

Belgian Institut for Space Aeronomy (BIRA-IASB)

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This document follows the PSS-05 Software Engineering Standards defined by ESA Board for Software Standardization and Control [1].

Abstract

The ESA Space Environment Information System (SPENVIS) is a web-based interface for assessing the space environment and its effects on spacecraft systems and crews. The system is used by an international user community for various purposes, e.g. mission analysis and planning, educational support, and running models for scientific applications. The system also includes extensive background information on the space environment and the environment models. Since 1996 the development of SPENVIS is achieved by the Belgian Institute for Space Aeronomy (BIRA-IASB) under the management of the European Space Research and Technology Centre (ESTEC).

The Final Report summarises the activities performed during the SPENVIS-4 project. The project started in 2006 for an initial duration of three years, after which a maintenance period was foreseen. Following a series of contract change notices, the project ended in November 2014. The Final Presentation of the project occurred on 5-Nov-2014 during the ESA Space Environment and Effects (TEC-EES) Final Presentation Days 2014 at ESTEC.

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1 Executive Summary

The SPENVIS system is used by spacecraft engineers for mission analysis and planning. In the frame of the SPENVIS-4 project [2-5], the SPENVIS system has been improved and further developed while maintaining an operational system available and supporting the user community. In order to better meet the expectations of the users, all new developments have been released in the operational version as soon as they have been validated.

The developments during the SPENVIS-4 project include:

- re-factoring the SPENVIS kernel and the overall system structure in order to support configuration management, model development by third parties, better system monitoring and possible implementation of a business plan;
- integration of applications based on the Geant4 particle transport toolkit and used for detailed 3D analysis of the space radiation impacts;
- implementation of additional models of the space environment;
- extension of the SPENVIS system to other planetary environments and integration of models of the Martian and Jovian environment;
- upgrade and improvement of different effect tools, in particular the ones for solar cell damage and single event upsets;
- addition of new effect tools, e.g. for effective dose and outgassing contamination; and
- an interface with relevant ECSS standards (E-ST-10-04C, E-ST-10-12C and E-ST-20-06C).

In addition to the above, the SPENVIS system has been promoted through active user support, presentations at conferences and organisation of user workshops: 2010 in Mechelen and 2013 in Brussels (both in Belgium). Due to the efforts achieved during the project, the SPENVIS system has become a reference when pre-assessing the effects of the space environment for spacecraft system design. From 2005 to 2014, the number of active users has increased from 840, with an average of 200 active users per month, to 3200, with a monthly average of more than 500 active users. In 2013, SPENVIS has exceeded the number of 10000 registered users.

The current version of the SPENVIS system (4.6.7, initially released on October 4, 2013) is available free of charge at www.spenvis.oma.be. Another version (4.6.4) re-deployed in the frame of ESA's Space Situational Awareness Programme is available from ESA SSA Space Weather portal (swe.ssa.esa.int).

2 Introduction

The planning of space missions requires an analysis of the space environment and its impact on space systems. The space environment includes the following hazardous environments:

- radiation environment due to the radiation belts, solar particles and cosmic rays;
- the plasma environments of the ionosphere and geomagnetic substorms;
- neutral gaseous environments, including upper-atmospheric atomic oxygen;
- micro-meteoroids and space debris;
- magnetic fields;
- solar emissions.

These environmental factors impact spacecraft components through the following effects:

- ionizing dose;
- non-ionizing energy loss;
- solar cell degradation;
- single event effects;
- human and biological radiation effects (stochastic, deterministic);
- spacecraft charging (surface and internal);
- surface erosion (atomic oxygen);
- sensor interference (solar and Earth infrared irradiation);
- micro-particle impacts and punctures;
- contamination;
- orbital decay.

Empirical or quasi-empirical models of these hazardous environments and effects have been developed by different organizations, often independent of one another. As a consequence, the availability of existing models is not always known to potential users. In addition, the issue of updating models and acquiring up-to-date versions is not straightforward.

In order to facilitate the access to the space environment models, BIRA-IASB has been developing for ESA the SPace ENVironment Information System (SPENVIS) since 1996. The SPENVIS system exposes a World Wide Web based interface to a comprehensive set of models of the space environment. It is accessed by a large international user community that use the system for various purposes, e.g. mission analysis and planning, educational support, and running models for scientific applications. The system also includes extensive background information on the space environment and the environmental models.

This Final Report summarises the activities performed during the SPENVIS-4 project. The project started in 2006 for an initial duration of three years, after which a maintenance period was foreseen. Following a series of contract change notices [6], the project ended in November 2014. In the framework of the SPENVIS-4 project, the system has been improved and further developed while maintaining an operational system available and supporting the user community. The main focuses of the project were:

-
- implement new models and methods;
 - take advantage of new software technologies to make the system more responsive and maintainable;
 - maintain the system at BIRA-IASB and its mirror sites at ESTEC;
 - continue the promotion of SPENVIS, including development and support of “stand-alone” versions, and follow-up of licensed copies;
 - development of an interface protocol for third party tools;
 - organization of user workshops.

The Final Report is structured as follow:

- An overview of the SPENVIS system in its current version (4.6.7) is provided in Chapter 3 where the different components of the framework, the architecture of the SPENVIS engine, the interface with the space environment models, the graphical user interface and the list of implemented models are described;
- Most of the model and tool enhancements that were executed during the SPENVIS-4 project are summarized in Chapter 4 with highlights on specific major upgrades as well as on some validation exercises;
- Activities linked with the promotion and use of the SPENVIS platform are outlined in Chapter 5 where statistics about the SPENVIS user community are detailed;
- The deliverables associated to the project execution are listed in Chapter 6;
- Conclusions are drawn in Chapter 7.

3 Overview of SPENVIS

The initial version of the SPENVIS system was developed by ESTEC and was implemented in the form of a menu driven system accessible via a TELNET session. The next versions were developed for ESA by BIRA/IASB in collaboration with different partners. Since then, the SPENVIS system was implemented as a World Wide Web (WWW) based interface allowing user personalised environment, streamlined production of results, both in graphical and textual form, background information and on-line help.

The current SPENVIS implementation is built around a CGI script written in C calling model execution codes usually written in FORTRAN and plot generating codes written in IDL. Most of the SPENVIS logic is stored in templates accessed by the CGI script to generate dynamic HTML and to execute the model or plot codes. The templates correspond to text files mixing HTML codes, pre-processing directives and form handling actions.

In 1998, a prototype was built to replace the WWW interface by a dedicated client and server applications both written in Java. In 2007, the replacement of the CGI script by new codes written in PHP was envisaged. Both alternatives were finally discarded. The current SPENVIS system (version 4.6.7) is still based on a CGI script kernel but some additional functionality has been developed with the support of PHP and MySQL. The system is available from URL <http://www.spenvis.oma.be>. A version is also re-deployed at the SWE Data Centre in the framework of the SSA Preparatory Programme.

3.1 Structure of the SPENVIS-4 system

The different components of the SPENVIS-4 system and their relationship are illustrated on **Figure 1**. The left-handed blue ovals are components accessible to normal users through the Main Portal. They include the SPENVIS-4 system, a discussion forum (based on phpBB) and bug tracking tool (based on MANTIS). The right-handed green ovals are components only accessible to developers through the Developer Portal. They include the project administration pages, a portal and repository for third-party developers to implement and test their models/ codes into SPENVIS, install and save new models, and, management tools for the SPENVIS developer team. These management tools and the main SPENVIS repository (the reddish oval, based on SVN) are located behind a firewall and are not accessible via the internet. The Main and Developer Portals are accessible through URLs <http://www.spenvis.oma.be/> and <http://dev.spenvis.oma.be/>, respectively.

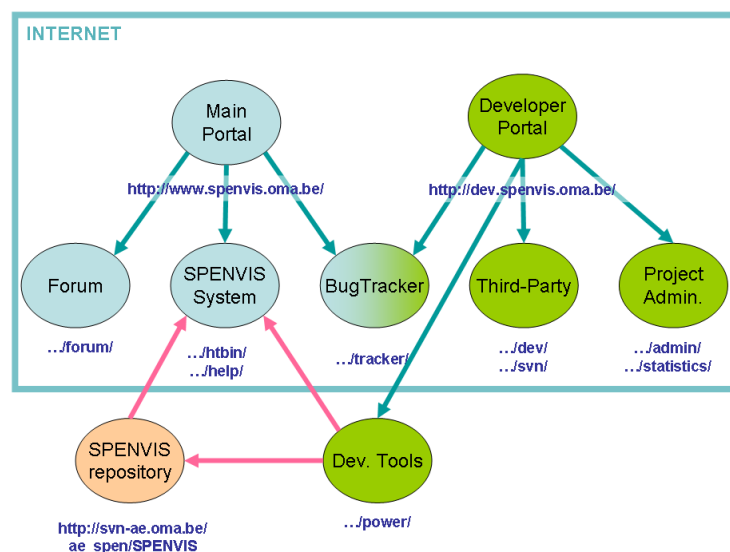


Figure 1 Components of the SPENVIS-4 system

The two main components of SPENVIS-4 are the “Main Portal” and the “SPENVIS system”. They are implemented through the different layers illustrated on **Figure 2**.

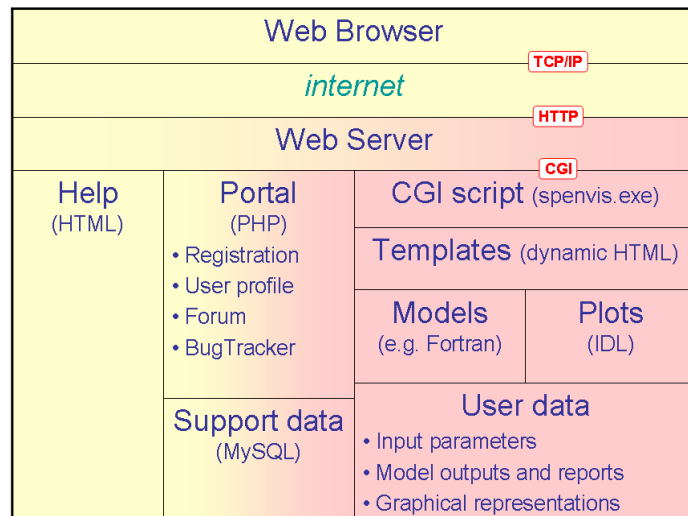


Figure 2 SPENVIS-4 functionality system layers

As SPENVIS is used through a web interface, the first layers are related to the web browser and server (Apache server). The remaining layers are divided in three columns, from left to right: the help part (static HTML pages); the “Main Portal” which supports the user registration, the user profile management, the forum and bug tracker (PHP script and MySQL user database); the core SPENVIS system is built around a CGI script written in C.

3.2 Architecture of the SPENVIS-4 system

The architecture of the SPENVIS-4 system is illustrated with **Figure 3** and corresponds to the following typical execution sequence:

- The system is accessed by the user through HTTP requests that are passed by the web server (i.e. Apache 2) to the SPENVIS engine implemented as a CGI script. The web server layer is mainly in charge of the user authentication, the provision of static content (e.g. help pages) and the dynamic provision of model result files (location of the file is specified by the SPENVIS engine through a redirect status);
- The SPENVIS engine analyses the user request which is composed of a set of parameters (name-value pair), a sequence of actions and possible uploaded data files, and executes the actions accordingly. The different actions address the archive and first check of model input parameters, the model execution, the user project management, the data persistency and the generation of the web presentation;
- Some actions could trigger the execution of a model or plot. The model input is composed of a FORTRAN namelist file (spenvis.nml) including a set of parameters and a series of files either directly uploaded by the users or resulting from the execution of another model. The model output consists of a report file (preferably in HTML format), a possible error message (spenvis.err), tabulated ASCII files and graphical binary files;

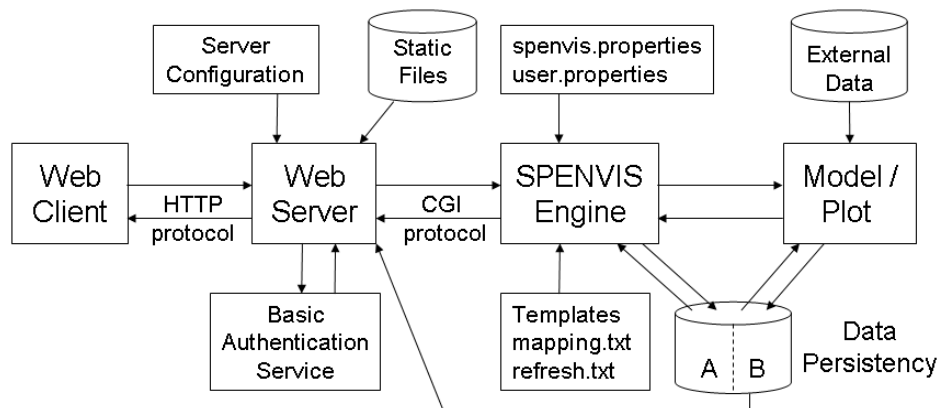


Figure 3 SPENVIS-4 System architecture

The data persistency is implemented by the archive on disk of both a) all the input parameters, and b) all the model results. The archive is organised by user and by project.

The controlling elements of the SPENVIS engine are the following files:

- `spenvis.properties` containing the top level configuration parameters (e.g. location of the data persistency archive);
- `user.properties` containing duplication of some user information from the “user profile” component;
- `mapping.txt` containing for each model the list of all the result files, including the graphical outputs, as well as the user-uploaded files. The content of `mapping.txt` is used by the SPENVIS engine for the web presentation, the deletion of obsolete result files and to determine if a model as already been executed;
- `refresh.txt` containing the forward dependency of each model and used by the SPENVIS engine to determine the list of obsolete result file before executing a model;
- The template files, a series of ASCII files mixing HTML code and SPENVIS-specific directives used by the SPENVIS engine to generate the web user interface. This custom macro language has been imagined at a time there was no such thing as PHP. In addition to the layout elements, a template contains basic information on each parameter (i.e. parameter name, data type, default, min and max values,...), some dependency logic between the parameters (e.g. `$selectcase()` directive), and the sequence of actions to be executed as next step.

Per model two or more template files are defined (at least one for the input page and one for the result page). The existing directives provide the functionalities of basic scripting languages allowing quite elaborate constructions. The template pages relative to the “combined run” (allowing advance users to execute a sequence of models without having to browse through each model pages) is an example of such elaborate construction (see files `radcomb_sel.html` and `radcomb_par.html`). The set of directives and actions handled by the SPENVIS engine is providing a robust scripting language for the development of the current SPENVIS system.

The interface between the models is implemented by the execution of each model in the same folder and the sharing of some files with fixed name.

3.2.1 Actions handled by the SPENVIS engine

The SPENVIS engine receives requests from the server in the form of a series of Action calls. Different types of Action are possible:

- Quick Action – e.g. saving parameters
- Slow Action – that could require a larger amount of time, e.g. running a model

- Reply Actions – which generate output, this is the final action in a sequence

A series always ends by a reply action and slow actions cannot be followed by any quick actions. The Actions are processed sequentially until either an error occurred or the execution of a slow action is consuming too much time. In the first case, the sequence is interrupted and a peculiar error page is returned. In the second case, a waiting page is returned while the remaining sequence is executed in the background. All the sequences can be executed in parallel except when a slow action is running in the background. In this case, any subsequent sequences related to the same user's project will be interrupted if they also include a potential slow action. This particular setting permits the user to continue navigating in the SPENVIS system while a model is executed in the background but prevents interference between models. The actions implemented in the SPENVIS-4 engine are summarized in **Table 3**.

Table 3 Actions of the SPENVIS-4 engine

Action signature	Cat.(*)	Description
#changeProject()	Q (int)	Changes the current project.
#cleanUp()	Q (int)	Cleans up the current project.
#defineProject()	Q (int)	Defines a new project.
#newSettings()	Q (int)	Defines new settings.
#finalizeProcess()	Q (int)	Finalises an internal process.
#zipProjectSelection()	Q	Compiles a ZIP file with the current project.
#namelist (section[cgi_name+...],...)	S	This action creates the namelist containing the specified sections. Each section contains the variables of the specified cgi-files.
#runIDL(model) #runIDLBatch(model) #runIDLOnline(model)	S	This action creates the plots for the specified model. In the first case the mode (batch or online) is determined by the project settings.
#runModel(model) #runModelBatch(model) #runModelOnline(model)	S	This action runs the specified model. It internally performs the removeResult action. In the first case the mode (batch or online) is determined by the project settings.
#deleteFile(file_name)	Q/S	This action deletes the specified project or result file.
#delRunningCgi()	Q/S (int)	Deletes the running CGI script execution.
#mergeForm(template) #mergeForm(template, cgi_name)	Q/S	This action has the same functionality as saveForm but instead of creating a new cgi-file it updates it by merging the values.
#removeResult(model)	Q/S	This action deletes the result files of the specified model (and all depending models).
#saveForm(template) #saveForm(template, cgi_name)	Q/S	This action checks the posted variables (using datatype and range) against the specified template. If unsuccessful it resends the page including error messages. If successful it creates the corresponding or specified cgi-file. The value of template may be NULL in which case the cgi-file is created without checking.
#properties()	R	This action displays some properties (script and environment) of the SPENVIS system.

#resetToPrevious(template) #resetToPrevious(template, cgi_name)	R	This action preprocesses the specified template, merges it with the values of the corresponding or specified cgi-file and sends the result to the user.
#sendPage(template)	R	This action preprocesses the specified template and sends the result (with the default values) to the user.
#sendResult(file_name) #sendResult(file_name, project_name)	R	This action redirects the browser to a result file (file_name) of a project, without having to specify the project result directory. When no project name is specified, the current project is assumed and the browser is redirected to the requested result file (file_name) of the current project. Otherwise the browser is redirected to the requested file (file_name) of the users requested project (project_name).
#waitWhileRunning(index)	R (int)	Waits while a job execution is running.
(*) Q=Quick action, S=Slow action, R=Reply action, (int)=action internally used by the system		

3.2.2 SPENVIS templates

Templates are a core element of the SPENVIS engine. They are activated from actions and are used to control the layout of the model pages, to manage the model parameters and to control the logic connecting the different pages. The SPENVIS templates are implemented as HTML files containing additional functionalities allowing dynamic rendering. The Templates contain directives that are interpreted by the SPENVIS engine. The syntax of SPENVIS directives is similar to the C programming language and the overall approach is similar in functionality to the Server Side Includes (SSI). Any directive is enclosed between the characters "\$" and ";". A directive can have one or more arguments and one or more "bodies". The SPENVIS-4 engine implements three categories of functions:

- Functional - Directive without body returning the result of an associated function.
- Logical - Directive performing a logical test and returning the content of the first body when the test is true, or the content of the optional second body when it is false.
- Iteration - Directives performing an iteration and processing the content of one or more bodies.

The SPENVIS engine is scanning a template until all directives are executed. Directives can be inserted as part of the argument or inside the body of other directives. The directives supported by the SPENVIS-4 engine are summarised in **Table 4**.

Table 4 Directives supported by the SPENVIS-4 engine

Directive signature	Cat.(*)	Description
baseURL	F	Returns an URL referring to the document root.
browseDir	F	Returns a filtered list of result files.
cgi_extract	F	Returns the value of a variable.
cgi_info	F	Returns the value of a system CGI variable from the web server.
dataFile	F	Returns the absolute path to a data file.
define	F	Creates, updates or deletes a variable.

expression	L	Evaluates a logical expression.
fileContent	F	Returns the content of a project or result file.
fileExist	L	Checks the existence of a project or result file.
formErrorMsg	F	Returns the formvalidation error message.
getLastSaved	F	Returns the last saved page.
hasRun	L	Checks if a model has been run.
import	F	Transforms a namelist section into variables.
include	F	Returns the content of a template.
isDefined	L	Performs a relational operator on a variable.
isPackage	L	Checks against the current package.
loop	I	Loop control statement.
loopCgi	I	Formats a list of variables.
loopProjects	I	Formats the list of projects.
loopResults	I	Formats a filtered list of result files.
menuBar	F	Returns a standard menubar.
package	F	Returns the current package.
packageName	F	Returns the description of the current package.
projectTitle	F	Returns the title of the current project.
selectCase	–	Case control flow statement.
scriptURL	F	Returns an URL referring to this instance of the script.
thisProject	F	Returns the current project.
defineMenuBar	F (int)	Returns a specific menubar.
getLastSaved	F (int)	Returns the last saved page.
loopResults	I (int)	Formats a filtered list of result files.
(*) F=Functional, L=Logical, I=Iteration, (int)=action internally used by the system		

3.3 SPENVIS-4 interface for models

3.3.1 Fortran namelist input file

In SPENVIS-4, the model parameters are input by the user in HTML forms and written to a FORTRAN namelist file (*spenvis.nml*). In turn, the namelist file is read by the model.

Note that a namelist file can contain more than one namelist. Each namelist begins with an ampersand (“&”) followed by the name of the namelist and ends with a backslash (“/”). The namelist parameters used by each model are described in TN1[7].

3.3.2 Comma separated value input/output files

Most models implemented in SPENVIS-4 produces one or more output files with file name *spenvis_xxx.txt* and containing ASCII text with coma separated values following a common format. In turn, some of those files are used as an input file for another SPENVIS model. Note that the same output file can be used as an input for a number of models. The SPENVIS-4 model interaction is explained in Section 2.4.4.

The coma-separated-value file, as used by SPENVIS-4 models, contains one or more independent blocks. Each block includes three sections: header, body and footer. In the following we describe the general structure of these three sections in some more details (see **Table 5**).

Header section

The records included in the header section contain general information on the data (project title, main parameters of the program used to generate the data, etc.) and a description of the content of the body section. The header section includes also a reserved area used to add annotation to plots produced in PostScript format. Note that the number of records varies with the application. The header section is directly followed by the body section.

Body section

Each record of the body section contains the values associated to all the variables of the data set, as described in the header section. All records of the body section have the same structure: they contain a suite of real numbers, the number of which is specified by the seventh element of the first record of the header section (*ncol*). For the sake of clarity, the values are usually written in fields with fixed width such that the fields from the different records are aligned in columns. In each record, the values are ordered the same way as the descriptions in the header section. The body can only include either scalar or one-dimensional variables.

The number of records contained in the body section is not explicitly determined. An expected value of this number is given by the eighth element of the first record of the header section (*nbody*). Practically, the end of the body section is defined by the detection of the footer section.

Footer section

The footer section consists of a single record that contains a character string. This character string should not start with an asterix (*), as this is reserved for internal use, and is used to detect the end of the body section. The text of the footer string can be used to pass information on the next part of the output file.

For the sake of uniformity the following character strings are suggested:

- 'End of Block', to indicate that the next part of the output file is related to the next namelist section;
- 'End of File', to indicate that the end of the output file has been reached;
- 'Section Break', to indicate that the next part of the output file is related to the same namelist section;

- 'End of Namelist', to indicate that, next to the current part, parts have been added in the output file which are not related to a namelist section.

Table 5 Record structure of the SPENVIS-4 input/output files

Record	Elements	Description
Header Records		
1	'*', <i>nheader</i> , <i>ntext</i> , <i>nmeta</i> , <i>nfut</i> , <i>nvar</i> , <i>ncol</i> , <i>nbody</i> , <i>npart</i>	The first record of the header section consists of a character string and eight integers. The character string serves as guard and shall always be set to a single asterisk ('*'). The integers provide the information on the size of the header and body sections: • <i>nheader</i> is the total number of records of the header section (including this record); • <i>ntext</i> is the number of text lines included in the first part of the header section; • <i>nmeta</i> is the number of metavariables; • <i>nfut</i> is the number of records added to the header section with a format specific to the application. In SPENVIS, this section is used for the annotation on PostScript graphical outputs; • <i>nvar</i> is the number of variables in the body section; • <i>ncol</i> is the number of columns in the body section. As variables can have more than one dimension, this number does not have to be equal to the number of columns; • <i>nbody</i> is the number of records in the body section (set to -1 when the length of the body section is unknown); • <i>npart</i> is the number of remaining blocks associated to the current namelist section. Note that part of the information is redundant since $nheader = 1 + ntext + nfut + nmeta + nvar$.
2 ... (<i>ntext</i> +1)	<i>atext</i>	Each record includes a single character string. These character strings can be used to identify the program used to produce the file (e.g. 'SPENVIS v3.1 - ORBIT GENERATOR - OpenVMS (BIRA/IASB)'), the project title, or other information such as the name of the model used to produce the data.
(2+ <i>ntext</i>) ... (1+ <i>ntext</i> + <i>nmeta</i>)	<i>ameta</i> , <i>ktyp</i> , <i>val_1</i> , <i>val_2</i> ,...	Each record contains the information on a specific metavariable, and starts by a character string (<i>ameta</i>) followed by an integer (<i>ktyp</i>). The string <i>ameta</i> contains the name of the metavariable. The integer <i>ktyp</i> specifies the type of the metavariable. When <i>ktyp</i> is equal to -1, the metavariable contains a character string, the value of which is set in the third element of the record (<i>val_1</i>). When <i>ktyp</i> is greater than 0, the metavariable contains a vector of <i>ktyp</i> real numbers, the values of which are set in the third and following elements of the record (<i>val_1</i> ... <i>val__{ktyp}</i>).
(2+ <i>ntext</i> + <i>nmeta</i>) ...		This area is used to write information about the annotation (position and content) used in the PostScript graphical outputs.

(<i>nheader-nvar</i>)		
(<i>nheader-nvar</i> +1) ... <i>nheader</i>	<i>aname</i> , <i>aunit</i> , <i>nelem</i> , <i>atitle</i>	Each record includes information on a specific variable of the data set. A variable is defined as a single real number or as a vector of real numbers. Each record contains four elements: • <i>aname</i>, a character string with the name of the variable; • <i>aunit</i>, a character string with the units of the variable; • <i>nelem</i>, an integer with the number of elements of the vector (set to 1 when the variable is a single real number); • <i>atitle</i>, a character string with a title for the variable that can be used on plots, etc... Optionally, the string <i>atitle</i> can be followed by a set of character strings with metavariable names (see below). Note that the sum over the <i>nvar</i> records of the <i>nelem</i> value shall be equal to <i>ncol</i>.
Data Records		
(<i>nheader</i> +1) ... (<i>nheader+nbody</i>)	comma separated	Variable values
(<i>nheader+nbody</i> +1)	text	Terminator string: 'End of Block'

3.3.3 Other input file formats

Geometry Definition Markup Language (GDML - <http://gdml.web.cern.ch/GDML>) files are used by Geant4 (<http://geant4.web.cern.ch/geant4/>) applications to describe the user geometry (see **Table 6**).

Table 6 GDML files exchanged between models in SPENVIS-4

File name	Generated by	Used by
spenvis_sec.gdml	SECTOR	GDML2NML
spenvis_gdm.gdml	GDML2NML	SSAT, GRAS

3.3.4 Metadata and variables exchanged between models

The diagram in **Figure 4** provides an overview of the interacting models present in SPENVIS 4.6.7. The interaction between models is implemented by the exchange of either files in specific format (such as GDML), parameters in namelist files, or metadata and variables in CSV/MF files.



Figure 4 SPENVIS-4 model interactions

In the figure, the ovals and the boxes represent the SPENVIS models and the exchanged files, respectively. The diagram does not include models and files that are not involved in any model interaction. The green boxes represent files in the CSV/MF format described in section 3.3.2. The associated exchanged metadata and variables are listed in **Table 13** and **Table 14** of Technical Note 1 [7].

On the same diagram, the orange boxes represent non CSV/MF format output files involved in some model interactions. The two “.gdml” are GDML files listed in the previous section. The two “.nml” files are model-generated FORTRAN namelist files that are read by other models (see **Table 14** in TN1 for the variables included in these files). Finally, “spenvis_rco.txt” is the output file from the RDC converter.

3.3.5 Illustration of the model interface

In this section, we use the trapped radiation model collection for Earth as an example for demonstrating how models are interfaced in the SPENVIS-4 system. This trapped radiation model collection includes:

- AP-8 and AE-8
- AE-8 MIN update ESA-SEE1
- CRRESPRO and CRRESELE
- SAMPEX/PET PSB97
- IGE-2006/POLE (only orbital version)

The trapped radiation model collection is implemented by three separate applications: TREP, TREPPPOS and TREPBL. These applications differ by the wrapping layer around the models: TREPBL provides almost a bare access to the models, TREPPPOS includes the conversions from geographic to magnetic coordinates and TREP takes into account the integration over a trajectory. While TREP is the most intricate application, it was the first of the three applications to be developed. In the following we present the different versions in more detail.

3.3.5.1 TREPBL

The TREPBL program (**Figure 5**) allows accessing the trapped radiation models by specifying directly the B, L coordinates (or associated parameters e.g. B/B₀), i.e. a grid of magnetic coordinates.

The trapped particle fluxes can be calculated as an energy spectrum for one pair of magnetic coordinates or for a single energy for a range of magnetic coordinates (spenvis_tbo.txt). With the second option, the user has the choice between varying L and keeping the second coordinate fixed, or varying the second coordinate while keeping L fixed.

The magnetic coordinates of the starting point are specified by a value of McIlwain's L and a value for one other magnetic coordinate. The coordinate range is defined by specifying the last value in the range and the increments between the first and last value (using a fixed step size or a fixed number of values, with linear or logarithmic spacing).

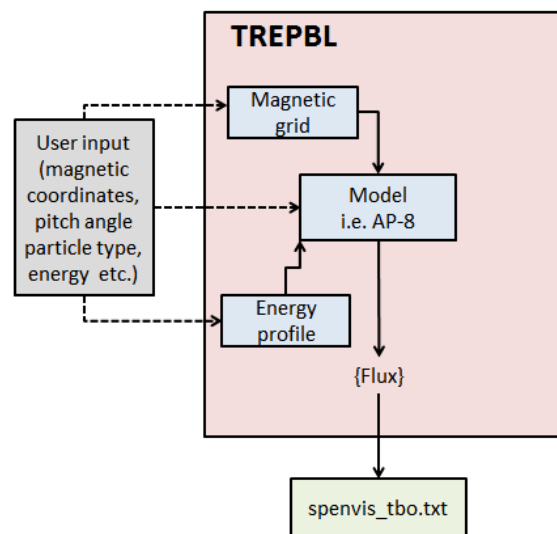


Figure 5 Implementation of TREPBL in SPENVIS-4

Finally, note that since TREPBL does not interact with other models it does not appear in **Figure 4**.

3.3.5.2 TREPPPOS

The TREPPPOS program (**Figure 6**) is a positional version of TREP. It calculates fluxes of trapped protons and electrons for the geographic points in the coordinate files (i.e. spenvis_pos.txt) produced by the SPENVIS-4 coordinate grid generator (GRID). The user can select the trapped radiation model, its mode and the particle energy. The output does not include averaged fluxes.

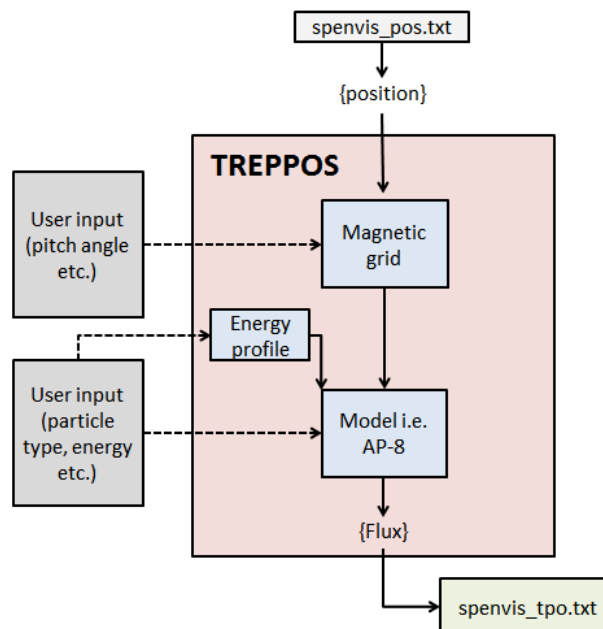


Figure 6 Implementation of TREPPPOS in SPENVIS-4

3.3.5.3 TREP

The TREP program (**Figure 7**) calculates orbital radiation environment fluxes for arbitrary spacecraft trajectories. It takes as an input the orbit file spenvis_sao.txt created by the SPENVIS-4 orbit generator SAPRE. In addition, the user can select the trapped radiation model, the mode of a particular model (e.g.

AP-8MAX or AP-8MIN), the particles flux thresholds and other statistical parameters specific for some of the models (e.g. index for confidence level of the AE-4 statistical model). In turn, it estimates fluxes of trapped particles in function of (E, B, L) coordinates and its output consists of:

- integral and differential omnidirectional flux spectra of trapped protons and trapped electrons at each point along the trajectory, for solar minimum or solar maximum conditions (spenvis_spp.txt and spenvis_spe.txt);
- trajectory-averaged spectra for trapped protons and electrons (spenvis_tri.txt);
- mission-averaged spectra for trapped protons and electrons in case of multi-segment mission.

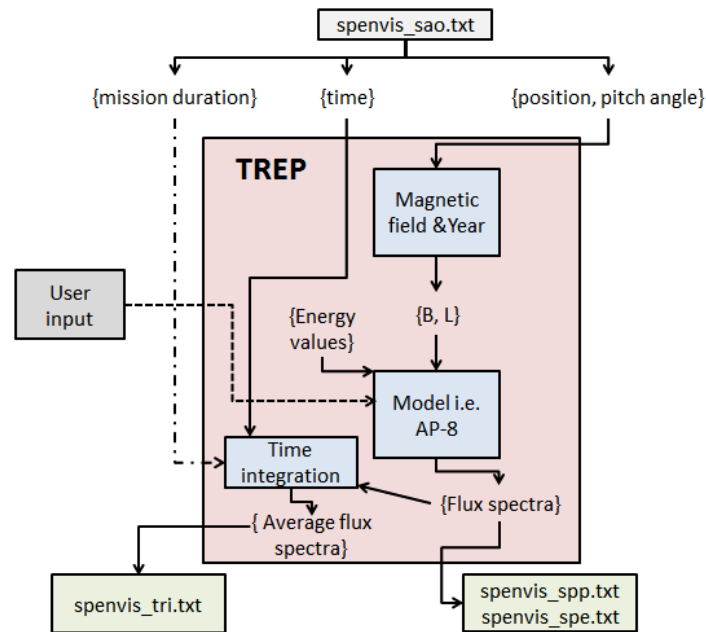


Figure 7 Implementation of TREP in SPENVIS-4

The output of TREP is used as an input by a number of other SPENVIS-4 models (**Figure 4**). More specifically, the trajectory-averaged spectra (spenvis_tri.txt) is used by

- the shielded flux model (MFLUX),
- the solar cell radiation damage models (EQFLUX and MC-SCREAM),
- the ionizing dose for simple geometry models (SHIELDOSE, SHIELDOSE-2 and SHIELDOSE-2Q),
- the non-ionizing energy loss for simple geometries model (NIEL),
- the effective dose and ambient dose equivalent model (SMUL),
- the short-term single event upsets model (NEWUPSETO),
- the long-term single event upsets model (LONGUPSET), and
- the Geant4 models MULASSIS, GEMAT and GRAS.

Finally, the output file spenvis_spp.txt is used by the trapped proton anisotropy model (ANISO) and the short-term single event upsets model (NEWUPSETO).

3.4 SPENVIS-4 user interface

Allowing comfortable project navigation, the SPENVIS user interface is consistent for all implemented models as illustrated on **Figure 8**. On top of every page is a blue stripe for the project navigation with access to the Project Management (underlined title), the Model Packages page (button “UP”), the Output page summarising all previous results (button “Output”) and the contextual Help (button “Help”). At the bottom of most pages is another blue stripe providing navigation to the announcement page, the user settings, the project sharing, the bug tracker, a report form, the user forum and the contact page, respectively.



Figure 8 SPENVIS User Interface explained

The content of main part of the page depends on the user navigation. **Figure 8** is a screen shot of the model page gathering the input parameters of the TREP application (see section 3.3.5.3). After entering the required model parameters, the user can execute the model by pressing “Run”. Depending on the model, the gathering of user input can be spread over several HTML-pages. By pressing “Reset” all parameters on the current page are set back to their default values. The model pages guide the user through the correct use of the models. For every model there is at least one such page.

The model pages are generally accessed from the "model package page" where the models are grouped in the following packages:

- Coordinate generator
- Radiation sources and effects
- Spacecraft charging
- Atmosphere and ionosphere
- Magnetic field
- Meteoroids and debris
- Miscellaneous
- Geant4 Tools
- ECSS Standard

The "model package page" takes into account the model dependencies by preventing access to models needing input from a not yet executed model (see section 3.3.4).

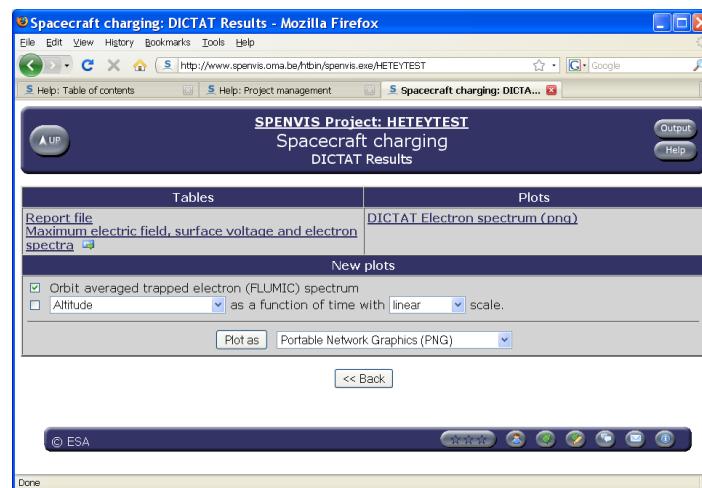


Figure 9 “Model Result” Page (accessed: 23.1.2015)

After successful execution of a model (or a series of models), a result page is returned as illustrated on **Figure 9**. From this page tabulated results can be accessed in the “Tables” section and figures are provided in the “Plots” section. New plots can be generated by pressing “Plot as”. Result plots can be generated in various formats.

3.4.1 Help System

The SPENVIS help is provided via static HTML-files. **Figure 10** shows the start page of the help with the table of contents.



Figure 10 SPENVIS Help: Table of Contents Page (accessed: 23.1.2015)

Navigation within the help is provided by links and the “Table of contents” box, which is present on top of every help page. The help is organised according to the structure of the SPENVIS system. The site following the link “Model packages” describes the coordinate generators and model packages. Other useful features are the glossary and frequently asked questions (FAQ).

3.4.2 ECSS Space Environment Standard

The SPENVIS system contains a copy of the European Cooperation for Space Standardization (ECSS) standard on space environment, see **Figure 11**. The official site (www.ecss.nl) is maintained by the ECSS secretariat at ESTEC.

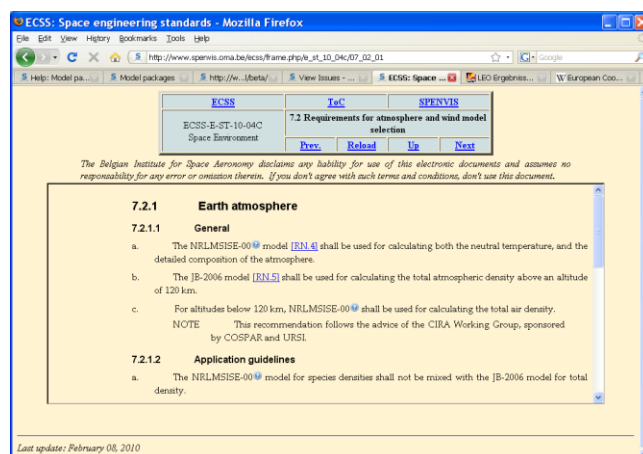


Figure 11 Screenshot of the ECSS Page (accessed: 23.1.2015)

The ECSS document is provided as web-pages. Navigation within the ECSS standard is facilitated by the table of contents (ToC) box, which is present on top of every page.

3.4.3 Combined run

A radiation analysis typically consists of running a number of models in sequence, e.g. the orbit generator followed by one or more radiation environment models and a number of radiation effects models. In the course of such an analysis, it is often necessary to run this model suite a number of times with different parameters, in order to study the effect of, for instance, the orbit configuration on the total mission dose.

The combined run feature facilitates this process: instead of having to run all models in a model suite consecutively, they can be selected as a batch and run in sequence without any further user interaction. Thus, it is not necessary to wait for the completion of one model, navigate to the input pages of the next model and start a model run. Instead, once a model suite has been set up by defining the necessary parameters, one run command is sufficient to complete the requested model runs and to have access to all the model outputs.

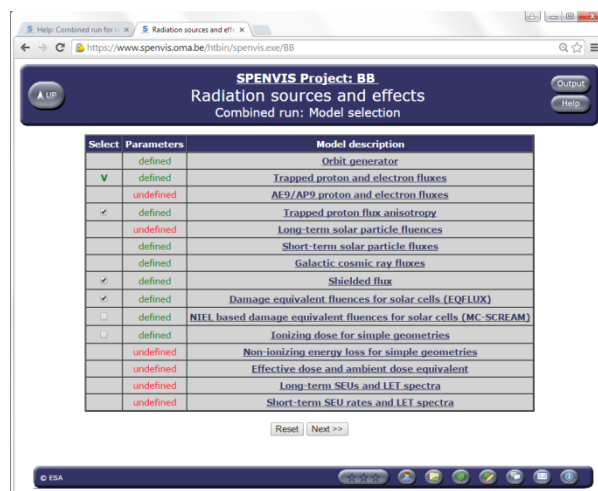


Figure 12 Combined Runs allows parametric studies by running dependent models

The variation of “Trapped proton and electron fluxes” (AE8/AP8) is illustrated with Figure 12. It is possible to select depending models (e.g. Trapped proton flux anisotropy, Shielded flux, ...), which take the (AE8/AP8) model output as their input, and then run the models altogether. This is achieved by clicking on “Combined Run” on the model page, see Figure 8.

3.5 Models implemented in SPENVIS-4

Table 7 gives an overview of the models implemented in SPENVIS. The model types are ordered in groups (Radiation sources and effects, Spacecraft charging, ...marked in bold) and sub-groups (Trapped particle flux, Trapped proton flux anisotropy, ...) according to the grouping in the SPENVIS userinterface. The table indicates for which planet the model is applicable and if an orbit or a grid definition is necessary.

Table 7 SPENVIS models

Type	Name	Planet	Orbit	Grid	Other
Radiation sources and effects					
Trapped particle flux (proton)	AP-8, CRRESPRO, SAMPEX/PET PSB97	Earth	Yes	Yes	BL grid (a)
	IRENE (h)	Earth	Yes	No	No
	D&G83, Salammbro	Jupiter (g)	Yes	No	No
Trapped particle flux (electron)	AE-8, AE-8 MIN update ESA-SEE1, CRRESELE	Earth	Yes	Yes	BL grid (a)
	IRENE (h)	Earth	Yes	No	No
	IGE-2006/POLE	Earth	Yes	No	No
	D&G83, Salammbro, GIRE	Jupiter (g)	Yes	No	No
Long-term solar particle fluences	JPL, King, ESP-PSYCHIC, Rosenquist et al. (2005, 2007)	Earth, Mars, Jupiter	Yes (f)	No	No
Short-term solar particle fluxes	CREME-86, CREME-96, Xapsos et al. (2000)	Earth, Mars, Jupiter	Yes	No	No
Galactic cosmic ray flux	ISO 15390, Nymmik-96, CREME-86, CREME-96 (Sol. Min, 1977)	Earth, Mars, Jupiter	Yes (f)	No	No
Trapped proton flux anisotropy	Badhar & Konradi 90 MAX, Watts et al 1989 VF1-MAX	Earth	Yes	No	No
Shielded flux	MFLUX (MULASSIS look-up tables)	Earth, Mars, Jupiter	Yes	No	No
Solar cell radiation damage	EQFLUX, MC-SCREAM	Earth, Jupiter	Yes (e)	No	No

Type	Name	Planet	Orbit	Grid	Other
Ionizing and non-ionizing dose models	SHIELDOSE, SHIELDOSE-2, NIEL	Earth, Jupiter (g)	Yes (e)	No	No
Effective dose and ambient dose equivalent	MULASSIS & Pellicioni-2000	Earth, Mars, Jupiter	Yes	No	No
LET spectrum and single event upset rates	CREME-86, Slowing/stopping ions (ESTEC), Variable LET (BIRA)	Earth, Jupiter, Mars	Yes	No	No
Geomagnetic cutoff	Smart & Shea (1967) Stoermer Stoermer upgrade	Earth	Yes (b)	Yes	No
Mars energetic radiation environment models (MEREM)	MEREM	Mars	Yes (f)	Yes	Yes
Spacecraft charging					
Internal deep electric charging	DICTAT (V.3)	Earth	Yes (f)	No	BL value (a)
Surface charging	EQUIPOT	Earth	No	No	Yes
Solar array and spacecraft structure potentials	SOLARC	Earth	No	No	Circular orbit
LEO environment parameters	LEOPOLD	Earth	No	No	Circular orbit
Atmosphere and ionosphere					
Atmosphere densities and temperature	NRLMSISE-00, MET-V 2.0, DTMB78, HWM93	Earth	Yes	Yes	No
Ionosphere densities and temperature	IRI2001, NeQuick v2.0	Earth	Yes	Yes	No
Atomic oxygen erosion	NRLMSISE-00, MET-V 2.0, DTMB78	Earth	Yes	No	No
Magnetic field					
Magnetic field vectors (internal)	IGRF	Earth	Yes	Yes	No
Magnetic field vectors (external)	Mead-Fairfield, Tsyganenko, Olsen-Pfitzer quiet, Olson-Pfitzer dynamic,	Earth	Yes	Yes	No

Type	Name	Planet	Orbit	Grid	Other
	Ostapenko-Maltsev, Paraboloid model				
Magnetic coordinates	Unilib	Earth	Yes	Yes	Driftshell (c)
Meteoroids and debris					
Meteoroids	Gruen	Earth	No	No	Circular orbit
Debris	NASA-90, MASTER-2005,2009	Earth	No	No	Circular orbit
Particle/wall interaction	ESABASE, NASA MMOD	Earth	No	No	Yes
Miscellaneous					
Satellite illumination	--	Earth	Yes	Yes	No
Visualization of magnetic drift shells	See group "Magnetic field"	Earth	No	No	Yes
Trapped particle flux	See group "Radiation sources and effects"	Earth	Yes	Yes	BL-grid
Coordinate transformation	--	Earth	No	No	Yes
RDC converter	JPL green + blue book	* (d)	No	No	Yes
Contamination	ECSS-E-ST-10-04C	Earth	No	No	Yes
View Factor	Adoptive Integration Method	Earth	No	No	Yes
Geant4 tools					
Radiation transport through a geometry	MULASSIS (i), GEMAT (i), GRAS (i)	Earth, Jupiter Mercury Mars	(e)	No	Yes
Sector shielding analysis	SSAT (i)	* (d)	No	No	Yes
Radiation transport into neighbouring planet	Magnetocosmics (i)	Earth	Yes	No	Yes
	Planetocosmics (i)	Earth, Mercury, Mars	No	No	Yes
JOREM tools					
Trapped particle flux (proton & electron)	JOSE, IEM	Jupiter	Yes	No	No

Type	Name	Planet	Orbit	Grid	Other
Plasma model	Divine & Garrett 83	Jupiter	Yes	No	No
Ionizing and non-ionizing dose model	SHIELDOSE-2Q	Jupiter	Yes	No	No
GA shield optimiser	GARSO / MULASSIS	Jupiter	Yes	No	No
Jovian moon environments	Planetocosmics-J	Jupiter	No	No	Yes

Comments:

- a) BL-grid: the evaluation of the trapped particle flux over a BL grid is available from the group Miscellaneous.
- b) Geomagnetic cutoff along an orbit is available when accessing the “LET spectrum and single upset rates”.
- c) Drift shell for Magnetic coordinates, see group “Miscellaneous”.
- d) The model is independent of a planet.
- e) For Earth and Jupiter, the model can use mission averaged values as input.
- f) The model only provides values integrated over the whole mission.
- g) See also the models in the group JORE²M² tools.
- h) Only for evaluation
- i) For model version see 8

3.5.1 Geant4 Applications

The Geant4 (GEometry AND Tracking) particle transport toolkit, initiated at CERN in 1994, is jointly developed by a world-wide Collaboration and is intended for a range of applications in HEP (high energy physics), medical field, and space physics and engineering.

In the recent years, space and astrophysics has become a significant user category, with applications ranging from instrument and detector response verification to space radiation, shielding optimisation, component effects, support of scientific studies, and analysis of biological effects. The following **Table 8** gives an overview of the various Geant4 applications and their versions implemented in SPENVIS-4.

Table 8 Model and Geant4 versions for Geant4 tools in SPENVIS

Model	Model version	Geant4 version
MULASSIS	1.23	4.9.5p02
	1.19	4.9.2
GEMAT	2.8	4.9.5p02
	2.4	4.9.0
GRAS	3.1	4.9.5p02
	2.3	4.9.2
SSAT	2.1	4.9.0
Magnetocosmics	2.0	4.7.1
Planetocosmics	2.0	4.8.1

The SPENVIS interface of all these tools simplifies the process of defining run parameters using a number of input pages.

3.5.2 Model dependencies

A more detailed description of the models and their input parameters can be found in the help pages. The table summarises if a model requires an orbit or a grid as input. But several models need additionally the result of other models. **Figure 13** explains the most important orbital model dependencies for planet Earth. There are no dependencies for the grid model versions.

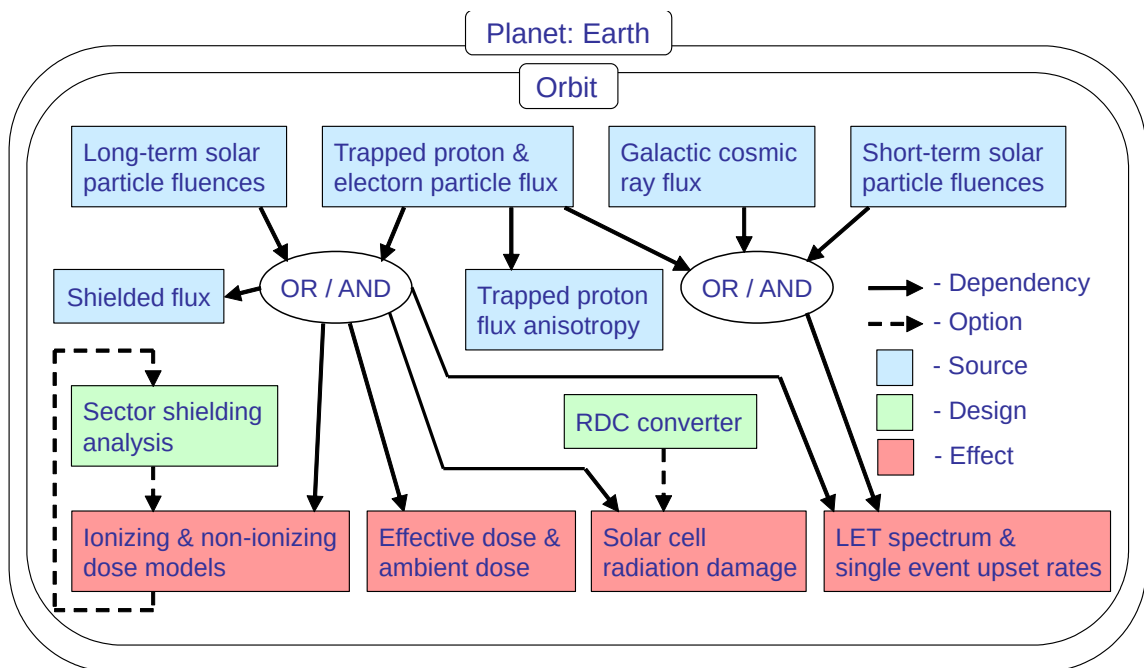


Figure 13 Model Dependencies

The figure explains the dependencies for the orbital models of the Earth. There are three model types:

- **Source** for calculation of the space environment,
- **Design** to compute parameters specific to the spacecraft/instrument design,
- **Effect** to determine the effects of the sources.

Dependency means that the dependent model must be used with the output from the other one. E.g. “Ionizing & non-ionizing dose models” need the result of either “Trapped particle flux” or “Solar particle fluences”. Some of the dependency is optional, e.g. “Solar cell radiation damage” may use output from “RDC converter”. More complicated is the dependency between “Sector shielding analysis” and “Ionizing & non-ionizing dose models”, which require as input a set of shielding thicknesses. When the Sector shielding analysis tool (SSAT) has run, the user gets the option to use the SSAT shielding distribution as input to the dose models. In that case, the dose models also provide a cumulated dose that takes into account the shielding distribution.

Since a dose curve could be uploaded into SSAT, the same result can be obtained through a reverse scenario where a dose model is first used to generate a dose curve which is used by SSAT to compute the cumulated dose. This second scenario is less straightforward (the dose curve has to be extracted and uploaded back into SPENVIS) and is reserved for “advanced users”. The second scenario is useful when computing a dose for several geometries within a fixed radiative environment.

4 Highlight on model and tool enhancement

During the course of the project, the SPENVIS system has been enhanced and extended in different domains and at different levels, ranging from the upgrade of existing tools up to the implementation of new methods or models. These enhancements are briefly summarized in **Table 9**. Some major enhancements are reviewed separately in the next sections.

Table 9 does not contain the improvements of the SPENVIS framework including the complete overhaul of the SPENVIS kernel, the introduction of user management components, the creation of a portal and software development kit for third-party model developers, and the integration of revision control system. While these improvements did not impact directly the users' experience, they have made evolve SPENVIS into a reliable system by improving considerably the availability, the maintainability and the operability of the system.

Table 9 Enhancements of SPENVIS models

Affected package	Enhancement	Summary
Spacecraft trajectories (orbit generator "SAPRE")	Hyperbolic orbit	Extension of SAPRE to hyperbolic orbits allowing the definition of flyby trajectories around Earth, Mars and Jupiter.
	Circular orbit	Modification of SAPRE to improve the simulation of the low altitude equatorial circular orbit around Earth (see Section 4.4).
	Martian orbit	Adaptation of SAPRE to support other planets and implementation of a Martian gravitational model.
	Jovian orbit	Implementation of a Jovian gravitational model including perturbation from Galilean moons (see Section 4.5.7).
	Trajectory upload	Definition and implementation of a text file format for uploading a spacecraft trajectory that supports different types of ephemerides.
Trapped radiation belt	IGE2006/POLE	Integration in the "TREP" tool of the routines implementing the IGE2006/POLE model for geostationary orbit.
	IRENE (AE9/AP9)	Deploying the IRENE package and developing wrapper codes allowing its integration into SPENVIS for evaluation purposes.
	Exposure threshold	Template modification allowing the specification of flux threshold for exposure.
	ONERA Jovian models	Development of a new tool ("TREP_JUP") integrating routines implementing Jovian models after significant adaptation of the original code provided by ONERA.
	AP-8 Unidirectional	Template modification allowing the use of the unidirectional version of the AP-8 models with the "TREP_POS" tool.
Solar energetic particles	Replacing LETORB	Developing a new tool "SEPFLARE" integrating the CREME-86 solar flare spectra initially implemented in the "LETORB" tool.
	PSYCHIC	Implementing the PSYCHIC (Xapsos et al. 2007, [8]) in the "SEP" tool and extending its energy range by using a log-log extrapolation.

Affected package	Enhancement	Summary
	Rosenqvist et al. (2005, 2007)	Implementing in the “SEP” tool the update of the JPL model as proposed by Rosenqvist et al. (2005, 2007) [9][10].
	CREME-96	Integrating the CREME-96 solar flare spectra in the “SEPFLARE” tool based on ECSS-E-ST-10-04C tables.
	Xapsos et al. (2000)	Implementing in the “SEPFLARE” tool the October 1989 events as formulated by Xapsos et al. (2000) [11].
	Mars & Jupiter	Implementing a scaling factor ¹ in both tools “SEP” and “SEPFLARE” allowing their use for interplanetary missions.
Galactic cosmic rays	Replacing LETORB	Developing a new tool “GCR” integrating the CREME-86 cosmic ray spectra initially implemented in the “LETORB” tool.
	ISO 15390	Implementing the ISO 15390 model in the “GCR” tool.
	Nymmik-96	Integrating in the “GCR” tool the variation on the ISO model proposed by Nymmik et al. (1996) [12].
	CREME-96	Integrating the CREME-96 cosmic ray spectra in the “GCR” tool based on Tylka et al. (1997) [13].
	Mars & Jupiter	Implementing the force field approximation in the “GCR” tool to propagate the spectrum at 1 AU to other locations within the heliosphere and allowing the tool to be used for interplanetary missions.
Magnetic shielding (SEP & GCR)	Common settings	Creating a set of common templates and routines for the magnetic shielding evaluation to be shared by the three tools “SEPFLARE”, “SEP” and “GCR”.
	Arrival direction	Adding an option for computing the rigidity cut-off either by integrating over all incoming directions or by only considering vertical arrival.
	Smart and Shea (1967)	Implementing the method computing the rigidity cut-off proposed by Smart and Shea (1967) [14].
	Upgrade of Størmer approach	Developing and implementing a new method for the rigidity cut-off by extending empirically the Størmer approach using results from the “Magnetocosmics” tool (see Section 4.1).
	Mercury & Jupiter	Including magnetic shielding for locations around Mercury and Jupiter by adding simplified dipole magnetic fields.
Shielded radiation (RB & SEP)	MULASSIS look-up table	Developing a new tool “MFLUX” to rapidly transport radiation flux through a Al/Ta shielding based on look-up tables generated with the “MULASSIS” tool.

¹ Scale factor: $(r/\text{AU})^{-2}$ for $r < 1\text{AU}$ and 1 for $r > 1\text{AU}$ (see ECSS-E-ST-10-04C recommendation)

Affected package	Enhancement	Summary
Solar cell radiation damage	RDC Converter	Developing a new tool to transform unidirectional RDCss for uncovered cells into omnidirectional ones including a cover glass for a fixed set of thicknesses. The tool is implementing the JPL methodology ² (Blue book) and supporting Si and GaAs solar cell as well as different types of cover glass. The tool “EQFLUX” has been modified in order to accept the result file from the RDC convertor.
	Cover glass thickness	Modification of the tool “EQFLUX” allowing the interpolation of the 1-MeV equivalence fluences for a cover glass thickness specified by the user.
	AZUR Cell data	Integration in the “EQFLUX” tool of the AZUR GAGET and 3G28 solar cell data after validation by Astrium SAS.
	EMCORE Cell data	Integration in the “EQFLUX” tool of the EMCORE ATJ solar cell data after validation by EMCORE Photovoltaics.
	Spectrolab Cell data	Integration in the “EQFLUX” tool of the Spectrolab UTJ and XTJ solar cell data after validation by Spectrolab Inc.
Ionizing dose	SHIELDOSE-2Q	Making available the QinetiQ version of the “SHIELDOSE” tool outside the JOREM package.
Effective dose	Pellicioni (2000)	Developing a new tool combining the coefficients of Pellicioni (2000) [16] with execution of MULASSIS for the evaluation of effective dose and ambient dose equivalent behind a shielding.
Single event upset	Short- & long-term	Duplicating the “UPSETO” tool in order to evaluate SEU both for a short-term scenario (using worst case solar flare flux spectra) and for a long-term scenario (using particle fluence spectra over a whole mission).
	Slowing/stopping ions	Implementing an algorithm for the slowing and stopping of ions as an alternative to the LET approach (see Section 4.2).
	Variable LET	Implementing a variable LET approach as an alternative to the traditional constant LET approach (see Section 4.2).
	Gallium Arsenide	Integrating physical data table for supporting GaAs devices.
	Multiple devices	Adapting the tool to evaluate the SEU rate for several devices in a single run.
	Device library	Providing a library of predefined devices based on data extracted from the literature (Petersen 1998 [17], Weatherford et al. 1991 [18] and Hash et al. 1994 [19]).
	Path length distribution	Modifying the tool with an option allowing to import path a length distribution in case of a non-RPP device.

² The Kinchin and Pease (1955) [15] formula evaluating the number of displaced atoms has been replaced by the power laws $N_{t, Si}(E) = 21.8 + 17 E^{0.9}$ and $N_{t, GaAs}(E) = 25.2 + 21 E^{0.9}$ (S. Messenger, 2009, private communication)

Affected package	Enhancement	Summary
	Cross-section method	Modifying the tool with the options: • Weibull method for both direct ionization upset rates and proton induced upset rates • input LET threshold value next to critical charge • PROFIT method for Si and GaAs, for proton induced upset rates • to provide experimental cross section data for proton induced upset rates combined with a Bendel fit, Weibull fit or linear interpolation between the data • to compute only direct ionization upset rates or only proton induced upset rates
Internal deep dielectric charging	DICTAT version 3	Upgrade “DICTAT” to version 3.
Surface charging	Low altitude environment	Implementing the worst case auroral environment from Davis and Duncan, 1992 (PL-TR-92-2232) [20].
	Burke SEE formula	Implementing the Burke’s equation (Burke, 1980 [21]) for secondary electron emission.
	Material parameters	Change of classification of oxidized aluminum from conductor to insulator.
Ionosphere	NeQuick v2.0	Integrating the NeQuick routines in the tools “ATOMOX” and “ATMOPOS”.
Geomagnetic field	DGRF	Upgrading the data sets storing the IGRF/DGRF coefficients with their last version.
Meteoroid and debris	Grun model	Removal of the upper altitude limit of 2000 km and extension of the user interface with the user options to enter a fixed mass and diameter.
	MASTER	Installing the MASTER 2005 and 2009 applications, and developing wrapper codes allowing their integration into SPENVIS.
Particle/wall interaction	ESABASE	Developing a tool to evaluate the ballistic limit equations based on the ESABASE/DEBRIS approach.
	NASA MMOD	Developing a tool to evaluate the ballistic limit equations based on the NASA/MMOD approach.
	Shielding material	Compiling the mechanical properties for a set of shielding materials for use with the NASA/MMOD approach.
Outgassing contamination	View factor	Developing a new tool to evaluate view factors between flat faces of a given geometry. The tool is implementing an adaptive integration method (G. Walton, 2002 [22]) supported by a Delaunay triangulation.
	ECSS-E-10-04B	Developing a new tool integrating the equations describing the time evolution of the contaminant mass on the different surfaces of a geometry. The equations depend on a matrix of view factors to be computed by the “view factor” tool.

Affected package	Enhancement	Summary
Geant4 tools	Geant4-based space applications	Integrating into SPENVIS additional Geant4-based space applications by developing specific wrappers to generate the correct input macro files based on the user input and results from other SPENVIS tools. Such wrappers have been created for GEMAT (micro-dosimetry analysis), SSAT (sector shielding analysis), MAGNETOCOSMICS (geomagnetic rigidity analysis), PLANETOCOSMICS (Planetary cosmic ray analysis) and GRAS (3D radiation analysis).
	Geant4 versions	Side-by-side deployment of several Geant4 versions (see Table 8) and of their associated dependencies (shared executable libraries and data files) allowing proper execution of the dynamically linked Geant4-based space applications.
	GRAS/MULASSIS	Integrating new versions of GRAS and MULASSIS (3.1 and 1.23, resp.) without removing access to the previous versions, and by improving the user interface and automating the selection of the physics models.
	GPS Macro	Developing an independent tool generating a Geant4 macro file with GPS commands that could be used by the latest version of GEMAT, MULASSIS and GRAS, for defining the source particles.
	Material definition	Revamping the templates for defining materials in MULASSIS interface and allowing jointly use by GEMAT interface.
	GDML upload	Developing an independent tool analysing uploaded GDML file in support to the interfaces and wrappers of GRAS and SSAT.
	Geometry tool	Developing a new JAVA web application allowing to create simple geometries from the combination of a set of predefined volumes. The application supports export to files in GDML format, GMSH format and the format required by the view factor tool.
Third party development	MC-SCREAM	Transferring and adjusting the third-party SPENVIS implementation of the “MC-SCREAM” tool evaluating NIEL based damage equivalent fluences for solar cells.
	MEREM	Transferring and adjusting the third-party SPENVIS implementation of the “MEREM” tools for evaluating the Martian radiation environment.
	JOE ² M ²	Transferring and adjusting the third-party SPENVIS implementation of the “JOE ² M ² ” package including a set of tools related to the radiation environment of Jupiter and its Galilean moons.
User interface	Planet selection	Addition of planet selection page (Mercury, Earth, Mars and Jupiter), model and package presentation as function of the selection, and insertion of constraints preventing improper combination of models.
	Short- & long-term	Template adaptation to support the introduction of short-term and long-term SEU scenarios.

Affected package	Enhancement	Summary
	Combined run	Complete overhaul of the templates supporting logic for the combined execution of several models (see Section 3.4.3). The new templates provide better control and support on the dependencies between models.
	ECSS Documents	Designing a hypertext version of the space engineering ECSS documents ST-10-04C (space environment) [23], ST-10-12C (radiation calculation method and design margin policy) [24] and ST-20-06C (spacecraft charging) [25], by splitting the documents in multiples HTML files and by adding hyperlinks to the SPENVIS system (models and help pages).
	IGE 2006 wizard	Designing a wizard template for assessing electron radiation at geostationary orbit.
	SPENVIS index	Creating a page with an alphabetic list of topics, models and features with relevant hyperlinks to model interface, model help page, background help page and/or ECSS page.
	Bug tracker	Deploying and integrating the bug tracker application MantisBT.
	Data export	Developing an application displaying the result MF files in HTML format for easy import into an MS-Excel sheet, as well as in VOTable format.

4.1 Upgrade of Stormer approach

The ability of charged particle radiation to penetrate into the magnetosphere from outside is limited by the Earth's magnetic field. The number of magnetic field lines a cosmic ray or a solar energetic particle must cross to reach a given point within the magnetosphere approximately determines the minimum energy it must possess. To cross more magnetic field lines more energy will be required. A particle's penetrating ability is determined uniquely by its momentum divided by its charge, a quantity called magnetic rigidity. Particles having low magnetic rigidity (i.e. momentum per unit charge) are preferentially turned back by the field, so they are unable to penetrate beyond some depth in the magnetosphere. For each point in the magnetosphere and for each direction of approach to that point, there exists a threshold value of magnetic rigidity, called the geomagnetic cutoff.

Using a dipole field approximation, the geomagnetic cutoff rigidity is given by the Størmer (1930) [26] formula

$$P_c(r, \lambda; \Omega) = \frac{P_k \cos^4 \lambda}{r^2 \left(1 + \sqrt{1 - \cos^3 \lambda \sin \theta \sin \phi}\right)^2}$$

where P_k is a constant related to the dipole moment, (r, λ) are the geomagnetic coordinates and $\Omega=(\theta, \phi)$ is the incidence direction for which θ is the zenith angle and ϕ is the azimuth angle measured clockwise from magnetic North.

The exposure factor $F(P)$ giving the fraction of the interplanetary flux with rigidity P that reaches a position in the magnetosphere can be evaluated by an integration at the position over all incidence directions:

$$F(r, \lambda; P) = \frac{1}{4\pi} \int_{4\pi} H(P - P_c(r, \lambda; \Omega)) d\Omega$$

where the step function only selects the direction for which the rigidity exceeds the rigidity cutoff. While an analytic expression of the exposure factor can be derived in the case of a dipole field approximation,

more accurate evaluation of the exposure factor requires backwards tracing of the energetic particles using realistic geomagnetic field models. The Geant4 application MAGNETOCOSMICS carries out such evaluation but is computer intensive.

In order to upgrade the expression of the exposure factor to a non-dipolar magnetic field, the Geant4 application MAGNETOCOSMICS has been used to generate a reference set of exposure factors for comparison with the Størmer formula. MAGNETOCOSMICS calculations have been carried out using the internal magnetic field was IGRF 2000 and the external magnetic field Tsyganenko 96 for 60 positions and two different times. The exposure factors have been computed on a Hardin-Grid with equal weights using 108 incidence directions, and for 30 rigidities.

Comparing the values of the rigidities corresponding to an exposure factor of 0.5 reaches to the following fit

$$\sqrt{\frac{\frac{1}{2}P_{mc}}{\frac{1}{2}P_{st}}} = (0.0141 - 0.189x) x + 1.0706$$

where the indices mc and st refer to MAGNETOCOSMICS and Størmer, respectively, and

$$x = \frac{R_E}{r} \sin \lambda \sin \varphi$$

with (r, λ, φ) the magnetic coordinates. The fit can then be used to scale the exposure factor with the formula

$$F(r, \lambda; P) = F_{st}(r, \lambda; R) \text{ using } \frac{R}{a} = \left(\frac{P}{a}\right)^{\ln(\frac{\frac{1}{2}P_{mc}}{a}) / \ln(\frac{\frac{1}{2}P_{st}}{a})} \text{ with } a = 1\text{GV}$$

where F_{st} is the analytical expression for the exposure factor obtained with the Størmer's formula.

4.2 SEU direct ionisation approaches

A basic assumption in the RPP formalism for calculating the direct ionisation upset rate is that the LET value of the ion when crossing the sensitive volume does not change. In this case the energy deposited by the ion is given by the LET value (L) at surface of the volume multiplied with the path length (s). This implies that the energy loss may be overestimated especially for long path lengths and that an upset occurs as long as $E_{dep} = L \cdot s > E_{crit}$, the critical energy to create an upset. To meet this drawback of the constant LET method two alternative approaches have been implemented in SPENVIS (named "variable LET" and "slowing and stopping ions"):

- Variable LET approach:

To account for the change of the LET value caused by the energy loss inside the sensitive volume, the LET is computed as function of energy and averaged over all particles as follows:

$$\langle L(E) \rangle = \frac{\sum_i (F_i(E) \cdot L_i(E))}{\sum_i F_i(E)}$$

with i the particle index, F the differential energy flux and L_i the LET value for particle i inside the material. When integrating over L at the surface of the volume to compute the upset rate, the average LET curve is used to calculate the minimum distance s_{min} that is required to deposit the critical amount of energy for an upset. The minimum distance is obtained by the condition:

$$\langle \Delta E(s_{min}) \rangle = \frac{\int_0^{s_{min}} P(s) \cdot \Delta E(s) ds}{\int_0^{s_{min}} P(s) ds} = E_{crit}$$

with $P(s)$ the probability of path length s and ΔE the average energy loss after crossing a distance s . using $\langle L(E) \rangle$.

- Stopping and slowing ions approach:

The "slowing and stopping ion" approach (suggested by Eamonn Daly, ESTEC) uses the differential ion energy spectrum as input instead of the LET spectrum. The condition for an upset is given by: $E_{dep} = E - E(R_E)$

$-s) > E_{\text{crit}}$ with R_E the range in the material of the ion with initial energy E . If $R_E - s < 0$ the ion has stopped inside the volume. The upset rate U is obtained by summing over all particles after integrating over the whole energy spectrum and path length range:

$$U = \pi \cdot A \sum_{Z=1}^{92} \left(\int_{s_{\min}}^{s_{\max}} D(s) \int_{E_{\text{crit}}}^{E_{\max}} F(E, Z) dE ds \right)$$

with $F(E, Z)$ the differential ion energy flux in $\# \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \cdot \text{MeV}^{-1}$ and $D(s)$ the differential path length distribution. The maximum energy $E_{\max}$ corresponds to the maximum energy in the spectrum.

4.3 Geant4 Normalisation factor

The SPENVIS Geant4 General Particle Source (GPS) tool calculates two normalisation factors (n_1 and n_2) based on input provided by the user. The calculation is done following the information provided in the F. Lei, P. R. Truscott (2004) [27].

The first normalisation factor n_1 is related to the number of particles in the energy range for the different flux/fluence spectra. In the following table the formulas of n_1 for all the possible types of incident particle spectra in SPENVIS are provided:

Energy distribution	Normalisation factor
Mono-energetic	$n_1 = I(E_0)$
Linear	$n_1 = \left[\frac{A}{2} E^2 + BE \right]_{E_{\min}}^{E_{\max}}$
Power law	$n_1 = \left[\frac{A}{a+1} E^{a+1} \right]_{E_{\min}}^{E_{\max}}$
Exponential	$n_1 = \left[-AE_0 e^{\frac{E}{E_0}} \right]_{E_{\min}}^{E_{\max}}$
User defined or SPENVIS-4 spectrum	$n_1 = (F)_{E_{\min}}^{\infty} - F)_{E_{\max}}^{\infty}$

where $I(E_0)$ is the fluence/flux intensity and F denotes the integral fluence/flux. For the User defined or SPENVIS generated spectrum, the normalisation factor is calculated by simply subtracting the fluence/flux at the maximum energy in the spectrum from the fluence/flux at the minimum energy.

The second normalisation factors n_2 is related to the assumed angular distribution:

Angular distribution	Normalisation factor
Omnidirectional	$n_2 = \frac{1}{4\pi} \int_0^{2\pi} d\varphi \int_{\theta_{\min}}^{\theta_{\max}} \cos \theta \sin \theta d\theta = \frac{1}{4} (\sin^2 \theta_{\max} - \sin^2 \theta_{\min})$
Point source	$n_2 = \frac{1}{4\pi} \int_0^{2\pi} d\varphi \int_{\theta_{\min}}^{\theta_{\max}} \sin \theta d\theta = \frac{1}{2} (\cos \theta_{\min} - \cos \theta_{\max})$

Parallel beam	$n_2 = 1$
---------------	-----------

Note that the one over 4π factor in the above formulas is because of the assumption that all of the particle spectra are omnidirectional, or have been integrated over 4π .

The two normalisation factors are recorded in the macro file generated by the SPENVIS GPS tool as aliases (NORM_FACTOR_SPECTRUM and NORM_FACTOR_ANGULAR) so they can be used by other Geant4 models included in SPENVIS such as MULASSIS, GEMAT and GRAS.

4.4 Circular orbit definition

It is known that the osculating orbit of a satellite moving in the equatorial plane of the Earth because of the perturbation effect due to the oblate Earth (J2 approximation) is elliptical in first order approximation even if the true orbit is always true, Jochim and Eckstein (1980) [28].

Thus, SAPRE has been modified accordingly in order to improve the simulation of the low altitude equatorial circular orbit. More specifically, a new subroutine was introduced for calculating the semi-major axis and the eccentricity of the osculating ellipse for a given radius of an equatorial circular orbit based on the work of Jochim and Eckstein (1980).

The new subroutine was tested by comparing the new results with the previous calculations of SAPRE for the semi-major axis using the following formula:

$$A = 0.5 (r_{apogee} + r_{perigee}) + R_{Earth}$$

where two separate cases were considered for R_{Earth} equal to the mean radius and the equatorial radius of Earth respectively.

Figure 14 shows the root-mean-square deviation (RMSD) related to the altitude calculation (using the three options mentioned above) as a function of the inclination for different circular orbits in SPENVIS (185, 200 and 500 km). One can see that the new subroutine gave reasonable results for inclination less or equal to 36 degrees (in theory only equatorial orbits should have been considered). Therefore, for a circular orbit with inclination greater or equal to 79 degrees the mean radius of Earth can be used for the calculation of the semi-major axis, otherwise the equatorial radius of Earth is used.

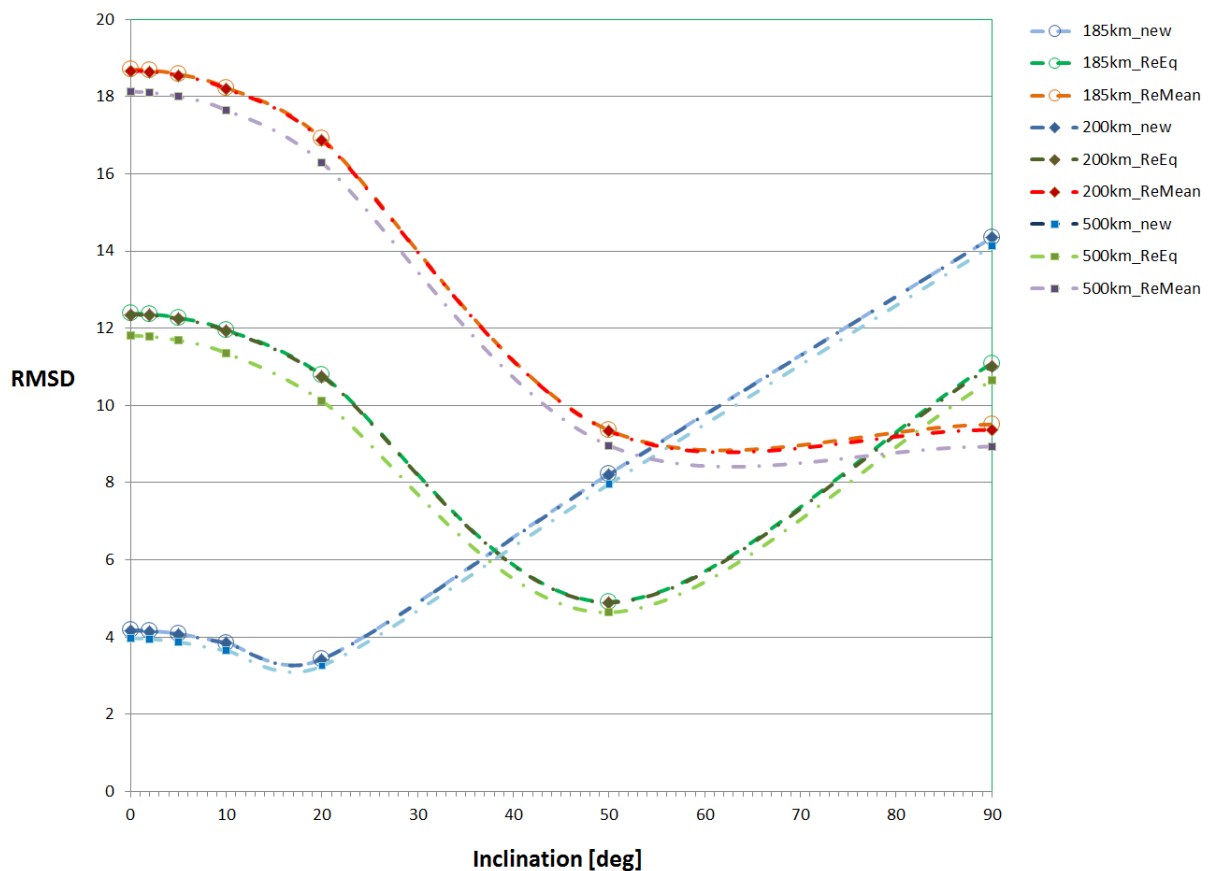


Figure 14 Root-mean-square deviation (RMSD) of SAPRE altitude calculations as a function of inclination for different circular orbits.

4.5 Validation exercises

4.5.1 Comparison of SPENVIS, CREME96 and OMERE4.3 Single Event Upset rate calculations

In this exercise SEU rate calculations obtained with SPENVIS are compared to CREME96 and OMERE4.3 for a given test case.

Test case for direct ionisation upsets:

- Orbit: Near Earth interplanetary (start: 01/01/2010, duration: 1 yr)
- Environments:
 - (1) GCR CREME96 Solar Minimum with ion range: H-U
 - (2) GCR CREME96 (H-U) Solar Minimum + CREME96 Solar flare (worst day) with ion range: H-U
- No Shielding
- Device (Si) : Hitachi 4 Mb HM628512 SRAM
 - Experimental data: Test report for Hitachi 4 Mbit SRAM heavy ion tests at BNL 9-2-92 Version 2.0 K.A. LaBEL CODE 735.1 NASA/GSFC Greenbelt, Md. 20771

LET (MeV.cm ² /mg)	σ (cm ² /bit)
1.35E+00	1.28E-11
1.48E+00	5.98E-11
1.60E+00	7.30E-10
1.85E+00	2.38E-09
2.22E+00	5.22E-09
2.83E+00	1.07E-08
3.20E+00	1.89E-08
4.80E+00	2.80E-08
6.77E+00	3.60E-08
1.12E+01	7.09E-08
1.54E+01	1.01E-07
1.98E+01	1.35E-07
2.28E+01	1.56E-07
2.65E+01	1.61E-07
3.23E+01	2.00E-07
3.99E+01	2.31E-07
4.97E+01	2.48E-07
5.47E+01	2.07E-07
5.92E+01	2.66E-07
6.97E+01	3.30E-07
7.95E+01	3.30E-07
8.94E+01	3.07E-07

- Dimensions: $x = y = \sqrt{\sigma_{lim}} = 5.75 \mu\text{m}$ en $z = 2 \mu\text{m}$
- Weibull fit to exp. data by SPENVIS (OMERE4.3):
 $W = 31.08$ (26.83) [MeV·cm²/mg]
 $S = 1.3$ (2.05)
 $L_0 = 1.35$ (0.67) [MeV·cm²/mg]
 $\sigma_{lim} = 3.30 \cdot 10^{-7}$ ($3.30 \cdot 10^{-7}$) [cm²/bit]
- Results: the seu rates are per bit per day

○ Environment (1)

Method	SPENVIS	CREME96	OMERE4.3
Weibull fit			
constant LET	3.1421E-06	3.0722E-06	3.5600E-06
variable LET	3.3754E-08		

slowing & stopping	4.9422E-06		
Experimental Data			
constant LET	5.5455E-06	5.5312E-06	
variable LET	4.0931E-10		
slowing & stopping	8.6589E-06		

o Environment (2)

Method	SPENVIS	CREME96	OMERE4.3
Weibull fit			
constant LET	4.6572	5.86513	6.52
variable LET	1.8128E-02		
slowing & stopping	5.7191		
Experimental Data			
constant LET	5.2357	6.72099	
variable LET	0.4461		
slowing & stopping	6.3798		

Remark:

Because the method with a variable LET makes use of an LET as function of energy averaged over all particles, mainly low LET values are obtained because of the dominating proton flux. This results in very low DI SEU rates.

Figure 15 resp. **Figure 16** show the calculated LET flux spectra for environment (1) resp. environment (2).

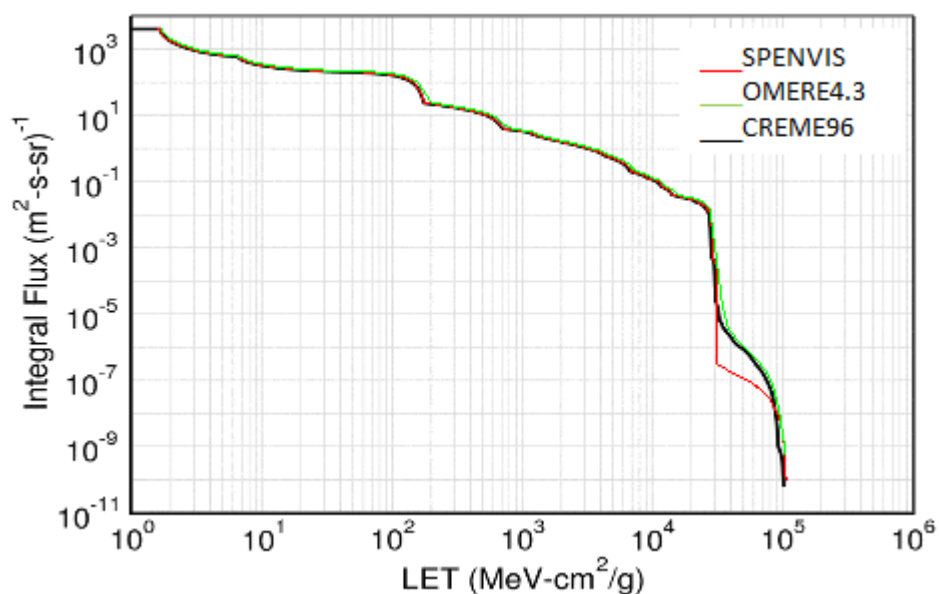


Figure 15 Calculated LET flux spectra for environment (1)

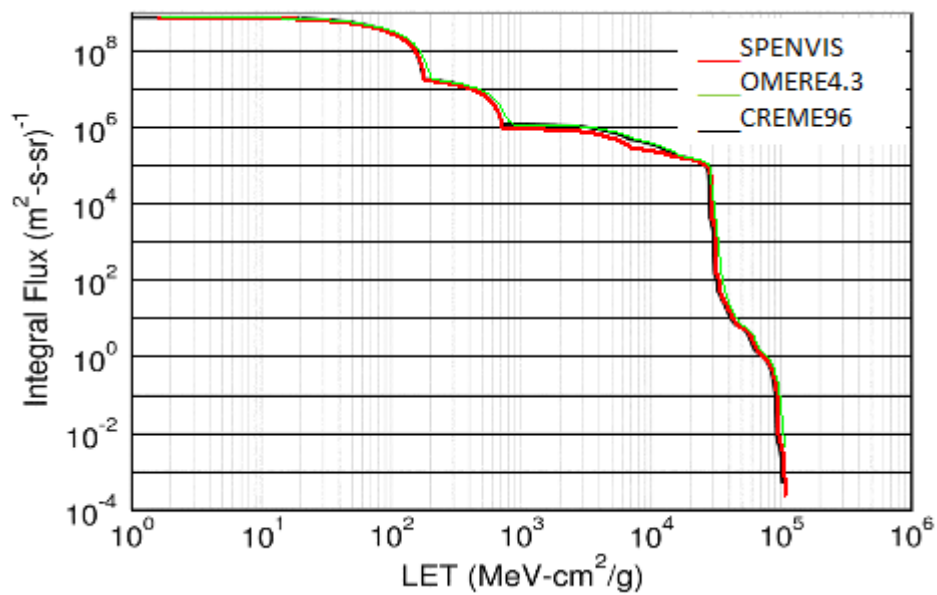


Figure 16 Calculated LET flux spectra for environment (2)

Test case for the proton induced upsets

- Orbit: ISS (start: 01/01/2010, 10 orbits)
- Environment: AP8MIN
- No Shielding.
- Device (Si): Hitachi 4 Mb HM628512 SRAM
 - Experimental data: email communication with C. Inguibert

E (MeV)	σ (cm²/bit)
18	2.19E-14
23	6.88E-14
44	1.06E-13
65	1.13E-13
200	8.78E-14

- Weibull fit to exp. data by SPENVIS (OMERE4.3):
 - $W = 5.9$ (1.36) [MeV]
 - $S = 0.37$ (0.32)
 - $E_0 = 18$ (17.99) [MeV]
 - $\sigma_{lim} = 1.13 \cdot 10^{-13}$ ($1.13 \cdot 10^{-13}$) [cm²/bit]

- Results: the SEU rates are per bit per day

Method	SPENVIS	CREME96	OMERE43
Weibull	1.0201E-07	8.3095E-08	1.1700E-07
Exp. Data			
Bendel fit	8.6776E-08		
Weibull fit	1.0221E-07		
Lin. Int.	9.7374E-08	8.1203E-08	
Profit	8.4075E-08		5.26E-08

Below, **Figure 17** shows the input proton flux spectra.

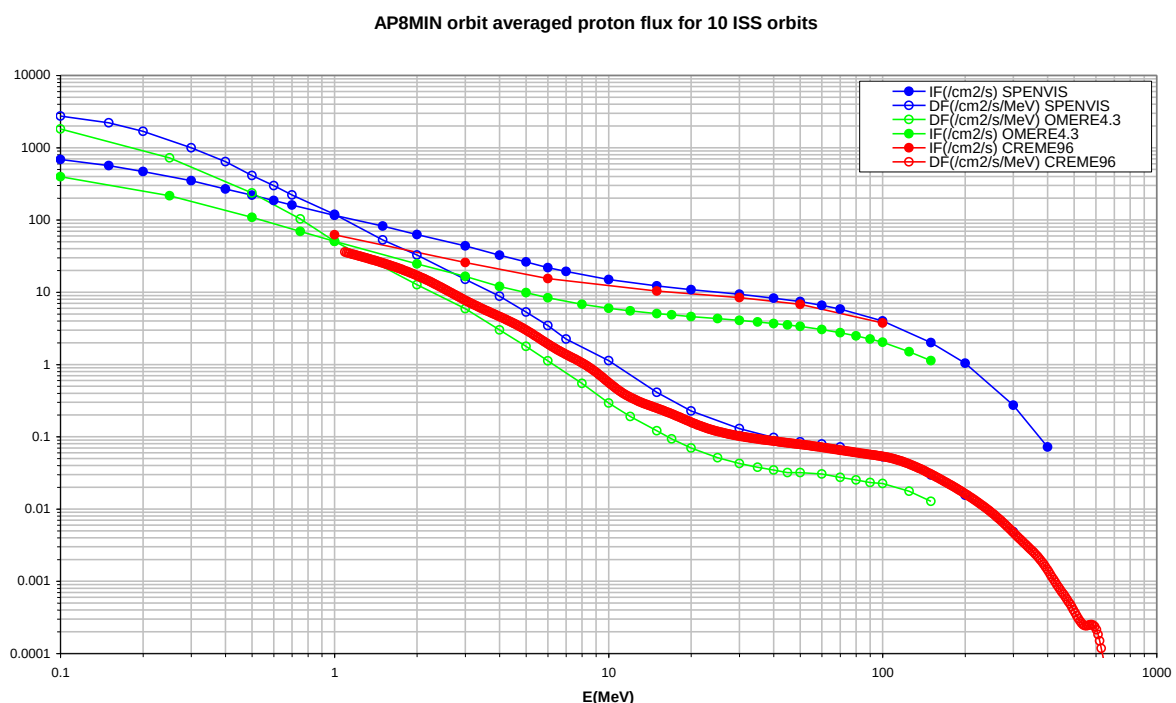


Figure 17 Calculated input proton flux spectra

4.5.2 The PSYCHIC algorithm for solar heavy ions

The PSYCHIC algorithm extends the ESP model to solar heavy ions by multiplying the differential fluence of 5.92 MeV protons, calculated with the ESP model, with a scaling factor. As an example for a mission with two solar max years and a 90% confidence level, the ESP calculation for protons gives a differential fluence of $1.32 \cdot 10^{10}$ p/cm²/MeV at 5.92 MeV. The scale factor for alpha particles at E = 0.173 MeV/nucleon is 20.23. This means that $20.23 \times 1.32 \cdot 10^{10} = 2.67 \cdot 10^{11}$ is the differential fluence for 0.173 MeV/nucleon alpha particles in units of alphas/cm²/(MeV/nucleon). A table of scaling factors for Z=2-92 and E=0.173-547.7 MeV/nucleon has been provided by M. Xapsos. **Figure 18** shows the differential fluence-energy spectra for protons, alpha particles, oxygen, magnesium, iron and summed spectra for Z > 28 elements for a 2-year mission during solar maximum at the 90% confidence level (Xapsos et al., 2007 [8]). The colored lines are the predictions from the SPENVIS implementation.

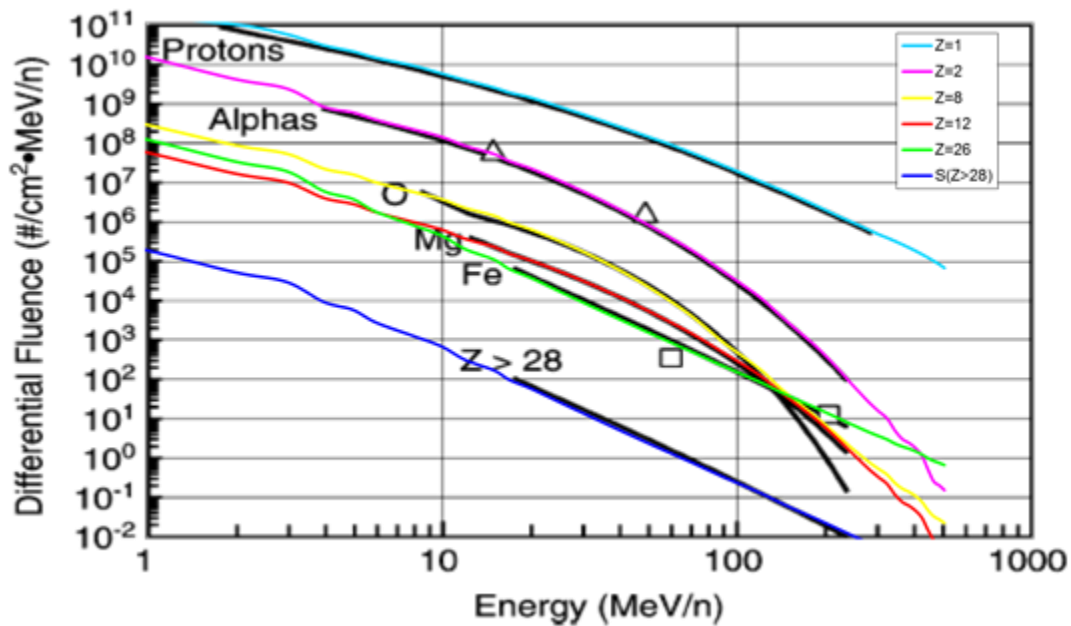


Figure 18 ESP-PSYCHIC predicted differential fluence-energy spectra for $Z=1, 2, 8, 12, 26$ and >28 : black lines (Xapsos et al., 2007), coloured lines (SPENVIS).

4.5.3 IGE 2006 electron model

This geosynchronous electron radiation belt model estimates the geosynchronous electron flux for an energy range from 1 keV to 5.2 MeV. Three fluxes are calculated corresponding to three hypothesis:

- upper flux (worst case)
- mean flux (average between worst and favorable cases)
- lower flux (favorable case)

Figure 19 shows the differential flux as function of energy for an 11 years mission, obtained with the IGE2006 model implemented in SPENVIS. For comparison **Figure 20** shows the same plot published in A. Sicard-Piet et al. (2008) [29].

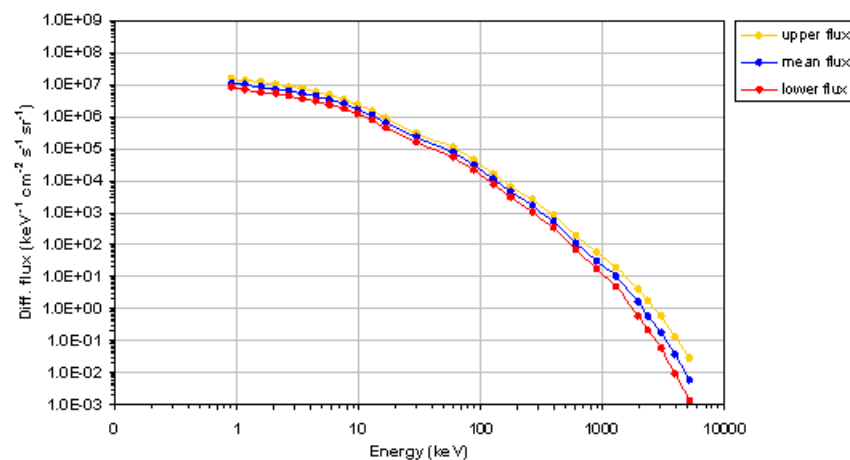


Figure 19 The differential electron flux as function of energy for an 11 years mission, predicted by the IGE-2006 model implemented in SPENVIS.

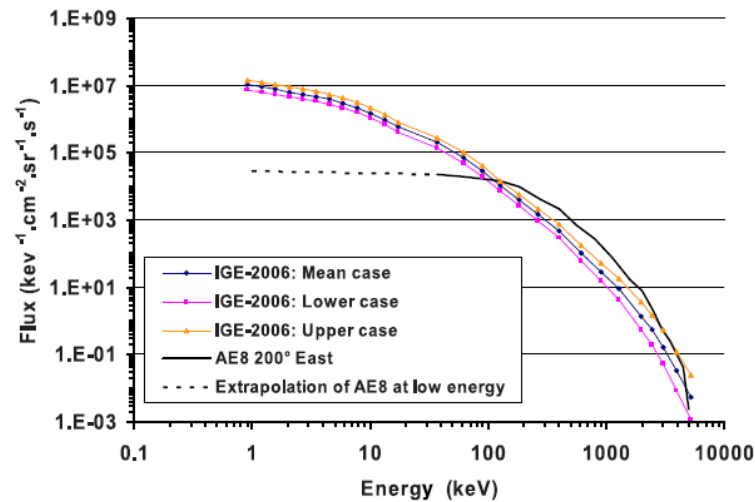


Figure 20 The differential electron flux as function of energy for an 11 years mission, from the paper by A. Sicard-Piet et al. (2008).

4.5.4 Relative Damage Coefficient (RDC) tool

This tool implemented in SPENVIS computes omnidirectional relative damage coefficients ($= D(E,t)$) for a solar cell covered with a glass layer of thickness t , starting from the unidirectional values for uncovered cells ($= D(E,0)$). The tool is based on the JPL procedure as described in Anspaugh (1996) [30].

Figure 21, **Figure** and **Figure 23** show the SPENVIS generated omnidirectional RDC curves for a glass covered GaAs solar cell superimposed on the plots from Anspaugh (1996), starting from the same unidirectional RDC curves for an irradiated uncovered GaAs solar cell. The applied cover glass thicknesses are 1, 3, 6, 12, 20, 30 and 60 mils.

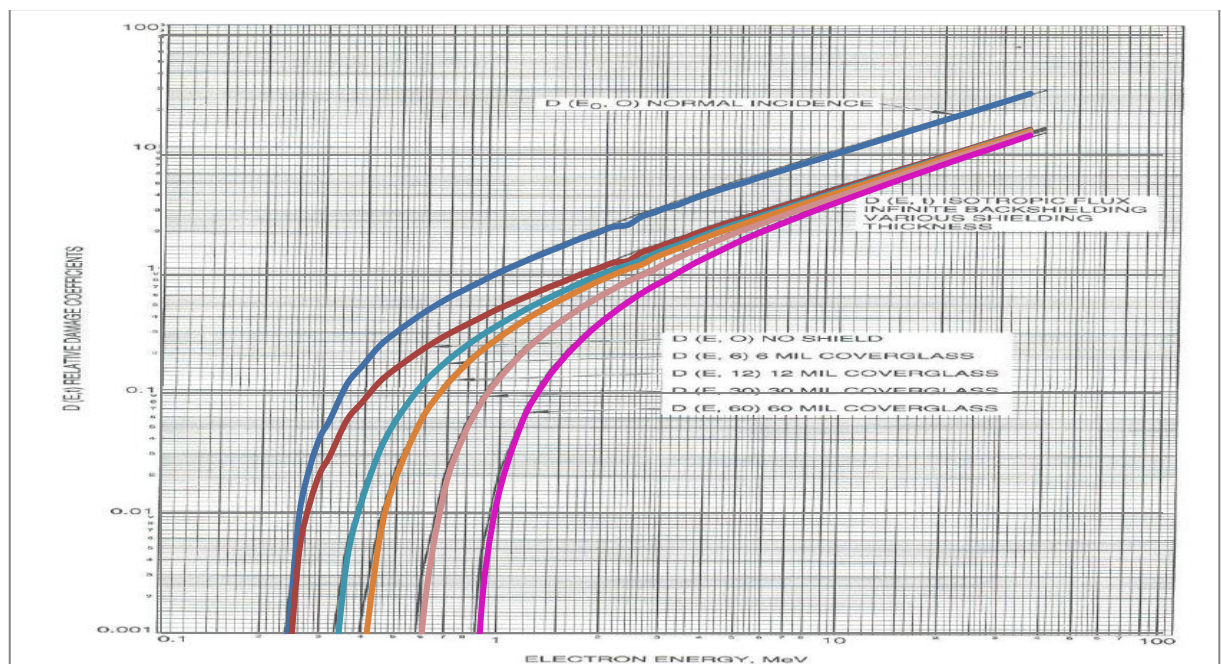


Figure 21 Electron RDCs for a GaAs solar cell: black curves (Anspaugh, 1996), colored curves (SPENVIS).

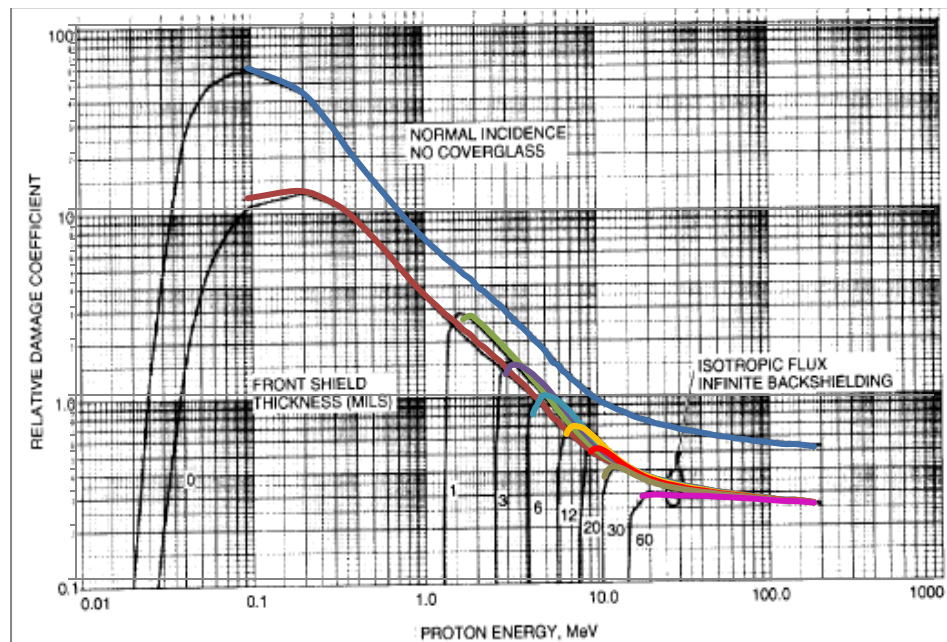


Figure 22 Voc or Pmax RDCs for a GaAs solar cell: black curves (Anspaugh, 1996), colored curves (SPENVIS).

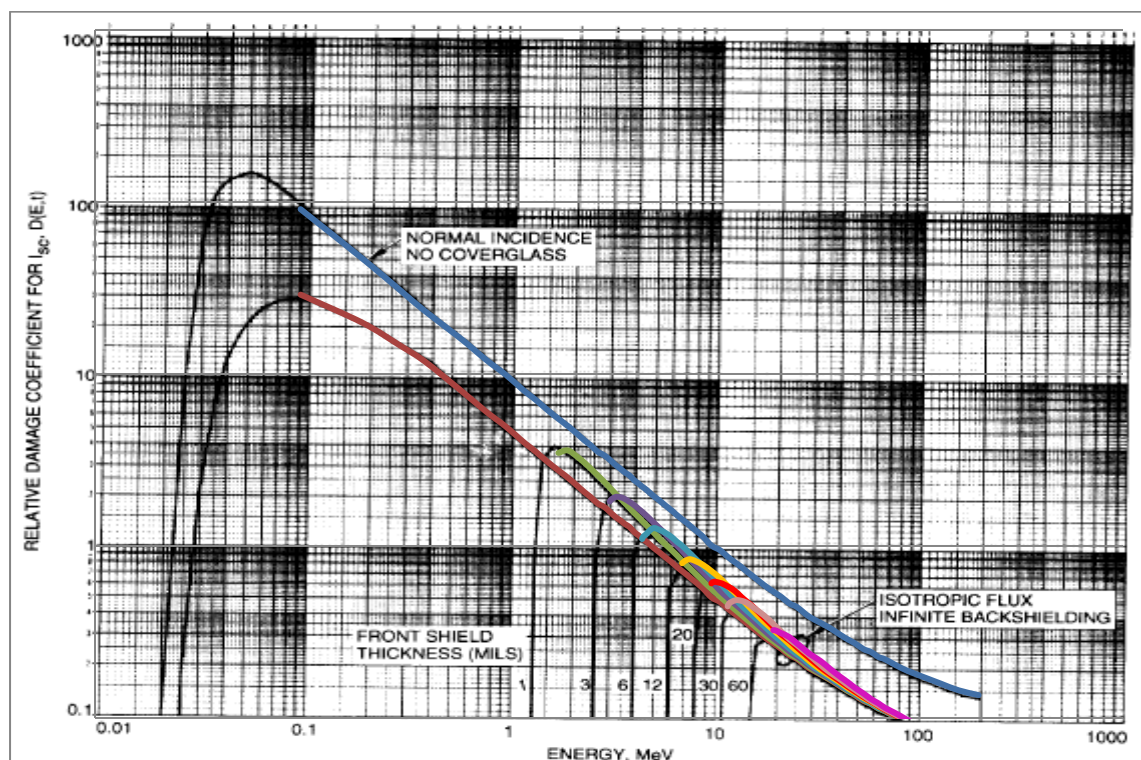


Figure 23 Isc RDCs for a GaAs solar cell: black curves (Anspaugh, 1996), colored curves (SPENVIS).

4.5.5 Viewfactor tool

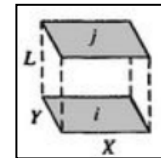
In the development of the contamination models, the view factor tool has been implemented. The tool is based on the “adaptive integration algorithm” whereby using a Delaunay triangulation. As an exercise viewfactors F_{ij} have been computed for the following simple geometries for which analytical solutions exist:

Input precision parameters: Delaunay limit = 10% Integration tolerance: 10^{-3}

Case 1: Two parallel rectangles ($x=1$, $y=0.5$, $L=0.5$)

Analytical F_{ij} : 0.2858754

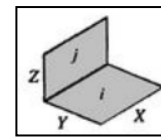
Calculated F_{ij} : 0.2870826



Case 2: Two perpendicular rectangles with a common edge ($x = 1$, $y = 1$, $z = 1$)

Analytical F_{ij} : 0.2000438

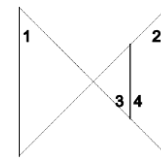
Calculated F_{ij} : 0.2000896



Case 3: Shapiro (1983) [31] test configuration.

Analytical F_{ij} : first row in cell

Calculated F_{ij} : second row in cell



F_{ij}	1	2	3	4
1	0 0	0.11562061 0.11782603	0.084204294 0.08436822	0 0
2	0.11562061 0.11782603	0 0	0 0	0.19861318 0.1986036
3	0.33681717 0.33810005	0 0	0 0	0 0
4	0 0	0.79445272 0.79438112	0 0	0 0

4.5.6 Ballistic limit equations

For given shield properties and impact conditions the particle/wall interaction tool in SPENVIS generates a ballistic limit curve for evaluating the micro-particle environment risk. As a test case the experimental verification made by Reimerdes et al. (2006, p. 653, fig 8) [32] has been considered whereby using the in SPENVIS implemented “Micrometeoroid and Orbital Debris (MMOD) Shield Ballistic Limit Analysis Program”.

Wall configuration: a metallic Whipple shield containing an Al 2024T3 bumper shield of 1.00 mm and an Al 7075 back-up wall with a 2.00 mm thickness and yield strength of 75 ksi. The projectile is made of 99.9 % aluminum and has a zero impact angle. **Figure 24** gives the SPENVIS results (red dots) whereby the modified Christiansen equations with $(t_s/d_p)_{crit} = 0.25$ (bottom) have been used. The results differ in the intermediate velocity regime because the formula for calculating the upper velocity limit in the low-velocity regime in NASA/TM–2009–214789 (formula 51, p. 19) [33] is slightly different from the one used by

Reimerdes et al. (2006). In the low and high velocity regime we find a perfect match. The black and white dots are experimental test results.

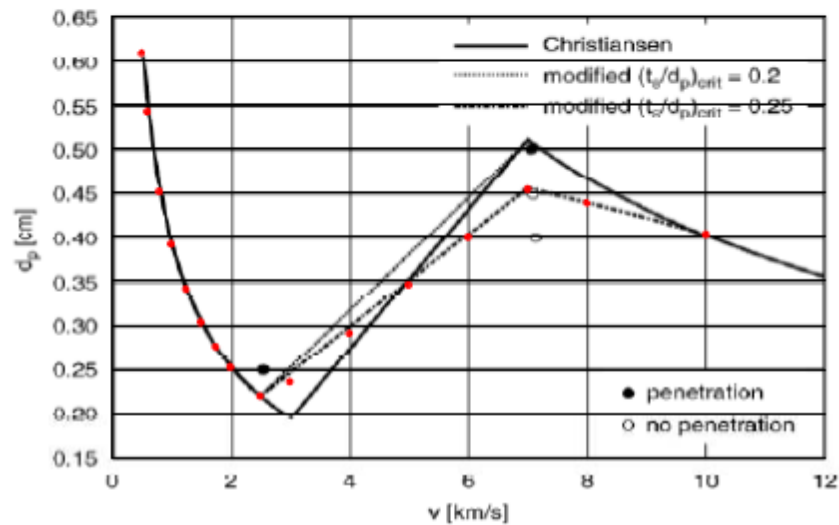


Figure 24 Double wall ballistic limit damage curves for the configuration described by Reimerdes et al. (2006). The red dots represent the SPENVIS results.

4.5.7 Orbit generator (SAPRE)

4.5.7.1 Orbits around Jupiter

For the implementation of the Jovian orbits the gravitational potential for Jupiter using the gravitational field spherical harmonics coefficients from Campbell & Synnott (1985) [34] was assumed. In addition, Ephemerides data for the Galilean moons were taken from Lieske's E5 Ephemerides (Lieske, 1998 [35]). R. A. Jacobson from JPL was also contacted about the more recent data from JUP230 (the last operational ephemeris used in the Galileo mission) but there are no publications available at that time. Finally, for the implementation of gravitational perturbations from the Galilean moons the data were taken from the 2006 report of the IAU/IAG Working Group (Seidelmann et al, 2007 [36]).

The SPENVIS implementation was then tested by comparing the location of the Galilean moons predicted by SAPRE and HORIZONS [37] for a period of 37 days. Note that HORIZONS is based on JUP230 ephemeris. The differences of both predictions are shown on Figure 1 (top left) in terms of an error 2-norm, expressed in km. This figure gives an indication on the SAPRE limitation in case of Galilean moon flybys. Similarly, **Figure 25** (top right) shows over the same time interval the error 2-norm of Sun's position, expressed in terms of the Jupiter-Sun mean distance. The difference on Galilean moon positions is probably due to the use of improved ephemeris by HORIZONS (JUP230 instead of E5). The difference on Sun position is small compared to the mean Jupiter-Sun distance.

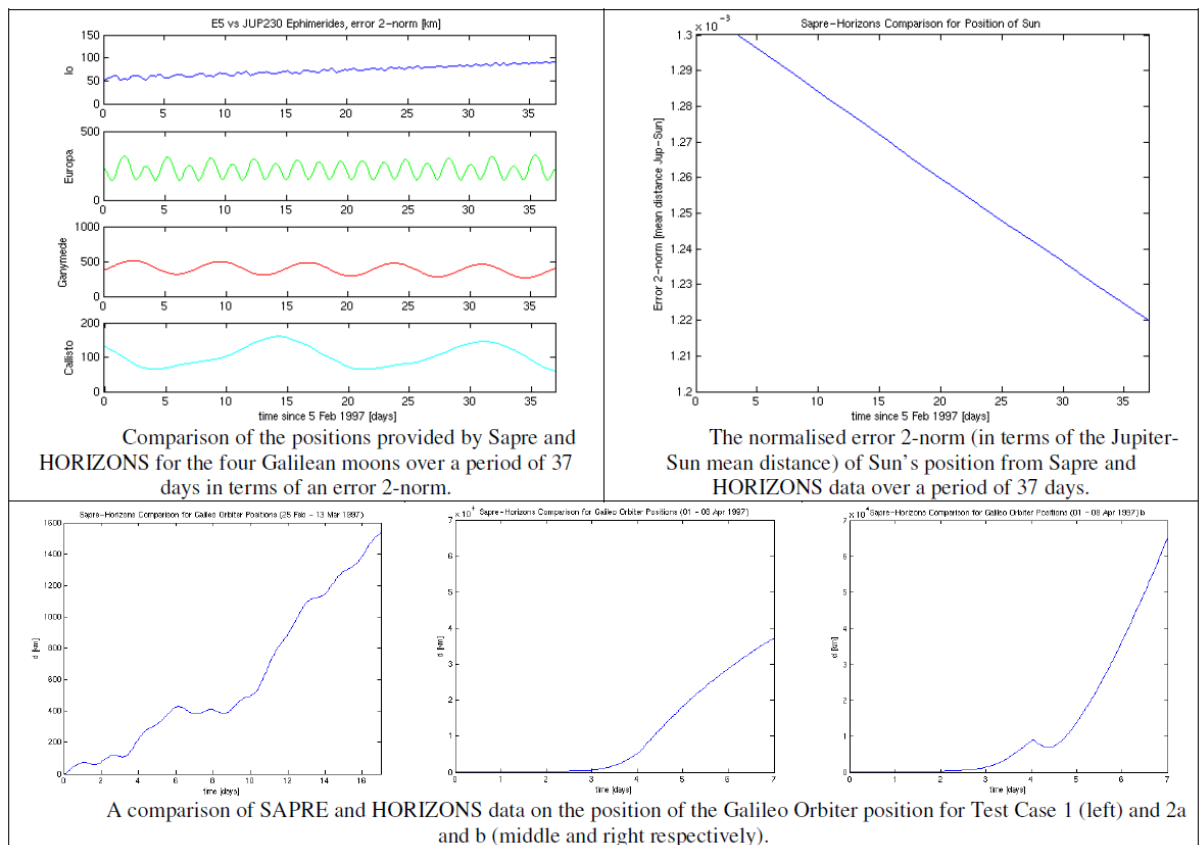


Figure 25 Testing the implementation of the Jovian orbits by comparing the location of the Galilean moons as predicted by SAPRE and HORIZONS.

As test cases, SAPRE was used to predict the Galileo spacecraft orbits (based on Wilson et al., 1997 [38]) and compared them with the JPL's HORIZONS data. More specifically, the test cases illustrated on **Figure 25** (bottom) are:

- Test Case 1: The 24 Feb – 13 Mar 1997 period located between manoeuvres OTM-21 and OTM-22 after third Europa encounter of the Galileo orbiter;
- Test Case 2a: The 01 – 08 Apr 1997 period located between manoeuvres OTM-23 and OTM-24, including encounters with both Europa ($t = 4$ days, $d = 23487$ km) and Ganymede ($t = 5$ days, $d = 3102$ km);
- Test Case 2b: The same as TC 2a but without taking into consideration the gravitational perturbations of the Galilean moons.

Test case 1 shows a good agreement between SAPRE and HORIZONS. This was expected since the Galileo orbiter was far from any of the Galilean moons. Test cases 2a and 2b show a different situation. There was an encounter with Ganymede, the most massive of the four Galilean moons. The closest encounter distance was at 3102 km while the error on the moon position was about 500 km (see **Figure 25** top left). Subsequently the Ganymede gravitational perturbation is not correctly taken into account by SAPRE. Nevertheless the orbit discrepancy was smaller than a computation without moon gravitational perturbations (bottom right panel of **Figure 25**).

4.5.7.2 Hyperbolic orbits and extension of upload trajectory option

The hyperbolic orbit generation (see e.g. Bate, Mueller and White, 1971 [39]) in SAPRE was implemented in order to allow users to define flyby orbits around Earth, Mars and Jupiter. More specifically, the option to specify the semi-major axis and the eccentricity of a hyperbolic orbit was made available. In addition, the upload trajectory option was extended for Mars and Jupiter by updating the SPENVIS upload file format .

Rosetta's first Earth flyby (04 Mar 2005 -22:10) was used as a validation test case. The SAPRE hyperbolic orbit generator was used to calculate the position vectors in Geocentric Equatorial Inertial (GEI) coordinate system. Note that the orbital elements that were used as an input to SAPRE were generated using HORIZONS. Then, the SAPRE results were compared against the Rosetta orbital data taken from http://homepage.eircom.net/~jackcelestia/spacecraft_helio.htm (Figure 26 and Figure 27).

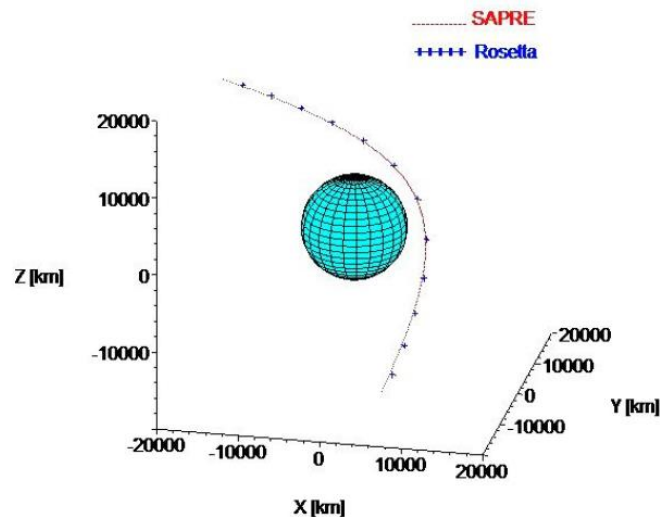


Figure 26 Comparison of SAPRE and Rosetta orbital data during the spacecraft's first Earth flyby (04 Mar 2005 – 22:10).

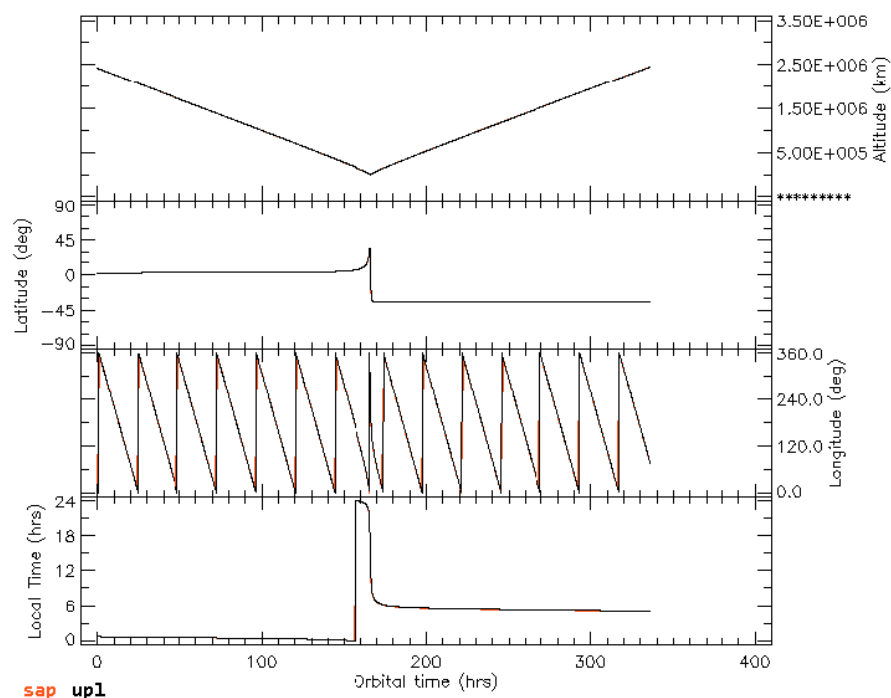


Figure 27 Comparison of the orbit parameters as a function of time from hyperbolic orbit generator (red) and upload trajectory file (black) for Rosetta's first Earth flyby.

4.5.8 Radiation belt models for Jupiter

A new SPENVIS-4 module (trep_jup) was created for implementing the Jovian radiation belt models based on the code provided by ONERA. The ONERA code was adapted so that:

- a user was able to call both electron and proton models in a single run;
- no external data files were needed i.e. all the external data-files associated with the Salammbô model for Jupiter were converted into block data.

The SPENVIS implementation of these models was validated using a number of test cases from the literature.

4.5.8.1 Electron fluxes integrated in energy for Pioneer 10 & 11 Jupiter flybys

First, two test cases based on Sicard & Bourdarie (2004) [40] were considered:

- 1) Electron fluxes integrated in energy from Pioneer [41] 10 Jupiter flyby (19:24 03 – 09:26 04 Dec 1973) for energy ranges > 21 and 31 MeV
- 2) Electron fluxes integrated in energy from Pioneer 11 Jupiter flyby (02:47 – 06:56 03 Dec 1973) for energy ranges > 21 and 31 MeV

At that time SAPRE was not able to produce these type of trajectories. Thus, the spacecraft's actual orbital data were transformed into an appropriate input file for the trep_jup program.

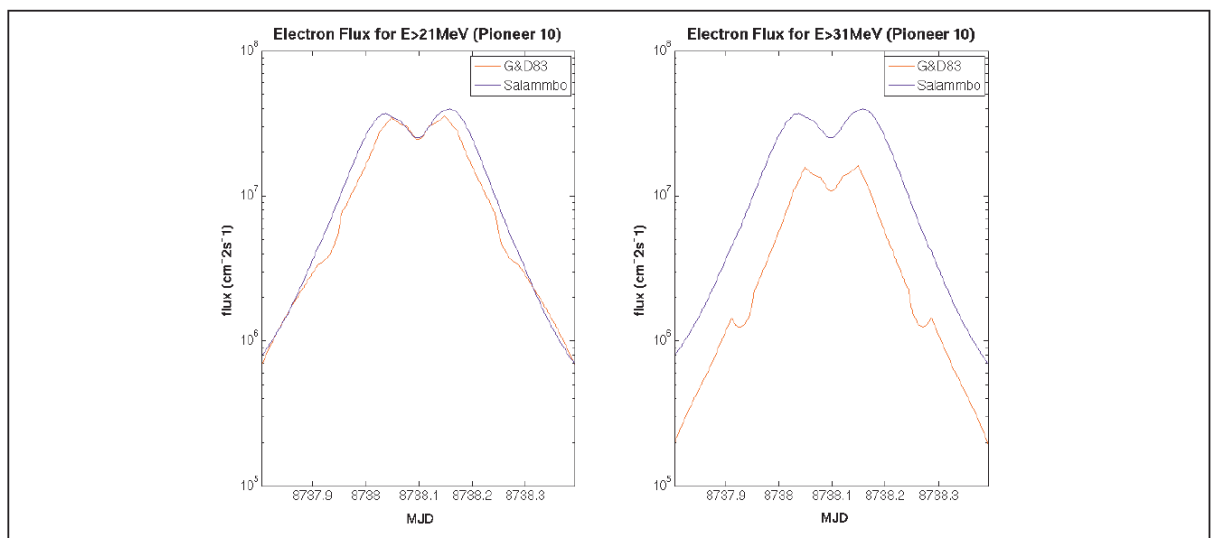


Figure 28 Plots of electron fluxes integrated in energy for Pioneer 10 Jupiter flybys

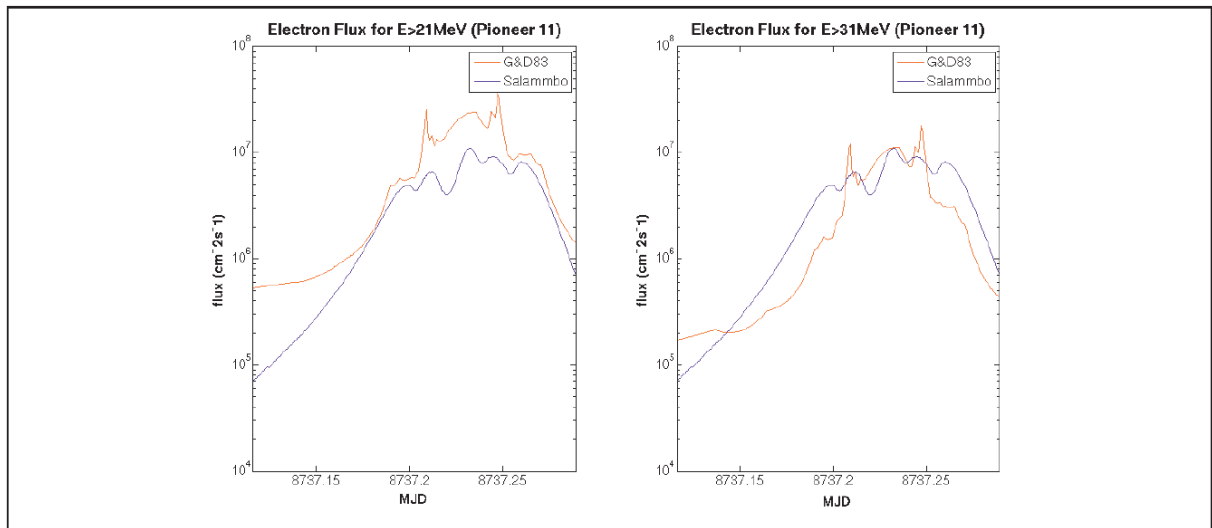


Figure 29 Plots of electron fluxes integrated in energy for Pioneer 11 Jupiter flybys

Figure 28 and **Figure 29** show the runs with a) only the Divine and Garrett (D&G) model (Divine and Garrett, 1983 [42]), b) D&G plus the Salammbo model. The plots are quite similar to the ones shown in the reference paper. However, there is a distinctive difference for higher electron fluxes of the Pioneer 10 data. In addition, a search was performed for the actual data from the Pioneer's Geiger Tube Telescope (GTT) Experiment but the data of interest were no more available by NASA. However, part of the data were also stored at the University of Iowa but in a VAX/VMS binary format. An IDL routine was written to transform the interesting records into an ASCII format.

4.5.8.2 Galileo orbiter's E4 encounter with Europa

An additional test was done using the Galileo spacecraft encounter with Europa on 19 December 1996 (E4 orbit). The SPENVIS output for the electron fluxes was qualitatively compared with what is given by Cooper et al (2001) [43] though their electron fluxes are directional. As is shown in **Figure 30**, the plots were quite similar and the fluxes have the same order of magnitude.

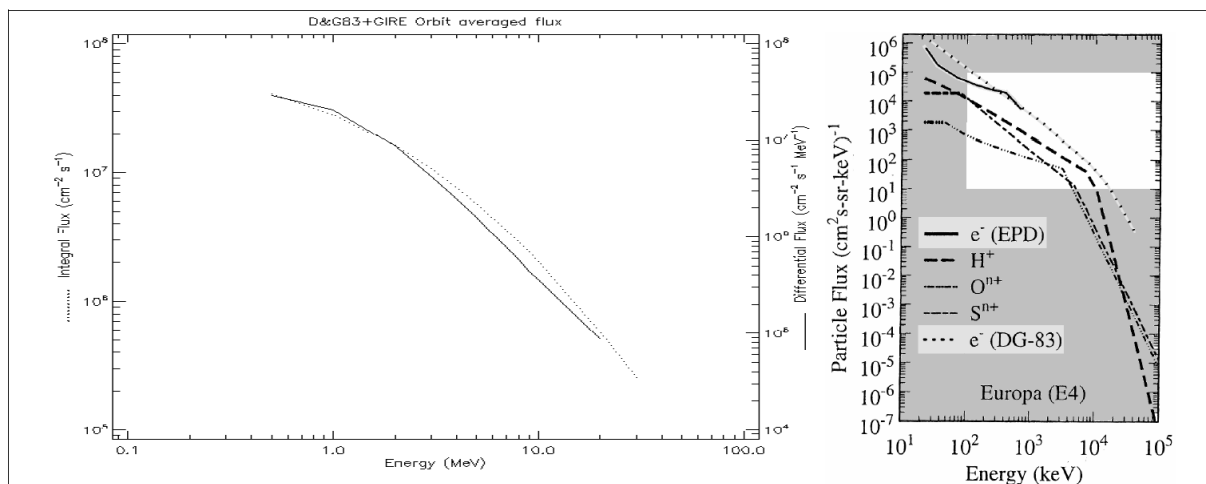


Figure 30 Electron flux spectra from Galileo orbiter's E4 encounter with Europa.

Figure 30 (left) shows the SPENVIS trapped electron omnidirectional flux spectra averaged over orbital data from the Galileo orbiter's E4 encounter with Europa. On the same figure (right), the differential directional particle flux spectra of trapped electron during E4 encounter as predicted by D&G83 model and measured by the Energetic Particle Detector are also displayed. Note that the white rectangle shows a region with the same energy range as the SPENVIS plot. One can easily see that the two plots are quite similar and the fluxes have the same order of magnitude.

5 Promotion and use of the framework

The SPENVIS platform is an operational software of the European Space Agency. One implementation of the platform is operated by the Belgian Institute for Space Aeronomy is freely accessible from the web (www.spenvis.oma.be) for peaceful purpose. Another version (release 4.6.4) is deployed in the framework of ESA's Space Situational Awareness Programme and is available from the Data Centre of the space weather segment (swe.ssa.esa.int). Other local versions can be deployed at other locations. This Chapter is focussed on the implementation operated by BIRA-IASB which has an international user community of about 10000 registered users.

The interaction with the user community occurs by different channels:

- the support tools linked to the platform (bug tracker, forum and mailbox);
- the SPENVIS user workshops; and,
- presentations and/or demonstrations during events.

Those interactions allow to better identify the user's requirements, to adjust the direction of new developments, and to improve the help pages and the user interfaces.

The SPENVIS usage statistics also improve our understanding of the typical profile of a SPENVIS user.

5.1 SPENVIS Users' Workshops

The main objective of these events is to bring the SPENVIS users together to share their experience and to identify their requirements. The workshops also focus on the new and forthcoming developments of SPENVIS. Two users' workshops have been organised during the execution of the SPENVIS-4 project, being a continuation of the previous workshops:

- 2002, 27-29 May at ESTEC, The Netherlands
- 2005, 3-7 Oct. in Leuven, Belgium (SpU + G4SU)
- 2006, 6-10 Nov. in Pasadena, USA (G4SU + SpU)

5.1.1 SUW 2010, Mechelen, Belgium, 7-9 June 2010

The fourth SPENVIS Users' Workshop was held in Mechelen which is situated halfway between Brussels and Antwerp. Mechelen is a town with many cultural sites, some of which are UNESCO World Heritage Sites. The workshop venue was at the Lamot Conference- and Heritage Centre. About 60 participants have taken part in the workshop. Following presentations were given:

Session 1: General presentation

- Welcome and introduction (M. Kruglanski)
- Belgian Science Policy (N. Parmentier)
- ESA and SPENVIS (E. Daly)
- SPENVIS in SSA Programme (A. Glover)
- Who is using SPENVIS? (M. Kruglanski)
- SPENVIS stand-alone version (S. Calders)

- SPENVIS Tutorial: mission concept (M. Kruglanski)

Session 2: Educational use

- Introduction: student accounts (S. Calders)
- Use of SPENVIS at Luleå University of Technology (J. Ejemalm)
- Space Weather class in the Master After Master at Katholieke Universiteit Leuven (G. Lapenta)

Session 3: Space Radiation and Damage

- SPENVIS Tutorial: radiation package (E. De Donder)
- Radiation damage and modelling techniques in solar cells (S. Messenger)
- Applications and SPENVIS upgrades for Single Event Effects Analyses (H. Evans)
- Energetic particle background observed in X-ray silicon detectors of SphinX experiment (S. Gburek)
- Proton fluence experienced by C1XS onboard Chandrayaan-1 (J.P.D. Gow)

Session 4: Geant4 Tools

- SPENVIS Tutorial: Geant4 package (N. Messios)
- GRAS (H. Evans)
- Reverse Monte Carlo (L. Desorgher)
- SPENVIS Geometry Definition Tool (L. Hetey)

Session 5: Third-party developments

- Future and 3rd party developments (M. Kruglanski)
- MarsRem (P. Truscott / D. Heynderickx)
- JOREM (P. Truscott / D. Heynderickx)
- Open data interface (D. Heynderickx)

The presentations are available at:

<https://www.spenvis.oma.be/download/suw2010/>

5.1.2 SUW 2013, Brussels, Belgium, 22-24 May 2013

The fifth SPENVIS Users' Workshop was held at the Royal Library of Belgium, Belgium's national and scientific library. It is one of the most important libraries in Europe since its history goes back to the 15th century. About 80 participants have taken part in the workshop. Following presentations were given:

Session 1: SPENVIS in general

- Welcome (M. Kruglanski)
- ESA perspectives (E. Daly)
- Overview of current and future SPENVIS and Organization Tutorials (M. Kruglanski)
- European Cooperation for Space Standardization (ECSS) (E. Daly)

Session 2: Space Radiation Environment

- AE9, AP9, and SPM: New Models for Radiation Belt and Space Plasma Specification (S. Huston)
- Tutorial: Radiation models in SPENVIS and their accuracy (D. Heynderickx)

- A comparison between high-energy radiation background models and SPENVIS trapped-particle radiation models (J. Krizmanic)
- Numerical estimation of Galactic Cosmic Ray (GCR) exposure in space - An Investigation of GCR models and shielding effects (A. I. Mrigakshi)

Session 3: Geant4 Tools

- Geant4 Radiation Shielding and Effects Analysis in SPENVIS: Past and Present, and Future Trends (P. Truscott)
- Tutorial: Geant4 Package in SPENVIS (N. Messios)
- SPENVIS JAVA Geometry Definition Tool (L. Hetey)
- Radiation analysis of a space instrument for observing Jupiter and Galilean moons, using JOREM and SSAT (L. Rossi)
- Image Sensor Dark Signal Non Uniformity modeling using GEANT 4 (C. Inguibert)
- Dose Assessments During Interplanetary Journeys with SPENVIS: Approach to the Issue and Comparison of Results with DREADCode (E. Cazzola)

Session 4: Single Event Effects

- Simulation of Single Event Effects and rate prediction. CODES an ESA tool (A. Keating)
- Tutorial: SEE modeling with SPENVIS (E. De Donder)
- An overview of the PROBA-II and PROBA-V SEE analysis flow and comparison to in-flight data (J. De Hert)

Session 5: Spacecraft Charging

- Internal charging: principles, tools and measurements (K. Ryden)
- Tutorial: SPENVIS spacecraft charging models (E. De Donder)
- Space Weather Radiation Effects on Geostationary Communication Satellite Solid State Power Amplifiers (W. Q. Lohmeyer)
- The SPIS (Spacecraft Plasma Interaction System) project: new evolutions (J. Forest)

Session 6: Miscellaneous

- The Dynamics of Inner Magnetosphere of the Earth (K. Borremans)
- The use of SPENVIS for space projects of Space research institute of Russia (V. Arefiev)
- The OMERE freeware for space radiation environment and effects (A. Varotsou)
- Next Generation SPENVIS: Current status - 3rd party developments - Release (SPENVIS-NG team)

The presentations are available at:

<https://www.spenvis.oma.be/download/suw2013/>

5.2 Presentations and demonstrations

This Section summarizes the additional promotion activities arranged during the execution of the SPENVIS-4 project.

5.2.1 Oral presentations at meetings

- 4th Geant4 Space Users' Workshop, November 6 - 10, 2006, Pasadena, California, USA
- EGU2009, SPENVIS presentation during splinter meeting ST14/NH9.6, April 2, 2009, Vienna, Austria
- 6th Geant4 Space Users' Workshop, May 19 - 22, 2009, Madrid, Spain
- TEC-EES Final Presentation Days 2010, February 1-2, 2010, Noordwijk, The Netherlands
- 38th COSPAR Scientific Assembly, July 18-25, 2010, Bremen, Germany
- 9th Geant4 Space Users' Workshop, March 4-6, 2013, Barcelona, Spain
- 7th CCMC Community Workshop, March 31 – April 04, 2014, Annapolis, Maryland, USA
- Space Environments and Effects Final Presentation Days 2014, November 4-5, 2014, Noordwijk, The Netherlands

5.2.2 Demonstrations during events

- RADECS2009, Industrial Exhibit, 14-19 September, 2009, Bruges, Belgium
- ESWW7, Fair, 17 November, 2010, Bruges, Belgium
- NSREC2014, Industrial Exhibit, 14-18 July, 2014, Paris, France
- ESWW11, Fair, 19 November, 2014, Liège, Belgium

5.3 User statistics

The SPENVIS user community has been growing during the project lifetime. The next sub-sections provides some statistics about the usage of the SPENVIS platform deployed at BIRA-IASB. Additional statistics are available online from the SPENVIS-4 statistics facility at:

<https://dev.spenvis.oma.be/statistics/>

5.3.1 User statistics (for year 2014)

The three Figures below give an overview of the profile of the SPENVIS user for the year 2014. **Figure 31** shows that most of the SPENVIS users originate from Europe but also that about 20% of the users originate from the United States of America. In Europe the most active countries are United Kingdom and Germany. One should note that the statistics for United Kingdom are biased by an unusual peak of activity in around August 2014. Usually the part of United Kingdom is about 5%. Outside Europe, the SPENVIS system is also accessed from countries such as Canada, China and South Korea.

While the 10.000th user registered to SPENVIS in February 2013, the number of active users is lower. In 2014 about 3300 users have accessed the SPENVIS system and executed at least one of the available models. **Figure 32** shows the monthly distribution of those users. In average about 500 users were active each month, of which 15% have just registered to SPENVIS. There is a seasonal variation with a maximum of users in March and November and a minimum of users in August.

Figure 33 illustrates the distribution of "seniority" and "experience" among the SPENVIS users active in 2014. The user's "seniority" is measured by the number of weeks since the user registration. About 45% of the active users are registered since less than five weeks, 58% less than one year. At the other edge about 25% of the active users are registered since more than 40 months, 10% more than 80 months. The user's "experience" is measured by the number of days when the user has been active since his/her registration. About 70% of users active in 2014 have been active at most 10 days. At the other edge, about 5 % have been active more than 80 days. Both distributions of Figure 23 show that the SPENVIS user community is

divided in two separate profiles: a large group of users using the system punctually on rare occasions, and a small group (about 150 users) using the system more regularly and intensively.

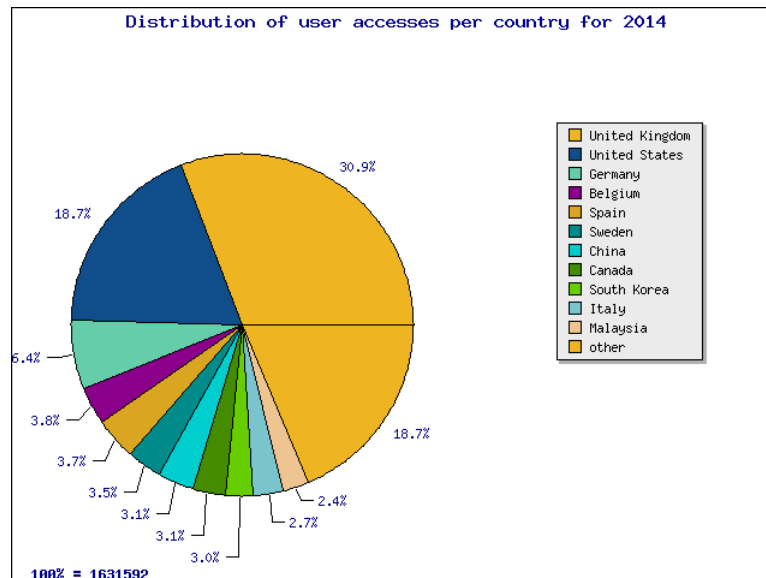


Figure 31 Country-wise distribution of SPENVIS-4 users in 2014

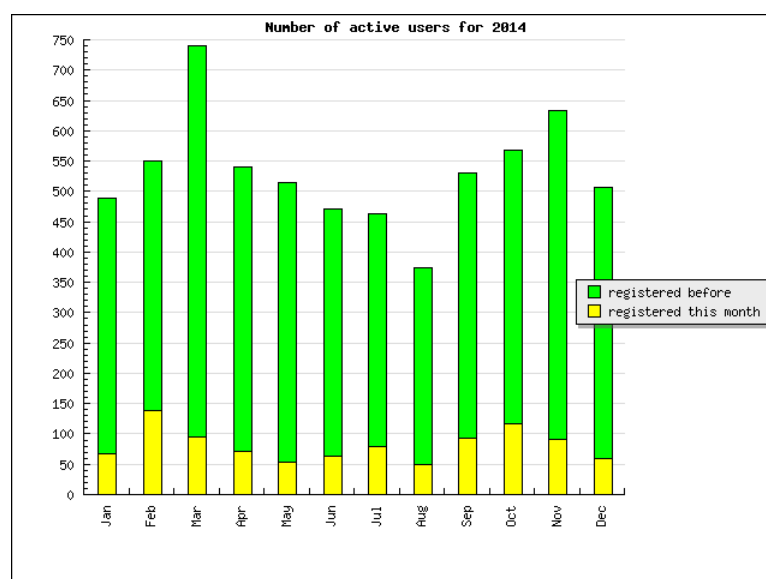


Figure 32 Active SPENVIS-4 users in 2014

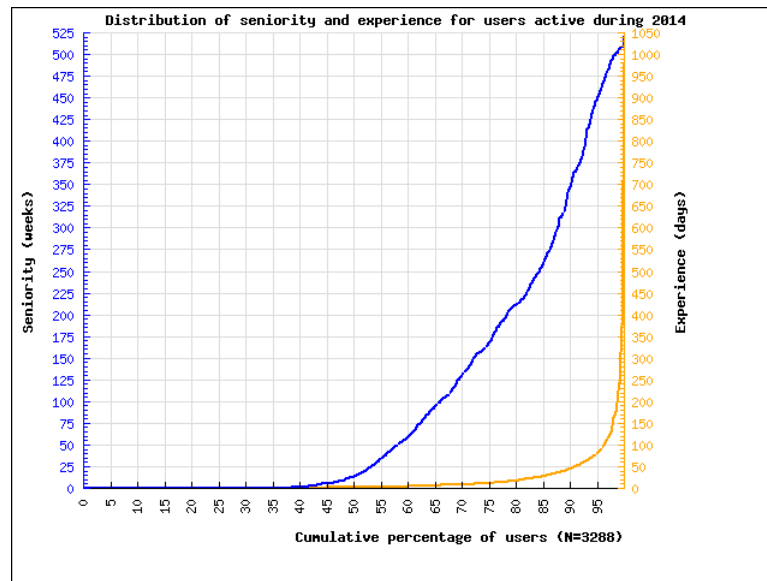


Figure 33 Seniority and experience of users in 2014

5.3.2 Model statistics (for year 2014)

Figures 34 and 35 provide an overview of the most popular models and tools in SPENVIS. Figure 35 show that the top 5 in 2014 are

- SHIELDOSE-2, a tool estimating the ionizing dose behind a simplified shielding
- SAPRE, the orbit generator used by the SPENVIS system
- TREP, a tool implementing different models of the Earth's radiation belts (such as AP-8/AE-8)
- EQFLUX, a tool evaluating damage-equivalent electron fluences for solar cells
- SEP, a tool implementing models to predict solar particle fluences during a space mission

However this order is probably affected by the peak of activity observed around August 2014 where an unusual number of SHIELDOSE-2 runs are recorded.

From Figure 34 it appears also a large variability in the model statistics except for SAPRE and TREP. The stability of SAPRE and TREP is explained by the dependencies of lot of models on the output of both tools.

Figure 36 shows the CPU time associated to the execution of the models and tools available in SPENVIS. The CPU doesn't show any correlation with the number of executions (Figure 34) or with the number of accesses (Figure 35). This is mainly due to the fact that most of popular models do not require lot of CPU time. Models or tools requiring more CPU time include:

- MULASSIS, a Geant4 application simulating the radiation transport through a one-dimensional geometry
- AE9/AP9, the model IRENE for specifying the trapped energetic particle environment provided for evaluation purpose only
- UPSETO, a tool evaluating single-event upset rate in micro-electronic devices

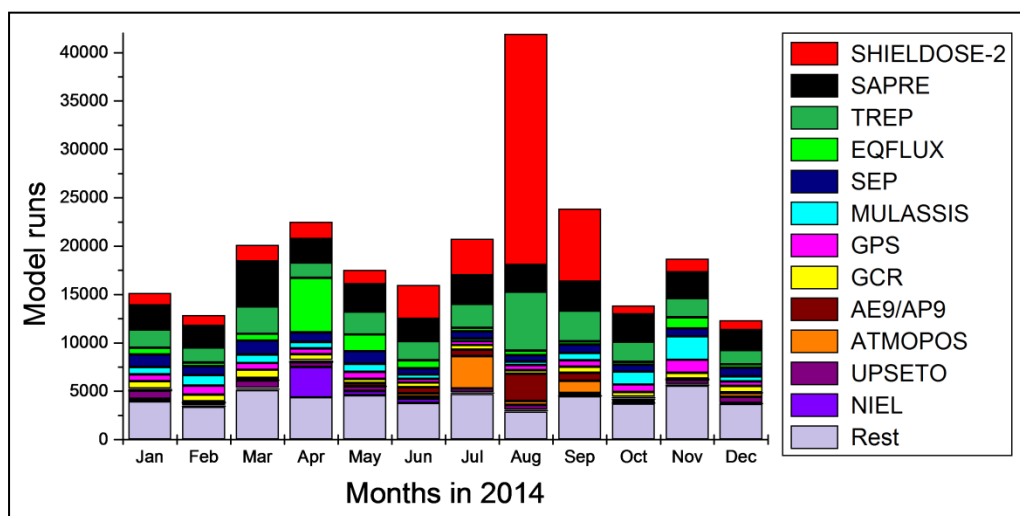


Figure 34 Total model executions per month in 2014

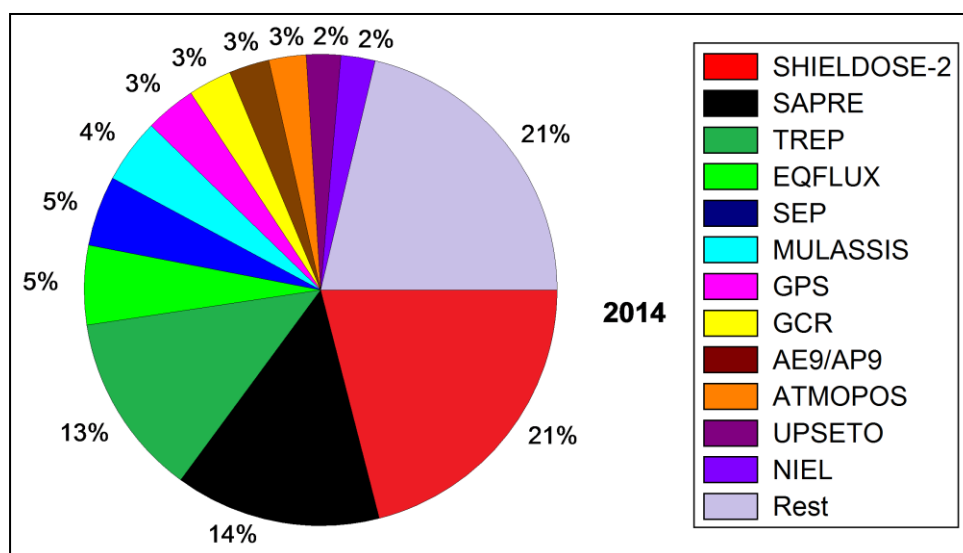


Figure 35 Model executions during 2014

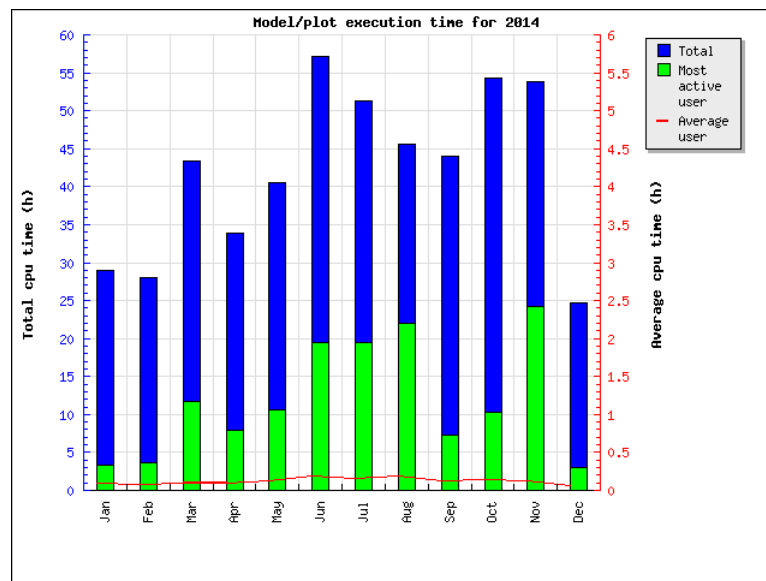


Figure 36 Number of model/plot executions in CPU time for 2014

5.3.3 Evolution over years (2006-2014)

Figures 37, 38 and 39 provide some statistics over the period 2006-2014. Figure 37 shows the evolution of the active users similarly to Figure 32. This evolution is stable since about 2010 with the typical seasonal variation already observed in Figure 32.

Ignoring the August 2014 anomaly, Figure 38 indicates that the access rate of the SPENVIS system has almost doubled since 2006 and is reaching a plateau of about $1.1 \cdot 10^6$ accesses per year. The distribution among the countries seems to be stable.

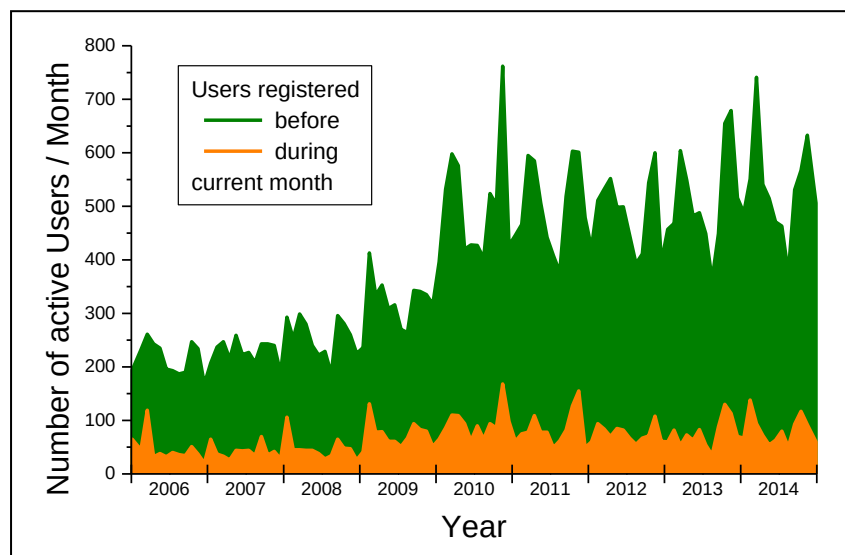


Figure 37 Evolution of active users during 2006-2014

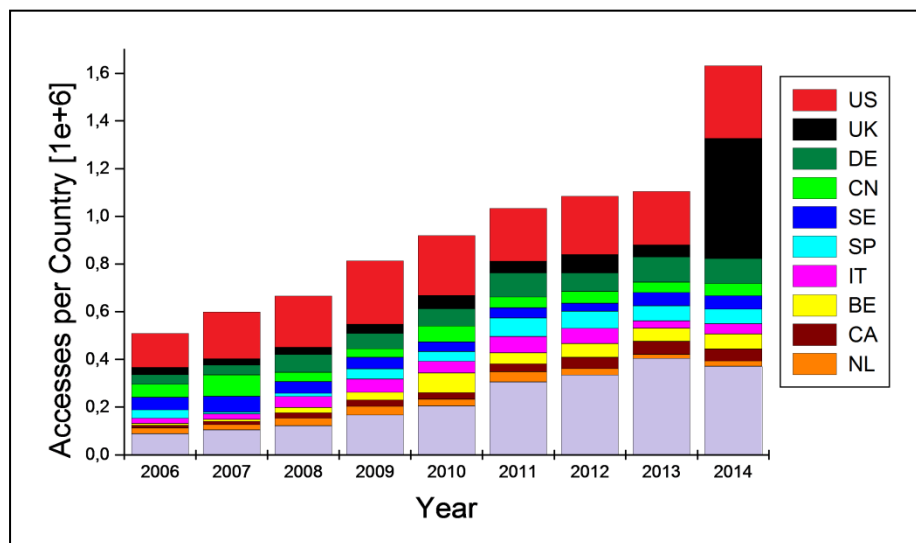


Figure 38 Evolution of total accesses during 2006-2014

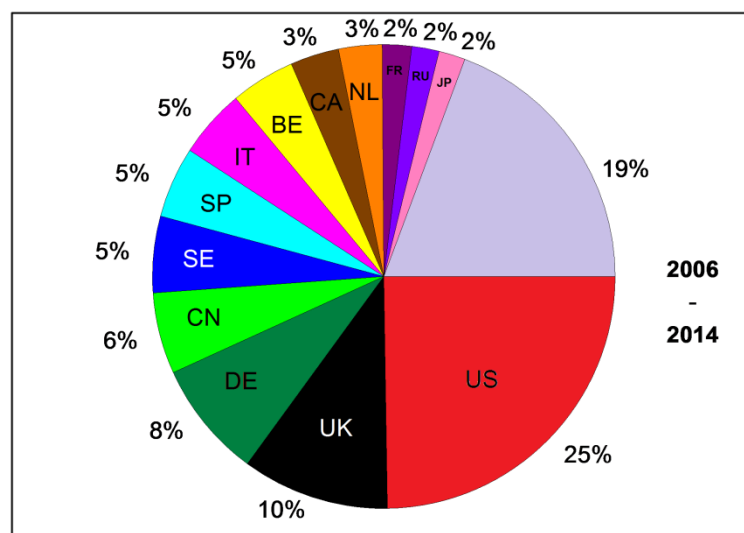


Figure 39 Evolution of total accesses during 2006-2014

6 Project deliverables

Technical Notes

- **TN01 [7]** – Analysis of SPENVIS models. Technical note detailing the input/output streams of the models implemented in SPENVIS.
- **TN12** – Exposure function from Magnetocosmics. Technical note detailing the generation of lookup table in order to upgrade the Størmer approach.
- **TN13** – Generation of total dose look-up tables using MULASSIS.
- **TN14** – Review of Thiel's work. Technical note reviewing the latest electron and proton NIEL calculations and available software tools.

Software Documentation

- **URD** – User Requirement Document
- **SSD** – System Specification Document
- **SQP** – Software Quality Plan
- **ATS** – Acceptance Test Specification
- **STD** – Software Transfer Document
- **SUM** – Software User Manual
- **PHD** – Project History Document

SN1 Software Documentation

- SPENVIS Configuration and Installation Guide
- SPENVIS Software Release Note
- SPENVIS User Requirement Document
- SSD, SUM, ATS as in the section above

Software Delivery via DVDs

The SPENVIS software is delivered with four DVDs. The content is listed in Table 9 of the STD and described in more detail in the STD and PHD. It contains:

- Technical and managerial documentation (TNs, Monthly reports, Minutes of meetings, documentation as listed above)
- Source code and an installation kit
- Toolkit for third-party developers
- Archive of the revision control system
- Merem and Master (2005 & 2009) data
- Stand-alone version of SPENVIS-4

7 Lessons learned and Conclusions

SPENVIS-4 is an internationally recognised expert system with a still growing large user community. The main factors of its success are its central management and development by a trusted group of experts, and the involvement of its user community. Possible additional reasons of SPENVIS success are:

- User friendly WWW interface (directly accessible by the user without any installation)
- Quality of the model input pages (ordering of the parameters, suggesting default values, hiding of unused parameters,...) and persistence of user input
- High-quality graphical representations allowing quick inspection
- Transparent interconnection of the different models
- Background help

The SPENVIS-4 system, which exists since the nineties with regular updates and model additions, has also a series of drawbacks:

- Rigid work flow for model access and no flexibility in model coupling
- Not easy plug-in of new models by model developers
- Splitting of the interface between orbital and positional models, preventing connection between those models
- Reduced capabilities for the import of user data (e.g. in replacement of some model-generated data)
- Lack of advanced machine-to-machine access (e.g. allowing access from VISPLANET)
- Organic software (the system has been firstly developed as a prototype and has grown with time)

From the above, the important points to be present in a future SPENVIS system are:

- User-friendly interface - new users should be able to rapidly use the system without a too long learning curve;
- Interoperability with other software tools - to facilitate the integration of SPENVIS with other tools used by the users;
- Persistence of the kernel - to insure the users (and third-party developers) a certain continuity between successive system upgrades
Maintaining continuity with the current user community - to ensure that the system is still in phase with the user expectations;

Appendix A Definitions, Acronyms and Abbreviations

API	Application Programming Interface
ATS	Acceptance Test Specification
BIRA-IASB	Belgian Institute for Space Aeronomy
BSSC	Board for Software Standardisation and Control
CCN	Contract Change Notice
CGI	Common Gateway Interface
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
GUI	Graphical User Interface
HTML	HyperText Markup Language
IDL	Interactive Data Language, dynamically typed data analysis programming language initiated in the 1970s by D. Stern (University of Colorado) and distributed by ITT Visual Information Solutions
MR	Monthly Report
OM	Operations and Maintenance
PHD	Project History Document
PSS	Procedures, Specifications and Standards
SPENVIS	Space Environment Information System
SQP	Software Quality Plan
SSD	Software Specification Document
STD	Software Transfer Document
SUM	Software User Manual

TN	Technical Note
URD	User Requirement Document
WP	Work Package
WWW	World Wide Web

Appendix B References

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