented to ensure redundancy where feasible. Specifically, ongoing developments within the EU-FARBES project could offer a secondary source of Kp index forecasts, as illustrated in Fig. 10 and Fig. 11. Regarding the latency in in-situ measurement retrieval, current efforts are underway with ESA/ESOC funding to automate the processing of geostationary measurements from the ICARE-NG2 instruments aboard Hotbird 13F and 13G, aiming for a retrieval and automated processing time of only a few minutes [26].

The results presented above demonstrate the promising capability of the RB-FAN framework to provide forecasts with an order of magnitude comparable to observations, while also identifying key areas for improvement related to the modeling of physical processes, the accuracy of input data, and data assimilation. Table 2 summarizes the main challenges to address in the future to further enhance this new framework.

Table 2. Lessons learned and RB-FAN remaining challenges synthesis

RB-FAN Lessons learned	RB-FAN related challenges
Going in the most useful direction for the end-users	Understanding their needs and converting them into as relevant as possible products
Modularity and interoperability is of prime importance	Pursue interfacing the most relevant inputs to RB-FAN
Improve the RB-FAN forecast accuracy	<ul style="list-style-type: none"> <li>- Real-time datasets on relevant orbits</li> <li>- Automatically cleaned and pre-processed datasets</li> <li>- Forecasted inputs of interest as accurate as possible (IMF Bz, ...)</li> <li>- Use the most up-to-date physics modelling</li> </ul>
Even if a Level 0-1 forecast (flux time series) is not accurate, an end-users product (Level 2-3) can be accurate	Use and manage this "anti-correlation" to design and provide new products useful and helpful for end-users

Currently, ONERA has been granted a second activity since 2023 to further improve the RB-FAN framework. This new phase of development focuses on proton forecasting, specifically predicting the probability of an upcoming solar flare reaching Earth. This enhancement would enable better anticipation of proton dynamics within the radiation belts and allow for the provision of improved products to end-users. Furthermore, while the underlying physics are being refined by leveraging European projects such as H2020-SAFESPACE ([24], [27], [28]), new products related to solar proton events and surface charging are also under development.

In conclusion, the RB-FAN project has successfully demonstrated the feasibility of defining and developing a comprehensive hybrid framework dedicated to forecasting radiation belt dynamics from its inception. The RB-FAN framework possesses significant potential for further enhancements to continue meeting end-user needs. Areas for improvement include efficiency, accuracy, interoperability, and the development of new products.

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