HELIOSPHERIC MODELLING TECHNIQUES

ESA CONTRACT NO. 4000133080/20/NL/CRS

EXECUTIVE SUMMARY (ES)

APPROVAL

Title	
Issue Number 1	**Revision Number** 2
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Approved By	**Date of Approval**
(Technical Approval) Gregoire Deprez	
(Technical Officer) Piers Jiggens	

CHANGE LOG

Reason for change	Issue Nr.	Revision Number	Date
Initial version	1	1	13/11/2023
Second version	1	2	04/12/2023

CHANGE RECORD

Issue Number 0	**Revision Number** 1		
Reason for change	**Date**	**Pages**	**Paragraph(s)**
Document Creation	13/11/2023	all	Text corrections
Second revision issue number 1	04/12/2023	all	Text corrections and inclusion of ESA remarks
Third revision			

DISTRIBUTION

Name/Organisational Unit
Project team + ESA

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1. Introduction

This is the Executive Summary (ES) of the activities and results of the project "heliospheric Modelling Techniques", ESA Contract No. 4000133080/20/NL/CRS. This ambitious project maintained and improved the implementation of the heliospheric wind and CME evolution model EUHFORIA in the VSWMC, improved and upgraded the model in several ways, and integrated the modelling of CME-shockwave driven SEPs with EUHFORIA. The new and improved models were installed in the VSWMC test environment and used to model complex plasma structures resulting from CME-CME interactions and CME-CIR interactions, including their effects on SEP acceleration. The models were also validated by comparison with actual data.

1.1. Applicable documents

The following documents, listed in order of precedence, contained requirements applicable to the activity:

[AD 1] ECSS-E-ST-10-04C "Space Environment", Available from http://www.ecss.nl/

[AD 2] ECSS-E-ST-40C "Software", Available from http://www.ecss.nl/

[AD 3] VSWMC – Part 3, Federate Template ICD, Iss.01, Rev.07, 16/07/2019

[AD 4] VSWMC – Part 2, EUHFORIA federate ICD, Iss.01, Rev.07, 16/07/2019

[AD 5] VSWMC – Part 3, System Requirements document (SRD), Iss. 002, Rev. 0, 02/05/2019

[AD 6} VSWMC Architectural Design Document, SSA-SWE-XIV-VSWMC3-ADD, iss. 3.1

[AD 7] VSWMC Detailed Design Document, SSA-SWE-XIV-VSWMC3-DDD, iss. 3.1

[AD 8] VSWMC Component Design and Configuration Files Document, SSA-SWE-XIV-VSWMC3-CD-CF, iss. 2.1

1.2. Referenced documents

The following documents contained relevant information for this project:

[RD 1] J. Pomoell and S. Poedts; 2018; EUHFORIA: European heliospheric forecasting information asset; J. Space Weather Space Clim. 2018, 8, A35; DOI:10.1051/swsc/2018020

[RD 2] J. Pomoell et al.; 2015; Modelling large solar proton events with the shock- and-particle model; J. Space Weather Space Clim., 5, A12; DOI: 10.1051/swsc/2015015

[RD 3] R. Vainio et al.; 2014; A semi-analytical foreshock model for energetic storm particle events inside 1 AU; J. Space Weather Space Clim. 4 A08, DOI: 10.1051/swsc/2014005

[RD 4] R. Rodríguez-Gasén et al.; 2014; Variation of Proton Flux Profiles with the Observer's Latitude in Simulated Gradual SEP Events; Solar Physics 289:1745– 1762; DOI: 10.1007/s11207-013-0442-1

[RD 5] N. Wijsen et al.; 2019; Modelling three-dimensional transport of solar energetic protons in a corotating interaction region generated with EUHFORIA; A&A 622, A28; DOI: 10.1051/0004-6361/201833958

[RD 6] D. Odstrcil et al.; 2002; Merging of coronal and heliospheric numerical two- dimensional MHD models; JGR Space Physics, Vol. 107, Iss. A12; DOI: 10.1029/2002JA009334

[RD 7] C.N. Arge; 2003; Improved Method for Specifying Solar Wind Speed Near the Sun; AIP Conference Proceedings 679, 190; DOI:10.1063/1.1618574

[RD 8] D. Odstrcil and V. J. Pizzo; 1999; Distortion of the interplanetary magnetic field by three-dimensional propagation of coronal mass ejections in a structured solar wind; JGR Space Physics, Vol. 104, Iss. A12; DOI: 10.1029/1999JA900319

[RD 9] VSWMC - Phase 2 Final Report, Version 1.3, 07/03/2019

[RD 10] https://www.spenvis.oma.be/

[RD 11] Guidelines for common validation in the SSA SWE Network, Version 1.0, 12/03/2019

[RD 12] User Requirements Document, AO10125-HMT-URD-i001_r002.docx

[RD 13] Software Design Document, AO10125-HMT-SDD.docx

[RD 14] Technical Note 1, AO10125-HMT-TN1-PARADISE.docx

[RD 15] Technical Note 2, AO10125-HMT-TN2-ICARUS.docx

[RD 16] Technical Note 3, AO10125-HMT-TN3-COCONUT.docx

[RD 17] Design Justification File, AO10125-HMT-DJF-with-annexes.docx

1.3. Acronyms and abbreviations

ADD	Architectural Design Document
AMR	Adaptive Mesh Refinement
AR	Acceptance Review
ATR	Acceptance Test Review
ATS	Acceptance Test Specification
AU	Astronomical Units
CDCF	Component Design and Configuration File
CDR	Critical Design Review
CFI	Customer Furnished Item
CIR	Co-rotating Interaction Region
CME	Coronal Mass Ejection
COCONUT	COolfluid COroNal UnsTructured
“ -CME	COolfluid COroNal UnsTructured with flux-rope CME superimposed

COOLFluiD	Computational Object-Oriented Libraries for Fluid Dynamics
CRD	Customer Requirements Document
DDD	Detailed Design Document
DJF	Design Justification File
ENLIL	Sumerian god of winds and storms
ESA	European Space Agency
ESP	energetic storm particle
ESTEC	European Space research and TEchnology Centre
EUHFORIA	EUropean Heliospheric FORecasting Information Asset
FR	Final Report
GSTP	General Support Technology Programme
ICD	Interface Control Document
IPR	Intellectual Property Rights
JUICE	Jupiter Icy Moons Explorer
KOM	Kick-off Meeting
MCI	Model Coupling Interface
MHD	Magnetohydrodynamic
MPI	Message Passing Interface
MPR	Monthly Progress Report
MSL	Mars Science Laboratory
MTR	MidTerm Review
N/A	Not Applicable
ODI	Open Data Interface
PARADISE	PArticle Radiation Asset Directed at Interplanetary Space Exploration.
P2-SWE-I	Reference number of the SSA Programme procurement covering development of the ESCs activity
P2-SWE-XIV	Reference number of VSWMC Part 2 procurement
PDR	Preliminary Design Review
PFSS	Potential Field Source Surface
QR	Qualification Review
RSA	Review of the State-of-the Art

SCD	Spacecraft Designers
SDE	Stochastic Differential Equation
SEP	Solar Energetic Particle
SIR	Stream Interaction Region
SoW	Statement of Work
SPE	Solar Particle Event
SRD	System Requirements Document
SRelD	Software Release Document
SRR	System Requirements Review
STP	Solar-Terrestrial Physics
SW	Solar Wind
TN	Technical Note
TO	Technical Officer
TRL	Technology Readiness Level
TRR	Test Readiness Review
UR	User Requirement
VSWMC	Virtual Space Weather Modelling Centre
VVP	Verification and Validation Plan
VVR	Verification and Validation Report
VVS	Verification and Validation Specification
WSA	Wang-Sheeley-Arge

2. Background and objectives

Space weather conditions can cause substantial damage to space and ground-based infrastructures. More accurate space weather forecasting using physics-based models is required to better analyse, understand and then predict these phenomena, incl. CMEs and solar energetic particle events. Existing models fail to take into account the magnetic structure of CMEs while this affects their interaction with the (also magnetized) background solar wind and determines the geo-effectiveness of their impact. This issue is addressed in this project with the inclusion of flux rope CMEs in the simulations.

In the current project, EUHFORIA (EUropean Heliospheric FORecasting Information Asset) was further developed and flux rope CMEs have been implemented. A 3D model of SEPs was also created using EUHFORIA to provide the background plasma conditions. The specific objectives were:

- To maintain and improve the existing EUHFORIA implementation in VSWMC and to support the running costs and expand the running infrastructure;
- To update the EUFHORIA implementation in the VSWMC with the updates and improvements developed in this activity (or else) and to test and validate the new implementation;
- To integrate the modelling of SEPs with MHD code with CME-driven shockwave, CIR shock and acceleration up to 2 AU;
- To model complex plasma structures resulting from interactions between multiple CMEs and/or high-speed streams, along with their effects on SEP acceleration;
- To validate the updated model version up to 2 AU against actual and future SC data, such as Bepi-Colombo, JUICE, Solo or Maven.

3. EUHFORIA maintenance and upgrade

The implementation of EUHFORIA in the VSWMC has been significantly upgraded. For both EUHFORIA Corona and EUHFORIA Heliosphere, an 'expert mode' button has been created in the GUI. Switching on the 'expert mode' gives access to many more input parameters enabling to exploit the full potential of the models. For instance, for non-expert users, EUHFORIA Corona has only one input parameter, viz. the magnetogram, which can be selected form the GONG or the GONG-ADAPT catalog or uploaded by the users. All other input parameters are set to standard values. In the new 'expert mode', however, also the magnetogram resolution, smoothing parameter, source surface radius, inner radius, outer radius, etc. can be adjusted by the user. Moreover, the units of the expected input variables are specified and a short description of the meaning of the parameters is given.

The same applies for the new standalone version of EUHFORIA Heliosphere where the 'expert mode' enables to alter the input values of the MHD relaxation period, the forecasting window, the outer boundary (up to 5 AU), etc. Also the frequency of the snapshot outputs can be varied.

4. New models developed

Another objective of this project was to improve both the coronal model (polytropic MHD) and the heliospheric model (incl. grid stretching and AMR), as well as the CME model (upgrade to flux-rope CMEs), and the implementation of CME model that is launched in the low corona, well before 0.1 AU.

4.1. COCONUT

COCONUT is a novel global 3D coronal MHD model, polytropic in its first stage and based on a time-implicit backward Euler scheme. It solves the MHD equations in 3 dimensions on *unstructured meshes*. The coronal heating is taken into account via a polytropic wind with adiabatic index close to 1 to simulate an isothermal corona. This model boosts run-time performance in comparison with contemporary MHD-solvers based on explicit schemes, which is particularly important when later employed in an operational setting for space-weather forecasting. It is data-driven in the sense that synoptic maps are used as inner boundary inputs for our potential-field initialization as well as an inner boundary condition in the further MHD time evolution. More precisely, it uses a Poisson-solver to reconstruct the Potential-Field Source Surface (PFSS) magnetic field extrapolation from GONG (http://gong.nso.edu/data/magmap/QR/) or GONG-ADAPT (ftp://gong.nso.edu/adapt/maps/gong/) magnetograms at the surface of the star, and relaxes it to a quasi-steady MHD wind solution up to 21.5 $R_\odot$. The coronal model is coupled to EUHFORIA's heliospheric model at 21.5 $R_\odot$, where the solar wind is already supersonic. It provides a good compromise between accuracy and speed, using an *implicit method*, allowing convergence times that are acceptable for operational use.

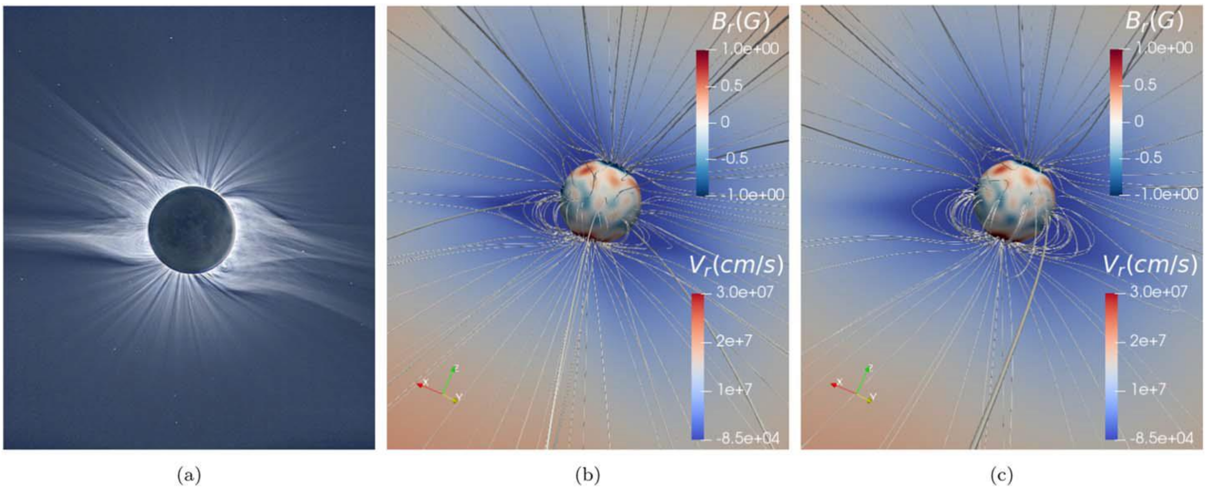


Fig. 1. *Comparison for 2008 August 1 GONG-corrected synoptic map case between a white-light composite eclipse picture (credits: J. C. Casado and D. López) (a), the COCONUT solution (b), and the Wind-Predict solution with its usual boundary conditions (c). For the simulations, the color scale shows the radial velocity V_r in units of centimeters per second. Magnetic field lines are traced in white. Source: Perri, Leitner et al. (2022).*

4.2. ICARUS

ICARUS is a new heliospheric model that has been implemented into the framework of the Message Passing Interface – Adaptive Mesh Refinement - Versatile Advection Code (MPI-AMRVAC; see Xia et al. 2018). Using a fixed grid, the functionality of the novel model is very similar to the ENLIL or EUHFORIA models. However, the MPI-AMRVAC framework enables us to explore the possibilities of using a (gradually) *radially stretched grid and AMR strategies* to further speed up the simulations. It was shown how grid stretching and solution AMR techniques can influence the performance and speed-up of 3D MHD solar wind and CME modelling. The computational domain of the model setup extends from 0.1 AU (21.5 $R_\odot$) to 2 AU in the radial direction. The latitudinal and longitudinal extent is ± 60 degrees and 360 degrees, respectively. Inner boundary conditions for the solar wind can be taken from any coronal model that produces solar wind conditions at 21.5 $R_\odot$, assuming that the conditions relating to the velocity and magnetic vector fields only contain radially outward or inward terms. Since the equations are solved in the co-rotating frame, and the inner corona is assumed to rigidly co-rotate with the Sun, the radial inner boundary conditions of the solar wind do not vary in time. At the outer radial boundary, at 2 AU (or further out if wanted/needed), continuous boundary conditions are used where the gradient of conserved variables is kept at zero by copying the variable values from the edges of the mesh into the ghost cells, while at the latitudinal boundaries a symmetric reflection is implemented.

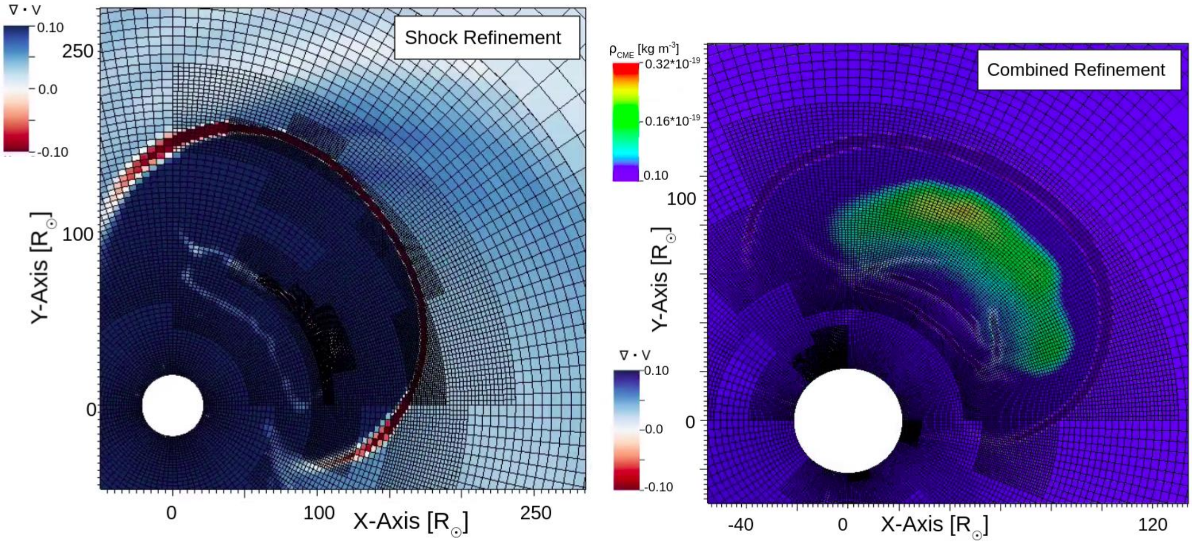


***Fig. 2**. Left: ($\nabla \cdot$ **V**) criterion from the AMR level 4 simulation run (yielding approximately the same radial resolution at L1 as a comparable equidistant grid simulation) focusing on the CME shock front. Blue and red denote areas of expansion and compression, respectively. Right: AMR level 3 for the combined AMR refinement criteria for the shock and CME density tracing functions. Source: Baratashvili et al. (2022).*

4.3. PARADISE

PARADISE (Particle Radiation Asset Directed at Interplanetary Space Exploration) is a model for energetic particle transport and acceleration in the solar wind that was developed by Dr. Nicolas Wijsen (PhD thesis Wijsen). It solves the focused transport equation by integrating the equivalent set of Itô stochastic differential equations forward in time for many pseudo-particles , while assuming a solar wind configuration obtained from a magnetohydrodynamic (MHD) model. PARADISE is written in C^{++} and uses the Message Passing Interface (MPI), to distribute the pseudo-particles over different threads. This is straightforward since the different pseudo-particles behave as test-particles, that is, they do not interact with each other, such that the SDE method represents an embarrassingly parallel problem. In PARADISE, the user can provide a list of individual spatial locations where the pseudo-particles need to be sampled, for example, corresponding to certain spacecraft locations. In addition, the user can prescribe an entire grid of sampling boxes covering large parts of the spatial domain, which allows to model in detail the spatial and temporal evolution of the differential intensity in large regions of the heliosphere but can be very memory consuming.

The PARADISE model has shown to be successful in modelling 3D transport of solar energetic protons in corotating interaction regions (generated with EUHFORIA), and to determine the interplanetary distribution of protons near a high-speed solar wind stream. It has been integrated in the VSWMC where it uses the time dependent MHD module of EUHFORIA to calculate different solar wind configurations that can contain CIRs, FSSs, and CMEs. Then it has been coupled to the upgraded version of EUHFORIA in the VSWMC framework.

To continuously inject particles at the CME-driven shock wave during gradual SEP events, it is crucial to have knowledge of the shock location and its jump conditions at every time step. Consequently, a shock tracer module has been integrated into the PARADISE toolchain. This Python module extracts CME-driven shock waves from the EUHFORIA data cubes and computes their properties by solving the Rankine-Hugoniot jump conditions at each point on the shock surface.

4.4. New flux-rope CME models

6.4.1 COCONUT-CME

The time-accurate evolution of modified Titov-Démoulin flux ropes have been implemented by superposing them on the COCONUT 3D MHD coronal model as an alternative to heliospheric simulations where transient structures are injected only at 0.1 AU. It was thus demonstrated that it is possible to use the new coronal model COCONUT to compute a detailed representation of a numerical CME at 0.1AU after its injection at the solar surface and propagation in a realistic solar wind, as derived from observed magnetograms.

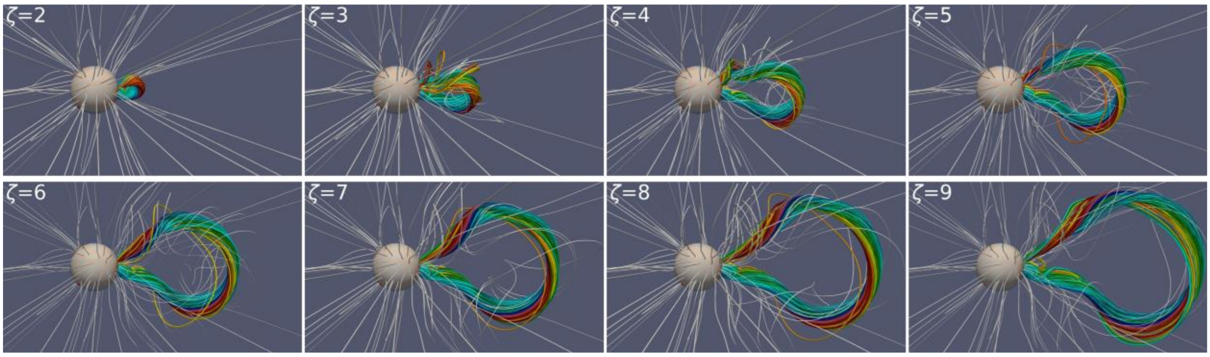


Fig. 3*. Visualization of all the flux ropes modeled in the solar wind reconstructed from a maximum of activity at the physical time t = 1:2 h. Source: Linan et al. (2023).*

The implementation of the modified Titov-Démoulin flux rope in COCONUT enables one to retrieve the major properties of CMEs at 0.1AU for any phase of the solar cycle. When combined with heliospheric simulations, COCONUT could lead to more realistic and self-consistent CME evolution.

6.4.2 Spheromak CME

The spheromak CME was already implemented in EUHFORIA (Verbeke et al., 2019), but it was not available to the VSWMC users. During this project, the GUI for the EUHFORIA model was upgraded, including an ‘expert mode’. The spheromak model is, however, available also to non-expert users even though it requires three additional input parameters, viz. helicity sign, tilt angle and magnetic flux, which are not straightforward to determine (Scolini et al., 2019). The fields to provide the values of these three extra parameters, appears in the menu when the spheromak CME model has been selected and the provided input values are verified, i.e., it is checked if they are in the expected range.

6.4.3 Flux-Rope in 3D (FRi3D)

The “Flux Rope in 3D” (FRi3D, Isavnin, 2016), is a coronal mass ejection (CME) model with global three-dimensional (3D) geometry. This advanced flux rope CME model has been implemented in the space weather forecasting tool EUHFORIA. By incorporating this advanced flux rope model in EUHFORIA, it is aimed to improve the modelling of CME flank encounters and, most importantly, the magnetic field predictions at Earth. After using synthetic events to showcase FRi3D’s capabilities of modelling CME flanks, the model has been optimized to run robust simulations of real events and test its predictive capabilities. Observation-based modelling has been performed of the halo CME event that erupted on

12 July 2012. The geometrical input parameters were constrained using the forward modelling tool included in FRi3D with additional flux rope geometry flexibilities as compared to the pre-existing models, incl. the spheromak model. The CME was evolved in EUHFORIA's heliospheric domain and a comparison of FRi3D's predictive performance with the previously implemented spheromak CME in EUHFORIA has been presented (Maharana et al., 2022).

6.4.4 Toroidal CME models

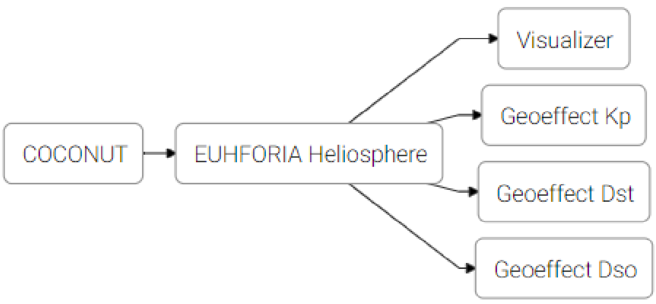
Also two analytical toroidal CME models have been implemented in EUHFORIA. One model is based on the modified Miller-Turner (mMT) solution, while the other is derived from the Soloviev equilibrium, a specific solution of the nonlinear Grad-Shafranov equation for the magnetic flux. The magnetic field distribution in both models is provided in analytic formulae, enabling a swift numerical computation. It was shown that the Soloviev model allows control over the shape of the poloidal cross section, as well as the initial twist. In EUHFORIA, different thermodynamic and magnetic profiles are obtained depending on the CME model used. The generated magnetic profiles reflect the initial magnetic field distribution of the chosen model. It was found that changing the initial parameters affects both the amplitude and the trend of the time profiles.

Both toroidal CME models have been successfully implemented in EUHFORIA and can be utilized to predict the geoeffectiveness of the impact of real CME events. Moreover, the current implementation could be easily modified to model other toroidal magnetic configurations.

5. New models couplings

The newly developed models, COCONUT and ICARUS, are alternatives for the coronal and heliospheric parts of EUHFORIA, respectively. They have been designed such that they are interchangeable, i.e., COCONUT can be coupled to EUHFORIA Heliosphere as well as to ICARUS, and also the original WSA-like coronal model in EUHFORIA can be coupled to ICARUS.

5.1. COCONUT+EUHFORIA



COCONUT has been coupled to EUHFORIA Heliosphere and to the EUHFORIA Visualizer and some empirical geo-effect index models (see the schematic representation of this model chain taken from the VSMWC). This model chain enables to extend the solar wind all the way to 1AU and beyond. However, it must be taken into account that the current version of COCONUT is a polytropic MHD model (like Wind-Predict). This means that the coronal heating and acceleration is achieved by considering a lower value of gamma, the ratio of specific heats., namely 1.05. As a result, the wind is accelerated to reasonable values but a polytropic MHD model does not yield a bimodal wind.

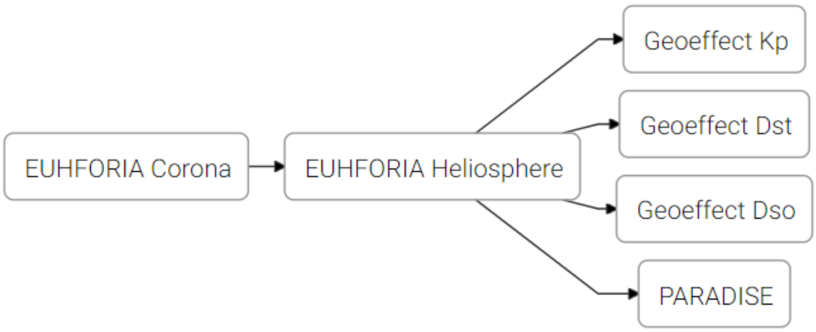
5.2. EUHFORIA Corona + ICARUS and COCONUT + ICARUS

In order to demonstrate the interchangeability of the coronal models, both EUHFORIA Corona and COCONUT were coupled to the novel heliospheric wind model ICARUS. The EUHFORIA Corona + ICARUS model chain has been tested and validated in detail by Verbeke et al. (2022), and by

Baratashvili et al. (2022). The COCONUT + ICARUS model chain does not yield a bimodal wind for the moment due to the fact the COCONUT is a polytropic MHD model.

5.3. EUHFORIA + PARADISE and COCONUT+ EUHFORIA + PARADISE

The particle acceleration and transport model PARADISE has been coupled with EUHFORIA within the VSWMC. These non-trivial model couplings require a lot of CPU time and computer memory/storage because the outer boundary of the heliospheric simulation needs to be further out, e.g., at 4 or 5 AU, and the full 3D results need to be stored with a frequency of at least 15 min, and preferable higher, 10 min or even 5 min. The COCONUT + EUHFORIA + PARADISE model chain in the GUI thus allows to provide the outer edge, as well as some other essential input parameters for PARADISE.



6. Complex CME-CME interactions and effect on SEPs

The integration of EUHFORIA and PARADISE has been validated using data from satellites for numerous complex SEP events.

6.1. 14 July 2021 SEP event

A study conducted by Wijsen et al. in 2022 used PARADISE and EUHFORIA to model the energetic storm particle (ESP) event that occurred on July 14, 2012. The results of this simulation provided valuable insights into the strengths and limitations of the employed models. The findings revealed that these models successfully captured essential structural features of the ESP event. However, there were areas where the simulations did not align with observations. The authors of the study identified and assessed the sources of errors within the modelling chain of EUHFORIA and PARADISE. They also discussed potential strategies for mitigating these errors in future simulations.

6.2. 9 October 2021 SEP event

Wijsen et al. in 2023 simulated the gradual SEP event 0g 9 Oct 2021. Using the EUHFORIA model, they accurately replicated both the solar wind conditions during the event and the associated CME that initiated it. Figure 4a provides a snapshot from this EUHFORIA simulation, revealing the CME and the high-speed solar wind stream driving the SIR. Subsequently, the EUHFORIA simulation was coupled with the energetic particle transport model, PARADISE. The authors of the study noted that the structure of the CME-driven shock wave was significantly impacted by the nonuniformity of the solar wind, particularly near the SIR. This nonuniformity led to notable variations in the shock wave's properties, including its compression ratio and obliquity. To achieve an accurate alignment between the PARADISE simulation and in situ measurements of ions with energies $\lesssim 5$ MeV, the authors scaled the emission of energetic particles from the shock wave to the compression of the solar wind at the shock. This scaling yielded an excellent match, as demonstrated in the top right panel of Figure 4, which highlights a comparison between ACE/EPAM data and the PARADISE simulations. The modelling results underscore that the intricate intensity variations observed at both ACE and BepiColombo were influenced by the nonuniform emission of energetic particles from the deformed shock wave. Furthermore, the study illustrated how even modest background solar wind structures can have a notable impact on the development of SEP events.

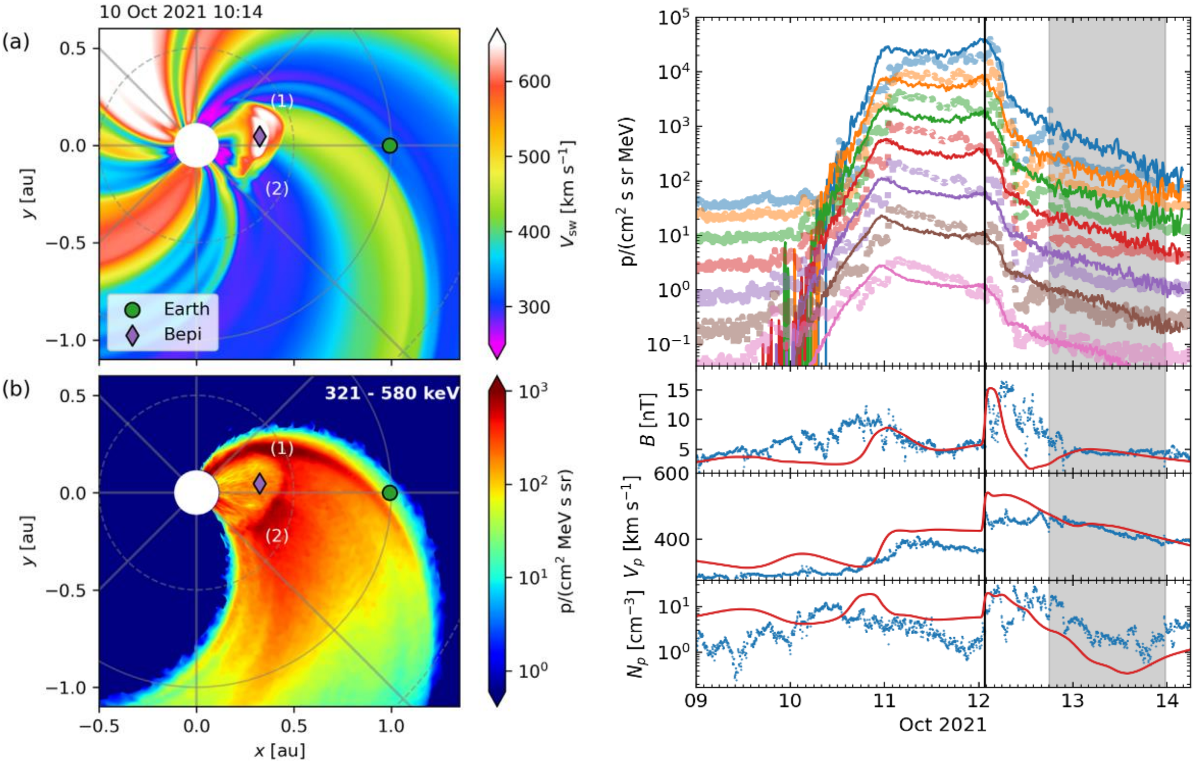


***Fig. 4**. Panel (a) shows a snapshot of the modeled solar wind speed on 2021 October 10 at 10:14 UT when the CME nose was 0.45 AU. Panel (b) displays the modeled omnidirectional 321–580 keV proton intensities for the same time. The right panel shows, from top to bottom, the energetic particle intensities, the magnetic field magnitude, the solar wind proton speed, and number density at Earth. The background dots represent spacecraft observations whereas the solid lines correspond to the PARADISE and EUHFORIA simulation results. Source: Wijsen et al. (2023).*

6.3. 15 March 2013 SEP event

The research conducted by Niemela et al. in 2023 used the EUHFORIA + PARADISE toolchain to examine the effects of perturbed solar wind conditions resulting from multiple Interplanetary Coronal Mass Ejections (ICMEs) on the evolution of SEP distributions. Additionally, it showcased the practical application of SEP models in assessing the accuracy of solar wind and CME models. To exemplify these principles, the study centered on modeling the gradual SEP event that transpired on March 15, 2013.

In this study, we utilized the 3D MHD model EUHFORIA to simulate the various ICMEs responsible for the highly perturbed solar wind conditions observed during the March 15, 2013 event. We conducted three separate EUHFORIA simulations, employing both non-magnetized and magnetized models for these ICMEs. Next, to analyze the behavior of energetic particles in simulated solar wind environments, the energetic particle transport and acceleration model PARADISE was employed.

7. Conclusions

Our recommendations for the next steps in the HMT development, based on the experiences and the developments in this project are:

- Upgrade the implemented models and model chains to the accessible VSWMC system. This is a lot of work as it requires the acceptance test procedure to be followed. This involves the development of an acceptance test plan, the acceptance tests themselves, and then an acceptance test report.
- The COCONUT model needs to be upgraded to full MHD, i.e., including appropriate combinations of heating and loss terms (radiation and thermal conduction), so that a bimodal wind is obtained which enables to better model the observed events.
- The COCONUT model needs to be coupled to EUHFORIA and/or ICARUS in a dynamic way, i.e., with a time dependent interface, so that the flux-ropes launched in COCONUT can travel through the boundary between the two models (at 0.1 AU) and evolve all the way to 1 AU and beyond. The current connection is only steady. A dynamic coupling is non-trivial but we already adopted ICARUS so that it can handle time-dependent input, e.g., varying magnetograms yielding an evolving background wind. This should also be implemented in the VSWMC.
- PARADISE should also be coupled to COCONUT so that the SEP events can be modelled form the low corona onwards. This is nontrivial because COCONUT uses an unstructured grid, so the shock tracer and particle tracer need to be adapted. Alternatively, one could interpolate the COCONUT corona on a regular spherical grid first, but it needs to be checked how robust and time consuming that is.
- The shock tracer in PARADISE needs to be upgraded so that it can handle multiple shocks, which is again nontrivial.
- The FRi3D and the new torus CME models should be implemented in the VSWMC version of EUHFORIA, i.e. the GUI should be adjusted to include these options.
- ICARUS currently includes only the cone and spheromak CME models. One could/should also implement FRi3D and the new torus CME models.
- The model chains can be extended to include more models so these can also profit form the upgrades of EUHFORIA implemented in this project.
- The users should be able to download all the output files of their simulations. These files are on the cluster but (not all) the users do not have an account on the cluster and only login to the VSWMC system which is installed on a virtual server. The data is so large that it cannot be copied to this server, so another solution must be worked out.