EEE Component Space Radiation Hardness Assurance and Dosimetry

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Ali Zadeh, European Space Agency
Presentation material by TEC-QEC and TEC-EES

ESA FACTS AND FIGURES

- Over 40 years of experience
- 19 Member States
- Five establishments in Europe, about 2200 staff
- 4 billion Euro budget (2012)
- Over 70 satellites designed, tested and operated in flight
- 17 scientific satellites in operation
- Six types of launcher developed
- Celebrated the 200th launch of Ariane in February 2011

19 MEMBER STATES AND GROWING

ESA has 19 Member States: 17 states of the EU (AT, BE, CZ, DE, DK, ES, FI, FR, IT, GR, IE, LU, NL, PT, RO, SE, UK) plus Norway and Switzerland.

Eight other EU states have Cooperation Agreements with ESA: Estonia, Slovenia, Poland, Hungary, Cyprus, Latvia, Lithuania and the Slovak Republic. Bulgaria and Malta are negotiating Cooperation Agreements.

Canada takes part in some programmes under a Cooperation Agreement.

European Space Agency

ACTIVITIES

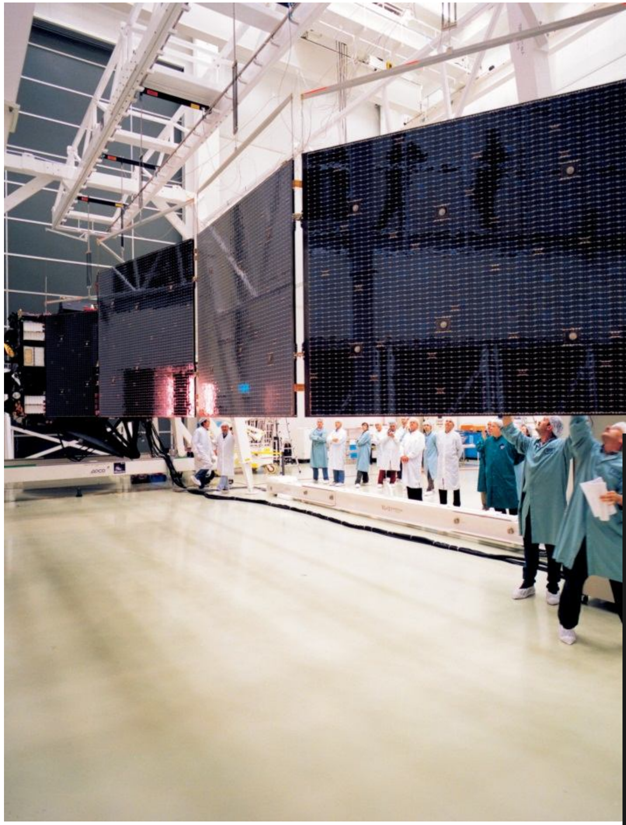
ESA is one of the few space agencies in the world to combine responsibility in nearly all areas of space activity.

- Space science
- Human spaceflight
- Exploration
- Earth observation
- Launchers
- Navigation
- Telecommunications
- Technology
- Operations

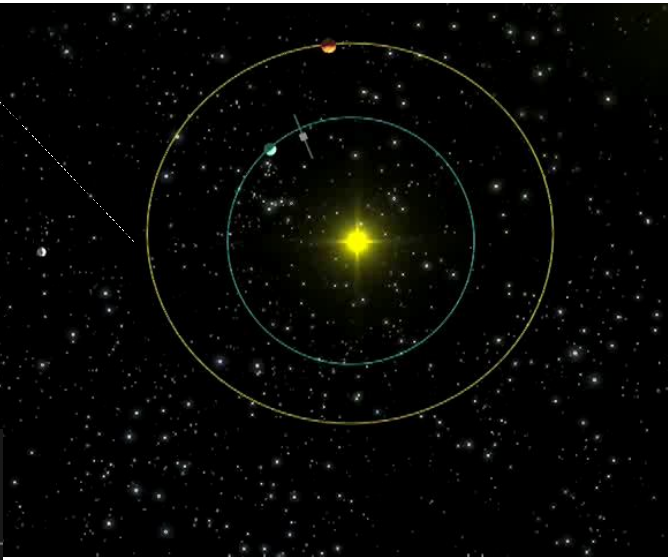
Effect of space radiation on spacecraft

- ESA fly spacecraft in many different orbits
- These spacecrafts operate in the natural space radiation environment consisting of a plethora of high energy particles of different species with different energies.
- The space radiation environment has a real and measureable adverse effect on EEE components, systems and subsequently of a spacecraft.
- The effects of radiation on spacecraft may be temporary or permanent.
- In most cases effects are predictable and mitigation techniques are in place to counteract them.
- However, in some cases radiation effects on EEE components propagate and may cause serious disruption of equipment/spacecraft performance or in the worst case lead to the loss of an equipment or an entire spacecraft.

Example radiation impact: Solar Cell degradation



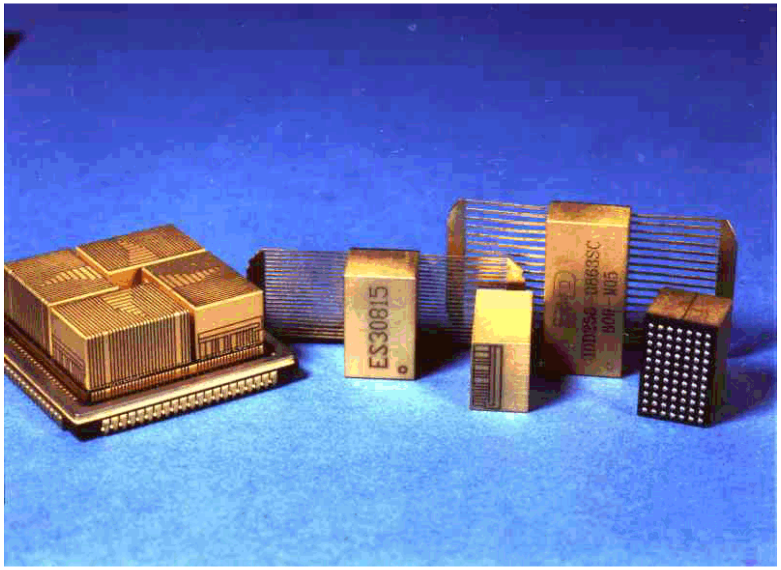
Rosetta solar cell span 32m. Solar cells gradually degrade with increasing radiation doses. Solar cells over-dimensioned to provide required power at spacecraft End-of-Life.



Rosetta trajectory towards asteroid Steins. Mission to comet Churyumov-Gerasimenko

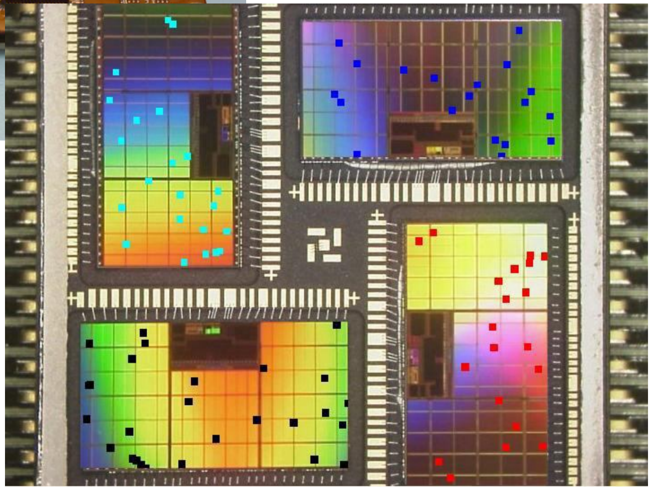
In-flight image of the back side of the Rosetta solar cells taken by the on-board PHILAE lender Camera CIVA (May 2004).

Example radiation impact: Memory devices



MCCS modules employed by Astrium GmbH to manufacture mass memory units of up to 320 Gbits.

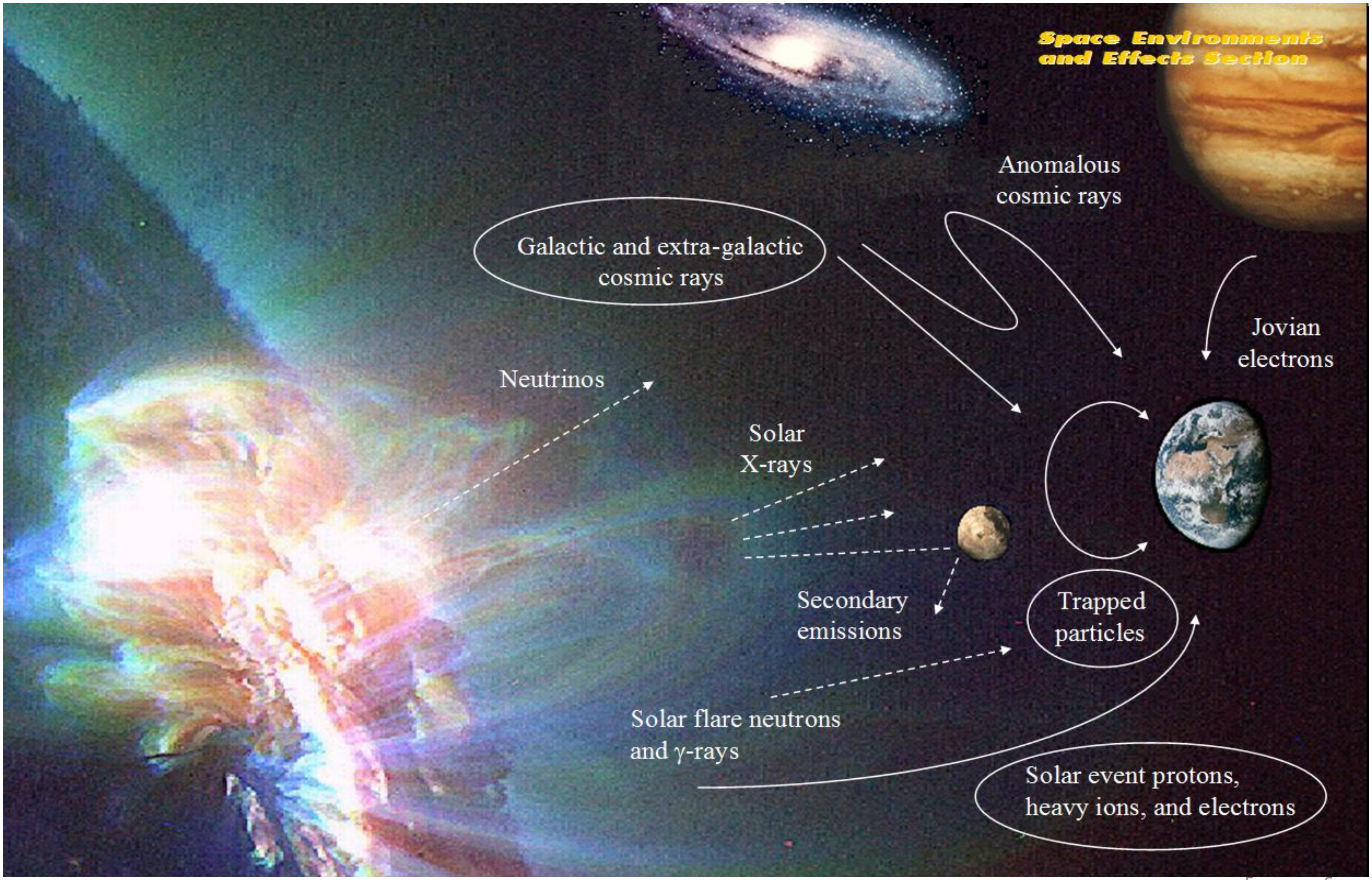
ESA Radiation Effects experiment (TDM) on board PROBA-**II** (low Earth orbit).



Radiation induced bit-flips distribution observed in an ATMEL AT68166 MCM device as part of the TDM experiment.

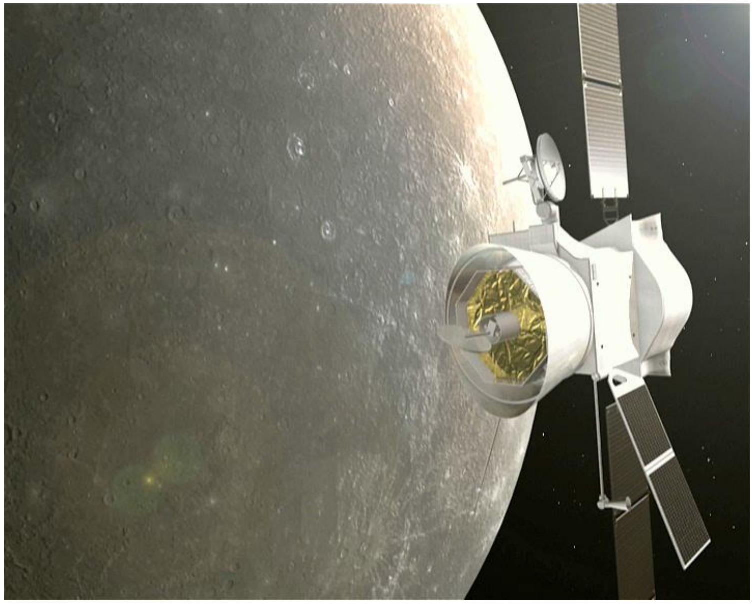
- Memory device may be affected by radiation in the form of changes to the memory content (single or multi bit modification), functionality or latchup (destructive event).

Space Radiation environment



Interplanetary orbits

NASA-ESA Cassini-Huygens (Saturn-Titan mission)

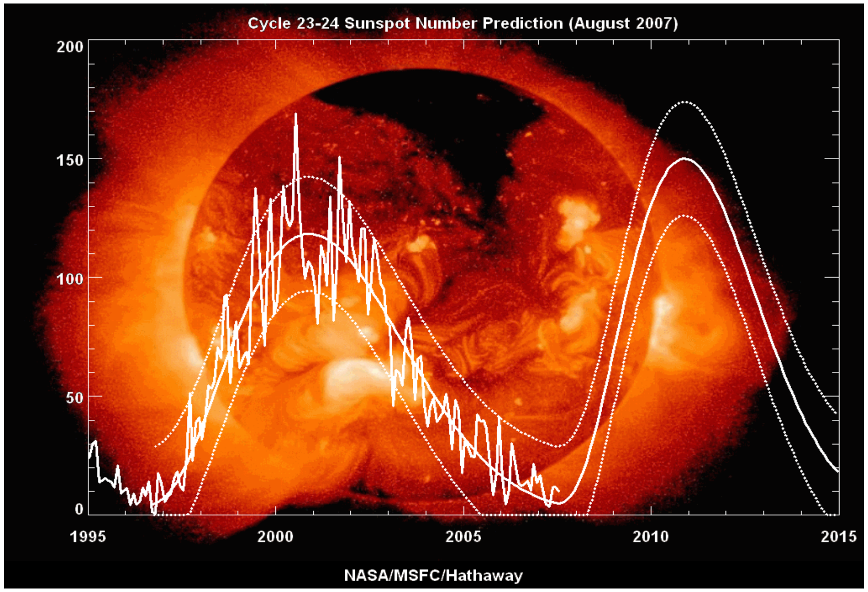


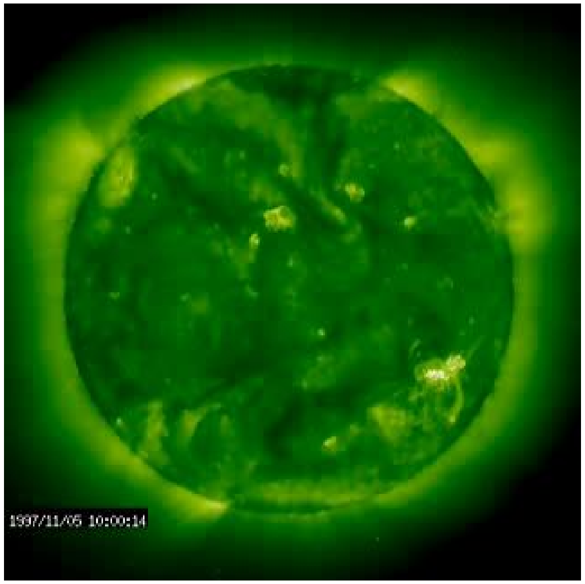
ESA Bepicolombo (Mercury mission)

- A number of ESA spacecraft such as Rosetta, Venus Express, Herschel, Gaia, etc. are or will operate in the interplanetary radiation environment.
- In this environment we are predominantly concerned about Extra galactic and galactic cosmic radiation and radiation due to solar flares.

Solar energetic particle events

- Radiation fluxes high for ~days
- Fluences high enough to cause damage => importance of proper shielding
- Include protons and heavy ions, Energy spectrum highly variable
- Essentially unpredictable, however efforts dedicated to address the problem in various Space Weather initiatives
- Analysis methods are *statistical*
- Also geomagnetically shielded





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Cosmic rays

- Flux ~ 4 particles /cm^2/sec in space, anticorrelation with solar activity
- Average person is crossed by ~ 100 relativistic muons per second
- Discovered in 1912 by Austrian Victor Hess
- Supernovae produce high energy cosmic rays, accelerated by moving shocks, as suggested by Enrico Fermi in 1949.
- Charged particles accelerated to near speed of light (can reach ~10^{20} eV range. The most powerful particle accelerators on Earth “weak” in comparison)
- Definitive model the CREME series by NRL, available in SPENVIS

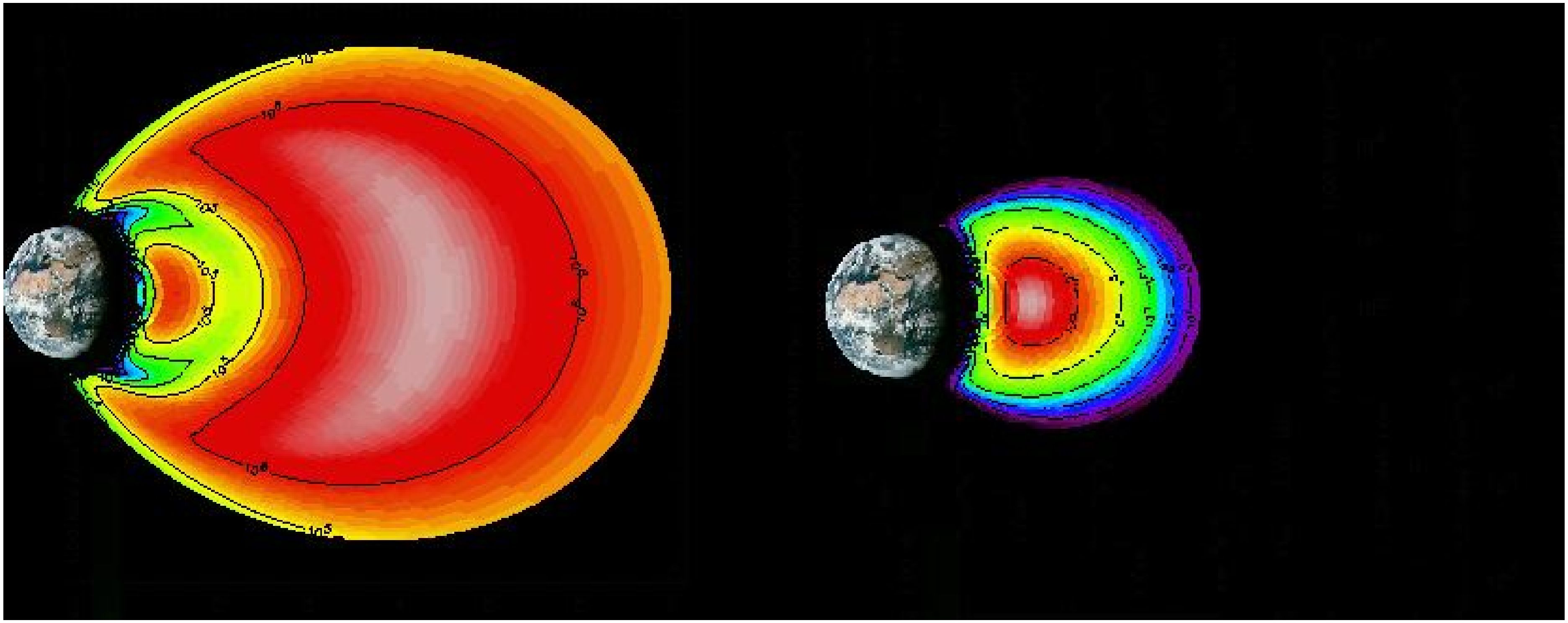
Earth radiation environment

ESA Sentinel-2 Earth Observation mission

International Space Station ESA Colombus module

- Most ESA spacecraft operate in the near Earth radiation environment.
- In this environment we are generally concerned with the Van Allen radiation belts , solar flare events and galactic cosmic rays.

Van Allen radiation belts,
Static picture AE-8 and AP-8

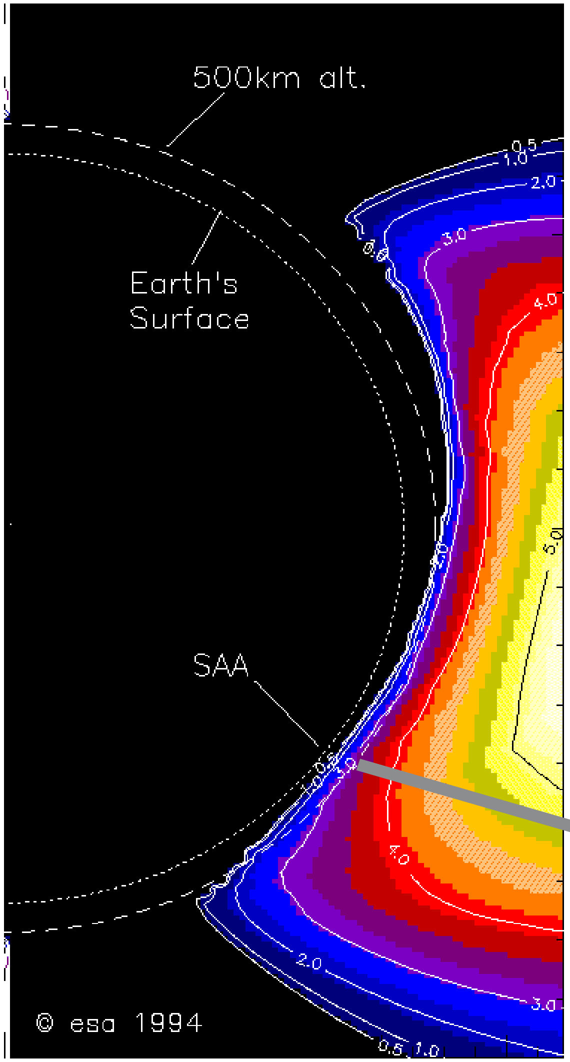


“Electron Belt” “Proton Belt”

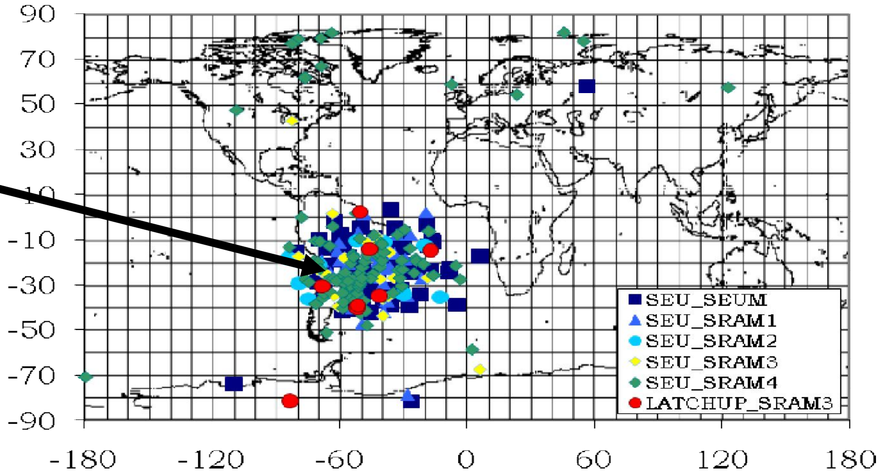
Features of radiation belts

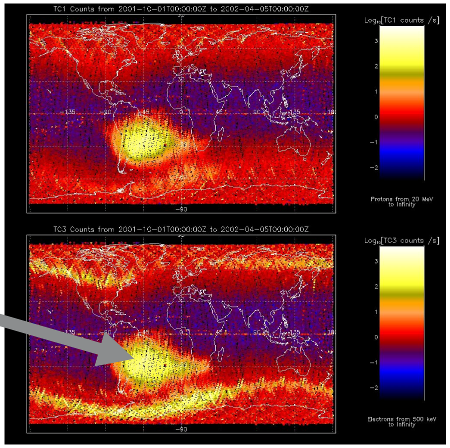
- Inner belt is dominated by a *static* population of energetic protons up to ~300 MeV energy range
  - Product of Cosmic-Ray Albedo Neutron Decay
  - Inner edge is encountered as the South Atlantic Anomaly (SAA)
  - Dominates the Space Station and LEO spacecraft environments
- Outer Belt is dominated by a *dynamic* population of energetic electrons up to ~5 MeV;
  - Frequent injections and dropouts associated with storms and solar material interacting with magnetosphere
  - Dominates the geostationary orbit environment and Navigation (Galileo, GPS) orbits, as well as certain Science missions in highly elliptic orbits (XMM-Newton, INTEGRAL)

South Atlantic Anomaly (inner belt)



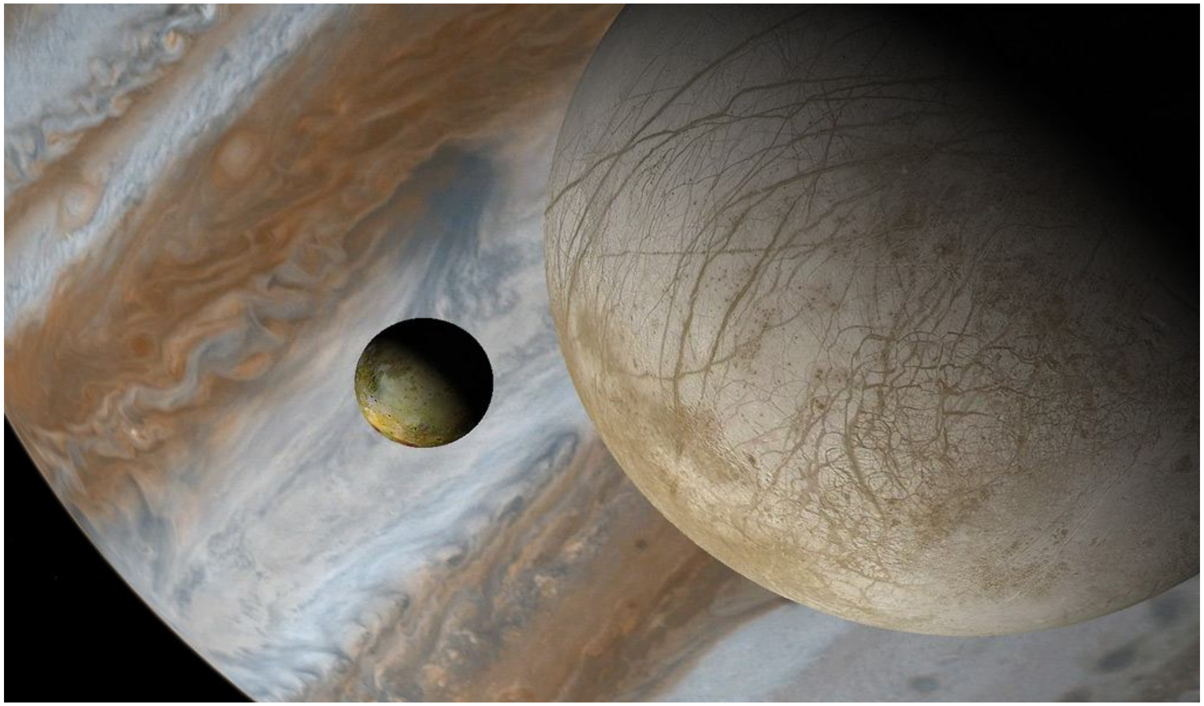
Single Event Upset (SEU) measurements by the ESA Technology Demonstration Module (TDM) clearly depicts proton induced SEUs in the SAA.





SREM SAA on board PROBA-I SAA measurement (protons upper image, electrons lower image)

Radiation environment on other planets



- ESA is assessing a challenging new mission to send a probe (JUICE) to the moons of Jupiter for 2024.
- The Jupiter radiation belt consist of electrons with higher energy and fluxes than those observed in the Earths electron belts. The Total Ionising Dose levels of JUICE (with margin) is currently estimated to 400krad.

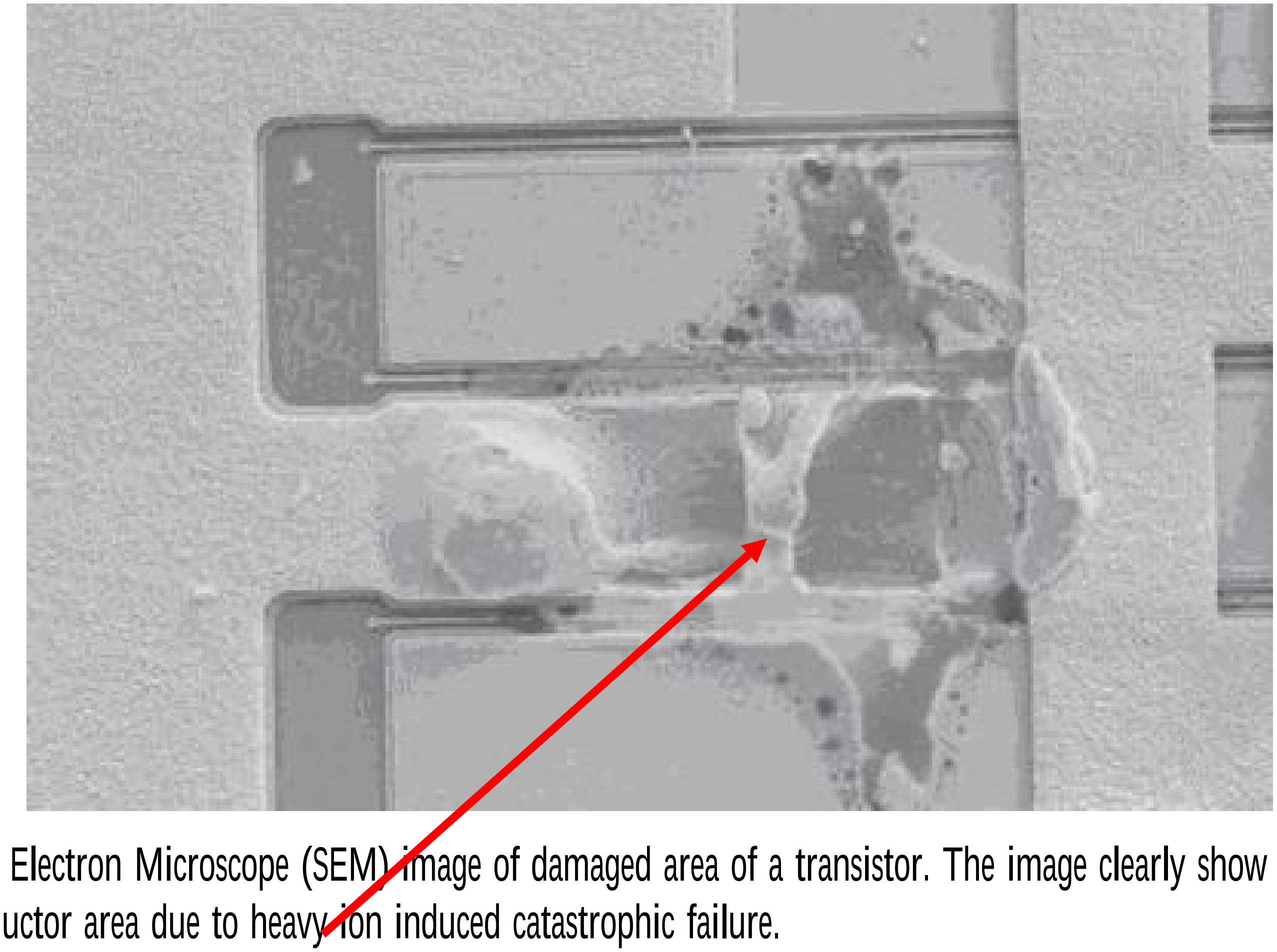
Measuring the space radiation environment

- ESA fly and plan to fly a number radiation monitors to improve the understanding of the radiation environment in which ESA spacecraft operate.
- The performance of monitors employed vary depending on their intended application.
- ESA radiation monitors:
  - Radiation Environment Monitor (REM), flown on MIR
  - Standard Radiation Environment Monitor (SREM), flying on PROBA-I, ROSETTA, INTEGRAL, HERSCHEL, PLANCK, GIOVEB.
  - RadFET (radiation sensitive FET, manufactured by Tyndall). Flying on Rosetta, Integral, HERSCHEL, PLANCK, GIOVE-B and some industrial spacecraft.
  - Energetic Particle Telescope (EPT), planned flown on PROBA-V.
  - Highly Miniaturised Radiation Monitor (under development)
  - Next Generation Radiation Monitor (under development)

The effect of radiation on EEE components

- The space radiation environment is harsh and may adversely affect EEE components and materials flown on ESA spacecraft
- Concerned with three major radiation effect types
    - Total Ionising Dose Effects
    - Total Non Ionising Dose (Displacement Damage) Effects
    - Single Event Effects
- TID and TNID are cumulative effects typically result in slow degradation of EEE components with increasing received dose
- SEE are transient effects resulting in non-destructive and destructive event.
- Radiation effects in EEE components may lead to catastrophic failures of components, sub-systems, systems or even entire spacecraft.
- To ensure that EEE Components are suitable for flight on ESA spacecraft a rigorous Radiation Hardness Assurance policy is implemented.

The effect of radiation on EEE components (example)



Scanning Electron Microscope (SEM) image of damaged area of a transistor. The image clearly show melted semiconductor area due to heavy ion induced catastrophic failure.

Radiation Hardness Assurance (RHA) definition

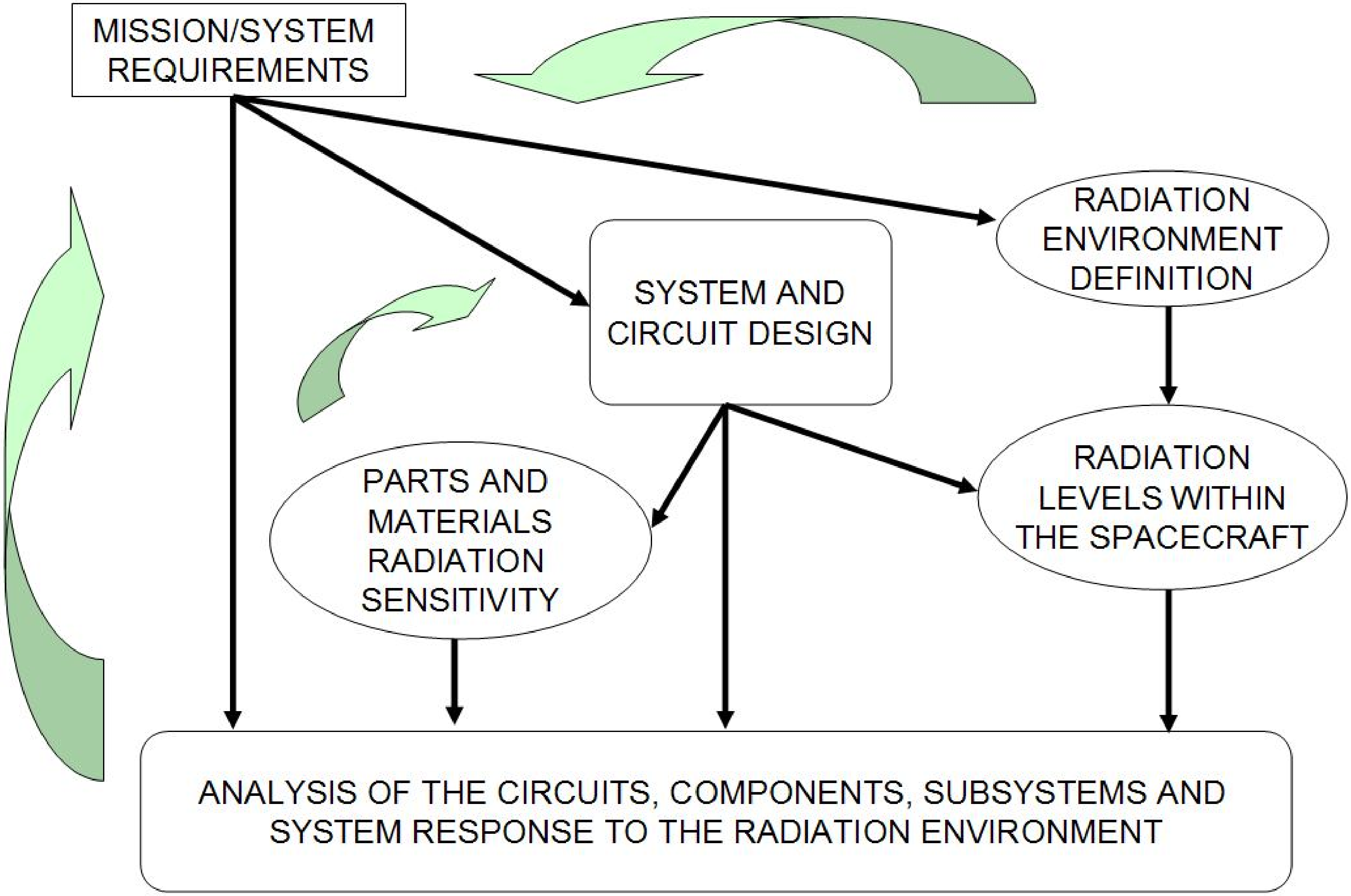
- RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their design specifications after exposure to the space radiation environment

- Deals with environment definition, part selection, part testing, spacecraft layout, radiation tolerant design, mission/system/subsystems requirements, mitigation techniques, etc.

- Radiation Hardness Assurance goes beyond the piece part level

- A number of European standards employed in the RHA process (ECSS and ESCC)

RHA overview



MISSION/SYSTEM REQUIREMENTS

RADIATION ENVIRONMENT DEFINITION

SYSTEM AND CIRCUIT DESIGN

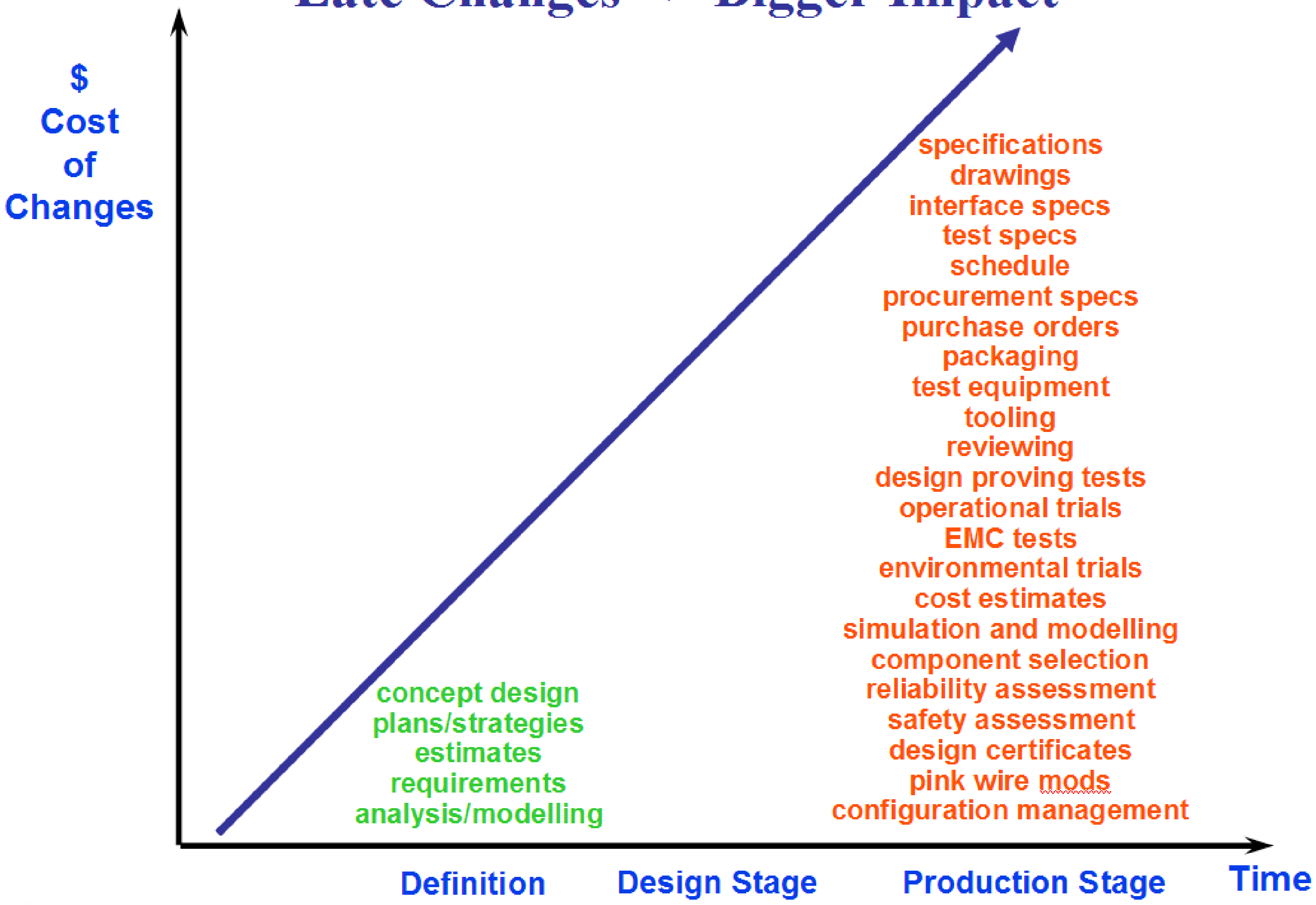
PARTS AND MATERIALS RADIATION SENSITIVITY

RADIATION LEVELS WITHIN THE SPACECRAFT

ANALYSIS OF THE CIRCUITS, COMPONENTS, SUBSYSTEMS AND SYSTEM RESPONSE TO THE RADIATION ENVIRONMENT

RHA early in project phases

Late Changes => Bigger Impact



$
Cost
of
Changes

concept design
plans/strategies
estimates
requirements
analysis/modelling

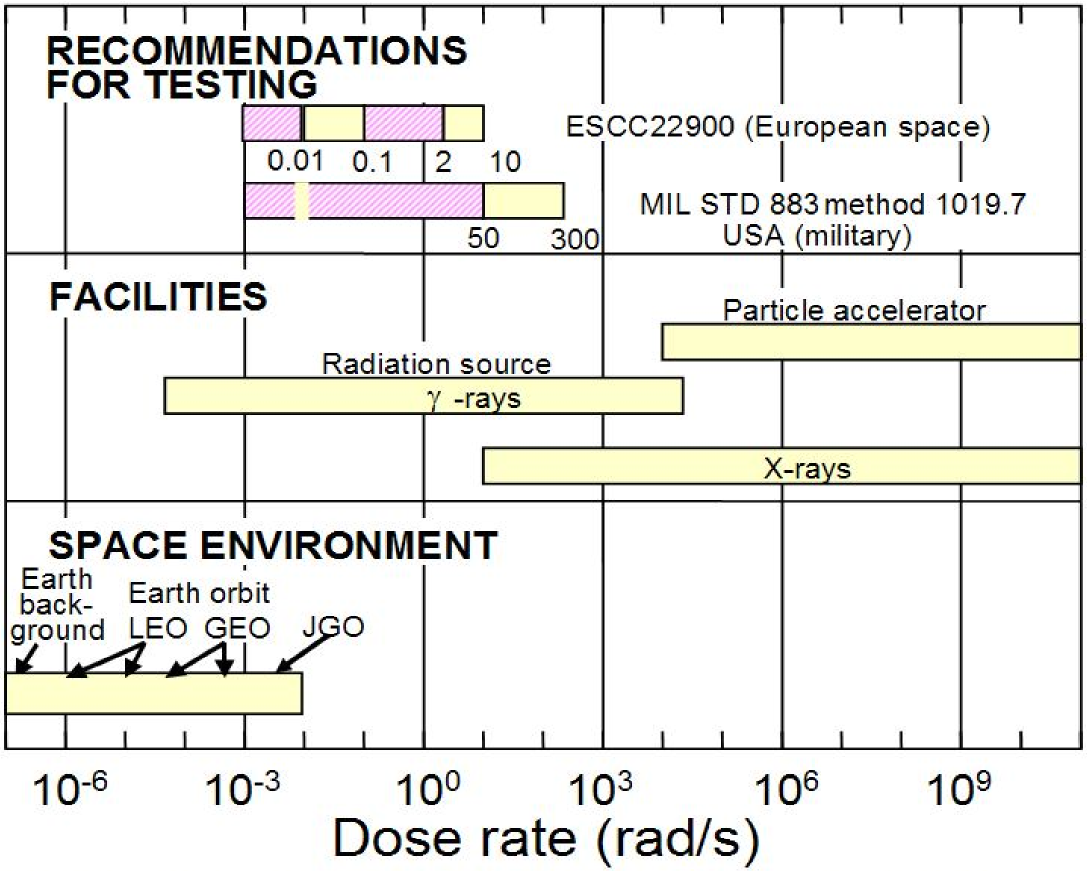
specifications
drawings
interface specs
test specs
schedule
procurement specs
purchase orders
packaging
test equipment
tooling
reviewing
design proving tests
operational trials
EMC tests
environmental trials
cost estimates
simulation and modelling
component selection
reliability assessment
safety assessment
design certificates
pink wire mods
configuration management

Definition
Design Stage
Production Stage
Time

TID testing: Radiation source

- ESCC22900 TID irradiation test guideline states that ^{60}Co, x-rays, electrons and protons may be used for TID irradiation testing.
- ^{60}Co and x-ray sources predominantly used for device characterization
- ^{60}Co sources normally used for hardness assurance testing of EEE components
- Charge yield for ^{60}Co and x-ray irradiations can be very different - especially at low electric fields
- Large differences in radiation-induced charge buildup in SOI buried oxides observed between x-ray and ^{60}Co irradiations
  - Fleetwood et al. 1988, Schwank et al. 2000
- Response of pMOSFET dosimeters observed to be different for ^{60}Co and proton irradiation
  - Pease et al., IEEE Trans. Nucl. Sci. 48, 908 (2001).

TID testing: Dose rate laboratory vs. in-flight dose rates



The laboratory dose rates are significantly higher than the actual space dose rates, testing according to test standards gives conservative estimates of CMOS devices TID sensitivity

After A Holmes Siedle and L Adams, Oxford Un. Press, 1993

TID testing: important notes

- When performing TID irradiation tests it is important to ensure that the radiation test facility comply with the appropriate standards.
- In particular, dosimetry is very important to ensure that radiation induced component parameter degradation is not over or under estimated.
- Dosimetry is usually performed by facility staff and accurate to ~ ±5% to ±10%
- The following dosimeters are typically employed for TID testing.
  - ion chambers
  - RadFETs
  - silicon surface barrier detectors
  - Geiger-müller,
  - Termo-luminescent dosimeters
  - Calculation based on initial source activity (and half-life) and distance to source.
- Human errors may occur when measuring received dose!
  - It is recommended that customers also perform their own dosimetry (in particular for test campaigns at particle accelerators)

ESTEC ^{60}Co facility (1)

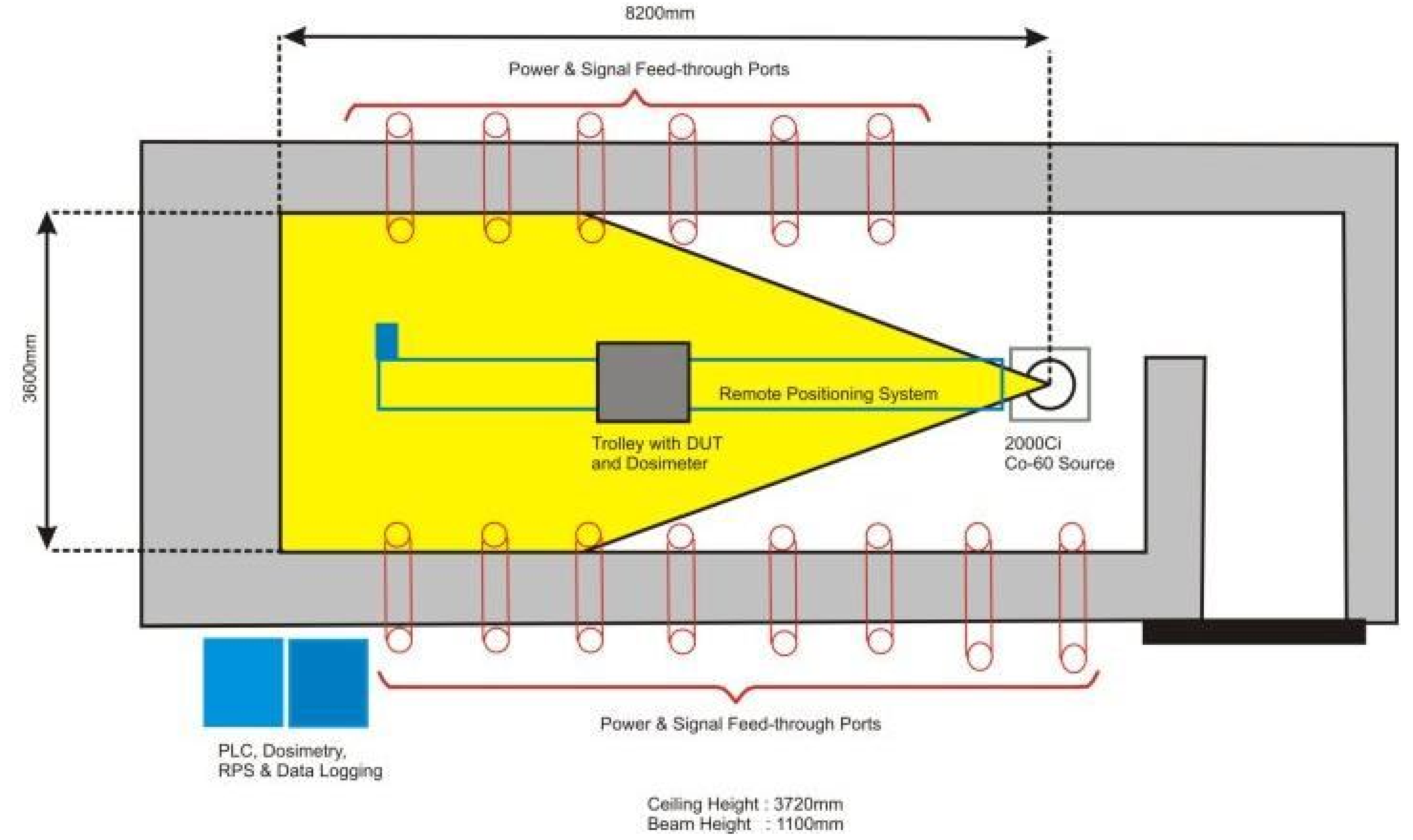


Diagram of the ESA (ESTEC) 60Co facility

European Space Agency

ESTEC ^{60}Co facility (2)

- The original facility was installed in 1988.
- The new ESTEC ^{60}Co facility was opened in 2007 (the old facility was decommissioned)
- 8m long irradiation room
- Dose rates from
  < 1 rad/min to > 100 rads/min
- Facility can run unattended 24 / 7
- Very high level of safety and security incorporated into the system.
- The ESA ^{60}Co facility has been operational for over 20 years.
- BOL source activity is 2000 Ci (74TBq) although the facility is licensed for up to 6000 Ci
- The ^{60}Co source is changed every 4 to 5 years.

ESTEC ^{60}Co facility (3)

- The facility is used for the TID testing of many types of electronic components, optical devices and materials.
- The facility is operated as a service for approved ESA projects and programmes only.
- Irradiation tests are performed according to ESCC22900 “Total dose steady state irradiation test method”
- EEE components are irradiated to various dose levels according to mission requirements. Various dose rates are used but all are “accelerated dose rates” compared to space radiation dose rates.
- Build-up material is employed to achieve charge equilibrium.
- Typical testing duration is from several hours to several months.
- Possibility to run 2 (or sometimes 3) tests in parallel depending on the individual test requirements.
- 3 independent calibrated dosimetry chains are available

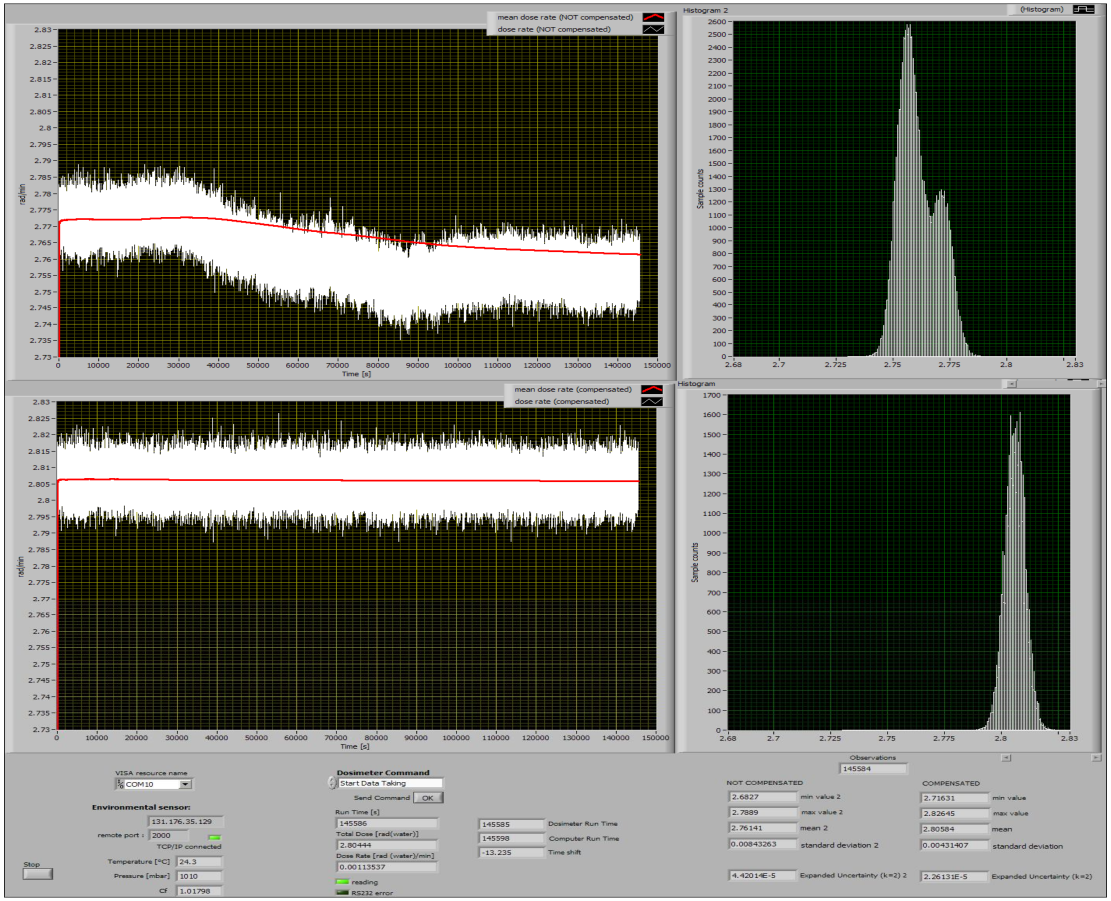
ESTEC ^{60}Co facility dosimetry

- Our dosimetry procedures are ISO17025 certified (based on the relevant requirements specified in the ESCC22900).
- Our customers can be confident in dose values and uncertainty budgets provided
- Dosimeters used:
  - Thermo Electron Farmer 2670 electrometer
  - Thermo Electron 0.6cc ionisation chamber type 2571
  - Each electrometer is associated with its own ionisation chamber (electrometer + ionisation chamber constitute a dosimeter chain)
- Dosimetry chains are :
  - Calibrated in-house annually against alanine dosimeters supplied by NPL (UK)
  - Checked monthly at a set distance from the source in a perspex (plexiglass) phantom

ESTEC ^{60}Co facility dose value correction

- Dosimeter values are corrected for temperature and pressure.

The variation in dose rate during a radiation run has been monitored during a test lasting 145K seconds. The results are shown in the graphs below, the upper graph showing the raw dose rate and the lower graph the dose rate corrected for temperature and pressure. Variations observed from -3% to +5%.



VISA resource name: COM10

Environmental sensor:

131.176.35.129

remote port : 2000

TCP/IP connected

Temperature [°C] 24.3

Pressure [mbar] 1010

Cf 1.01798

Dosimeter Command: Start Data Taking

Send Command OK

Run Time [s] 145586

Total Dose [rad(water)] 2.80444

Dose Rate [rad (water)/min] 0.00113537

reading

RS232 error

145585 Dosimeter Run Time

145598 Computer Run Time

-13.235 Time shift

Observations 145584

NOT COMPENSATED		COMPENSATED	
2.6827	min value 2	2.71631	min value
2.7889	max value 2	2.82645	max value
2.76141	mean 2	2.80584	mean
0.00843263	standard deviation 2	0.00431407	standard deviation
4.42014E-5	Expanded Uncertainty (k=2) 2	2.26131E-5	Expanded Uncertainty (k=2)

ESTEC ^{60}Co facility dose uncertanty budget

- Our requirements state:
  - ESCC22900: “The dose at the device under test shall be measured to a resolution of better than 10% and the non-uniformity of the radiation field in the test area shall be a maximum of 10%.”
  - ESCC21500: ““The gamma-ray dose rate of a Cobalt 60 source shall be calibrated in accordance with the requirements of ESCC Basic Specification No. 21500 to 5% or better. Dosimetry shall be traceable to national standards.”

- We have a traceable absorbed dose to water calibration of the ionization chamber / electrometer combination with an uncertainty of 4.2% (k=2), i.e. within the 5% specification.
- This uncertainty budget is valid for dose measurements greater than 60 minutes.
- For shorter runs, the ion chamber equilibrium must be taken into account.
- Our uncertainty budgets have been validated via inter-laboratory comparison in the range 0.812 -78.7 Gy/h Air Kerma (1.5 to 145 rad/min in water).
  - LNK Ghent, Belgium Nuclear Research Centre (SCK-CEN)
  - DLD, Department of Defence Laboratories, Belgium

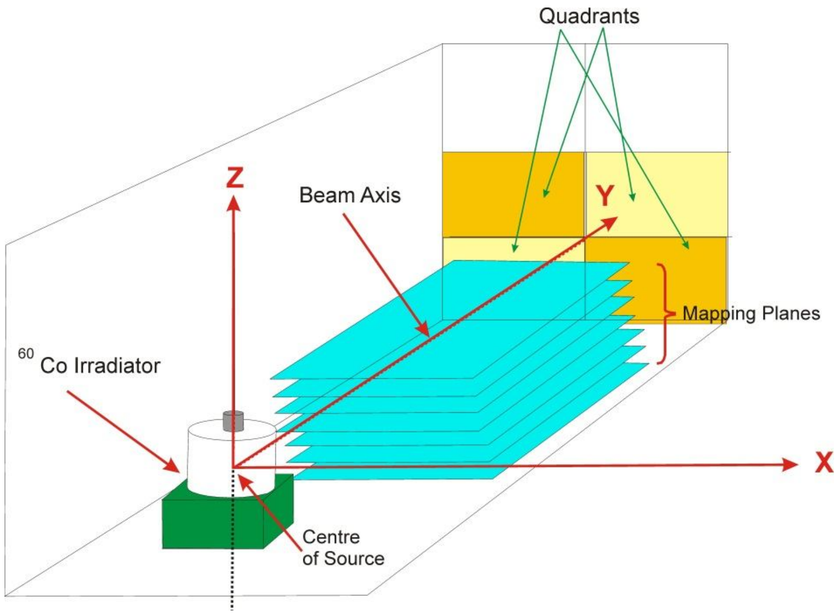
ESTEC ^{60}Co facility dose uncertanty budget calculation

Source	Value	Probability distributio n	Divi-sor	Relative u_{iA}	Relative u_{iB}	ν_i	Comments
Calibration of alanine dosimeters	2.6 %	normal	2		1.3 %	∞	From NPL calibration certificate
Alanine temperature correction	0.28 %	rect.	√3		0.16 %	∞	Temp. coeff. 0.14 % per °C. Assume ± 2 °C
Irradiator timing							Not applicable when total dose measured.
Chamber temperature and pressure corrections	1.0 %	rect.	√3		0.6 %	∞	Assume max. ± 10 mbar pressure change over irradiation. Temp. negligible
Statistical variability of alanine / chamber readings	0.5 %	normal	1	0.5 %		5	
Stability of the system	2.5%	rect.	√3		1.44	∞	Based on the action limit for an acceptable change between calibrations.
Quadrature summation				0.5 %	2.04 %		
Combined standard uncertainty		normal		2.1 %		~1500	Round up
Expanded uncertainty		normal (*k*=2)		4.2 %			

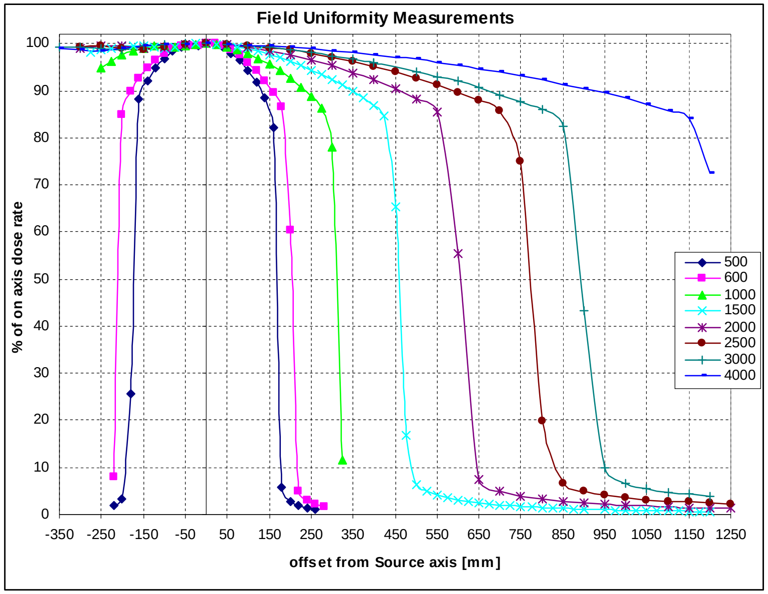
Uncertainty budget associated with absorbed dose to water measurements

ESTEC ^{60}Co facility radiation field uniformity

- Irradiation tests are performed at various positions in the radiation cell. Radiation field uniformity is therefore measured to identify compliance with ESCC22900 requirement.

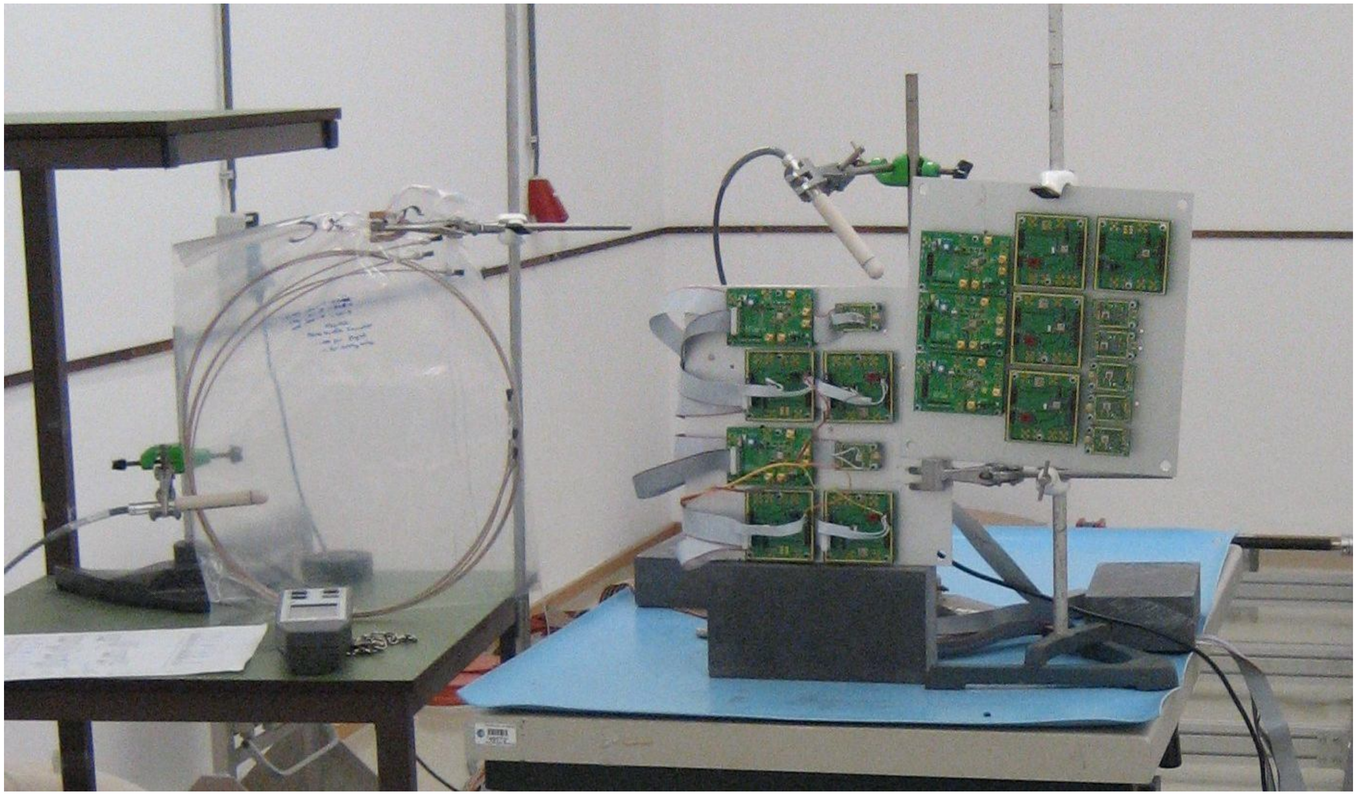


Radiation Field measurement steps



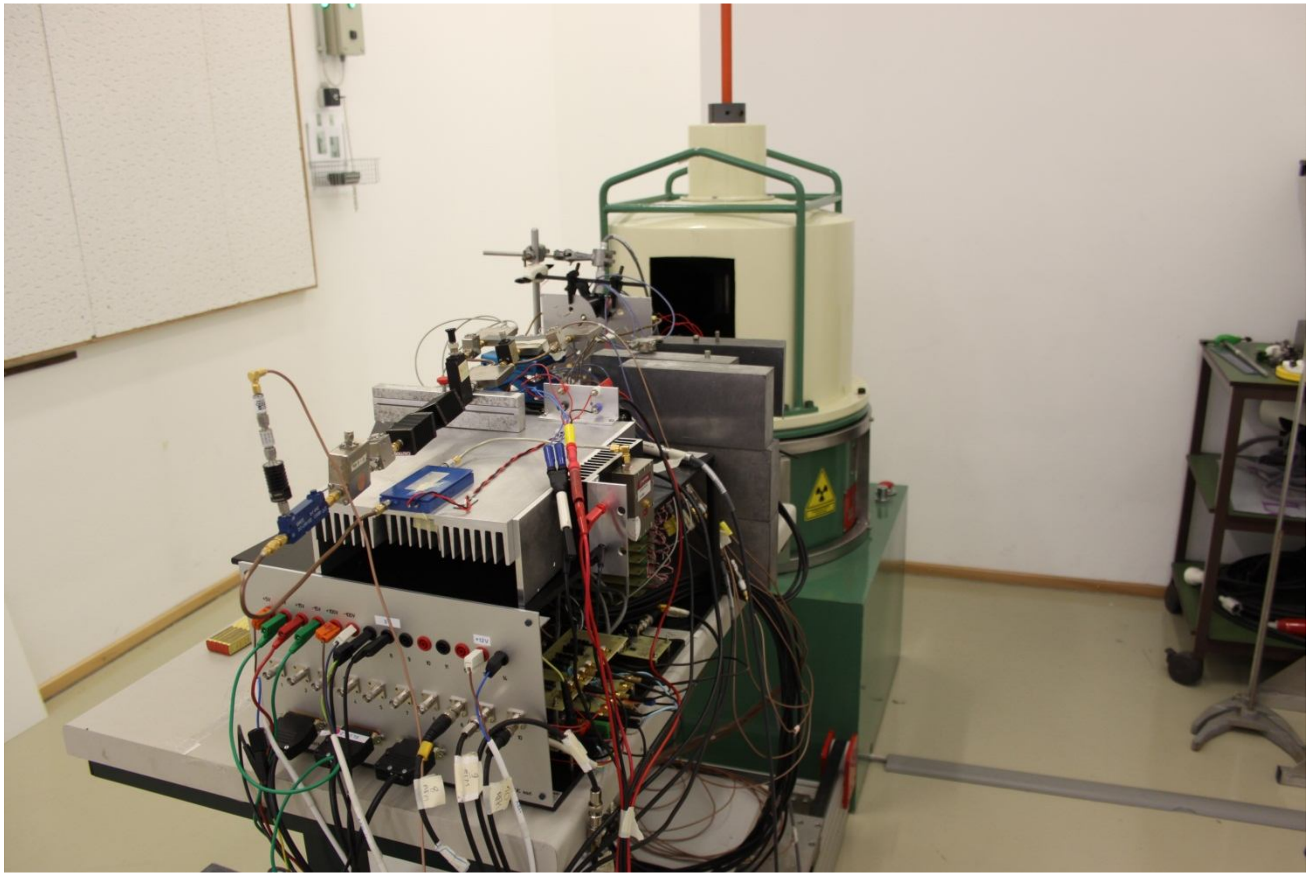
Radiation Field measurement results

TID irradiation test example 1



Demonstrating 2 tests running in parallel. The main test (right hand side) are GPS on a chip modules and the left hand test is a spool of fibre optic cable. Both tests have individual dosimeters.

TID irradiation test example 2



A complex set-up for MEMs accelerometers with a large amount of shielded auxiliary equipment

Conclusion

- ESA fly many spacecraft in the harsh space radiation environment
- A Radiation Hardness Assurance (RHA) process is implemented to ensure suitability of EEE components flown on ESA spacecraft.
- Irradiation testing of EEE components is an important part of the RHA process.
- The ESA TID irradiation test facility employed to test EEE components and materials
- Proper dosimetry is crucial to maintain confidence in TID test results
- The ESA TID test facility dosimetry procedures are ISO17025 certified
- The ESA TID facility is the space related standard test facility for tests performed in accordance with ESCC22900 requirements.
- Irradiation tests performed at proton, neutron and heavy ion facilities to test for displacement damage and Single Event Effects Tests.
- Proper dosimetry critical also at neutron, proton and heavy ion facilities.
- Radiation facility users responsible to ensure dosimetry is performed correctly.

More information

- ECSS-Q-ST-60-15 Space Radiation Hardness Assurance Standard (to be released Q3 2012): http://www.ecss.nl/
- ECSS-E-ST-10-04 Space Environment Standard: http://www.ecss.nl/
- ECSS-E-ST-10-12 Method for calculation of radiation received, and policy for design margins: http://www.ecss.nl/
- ESCC22900 Total Dose Steady State Irradiation Test Method: https://spacecomponents.org/
- ESCC25100 Single Event Effect Test Method and Guideline: https://spacecomponents.org/
- Space Environment Information System (SPENVIS): http://www.spenvis.oma.be/
- GEANT4 for Space: http://geant4.esa.int/
- ESA Space Weather site: http://esaspaceweather.net/index.html

Radiation Effects at ESA

- TEC-QEC (Technical and quality management /PA/Material and Component Evaluation Division/Component)
  - Radiation Effects (characterization, testing)
  - Radiation Hardness Assurance (RHA)
  - For more info contact ali.mohammadzadeh@esa.int
  - Homepage: https://escies.org/ReadArticle?docId=227

- TEC-EES (Technical and quality management/Electrical Engineering/ Electromagnetic & Space Environment Division/Space Environment)
  - Radiation Environment
  - Radiation Effects (modelling)
  - For more info contact eamonn.daly@esa.int
  - Homepage: http://space-env.esa.int/R_and_D/overview_rev.htm