Documents Applicable to WP3-4 System Level Review

Scope

The present document contains a collection of notions about system level testing methodologies, analyses and results performed within *RADSAGA WP3 – System Level Qualification Requirements*. Currently, two ESRs are working on this work package, *ESR12 - System-in-Package radiation qualification requirements* and *ESR13 - Bridging methodology from component to system-level for the assessment of coupled radiation and degradation constraints in digital systems*. A collaboration with DLR in the frame of the ESR14 activity (*Radiation Tolerant communication links to be used for distributed systems and mixed-field radiation environments*) is also of central relevance for this review.

A link with *WP2 – Component Level Reliability and Testing* is provided by the component-to-system reliability and testing assessment provided by *ESR7 – Coupled radiation effects on emerging power devices*. A link with *WP4 – Methodologies and Guidelines* is provided by the additional system level testing and guideline tailoring of *ESR15 – Relevance, Guidelines and Tools for rad-hard design and radiation testing of components and systems in complex environments*.

The document is intended to be only a summary about current RADSAGA achievements, focusing on the preparation of the WP3/WP4 System Level review. Detailed analyses can be found in the cited documents.

Applicable Documents

RADSAGA TEST REPORTS

1. GANIL Test Report

Name: RADSAGA_Test_Report_01_GANIL
EDMS number: 2086126 v.2
https://edms.cern.ch/ui/#!master/navigator/document?P:100135998:100324224:subDocs

   a. Section #5 for ESR12's experiment.

2. CHARM Test Report #1

Name: RADSAGA_Test_Report_02_CHARM
EDMS number: 2086128 v.3
https://edms.cern.ch/ui/#!master/navigator/document?P:100135998:100368856:subDocs

   a. Section #5 for ESR7's experiment;
   b. Section #6 for ESR12's experiment.

3. CERN HI Test Report

Name: RADSAGA_Test_Report_05_CERN_HI
EDMS number: 2215703 v.1
https://edms.cern.ch/ui/#!master/navigator/document?P:100135998:100442096:subDocs

   a. Section #5 for ESR12's experiment.

4. CHARM Test Report #2

Name: RADSAGA_Test_Report_06_CHARM
EDMS number: 2215709 v.1
https://edms.cern.ch/ui/#!master/navigator/document?P:100135998:100442102:subDocs

   a. Section #3 for ESR15's experiment;
   b. Section #4 for DLR's experiment.

5. CHIPIR Test Report

Name: RADSAGA_Test_Report_08_CHIPIR
EDMS number: 2215712 v.1
https://edms.cern.ch/ui/#!master/navigator/document?P:100135998:100442105:subDocs

a. Section #4 for ESR13's experiment.

RADSAGA DELIVERABLES

1. Deliverable 3.1 - Progress Report on System Level Test Methodology compared with Component test results.

https://espace.cern.ch/RADSAGA-ITN/Deliverables%20and%20Milestones/Deliverable%20and%20Milestone%20Reports/D3-1/D3.1%20Progress%20Report%20on%20system%20level%20test%20methodology.pdf

2. Deliverable 4.1 – Evaluation Report of 14 MeV Neutron Test Methodology.

https://espace.cern.ch/RADSAGA-ITN/Deliverables%20and%20Milestones/Deliverable%20and%20Milestone%20Reports/D4.1/D4.1%20Evaluation%20report%20of%2014%20MeV%20neutron%20test%20methodology.pdf

LITERATURE

1. K. Niskanen, A. Touboul, R. Germanicus, A. Michez, F. Wrobel, J. Boch, V. Pouget, P. Giroud, S. Morand, O. Crepel, C. Weulersee, C. Binois, F. Saigné, ``Silicon Carbide Power MOSFETs under Neutron Irradiation: Failure in Time Demonstration and Long Term Reliability Degradation Evaluation'', NSREC 2019.
2. J. Budroweit, S. Mueller, M. Jacksh, R. Garcia Alia, A. Coronetti, A. Koelpin, ``In-Situ Testing of a Multi-Band Software-Defined Radio Platform in a Mixed-Field Radiation Environment'', NSREC 2019.
3. T. Rajkowski, F. Saigné, V. Pouget, F. Wrobel, A. Touboul, J. Boch, P. Kohler, P. Dubus, P. Wang, ``Analysis of SET Propagation in a System-in-Package Point-of-Load Converter'', RADECS 2019.
4. A. Coronetti, F. Manni, J. Mekki, D. Dangla, C. Virmontois, N. Kerboub, R. Garcia Alia, ``Mixed-Field Qualification of a COTS Space On-Board Computer with its CMOS Camera Payload'', RADECS 2019.

Summary of tests, achievements and conclusions

This summary is meant to provide an overview about achievements related to system level testing and related methodology within RADSAGA. Tests from each ESR were performed with different final objectives. The main two were to establish component-to-system propagation of radiation effects due to SEE and TID (mainly ESR12, ESR13 and ESR7) and the assessment of alternative radiation hardness assurance techniques for space electronics (ESR15, DLR).

As a first achievement, the suitability of certain facilities for system level testing was established. Most of the test took place in CHARM, which is a facility conceived for system level test. Another test relied on a deeply penetrating beam, such as the neutron spallation beam at ChipIr. One of the limitations of ChipIr may be related to the smaller beam compared to CHARM. However, given the beam penetration and the spectra characteristics, ChipIr is the best proxy to CHARM. Some more atypical facilities were used. They allowed to perform system level tests with deeply penetrating highly energetic heavy ions. This was the case of GANIL (typical ion energies 20-50 MeV/n, LET 20-100 MeV.cm^2/mg), whose field size allows irradiating a bunch of components on a PCB. The samples still require the pre-test delidding and, when applicable, adapting 3D structures to 2D. It was also the case for the CHARM heavy ion run (typical ion energies 6 GeV/n, LET 8 MeV.cm^2/mg), which is characterized by very strong pulsed fluxes and does not require sample preparation due to the very large penetration. With GANIL excepted, all other facilities allows testing of stacked PCBs or systems with three-dimensional layout. CHARM is also the only facility allowing assessment of synergistic effects which are more relevant at system level.

Tests performed to establish component-to-system propagation of radiation effects were performed by increasing the level of observability inside the system. In analog systems this is achieved by increasing the number of measurement points/channels in order to sample specific signals at certain nodes in the systems which are fed by certain components. In digital systems this is achieved by including some code level instrumentation in the software to monitor how data are processed through successive steps of an application and identify where the fault occurred.

Some important achievements in this kind of system level evaluation were attained by ESR12 who had the chance to test a Point-of-Load DC-DC Converter manufactured by 3DPlus in many different facilities for SEE, TID and synergistic effects. Most of the components of such systems were previously qualified at component level by 3DPlus. The tests allowed to observe new SET propagation effects not expected from the component level tests. Some of these 'new' events were capable of propagating at system level with the existing mitigation techniques implemented to cope with expected component level SETs. The tests also allowed observing TID degradation affecting multiple devices at once. This led to parameter drifts that could cause the enabling of certain protection electronics, e.g. undervoltage protection. Thanks to the many points of measurement, most of the component level information could be retrieved, such as the absence of SEL from the devices installed on the PCB.

The tests were often performed with three different versions of the SUT (System Under Test). The original product from 3DPlus (which has a 3D layout), the equivalent 2D PCB holding same components and a 2D PCB holding some components more sensitive to radiation. One of these components had a very small SEL LET threshold (1.2 MeV.cm^2/mg) and was thus discarded for the final version of the system. However, in mixed-field the component didn't exhibit any SEL. This can have two possible explanations: a) very low cross section at typical LET of hadron fragments, b) within the system the component was used in a derated mode which contributed to reduce its sensitivity to SEL. This shows that it is important to assess how each component is used within the system and that the pass/fail logic from system level can be more relaxed than at the component level.

The system level test can allow assessing the effectiveness of mitigation techniques implemented at system level. It is clear, however, that not having any knowledge about the component may render more complicated designing certain mitigation techniques which are strictly related to SET signatures. In addition, even though here it was not the case, knowledge about the expected radiation effects can help planning the facility to be used and the respective test methodology.

Other interesting observations were related to different TID degradations from the SUT in 2D configuration or in 3D packaging. The packaging effect on TID drifts of the system (observed for the input current) was observed by both heavy ion tests and TID X-ray testing. Finally, laser facilities were shown to be a useful mean for recreating and injecting effects observed during the irradiation.

The digital system analysis (based on SoCs) from ESR13 can experience from a smaller set of tests and it mainly benefits from the ChipIr testing opportunity. The digital system radiation response was explored by running both an avionics application and a low-level code instrumentation to track data errors within the system processing. Separate beam runs were used to test single components within the SoC as well as on the PCB. A low level code implementation allows connecting system level effects to a certain component response only to a limited extent. The SoC reliability in the PS (Processing unit) and PL (Programmable Logic) are strictly a function of the software and firmware, so they may result to be independent from the component tests. Only a very high level of code instrumentation can shed light on the device originating the system error.

The component level test was also performed to assess performance variations among fresh components and aged components. Depending on the type of IC and circuit the results may vary. Sometimes fresh components are more reliable than aged, sometimes they are less.

The radiation qualification tests from ESR15 and DLR were less devoted to a strict assessment of component response and more related to the evaluation of reliability and availability of the space SUT. ESR15's experiment was performed in partnership with CNES. It consisted of a COTS-based On-Board Computer tested in tandem with its payload (a CMOS Camera). The DLR system was a Software-defined Radio and it had a similar logic to the CNES system since there was a processing unit commanding a RFIC. As a first measurable parameter, both system level tests didn't point out any destructive event affecting the systems.

Both tests were performed at CHARM in a mixed field environment, whereas the operational environment of the final systems will be the proton-dominated Earth's radiation belt. A first take-away is based on how to predict SEE rates in space starting from the single CHARM HEH cross section (which encompasses all particles and a wide energy spectra). To this end, the DLR system was also tested at KVI-CART with high energy protons (standard space characterization) and the SEFI cross section at 190 MeV was found to agree with the CHARM HEH SEFI cross section.

To confirm that the SEFI cross sections strongly depends on the software running on the processing unit device, both the CNES and the DLR experiment were based on the same component (Zynq SoC), but the SEFI cross section of the DLR system was found to be 2 orders of magnitude higher than that of the CNES system. This is blamed on the use of the Linux operating system in the DLR system. The CNES system was making use of a much leaner supervisory logic. In any case and despite its enhanced sensitivity, the DLR SEFIs were successfully handled by the automated supervision (i.e. successful reboots, etc.) and their expected rate in LEO orbit can be considered as acceptable for a broad range of applications.

Both systems relied on use of a watchdog to maintain the system autonomous during the long irradiation runs. Due to the high TID levels, the implementation of this protection became an issue for the CNES experiment due to the combined electrical stress and TID of the I/O pin of the SoC responsible for sending the refresh signal to the watchdog. This is a kind of failure that cannot be seen at component level unless pins of the SoC are purposely strongly stressed.

ESR15's experiment was run in two different positions within CHARM (G0 and R5). G0 is used to mainly assess the effect of neutrons on accelerator mixed field SEE rates, whereas R5 has a HEH spectra resembling the proton spectra of LEO. The flux in G0 is about a factor 10 milder than in R5. Nonetheless, same SEE signatures were observed in both positions. Due to the lower SEFI rate in G0, it was possible to retrieve more debug information about errors as opposed to R5. Different positions in CHARM can potentially be used for a system level evaluation (G0) and as an orbit rate prediction test (R5).

The DLR system was running a finished flight software, whereas for the SoC part, the CNES system was running a sort of semi-component/semi-system test. SoC components were tested, but the errors were not measured down to the single bit upset. For some of the test a cross section would have to be calculated as cm^2/word or cm^2/test. The component tests were also not run individually, but all the single tests were run within a master cycle.

Determining root causes while running an application at system level may provide quite strong overhead if the logging is not kept as simple as possible. A possible instance comes from analog measurements performed on the PCB by the control logic device itself. When an aberrant value was found it was not possible to discern if the error was due to a wrong analog measurement, to a faulty analog-to-digital conversion or to a faulty hexadecimal to decimal conversion due to the logging scheme implemented.

Determining if an error is correctable or uncorrectable requires at least two consecutive iterations to be concluded and logged. This was usually the case except if the system SEFI cross section was too high or if a test was run in debug mode (for instance by plotting all error addresses to a slow UART logging connection). In this case, trying to get more information about error signatures resulted in an actual loss of information (it was not possible to determine the total amount of errors) since a SEFI occurred before all erroneous data could be logged.

A trade-off between data amount and test speed has to be performed in order to retrieve valuable information about error signatures, but also to get enough statistics. In this sense, either running the experiment in different positions at CHARM or running the experiment at different test speeds may help out achieving both objectives.

Running multiple tests together can highlight possible weaklings or criticalities in the digital design that, as a radiation induced effect, will lead to errors being flagged on multiple tests at the same time with potentially complicated signatures. Reported to a flight software, such issue could dramatically disrupt the system functionality.

The coupling of sophisticated digital components within a system, such as a SoC and a CMOS Camera, is a careful operation that shall account for how the single component failure modes may impact the functionality of the second one. Single and full recovery methodologies shall also be carefully assessed in order to avoid prolonged functionality interruptions. A higher level of self-diagnosis may be helpful.

ESR7 is studying the failure mechanisms of wide bandgap power MOSFETs and their consequence at system level. His initial spice studies on the use in ‘degraded mode’ of failed components within a system have evolved in the implementation of a DC-DC converter. The study shows that the system may still maintain its functionality (i.e. delivering the required output voltage) within a certain tolerance.

Guideline development

There’s currently plenty of radiation methodologies standards and guidelines distributed by several authorities for space, avionics and ground applications. None of them deals explicitly with system level radiation testing. The main challenge of writing such a guideline stands in the wide complexity (from a small bunch of components on a PCB or integrated in the same chip to entire satellite, airplane or car control systems) and multiple scale variability of different systems (analog and digital, COTS systems and custom systems designed on COTS, various radiative environments, data portability from one system to another, etc.).

The general scope of such a guideline would be to present in the most complete way the many features and potential criticalities related to system level radiation testing while remaining general. The idea of the guideline would be to provide notions about system level design with an eye on radiation effects as well as to explain the required steps to move from a generic system design to a radiation assessment of the system reliability through testing.

It is clear that the amount of material and experience required to write such a guideline may go beyond what can be covered within the RADSAGA project. However, the experiments held so far already reinforce many important system level concepts (such as observability at the top system level, which considerations shall be made to increase observability to lower levels, potential issues emerging from the selected setups, facilities constraints). Efforts also went into the direction of understanding how to use the recovered data to compare component and system level approaches as well as for radiation hardness assurance consideration.

The guideline will focus on custom systems whose design is based on COTS and whose frame of application will be the radiation environments relevant to RADSAGA. It will cover testing considerations for both analog and digital systems and, since stochastic and cumulative effects in a system may not be disentangled as easily as for components, will keep its generality by encompassing the testing of system robustness to all the radiation effects.