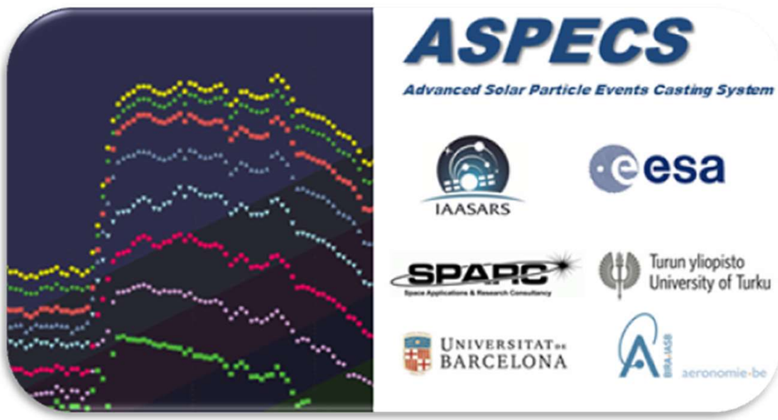
Advanced Solar Particle Events Casting System
ASPECS



Solar Energetic Particle (SEP) Advanced Warning System (SAWS)

ESA Contract No. 4000120480/17/NL/LF/hh

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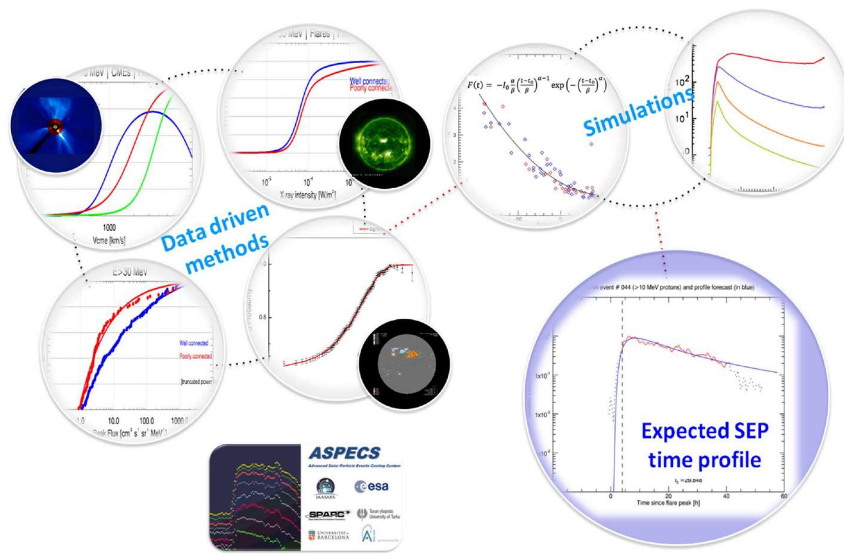
Abstract

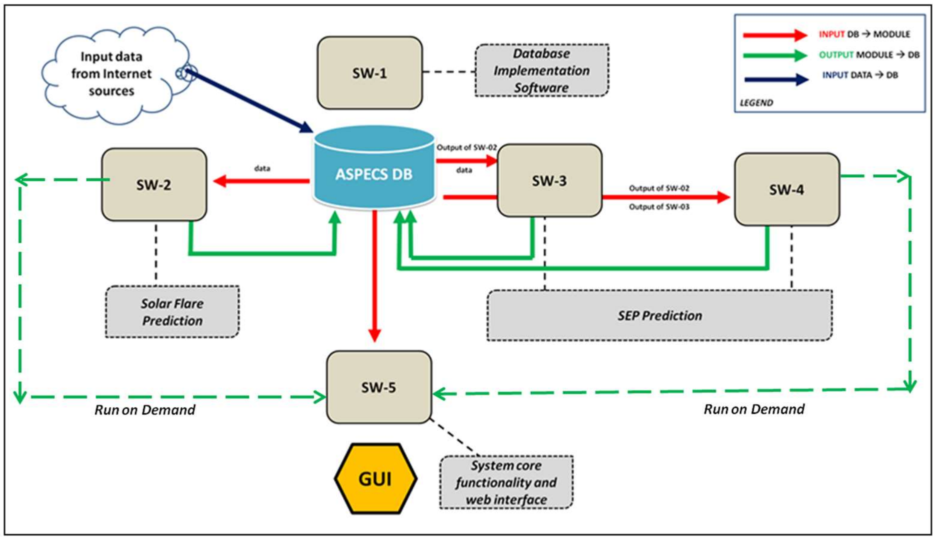
The SAWS-ASPECS system provides SEP occurrence probabilities as well as the time profile of the expected SEP event based on data driven statistical analysis and simulations starting from solar flare and CME characteristics. The SAWS-ASPECS system incorporates two basic operational modes: the forecasting (pre-event or pre-flare) and the nowcasting (post-event) mode. Concerning the pre-event forecasting mode, the starting point is the flare prediction, provided by SW-2. The outputs of the flare prediction are utilized by SW-3 and SW-4 to provide a conditional likelihood of SEP occurrence and an estimation of the expected characteristics (e.g. peak flux and duration) of the forthcoming SEP event, with errors for different energies and as a function of different forecasting horizons. The main idea of the system is presented in the Figure below.



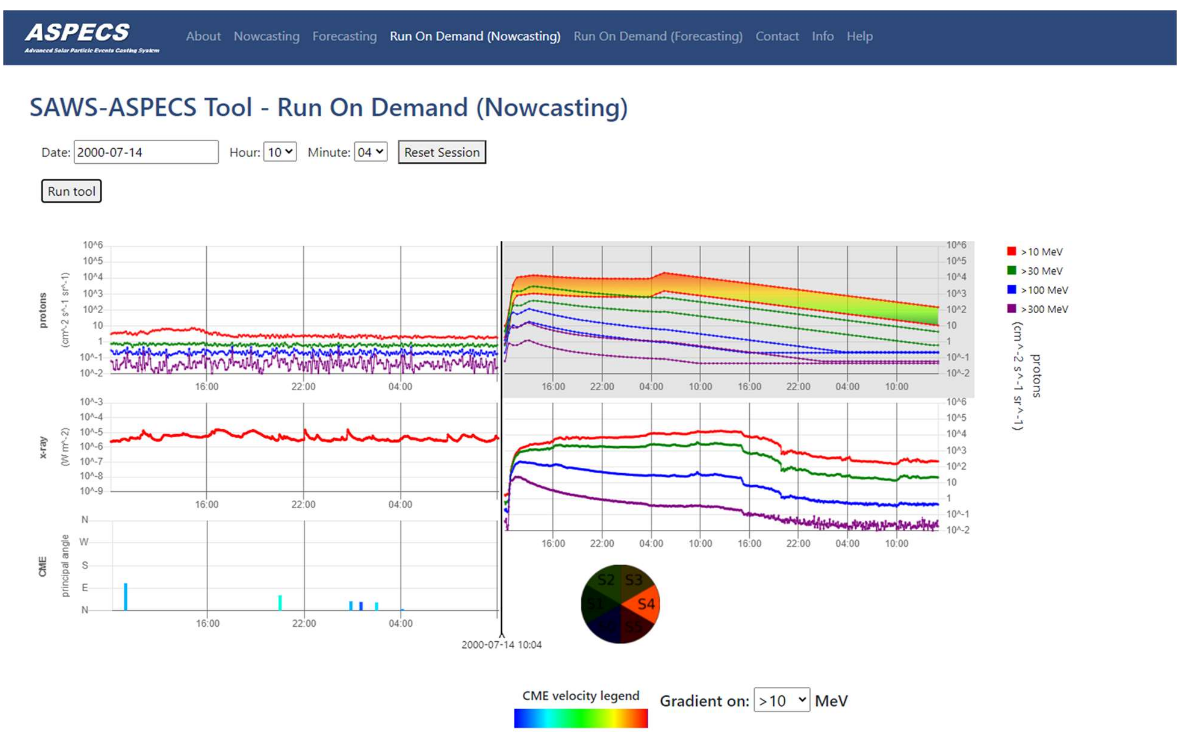
Research developments in the core of SAWS-ASPECS system

Furthermore, in the post-event nowcasting mode, different inputs from external data are utilized. In particular, SAWS-ASPECS make use of the SXR information (longitude and SXR peak flux), the width and speed of the CME, as well as possible combinations of both solar inputs (i.e. flare, CME). In addition, once a parent solar event signifies an enhanced probability for the occurrence of an SEP event, *in-situ* electron recordings are considered in order to identify the opening of magnetic field lines and the release of electrons into open magnetic field lines. This is used as an indicator that particles are not confined and thus that an actual SEP event is expected. Moreover, the recordings of near-relativistic protons from ground based neutron monitors are also utilized in a similar manner. In this mode, the time profile of the expected SEP event is also provided for a set of pre-defined energies.

The technical set up of the SAWS-ASPECS system is presented in the Figure at the top of next page. The ASPECS database (SW-1) holds a central role in this design since all other modules (SW-2 to SW-4) receive data and send their outputs from and to the SW-1, respectively. Finally, the web interface and the GUI (SW-5) have direct access to SW-1 and communicate the derived outputs to end users. An example of the output of ASPECS for the case event of July 2000 is presented in the Figure at the bottom of next page.



A schematic representation of the SAWS-ASPECS technical set up, which is being implemented around SW-1 (ODI database)



Run-on-demand for the case study of 14th July 2000.

Contents

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Summary Report

Solar eruptive events, such as solar flares and coronal mass ejections (CMEs), often produce space storms that affect the interplanetary and near-Earth environment. Flares are violent eruptions that take place in active regions whereas the CMEs are ejected from the Sun during several hours. Solar flares can spew vast quantities of electro-magnetic radiation (gamma and X-rays) and energetic particles (protons and electrons) into space while CMEs disrupt the flow of the solar wind and produce disturbances that strike the Earth with sometimes catastrophic results.

Solar Energetic Particle (SEP) radiation storms occur when solar eruptive events accelerate particles resulting into enhanced levels of radiation. Such enhancements pose a significant risk for satellites, communications, launchers and humans in space and on polar aircraft flight paths orbits. Although the scientific community managed to overcome certain past obstacles and developed forecasting tools able to issue alerts on SEP events and thus provide forewarning, forecasting SEP events, because of their sporadic nature, remains a non-trivial task. Furthermore, full understanding of the mechanisms associated to the generation, acceleration and propagation of SEP events is still missing due to its inherent three-dimensional nature, the lack of widely spatially distributed in situ observations and the complex nature of the underlying physical processes.

Improvement of forecasting capabilities for both solar eruptive and SEP events is therefore a vital necessity. To this end, the objective of the ASPECS activity is to advance and develop reliable and operational tools for the prognosis of SEPs, solar flares and CMEs. Although from the modeling point of view solar flares, CMEs and SEPs are closely related to each other, from the forecasting and warning viewpoint these phenomena are quite different due to the very different time scales in which they reach the Earth's orbit.

The main objective of ASPECS is to develop a web based tool capable of making 3-tier forecasts and nowcasts of solar flares and SPEs, to support ESA operations (such as, launch and spacecraft operations and human spaceflight as well public airlines). The tool consists of five modules/elements: the database supporting handling of external and internal data (SW-1), a module for forecasting the likelihood of upcoming solar flare eruptions (SW-2), a module targeting the forecasting/nowcasting of the occurrence of SEPs (SW-3), a module aiming on the forecast/nowcasting of the SEP flux profile for an upcoming event including synoptic information on the peak intensity and duration (SW-4), and finally a module for the presentation of results to the targeted end user community (SW-5). The approach delivered by ASPECS aims to give end users sufficient lead time to implement necessary preventive measures.

Solar Flares

Solar flares (SFs) are sudden, violent and very energetic explosions occurring in active regions (ARs) around sunspots. They are powered by sudden large changes of the local magnetic field topology through reconnection processes that lead to huge releases of magnetic energy [RD03]. This energy release in turn leads to plasma heating, particle acceleration and mass transport and produces electromagnetic radiation across the electromagnetic spectrum at all wavelengths from long wave radio to the shortest wavelength gamma rays. During a large solar flare, the X-ray flux increases by many orders of magnitude compared to the pre-flare X-ray levels.

Coronal Mass Ejections - CMEs

Coronal mass ejections (CMEs) are magnetized structures which are ejected from the solar upper atmosphere. When a CME is produced over an active region, it is very likely to have enough energy in order to propagate into the interplanetary medium. These interplanetary counterparts of CMEs which are produced at the Sun are the interplanetary CMEs (ICMEs). The arrival of these ICMEs at Earth often produces geomagnetic effects as they interact with the magnetosphere of the Earth and as a result geomagnetic storms occur [RD04].

Solar Energetic Particles - SEPs

Solar Energetic Particles (SEPs) are observed as flux increases above a background level, and their energies range from ~ 10keV to 10GeV/nuclei, while their duration can last from a few hours to several days. SEPs consist of electrons, protons, alpha particles and heavier ions up to Fe and their arrival to Earth spans from hours to a few days [RD03].

The classical paradigm is to divide SEP events into two categories: the impulsive and the gradual ones based on their parent solar events [RD03]. Impulsive SEP events are considered to be associated to SFs, while the gradual ones are considered to be accelerated by CME--driven shocks. Both the impulsive and gradual SEP events are defined by the magnetic topology of their parent solar sources with the underlying fundamental difference between the two categories of SEP events being present in the acceleration mechanisms: impulsive SEP events stem from resonant stochastic acceleration, while gradual SEP events from shock acceleration.

Nonetheless, this "two class" picture has proved to be an oversimplification and does not match the diversity and wealth of the observed SEP event properties. Furthermore, observations have shown that there is a third category of evens, the so--called hybrid or mix events during which both SFs and CME--driven shocks accelerate particles that contribute to large SEP events. These hybrid events look like gradual events but demonstrate properties of impulsive ones. Such hybrid SEP events may result from the re-acceleration of remnant ions from previous impulsive and gradual SEP events by shock waves and from the interaction of CMEs.

Furthermore, the time-profile of SEP events is organized with respect to the relative position of the spacecraft to the longitude of the parent solar source. ***Figure 1*** presents that multi-spacecraft view of SEP events.

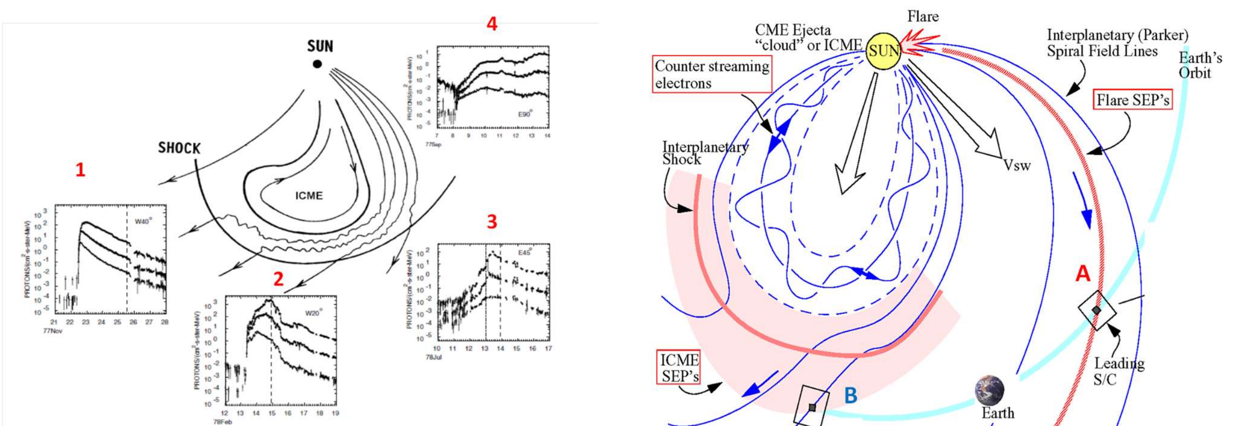


Figure 1: An illustration of the multi-spacecraft scheme and the expected time-profile of the SEP event with respect to its position

1.1. SW-1

SW-1 refers to the implementation of the database of time series data of the system. This database is based on MySQL using the ODI[1] system. ODI consists of a set of scripts and libraries to aid in storing, updating and querying data and metadata. As ODI has clients for Java, Python (via a Python library or the REST API), PHP, Matlab, and IDL it permits the use of the respective language libraries to read data from an ODI dataset into the preferred language's native data structures for a certain time range. In ASPECS the SW-2 to SW-5 components use the ODI API to query data (either latest real-time data or historical data) from the available datasets.

Downloading, parsing and ingestion processes are performed periodically for each dataset under cron control. ODI coordinates these actions and executes them periodically; the (download, parsing) software created for ASPECS uses the ODI conventions to define these scripts for each dataset. By adhering to the ODI conventions, external dataset definitions and parsers are not specific to ASPECS and can be extracted from the SAWS-ASPECS system and reused in other work, or included in the ODI distribution maintained by ESA.

The data distribution into the SAWS-ASPECS modules is based on the HTTP ODI REST interface making the input data to the SAWS-ASPECS modules available in JSON or CSV format. Data access is available exclusively to the SAWS-ASPECS modules with standard access control mechanisms imposed by the ASPECS system network. The network is a LAN where all system internal services are unauthenticated but non-accessible from the wider network, except for the SW-5 frontend which serves a public facing web service.

There are multiple containers implemented that hold: (i) the ODI database, (ii) the API of the database, (iii) SW-2 and its API, (iv) SW-3 and its API, (v) SW-4 and its API and (vi) the web-server and front end of the SAWS ASPECS tool.

The connections between the different containers is depicted in ***Figure 2***

[1] ODI reference: https://spitfire.estec.esa.int/trac/ODI/wiki/OdiManual

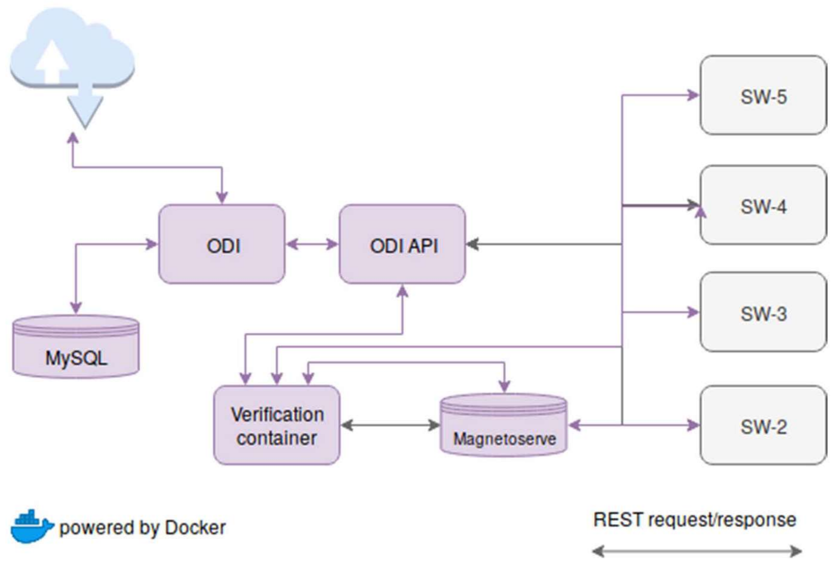


Figure 2: The connections/communication between the containers of the SAWS-ASPECS tool

1.2. SW-2

The analysis for the Bayesian conditional flaring cumulative probabilities for the next 6, 12, 24, 48 and 72 hour forecasting windows was performed using as predictor the B_{eff} LOS (line of sight) historical data for the period September 2012 – December 2018, for 2313 days in total, using FLARECAST property service. The FLARECAST property service provides data for more than 100 flaring predictors about active regions which identified on the Sun by time, location and HARP number.

The Solar Flare prediction module (SW-2) is built upon the operation flare-prediction method introduced by [RD05], utilizing the "effective connected magnetic field strength" (B_{eff}) prediction metric. This is given by

$$B_{eff} = \sum_{i=1}^{N_+} \sum_{j=1}^{N_-} \frac{\Phi_{ij}}{L_{ij}^2}$$

The B_{eff} metric has been successfully used within the FORSPEF and A-EFFort ESA activities, while its results have been validated in detail [AD03]. In the FORSPEF precursor activity, B_{eff} was automatically applied to routinely downloaded latest solar magnetograms from SDO/HMI identified by ARIA, leading to typical 24-hour flare forecast windows, with forecasts renewed every 3 hours [RD05].

SW2 of the ASPECS activity implements the forecasting of the occurrence of a solar flare based on the existence or not of an active region. For a given SHARP magnetogram of an AR the B_{eff} value is been calculated using a submodule (B_{eff} calculation) and then this value of B_{eff} is imported to an another submodule (Flaring probabilities) which is based on the double sigmoidal functions that were identified through the Bayesian analysis of the data obtained by FLARECAST database.

The output of this submodule contains the C1 up to X10+ (28 classes) flaring probabilities for the next 6, 12, 24, 48 and 72 hours forecasting window. Finally, the flaring probabilities are implemented to the final submodule of SW2. This final output file contains the CME likelihood probabilities for each one case of the 28 previous solar flare classes as well as the maximum linear speed near the Sun of the associated CME (***Figure 3***).

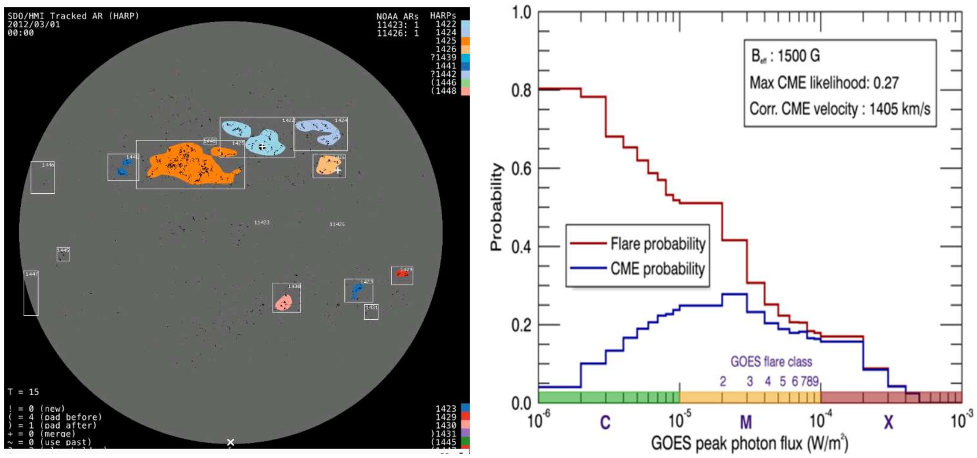


Figure 3: An SDO/HMI magnetogram processed with SHARP (panel on the left hand side) and the corresponding outputs of SW-2 (panel on the right hand side).

The SAWS-ASPECS SW-2 module baseline features the following *sub-modules*:

1. Reliance on the SDO/HMI near real-time SHARP region-of-interest data. Calculation of B_{eff} for each HMI SHARP magnetogram.
2. For the calculated B_{eff} value from the previous sub-module the 6, 12, 24, 48 and 72-hour cumulative flare forecasts are calculated for GOES flare classes from C1.0 to X10.0+, without latency. Renewal of flare forecasts every 3 hours.
3. 6, 12, 24, 48 and 72-hour CME likelihood probabilities for GOES flare classes from C1.0 to X10.0+ to be eruptive as well as the maximum near the Sun CME speed.

A schematic of SW-2 is provided in ***Figure 4***.

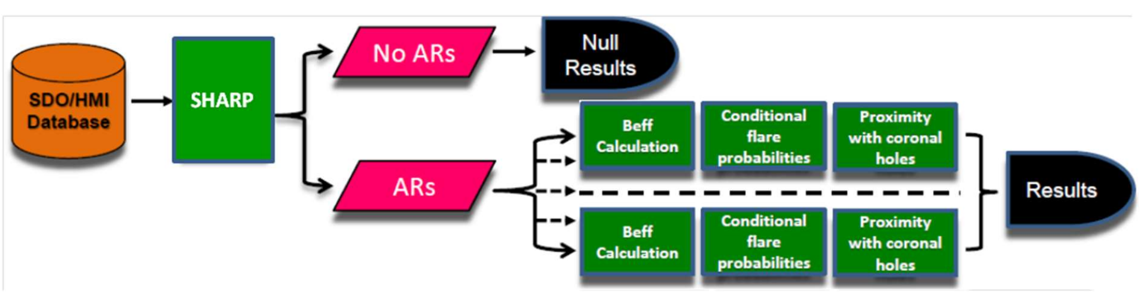


Figure 4: A schematic representation of the extension of the B_{eff} metric technique for SAWS-ASPECS utilizing SHARP

The reliance on HMI SHARPS in *sub-module 1* above eliminates the limited CMD issue that ARIA used to have. ARIA was applied up to 70° EW CMD, while SHARPs are obtained over the entire Earth-facing solar hemisphere, from E to W limb.

The discontinuation of the HMI-to-MDI emulation in *sub-module 2* above, applied so far in order to make use of the MDI database where the statistics of B_{eff} were based, is made possible due to the exploitation of the FLARECAST predictor database. Working since the SHARP database initiation in September 2012, the EU FLARECAST project has generated an openly accessible database of B_{eff} (and about 100 more flare predictors) with a cadence of 3 hours and, hence, with sufficient statistics to build cumulative distribution functions (CDFs) in the same way these were built using SOHO/MDI statistics.

1.3. SW-3

The SW-3 of the ASPECS activity implements both the forecasting and the nowcasting of the occurrence of an SEP event. The former utilizes the input provided by SW-2 while the latter depends on near real-time solar data ingested in SW-1 and then parsed to the module. The nowcasting module incorporates several sub-modules depending on the actual parent solar event utilized at each time. In particular there are three basic sub-modules: one that utilizes CME input, one that utilizes solar flare inputs and one that takes into account both inputs. These sub-modules provide the expected probability for the SEP occurrence together with the error for given confidence levels.

The basic input of the nowcasting sub-modules of SW-3 are the near-real time external data continuously ingested in SW-1, namely:

- CACTus - that provides a near-real time identification of CMEs with a refreshing rate of six hours.
- GOES soft X-rays measurements, updated every 1 and every 5-min respectively
- GOES latest flare reports, that provide identification of the actual flare characteristics (i.e. start time, peak time, peak flux, end time)
- GOES latest identification reports that provide the associated Active Region (AR) of the parent solar flare[2]

The SEP prediction scheme is based on a statistical approach relying on an extensive database of SEP events including information on their parent solar events [AD03, RD03]. For a given solar flare with known characteristics (e.g. magnitude, location) and /or coronal mass ejection (CME) (i.e. width, velocity) ASPECS is in place to provide forecasts (and/or nowcasts) of the SEP occurrence and the corresponding SEP characteristics in terms of confidence levels, using processed catalogues of

[2] This part refers to *https://services.swpc.noaa.gov/text/solar-geophysical-event-reports.txt* which is updated every 5-minutes. However, we are currently testing a combination of *https://services.swpc.noaa.gov/json/solar_regions.json* for the identification of the location and *https://services.swpc.noaa.gov/products/latest-xray-event.json* for the identification of the latest flare records.

historical data. All data on parent solar events (i.e. flares and CMEs), as well as the forecasted (nowcasted) SEP occurrence probability is stored in the ODI database (SW-1).

Effort has been assigned to the implementation of this database and currently it spans from 1976 to 2017 (May) - almost 3 1/2 solar cycles (SCs). Our initial sample consists of 49546 ≥ C-class SFs that cover the whole aforementioned time period. However, the unobstructed monitoring of CMEs practically started with the launch of the SOHO and in particular with the use of LASCO in the end of 1996 with the data flow stabilized in the start of 1997. This leads to a gap of continuous CME data between 1976 and 1997.

In parallel a search for SEP events was conducted. This is based on the scanning of the 7.23 - 10.46 MeV differential energy channel of the SEPEM reference dataset. An initial list compiled by UdB during the SOL2UP project and spans from 1988 to 2013 and includes a total of 172 SEP events. It includes protons from the SEPEM-RDS-v2-01 set, covering the differential energies from 5 up to 200 MeV.
Based on the SEP list of the SOL2UP the integral fluxes for a set of energies (i.e. E>10-; >30-; >60- and > 100 MeV) have been calculated based on the SEPEM reference data set (RDS) (***Figure 5***).

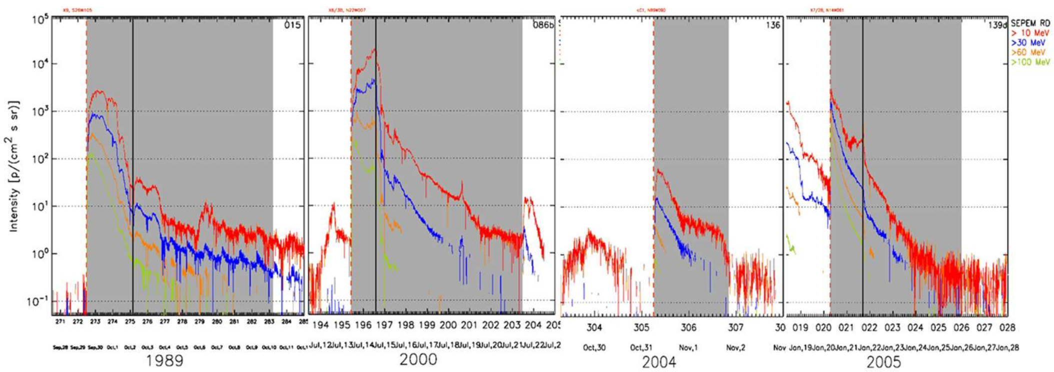


Figure 5: Examples of the calculated integral fluxes for several SEP events (E>10 - red line; E>30 MeV - blue line; E>60 MeV - orange line and E>100 MeV - green line)

It further ingests data for high energy protons from GOES HEPAD creating a dataset at E>300 MeV spectrally consistent with the SEPEM RDS, as well as near-relativistic electron measurements from ACE/EPAM within the energy range 0.047 to 1.060 MeV. The SEP part of the statistical core is completed with high energy recordings from neutron monitors, up to approximately 4.15 GeV (5 GV in rigidity), for the SEP events of our sample that also give rise to ground level enhancements (GLEs).

The differential energy channels are used as input for the calculation of the integral energies that are the outputs of the ASPECS system. These energy channels are E>10-; >30-; >100- and >300 MeV.

The SEP onset forecast module of SW-3 calculates a probability distribution function for SEP occurrence based on historical data. It provides a total probability of SEP occurrence using as input the output of SW-2 and should the calculated probability exceed a certain threshold it issues an alert. The inputs used are:

- The Active Region (AR) solar longitude

- The cumulative flare distribution from SW-2.
- An historical dataset of 2187 flares containing the respective AR solar longitude, the flare magnitude, an SEP occurrence index (0/1) for the 10 MeV, 30 MeV, 60 MeV, 100 MeV, and 300 MeV integral flux and the accompanying SW-2 output. The datasets spans the period from 1997/04 to 2006/09.

For each monitored AR the module derives a probability of SEP occurrence which is essentially a bound probability given that a flare with magnitude within a bin's limits value has also occurred. The product of the flare and SEP probabilities produces the final output. The flare and SEP probabilities are binned into 6 bins of flare magnitude, specifically: C1-C4, C4-C7, C7-M1, M1-M6, M6-X1, X1-X10+.

A probabilistic approach has been considered across all sub-modules in the ASPECS project. In particular, as concerns the developed methodology, we first considered the conditional CDFs of SEP and non SEP events. In order to implement the resulting distributions for the CME inputs we first imposed three angular width ranges: ***full halo*** (AW = 360°), ***partial halo*** (120° ≤ AW ≤ 359°) and ***non-halo*** (AW ≤ 119°) and then we sorted the data for each bin based on their CME speed.

A similar probabilistic approach was further applied for solar flare inputs imposing two longitudinal width ranges: ***well connected*** (lon ≥ 20°), ***poorly connected*** (lon ≤ 20°). This method is implemented in the system.

Once a solar flare (with known magnitude and longitude) or a CME (with known angular width and speed) has been identified, we can nowcast the probability of the SEP occurrence. In particular, the obtained fits are used under the Bayes method but enforcing more conditions, depending on the obtained characteristics (e.g. flare longitudinal bin and magnitude, CME width and velocity). In this case, all combinations should be considered (e.g. Halo, Partial halo and Non halo, with well and poorly connected) for all respective energies. ***Figure 6*** depicts derived probability of SEP occurrence using both flare and CME inputs for the case of Halo and well connected events.

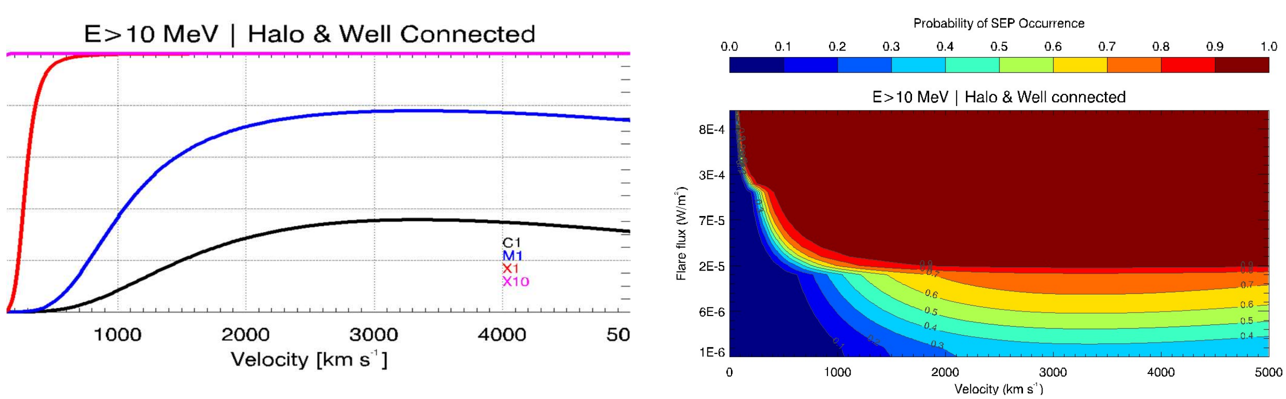


Figure 6: The derived probability functions per flare magnitude, for Halo and well connected events as a function of the velocity of the CME (left hand side) and a corresponding contour plot (right hand side)

1.4. SW-4

The SW-4 of the ASPECS activity implements both the forecasting and the now-casting of the SEP time-profile.

In the *forecasting mode* the SEP time profile is based on the estimated I_{peak} from SW-3 and the simulated SOLPENCO-2 profile closest to the origin of the event, since no SEP event is actually in progress while this mode is in operation. A pre-selection of the profiles is performed based on the predicted flux of the event at high energies; e.g., if an event is predicted to be above background at >300 MeV channel, only a subset of SOLPENCO-2 curves are used.

Once an SEP probability of occurrence is established (SW-3), we can further, identify the expected characteristics of the SEP event (SW-4). We compared the SOLPENCO2 approach with the empirical approach by Kahler and Ling by fitting the dozen events that are the basis of the SOLPENCO2 tool with the modified Weibull functions in the 7.23 - 10.46 MeV energy channel. The fitting results were statistically consistent with the full set of 217 SEP events that we studied to establish the empirical prediction model: a consistent fraction of events could be well represented by the modified Weibull profiles and the parameters of the fitted SOLPENCO2 events were not outliers in the full sample. This similarity suggests a way forward to integrate these approaches in the following way:

Before the commencement of the flare, we use the most probable (or chosen at some confidence level) predicted flare parameters (location and time of peak intensity of the flare and predicted peak flux in the high-energy channels) to select the input to SOLPENCO2 model for the intensity time profile of the event. This is used as the prediction of the SEP event modifying the prediction as the predicted flare parameters change over time. For example, once SW-2 provides the location of the AR and the expected maximum CME velocity, these are used as proxies from the ASPECS database, fed to the database of SOLPENCO2 and from there derive the simulated time profile of the expected SEP event in respective pre-defined energies.

As soon as a flare commences, the tool switches to using the observed flare as the input to SOLPENCO2. This prediction is used as long as the prediction of the SEP time-intensity profile is not at odds with the observations of the SEP flux.
In case no SEP event is observed although SOLPENCO2 would already predict that one is commencing, the tool switches to using the appropriate SOLPENCO2 profile for the event. After 8 hours of no SEP flux detection, the model considers the prediction to be a false positive and switches to no SEP event.

In case the SEP event proceeds, the SOLPENCO2 profile (renormalized) is used for the first 8 hours of the event. Following this, a modified Weibull profile is fitted in parallel to the observed data and the statistical goodness of these two models vis-a-vis the observations is compared. The alternative providing the better fit is chosen as the result.

In the case of flare and CME inputs (e.g. flare flux and CME speed) we derive fits per case and integral energy (e.g. E>10-MeV) (***Figure 7***). In this particular example the SEP event is expected to reach E>10 MeV and thus this is the filter used. We employ three bins for solar flare magnitude (i.e. solar flare class (SFC) ≤ M3.0, M3.0< SFC ≤ X1.0 & SFC > X1.0) and two bins for the CME speed

(V_{CME} < 1250 km/s & V_{CME} ≥ 1250 km/s). The continuous lines are linked to slower CMEs and the dashed lines are linked to faster CMEs.

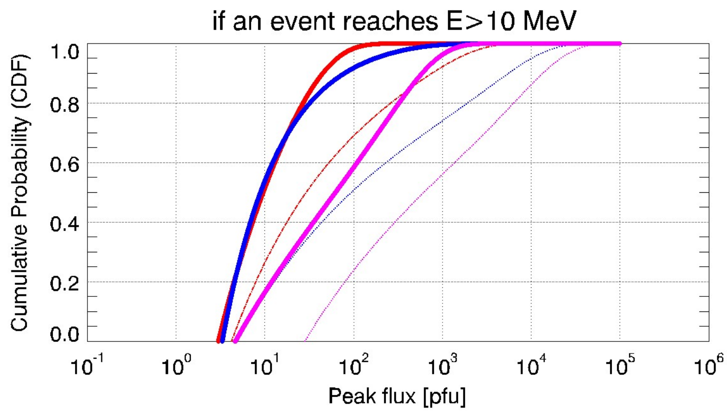


Figure 7: CDFs with respect to the peak proton flux for E>10 MeV utilizing flare flux and CME speed fits. The dashed lines are linked to faster CMEs (V>1250 km/s) while the solid ones are linked to slower CMEs (V<1250 km/s). The three colors of red, blue and magenta are representing the associated solar flare classes (SFC) ≤ M3.0, M3.0< SFC ≤ X1.0 & SFC > X1.0, respectively.

1.5. SW-5

The SW-5 of SAWS-ASPECS tool is actually the user interface. It consists of two major parts: the passive user interface and the interactive user interface. For the first one there are three components: (i) the real-time data, (ii) the pre-flare conditions based on the SW-2 flaring probabilities and (i) the past predictions, while for the latter one there are two components: (ii) the archived data and forecasts and (iii) the run on demand feature.

The Web page of the ASPECS system is developed using HTML, CSS, NodeJs and JavaScript. HTML and CSS are used for the main layout and appearance of the web page. NodeJs is used for the connection of the web page with the APIs of the SW1-4 and handling of the server files and sessions. The use of Javascript, especially with the jQuery framework and ChartJs library is for applying several effects on the page (slider, page navigation, graphs, etc.), while a combination of them with the event-driven calls is used for making the website dynamic. An NGINX server along with NodeJs is installed to handle all the incoming requests. All the above-mentioned are included in the aspecs_web container in the same fashion as the other containers for SW1-SW4.

When entering the SAWS-ASPECS tool webpage, the user is presented with plotted graphs for the real data sets and also the predictions that the tool makes, which are all fetched from our database. When the page loads, the web server, with javascript asynchronous calls, retrieves the needed data from the database. That is the current values of the data that are shown to the user and also the results of the modules (forecasts).

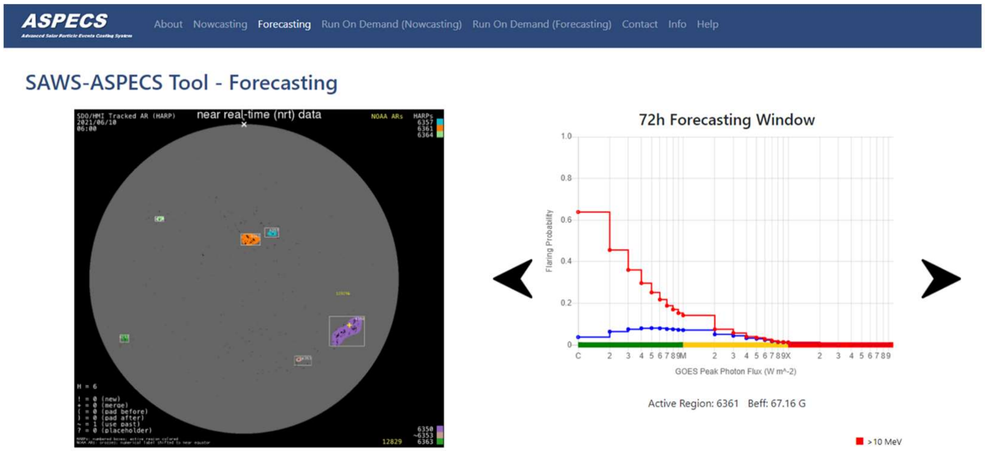


Figure 8: Display of the real-time forecasts made available through SAWS-ASPECS in the pre-flare mode

Figure 8 shows the pre-flare/pre-event predictions. This information is also present in the ASPECS website. All information considering the pre-event predictions is saved in the database and is fetched by the website.

Different options produce a different query that is translated into a query. This query then is sent directly to the application tier (e.g. modules) for a “run-on-demand”. The requested graphs constructed as information in our server and sent to the client side where they are actually constructed as interactive plots.

An example of a “Run-on-demand (Nowcasting)” for the case study of the event on 2000-07-14 is presented in ***Figure 9***.

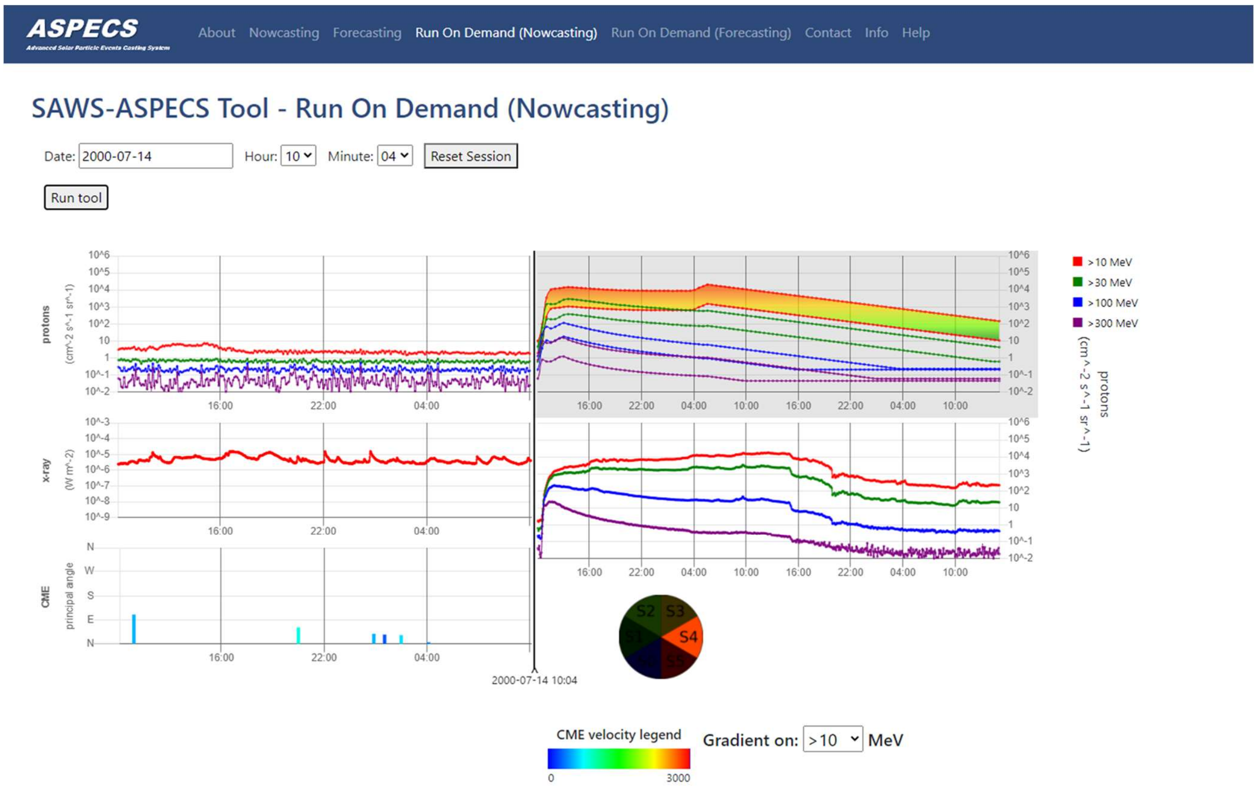


Figure 9: Run-on-demand for the case study of 14th July 2000.

On top of the previous interactive functionalities, a validation toolbox has been constructed. At its current stage, this toolbox focuses on specific SEP case studies, however a component for the calculation of statistical metrics/scores is underway. In the current set up the user provides the desired time span with a start and end date. The tool sends a query to the database (SW1) and searches for all solar flares and CMEs included in the backend for that time period. Consequently, different sub-modules are triggered in different times - driven by the identification of the parent solar event (i.e. flare and/or CME). The user receives, for each of the sub-modules (i.e. triggered by flares, CMEs or combinations hereof), interactive plots of: (a) the probability of SEP occurrence per integral energy from SW3 displayed as a bar plot; (b) the predicted SEP time profiles from SW4 with direct comparison to the actual data for the specific energy; (c) a scatter plot of the predicted versus observed peak fluxes per channel and confidence level and (d) a spectrum for the 50% CL (lower limit) and 90% CL (upper limit) using the identifications at E>10-; >30- and >100 MeV. In particular, an inverse power-law is assumed and a fit is applied through the predicted peak flux values. The exponent for each case is printed on the plot (e.g. γ) and an estimation of the lower and upper limit of the radiation environment is straightforward. These spectra are provided for each run and event and can be incorporated to other related tools and services providing a quick view of the predicted radiation environment.

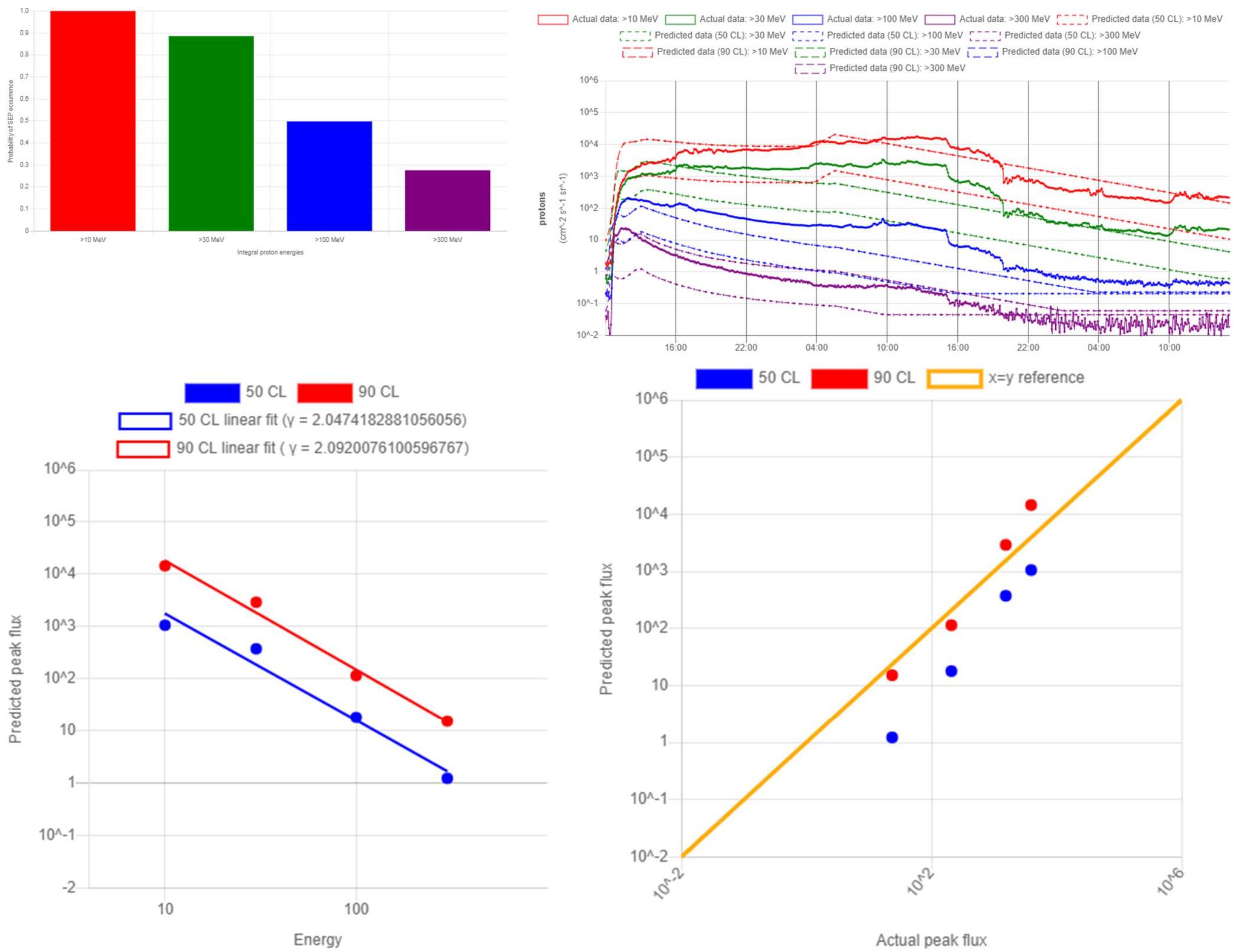


Figure 10: The outputs of the validation toolbox, for the case study of 14th July 2000, based on the default sub-module utilizing solar flare inputs.

1.6. Testing, Verification and Validation Analysis

Definitions

Verification:

Is the process of evaluating a system or component to determine whether the products/outputs at a given development phase, satisfy the conditions imposed at the start of the phase. Practically, ***verification*** provides evidence that the system, software and its associated products conform to specifications.

Validation
Is the process of evaluating a system or component during or at the end of the development phase, in order to determine whether it satisfies specified requirements. In practice, ***validation*** provides evidence that the system, software and its associated products satisfy intended use and user needs.

Verification measures
Typically, ***verification*** is divided into three steps: [a] the unit testing; [b] the integration testing and [c] the system testing.

[a] **Unit testing** *verifies* that the smallest entity (software component) functions as expected when isolated. This part of the testing is used primarily to eliminate bugs/issues in the software.

[b] **Integration testing** *verifies* that modules (created and tested independently) can coexist and communicate among themselves.

[c] **System testing** verifies that functional (e.g. to verify that the system has a function it is only necessary to exercise the function) and non-functional (e.g. those for reliability) software requirements have been met.

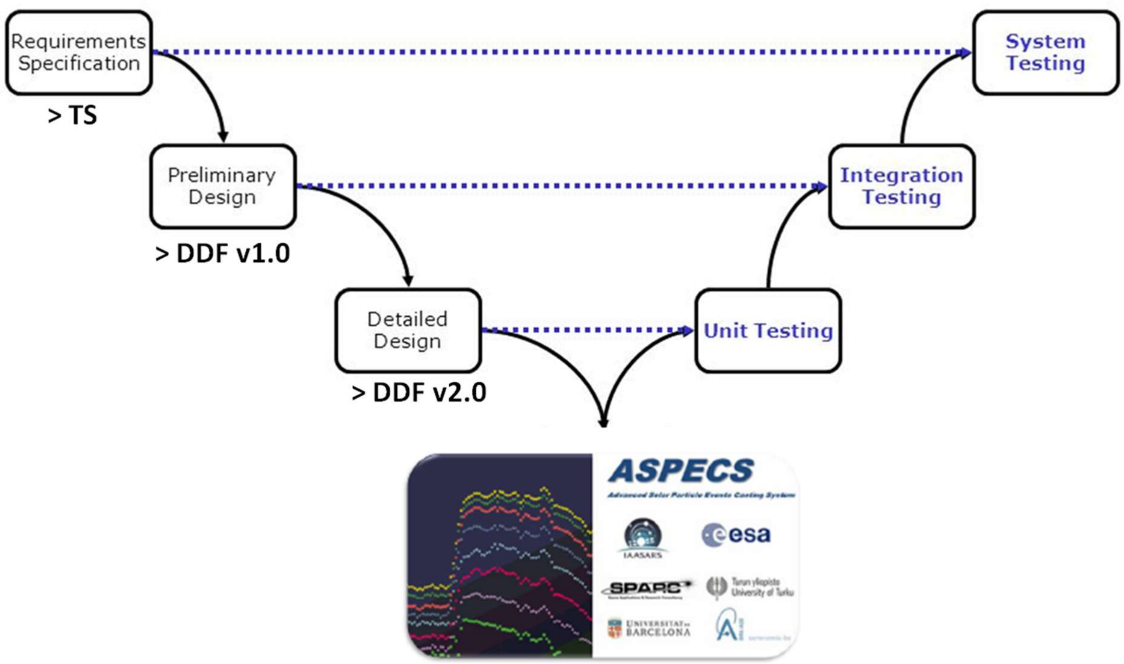


Figure 11: The life cycle verification approach. Software development starts in the top left-hand corner, progresses down the left hand 'specification' side to the bottom of the 'V' and then onwards up the right-hand 'production' side.

All unit testing was performed and pass successfully and the software was installed and configured to work on ESA infrastructure.

The validation of the SW-2, SW-3 and SW-4 forecasting (nowcasting) modules as well the ASPECS system as a whole (SW-5) was achieved with a two-level approach:

- The *first level of validation* requires detailed case studies of important solar flare and SEP events that have already been reported in literature. These case studies shall be a subset of the statistical samples to be accounted for in the second level, and show how the ASPECS system performs for these specific events. It should be noted that this *first level of validation* does not provide the full picture of the performance of the system (since it is restricted to specific cases) and thus validation metrics shall not be established at this level. Blind tests, focused on the fulfillment of the requirements [RD01] and the functionality of the system [RD02], were conducted by feeding archived data of these events to the various software modules (SW-2 to SW-4), and the ASPECS system in order to compare the derived characteristics of solar flares (e.g. magnitude) and SEPs (e.g. peak flux, duration, rise and decay phase, time profile), against archived respective observations. This ensures that each of the modules performs as expected. Moreover, since ASPECS is a dynamic system these trials further test the performance of the ASPECS database (SW-1).

- The *second level of validation* requires an extensive statistical study on a significant large archived sample of solar flare and SPEs. This statistical study includes scatter plots of observed vs. predicted solar flare and SEP properties, a dynamical range analysis, correlation coefficients and subsequent confidence levels, reliability diagrams, categorical scores, warning times. It also involves derivation of success indices and skill scores for the predictions of the modules and the ASPECS system as a whole. Such a statistical analysis was performed with a different archived data set than the training data set itself, for *a posteriori* predictions with the different modules and the ASPECS system. In addition, data of solar flare and SPEs is stored within the duration of the ASPECS project (SW-1) and can further act as part of the pool (sample) for either training and/or validation *data* sets. This random selection takes into account different points within the available timeline. Finally, different scenarios for the validation were employed covering all possible circumstances for which a warning is issued, as well as for all-clear conditions.

The validation is performed at two levels: the first level of validation is on a selected set of test cases, while the second level is performed on a longer time period. The table below lists all the test cases for the different forecast modules that form part of the validation plan.

Test	Description
ASPECS-VT-SW2-001	First level validation of the solar flare prediction module
ASPECS-VT-SW3-001	First level validation of the solar flare based pre-event SEP forecast
ASPECS-VT-SW3-002	First level validation of the solar flare post-event SEP forecast
ASPECS-VT-SW3-003	First level validation of the CME post-event SEP forecast
ASPECS-VT-SW3-004	Second level validation of the CME post-event SEP forecast
ASPECS-VT-SW3-005	First level validation of the combined flare & CME post-event

	SEP forecast
ASPECS-VT-SW4-001	First level validation of the pre-event SEP peak flux forecast
ASPECS-VT-SW4-002	First level validation of the pre-event SEP flux time profile forecast
ASPECS-VT-SW4-003	First level validation of the post-event SEP peak flux forecast
ASPECS-VT-SW4-004	First level validation of the post-event SEP flux time profile forecast
ASPECS-VT-SW4-005	Second level validation of the post-event SEP flux time profile forecast

For the chosen cases the results were as follows:

<u>September 2017 (non-) events: 4/9, 6/9, 9/9, 10/9, 17/9</u>

For the 17/9/2017 there is no information on the location of the solar flare and thus there is no prediction.

For all the other cases, the largest probabilities are obtained for 4/9 (SHARP time 2017-09-03 23:58 UT). For this case the flare probabilities and CME likelihood for each window are provided, here below.

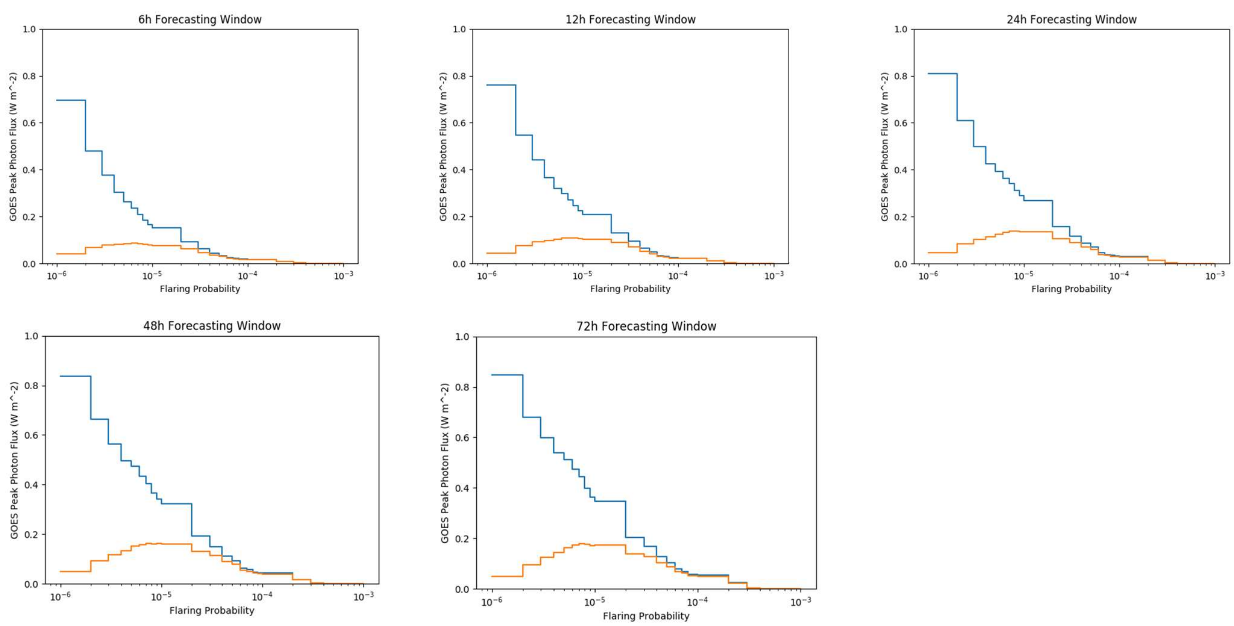


Figure 12: The outputs of SW-2 for AR12673 at 2017-09-03 23:58 UT. Each panel corresponds to one of the prediction time windows

Nowcasting of SEP events based on Flare and CME inputs

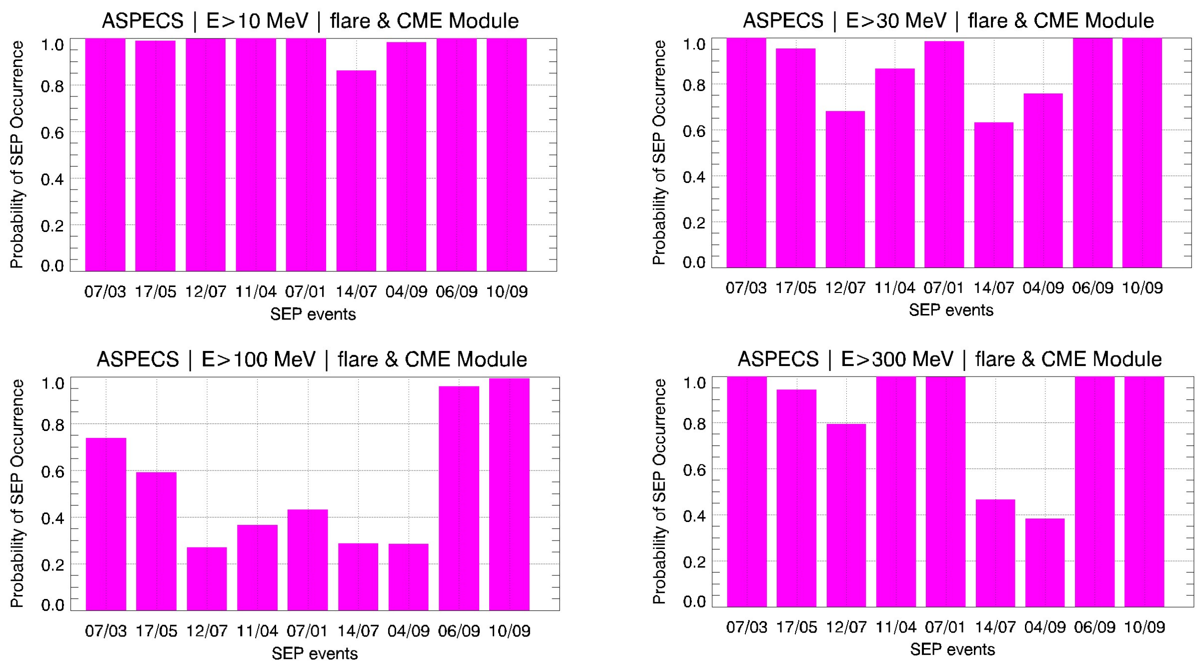


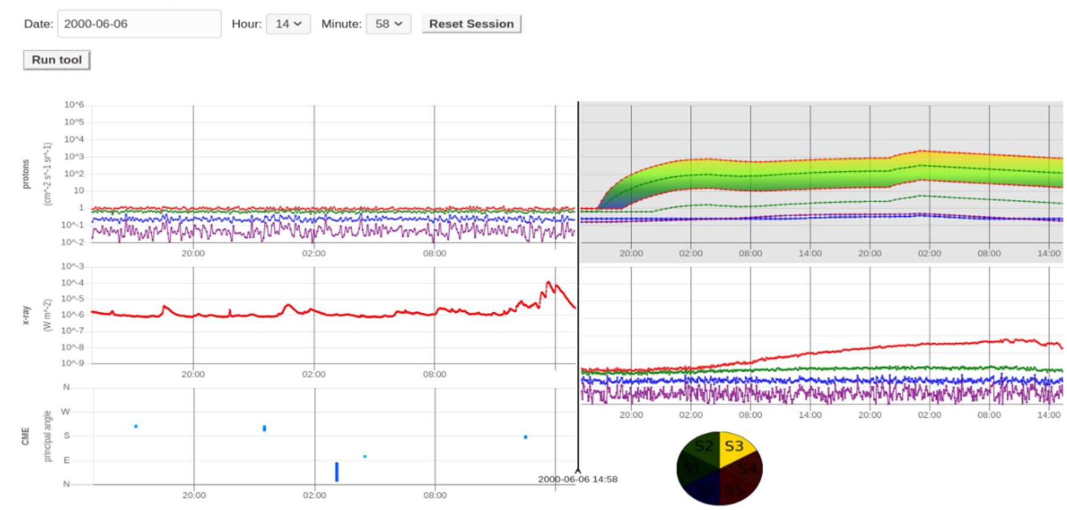
Figure 13: The Probability of SEP occurrence derived from PROSPER (included in the SW3 module of the ASPECS tool) based on solar flare & CME inputs. All dates (x-axis) are presented in DD/MM format. Each plot corresponds to a different integral energy noted on the plot.

Figure 13 presents the obtained probabilities of SEP occurrence per case (event) for the same events of Table 24, but for the flare and CME module. As it can be seen, the hit rate is 100% for the flare & CME module (i.e. 9/9 events for which both flare and CME inputs were available). Finally, the three of SEP events that are mentioned above and were "missed" by the flare (i.e. 14 July 2017) and the CME (i.e. 12 July 2012 & 11 April 2013) modules result to significant probabilities of the SEP occurrence in the flare and CME module and thus the ASPECS tool would have predicted these events under this module.

Besides the first level validation of the shine events using the separate flare, CME and flare+CME modules, the probabilities were also obtained using the Validation Tool that runs SW4. The probabilities provided at the peak time of the flare are provided in Table 25. SHINE event 5 is not included here as the SW4 module needs a flare to be triggered.

The obtained SEP time profiles from the ASPECS tool for the June 6, 2000 case for which a significant P(SEP) was marked is presented here:

06 June 2000



This part of the validation is run over 9 out of the 10 SHINE events. Event 5 is not included as the SW4 module needs a flare to be triggered. The comparison between the predicted flux time profiles at 50% and 90% CL and observed flux for the first 4 SHINE events at the peak time of the flare as provided by the Validation Tool is shown in Figures 88-91. The predicted and observed profiles for 25 consecutive steps of 30 minutes from the eruption time onwards are shown in Appendix B Section 3 of DJF file for each of the 9 SHINE events.

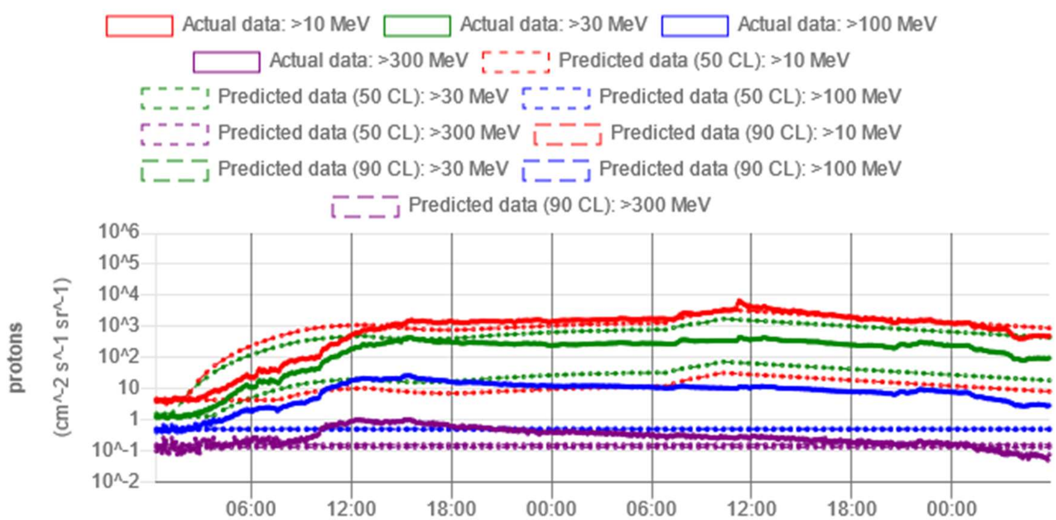


Figure 14 The predicted peak flux at 50% and 90% CL and observed flux for the energy ranges >10 MeV, >30 MeV, >100 MeV and >300 MeV for SHINE event 1.

Applicable Documents

Ref.	Document Name
[AD01]	Statement of Work, ESA Express Procurement EXPO, Solar Energetic Particle (SEP) Advanced Warning System (SAWS) (ESA, T704-502EE)
[AD02]	ESA Contract No. 4000120480/17/NL/LF/hh, May 2017
[AD03]	FORSPEF: Final Report (FR), Issue 1, Revision 2, ESA Contract No. 4000109641/13/NL/AK, February 2016
[AD04]	FORSPEF: Design Defintion File (DDF), Issue 1, Revision 6, ESA Contract No. 4000109641/13/NL/AK, January 2016
[AD05]	SEPsFLARES: Final Report -CCN (FR-CCN), Issue 3, Revision 0, ESTEC/ITT AO/1-7430/13/NL/AK, May 2016
[AD06]	ASPECS Technical Specification (TS) Document, Issue 1, Revision 2, ESA Contract No. 4000120480/17/NL/LF/hh, February 2018
[AD07]	ASPECS: Proposal in response to ESA ITT: AO/1-8765/16/NL/LF/hh, Solar Energetic Particle (SEP) Advanced Warning System (SAWS), November 2016

Reference Documents

Ref.	Document Name
[RD01]	A. Papaioannou, I. Sandberg, A. Anastasiadis, A. Kouloumvakos, M.K. Georgoulis, K. Tziotziou, G. Tsiropoula, P. Jiggens, A. Hilgers: 'Solar flares, coronal mass ejections and solar energetic particle event characteristics', J. Space Weather Space Clim., 6, A42, DOI: 10.1051/swsc/2016035, 2016
[RD02]	S.W. Kahler, The role of the big flare syndrome in correlations of solar energetic proton fluxes and associated microwave burst parameters, J. Geophys. Res., 87.A5: 3439-3448, 1982
[RD03]	I. G. Richardson and H.V. Cane, Near-Earth Interplanetary Coronal Mass Ejections During Solar Cycle 23 (1996 – 2009): Catalog and Summary of Properties, Solar Phsyics, 264, 189–237, 2010
[RD04]	E. Paouris and H. Mavromichalaki, Interplanetary Coronal Mass Ejections Resulting from Earth-Directed CMEs Using SOHO and ACE Combined Data During Solar Cycle 23, Solar Physics, 292, 30, 2017
[RD05]	M. K. Georgoulis, Magnetic complexity in eruptive solar active regions and associated eruption parameters, Geophys. Res. Lett., 35, L06S02, doi:10.1029/2007GL032040,2008
[RD06]	A. Anastasiadis, A. Papaioannou, I. Sandberg, M.K. Georgoulis, K. Tziotziou, A. Kouloumvakos, P. Jiggens: 'Predicting Flares and Solar Energetic Particle Events: The FORSPEF Tool', Solar Physics, 292, 134, DOI: 10.1007/s11207-017-1163-7, 2017
[RD07]	A. Papaioannou, A. Anastasiadis, I. Sandberg, P. Jiggens: 'Nowcasting of Solar Energetic Particle Events using near real-time Coronal Mass Ejection characteristics in the framework of the FORSPEF tool', J. Space Weather and Space Climate, accepted, 2018
[RD08]	M. Dierckxsens, K. Tziotziou, S. Dalla, I. Patsou, M.S. Marsh, N.B. Crosby, O. Malandraki, G. Tsiropoula: 'Relationship between Solar Energetic Particles and Properties of Flares and CMEs: Statistical Analysis of Solar Cycle 23 Events', Solar Physics, 290, 841, DOI:

	10.1007/s11207-014-0641-4, 2015
[RD09]	S.W. Kahler and A.G. Ling, Characterizing Solar Energetic Particle Event Profiles with Two-Parameter Fits, Solar Physics, 292, 59, DOI: 10.1007/s11207-017-1085-4, 2017
[RD10]	ASPECS Design Justification File (DJF) Document, Issue 1, Revision 0, ESA Contract No. 4000120480/17/NL/LF/hh, March 2018
[RD11]	Engell, A. J., Falconer, D. A., Schuh, M., Loomis, J., & Bissett, D., SPRINTS: A framework for solar-driven event forecasting and research. Space Weather, 15, 1321–1346, 2017
[RD12]	Núñez, M., T. Nieves-Chinchilla, and A. Pulkkinen, Prediction of Shock Arrival Times from CME and Flare Data, Space Weather, 14, 2016
[RD13]	Georgoulis, M. K., & Rust, D. M. (2007). Quantitative forecasting of major solar flares. The Astrophysical Journal Letters, 661(1), L109.
[RD14]	Georgoulis, M. K. (2012). Are solar active regions with major flares more fractal, multifractal, or turbulent than others?. Solar Physics, 276(1-2), 161-181.
[RD15]	Aran, A., D. Pacheco, N. Agueda, and B. Sanahuja. Updating SOLPENCO2 and New Analysis on Downstream Fluence (SOL2UP) Project. Final Report, ESA/ESTEC Contract 4000114116/15/NL/HK, 1–90, 2017
[RD16]	Aran, A., D. Pacheco, and B. Sanahuja. SOL2UP WP2000: Radial dependencies of the reference SEP events. SOL2UP Technical Report TN2-b, ESA/ESTEC Contract 4000114116/15/NL/HK, 1–49, 2016
[RD17]	SEPEM Reference Data Set v. 2.00, ESA
[RD18]	Sandberg I., P. Jiggens, D. Heynderickx, and I. A. Daglis . Cross-calibration of NOAA GOES solar proton detectors using corrected NASA IMP-8/GME data , Geophysical Research Letters, DOI: 10.1002/2014GL060469, 2014
[RD19]	ftp://ftp.estec.esa.int/private/pjiggens/anonymous/SEPEM_RDS_v2-00.zip
[RD20]	Smart D. F. and M. A. Shea. A simplified model for timing the arrival of solar-flare initiated shocks. J. Geophys. Res., 90(A1), 183–190, doi:10.1029/JA090iA01p00183, 1985

Definitions

None

Acronyms

AD	Applicable Document
API	Application Programming Interface
AR	Active Region
ARIA	Active Region Identification Algorithm
ASCII	American Standard Code for Information Interchange
ASPECS	Advanced Solar Particle Event Casting System
CMD	Central Meridian Distance
CME	Coronal Mass Ejection
CRD	Customer Reference Document
CSS	Cascading Stylish Sheets
ESA	European Space Agency
FORSPEF	Forecasting Solar Particle Events and Flares
GOES	Geostationary Operational Environmental Satellite
GUI	Graphical User Interface
HEK	Heliophysics Events Knowledgebase
HMI	Helioseismic and Magnetic Imager
ICME	Interplanetary CME
MDI	Michelson Doppler Imager
NRT	Near Real Time
ODI	Open Data Interface
RD	Reference Document
SDO	Solar Dynamics Observatory
SEP	Solar Energetic Particle
SEPsFLAREs	Solar Events Prediction system For space Launch Risk Estimation
SF	Solar Flare
SHARP	Spaceweather HMI Active Region Patch
SoW	Statement Of Work
SSA	Space Situational Agency
TBC	To Be Confirmed
TBD	To Be Decided
TS	Technical Specifications
UdB	Universidat de Barcelona
UTU	University of Turku