14th Geant4 Users' and Collaboration Workshop
Catania, 15-22 October 2009

Applications of Geant4 in space (recent developments)

Giovanni Santin*, Petteri Nieminen

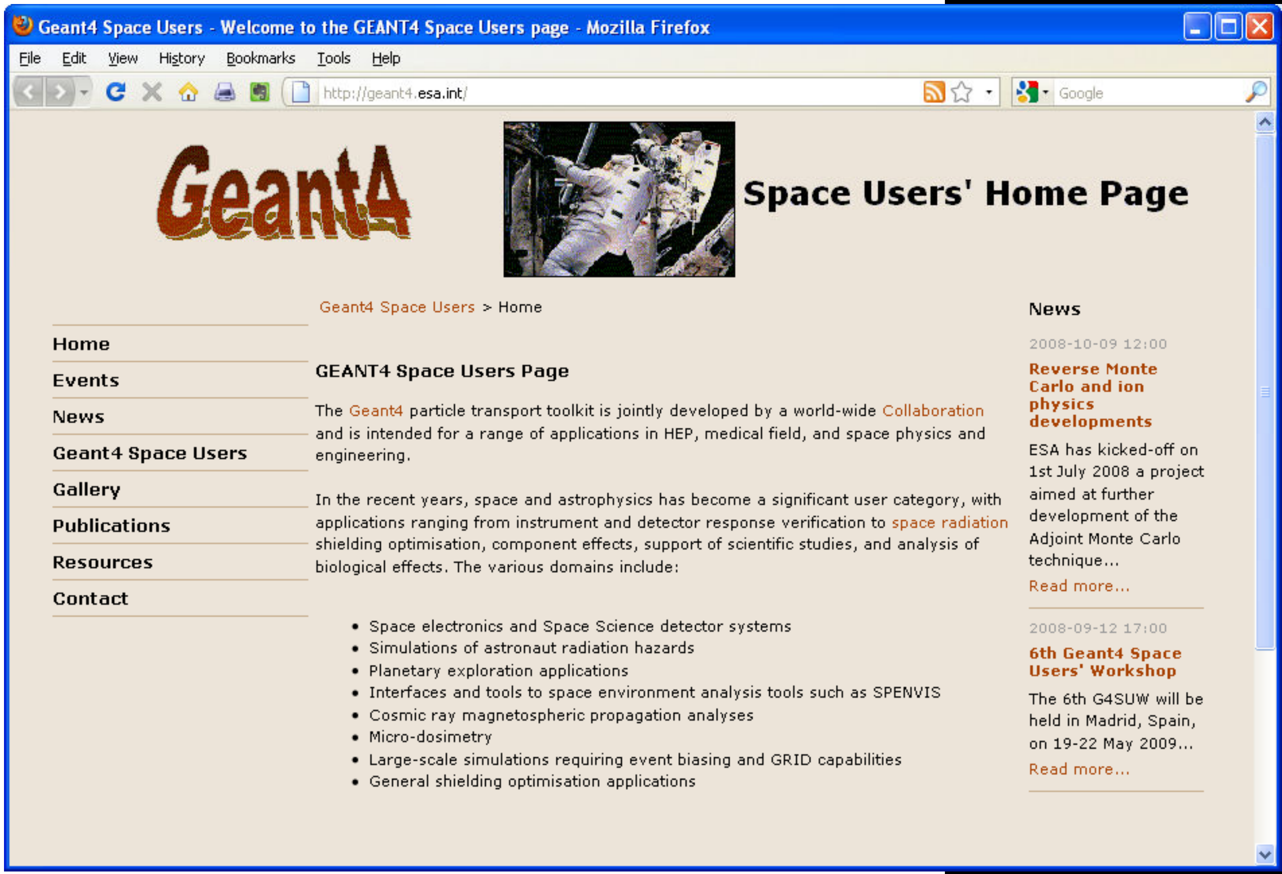
Space Environments and Effects Analysis Section
European Space Agency
ESTEC
** on loan from RHEA Tech Ltd*

Outline

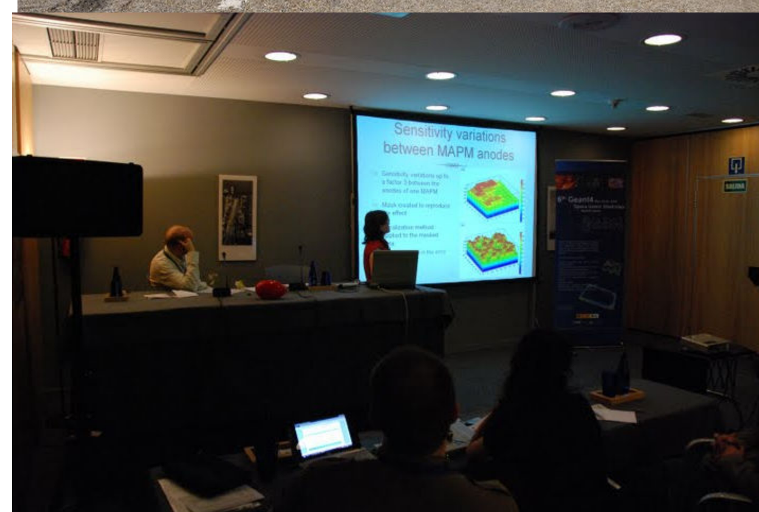
- Geant4 Space Users' community
- Highlights from 2009 workshop (Madrid)
- Other Geant4 based work
- Enabling developments

Geant4 Space Users' community

- Geant4 Space Users' web page
  - Users, publications, news
  - http://geant4.esa.int
  - Feedback appreciated
- Space Users' Workshops (since 2003)
- Hyper-news: "Space applications" forum



- http://www.inta.es/g4suw2009/
- ~60 participants
  Wide range of interests and applications
- The following section contains an arbitrary, non exhaustive selection of contributions from the event



Geant4 Space Users' 2009
Planetary exploration

MarsREM

- ESA exploration programme
- Physics:
  - High energy – high Z ion interactions (radiation safety)
  - Filling gaps identified in previous HSF-related studies, e.g. ESA DESIRE (T.Ersmark, KTH)
  - DPMJET2.5 interface
- Tool development
  - dMEREM
  - eMEREM – addressing engineering requirements
  - Active magnetic shielding
- SPENVIS interface
- *Presented by P.Truscott at NSREC 2008, IAC 2008*

esa

ESA contract

(QinetiQ, LIP, BIRA, DHC, SpaceIT)

MarsREM – DPMJET interface

Implementation of DPMJET-II.5 model in Geant4

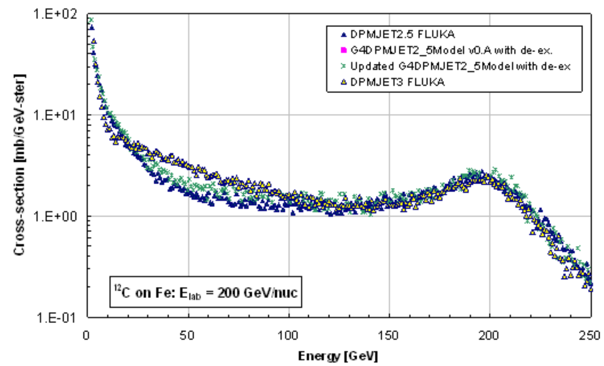
- Priority to extend the high-energy regime of Geant4 to ultra-relativistic energies
- Existing FORTRAN code DPMJET-II.5 to act as an event generator: 5GeV/nuc to 1E+11 GeV/nuc
- Geant4 DPMJET-II.5 interface: G4DPMJET2_5Model class now developed and tested, covers projectiles from A=2 to A=58 on targets from A=2 to A=58

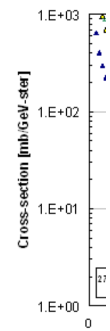
  Currently extending this to projectiles from A=2 to A=240 on targets from A=2 to A=240

- After prompt nuclear-nuclear collisions, nuclear de-excitation treated using other Geant4 models (precompound, evaporation, Fermi break-up)
- Total inelastic cross-section class G4DPMJET2_5CrossSection also created to estimate mean-free-path between nuclear-nuclear collisions, and also covers projectiles from A=2 to A=58 on targets from A=2 to A=58

  (similarly being extended to A=240)

- Models used on Detailed Mars Energetic Radiation Environment Model (dMEREM) to be presented





QinetiQ

LIP

Space IT

esa

ESA contract

(QinetiQ, LIP, BIRA, DHC, SpaceIT)

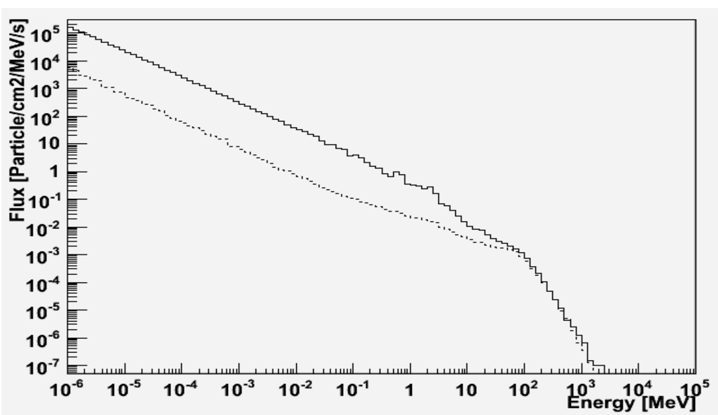
MarsREM - eMEREM

- Fast, engineering tool
- Response matrices (note: generated with FLUKA)
- Rapid calculation of
  - radiation particle fluence and LET spectra.
  - radiobiological dose
- Available on ESA SPENVIS system
- Future work includes heavy ions contribution.

P.Truscott et al., NSREC 2008

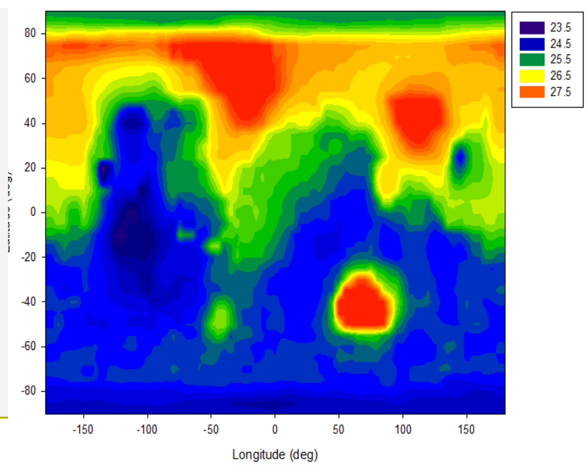
ESA contract

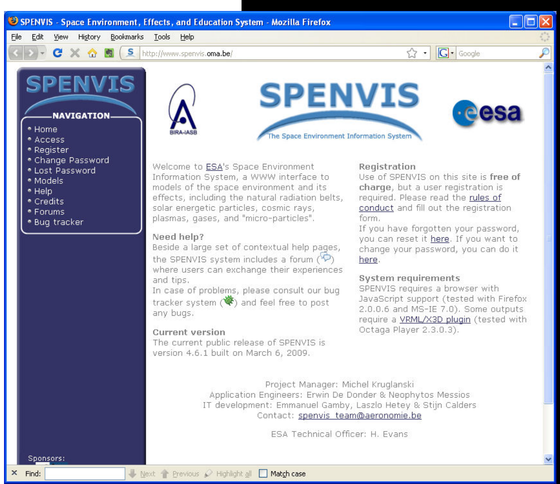
(QinetiQ, LIP, BIRA, DHC, SpaceIT)



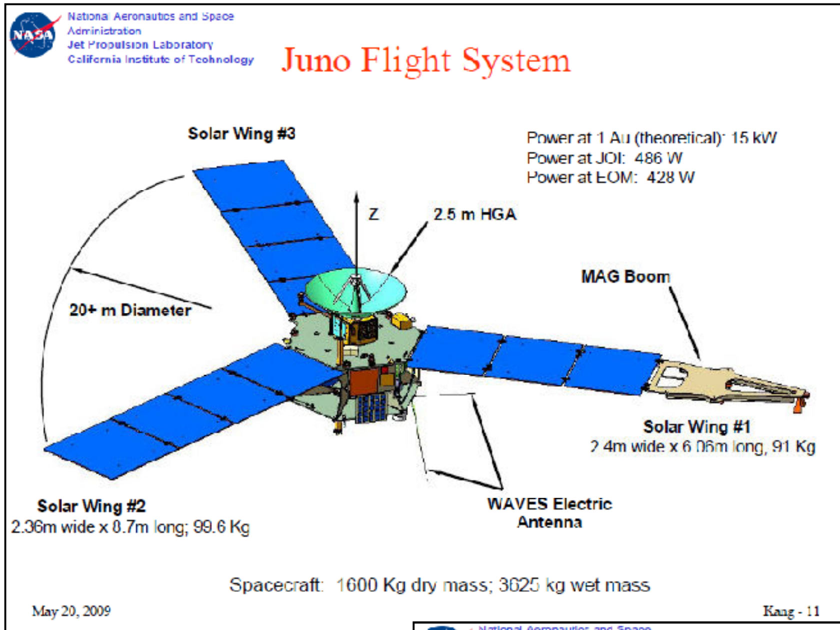
Neutron spectra (upwards):

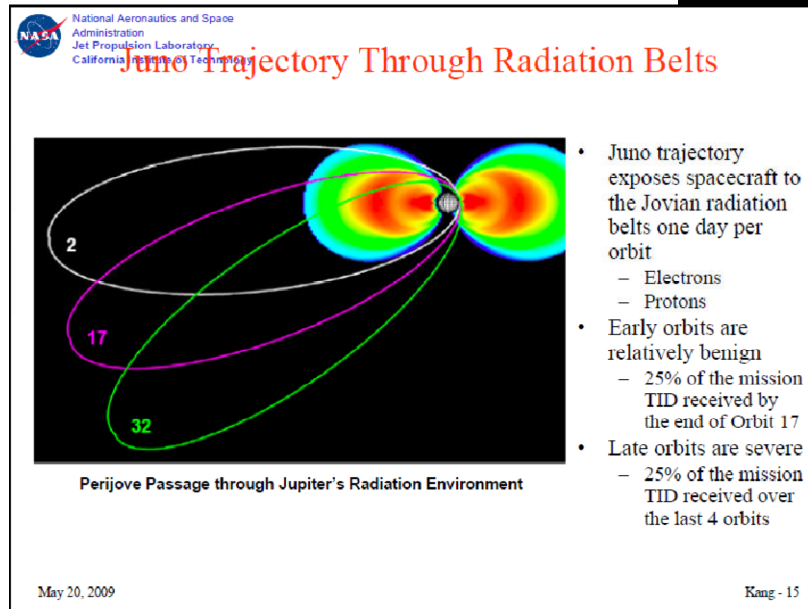
average soil composition (solid) and water ice (dashed)

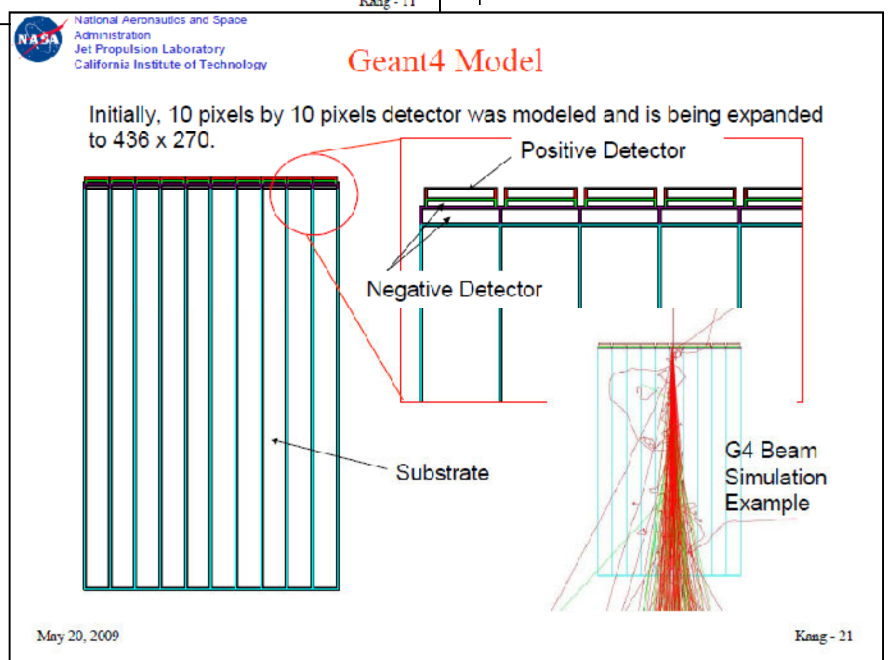




Jupiter - JUNO





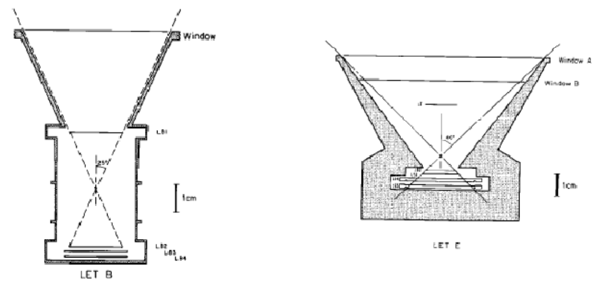


- Shawn Kang, Insoo Jun, JPL

Jupiter - Galileo

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Heavy Ion Counter (HIC)

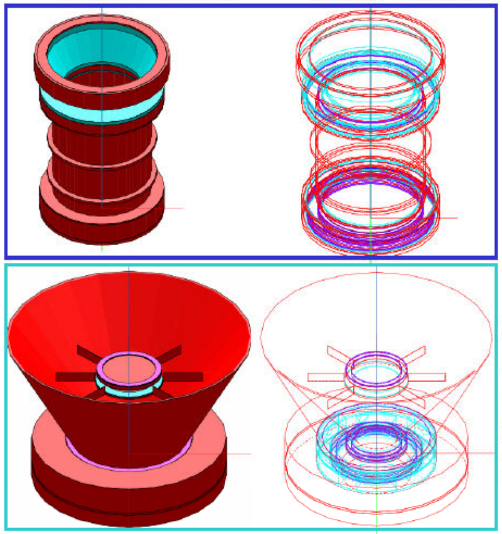


- Monitor the flux of heavy ions (C to Ni) to gather information on this form of radiation.
- Compliment the science observation made by other Galileo instruments.
- Improve and extend observation made by the Voyager and Pioneer mission.

May 20, 2009 Kang - 32

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Geant4 Model



LET-B

Four Detectors

LB1, LB2, LB3, and LB4

Logic example

LB1.LB2.LB3.!LB4

(Detected by LB1, LB2, LB3, but not by LB4)

LET-E

Five Detectors

LE1, LE2, LE3, and LE5

Logic example

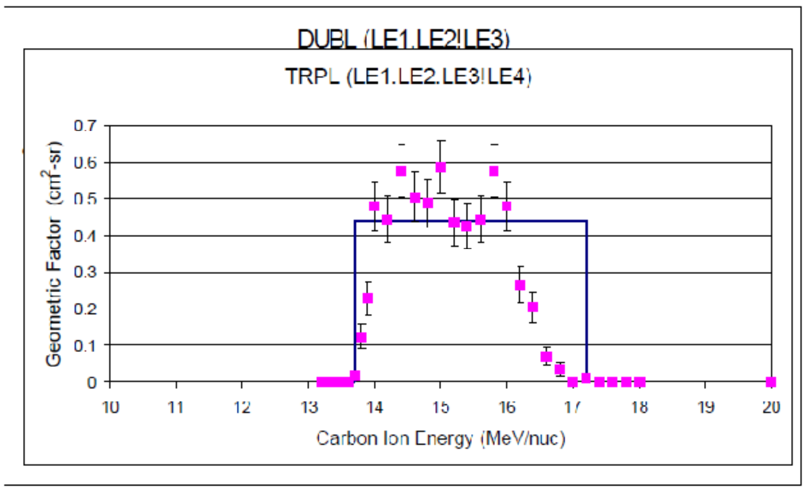
LE1.LE2.LE3

(Detected by LE1, LE2, but not by LE3, LE4, or LE5)

Kang - 35

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

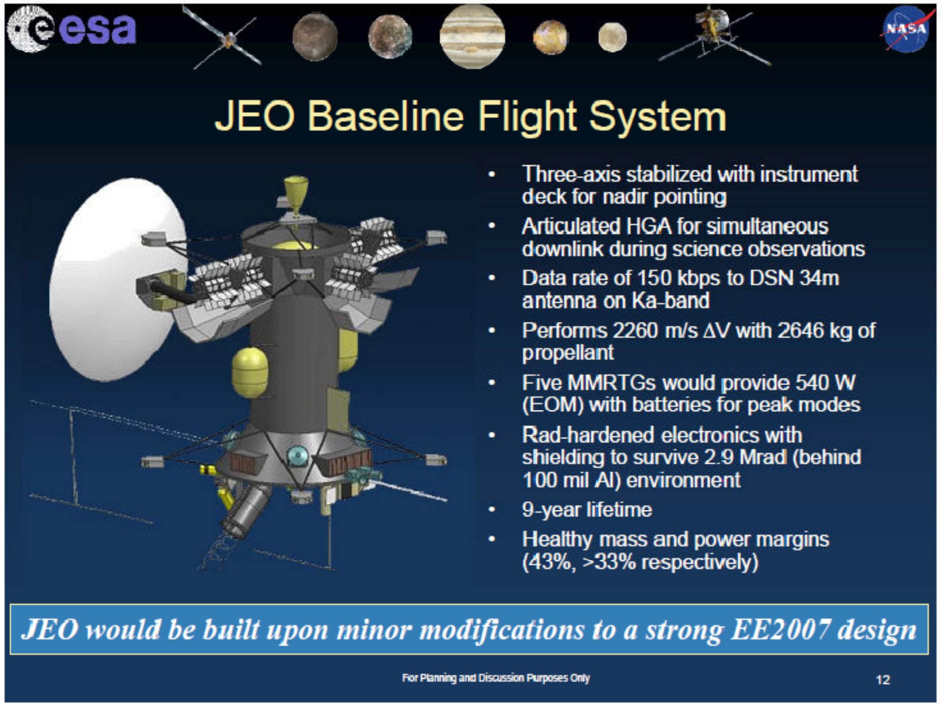
LET E: Carbon Ions – G4 Simulation Result for "DUBL" and "TRPL" cases (low energy cases)

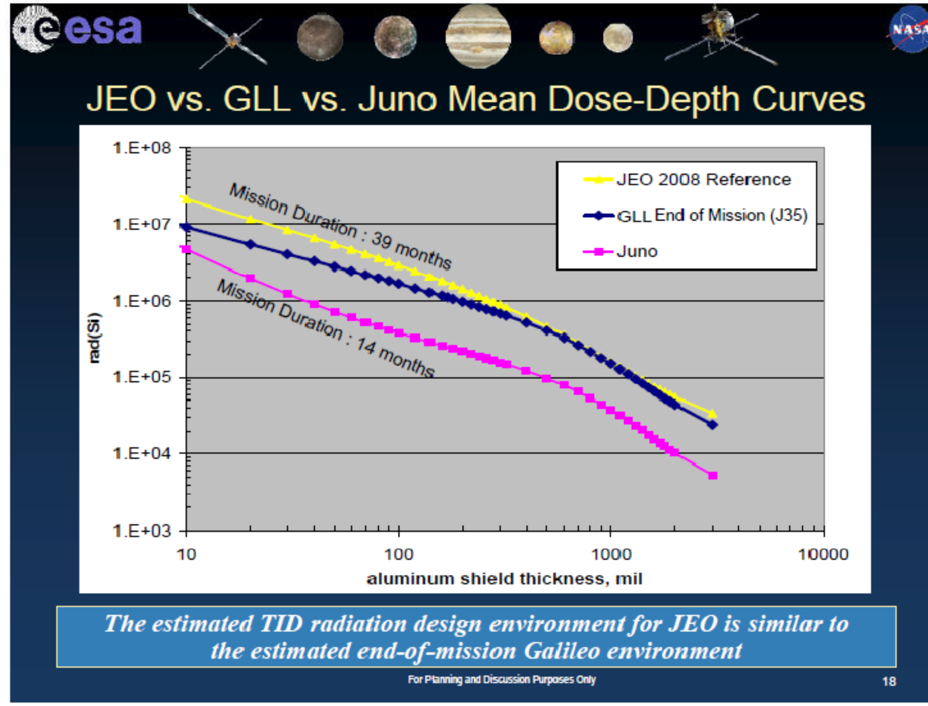


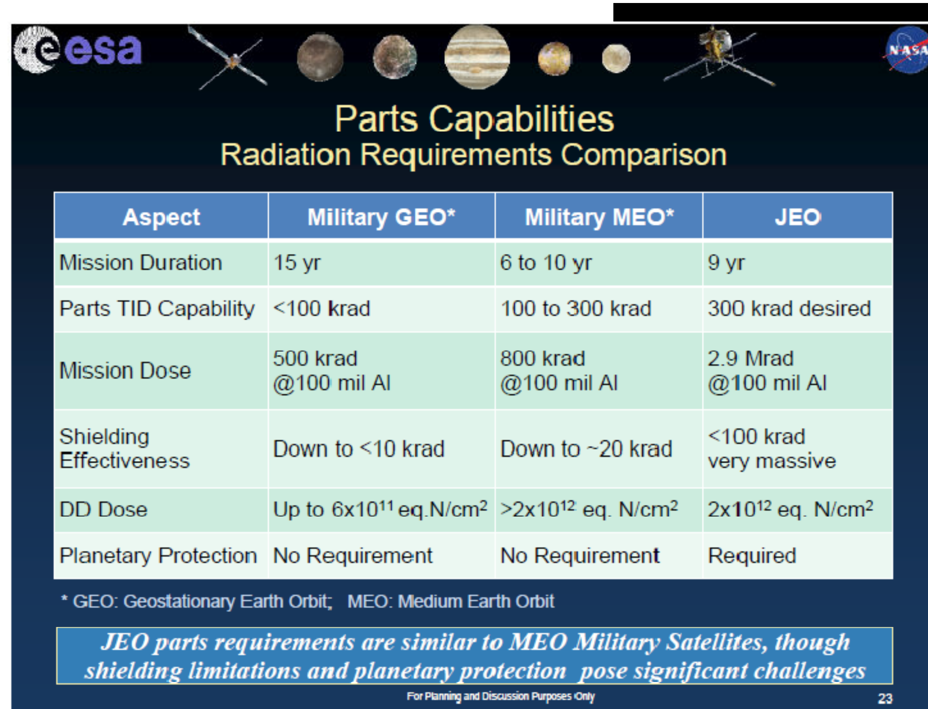
May 20, 2009 Kang - 39

- Shawn Kang, Insoo Jun, JPL

Jupiter - JEO







Aspect	Military GEO*	Military MEO*	JEO
Mission Duration	15 yr	6 to 10 yr	9 yr
Parts TID Capability	<100 krad	100 to 300 krad	300 krad desired
Mission Dose	500 krad @100 mil Al	800 krad @100 mil Al	2.9 Mrad @100 mil Al
Shielding Effectiveness	Down to <10 krad	Down to ~20 krad	<100 krad very massive
DD Dose	Up to $6x10^{11}$ eq.N/cm^2	>$2x10^{12}$ eq. N/cm^2	$2x10^{12}$ eq. N/cm^2
Planetary Protection	No Requirement	No Requirement	Required

- Insoo Jun, JPL
  Jupiter Europa Orbiter

JORE^{2}M^2

Jupiter Radiation Environment & Effect Models and Mitigations

- http://reat.space.qinetiq.com/jorem/

- Engineering tools for the prediction of the environment and effects/mitigation analysis
- Proton and electron flux-maps in B-L* space for the complete Jovian environment
- Development of models for the energetic ion environment (helium, carbon, oxygen and sulphur)

Of relevance here:

- Review of radiation effects analysis tools (not only Geant4-based)

- Implementation of updated version of PLANETOCOSMICS
  - trapped particle radiation incident upon the Galilean moons
  - including consideration of the Jovian and local fields.

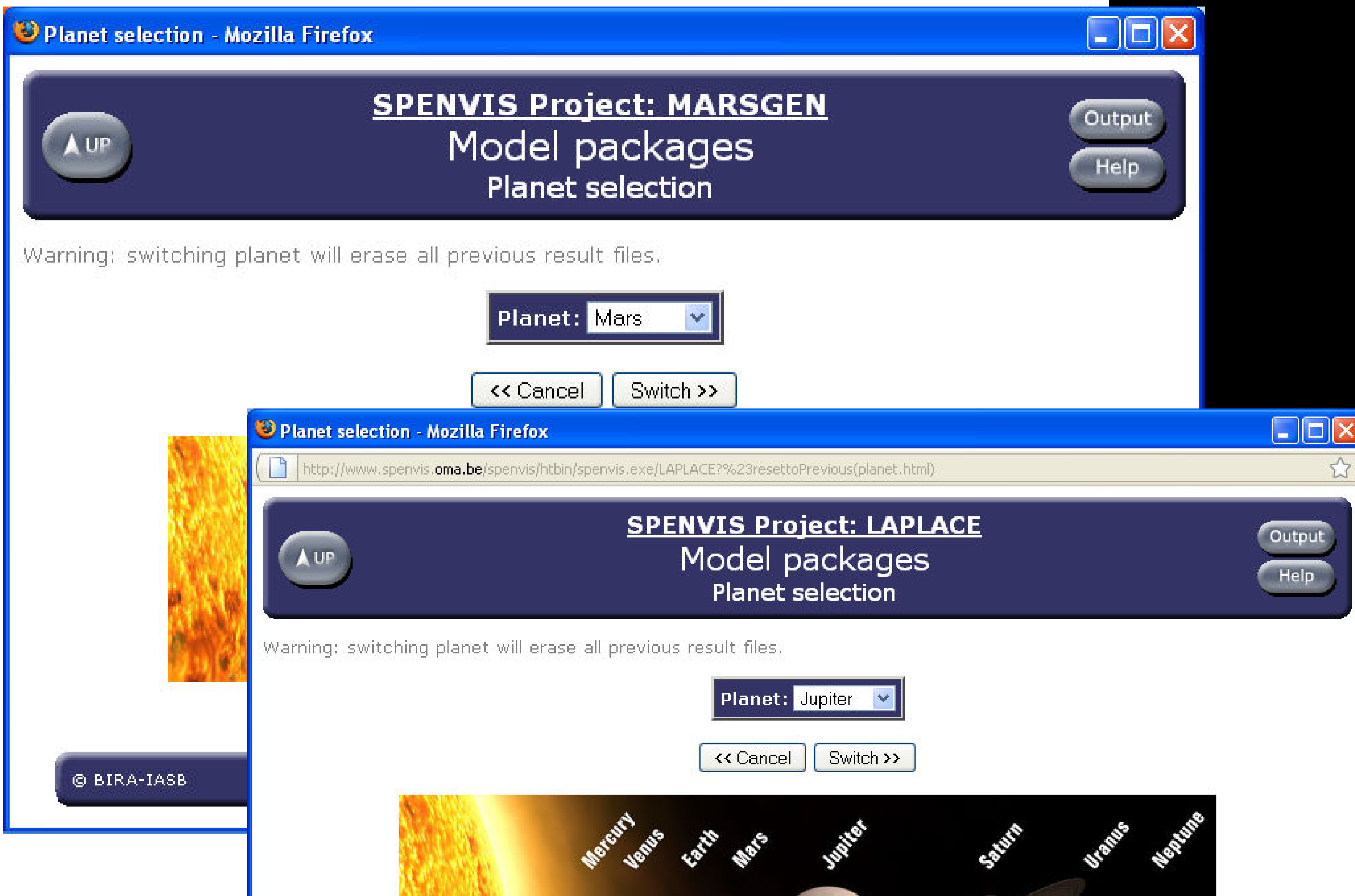
- New tool based on genetic algorithms and MULASSIS
  - optimisation of radiation shields in combined e^- and proton environment.

ESA contract

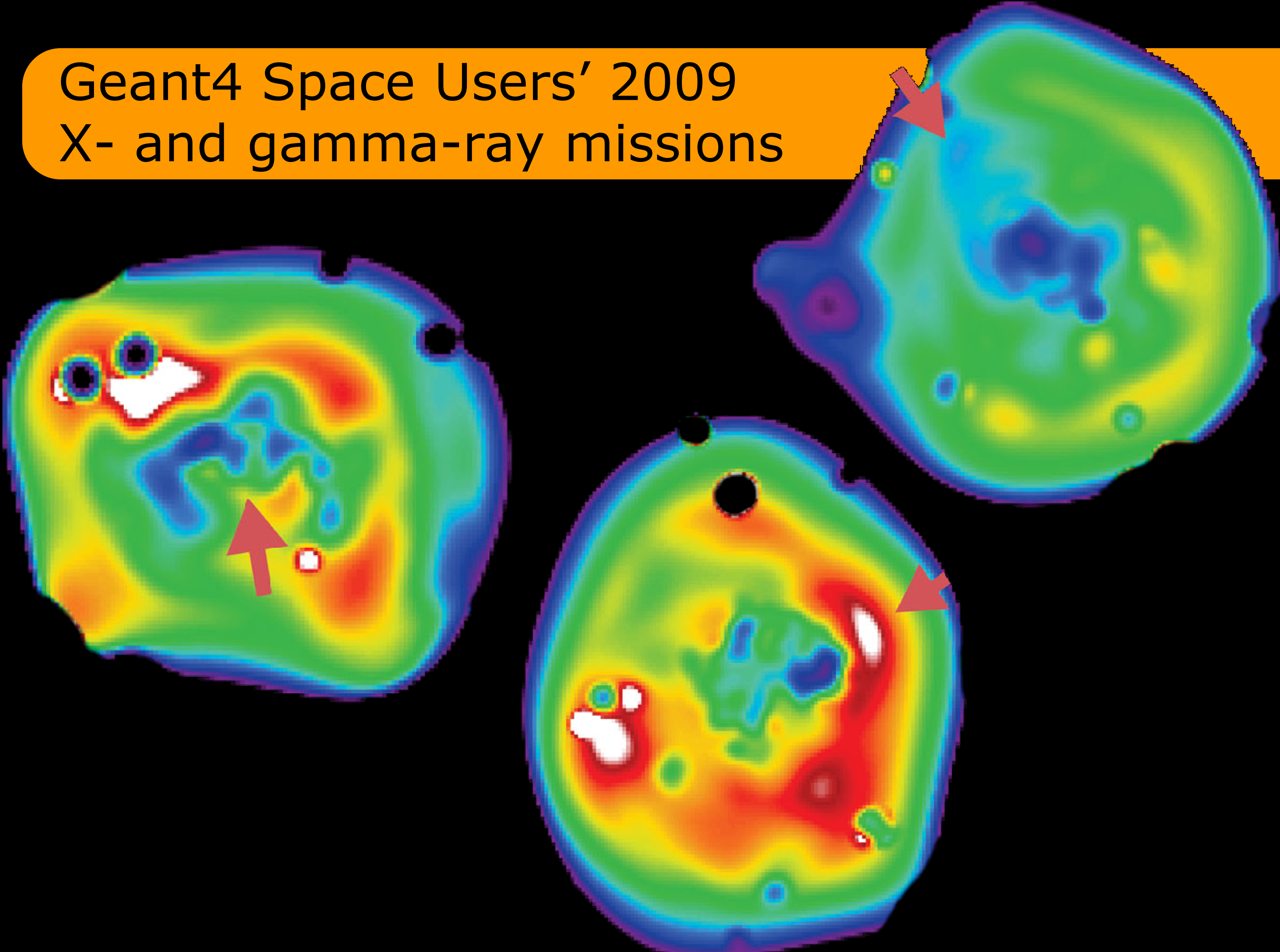
(QinetiQ, Onera, DHC)

SPENVIS: other planets

- Mars, Jupiter



Geant4 Space Users' 2009
X- and gamma-ray missions



Highlights from 2009 Space Users' workshop

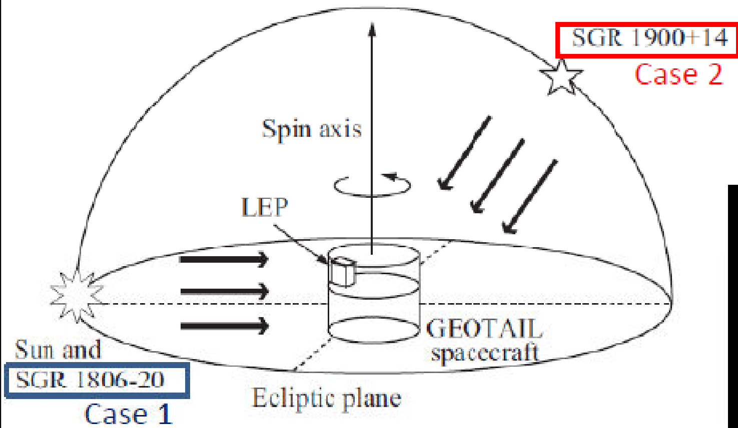
Geant4 in JAXA

Application to JAXA's Science Missions

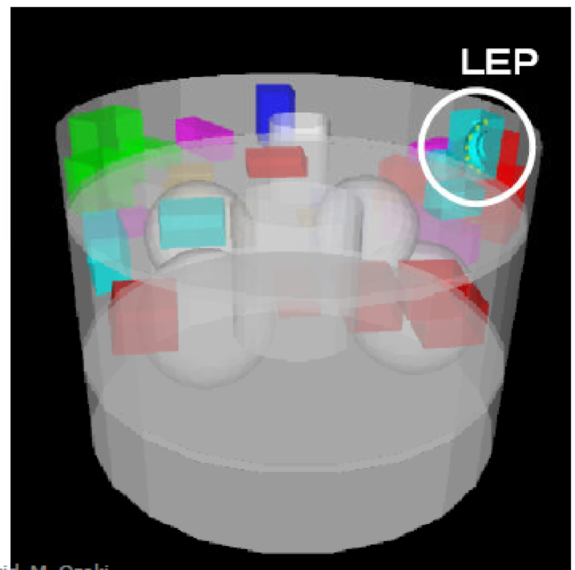
Masanobu Ozaki (ISAS/JAXA)

Geotail

Detection efficiency estimation by Geant4



Celestial gamma-rays can comes from any direction.



The lower energy range of MCP is dominated by the shielding effect of the spacecraft structure: this changes direction by direction.

Ph.D. thesis by Y. Tanaka (University of Tokyo, 2009)

Geant4 in JAXA

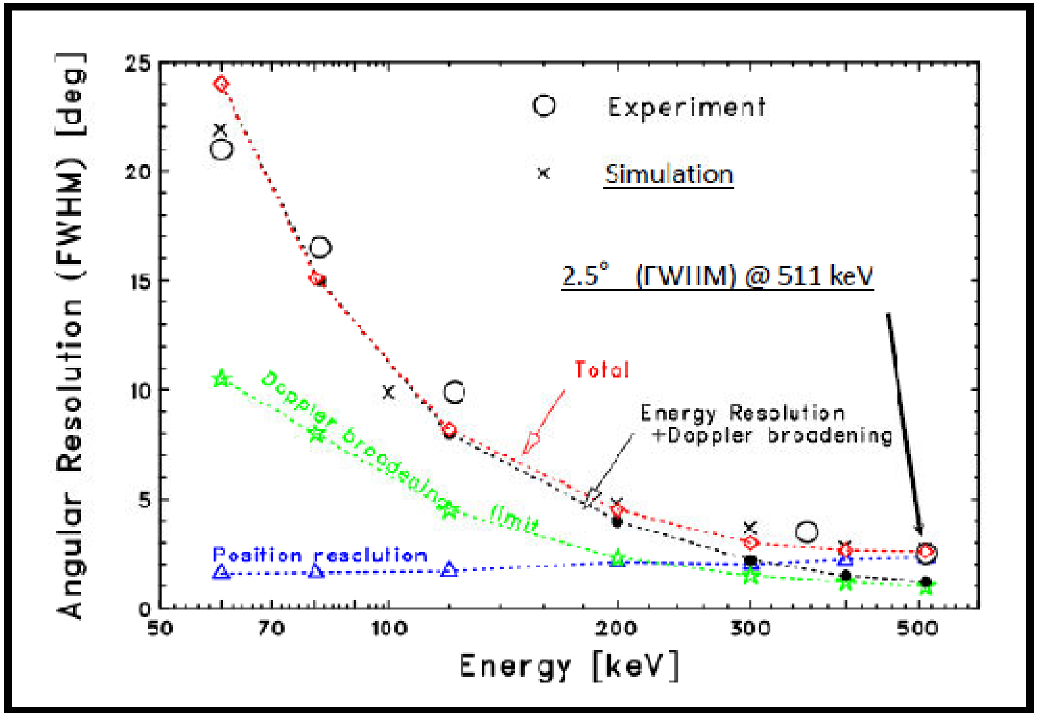
Application to JAXA's Science Missions

Masanobu Ozaki (ISAS/JAXA)

Gamma ray astronomy

Ph.D. thesis by S. Takeda (University of Tokyo, 2009)

Geant4 simulation: angular resolution



The energy dependency of the angular resolution is represented well.

- Position resolution, energy resolution and Doppler broadening are taken into account

Highlights from 2009 Space Users' workshop

Geant4 in JAXA

Application to JAXA's Science Missions

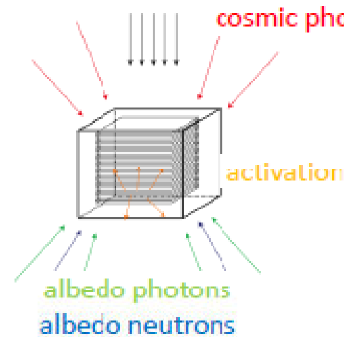
Masanobu Ozaki (ISAS/JAXA)

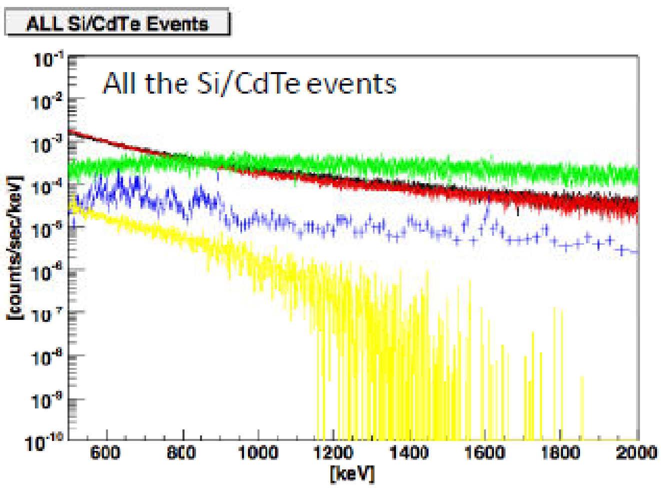
Gamma-ray astronomy

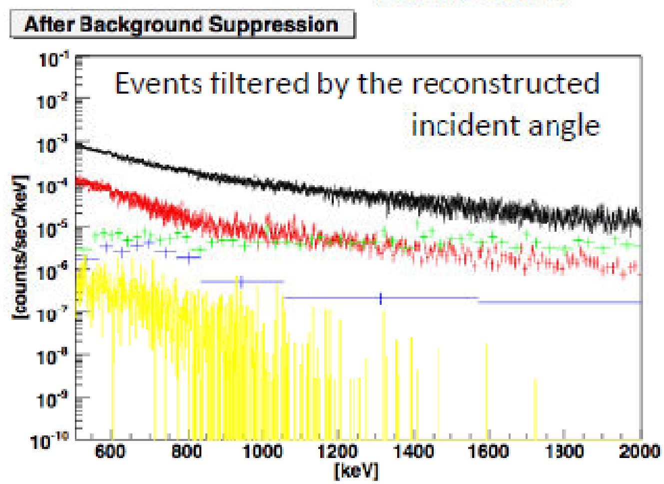
Ph.D. thesis by S. Takeda (University of Tokyo, 2009)

Geant4 simulation: on-orbit BGDs

- BGD src: albedo neutrons, albedo photons, cosmic photons and activation by cosmic protons
- LEO (low activation by cosmic protons)



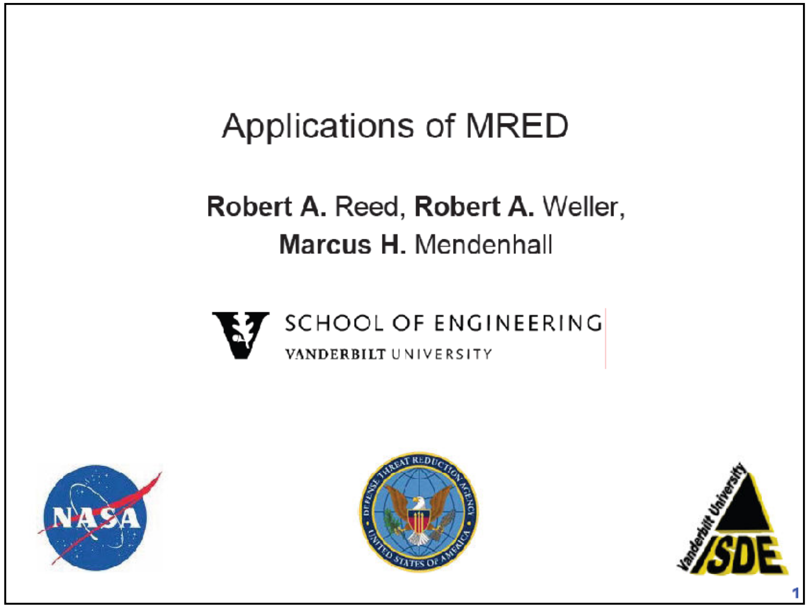


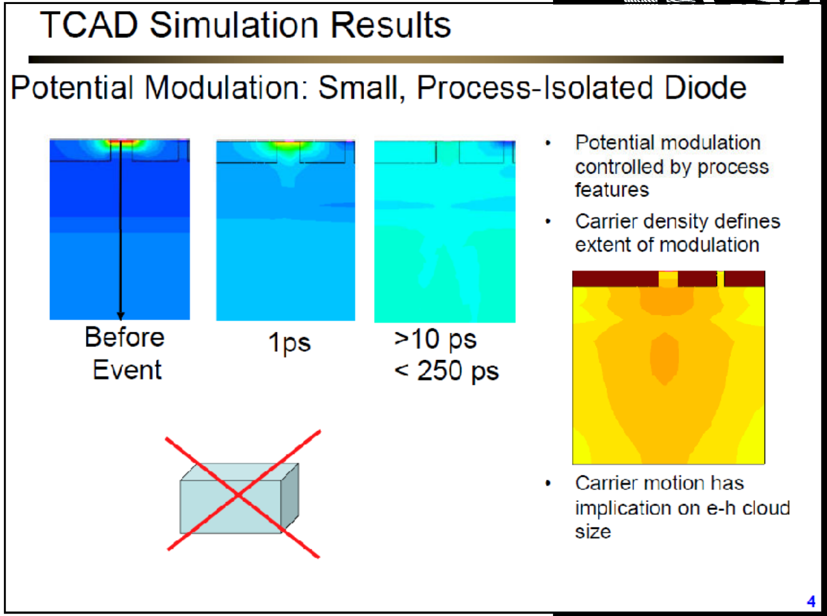


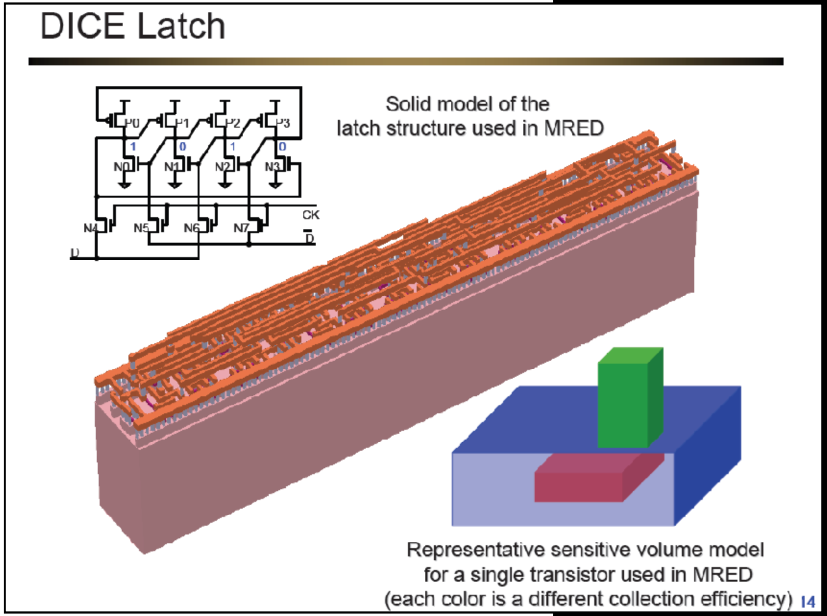
BGD rejection is crucial for high sensitivity

Geant4 Space Users' 2009
Single Event Effects

MRED







- Robert Reed, Vanderbilt University
- Geant4 integration with TCAD and SPICE

SEE basic mechanisms

Geant4 Space Users Workshop, 2009

Fundamental Aspects of Radiation Event Generation for Simulation of Space Electronics

R. A. Weller[1], M. H. Mendenhall[1], R. A. Reed[1], M. A. Clemens[1], N. A. Dodds[1], B. D. Sierawski[1], K. M. Warren[1], R. D. Schrimpf[1], L. W. Massengill[1], T. Koi[2], D. Wright[2], and M. Asai[2]

[1]Institute for Space & Defense Electronics, Vanderbilt University
[2]Stanford Linear Accelerator Laboratory, Stanford University
USA

Acknowledgements:
- DTRA 6.1: HDTRA1-08-1-0034 and HDTRA1-08-1-0033
- DTRA 6.2: Radiation Hardened Microelectronics Program
- NASA GSFC: NASA Electronic Parts and Packaging (NEPP) Program
- NASA MSFC: Radiation Hardened Electronics for Space Exploration (RHESE) Program

General SEU Rate Prediction

The general rate expression:

$$R = -\sum_z \int_{All\,E} dE \int_{\hat{n}\cdot\hat{e}<0} d\Omega \oint d\vec{A}\cdot\vec{\Phi}(z,E,\hat{e},\vec{x}) \times P_u(z,E,\hat{e},\vec{x})$$

Definitions: $p_c(l) = \frac{1}{\pi A}\int d^2x \int d\Omega(-\hat{e}\cdot\hat{n}(\vec{x}))UnitStep(-\hat{e}\cdot\hat{n}(\vec{x}))\delta(l-h(\hat{e},\vec{x}))$

Assumptions:

$$\vec{\Phi}(z,E,\hat{e},\vec{x}) = \Phi(z,E)\hat{e}$$

$$F(s) = \sum_z \sum_i \frac{\Phi(z,E_i)}{\left|\left(\frac{dS(z,E)}{dE}\right)_{E=E_i}\right|}, \quad s = S(z,E_i)$$

$$P_u(z,E,\hat{e},\vec{x}) = \int P_d(z,E,\hat{e},\vec{x},E_d) \times P_u(E_d)dE_d$$

$$P_d(z,E,\hat{e},\vec{x},E_d) = \delta(E_d - h(\hat{e},\vec{x})\cdot S(z,E))$$

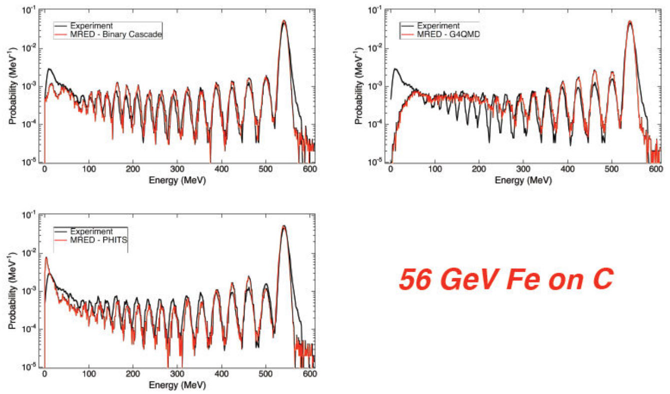
$$P_c(l) = \int_l^\infty p_c(x)\,dx$$

$$P_u(E_d) = UnitStep(E_d - E_c)$$

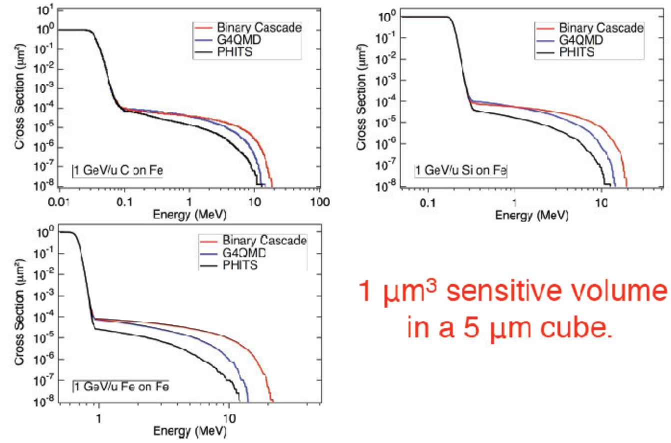
Math!

$$R(E_c) = \pi A \int_{s_{min}}^{s_{max}} F(s)\cdot P_c\left(\frac{E_c}{s}\right)ds$$

LET Spectra Comparison



Energy Deposition in an Fe Cube



1 μm³ sensitive volume in a 5 μm cube.

- later expanded for RADECS 2009 short course
- Bob Weller, Vanderbilt University

Geant4 Space Users' 2009
Uncertainties in standard practice and margins

VALCOMPT

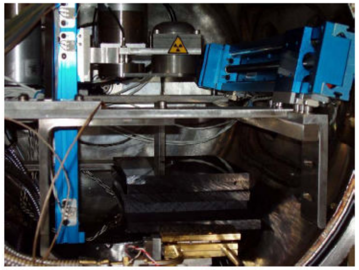
Comparison and Validation of 3D Shielding Analysis Tools for Space Applications

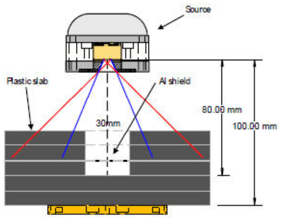
Fan Lei, Pete Truscott
Aerospace Division, QinetiQ

Giovanni Santin and Petteri Nieminen
ESTEC,ESA

Geant4 Space User Workshop
Madrid, 21/05/2009

REEF Experiment Setup





RADFET: REM TOT600 type from REM Oxford Ltd.

TLDs: Harshaw EXTRAD type

3D Geometries & Detector locations

Shell/wall thickness: (mm)	0.1, 0.5, 1, 5, 10, 20
Overall dimensions :	
Spherical shell:	1m (∅)
Box:	1m x 1m x 0.5m
Cylindrical shell:	1m (∅) x 0.5m

The details of the geometry model used in the study.

Det.No.	1	2	3	4	5
X-pos (mm)	0	100	200	300	400
Distance to nearest surface	500	400	300	200	100

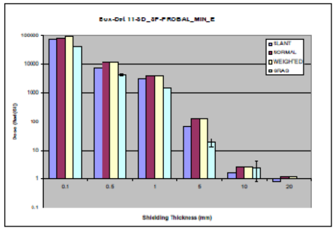
The detector locations in spherical shell geometries.

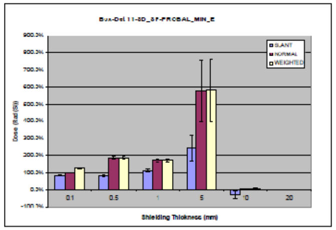
Det. No.	1	2	3	4	5	6	7	8	9	10	11
X-pos (mm)	0	100	200	300	400	0	0	100	200	300	400
Z-pos (mm)	0	0	0	0	0	100	200	200	200	200	200
Distance to nearest surface	250	250	250	200	100	150	50	50	50	50	50

The detector locations in box and cylindrical shell geometries.

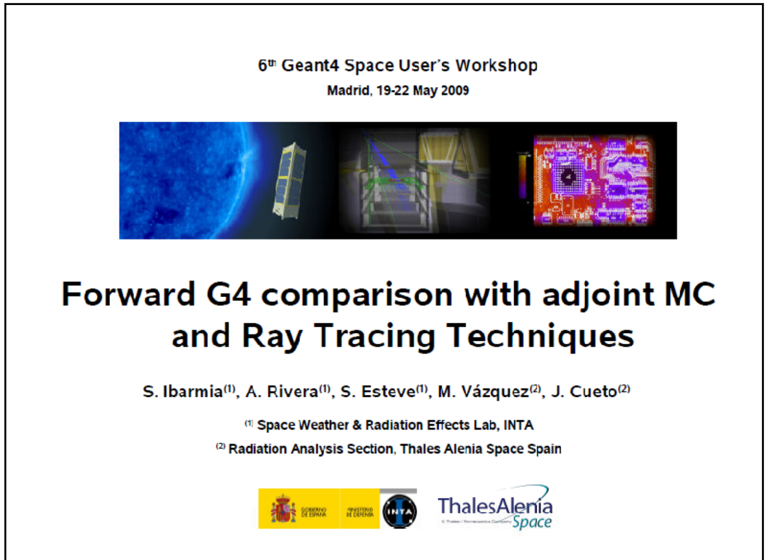
Created in GDML format, used by both the SSAT and GRAS tools

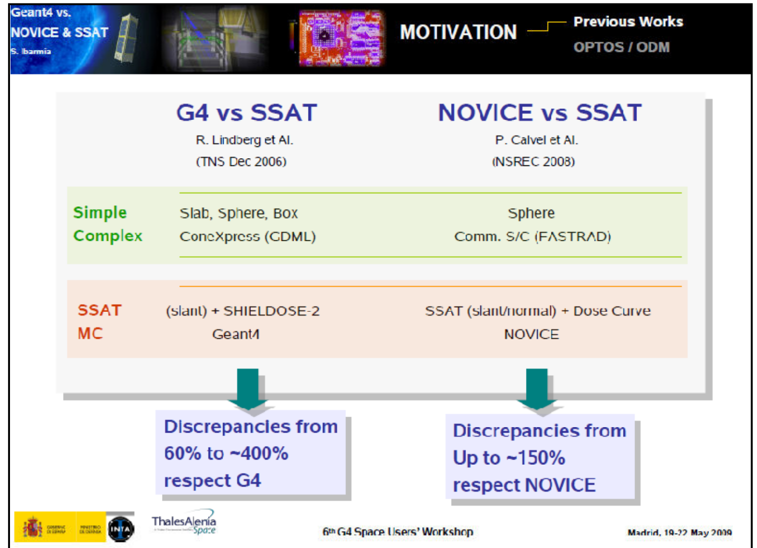
Results -2

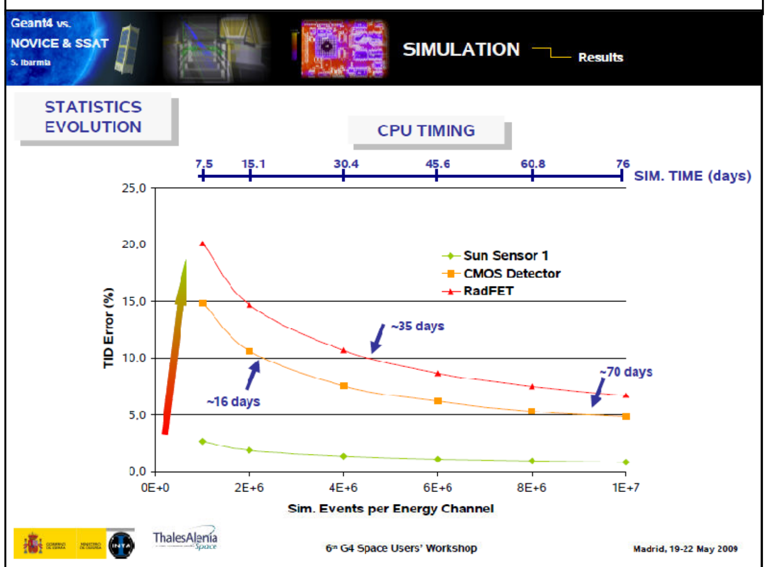


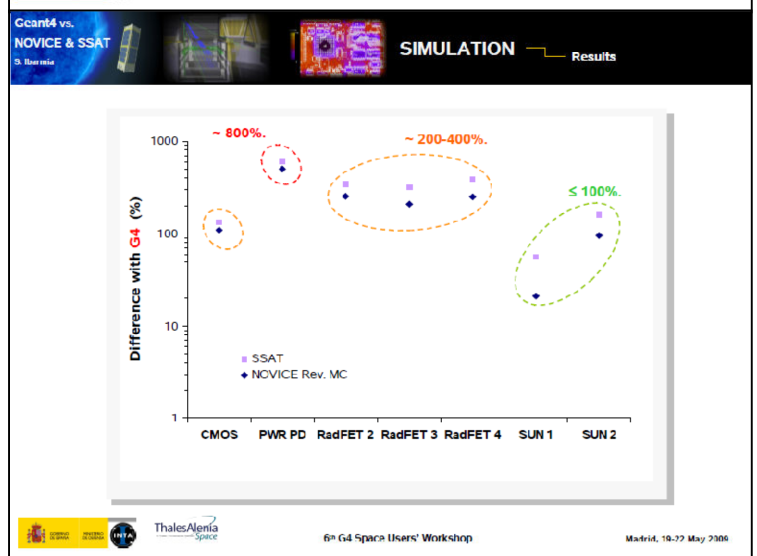


Geant4 VS NOVICE adjoint and ray-tracing







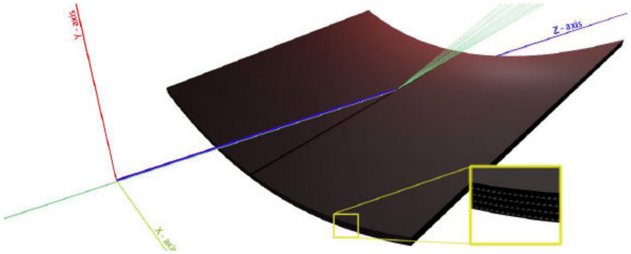


Other published work

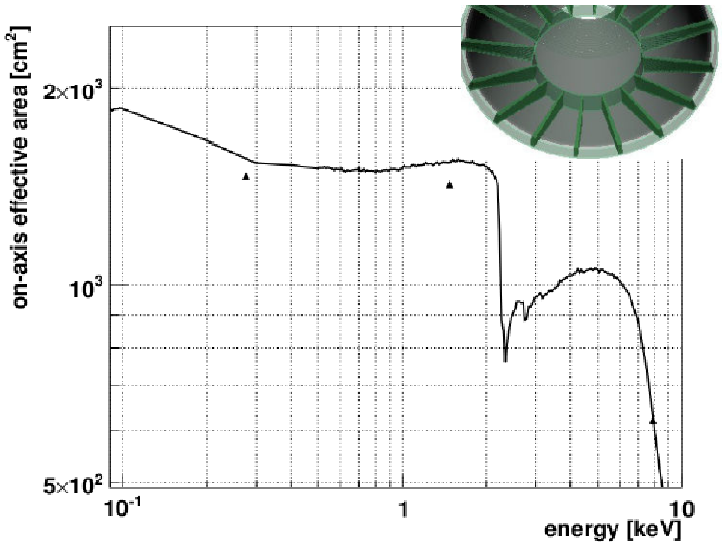
A generic X-ray tracing toolbox in Geant4

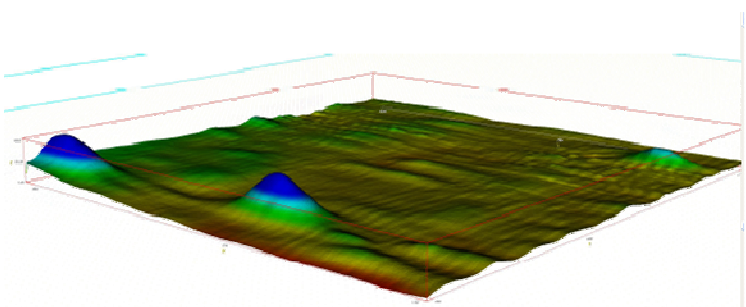
Giuseppe Vacanti, Ernst-Jan Buis, Maximilien Collon, Marco Beijersbergen, Chris Kelly
cosine, Niels Bohrweg 11, 2333 CA, Leiden, The Netherlands

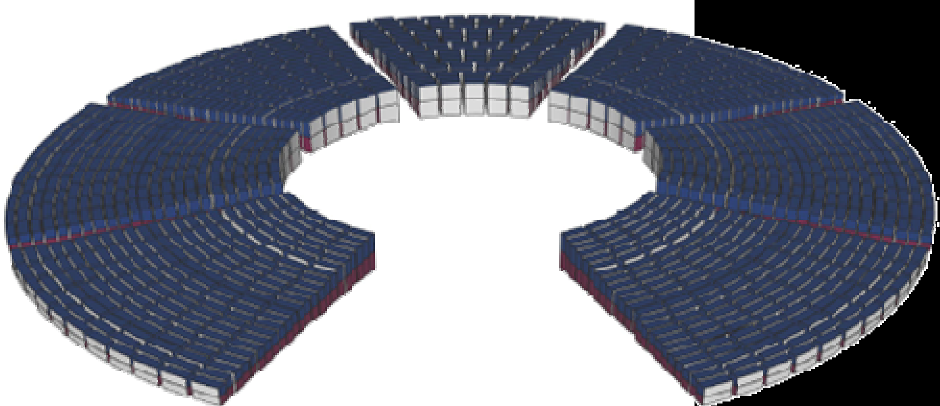
Proc. of SPIE Vol. 7360 736002-1



- **New X-ray reflection process: G4XrayGrazingAngleScattering**
- **Validation with simplified XMM**
  - **Simulated effective area within 5% of measured one**
- **Metrology model input**
- **Applied to IXO mirror design**
- **Developments offered to the Geant4 collaboration**





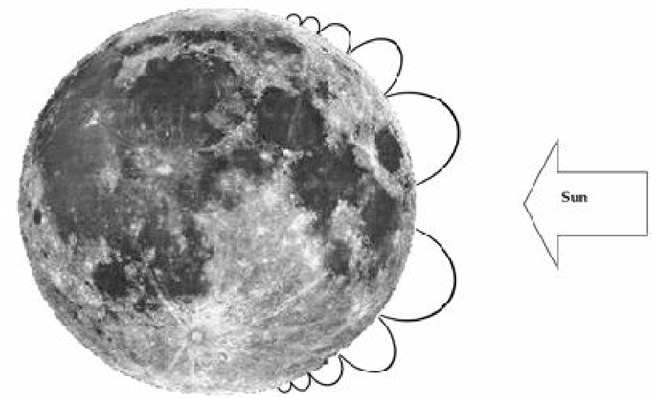


Selected publications

http://geant4.esa.int

High Energy X-ray Spectrometer on Chandrayaan-1

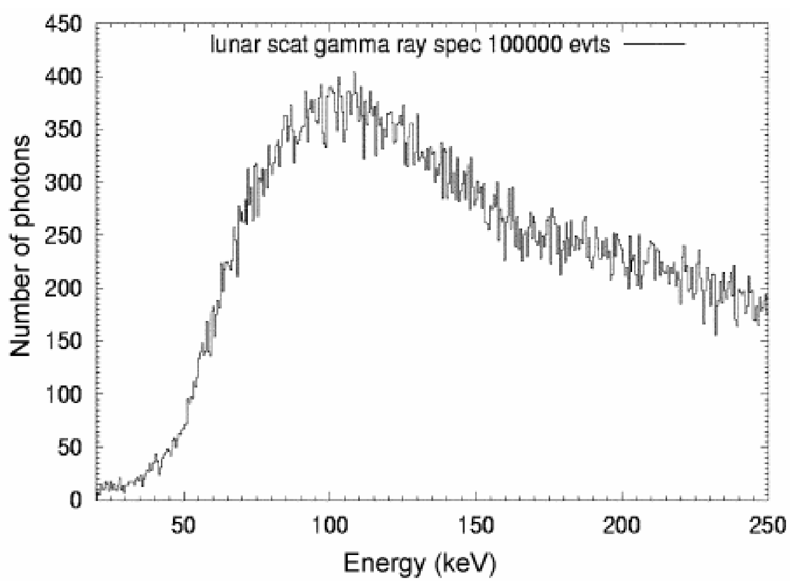
P. Sreekumar[1,*], Y. B. Acharya[2], C. N. Umapathy[1], M. Ramakrishna Sharma[1], Shanmugam[2], A. Tyagi[1], Kumar[1], S. Vadawale[2], M. Sudhakar[1], L. Abraham[1], R. Kulkani[1], S. Purohit[2], R. L. Premlatha[1], D. Banerjee[2], M. Bug[1] and J. N. Goswami[2]
[1]ISRO Satellite Centre, Bangalore 560 017, India
[2]Physical Research Laboratory, Ahmedabad 380 009, India



Selected publications

http://geant4.esa.int

- India's first planetary exploration lunar mission
- High Energy X-ray spectrometer (HEX)
  30–270 keV natural gamma rays from surface
- Transport of volatiles on the lunar surface
  - Detected from 46.5 keV line ^{210}Pb decay (from volatile ^{222}Rn)



- Geant4: continuum from GCR interaction in regolith
- High energy tail attenuated by Compton in soil
- Rejection of partial energy deposit events (Compton) by CsI(Tl) anticoincidence

Gamma-ray detector on board lunar mission Chang'e-1

J. Chang[1]*†, T. Ma[1], N. Zhang[1], M.S. Cai[1], Y.Z. Gong[1], H.S. Tang[1], R.J. Zhang[1], N.S. Wang[1], M. Yu[1], J.P. Mao[1], Y.L. Zhou[2], J.Z. Liu[2], A.A. Xu[3] and L.G. Liu[3]

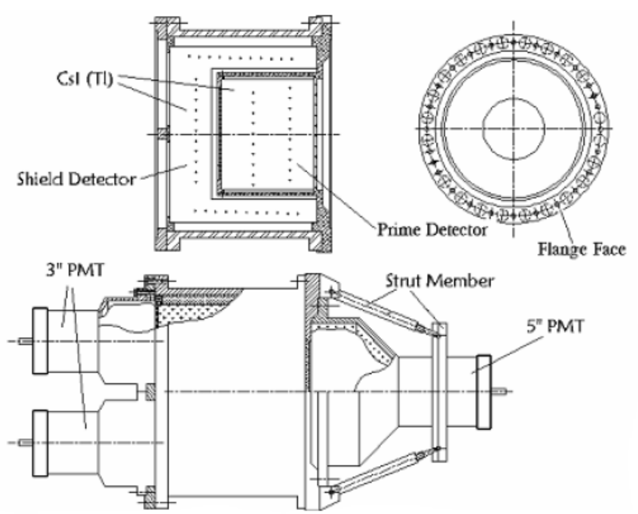
[1] *Purple Mountain Observatory, 2 West Beijing Road, Nanjing 210008, China*
[2] *National Astronomical Observatory, 20A Datun Road, Beijing 100012, China*
[3] *MACAU University of Science and Technology, Avenida Wai Long, Taipa, Macau, China*

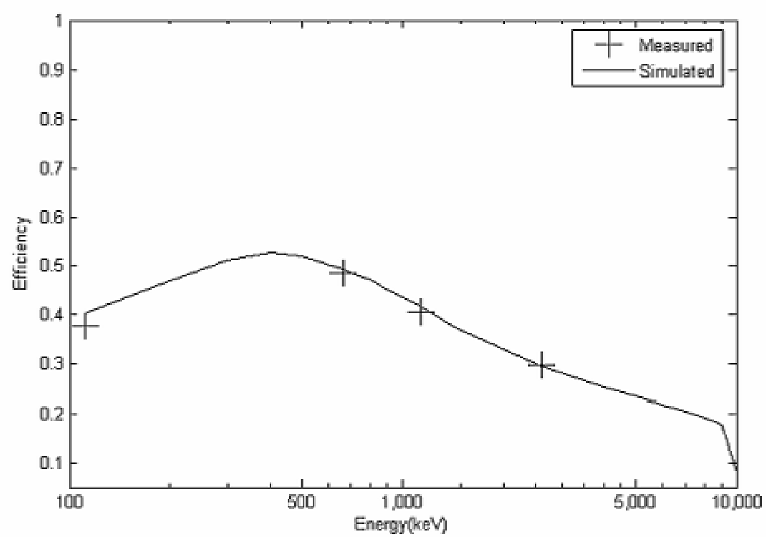
- First Chinese lunar mission
  Launched in 24th October 2007

GRS instrument

- Study of chemical element distribution on the Moon surface

- Experimental calibration
  - Gamma-ray sources
  - Geant4 validation



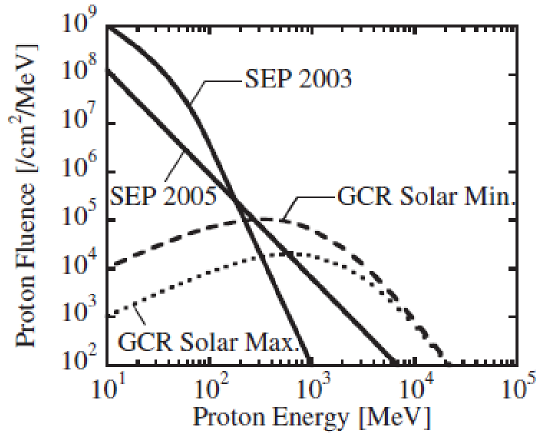


HZE Particle and Neutron Dosages from Cosmic Rays on the Lunar Surface

Kanako HAYATSU*, Makoto HAREYAMA, Shingo KOBAYASHI, Naoyuki YAMASHITA, Kunitomo SAKURAI and Nobuyuki HASEBE

Research Institute for Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku, Tokyo 169-8555, Japan

Proc. Int. Workshop Advances in Cosmic Ray Science
J. Phys. Soc. Jpn. **78** (2009) Suppl. A, pp. 149-152



Selected publications

http://geant4.esa.int

- Ambient dose equivalent at Moon surface
- Galactic Cosmic Rays
  - Secondary neutrons / gammas
- SEP protons and ions

- Shielding effectiveness

	Al shield thickness [g/cm²]	$H^*(10)_{SEP}$ [mSv] H	He	O
SEP 2003/10/28	0.0	2045.7	113.0	30.8
	1.0	1178.4	53.4	2.5
	2.0	663.7	24.4	0.0
	5.0	287.4	7.0	0.0
	10.0	3.3	0.0	0.0
SEP 2005/1/20	0.0	216.7	16.8	11.0
	1.0	155.1	12.0	5.0
	2.0	113.6	8.7	0.2
	5.0	82.4	6.3	0.3
	10.0	10.2	0.8	0.1
GCR Solar Min.	0.0	39.6	17.5	110.0
	1.0	39.7	17.5	121.2
	2.0	39.7	17.4	31.4
	5.0	41.0	18.2	37.5
	10.0	32.0	11.8	22.0

	$H^*(10)$ [mSv/yr] for GCRs				$H^*(10)$ [mSv] for SEPs	
	highland region			mare region	highland region	
	Solar Min.	Solar Avg.	Solar Max.	Solar Avg.	2003	2005
Primary	758.5	519.8	265.8	519.8	2189.5	246.4
Neutron	72.9	51.9	25.4	56.3	5.9	–
Gamma Ray	3.3	2.5	1.6	2.5	0.9	–
Total	834.7	574.2	292.8	578.6	2196.3	246.4

More papers…

- Simulation of ALTEA calibration data with PHITS, FLUKA and GEANT4
  NIM B, in press
  C. La Tessa et al.

- Instrument Simulation for the Analysis of Cosmic Ray Electron with the FERMI LAT
  Proc. of the 31st ICRC, Lódz
  C. Sgrò et al.

- …

Enabling developments for space applications

SEENoTC

Space Environment and Effects Network of Technical Competencies

- Goal

  “reinforce the coordination of existing and planned space environments and effects related activities in Europe, through the implementation of a coherent European programme of activities in the domain.”

- Roadmap on radiation analysis tools includes
  - Coordination in the development of tools for radiation effects analysis, supporting the development of infrastructure to support real-time analysis and/or forecast and ultimately ensuring that users have access to well documented and validated tools

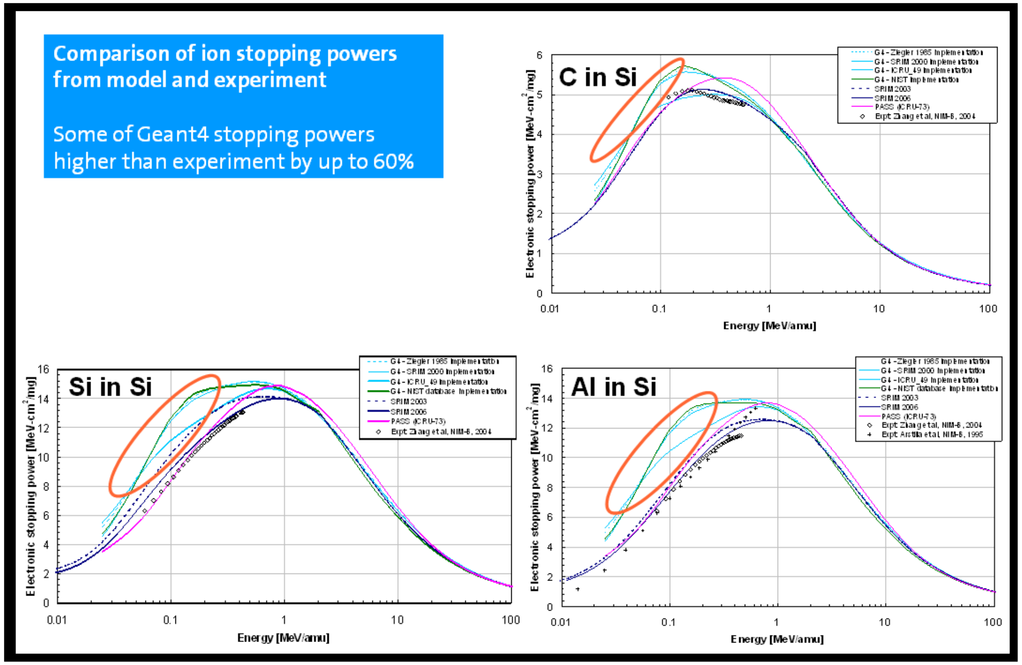
- Usability, accuracy, speed are high priority requirements

Accuracy: Low energy ion stopping power – range

- Impact e.g. on
  - SEE ground testing of EEE components
  - Recoil ion contribution to SEE prediction

- Geant4 review (April 2007)
  - “Recommendation 2: We recommend rapid integration of the ICRU 73 heavy ion stopping power model”

- Ion physics simulation requirements (Pete Truscott, QinetiQ)
  - Performance of available Geant4 models
  - Overview of other models / data
  - Significant differences



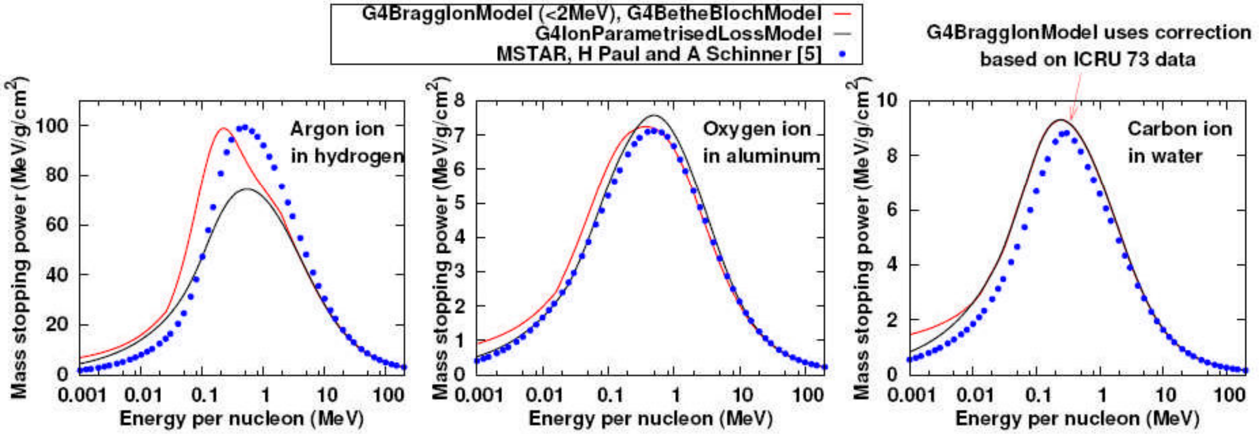
ESA contract:

RRMC

(QinetiQ, SpaceIT, TRAD)

ICRU-73 implementation

- ICRU-73 tabulated stopping powers (PASS code results)
  - 16 incident ions 2 < Z < 19, plus Iron Z=26
  - Simple and composite materials of interest for space applications
- New Geant4 “models” (V. Ivantchenko, A. Lechner)
  - Beta version released within Geant4 release 9.2
  - Poster at IEEE NSS 2008
- First comparisons



- New models also available as option in GRAS physics list
- Future areas for improvement identified
  - Straggling models
  - Effective charge approach
  - Delta ray production at low energies
- Requirements include projectiles and materials not included in ICRU-73 publication
  - Collaboration started with Peter Sigmund (author of PASS code)

esa

ESA contract:

RRMC.

Enabling technologies: Reverse MC

- Implemented Reverse Processes:
  - Ionisation for e^-, protons, ions (with delta-ray production, continuous energy loss and multiple scattering)
  - e^- Bremsstrahlung
  - Gamma: Compton scattering, Photo-electric effect

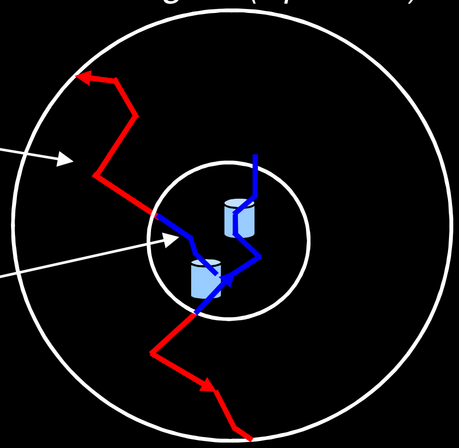
Requirement from space industry

- Tallying in sub-micron SV inside macroscopic geometries

Simulation approach:

- Reverse tracking from the boundary of the sensitive region to the external source
  Based on "adjoint" transport equations
- Forward tracking trough the SV to compute the detector signal
  Same code than in a forward MC simulation

Laurent Desorgher (Space IT)



Computing time focused on tracks that contribute to the detector signal

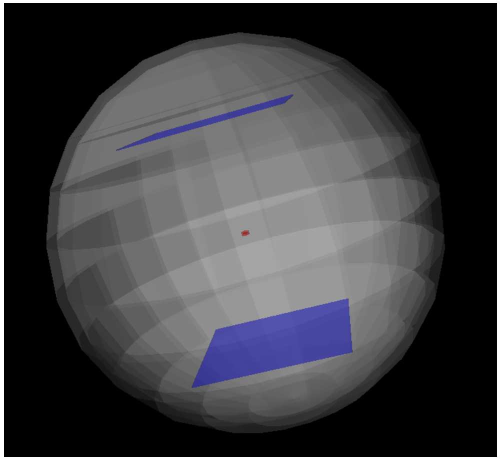
- Capability added to GRAS

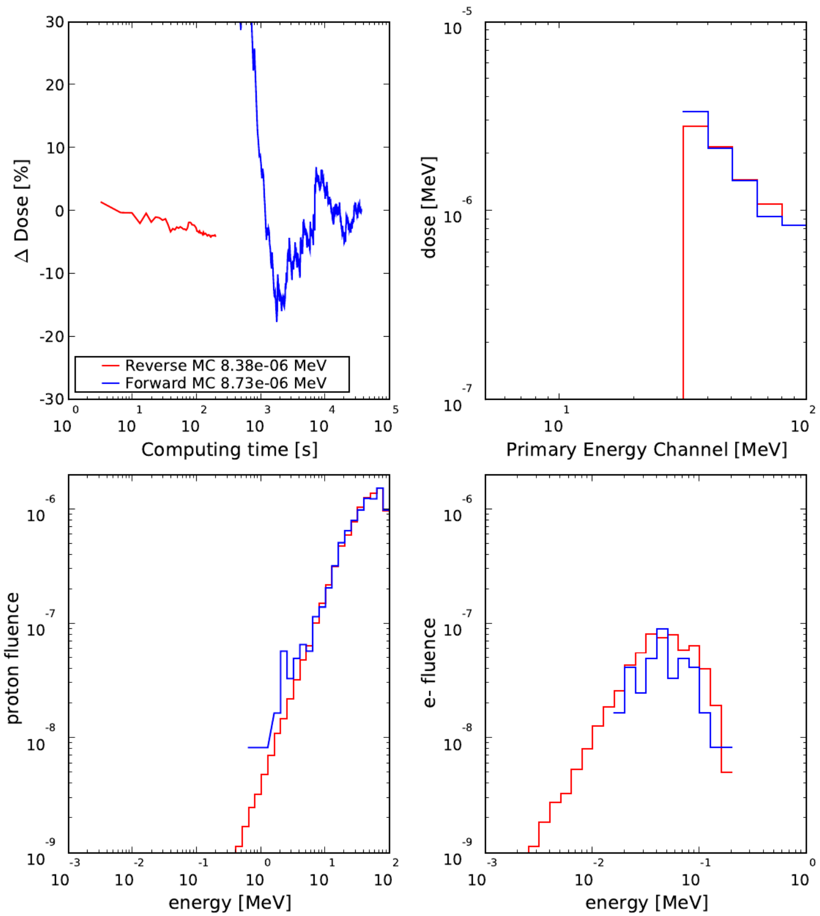
ESA REAT-MS and RRMC contracts

Partly already included in Geant4 9.2

Reverse MC: comparison VS forward Protons, simple geometry

Laurent Desorgher (Space IT)





- Difference in total computed dose <~5%
- Reverse MC method is for this case 100-500 times more rapid than the forward MC method
- Realistic space component dosimetry involve sub-micron SV in ~1m spacecraft

Enabling technologies: CAD geometry interface
(and 3D modelling GUI)

- CAD (ESA REAT-MS)
  - Using G4TessellatedSolid by P.Truscott

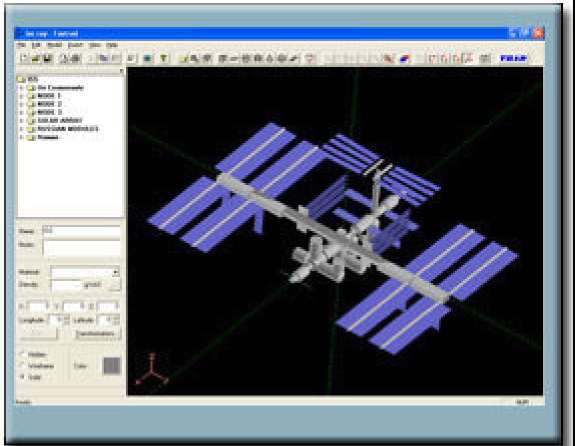
    [Old prototype used to require ST-Viewer commercial S/W
    - GDML module to read ST-Viewer files]

  - New: CAD STEP interface (and normal 3D models) via external 3D modelling tools tools (ESA contract REAT-MS-2)
    Direct GDML output
- STEP for Space Environment standard (STEP-SPE)
- GDML upgrade (CERN)
  - Tetrahedron and Tessellated volumes, modular models, loops
- FASTRAD, ESABASE2
  - GUI for 3D modelling
  - GDML output
  - Licensing policy under discussion

esa

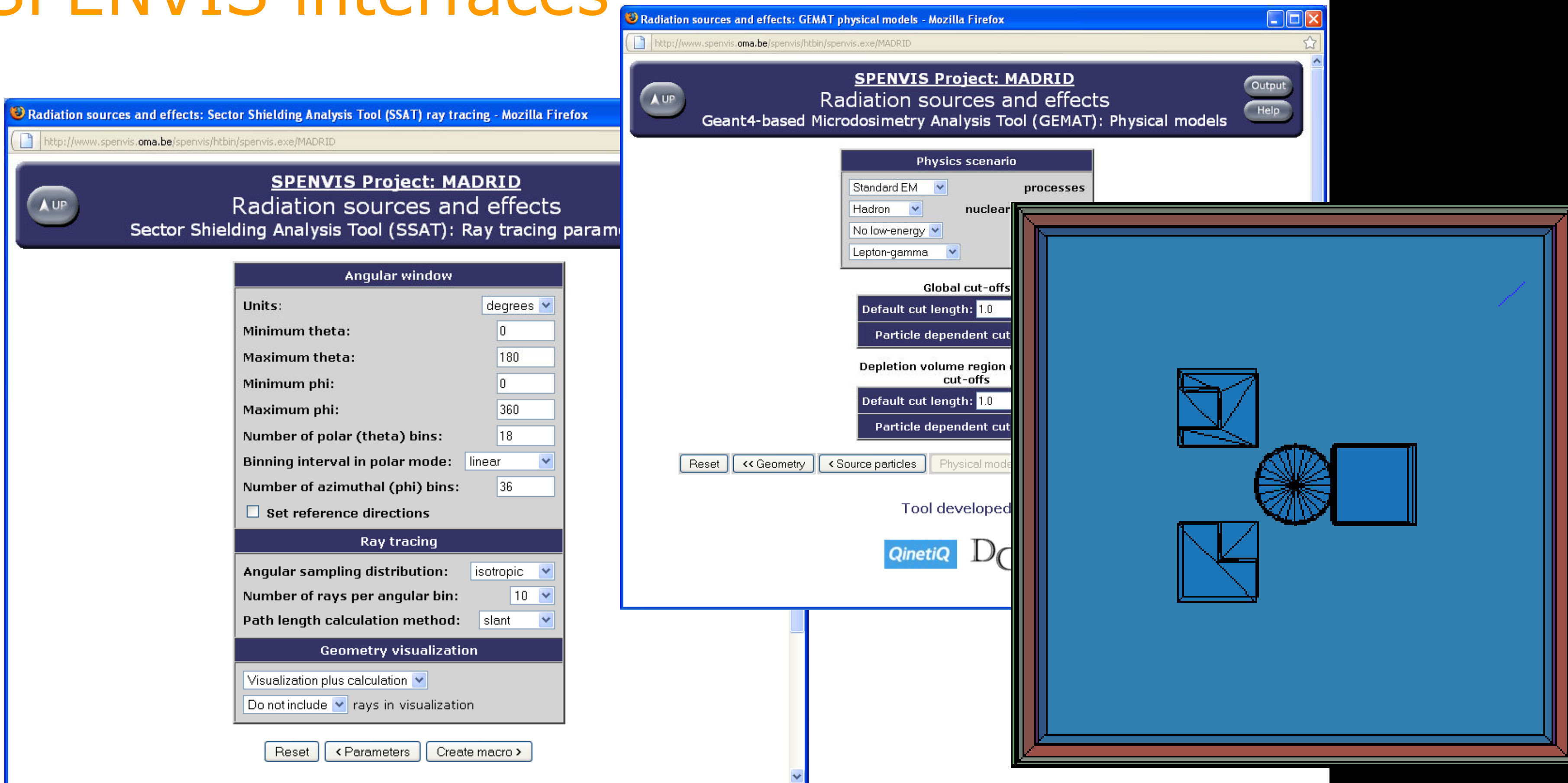
ESA contract:

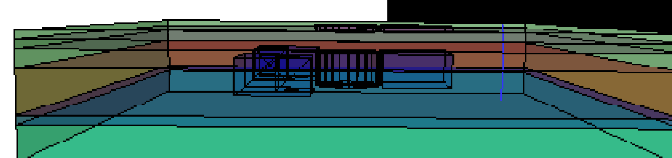
REAT-MS (QinetiQ, TRAD, eta_max)



Modèle de la station internationale sur FASTRAD

Usability:
SSAT, MULASSIS, GEMAT, GRAS SPENVIS interfaces





- GRAS interface under development

Usability: GRAS

Requirements:

- **Ready-To-Use tool**

  Multi-mission approach

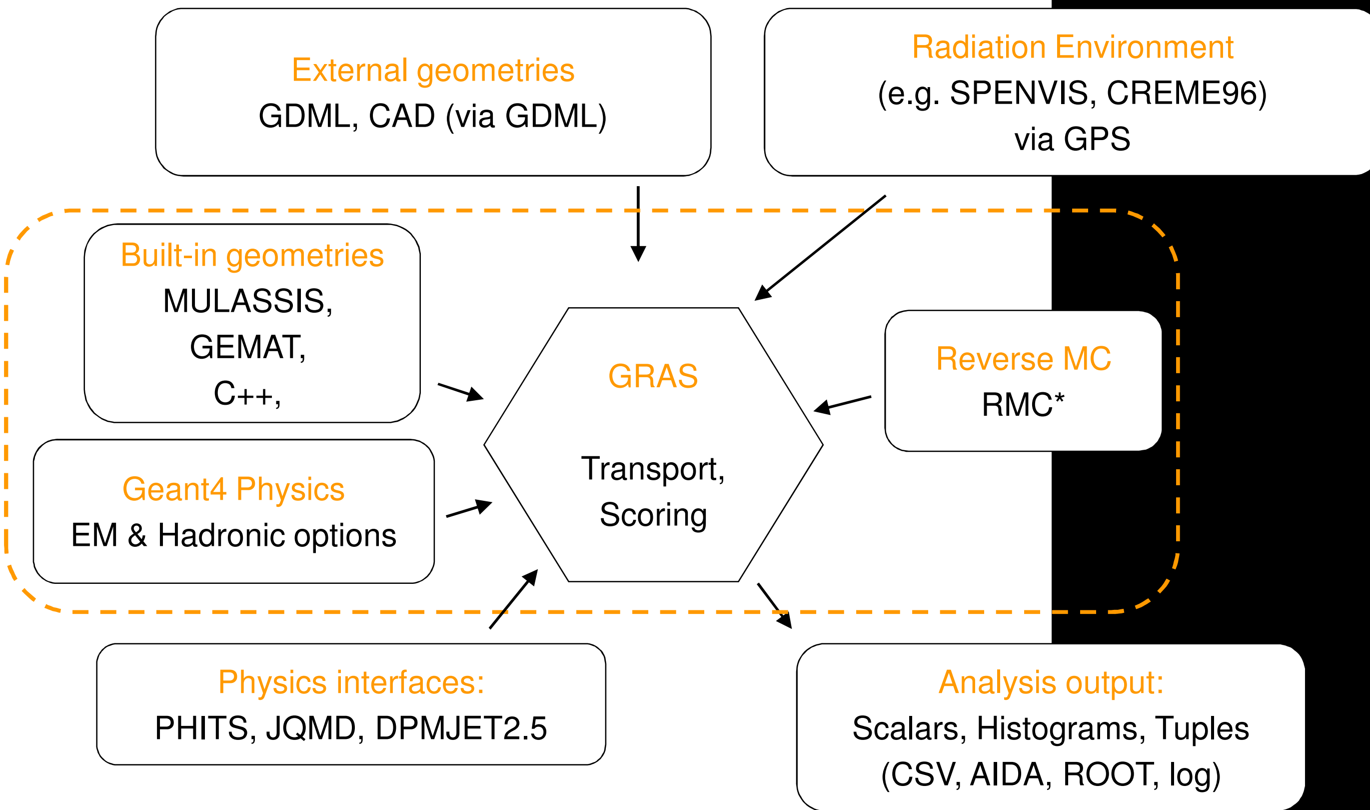
- **Quick assessments**

  Ray-tracing ↔ MC

  1D ↔ 3D

  EM ↔ Hadronics

  LET ↔ SV details



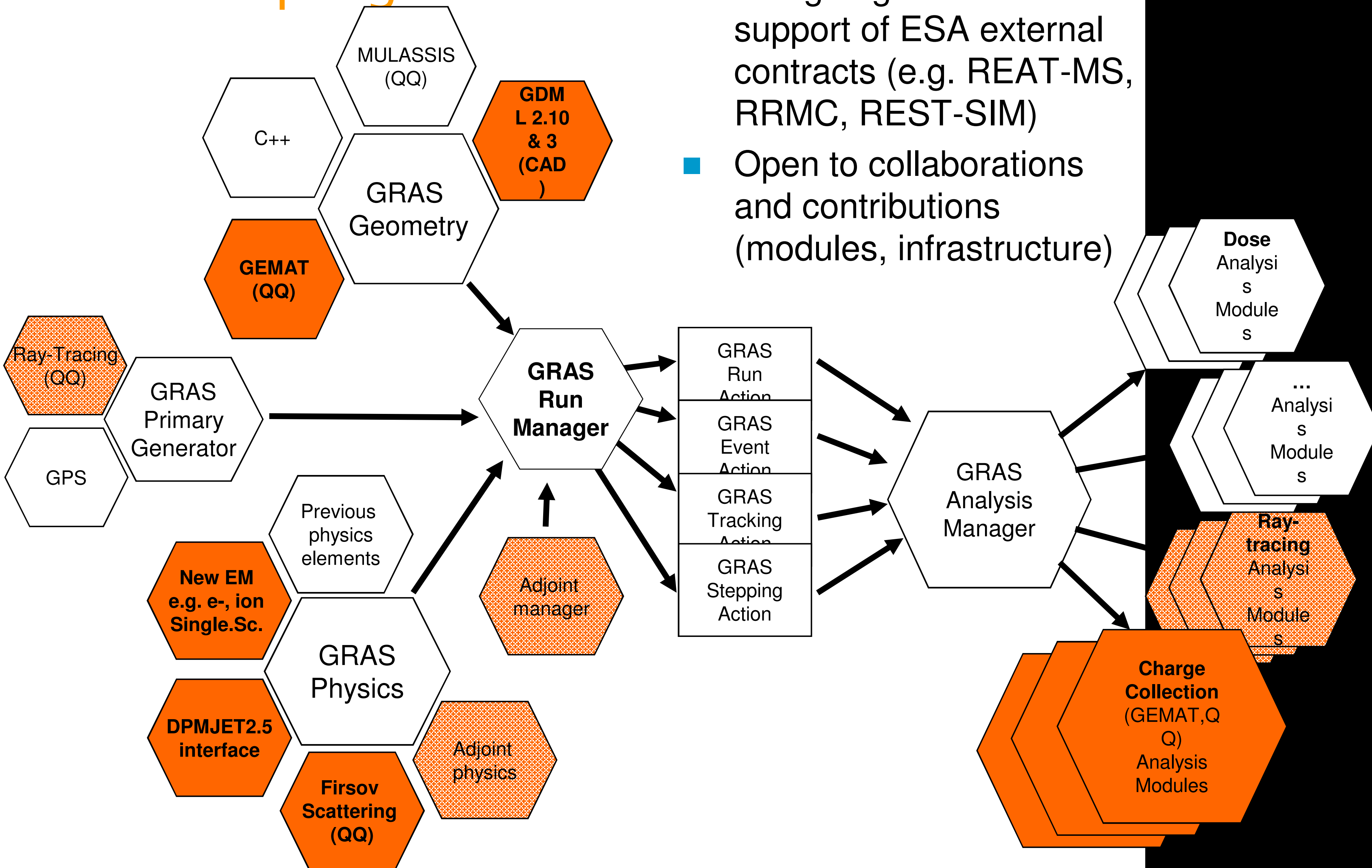
G Santin, V Ivantchenko et al, IEEE Trans. Nucl. Sci. 52, 2005

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

** in progress*

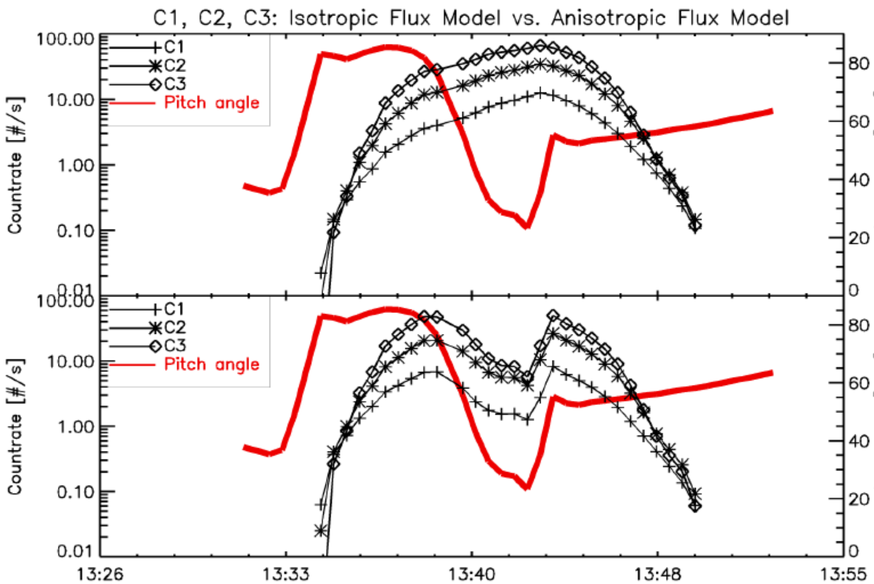
GRAS (v2.4)
Modular progress

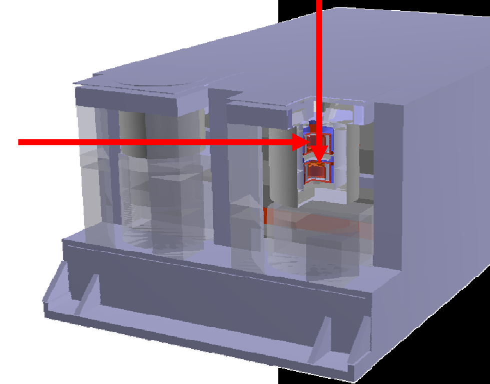
- ESA facility
- Being augmented with support of ESA external contracts (e.g. REAT-MS, RRMC, REST-SIM)
- Open to collaborations and contributions (modules, infrastructure)

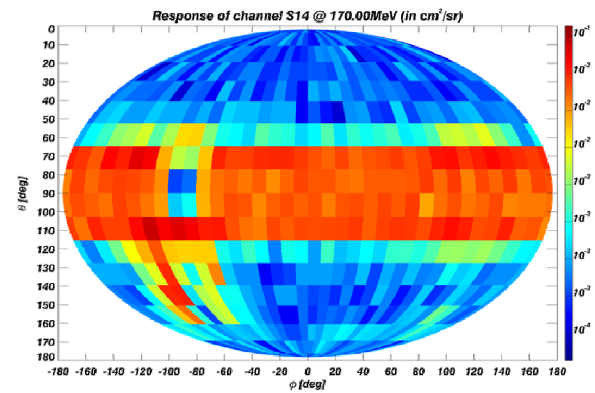


SREM Response (Proba-1)

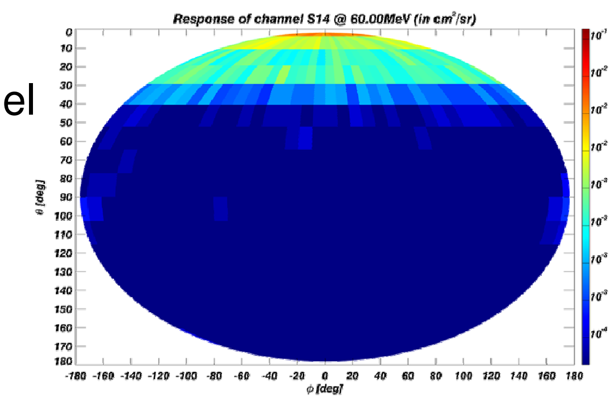
- Directional response function for all output channels
- Geant4 / GRAS simulations



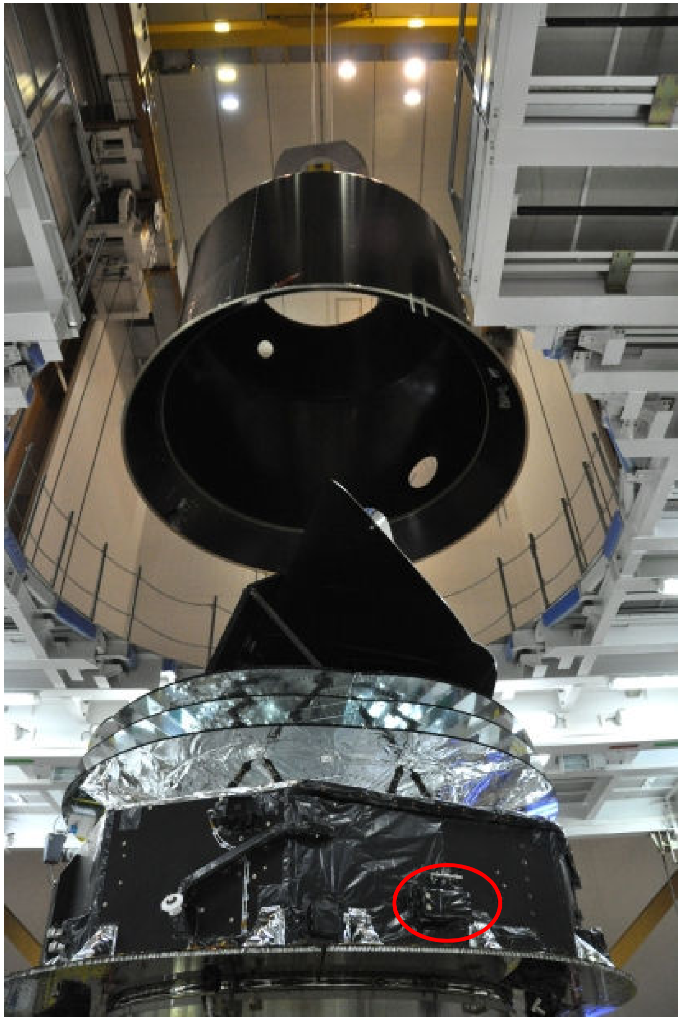




- Inner Belt Anisotropy Investigations
  - AP-8 and Badhwar-Konradi pitch angle distribution model
  - Comparison with observations onboard PROBA-1
- Martin Siegl's Master's Thesis, 2009
- Presented at RADECS 09, submitted to IEEE TNS

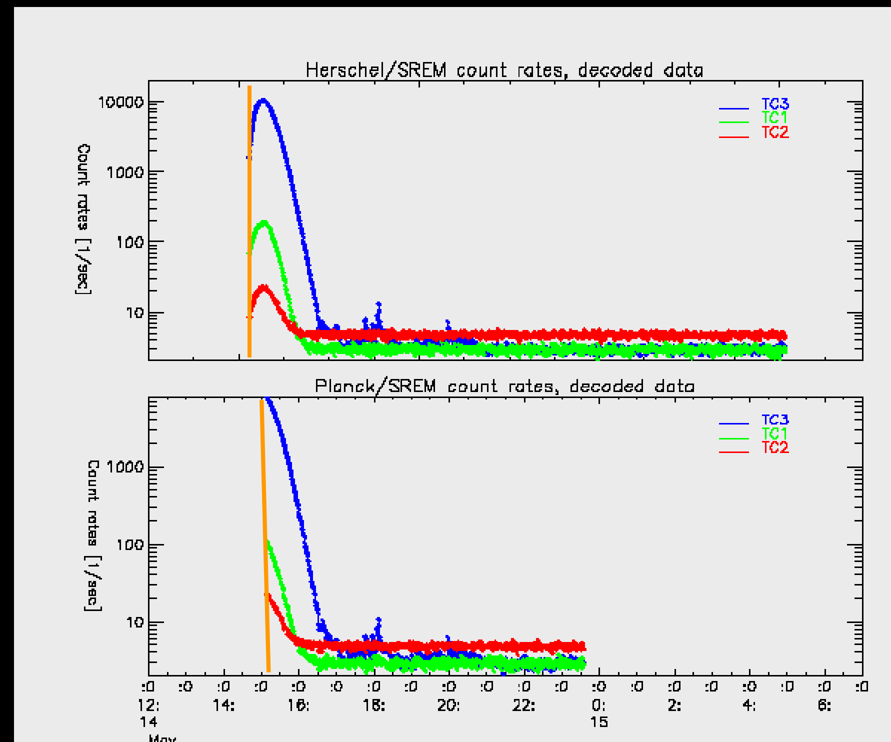


Herschel and Planck



Herschel and Planck

Launch 14.5. 2009



First SREM data 14.5. 2009

Summary

- Wide and diverse Geant4 space users' community
- Interests ranging from cosmology, to planetary science, to spacecraft electronics engineering
- In all these domains requirements continue to emerge for new physics, improved usability, or even new technologies for Geant4-based tools

- Next Geant4 Space Users' Workshop:
  Boeing Co., Seattle
  August 18th (Wed) - 20th (Fri), 2010