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PROJECT FINAL REPORT

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Project acronym: SEPSERVER

Project title: Data Services and Analysis Tools for Solar Energetic Particle Events and Related Electromagnetic Emissions

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4.1 Final publishable summary report

4.1.1 Executive Summary

Solar energetic particle (SEP) events are huge releases of energetic particle radiation from the Sun, which occur in association with solar flares and coronal mass ejections (CMEs). Large SEP events pose a radiation hazard to spacecraft and humans in space. Despite of some 50 years of spacecraft observations of SEPs, the mechanisms for the acceleration of energetic particles and their transport from the source to the Earth's orbit are still under debate. One of the main reasons for lack of progress in the field has been the scattered nature of observational information needed to make firm conclusions on the origin of SEP events. In addition to SEP fluxes, an analysis of related solar electromagnetic (EM) emissions is required in order to be able to make conclusions on the particle acceleration and release from the Sun.

The SEPServer project has produced a versatile web-based tool for the analysis of SEP events, the SEPServer. The server contains a comprehensive set of observations of SEPs in the interplanetary medium and of the related solar EM emissions stored in a relational database. In addition, the server provides access to state-of-the-art modelling tools to infer the characteristics of particle emission from the Sun.

The server is accessible through server.sepserver.eu. After registration, the user can utilise several functionalities:

- Access metadata
- Browse event lists
- Plot event data
- Browse event catalogues
- Access simulation datasets
- Perform forward modelling of SEP events
- Download software for inversion modelling of SEP events

The project has made a large effort to assess the quality of the observations. Assessment reports can be accessed at the project website www.sepserver.eu.

In order to make sure that the server fulfils its purpose, the consortium has made use of the datasets and analysis tools. The scientific analysis in the project has concentrated mainly on the preliminary analysis of the hundreds of SEP events identified in the data. This involves the determination of the SEP event onset time (at the observer's location) in various energy channels for electrons and protons, and making use of these times to deduce the solar release time (SRT) of the particles. Once the solar release time has been found, it has been compared with EM observations. Summary plots have been prepared where the light curves, dynamic radio spectra and radio images are compared with the particle release times. These results are stored and distributed in electronic and re-usable form for the science community in the SEPServer event catalogues.

Besides preliminary analysis results, we have analysed a smaller number of events in detail using the maximal amount of data and also advanced simulation based analysis methods (inverse methods and forward modelling) to obtain more detailed knowledge on the solar release and interplanetary transport of SEPs. The consortium also performed theoretical simulation studies of particle acceleration at shock waves driven by CMEs and current sheets forming in flaring regions as well as radio emissions resulting from accelerated electron beams.

The project has also made use of the results in education, producing a set of lecture notes for a master-level course on Solar Eruptions and Space Environment. The notes are based on an actual 5-credit-point course in the Master's Degree programme of the University of Helsinki, taught in spring 2013.

4.1.2 A summary description of project context and objectives

The SEPServer project addressed the following topics of the Work Programme 2010, Theme 9 – Space:

- SPA.2010.2.1-03: Exploitation of space science and exploration data (primary; this topic was directly addressed by the objectives of the project);
- SPA.2010.2.3-01: Security of space assets from space weather events (secondary; this topic was and will be supported through the impact of the project).

The project aimed at producing

- a sustainable tool for a broad research community – to investigate solar energetic particles (SEPs) and their origin – through the creation of a server of SEP data, related electromagnetic (EM) observations, and analysis tools;
- new knowledge on the production and transport of high energy particles during solar eruptions, by performing detailed analyses of an extensive set of measurements of SEP in the interplanetary (IP) medium, along with concurrent observations of EM emissions from radio to gamma-ray frequencies.

The meaningful forecasting of solar radiation storms, consisting of energetic charged particles emitted during solar eruptions, is still virtually impossible. Yet, solar radiation storms are among the most important risks for the launch and operation of space vehicles, for space missions to the inner solar system, where the radiation levels are highest, and for human exploration of the Moon and Mars. One of the main reasons for the poor capability to predict these storms is the lack of understanding of the processes that accelerate particles to high energies close to the Sun during solar eruptions, i.e. flares and coronal mass ejections (CMEs).

Data on SEPs, their related EM emissions and the prevailing properties of the in-situ plasma and magnetic field have been measured for decades, and European research groups have been in a major role in many such experiments. To secure the exploitation of these data to the full extent, data sets relating to the direct particle measurements and to the EM emissions of the parent solar activity must be analysed together, and, before, must become easily available. The key observations are directional fluxes of energetic electrons and ions extending to relativistic energies; elemental and isotopic abundances of ions at various energies; the interplanetary magnetic field (IMF) and the bulk properties of the solar wind plasma; the fluxes and energy spectra of solar EM emissions from radio to gamma-ray frequencies produced by accelerated particles interacting with the coronal plasma; and imaging observations of the solar corona ranging from radio to gamma-ray frequencies.

Such a synergistic approach to SEP analysis, prior to SEPServer, was hampered by the difficult access to the data on the one hand, and by the user's lack of expertise with many of the different data sets to be handled on the other. While the Internet has made the access to data easier than ever before, the data themselves have become more diversified. Key data such as directional particle intensities could only be obtained from the numerous Principal Investigators (PIs) of different experiments. Data formats are instrument-specific, and the quality and reliability of the data cannot be evaluated by most users. Finally, numerical simulation models, by which the temporal evolution and spectral characteristics of the solar particle injections can be inferred, have in general not been available at all for public use. All these facts have contributed to the under-exploitation of available tools, both data and models, prior to SEPServer.

SEPServer has contribute to new knowledge on the outstanding problem of solar particle acceleration by providing a preliminary analysis of the onset time of a hundreds of SEP events and their SEP release times. In addition, for a limited set of well-observed events, it has provided the release-time profiles inferred using simulation-based analyses. The comparison of the release timings with the related solar EM emissions will be made available.

The main objective of the project was to facilitate the coordinated exploitation of the various data sets relevant to the problem by developing a server providing, by the end of the project,

1. access to directional fluxes and compositional data of SEPs and the EM solar emission observations related to the catalogued events, and data on interplanetary plasma and field conditions prevailing during these SEP events;
2. assessment reports (to be written during the project) on the quality of the various data sets;
3. numerical modelling results and inversion methods (to be developed during the project) that can be used for the analysis of particle transport in the interplanetary medium and particle acceleration and EM emission processes close to the Sun;
4. a comprehensive catalogue of the SEP events of the 23rd solar cycle (1996–2008) extended by selected well-observed SEP events from the 21st, 22nd and 24th solar cycles;
5. scientific analysis results on (1) all the catalogued SEP events using direct observational methods, and on (2) a carefully selected sub-set of best-observed events using simulation-based inversion methods; and
6. outreach and educational material for increasing the public awareness on solar eruptions and the data and analysis results obtained in the consortium.

The project successfully developed and released an Internet server for the community, which answers to all the topics 1–6 listed above. Thus, the output from the SEPServer project has great potential to significantly enhance the effectiveness and productivity of the European and international SEP and space weather research communities, as intended.

By effectively exploiting the historical, the present and the future SEP and solar EM data sets in an interdisciplinary manner we also obtained new knowledge on particle acceleration and transport processes at and near the Sun and expect new discoveries on these topics to emerge from the research following the project. As a result of the delivered server, the completed project allows the heliophysical and space weather research community at large to take full advantage of the SEP and other eruption data. As a direct impact of the new knowledge and improved access to the data, the space weather research community will have improved capabilities to develop systems for early forecasting of solar radiation storms. The new and accurately characterised data sets may also be used in developing improved engineering models of SEP fluxes and fluences encountered by spacecraft in the IP medium.

To achieve the goals of the project, we employed a consortium consisting of a group of internationally recognised experts in Europe in the fields of SEP observations, SEP simulation modelling, and solar radio, X-ray and gamma-ray astronomy. Because the data sets utilised are obtained from European and US space missions and from ground-based observatories in several countries, the project goals well exceeded national efforts – an integrated European approach was mandatory to achieve the objectives of SEPServer.

The SEPServer project was also extremely timely. It performed research in the emerging field of heliophysics. Heliophysics is a European and international priority as evidenced, for example, by the successful International Heliophysical Year 2007–2009 (IHY) that celebrated the 50th anniversary of the International Geophysical Year 1957 by extending the scope of interest of the community from the geospace to the processes that govern the Sun, the Earth and the heliosphere. The next generation of heliophysics missions, i.e., Solar Orbiter – a mission for ESA's Cosmic Vision Programme – and Solar Probe Plus of NASA, is currently being constructed. The communities developing these new missions to the innermost heliosphere need to concentrate their efforts on the most important questions to which the historical and ongoing missions cannot provide clear answers. By its joint reanalysis of a broad set of SEP and EM data and the dissemination of results to the heliophysics community, SEPServer will continue to contribute to sharpen questions on the Sun–heliosphere connection that will be addressed by these missions. By providing such input to ESA's Cosmic Vision programme, the project contributes directly to the goals set up in the European Space Policy supporting the Foundations of Space science and Technology.

The SEPServer project utilised results from and fed its own results to many previous and ongoing European projects that are related to heliophysics, solar–terrestrial physics, and space weather research. These included

- FP7 projects: Heliophysics Integrated Observatory (HELIO), Neutron Monitor Database (NMDB), Protecting space assets from high energy particles by developing European dynamic modelling and forecasting capabilities (SPACECAST), and Coronal Mass Ejections and Solar Energetic Particles (COMESEP);
- ESA's Space Weather Working Team (SWWT) and ESA projects: Solar Energetic Particle Environment Modelling (SEPEM), Open Data Interface (ODI), Interplanetary and Planetary Radiation Model for Human Spaceflight (IPRAM), and Energetic Solar Heavy Ion Environment Models (ESHIEM);
- COST Action ES0803, Developing Space Weather Products and Services in Europe (2008–2012).

Coordination of efforts with these projects and scientific communities like Community of European Solar Radio Astronomers (CESRA) was regarded important so that no duplication of effort was done, an optimum compatibility of technical solutions was guaranteed, and that the results were effectively disseminated to the European lead user communities.

International collaboration with researchers outside Europe was also a very important part of our project. We collaborated extensively with several research groups in the US, bringing in data sets that are complementary to the European ones. The US hosts also the largest potential user community of our results, so the collaboration is very much in the interest of both parties.

4.1.3 A description of the main S&T results/foregrounds

The most important result of the SEPServer project is the Internet server providing access to a number of SEP datasets and related EM observations. In the following, we describe the contents and functionalities of this server. We also describe the most important results of our scientific analysis and the educational material that was produced in the project.

4.1.3.1 Server homepage

The server developed in the project can be accessed at server.sepserver.eu. A screenshot of the server homepage is depicted in Figure 1.

Figure 1: Server homepage

Prior to login, the user has only the option to view the Event catalogues providing analysis results, not access the data itself. New users have an option to register as users to the database.

After the login, the menu on the left hand side expands to show all the functionalities the user has access rights to. An example of the result of the login process is shown in Figure 2.

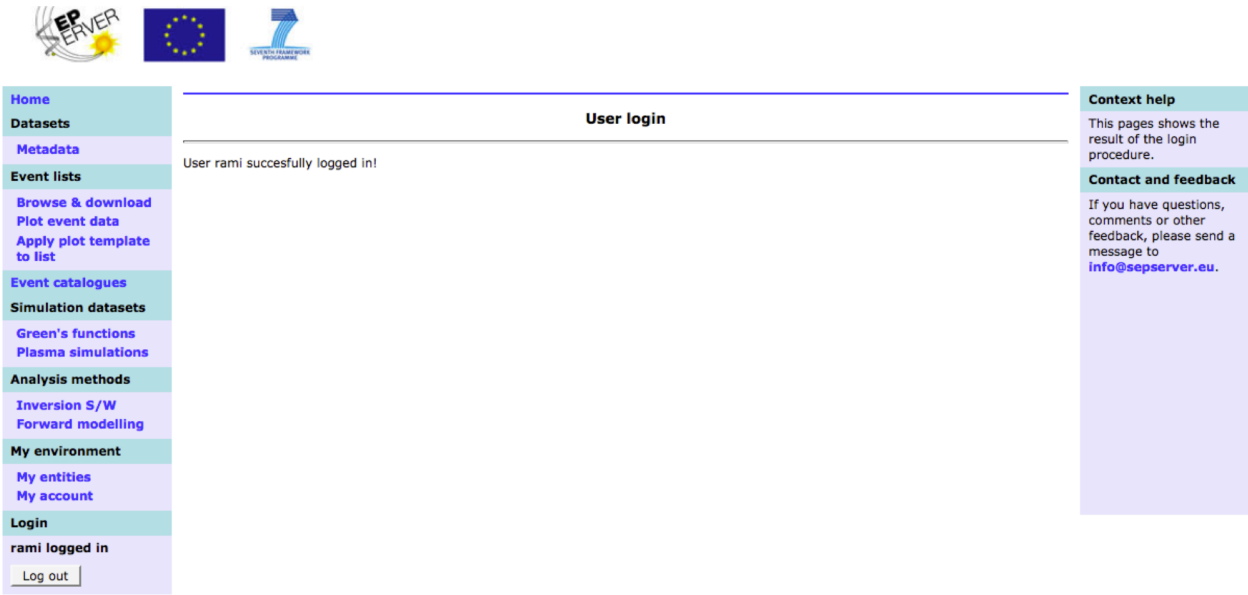


Figure 2: The result of the login process. The menu on the left now shows the functionalities of the server.

The functionalities of the server are divided in browsing the metadata, browsing and downloading the event lists, plotting event data with or without a plot template, browsing event catalogues, browsing and downloading simulation datasets, applying/downloading simulation based analysis tools, and browsing the users own environment.

4.1.3.2 Server functionalities

Metadata

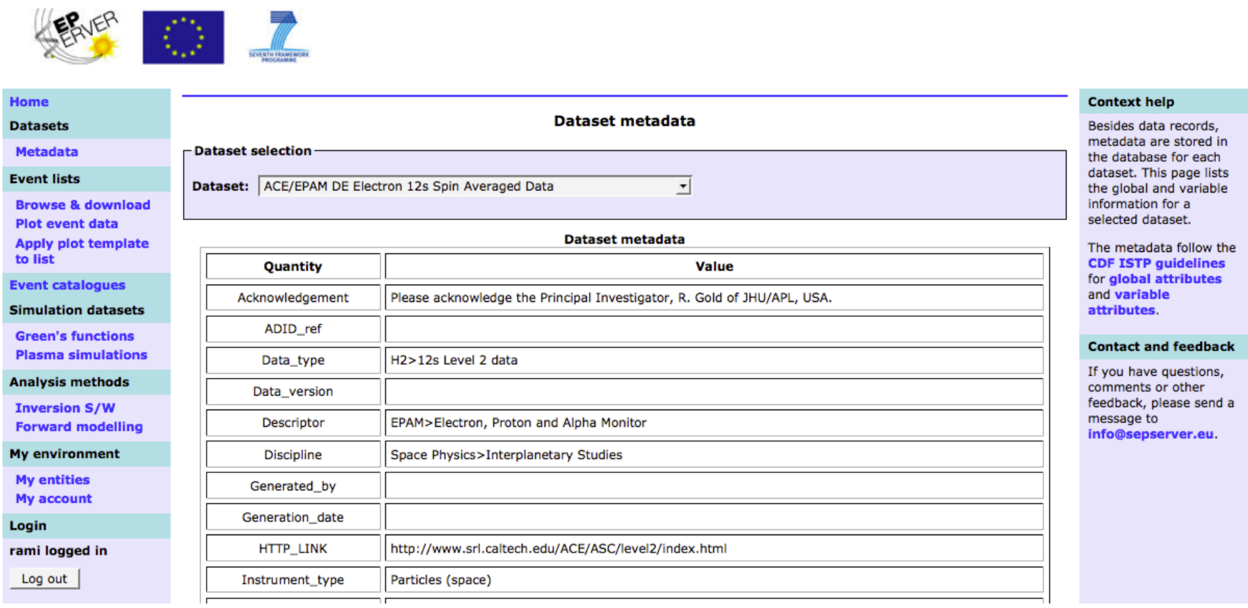


Figure 3: An example of a page showing metadata for a dataset stored in the database

Each dataset stored in the database has a comprehensive description of its contents in the SEPServer metadata database. An example of metadata stored for a dataset is provided in Figure 3. Metadata are shown for the dataset globally, and for each variable in the dataset individually. This allows the user to have quick access to comprehensive up-to-date knowledge of each of the distributed datasets.

Event lists

SEPServer provides event lists for six spacecraft (HELIOS-A & B, STEREO-A & B, Ulysses and SOHO). These lists result from scans of energetic proton data over the mission durations, identifying SEP events from the observations. They also cover altogether a time span of more than three solar cycles (SC), starting from SC 21 and ending around the maximum of SC 24, with SC 22 not covered in full. The event lists can be used as a basis for browsing the actual observations, which makes browsing easy for the user. The event list selection in the browsing tool is shown in Figure 4. After selecting the list, the user can download it or plot the list contents as event duration against the start time of the event.

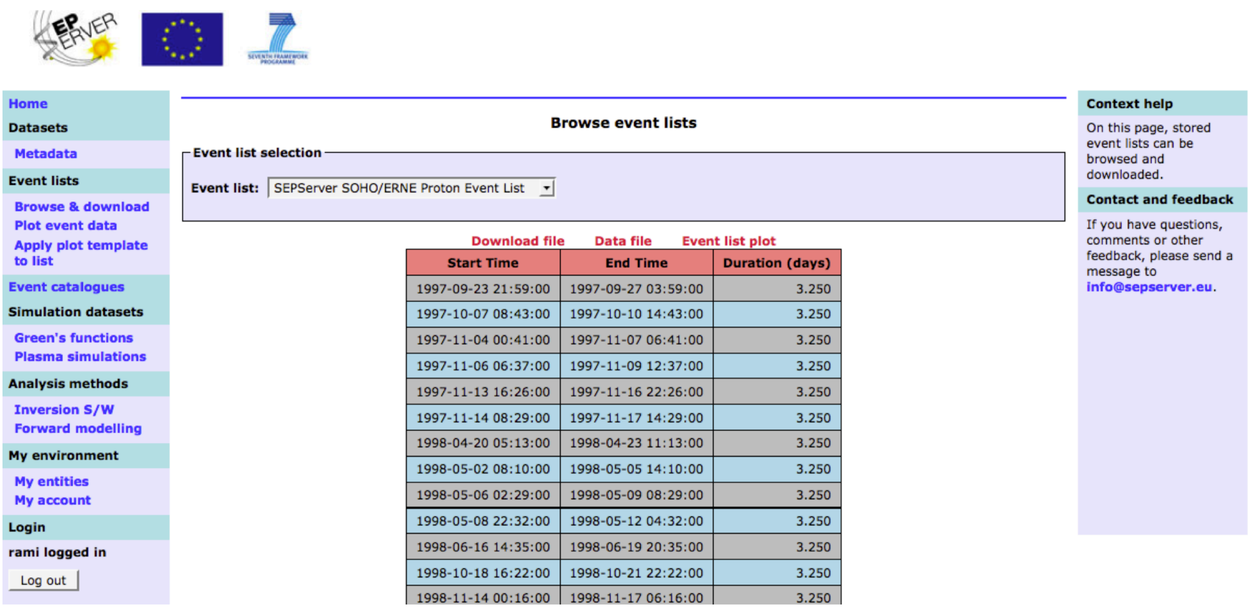


Figure 4: Page for browsing and downloading event lists

Plotting event data

The main data-browsing tool in SEPServer can be accessed via the main level by clocking "plot event data". The user first selects how to define the time range (event timing based on the predefined event lists or by specifying the epoch range). After the method has been chosen and the time range defined, the user starts to construct panels for a plot from the menu. All panels in the plot are presenting a scalar or 1D array quantity as a function of time. Several types of data panels can be chosen: particle intensity, sectored intensity, X-ray intensity, light curve, spectrogram, 1D radio image, radio intensity, angleogram, solar wind, and magnetic field data. (Some data types are not available for all events.) The user can pick a one to five data channels per panel and a number of panels to be stacked on top of each other (see Figure 5). Thus, a comprehensive plot of the event observations can be constructed easily. Once the panels are ready, the user can plot the results by clicking the "Produce Plot" button. The server then produces a plot, which the user gets as a high-resolution png image. A simple example of a plot produced by SEPServer is given in Figure 6.

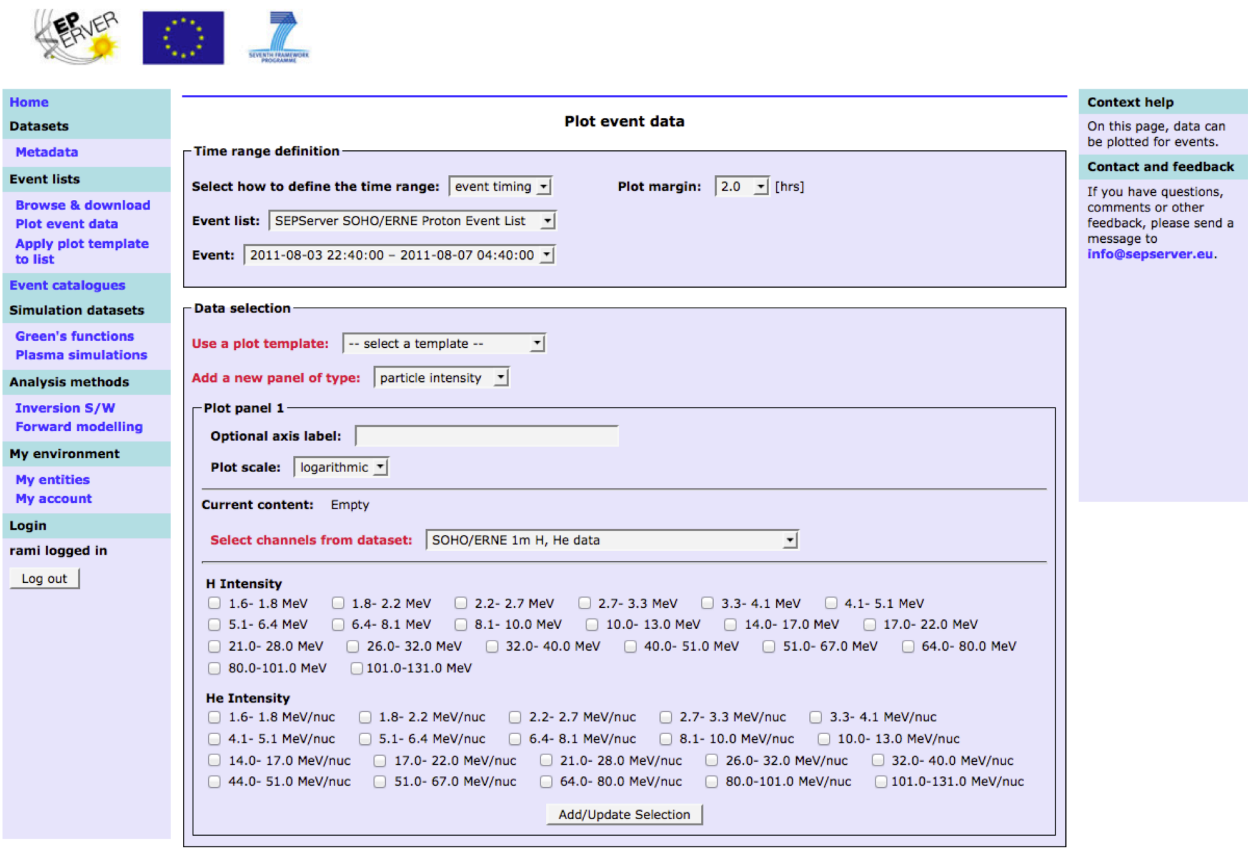


Figure 5: Plotting event data

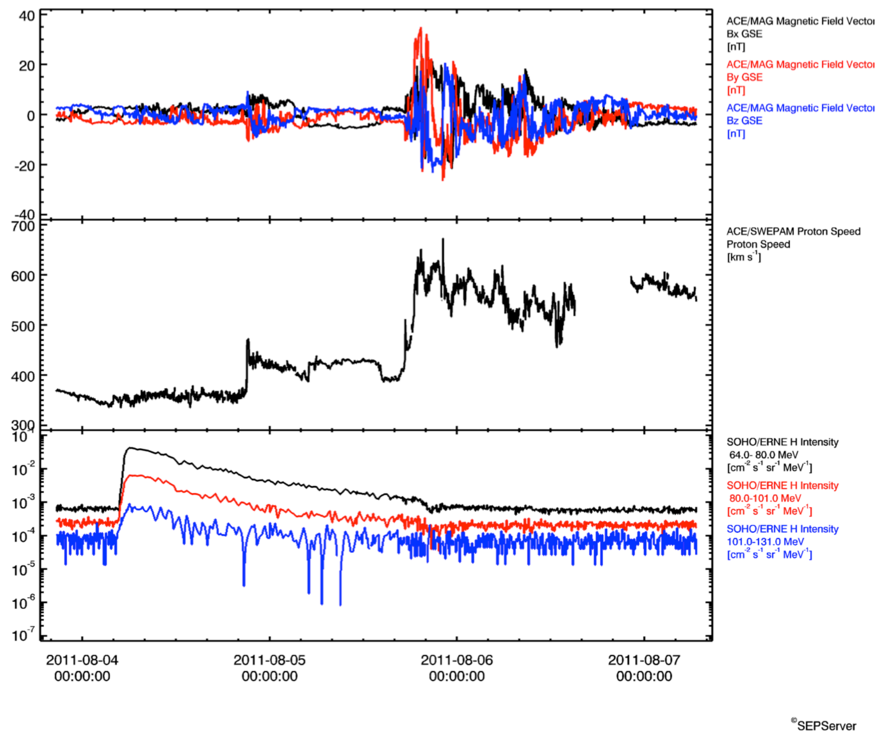


Figure 6: Example plot from the SEPServer showing magnetic field and solar wind speed with energetic proton fluxes observed by SOHO/ERNE

The user has also a possibility to save the plot he has constructed for later use as a plot template. The saved templates can be used to produce identical panel plots from different events using one event as the basis for constructing it and then applying to others. Templates can also be used for all events on a given event list by choosing "Apply plot template" from the menu. In that case, the user gets access to a zip file containing the plots made with the same template for all events on the list.

In November 2013, there are altogether 112 datasets in the SEPServer database. They are listed in alphabetical order in Table 1.

Table 1: Datasets in the SEPServer database

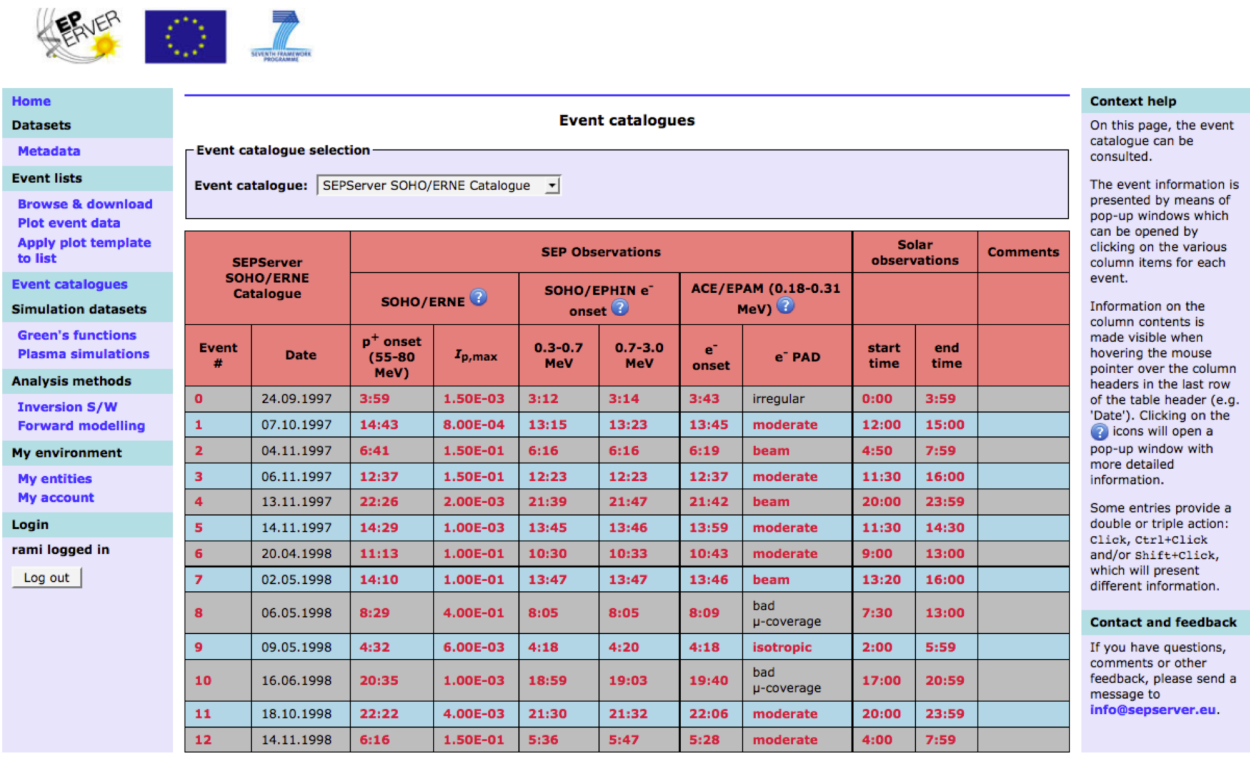
Dataset	Start Date	End Date	Nr of Records
ACE/EPAM 12s DE electron data	1997-08-30 17:01:46	2013-07-11 23:53:45	38752268
ACE/EPAM 12s LEFS150 electron data	1997-08-30 17:01:46	2013-07-11 23:53:45	38752268
ACE/EPAM 12s LEFS60 electron data	1997-08-30 17:01:46	2013-07-11 23:53:45	38752268
ACE/EPAM 12s LEMS120 ion data	1997-08-30 17:01:46	2013-07-11 23:53:45	38752268
ACE/EPAM 12s LEMS30 ion data	1997-08-30 17:01:46	2013-07-11 23:53:45	38752268
ACE/EPAM DE sectored electron data	1997-08-30 17:01:00	2013-07-11 23:53:00	8272142
ACE/EPAM LEFS150 sectored electron data	1997-08-30 17:01:00	2013-07-11 23:53:00	8272142
ACE/EPAM LEFS60 sectored electron data	1997-08-30 17:01:00	2013-07-11 23:53:00	7790288
ACE/EPAM LEMS120 sectored ion data	1997-08-30 17:01:00	2013-07-11 23:53:00	8272142
ACE/EPAM LEMS30 sectored ion data	1997-08-30 17:01:00	2013-07-11 23:53:00	8270710
ACE/MAG 16s magnetometer data	1997-09-02 00:00:12	2013-02-19 23:59:48	30752996
ACE/SIS 256s He data	1997-08-29 00:00:26	2013-05-10 23:59:58	1935229
ACE/SIS 256s ion data	1997-08-29 00:00:26	2013-05-10 23:59:58	1935229
ACE/SWEPAM 64s solar wind parameters	1998-02-04 00:00:31	2013-03-18 23:59:16	7454713
ARTEMIS/SWEEP spectrograms	2003-10-28 10:02:00	2011-09-22 12:50:00	163209
ARTEMIS/SWEEP spectrograms (old format)	1998-05-02 13:33:00	2002-04-17 10:39:59	42300
GOES 1 min X-ray data	1995-01-01 00:00:00	2009-12-31 23:59:00	7884000
HELIOS-A/E6 15m omnidirectional group 0 data	1974-12-11 00:00:00	1986-02-07 22:26:30	201500
HELIOS-A/E6 15m omnidirectional group 1 data	1974-12-11 00:00:00	1986-02-07 22:25:35	200431
HELIOS-A/E6 15m omnidirectional group 2 data	1974-12-11 00:00:00	1986-02-07 22:26:03	200472
HELIOS-A/E6 15m Sectored group 0 data	1974-12-11 00:00:00	1986-02-07 22:26:30	201500
HELIOS-A/E6 15m sectored group 1 data	1974-12-11 00:00:00	1986-02-07 22:25:35	200431
HELIOS-A/E6 15m sectored group 2 data	1974-12-11 00:00:00	1986-02-07 22:26:03	200472
HELIOS-A/E6 1hr omnidirectional group 0 data	1974-12-11 00:00:00	1986-02-07 22:27:51	71489
HELIOS-A/E6 1hr omnidirectional group 1 data	1974-12-11 00:00:00	1986-02-07 22:28:18	71052
HELIOS-A/E6 1hr omnidirectional group 2 data	1974-12-11 00:00:00	1986-02-07 22:27:24	70996
HELIOS-A/E6 1hr Sectored group 0 data	1974-12-11 00:00:00	1986-02-07 22:27:51	71489
HELIOS-A/E6 1hr sectored group 1 data	1974-12-11 00:00:00	1986-02-07 22:28:18	71052
HELIOS-A/E6 1hr sectored group 2 data	1974-12-11 00:00:00	1986-02-07 22:27:24	70996
HELIOS-A/E6 1m omnidirectional group 0 data	1975-01-05 00:00:00	1985-02-18 15:45:47	100173
HELIOS-A/E6 1m omnidirectional group 1 data	1975-01-05 00:00:00	1985-02-18 15:16:59	99815
HELIOS-A/E6 1m omnidirectional group 2 data	1975-01-05 00:00:00	1985-02-18 15:31:23	99831
HELIOS-A/E6 1m Sectored group 0 data	1975-01-05 00:00:00	1985-02-18 15:45:47	100173
HELIOS-A/E6 1m sectored group 1 data	1975-01-05 00:00:00	1985-02-18 15:16:59	99815
HELIOS-A/E6 1m sectored group 2 data	1975-01-05 00:00:00	1985-02-18 15:31:23	99831
HELIOS-B/E6 15m omnidirectional group 0 data	1976-01-16 00:00:00	1980-03-08 17:38:55	91728
HELIOS-B/E6 15m omnidirectional group 1 data	1975-12-31 00:00:00	1980-03-08 17:39:04	90959
HELIOS-B/E6 15m omnidirectional group 2 data	1975-12-31 00:00:00	1980-03-08 17:39:13	91030
HELIOS-B/E6 15m Sectored group 0 data	1976-01-16 00:00:00	1980-03-08 17:38:55	91728
HELIOS-B/E6 15m sectored group 1 data	1975-12-31 00:00:00	1980-03-08 17:39:04	90959
HELIOS-B/E6 15m sectored group 2 data	1975-12-31 00:00:00	1980-03-08 17:39:13	91030
HELIOS-B/E6 1hr omnidirectional group 0 data	1976-01-16 00:00:00	1980-03-08 17:24:31	32864
HELIOS-B/E6 1hr omnidirectional group 1 data	1975-12-31 00:00:00	1980-03-08 17:25:34	32615
HELIOS-B/E6 1hr omnidirectional group 2 data	1975-12-31 00:00:00	1980-03-08 17:25:16	32592
HELIOS-B/E6 1hr Sectored group 0 data	1976-01-16 00:00:00	1980-03-08 17:24:31	32864
HELIOS-B/E6 1hr sectored group 1 data	1975-12-31 00:00:00	1980-03-08 17:25:34	32615
HELIOS-B/E6 1hr sectored group 2 data	1975-12-31 00:00:00	1980-03-08 17:25:16	32592
HELIOS-B/E6 1m omnidirectional group 0 data	1976-03-19 00:00:00	1980-02-06 23:49:30	58662
HELIOS-B/E6 1m omnidirectional group 1 data	1976-03-19 00:00:00	1980-02-06 23:42:18	58491
HELIOS-B/E6 1m omnidirectional group 2 data	1976-03-19 00:00:00	1980-02-06 23:45:54	58507
HELIOS-B/E6 1m Sectored group 0 data	1976-03-19 00:00:00	1980-02-06 23:49:30	58662
HELIOS-B/E6 1m sectored group 1 data	1976-03-19 00:00:00	1980-02-06 23:42:18	58491
HELIOS-B/E6 1m sectored group 2 data	1976-03-19 00:00:00	1980-02-06 23:45:54	58507
INTEGRAL/ACS Gamma ray count rates	2002-11-09 12:24:04	2005-09-13 20:45:27	154436
INTEGRAL/SPI light curves	2003-10-28 10:00:00	2005-09-07 18:53:20	23353
INTEGRAL/SPI spectrograms	2003-10-28 10:48:20	2005-09-07 18:19:00	155

Table 1: (cntd)

Dataset	Start Date	End Date	Nr of Records
NDA/SWEEP spectrograms	1997-10-07 12:30:00	2010-08-14 10:40:00	254274
NRH images (150.9 MHz)	2003-10-28 10:00:00	2006-12-05 10:00:07	9
NRH images (164.0 MHz)	1997-10-07 12:30:28	2006-12-05 10:00:07	47
NRH images (236.6 MHz)	1997-10-07 12:30:28	2006-12-05 10:00:07	47
NRH images (327.0 MHz)	1997-10-07 12:30:28	2006-12-05 10:00:07	47
NRH images (410.5 MHz)	1997-10-07 12:30:28	2006-12-05 10:00:07	47
NRH images (432.0 MHz)	1997-10-07 12:30:28	2006-07-06 08:23:33	42
OSRA/SWEEP radio intensities	1977-09-19 05:36:40	1982-12-26 14:28:10	130461
OSRA/SWEEP spectrograms	1997-10-07 05:57:00	2006-07-06 19:16:59	1781978
RHESSI light curves	2002-02-20 06:15:00	2012-09-08 11:29:56	230835
SOHO/EPHIN 1m corrected data	1995-12-08 00:01:16	2013-03-11 23:59:59	8117157
SOHO/EPHIN 1m omni data	1996-01-01 00:01:14	2013-09-09 23:59:04	8342154
SOHO/ERNE 1m H, He data	1996-05-01 00:00:30	2013-05-31 23:59:12	7761288
SOHO/ERNE 1m ion data	1997-09-23 00:00:47	2012-10-02 23:59:32	912676
STEREO-A/IMPACT/LET 1m sectored data	2007-01-01 00:00:45	2013-08-31 23:58:22	3459819
STEREO-A/IMPACT/LET 1m summed H data	2007-01-01 00:00:45	2013-08-31 23:58:22	3459819
STEREO-A/IMPACT/LET 1m summed He data	2007-01-01 00:00:45	2013-08-31 23:58:22	3459819
STEREO-A/IMPACT/SEPT 1m anti-Sunward electron data	2007-01-19 23:59:43	2013-10-09 20:34:17	3535000
STEREO-A/IMPACT/SEPT 1m anti-Sunward ion data	2007-01-19 23:59:43	2013-10-09 20:34:17	3535000
STEREO-A/IMPACT/SEPT 1m northward electron data	2007-01-19 23:59:43	2013-10-09 20:34:17	3535000
STEREO-A/IMPACT/SEPT 1m northward ion data	2007-01-19 23:59:43	2013-10-09 20:34:17	3535000
STEREO-A/IMPACT/SEPT 1m southward electron data	2007-01-19 23:59:43	2013-10-09 20:34:17	3535000
STEREO-A/IMPACT/SEPT 1m southward ion data	2007-01-19 23:59:43	2013-10-09 20:34:17	3535000
STEREO-A/IMPACT/SEPT 1m Sunward electron data	2007-01-19 23:59:43	2013-10-09 20:34:17	3533780
STEREO-A/IMPACT/SEPT 1m Sunward ion data	2007-01-19 23:59:43	2013-10-09 20:34:17	3535000
STEREO-B/IMPACT/LET 1m sectored data	2007-01-01 00:00:59	2013-08-31 23:59:11	3448917
STEREO-B/IMPACT/LET 1m summed H data	2007-01-01 00:00:59	2013-08-31 23:59:11	3448917
STEREO-B/IMPACT/LET 1m summed He data	2007-01-01 00:00:59	2013-08-31 23:59:11	3448917
STEREO-B/IMPACT/SEPT 1m anti-Sunward electron data	2007-01-19 23:59:54	2013-10-10 05:18:15	3535524
STEREO-B/IMPACT/SEPT 1m anti-Sunward ion data	2007-01-19 23:59:54	2013-10-10 05:18:15	3535524
STEREO-B/IMPACT/SEPT 1m northward electron data	2007-01-19 23:59:54	2013-10-10 05:18:15	3535524
STEREO-B/IMPACT/SEPT 1m northward ion data	2007-01-19 23:59:54	2013-10-10 05:18:15	3535524
STEREO-B/IMPACT/SEPT 1m southward electron data	2007-01-19 23:59:54	2013-10-10 05:18:15	3535524
STEREO-B/IMPACT/SEPT 1m southward ion data	2007-01-19 23:59:54	2013-10-10 05:18:15	3535524
STEREO-B/IMPACT/SEPT 1m Sunward electron data	2007-01-19 23:59:54	2013-10-10 05:18:15	3535524
STEREO-B/IMPACT/SEPT 1m Sunward ion data	2007-01-19 23:59:54	2013-10-10 05:18:15	3535319
Ulysses/COSPIN/KET Omnidirectional data	1990-10-23 18:24:26	2009-06-30 16:36:02	2866299
Ulysses/COSPIN/KET Sectored data	1990-10-24 00:26:59	2009-06-30 16:10:31	2623845
Ulysses/COSPIN/LET 10m data	1991-01-01 00:00:00	2009-06-30 23:50:00	966672
Ulysses/HISCALE 12s DE electron data	1991-01-01 01:10:51	2009-06-30 18:59:04	30361179
Ulysses/HISCALE 12s LEFS150 electron data	1991-01-01 01:10:51	2009-06-30 18:59:04	30361179
Ulysses/HISCALE 12s LEFS60 electron data	1991-01-01 01:10:51	2009-06-30 18:59:04	30361179
Ulysses/HISCALE 12s LEMS120 ion data	1991-01-01 01:10:51	2009-06-30 18:59:04	30361179
Ulysses/HISCALE 12s LEMS30 ion data	1991-01-01 01:10:51	2009-06-30 18:59:04	30361179
Ulysses/HISCALE DE sectored electron data	1991-01-01 01:10:00	2009-06-30 18:57:00	8735286
Ulysses/HISCALE LEFS150 sectored electron data	1991-01-01 01:10:00	2009-06-30 18:57:00	8736716
Ulysses/HISCALE LEFS60 sectored electron data	1991-01-01 01:10:00	2009-06-30 18:57:00	8736716
Ulysses/HISCALE LEMS120 sectored ion data	1991-01-01 01:10:00	2009-06-30 18:57:00	8735334
Ulysses/HISCALE LEMS30 sectored ion data	1991-01-01 01:10:00	2009-06-30 18:57:00	8378297
Ulysses/VHM-FGM 64s data	1990-10-25 16:50:59	2009-01-01 00:03:38	12465271
Wind/3DP 1m omnidirectional electron data	1994-11-15 00:00:00	2012-12-31 23:59:00	8719200
Wind/3DP 1m sectored electron data	1994-11-15 00:00:00	2012-12-31 23:59:00	8615520
Wind/3DP 5m omnidirectional proton data	1994-11-15 00:00:00	2012-12-31 23:55:00	1764000
Wind/3DP 5m sectored proton data	1994-11-15 00:00:00	2012-12-31 23:55:00	1774080
Wind/WAVES/RAD1 spectrograms	1997-09-24 00:00:00	2006-12-13 23:59:00	24068
Wind/WAVES/RAD2 spectrograms	1997-09-24 00:00:00	2006-12-13 23:59:00	24068

Event catalogues

The SEPServer consortium has made a preliminary scientific analysis of all the SEP events found when scanning the observations to produce the event lists. The results of these analyses have been made available to the users via the server in the form of event catalogues. As an example, the front page of the event catalogue based on ERNE observations is presented in Figure 7.



SEPServer SOHO/ERNE Catalogue		SEP Observations						Solar observations		Comments
		SOHO/ERNE		SOHO/EPHIN e⁻ onset		ACE/EPAM (0.18-0.31 MeV)				
Event #	Date	p⁺ onset (55-80 MeV)	$I_{p,max}$	0.3-0.7 MeV	0.7-3.0 MeV	e⁻ onset	e⁻ PAD	start time	end time	
0	24.09.1997	3:59	1.50E-03	3:12	3:14	3:43	irregular	0:00	3:59	
1	07.10.1997	14:43	8.00E-04	13:15	13:23	13:45	moderate	12:00	15:00	
2	04.11.1997	6:41	1.50E-01	6:16	6:16	6:19	beam	4:50	7:59	
3	06.11.1997	12:37	1.50E-01	12:23	12:23	12:37	moderate	11:30	16:00	
4	13.11.1997	22:26	2.00E-03	21:39	21:47	21:42	beam	20:00	23:59	
5	14.11.1997	14:29	1.00E-03	13:45	13:46	13:59	moderate	11:30	14:30	
6	20.04.1998	11:13	1.00E-01	10:30	10:33	10:43	moderate	9:00	13:00	
7	02.05.1998	14:10	1.00E-01	13:47	13:47	13:46	beam	13:20	16:00	
8	06.05.1998	8:29	4.00E-01	8:05	8:05	8:09	bad μ-coverage	7:30	13:00	
9	09.05.1998	4:32	6.00E-03	4:18	4:20	4:18	isotropic	2:00	5:59	
10	16.06.1998	20:35	1.00E-03	18:59	19:03	19:40	bad μ-coverage	17:00	20:59	
11	18.10.1998	22:22	4.00E-03	21:30	21:32	22:06	moderate	20:00	23:59	
12	14.11.1998	6:16	1.50E-01	5:36	5:47	5:28	moderate	4:00	7:59	

Figure 7: Event catalogue based on SOHO/ERNE observations

Each of the catalogue entries appearing as red is actually a link or a collection of links to analysis results connected to that entry. The user can retrieve plots and text files providing the details of the scientific analysis by Clicking, Shift+Clicking or Ctrl+Clicking the links. The first column, giving the number of the event, provides a link to the “Plot event data” function with the event in question preselected for further analysis.

Electromagnetic data are associated with each SEP event. The user gets access to overview plots through the event catalogue interface (see Figure 7, by clicking on the «Solar Observations» columns). These plots have a fixed pdf format, showing time histories of different types of EM observations, depending on the available data. An example is shown in the left column of Figure 8. At the top the onset time of the SEP event – here the ERNE protons – and, whenever available, an estimate of the initial solar release time are given for reference. These times were used to select time intervals of the EM data relevant for the SEP event. Similar to the plot of SEP data discussed above, users can generate their own data plots, picking up several types of data. For instance, in the right panel of Figure 8, the hard X-ray time profile (INTEGRAL/ACS), the dynamic radio spectra from two instruments (OSRA-AIP, NDA) and the soft X-ray time profile (GOES) are plotted for a subsection of the time interval in the overview plot. These data and the plot can be downloaded by a simple click. Plot panel templates can be saved and re-used as discussed above with respect to the SEP data.

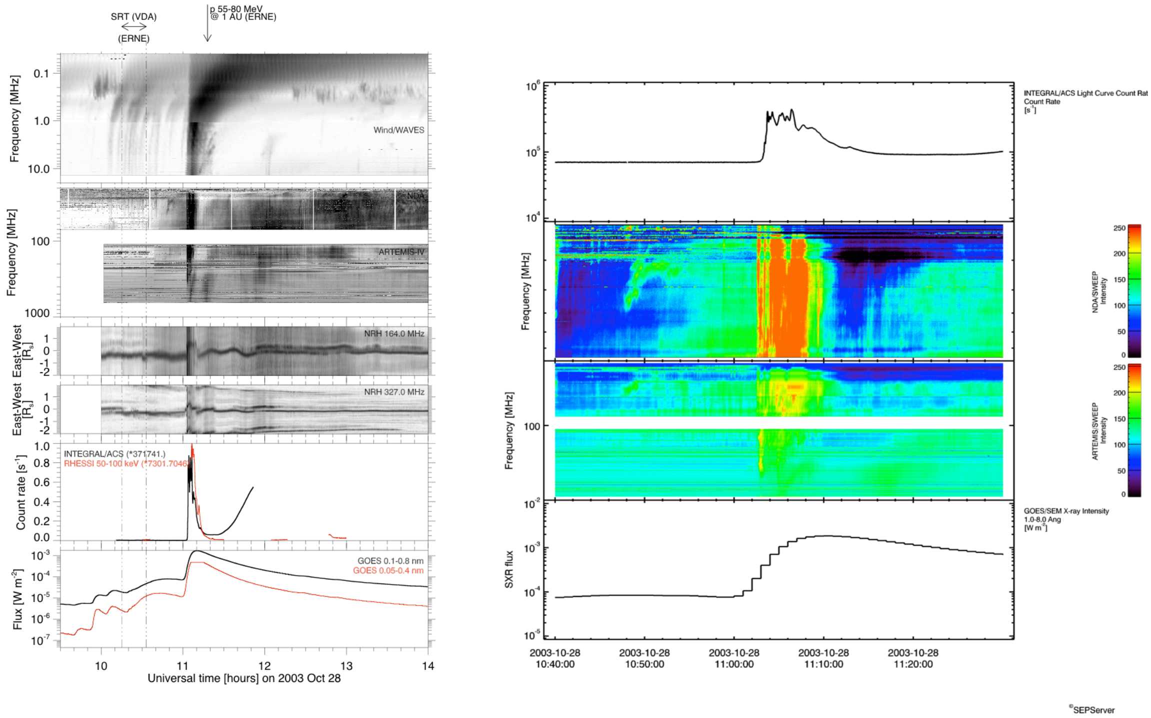


Figure 8: Example plots from the SEPServer showing quicklook data (left) and a user-generated plot of the data provided by the server (right)

Simulation datasets

The simulation datasets provided through SEPServer consists of two types of results: the so-called Green's functions for interplanetary particle transport and self-consistent plasma simulations.

<u>Green's functions</u>

Green's functions of interplanetary transport are simulated responses of idealised particle detectors in the interplanetary space (typically at 1 AU) to impulsive injections of energetic particles from the Sun. The transport simulations model the different processes that affect the propagation of particles: streaming along the interplanetary magnetic field lines, magnetic focusing collimating the particles along the magnetic field, pitch-angle scattering off magnetic irregularities in the field and adiabatic cooling due of the expansion of the solar wind. Particle transport is affected primarily by the solar wind speed and the strength of scattering, i.e., the level of turbulence of the medium. We have computed a database of thousands of Green's functions corresponding to different transport scenarios and assumptions on the energy spectrum of the injected particles. We provide the functions for protons and electrons at 1 AU for energy channels corresponding to several spacecraft experiments. For electrons, we also provide the functions at four locations in the outer heliosphere along the trajectory of the Ulysses spacecraft. Finally, we provide Green's functions for near-relativistic and relativistic particles at 1 AU for several monoenergetic channels. These Green's functions can be used for the analysis of ground-based neutron monitor data. All these functions are stored in the SEPServer database and can be accessed (downloaded and plotted) through a web interface (Figure 9).

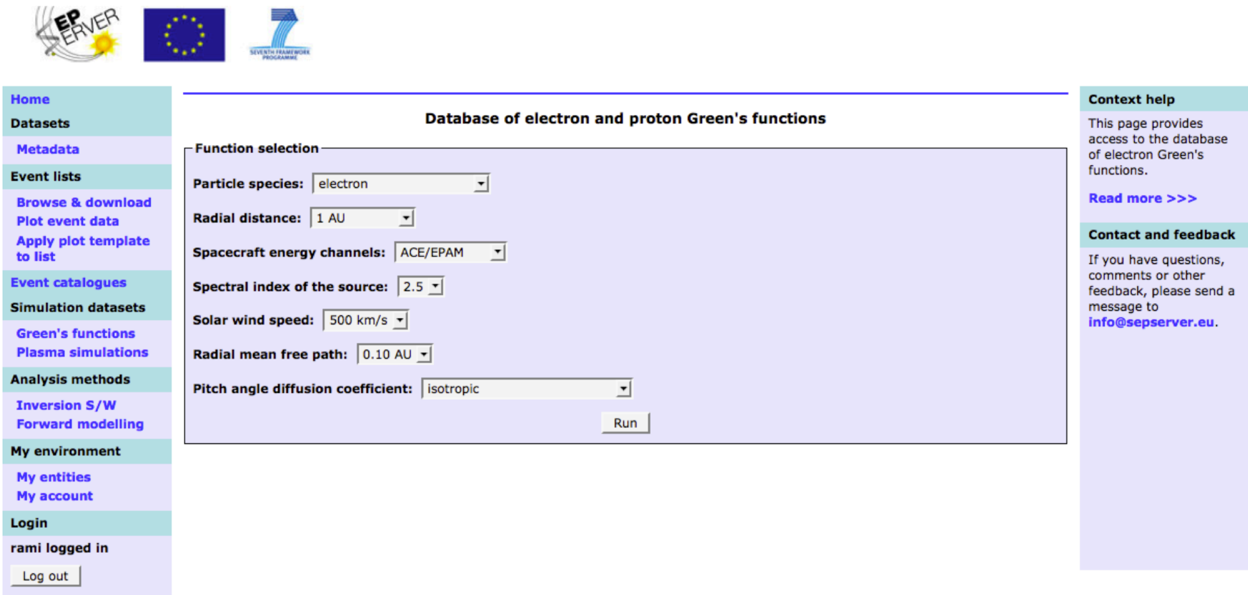


Figure 9: Database of electron and proton Green's functions

Plasma simulations

Another set of simulations accessible from the server website is providing results on self-consistent plasma simulations performed during the SEPServer project. The simulations provide results on ion acceleration at shocks, electromagnetic fields at shocks and magnetic reconnection regions as well as electromagnetic emissions from electron acceleration regions. The user will have access to the raw data from the simulations using visualisation tools developed by the SEPServer team. The data files are very large and, thus, the access is provided off-line, i.e., the user has to download the data files and visualisation tools to a local system in order to make use of them. Figure 10 shows the top of the SEPServer Self-consistent Plasma Simulations Data and Software Download page. The intended use for the self-consistent plasma simulations is to aid the interpretation of observations in terms of different mechanisms and sites of acceleration and radiation due to accelerated particles.

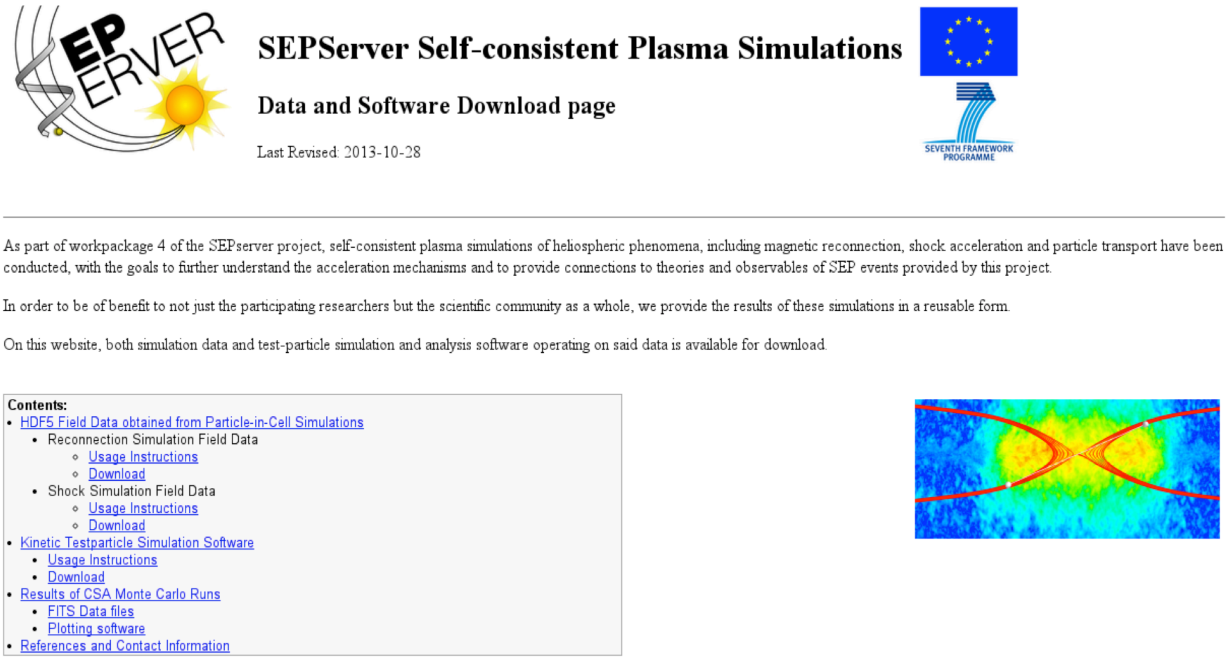


Figure 10: Self-consistent plasma simulations Data and software download page

Data analysis methods

The SEPServer consortium also provides the user with state-of-the art data analysis methods based on the simulated Green's functions of particle transport (see above) and knowledge of the direction of the local interplanetary magnetic field. Two types of methods are provided: inversion methods and forward modelling tools. In both cases, the idea is to make use of interplanetary SEP observations to deduce the solar injection time profile and energy spectrum of SEPs, eliminating the effects of interplanetary transport in the observations.

Forward modelling

The most straightforward way to utilise the Green's functions is to apply them in forward modelling. There one models the injection from the Sun with a temporally extended function and computes a convolution of the source function and injection. This means that at 1 AU, the modelled flux is a superposition of several Green's functions with different weights and timing, as depicted in Figure 11.

In the forward modelling tool of SEPServer, the user is able to model the injection function as a superposition of as many as ten exponentially decaying injections with different amplitudes. All simulated Green's functions are available for the analysis. Once the user has selected the Green's function to use and provided the parameters of the source, the system will compute the response at 1 AU. The results are available to the user as a plot (intensity as a function of time and pitch angle) in png and eps formats and for download as an ASCII file. This is the first time a non-expert user can make use of transport simulation results in the analysis of SEP events.

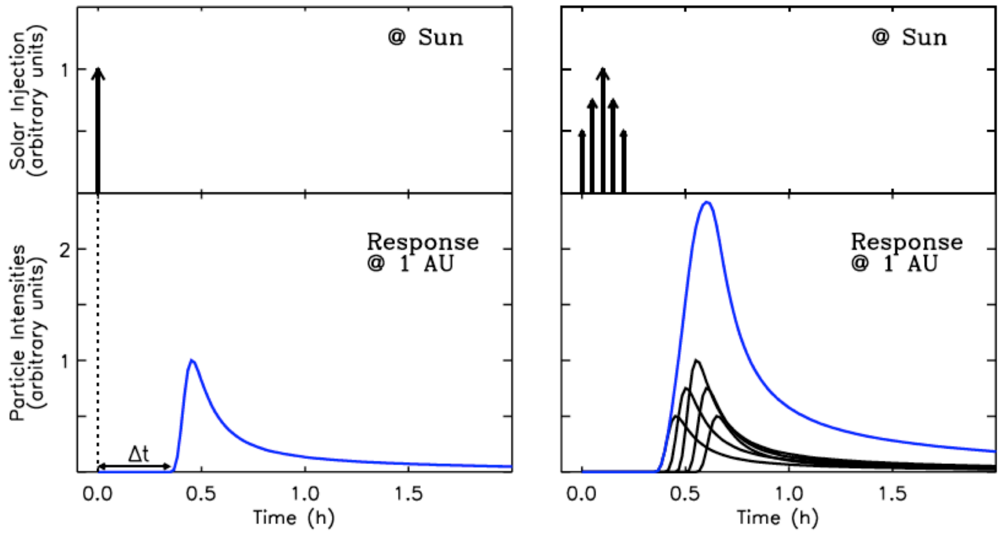


Figure 11: The relation between a Green's function (left) and forward modelling of extended injections (right). The response to a temporally extended injection profile can be modelled as a superposition of response to several impulsive injections.

Inversion methods

The application of the Green's functions in forward modelling requires an assumption of the mathematical form of the injection function. In inverse modelling, this assumption is unnecessary and the observations at 1 AU are used both to deduce the best-fit interplanetary scattering conditions (i.e., the appropriate Green's function) and injection profile at the Sun without a priori assumptions. The constraint applied in this analysis is that the injection function cannot have negative values. As a result of fitting the observations with the model we get a solar injection profile, which can be directly compared to EM observations to identify the solar source of particles observed in near-Earth space.

The inversion methodology delivered to the users is written in IDL, and since the software requires quite a lot of computational resources, it is not run at the server. Instead, the user can download the software from a dedicated download page (Figure 12) and make use of it in a local computation environment. This means that in order to use the software, the user must have access to IDL, which is commercial software. That is clearly a limitation but on the other hand users capable of interpreting the inversion results are space physicists performing research on solar eruptive events quite often using IDL. Thus, this requirement is not severely limiting the number of users of the software.

To apply the software, the user needs to have access to the directional intensity data and, in most cases, the observations of magnetic field in spacecraft coordinates. The latter are not available for download through SEPServer because of IPR limitations. These data can, however, be obtained for analysis through contacting either the Principal Investigator of the magnetometer instrument directly or the SEPServer project.

SEPinversion

IDL Software for Analyzing Solar Energetic Particle Events

Last Revised: 03/07/2013

FAQ

1. **What is this software for?**

   This software is intended to facilitate the study of the sources of solar energetic particle (SEP) events observed by spacecraft in the heliosphere, as well as the conditions under which SEPs propagate in interplanetary space, from the source to the spacecraft.

2. **What does this software do?**

   It fits SEP observations by the *ACE*, *Ulysses*, *Wind* and *STEREO* spacecraft. It makes use of a database of simulation results of a transport model to fit the observations. The problem is constrained by using the most direct form of directional SEP intensities provided by each spacecraft, such as sectored intensities for *ACE* and *Ulysses*, fields of view intensities for *STEREO* and pitch-angle distributions for *Wind*.

3. **What do I need to run this software?**

   You need a Linux machine and a non-ancient version of IDL (i.e., at least IDL Version 6.0).

4. **Where can I get this software?**

   The software can be downloaded as a zip archive.

5. **What do I get with the package?**

   You get a set of IDL routines for reading observational data and simulations results, solve the inversion problem (taking into account the instrument angular response, if necessary), and plot the results. The software consists of 39 routines, of which 33 were developed at the University of Barcelona while the remaining six are external to SEPServer. These include two routines from the IDL Astronomy User's Library (ydn2md.pro and ymd2dn.pro) and four routines from the IDL NNLS package developed to solve the non-negative least squares problem.

Figure 12: SEP inversion software download page

My Environment

In addition to the functionalities described above, the user has access to his/her account information and all entities he/she has created and saved when using the server through the "My environment" section of the main menu. At present, the entities include only plotting templates.

4.1.3.3 Assessment reports

Quality assessments of all the delivered data, observed and simulated, have been performed during the project. *Delivery Reports* on *SEP Data*, *EM Data* and *Simulations and Inversion Methods* have been written and will be available to the SEPServer user via the project website. These documents are very comprehensive but short instrument descriptions can be accessed via the catalogue pages.

4.1.3.4 Scientific analysis results

The scientific analysis in the project has concentrated mainly on the preliminary analysis of the hundreds of SEP events identified in the data. This involves the determination of the SEP event onset time (at the observer's location) in various energy channels for electrons and protons, and making use of these times to deduce the solar release time (SRT) of the particles. The analysis has been done by using the so-called time-shifting analysis (TSA) method and/or the velocity dispersion analysis (VDA) method. In the former, one assumes a path length that the particles have to travel in the interplanetary medium (typically of the order of 1.2 astronomical units) before being detected. Knowing the velocity of the particles allows one to trace the particles back in time to the Sun and derive the solar release time of the first observed particles. The velocity dispersion analysis makes the additional assumption that particles of a single species are all released from the Sun simultaneously, which allows one to treat the path length as a free parameter and find the one best matching the observations by combining information from several energy channels. Thus, this analysis provides a SRT and a path length simultaneously.

Once the solar release time has been found, it has been compared with EM observations. Summary plots have been prepared where the X-ray light curves, dynamic radio spectra and 1-dimensional (east–west / north–south) radio images, when available, are compared with the particle release times. These results are stored and distributed in electronic and re-usable form for the science community in the SEPServer event catalogues.

Besides preliminary analysis results, we have analysed a smaller number of events in detail using the maximal amount of data and also advanced simulation based analysis methods (inverse methods and forward modelling) to obtain more detailed knowledge on the solar release and interplanetary transport of SEPs.

We have also performed theoretical simulation studies of particle acceleration at shock waves driven by CMEs and current sheets forming in flaring regions as well as radio emissions resulting from accelerated electron beams.

Most of the scientific analysis results have been published in peer-reviewed journals.

4.1.3.5 Educational material

During the SEPServer project, a master-level course of 5 credit points on *Solar Eruptions and Space Environment* was held in the University of Helsinki, Department of Physics, which led to a set of lecture notes available to the users (Figure 13). The notes are suitable for university students from advanced bachelor level to PhD level for learning the basics about solar energetic particles and related eruptive phenomena, theories behind particle transport and acceleration during these events, and instrumentation and data-analysis techniques used for their observation. They can also be freely used by the academia for their own lecture courses. The notes can be downloaded from the project website for free and used for academic and educational purposes as long as the source of the material is mentioned.

Contents

Figure 13: Table of contents of the lecture notes on Solar eruptions and space environment

4.1.4 The potential impact and the main dissemination activities and exploitation of results

The results from the SEPServer project directly match the expected impacts of the project, listed in the work programme of the call.

SEPServer

- adds value to space missions and earth based observations by significantly contributing to the effective scientific exploitation of collected data enabling space researchers to take full advantage of the potential value of the data sets related to SEP events. This expected impact is achieved through the advanced data-analysis tools that have been developed for the analysis of SEP observations. These tools enable the researchers to objectively deduce the timing and energy spectrum of SEP injections from the solar corona. The project also provided new key data products that have not been available to the community before.
- contributes to the coordination of the exploitation of existing and future data collection and thereby enhances the possibility to base research on data sets providing comprehensive or full coverage. This expected impact will be achieved through the integrated approach provided by SEPServer, enabling the coordinated use of several types of datasets: SEP observations and the related EM observations from space and ground. Furthermore, the delivered SEP observations, combining data from a large number of simultaneous space missions and ground-based neutron monitors, have spatial coverage from the inner heliosphere out to the orbit of Jupiter and from the ecliptic plane to the polar regions of the heliosphere; energy coverage extending to relativistic energies for both ions and electrons; and comprehensive temporal coverage of the 23rd solar cycle and additional measurements from earlier time periods and the present solar cycle. The delivered EM data are from wavelengths most directly linked to the particle acceleration problem, i.e., hard X-ray, gamma-ray and radio data.
- facilitates access to and appropriate use of data for those scientists who are not part of the team having obtained it. The server facilitates public access, from a single access point, to an unprecedented variety of data relevant to the SEP event problem including numerous data sets that have previously been available only per request from the PI institute. In addition, the server distributes assessments of the quality and uncertainties of the data sets, which is an essential measure to facilitate the appropriate use of the distributed data sets. It also provides analysis results obtained using the data and the related analysis tools, which allows the researcher community to base part of the further research on the results. They are delivered in form of the on-line catalogues of the SEP events providing the analysis results for the events and access to the data that the results were based on.
- adds value to existing activities on European and national levels. The SEPServer project has brought together efforts and expertise from six European countries that have a long tradition in solar-eruption-related research. The national efforts in this field, facing the limited knowledge potential and resources, are implemented using a rather focused approach. None of the countries involved in this proposal could alone have mobilised the expertise and infrastructure required for this research. However, most of the background knowledge and infrastructure of this project (instrumentation, simulation tools) has been and is being developed on national funding. By combining the human resources and the background infrastructure, the SEPServer project produced an output that is much more than the sum of its parts and therefore adds tremendous value to the activities on national levels. In a similar manner, the European facilities alone will still not be sufficient to tackle the SEP acceleration problem using the best possible data. Therefore, by making use of the US resources provided to the consortium by the collaborating third parties, the SEPServer project also added value to the research field on a European level. In return, the European data sets, the data analysis tools, the assessment studies, and the integrating platform provided by the SEPServer project will add value to the efforts of the US national activities.

- raises the awareness of coordination and synergy efforts among stakeholders. The SEPServer consortium has members closely linked to the stakeholders of the project. The most important external stakeholders have been directly involved in the project through the Advisory Board (AB), which was formed from representatives of the US and European data providers, representatives from other projects with complementary objectives, and representatives from key lead user groups. The AB provided a forum to raise the awareness of the coordination and synergy efforts of the consortium. As detailed in the next section, lead user communities have been targeted through the scientific workshop organised on SEP event analysis and through direct contacts to or membership in these communities. Several lead-user forums have been exploited. In addition, the consortium members are active members of the European and international space research communities, which has enabled and will continue to enable them to effectively disseminate the results to these communities at large.

The SEPServer project also produced results that may support future EU projects on Security of space assets from space weather events. The service developed provides greatly facilitated access to high-quality observations of SEP fluxes and related EM emissions. These data are essential ingredients in developing *early warning and forecasting methods to allow for a mitigation of space weather effects on humans in aerospace vehicles and on vulnerable technologies in space (in particular satellites, communication and navigation systems)* and for validating *space weather models to improve specification and prediction capabilities, with emphasis on the linkage of the different physical processes that occur simultaneously or sequentially in many domains*. The SEPServer collaboration is willing to support the goals of such projects (and the goals of similar projects launched by ESA or national agencies).

The European Space Policy emphasizes the need of harnessing space sciences in increasing the interest of young people in science, engineering and technology: "*Space-based activities are strongly evocative of frontier technology and have the potential to attract the interest of the younger generations.*" SEPServer project has had also efforts in public outreach and educational activities.

Dissemination of SEPServer results to the lead user communities has been matched to each community in an efficient manner. The main results of the SEPServer project (column 1), their different lead users (column 2), the ways how these users describe the results (column 3) and the dissemination methods (column 4) to communicate the results to the users are summarised in Table 2. The table also shows the sources of funding foreseen to be utilised by the lead users to exploit the SEPServer results.

Several dissemination methods, targeted to different user groups, have been and will be used in future efforts:

- The Advisory Board (AB) was established in the beginning of the project. It consists of some senior consortium members and key stakeholders to the project, most of who are future users of the server. The AB meetings (in July 2011 and September 2013) provided direct information about the project to key stakeholders external to the consortium.
- SEPServer Workshop on the scientific analysis of SEP events organised in Paris in March 2013 held discussions on the analysis methods developed by the project, fostered the exchange of ideas between SEPServer and key stakeholders, identified some open problems and addressed solutions to them, and confronted different views in the interpretation of SEP events. The workshop reached the science community closest to the project.
- Wider researcher communities, which many of the partners of the consortium are actively participating, have been reached via other scientific conferences and workshops

- The conferences and workshops of the European Solar Physics Division (ESPD) and of the Community of European Solar Radio Astronomers (CESRA): solar eruption research community.
- Space Weather Weeks: space weather research community
- Instrument / Mission science team meetings (of, e.g., Solar Orbiter): Communities preparing the next generation of missions to the inner heliosphere.
- COSPAR, EGU and AGU assemblies: the space research community at large

- The educational sector, including university professors and lecturers as well as graduate students will be targeted through the Consortium Website, academic networks participated by the partner organisations (e.g., ERASMUS) and national meetings of the physical, geophysical and astronomical societies.
- Undergraduate students, high-school students and the public at large have been and will be targeted using several methods
  - Consortium Website
  - Outreach events (e.g., public lectures)
  - National media (e.g., radio and TV interviews, newspaper and magazine articles)

The different lead user communities exploit the results in different ways. Most of the communities consist of researchers, who will exploit the results in further research projects. To enable this, the researchers will have to obtain funding, typically from their national funding agencies or from European sources. The educational user communities may freely use the lecture note material produced, so funding for the exploitation of these results is provided by the Universities and schools employing the lectures. All results of the SEPServer consortium can be freely used for academic and educational purposes. For all other types of use, an explicit permission for use is required from the IIPR holders of the background and foreground results. The requests for use are treated case by case according to rules to be detailed in the Consortium Agreement. Direct commercial exploitation of the SEPServer results may thus be possible, e.g., for SMEs working under ESA contracts on space weather modelling or tool development.

Also many other European projects have exploited and may still exploit the results of the SEPServer project. We have coordinated our efforts closely with other FP7 projects, especially with HELIO (PI: R.D. Bentley, University College London) and SOTERIA (PI: G. Lapenta, KU Leuven), SPACECAST (PI: R.B. Horne, British Antarctic Survey), and COMESEP (PI: N.B. Crosby, BIRA).

Table 2: Exploitation of SEPServer results

Result	Lead User	How the Lead User describes the result	Dissemination	Funding of Exploitation
SEPServer database with analysis / visualisation tools	Researcher studying SEP events (incl. Consortium partners)	Integrated tool for the analysis of SEP events providing easy access to relevant data	Advisory board SEPServer Workshop CESRA, SHINE	National funding
	Researcher / SME working on radiation environment modeling	Database of SEP flux observations providing quality assessments of the data	SWWT ESWW	National funding ESA contracts H2020 projects
	Researcher / SME working on space weather prediction methods	Relational database providing means for exploring causal relationships between different data sets	SWWT ESWW	National funding ESA contracts H2020 projects
SEP Event Catalogue	Heliophysics researcher	Comprehensive graphical summary information on SEP events with access to original observational data	EGU, AGU, ECRS, ICRC, COSPAR	National funding H2020 projects
Reports on Data assessment and Scientific analysis results	Astrophysicist / Space physicist	Fundamental knowledge on particle acceleration and transport in space plasmas	EGU, AGU, ECRS, ICRC, COSPAR	National funding
	Instrument PI ESA / NASA program scientist	Identification of key SEP measurements on future missions	Instrument / Mission Science Team Meetings Direct contact	Agencies
Lecture notes on solar eruptions and space environment	University professor / lecturer	Lecture notes for a post-graduate course or independent studies of solar activity / eruptions	Project Website Academic networking National meetings	Universities
	Graduate student			–

4.1.5 Project information

Main website of the project: www.sepserver.eu

Website of the server: server.sepserver.eu

Email of the project office: info@sepserver.eu

Project logo