Radiation effects on sensors and technologies for JUICE

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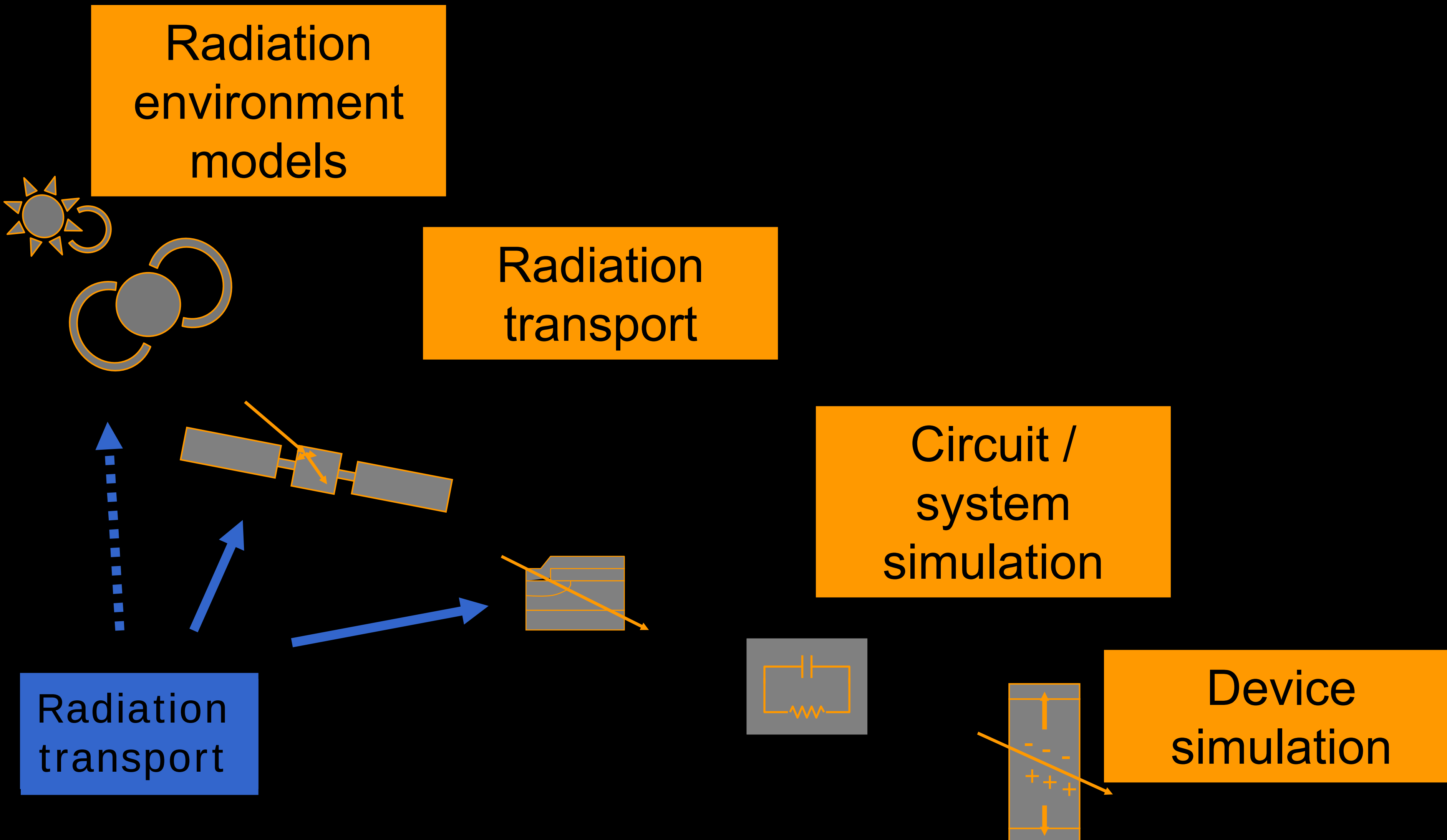
JUICE Instrument Workshop
9 – 11 November 2011

* on loan employment from RHEA Tech ltd

Outline

- Radiation effect analysis
  - Recent developments of relevance for this community
- (3-D) Monte Carlo and related tools
  - Mainly Geant4 / GRAS / REST-SIM
- Uncertainties, margins

Particle radiation transport in space radiation effect analyses

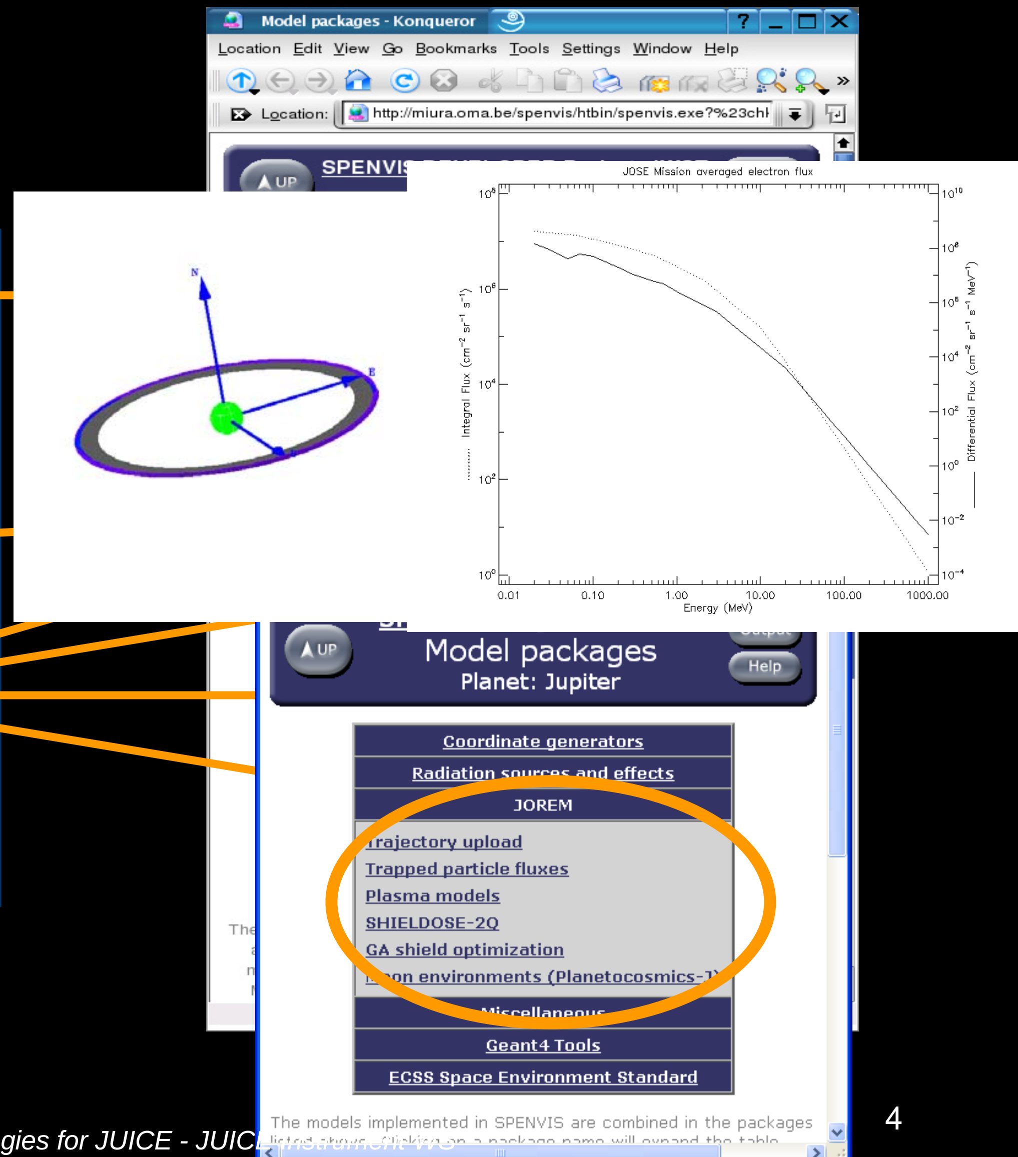


Engineering tools

Environments - Geometry - Visualisation – Analysis

SPENVIS

- Models and tools for the space environments effects analysis
- Web Interface
  - Mission model
    - Orbit, attitude
  - Space environment models
  - Radiation transport
    - Simulation engine
  - Effects Analysis
    - Damage mechanisms
    - Charging
    - SEE
    - Effects to humans



- Recent additions of Jupiter-related models and tools under “JOREM”: JOSE environment, shielding assessment

Sector Shielding Analysis Tool SSAT

- Ray tracing: from a user-defined point within a Geant4 geometry
- NORM, SLANT and MIXED tracing

SHIELDING

- shielding levels

  fraction of solid angle for which the shielding is within a defined interval

  global and from single materials

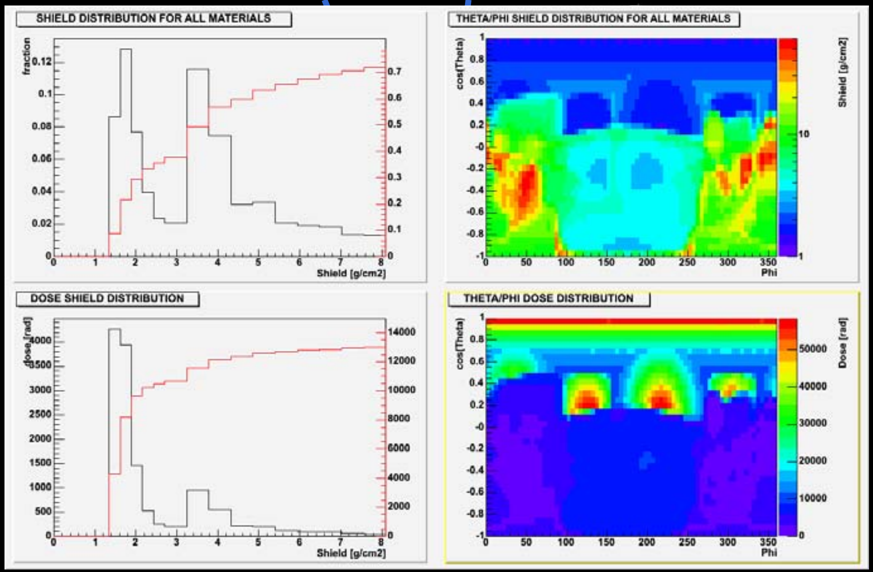
- shielding distribution

  the mean shielding level as a function of look direction

- It utilizes geantinos

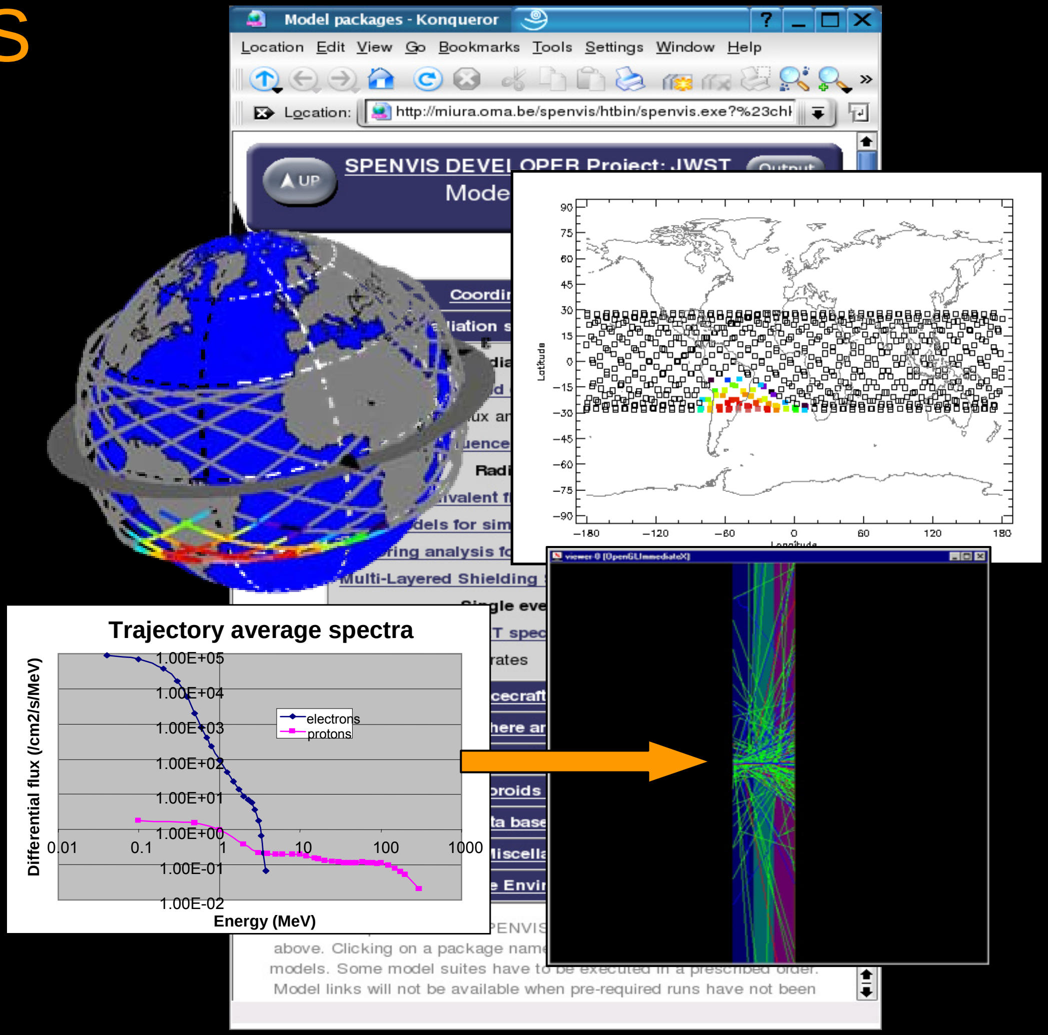
DOSE

- Estimate of the dose at a point
  - Based on external Dose-Depth curve e.g. SHIELDOSE-2
  - Ray-by-ray dose calculation
  - All materials scaled to Aluminium
- Results:
  - Total dose
  - Dose-Depth profile
  - Dose directionality



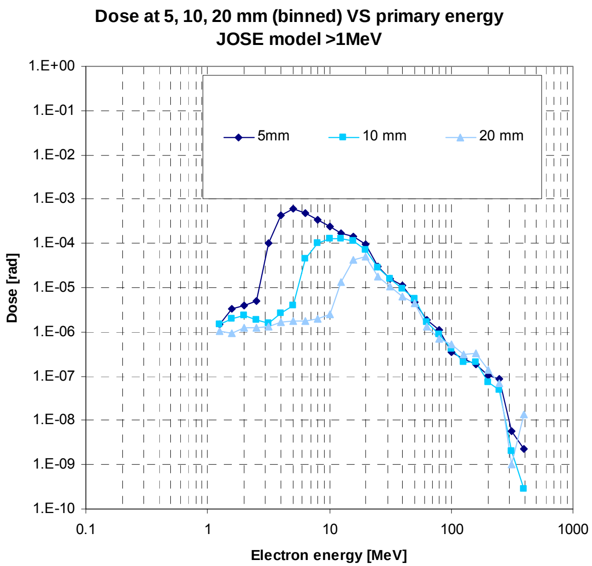
MULASSIS in SPENVIS

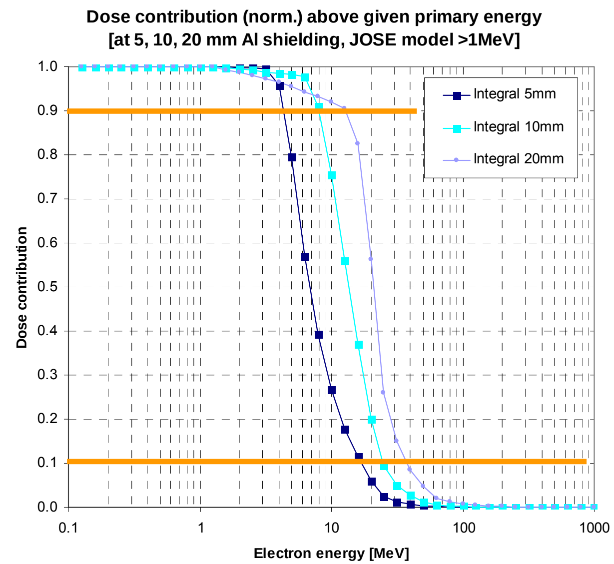
- 1.5-D layer geometry
  - Slab / sphere
  - Full Monte Carlo transport
- Physics list choice
  - Detailed material description
- Analysis options
  - TID
  - Fluence
  - Pulse Height Spectrum
  - Dose-Equivalent
  - NIEL
- Output
  - SPENVIS CSV with data
  - ASCII report file



Lei et al, IEEE Trans. Nucl. Sci. 49, 2002

Dose response function (1-D)





ESA Memo TEC-EES/2011.812/GS

- JOSE model extends in energy up to 1 GeV, but impact of the highest portion of the spectrum (above 50 MeV) is rather limited for TID
- Only 10% of the dose is coming from electrons of energy
  - >~15 MeV for 5mm Al
  - > ~25 MeV for 10 mm Al
  - >~35 MeV for 20 mm Al.
- This might not apply to other radiation effects, e.g. background, where high energy tail can affect signals of deeply shielded sensors

Shielding material effectiveness
Graded shielding

MEO

Electron source
Isotropic
(cosine-law bias)

Ref.: TEC-EES/2010.613 /GS/1.0

Investigation on the effects of combinations of shielding materials on the total ionising dose for the LAPLACE mission

G. Santin

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 43, NO. 6, DECEMBER 1996

Effects of Material and/or Structure on Shielding of Electronic Devices

R. Mangeret, T. Carrière, J. Beaucour
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T. M. Jordan
EXPERIMENTAL AND MATHEMATICAL PHYSICS CONSULTANTS
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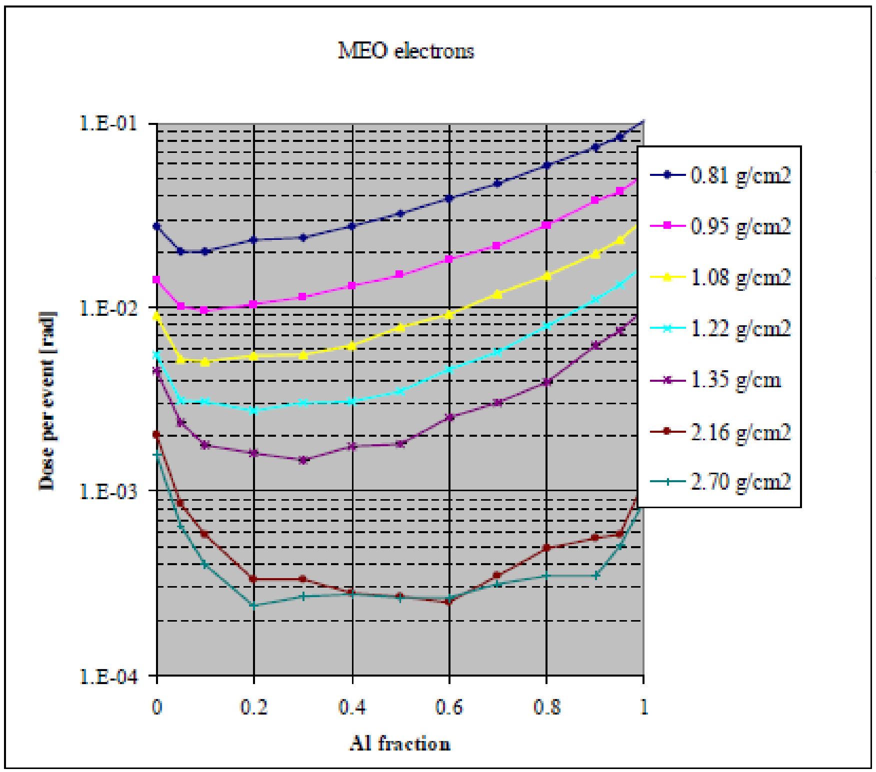


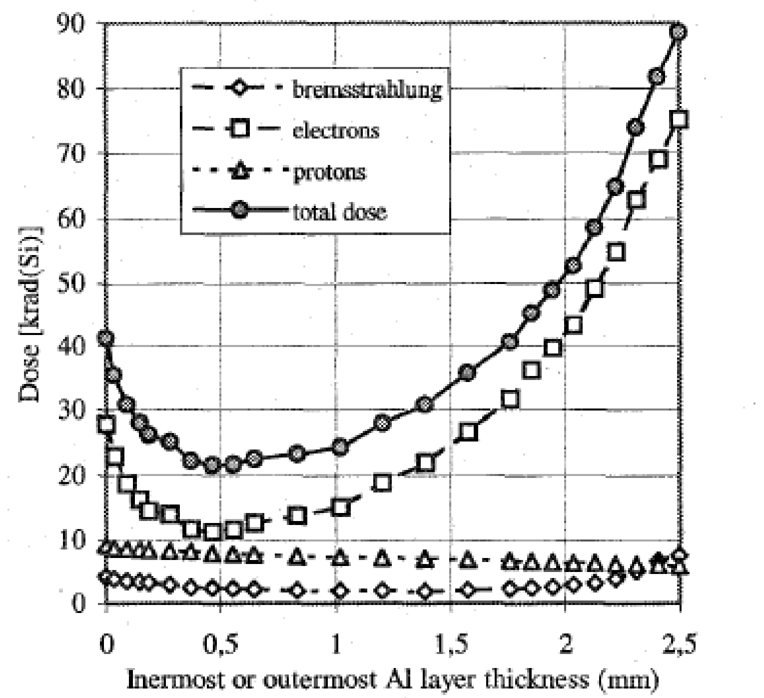
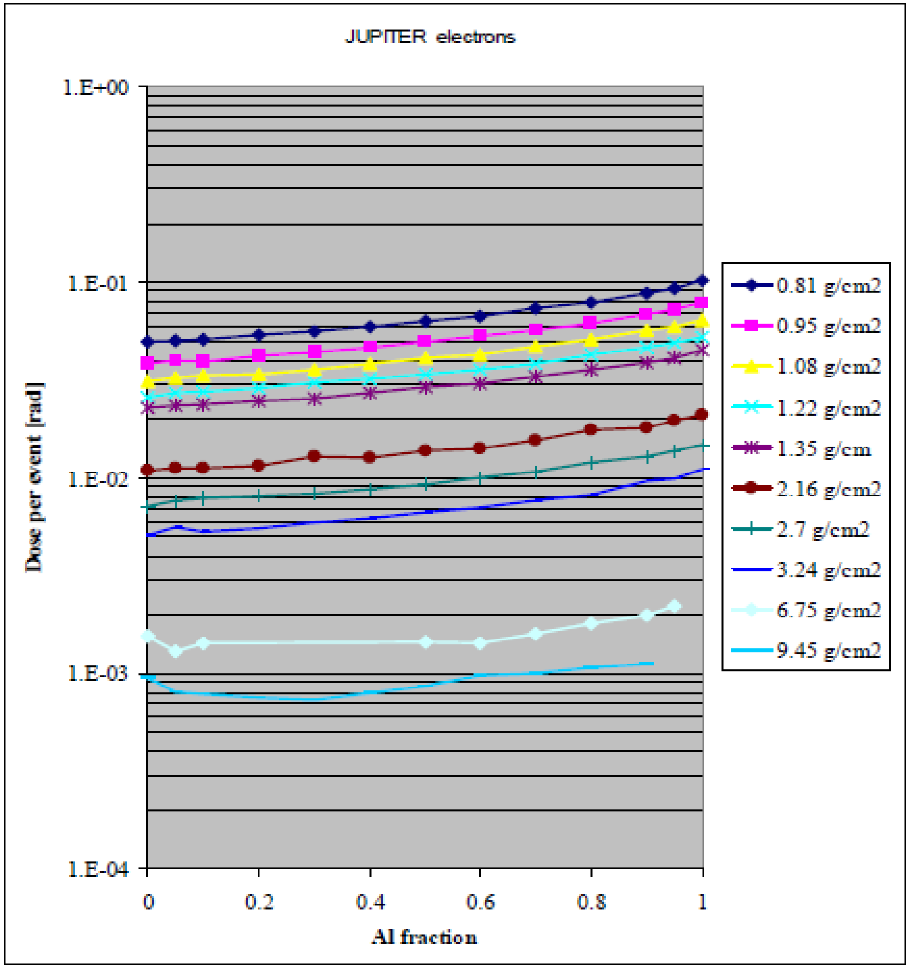


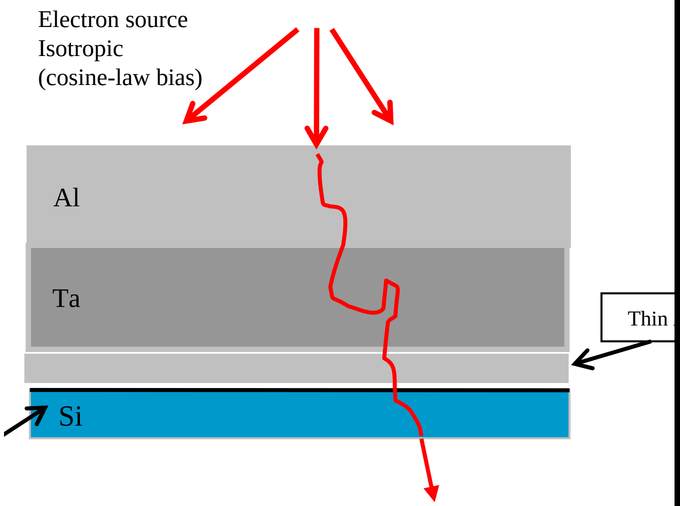
Fig. 7. Attenuated dose versus internal or external Aluminium thickness at a shield "mass thickness" of 1,35 g/cm^2.

Shielding material effectiveness
Graded shielding

Jupiter

Ref.: TEC-EES/2010.613 /GS/1.0

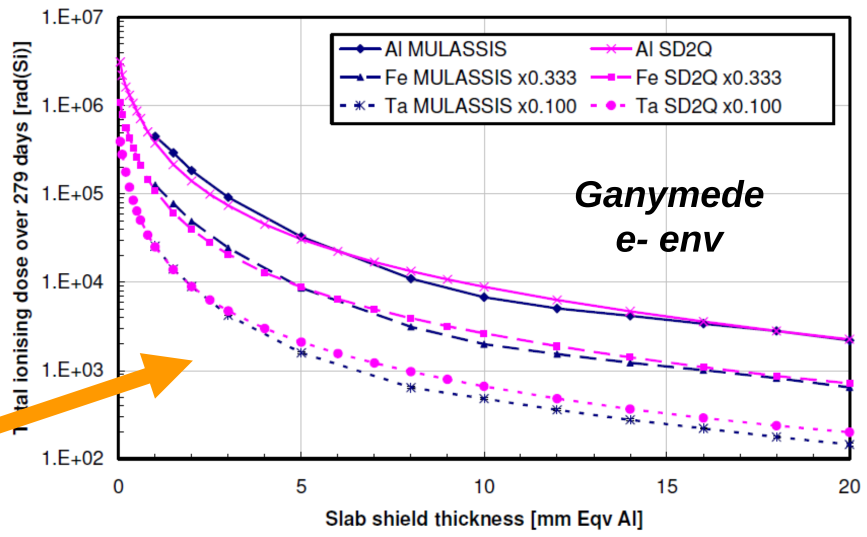


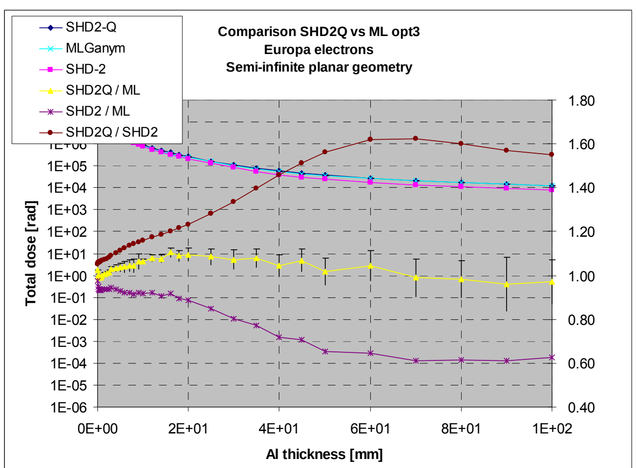


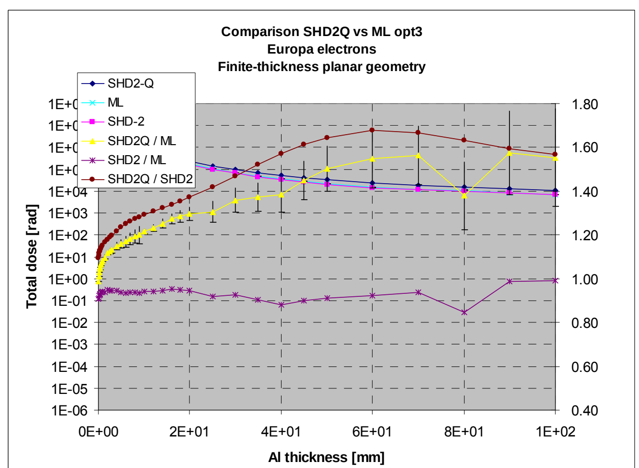
- Maximum dose reduction factor ~2
- For a given dose: mass saving for pure Ta vs. pure Al factor ~1.5
  - E.g.
    3.24 g/cm2 (Al) ~ 2.16 g/cm2 (Ta),
    and
    1.22 g/cm2 (Al) ~ 0.81 g/cm2 (Ta)
- General message:
  Rescaling to Aluminium not satisfactory

SHIELDOSE-2Q

- SHIELDOSE and SHIELDOSE-2 have been standard tools for S/C shielding analysis for over twenty years
  - Whilst not physically precise, these are much easier to use and generate results very rapidly
- SHIELDOSE-2Q extends range of shielding (including Fe, Ta, Cu-W alloy, Al-Ta bilayer) and target materials
- Available in SPENVIS
- Some validation efforts at ESA

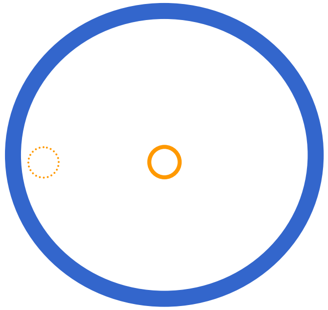




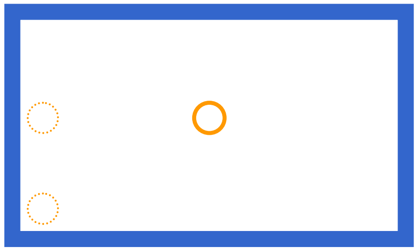


ESA JORE²M² project, Final Report, QinetiQ UK

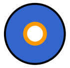
Dose in 3D simple geometries (1)



Spherical shell with detectors at the centre and close to the inner surface



Box with detectors at the centre and, close to the inner surface, at the centre of a face, next to an edge and next to a corner



“Solid sphere” with a detector at the centre

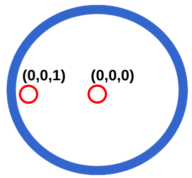
Dose at centre **[krad/310d]**

Shielding [mm]	**Solid sphere** **SHD2**	**Solid sphere** Al-Si-Vac R_Si=T/10 T_Si=10um	**Box** 2x2x3m^3 R_Si=10cm T_Si=10um	**Sphere** R=1.5m R=10cm T_Si=10um
5mm	1016	1030	345	377
10mm	266	283	83	104
20mm	62	57	18	25

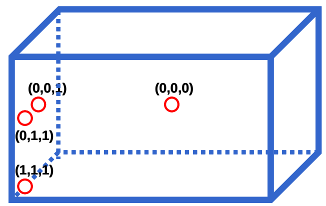
- Geant4 / GRAS 3-D Monte Carlo

ESA Memo TEC-EES/2011.812/GS

Dose in 3D simple geometries (2)



Spherical shell with detectors at the centre and close to the inner surface



Box with detectors at the centre and, close to the inner surface, at the centre of a face, next to an edge and next to a corner

"Solid sphere" with a detector at the centre

Solid sphere	**Dose 310 days [krad]**		
	Target 000		
5 mm	1030	+/-	1.3
10 mm	283	+/-	0.8
20 mm	57	+/-	0.4

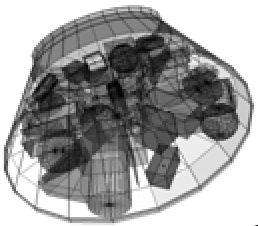
Sphere	**Dose 310 days [krad]**					
	Target 000			**Target 001**		
5 mm	377	+/-	5	374	+/-	5
10 mm	104	+/-	3	89	+/-	2
20 mm	25	+/-	2	18	+/-	1

Box	**Dose 310 days [krad]**											
	Target 000			**Target 001**			**Target 011**			**Target 111**		
5 mm	345	+/-	5	375	+/-	5	395	+/-	5	408	+/-	5
10 mm	83	+/-	2	93	+/-	2	98	+/-	3	99	+/-	2
20 mm	18	+/-	1	18	+/-	1	21	+/-	1	22	+/-	1

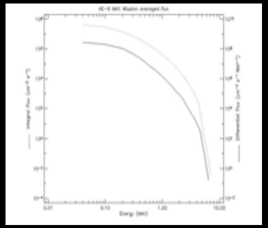
Message:

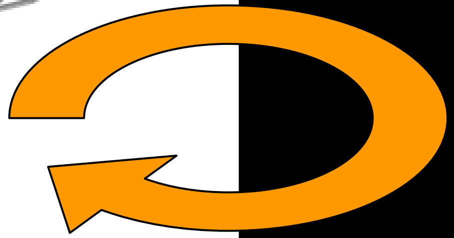
- Dose-depth curve should only be taken as first order approximation of radiation environment severity
- 3-D Monte Carlo calculations mandatory
- Note: Results may be strongly dependent on geometry details

Engineering margins
Confidence in simulation results

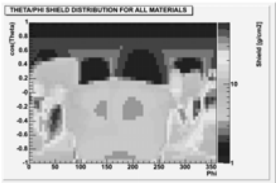


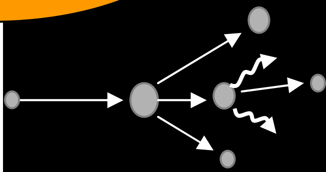
ConeXpress, R.Lindberg, ESA



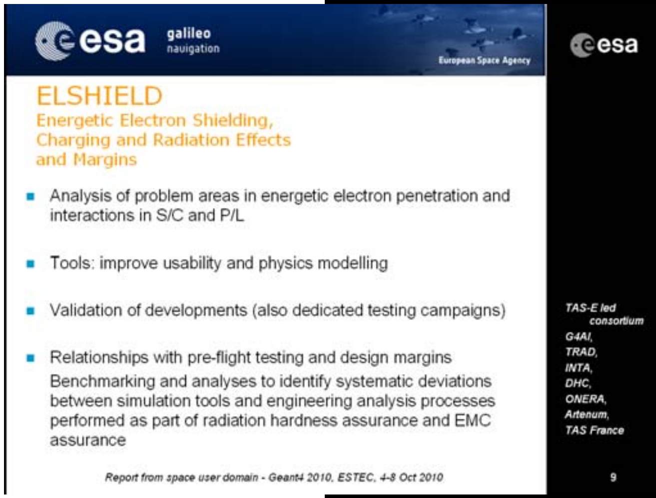


- Typical radiation analysis is iterative process with chain of calculations based on models, each with statistical and systematic uncertainties
  - Engineering margins should account for known and unknown unknowns to ensure mission survival in hostile environments
  - High margins imply extra costs (e.g. from weight of thick shielding, or system redundancy) and are sometimes showstoppers in feasibility studies – should be reasonable





- 3-D Monte Carlo is assumed to be more accurate than approximations based on 1-D calculations or ray tracing.
  - Is it always so? Several contributions to the global uncertainties to be monitored: choice of particle transport models? mistakes in MC tracking parameters, or misjudged confidence in physics model?
  - We should increase and quantify the confidence in our Monte Carlo engineering calculations


esa galileo navigation

European Space Agency

esa

ELSHIELD

Energetic Electron Shielding, Charging and Radiation Effects and Margins

- Analysis of problem areas in energetic electron penetration and interactions in S/C and P/L
- Tools: improve usability and physics modelling
- Validation of developments (also dedicated testing campaigns)
- Relationships with pre-flight testing and design margins

  Benchmarking and analyses to identify systematic deviations between simulation tools and engineering analysis processes performed as part of radiation hardness assurance and EMC assurance

TAS-E led consortium
G4AI,
TRAD,
INTA,
DHC,
ONERA,
Artenum,
TAS France

Report from space user domain - Geant4 2010, ESTEC, 4-8 Oct 2010

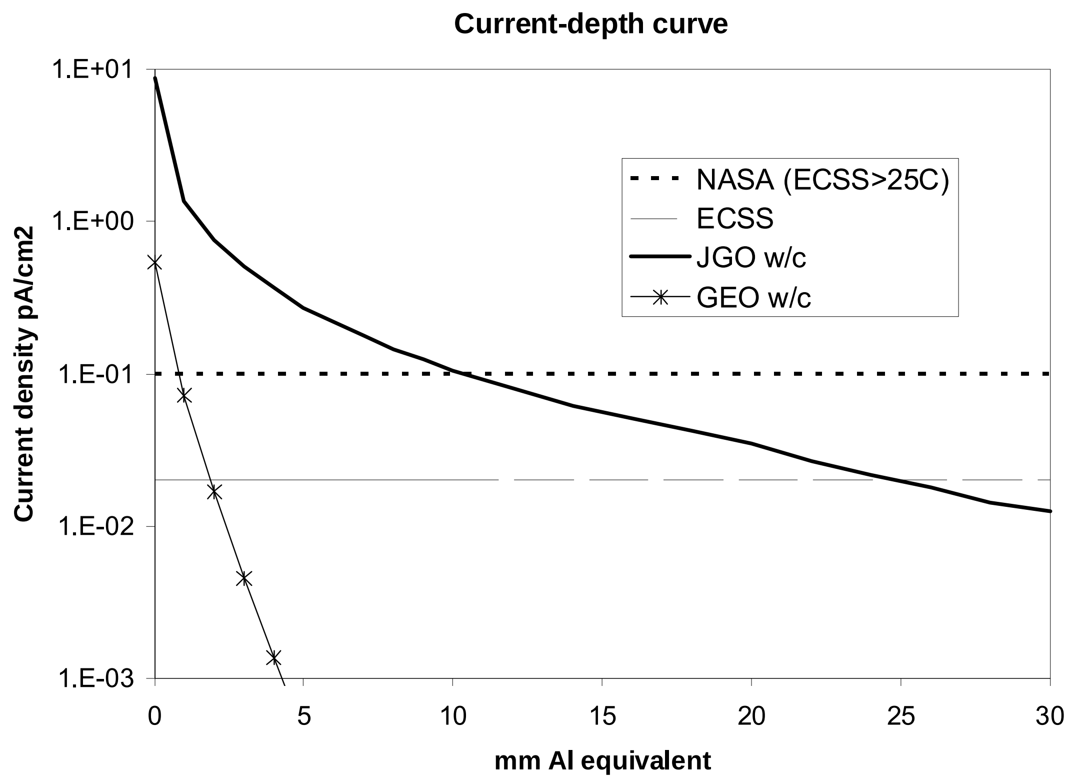
9

Critical Internal Charging Currents v Jovian environment

Critical charging currents from the standards

- 0.1pA/cm2
  - NASA-HDBK-4002
  - ECSS-E-ST-20-06C (>25ºC)
- 0.02pA/cm2
  - ECSS-E-ST-20-06C (<25ºC)

[JGO w/c is without Europa flyby]



Shielding to below critical charging current is difficult around Jupiter.

Hence we need to show that the internal charging level is acceptable by simulation.

David Rodgers, ESA

Internal charging simulation via DICTAT

Internal charging simulation is part of the spacecraft design process.

– Maximum electric field v Dielectric strength
– Maximum surface potential v Blow-off potential

Dielectric Internal Charging Threat Assessment Tool (DICTAT)

- Accessible via SPENVIS (www.spenvis.oma.be), or stand-alone
- 1-d analytical code
- Planar or cylindrical geometry
- Models:
  - Electron transport and deposition
  - Dose-rate
  - Conductive flow
  - Conductivity variation with temperature, dose-rate and electric field
- Currently version 3 available

David Rodgers, ESA

Calculation of deposited charge

DICTATv3 calculates deposited charge based on Range and straggle

- Electron Range formula of [Weber 1964] validated up to 10MeV
- Straggle formula of [Sorensen 1996]
- assumes all materials can be equated to Aluminium

At Jupiter

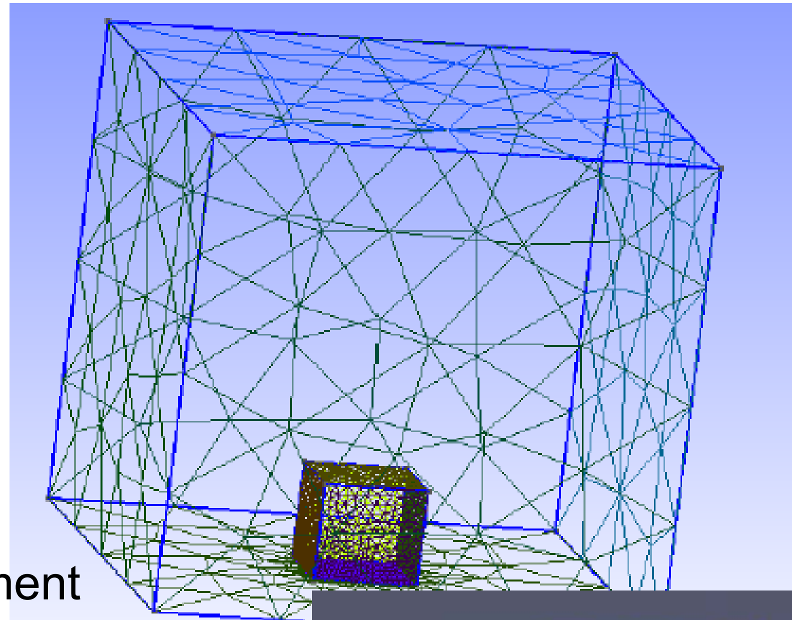
- We need to simulate higher energy electrons (up to 30MeV)
- We need to model other (high-Z) materials, e.g. Tantalum

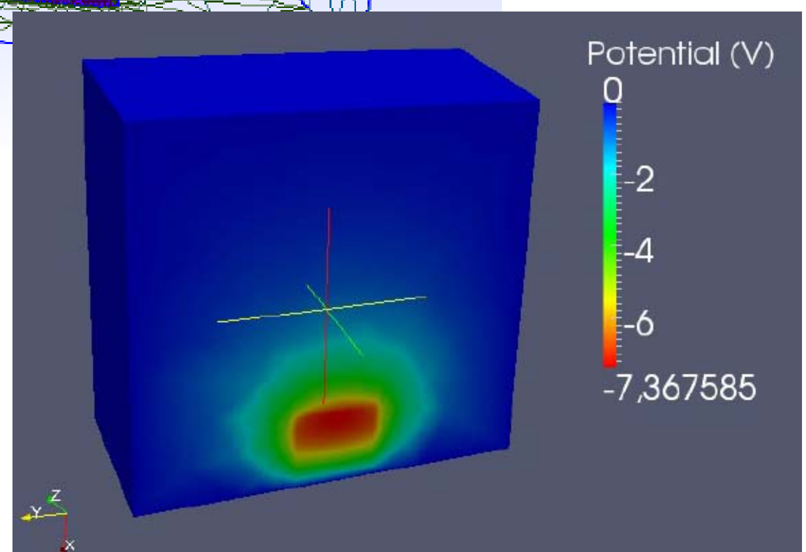
DICTATv4 also uses Range and straggle

- Range formula of [Tabata, Ito & Okabe, 1972], applicable to a wide range of materials (Z=6-92) and up to 30MeV
- New straggle formula based on fits to Mulassis that is consistent with new Range and considering net (forward – backward) current
- Otherwise the same as DICTATv3

David Rodgers, ESA

ELSHIELD
3D internal charging tool





- Under development
- New 3D deep charging analysis capability, based on novel interfaces between CAD, Monte Carlo particle transport, circuit solvers
- Completion: 1st half 2012

ESA ELSHIELD project

TAS-E with ONERA, ARTENUM, TRAD, INTA, G4AI DHC

Operational radiation transport tools
Development lines

Particle Physics Research

- Physics extensions
- Accuracy improvement
- Technical transport implementation
- Geometry capabilities

- Ease of use
- Engineering interfaces (CAD,…)
- Tallying options
- Computational speed
- Tool integration

Space Weather Operations

Scientific approach

1. Accuracy
2. Usability
3. Speed

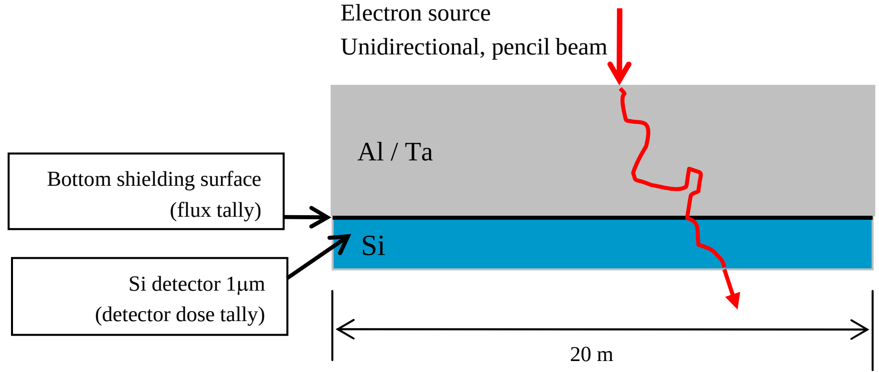
Missions support

Usability

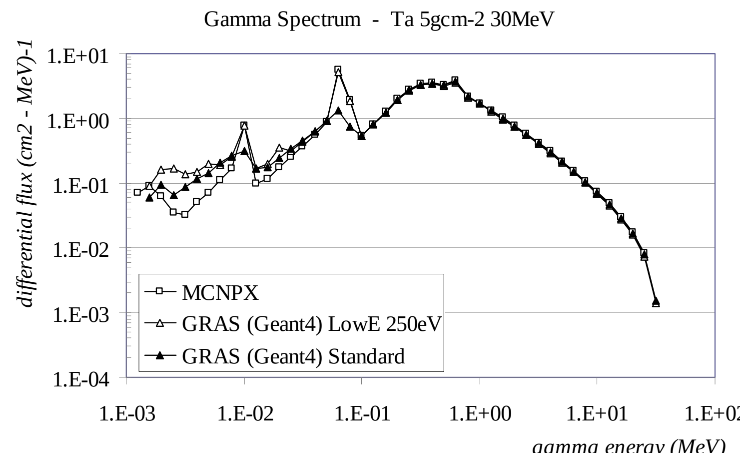
Speed

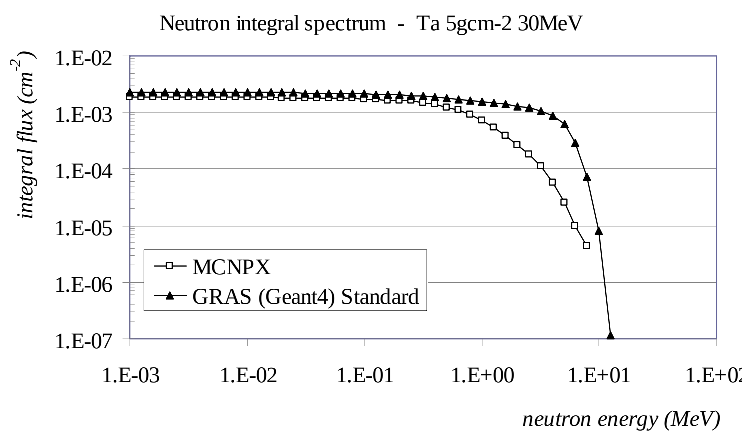
Accuracy

Validation efforts for EJSM



- Shared effort JPL – ESA
- Prediction capabilities of Geant4 and MCNPX
  - From single materials
    to multi-layered shielding options
  - Mono-energetic e- and realistic spectra
  - TID, electron, gamma and also neutron fluxes
- Selection of input parameters and models for Geant4 non-trivial
- Agreement generally good, with some notable differences
- Providing benchmarks for potential instrument providers to validate their own choice of transport tools





Presented at EJSM Instrument Workshop, ESTEC

Validation efforts for Earth orbits ELSHIELD

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- Tools: improve usability and physics modelling
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TAS-E led consortium

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TAS France

Modelling speed in 3-D realistic S/C

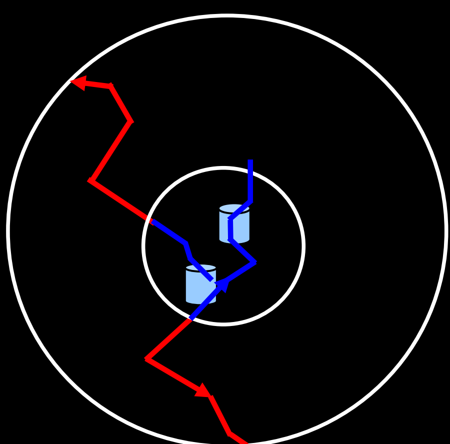
CAD geometry interface

- CAD STEP and IGES interface (and normal 3D models)
  - via external 3D modelling tools tools
  - Direct GDML output for Geant4
- FASTRAD, ESABASE2

Speed: Reverse MC

Requirement from space industry

- Tallying in sub-micron SV inside macroscopic geometries
- Reverse tracking from the boundary of the sensitive region to the external source
  Based on “adjoint” transport equations
- Computing time focused on tracks that contribute to the detector signal

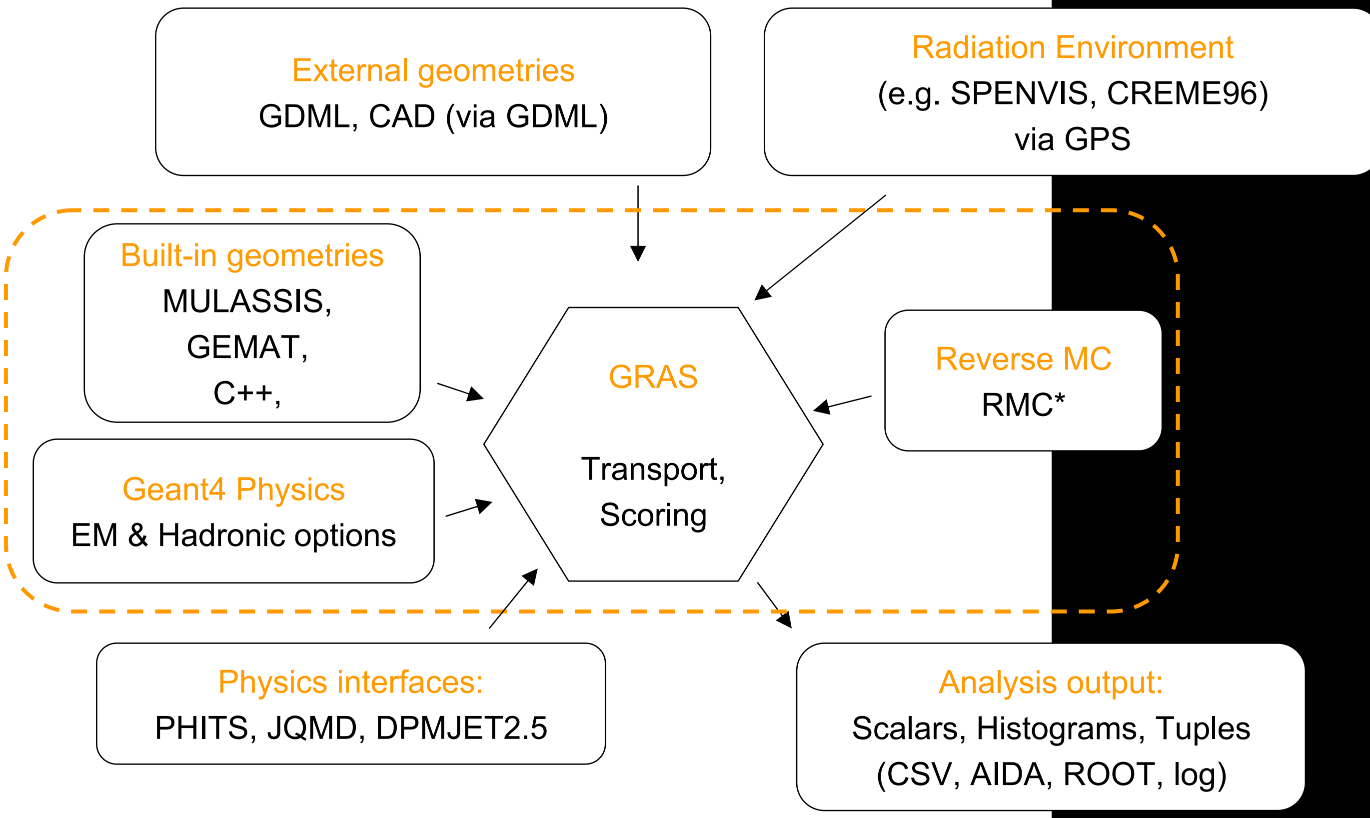


Laurent Desorgher (Space IT)

Geant4 tool integration: GRAS

Requirements:

- Ready-To-Use tool
  - Multi-mission approach
- Quick assessments
  - Ray-tracing ↔ MC
  - 1D ↔ 3D
  - EM ↔ Hadronics
  - LET ↔ SV details
- Modular progress
  - Open to collaborations and contributions
- Currently GRAS v2.5.2, also available in SPENVIS
- GRAS v3.0 in preparation
  - By end of Nov 2011



G Santin, V Ivantchenko et al, IEEE Trans. Nucl. Sci. 52, 2005

http://space-env.esa.int/index.php/geant4-radiation-analysis-for-space.html

GRAS: script driven

Santin et al, RADECS, 2005

Geometry

1

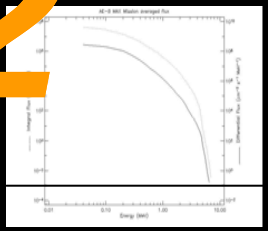
Parameters for
built-in geometries
or
External files

```
/gras/geometry/type gdml
/gdml/file geometry/conexpress.gdml
```

Source

2

RADIATION
ENVIRONMENT



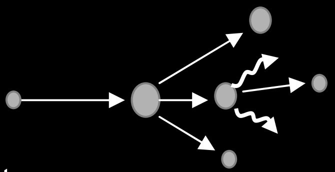
```
/gps/pos/type Surface
/gps/pos/shape Sphere
...
/gps/ang/type cos
/gps/particle e-

...
```

Physics

3

Physics lists

or single components

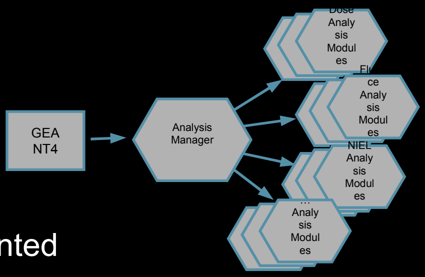


```
/gras/phys/addPhysics em_standard_opt3
/gras/phys/addPhysics QGSP_BIC_HP
/gras/phys/addPhysics raddecay

/gras/physics/setCuts 0.1 mm
/gras/physics/stepMax 0.01 mm
```

Analysis

4

Object Oriented
scripting




```
/gras/analysis/dose/addModule doseB12
/gras/analysis/dose/doseB12/addVolume b1
/gras/analysis/dose/doseB12/addVolume b2
/gras/analysis/dose/doseB12/setUnit rad
```

REST-SIM

Radiation Effects on Sensors and Technologies for Cosmic Vision SCI Missions

Figure of Merit (risk?)

- Technology mapping & effects
- Impact on mission risk assessment

- The susceptibility of the various technologies to the specific space environments:

$$f = \log\left(250 \times Env \times \frac{\#effects}{8} \times \frac{1}{TRL}\right)$$

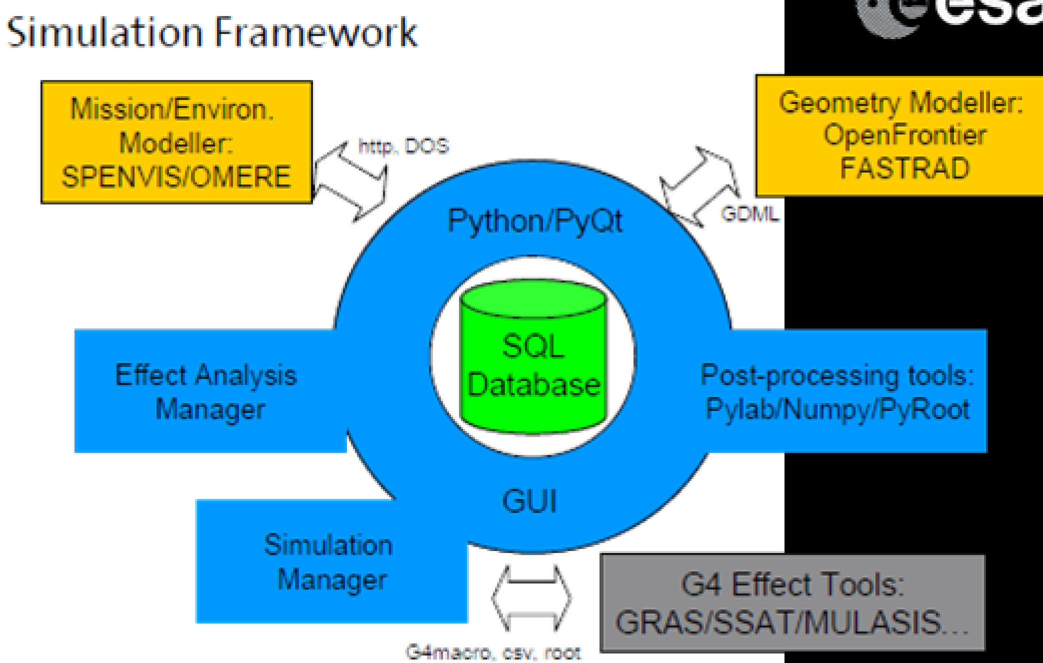
  - ***Env***: a scaling factor that takes into account the space environment (e.g. distance from the sun) and mission duration
  - ***#effects***: the number of effects a technology is susceptible to
  - ***TRL**:* the technology readiness level

- Traffic-light colour coding!

		L-Class							
Technology	**Effect**	**IXO**	**LISA**	**JGO**	**EUCLID**	**MP**	**PLATO**	**SPICA**	**SO**
CCD	TID	1.2			0.9		1.0		
	DD	1.2			0.9		1.0		
	SEE	0.5			0.2		0.3		
Photodiodes	TID	1.2	0.9	2.2		1.1			1.9
	DD	0.8	0.5	1.5		0.7			2.1
	SEE	0.5	0.2	0.4		0.4			0.5
Si Drift Diode Array	TID	1.6							
	DD	1.2							
	SEE	0.9							
Laser Pump Diodes	TID	0.8		1.8		0.6			
	DD	0.8		1.4		0.6			
	SEE								
APS	TID	1.0		2.0		0.8			1.7
	DD	1.2		1.9		1.1			2.5
	SEE	0.8		0.7		0.7			0.8
Hybrid CMOS ROIC Multiplex	TID			1.8	0.5	0.7			1.5
	DD								
	SEE			0.7	0.5	0.7			0.8
HgCdTe	TID			1.8	0.5	0.7			1.5
	DD			1.5	0.5	0.7			2.1
	SEE			0.4	0.2	0.4			0.5
PhotoDetectors	TID		0.7	2.0					
Ga:As	DD								
	SEE		0.2	0.4					
PhotoConductors	TID							0.5	
Ge:Ga	DD								
	SEE							0.0	
Si Bolometers	TID			2.2		1.0		0.7	
	DD								
	SEE			0.5		0.5		0.2	
TES Bolometers	TID								
	DD								
	SEE	0.8						0.3	
SQUID Amplifier	TID								
	DD								
	SEE	0.8						0.3	
KID Detectors	TID								
	DD								
	SEE							0.4	
CdZnTe	TID	0.8							
CdTe	DD	0.8							
	SEE	0.5							
MCP	TID								
	DD								
	SEE			0.4		0.4			0.5
Solid State Oscillator	TID								
	DD								
	SEE								
Crystal Oscillator	TID			1.5					
	DD								
	SEE								
Glass, Fibres, Laser Rods	TID	0.5	0.2		0.2		0.3		
	DD								
	SEE								
Si Pore Optics	TID								
	DD								
	SEE								
CsI Scintillator	TID								1.2
	DD								1.8
	SEE								
Fluxgate Sensors	TID								
Search coil magnetometer	DD								
	SEE			0.4					0.5
Gas Pixel Detector	TID								
	DD								
	SEE	1.0							

REST-SIM
Simulation Framework

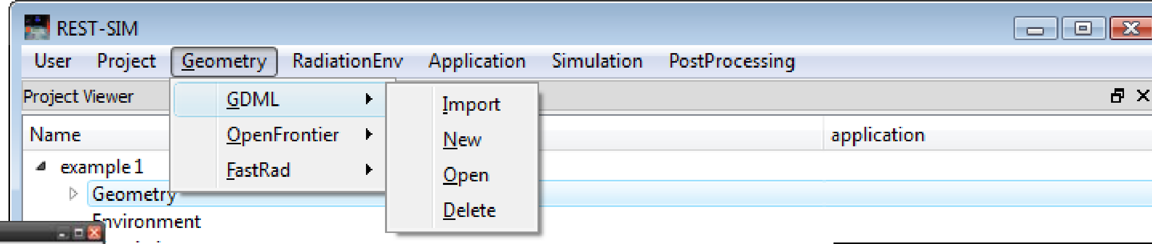
- Mission specification and environment modeller
- S/C and P/L geometry modeller
- Effects analysis tools
  - Geant4-based applications (GRAS, SSAT, MULASSIS)
- Simulation manager
- Post-processing manager
  - Visualisation, plots
  - Response matrices / formulae / algorithms

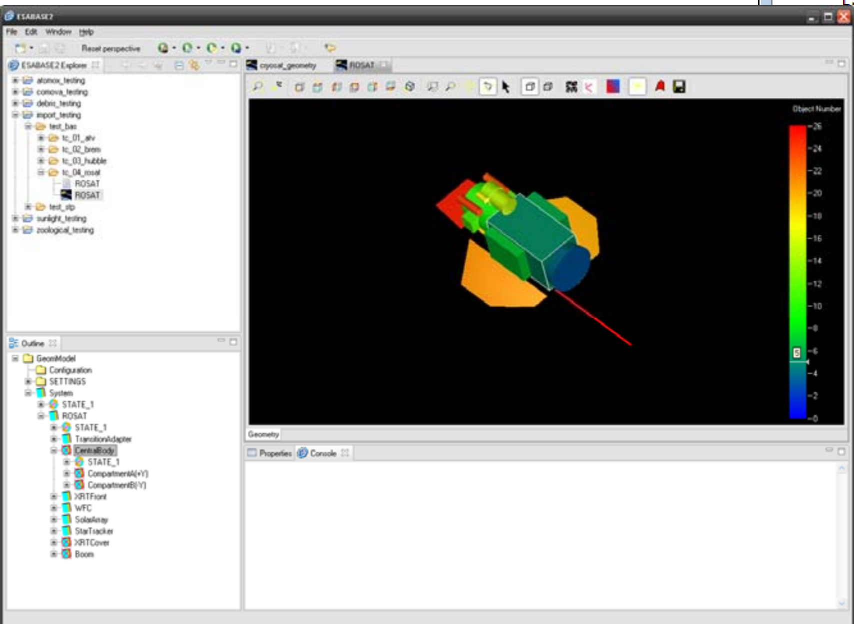


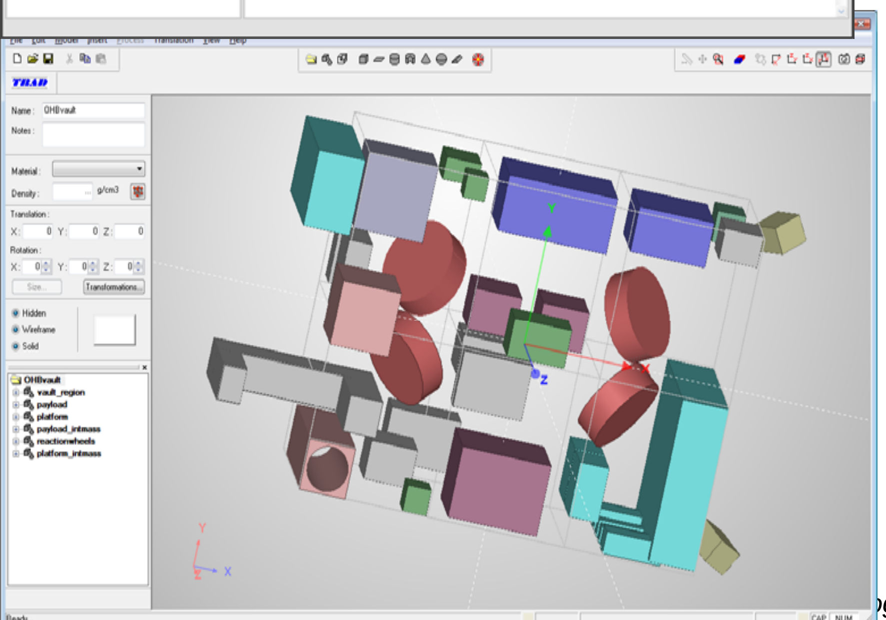
- Key s/w technologies:
  - Python and PyQT
    main programming lang. and GUI
  - GRAS/Geant4
    particle transport and effects simulation tool
  - NumPy, SciPy & Matplotlib
    post-processing
  - MySQL
    internal database

REST-SIM

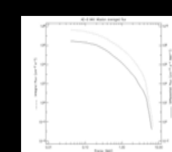
Geometry

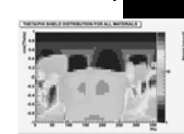


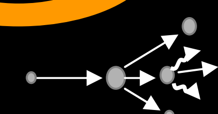




- CAD Tool -> GDML -> Geant4:
  - Stored in the database in GDML format – Geometry Description Markup Language
- Geometry modelling:
  - import or build
- Two CAD tools are integrated into REST-SIM:
  - Open Frontier: Further developments in this project
  - FASTRAD: by TRAD with CNES/ESA funding
  - Models constructed from
    - CSGs
    - STEP import

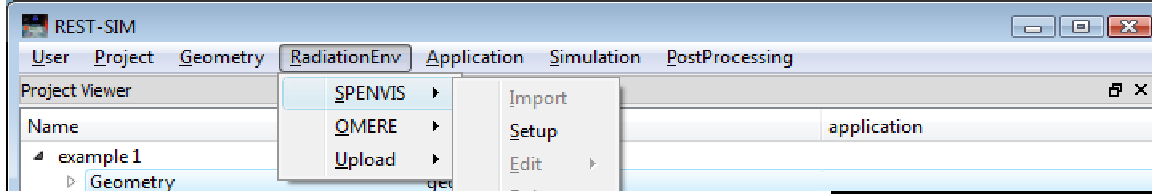




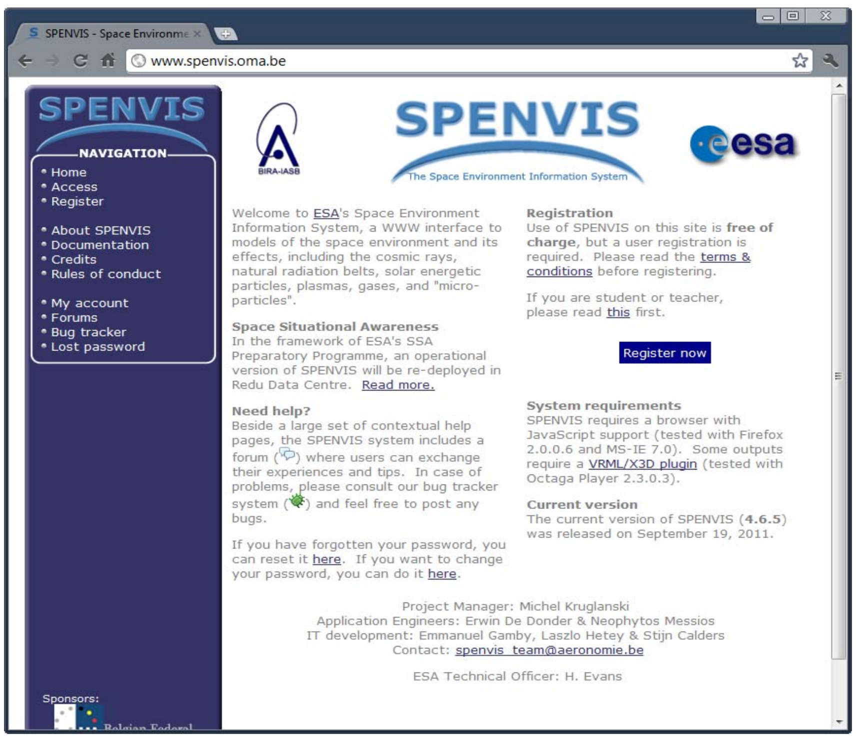


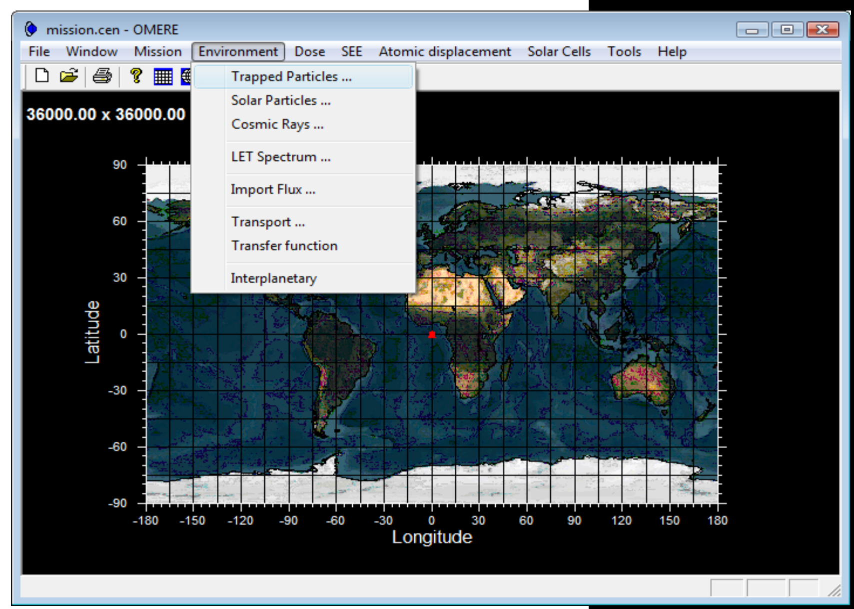
REST-SIM

Radiation environment



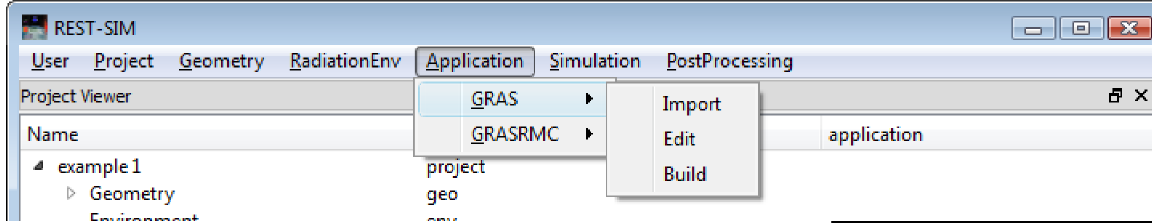
- Mission environments can be modelled using SPENVIS and OMERE
  - run from REST-SIM
  - environ. data are imported and saved in the project database
- User can also upload environ. specifications directly



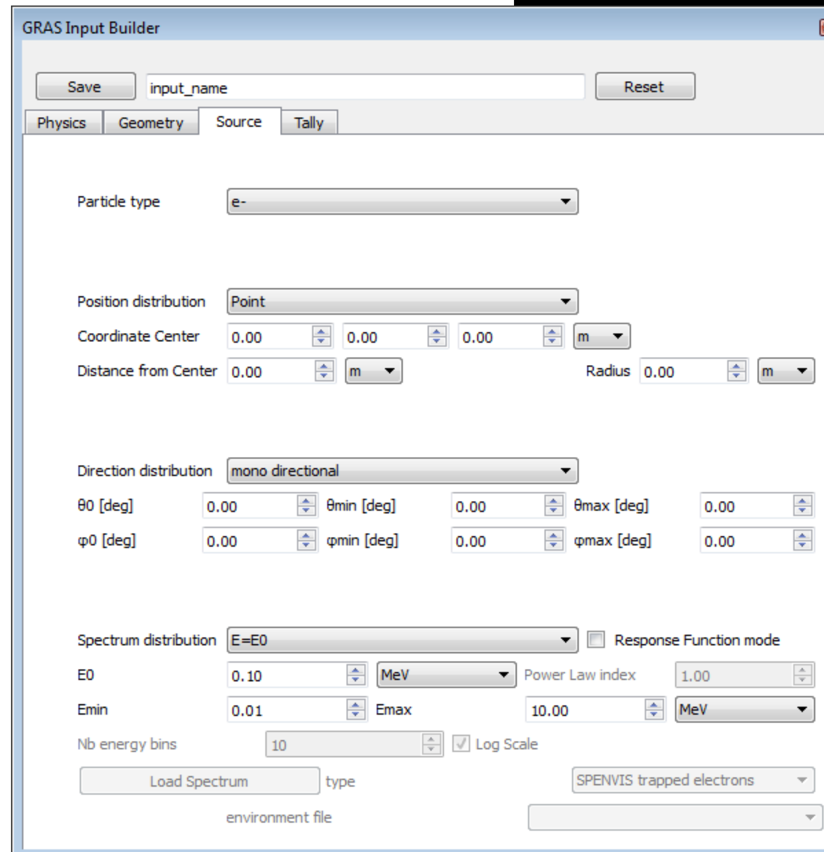


REST-SIM

Effects Analysis

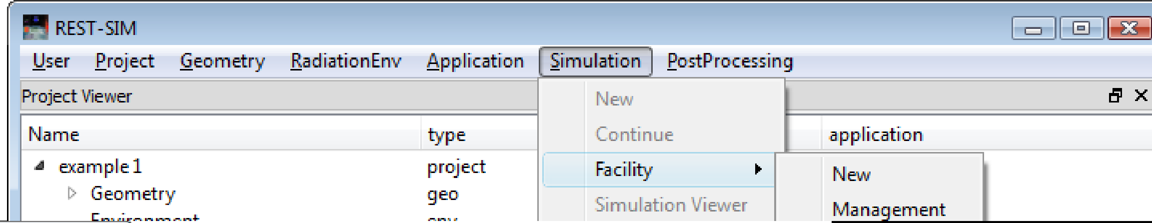


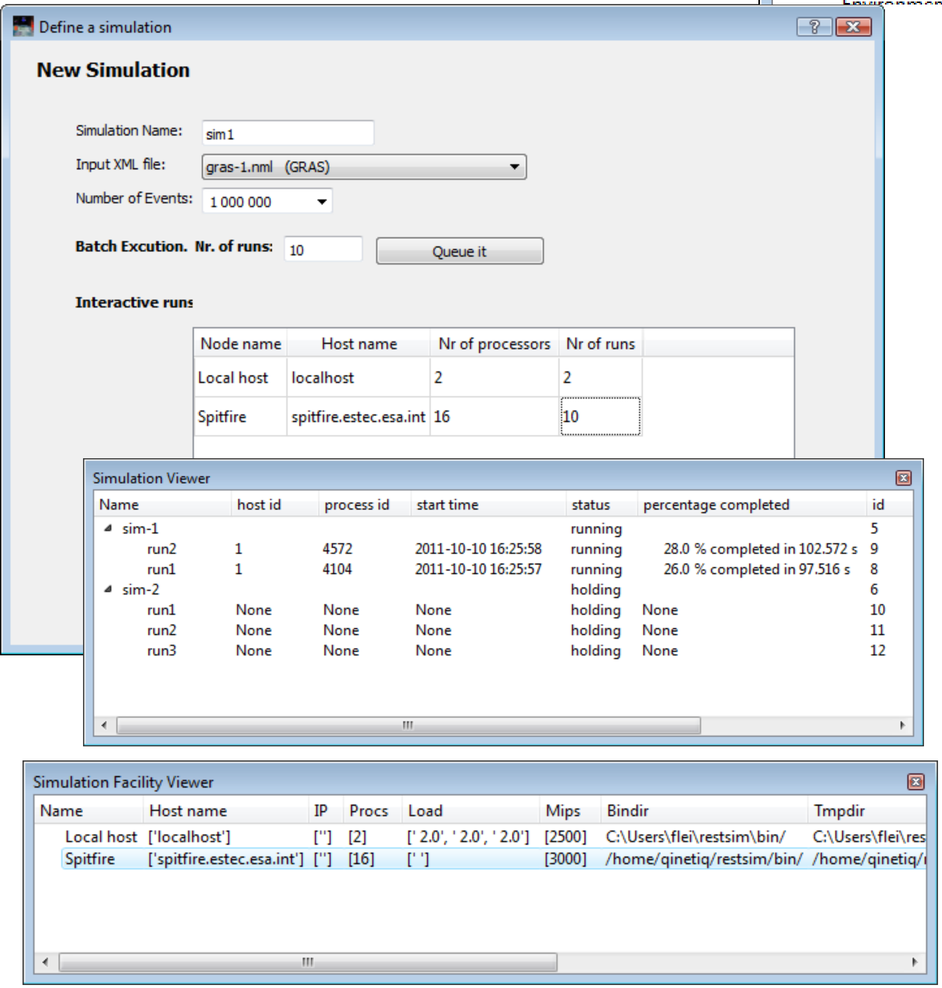
- Geant4 based analysis tools: GRAS (w/ reverse MC)
- Geometry and Environment from the DB
- Full control of Geant4 physics
- Type of effects/analysis:
  - Fluence/Current -- Dose
  - PHS -- Dose_equivalent
  - Equivalent_dose -- LET
  - NIEL -- Path_Length
  - Charging -- Charge_collection
- Parameteric analyses



REST-SIM

Simulation manager

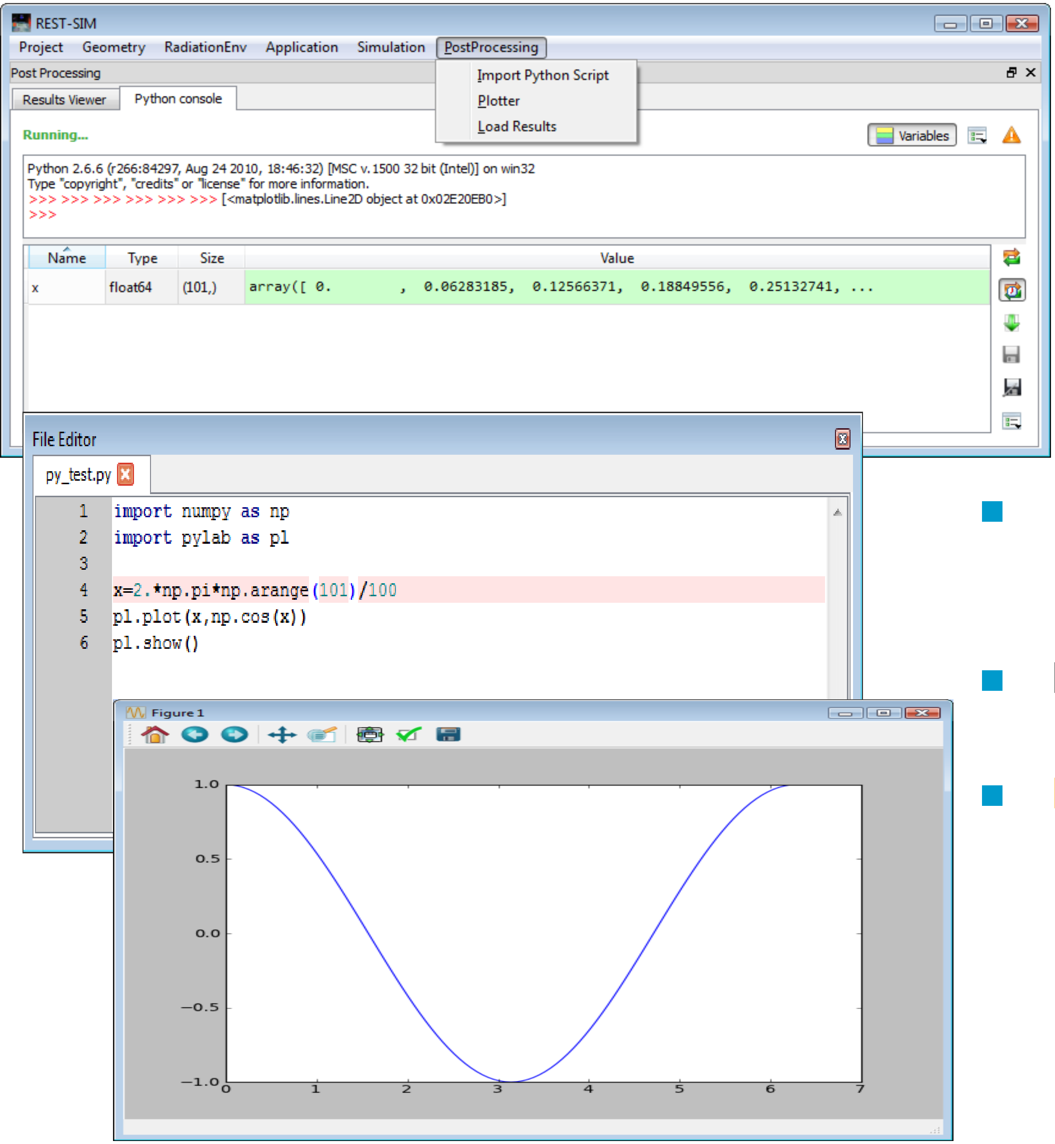




- Simulation facilities:
  - Local host, or remote (SSH)
  - Linux, or Windows (local)
- Two execution modes:
  - Interactive, forced runs
  - Batch queue
- Automated parallelisation:
  - Load balance
  - Results - auto collection, merge
- Execution monitoring/management:
  - Check progress:
    % completed
  - Stop/Kill/Remove

REST-SIM

Post-processing



- Interactive Python scripts
  - NumPy, SciPy, Matplotlib
  - Python console and editor
- Plotting:
  - 1d/2d histograms
- Post-processing:
  - Operation on histograms
  - Derivative parameter analysis
  - Analysis based on response functions
  - …

REST-SIM
Demonstration Application: JUICE

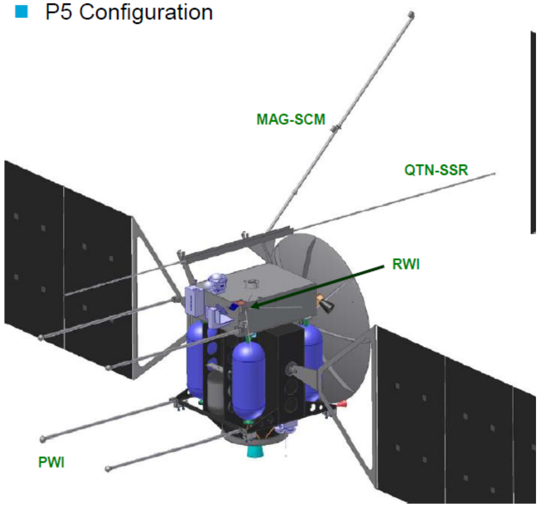
- Two demonstration applications:
  - Laplace / JUICE
  - Solar Orbiter

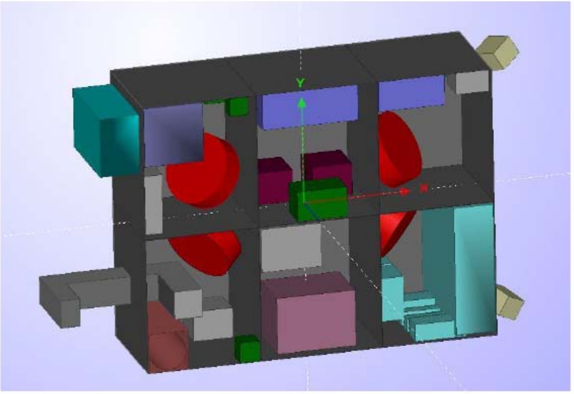
- Laplace / JUICE:
  - Environments: Latest ESA Specifications
  - Geometry Model:
    - Simplified OHB study configuration
    - Detailed geometry model of the StarTracker/APS
    - Modelled with FASTRAD
  - Analysis:
    - TID/NIEL of the APS/StarTracker
    - Background noise
    - Comparison with SSAT results

- REST-SIM tool release

Available to the community begin 2012

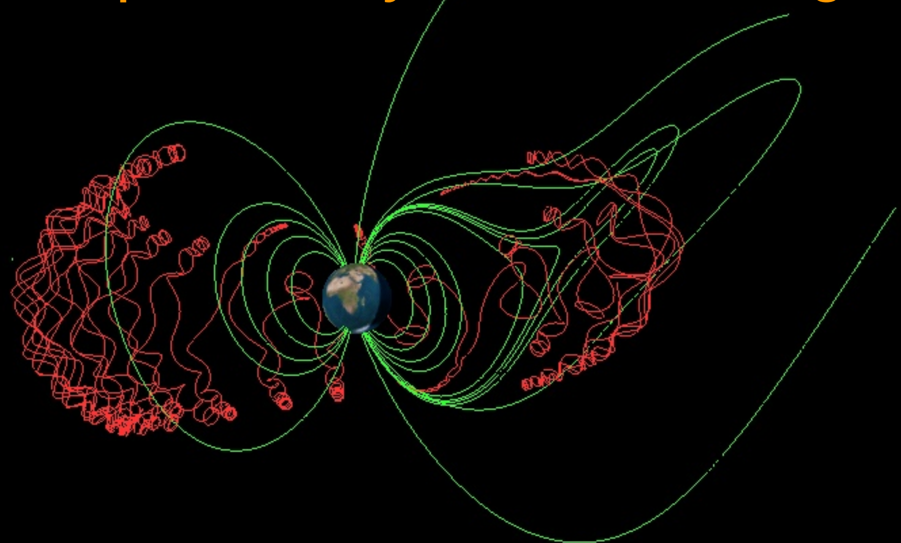
- P5 Configuration

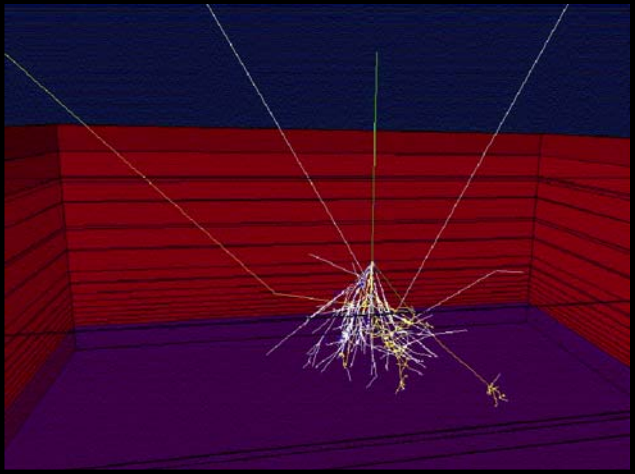




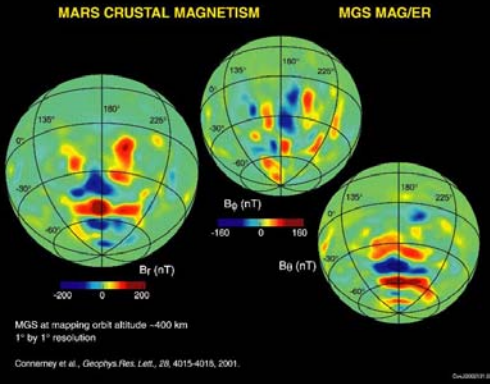
PlanetoCosmics

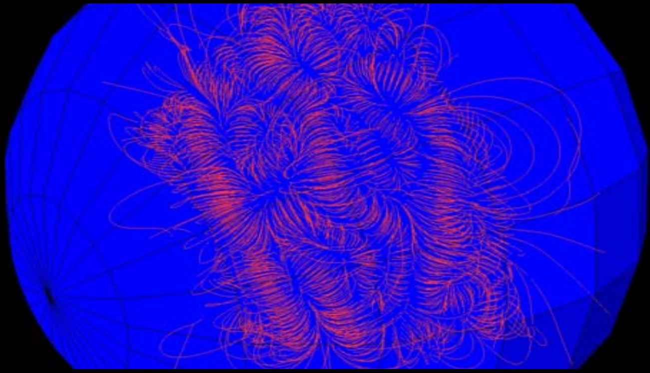
Geant4 simulation of Cosmic Rays in planetary Atmo- / Magneto- spheres





- Originally for Earth environment
- Extended to
  - Mars (local magnetic fields)
  - Mercury
- Under development
  - Jupiter
  - Saturn
  - Jovian moons





Geant4 implementation L. Desorgher, Space IT

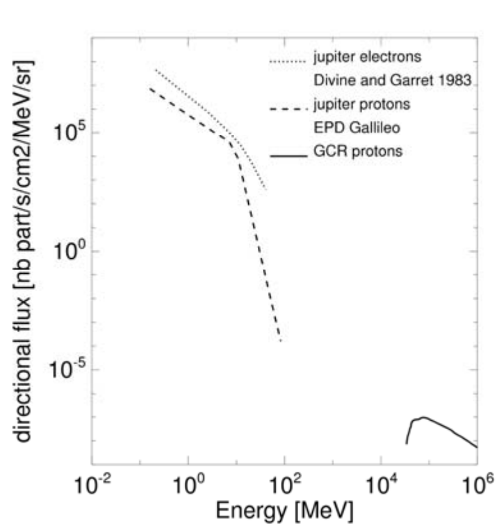
http://cosray.unibe.ch/~laurent/planetocosmics/

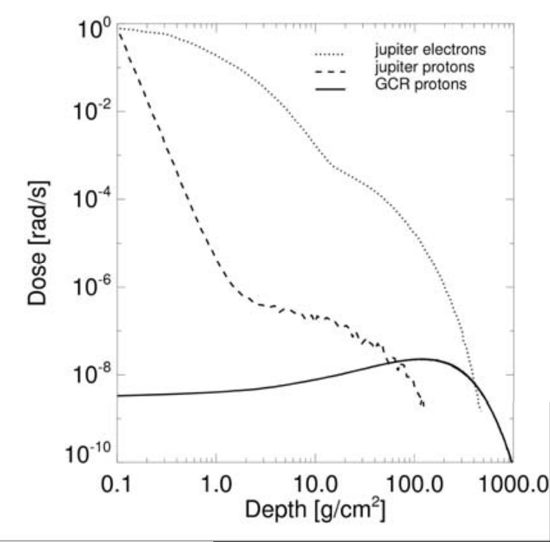
Planetocosmics at Jupiter

Early work by

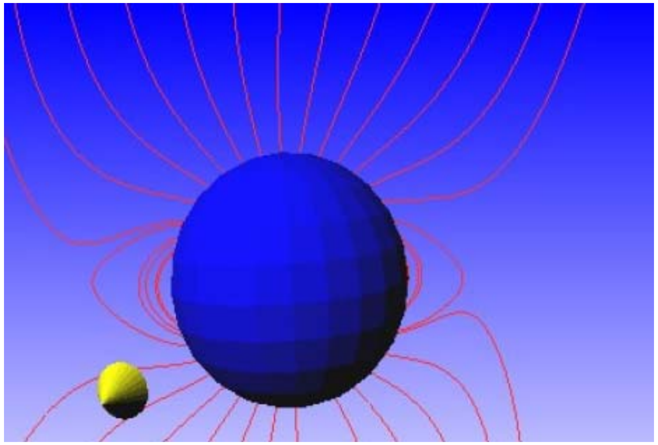
L.Desorgher (SpaceIT), 2008

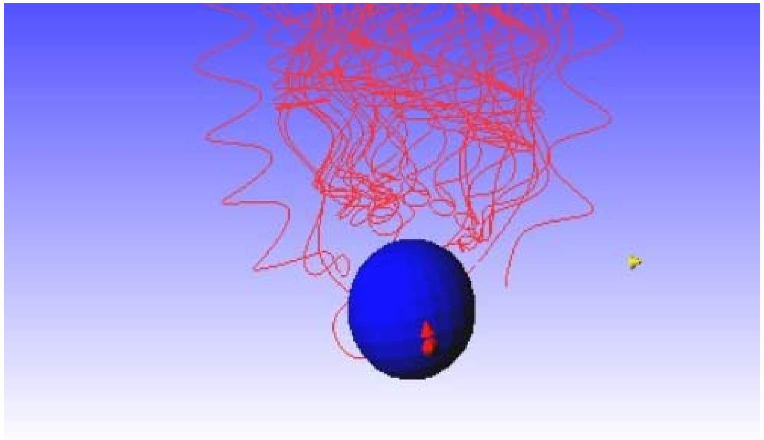
- Radiations at Europa
- Dose in Europa soil (ice)





Planetocosmics-J





P. Truscott, D. Heyndericks, R. Nartallo, Fan Lei, A. Sicard-Piet, S. Bourdarie, J. Sorensen and L.Desorgher, “Application of PLANETOCOSMICS to Simulate the Radiation Environment at the Galilean Moons”, Vol. 5, EPSC2010-808, 2010

- Available in SPENVIS

ESA JORE^{2}M^{2} project, Final Report, QinetiQ UK

Summary

- Severity and new features in Jupiter radiation environment impose use of appropriate (MC-based) tools for study of countermeasures
- New tools are being made available to the community
  - DICTAT v4 / ELSHIELD 3D internal charging
  - SHIELDOSE-2Q
  - GRAS v3 / REST-SIM

  Most available via SPENVIS, or from provided URLs
- Uncertainties and impact on margins

Parallel session on day 2:

Issues in modelling rad effects

- Discussion / collection of requirements
- Radiation effects modelling
  - TID, DD, background
  - Exposed surfaces (no / thin shielding)
- Tools
  - Ray-tracing vs Monte Carlo
  - SSAT, MULASSIS, GEMAT, GRAS, REST-SIM NOVICE, FASTRAD,…
- Monte Carlo calculations
  - Solutions to technical challenges
  - Potential pitfalls
  - Geometry models, CAD exchange, etc
  - Computational resources
  - Biasing options
  - Response function and rescaling
  - Normalisation
  - Self shielding
- REST-SIM radiation tool - details
  - GUI
  - GRAS / Geant4 tool