European Space Agency EEE Component Radiation Hardness Assurance related R&D activities

Cesar Boatella Polo
Ali Zadeh
Véronique Ferlet Cavrois
Christian Poivey
Introduction

- ESA spacecraft are designed to carry out a variety of missions covering Space Science, Earth Observation, Telecommunication, Navigation, Human Spaceflight and technology demonstration type programmes. Launcher development is also part of the ESA mandate.

- The space environment for which ESA spacecraft operate is in many aspects different from the terrestrial environment. We are concerned about environments such as:
  - vacuum
  - thermal environment
  - Atomic oxygen
  - UV radiation
  - high energy particle radiation environment.
  - Etc.
The space radiation environment detrimentally affects EEE components flown on ESA space missions. The impact on electronic components vary from slow degradation of electrical parameters, due to cumulative effects to sudden unwanted events due to transient effects.

The interplay between energetic particles impinging components in space, the particular radiation effect(s) induced and the subsequent electronic component response is complex.

The manner for which a EEE component behaves in its application depends on a number of factors such as:

- Spacecraft orbit
- The location of the component in the spacecraft (shielding conditions)
- Thermal environment
- Application conditions
Introduction

- To ensure that EEE components are suitable for flight in their applications on ESA space missions, strict RHA processes are followed.

What is Radiation Hardness Assurance

- RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their design specifications after exposure to the space radiation environment.
- RHA deals with:
  - environment definition,
  - part selection,
  - part testing,
  - spacecraft layout,
  - radiation tolerant design,
  - and mission/system/subsystems requirements.
This presentation is divided in two parts

1. Description of ESA’s RHA requirements

2. Radiation related R&D activities in the frame of ESA’s JUICE mission
Radiation Harness Assurance

Automated Transfer Vehicle (ATV) approaching the International Space Station (ISS)
RHA Overview

MISSION/SYSTEM REQUIREMENTS

SYSTEM AND CIRCUIT DESIGN

PARTS AND MATERIALS RADIATION SENSITIVITY

RADIATION LEVELS WITHIN THE SPACECRAFT

RADIATION ENVIRONMENT DEFINITION

ANALYSIS OF THE CIRCUITS, COMPONENTS, SUBSYSTEMS AND SYSTEM RESPONSE TO THE RADIATION ENVIRONMENT
The smallest System shown is at 'Building Block' level (e.g. a circuit board), made up from 'Components'.
Project Requirements Flow-Down

- Mission objectives
- Orbit
- Mission duration
- Schedule and cost

- Subsystem impacted
- Verification level
- Verification method

Radiation Specifications

- Performance requirements
- Electrical and mechanical interface requirements
1. European Component Space Standardisation (ECSS)
   a. ECSS-Q-ST-60-15C, Issue 1, October 2012

2. Examples of ESA tailoring
   a. ESSB-AS-Q-008, Issue 1, October, 2013
      - Adoption notice of ECSS-Q-ST-60-15C
   b. The standard has also been tailored for projects such as:
      - MTG (Earth Observation Mission)
      - JUICE (Jupiter Mission)

• Used as stand alone applicable documents or included in systems/Subsystems or Payload Requirement document:
  • Product Assurance Requirement Documents (PARD)
  • User Requirement Document (URD)
  • Experiment Interface Document – Part A (EIDA)
Mission Radiation Environment Specification

1. Depends on orbit and mission duration
   a. Particle fluxes, incident and shielded
   b. Dose versus depth curve
   c. Displacement Damage versus depth curve
   d. LET spectra (used for SEE rate prediction)

2. ECSS-E-ST-10-04

- Used as stand alone applicable documents or included in systems/Requirement document:
  - Satellite Environment and Test Specification (EDTRS)
Other requirements related to RHA

1. **ECSS-E-ST-10-12C**, Methods for the calculation of radiation received and its effects, and a policy for design margin


2. **ECSS-Q-ST-60**, EEE components [AD-Q60]
5. **ESCC22900**, TID test method
6. **ESCC25100**, SEE test method
7. **MIL-STD-750 method 1080**, SEB/SEGR testing
ESA Radiation Hardness Assurance requirements.

ESA applies a tailored version of the ECSS-Q-ST-60-15C on its space projects.

ESA regularly develops one-off type space missions operating in highly varying environments, shielding configurations and applications.

Although the basic RHA standard applied is the same. In some cases the RHA standard requires further tailoring due to the uniqueness of the ESA space missions.

The RHA standards covers Total Ionising Dose (TID), Total Non-Ionising Dose (TNID) and Single Event Effects (SEE).
RHA for TID and TNID

- **TID and TNID are cumulative effects**

- **TID:**
  - Ionizing Radiation Creates Oxide- And Interface-Trap
  - Energy deposited by photons or ions: uniformed or localized
  - Leads to gradual electrical parameter changes

- **TNID:**
  - Defect creation via elastic or inelastic collision of particles with semiconductor lattice atoms.
  - Concentration of defects depends only on Non Ionising Energy Loss and not on the type and initial energy of the particle
  - Defects lead to gradual electrical parameter changes
Radiation Design Margin

To account for uncertainties in parameters such as part-to-part variations, environment definition and models, Radiation Design Margins are applied. RDM is associated with cost and shall be selected to ensure the components function within required specification for the duration of the spacecraft lifetime.

Philae separation from Rosetta. Rosetta is a long duration interplanetary mission and had an RDM requirement of 2.
Radiation Design Margin for TID and TNID

- Radiation Design Margin is an important part of RHA.
- TID and TNID RDMs are defined already in the initial RHA requirements.
- To prove that EEE components are compliant with the RDM requirement two parameters are required:
  - **TIDL and TNIDL** calculated TID and TNID level received by the part at the end of the mission.
  - **TIDS and TNIDS** level at which the part exceeds its parametric/functional requirements.
- **RDM is calculated by**
  - TIDS/TIDL and TNIDS/TNIDL.
### Generic table of the TID level (TIDL) for which TID analysis of EEE components is required

<table>
<thead>
<tr>
<th>EEE part family</th>
<th>Sub family</th>
<th>TIDL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diodes</td>
<td>Voltage reference</td>
<td>all</td>
</tr>
<tr>
<td></td>
<td>Switching, rectifier, schottky</td>
<td>&gt; 300 Krad-Si</td>
</tr>
<tr>
<td>Diodes microwave</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 300 Krad-Si</td>
</tr>
<tr>
<td>Integrated Circuits</td>
<td></td>
<td>all</td>
</tr>
<tr>
<td>Integrated Circuits microwave</td>
<td></td>
<td>all</td>
</tr>
<tr>
<td>Oscillators (hybrids)</td>
<td></td>
<td>all</td>
</tr>
<tr>
<td>Charge Coupled devices (CCD)</td>
<td></td>
<td>all</td>
</tr>
<tr>
<td>Opto discrete devices, Photodiodes, LED, Phototransistors, Opto couplers</td>
<td></td>
<td>all</td>
</tr>
<tr>
<td>Transistors</td>
<td></td>
<td>all</td>
</tr>
<tr>
<td>Transistors microwave</td>
<td></td>
<td>&gt; 300 Krad-Si</td>
</tr>
<tr>
<td>Hybrids</td>
<td></td>
<td>all</td>
</tr>
</tbody>
</table>
Generic table of the TNID level (TNIDL) for which DD analysis of EEE components is required

<table>
<thead>
<tr>
<th>Family</th>
<th>Sub-Family</th>
<th>TNIDL</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD, CMOS APS, opto discrete</td>
<td>all</td>
<td>all</td>
</tr>
<tr>
<td>devices</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated circuits</td>
<td>Silicon monolithic bipolar or</td>
<td>&gt; 2x10^{11} p/cm^2 50 MeV equivalent proton fluence</td>
</tr>
<tr>
<td></td>
<td>BiCMOS</td>
<td></td>
</tr>
<tr>
<td>Diodes</td>
<td>Zener Low leakage Voltage</td>
<td>&gt; 2x10^{11} p/cm^2 50 MeV equivalent proton fluence</td>
</tr>
<tr>
<td></td>
<td>reference</td>
<td></td>
</tr>
<tr>
<td>Transistor</td>
<td>Low power NPN Low power PNP High</td>
<td>&gt; 2x10^{11} p/cm^2 50 MeV equivalent proton fluence</td>
</tr>
<tr>
<td></td>
<td>power NPN High power PNP</td>
<td></td>
</tr>
</tbody>
</table>
TIDL (TNIDL) Top Level Requirement versus actual dose levels

- TIDL (TNIDL) are calculated employing space radiation environment and spacecraft shielding information.
- TIDL and TNIDL vary for equipment at different locations of the spacecraft.

![Graph showing ST5 - Total Mission Dose on electronic parts](image_url)

**ST5 - Total Mission Dose on electronic parts**

- Top level Requirement (dose level at the center of an Aluminum solid sphere of 5mm radius)
TIDS (TNIDS) is measured by performing TID (TNID) irradiation tests on EEE components.
TID / TNID - Analysis Flow

TID/DD ENVIRONMENT DEFINITION → SHIELDING ANALYSIS → TID/TNID REQUIREMENT

RADIATION DESIGN MARGIN

MISSION REQUIREMENTS
  → SUBSYSTEM REQUIREMENTS
  → COMPONENT REQUIREMENTS

DESIGN WORST CASE ANALYSIS

Requirements Satisfied?

NO

YES

DESIGN VALIDATED

TIDL

TIDS

RDM = TIDS / TIDL

TEMPERATURE

AGING

RADIATION
1. DAC8800 on GAIA
   - Spec Total Unadjusted Error (TUE): +/- ½ LSB
     - Out of spec limit after 2 Krad
     - TUE > 100 LSB after 5 Krad

2. OP267 on SWIFT
   a. Functional failure after 1 Krad
Variability of TID response, example LM311

TID response may vary significantly between EEE component manufacturers even for the same component type.

It is crucial to perform irradiation tests to identify EEE component performance when exposed to high energy particle radiation.

Radiation performance of LM311 from different manufacturers.
ELDRS of bipolar devices, Example

- Devices that contain bipolar transistors are tested at a dose rate of 36 rad/h to 360 rad/h (ECSS-Q-ST-60-15C).

- ESA Tailoring states: Devices that contain bipolar transistors are tested at a dose rate of 36 rad/h unless pertinent test data from previous tests have demonstrated the worst case condition at a different dose rate.
Radiation performance of LM124 for biased and unbiased devices.

The biasing conditions of a EEE component can have significant impact on the performance of EEE components when exposed to high energy particle radiation.
Lot to Lot Variability and RDM

Bipolar based ICs may show large lot-to-lot radiation performance variation.

Irradiation characterisation of every lot of bipolar based ICs is therefore an ESA requirement,

Reduction of quantum efficiency due to Displacement Damage effects in a HAS2 CMOS image sensor
Example TNID test on optoelectronics.

APS

Increase of Dark Signal Non Uniformity due to Displacement Damage effects in a HAS2 CMOS image sensor

DSNU distribution with respect to radiation for 1 second integration time.

Increasing radiation levels
Optoelectronics are highly sensitive to TNID degradation of the minority carrier lifetime.

4N49 optocoupler: relative CTR with respect to fluence

RHA for SEE

• **SEE is a transient effect**

• **SEE induced by:**
  
  - Direct energy deposition by an ion along its track through the EEE component semiconductor material.
  
  - Energy deposited by fragments nuclei, from inelastic collision between a proton and a silicon nucleus in the semiconductor material of a EEE component.

• **Many different SEE types:**
  
  
SEEs are random events
PROBA2 SEL experiment, ISSI IS61LV5128AL

Slope of 1: Signature of random events

After d’Alessio, RADECS 2013
SEE are random events
JASON2 SEL events on Cypress
CY7C1069 SRAM

SEL count during June-August 2008 period
*After R. Ecoffet, RWG presentation, 2009*
Requirement for the type of EEE components to be analysed for SEEs.

<table>
<thead>
<tr>
<th>Family</th>
<th>Sub-family</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated Circuits</td>
<td>all</td>
</tr>
<tr>
<td>Integrated Circuits Microwave</td>
<td>all</td>
</tr>
<tr>
<td>Transistors</td>
<td>FET N channel</td>
</tr>
<tr>
<td>Transistors Microwave</td>
<td>FET P channel</td>
</tr>
<tr>
<td>Transistors Microwave</td>
<td>all</td>
</tr>
<tr>
<td>CCD, CMOS APS, opto discrete devices</td>
<td>all</td>
</tr>
</tbody>
</table>
SEE - Analysis Flow

- RADIATION ENVIRONMENT PREDICTION
- PART SEE SENSITIVITY
- SEE RATE PREDICTION
- SEE CRITICALITY ANALYSIS
- FUNCTIONAL SEE REQUIREMENTS
- DECISION TREE ANALYSIS
- MISSION REQUIREMENTS
Single Event Effect Severity Assessment

Include effects of any error mitigation in design

Function is Error-functional

Large number of SEEs can be tolerated

YES

Procure Components so that Predicted Error Rate for Function Meets Requirement

NO

Add additional Mitigation for SEE to Design

Function is Error-vulnerable

Very low number of SEEs can be tolerated

YES

Additional Error Mitigation Useful/Cost-effective

NO

Function is Error-critical

No SEEs permitted

YES

Procure Components so that Predicted Error Rate for Function is ~0

NO

Additional Error Mitigation Useful/Cost-effective

Additional conditions for when SEE analysis shall be performed. Depends on the SEE LET threshold (the lowest LET level at which SEEs occur). SEE irradiation testing is required to identify the SEE LET threshold.

<table>
<thead>
<tr>
<th>SEE LET Threshold</th>
<th>Analysis Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 60 MeVcm²/mg</td>
<td>SEE risk negligible, no further analysis needed</td>
</tr>
<tr>
<td>15 MeVcm²/mg&lt;\text{LET}_{\text{threshold}}&lt;60 MeVcm²/mg</td>
<td>SEE risk, heavy ion induced SEE rates to be analyzed</td>
</tr>
<tr>
<td>\text{LET}_{\text{threshold}}&lt;15 MeVcm²/mg</td>
<td>SEE risk high, heavy ion and proton induced SEE rates to be analyzed</td>
</tr>
</tbody>
</table>
Use of models (SIMPA, PROFIT) to derive protons SEE information from Heavy ion data can be acceptable in certain situations (for memory devices). However, strict conditions and application of large margins is required.

For the SET criticality analysis of SET in analogue ICs, worst case SET templates in the Table below may be used in the absence of acceptable test data (ECSS-Q-ST-60-15C)

<table>
<thead>
<tr>
<th>Device Function</th>
<th>SET template</th>
</tr>
</thead>
<tbody>
<tr>
<td>Op-amps</td>
<td>$\Delta V_{\text{max}}=+/-V_{cc}$ &amp; $\Delta t_{\text{max}}=15$ $\mu$s</td>
</tr>
<tr>
<td>Voltage Comparators</td>
<td>$\Delta V_{\text{max}}=+/-V_{cc}$ &amp; $\Delta t_{\text{max}}=10$ $\mu$s</td>
</tr>
<tr>
<td>Voltage Regulators</td>
<td>$\Delta V_{\text{max}}=+/-V_{cc}$ &amp; $\Delta t_{\text{max}}=10$ $\mu$s</td>
</tr>
<tr>
<td>Voltage Reference</td>
<td>$\Delta V_{\text{max}}=+/-V_{cc}$ &amp; $\Delta t_{\text{max}}=10$ $\mu$s</td>
</tr>
<tr>
<td>Optocouplers</td>
<td>$\Delta V_{\text{max}}=+/-V_{cc}$ &amp; $\Delta t_{\text{max}}=100$ ns</td>
</tr>
</tbody>
</table>
1. SET templates are not always worst case

The template for op-amps indicate an SET duration of 15us.

The OP293 illustrate SETs > 15us.
For components in the critical path of the design testing shall be performed.

After Ladbury, NASA GSFC test report
COTS variability, example
Samsung 4M SRAM K6R4016V1D

DC220 or DC328: ~ 1 SEL every 3 days on LEO polar orbit
SEE Radiation Design Margins

1. ECSS-Q-ST-60-15C
   a. 1 for heavy ion induced rates
   b. 1 for proton induced rates based on data
   c. 10 for proton induced rates based on models
Power MOSFETs

1. Power MOSFETs SEB/SEGR analysis is either based on rate analysis or $V_{DS}$ versus $V_{GS}$ Safe Operating Area (SOA)
2. There is no commonly agreed method to calculate SEB/SEGR rates
3. There is no agreement about minimum LET and ion range requirements to define SOA.

Practical implementation of the method used to assess power MOSFET SEB/SEGR sensitivity shall be defined by the supplier and submitted to customer for approval (ECSS-Q-ST-60-15C)
JUICE one of ESA’s future Large Class Space Science Missions and Radiation Related R&D activities.

• ESA develops spacecraft and launchers for numerous applications. More than 50 missions are currently in operation, being developed or are planned developed.

• Due to time constraints only the JUICE mission and radiation related R&D activities are presented here. JUICE is of particular interest in this context due to its harsh radiation environment.

• General considerations:
  • In some cases significant number of radiation related R&D activities are carried out to identify the feasibility of a planned mission (e.g. JUICE). In other cases only one or a few number of R&D activities are required (e.g. identify radiation performance of main detector for a specific payload).
JUICE mission details

• JUICE - JUpiter ICy moons Explorer - is the first large-class mission in ESA's Cosmic Vision 2015-2025 programme.

• **Key science goals:** The emergence of habitable worlds around gas giants. Characterise Ganymede, Europa and Callisto as planetary objects and potential habitats Explore the Jupiter system as an archetype for gas giants.

• Planned for launch in 2022 and arrival at Jupiter in 2030, it will spend at least three years making detailed observations of the giant gaseous planet Jupiter and three of its largest moons, Ganymede, Callisto and Europa.

Due to the harsh radiation environment that will be experienced by JUICE, a number of radiation related R&D activities were initiated to identify the feasibility of the mission.

R&D activities for 5 key technology areas were initiated:

- Analogue Power/Linear devices
- Front end ASICs
- Mixed signal ASICs
- Optoelectronics (e.g. optocouplers)
- Memory devices (e.g. for solid state mass memory applications)

Pure digital electronics (e.g. digital ASICs) were considered to be suitable for the JUICE applications. DARE+ library developed under ESA funding has a high TID tolerance.
The purpose of this activity was to identify whether a power system could be developed based on typical space qualified components flown on ESA missions when they were exposed to dose levels exceeding their guaranteed TID tolerance by manufacturer.

Characterize selected part types to the combined effects of TID up to 400 Krad-Si (was initially 150 Krad and extended to 400 Krad with a CCN) and TNID up to a 60 MeV protons fluence of $2 \times 10^{11}$ #/cm$^2$.

The study shows that many electrical parameters go out of specification before 100krad. However, only one part illustrated functional failure.

The study also shows the importance of performing DD and TID tests on linear bipolar rad power converter/system design and prototyping to select devices based on their combined DD and TID JUICE radiation environment.

The results from this activity was employed to design a power system suitable for operation in the JUICE environment.
Survey of Critical Components for Si power system design

Activity irradiation test sequence

Initial Measurements
12 samples + 2 control

Proton irradiation
60 MeV, 2E11 p/cm²
6 samples + 1 control

Electrical Measurements
6 samples + 1 control

TID exposure
3 ON samples
10, 20, 50, 100 Krad
DR < 36 rad/h

150 Krad
DR < 100 rad/h

200, 250, 50, 300,
350, 400 Krad
DR < 300 rad/h

Annealing
24h at 25°C
+ 168h at 100°C

TID exposure
3 OFF samples
10, 20, 50, 100 Krad
DR < 36 rad/h

150 Krad
DR < 100 rad/h

200, 250, 50, 300,
350, 400 Krad
DR < 300 rad/h

Annealing
24h at 25°C
+ 168h at 100°C

TID exposure
3 ON samples
10, 20, 50, 100 Krad
DR < 36 rad/h

150 Krad
DR < 100 rad/h

200, 250, 50, 300,
350, 400 Krad
DR < 300 rad/h

Annealing
24h at 25°C
+ 168h at 100°C

TID exposure
3 OFF samples
10, 20, 50, 100 Krad
DR < 36 rad/h

150 Krad
DR < 100 rad/h

200, 250, 50, 300,
350, 400 Krad
DR < 300 rad/h

Annealing
24h at 25°C
+ 168h at 100°C
### Survey of Critical Components for 150 Krad-Si power system design

**Summary, September 2012**

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>PART-TYPE</th>
<th>MFR</th>
<th>FOR TESTING</th>
<th>TECHNOLOGY</th>
<th>TID</th>
<th>ELDRS</th>
<th>PROTONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPN POWER SILICON SWITCHING TRANSISTOR</td>
<td>2N5154</td>
<td>MSC</td>
<td>JANSF2N5154</td>
<td>BIPOLAR</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>NPN SILICON SWITCHING TRANSISTOR</td>
<td>SOC2222A</td>
<td>STM</td>
<td>SOC2222AK2</td>
<td>BIPOLAR</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>DUAL-TRANSISTOR, NPN, SILICON</td>
<td>2N2920A</td>
<td>STM</td>
<td>SOC2N2920AK2</td>
<td>BIPOLAR</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>PNP SILICON AMPLIFIER TRANSISTOR</td>
<td>2N3637</td>
<td>MSC</td>
<td>JANSR2N3637</td>
<td>BIPOLAR</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>PNP SMALL SIGNAL SILICON TRANSISTOR</td>
<td>SOC2907A</td>
<td>STM</td>
<td>SOC2907AK2</td>
<td>BIPOLAR</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>DUAL-TRANSISTOR, PNP, SILICON</td>
<td>2N3810</td>
<td>STM</td>
<td>SOC2N3810AK2</td>
<td>BIPOLAR</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>LOW POWER, NPN (&lt; 2WATTS)</td>
<td>2N3700</td>
<td>STM</td>
<td>SO3700SW</td>
<td>BIPOLAR</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>RAD HARD HIGH FREQUENCY HALF BRIDGE DRIVER</td>
<td>HS-2100RH</td>
<td>INTERSIL</td>
<td>IS9-2100ARH/PROTO</td>
<td>DI RSG</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>DUAL, NON INVERTING POWER MOSFET DRIVERS</td>
<td>HS-4424BRH</td>
<td>INTERSIL</td>
<td>HS9-4424BRH/PROTO</td>
<td>DI RSG</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>LOW POWER QUAD BIPOLAR OPERATIONAL AMPLIFIER</td>
<td>LM124AW</td>
<td>NATIONAL</td>
<td>5962R9950402V**</td>
<td>BIPOLAR</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>LOW POWER QUAD BIPOLAR OPERATIONAL AMPLIFIER</td>
<td>RHF43</td>
<td>STM</td>
<td>RHF43K2</td>
<td>BIPOLAR</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>RAD TOLERANT VERSION OF 4N49</td>
<td>OLS449</td>
<td>ISOLINK</td>
<td>OLS449</td>
<td>-</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>LINEAR OPTOCOUPLER</td>
<td>OLH7000</td>
<td>ISOLINK</td>
<td>OLH7000-0011</td>
<td>-</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>SEE HARD HIGH SPEED, CURRENT MODE PWM</td>
<td>IS-1845ASRH</td>
<td>INTERSIL</td>
<td>IS7-1845ASRH/PROTO</td>
<td>DI RSG</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>SEE HARD HIGH SPEED, DUAL OUTPUT PWM</td>
<td>IS-1825ASRH</td>
<td>INTERSIL</td>
<td>IS1-1825ASRH/PROTO</td>
<td>DI RSG</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>SEE HARD QUAD VOLTAGE COMPARATOR</td>
<td>IS-139ASRH</td>
<td>INTERSIL</td>
<td>IS9-139ASRH/PROTO</td>
<td>DI RSG</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>RAD HARD 2.5V REFERENCE</td>
<td>IS-1009RH</td>
<td>INTERSIL</td>
<td>IS2-1009RH/PROTO</td>
<td>DI EBHF</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

*Parts tested in this activity*
TID influence on the SEE sensitivity of EEE components.

- During their in-flight operation, EEE components are subject to TID and SEE at the same time. However, RHA requirements dictates that TID and SEE characterisation is performed independently.
- There is not much information regarding the synergetic effects of TID and SEE. Considering the harsh Jupiter radiation environment, an activity has been initiated to investigate synergetic effects.
- The project will initially perform TID irradiation tests separately with subsequent SEE characterisation of the TID irradiated devices.
- The following devices are being tested:
  - ADC (AD9042, Analog Devices), DAC (AD558, Analog Devices), NAND FLASH (MT29F408AAC, Micron), SRAM (R1RW0416, Renesas)
TID influence on the SEE sensitivity of EEE components.

TID + SEE synergy effect test approach

From CNES/ESA radiation effects final presentation days 2015 by TRAD.
TID influence on the SEE sensitivity of EEE components. Results.

AD558

Differential nonlinearity MAX

From CNES/ESA radiation effects final presentation days 2015 by TRAD.
TID influence on the SEE sensitivity of EEE components.

- This activity is still on-going. However, preliminary results indicate that no significant synergetic effects are observed for the tested devices.

From CNES/ESA radiation effects final presentation days 2015 by TRAD.
The purpose of this activity was to identify the radiation performance of state of the art memory devices with possible use for the JUICE mission.

In collaboration with the JUICE project it was decided that the focus of the activity be placed on DDR3 and NAND FLASH devices.

The following project requirements were applied:

- **TID**: Level of interest >400krad. Minimum level >50krad
- **SEE**: Standard ECSS-Q-ST-60-15C requirement (SEE LET threshold >60MeV cm²/mg)
- Memory density > 4Gb
- High Speed and low power

This activity was awarded to Airbus DS and IDA
Memory irradiation characterisation activity for JUICE

Part Selection:

4 Gb DDR3:
- Elpida EDJ4208BASE-DJ-F (obsolete)
- SK Hynix H5TQ4G83MFR-H9C
- Micron MT41J512M8RH-093:E
- Samsung K4B4G0846B-HCH9
- Nanya NT5CB512M8CN-EK

2 Gb DDR3 (2Gb DDR3 were also characterised for comparison purposes)
- SK Hynix H5TQ2G83BFR-H9C
- Nanya N5CB256M8BN-CG
- Micron MT41J256M8HX-15E:D
- Samsung K4B2G0846B
- Samsung K4B2G0846D

NAND FLASH Reference:
- Samsung K9WBG08U1M (SLC, 4 x 8 Gb, 51 nm)
- Micron MT29F8G08AAAWP-ET:A (SLC, 8 Gb, 50 nm)

NAND FLASH Focus on state-of-the-art technology:
- Micron MT29F16G08ABACA WP-IT:C (SLC, 16 Gb, 25 nm)
- Micron MT29F32G08ABAAA WP-IT:A (SLC, 32 Gb, 25 nm)

A large number of devices were tested during this activity
The figure illustrates the TID performance of the NAND FLASH devices.

NAND FLASH SEU cross section as a function of LET

From CNES/ESA radiation effects final presentation days 2015 by Airbus DS and IDA.
The Micron 16Gb devices show lower SEU cross section than the 8Gb Samsung device.

NAND FLASH SEU cross section as a function of LET

From CNES/ESA radiation effects final presentation days 2015 by Airbus DS and IDA.
Memory irradiation characterisation activity for JUICE

Transient SEFIs classified into Column, Row and Block errors.

The cross sections per device is lower than observed for SEUs.

From CNES/ESA radiation effects final presentation days 2015 by Airbus DS and IDA.
Persistent SEFIs classified into Column, Row and Block errors.

The cross sections per device is lower than observed for SEUs.

From CNES/ESA radiation effects final presentation days 2015 by Airbus DS and IDA.
Memory irradiation characterisation activity for JUICE

Error density as a function of dose for the Samsung 4 Gbit NAND FLASH. There is a large part to part variation.

The Hynix device did not show any errors up to a TID value of 400krad.

From CNES/ESA radiation effects final presentation days 2015 by Airbus DS and IDA.
Memory irradiation characterisation activity for JUICE

DDR3 SEU cross section as a function of LET. The 2-Gbit Hynix device showed the best SEU performance.

DDR3 Hard SEU cross section as a function of LET. Hard SEUs cannot be removed by rewriting.

From CNES/ESA radiation effects final presentation days 2015 by Airbus DS and IDA.
Memory irradiation characterisation activity for JUICE

DDR3 heavy ion row SEFI cross section as a function of LET

DDR3 heavy ion column SEFI cross section as a function of LET

From CNES/ESA radiation effects final presentation days 2015 by Airbus DS and IDA.
Memory irradiation characterisation activity for JUICE

Main Conclusion:
• TID Tolerance:
  • The best NAND Flash: ≈ 30 krad
  • The best DDR3 SDRAM: ≈ 400 krad (Hynix). However, the device from Micron only managed approximately 70 krad.
• SEE Tolerance:
  • Both types suffer from SEE error mechanisms with data loss.
  • NAND Flash: destructive failure (DF) observed
  • DDR3 SDRAM: device SEFI observed
  • Both types are latch-up free
  • Parts with good test coverage:
The objectives of the activity is:
• To test radhard optocouplers currently available and identify whether they are capable of withstanding the harsh Jovian environment. Total Ionising Dose and Displacement Damage effects will be investigated.

• To improve the characterisation of radiation induced degradations of a candidate APS detector for Laplace (HAS2 from Onsemi) used on Star trackers. Total Ionising Dose, Displacement Damage and Single Event Effects sensitivity will be evaluated. Neutron test campaigns will allow to isolate displacement damage specific degradation mechanisms.
Radiation characterization of Laplace/Tandem critical RH optocouplers sensors and detectors

Optocouplers selected for this activity

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Part type</th>
<th>Date Code</th>
<th>LED Structure</th>
<th>Photodetector type</th>
<th>Structure</th>
<th>Radiation information</th>
</tr>
</thead>
<tbody>
<tr>
<td>MICROPAC</td>
<td>66179-002</td>
<td>1124</td>
<td>GaAlAs(^1)</td>
<td>660nm(^1) silicon planar NPN Output phototransistor</td>
<td>Lateral</td>
<td>High radiation immunity</td>
</tr>
<tr>
<td></td>
<td>66193-002</td>
<td>1120</td>
<td>GaAlAs(^1)</td>
<td>660nm(^1) silicon planar phototransistor</td>
<td>Lateral</td>
<td>Proton radiation tolerant LED</td>
</tr>
<tr>
<td></td>
<td>66221-103</td>
<td>1122</td>
<td>GaAlAs(^1)</td>
<td>850nm(^1) silicon planar phototransistor</td>
<td>Lateral</td>
<td>Proton radiation tolerant</td>
</tr>
<tr>
<td></td>
<td>66224-105</td>
<td>1038, 1111</td>
<td>GaAlAs(^1)</td>
<td>850nm(^1) silicon planar phototransistor</td>
<td>Lateral</td>
<td>Proton radiation tolerant</td>
</tr>
<tr>
<td>AVAGO</td>
<td>HCPL5431</td>
<td>1116</td>
<td>AlGaAs</td>
<td>850nm(^1) integrated high gain photon detector.</td>
<td>Sandwich</td>
<td>High Radiation Immunity</td>
</tr>
<tr>
<td></td>
<td>HCPL5501</td>
<td>1105</td>
<td>GaAsP</td>
<td>-</td>
<td>Sandwich</td>
<td>High Radiation Immunity</td>
</tr>
<tr>
<td></td>
<td>HCPL5701</td>
<td>1116</td>
<td>GaAsP</td>
<td>-</td>
<td>Sandwich</td>
<td>High Radiation Immunity</td>
</tr>
<tr>
<td>ISOLINK</td>
<td>OLH400</td>
<td>1048</td>
<td>AlGaAs double heterojunction(^1)</td>
<td>700nm(^1) integrated photodiode-darlington detector IC</td>
<td>Lateral</td>
<td>Radiation Tolerant</td>
</tr>
<tr>
<td></td>
<td>OLS0449</td>
<td>0949</td>
<td>AlGaAs double heterojunction(^1)</td>
<td>830nm(^1) NPN silicon phototransistor</td>
<td>Lateral</td>
<td>Radiation Tolerant Phototransistor</td>
</tr>
<tr>
<td></td>
<td>OLH7000-0010</td>
<td>0721</td>
<td>AlGaAs double heterojunction(^1)</td>
<td>870nm(^1) two PIN photodiode detectors</td>
<td>Lateral</td>
<td>Displacement damage tolerant LED</td>
</tr>
</tbody>
</table>

APS selected for this activity
- HAS2 from Onsemi (the HAS2 results will not be discussed in this presentation)
Radiation characterization of Laplace/Tandem critical RH optocouplers sensors and detectors

For optocoupler the following tests were performed:

- 1 MeV neutrons for TNID effects
- 3 proton energies (30, 60 and 190MeV) for TNID and TID effects
- 60Co irradiation for TID effects

- Neutron and proton results were converted to 10MeV equivalent proton energy

- Following the 60Co irradiation tests two annealing steps were performed.
  - 24h at +25 degree C
  - 168h at +100 degree C
Impact of bias condition on CTR degradation.

- Whatever the bias condition (ON1, ON2, OFF), CTR1 (Vce = 5V, If = 1mA) is the most sensitive configuration whereas CTR4 (Vce = 5V, If = 20V) exhibits the smallest average parameter drift.
- In all cases, the lower the forward current, the higher the degradation.

From CNES/ESA radiation effects final presentation days 2015.
Radiation characterization of Laplace/Tandem critical RH optocouplers sensors and detectors

TID performance of all optocouplers tested.
- The AVAGO parts perform well following TID exposure.
- Three of the Micropack devices and one Isolink devices did not reach the 83 krad level.

From CNES/ESA radiation effects final presentation days 2015.
The data illustrates that there are some dissimilarities between the neutron and the proton irradiation tests. In particular the Micropack 66224 shows larger degradation following neutron irradiation. Considering this parts poorer TID performance it would have been expected to see better performance in the neutron data.

From CNES/ESA radiation effects final presentation days 2015.
Conclusion:

- TNID damage at different fluence seem to be proton energy dependent. Additionally, some parameter degradation indicate proton energy dependence.

- Based on the results and to identify the worst case irradiation conditions, it is recommended to perform proton irradiation testing at different proton energies.

- The Micropack devices show the largest lot-to-lot variation. AVAGO devices show little lot-to-lot variation.

- Irradiation characterisation of every optocoupler lot is required.

- Optocouplers compliant with JUICE RHA requirements are available but have to be well characterised.
Other radiation related R&D activities carried out or planned for carried out for JUICE

- Irradiation characterisation of Front-End ASICs
- Irradiation characterisation of mixed signal ASICs
- Validity of $^{60}$Co TID characterisation with respect to high energy electrons
- ...

European Space Agency

70
- Electronics are potentially very sensitive to radiation effects, keep in mind radiation sensitivity in design and part selection.
- Radiation constraints can be very different from one mission to another.
- Do not use parts for which no radiation information is available. It is better to fly what you know even with some radiation sensitivity.
- Avoid components sensitive to destructive events.
- Radiation sensitivity depends strongly on biasing conditions.
- Test enough parts to get statistics on part to part variation.
- Lot to lot variation must be considered, you may have radiation data on the same part type but your actual device may contain a completely different die.
- Mitigation is often possible through good design practices but in most of the cases radiation testing is unavoidable.
- If you have any doubt about RHA standards, ask a radiation expert.