Radiation Hardness Assurance at ESA: from low to high-risk missions!

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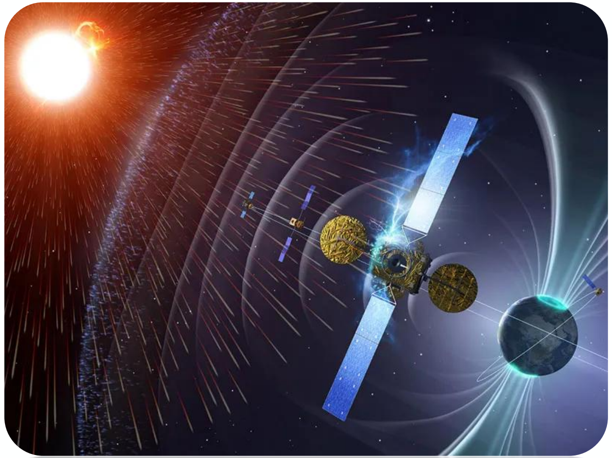
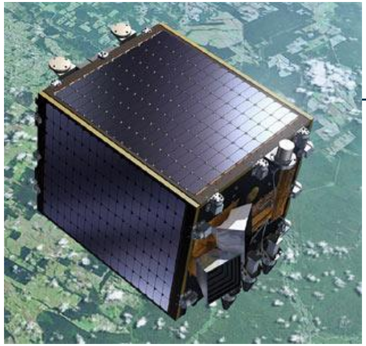
Table of content

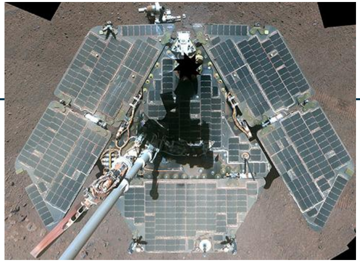
1. What is RHA?
2. Space radiation environment & it’s effects on EEE components
3. What is the ESA mission classification?
4. How is RHA applied in ESA low-risk missions?
5. How is RHA applied in ESA high-risk missions?

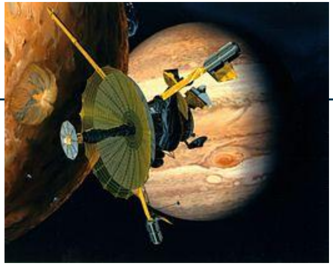


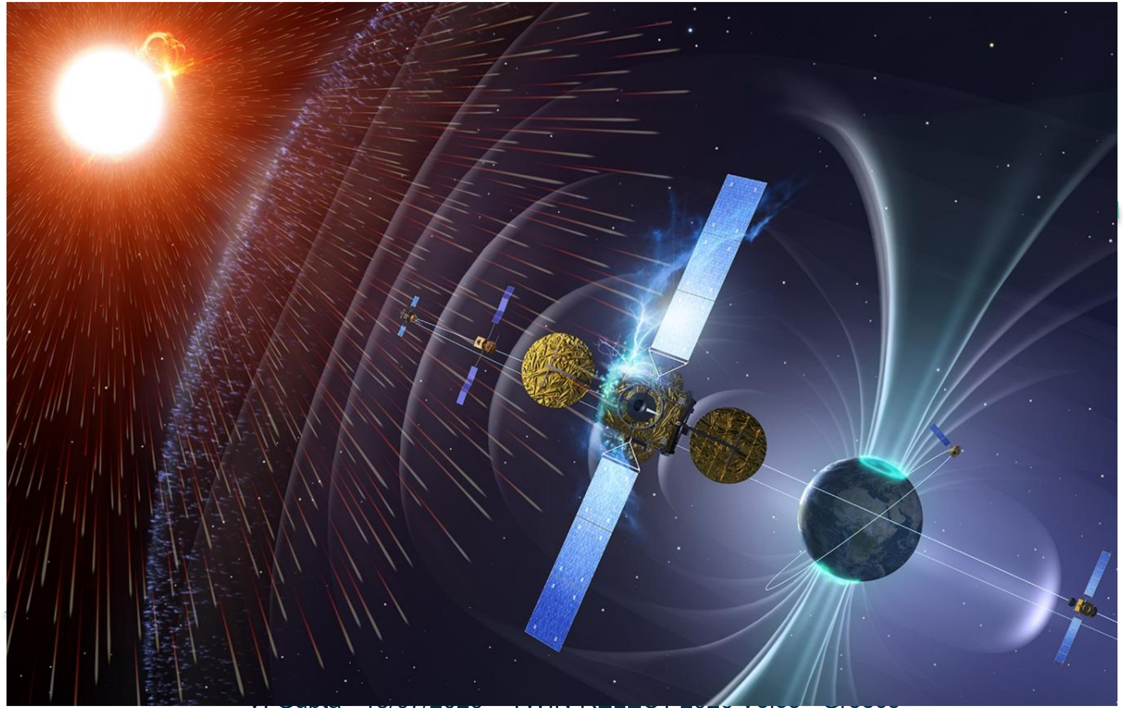
NOTE 1: The presentation only covers RHA on EEE components (& not solar panels)!

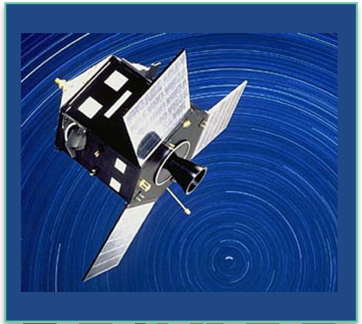
NOTE 2: Only a brief overview ☺





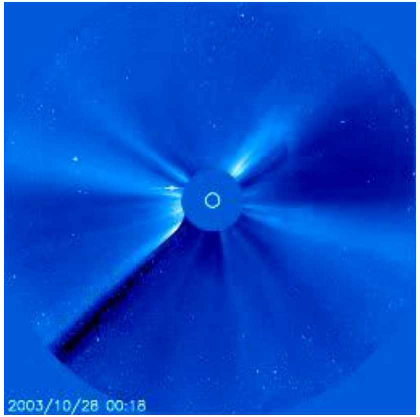






Why are we concerned about radiation in Space?

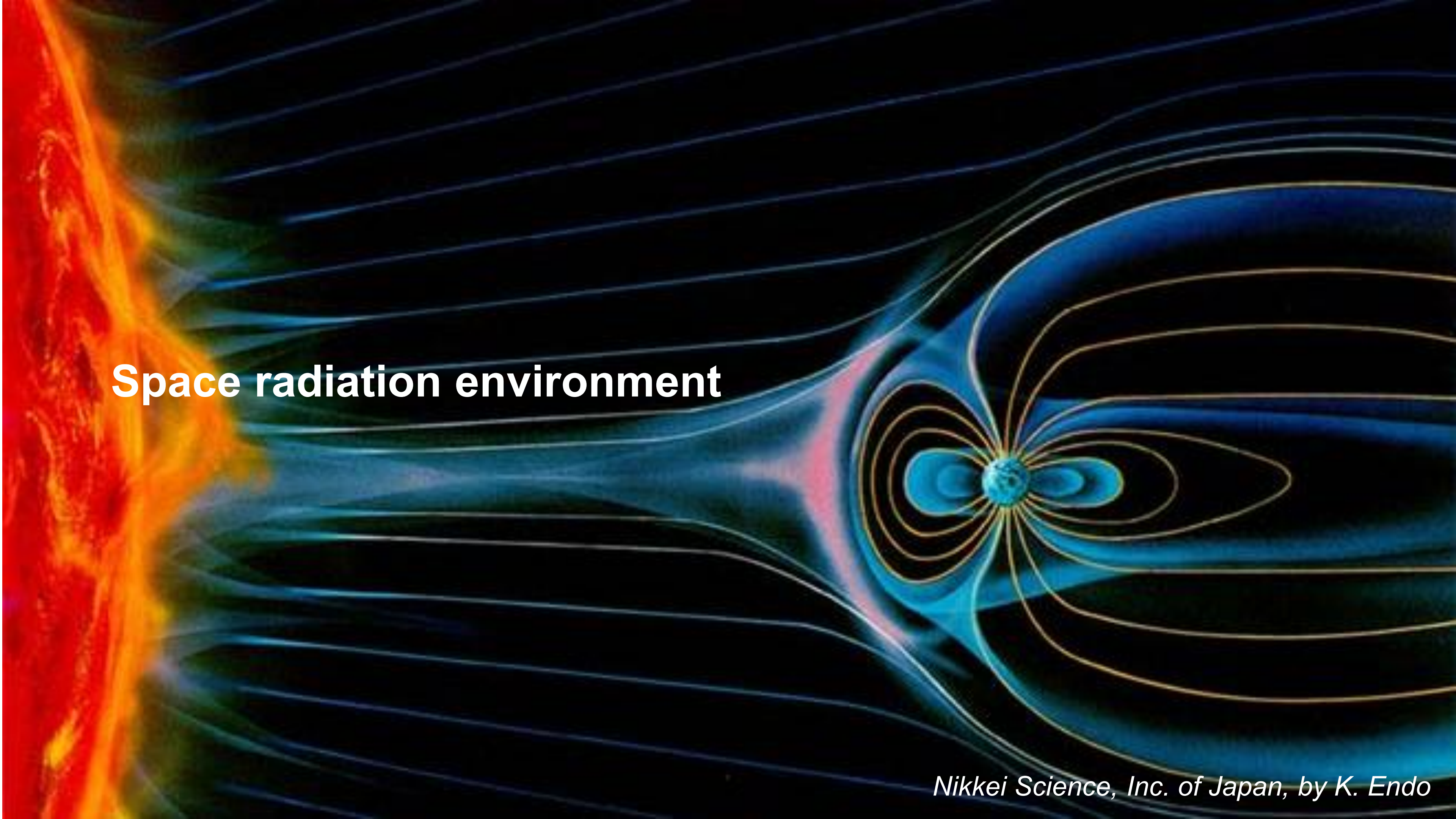
- Space environment includes radiation contribution which is **harsh**
- Ionizing radiation can **affect external & internal EEE components** on a spacecraft
  - Also materials, coatings, biological cells, solar panels ➔ Not covered in this presentation
- Radiation effects can induce a **total failure** of the mission
- Radiation effects can induce **partial failures**
  - availability, requirements not met, partial degradation…
- **Repairs are not possible** & **high cost** of space missions
- **High reliability** is usually required for a space mission
- **On-going understanding**: new components, new effects, new risk-profiles…
  - Active research, studies in the radiation community
- (…)



SOHO video. The effect of solar Coronal Mass Ejection resulting in a strong high energy proton event. Proton impinging on the imaging sensor of the instrument are observed as bright pixels or streaks.

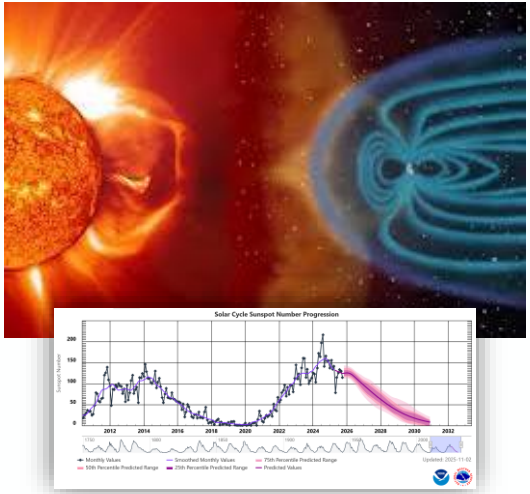
A radiation induced failure of a component, even temporary, can have huge consequences on the overall mission!

Space radiation environment



Nikkei Science, Inc. of Japan, by K. Endo

Radiation types & sources

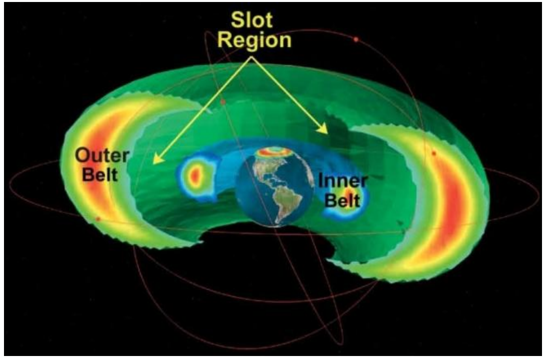


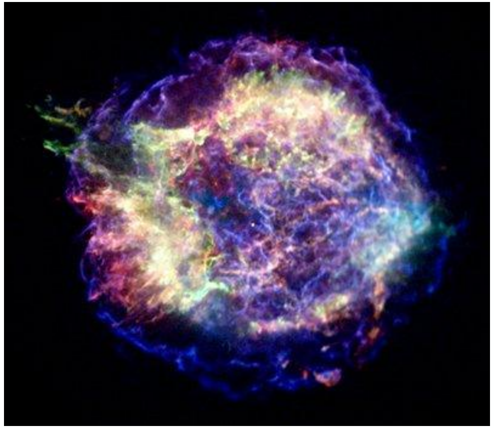
Solar Energetic Particles:

- <u>Solar flares</u>
  (electrons + protons/heavy-ions?)
- <u>Coronal Mass Ejections (CME)</u>
  (protons + heavy-ions)

Van Allen belts:

- <u>Internal</u>
  (protons + electrons)
- <u>External</u>
  (electrons)

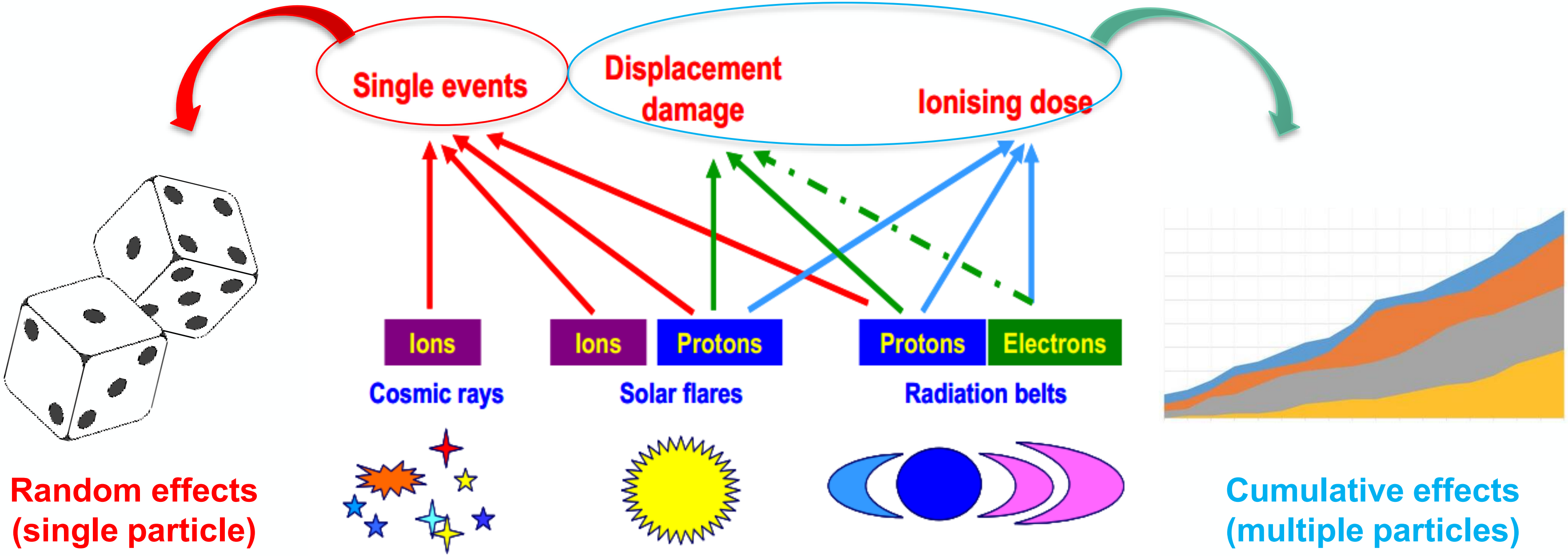




Cosmic Galactic Rays:

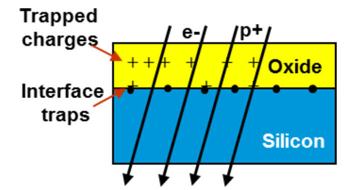
(protons & heavy-ions)

Radiation effects on EEE components



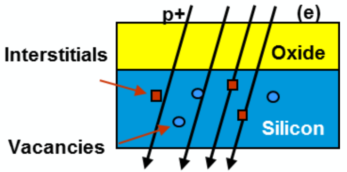
Source: R. Ecoffet, "Spacecraft Anomalies Associated with Radiation Effects", in RADECS 2013 Short Course Proceedings, Chap. VIII, 2013.

Radiation effects on EEE components



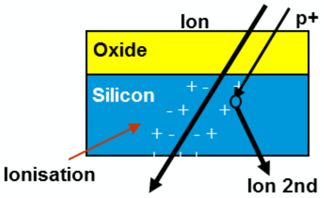
Total Ionising Dose

Electron-hole pairs generation in semiconductor oxides



Displacement Damage

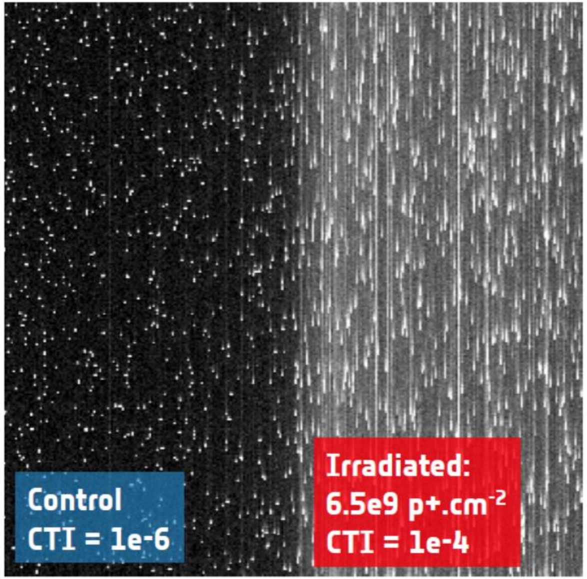
Lattice Displacement Damage caused by energetic particles



Single event effects

Ion deposits significant charge within device that directly affects its operation

TNID and TID Examples

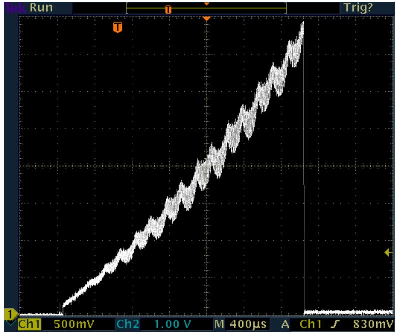


PLATO E2V CCD270, Image acquired while Illuminated by Fe55 X-ray source

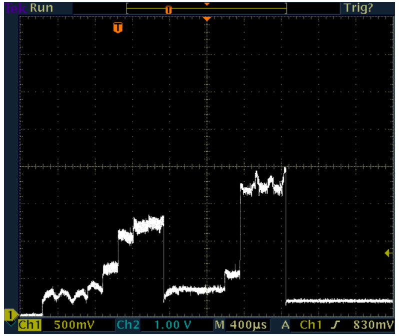
(Prod'homme ESWW2016)

DAC, transfer curve degradation with TID

0 krad(Si)

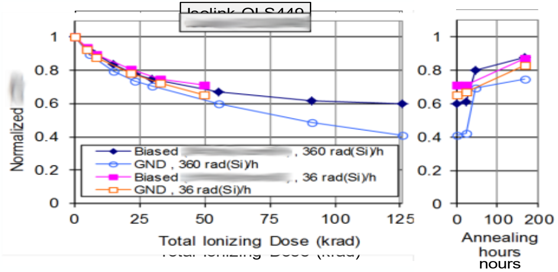


2 krad(Si)



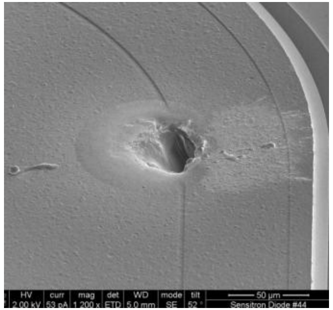
5 krad(Si)

Example of a component parameter degradation due to TID



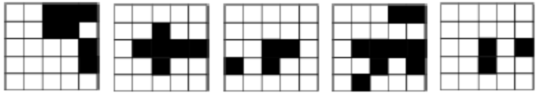
Single Event Effects (SEE)

SEB in a Schottky diode

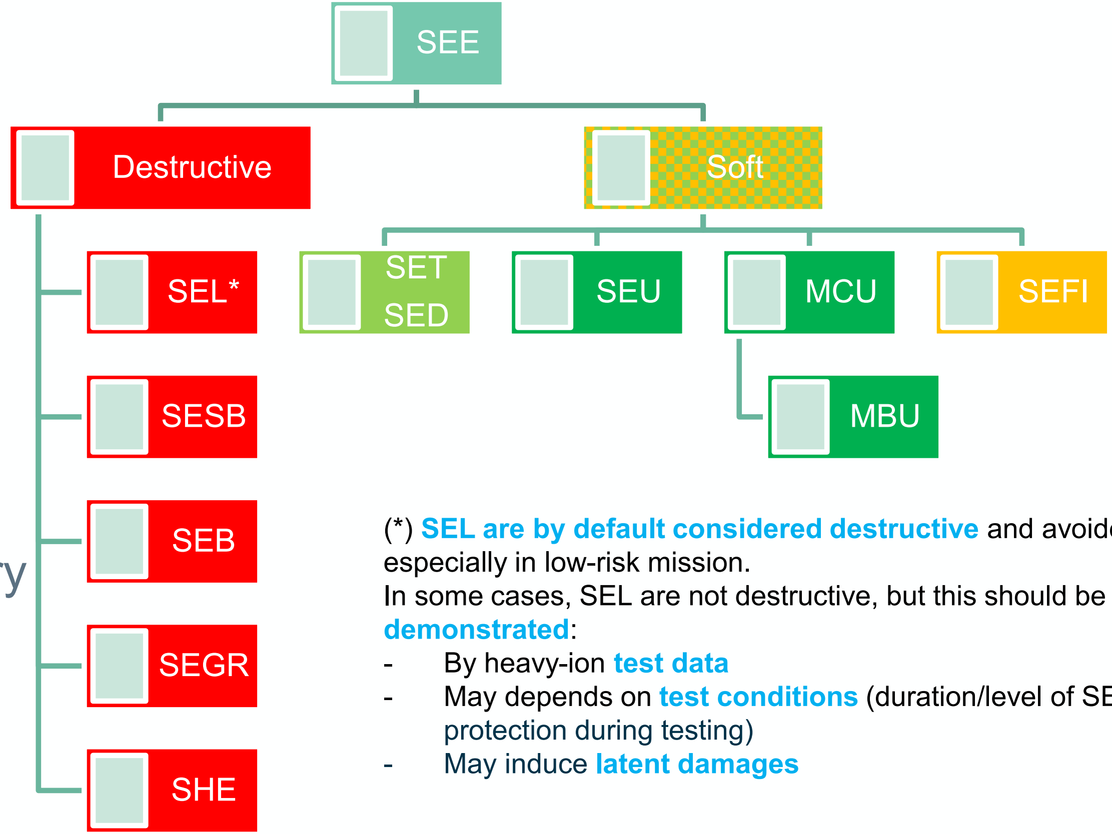


Source: J.S. George, NSREC REDW 2013

MCU in a SRAM memory



Source: Tsiligiannis, TNS 2014



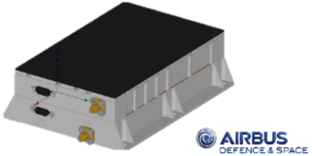
(*) **SEL are by default considered destructive** and avoided, especially in low-risk mission.
In some cases, SEL are not destructive, but this should be **demonstrated**:

- By heavy-ion **test data**
- May depends on **test conditions** (duration/level of SEL protection during testing)
- May induce **latent damages**

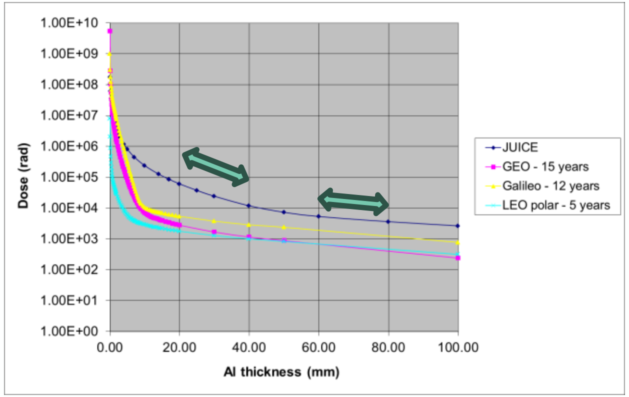
Mitigations against radiation effects

- **In general, TID & TNID can be efficiently mitigated with shielding**
  - In one ESA projects, we increase the top casing thickness of an equipment by 1 mm. This allowed to reduce the TID levels from 10 krad(Si) down to the requirements of 7 krad(Si)

Equipment



FASTRAD Radiation Model



  - **For CubeSats, adding additional shielding is not easy. The main driver for TID is the orbital lifetime.**
- **In general, SEE cannot be efficiently mitigated with shielding**
  - Most particles (heavy-ion, protons) able to penetrate within the S/C where most EEE components are located have high energies
  - In some cases shielding can worsen SEE effects (e.g. high Z)
  - Default use of 1 g/cm² (Al 3.7mm) in most cases.
  - **Hence importance of having robust components & design mitigations & if effects are present, analyse them & impact at system-level!**

100 mils = 2.54 mm

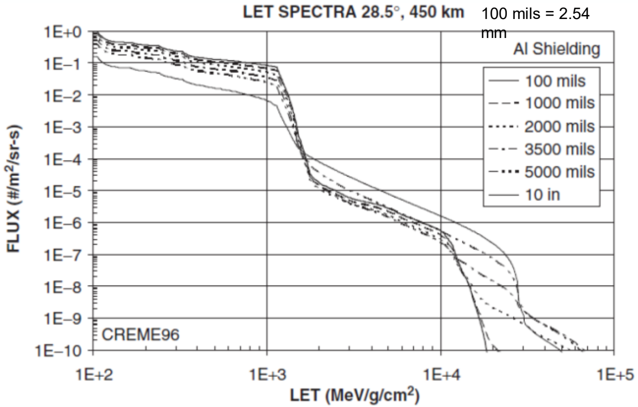
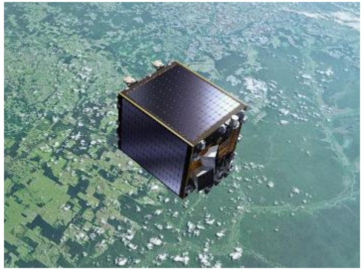
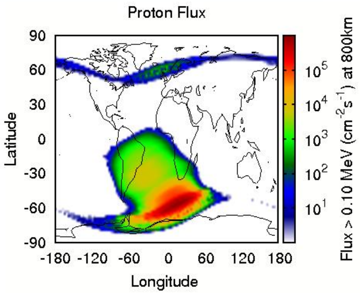
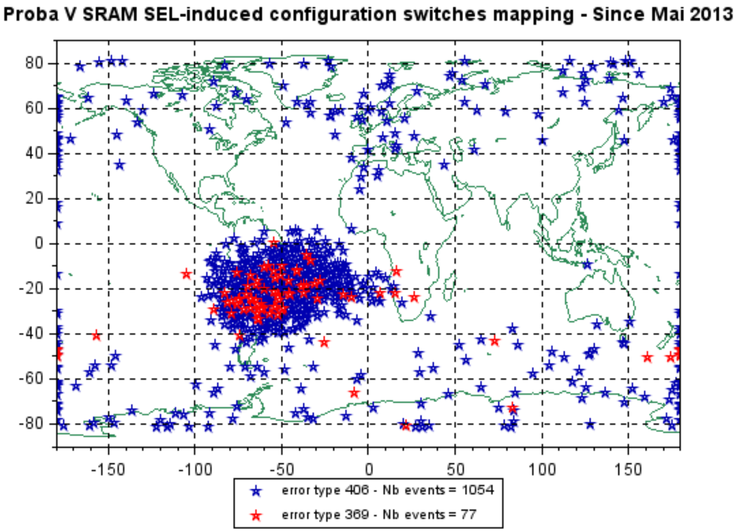


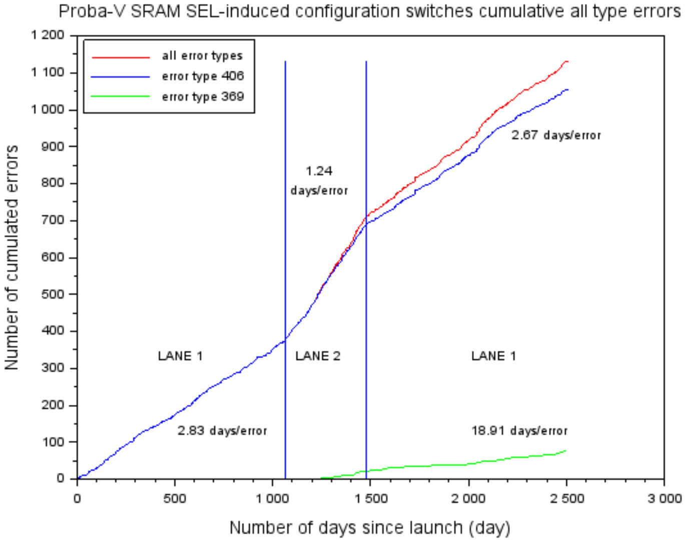
Illustration of the worsening effect of shielding in the LET spectra seen by component in a LEO orbit (450 km altitude, 28.5°) [Petersen, 2011]

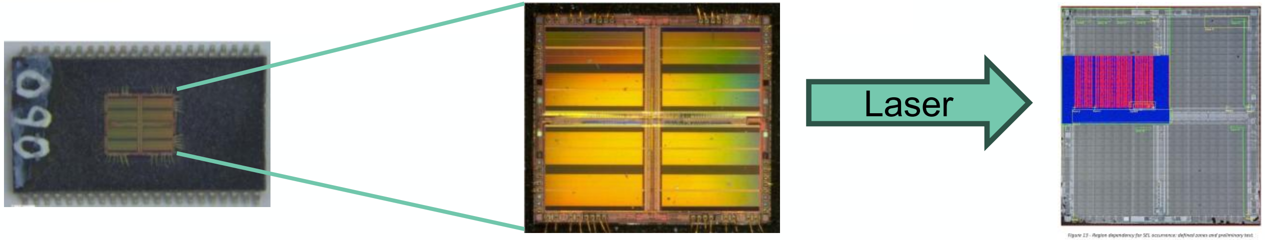
Proba-V SRAM memory: ex. of in-orbit SEE data





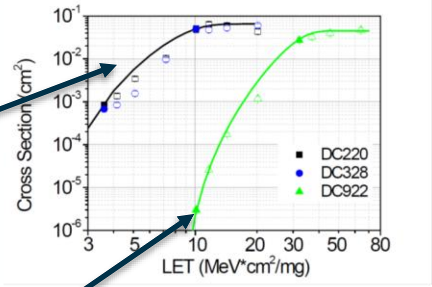


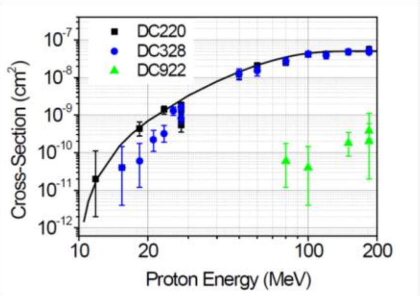


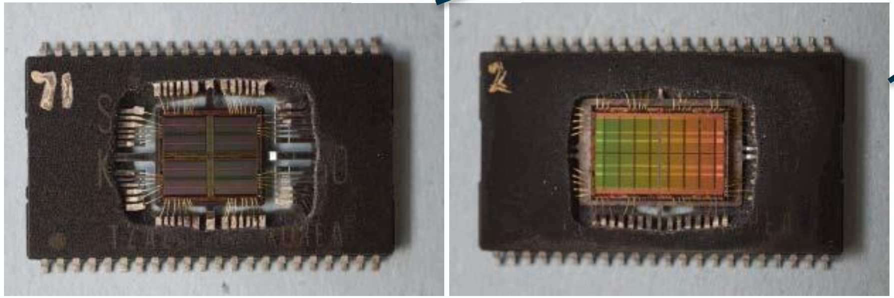


Traceability of COTS:

- ## Example of 4M SRAM K6R4016V1D on Proba-V







Die rev D – more sensitive to SEL

Die rev C – more robust to SEL

DC220 or DC328: ~ 1 SEL every 3 days on LEO polar orbit

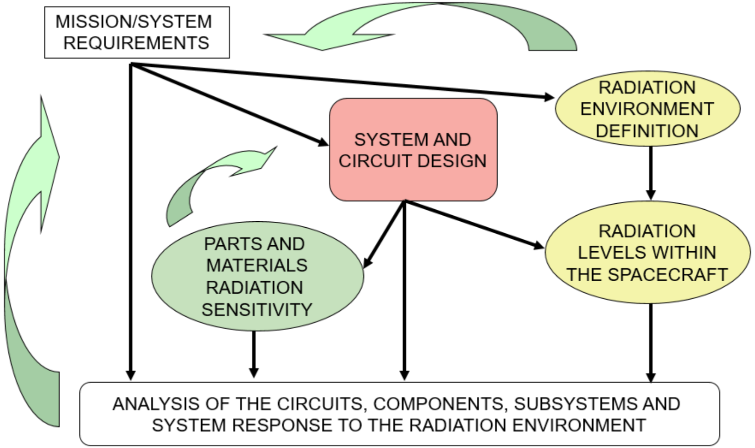
- Traceability of COTS remains an issue
- But now there are options “in between”: COTS+/SEP/SP/RadTol types of part
- However, this is **not for all part types** & in some cases these parts remain “**too expensive**” or high MOQ needed

What is RHA?

- **ECSS-Q-ST-60-15C 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 environment.**

- Radiation Hardness Assurance (RHA) is a **PA discipline.**
  - The RHA engineer reports to the PA Manager in a project & discusses with other experts, SE…

- RHA deals with:
  - **Radiation environment definition**
  - **Mission/system/subsystem requirements (impacting RHA)**
  - **Radiation requirements**
  - **Spacecraft layout**
  - **Radiation tolerant design & mitigations**
  - **Part selection**
  - **Radiation testing**

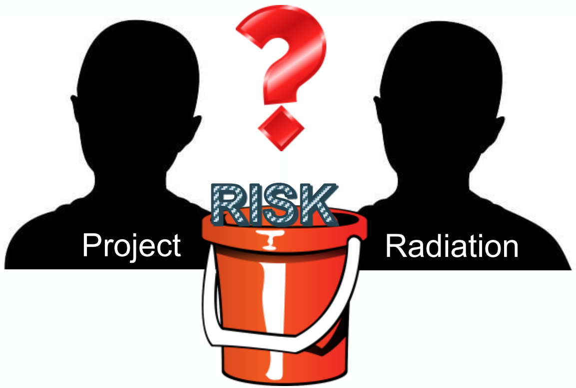


It’s all about risk (against radiation)!

High-class mission

In-orbit demonstration

Educational mission



It depends on the mission/orbit/requirements (reliability, availability) and equipment criticality…and the **radiation-induced risk** you are willing to take.

Only a **good knowledge** of the existing radiation-induced risks for a given mission & the mission “constraints” (budget, criticality…) allow to define the most adequate RHA Plan tailored to a mission.

The overall **RHA Plan** (in the PA Plan) as well as additional requirements defines the level of RHA activities to be performed. *Note: RHA Plan is an answer to the PARD (PA Requirement Document)*

Most of the time, radiation test data is required. **No data = No RHA** => Risk becomes a project one!

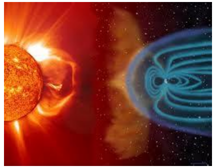
RHA: When & How?

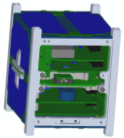
When:

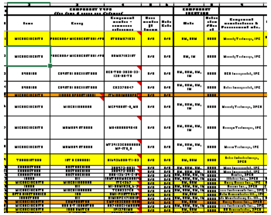
- From the **start of the project**, up to "CDR" (bulk of work)…until in-orbit anomaly investigations!
- Radiation tests, as part of RHA, are done before CDR…but also after CDR for RADLAT.

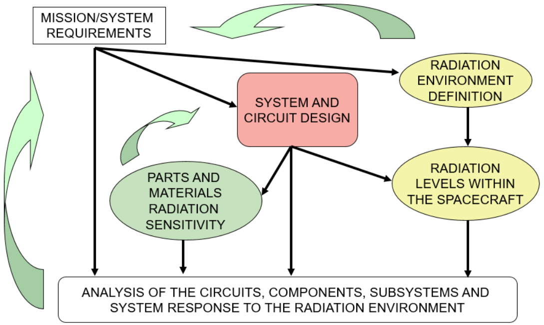
How:

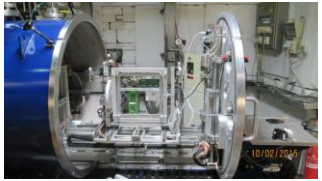
- RHA engineer + **interaction** with PA manager & other engineers from several disciplines
- **Iterative** process but which should start early during the project lifecycle
- Summarised in the **Radiation Analysis Report**
- **Other documents**: PARD, PA Plan, Rad. Environment Specifications, WCA, PSA, FMECA, Radiation TID/TNID/SEE Test Plan & Test Reports…
- Most important review: **RCB**





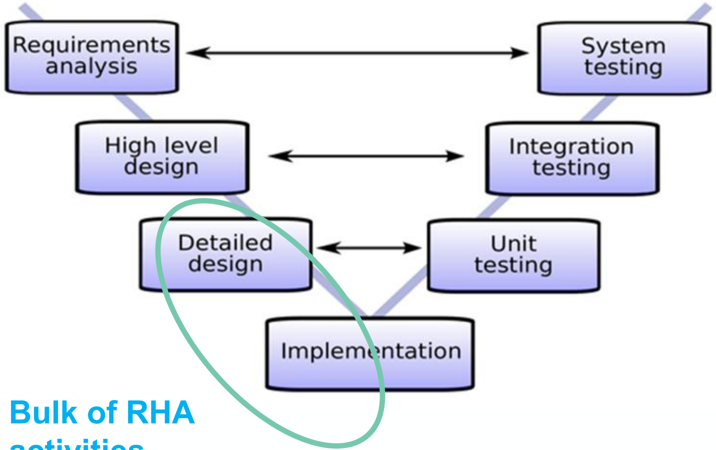






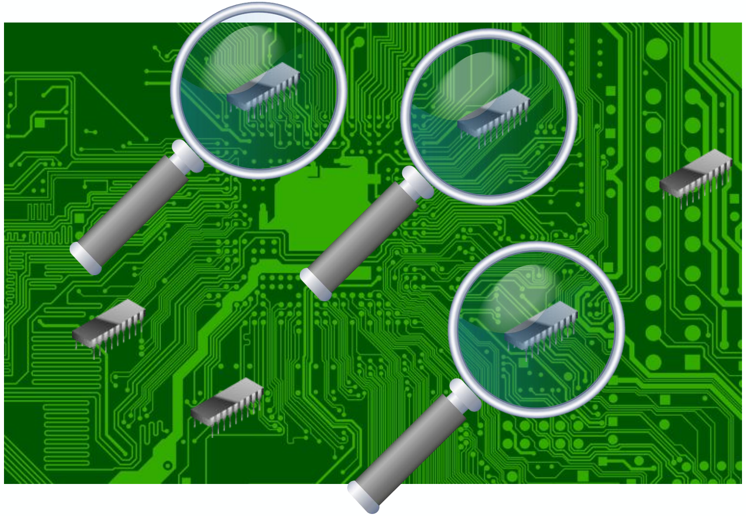
RHA and project phases

- **Pre-Phase A, Phase A**
  - Draft environment definition
  - Draft hardness assurance requirements (top level)
  - Preliminary studies
- **Phase B up to PDRs**
  - Final environment definition
  - Electronic design approach
  - Preliminary spacecraft layout for shielding analysis
  - Preliminary shielding analysis
    & hardness assurance requirements update
- **Phase C up to CDRs**
  - **Radiation test results**
  - Final shielding analysis & final hardness assurance requirement
  - **As-designed RCB (Radiation Control Board)**
  - Circuit design analysis results
- **Phase D**
  - Radiation Lot Acceptance Tests (RLAT)
  - **As-built RCB (Radiation Control Board)**
- **Phase E**
  - Failure analysis



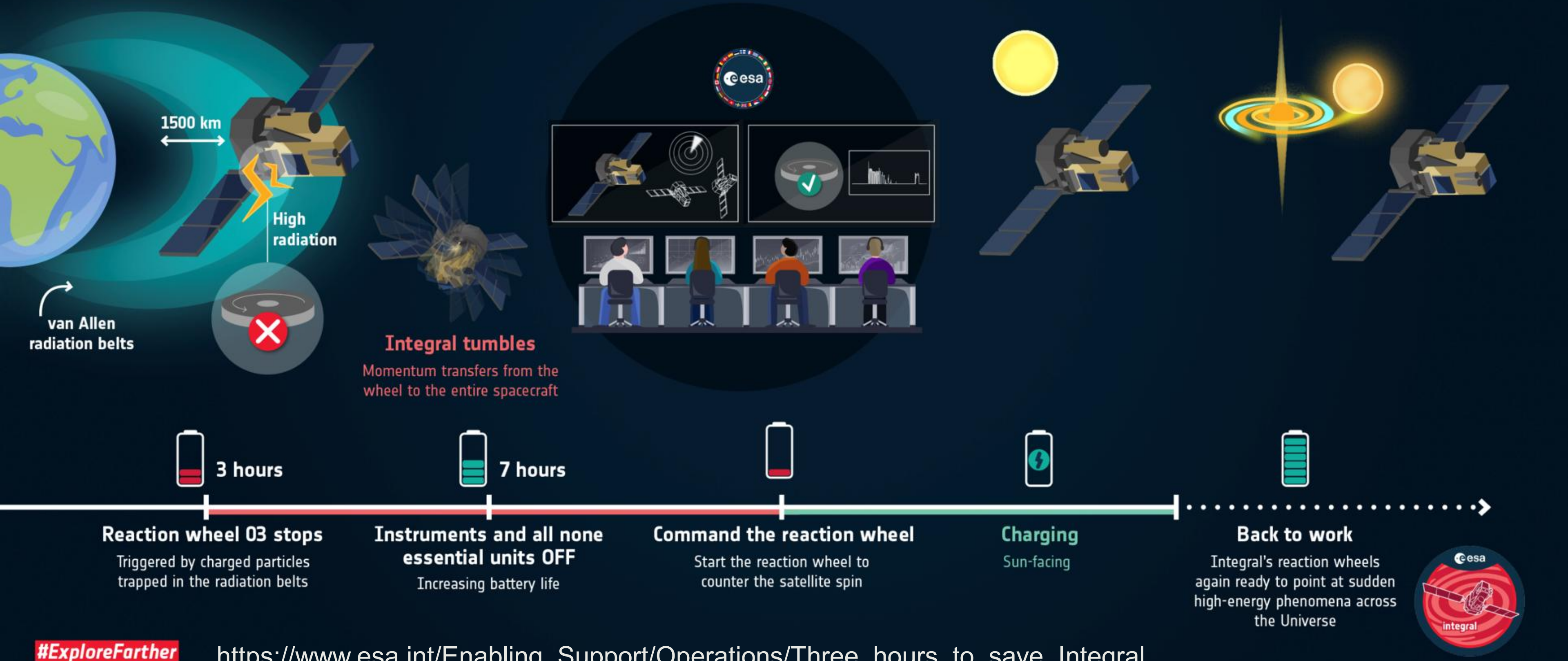
Bulk of RHA activities

From parts to system level assessment



RESCUING AN UPSET INTEGRAL

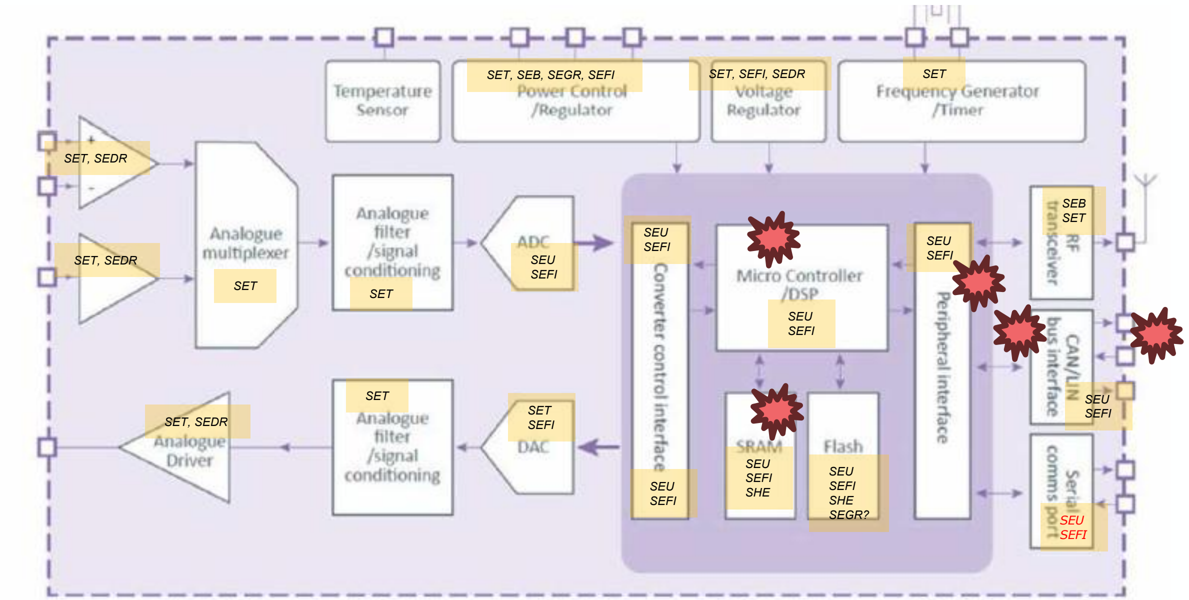
On 22 September, one of three active 'reaction wheels' onboard ESA's Integral spacecraft turned off without warning and stopped spinning, causing a ripple effect that meant the satellite itself began to rotate.
As its solar panels turned away from the Sun, its batteries began to lose energy. There were **only three hours left to save the mission.**



#ExploreFarther

https://www.esa.int/Enabling_Support/Operations/Three_hours_to_save_Integral

Radiation effects on complex electronics

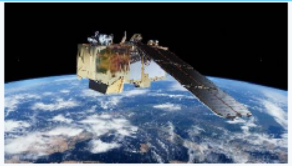
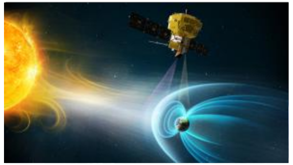
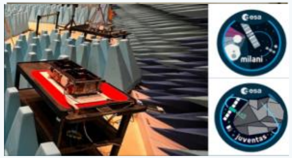


Source: [www.swindonsilicon.co.uk] for the functional block diagram.

- SEE affects complex systems made of several components.
- Digital & analog circuits but also using mixed signal ASICs.
- SEE may affect a single component but may also propagate to other blocks.
- Same for TID/TNID parameter degradations

After understanding how each component respond to various radiation-induced effects, it is important to understand how they **propagate** & their **impact at system-level**!

Mission Classification: 4 classes

ALPHA	• Top class missions • Extremely critical and strategic for ESA. • Budget > 400 M€ • Lifetime > 7 Years. • Requirements are high, risk is very low.		✓ Critical strategy/safety (e.g. manned missions) ✓ High level of requirements and low risk. ✓ Performances should be met whatever it takes
BETA	• High class missions, • Highly critical and strategic for ESA • Budget 200 to 400M€, • Lifetime 5 to 7 Years, • Requirements are relatively high, and the risk is low.		✓ Finding the best compromise between risk and cost to deliver the mission
GAMMA	• Medium class missions, (e.g. hosting New Space type of mission) • Medium critical and strategic for ESA Budget 25 to 200M€ • Lifetime 2 to 5 Years, • Requirements are moderate with a non-negligible risk.		✓ Mission is designed according to a hard cost limit (affordability approach)
DELTA	• Low class mission, • Low critical and strategic for ESA • Budget < 25M€, • Lifetime <2 years • Requirements are very limited with a significant risk.		✓ Almost full delegation to industry (Minimum requirements but increased risk)

ESA Mission Classification – Alpha to Delta Tailoring

(latest internal updates – pending finalisation before release)

	Class Alpha	Class Beta	Class Gamma	Class Delta
Traceability	High	High but low acceptable (procurement lot)	Low is sufficient*	Low is sufficient*
TID	ECSS	As ECSS, component or board level testing (3 boards)	If TIDL > 5 krad (DDC)/2.5 krad (Ray Tracing), component or board level testing (2 boards)	if TIDL > 5 krad on components in critical functions, component or board level test (1 board)
TNID	ECSS	As ECSS component or board level testing (3 boards)	*Limited to optoelectronic parts if TNID > 40 TeV/g(Si) (DDC), component or board level test (2 boards)*	Limited to optoelectronic parts in critical functions if TNIDL > 40 TeV/g (Si) (DDC), component or board level test (1 board)
RDMmin (TID/TNID)	ECSS	2 if low traceability or board testing 1 if high traceability	2 if low traceability or board testing 1 if high traceability (parts used in critical functions)	2 if low traceability or board testing 1 if high traceability (parts used in critical functions)
RVT	ECSS + additional requirements for bipolar ICs	ECSS	No RVT*	No RVT*
SEE HI	ECSS	As ECSS, component or board level testing (2 boards)	Critical parts (MOSFETS,..) or parts used in critical functions, component or board level testing (2 boards)	Parts used in critical functions for destructive events, component or board level testing (1 board)
SEE proton	ECSS	As ECSS, component or board level testing (2 boards)	All potentially SEE sensitive parts, component or board testing (2 boards)	Parts used in critical functions, component or board level testing (1 board)
SEE LETth(Si)	ECSS (60 MeV.cm^2/mg)	38 MeV.cm^2/mg	38 MeV.cm^2/mg	38 MeV.cm^2/mg
SEE Mitigations	ECSS	ECSS	DSEE mitigation (derating, SEL protection), NDSEE mitigation	DSEE and NDSEE mitigation in critical functions, recommended for other functions
Rad. Review/Analysis	ECSS	ECSS	Review and analysis based on test data & mitigations & SEE criticality analysis & SEE rates	Review and analysis based on available test data & mitigations & SEE criticality & available SEE rates

ESA Mission Classification – Additional clarifications

- TNID board level testing: proton beam focused on optoelectronic part

- For Power MOSFETs < 200V, no HI data required if (a) Vds < 30% Vds_{max}, (b) Vgs < 50% Vgs_{max} and (c) Vgs_{off} > 0V for N channel and Vgs_{off} < 0V for P channel

- Definition of Criticality:
  - Critical parts: Parts known as potentially very sensitive to destructive events:
    - Power MOSFETs
    - Power devices (e.g. POL, DC-DC, gate drivers)
    - Parts used in overcurrent protection circuitries
  - Critical functions:
    - Interfaces with higher class units (when applicable) to assure no failure propagation
    - Deorbiting functions
    - Functions of high impact on the mission success

- RVT for classes gamma and delta

  Low traceability: test data required on the samples from the same procurement batch

  - procurement batch: multiple samples of a part reference is procured either directly or via a reliable distributor in a single procurement.

RHA requirements: the essential points!

RHA requirements mainly come from:

- Environment
- Risk
- Mission objectives

Drive the RHA requirements which can be grouped in the following:

Engineering

Error types, impact & propagation

- Soft error rate calculation
- Radiation induced availability impact assessment
- Methodology
- Criticality assessment
- Etc…

Availability

No destructive/ permanent effects

- Destructive SEE LET threshold
- Ensuring also no destructive effects due to SEE propagation
- Derating
- WCA analysis
- Etc…

Reliability

Product Assurance

Margins

- RDM for TID, TNID
- Environment margins
- Component margins
- Etc…

RHA methodology/ quality

- Which parts to assess for which effect?
- How/when to test?
- Documentation vs. project phases
- Traceability & RVT
- Calculation methodologies
- Latest knowledge in RHA field
- Etc…

Radiation Analysis Report

Radiation Analysis Report

- What are the **applicable documents**
- Which are the sensitive parts & to which **effects**
- Which are the received **levels**, environment, modelling
- Which is the **RDM** (TID & TNID)
- Analysis of **TID & TNID effects**: drifts, etc…, design mitigations
- Analysis of **SEE effects**: assumptions, test data, calculations, propagation, design mitigations
    - Destructive and non-destructive effects
- Analysis of radiation induced **availability** impact
- **Conclusion & compliance** to project requirements

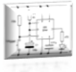
B.1.2 Purpose and objective

The purpose of the equipment Radiation Analysis report is to document in a single place all baseline information (data, assumptions, methods and techniques) used for the radiation analyses, and the results obtained.

Note: Generic template in the ECSS-ST-Q-60-15C Rev.1 Annex B

Radiation Control Boards

INPUTS



- DCL mature
- Design mature

- **Radiation Analysis**
- TID, TNID, SEE test reports

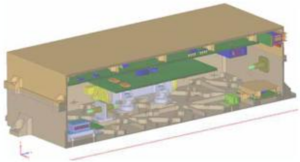
- FMEA
- WCA
- PSA

- Radiation Environment Specification
- Radiation Shielding Analysis

- PAD
- RFD/RFW
- Alerts

As-design RCB (equipment)

- Assessment of parts & potential effects
- Assessment of radiation levels on parts
- Applicability of radiation data (incl. traceability, test conditions, etc…)
- **Assessment on impact of effects at equipment & system level** (criticality, availability…)
- List of actions resulting from "holes"
- Etc…



Equipment & parts approved (*) from RHA point of view for the **given** project.

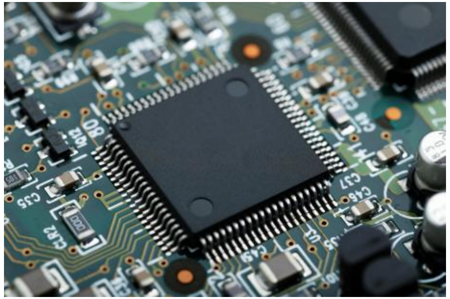
(*) at the current state!

NOTE: **As-built RCB:** Check of deltas, RVT, RFD/RFW….

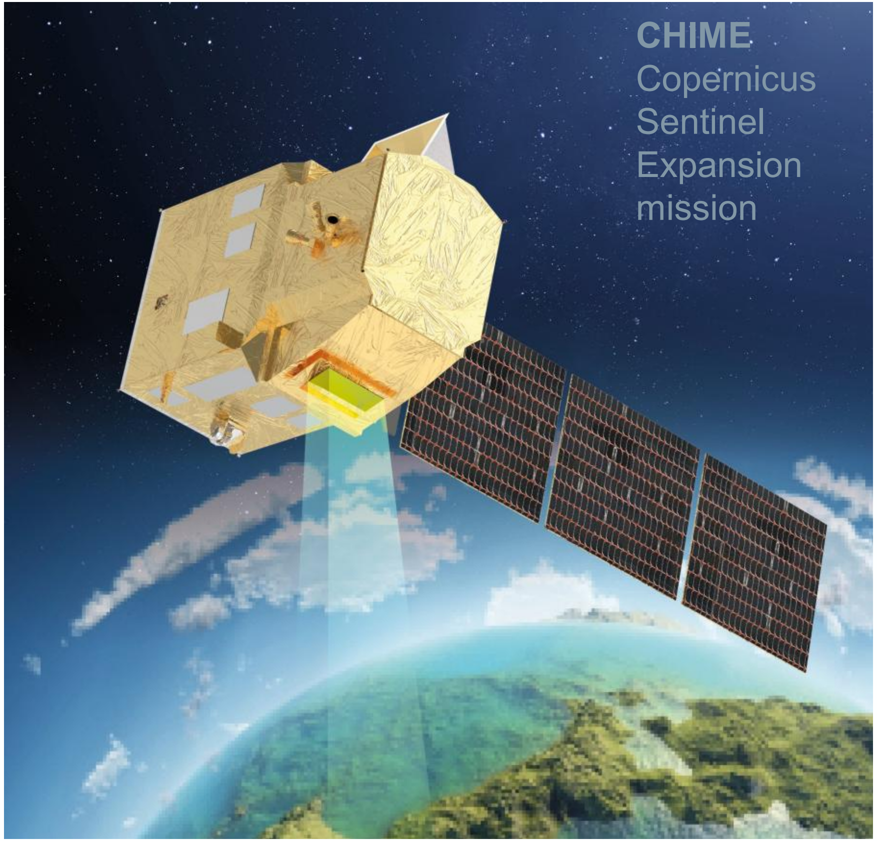
Declared Component List (DCL) – Example

Line Item	ESA Family Code	ESA Group Code	Designation	Designation 2	Generic Type	Value	Package	Manufacturer's Part No	Manufacturer/Country	Detail Specification	Space Qual.	Quality Level	RVT	Procurement Agency	PAD reference
40	4	4	Diode	Zener	1N4104UR-1	10V	DO-213AA	JANS1N4104UR-1	Microsemi/US	MIL-PRF-19500/435	Yes	JANS	No	BGS	
41	4	4	Diode	Zener	1N4106UR-1	12V	DO-213AA	JANS1N4106UR-1	Microsemi/US	MIL-PRF-19500/435	Yes	JANS	No	BGS	
42	4	4	Diode	Zener	1N4107UR-1	13V	DO-213AA	JANS1N4107UR-1	Microsemi/US	MIL-PRF-19500/435	Yes	JANS	No	BGS	
43	7		Magnetic	Power Inductors	SESI_9.1	150uH		320100905151K 320100905C151K	Microspire/FR	ESCC 3201/009	Yes	ESCC	No	BGS	
44	7		Magnetic	Inductor Custom	E25-I-5748		EFD25	E25-I-5748B	Flux/DK	S-QSTD-SPC-00110-RSE	No	Level B	No	BGS	TBD
45	7		Magnetic	Inductor Custom	VT-I-5764			VT-I-5764B	Flux/DK	S-QSTD-SPC-1062965-RSE	No	Level B	No	BGS	TBD
46	7		Magnetic	Bus Interface Transformer	DBIT-5-7S		SMD	MS09685-02 MS09685-02C	Microspire/FR	MSP-003	No	ESCC equivalent	No	BGS	TBD
47	7		Magnetic	Transformer Custom	E30-T-5778		EFD30EX	E30-T-5778B	Flux/DK	S-QSTD-SPC-1134142-RSE	No	Level B	No	BGS	TBD
48	7		Magnetic	Current Sense Transformer	CT91-200-1WR			MS08222A-02 MS08222A-02C	Microspire/FR	MSP-004	No	ESCC equivalent	No	BGS	TBD
49	8	53	IC Analogue	Comparator	LM139A		14-FP	5962-9673801VDA	Texas Instruments Inc/US	SMD 5962-96738	Yes	QML-V	Yes	BGS	TBD
50	8	50	IC Analogue	OpAmp	ISL70227SEH		10-FP	5962R1222301VXC	Intersil/US	SMD 5962-12223	Yes	QML-V	No	BGS	
51	8	50	IC Analogue	OpAmp	RH1014		14-FP	RH1014MW	Analog Devices/US	05-08-5014	No	QML-V Equivalent	No	BGS	TBD
52	8		IC Analogue	Voltage Reference Serie	ISL71090SEH12		8-FP	5962R1321101VXC	Intersil/US	SMD 5962-13211	Yes	QML-V	No	BGS	
53	8		IC Analogue	Voltage Reference Serie	ISL71090SEH25		8-FP	5962R1321102VXC	Intersil/US	SMD 5962-13211	Yes	QML-V	No	BGS	
54	8		IC Analogue	Voltage Reference Serie	ISL71090SEH50		8-FP	5962R1321103VXC	Intersil/US	SMD 5962-13211	Yes	QML-V	No	BGS	
55	8	52	IC Analogue	Voltage Reference Shunt	LT1009		TO-46	JM38510/14802SXA	Linear Technology/US	MIL-M-38510/148	Yes	Class S	Yes	BGS	TBD
56	8	52	IC Analogue	Voltage Reference Shunt	RH1009		TO-46	5962R8961002VXC	Analog Devices/US	5962-89610	Yes	QML-V	No	BGS	
57	8	52	IC Analogue	Voltage Reference Shunt	RH1009		10-FP	5962R8961002VHA	Analog Devices/US	5962-89610	Yes	QML-V	No	BGS	
58	8	69	IC Analogue	Pulsewidth Modulator	ISL78845ASRH		8-FP	5962R0724908VXC	Intersil/US	SMD 5962-07249	Yes	QML-V	No	BGS	
59	8	69	IC Analogue	Pulsewidth Modulator	UC1825A-SP		16-DIL	5962-8768105VEA	Texas Instruments Inc/US	SMD5962-87681	Yes	QML-V	Yes	BGS	TBD
60	8	42	IC Analogue	Mixed Signal ASIC	EOCD		64-QFP	114916601R	HCM.SYSTREL/FR	S-QSTD-SPC-1149166-RSE	No	ESCC equivalent	Yes	BGS	TBD
61	8	42	IC Analogue	Mixed Signal ASIC	M2		172-QFP	0009303R	Micross Components/UK	S-QSTD-SPC-00093-SE	No	ESCC equivalent	Yes	BGS	TBD
62	8	55	IC Interface	Line Driver, CMOS	26C31		16-FP	5962F9666301VXC	Intersil/US	SMD5962-96663	Yes	QML-V	No	BGS	
63	8	56	IC Interface	Line Receiver, CMOS	26C32		16-FP	5962F9568901VXC	Intersil/US	SMD5962-95689	Yes	QML-V	No	BGS	
64	8		IC Interface	Tranceiver	UT63M147		24-FP	32-00077-8/5962R9322603VYA-1 5962R9322603VZA	Cobham Colorado Springs/US	SMD 5962-93226+ AID 32-00077 SMD 5962-93226+S-QSTD-SPC-00114-RSE	Yes	QML-V	No	BGS	TBD
65	8	80	IC Logic	Advanced CMOS	54AC02		14-FP	5962F8761201VYA/RHFAC02K04V 5962F8761201VXA/RHFAC02K02V	ST Microelectronics/FR	SMD 5962-87612	Yes	QML-V	No	BGS	
66	8	80	IC Logic	Advanced CMOS	54AC04		14-FP	5962F8760901VYA/RHFAC04K04V 5962F8760901VXA/RHFAC04K02V	ST Microelectronics/FR	SMD5962-87609	Yes	QML-V	No	BGS	
67	8	80	IC Logic	Advanced CMOS	54AC08		14-FP	5962F8761501VYA/RHFAC08K04V 5962F8761501VXA/RHFAC08K02V	ST Microelectronics/FR	SMD 5962-87615	Yes	QML-V	No	BGS	
68	8	80	IC Logic	Advanced CMOS	54AC14		14-FP	5962F8762401VYA/RHFAC14K04V 5962F8762401VXA/RHFAC14K02V	ST Microelectronics/FR	SMD 5962-87624	Yes	QML-V	No	BGS	
69	8	80	IC Logic	Advanced CMOS	54AC32		14-FP	5962F8761401VYA/RHFAC32K04V 5962F8761401VXA/RHFAC32K02V	ST Microelectronics/FR	SMD 5962-87614	Yes	QML-V	No	BGS	
70	8	80	IC Logic	Advanced CMOS	54AC174		16-FP	5962F8762602VYA/RHFAC174K04V 5962F8762602VXA/RHFAC174K02V	ST Microelectronics/FR	SMD5962-87626	Yes	QML-V	No	BGS	
71	8	80	IC Logic	Advanced CMOS	54AC244		20-FP	5962F8755201VYA/RHFAC244K04V 5962F8755201VXA/RHFAC244K02V	ST Microelectronics/FR	SMD 5962-87552	Yes	QML-V	No	BGS	
72	8	80	IC Logic	Advanced CMOS TTL	54ACT02		14-FP	5962F8979101VYA/RHFACT02K04V 5962F8979101VXA/RHFACT02K02V	ST Microelectronics/FR	SMD5962-89791	Yes	QML-V	No	BGS	
73	8	80	IC Logic	Advanced CMOS TTL	54ACT04		14-FP	5962F8973403VYA/RHFACT04K04V 5962F8973403VXA/RHFACT04K02V	ST Microelectronics/FR	SMD5962-89734	Yes	QML-V	No	BGS	
74	8	80	IC Logic	Advanced CMOS TTL	54ACT244		20-FP	5962F8776003VYA/RHFACT244K04V 5962F8776003VXA/RHFACT244K02V	ST Microelectronics/FR	SMD5962-87760	Yes	QML-V	No	BGS	
75	8	24	IC Memory	EEPROM Module	3DEE4M08VS4145		40-TSOP_CUBE	3DEE4M08VS4145-MS R00ML	3D-Plus/FR	3DPA-3000	No	Spce Grade	Yes	BGS	TBD
76	8	20	IC Memory	SRAM Module	3DSR32M32VS8501		68-SOP_CUBE	3DSR32M32VS8501-MS R12ML	3D-Plus/FR	3DPA3270	No	Spce Grade	Yes	BGS	TBD
77	8	30	IC Complex	FPGA	RTAX1000S		624-CGA	RTAX1000S-CG624E (5962-0422003QUA)	Microchip/US	SMD 5962-04220	Yes	QML-Q, E-Flow	No	BGS	TBD
78	18		Optoelectronic	Optoisolator	66224		LCCC6	66224-300	Micropac Industries/US	SCD# Mii22042010	No	JANS equivalent	Yes	BGS	TBD
79	9	2	Relay	Latching	D	26V	1/6CC_02	360201902B26V	LEACH International Europe/FR	ESCC3602/019	No	ESCC equivalent	No	BGS	TBD
80	10	9	Resistor	Chip, Thick Film	RCZ0603	0.00ohm		M32159B12T	Mini-Systems/US	MIL-PRF-32159/12	Yes	Failure Rate S	No	BGS	
81	10	9	Resistor	Chip, Thick Film	RM0603	1.00ohm- 2.15Mohm		M55342K12BxxxxS	Mini-Systems/US	MIL-PRF-55342/12	Yes	Failure Rate S	No	BGS	
82	10	9	Resistor	Chip, Thick Film	RM1206	0.00ohm		M32159B07T	Mini-Systems/US	MIL-PRF-32159/7	Yes	Product Level T	No	BGS	
						1.00ohm-									

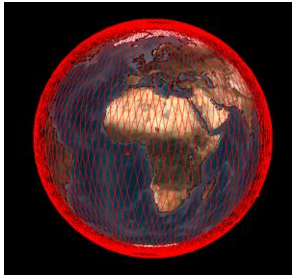
Ex. of a critical activity in low-risk missions: CHIME



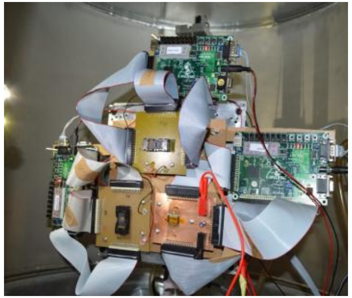
- Critical : 1 FPGA to perform the processing & compression of all 3 instruments
- FPGA: Complex devices = complex to test
- What is the best approach?
- Iterations within ESA:
  - FPGA engineer
  - Data Handling engineer
  - On-board data processing engineering
- Iterations with Industry:
  - PRIME
  - Subco



SEE error rate calculation – non DSEE/NDSEE



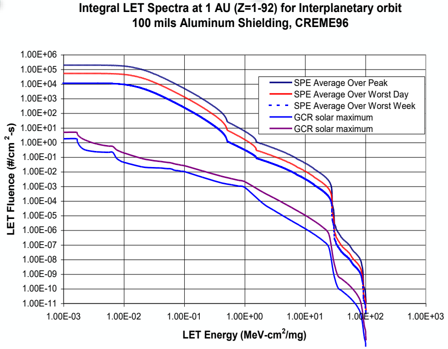
Environment



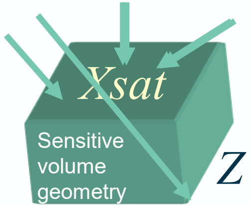
Sensitivity

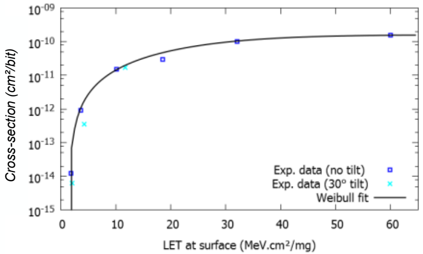
Source: V. Gupta, PhD manuscript

SPENVIS, OMERE, etc…



IRPP Method





=

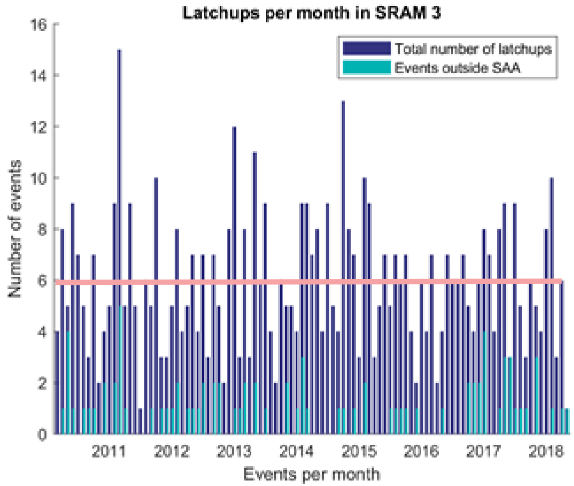
6.64×10^{-5} error/day/device

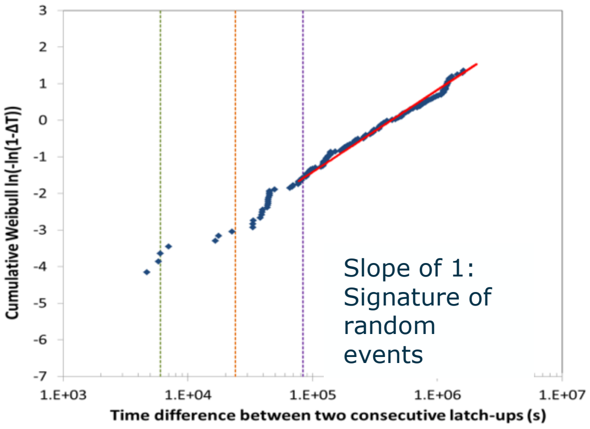
(average value, sometimes "/bit")

Careful in interpreting this rate!

Rate of occurrence is not steady, it varies randomly

SEEs are random events

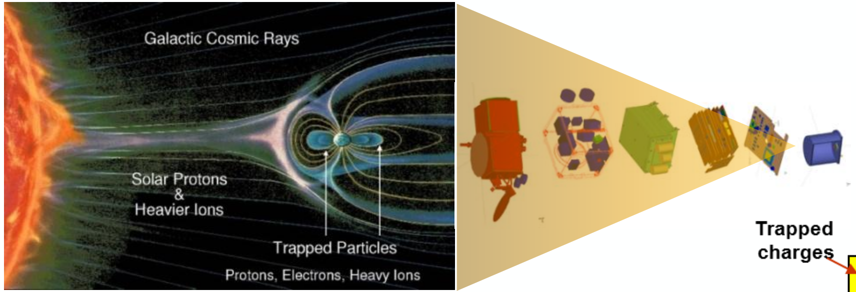


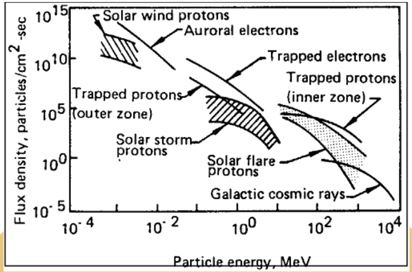


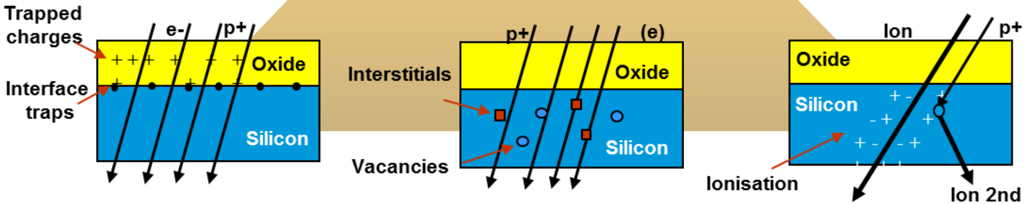
PROBA-2 SEL experiment, ISSI IS615128 SRAM *(ESA data)*

- **A SEE with a low probability of occurrence can occur the first day of a mission**
  - ➢ MBU rate in AT65609 ATMEL SRAM: 1 event every 40 years on GEO, one **MBU occurred after less than one month of flight**
  - ➢ SEB (destructive) on UCC1802 PWM: 1 event every 300 years for the mission. **1 failure occurred after ~1 year of flight**

From space environment to EEE testing



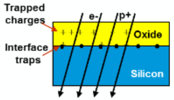


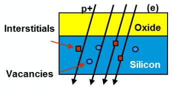


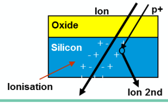
Radiation/Matter interaction	Ionising process	Non-ionizing process	Charge deposition
Radiation effects on semiconductors: 3 Mechanisms Model	Total Ionising Dose	Displacement Damage	Single Event Effects
Standard source to create these effects in LABORATORY	High energy **photons (60Co)**	High energy **protons**	High energy **heavy-ions & protons**

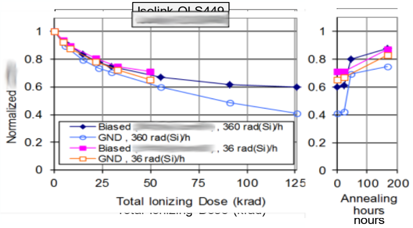
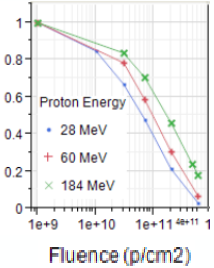
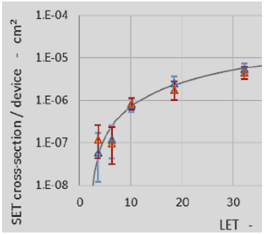
To which complementary (not alternative) methods can be used: e.g. **laser**, **pulsed X-ray** (“new”)….

How do we test?



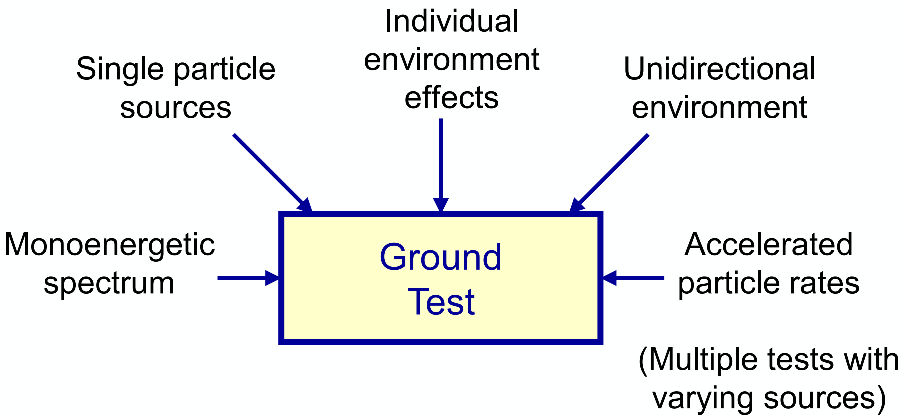




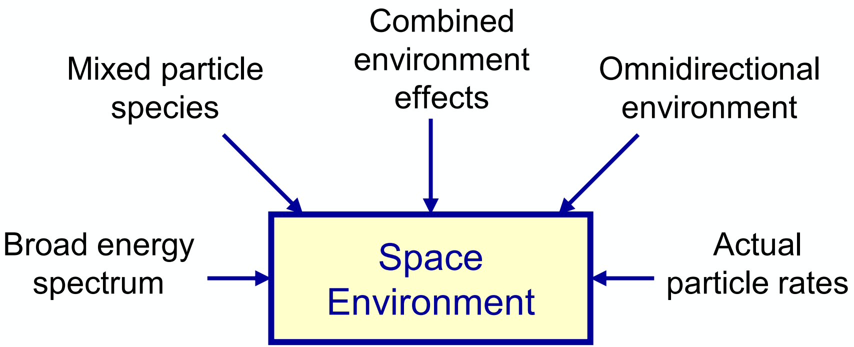
Total Ionising Dose	Displacement Damage	Single Event Effects
Cumulative effect: Gradual global degradation of device parameter		Probabilistic effect: transient, permanent or static errors.
PERFORMANCE DEGRADATION as function of :		CROSS SECTION (=Probability of SEE occurrence) as function of:
Total dose [rad(Si)] [Gy(Si)]	Fluence [p/cm^2]	LET [MeV/mg/cm2] or E [MeV]
		
Other parameters: Dose rate [rad(Si)/s] [Gy(Si)]	Other irradiation test parameter: Proton Energy [MeV], Flux [p/cm^2/s]	Other irradiation test parameter: Flux[p/cm^2/s] , particle range [um]

Limitations of testing on-ground

Ground testing conditions



Actual conditions



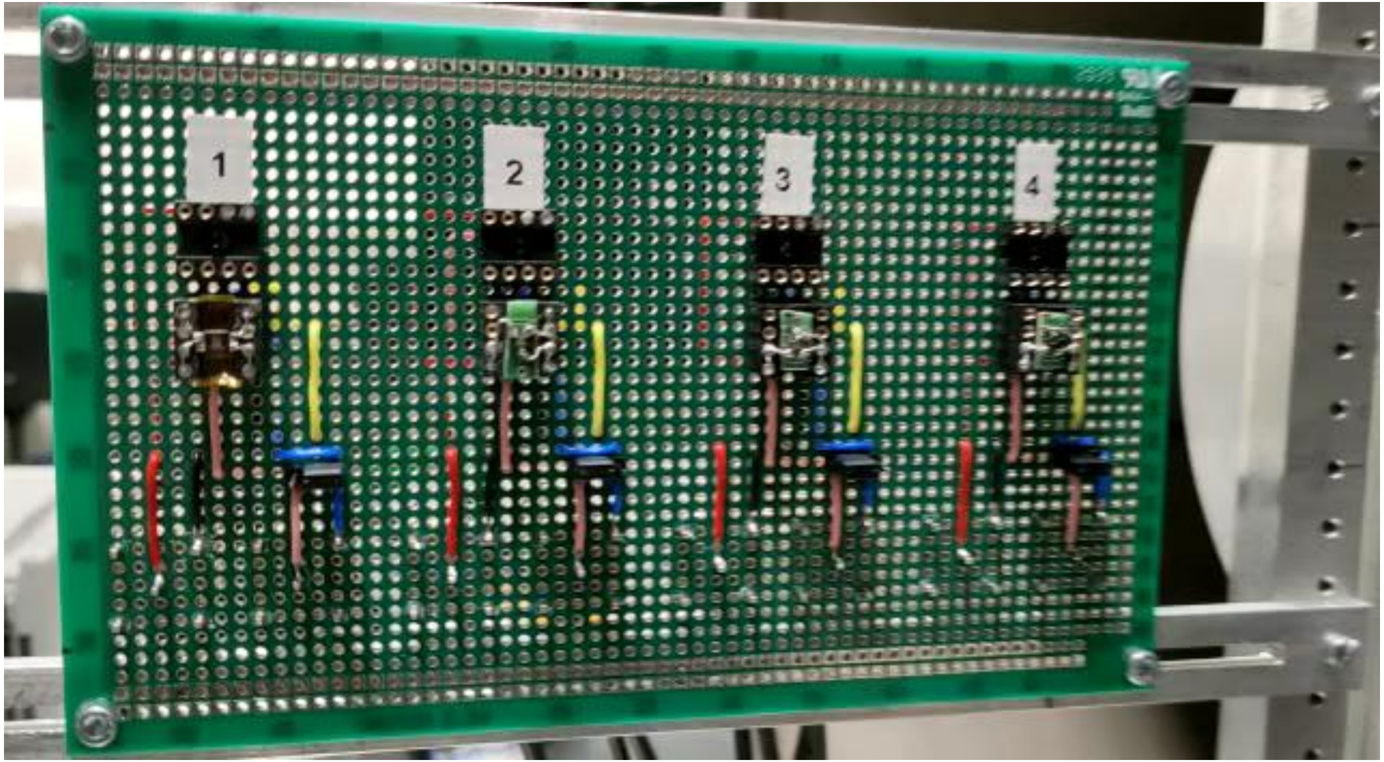
(After LaBel & Stassinopoulos)

Testing according test standards provide a conservative estimate of in-flight degradation

Heavy-ion testing (SEE) – UCLouvain Facility

Example of a test campaign: SET testing of Bandgap References @UCLouvain in Belgium Nov 2021

Heavy-ion testing (SEE) – UCLouvain Facility



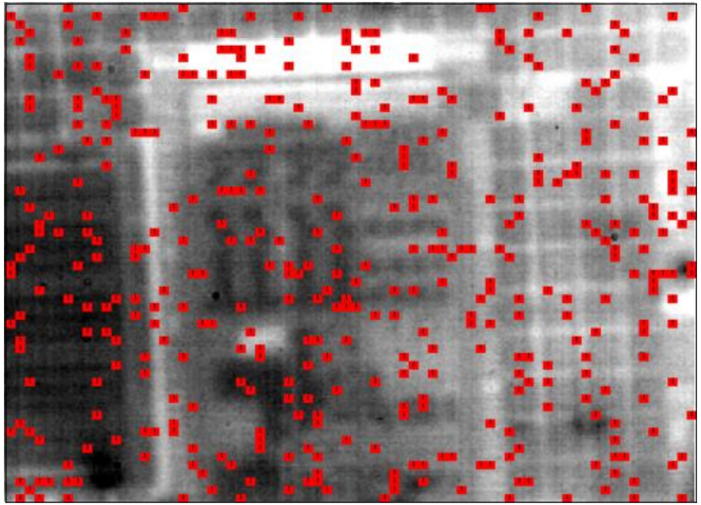
Example of a test campaign: SET testing of Bandgap References @UCLouvain in Belgium Nov 2021

Radiation testing – Co60 TID

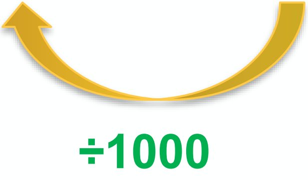
Proton vs. Heavy-ion testing

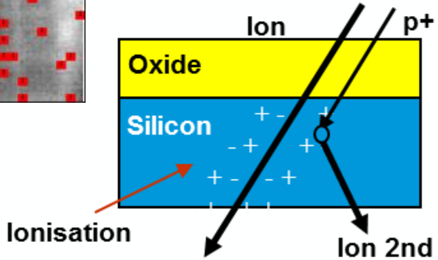
60×70μm2 portion of Hitachi EDS5108 512 Mbit SDRAM

10^7 ions/cm^2 typical of HI SEE test

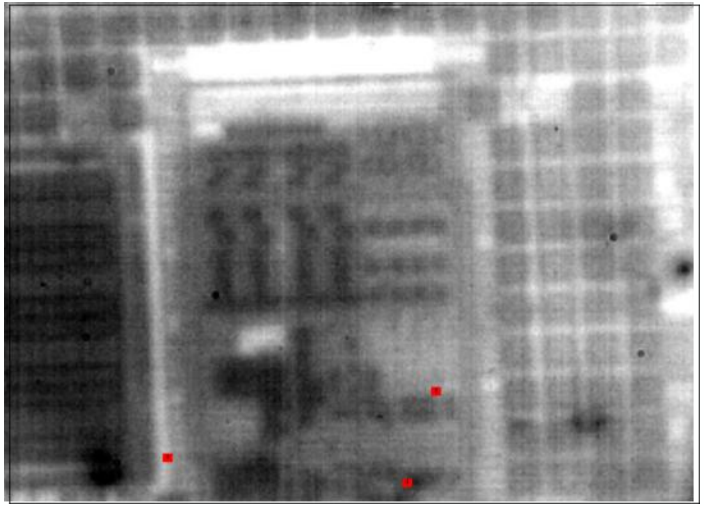


[Ladbury, Short Course, NSREC 2017]





Recoil ions due to 10^{10} protons/cm^2



[Ladbury, Short Course, NSREC 2017]

Testing for Space at ESA: T.I.N.A

- Developing new methods & technics are part of the constant search for improvements of RHA processes

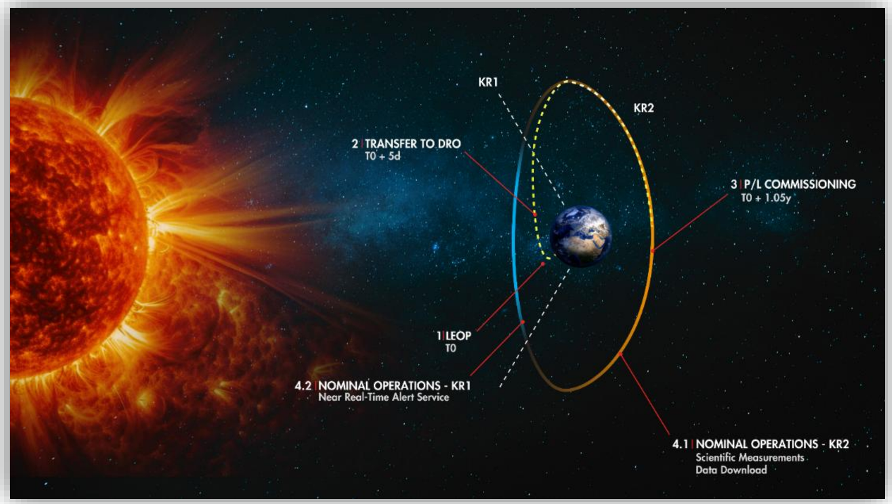
- However currently and, at least at ESA, **there is no alternative testing methods** accepted than the traditional ones:
  - **SEE: heavy-ion and if/when required high-energy protons**
  - **TID: Cobalt 60**
  - **TNID: Protons**

- Alternative methods, in some cases, can **complement** traditional based methods, or provide **preliminary inputs** before radiation testing is performed:
  - Laser
  - Californium
  - Etc…

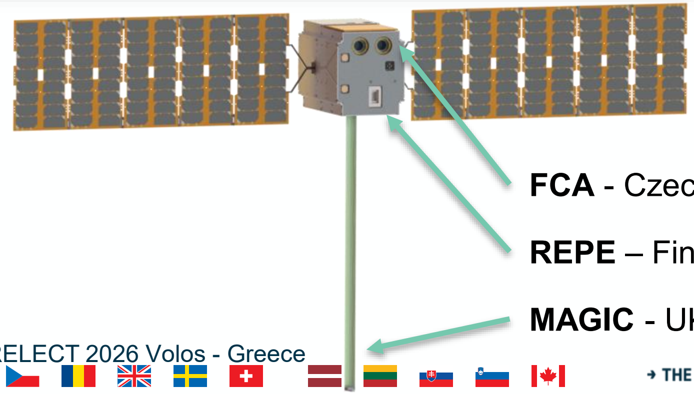
©Sébastien Vassant, Alternatives Economiques website

HENON: Space Weather Warning Demo Mission

- **Programme:** GSTP Fly element
- **Project:** HEliospheric pioNeer for sOlar and interplanetary threats defeNce (HENON)
- **Contractor:** Argotec (prime IT), INAF, Uni. Calabria, Uni. Florence, SpaceDys, IMT, Mars Space, Imperial College London, ASRO/Turku
- **Platform:** 16 CubeSat
- **Payloads:**
  - Energetic particle flux telescope (REPE)
  - Magnetometer on boom (MAGIC)
  - Faraday Cup Analyzer (FCA)
- **Mission:**
  - **Space weather** measurements in Distant Retrograde Orbit (DRO) for 4-10 hour advanced warning of solar storms (when on sunward side)
  - **Transfer** from Sun-Earth L1/L2 to DRO using electric propulsion
  - **Demo of European Deep Space CubeSat technologies**: Transponder, Electrical Propulsion...



Michel Hénon
(French mathematician & astronomer)



FCA - Czech Republic

REPE – Finland

MAGIC - UK

RHA in the frame of HENON

1. **Risk level & requirements (ESA):** Class Gamma
2. **Scope of the activity (ESA):**
   - ➢ Which units to work on, which not
   - ➢ Tuning RHA approach to project constrains & balance approach
3. **RHA Workshops (ESA & teams):**
   - ➢ Several iterations with each unit responsible (DCL & design)
   - ➢ Iteration on parts & design improvement discussions
   - ➢ Balance between parts to test & RadTol/COTS+ selection
   - ➢ Test strategy definition: HI (part level), P (board level), - (if designed with "good parts" & critical effects mitigated
4. **Testing(teams & ESA):** RADEF (Finland), UCL (Belgium), PSI (Switz.)
5. **Reporting (teams) :** Test reports & Radiation analysis (required for all)

Some lessons learned:

- RHA Workshop discussions:
  - Start early: impact on radiation activities later.
  - Consider the right balance in COTS vs. COTS+/RadTol/(RadHard)
  - For parts to be tested: ensure design retro-compatibility with back-up options if possible
- Testing:
  - Consider EEE part procurement delays & "procurement lot"
  - Consider testing complexity: outsourcing an option?
- Schedule:
  - Careful with underestimating test facility availability (3-6 months)
  - Careful with underestimating readiness of set-up
- Reporting:
  - Availability (if critical) & impact propagating outside equip. besides reliability & other considerations.

NOTE: TID for this mission was not a driver, focus was on SEE

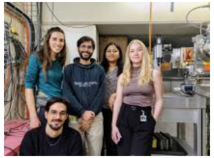
UNIT	DESIGN OWNER	RAD. TEST	Rad. Analysis Report
REPE (PL)	ASRO-UTU	HI & P	Yes required
FCA (PL)	Charles University	HI & P	Yes required
MAGIC (PL)	Imperial College London	P	Yes required
OBC	Argotec	-	Yes required
PCDU	Argotec	-	Yes required
RADIO & uSADA	IMT	HI	Yes required
E-PROP - PPU	TechLine	HI	Yes required
E-PROP - TPME	AVS	-	Yes required

HI test ESA for MAGIC

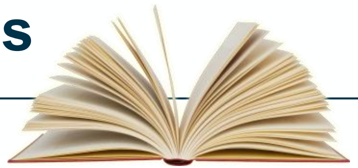
HI tests UCL with TechLine

P tests PSI with FCA/Argotec

P tests PSI with REPE/Argotec



European space radiation standards/guidelines



ESCC Radiation Test Methods and Guidelines:

- SEE Test Method and Guidelines: ESCC 25100
- TID Steady-state Irradiation Test Method: ESCC 22900
- Guidelines for Displacement Damage Irradiation Testing: ESCC 22500

ECSS Standards and Handbooks:

- RHA – EEE Components: ECSS-Q-ST-60-15C rev1
- Space environment: ECSS-E-ST-10-04C
- Calculation of radiation, effects and margin ST: ECSS-E-ST-10-12C

- Calculation of radiation, effects and margin HB: ECSS-Q-HB-10-12A
- Radiation Mitigation in ASIC and FPGA HB: ECSS-Q-HB-60-02A

CubeSat RHA:

- RHA chapter - Engineering Guidelines for ESA IOD CubeSat Projects: ESA-TECSPC-MAN-2023-002445

New issue of the ECSS-Q-ST-60-15 rev1

Some major highlights:

- Self-sustained (no open points):
  - Minimum RDM (=1.2) & excludes environment margin
  - RVT margin
- Introduction of new part families
- Formal introduction to RCBs (as designed, as built)
- Focus on optocoupler SETs (template & testing)
- If SET impact is critical then testing is required
- Acceptability to use SEL sensitive devices if proved non-destructive
- Update of the Radiation Analysis Report (more details)
- More details on modelling
- Etc…

4.5 Radiation reviews

Equipment, subsystem, and system radiation analysis reports are part of project reviews data packages (from PDRs (all levels) to CDRs (all levels), QRs (all levels), and, finally, SAR. Radiation data on parts and part radiation testing are also reviewed during PAD review process. However, PAD approval for a part is only a provisional approval. As far as radiation effects are concerned, use of a part in a specific application is only validated when corresponding equipment radiation analysis and WCA reports are approved.

As-designed Equipment radiation reviews (ERCBs) held in after equipment PDR, are also performed on customer request. These reviews are useful to review available radiation test data, define the radiation tests to perform, define or review the test plans, review shielding strategy and preliminary shielding analysis. Then, another as-built ERCB, is held between MRR and TRR. The main goal of this review is to check if radiation data on flight parts is in conformity with radiation analysis. The timeline of the ERCBs is presented in Figure 4-2.

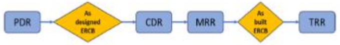


Figure 4-2: Timeline of ERCBs

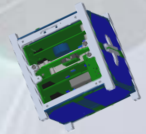
TEST STANDARDS

- **TID**
  - **ESCC22900, issue 5, 2016, Total Dose Steady-State Irradiation Test method**
  - MIL-ST-883/750, method 1019, Ionizing radiation (total dose) test procedure
  - ASTM F1892-04, Standard guide for ionizing radiation (total dose) effect testing of semiconductor devices
- **TNID/DD**
  - **ESCC22500, issue 2, 2021, Guidelines for Displacement Damage Irradiation Testing**
  - ASTM F1190-99, Standard guide for neutron irradiation of unbiased electronic components
- **SEE**
  - **ESCC25100, issue 2, 2014, Single Event Effect Test Method and Guidelines**
  - MIL-STD-750, method 1080, Single Event Burnout, Single Event Gate Rupture
  - ASTM F1192-00, Standard guide for the measurerment of SEP induced by heavy ion irradiation of semiconductor devices
  - JEDEC, JESD 57, test procedures for the measurement of SEE in semiconductors devices from heavy ion irradiation

Conclusion

- Radiation effects on electronics in space have a direct impact on the reliability and availability of a system and, therefore, on the success of a mission.
- Radiation Hardness Assurance (RHA) process shall be implemented to ensure that the electronics and materials of a space system perform to their design specifications after exposure to the space environment.
- RHA requires a considerable effort throughout the development of a space system from the early phases of a program development
- The RHA approach on space systems is based on risk management and not on risk avoidance. It requires radiation effect mitigation and tolerant electrical designs.
- RHA tailoring on mission classes:
    - From an exhaustive check of all parts…
    - …toward only addressing critical parts
    - However, need of a careful top-down/down-up & balanced approach at system level
        - Focusing all the RHA activities on a given subsystem & neglecting is not great!
- This presentation is only a brief introduction, many aspects not covered (margin RDM, modelling, testing, RVT…and so on…)

Efharisto!



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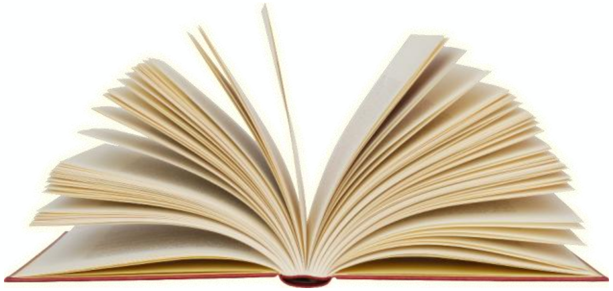
  - by the author
    - from the ESA Academy Training & Learning sessions (Spacecraft Testing & CubeSat Training Week)
    - from other ESA internal & external events



List of acronyms

ASIC	Application Specific Integrated Circuit
CME	Coronal Mass Ejection
COTS	Commercial Off The Shelf
CPU	Central Processing Unit
DD	Displacement Damage
ECSS	European Cooperation For Space Standardisation
ECC	Error Correction Code
EEE	Electrical, Electronic & Electromechanical
ESA	European Space Agency
FM	Flight Model
FMECA	Failure Mode, Effects & Criticality Analysis
FPGA	Field Programmable Gate Array
FYS	Fly Your Satellite!
HDR	High Dose Rate
H/W	Hardware
LEO	Low Earth Orbit
LET	Linear Energy Transfer
LDR	Low Dose Rate
MBU	Multiple Bit Upset
MCU	Multiple Cell Upset
NIEL	Non-Ionizing Energy Loss
NV	Non-Volatile
OBC	On-Board Computer
OCP	Over-Current Protection
PA	Product Assurance
PCB	Printed Circuit Board
RADLAT	Radiation Lot Acceptance Tests
RCB	Radiation Control Board
RFW	Request for Waiver
RHA	Radiation Hardness Assurance
RM	Radiation Model
SAA	South Atlantic Anomaly
SEB	Single Event Burnout
SED	Single Event Disturb
SEE	Single Event Effect
SEFI	Single Event Functional Interrupt
SEGR	Single Event Gate Rupture
SEL	Single Event Latchup
SER	Soft Error Rate
SESB	Single Event Snapback
SET	Single Event Transient
SEU	Single Event Upset
SHE	Single Hard Error
S/W	Software
TID	Total Ionizing Dose
TMR	Triple Modular Redundancy
TNID	Total Non Ionizing Dose
uC	Micro-controller