Radiation effects on space electronics

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Background

- The presence of radiation in space causes effects in electronic devices.
- The effects range from degradation of performance to functional failures.
- As a result, satellites may experience shortened lifetimes, major failures or even complete "destruction".

- Affect TV and telephone broadcasting
- Affect navigation systems - GPS interruption

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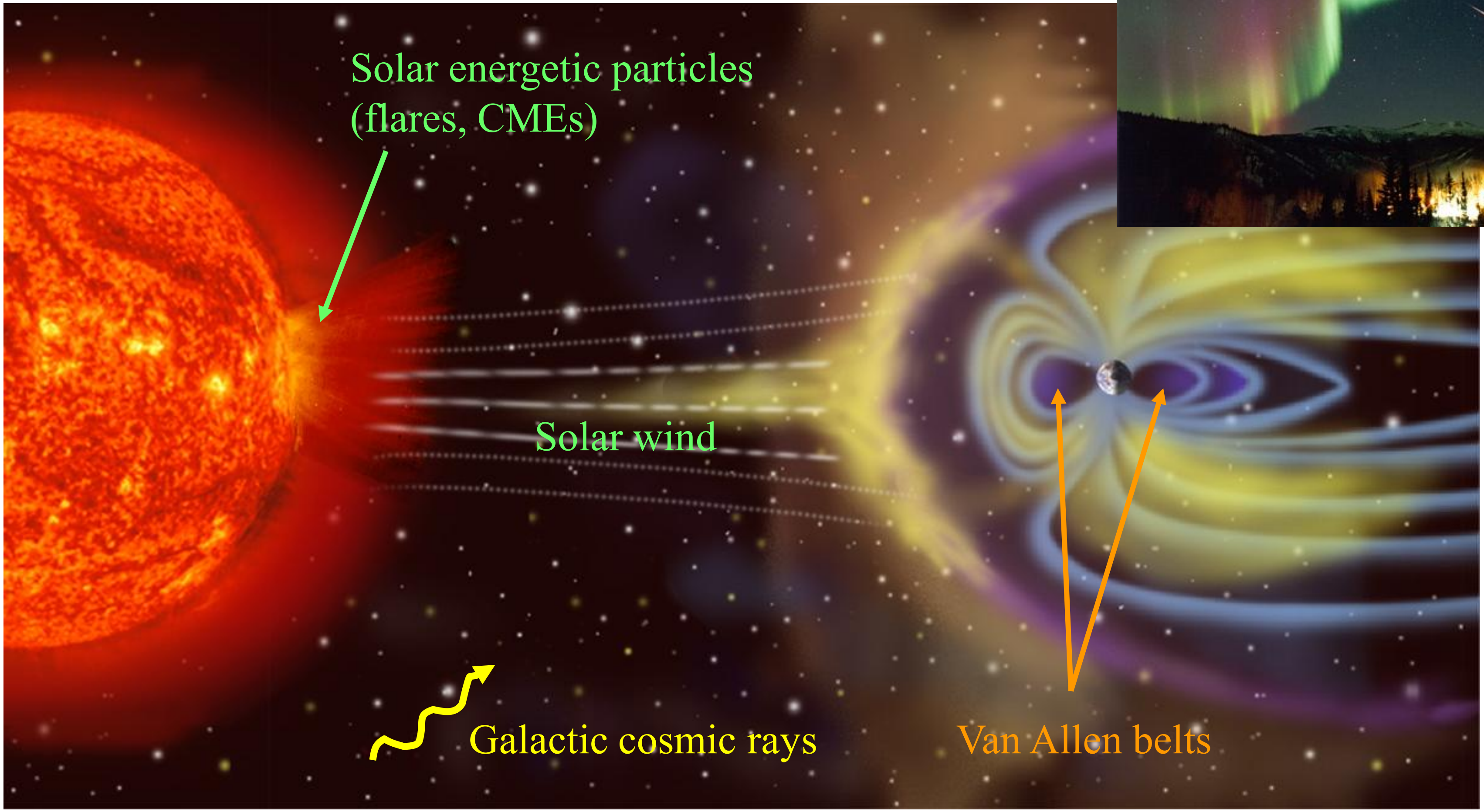
Presentation Outline

- Space radiation environment
- Radiation effects on electronics
- Radiation countermeasures
- COTS/Rad-hard electronics
- Technology trends

Space Radiation Environment



Space Radiation Environment

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- Trapped particles:
  - **Van Allen belts**: electrons, protons, heavy ions
- Solar wind: electrons and protons
- Solar Energetic Particles (SEP): protons, heavy ions, electrons
  - Flares, Coronal Mass Ejections (CMEs)
- Galactic Cosmic Rays (GCR): protons and heavy ions

$$1 \text{ eV} = 1.602 \cdot 10^{-19} \text{ J}$$

MAXIMUM ENERGIES OF PARTICLES

Particle Type	Maximum Energy
Trapped Electrons	10s of MeV
Trapped Protons & Heavy Ions	100s of MeV
Solar Protons	GeV
Solar Heavy Ions	GeV
Galactic Cosmic Rays	TeV

From J. L. Barth et al., "Space, atmosphere, and terrestrial radiation environments", IEEE transaction on nuclear science, Vol. 50, No.3, 2003

Radiation in Different Orbits

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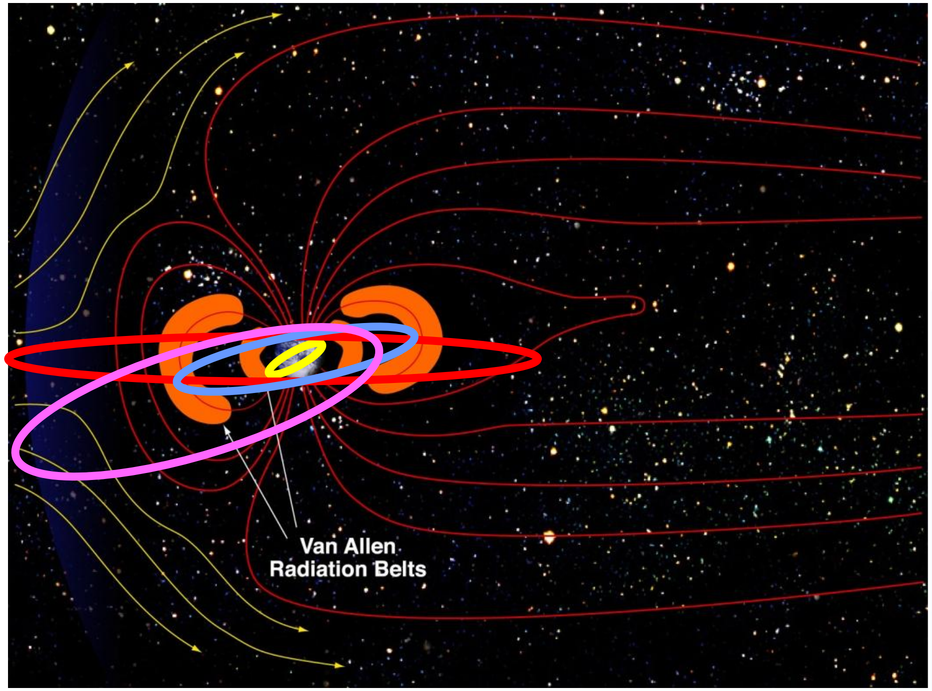
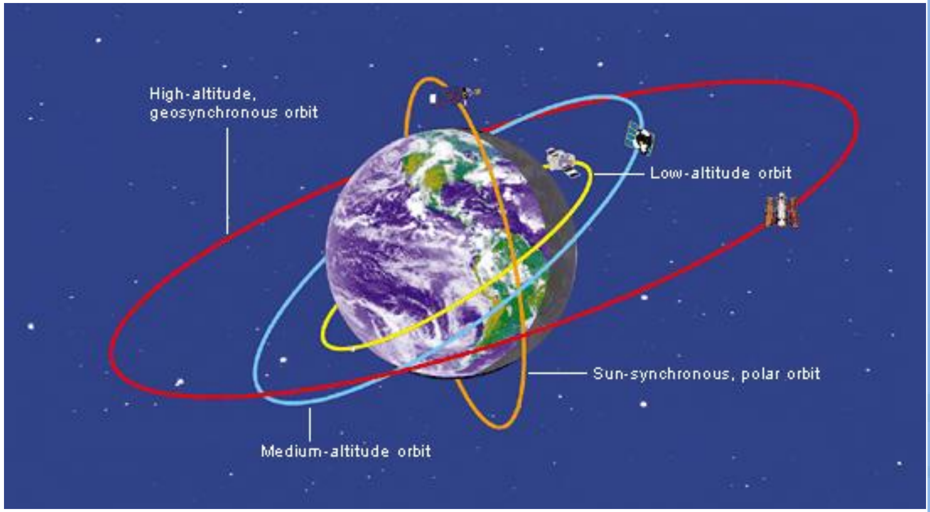
- Van Allen belts:
  - Inner belt (protons)
  - Outer belt (electrons)



- Orbits:
  - LEO
  - MEO
  - HEO
  - GEO
  - Polar orbits



Radiation Effects on Electronics

- Total ionizing dose (TID) effects
  - Accumulation of ionizing dose deposition over a long time.

- Displacement damage (DD)
  - Accumulation of crystal lattice defects caused by high energy radiation.

- Single event effects (SEE)
  - A high ionizing dose deposition, from a single high energy particle, occurring in a sensitive region of the device.

Total Ionizing Dose (TID) effects

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- Mainly caused by trapped particles in the Van Allen belts.
- Ionization creates charges (electron-hole pairs).
- Accumulated positive charge buildups in insulators/oxides.

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- Circuit parameters are changed
- Ultimately, the circuit ceases to function properly

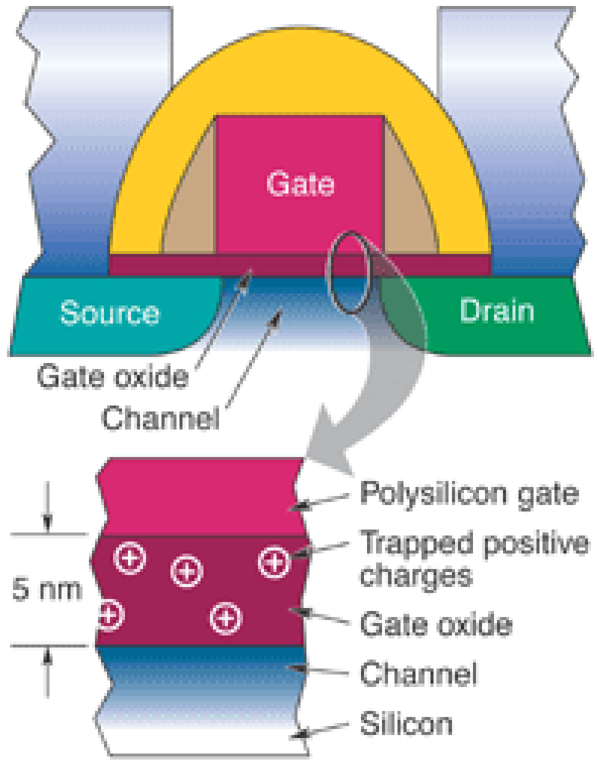

Illustration by J. Scarpulla et al.

TID: a measure of the absorbed energy, measured in rad (radiation absorbed dose)

1 rad = an absorbed energy of 0.01 J/kg of material.

1 Gray = 100 rads

TID Example: NMOS-transistor

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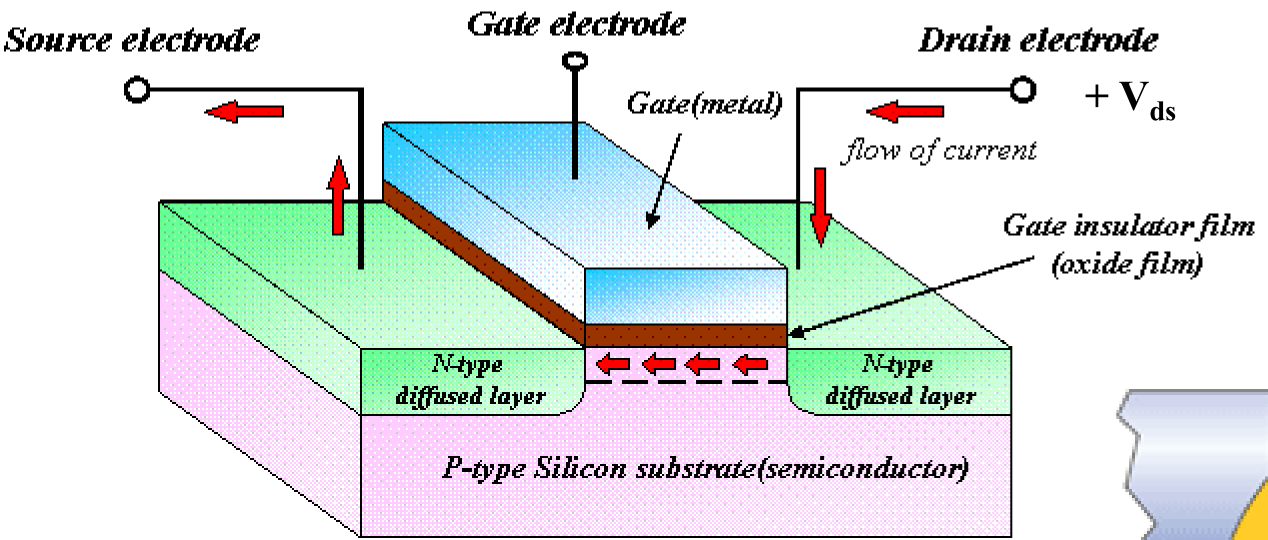
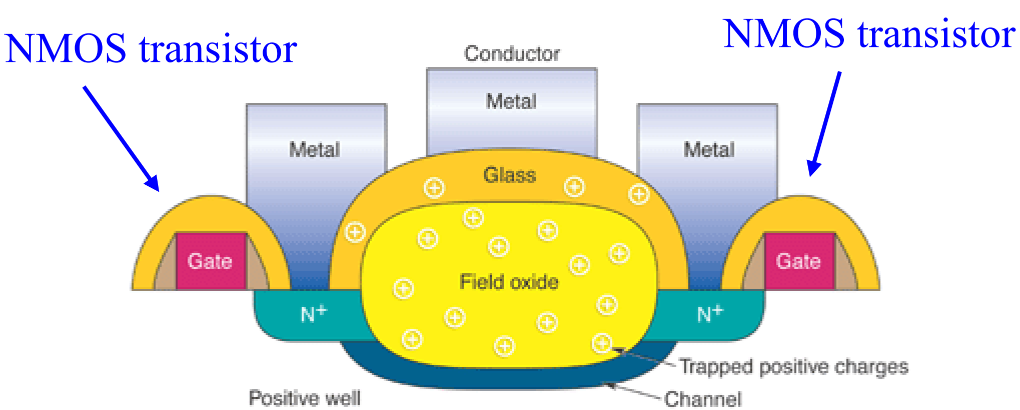


structure of MOSFET



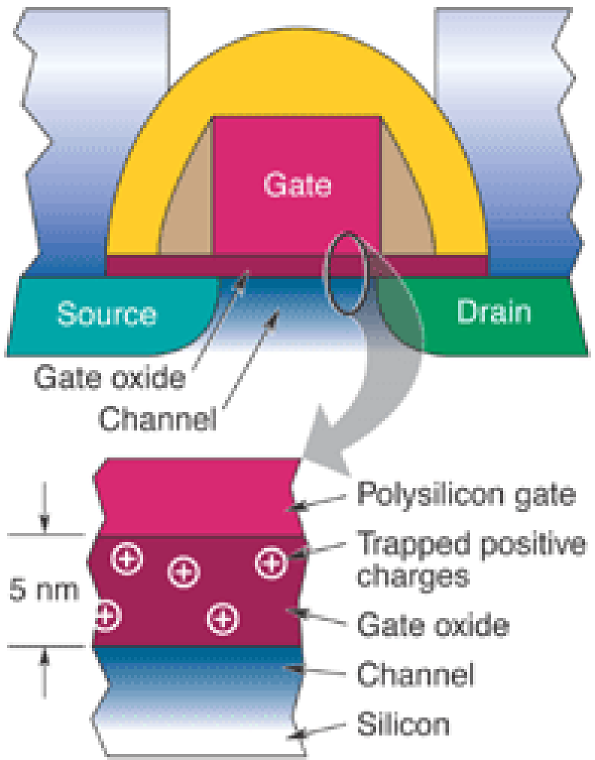


Illustration by J. Scarpulla et al.

Displacement Damage effects

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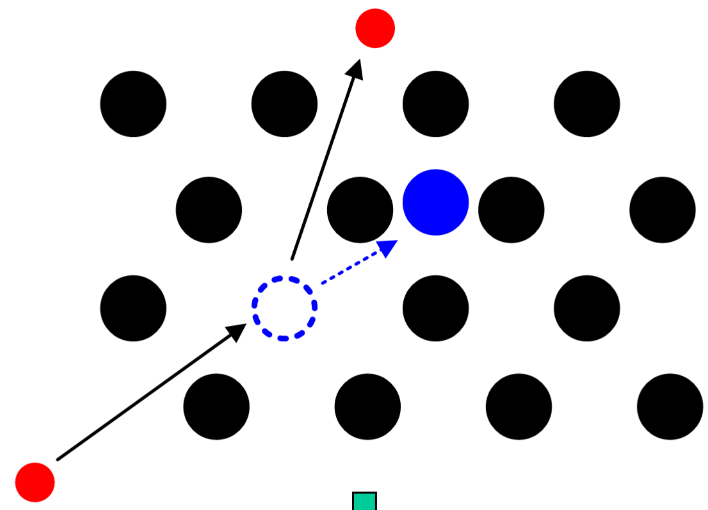
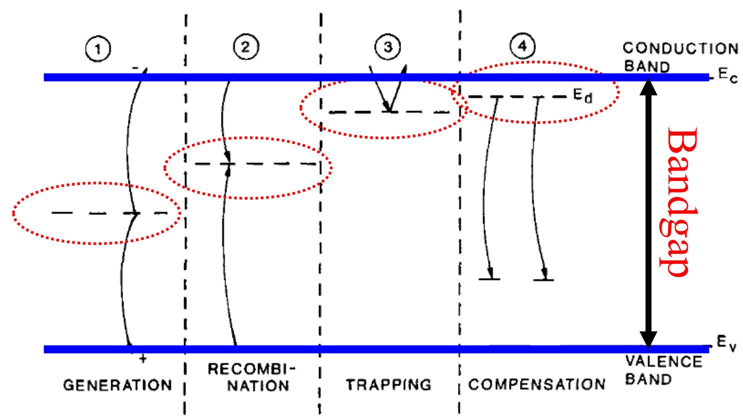
- Energetic particles (protons/ions) displace Si-atoms from their proper crystal lattice locations.
- Creates crystal defects

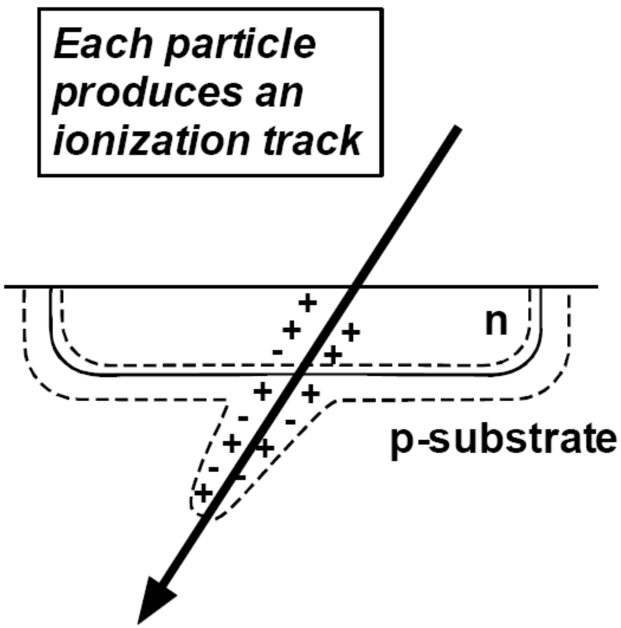




- The electrical properties of the device are changed.
- Ultimately, it may cause circuit failures.

Important for solar panels, where DD effects gradually reduce the power output

Single Event Effects



NMOS transistor

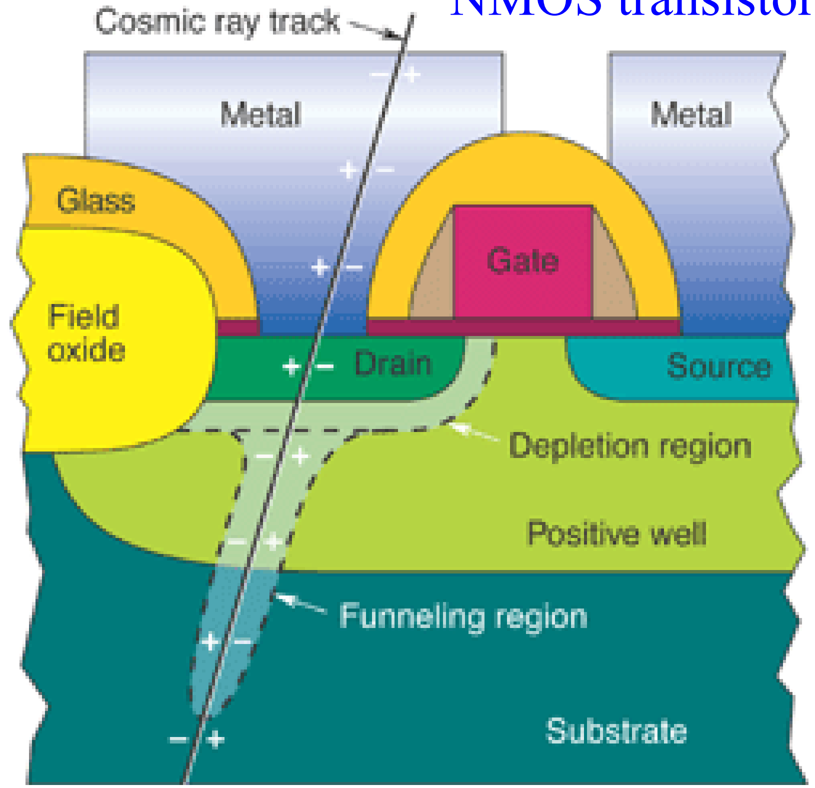


Illustration by J. Scarpulla et al.

- Single event upset (SEU)
- Single event transient (SET)
- Single event latchup (SEL)
- Single event burnout (SEB)

Single event upset (SEU)

- Internal charge deposition causes a ”bit flip” in a memory element or change of state in a logic circuit.
- SEU occurs in e.g. computer memories and microprocessors.

Possibly non-Destructive effects:

• Corruption of the information stored in a memory element.

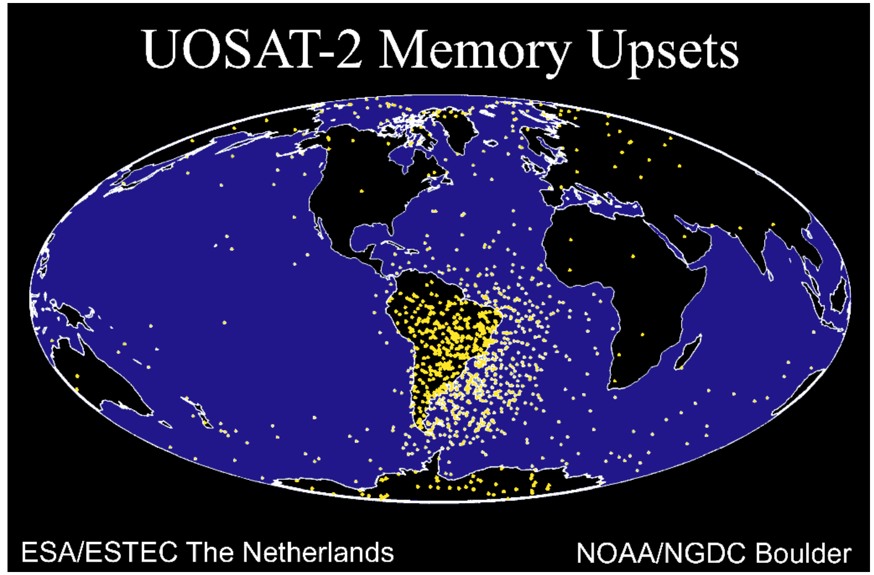
• Usually not permanent damage; a memory element/logic state can be refreshed with a new/correct value if the SEU is detected.

Possibly destructive effects:

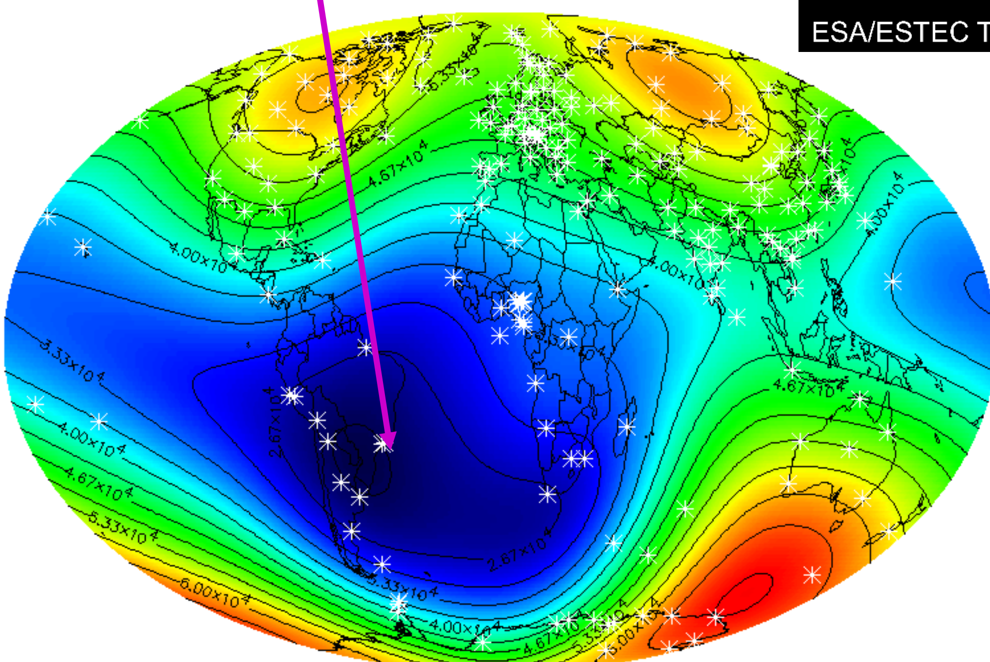
• Microprocessor program corruption.

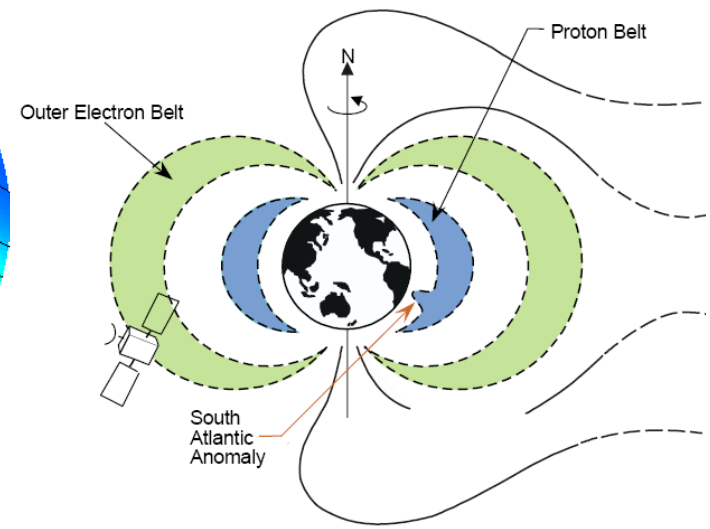
→ Calculation errors, freeze (requires a reset), wrong command execution.

Example: Single event memory upsets



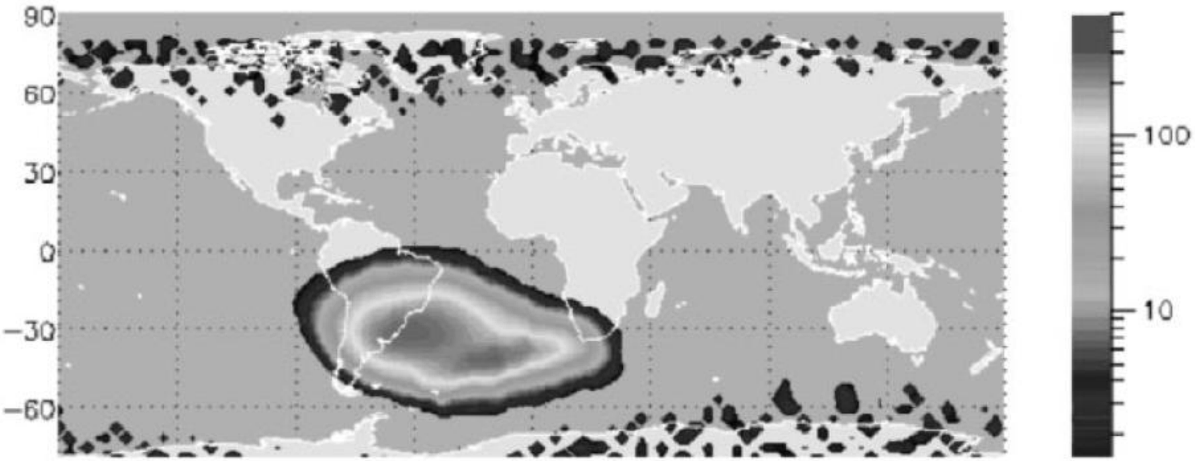
South Atlantic Anomaly (SAA)





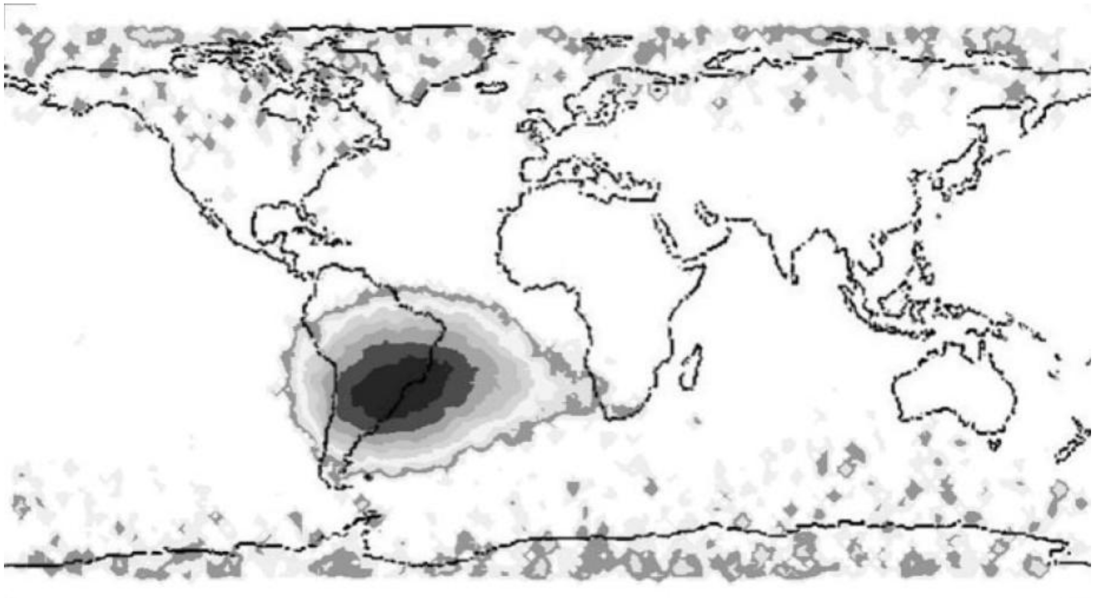
Earth's magnetic field

Example: Single Event Upsets



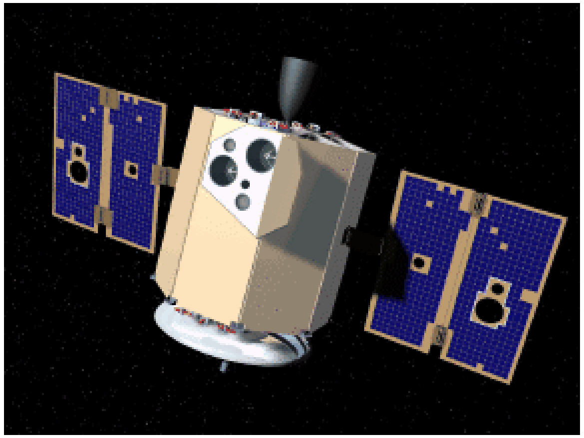
10-MeV proton fluxes measured by the Earth observation satellite SAC-C (January – March 2001);

D.Falguère et al.



Mapping of the **SEU** density (memory upset)

Clementine failure

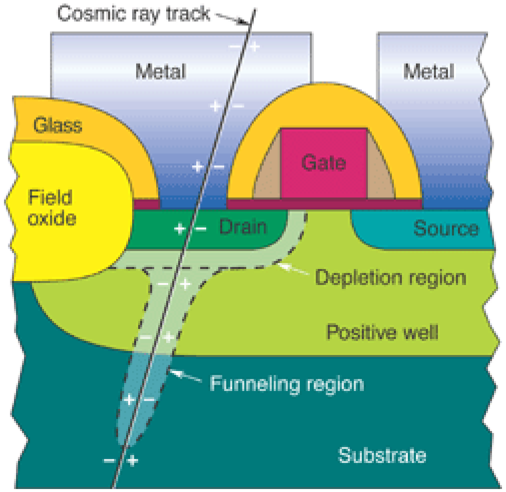


Clementine

- Launched on January 25 1994, in order to qualify component technologies and make scientific observations of the Moon and a near-Earth asteroid.
- On May 7 1994 its main on-board computer sent out an unintentional command that caused one of the attitude-control thruster to fire, before the computer crashed. By the time the ground control had rebooted the computer the attitude control fuel tanks were empty, and the spacecraft was spinning very fast.
- This made it impossible to continue the mission.
- This failure was probably caused by a SEU.

A single bit flip could have no consequences at all or, if unlucky with when and where it happens, could completely destroy a spacecraft.

Other single event effects



- **Single event transient (SET)**
  - A transient current or voltage spike.
  - May propagate through logic gates, and produce system failures.
  - If this spike is captured by a storage element, the SET becomes a SEU.
- **Single event latchup (SEL)**
  - Unintentional currents flow (short) between components on an integrated circuit, causing circuit malfunction.
  - A latchup causes a bit-flip to be permanent; can not exit from the selected logic state.
  - The circuit must be powered down to correct the condition.
- **Single event burnout (SEB)**
  - The current in the SEL is not limited, and the device is destroyed.
  - Most dangerous form of singe event effect, since the failure is permanent.

Radiation Countermeasures

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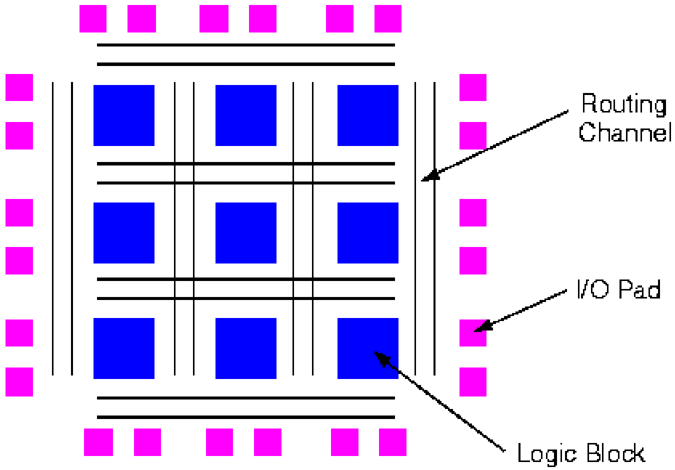
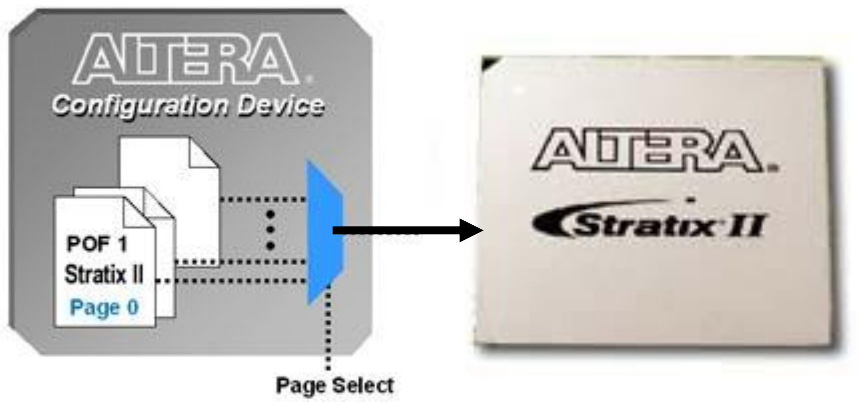
- If possible, chose an orbit with a reduced level of radiation.
- Shielding to lower the radiation dose level (using e.g. Al, Cu)
  - Unable to deal with high-energy particles.
- Radiation hardened (rad-hard) components
  - Special manufacturing processes of the electronics, like Silicon-On-Insulator (SOI) technology.
- System-level error corrections (radiation-hardening by design)
  - Error detection and correction of memory (parity bits, Hamming code)
  - Triple Redundancy and Voting (TMR)
    - Three copies of the same circuit + a voter performing a "majority vote".
    - E.g. three separate microprocessors, all doing the same computations.
  - Watchdog timer to avoid processor crash; resets the system automatically if an error is detected.
- Turn off supply voltage before entering a part of the orbit where high radiation is expected
  - Reduce the effect of the ionization.

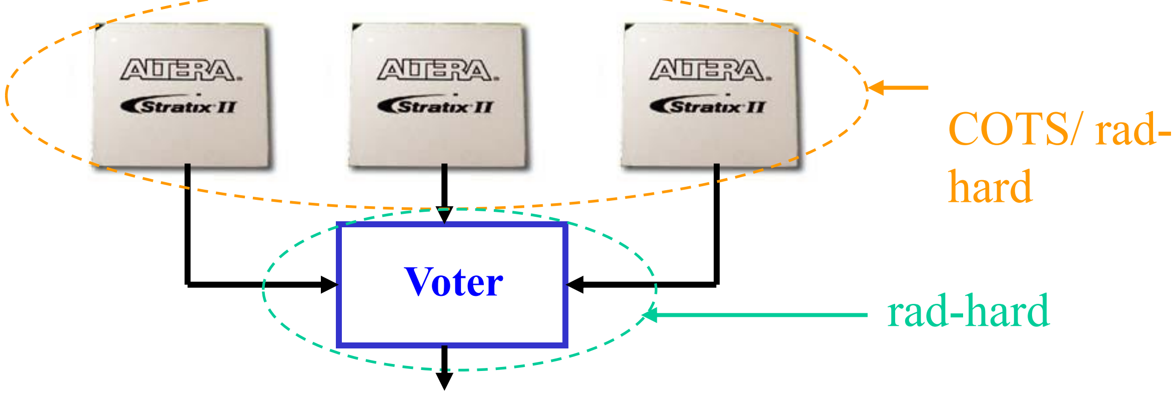
Example: FPGAs

- FPGA = Field Programmable Gate Array





Fault-tolerant FPGA design:



COTS vs rad-hard electronics

COTS = Commercial Of The Shelf

- Accumulated radiation before failure, typical values:
  - Rad-hard components: Dose ≥ 100 krad(Si) - Mrad(Si)
  - COST components : Dose ~3-30 krad(Si);   some up to 100 krad(Si)
- The technological development of rad-hard components is 5 – 7 years after COTS components.
- Rad-hard components are very expensive compared to COTS components.
- Rad-hard components may be difficult to obtain.

Technology Trends

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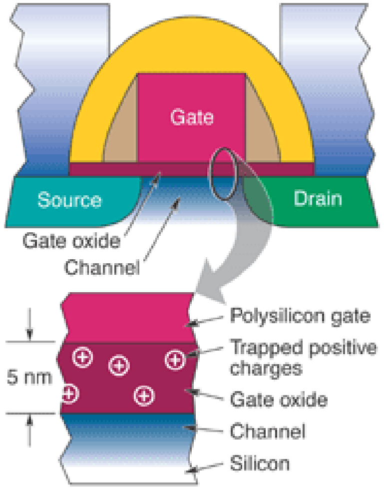
- Miniaturization
  - The scale down of the gate oxide thickness decreases the TID effects.
  - SEU increases with scaling (it takes less energy to produce SEU).
  - Minimization of spacecraft (S/C) size means that the shielding from the S/C structure is reduced.
- Circuit speeds increase
  - Single event transients (SETs) becomes SEUs, increasing the number of SEUs. This makes SETs more critical.
- More complex circuits/devices
  - Gives numerous failure modes.
- More use of COTS-components
  - Generally much more sensitive to radiation
  - Component testing is crucial.



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