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Space Environment Information System: Applicability for mission design and operations

Gareth Lawrence[1] and Simon Reid[2]
Rhea System SA, Louvain-la-Neuve, B-1348, Belgium

Michel Kruglanski[3]
Belgian Institute for Space Aeronomy, Uccle, B-1180, Belgium

ESA's Space Environment Information System (SPENVIS) is a system of models of the space environment and its effects on materials (e.g. spacecraft). It covers the natural radiation belts, solar energetic particles, cosmic rays, plasmas, and micro-particles. SPENVIS currently integrates 35 distinct models, with new ones being added regularly. The underlying models arise from many years of research, supported by national and international space agencies, resulting in a variety of tools to investigate the Sun-Earth connection and near-earth environment. SPENVIS was originally developed as a browser-based research tool that collects these tools together, being capable of recreating the full range of conditions in most of the solar system. In recent years SPENVIS has been further developed into an Operational System. In addition to enhancing the modeling capabilities, this required an enhancement to the customer perspective, i.e. ease-of–use, consistency, stability, runtime, support, etc. SPENVIS is now available as a web-based or standalone application. As a Spacecraft Operational Support System, SPENVIS is further tailored to preferentially reproduce the current radiation environment for a range of common LEO, MEO and GEO orbits, and predict likely future variability and effects via a purpose designed user interface. It will also accept autonomous input data regarding the real-time space environment via a variety of ISES-standard alerts and reports. This paper presents the latest developments, with particular significance for the satellite operations community.

I. Introduction

THE Space Environment Information System (SPENVIS)[1] is an ongoing European Space Agency (ESA) project compiling a suite of models and tools to both describe the space environment and study the effects upon materials within it. The system is accessed online and registered users work directly on the server at the host institute, which provides easy access and simple start-up for beginners, with no installation or maintenance overheads for administrators. The host system has strict maintenance requirements and protocols to avoid service outages. A stand-alone version is intended for users for whom online access is not adequate for certain projects. The project homepage can be found at http://www.spenvis.oma.be.

The environment may be the so-called ‘space weather’ (SWE) type - e.g., trapped or energetic solar radiation, electromagnetic plasma, micro-particles - or space debris – including both man-made objects and trapped micro-meteoroids - and is described via a range of reference models. The models are selected via a consistent and logical set of drop-down menus, with some pre-set parameters that can be selected from lists, and other free parameters that can be user-specified. Consistency and sanity checks are employed at every step of the user input process, and runaway process rigorously checked for. As a result of many years of development SPENVIS has already reached a level of maturity and stability sufficient to be considered for redeployment within ESA’s new Space Situational Awareness framework as a Category 1 product, with only minor modifications anticipated.

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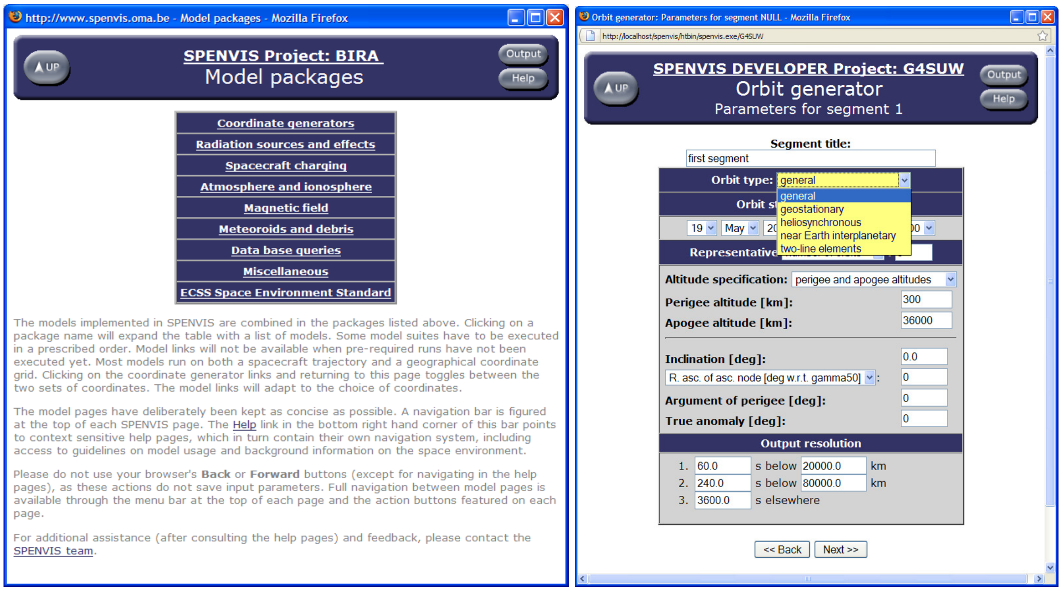
[1] Space Environment Business Engineer, New Tech Center, Avenue Einstein 2A, 1348 Louvain-la-Neuve, Belgium.
[2] Chief Engineer, New Tech Center, Avenue Einstein 2A, 1348 Louvain-la-Neuve, Belgium.
[3] Senior Staff Scientist, Avenue Circulaire 3, 1180 Uccle, Brussels, Belgium



The models implemented in SPENVIS are combined in the packages listed above. Clicking on a package name will expand the table with a list of models. Some model suites have to be executed in a prescribed order. Model links will not be available when pre-required runs have not been executed yet. Most models run on both a spacecraft trajectory and a geographical coordinate grid. Clicking on the coordinate generator links and returning to this page toggles between the two sets of coordinates. The model links will adapt to the choice of coordinates.

The model pages have deliberately been kept as concise as possible. A navigation bar is figured at the top of each SPENVIS page. The Help link in the bottom right hand corner of this bar points to context sensitive help pages, which in turn contain their own navigation system, including access to guidelines on model usage and background information on the space environment.

Please do not use your browser's **Back** or **Forward** buttons (except for navigating in the help pages), as these actions do not save input parameters. Full navigation between model pages is available through the menu bar at the top of each page and the action buttons featured on each page.

For additional assistance (after consulting the help pages) and feedback, please contact the SPENVIS team.

Segment title: first segment

Orbit type: general

Altitude specification: perigee and apogee altitudes

Perigee altitude [km]: 300

Apogee altitude [km]: 36000

Inclination [deg]: 0.0

R. asc. of asc. node [deg w.r.t. gamma50]: 0

Argument of perigee [deg]: 0

True anomaly [deg]: 0

1. 60.0 s below 20000.0 km
2. 240.0 s below 80000.0 km
3. 3600.0 s elsewhere

Figure 1. The SPENVIS front end, and the orbit generator.

Once the model has completed its run, the calculated space environment can be visualized studied as a global system on fairly coarse spatial scales if required but SPENVIS has built in to its kernel a sophisticated orbit generator. The generator works in invariant co-ordinates which can then be transformed to a variety of representations to best suit the user's requirements. This way the specific space environment can be analysed in fine detail for a broad range of mission orbits. An imminent future upgrade will be to allow the user to upload a pre-defined orbit file. SPENVIS originally treated only the terrestrial environment, but the system has now been extended to include martian and jovian models. These recent augmentations have required careful implementations of orbit generators for both planets, and a range of reference models for their radiation and plasma environments. It is planned for additional planets to be included in future versions, e.g., Saturn, Mercury and Venus.

The information thus generated regarding the space environment that an operational satellite will encounter along its orbit is of course interesting in its own right, but perhaps more so is the ability to study the subsequent effects of the environment on the satellite. SPENVIS utilizes a variety of tools to do so, including several state-of-the-art tools adapted from the Geant4 toolkit under development at CERN. Geant4 is a vast project to fully understand and detail how radiation interacts with matter and materials and combines advanced computer modeling and high-energy experiment results. Some of the Geant4 tools which are applicable to a space (as opposed to laboratory) setting have been adapted to reflect modifications to their usage, and fully incorporated into SPENVIS for ease-of-use. The result is the most powerful software application currently available to comprehensively study space environment, effects and impacts on mission design and operations.

II. SPENVIS Models and Environment Tools

Most of the models implemented in SPENVIS require as input a set of point on a spacecraft trajectory or a user-defined set of geographic points. These sets of points are produced by two tools: the orbit generator and the coordinate grid generator. In general, one of these tools has to be used before the models themselves can be accessed; if this is not the case, the system issues an error message prompting the user to run the orbit or coordinate grid tool, after which the model in question can be run. Thereafter, the model menu on the packages page will adapt automatically to the selection of trajectories or grids. This allows the likely space environment encountered by a wide range of low-earth orbit (LEO, e.g., human spaceflight, earth observations, meteorology), mid-earth orbit (MEO, e.g., global navigation systems), geosynchronous/geostationary (GEO, e.g., telecommunications) and interplanetary (e.g., scientific research) missions to be parametrised and studied. The range of models described here spans the breadth of the SWE and SSA domain, heightening the versatility of the SPENVIS system.

For the majority of users studying LEO, MEO and GEO environments, the trapped radiation models are of primary interest. When using these models, if a grid coordinate system is selected, then trapped particle models can be evaluated and visualised over the grid. Note that at low latitudes both the South Atlantic Anomaly (SAA) and trapped proton anisotropy ('East-West Effect") are treated rigorously. The main models of trapped radiation used by SPENVIS are the NASA reference models AE-8 and AP-8 (for electrons and protons, respectively); also available are: CRRESPRO and CRRESELE, PSB97, IGE2006/POLE, ESA-SEE1 and SAMPEX/PET. In addition to trapped radiation, SPENVIS can treat energetic cosmic radiation such as solar energetic particle (SEP) fluxes via the reference JPL-91, King and ESP models plus the newer Xapsos model. Galactic cosmic rays (GCRs)are treated via the reference ISO-15390 and Nymmik models.

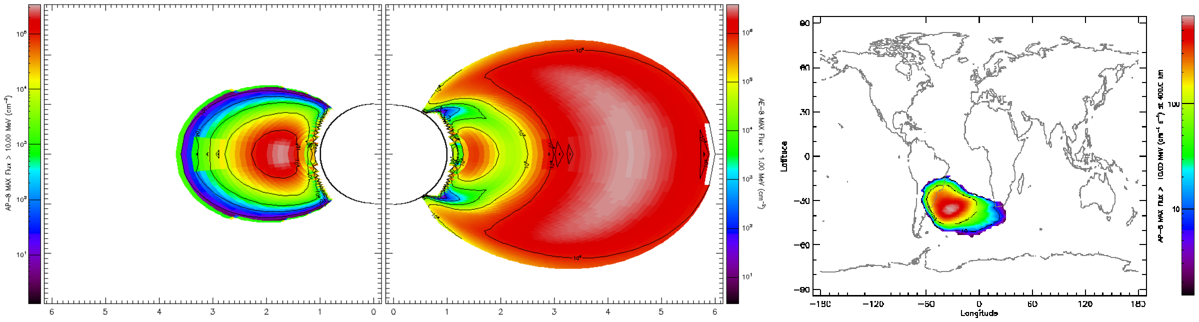
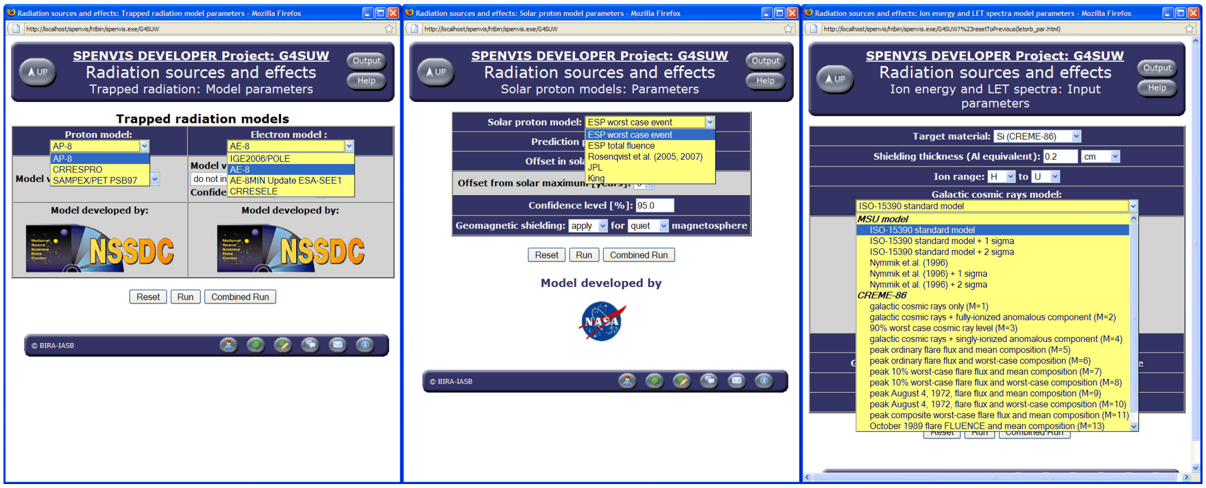


Figure 3. Sample trapped radiation model output for different energies and graphical representation.

Whilst the trapped radiation environment is clearly important, it arises due to the existence of the geomagnetic field and upper atmosphere and ionosphere. The geomagnetic field is represented by: the DGRF/IGRF suite, Jensen & Cain and GSFC12/66 for the internal field, and Mead-Fairfield, Olson-Pfitzer and Tsyganenko (various) for the external field; the upper atmosphere and ionosphere system by NRLMISE-00, MET-v2.0, DTMB78, HWM93, IRI2001 and NeQuick-v2.0. Some of these models are used automatically (where relevant) by the orbit generator to calculate spacecraft drag.

As well as the environment at microscopic scales described above, SPENVIS can also treat larger threat, ranging from micro-meteoroids to man-made space debris. The main models implemented for these are the Grün meteoroid model and NASA90 debris model. Also being implemented are the wall penetration model for meteoroids, and ORIEN96 for man-made debris. Moving away from the near-Earth environment, the orbit generator has been extended to fully describe the martian and jovian systems, including their moons. For the former, energetic radiation is modeled via MARSREM while for the latter a range of trapped radiation models are implemented, including Divine and Garret, JIRE and ONERA/Salammbô.



SPENVIS DEVELOPER Project: G4SUW
Radiation sources and effects
Trapped radiation: Model parameters

Trapped radiation models

Proton model: AP-8
AP-8
CRRESPRO
SAMPEX/PET PSB97

Electron model : AE-8
IGE2006/POLE
AE-8
AE-8MIN Update ESA-SEE1
CRRESELE

Model developed by: NSSDC

SPENVIS DEVELOPER Project: G4SUW
Radiation sources and effects
Solar proton models: Parameters

Solar proton model: ESP worst case event
ESP worst case event
ESP total fluence
Rosenqvist et al. (2005, 2007)
JPL
King

Confidence level [%]: 95.0

Geomagnetic shielding: apply for quiet magnetosphere

Model developed by

SPENVIS DEVELOPER Project: G4SUW
Radiation sources and effects
Ion energy and LET spectra: Input parameters

Target material: Si (CREME-86)

Shielding thickness (Al equivalent): 0.2 cm

Ion range: H to U

Galactic cosmic rays model: ISO-15390 standard model

MSU model
ISO-15390 standard model
ISO-15390 standard model + 1 sigma
ISO-15390 standard model + 2 sigma
Nymmik et al. (1996)
Nymmik et al. (1996) + 1 sigma
Nymmik et al. (1996) + 2 sigma

CREME-86
galactic cosmic rays only (M=1)
galactic cosmic rays + fully-ionized anomalous component (M=2)
90% worst case cosmic ray level (M=3)
galactic cosmic rays + singly-ionized anomalous component (M=4)
peak ordinary flare flux and mean composition (M=5)
peak ordinary flare flux and worst-case composition (M=6)
peak 10% worst-case flare flux and mean composition (M=7)
peak 10% worst-case flare flux and worst-case composition (M=8)
peak August 4, 1972, flare flux and mean composition (M=9)
peak August 4, 1972, flare flux and worst-case composition (M=10)
peak composite worst-case flare flux and mean composition (M=11)
October 1989 flare FLUENCE and mean composition (M=13)

Figure 4. Sample model selection pages: trapped radiation, SEPs and GCRs

III. SPENVIS Effects Tools

From a scientific viewpoint the information regarding the space environment derived by the methods described in Section II are interesting, but from an engineering aspect any effects that the SWE environment has on materials – ie, hardware – exposed to it are as important. To this end the SPENVIS team has adapted a number of carefully selected tools from CERN's Geant4 toolbox and a number of other individual projects, into SPENVIS applications. This is generally a far-from-trivial task given the great differences between conditions encountered in heliospheric space and a terrestrial laboratory, but the end result is a sophisticated and comprehensive suite of tools that can model the range of effects and hazards which space engineers can expect to encounter.

In Sections IV and V we discuss how the combination of environment models and effects tools can be effectively applied to both mission design and mission operations. First we describe the various effects tools currently and imminently available. The various SSA-related hazards posed to operational orbiting hardware are illustrated below as a function of energy:

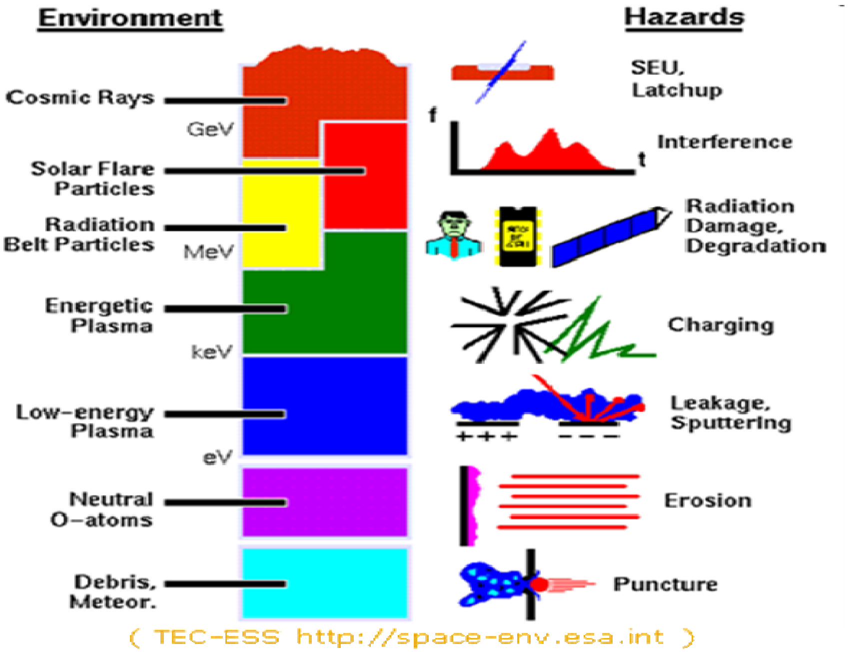


Figure 5. Common space environment hazards as a function of energy.

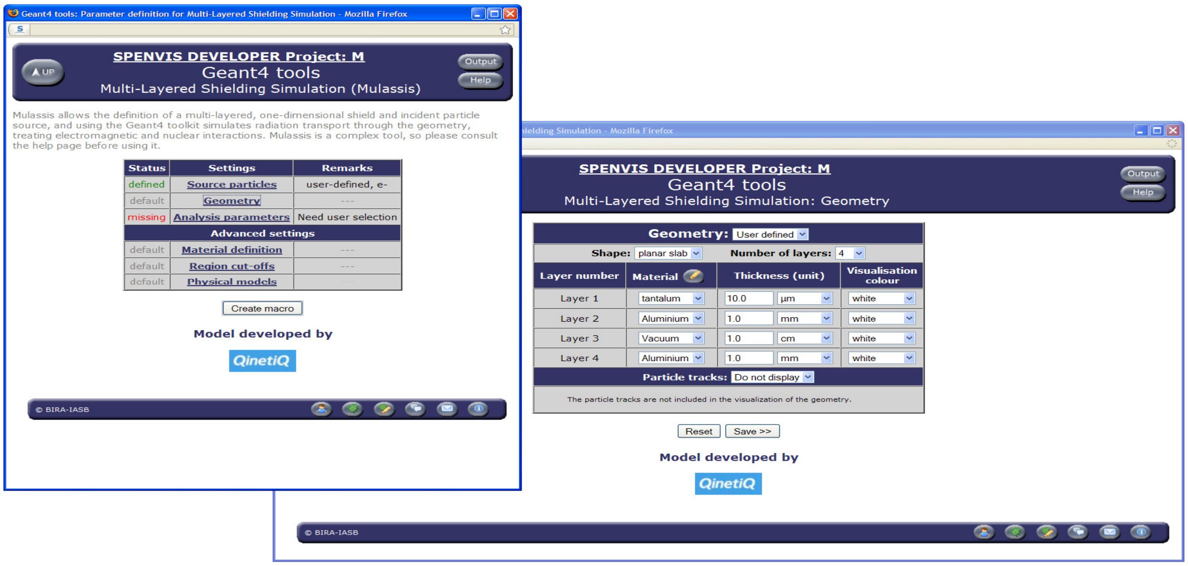
GCRs and SEPs are known causes of single event upsets (SEUs) such as latch-ups in onboard electronics systems, often resulting in instruments and even platform automatically going to safe mode, and in the worst case causing terminal damage. SEP events can disrupt telecommanding and data telemetry as a result of the interference in data systems, and the data itself is often worthless due to high levels of noise. Trapped radiation in the radiation belts leads to degradation of components as a result of prolonged dose, with processors, detectors and solar cells particularly vulnerable. A satellite passing through energetic charged plasma will experience a range of charging effects, both on the surfaces and internally within electrical systems, and these charge differentials can lead to sudden discharges and subsequent failure of electrical systems. Less energetic plasma also poses problems, with discharge and sputtering often leading to secondary electron emission and subsequent associated charging problems. Even the neutral atmosphere can be hazardous, with neutral atomic oxygen known to lead to surface erosion of the platform materials, potentially compromising the surface and leading to surface charging. A greater risk to surface integrity comes in the form of debris and micro-meteoroids which can compromise and puncture materials due to their high kinetic and potential energies.

An added and highly emotive risk pertains to human spaceflight, since prolonged exposure to elevated levels of radiation is clearly a major risk to astronauts. This is generally not a very serious problem for missions to the International Space Station (ISS) which is protected by the magnetosphere in its comparatively low orbit, but future manned interplanetary missions e.g., as proposed by the Constellation program will face radiation exposure issues orders of magnitude greater than during the Apollo program, due to their duration. One of the most intense SEP events on record occurred on August 1972, between the Apollo 16 and 17 missions; had it occurred during either the crew would likely have received one-time radiation doses significantly in excess of safe lifetime doses.

SPENVIS' radiation effects tools allow such to be studied in detail. SEU rate and probability due to energetic trapped and solar protons and cosmic rays can be studied using CREME-86 for a variety of materials including Gallium Arsenide. Solar cell damage can be analysed using EQFLUX and more recently MC-SCREAM, both of which now benefit from enhanced relative damage coefficients (RDC), again for a range of materials. The energy depositions for a given radiation dose is given by SHIELDOSE and NIEL in the ionising and non-ionising cases, respectively. Surface charging is tackled by EQUIPOT and SOLARC to calculate the surface and structural charge, while DICTAT takes care of deep dielectric charging.

Several of the above are well-established reference tools and while they offer accurate results in short runtime for some cases, the Geant4 tools represent the state-of-the-art in this field. So far, the following G4 tools have been adapted into SPENVIS applications:

- the Geant4-based Microdosimetry Analysis Tool (GEMAT), a computer code to study microdosimetry effects of space radiation on micro-electronics and micro-sensors
- the Multi-Layered Shielding Simulation (Mulassis) tool, to allow the definition of a multi-layered, one-dimensional shield and incident particle source, and simulates radiation transport through it
- the Sector Shielding Analysis Tool (SSAT), which generates a shielding distribution from a GDML file supplied by the user of produced by the geometry definition tool; the latter is not yet fully implemented in SPENVIS (though nearing completion) so the GDML file is generated independently and then imported.
- Magnetocosmics and Planetocosmics; allowing the computation and visualisation of charged particle trajectories and magnetic field lines, as well as the computation of cut-off rigidities as a function of position, for different types of magnetic field models at Earth, Mars and Mercury
- The Geant4 Radiation Analysis for Space (GRAS) tool, combining most common radiation analyses types with generic 3D geometry models via a flexible and modular application (not yet fully integrated).



SPENVIS DEVELOPER Project: M
Geant4 tools
Multi-Layered Shielding Simulation (Mulassis)

Mulassis allows the definition of a multi-layered, one-dimensional shield and incident particle source, and using the Geant4 toolkit simulates radiation transport through the geometry, treating electromagnetic and nuclear interactions. Mulassis is a complex tool, so please consult the help page before using it.

Status	Settings	Remarks
defined	Source particles	user-defined, e-
default	Geometry	---
missing	Analysis parameters	Need user selection
Advanced settings		
default	Material definition	---
default	Region cut-offs	---
default	Physical models	---

Model developed by

SPENVIS DEVELOPER Project: M
Geant4 tools
Multi-Layered Shielding Simulation: Geometry

Geometry: User defined
Shape: planar slab
Number of layers: 4

Layer number	Material	Thickness (unit)		Visualisation colour
Layer 1	tantalum	10.0	µm	white
Layer 2	Aluminium	1.0	mm	white
Layer 3	Vacuum	1.0	cm	white
Layer 4	Aluminium	1.0	mm	white

Particle tracks: Do not display

The particle tracks are not included in the visualization of the geometry.

Model developed by

Figure 6. Sample Geant4 effect tool: Mulassis.

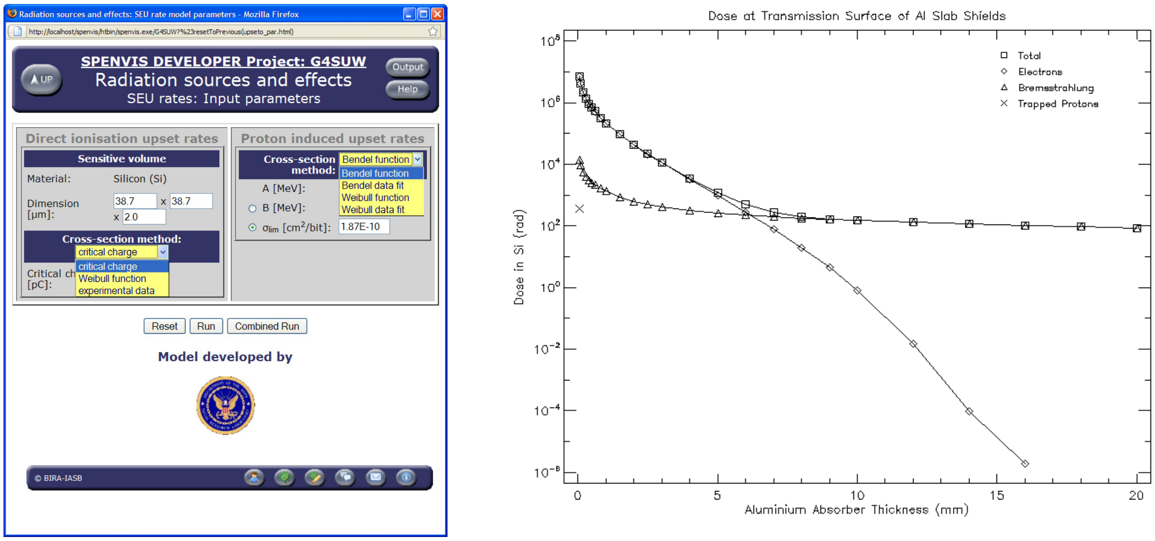
IV. Using SPENVIS during Mission Design

Since the first effects tools were integrated into the system, SPENVIS has been used regularly as a space engineering tool during mission and instrument design. An engineer can use the various geometry tools and selected materials within SPENVIS to construct a realistic representation of a piece of hardware intended for in-orbit operations. This piece of hardware could be a new technology detector or solar panel, for instance, and furthermore such an object can be encased within and surrounded by other objects and constructs to accurately represent either a single instrument or whole satellite.

Having parametrised the orbit using the orbit generator, the hardware mock-up can then effectively 'be flown' for various epochs of the nominal mission, and the effects of the environment upon it quantified and analysed. For instance, the susceptibility to SEUs over a month versus a year can be compared at various periods during the 11-year solar cycle to set safety thresholds, or the total damage on a year-by-year basis due to both ionising and non-ionising radiation for a choice of solar panels. These are just two very specific examples of SWE and space environment effects that need to be fed into the design of a mission. The engineer then has freedom to alter geometries and materials - within known constraints - to modify the shielding characteristics and optimize the design according to the profile and requirements of the mission. Clearly this is far quicker and more cost effective than extensive testing in the laboratory, although SPENVIS clearly cannot and is obviously not intended to replace this essential phase entirely, simply augment it during early stages.

SPENVIS has been used extensively by ESA within the overall framework of the Galileo global navigation system. The Galileo fleet will operate at an altitude of ~23,200km, above both the GPS and GLONASS fleets through necessity. This places it further into the outer, mainly electron, trapped radiation belt, and therefore in a very different and more hostile operating environment. Indeed, this is the first time that a complex and safety-critical mission providing a range of service level agreement-bound services will have to be operated in that environment which raises particular challenges. Data taken by the pair of testbed satellites GIOVE-A and –B have been fed into SPENVIS along with representative geometries and materials to predict the long term-effects – each Galileo satellite will be expected to operate for up to 12 years, after all – and optimize the design. The alternative at this stage is to heavily over-engineer the operational satellites as they are built, with large cost and time overheads.

SPENVIS has also been used during the instrument design phase for the Juno mission to Jupiter, due for launch in 2011 as part of NASA's New Horizons programme. Mulassis was used extensively in conjunction with both the Divine & Garrett model of jovian radiation and various SEP and GCR models to optinmise instrument design. Following that experience discussions are currently underway to optimise the GIRE and Salammbô models to use in conjunction with GRAS during the instrument and mission phases for the future joint ESA/NASA outer planet flagship mission, the Europa-Jupiter System Mission (EJSM).


Radiation sources and effects: SEU rate model parameters - Mozilla Firefox

http://localhost/spenvis/htbin/spenvis.exe/G4SUW?%23resetToPrevious(upseto_par.html)

SPENVIS DEVELOPER Project: G4SUW
Radiation sources and effects
SEU rates: Input parameters

Direct ionisation upset rates

Sensitive volume

Material: Silicon (Si)

Dimension [μm]: 38.7 x 38.7 x 2.0

Cross-section method: critical charge

Proton induced upset rates

Cross-section method: Bendel function

○ B [MeV]:

● σ_{lim} [cm^2/bit]: 1.87E-10

Model developed by

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Figure 7. Sample input (SEU rates) and output (shielded dose) of SPENVIS for GIOVE-A.

V. Using SWE Tools, Data and Products during Mission Operations

Many key assets needed to safeguard mission operations against SWE effects already exist – they can readily be used within the operations domain, and frequently are. Section III outlined various SWE hazards (as well as some tools for studying their effects) but there is still a disconnect between the SWE event initiation and the likely impacts feeding back to the operators and into the operations plan. As well as SPENVIS, some examples of SWE tools currently used in the operations domain are: DIADEM, EDID, ESABASE2, IONMON, SEDAT, SEIS-SEISOP, SREM, and SWENET. For the most part, these services are themselves comprised of lower-level services and products chosen strategically and combined to give added value. A spacecraft operator therefore can choose between using the high level products listed above, or identifying the combination of lower level products most appropriate to their requirements and using them directly. For some applications it is preferable to retain the greater scope and flexibility of the high level products, while the speed and simplicity of use of the lower-level components will win out at other times. Also, the requirements for each mission are likely to vary over time, especially since SWE events and effects vary strongly with the solar activity cycle.

Some examples of low-level SWE data used on a routine basis within mission operations are the forecasts and nowcasts of: solar flares, energetic particle storms, geomagnetic storms, and upper atmosphere electrons. These events are known to be linked to radio frequency interference, SEUs/latch-ups, radiation damage, charging, and telemetry signal degradation, and probability forecasts and real-time nowcasts are routinely issued by a number of institutions. The International Space Environment Service (ISES) co-ordinates the activities of a network of Regional Warning Centres (RWCs), distributed globally to optimize the overall level of service provided. Each of the 12 centres provides specialist services to end users within a region, often utilizing unique instrumentation and facilities located within it - the effects of SWE events are normally manifest at different local times at the various centres, and with regional variations. A central hub gives access to all the diverse data, products and services from a single point. These data can be obtained either directly from the issuers (e.g., SIDC, Brussels) or the central hub (SWPC, Boulder), or via a SWE tool such as SWENET; both routes provide the means for customization to best suit the end user, so that the optimal configuration for a given mission operations plan can be defined. Thus on a routine basis the operations team are provided with consistent and reliable forecasts, nowcasts, alerts and bulletins for SWE events. This then allows the operations team to further investigate the likely risk to nominal operations.

Figure 8. Geographical distribution of the ISES RWCs.

Depending on requirements, this could then be a relatively simple or complex process. If the hardware is particularly robust or the direct effects are unlikely to be strong at a particular orbit, then perhaps no action will be taken. On the other hand, if some new technology is being tested then the standard response could be to switch to safe mode until the threat has passed. For the most part, though, further detailed information is needed, which is where the added-value of the high-level products is introduced. For example, by using SWE-type data as initial conditions to SPENVIS or SEISOP and propagating the results to the effects tools, and likely impacts on operations quantified. If, for instance, during the early stages of an SEP event the predicted risk of a latch-up is found by SPENVIS to exceed a threshold then the platform can be put in safe mode until the risk is lower. Similarly, if potentially damaging levels of deep dielectric charging are predicted by SEISOP during an imminent geomagnetic storm then an instrument can be switched off to protect the electrical systems. Alternatively, if a particularly intense and prolonged geomagnetic storm is forecast for low LEO orbits then the risks from debris can be recalculated via ESABASE2 to account for changes in drag arising from increased atmospheric density experienced by both satellites and nearby known objects.

The three scenarios outlined above are based on known anomalies due to actual SWE events during the most recent solar cycle – such impact are not exclusively as a result of the most extreme events of all. LEO orbits are increasingly crowded with each new launch; the MEO orbit deep into the outer radiation belt chosen for Galileo will be the most hostile operational environment yet used; while GEO satellites are constantly vulnerable to solar and other energetic particles which are still very difficult to forecast in accurate and constant detail. Many of the high-level tools SWE incorporate static models; for example, the AP-8 and AE-8 trapped radiation models. Over the entire course of a mission's duration, 'transient' effects like SWE events will essentially average out for the most part. This is often a basic assumption when compiling such models, and whilst it may hold well in terms of overall mission design specification, it does not cover all eventualities when compiling (and subsequently executing) mission operations plans. An iterative approach should ideally be adopted during the definition phase of the missions operations planning as well as during routine operations, so that the thresholds are defined rigorously and optimally to ensure minimal disruption once in orbit. The procedures can be refined and finalized during LEOP. An alternative might be to implement blanket policies based on the lower-level SWE alerts alone – e.g., powerful solar flares, SEP events, imminent geomagnetic storms – but the various high-level SWE tools currently available offer the capability of customizing each mission's contingencies according to its definition and requirements. This approach greatly reduces the likelihood of disruption to mission operations due to SWE events; while conversely, the probability of platform downtime due to 'false alarms' resulting from a blanket policy is minimised, an equally important consideration.

VI. Conclusion

We have presented an overview of the general capabilities of SPENVIS and its applicability to both mission design and mission operations. Since SPENVIS was developed as a space engineering tool its suitability for mission design is obvious, but less so its capabilities for SWE studies and space mission operations. We have described some important contributions made by SPENVIS in this field, and have described more generally how the various high-level SWE tools currently available can make important contributions to the design and implementation of spacecraft operations plans. Such capabilities can be expected to be developed during the next-generation SPENVIS project, and the full integration of ESA's SSA framework.

Acknowledgments

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