Fourth Barcelona TechnoWeek

Course on Nanosatellites

Institute of Cosmos Sciences, Barcelona, 17-21 June 2019

Radiation Aspects

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Why this talk?

Once upon a time....

~~Death~~ star ?

- Telstar 1 satellite was launched on July 10, 1962
- Communications satellite
- Relayed first telephone call tx through space, TV, etc

Telstar 1 (1962)

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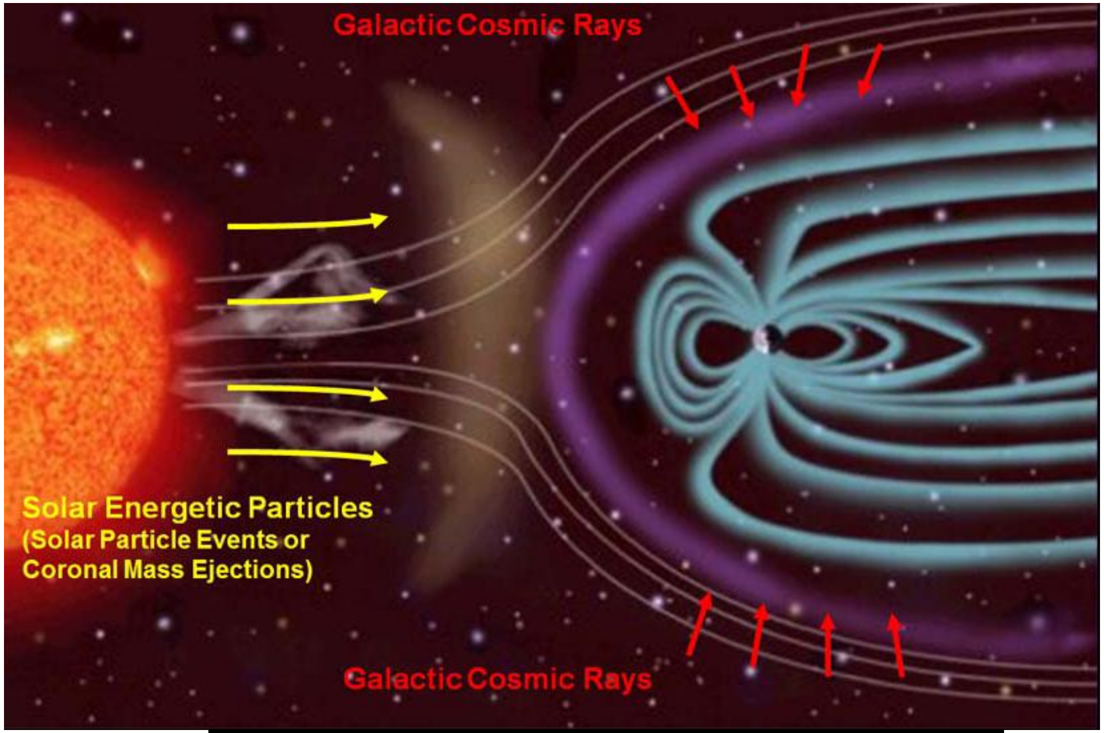
Why this talk?

- Telstar went out of service only 4 months later (Nov. 1962)
- Why?
  - Go back in time…
  - 1 day before Telstar was launched
- **Starfish prime** was a high-altitude nuclear test conducted by the US
- Energized the Earth's Van Allen Belt
- Vast increase in a radiation belt + USSR blasts damaged Telstar electronics

The flash created by the explosion as seen through heavy cloud cover from Honolulu

Why this talk?

- Hopefully, no more nuclear bomb blasts should happen
- So, are statellites and spacecrafts safe out there ?
  - Unfortunately not
  - There are many “natural” radiation sources in space



Sources of Ionizing Radiation in Interplanetary Space
http://photojournal.jpl.nasa.gov/catalog/PIA16938

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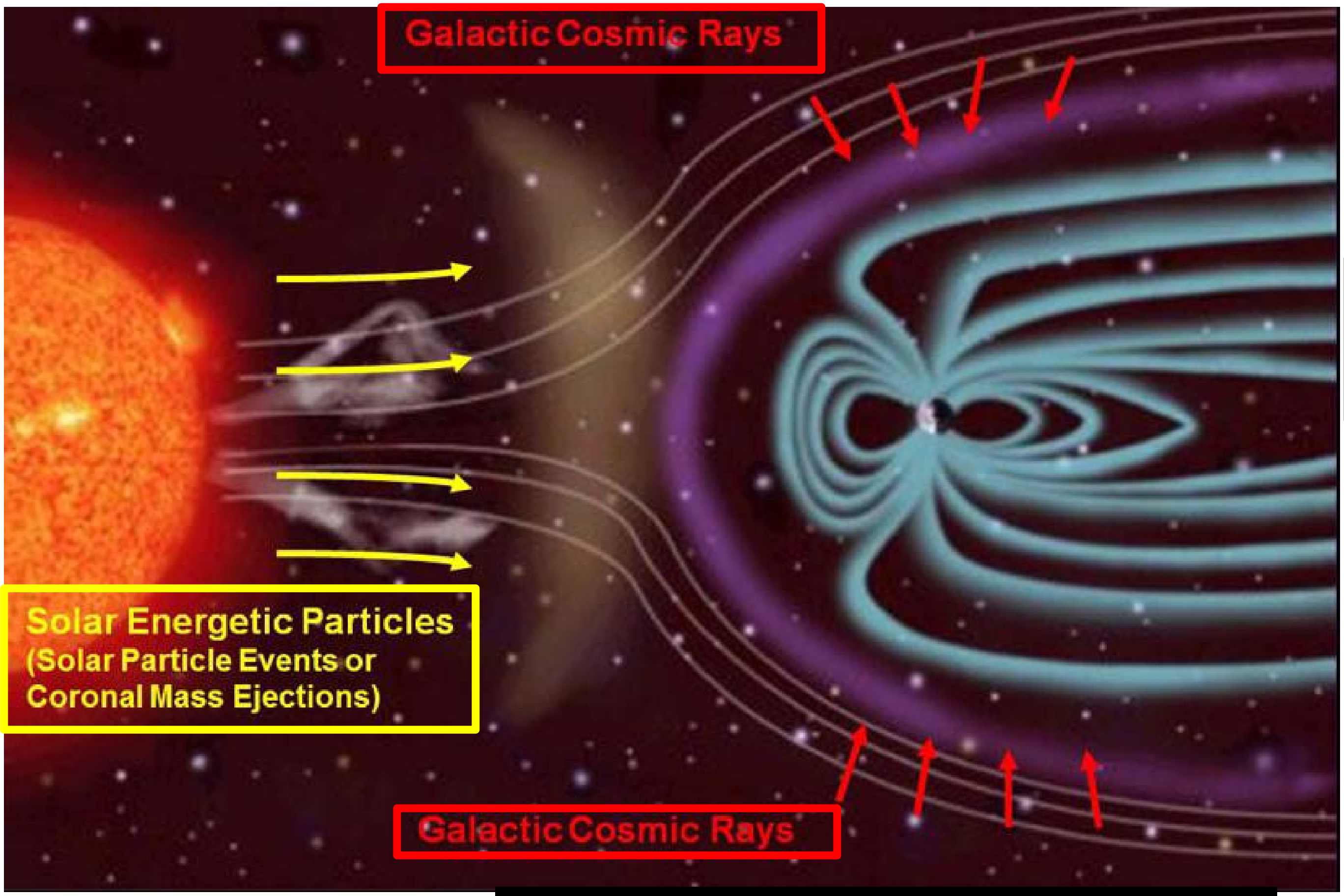
Outlook

1. **Radiation space environment**
2. Radiation effects
3. Radiation qualification
4. Design hardening methodologies for mixed signal circuits
5. Fault tolerance in digital circuits
6. Design hardening at system level

High Energy Particle radiation in space



Trapped particles (Van Allen Belt)

Sources of Ionizing Radiation in Interplanetary Space
http://photojournal.jpl.nasa.gov/catalog/PIA16938

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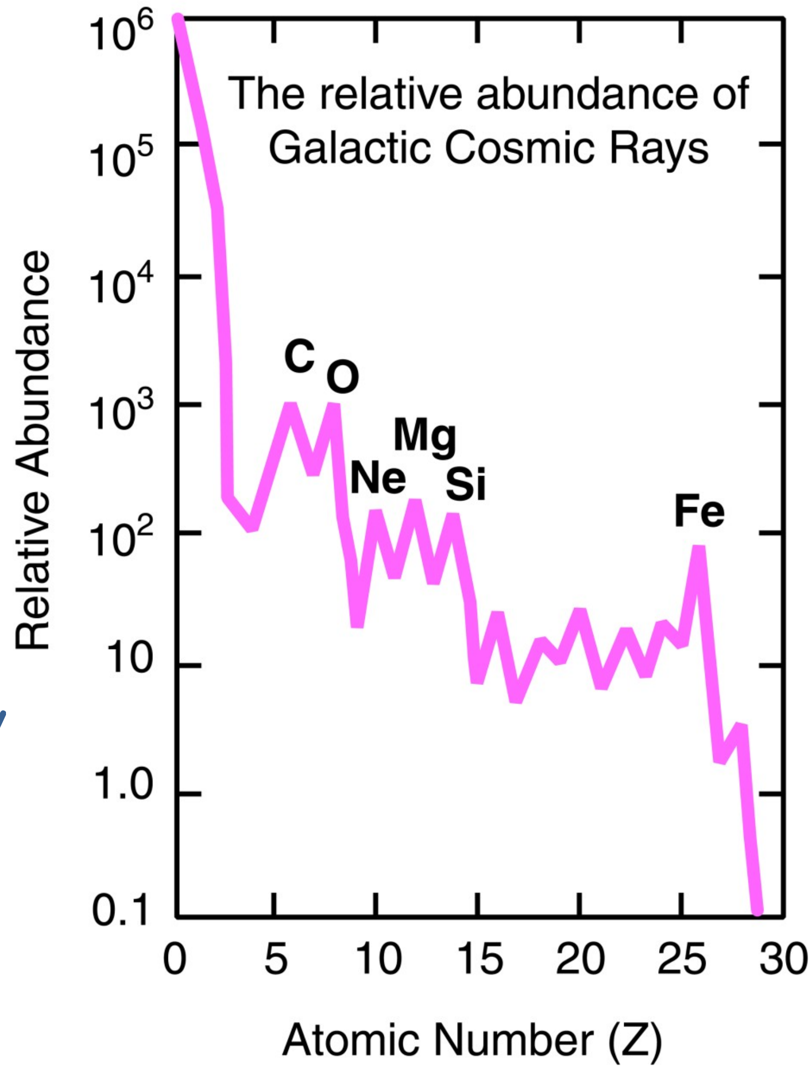
Radiation space environment GCR

- Galactic cosmic rays (GCR) are high-energy charged particles that originate outside our solar system.
- Believed to be remnants from supernova explosions.

Image of part of a stellar remnant
http://www.eso.org/public/images/eso0923a/

Radiation space environment GCR

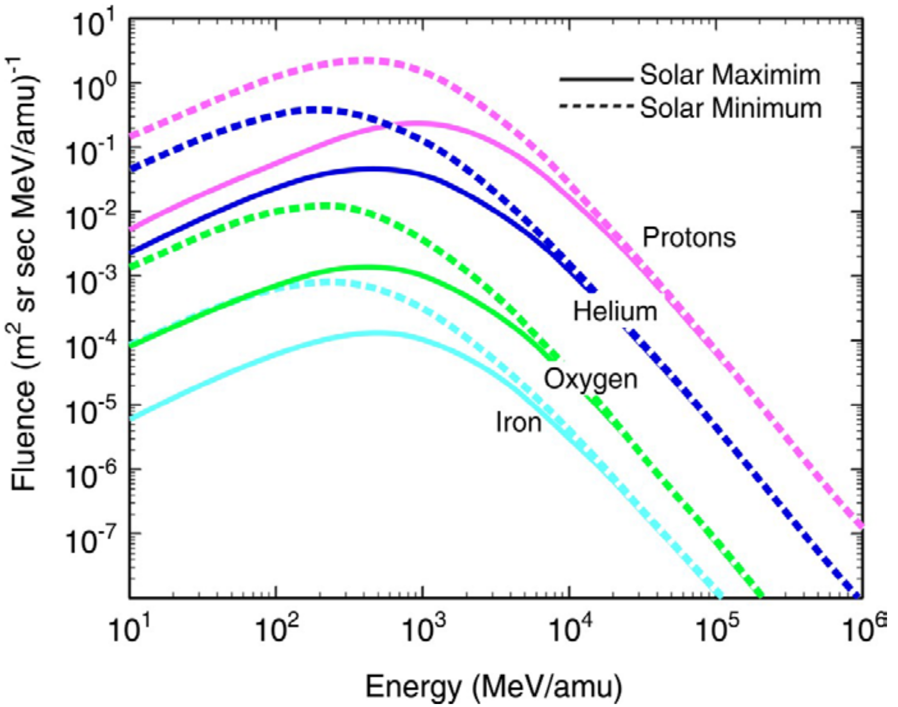
- GCR properties
- Composed of all naturally occurring elements:
  - 87% protons
  - 12% alpha particles
  - 1% heavier ions
- Energies: up to 10^{11} GeV!
- Fluxes: 1 to 10 $cm^{-2}s^{-1}$
- Anticorrelated with solar activity
  - High flux during solar low



Radiation Impacts on Satellites due to GCRs and SEPs, M. Xapsos.
Space Weather Training for Mission Operators and Engineers NASA/GSFC, **2014**

Radiation space environment GCR

- GRC radiation is nearly isotropic before magnetosphere
  - But radiation couples to the Earth's magnetic field and its isotropy is not preserved
- Energy spectra tend to peak around 0.3 to 1 GeV/ nucleon.
- Fluxes modulated by magnetic field in sun and solar wind
- <u>**Shielding is not effective for GCRs**</u>



Radiation Impacts on Satellites due to GCRs and SEPs, M. Xapsos.
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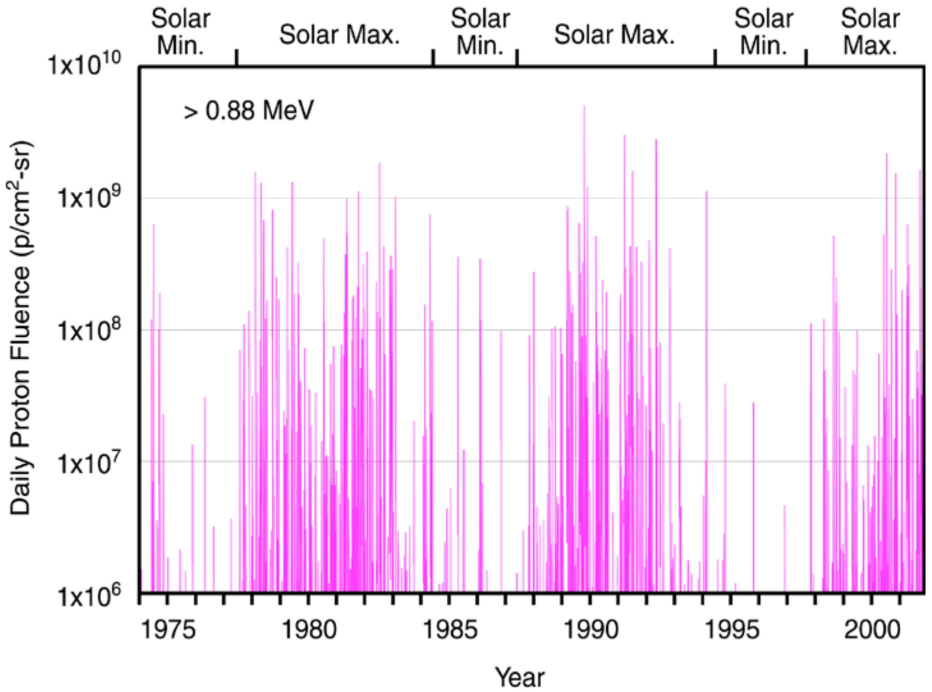
Radiation space environment
SEP events

- Major disturbances in interplanetary space and in Earth's magnetosphere
- Energy is released in the form of e, p, heavy ions and electromagnetic radiation
  - We do not consider EM radiation here
- Two types of solar sources to be considered
  - Coronal Mass Ejection (CME)
  - Solar flares

CME on August 31, 2012
NASA Goddard Space Flight Center

Radiation space environment SEP events

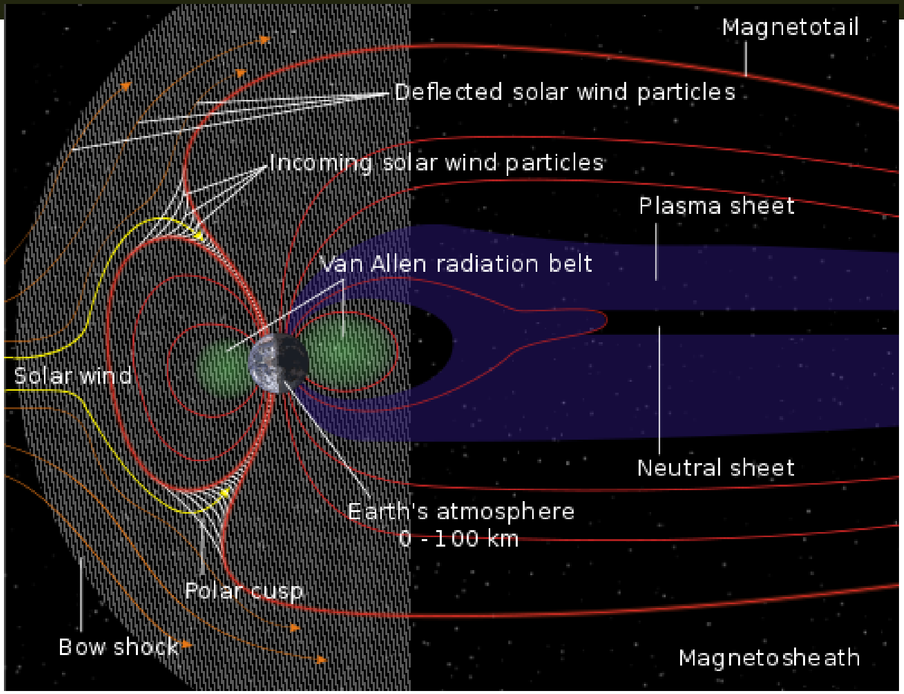
- Gradual events: several days
  - SEPs accelerated by (coronal and interplanetary) shock waves driven by CMEs
  - Protons and heavy ions
    - Up to 1 GeV/nucleon
    - Typically 0.1 -100MeV/nucleon
    - Benchmark event: 08/1972
- Impulsive events involve large emission of heavy ions
  - 10s MeV-100s GeV per nucleon
  - 09/1997 and 10/1992
- Dependent on solar cycle



Radiation Impacts on Satellites due to GCRs and SEPs, M. Xapsos.
Space Weather Training for Mission Operators and Engineers NASA/GSFC, 2014

Radiation space environment
Solar wind

- Plasma of charged particles released from the upper atmosphere of the Sun
  - Mostly electrons, protons and alpha particles
  - Energies between 1.5 and 10 keV
  - Density: 1 to 30 particles / cm^3.



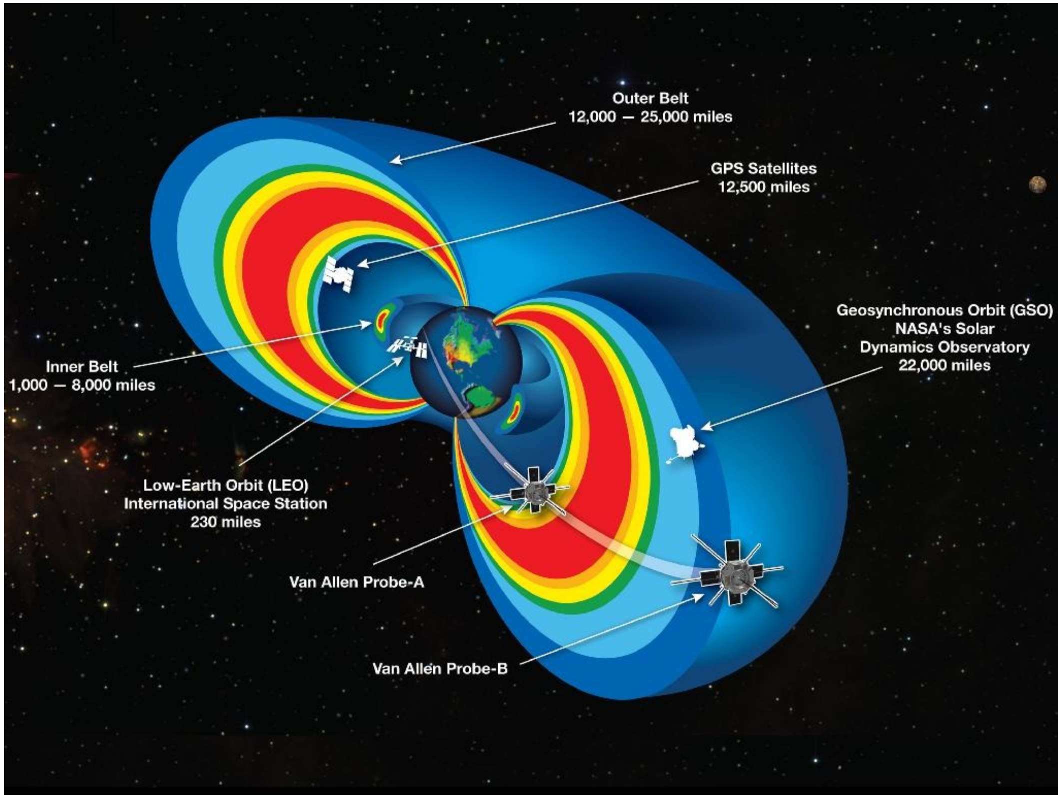
Schematic of Earth's magnetosphere. The solar wind flows from left to right.

- Variations of solar wind cause disturbation of magnetosphere:
  - Geomagnetic storms

- Main effect of solar wind plasma is charging phenomena
  - Beyond the scope of the talk

Radiation space environment
Radiation belts

- Particles trapped by planet's magnetic field
  - Inner belt
    - Electrons of 100s KeV
    - Protons of 100s MeV
  - Outer belt: mainly 1-10 MeV electrons
- Magnetic storms can cause temporary belts
  - Can reach higher energies
- Heavy ions can also be trapped
  - Primary made of light ions with low energies
    - Not problematic for electronics but for astronauts



Earth Belts, also known as Van Allen belts The inner belt extends from about 1000 to 8000 miles above Earth's equator. The outer belt extends from about 12,000 to 25,000 miles. http://www.nasa.gov/mission_pages/sunearth/news/gallery/20130228-radiationbelts.html
NASA, 2013

Outlook

I. Radiation space environment

II. Radiation effects

III. Radiation qualification

IV. Design hardening methodologies for mixed signal circuits

V. Fault tolerance in digital circuits

VI. Design hardening at system level

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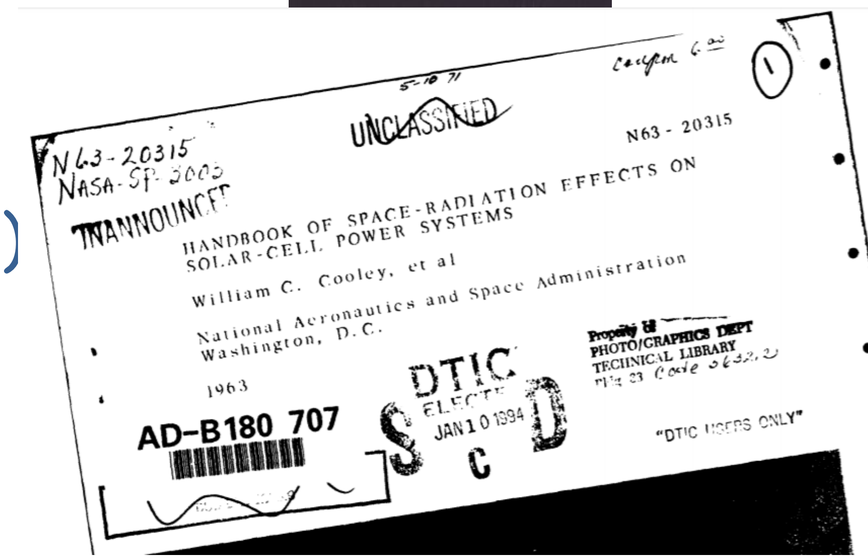
Radiation effects

- Ionizing & Non-Ionizing cumulative effects (dose)
  - Degradation of micro-electronics
  - Degradation of optical components
  - Degradation of solar cells

- Single Event Effects (SEEs)
  - Data corruption
  - Noise on Images
  - System shutdowns
  - Circuit damage



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HANDBOOK OF SPACE-RADIATION EFFECTS ON SOLAR-CELL POWER SYSTEMS

William C. Cooley, et al

National Aeronautics and Space Administration
Washington, D.C.

1963

AD-B180 707

DTIC ELECTE JAN 10 1994

PHOTO/GRAPHICS DEPT
TECHNICAL LIBRARY

"DTIC USERS ONLY"

Handbook of Space-Radiation Effects on Solar-Cell Power Systems, http://www.dtic.mil/dtic/tr/fulltext/u2/b180707.pdf

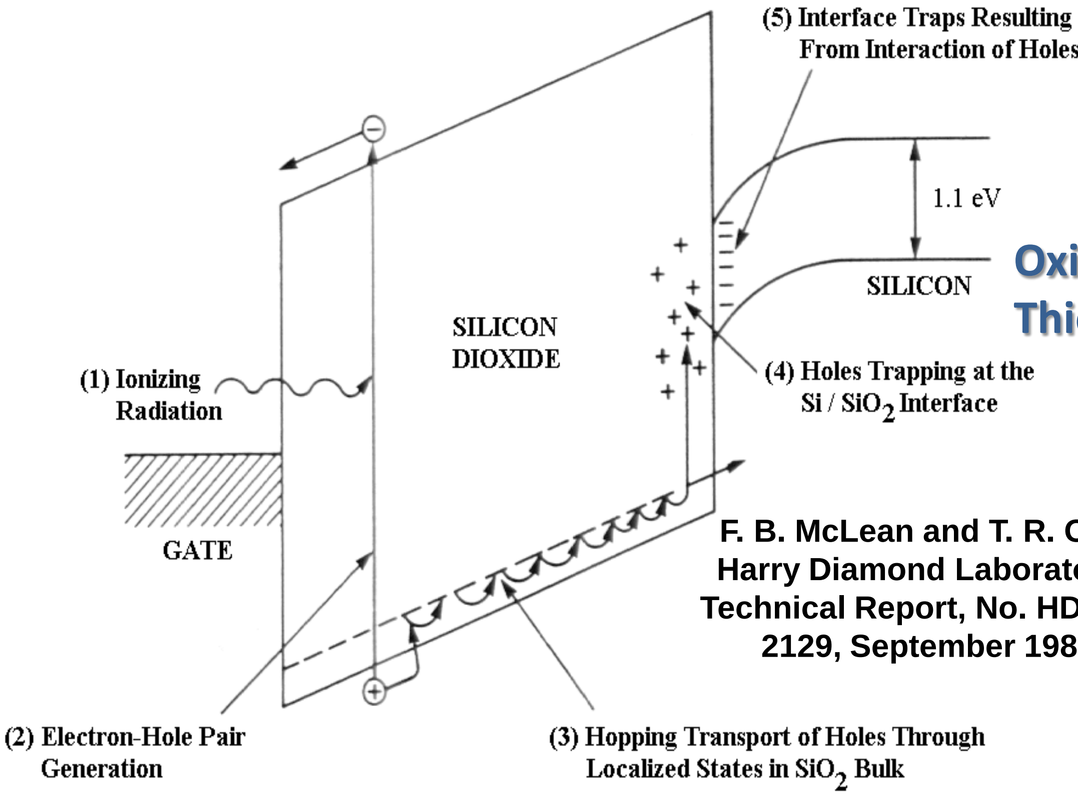
Radiation effects
Cumulative effects: TID

- Total Ionising Dose (TID)
  - Energy deposited in the electronics by radiation in the form of ionization
  - Dose = energy deposited per unit mass of material in the sensitive volume
  - 1 rad = 100 erg/g
  - Unit: Gray (Gy), 1 Gy = 100 rad
  - Affects all electronics devices
    - Many effects on MOS transistors
    - Decrease output of solar cells…

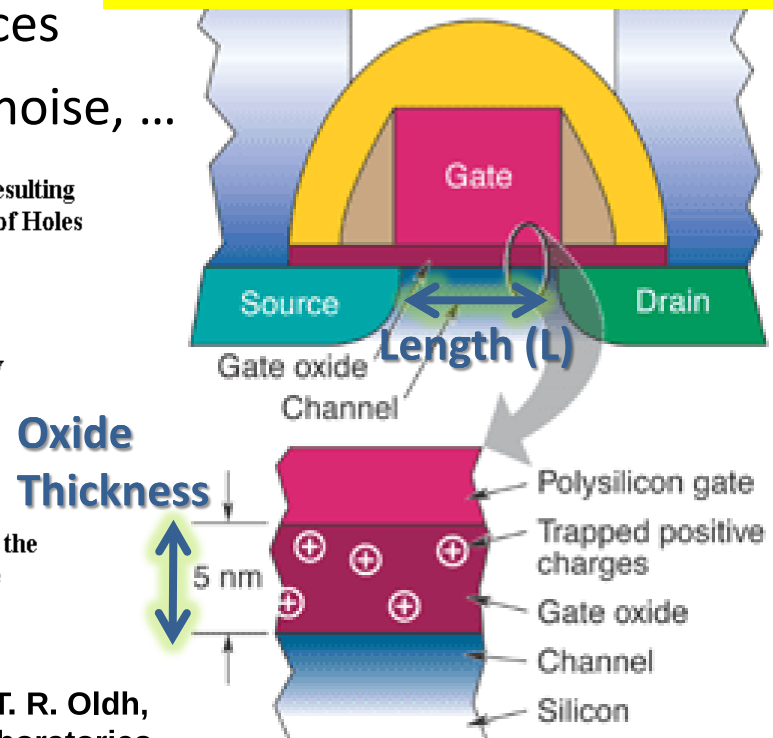
Radiation effects
Cumulative effects: TID

- Effects on MOS transistors:
  - Charge trapping in oxides and interfaces
  - Vt shift, change gm, leakage current, noise, …

CMOS (complementary metal-oxide-semiconductor) transistor



F. B. McLean and T. R. Oldh, Harry Diamond Laboratories Technical Report, No. HDL-TR-2129, September 1987.



http://propagation.ece.gatech.edu/

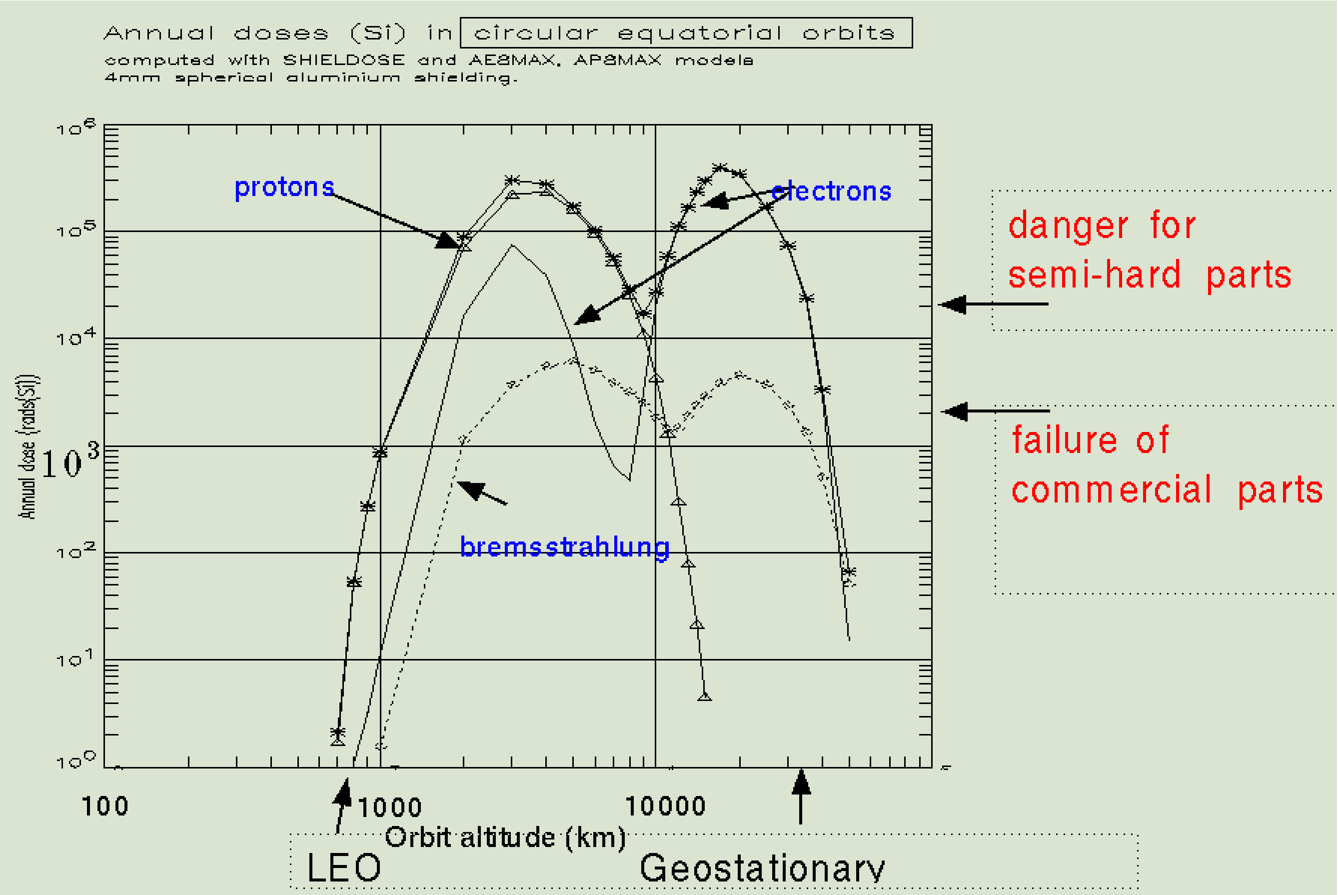
As technology advances both channel lenght and oxide thickness shrink

Radiation effects
Cumulative effects: TID

- TID can electronics withstand depends on the technology
  - Modern CMOS devices above 100's of krad
    - “Old” echnologies above 180 nm sensitive in 10’s krad region
  - CMOS rad hard devices are in the range > 1 Mrad
  - Standard Bipolar can withstand a TID in the range of 10's to 100 krad.
  - AsGa is intrinsically TID hardened: 1 Mrad or even more.
- But there are a lot of dependence factors:
  - Dose rate (there is a low dose rate enhancing for bipolar technologies contrary to high dose rate enhancing for MOS technologies)
  - Bias during and after irradiation
  - Time after irradiation (annealing)
  - Lot to lot dependence

Radiation effects
Cumulative effects: TID

- TID depends on orbit altitude and inclination

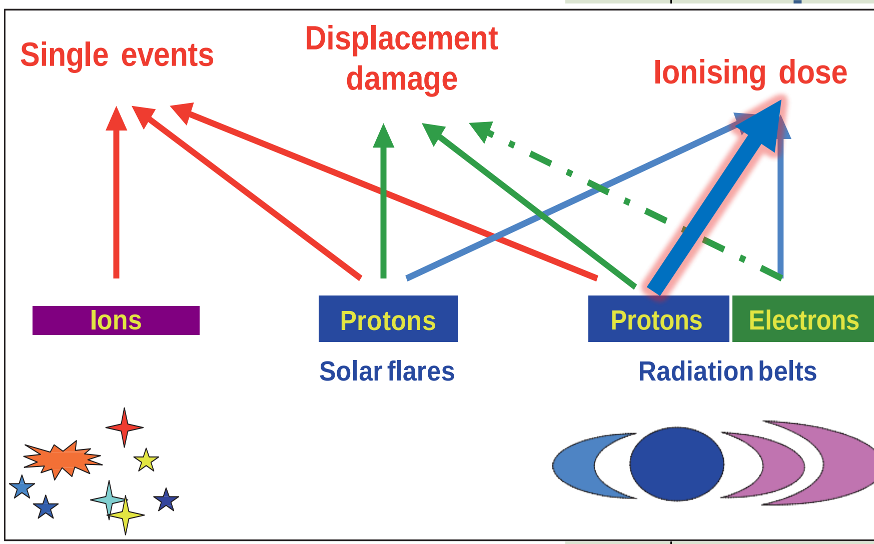


E.J. Daly, A. Hilgers, G. Drolshagen, and H.D.R. Evans, Space Environment Analysis: Experience and Trends," ESA 1996 Symposium on Environment Modelling for Space-based Applications, Sept. 18-20, 1996, ESTEC, Noordwijk,

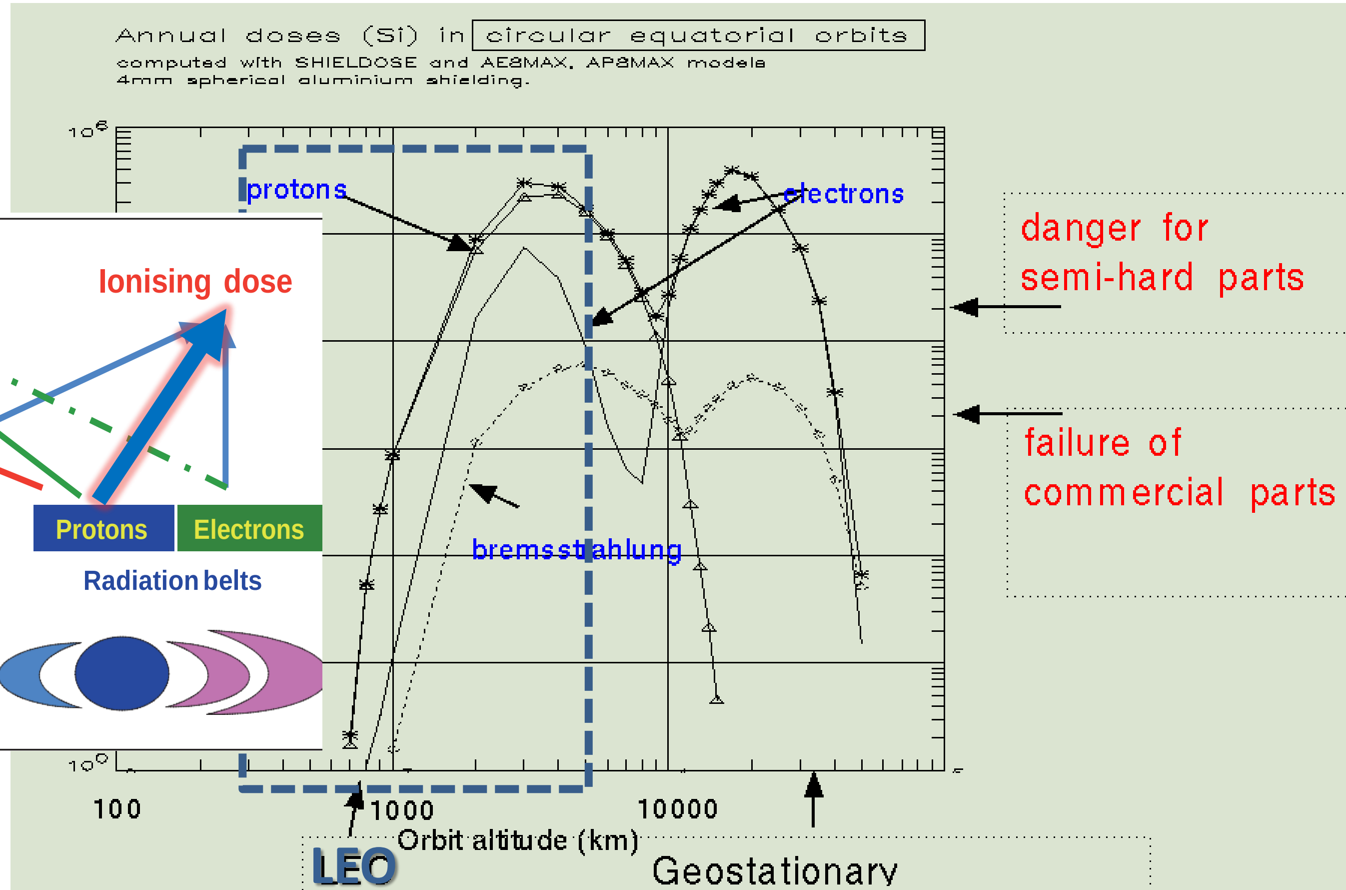
Radiation effects
Cumulative effects: TID

- TID depends on orbit altitude and inclination

Low earth orbit (LEO): electrons and <u>protons</u> (inner belt)



R. Ecoffet. (2007). In-flight Anomalies on Electronic Devices. In R. Velazco (Ed.), *Radiation Effects on Embedded Systems.*



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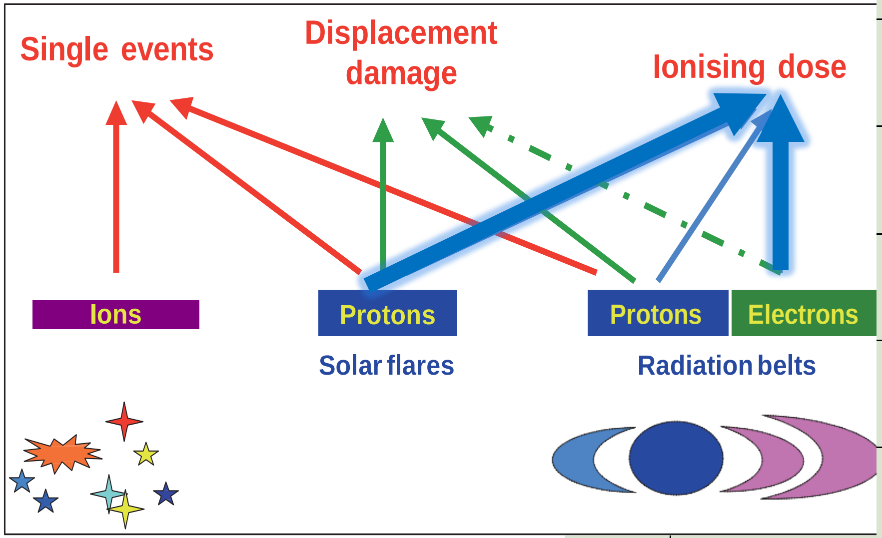
Radiation effects
Cumulative effects: TID

- TID depends on orbit altitude and inclination

Geostationary and Medium earth orbits (GEO/MEO): electrons (outer belt) and solar protons.



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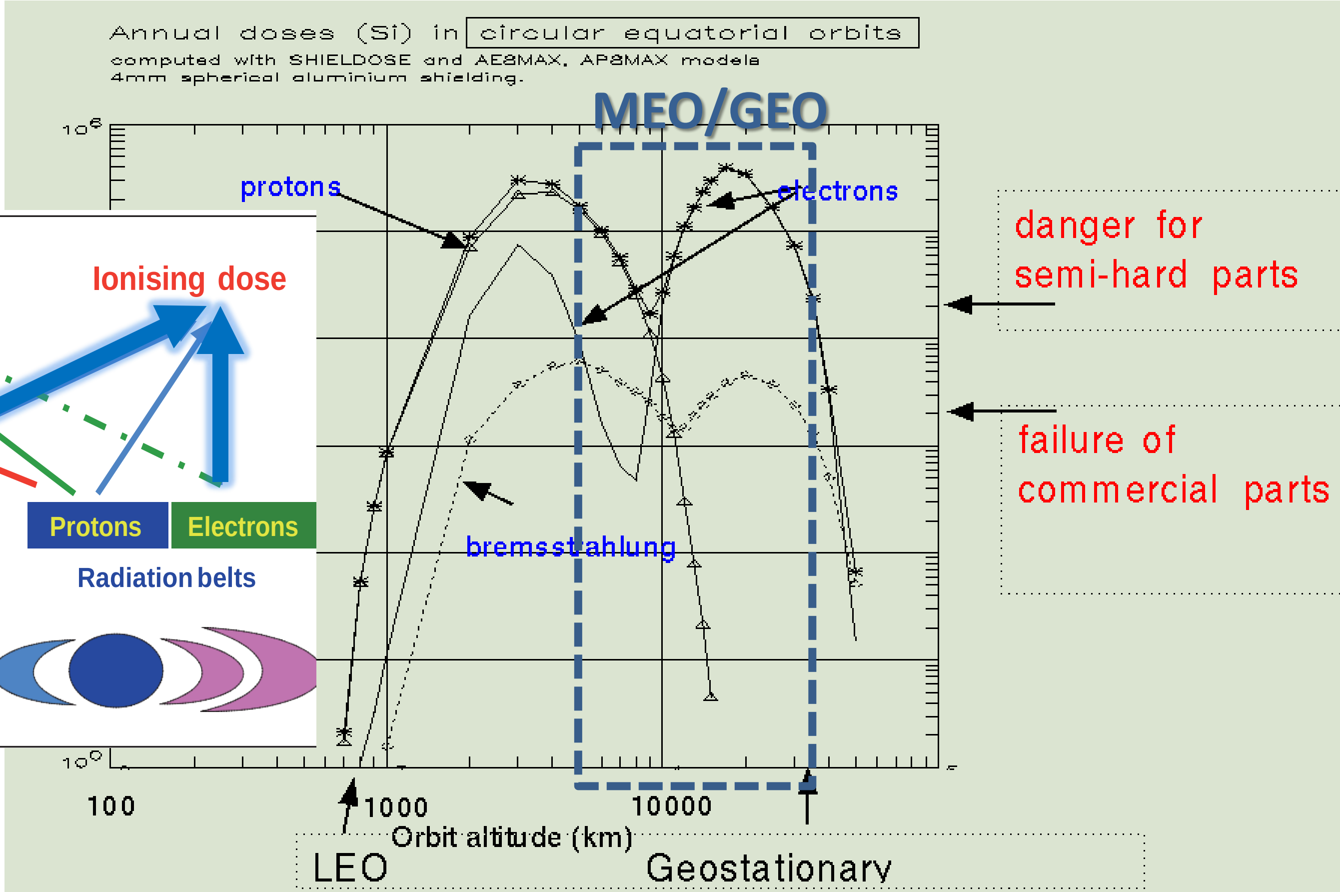

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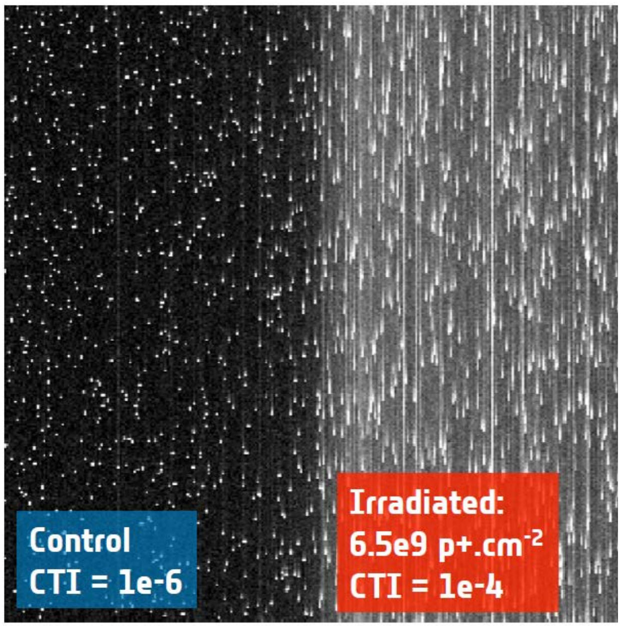
Radiation effects
Cumulative effects: TID

- Average space distribution of particles is inhomogeneous at LEO (300-5000 Km):
  - The outer electron belt is close to the Earth at high latitudes (polar horns)
  - The region centered on the south Atlantic (South Atlantic Anamoly, SAA) has a high level of trapped particles (electrons and protons)
  - Sats at very low equatorial orbit (300 km) sustain little radiation
  - Sats over 1400 km heavily impacted by proton belt (even more than GEO)
- Shielding is useful @ MEO/GEO (5000-36000 Km) because shielding is very effective for electrons
  - For a 18 years GEO, TID is 100 krad behind 5 mm of aluminium, and 10 krad behind 10 mm.
  - A satellite placed at 2000 km (LEO) of altitude is, for 5 years and behind 10 mm aluminum shielding, in the range of 300 krad.

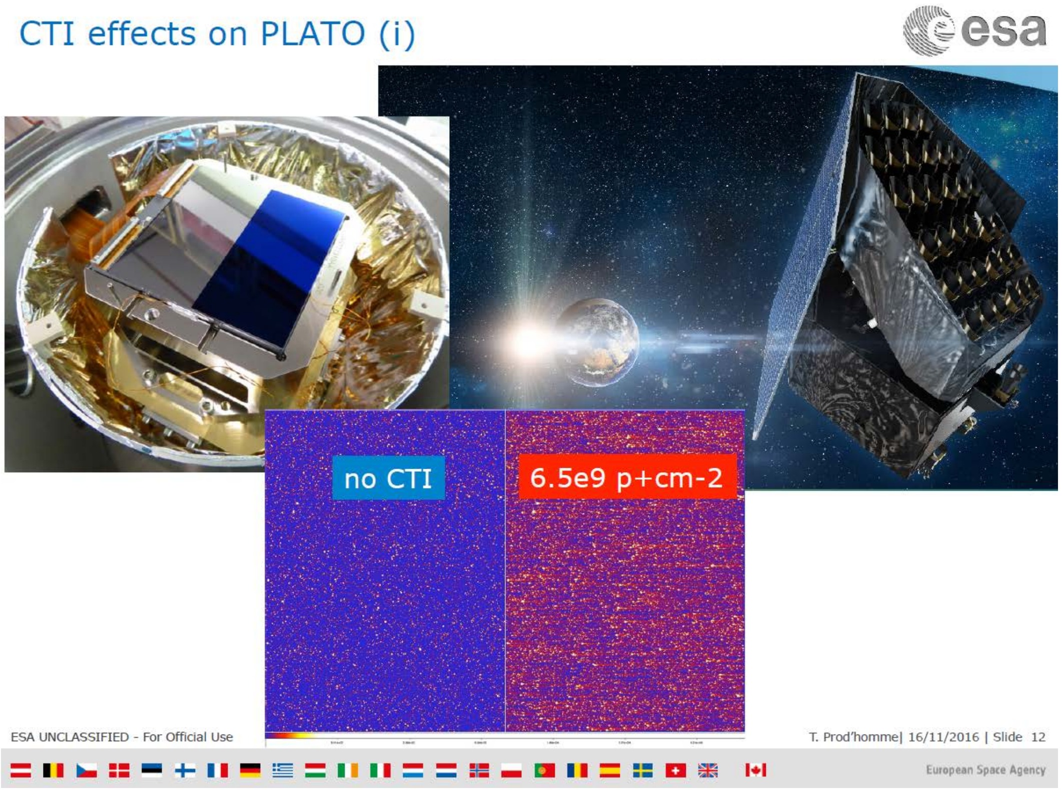
Radiation effects
Cumulative effects: TID

- Examples of proton TID effects on imagers



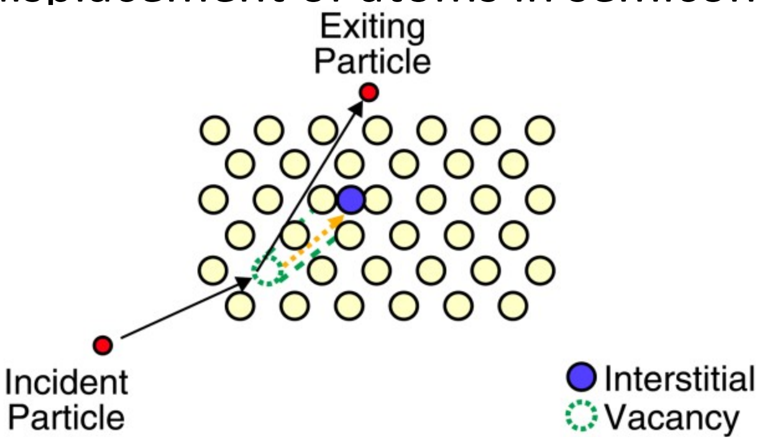
PLATO e2v CCD270 :
image acquired while illuminated by Fe55 X-ray source

CTI effects on PLATO (i)



Radiation effects
Cumulative effects

- Non Ionising Energy Loss (NIEL), Displacement Damage (DD)
  - Cumulative damage resulting from displacement of atoms in semiconductor lattice structure causing:
    - Carrier lifetime shortening
    - Mobility degradation

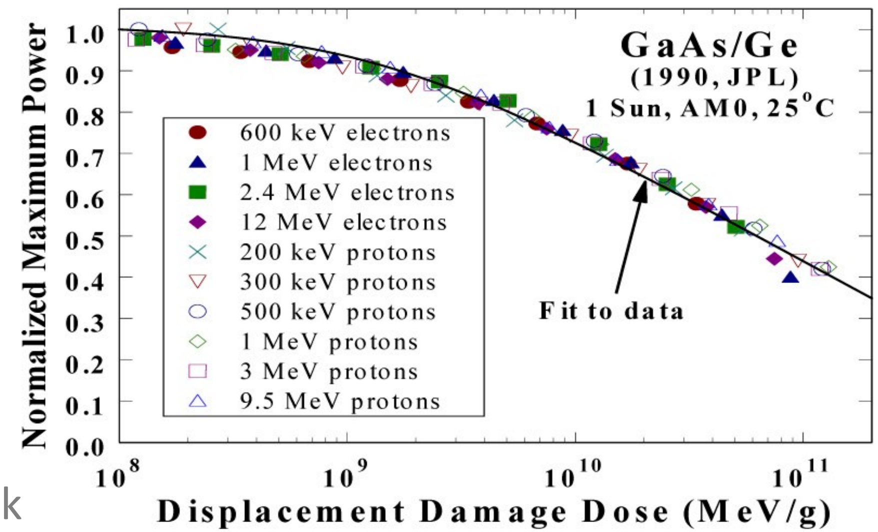


- Two metrics used:
  - Displacement Damage Dose: energy going into displaced atoms (nonionizing energy) per unit mass of material in the sensitive volume
  - The displacement damages is often normalized to displacement damages induced by 1 MeV neutron or 10 MeV proton

Radiation effects
Cumulative effects

- Non Ionising Energy Loss (NIEL)
  - CMOS devices are not affected
  - It affects bipolar devices, diodes and solar cells among others:
    - o 10^{15} n(eq 1 MeV).cm^{-2} for AsGa
    - o 10^{14} n(eq 1 MeV).cm^{-2} for MOS
    - o 10^{12} n(eq 1 MeV).cm-^{2} for bipolar
    - o 10^{11} n(eq 1 MeV).cm-^{2} for CCD & optolink
- For LEO between 1400 and 2000 Km the displacement damage is between 10^{12} n/cm^2 to $3{\cdot}10^{12}$/cm^2
  - CCD and analog electronics !

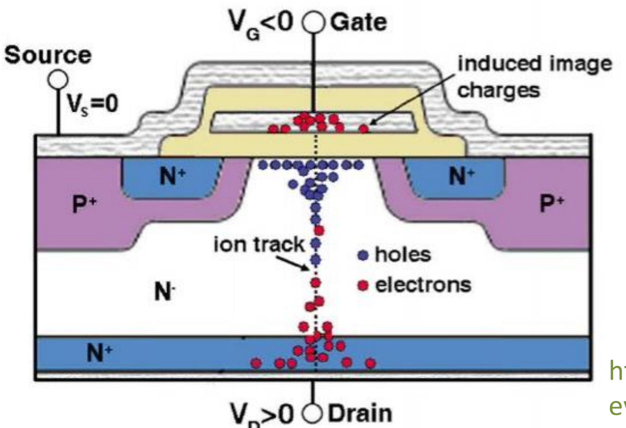
Solar Array Degradation



Radiation Impacts on Satellites due to GCRs and SEPs, M. Xapsos.
Space Weather Training for Mission Operators and Engineers NASA/GSFC, 2014

Radiation effects
SEEs

- SEEs may be caused by:
  - Direct ionization (usually the case for incident heavy ions)
  - Nuclear reaction products (usually the case for incident protons)



M. J. Beck, B. R. Tuttle, R. D. Schrimpf, D. M. Fleetwood, and S. T.Pantelides, "Atomic Displacement Effects in Single-Event Gate Rupture," Nuclear Science, IEEE Transactions on, vol. 55, pp. 3025-3031, 2008

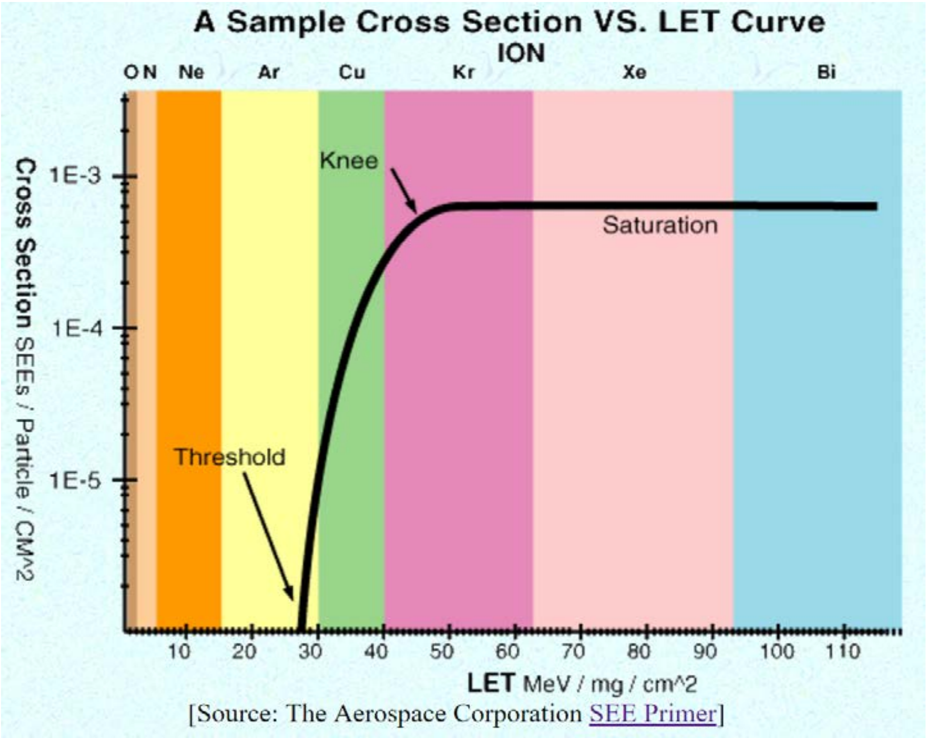
M. J. Beck, Y. S. Puzyrev, N. Sergueev, K. Varga, R. D. Schrimpf, D. M.Fleetwood, and S. T. Pantelides, "The Role of Atomic Displacements in Ion-Induced Dielectric Breakdown," Nuclear Science, IEEE Transactions on, vol.56, pp. 3210-3217, 2009.

https://www.semiwiki.com/forum/content/3646-modeling-analysis-single-event-effects-see.html?s=ff37d845d8a5f3452af94478045be3b2

- Metric commonly used for heavy ion induced SEE is Linear Energy Transfer (LET)
  - LET: energy lost by ionizing particle per unit path length in sensitive volume
    - Depends on the nature of the radiation and on the material traversed
    - **LET units** commonly used **are MeV·cm^2/mg**: energy lost by the particle to the material per unit path length (MeV/cm) divided by the material density (mg/cm^3)

Radiation effects
SEEs

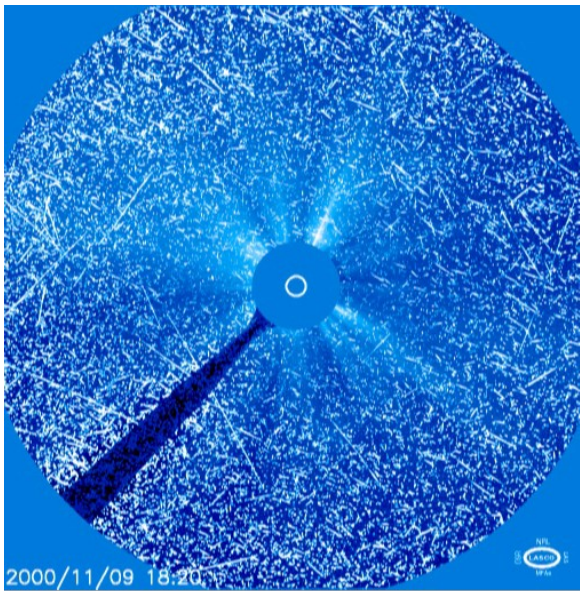
- Two parameters are needed to quantify the vulnerability of an electronic device:
  - Threshold LET: if the LET is greater than a threshold, the energy deposition can triggered the effect
  - Cross section: ratio of the number of upsets to the particle fluence
    - To determine the device error rate, integrate the cross section and sensitive device volume with the LET spectrum



http://holbert.faculty.asu.edu/eee560/see.html

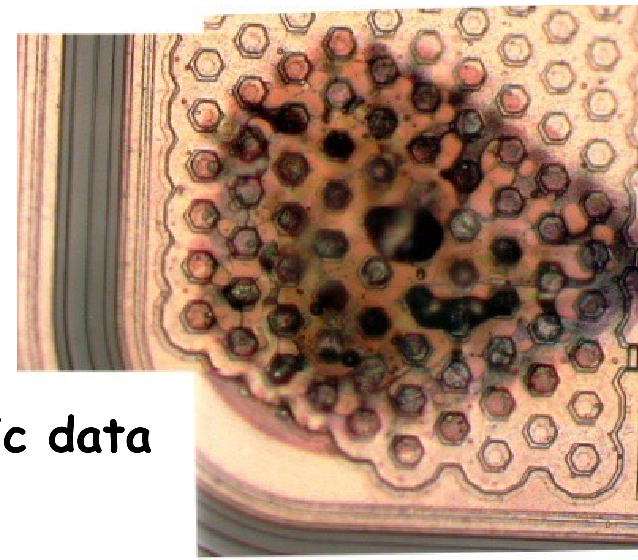
Radiation effects
SEEs

- Single Event Effect can be non-destructive or destructive:



Noise seen on the SOHO/LASCO instrument imager during the November 8-9, 2000 solar particle event

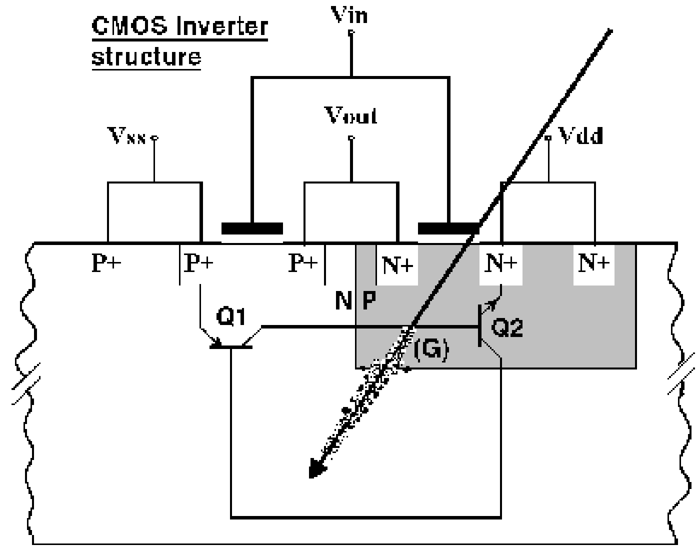
- ❑ Loss of scientific data
- ❑ Noise on images
- ❑ Circuit damage
- ❑ System shutdown



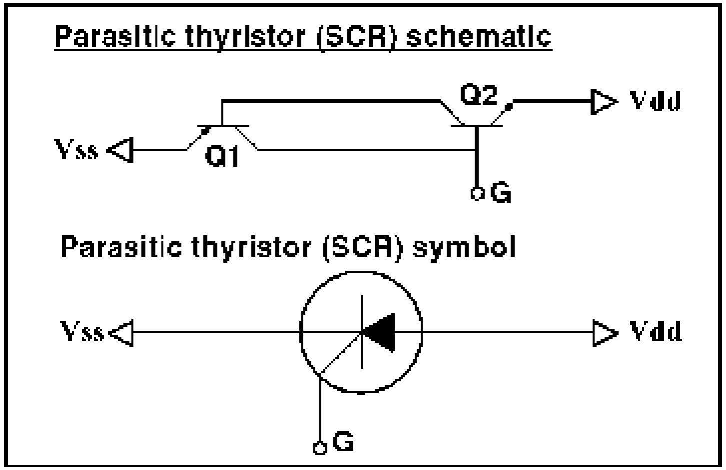
Destructive event in a COTS 120V DC-DC Converter

Radiation Impacts on Satellites due to GCRs and SEPs, M. Xapsos.
Space Weather Training for Mission Operators and Engineers NASA/GSFC, 2014

- The associated "iono-current" can induced several effects such as :
  - SEU (Single Event Upset) which is a transient effect, affecting mainly memories (bit flip)
  - SET (Single Transient Effect), transient effect in combinatory logic
  - SEL (Single Event Latch-up), which can destroy the component, affecting mainly CMOS structure
  - SEB (Single Event Burnout), which has destructive impact; affecting mainly power MOSFETS

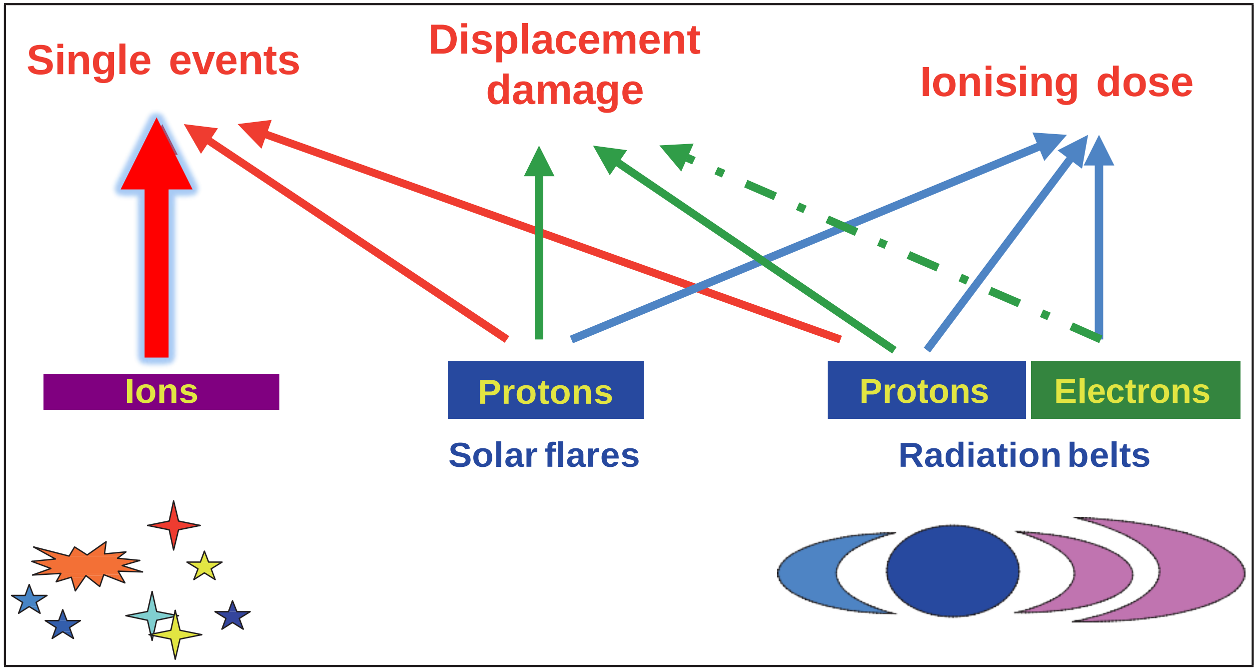


SEL (Single Event Latch-up)



Radiation effects
SEEs

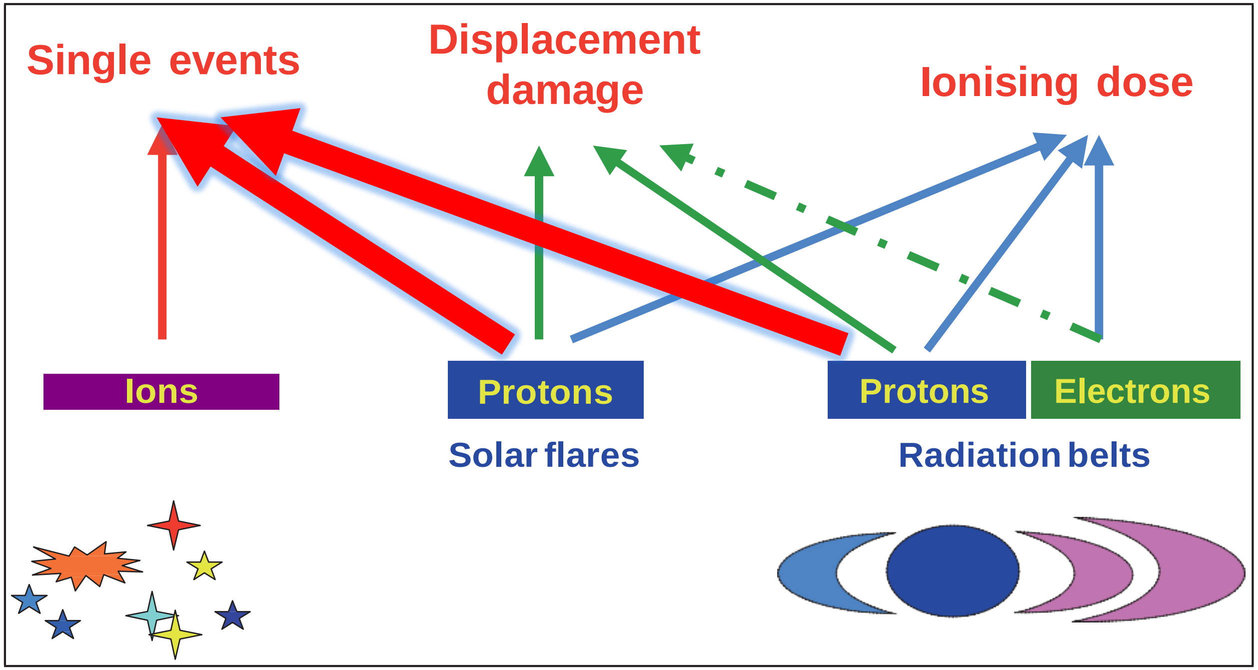
- Heavy ions environment
  - Remember origin: mainly GCRs
  - GEO orbit corresponds to the maximal constraint
    - It doesn't benefit of magnetosphere shielding.
    - As the altitude of the orbit decreases, and as the inclination of the orbit decreases to, the magnetosphere shielding is more and more effective



R. Ecoffet. (2007). In-flight Anomalies on Electronic Devices. In R. Velazco (Ed.), *Radiation Effects on Embedded Systems.*

Radiation effects
SEEs

- Protons can produce heavy ions by nuclear reaction
  - Main sources of indirect heavy ions are:
    - Proton-emitting solar flares (for geostationary and low polar orbits)
    - Trapped protons for medium orbits (MEOs)
    - The SAA for low earth orbits
  - Magnetosphere offers a natural screen against protons
    - Depends on the type of orbit and the date of the mission



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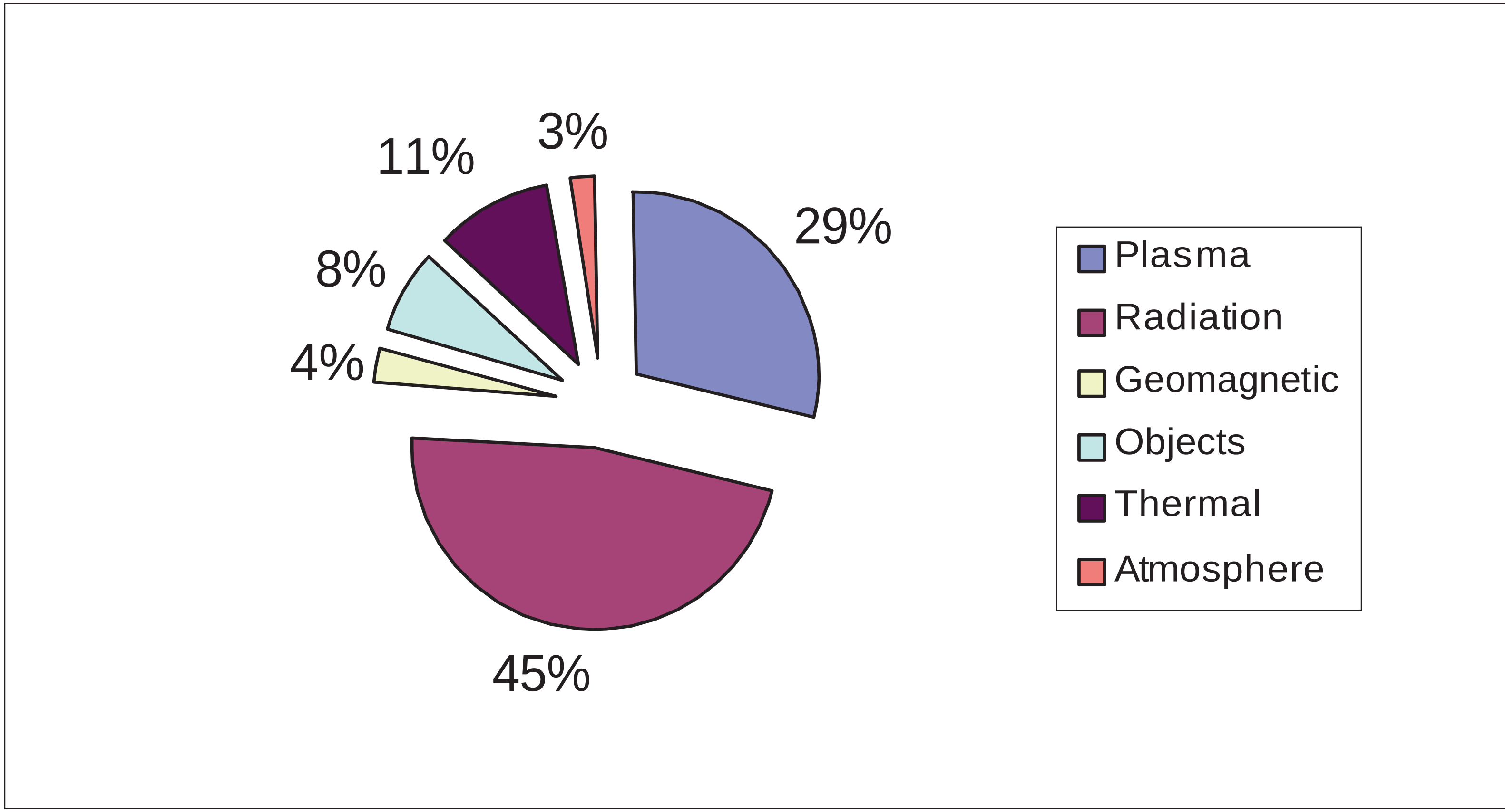
Radiation effects

Summary

- Spacecraft anomalies due to the space environment
  - Considering also problems not related with radiation



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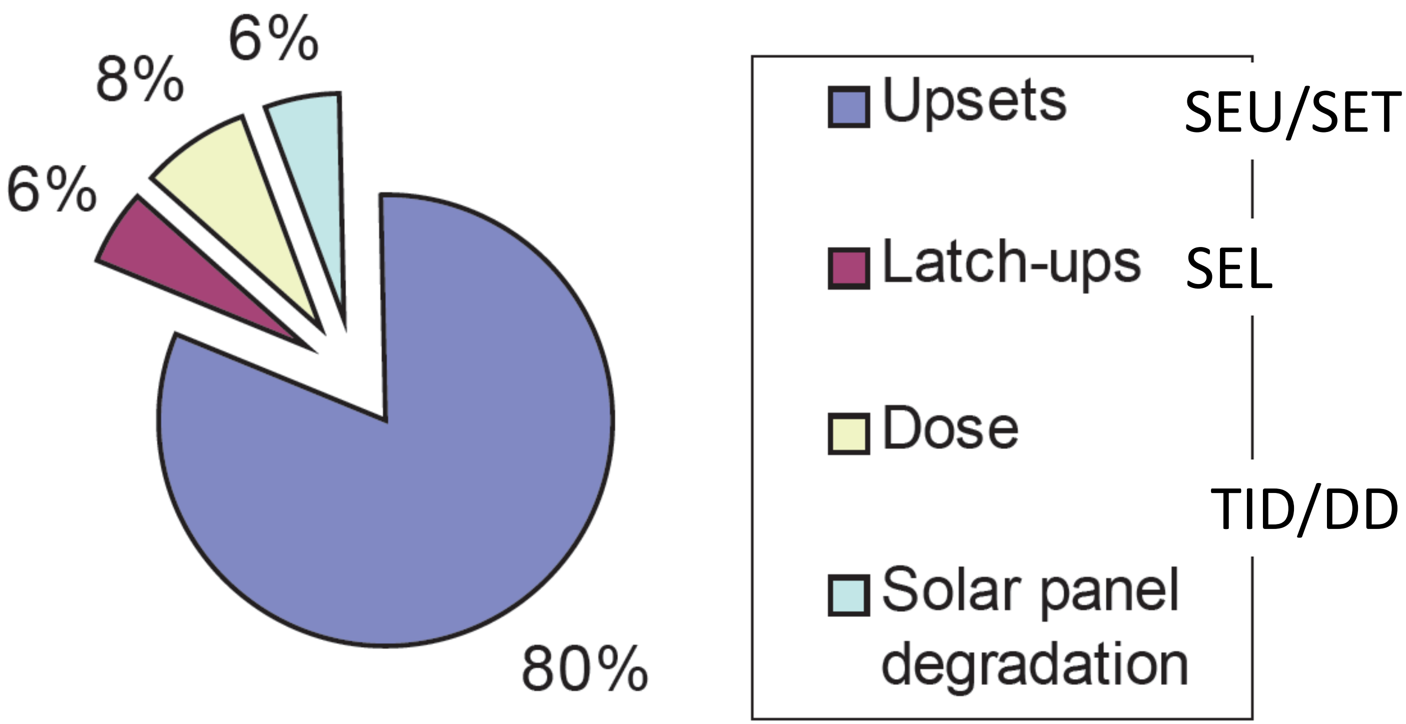
Radiation effects
Summary

- Repartition of radiation spacecraft anomalies



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Outlook

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Radiation qualification
Rad hard devices vs COTS

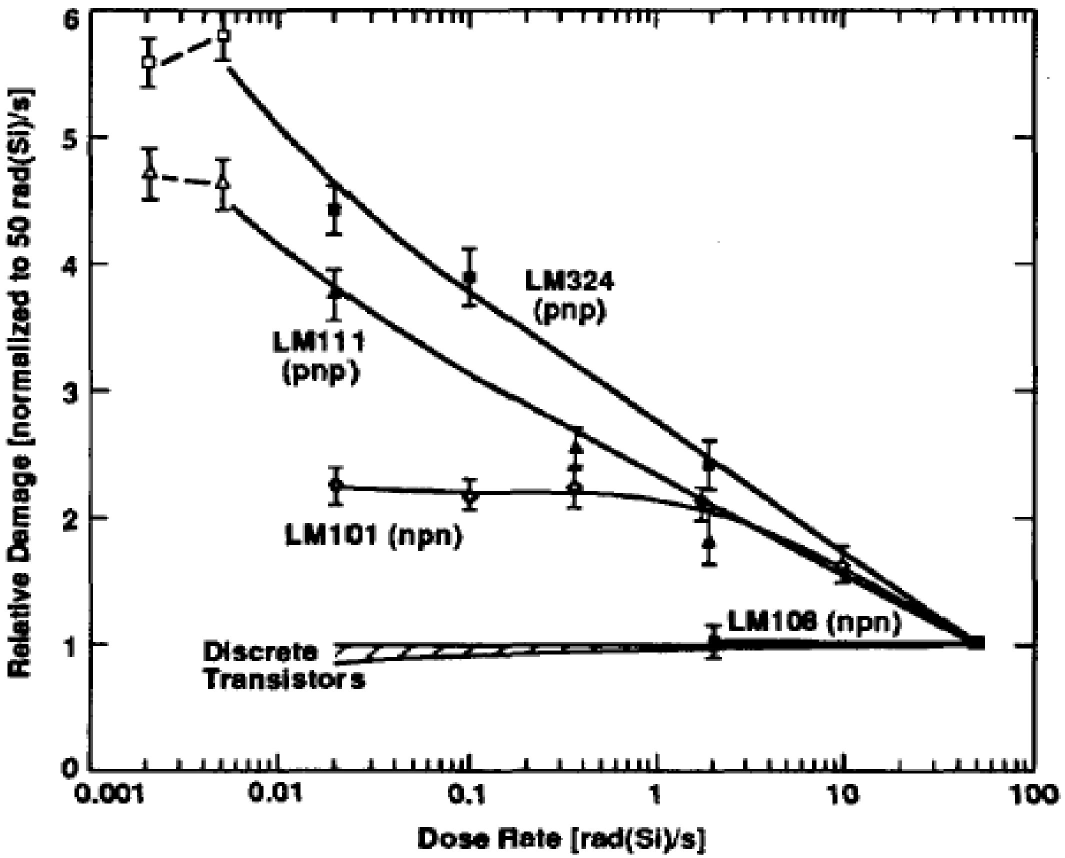
- For many years baseline in space missions has been to use space qualified components
  - So-called "hardened" (or radiation hard) with respect to radiation effects at the design and/or the manufacturing level
- However, there is a strong drive to utilize standard commercial off-the-shelf (COTS) and military devices
  - To minimize cost and development time as compared to radiation-hardened devices
  - <u>*This is certainly the case for nanosats*</u>
- Using COTS components requires
  1) Component qualification (this section)
  2) Using fault-tolerant techniques to ensure reliability (next sections)

Radiation qualification Methodology

- The test methodology strongly differs depending on the phenomenon at concern:
  - SEE characterization of devices requires real-time testing under exposure
    - Functional testing mainly
    - Particle accelerators
  - TiD assessment implies the full parametrical characterization
    - Different step of dose levels received (sequence of irradiation/testing phases).
    - 60Co sources are used for irradiating
    - Dose rate might be important !
  - NIEL or Displacement Damage (DD) testing is quite similar to TiD characterization
    - Parametrical measurements
    - However, DD testing requires the use of particle accelerators.

Radiation qualification
Dose Rate effect

- Example of dose rate importance:
  - Enhanced Low Dose Rate Sensitivity (ELDRS)



A. H. Johnston, IEEE Tran. Nuc. Sci. Vol41, NO 6, December 1994.

Radiation qualification Standards

- Radiation qualification has been standarized:

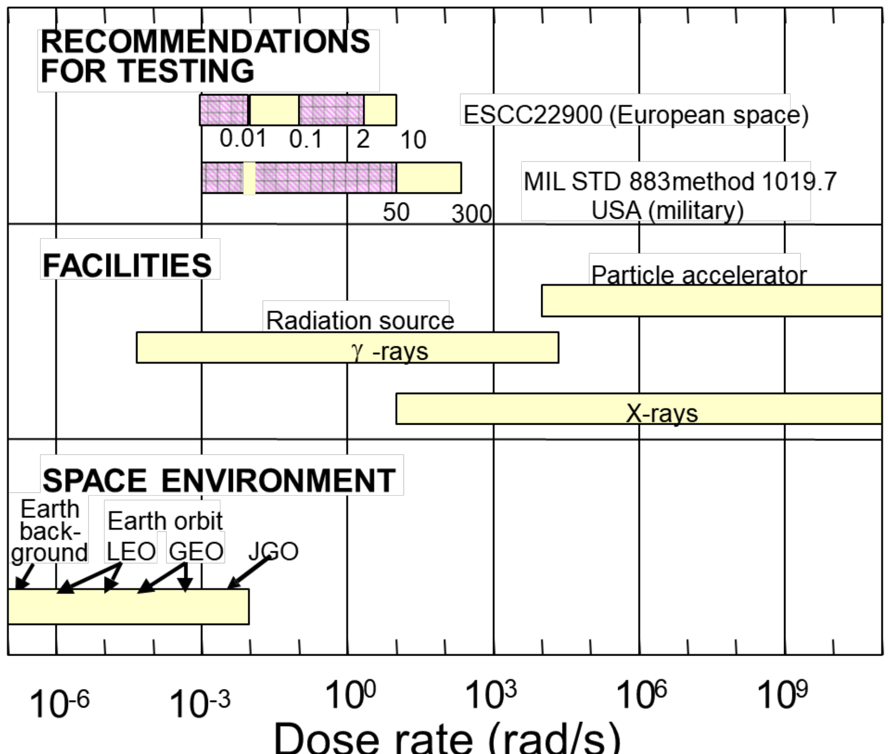
Standards	Effect	Parameters of concern	Means
ESA-SCC 22900.4	TID	Total dose, dose rate	**60Co sources**
MIL-STD 883E Method 1019.6	TID	Total dose, dose rate	**60Co sources**
ESA-SCC 25100.1	SEE	LET/range (heavy ions), Energy (protons)	**Accelerators of particles**
JESD57	SEE	LET/range (heavy ions)	**Accelerators of ions (Z>1)**
ESA-SCC 22900.4	DD	Energy	**Accelerators of particles (electrons, protons, neutrons)**

Duzellier, S. (2007). Test Facilities for SEE and Dose Testing.
In R. Velazco (Ed.), *Radiation Effects on Embedded Systems.*

Radiation qualification TID testing

- 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

TID - Radiation Sources and Dose Rates



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

Radiation qualification Facilities for TID test

- TID irradiation facilities types:

Radiation type	Main advantages	Main drawbacks
Electrons (accelerator)	High dose rate available Representative of some orbits	Costly Not adequate for low dose rates
Protons (accelerator)	High dose rate available Representative of some orbits	DD contribution Costly
X rays (photons)	High dose rates available Low cost	Dose enhancement effect Not adequate for low dose rates
Cs137 & Co60 sources (gamma rays)	Very large dose rate range Dose uniformity	Heavy shielding necessary Non-dominant in orbit

Duzellier, S. (2007). Test Facilities for SEE and Dose Testing. In R. Velazco (Ed.), *Radiation Effects on Embedded Systems.*

- Exhaustive list of facilities (2011):

https://twiki.cern.ch/twiki/pub/FPGARadTol/InformationOfInterest/IrradiationFacilitiesCatalogueRADECS2011.pdf

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Radiation qualification DD test

- Standard method does not yet exist for DD:
  - Modes of degradation are very complex
  - The induced electrical effects are very application dependent,
  - Annealing occurs depending on type of devices and application.
- DD testing is always designed and performed according to specific requirements and applications
- However, some recommendations can be provided

species	energy	comment
proton	50-60 MeV	Representative of "shielded" space environment Good penetration into package and device
proton	10 MeV	Detector array
electrons	1-3MeV	Solar cells

Duzellier, S. (2007). Test Facilities for SEE and Dose Testing. In R. Velazco (Ed.), *Radiation Effects on Embedded Systems.*

- Exhaustive list of facilities (2011):

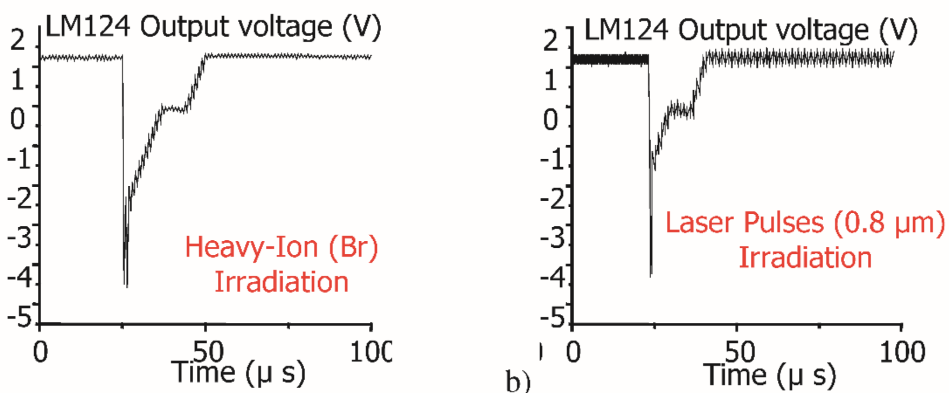
https://twiki.cern.ch/twiki/pub/FPGARadTol/InformationOfInterest/IrradiationFacilitiesCatalogueRADECS2011.pdf

Radiation qualification
SEE test

- SEEs are typically tested in heavy ions facilities

High Energy (100 MeV/amu)	France – GANIL
Medium Energy (> 10 MeV/amu)	Belgium – CYCLONE / Finland – JYFL
Low Energy (< 10 MeV/amu)	France – IPN / Italy – LNL

- Lasers are a complementary tool to study SEE sensitivity:
  - Focused lasers (< 1 µm) allows for performing localized
  - Correlating a structure or part of a circuit to an observed failure mode
  - Can also be triggered by the test application permitting the temporal characterization of the anomaly



R. Velazco (Ed.), *Radiation Effects on Embedded Systems, 2007.*

Outlook

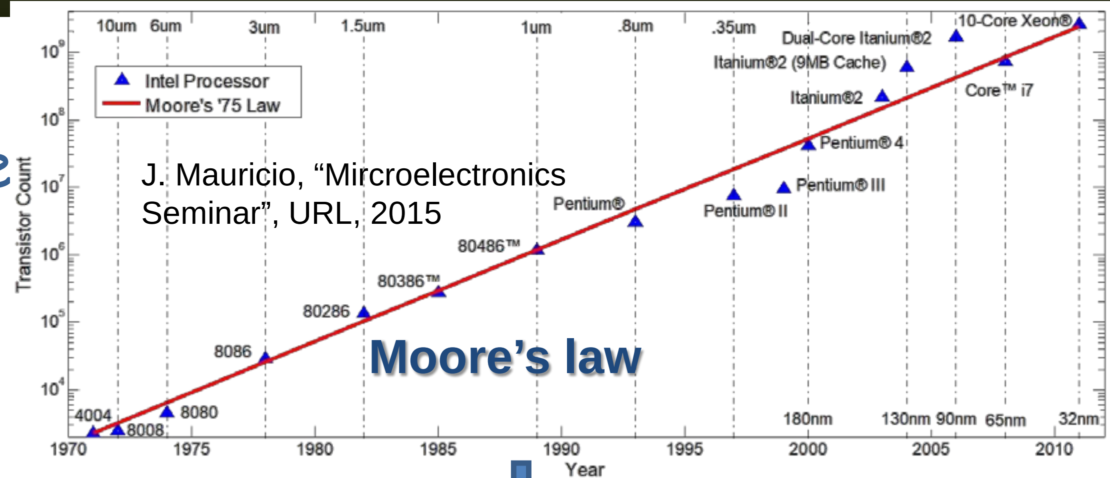
I. Radiation space environment
II. Radiation effects
III. Radiation qualification
IV. Design hardening methodologies for mixed signal circuits
V. Fault tolerance in digital circuits
VI. Design hardening at system level

Design hard. method. Technological aspects

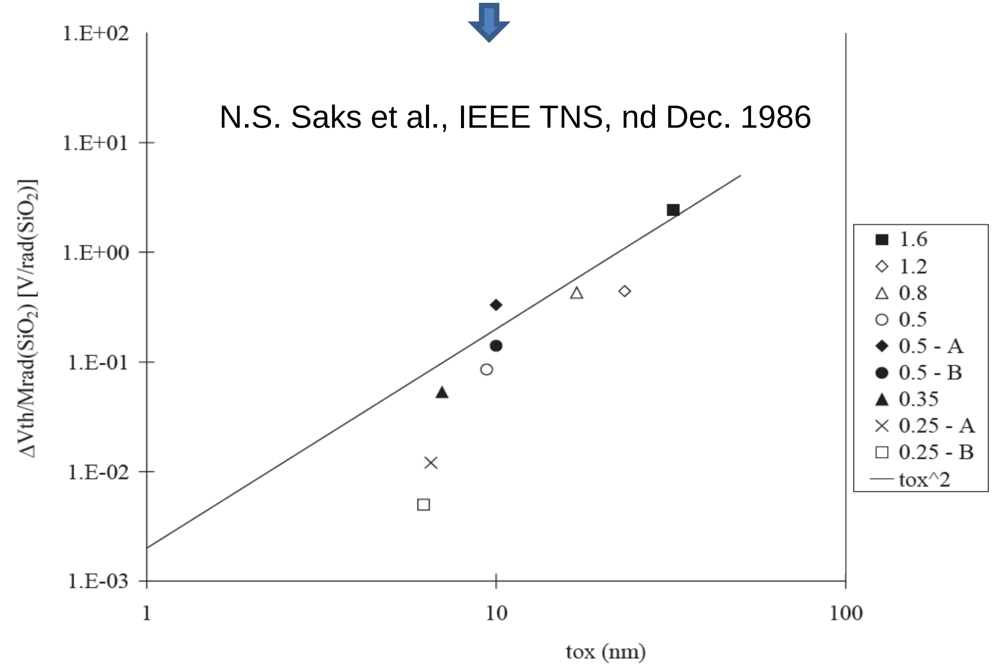
- Design hardening methods for full custom A/D design
  - E.g. Application Specific Integrated Circuits (ASICs)
  - Even if you don't design at full custom level some technological considerations are useful to choose COTS
    - Commercial ICs, programmable logic, sensors, etc
- CMOS technology is the baseline technology nowadays
  - Dedicated processes for space are only affordable for particular cases
  - Silicon On Insulator (SOI) is sometimes used
    - Low SEU rates, latch-up free, some concerns on TID
    - SOI is less readily available, analog IP need to be re-developed
- Dose effects
  - Most space missions are limited to 100 krad dose
    - Below 180 nm CMOS devices TID protection might be limited to screening
  - Some long duration, deep space missions are in the Mrad domain, requires special mitigation techniques

Design hard. method. Technological aspects

- Modern nanometric CMOS technologies are inherently radiation hard at 100 Krad level
  - Insensitive to DD
  - TID effects in SiO2 layers decrease quadratically with the oxide thickness
- Displacement damage is still a concern for
  - Bipolar (or BiCMOS) technologies
  - Optical components



In terms of radiation tolerance



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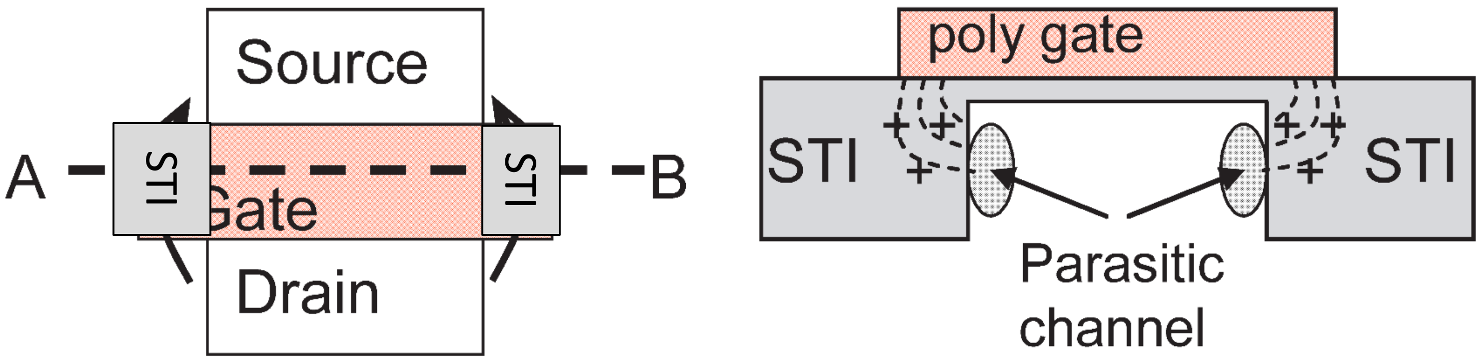
Design hard. method.
TID hardening @ Mrad level

- But leakage current can still be a problem at Mrad level
  - Oxides < 5 nm are free from dose effects even at Mrad level
  - BUT holes can be trapped in Shallow Trench isolation (STI) placed at the end of the active area (end of n+ region below gate for a NMOS transistor)
  - Positive charges builds up an electric field that ultimately inverts the p-doped silicon underneath the STI
  - Increase in leakage current and finally lost of functionality

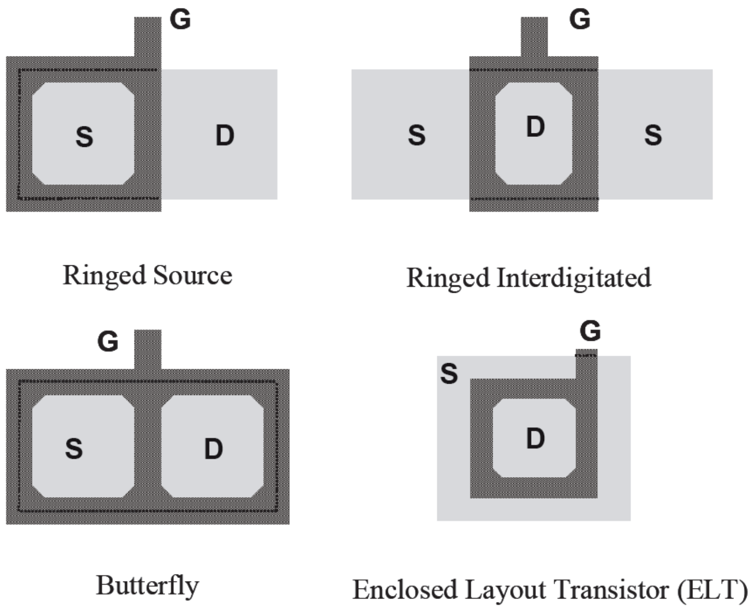


Faccio, F. (2007). Design Hardening Methodologies for ASICs. In R. Velazco (Ed.), *Radiation Effects on Embedded Systems.*

Design hard. method. TID hardening @ Mrad level

- Solution is to avoid the contact between the STI oxide and any p-doped region
  - Surround completely one of the two n+ diffusions (source or drain) with the thin gate oxide
  - Several layouts are possible, ELT is more used (better compatibility with fabrication rules)

The solid line in each design evidences the end of the active area, or the beginning of the STI oxide

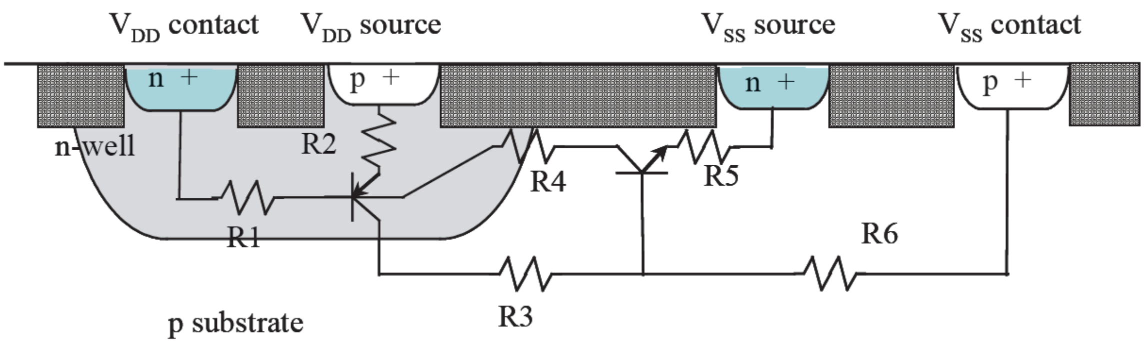


Faccio, F. (2007). Design Hardening Methodologies for ASICs. In R. Velazco (Ed.), *Radiation Effects on Embedded Systems.*

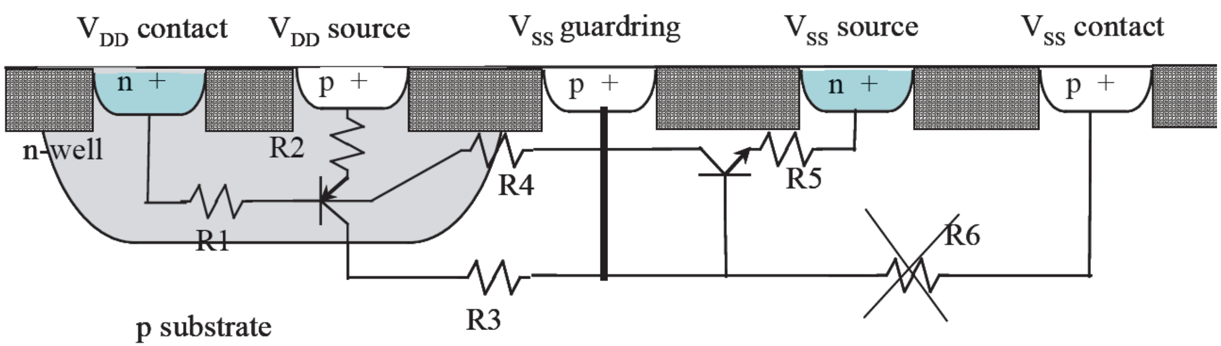
Design hard. method. SEL hardening

- Hardening against SEL:
  - Reduce the gain of parasitic transistors
  - Reduce the parasitic resistances

➢ Increase distance p to n MOS
➢ Use guardrings with contact distance < 10 um



No guard ring

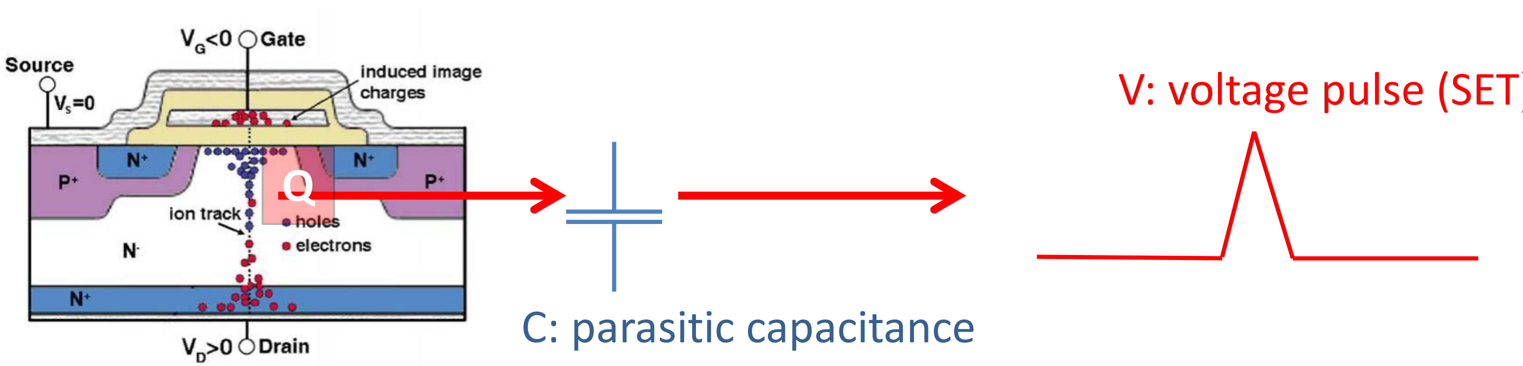


With guard ring

Faccio, F. (2007). Design Hardening Methodologies for ASICs. In R. Velazco (Ed.), *Radiation Effects on Embedded Systems.*

Design hard. method. SEU/SET hardening

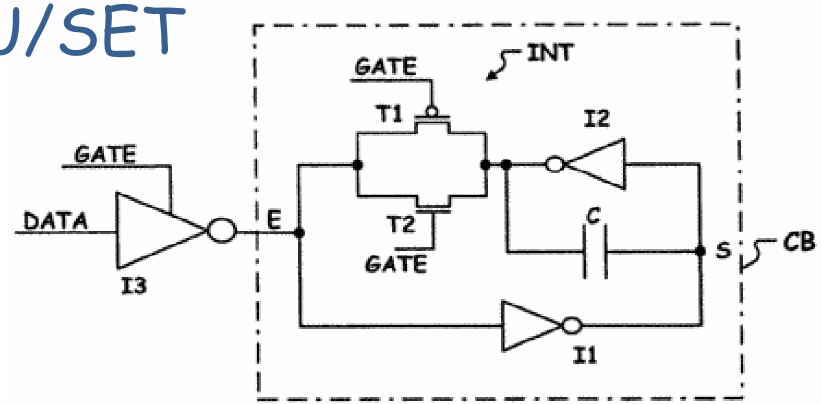
- Hardening against SEUs/SETs:
  - Low capacitance nodes are the most sensitive elements (V=Q/C !)
    - The amount of charge need to upset a cell is called the “critical charge”
    - Note that technology down-scaling goes against SEU hardening

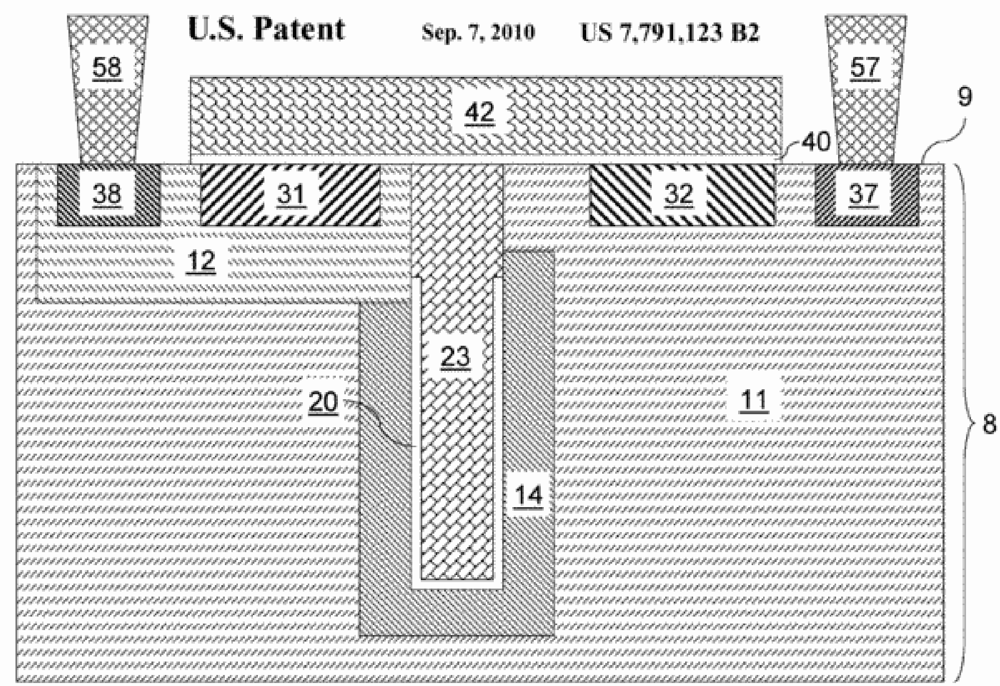


  - Memory cells and latches are typically the most vulnerable elements
    - Modify the cell layout or architecture to decrease its sensitivity
    - Simplest method of hardening a memory or latch cell is adding some capacitance to the sensitive nodes
    - Radiation environment determines the type of protection
      - Heavy ion environment is very different to proton/electron/neutron environment

Design hard. method. SEU/SET hardening

- Capacitive hardening against SEU/SET
- Trench capacitors
  - embedded DRAM cells can be used to minimise the area penalty
  - IBM patent





U.S. Patent Jun. 26, 2007

US 7,236,031 B2

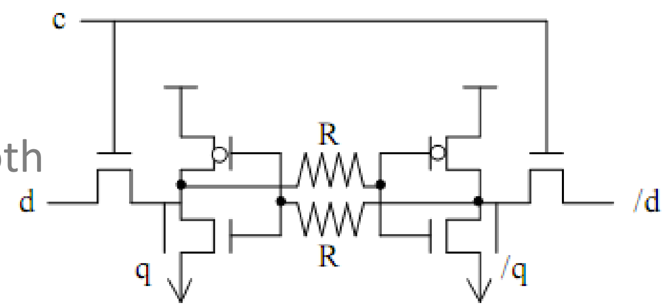
- Transmission gates
  - feedback path is cut off during write cycles to reduce the speed penalty
  - ST patent

"Single Event Effect Mitigation in Digital Integrated Circuits for Space", R. Weigand (ESA) TWEPP 2010.

Design hard. method. SEU/SET hardening

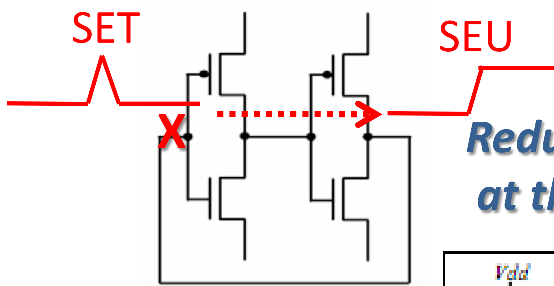
- SEU hardening of flip-flops and SRAM
  - Based on redundancy
  - Redundant inverters have to be spaced
    - Single particle strike could induce a glitch in in both

Resistor memory cell



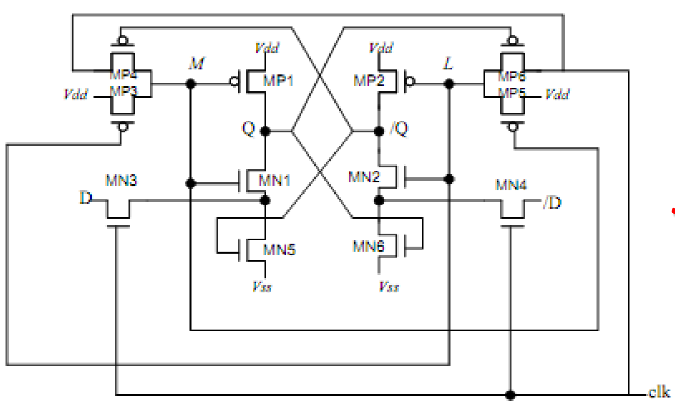
Faccio, F. (2007). Design Hardening Methodologies for ASICs. In R. Velazco (Ed.), *Radiation Effects on Embedded Systems.*

“Single Event Effect Mitigation in Digital Integrated Circuits for Space”, R. Weigand (ESA) TWEPP 2010.



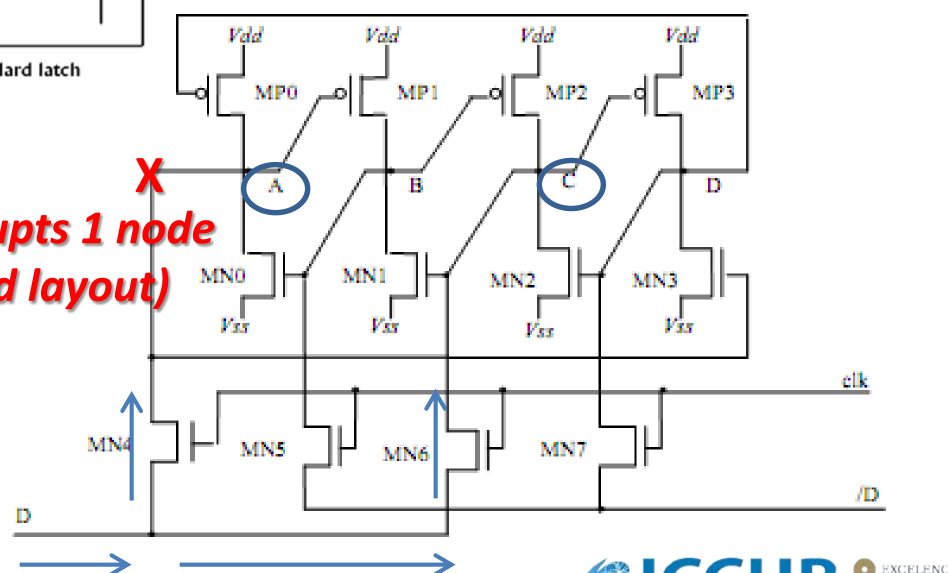
standard latch

Redundancy: 2 nodes must be written at the same time to change the state



HIT memory cell

SEU corrupts 1 node (if good layout)



DICE hardened memory cell

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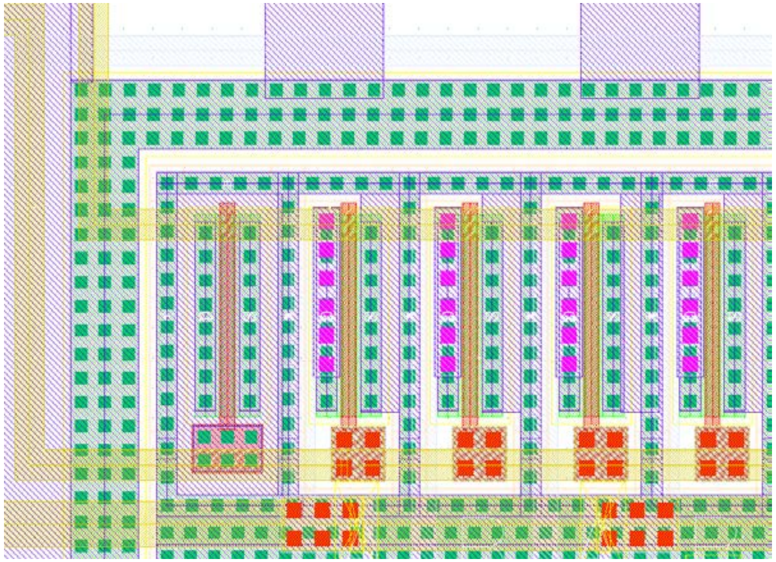
Design hard. method.

- Resistor Memory Cell
  - H. T. Weaver, C. L. Axness, J. D. McBrayer, J. S. Browning, J. S. Fu, A. Ochoa, R. Koga, "An SEU Tolerant Memory Cell Derived from Fundamental Studies of SEU Mechanisms in SRAM," Nuclear Science, IEEE Transactions on , vol. 34, no. 6, pp. 1281-1286, Dec. 1987
- HIT = Heavy Ion Tolerant storage cell
  - D. Bessot R. Velazco, "Design of SEU-hardened CMOS memory cells: the HIT cell" RADECS, 1993
- DICE = Dual Interlocked storage CEll
  - R. Velazco, D. Bessot, S. Duzellier, R. Ecoffet, R. Koga, "Two CMOS memory cells suitable for the design of SEU-tolerant VLSI circuits," Nuclear Science, IEEE Transactions on , vol. 41, no. 6, pp. 2229-2234, Dec. 1994.
- Examples of hardened libraries around the world
  - ATMEL MH1RT (350 nm) and ATC18RHA (180 nm) technologies – http://www.atmel.com
  - DARE (Design Against Radiation Effects) library for UMC 180 nm and 90 nm (development)
    - http://microelectronics.esa.int/mpd2010/day1/MPD-IMEC-DARE-30March2010.pdf
  - ST Microelectronics library for 65 nm under development
    - http://microelectronics.esa.int/mpd2010/day2/DSM65nm.pdf
  - Ramon Chips library for 180 nm Tower Semiconductors (130 nm under development)
    - http://nepp.nasa.gov/mapld_2008/presentations/i/05%20-%20Ginosar_Ran_mapld08_pres_1.pdf
  - Aeroflex (600, 250, 130, 90 nm) – http://www.aeroflex.com/RadHardASIC
  - MRC Microelectronics on TSMC (0.35/0.25), UTMC/AMI, HP, NSC, Peregrine
    - http://parts.jpl.nasa.gov/mrqw/mrqw_presentations/S4_alexander.ppt
  - HIREC/JAXXA - Fujitsu 0.18, OKI 0.15 SOI (NSREC2005)

Design hard. method.

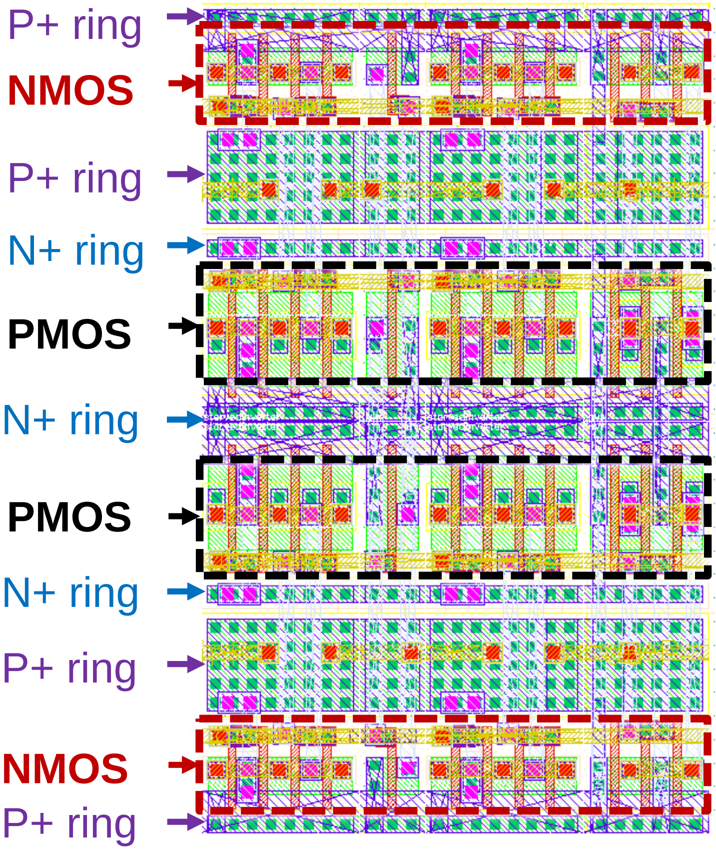
- Example of SEL hardened library designed at ICCUB



"Radiation hard programmable delay line for LHCb calorimeter upgrade" J Mauricio et alt, ‚Journal of Instrumentation, Volume 9, January 2014

Digital blocks extra design rules:

1. ≥ 5um between N-DIFF layer and NWELL.
2. Guard rings between PMOS and NMOS.



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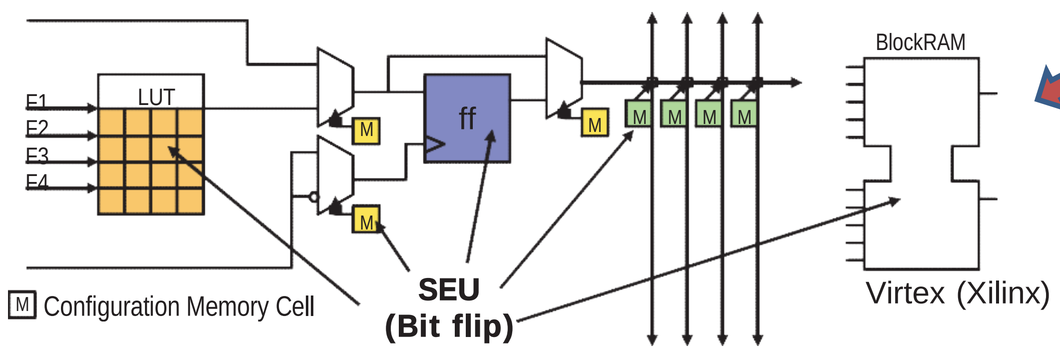
Outlook

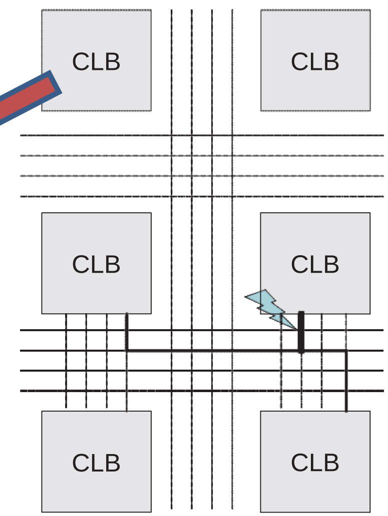
I. Radiation space environment
II. Radiation effects
III. Radiation qualification
IV. Design hardening methodologies for mixed signal circuits
V. Fault tolerance in digital circuits
VI. Design hardening at system level

- We will now focus on design techniques for programable digital circuits (mostly FPGAs)
  - High flexibility and reconfigurability feature
  - Recent devices allow HW/SW co-design embedding microprocessors
- SRAM-based FPGAs can offer an additional benefit for remote missions.
  - In-orbit design changes thanks to re-programmability,
  - Reducing the mission cost by correcting errors or improving system performance after launch
- Flash or Antifuse FPGA can be an alternative in some cases:
  - Neutron and alpha radiation do not have adverse effects on the configuration for some hardened FPGAs
    - https://www.microsemi.com/products/fpga-soc/reliability/see
  - Typically lower performances (# gates and speed) than SRAM-FPGAs

Fault tolerance in digital circuits
Fault tolerant systems in FPGAs

- SRAM-FPGA configuration can be corrupted by SEUs/SETs
  - Example: Xillinx Virtex®
    - Virtex® devices consist of a flexible and regular architecture composed of an array of configurable logic blocks (CLBs)
    - Surrounded by programmable input/output blocks (IOBs)
    - The CLBs are interconnected through a general routing matrix (GRM)
    - Configuration bitstream: Look-up tables (LUT) and flip-flops, CLBs configuration cells and interconnections:
      - ❑ All SEU/SET sensitive !

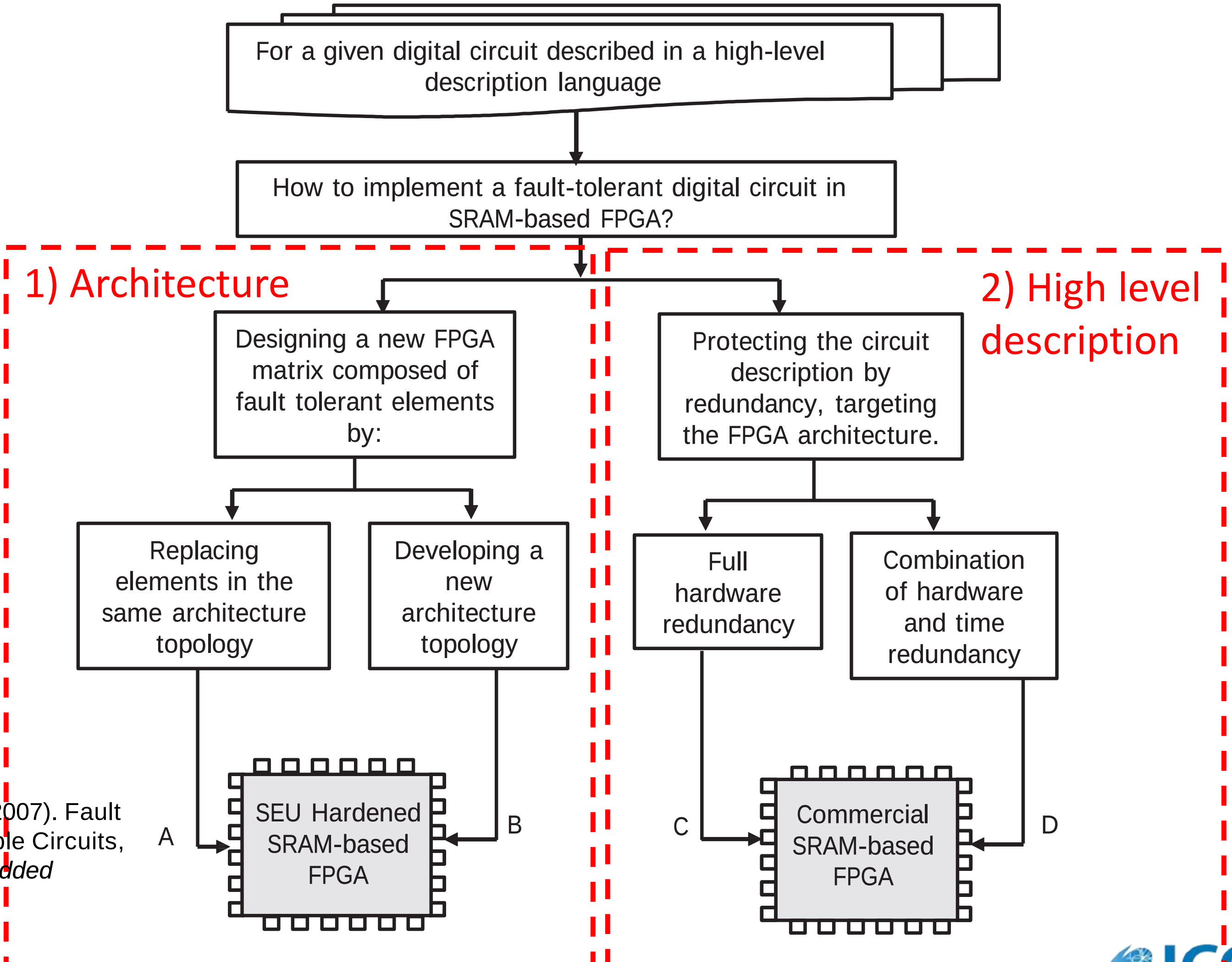




F. Kastensmidt, R. Reis. (2007). Fault Tolerance in Programmable Circuits, *Radiation Effects on Embedded Systems.*

Fault tolerance in digital circuits
Fault tolerant systems in FPGAs

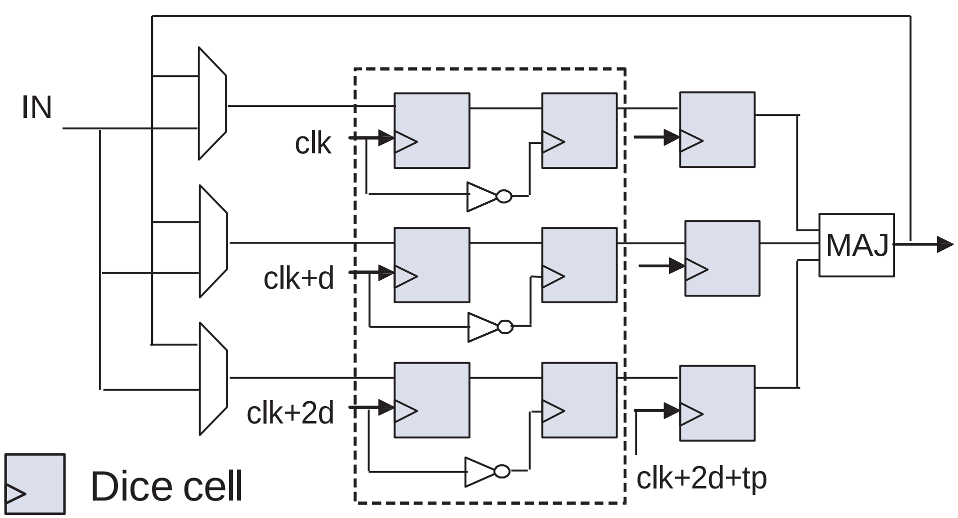
- 2 ways to implement fault-tolerant circuits in SRAM- FPGAs:



F. Kastensmidt, R. Reis. (2007). Fault Tolerance in Programmable Circuits, *Radiation Effects on Embedded Systems.*

Fault tolerance in digital circuits
FPGA with fault tolerant elements

- Fabrication process-based techniques
  - Epitaxial CMOS processes and advanced process such as SOI
- Design-based techniques
  - Triple modular redundancy (TMR) or SEU hardeneded flip-flops (DICE, etc)
    - Also applicable to ASICs
  - Time redundancy
  - EDAC (error detection and correction coding)

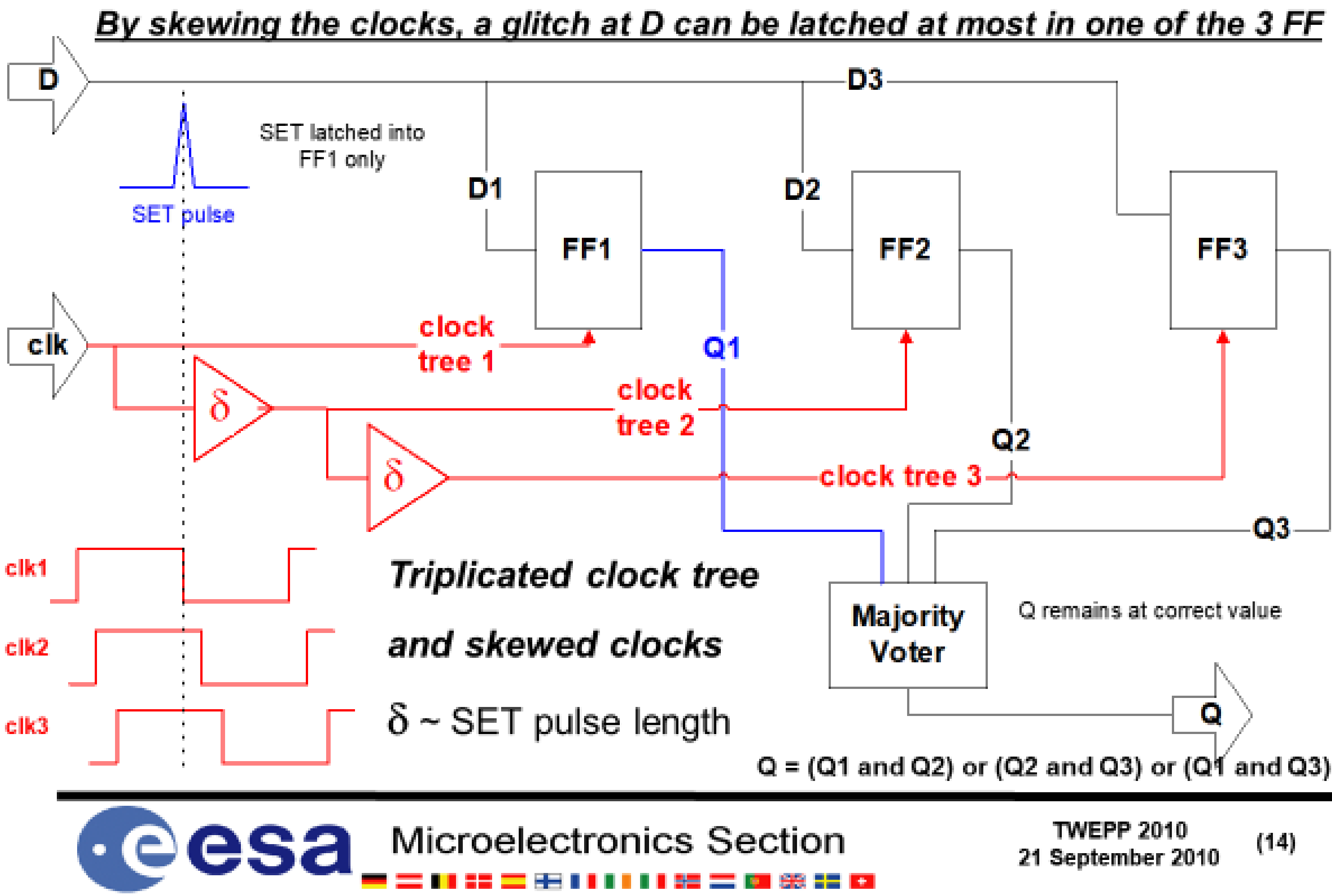


- SET at MUX output in CLB could be a problem
  - Even with SEU hard flip-flops (DICE) !
- TMR combined with DICE offers the best protection
  - All logic elements are redundant (x3)
  - A majority voters detects any difference and corrects the errors
  - Clocks (and reset) signals should be skewed because of possible SET in clk/rst

F. Kastensmidt, R. Reis. (2007). Fault Tolerance in Programmable Circuits, *Radiation Effects on Embedded Systems.*

Fault tolerance in digital circuits
FPGA with fault tolerant elements

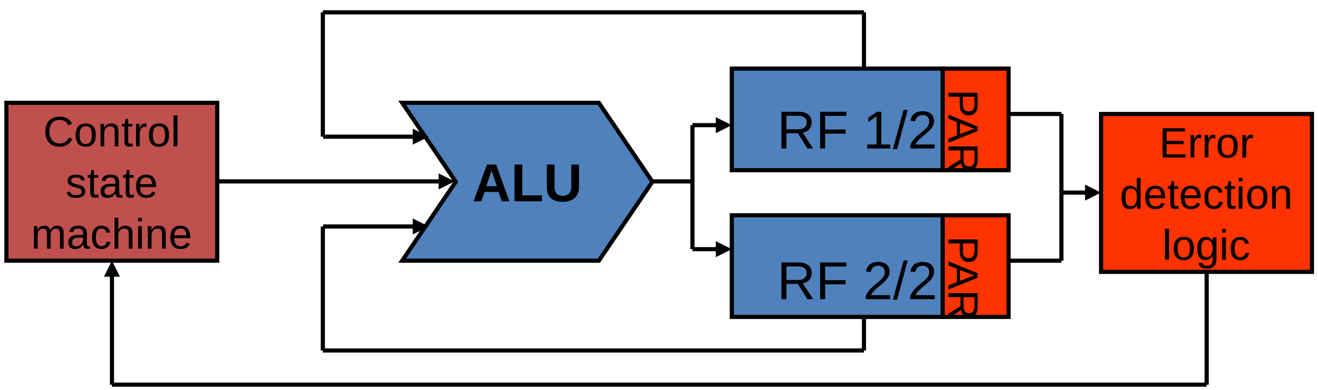
STMR: TMR with triple skewed clock



R. Weigand

Fault tolerance in digital circuits
FPGA with fault tolerant elements

- XOR Parity bits
  - Employed for a long time, also in ground-based computers
  - Error handling: correction/reload by HW state machine or software (reboot)
  - Loss of data, unless redundant data is available elsewhere in the system…



- Use hamming codes or other EDAC codes:
  - Example – ACTEL core: www.actel.com/documents/EDAC_AN.pdf

"Single Event Effect Mitigation in Digital Integrated Circuits for Space", R. Weigand (ESA) TWEPP 2010.

Fault tolerance in digital circuits
High level techniques

- Architectural techniques require dedicated hardened elements
  - Expensive and long development times
- Alternative is to achieve radiation tolerance using high level synthesis techniques
  - SEU mitigation technique used nowadays to protect designs synthesized in the Virtex® architecture is mostly based on TMR combined with scrubbing
    - Reload the bitstream : external oscillator generates the configuration clock that drives the FPGA and PROM that contains the "gold" bitstream.

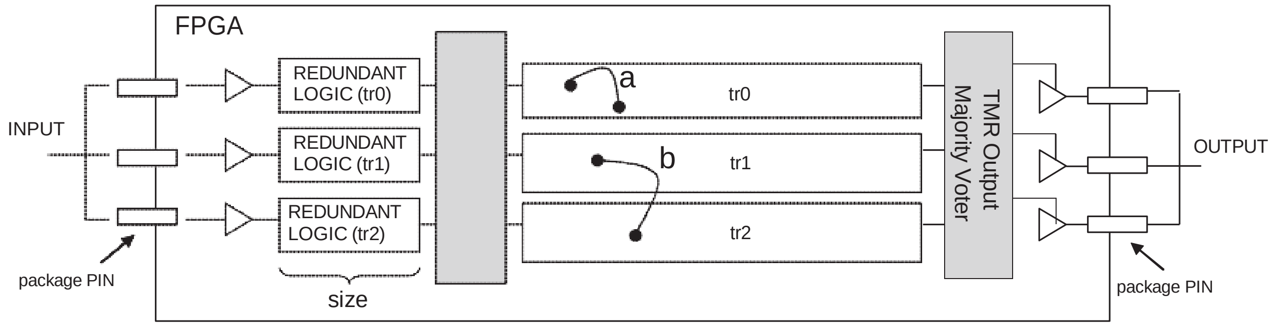
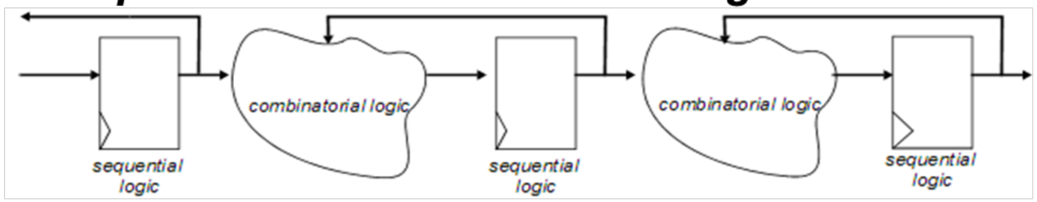


Figure 10. Triple Modular Redundancy for Xilinx FPGAs.

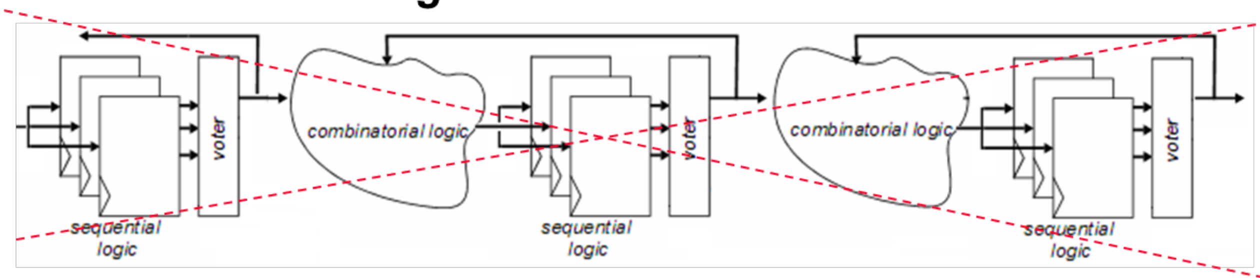
F. Kastensmidt, R. Reis. (2007). Fault Tolerance in Programmable Circuits, *Radiation Effects on Embedded Systems.*

Fault tolerance in digital circuits
High level techniques

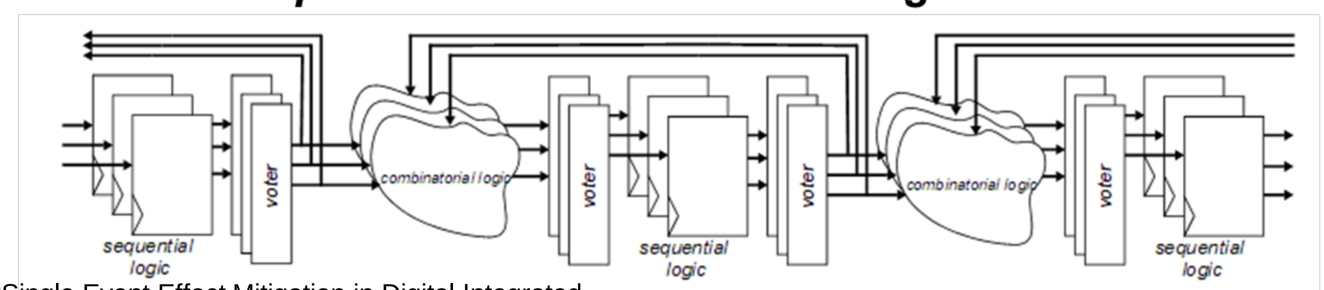
- ALL THE LOGIC MUST BE TRIPLICATED FOR SRAM-FPGAs
  - *Plain sequential and combinatorial logic*



  - *Standard TMR with single voters – not for SRAM FPGA*



  - *TMR for sequential and combinatorial logic and voters*



"Single Event Effect Mitigation in Digital Integrated Circuits for Space", R. Weigand (ESA) TWEPP 2010.

Fault tolerance in digital circuits
FPGA Wrap-up

- Increasing interest for SRAM based RFPGA
  - Lower NRE cost than ASIC
  - In-flight reconfiguration capability
  - High performance and complexity allowing System-On-FPGA
- SEU in configuration memory
  - Affect not only user data or state (as in ASIC) …
  - … but alter the functionality of the circuit itself
  - … turn the direction of I/O pins
- SEU mitigation for reprogrammable FPGA
  - Configuration scrubbing or read-back and partial reconfiguration
  - Triplication of registers and combinatorial logic
  - Voting of logical feedback paths
  - Redundancy for user memory
  - Voting of the outputs
  - Triplication of I/Os

"Single Event Effect Mitigation in Digital Integrated Circuits for Space", R. Weigand (ESA) TWEPP 2010.

Fault tolerance in digital circuits
State of the art

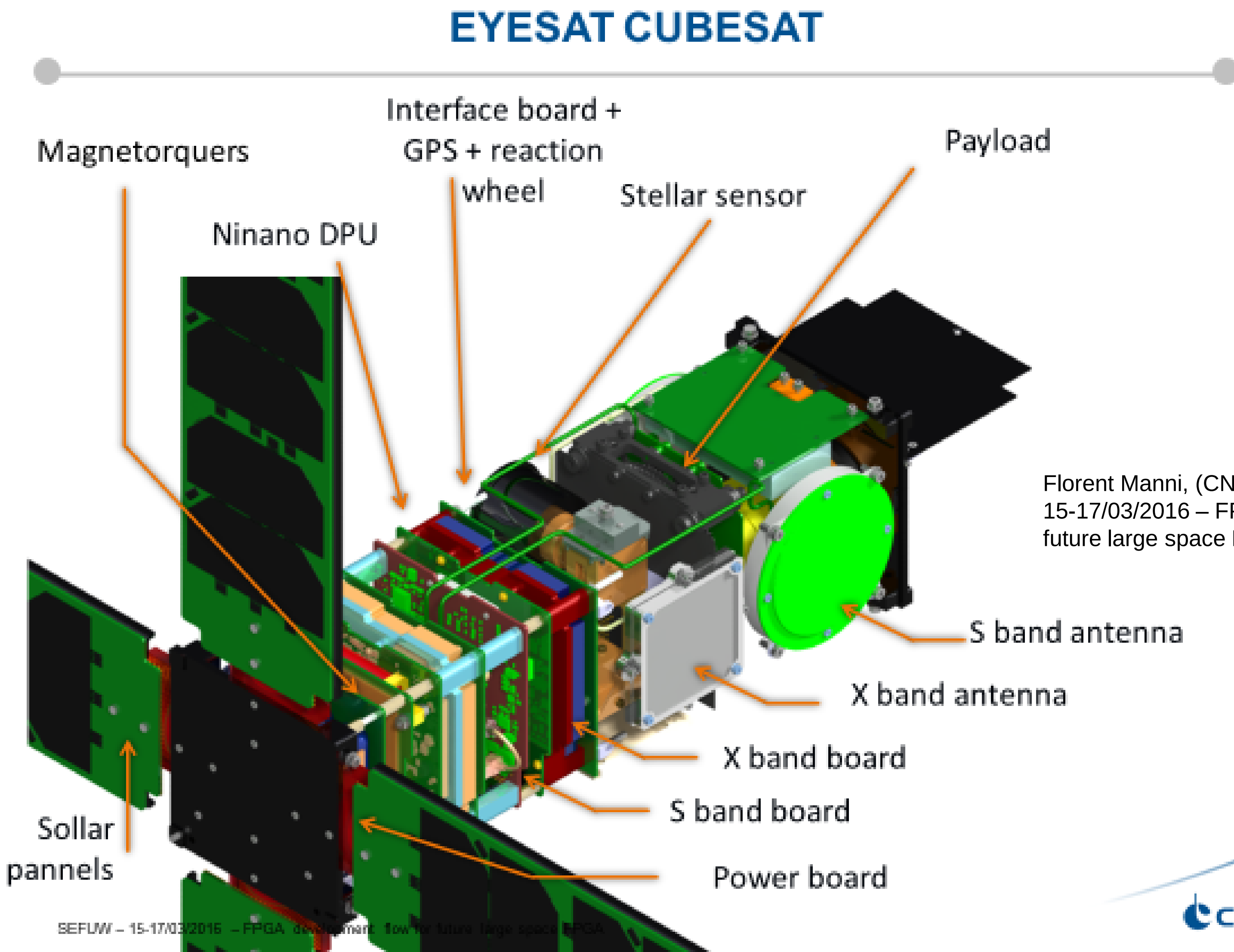
- Some standard rad hard FPGAs

Xilinx	Atmel	Actel (Microsemi)
Virtex®-5QV FPGA XQR5VFX130 – 65 nm Re-programable Estimated 1,4M gates	ATF280F EEPROM 280K gates (50% typ. routable)	RTAX4000 Anti-fuse 500k gates

Florent Manni, (CNES-DCT/TV/IN), SEFUW – 15-17/03/2016 – FPGA development flow for future large space FPGA

- Nowadays advanced FPGAs include embedded soft processors, interfaces, peripheral and also high speed digital signal processing application:
  - System on Chip (SoC)
  - Extremely appealing for nanosats: lower cost and flexibility !

Fault tolerance in digital circuits
State of the art

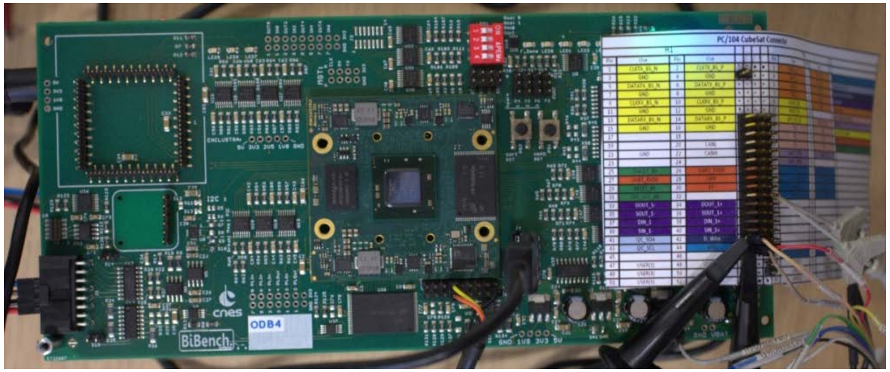


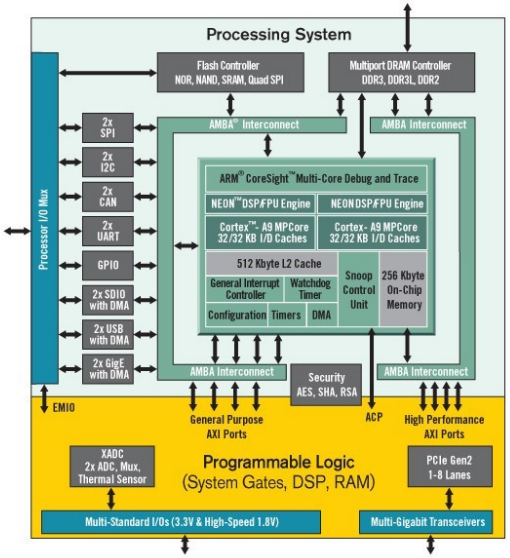
Florent Manni, (CNES-DCT/TV/IN), SEFUW – 15-17/03/2016 – FPGA development flow for future large space FPGA

Institute of Cosmos Sciences

Fault tolerance in digital circuits
State of the art

- The Xilinx Zynq XC7Z030 (28 nm) is a SoC FPGA used as main processing unit for the student nanosatellite Eyesat
  - Zynq component handles both payload and platform functions
  - ARM processor will handle platform and payload software using Time and Space Partitioning (Xtratum)
  - FPGA will handle communication with every equipment (band X, camera, mass memory...)





Florent Manni, (CNES-DCT/TV/IN), SEFUW – 15-17/03/2016 – FPGA development flow for future large space FPGA

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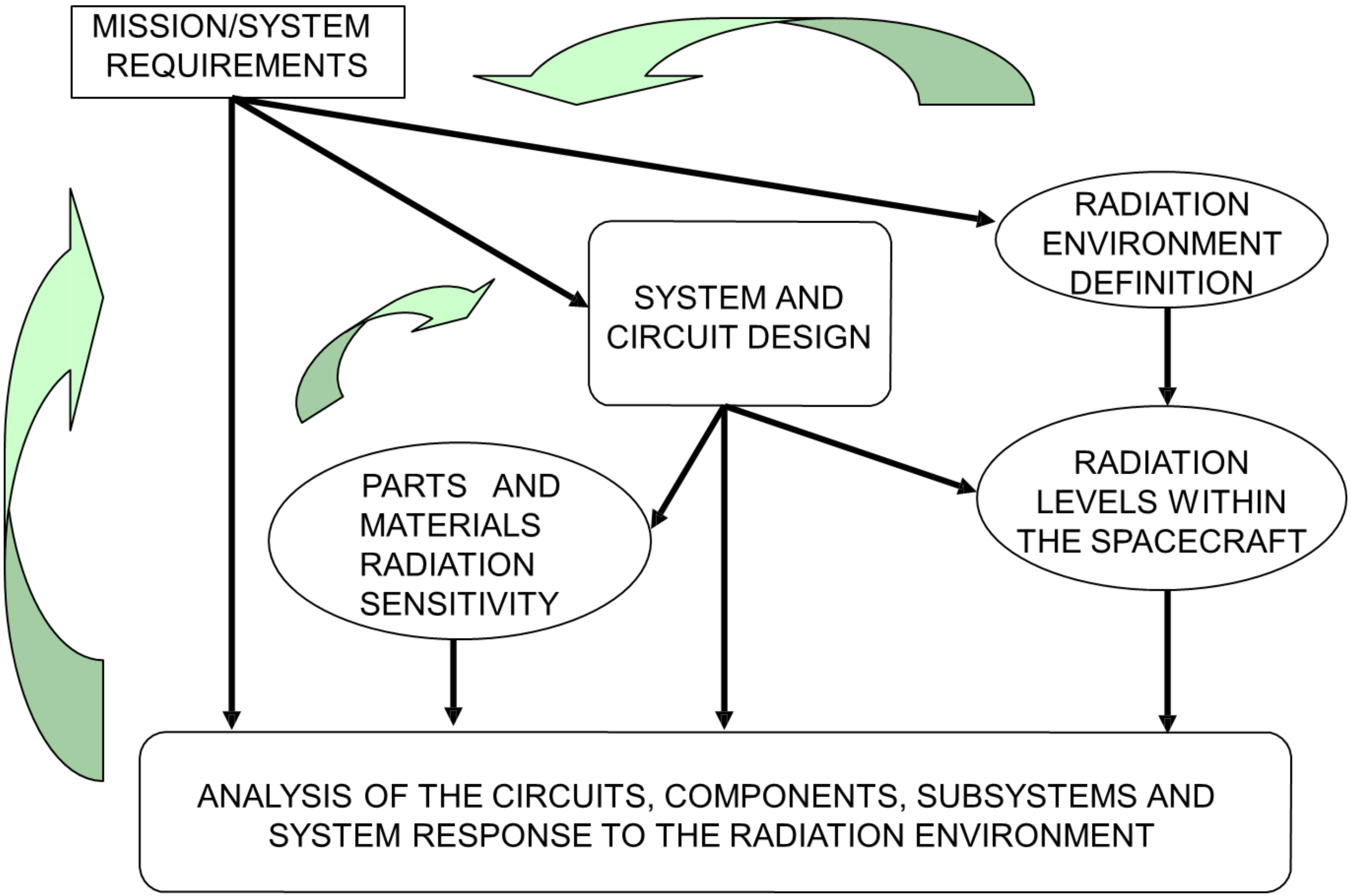
Design hardening at system level
RHA methodology

- So far we have been looking the problem at device level
  - Radiation Hardness Assurance (RHA) goes beyond the piece part level
- RHA should consider the space system as a whole:
  - Deals with environment definition
  - Part selection and part testing
  - Spacecraft layout
  - Radiation tolerant design
  - Mission/system/subsystems requirements
  - Mitigation techniques, etc.

Ali Zadeh, ESA, “Radiation Hardness Assurance & Test Facilities”, EJSM Workshop ESTEC, 18 to 20 January 2010

Design hardening at system level
RHA methodology

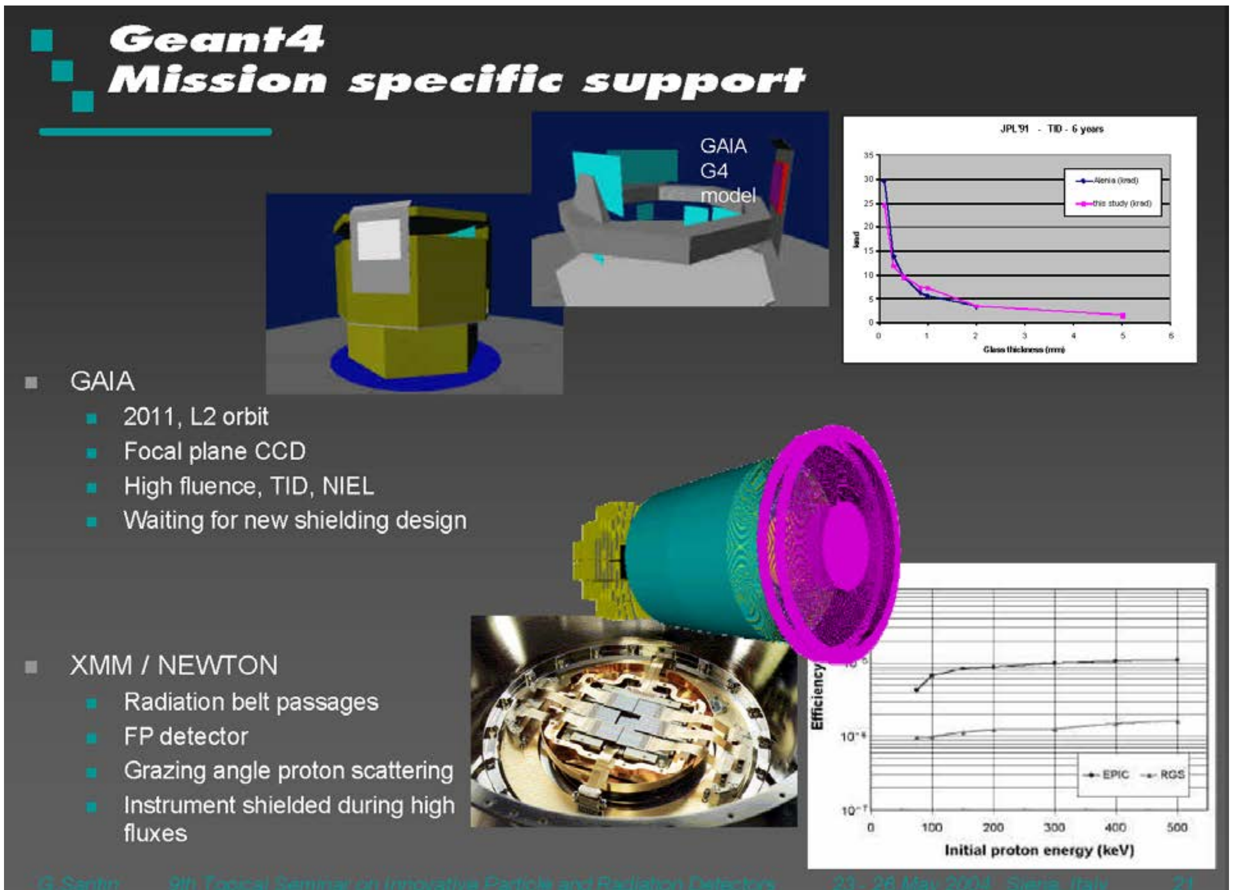
- RHA overview



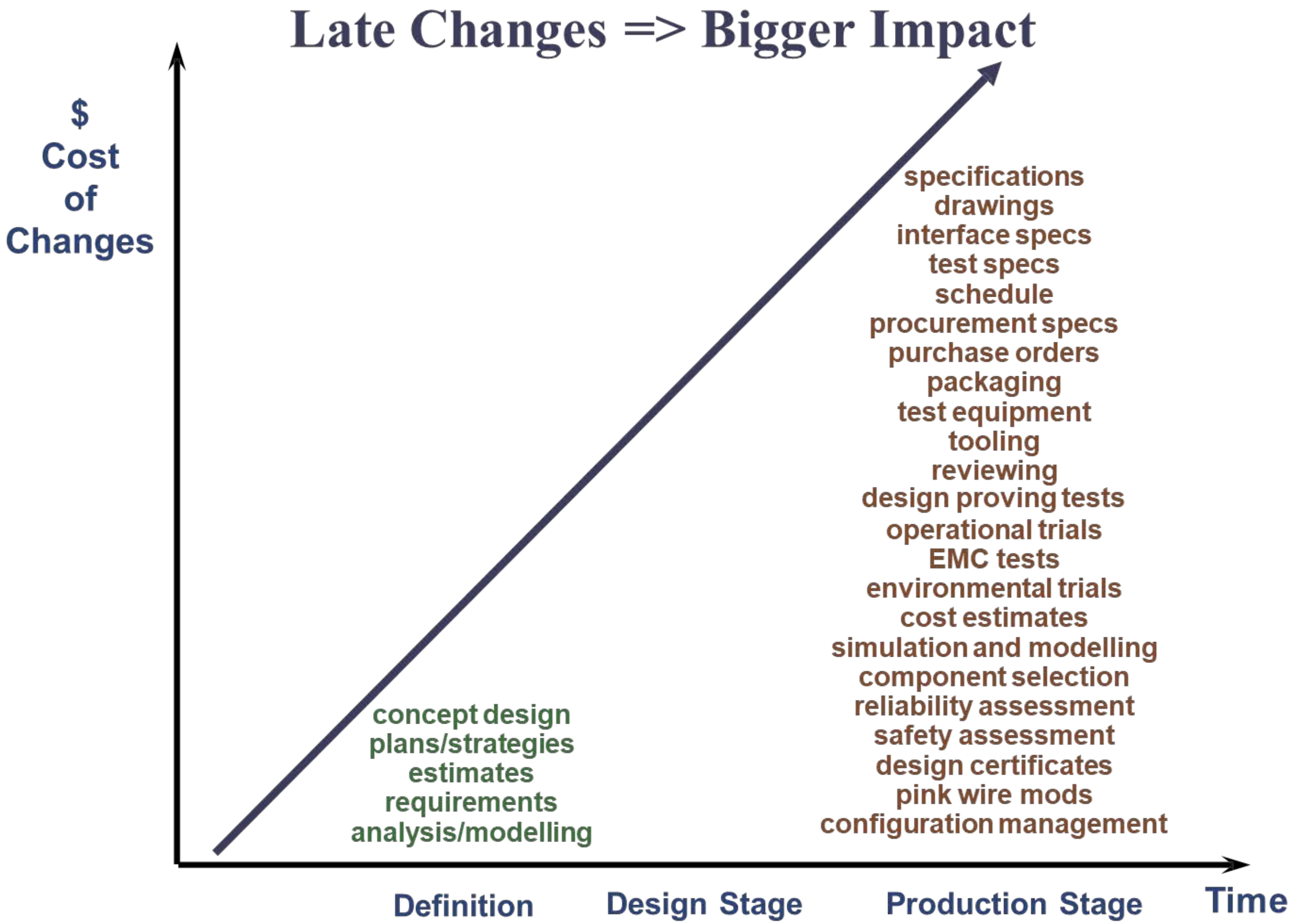
Ali Zadeh, ESA, "Radiation Hardness Assurance & Test Facilities", EJSM Workshop ESTEC, 18 to 20 January 2010

Design hardening at system level
RHA simulation

- Detailed radiation "transport" Monte Carlo simulation:
  - Particle numbers, species, energy, and direction of propagation
  - Accurate part level dose calculation necessary
  - Structural and shielding optimization



Design hardening at system level
RHA methodology



Ali Zadeh, ESA, “Radiation Hardness Assurance & Test Facilities”, EJSM Workshop ESTEC, 18 to 20 January 2010

Design hardening at system level
RHA during program life

- Pre Phase A, Phase A – (System Requirement Review, SRR)
  - Draft environment definition
  - Draft hardness assurance requirements (top level)
  - Preliminary studies (possible irradiation characterisation of critical components, sensors, etc.)
- Phase B – (Preliminary Design Review, PDR)
  - Final environment definition
  - Electronic design approach
  - Preliminary spacecraft layout for shielding analysis
  - Preliminary shielding analysis & hardness assurance requirements update
  - Preliminary Radiation Analysis Report
- Phase C – (Critical Design Review)
  - Radiation test results
  - Final shielding analysis & final hardness assurance requirement
  - Final Radiation Analysis Report (including Worst Case Analysis (WCA) and Failure Mode Effect Criticality Analysis (FMECA))
- Phase D
  - Radiation Lot Acceptance Tests (RLAT, typically before MRR)
- Phase E (Utilisation)
  - Failure analysis (Lessons learned)

Ali Zadeh, ESA, "Radiation Hardness Assurance & Test Facilities", EJSM Workshop ESTEC, 18 to 20 January 2010

Design hardening at system level
Approach for nanosats

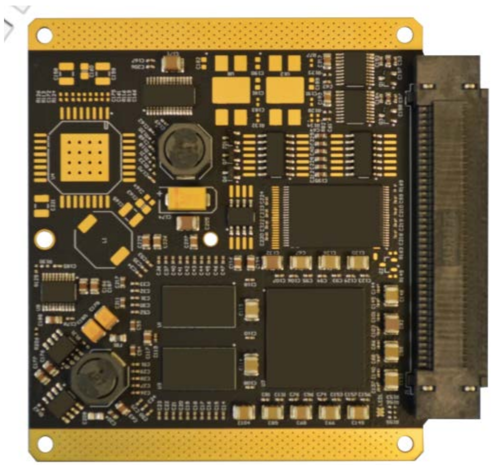
- Standarised solutions are probably the path for nanosats
  - Standard platforms: RHA, shielding, etc validated (orbit/app)
- Still one needs to optimize payloads
  - Scrubbing for configuration RAM
  - SEU/SET for FPGAs, ASICs, etc
  - ECC or parity checks (user memories in both ASICs and)
  - SW-implemented fault tolerance (SWIFT)
  - Watchdog timers
  - De-latching for SEL prevention

A. Stoddard at al., "High-speed PCAP configuration scrubbing on Zynq-7000 All Programmable SoCs," *2016 26th International Conference on Field Programmable Logic and Applications (FPL)*, Lausanne, 2016. doi: 10.1109/FPL.2016.7577301

G. A. Reis et alt., "SWIFT: software implemented fault tolerance," *International Symposium on Code Generation and Optimization*, 2005, pp. 243-254.

- Example: Radiation/Fault Tolerant Space Computer
  - o Zynq device
  - o 1 U form factor
  - o Developped by CHREC NSF center

http://www.spacemicro.com/assets/datasheets/digital/slices/CSP.pdf



CubeSat Space Processor Engineering Model

Close to end…

Concluding remarks

- There are no universal recipies to deal with radiation
- You need to study very well your project:
  - Orbit and lifetime
  - Application
  - Platform characteristics
- Trade-off: cost versus hardening
  - Component selection
  - Design: hardening takes resources !
- Design hardening methods have to be adopted
  - At early stage
  - Considering the global/system design

References

Many references given through the slides and few more next…

References

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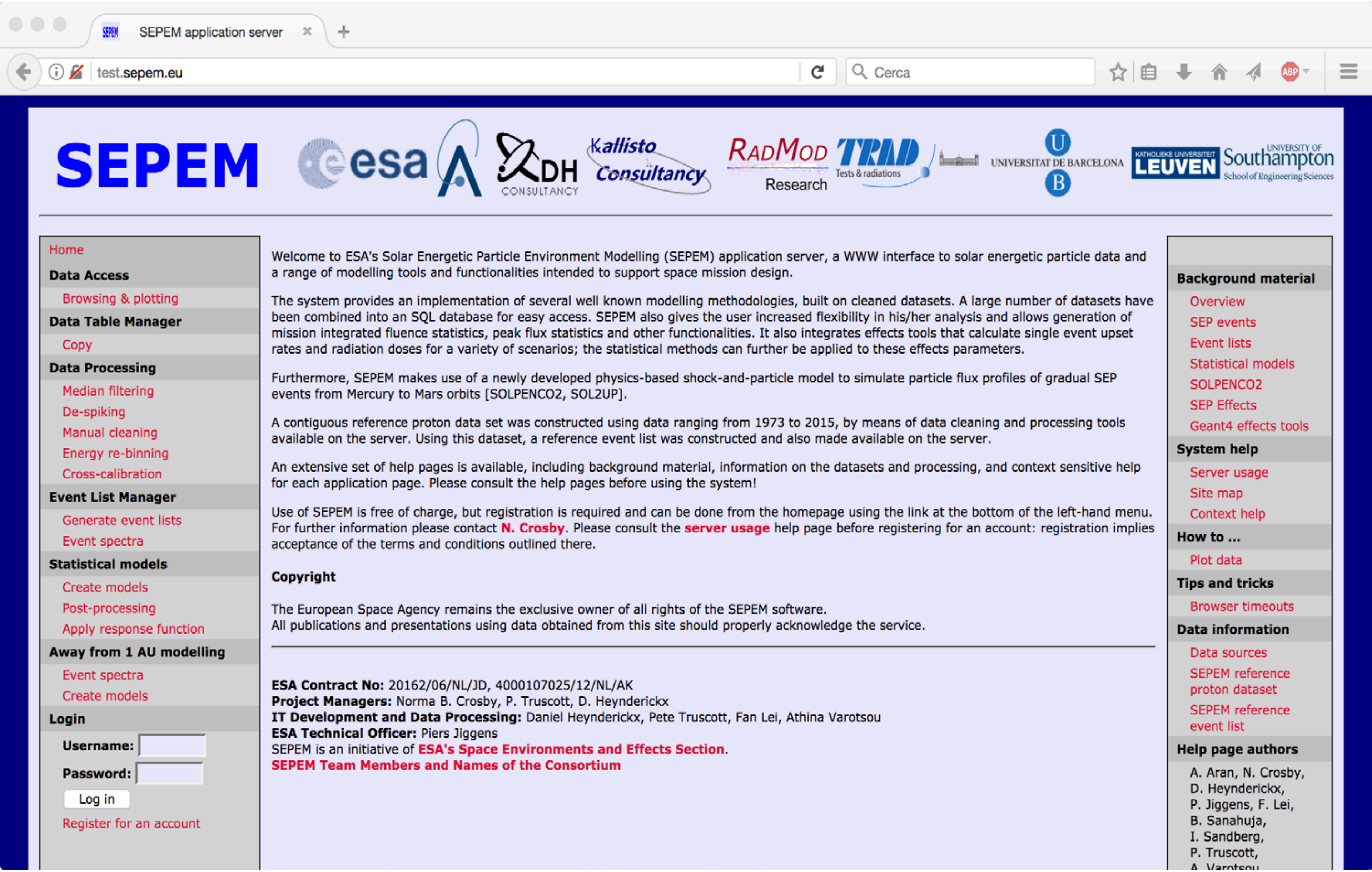
2. Alan Tribble : The space environment. Implications for spacecraft design, Princeton University Press (1995)
3. Andrew Holmes-Siedle and Len Adams : Handbook of radiation effects., Oxford science publications (1993)
4. Maurer et al. (2008). Harsh Environments: Space Radiation Environment, Effects, and Mitigation. Johns Hopkins APL Technical Digest. 28(1).
5. “Spacecraft system failures and anomalies attributed to the natural space environment”, NASA reference publication 1390, August 1996.
6. Poivey, C., “Radiation Hardness Assurance for Space Systems,” in Proc. IEEE NSREC Short Course, 2002
7. Nasa. Radiation Effects on Digital Systems. USA, 2002.
8. Hardware and Software Fault-Tolerance of Softcore Processors Implemented in SRAM-Based FPGAs, Nathaniel H. Rollins, NSF Center for High-Performance Reconfigurable Computing (CHREC), Brigham Young University, 2011
9. SEFUW_ SpacE FPGA Users Workshop, 3rd Edition (15-17 March 2016): https://indico.esa.int/indico/event/130/overview

References
Resources

1. ESA Space Environments and Effects Section (TEC-EES):
   - Analysis of space environments and their effects on space systems
   - Website: http://space-env.esa.int/index.php/online-resources.html
2. ESA Radiation Effects and Analysis Techniques Section (TEC-QEC).
   - Analysis at component level and radiation testing:
   - Website https://escies.org
3. ESA Microelectronics Section (TEC-EDM).
   - Availability of appropriate technologies and development methods.
   - Availability of space-specific standard components and IP.
   - Development support to projects.
   - Analysis and mitigation of SEE at design level.
   - Website: http://www.esa.int/TEC/Microelectronics
4. NASA radiation effect & analysis:
   - Website: https://radhome.gsfc.nasa.gov
5. SPENVIS: ESA's SPace ENVironment Information System.
   - Space environment and its effects; including cosmic rays, natural radiation belts, solar energetic particles, plasmas, gases, and "micro-particles"
   - Website https://www.spenvis.oma.be/intro.php
6. SEPEM: ESA's Solar Energetic Particle Environment Modelling Project
   - Website: http://test.sepem.eu

SEPEM Project (http://test.sepem.eu)



SEPEM application server

test.sepem.eu

SEPEM

Home

Data Access

Browsing & plotting

Data Table Manager

Copy

Data Processing

Median filtering

De-spiking

Manual cleaning

Energy re-binning

Cross-calibration

Event List Manager

Generate event lists

Event spectra

Statistical models

Create models

Post-processing

Apply response function

Away from 1 AU modelling

Event spectra

Create models

Login

Username:

Password:

Log in

Register for an account

Welcome to ESA's Solar Energetic Particle Environment Modelling (SEPEM) application server, a WWW interface to solar energetic particle data and a range of modelling tools and functionalities intended to support space mission design.

The system provides an implementation of several well known modelling methodologies, built on cleaned datasets. A large number of datasets have been combined into an SQL database for easy access. SEPEM also gives the user increased flexibility in his/her analysis and allows generation of mission integrated fluence statistics, peak flux statistics and other functionalities. It also integrates effects tools that calculate single event upset rates and radiation doses for a variety of scenarios; the statistical methods can further be applied to these effects parameters.

Furthermore, SEPEM makes use of a newly developed physics-based shock-and-particle model to simulate particle flux profiles of gradual SEP events from Mercury to Mars orbits [SOLPENCO2, SOL2UP].

A contiguous reference proton data set was constructed using data ranging from 1973 to 2015, by means of data cleaning and processing tools available on the server. Using this dataset, a reference event list was constructed and also made available on the server.

An extensive set of help pages is available, including background material, information on the datasets and processing, and context sensitive help for each application page. Please consult the help pages before using the system!

Use of SEPEM is free of charge, but registration is required and can be done from the homepage using the link at the bottom of the left-hand menu. For further information please contact **N. Crosby**. Please consult the **server usage** help page before registering for an account: registration implies acceptance of the terms and conditions outlined there.

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The European Space Agency remains the exclusive owner of all rights of the SEPEM software.
All publications and presentations using data obtained from this site should properly acknowledge the service.

ESA Contract No: 20162/06/NL/JD, 4000107025/12/NL/AK
Project Managers: Norma B. Crosby, P. Truscott, D. Heynderickx
IT Development and Data Processing: Daniel Heynderickx, Pete Truscott, Fan Lei, Athina Varotsou
ESA Technical Officer: Piers Jiggens
SEPEM is an initiative of **ESA's Space Environments and Effects Section**.
SEPEM Team Members and Names of the Consortium

Background material

Overview

SEP events

Event lists

Statistical models

SOLPENCO2

SEP Effects

Geant4 effects tools

System help

Server usage

Site map

Context help

How to ...

Plot data

Tips and tricks

Browser timeouts

Data information

Data sources

SEPEM reference proton dataset

SEPEM reference event list

Help page authors

A. Aran, N. Crosby, D. Heynderickx, P. Jiggens, F. Lei, B. Sanahuja, I. Sandberg, P. Truscott, A. Varotsou general studies programme

esa

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ECSS

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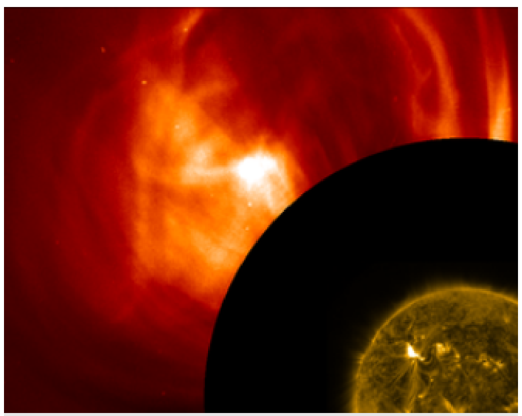
Minimum System - N

INTERPLANETARY AND PLANETARY RADIATION MODEL FOR HUMAN SPACEFLIGHT



5 July 2012 Research in the field of Space Radiation provides a major contribution to determine the feasibility for future manned spaceflight beyond the Earth's magnetic field. The GSP funded study "Interplanetary and Planetary radiation model for human spaceflight" investigates the most important drivers in the domain of interplanetary and planetary radiation environments identifying appropriate data sources and modelling methods to address needs of future interplanetary manned mission design and operation.

Participating Companies

The project is being carried out by an international consortium consisting of:

- DH Consultancy BVBA, Belgium
- Kallisto Consultancy Ltd, UK
- RadMod Research Ltd, UK
- University of Helsinki, Finland

With additional consultancy provided by:

- University of Barcelona, Spain
- Naval Research Laboratory, USA

IPRAM

D. Heynderickx, *Member, IEEE*, Angels Aran, Eamonn J. Daly, *Member, IEEE*, Piers Jiggens, *Member, IEEE*, F. Lei, *Member, IEEE*, B. Sanahuja, P. Truscott, *Member, IEEE*, A. Tylka and R. Vainio

Thanks a lot for your attention !

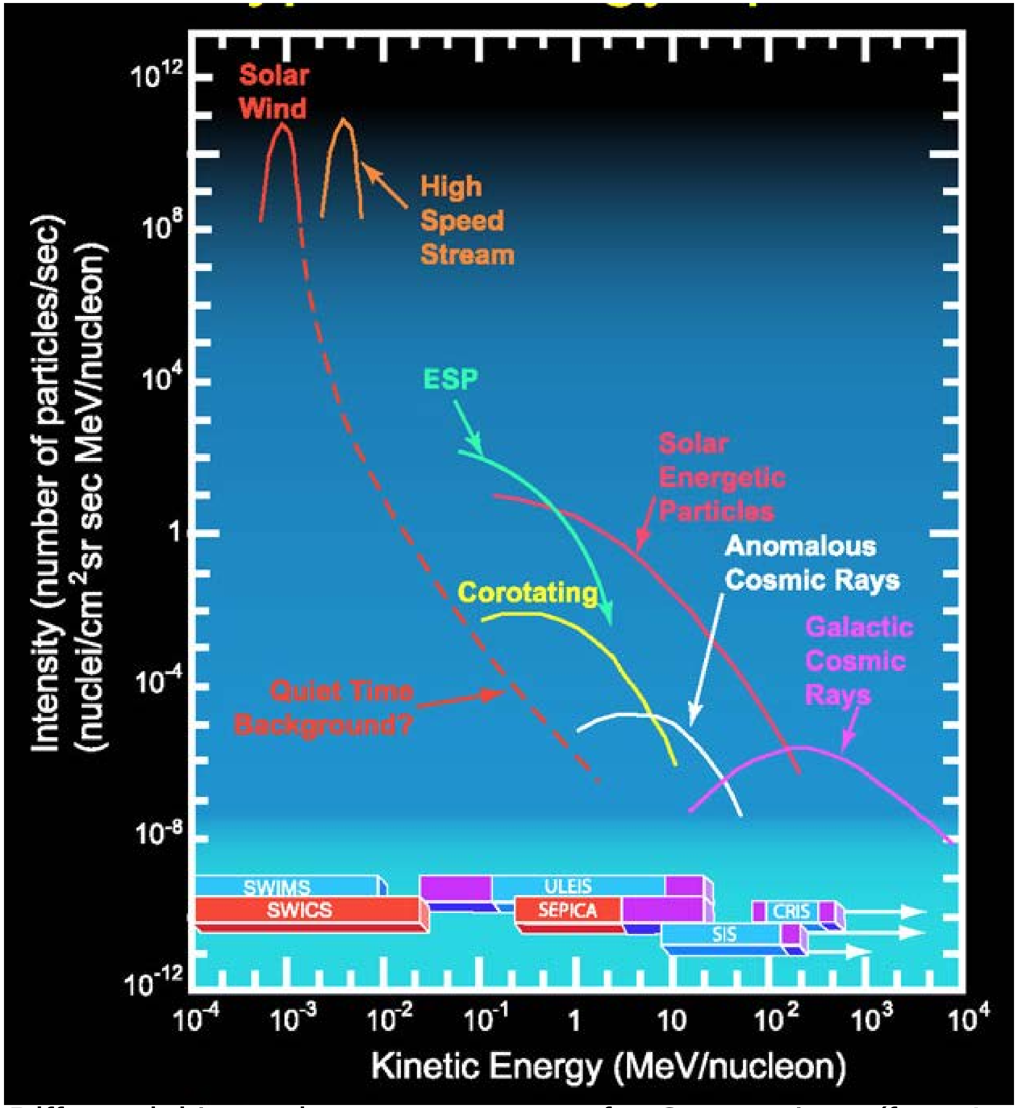
dgascon@fqa.ub.edu

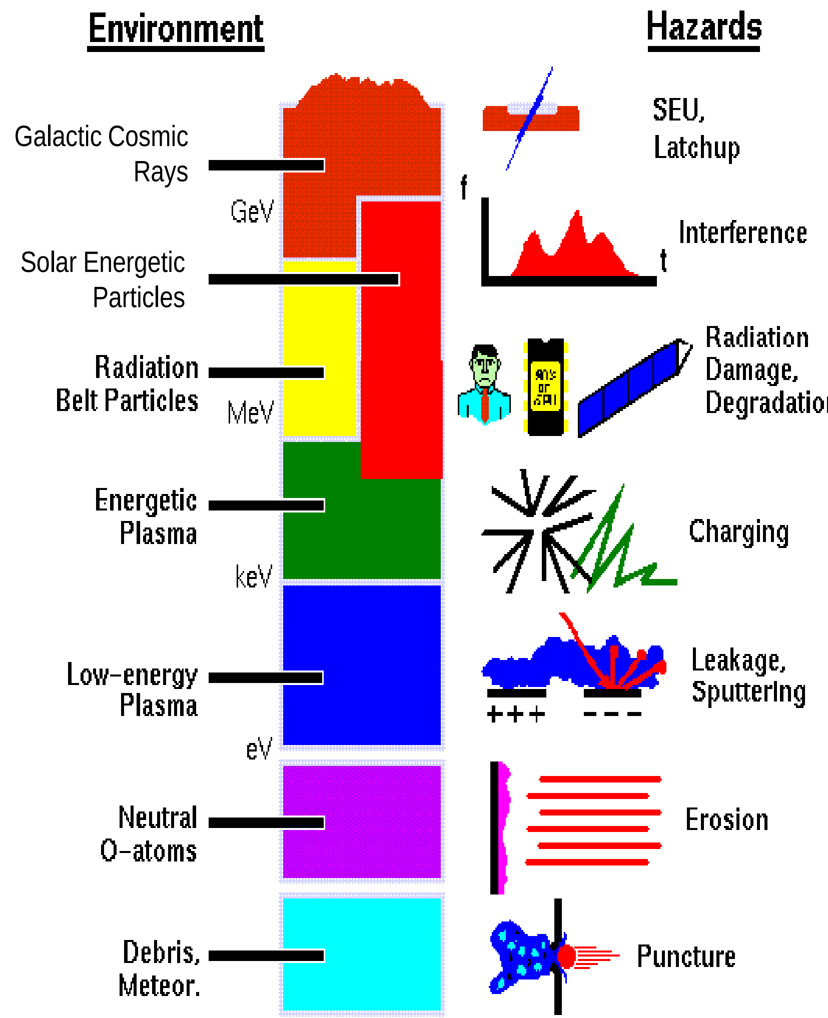
ICCUB Institute of Cosmos Sciences EXCELENCIA MARÍA DE MAEZTU

UNIVERSITAT DE BARCELONA

IEEC

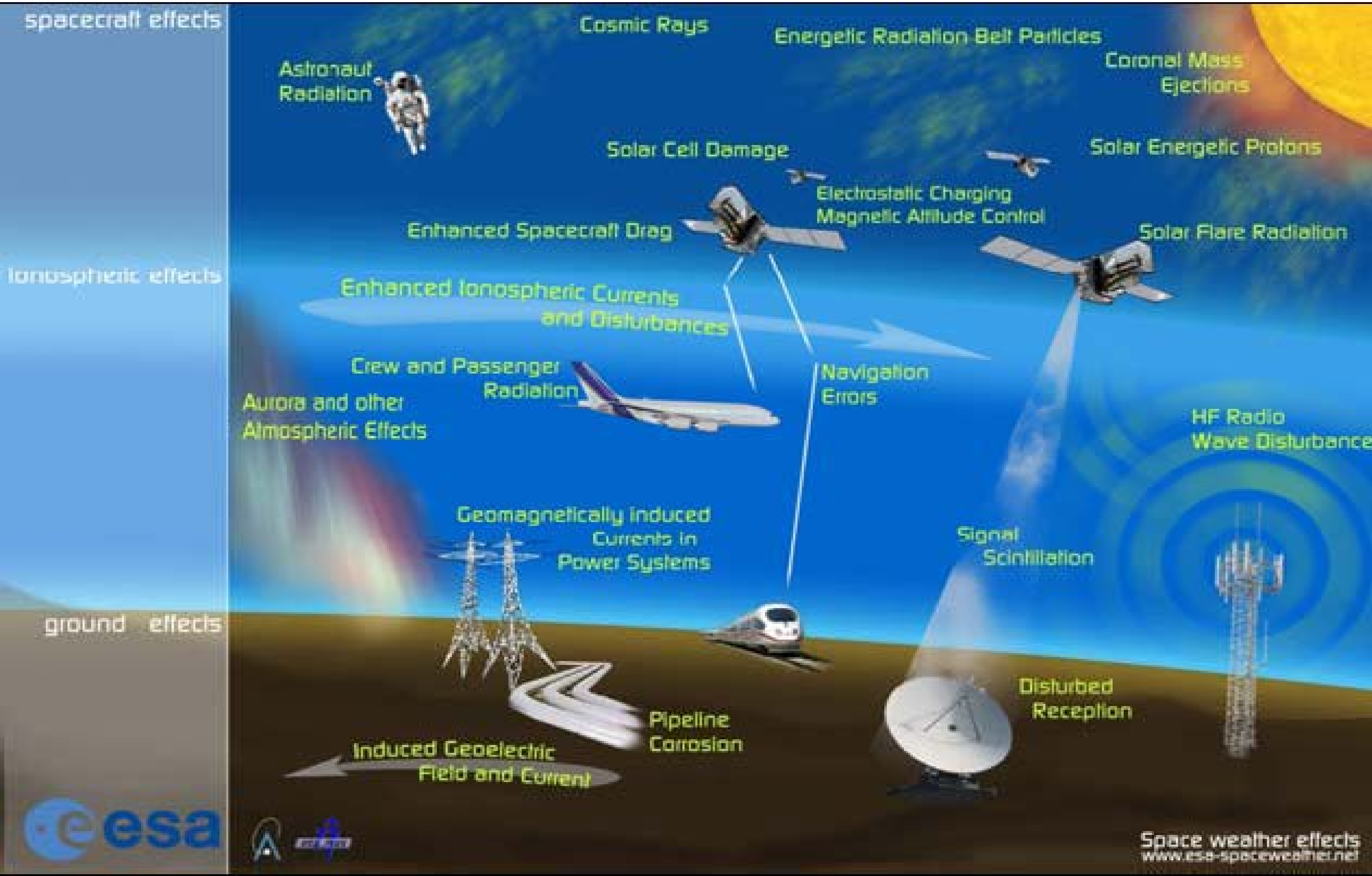
Particles in the Heliosphere





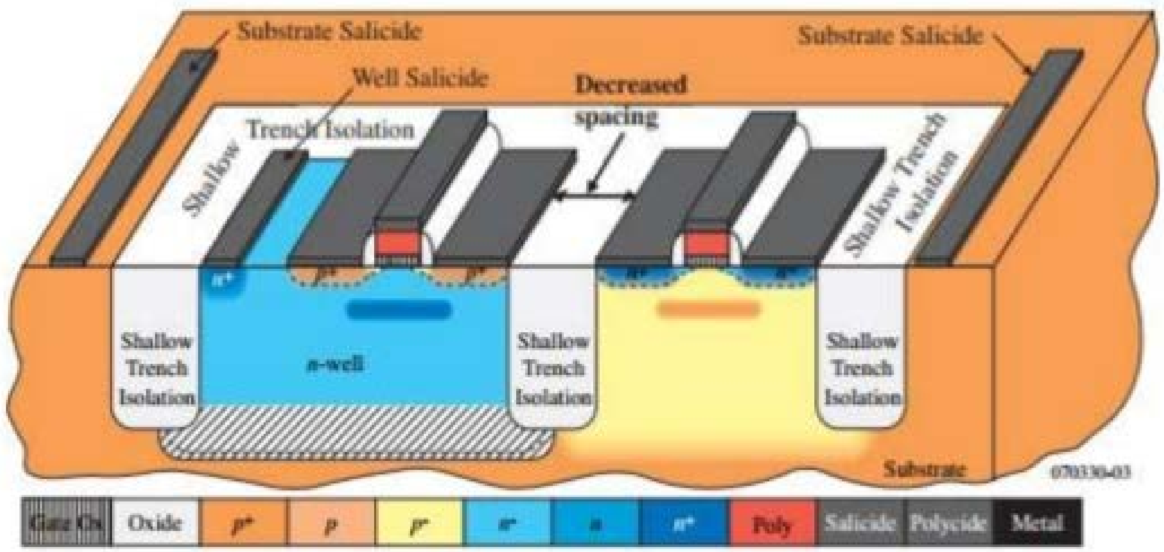
(Credit: TEC-EES http://space-env.esa.int)

Differential Intensity energy spectra for Oxygen Ions (from Lee, Mewaldt and Giacalone, 2012, Shock acceleration of Ions in the Heliosphere, Space Science Reviews, 173, 247-281)


spacecraft effects
Cosmic Rays
Energetic Radiation Belt Particles
Coronal Mass Ejections
Astronaut Radiation
Solar Cell Damage
Solar Energetic Protons
Electrostatic Charging
Magnetic Attitude Control
Enhanced Spacecraft Drag
Solar Flare Radiation
ionospheric effects
Enhanced Ionospheric Currents and Disturbances
Crew and Passenger Radiation
Navigation Errors
Aurora and other Atmospheric Effects
HF Radio Wave Disturbance
Geomagnetically Induced Currents in Power Systems
Signal Scintillation
ground effects
Disturbed Reception
Pipeline Corrosion
Induced Geoelectric Field and Current
esa
Space weather effects
www.esa-spaceweather.net

USE OF SHALLOW TRENCH ISOLATION TECHNOLOGY

- Use of Shallow Trench Isolation Technology: Shallow trench isolation (STI) allows closer spacing of transistors by eliminating the depletion region at the surface.



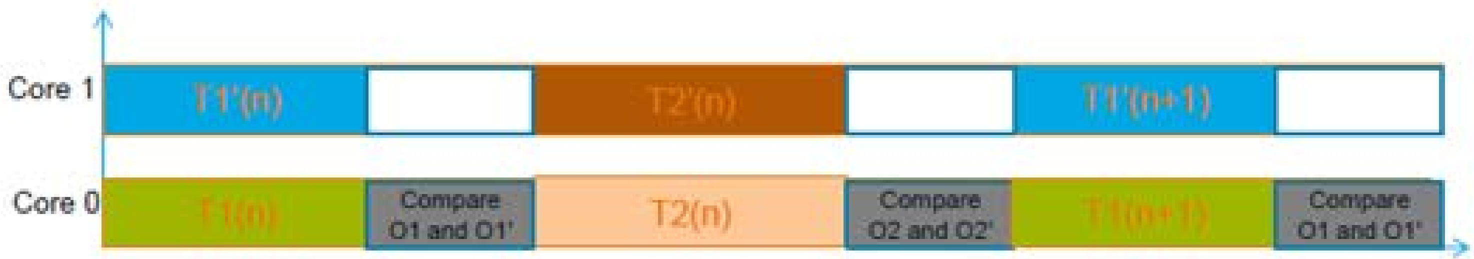
OBC NINANO

- **Xilinx ZYNQ® All Programmable SoC**
  - **Dual-core ARM® Cortex™-A9** processor with NEON™ DSP/FPU Engines - **Up to 1GHz**
  - Programmable logic module: **Kintex®-7 FPGA**
- **1Gbyte DDR3 or 512Mbyte EDAC protected**
- **128Gbyte NAND flash for data storage**
- **3-axis magnetometer**
- **2 SpaceWire**
- **Low Power : 3,1 W** *(for two core @ 400MHz / DDR3 @ 800MHz / PL @ 200MHz)*
- **Mass : 120 g**
- **SEL protected**
- **ITAR free**

eyesat

OBC NINANO + XTRATUM

- **Hypervisor: temporal + spatial partitioning for safety critical applications:**
  - Strong temporal isolation: fixed duty planner
  - Strong spatial isolation: all partitions are executed in a user processor mode
  - Basic resource Virtualization: clock and timer, interrupt, memory, CPU
  - Real-time scheduling for partitions
  - Deterministic hypercalls (hypervisor system calls)
- **Easy fault mitigation (DMT or DT2 fault-tolerant architectures)**



Design hardening at system level
Fault injection

- Soft Errors caused by particle hits are a serious problem to debug complex digital systems
- Mitigating the transient faults in a cost effective manner
  - Identifying the most sensitive parts of a design
  - Select the most effective solutions
- Fault Injection is a consolidated technique used for the dependability evaluation of computer-based systems

Abstraction level	Behavioral	Structural	Physical
System		Fault injection at the system level	
Register Transfer	Fault injection at the register-transfer level	Fault injection at the register-transfer level	
Logic		Fault injection at the gate level	
Device			Fault injection at the transistor level

Domain of representation

Processor, memory modules, input/output devices, etc.

Registers, arithmetic and logic units, bus structures, etc.

Gates, memory elements, etc

Transistors, devices, etc

Multi-level Fault Effects Evaluation, In R. Velazco (Ed.), *Radiation Effects on Embedded Systems.*