ESR15
On-Board Computer and Camera for Space Applications

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RADSAGA System Level Test Review
November 13th, 2019

RADSAGA

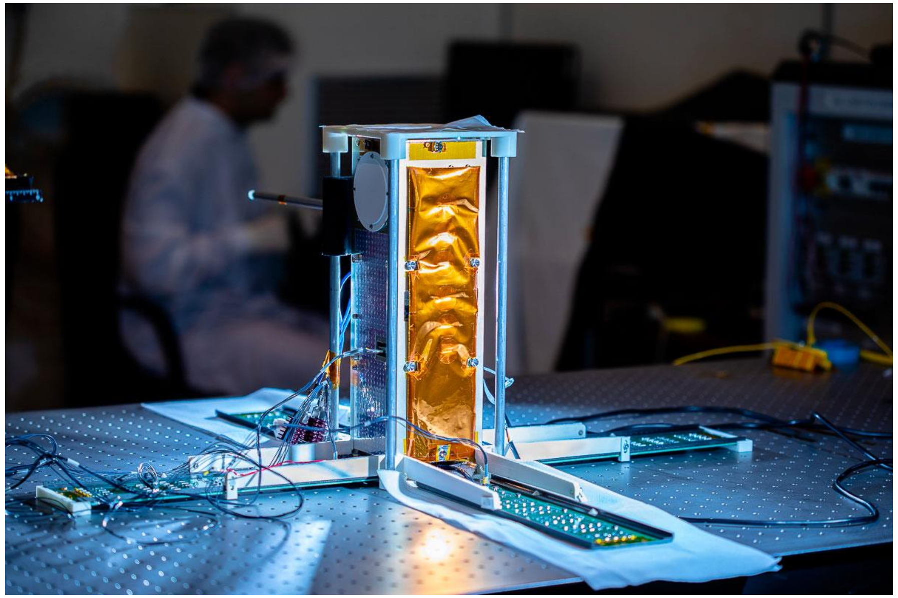
RADSAGA is a project funded by the European Union's Horizon 2020 research and innovation programme under the MSC agreement no. 721624.

CERN

Context

- Eyesat student nanosatellite
  - Scientific mission (study zodiacal light of Milky Way)
- All components are COTS
- **High risk acceptance** space mission
  - LEO (low fluxes, mainly trapped protons)
  - Short lifetime (1.5 year)
- **Cost-effective qualification approach?**

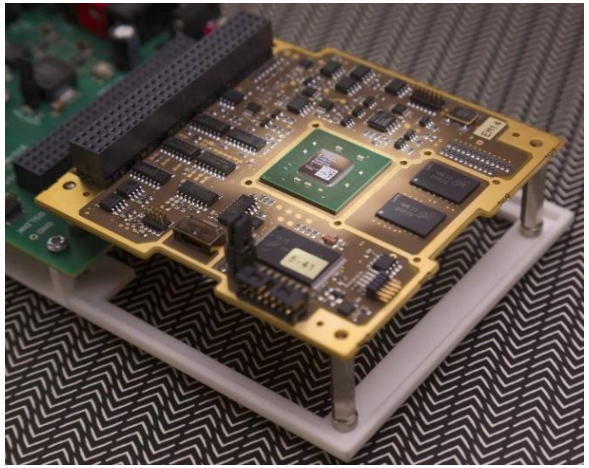
Requirements:
- TID tolerance > 100 Gy(Si)
- Hard SEE rate on OBC and Camera > 1 per 6 months



Overview

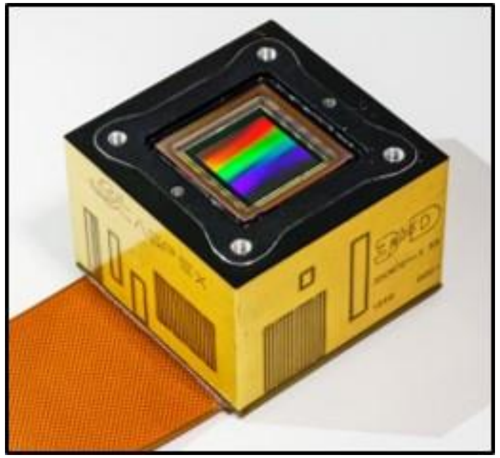
- RADSAGA partners
- CERN-CNES Collaboration agreement
- CNES development of the On-Board Computer
- 3DPlus-CNES joint development of the Camera
- CERN-CNES cooperation for the test bench development
- Application areas:
  - Low cost space missions
  - COTS-based systems

Topical elements of the test



OBC
- PCB **available commercially** from Steel Electronics
- More than 50 COTS components
- Main component is a SoC (highly integrated system with multiple functionalities)
- **Traceability only for SoC**
- Hypervisor running on the OBC

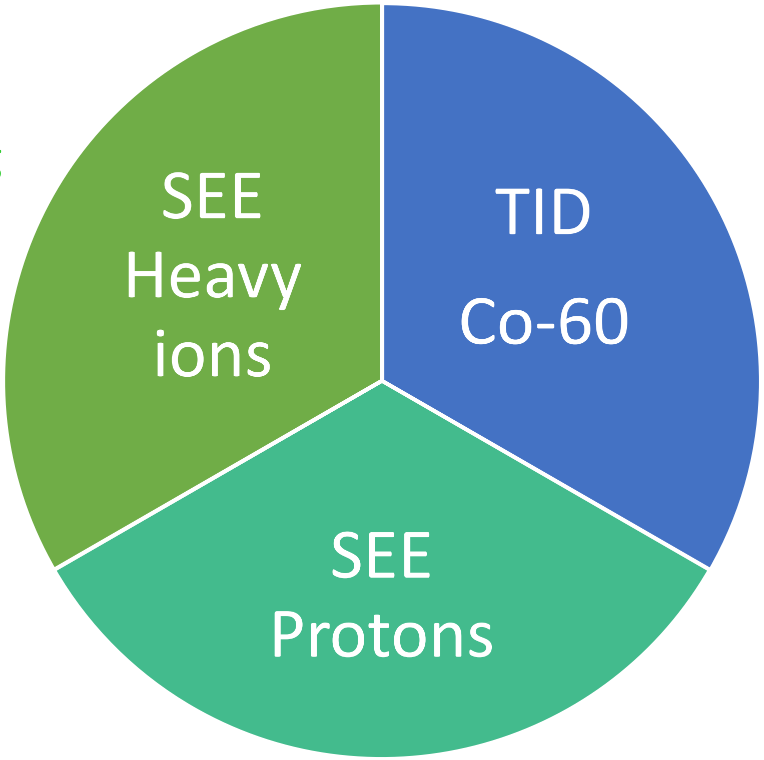
Camera
- **Commercial product** available from 3DPlus
- Space qualified
- **3D layout, stacked PCBs**
- All internal components are COTS
- Black box for the test at CHARM



Link to Existing Standards

Zynq7000 SoC
- SEL free up to 60 $MeV.cm^2/mg$

CMOS Camera
- SEL cross section



Zynq7000 SoC
- Dose level device is not functional anymore

CMOS Camera
- Functional at 500 Gy(Si)
- Dark current measurements

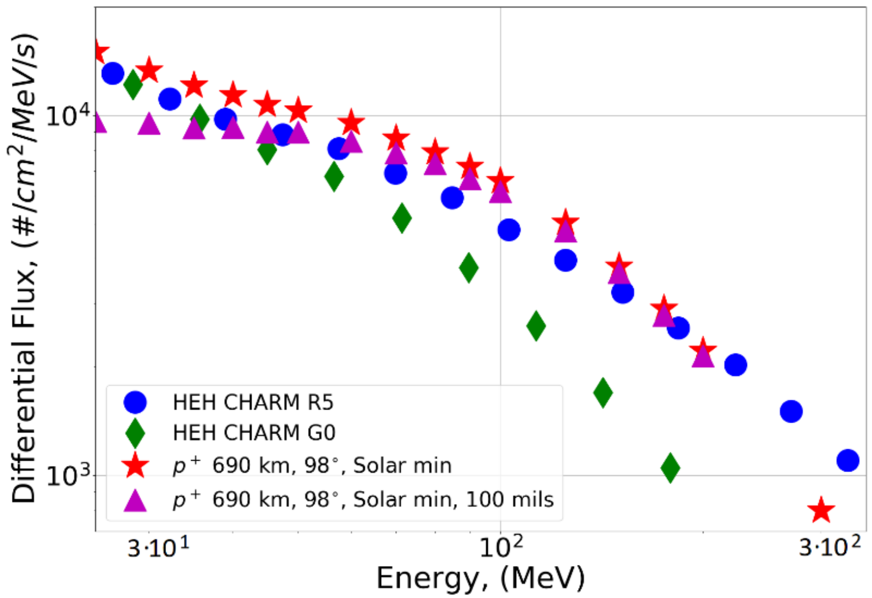
Experiments performed independently by CNES

No standard proton testing

- **Other components** on the PCB?
- **Soft SEEs** from the Zynq?
- **Global functionality**?
- **HW/SW integration** of OBC and payload?

Suitable facilities

- **Other components** on the PCB?
- **Soft SEEs** from the Zynq?
- **Global functionality**?
- **HW/SW integration** of OBC and payload?



- **Deep penetrating beam**
  - No heavy ions, only hadrons
- **Wide beam field size**
  - Allow testing of both OBC and payload
- **Environment representativeness**
  - High energy hadron spectra similar to LEO proton spectra

Suitable facilities in Europe:

- CHARM
- ChipIR
- KVI-CART, PSI

Component level standards shortcomings

- Limitations in SEE standards for complex ICs/boards
  - **SEL**
    - **Feasible** if delidding is possible
  - **SEU**
    - Shall you test individually any subparts of a SoC/FPGA?
      - JEDEC standard and NASA guideline point out which elements shall be tested, however
      - Real applications make simultaneous use of a **set of resources**
      - Cross section varies with **embedded software and firmware**
      - Not easy to define all failure modes before a test
      - **Common mode failures** can be missed

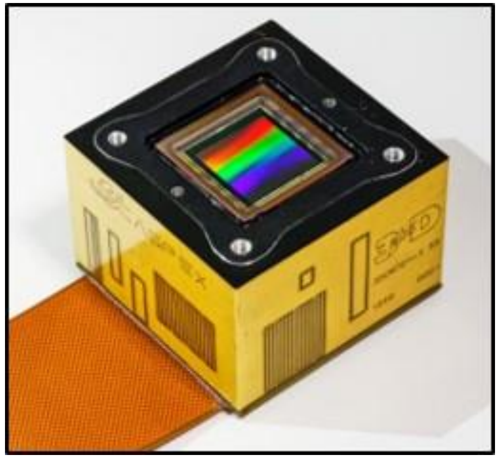
Example:

- During the CHARM test large bunches of errors appeared simultaneously on different elements
  - Not SEU on the sub-components themselves
  - Errors due to a fault of the common GPIO port defined in the digital design
  - 40% of logged errors on the ECC protected BRAM, 12% of total OBC SEFI

Component level standards shortcomings

- How to deal with **3D Layout** devices?
  - In general, no corresponding 2D board is available
  - **Traceability** of internal components?
  - **How to interpret and use information** provided by the manufacturer?
    - The Camera datasheet reports that the device is SEL-free up to 60 MeV.cm^2/mg

  - During system level test at CHARM **Camera configuration resets** were observed
    - Heavy ion test demonstrated SEL sensitivity down to 11 MeV.cm^2/mg
    - Camera is equipped by the manufacturer with **anti-latchup system**
      - No HW damage
    - But **no mitigation at SW level** in the OBC
      - To acknowledge SEL happened
      - To react and increase payload availability



System level testing: What to look for

- Potential **destructive events at board level** (SEL)
  - Detectable and with protection function
  - No SEL observed
- **TID performance degradation**
  - Telemetry of the Zynq (not affected during the test)
  - Unmonitored for other elements
- **SEFI** on OBC and **rate prediction** for mission
  - Cause of error identifiable by logging of the hypervisor
    - Processor crash vs. FPGA fault
  - Different **self-recovery techniques** tested
    - Power cycling
    - SW reset on the FPGA
    - SW reset on the partition

System level testing: What to look for

- System run with all mitigations used for the final application
  - **Ability to perform self-recovery**
    - Satisfactory
      - Full functionality recovered in less than 10 seconds
      - Rate for orbit (once every 2.5 years) is compatible with the mission
      - Rare deadlocks on SW reset (1 every 100 reboots)
  - **Ability to recognize permanent data corruption**
    - Not very satisfactory
      - All corrupted sequences ended in reboots
      - But mean time to reboot was 60 minutes in a strong flux environment
      - Data may remain corrupted longer in milder flux environment (e.g. 150 minutes to reboot in G0)
- **Data logging** with raw data

System level testing: What to look for

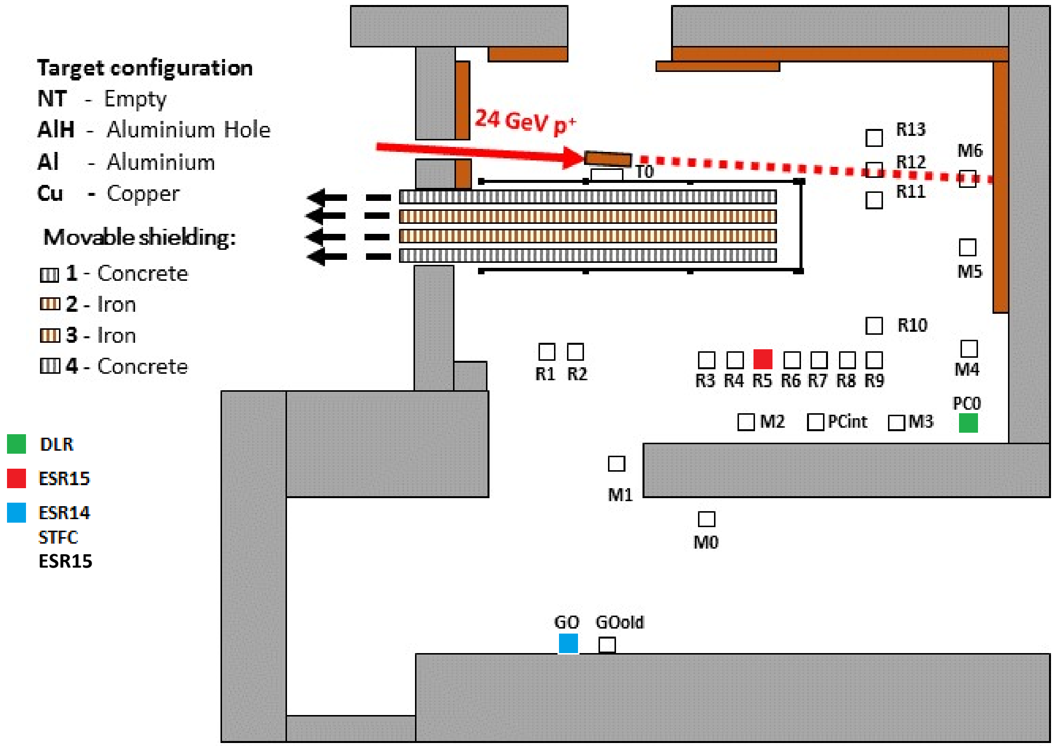
- Coupling of sophisticated devices
  - Use of flight software on the OBC to run the Camera
  - OBC controlling the Camera with the flight software embedded
    - Communication protocol run through spacewire
    - SEL of the camera are mitigated at HW level by internal anti-latchup (no damage on camera)
    - But they were not mitigated at SW level in the OBC
      - **44% unavailability** of the camera during the test
  - **OBC disrupting Camera operations**
  - Picture **data corruption**
    - Data stored in Camera and OBC memories

Chosen facility possibilities and inconveniences

Tests performed in **G0** and **R5**:

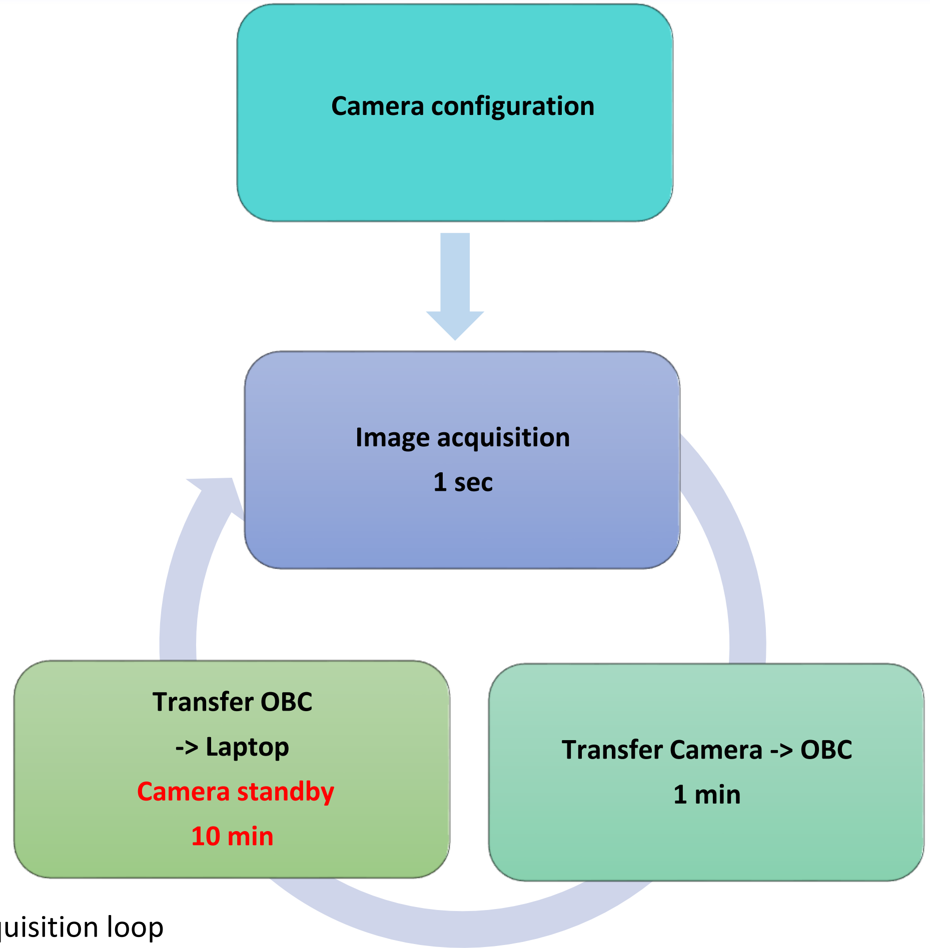
- G0 has milder flux, but more thermal neutrons (not a thing in space)
- R5 has environment representativeness and about **x15** higher flux
  - $1.5 \cdot 10^7$ HEH/cm²/s (instantaneous)
  - $1.4 \cdot 10^6$ HEH/cm²/s (averaged)

- Observations:
  - OBC SEFI cross-section and common mode failure cross-section about **3 times higher in G0**
    - **Thermal neutron** dependence?
  - **Same error signatures** seen in the two positions
    - **Independence from high energy (GeV)**
    - More debugging information while in G0



Mitigations

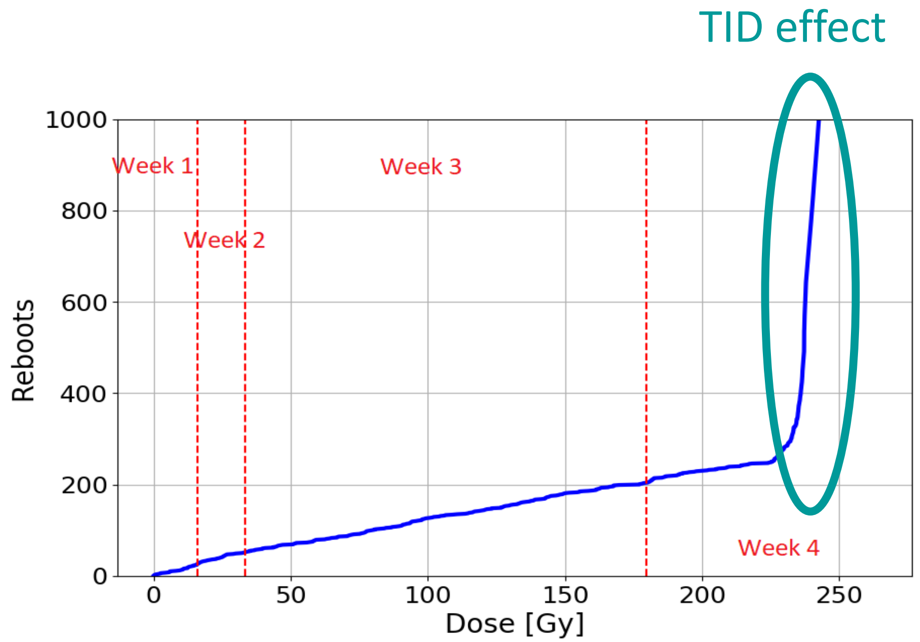
- Camera reset once every 6 years
- Make camera resets **transparent** at system level
- Camera managed by the OBC
- The number of mitigations depends on the **implemented acquisition loop**
- Camera configuration added to the loop
- Additional watchdogging needed in the OBC



Camera acquisition loop

Effects not seen at component level

- Co-60 TID test of the Zynq pointed out failures between 240-480 Gy(Si)
- At CHARM Zynq received 260 Gy(Si), still operational
- However:
  - **Stress + TID** parametric degradation of I/O pin of the Zynq at 230 Gy(Si)
    - High frequency stressing not covered during component testing
    - Caused unnecessary reboots due to degradation of refresh signal to the watchdog
    - With external watchdog disabled, Zynq working correctly



Qualification methodologies

Applicable to these kinds of space missions

Recall requirements:
- TID tolerance > 100 Gy(Si)
- Hard SEE rate on OBC and Camera > 1 per 6 months

- Pre-screen of **destructive SEEs** through heavy ion component level testing
  - **Critical** components for the system
  - Suitable for **system level hardening**
  - Suitable for system test-bench definition
- Soft error testing of complex ICs covered through system level testing
  - **Too many tests** to be done on sub-components
  - Use of **flight SW, firmware, application**
  - Concurrent management of all peripherals
- **TID** test can be integrated in the system level test

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When and how to use System Level testing for space

Based on space radiation environments and mission lifetime

	LEO equatorial	LEO polar	MEO, GEO, Interplanetary
>3 years	Moderate Dose, Attenuated GCR, Trapped Protons, Some Solar Proton dependence	High Dose, Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence	High Dose, High GCR, High Solar Proton Variability
1-3 years	Manageable Dose, Attenuated GCR, Trapped Protons, Some Solar Proton dependence	Moderate Dose, Higher GCR, Trapped Protons, Some Solar Proton dependence	High Dose, High GCR, High Solar Proton Variability
<1 year	Manageable Dose, Attenuated GCR, Trapped Protons, Some Solar Proton dependence	Moderate Dose, Higher GCR, High Energy Trapped Protons, Some Solar Proton Dependence	Moderate Dose, High GCR, High Solar Proton Variability

Credit: M. Campola, 2019 RADECS short course

When and how to use System Level testing for space

Based on space radiation environments and mission lifetime

	LEO equatorial	LEO polar	MEO, GEO, Interplanetary
>3 years	Can replace TID of non-critical components and soft SEE testing of all components	Can replace TID of non-critical components and soft SEE testing of all components	Can complement component level TID and SEE testing of all components
1-3 years	Can replace TID and soft SEE testing of all components	Can replace TID of non-critical components and soft SEE testing of all components	Can complement component level TID and SEE testing of all components
<1 year	Can replace TID and soft SEE testing of all components	Can replace TID and soft SEE testing of all components	Can replace TID and soft SEE testing of non-critical components

Destructive SEEs always tested at component level