SERESSA 2022

5th to 9th of December at CERN, Geneva

System-Level Design and Radiation Test Methodologies based on a novel Software-Defined Radio Architecture for Space Applications

Jan Budroweit, DLR

Agenda

- ❑ DLR at a Glance
- ❑ Background and Motivation
- ❑ Risk Assessment for Space Hardware Design
  - Excursion: Standards for Space Missions
- ❑ Best practice and experience on a Software-Defined Radio
  - Radiation Testing on complex RFIC
  - System-Level Verification
- ❑ Conclusion

About the Speaker

Jan Budroweit

- Studied Communication and Information Technologies
- Since 2013 at DLR as research and communication subsystem engineer
- Responsible engineer for the communication subsystem at the Eu:CROPIS mission (launched in 2018 – second satellite mission fully supported by DLR)

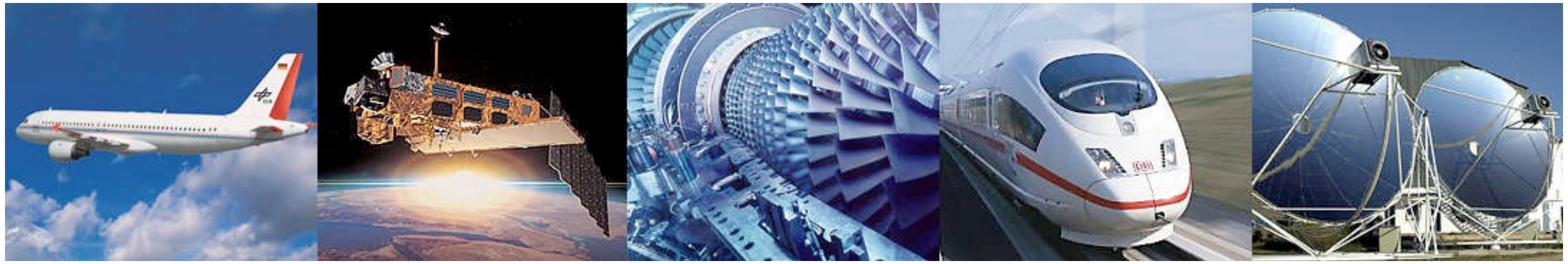
- Research activities
    - Future radio systems for space missions (communications and RF payload)
    - Radiation effects on electronics and systems

DLR at a Glance

DLR at a Glance

- Research Institution
- Space Agency
- Project Management Agency

- >9000 employees across
  - 38 institutes and facilities at 20 sites



DLR at a Glance

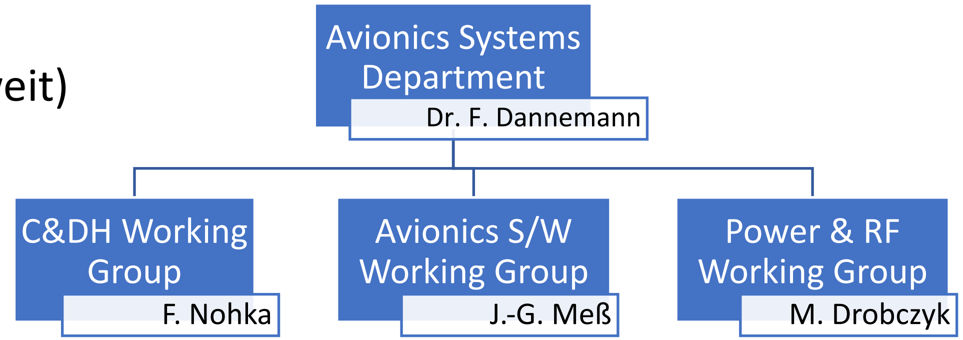
Institute of Space Systems, Bremen

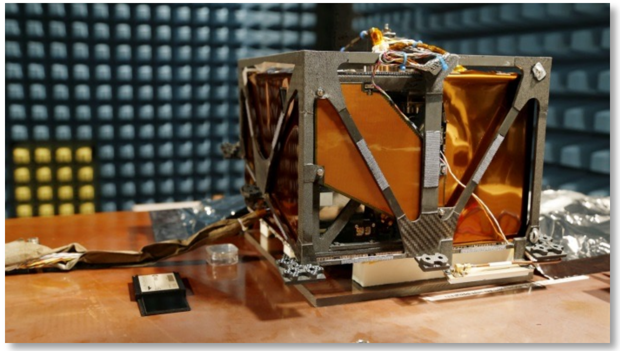
- Founded 2006, 170+ employees
- Studies and analyses of launch vehicles and orbital systems
- Design and development of spacecraft / missions (small satellites, lander vehicle)
- Development of technologies for
  - Cryogenic Propellant Management
  - Planetary Landing
  - Satellite Subsystems & Avionics
  - Guidance Navigation and Control
  - High Precision Optical Measurements
  - Habitation & Life-Support-Systems

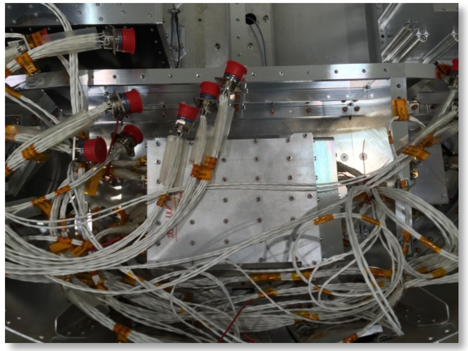
DLR at a Glance

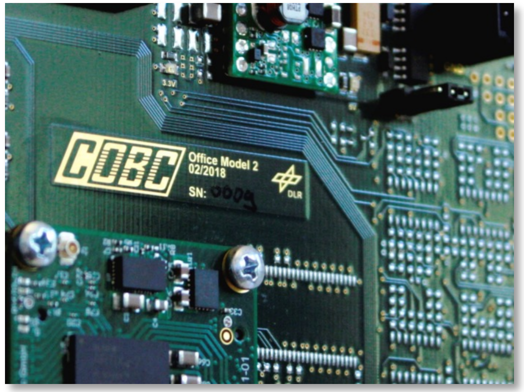
<u>Avionic System Department</u>

- 3 Working Groups
  with 7-9 Scientists each plus
  - Expert Group „Radiation Effects in Space Systems" (J. Budroweit)
  - 3 Test- & Integrations Labs
  - 2 Project/Team-Assistants
- Design of avionic Systems
- Subsystems Engineering (Power, COM, CDH, EMC, Radiation,…)
- Hardware Design
- Software Design









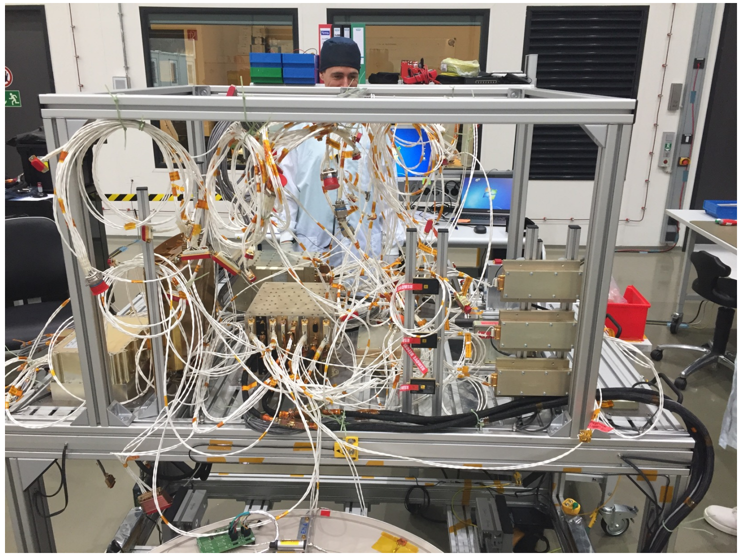
Background and Motivation

Integrated Core Avionics

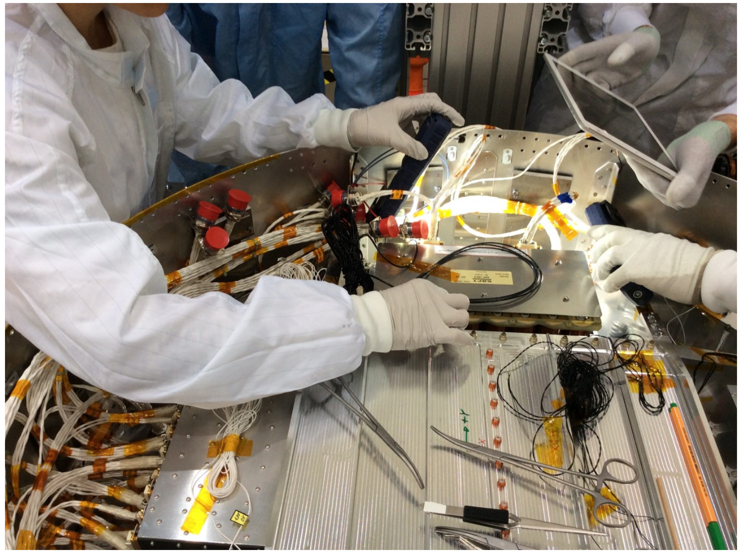
Complexity in satellite busses

- Key Bus Subsystems
  - On-board Data Handling
    - Hardware
    - Software
  - Power
  - Communication
  - AOCS

- Issues:
  - Designed for specific mission requirements
    - From scratch design and procurement
    - Often not re-usable
  - Complex AIV
    - Harness and accommodation
    - Testing
    - Extremely time consuming



Eu:CROPIS Flatsat Model, DLR



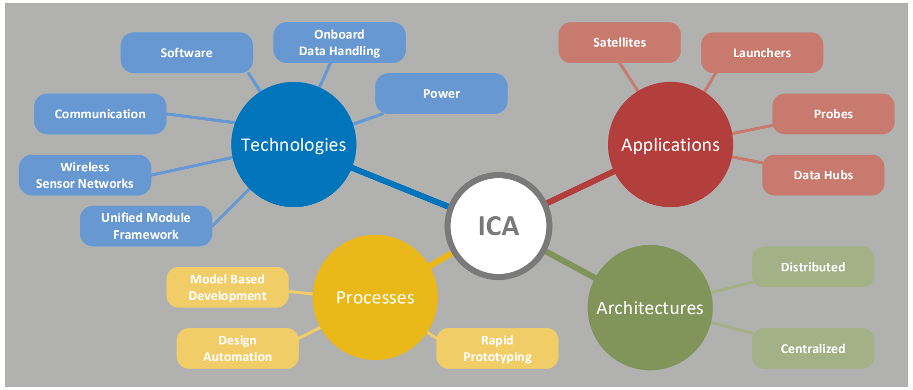
Eu:CROPIS integration, DLR

Integrated Core Avionics

Complexity in satellite busses

- Integrated Core Avionics (ICA)
  - Framework to address wide variety of mission scenarios
  - Innovative and developer friendly fashion
  - Coherent and scalable solution for
    - On-board Data Handling
    - Power
    - Radio/Communication
    - Software
  - Motivation:
    - Easy to scale for different applications and spacecraft classes
    - Easy to extend with new functionalities and external technologies
    - Easy to update with latest research findings

➢ We need to use state-of-the art electronics and technologies!



Concept of ICA, DLR

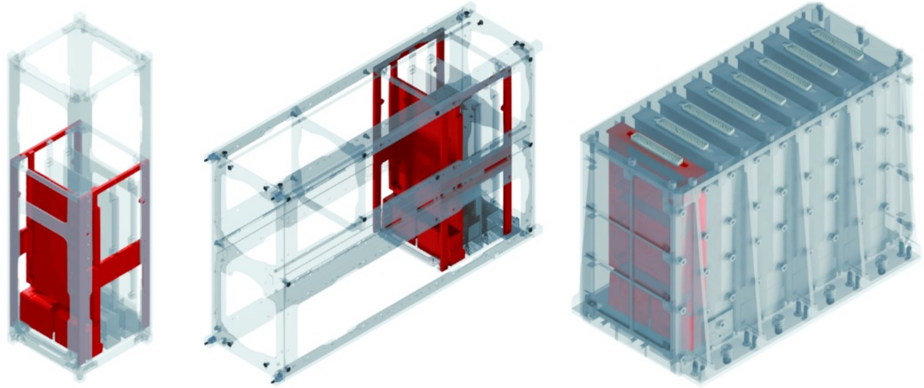


Illustration of ICA Structure, DLR

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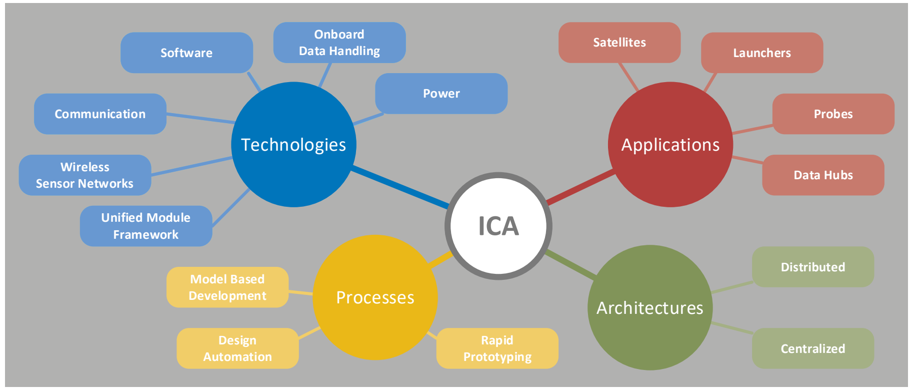

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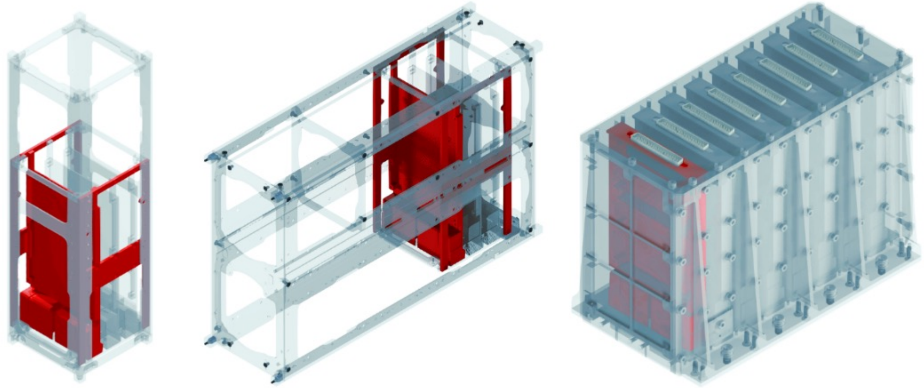


Illustration of ICA Structure, DLR

State-of-the art radio systems for space missions

- Radio systems for spacecraft/satellites are usually designed and develop for one specific application:
  - ➢ GPS-Receiver
  - ➢ TV-Broadcasting
  - ➢ Satellite communication (TM&TC)
  - ➢ Radio and RF Payloads (e.g. AIS, ADS-B, …)
  - ➢ …

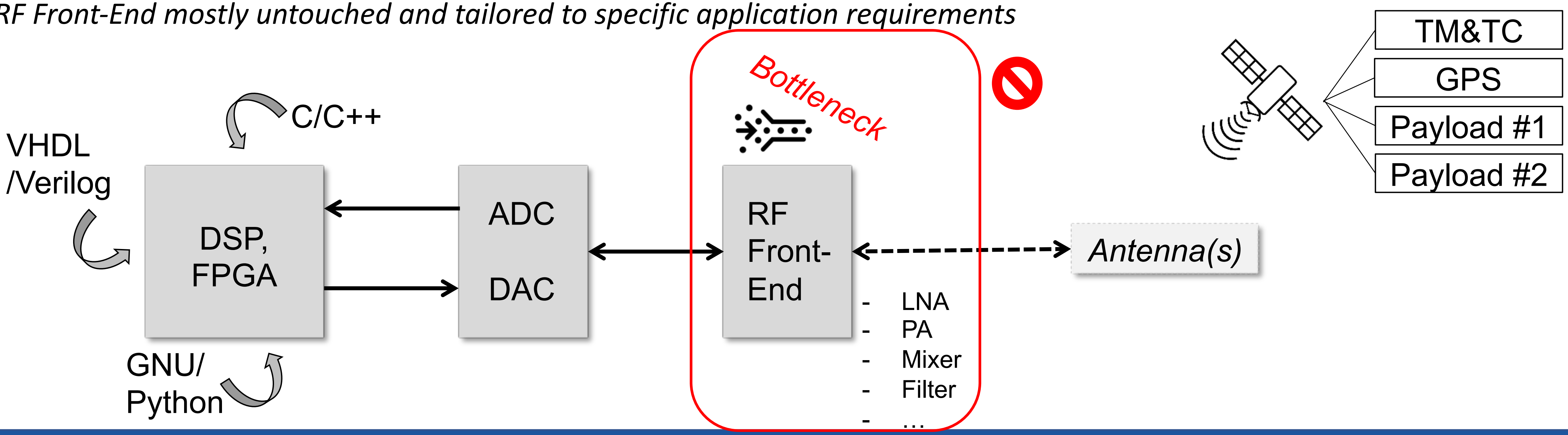
- In the beginning, such radio systems were designed discretely (early 60's and 70's)
  - ✓ Very robust and reliable
  - – No flexibility
  - – Very large systems

- Software-Defined Radio (SDR) systems were already established over the past decade(s) in space
  - ✓ More flexibility in terms of data/signal processing adaption
  - ✓ Smaller system design
  - – Just for a single application (e.g. GPS receiver)

What is a Software-Defined Radio (SDR)

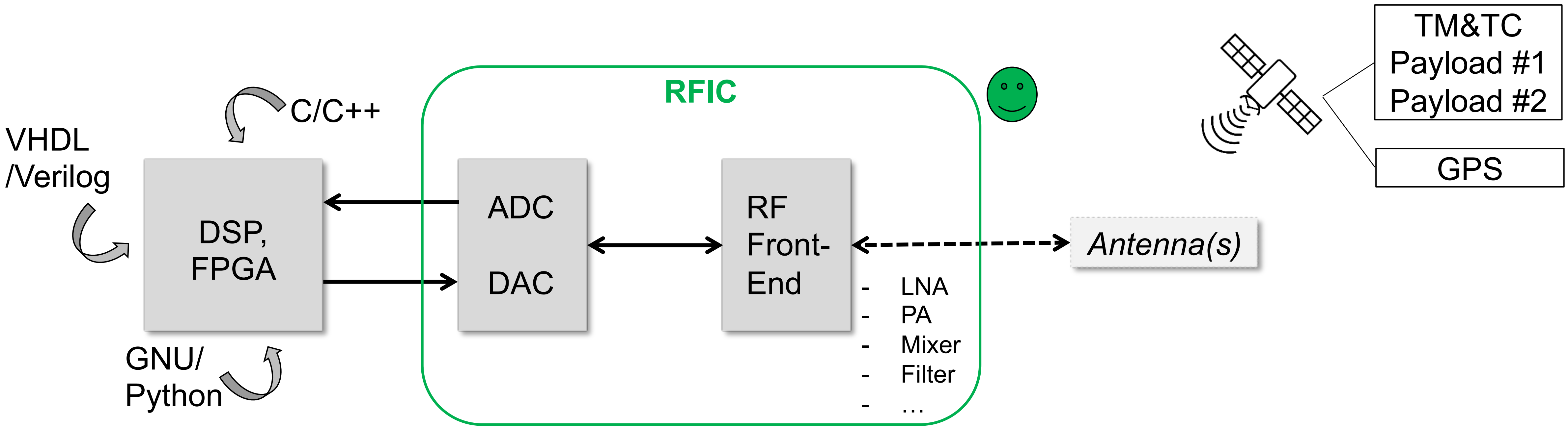
- A SDR usually defines the signal processing in software:
  - Implementation on a DSP or FPGA
- Also consist of:
  - ADC and DAC
  - RF Front-End

➢ *RF Front-End mostly untouched and tailored to specific application requirements*



What is a Software-Defined Radio (SDR)

- RF Front-Ends can now be configure by software thanks to RF Integrated Circuits (RFIC)
  - ➢ A single hardware (radio) for operating multiple applications (two/three/four in one)
    - 10%: TM&TC SatCom <-> 90%: RF payload (ADS-B receiver, AIS receiver, spectral monitoring, …)
  - ➢ **Better utilization of limited resources (size, weight, power, …) on a spacecraft**



Contraints with RFICs

- RFIC devices (e.g. AD9361) for SDR systems

  - Pros
  - ✓ Commercial off-the-shelf
  - ✓ Frequency selection: 70 MHz to 6 GHz
  - ✓ Adaptive sample rates: up to 64 MSPS
  - ✓ Integrated RF technology (e.g. amplifiers, filter, ...).
  - ✓ Small device
  - ✓ "Low" power consumption

  - Cons
  - – Limited availability and manufacturers
  - – Very complex and highly integrated ICs
  - – High requirements (power, noise, stability, …)
  - – Compatibility to FPGAs or processors
  - – **Not designed for the use in space!**

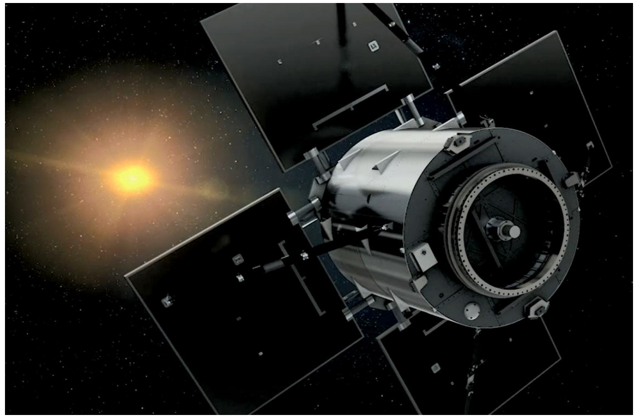
→ Use of COTS devices for space applications?

Risk Assessment for Space Hardware Design

Space mission survey (then)

Traditional space missions

- High costs
- Low risk acceptance
- Intense QA
- **Avoidance of COTS**
- Long development time
- Standardization (ECSS)
  - High success



Eu:CROPIS, source: DLR

Huge gap between both mission approaches

CubeSat space missions

- Low costs
- High risk acceptance
- No or minor QA
- **COTS only**
- Fast development time
- No standardization
  - Low success

Qtum's CubeSat , source: Qtum Foundation

Space mission survey (now)

Traditional space missions

- High costs
- Low risk acceptance
- Intense QA
- **Avoidance of COTS**
- Long development time
- Standardization (ECSS)
  - ➢ High success

NewSpace missions

- *Lower costs*
- *Medium risk acceptance*
- *COTS usage preferred*
- *Faster development time*

New Approach, no standards defined yet

CubeSat space missions

- Low costs
- High risk acceptance
- No or minor QA
- **COTS only**
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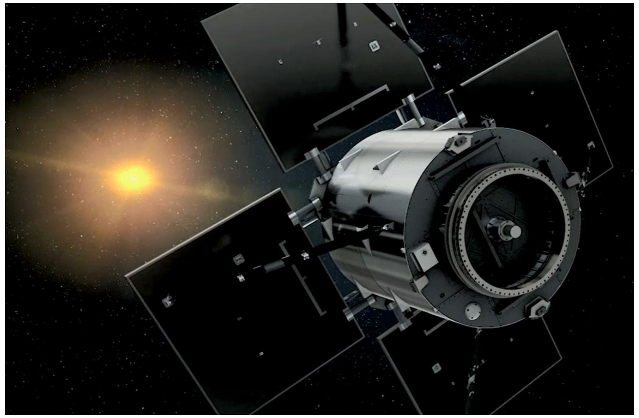
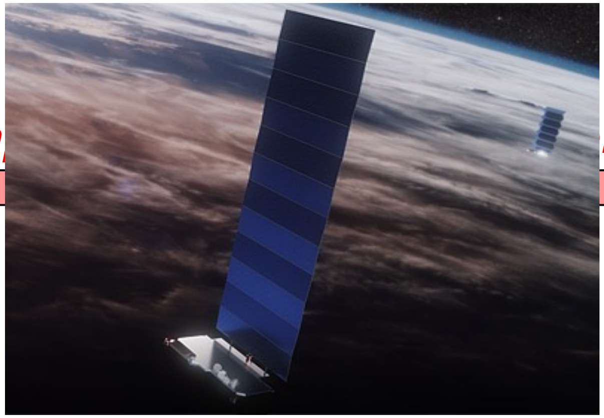
- No standardization
  - ➢ Low success



Eu:CROPIS, source: DLR

Huge ga … *roaches*



SpaceX StarLink Satellite(s), source: GunterSpace

Qtum’s CubeSat , source: Qtum Foundation

Consideration for the use of COTS

STRENGTHS

- Functional performance
- Latest technologies
- Availability on stock (*usually*)
- Fast proof-of-concept
- Competitive market
- Low costs compared to space EEE parts
- No export regulations (ITAR)

WEAKNESSES / ISSUES

- Poor control of supply chain
- Obsolescence and counterfeit
- Limited technology insight
- Limited qualification from manufacturer
- Testability of devices
- Unknown reliability for space environment

OPPORTUNITIES

- innovative system designs
- obsolescence strategies
- growing experience
- repackaging
- dual-use as fallback

THREATS

- absence of adequate components
- short product lifecycle (EOL / PCN)
- unpredictable process variability
- residual risk

Environmental considerations for space

- Environmental conditions
  - Mechanical stress
    - Launch (vibration)
    - Separation (shock)
  - Vacuum
    - Thermal issues
    - Outgassing
  - **Radiation**
    - X-Ray
    - Gamma-Rays
    - Particles
      - Protons
      - Heavy Ions
      - *Neutrons*

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⇩

Automotive Grade (AEC-Q) EEE parts fulfill many requirements

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    - X-Ray
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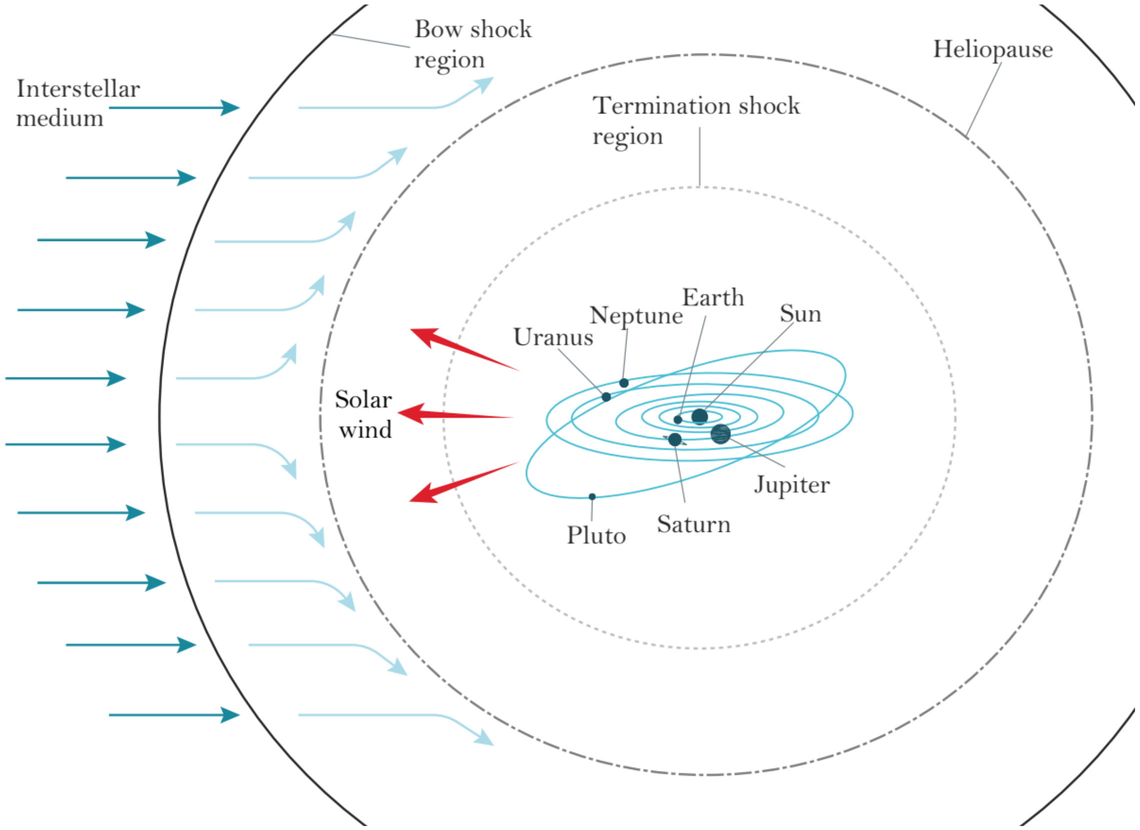
      - Protons
      - Heavy Ions
      - *Neutrons*
  - Radiation sources
    - Galactic cosmic rays (GCR)
    - Solar radiation



PhD thesis, source: Budroweit

Environmental considerations for space

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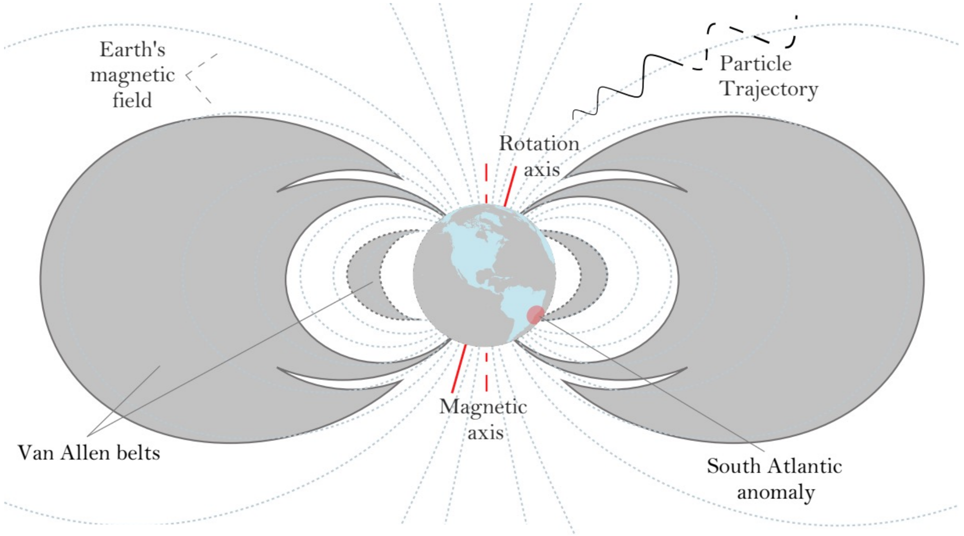
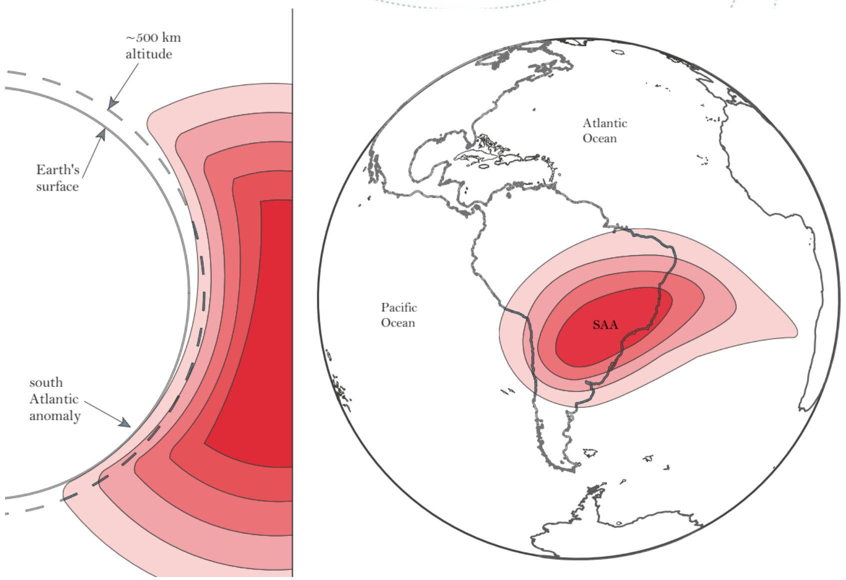
  - Vacuum
    - Thermal issues
    - Outgassing
  - **Radiation**
    - X-Ray
    - Gamma-Rays
    - Particles
      - Protons
      - Heavy Ions

  - <u>Radiation sources</u>
    - Galactic cosmic rays (GCR)
    - Solar radiation
    - Radiation belts
    - South Atlantic anomaly

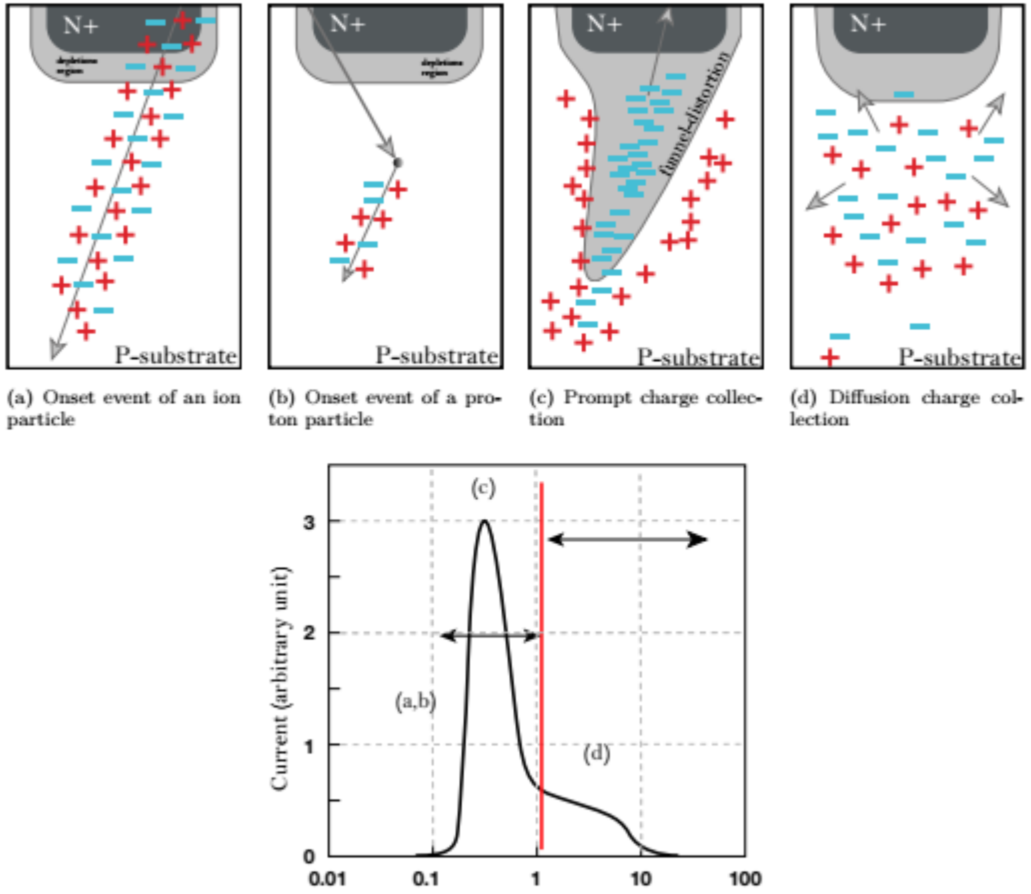




PhD thesis, source: Budroweit

Environmental considerations for space

- Types of radiation effects
  - Ionizing dose effects (**TID**)
    - Cumulative effect
    - Generation, transport and trapping of holes in the insulat in MOS and bipolar device
    - Drift of parametric (e.g. current supply)
  - Single event effects (**SEE**)
    - Particle interaction with matter
    - Destructive effects
      - Single event latchup (SEL)
      - Single event burnout (SEB)
      - …
    - Non-Destructive effects
      - Single event upset (SEU)
      - Single event transient (SET)
      - Single event functional interrupt (SEFI)
      - …
  - *Displacement damages (**DD**)*



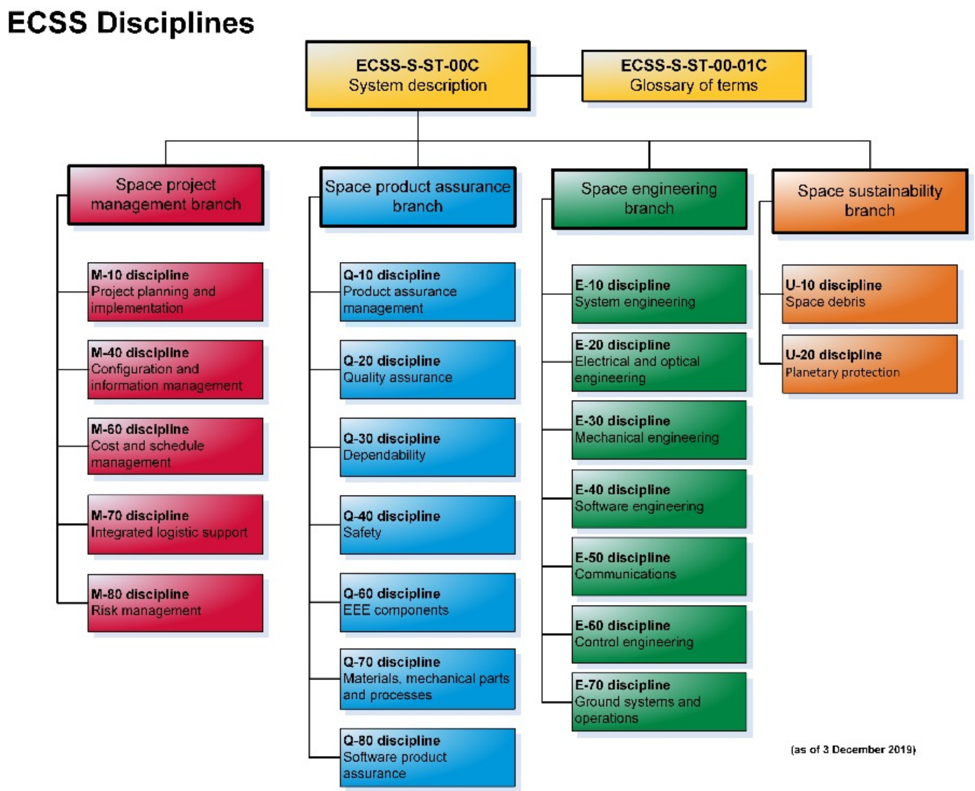
(a) Onset event of an ion particle
(b) Onset event of a proton particle
(c) Prompt charge collection
(d) Diffusion charge collection
(e) Transient charge vs. time

PhD thesis, source: Budroweit

Excursion:
Standards for Space Missions

What are standards for?

- Standards are mandatory to establish a common methodology and procedure
- They are important in terms of quality assurance and risk reduction
- They don't give any warranty
- More seen as guideline and recommendation
- Space manufacturers and project managers are not required to follow any standards, however, due to risk and costs standards are very meaningful.
- Following standards often means a lot of more effort (paper work!)



Source: https://ecss.nl/standards/ecss-document-tree-and-status/

What standards are available?

- ECSS – European Cooperation for Space Standardization
- Example: Testing, ECSS-E-ST-10-03C
- Founded in 1993
- Standardization of space segment in Europe
- Members:
  - Agencies
  - Industries (Eurospace as representative)
- Goal: Development of space standards for Europe
- Comprehensive and uniform
- One set of standards
- Used for (all) European space projects
- User friendly
- Needs to be fulfill by ESA mission

➢ www.ecss.nl

What standards are available?

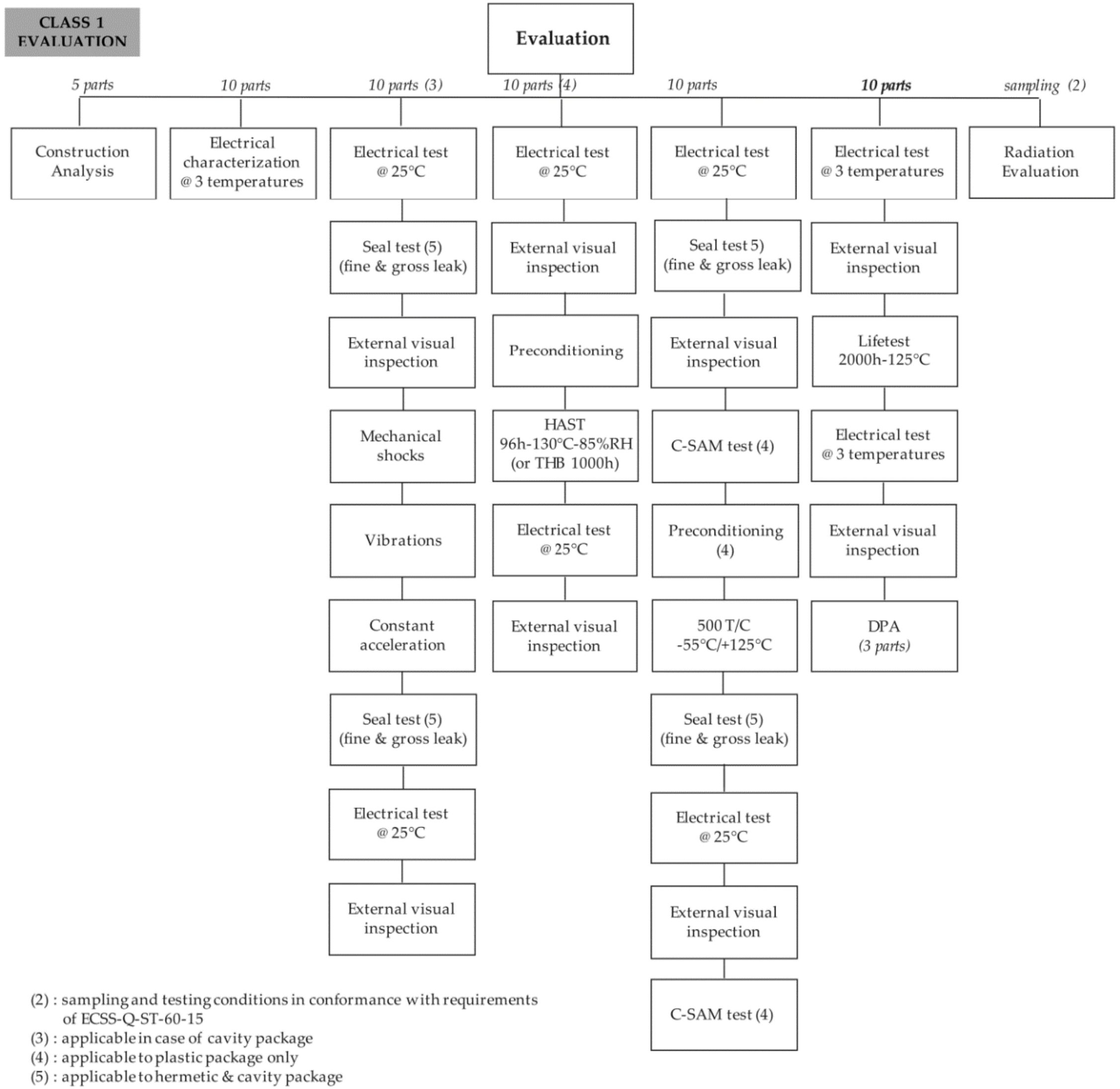
- NASA General Environmental Verification Standard (GSFC-STD-7000)
- Status: 2013 (revised in 2019)
- Provides requirements and guidelines for environmental verification programs for GSFC payloads, subsystems and components and describes methods for implementing those requirements.
- Contains a baseline for demonstrating by test or analysis the satisfactory performance of hardware in the expected mission environments, and that minimum workmanship standards have been met.
- Elaborates on those requirements, gives guideline test levels, provides guidance in the choice of test options, and describes acceptable test and analytical methods for implementing the requirements.

➢ https://standards.nasa.gov/standard/gsfc/gsfc-std-7000

Issues with given standards

- Standards from component-level qualification up to system-level (unit or spacecraft)
  - For component the qualification levels are extremely high (often not suitable for COTS)
  - Testing is generally very expensive
  - Automotive qualification (AEC-Q) follows a similar evaluation flow (**except radiation**) but only qualifies the process not the waver/parts itself

➢ But: Is that really mandatory?
(we will see another approach later)



Issues with given standards

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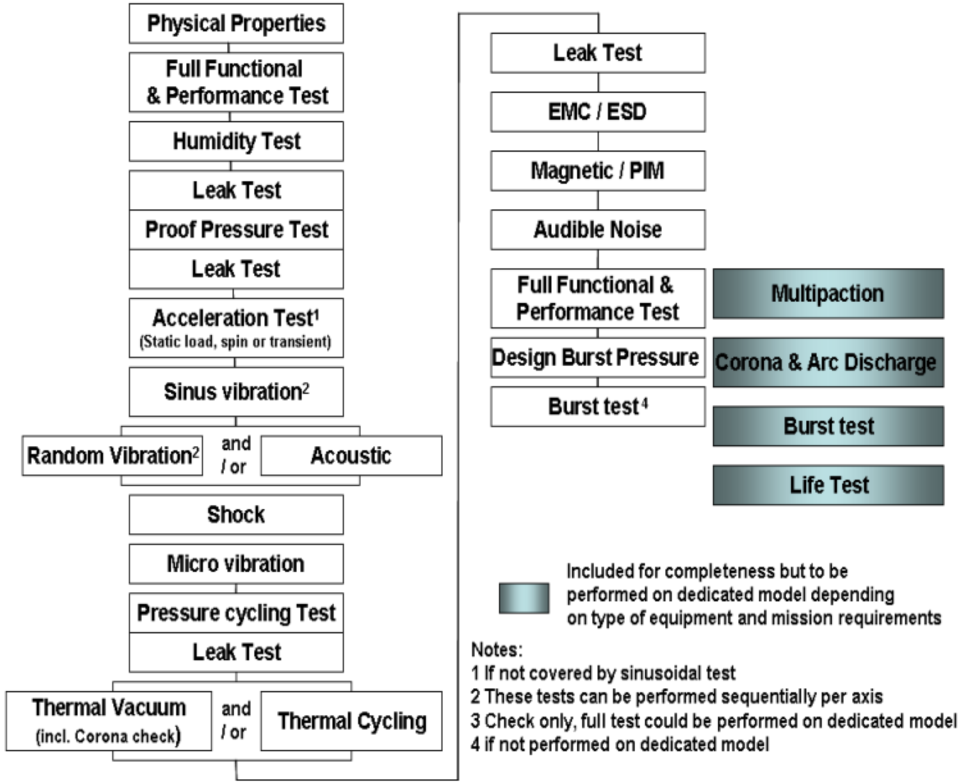
  - ➢ For component, the qualification levels are extremely high (often not suitable for COTS)

<u>For unit qualification:</u>

- Different model and qualification strategies (durations, level etc.)
- Acceptance, proto-flight and qualification procedures
- Different rankings and orders of testing between ECSS and NASA
- Usually: Test as you fly (launch (sinus + random), separation (shock), in-orbit (thermal vacuum and radiation).
- Levels are often not specified by standards (e.g. Temperature ratings), Shock and Vibration loads -> Test against what if the launcher is not know yet?
- At least NASA GEVS has a meaningful set of test levels that are not totally overloaded.

Issues with given standards



Test	Prototype Qualification	Protoflight Qualification	Acceptance
Structural Loads[1] Level	1.25 x Limit Load	1.25 x Limit Load	1.0 x Limit Load
Duration Centrifuge/Static Load[6]	1 minute	30 seconds	30 seconds
Sine Burst	5 cycles @ full level per axis	5 cycles @ full level per axis	5 cycles @ full level per axis
Acoustics Level[2] Duration	Limit Level + 3dB 2 minutes	Limit Level + 3dB 1 minute	Limit Level 1 minute
Random Vibration Level[2] Duration	Limit Level + 3dB 2 minutes/axis	Limit Level + 3dB 1 minute/axis	Limit Level 1 minute/axis
Sine Vibration[3] Level Sweep Rate	1.25 x Limit Level 2 oct/min	1.25 x Limit Level 4 oct/min	Limit Level 4 oct/min
Mechanical Shock Actual Device	2 actuations	2 actuations	1 actuations
Simulated	1.4 x Limit Level 2 x Each Axis	1.4 x Limit Level 1 x Each Axis	Limit Level 1 x Each Axis
Thermal-Vacuum	Max./min. predict. ± 10°C	Max./min. predict. ± 10°C	Max./min. predict. ± 5°C
Thermal Cycling[4,5]	Max./min. predict. ± 25°C	Max./min. predict. ± 25°C	Max./min. predict. ± 20°C
EMC & Magnetics	As Specified for Mission	Same	Same

- ECSS Test sequence
- NASA does not recommend a sequence

- NASA duration and loads for different Models
- ECSS has similar loads and duration

Issues with given standards

- Example: Radom Vibration:
- NASA GEVS has a meaningful set of Test levels that are not totally overloaded (14.1 G_{rms} @ EUT < 50lb, or 22.7kg)
- ECSS had also a equation to in revision ECSS-ST-E-10-03A (2003), that leaded to extreme loads the smaller the weight of the EUT is:

Location	Duration	Levels	
Equipment located on "external panel [a] or with unknown location	Vertical [b] 2,5 min/axis	(20 - 100) Hz	+3 dB/octave
		(100 - 300) Hz	PSD(M) [c] = 0,12 g^2/Hz × (M + 20 kg)/(M + 1 kg)
		(300 - 2 000) Hz	-5 dB/octave
	Lateral [b] 2,5 min/axis	(20 - 100) Hz	+3 dB/octave
		(100 - 300) Hz	PSD(M) [c] = 0,05 g^2/Hz × (M + 20 kg)/(M + 1 kg)
		(300 - 2 000) Hz	-5 dB/octave
Equipment not located on "external" panel [a]	All axes 2,5 min/axis	(20 - 100) Hz	+3 dB/octave
		(100 - 300) Hz	PSD(M) [c] = 0,05 g^2/Hz × (M + 20 kg)/(M + 1 kg)
		(300 - 2 000) Hz	-5 dB/octave

a Panel directly excited by payload acoustic environment.

b Equipment vertical axis = perpendicular to fixation plane.
Equipment lateral axis = parallel to fixation plane.

c M = equipment mass in kg, PSD = Power Spectral Density in g^2/Hz.

- According to ECSS, a 5kg unit will see >25 G_{rms}

Issues with given standards

- What about radiation?
  - Component-level standards are available
    - ECSS-22900 (TID)
    - ECSS-25100 (SEE)
    - …

- System-Level Qualification?
  - No standards are currently available covering the system-level aspect
  - Agencies, like NASA is working on that topic and already published guidelines
  - EU Project RADNEXT has a dedicated Working Group / Work package for system-level qualification approaches.

Back to:
Risk Assessment for
Space Hardware Design

Radiation Hardness Assurance (RHA) for COTS

- Using COTS in space is not new, but becomes more and more important due to NewSpace approach
- Usually, for traditional space missions, those COTS devices were completely up-screened (e.g., according to ECSS)
  - ➢ ***Not unlikely that up-screening costs are higher than a comparable space-qualified EEE part***

- To avoid the expensive up-screening, RHA can be mainly considered since radiation is the most critical environmental stress.

✓ Certain publications were published for RHA on COTS (also given as guidelines from NASA).
  - RHA approaches mainly based on engineering judgment or does not cover a system-point of view (e.g. in terms of failure propagation)

  - ➢ **A numerical-based criticality analysis for RHA would be beneficial**
  - ➢ **A RHA approach that also covers the system perspective of view**
  - ➢ **A guidance on how to select between COTS and RadHard / space-qualified EEE parts**

FMECA-based RHA approach

- The proposed RHA approach is based on the Failure Mode, Effects and **Criticality** Analysis (FMECA)
- Well known tool in space quality assurance for criticality analysis
- Based on three parameter:

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- Based on three parameter:
  - Severity Number (**SN**)

Severity level	**Severity number (SN)**	**Severity category**	**Failure effect**
1	4	Catastrophic	Propagation of failure to other systems, assemblies or equipment
2	3	Critical	Loss of functionality
3	2	Major	Degradation of functionality
4	1	Negligible	Minor or no effect

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- Well known tool in space quality assurance for criticality analysis
- Based on three parameter:
  - Severity Number (**SN**)
  - Probability Number (**PN**)
  - Detection Number (**DN**)

Severity level	Severity number (SN)	Severity category	Failure effect
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PN level	PN limits	PN/DN	DN level
Very likely	$P > 1 \times 10^{-1}$	4	Extremely unlikely
Likely	$1 \times 10^{-2} < P \leq 1 \times 10^{-1}$	3	Unlikely
Unlikely	$1 \times 10^{-4} < P \leq 1 \times 10^{-2}$	2	Likely
Extremely unlikely	$P \leq 1 \times 10^{-4}$	1	Very likely

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$$CN = SN \times PN \times DN$$

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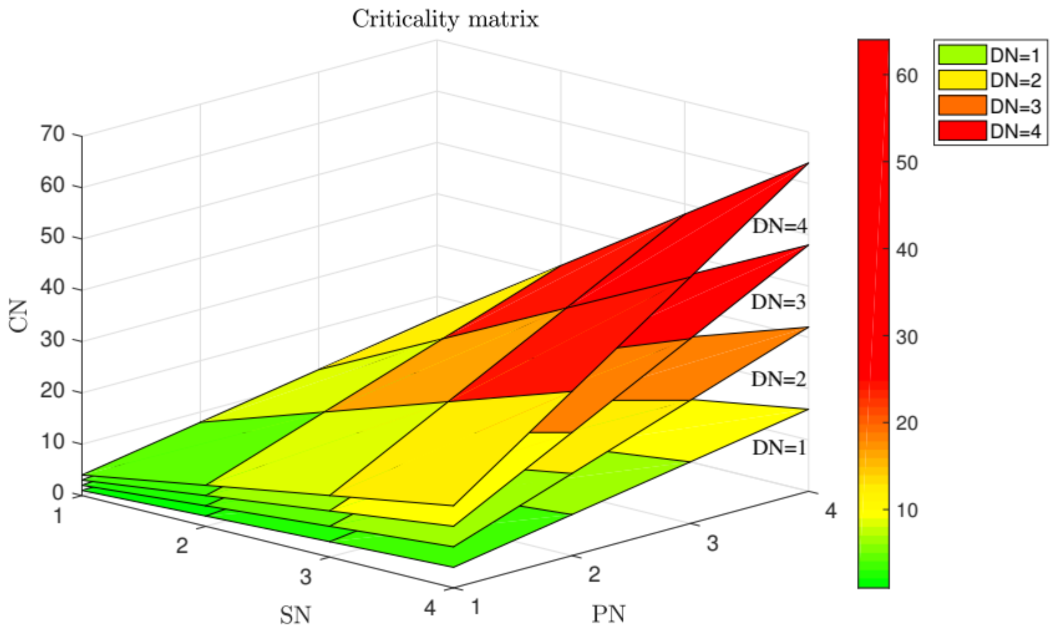
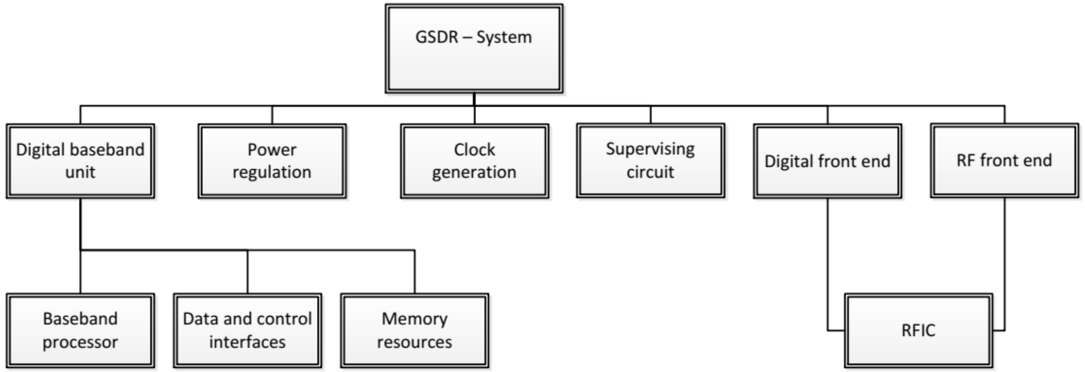
Likely	$1 \times 10^{-2} < P \leq 1 \times 10^{-1}$	3	Unlikely
Unlikely	$1 \times 10^{-4} < P \leq 1 \times 10^{-2}$	2	Likely
Extremely unlikely	$P \leq 1 \times 10^{-4}$	1	Very likely



10.3390/electronics10091008, source: Budroweit et. al

FMECA-based RHA approach

- The FMECA-based RHA approach follows the following stages:
  - *Step 1*: System level breakdown structure into functional block design
  - *Step 2*: FMECA-based severity analysis performed on functional blocks
  - *Step 3*: Technology assessment and rating on functional blocks
  - *Step 4*: Evaluation of the FMECA-based criticality of selected devices.



FMECA-based RHA approach

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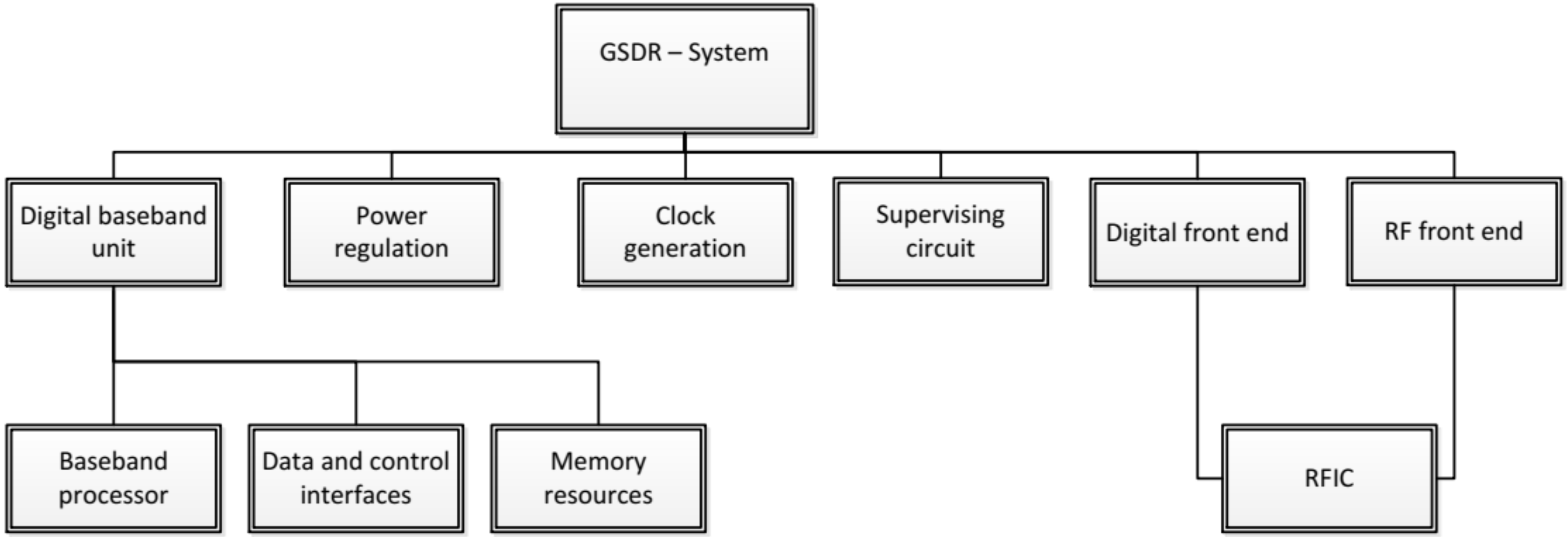

FMECA-based RHA approach

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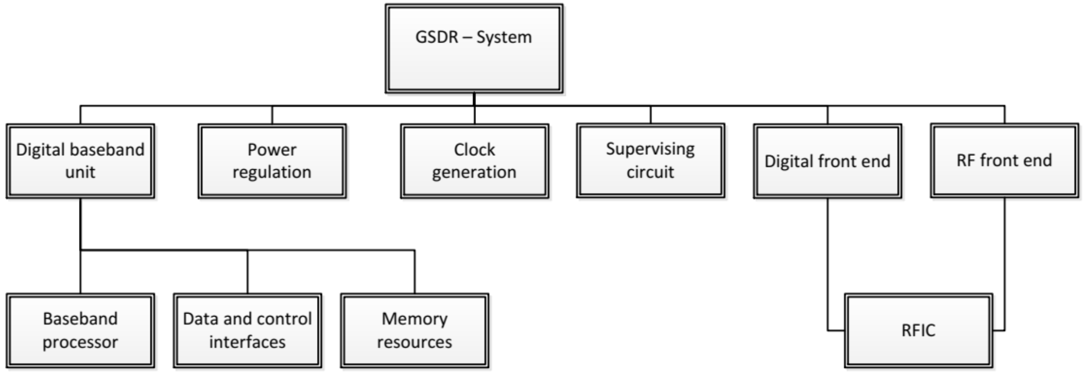

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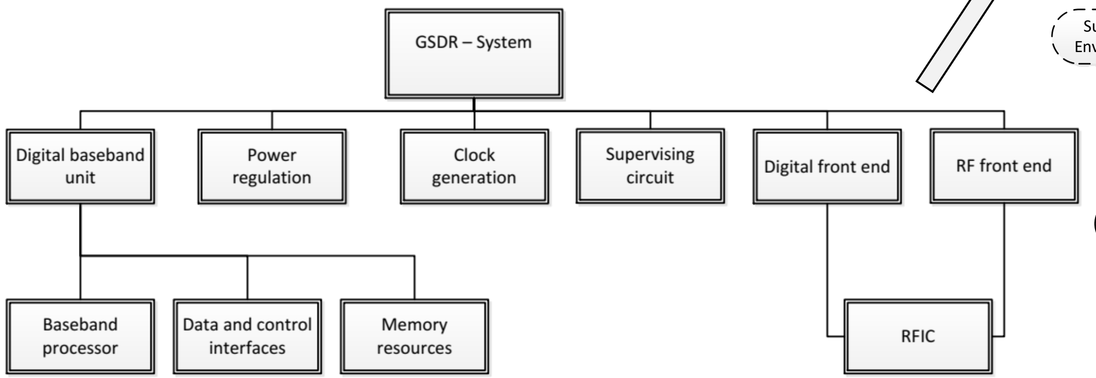
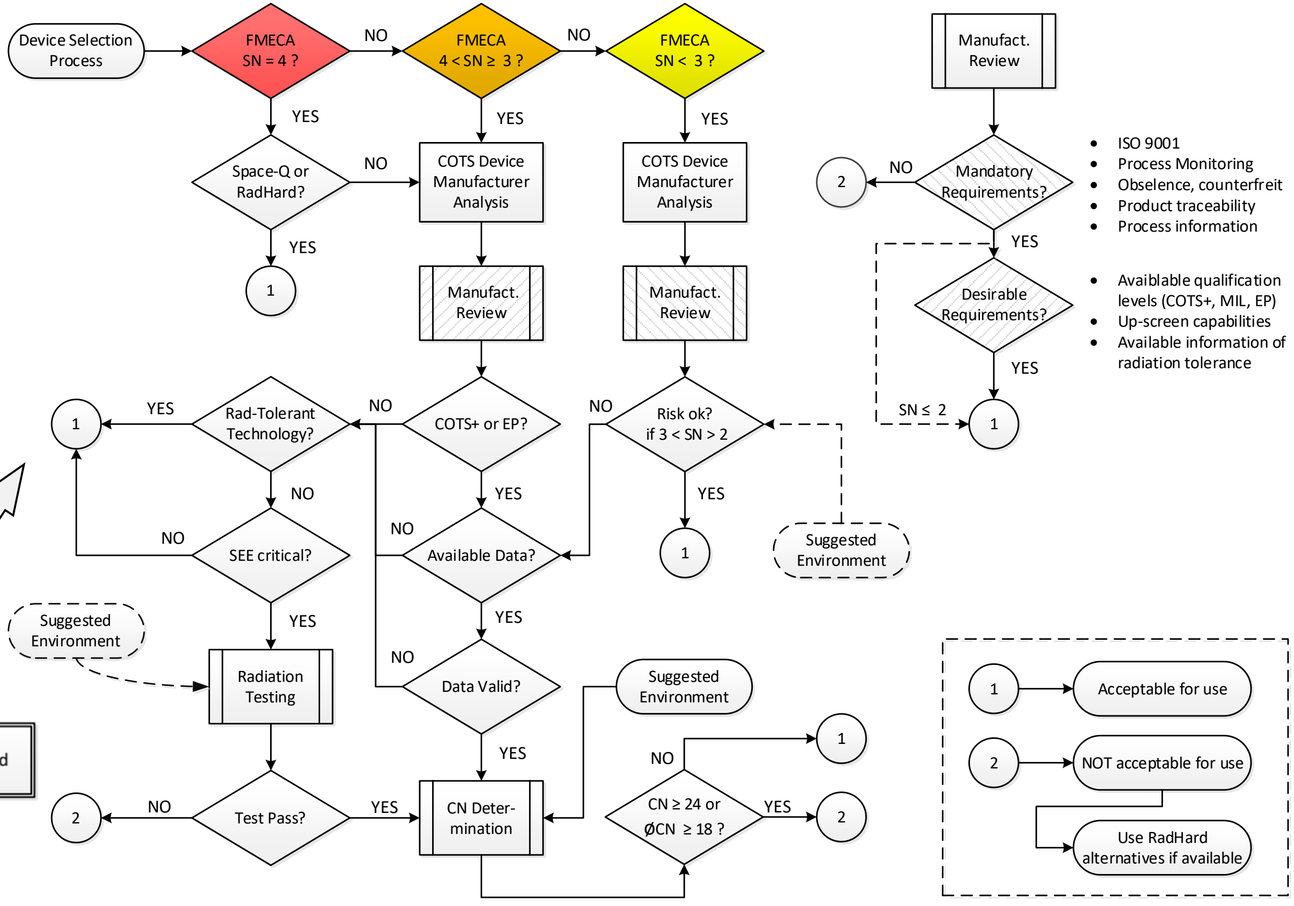
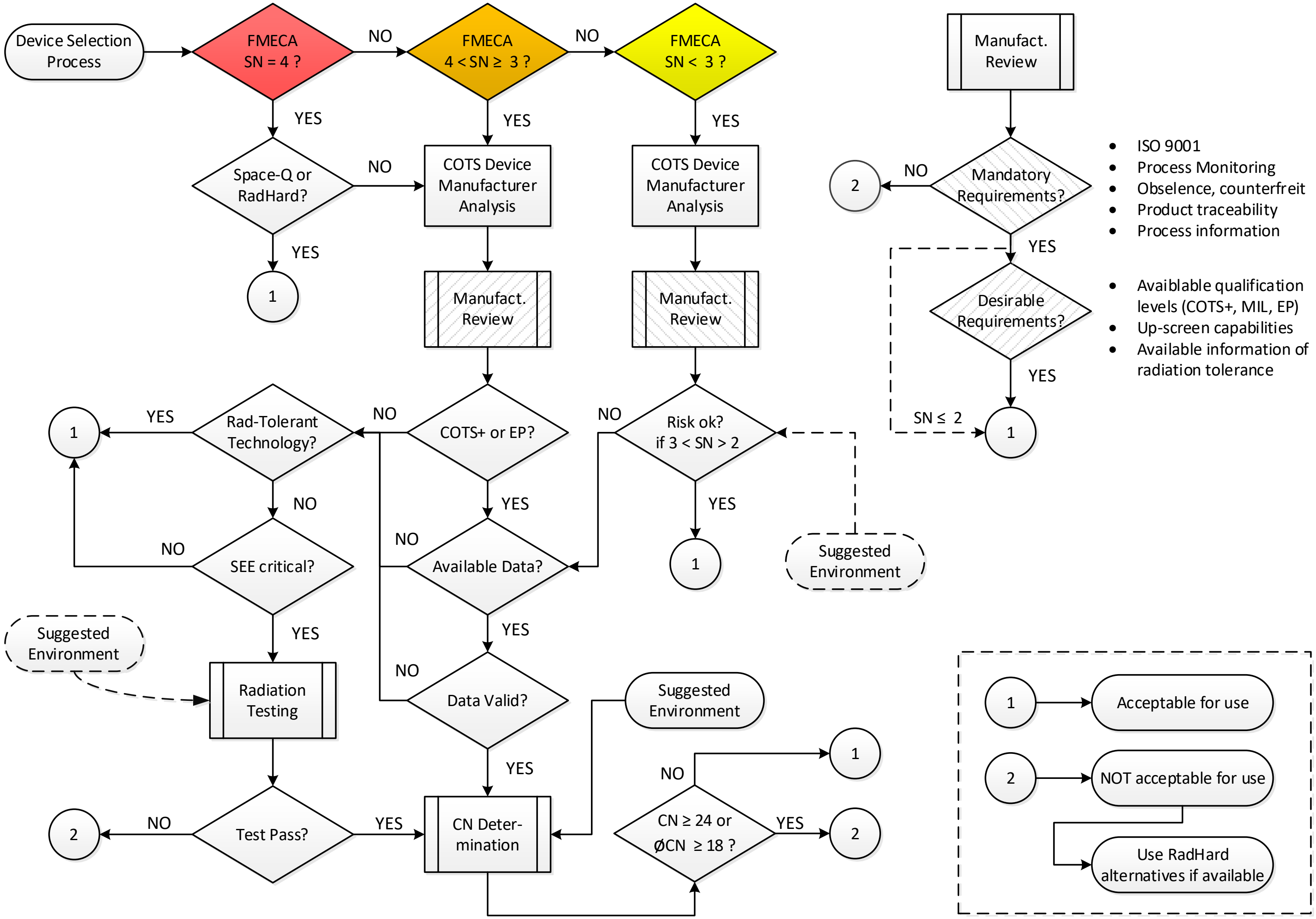




10.3390/electronics10091008, source: Budroweit et. al

FMECA-based RHA approach



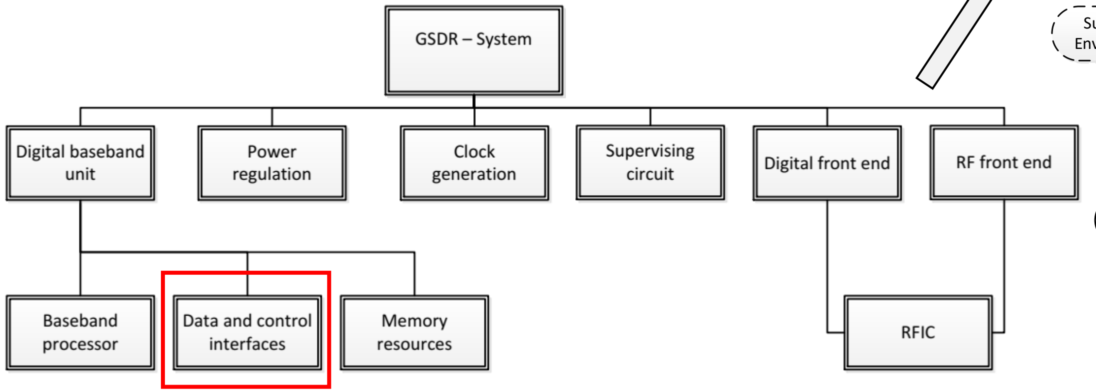
- ISO 9001
- Process Monitoring
- Obselence, counterfreit
- Product traceability
- Process information

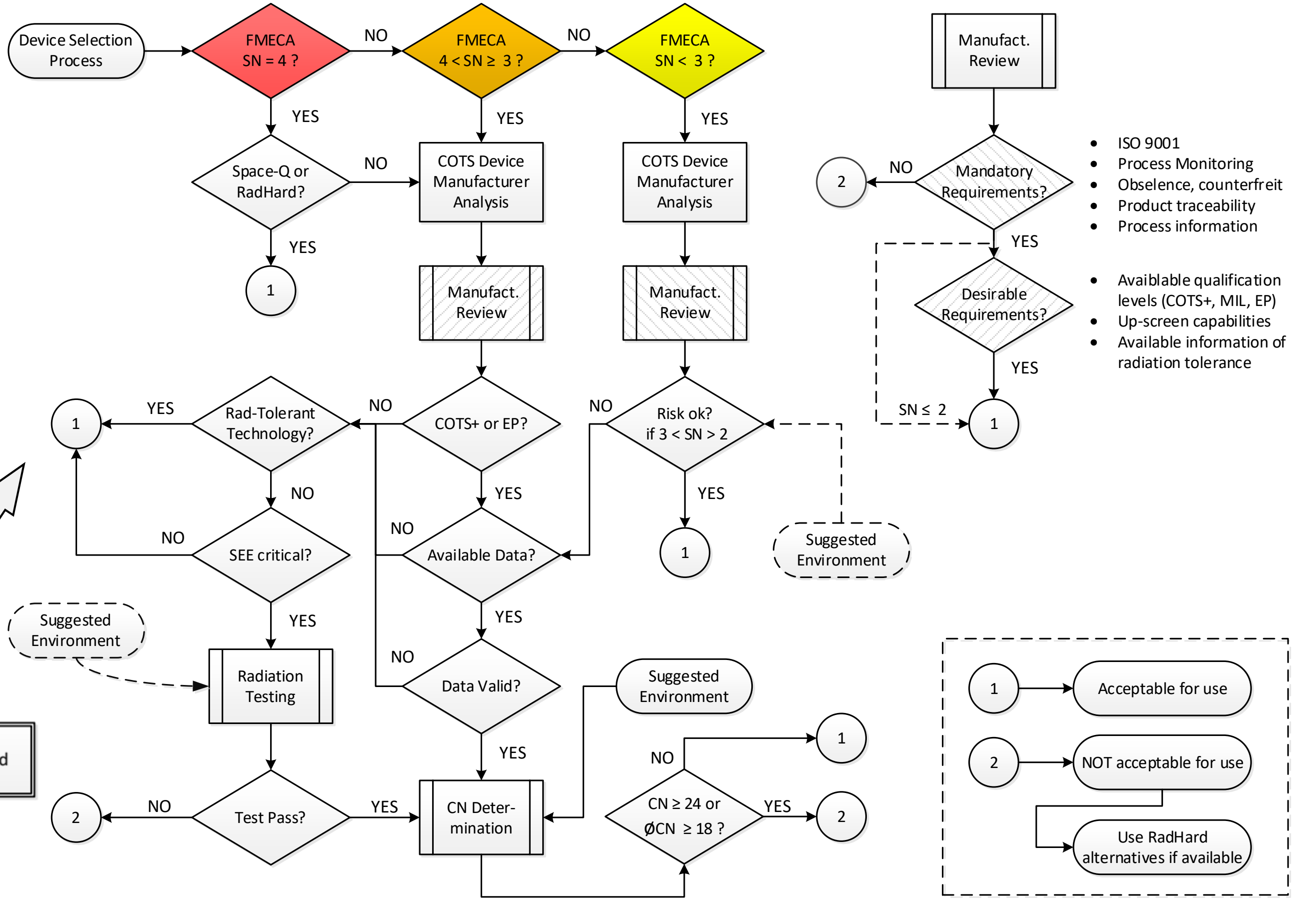
- Avaiblable qualification levels (COTS+, MIL, EP)
- Up-screen capabilities
- Available information of radiation tolerance

10.3390/electronics10091008, source: Budroweit et. al

FMECA-based RHA approach: Example on data interface

- The FMECA-based RHA approach follows the following stages:
  - ➢ *Step 1*: System level breakdown structure into functional block design
  - ➢ *Step 2*: FMECA-based severity analysis performed on functional blocks
  - ➢ *Step 3*: Technology assessment and rating on functional blocks
  - ➢ *Step 4*: Evaluation of the FMECA-based criticality of selected devices.





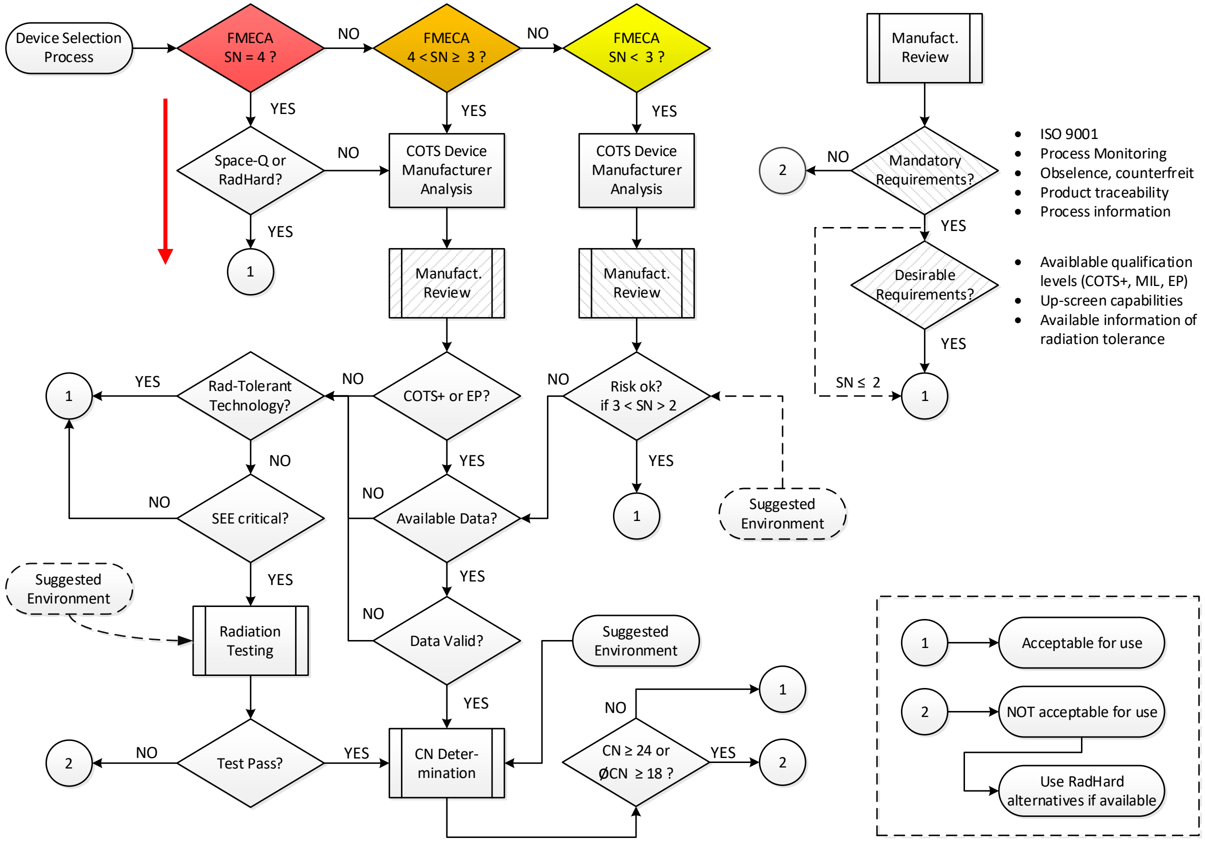
10.3390/electronics10091008, source: Budroweit et. al

FMECA-based RHA approach: Example on data interface

Step 2: Severity analysis

ID	Failure mode	Failure causes	Failure effects	SN
CRTL.1	HW Failure	SELs or high current states	catastrophic failure affecting external systems	4
CRTL.2	HW Failure	TIDs, long-term degradation	catastrophic failure affecting external systems	4
CRTL.4	HW Failure	SETs, critical transients	catastrophic failure affecting external systems	4
CRTL.5	HW Failure	TIDs, long-term degradation	permanent loss of system functionality	3
CRTL.6	HW Failure	SETs, critical transients	permanent loss of system functionality	3
CRTL.7	HW Failure	SETs, non-critical transients	corrupted data transmission/interpretation	2

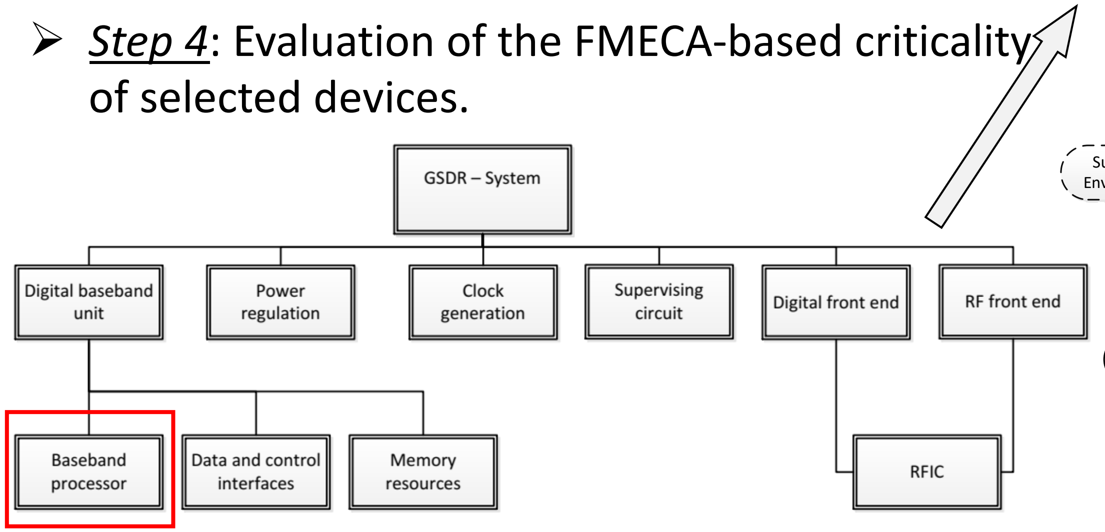
- Data interface represents a direct connection to the spacecraft (bus)
  - ➢ Severity number: **4**
  - ➢ Space-Qualified / RadHard device recommended

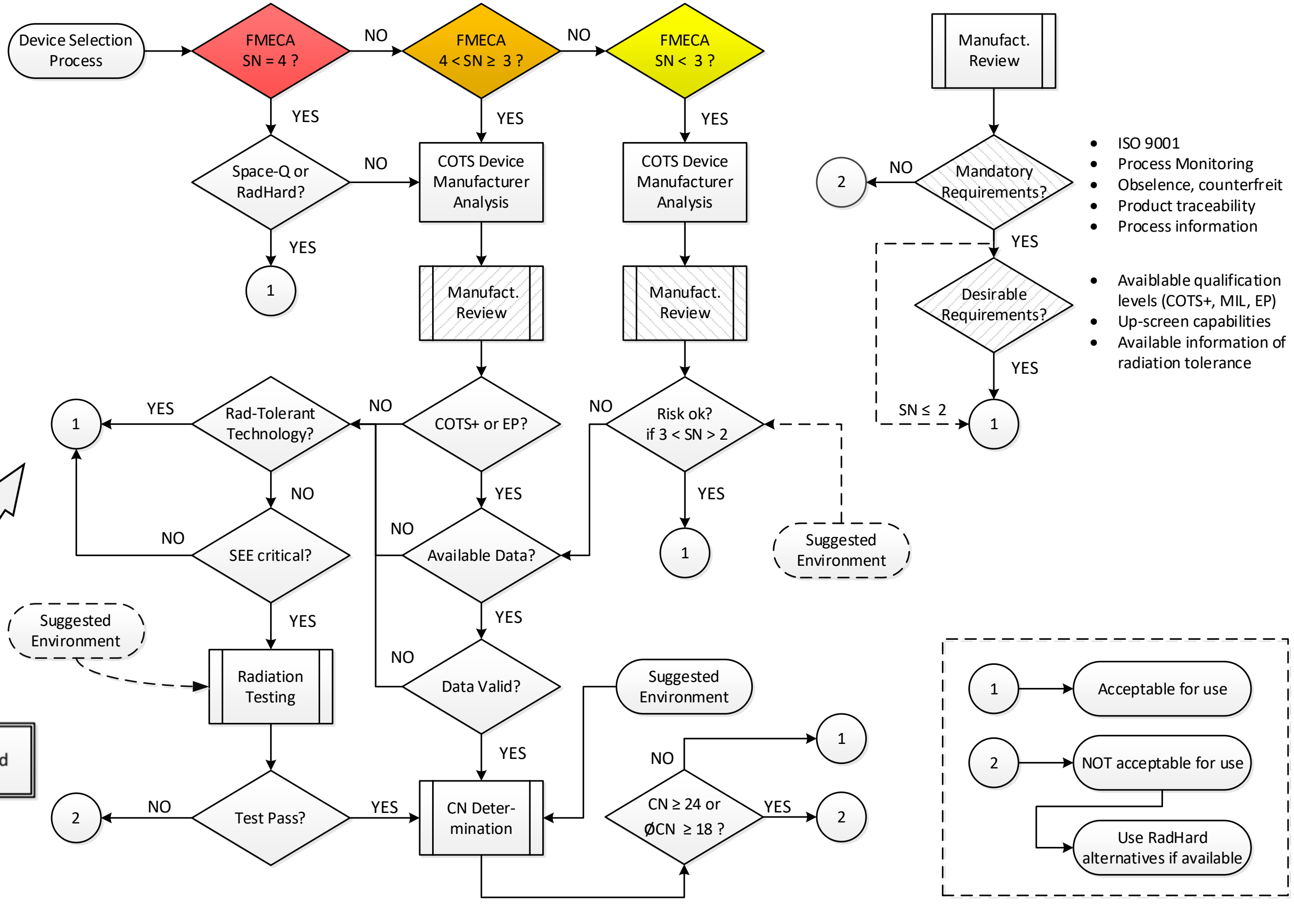


10.3390/electronics10091008, source: Budroweit et. al

FMECA-based RHA approach: Example on a baseband processing unit

- The FMECA-based RHA approach follows the following stages:
  - ➢ ***Step 1***: System level breakdown structure into functional block design
  - ➢ ***Step 2***: FMECA-based severity analysis performed on functional blocks
  - ➢ ***Step 3***: Technology assessment and rating on functional blocks
  - ➢ ***Step 4***: Evaluation of the FMECA-based criticality of selected devices.





10.3390/electronics10091008, source: Budroweit et. al

FMECA-based RHA approach: Example on a baseband processing unit

Step 2: Severity analysis

ID	Failure mode	Failure causes	Failure effects	SN
BBP.1	HW Failure	SELs or high current states	permanent loss of system functionality	3
BBP.2	HW Failure	TIDs, long-term degradation	permanent loss of system functionality	3
BBP.3	HW Failure	SHEs, non-recoverable state	permanent loss of system functionality	3
BBP.4	HW Failure	SEFIs, recoverable state	temporary loss of system functionality	2
BBP.5	SW Failure	SEU/MBU/SEFIs, OS crash	temporary loss of system functionality	2
BBP.6	SW Failure	SEU/MBU/SEFIs, SW thread/process crash	temporary loss of system-parts' functionality	1

- Baseband processor does not directly affecting external systems
  - Severity number: **< 4**
  - COTS can be considered
  - Review of potential technologies and the manufacturing processes

Step 3: Technology and device survey

Device	Techno.	Level	Review	Complex.	Perform.	Costs	Data
DSP	n.a.	All	n.a.	++	-	++	-+
ASIC	n.a.	All	n.a.	-	++	- -	n.a.
FPGA	n.a.	All	n.a.	+	-+	+	++
SoC	n.a.	All	n.a.	-+	+	+	++

Device	Techno.	Level	Review	Complex.	Perform.	Costs	Data
Xilinx Zynq-7000	28 nm CMOS	Mil.	+	-+	-+	++	++
Xilinx Ultra-scale	16 nm FinFET	Mil.	+	-	-+	-+	+
Altera Cyclone-V	28 nm CMOS	Auto.	-+	-+	-+	++	+
Microsemi Smart-Fusion	130 nm CMOS	Mil.	+	-+	-+	++	+

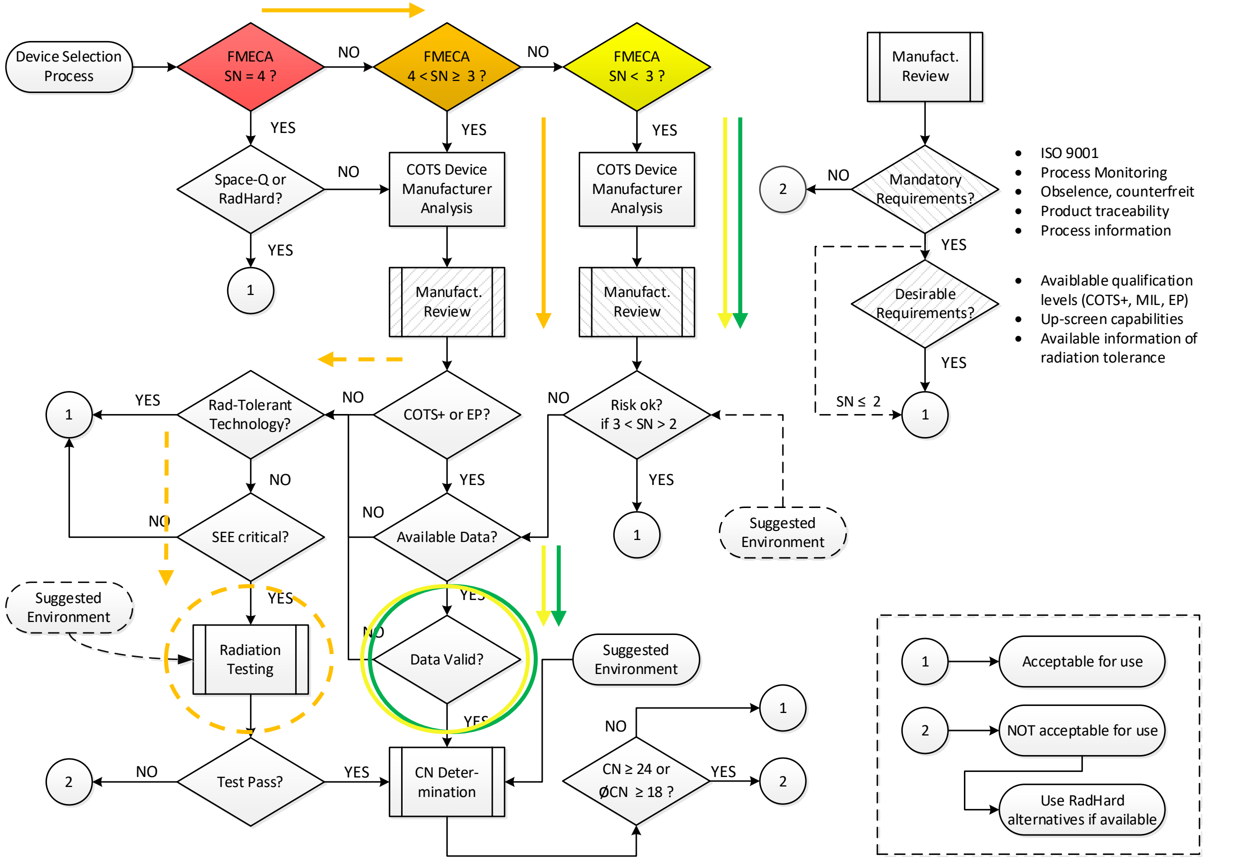
PhD thesis, source: Budroweit

FMECA-based RHA approach: Example on a baseband processing unit

Step 3: Device survey and criticality analysis

ID	Failure mode	Failure causes	Failure effects	SN
BBP.1	HW Failure	SELs or high current states	permanent loss of system functionality	3
BBP.2	HW Failure	TIDs, long-term degradation	permanent loss of system functionality	3
BBP.3	HW Failure	SHEs, non-recoverable state	permanent loss of system functionality	3
BBP.4	HW Failure	SEFIs, recoverable state	temporary loss of system functionality	2
BBP.5	SW Failure	SEU/MBU/SEFIs, OS crash	temporary loss of system functionality	2
BBP.6	SW Failure	SEU/MBU/SEFIs, SW thread/process crash	temporary loss of system-parts' functionality	1

- Baseband processor does not directly affecting external systems
  - Severity number: < 4
  - COTS can be considered
  - Review of potential technologies and the manufacturing processes
  - **Radiation test data availability and validity on Xilinx Zynq-7000 SoC**



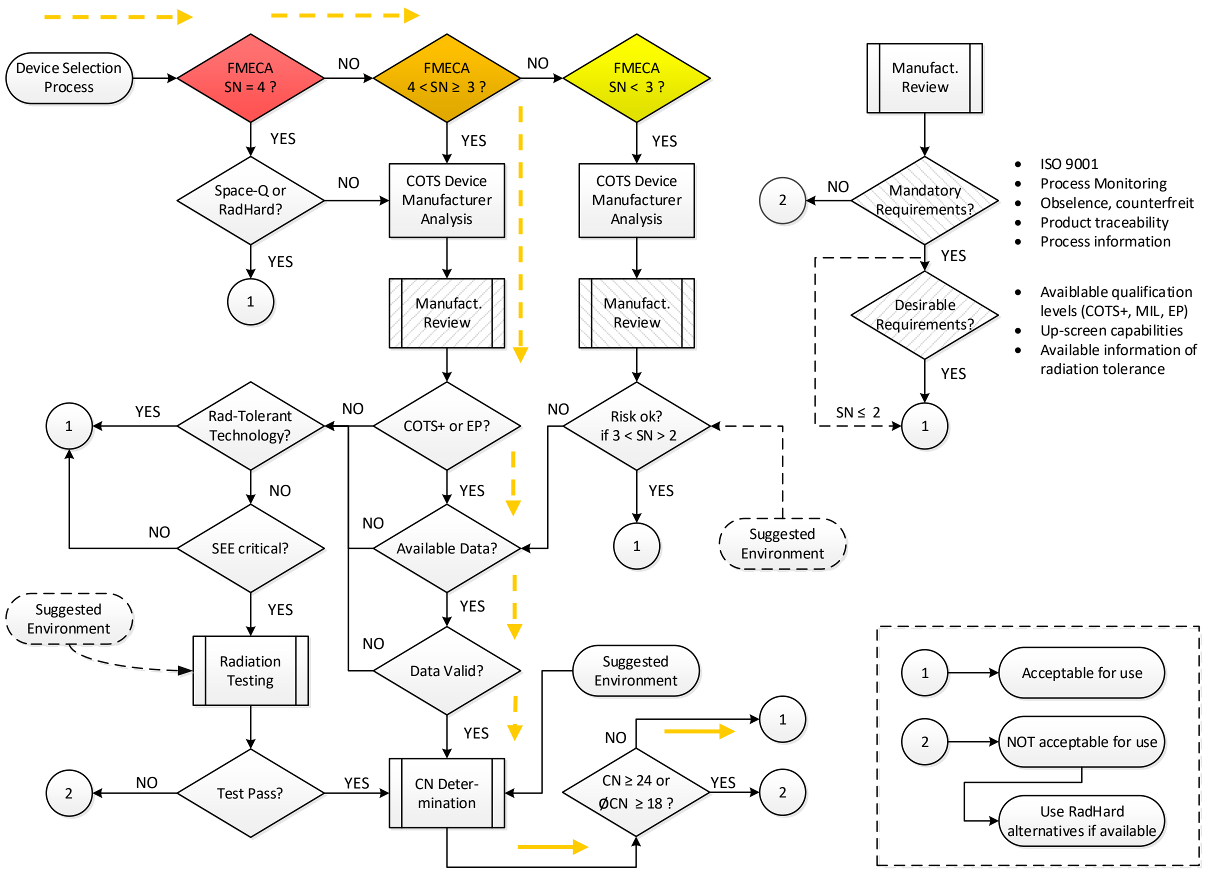
PhD thesis, source: Budroweit

FMECA-based RHA approach: Example on a baseband processing unit

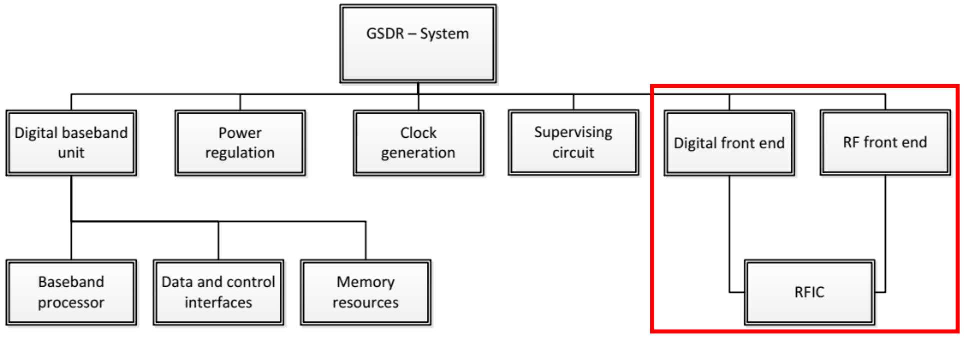
Step 4: Criticality analysis

ID	Orbit	Failure causes	Failure effects	SN	PN	DN	CN
BBP.1	LEO	SELs or high current states	permanent loss of system functionality	3	1	2	6
BBP.1	GEO			3	2	2	12
BBP.2	LEO	TIDs, long-term degradation	permanent loss of system functionality	3	1	2	6
BBP.2	GEO			3	2	2	12
BBP.3	LEO	SHEs, non-recoverable state	permanent loss of system functionality	3	0	-	0
BBP.3	GEO			3	0	-	0
BBP.4	LEO	SEFIs, recoverable state	temporary loss of system functionality	2	3	3	18
BBP.4	GEO			2	3	3	18
BBP.5	LEO	SEU/MBU/SEFIs, OS crash	temporary loss of system functionality	2	3	3	18
BBP.5	GEO			2	3	3	18
BBP.6	LEO	SEU/MBU/SEFIs, SW thread/process crash	temporary loss of system-parts functionality	1	3	3	9
BBP.6	GEO			1	3	3	9
BBP.Total			**Average CN (LEO):**				**9.5**
BBP.Total			**Average CN (GEO):**				**11.3**

PhD thesis, source: Budroweit

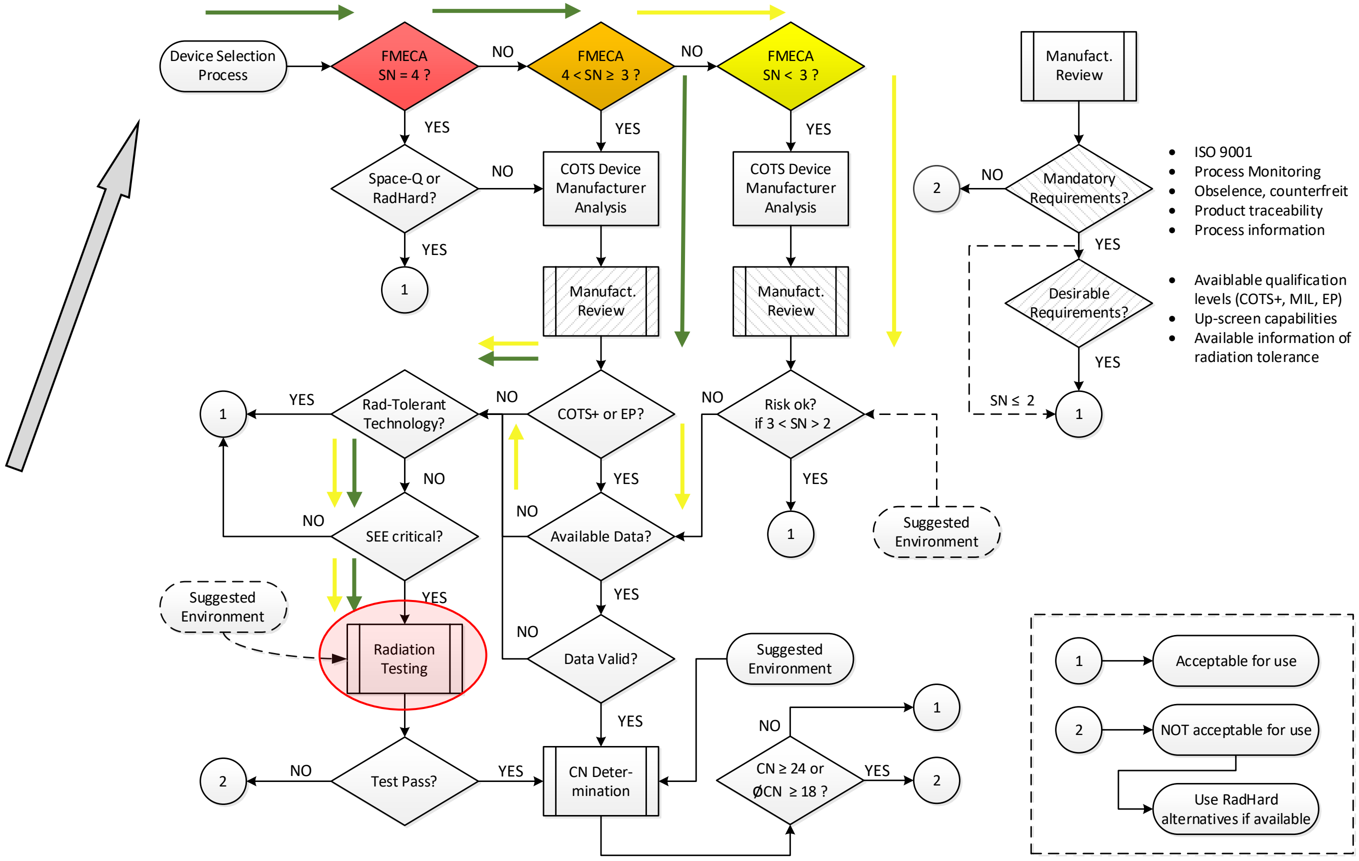


FMECA-based RHA approach: RF-Transceiver



ID	Failure mode	Failure causes	Failure effects	SN
RFIC.1	HW Failure	SELs or high current states	permanent loss of system functionality	3
RFIC.2	HW Failure	TIDs, long-term degradation	permanent loss of system functionality	3
RFIC.3	HW Failure	SHEs, non-recoverable state	permanent loss of system functionality	3
RFIC.4	HW Failure	SEFIs, recoverable state	temporary loss of system functionality	2
RFIC.5	HW Failure	SEUs/MBUs/SEFIs, invalid data	corrupted data for transmission or reception	2
RFIC.6	HW Failure	SETs, invalid data	corrupted data for transmission or reception	2

Device	Techno.	Level	Review	Complex.	Perform.	Costs	Data
AD936X	65 nm CMOS	Indust.	+	-	++	-+	-
LMS7002M	65 nm CMOS	Indust.	-	-	+	+	- -



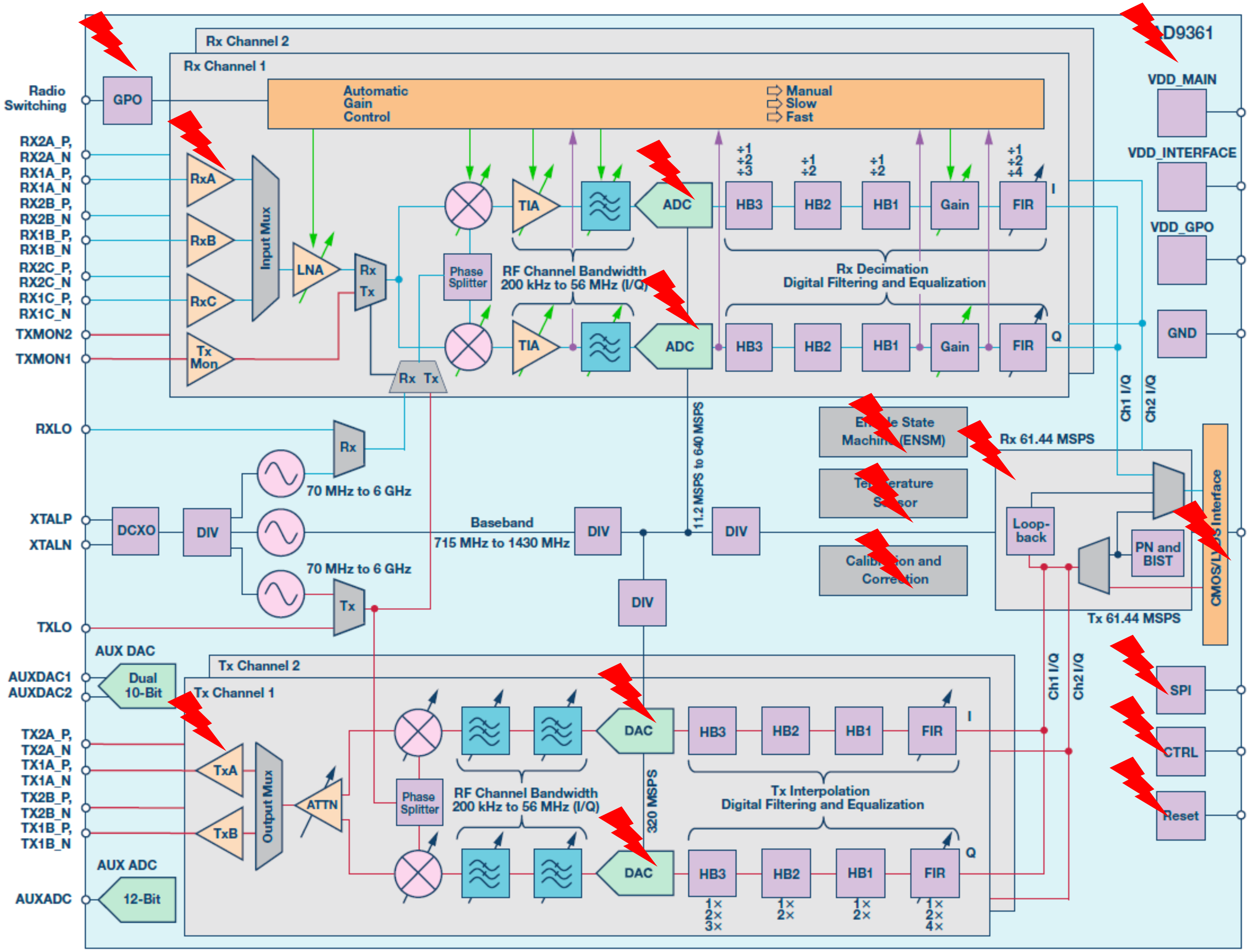
Best practice and experience on a Software-Defined Radio

- Radiation Testing on complex RFIC -

Radiation Testing on complex RFIC

- AD9361
  - ➢ Based on 65nm CMOS
  - ➢ ADC/DAC
  - ➢ Analog technologies (e.g. Amps)
  - ➢ Synthesizer
  - ➢ Register
  - ➢ State machine
  - ➢ Digital interfaces
  - ➢ …
- SEE susceptibility
  - ➢ SELs
  - ➢ SEUs, MBUs
  - ➢ SETs
  - ➢ SEFIs

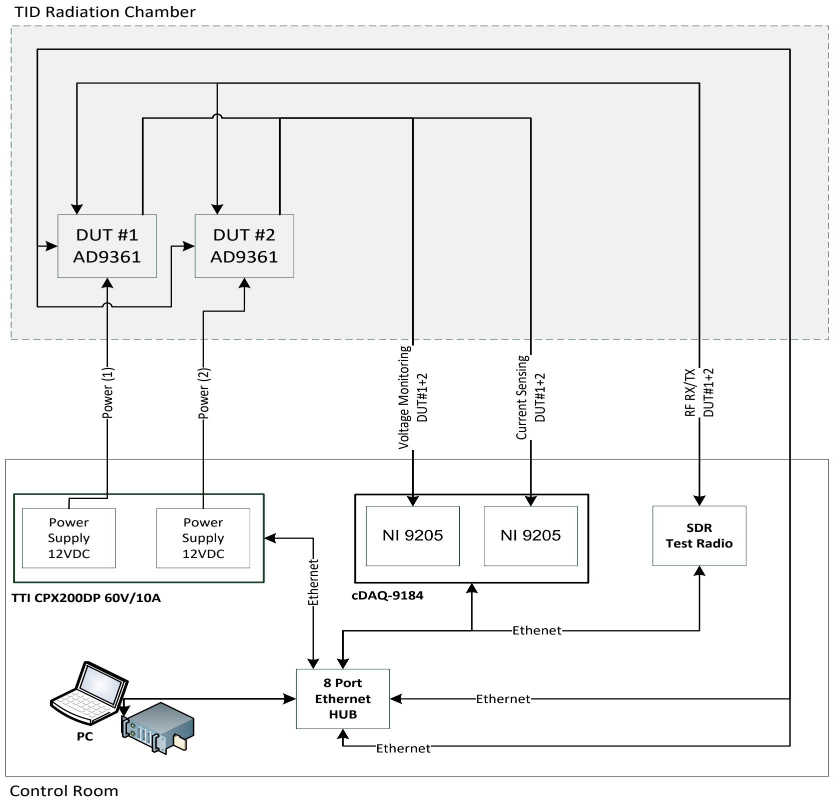
How to test such a complex device?!

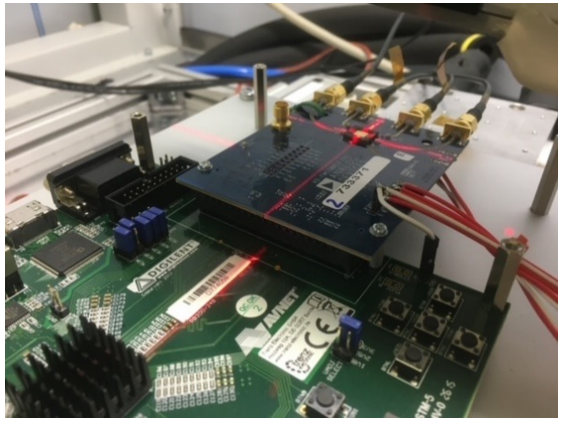


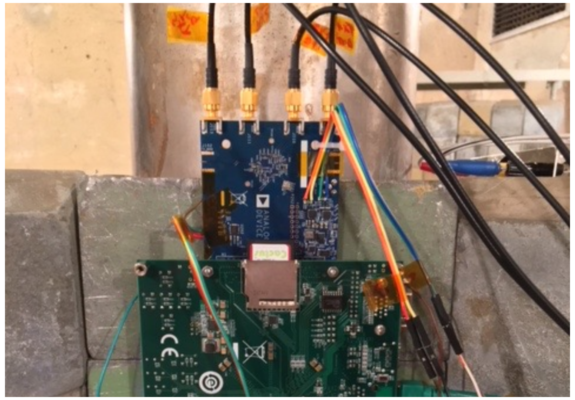
AD9361, source: Analog Devices

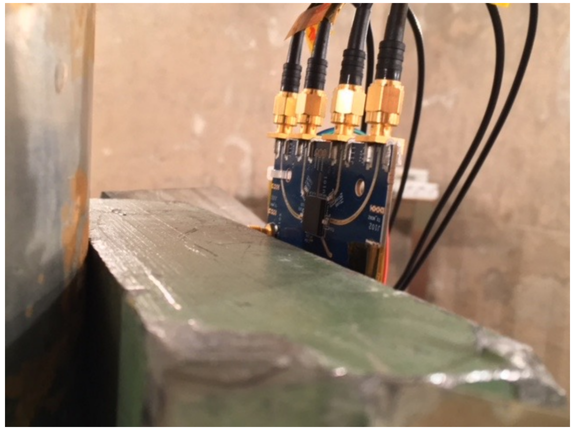
Radiation Testing on complex RFIC

- Automatic test procedure that allows detailed investigation:
  - ➢ Current condition
  - ➢ State machine control
  - ➢ RX/TX Amplifiers
  - ➢ Mixer
  - ➢ Synthesizer/ADC/DAC
  - ➢ Filter response
  - ➢ …
- AD9361 is installed on daughterboard (blue) and is not surrounded by other sensitive devices (good DUT isolation)
- Carrier-board interfaces DUT and allows data access and controlling (shielded by lead bricks)



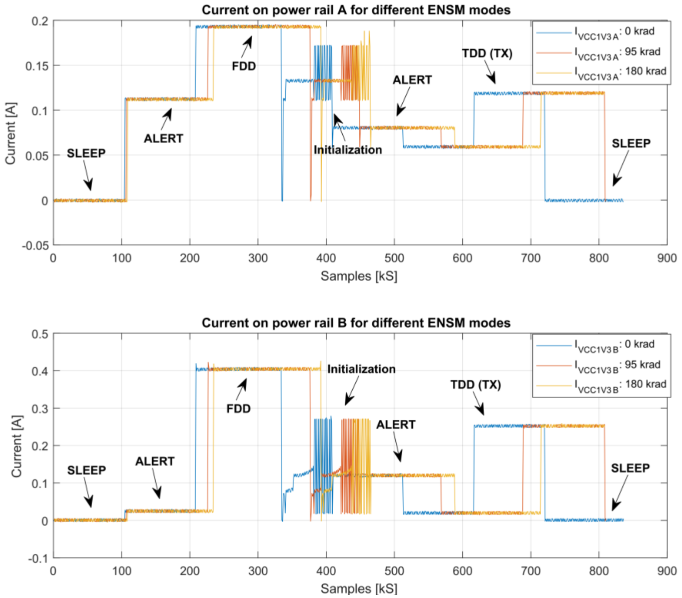


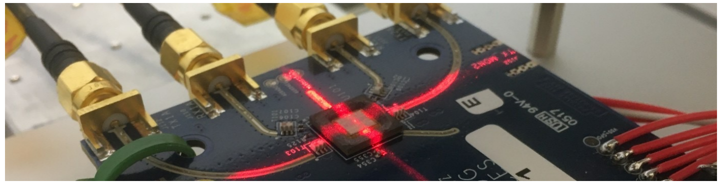


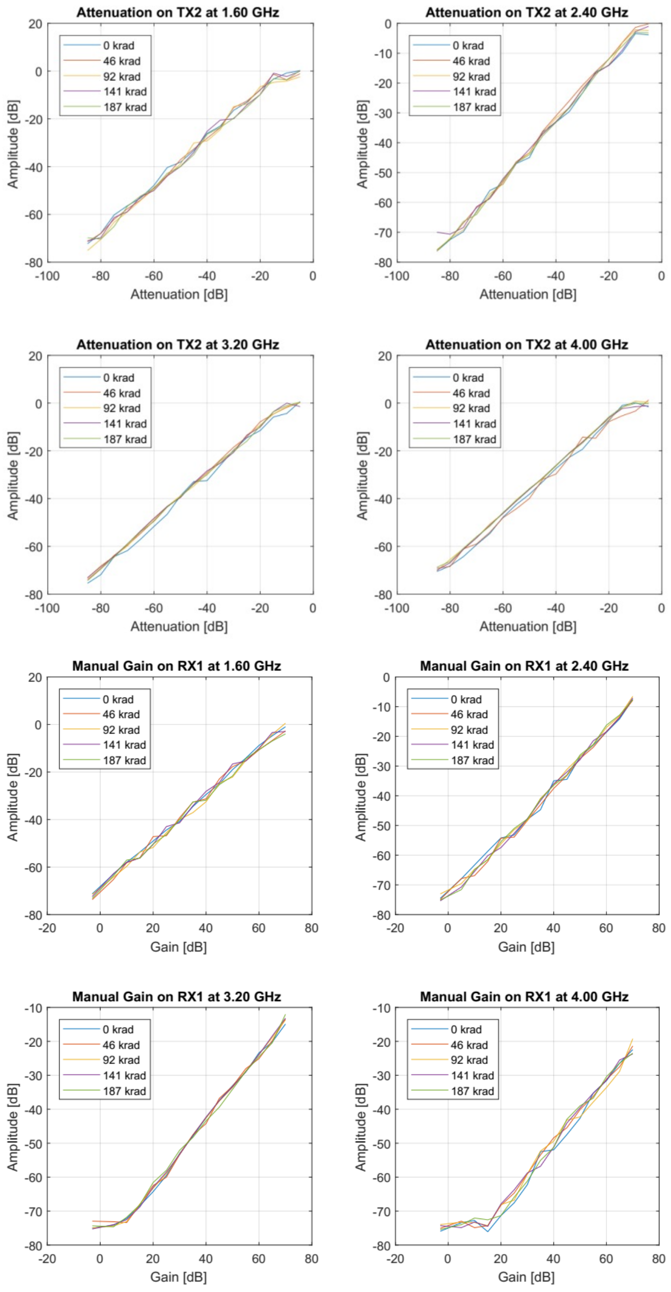


Radiation Testing on complex RFIC

- Co-60 Source of HZB (Potsdam) and X-Ray machine from CERN
- Three tests in total:
  - ➢ Co60: 2015 + 2018
    - ○ Target dose: ~190 krad(SiO2)
    - ○ Dose rate: 11.5 krad(SiO2)/h
    - ○ Samples: 2
  - ➢ X-Ray: 2019
    - ○ Target dose: 80Mrad(SiO2)
    - ○ Dose rate: 4.1 Mrad(SiO2)/h
    - ○ Samples: 2
    - – **Loss of function ~45MRad(SiO2)**
    - ✓ **Annealing successful**

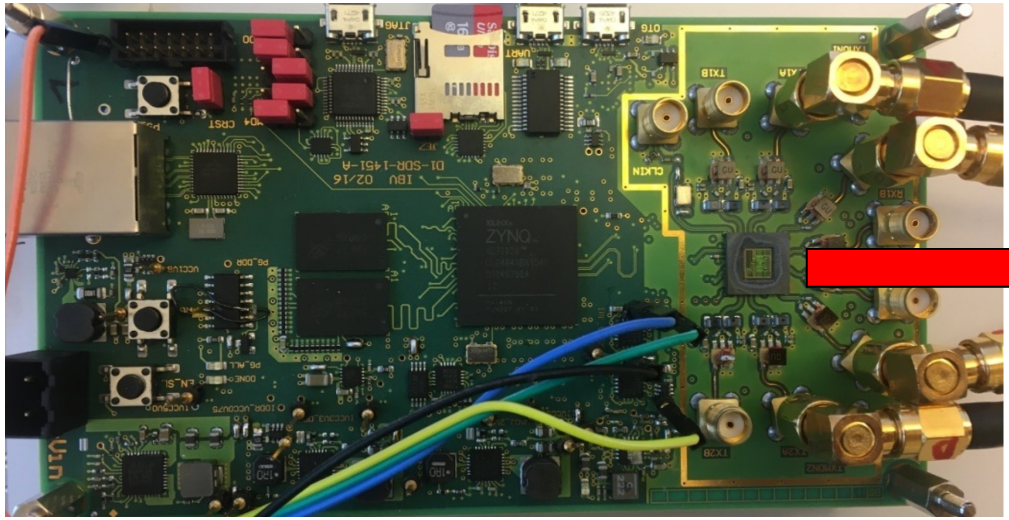


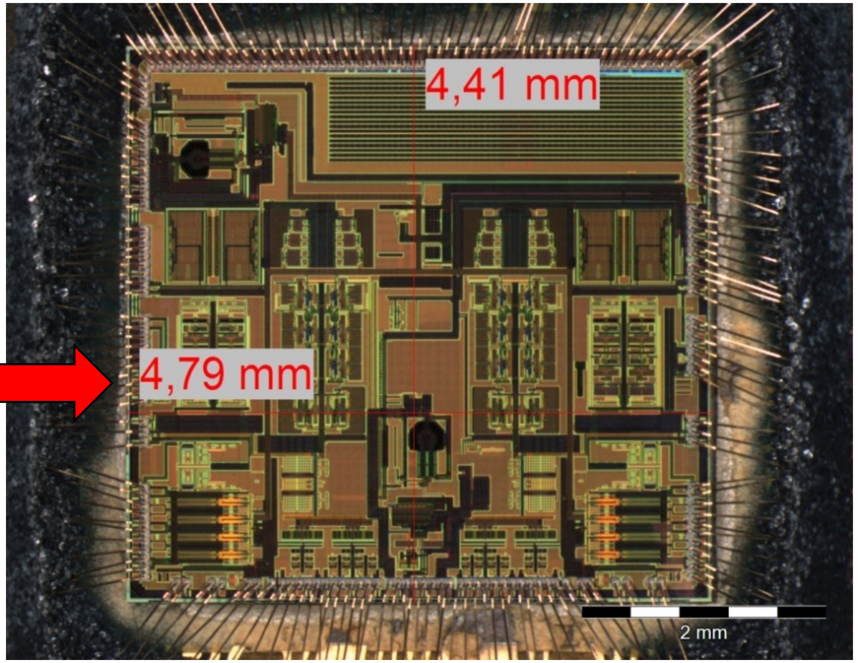




Radiation Testing on complex RFIC

- Single Event Effects testing performed under proton and heavy ion
  - Proton: up to 194 MeV (@KVI, Groningen, NL)
  - Heavy ion: up to $LET_{(eff)}$ = 125 MeV.cm²/mg (@ UCL, Louvain la Neuve, BL)
- Test board has been developed for this propose
- Decapping required for heavy ion testing
- Two samples tested

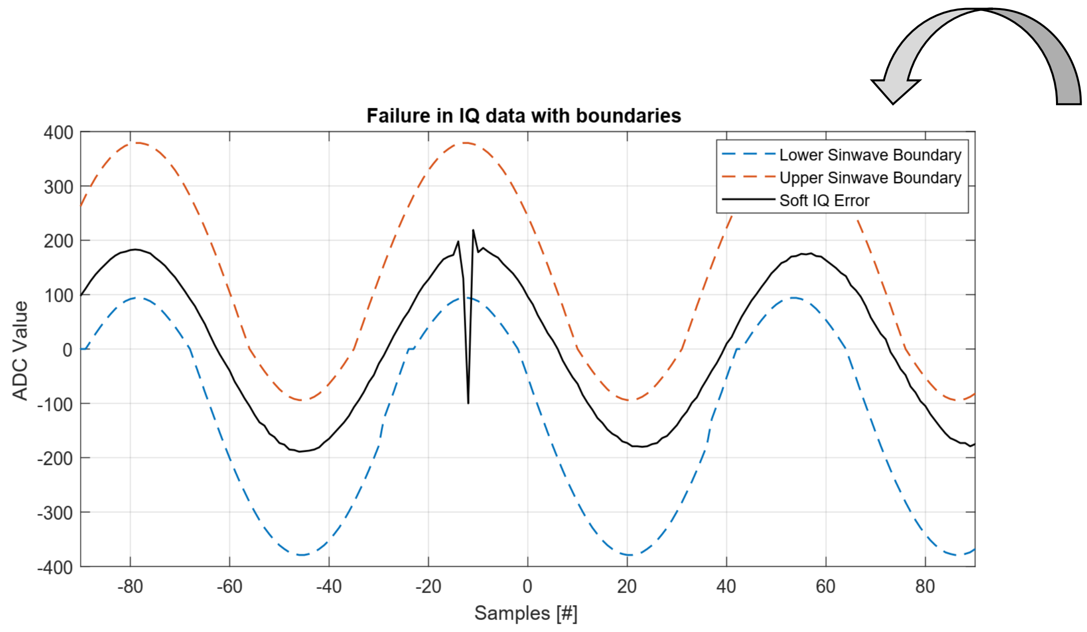


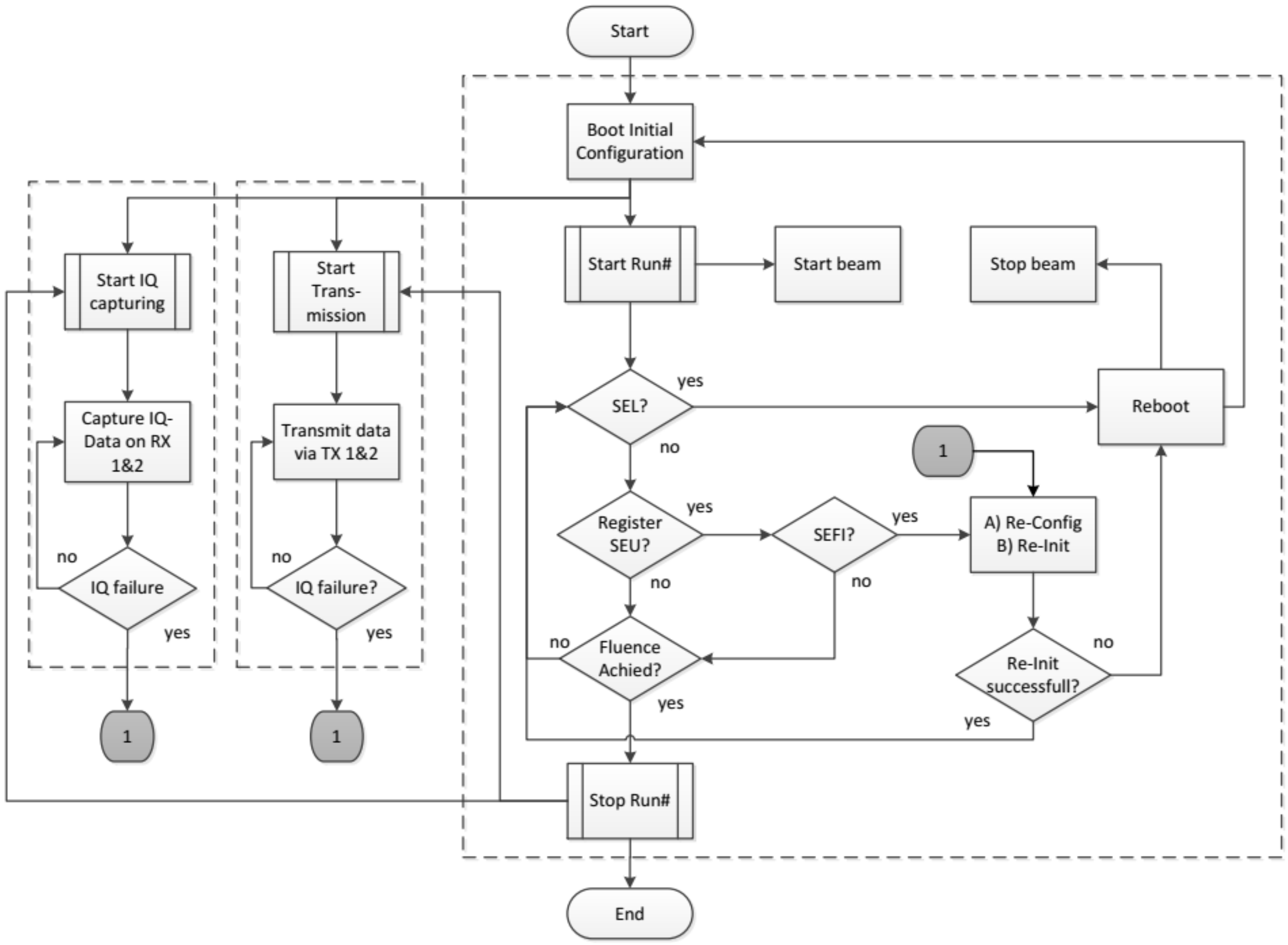


/10.3390/aerospace7020014, source: Budroweit

Radiation Testing on complex RFIC

- Complex test setup and procedure
- Scrubbing of registers
- Functional validation
- Independent RF data evaluation (IQ data)
- Automatic recovery

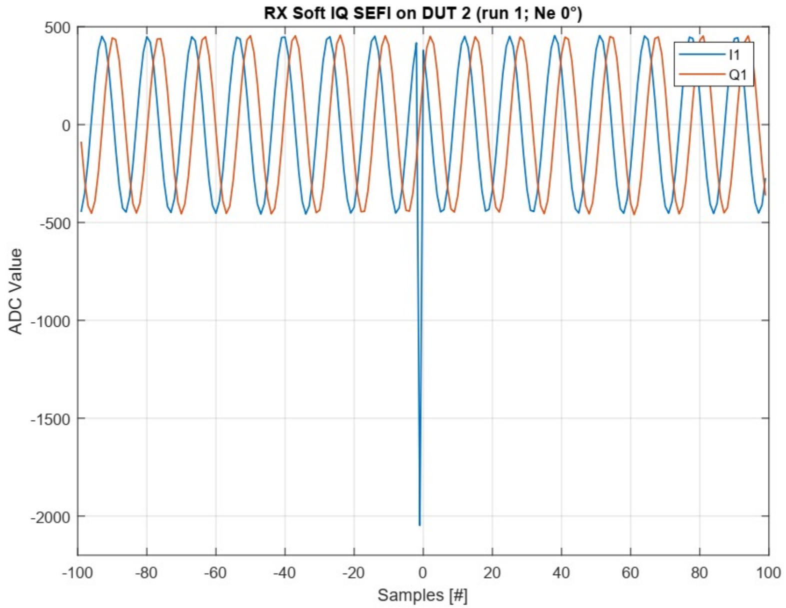




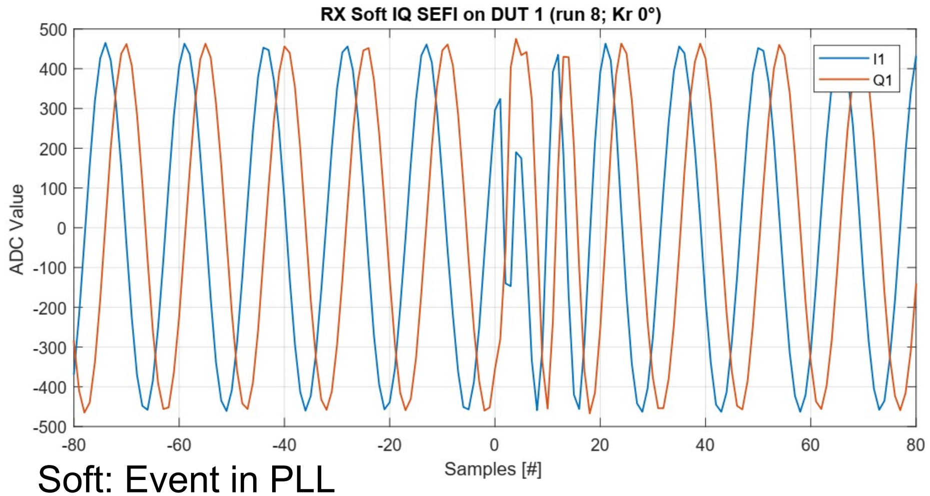
/10.3390/aerospace7020014, source: Budroweit

Radiation Testing on complex RFIC

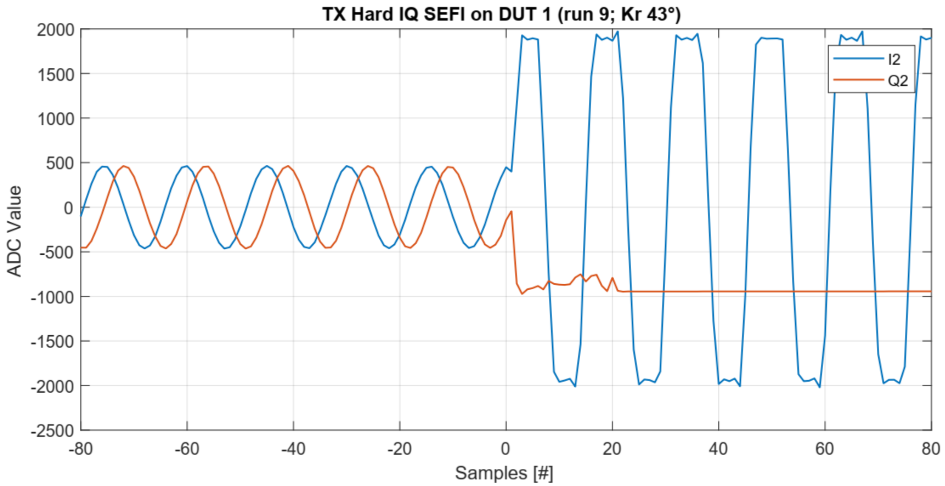
<u>Examples of IQ failures / signatures</u>



Soft: SEU in ADC



Soft: Event in PLL



Hard: Loss of IQ data

PhD thesis, source: Budroweit

Radiation Testing on complex RFIC

- No destructive events
- Very good SEE response
- Many SEUs observed, often not critical for functionality
- Mainly recovered by re-configuration
- IQ failures: ~50% hard; ~50% soft
- Hard IQ failure recovered by re-initialization

- Results presented for heavy ions
- Proton response much lower (in order of ~10 events)
- Performing the FMECA-based RHA results into a very low criticality:

  GEO (15 yr) and LEO (2 yr, 800 km, SSO) reference mission:
  - ➢ Nominal conditions: YEARS for failure
  - ➢ Worst conditions: DAYS for failure

SEE Type	Orbit	LET threshold [MeV·cm²/mg]	Limit cross-section [cm²/bit;dev]	Events/day (nominal).	Events/day (worst)
SEU	GEO	1.00×10^{-3}	2.80×10^{-8}	2.23×10^{-7}	4.44×10^{-5}
SEU	LEO	1.00×10^{-3}	2.80×10^{-8}	1.39×10^{-7}	1.04×10^{-5}
MBU	GEO	1.00×10^{-3}	2.71×10^{-9}	2.76×10^{-9}	6.30×10^{-7}
MBU	LEO	1.00×10^{-3}	2.71×10^{-9}	2.01×10^{-9}	1.50×10^{-7}
$SEFI_{cfg}$	GEO	1.00×10^{-3}	8.01×10^{-6}	1.30×10^{-3}	2.84×10^{-1}
$SEFI_{cfg}$	LEO	1.00×10^{-3}	8.01×10^{-6}	6.65×10^{-4}	6.56×10^{-2}
$SEFI_{init}$	GEO	$4.56 \times 10^{+1}$	1.00×10^{-6}	3.92×10^{-8}	3.91×10^{-6}
$SEFI_{init}$	LEO	$4.56 \times 10^{+1}$	1.00×10^{-6}	1.04×10^{-8}	1.03×10^{-6}
IQ_{soft}	GEO	1.00×10^{-3}	1.95×10^{-5}	1.46×10^{-3}	3.20×10^{-1}
IQ_{soft}	LEO	1.00×10^{-3}	1.95×10^{-5}	7.68×10^{-4}	7.41×10^{-2}
IQ_{hard}	GEO	1.00×10^{-3}	1.25×10^{-5}	4.02×10^{-4}	8.70×10^{-2}
IQ_{hard}	LEO	1.00×10^{-3}	1.25×10^{-5}	2.11×10^{-4}	2.02×10^{-2}

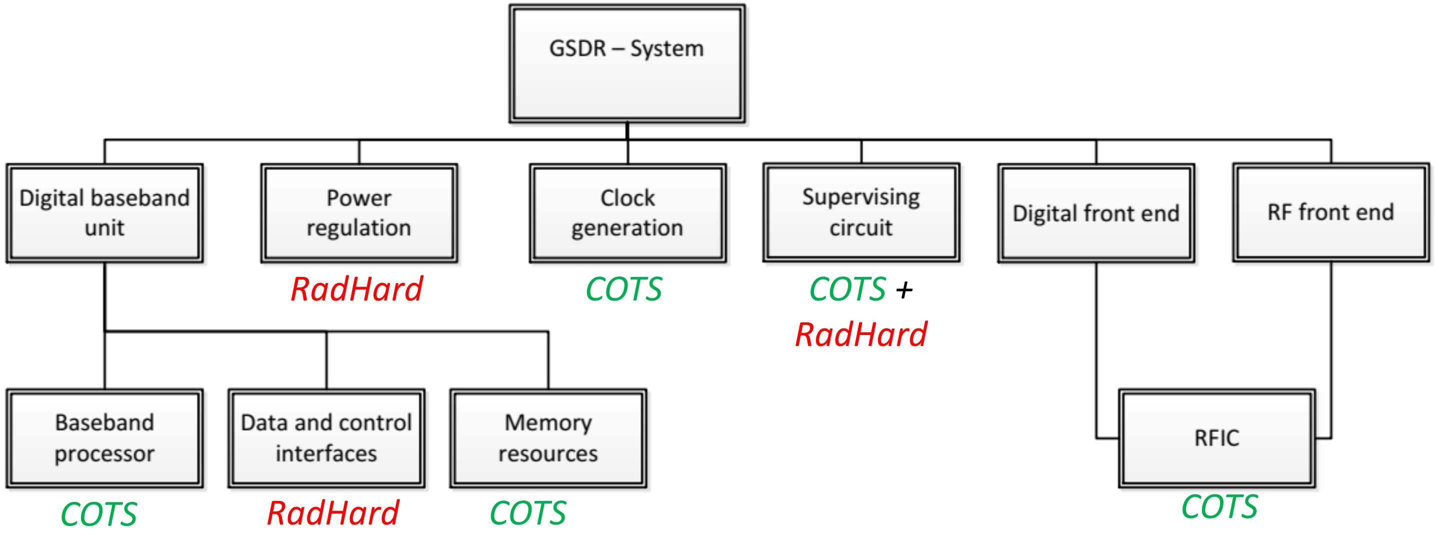
ID	Orbit	Failure causes	Failure effects	SN	PN	DN	CN
RFIC.1	LEO	SELs or high current states	permanent loss of system functionality	3	1	1	3
RFIC.1	GEO			3	1	1	3
RFIC.2	LEO	TIDs, long-term degradation	permanent loss of system functionality	3	1	2	6
RFIC.2	GEO			3	1	2	6
RFIC.3	LEO	SHEs, non-recoverable state	permanent loss of system functionality	3	0	-	0
RFIC.3	GEO			3	0	-	0
RFIC.4	LEO	SEFIs, recoverable state	temporary loss of system functionality	2	2	2	8
RFIC.4	GEO			2	4	2	16
RFIC.5	LEO	SEUs/MBUs/SEFIs, invalid data	corrupted data for transmission or reception	2	2	2	8
RFIC.5	GEO			2	2	2	8
RFIC.6	LEO	SETs, invalid data	corrupted data for transmission or reception	1	3	3	9
RFIC.6	GEO			1	4	3	12
RFIC.Total			Average CN (LEO):				5.7
RFIC.Total			Average CN (GEO):				7.5

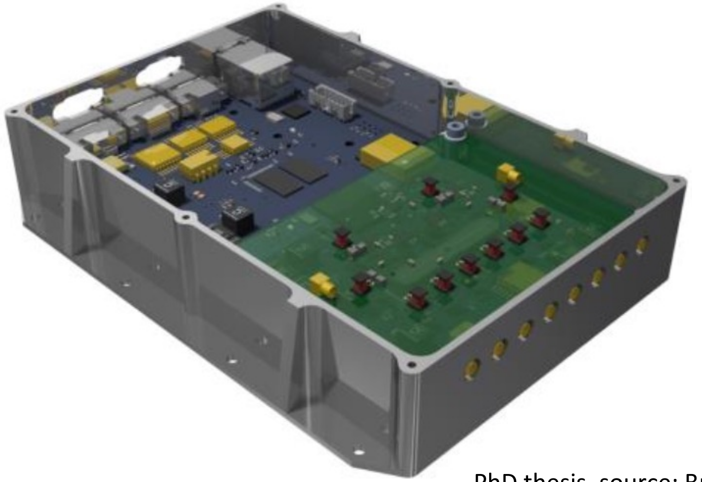
PhD thesis, source: Budroweit

Best practice and experience on a Software-Defined Radio

- System-Level Verification -

System-Level Verification





- Hybrid system design of *COTS* and *RadHard* devices
- Selected by the FMECA-based RHA approach
- An essential part of the system functionality is the software and the operating system:
  - General functionality
  - Control of system
  - Detection of failures and recovery mechanism

PhD thesis, source: Budroweit

System-Level Verification

Purpose of system-level verification:

- Different task forms the overall system functionality
- A single failures can cause functional losses of the system
- Verification of failure detection and potentially recovery

For TID:

- ✓ Co60-Source can be used (no limitation in space)

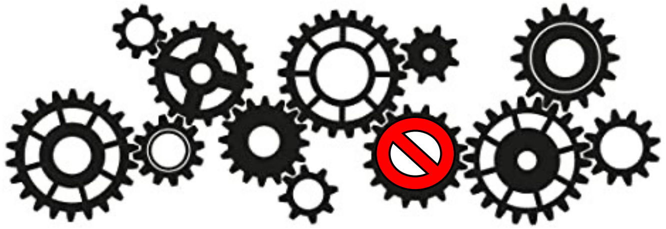
For SEE:

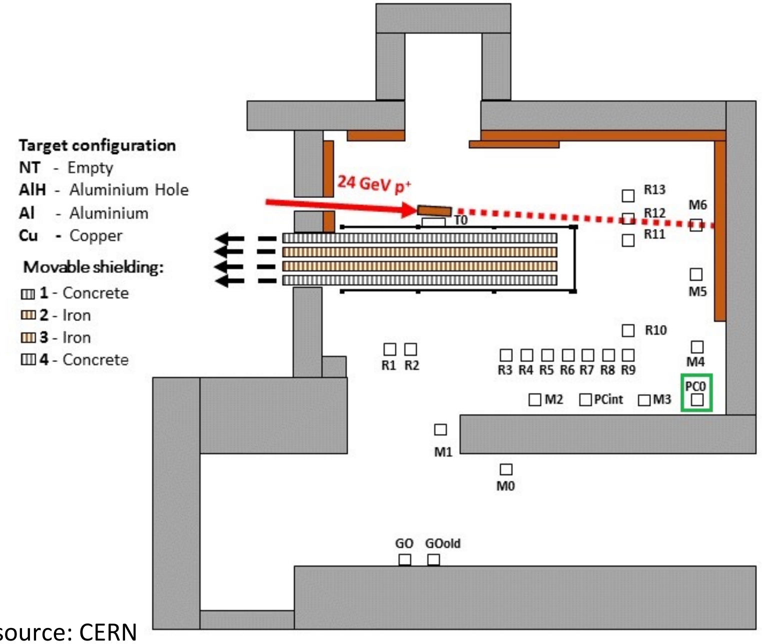
- – Particle accelerators have only a narrow beam (<100 mm diameter)
- – Local irradiation (single devices or groups of the system)
- – Failure propagation unclear
- ➢ *How to test on system-level that exceed the narrow beam?*
- ➢ *What about multi-point of failures?*

Possible solution for (soft) SEE:

✓ CHARM - Mixed-Field Radiation Facility (Neutron, Protons, Electrons)

System

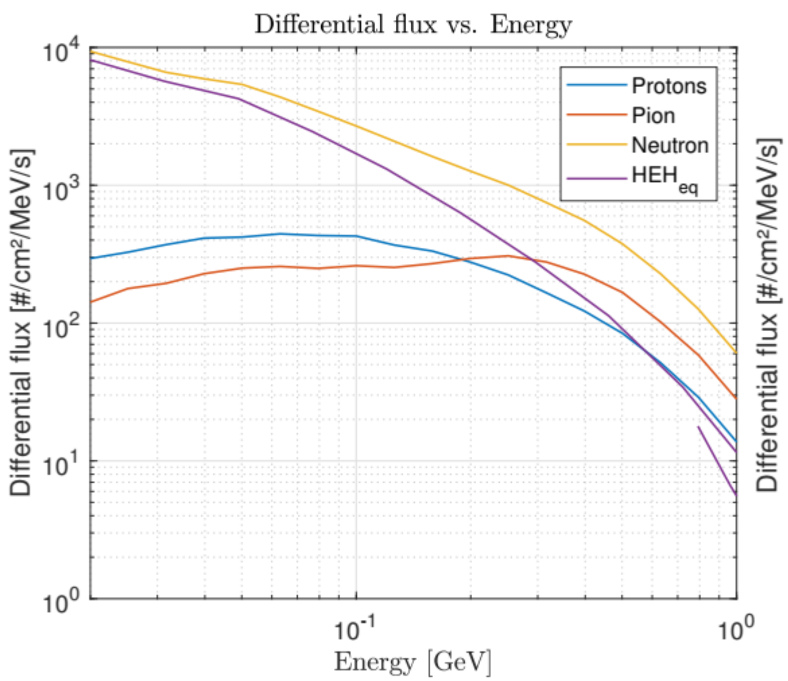


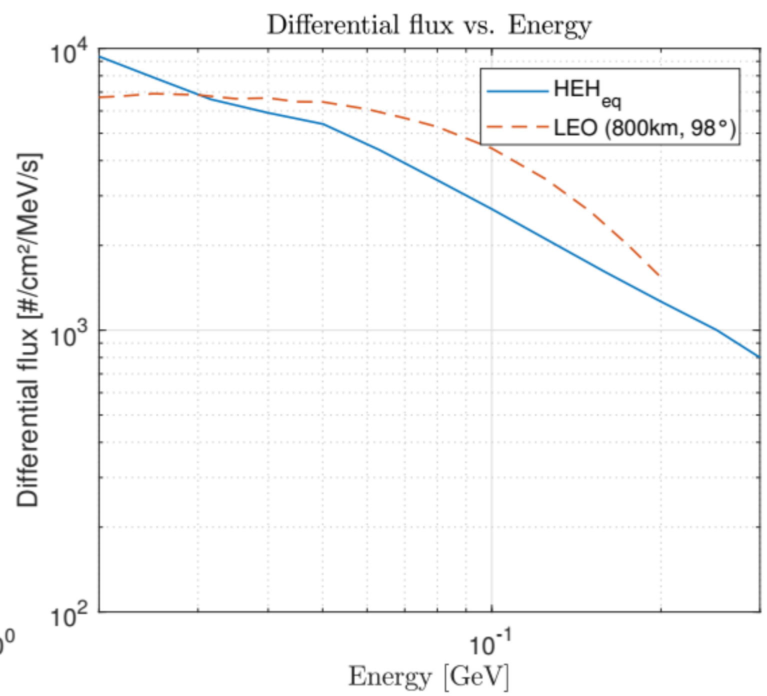


CHARM, source: CERN

System-Level Verification

- Similar differential flux compared to LEO mission (800 km, SSA)



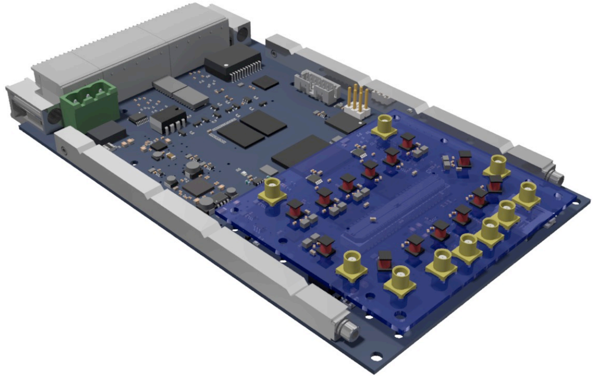


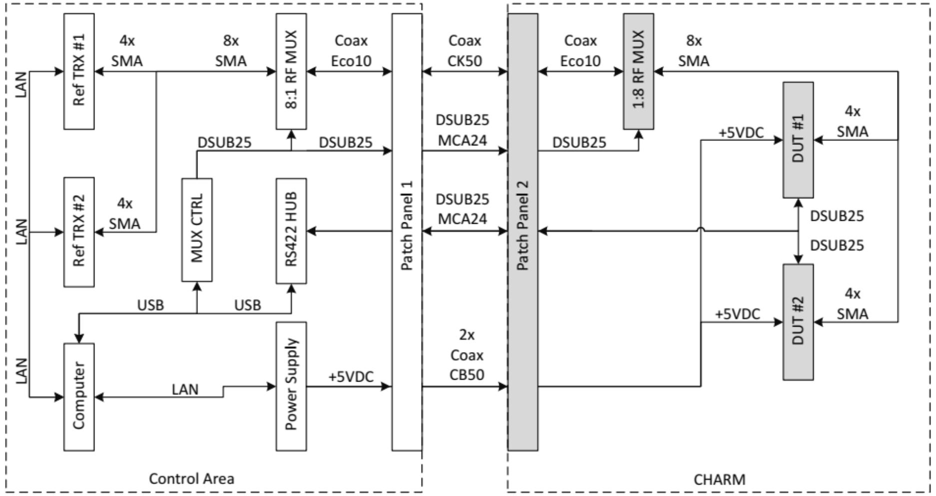
PhD thesis, source: Budroweit, CERN

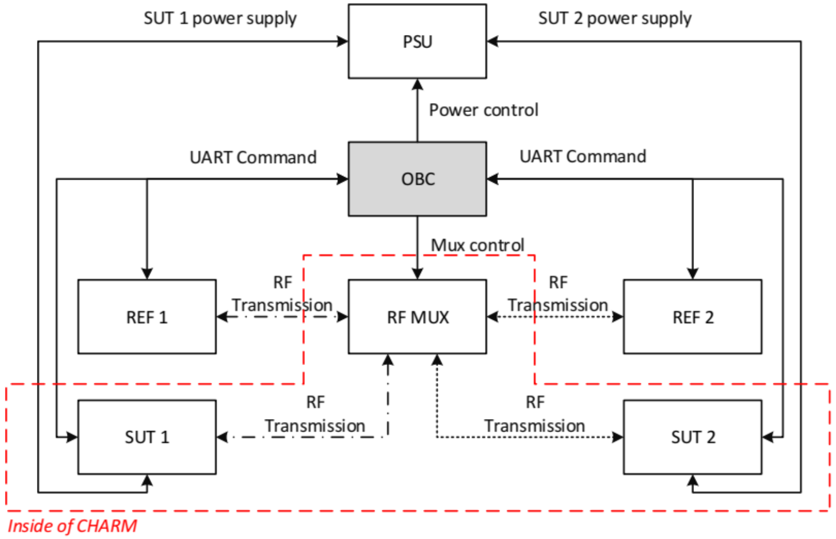
System-Level Verification

- Similar differential flux compared to LEO mission (800 km, SSA)
- 2x GSDR prototypes (Rev B.)
- Complete autonomous setup
  - ➢ Exchange of RF and digital data
  - ➢ On-board data processing (e.g. for RF data)
  - ➢ Overvoltage and current detection and protection
  - ➢ System-Watchdog executes reset if heart-beat disappears
  - ➢ Time-Out of command response (power-cycle)
  - ➢ Soft-Watchdog (on program/application level)
  - ➢ Memory scrubbing (NAND boot device)
  - ➢ RFIC verification
  - ➢ …

- Two types of major failures
  - ➢ Self-recovered SEFI event
  - ➢ Power-cycle SEFI event







PhD thesis, source: Budroweit

System-Level Verification

- System(s) run with multiple tasks on request
  - ➢ HK-Data, RF-Data aq., Spectrogram, …

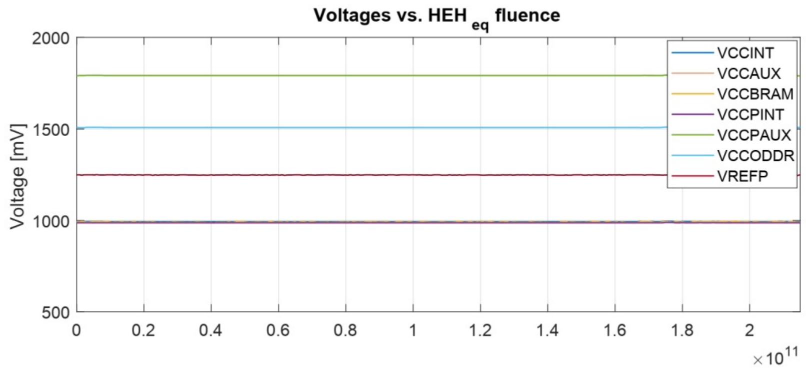
✓ No degradation of voltage and current due to TID
✓ No SELs or destructive failures (not expected)
✓ Ability to perform self-recovery verified

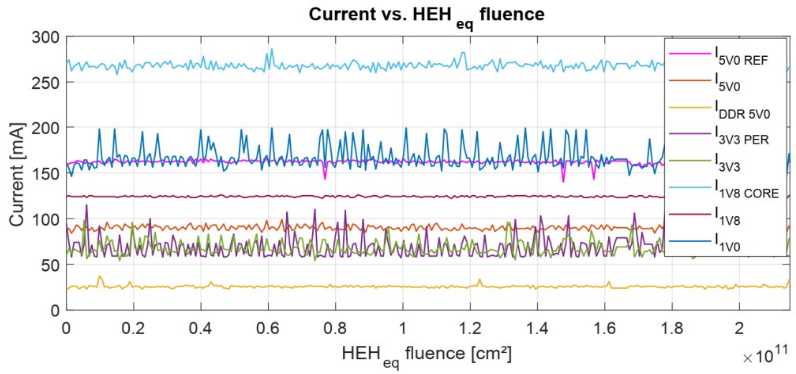
✓ 100 % recovery from failure to valid system operation
  - ➢ 95 % of all failures were system crashes (Zynq + DDR3)
  - ➢ 98 % self-recovered SEFI events

✓ No interrupted boot-processes observed (process takes ~15 s)
✓ No invalid data on boot devices (NAND flash)
✓ Minor errors observed on RFICs

<u>**But:**</u>

– Data fly-by storage on SD-Card critical (SD-Card broken)
  - ➢ *SUT#2 (partially) not able to response on requested tasks*



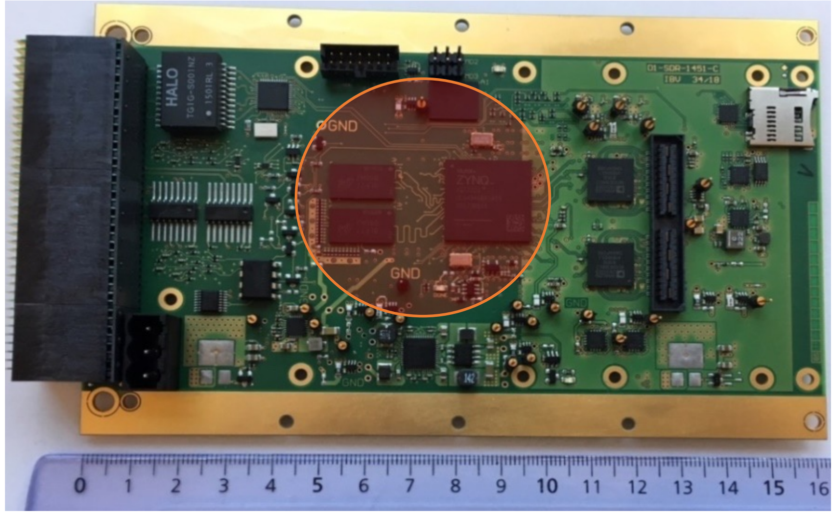


SUT	SEE	#Spills	#Events	HEH_{eq} fluence [#/cm^2]	Cross-section [device/cm^2]	TID [krad(Si)]
1	Self-recover	21236	5320	$2.17 \times 10^{+11}$	2.45×10^{-8}	10
1	Power-cycle	21236	75	$2.17 \times 10^{+11}$	3.46×10^{-10}	10
1	AD9361 SEU	21236	355	$2.17 \times 10^{+11}$	1.64×10^{-9}	10
1	AD9361 SEFI	21236	8+5	$2.17 \times 10^{+11}$	6.00×10^{-11}	10

PhD thesis, source: Budroweit

System-Level Verification

- GSDR system has been irradiated to Protons (max. 194 MeV)
  - Two test campaigns
  - Focusing on sensitive parts (Zynq, DDR3 SDRAM, NAND and RFIC)
  - Same configuration and software were used as in CHARM (only exception: SD-Card removed)
  - Fluence:
    - GSDR Rev B.: 5.0×10^8 #/cm^2
    - GSDR Rev C.: 2.5×10^9 #/cm^2



GSDR. Rev B, source: Budroweit

GSDR. Rev C, source: Budroweit

System-Level Verification

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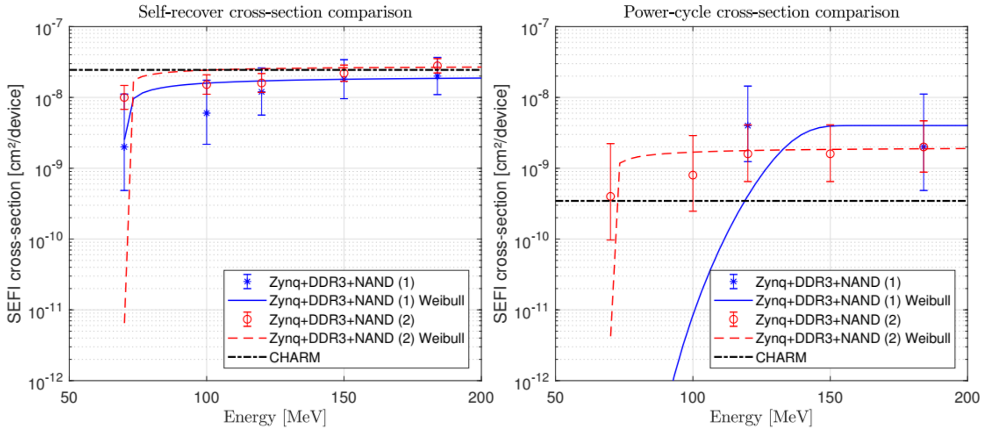


(a) Self-recovered (b) Power-cycled

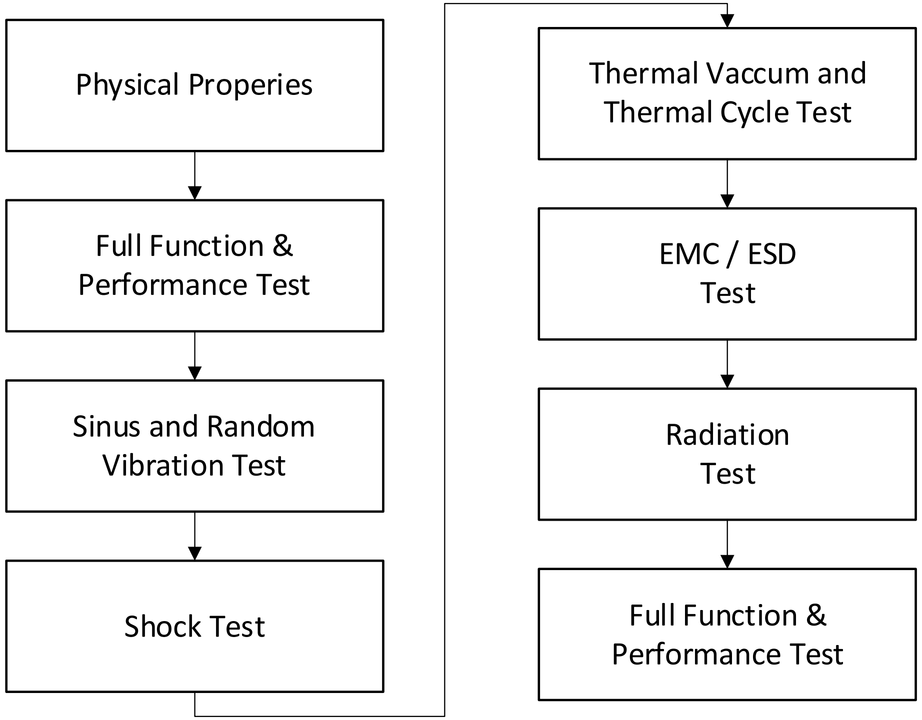
- Comparable saturation of cross-section (for self-recovery)
  - ~1.9×10^{-8} cm²/device (proton #1)
  - ~2.6×10^{-8} cm²/device (proton #2)
  - 2.45×10^{-8} cm²/device (CHARM)

SEE Type	Orbit	LET threshold	Limit cross-section	Events/day (nominal)	Events/day (worst)
$SEFI_{Self}$	GEO	$7.00 \times 10^{+1}$	2.18×10^{-8}	1.95×10^{-2}	$1.12 \times 10^{+0}$
$SEFI_{PC}$	GEO	$7.00 \times 10^{+1}$	1.57×10^{-9}	1.32×10^{-3}	6.97×10^{-2}
$SEFI_{Self}$	LEO	$7.00 \times 10^{+1}$	2.18×10^{-8}	8.62×10^{-2}	3.50×10^{-1}
$SEFI_{PC}$	LEO	$7.00 \times 10^{+1}$	1.57×10^{-9}	5.71×10^{-3}	2.22×10^{-2}

PhD thesis, source: Budroweit

System-Level Verification

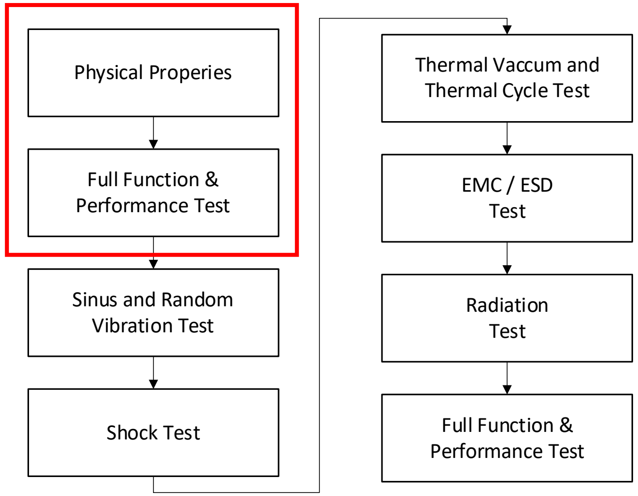
- Usually: Test as you fly (in order)
- According to ECSS-ST-10-03C (and NASA GEVS)
- Additional Radiation Test

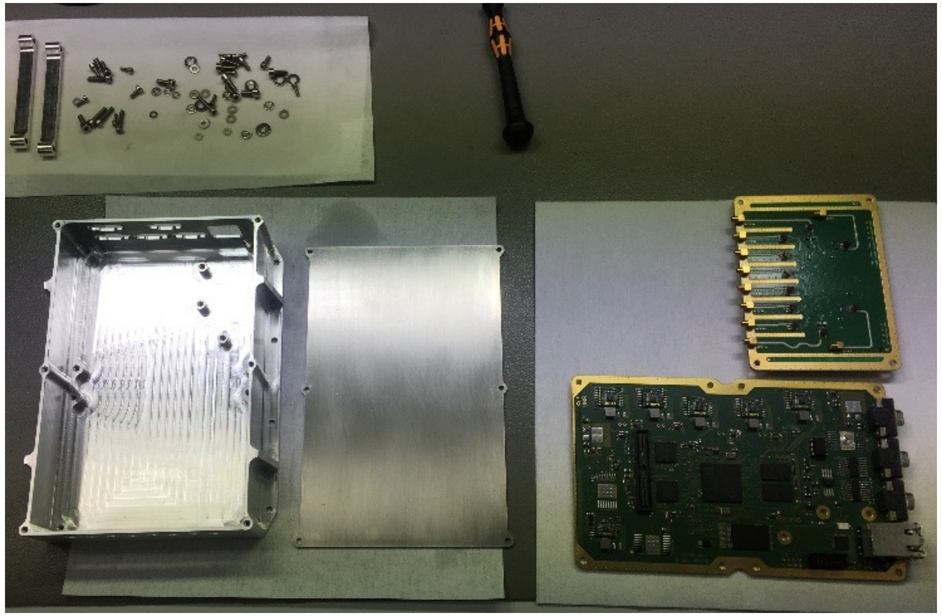


PhD thesis, source: Budroweit

System-Level Verification

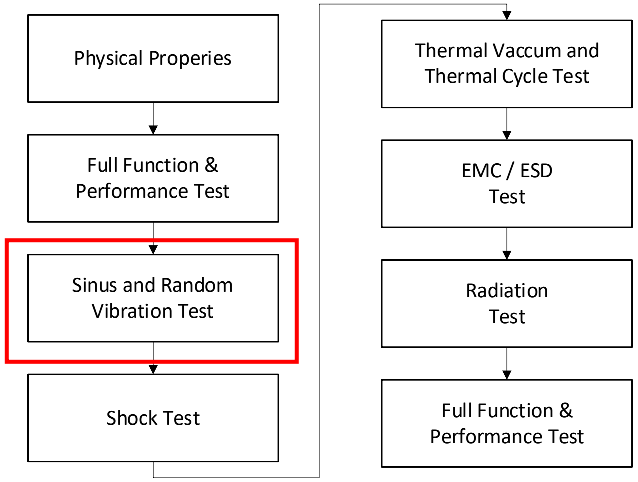
- The full functional and performance test shall verify the intended operation prior test stress to the device
- For the software-defined radio we tracked:
  - Voltage and current values (from power supply up to internally measured data)
  - The RF performance, e.g. output power and frequency stability
  - Functional capabilities (e.g. command and control of the unit)
- The performance test shall include the necessary information that may change by environmental stresses
- Due to self-heating, the performance test shall conduct as long as a stable condition is achieved

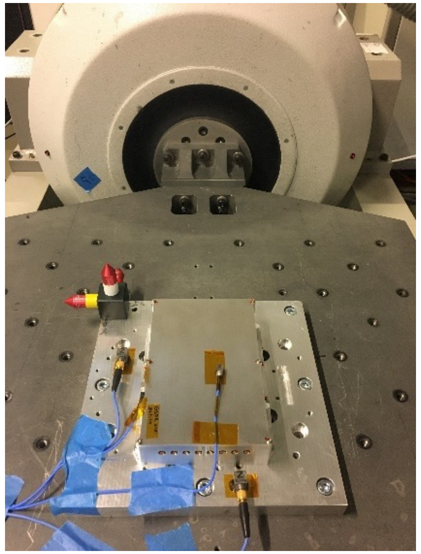


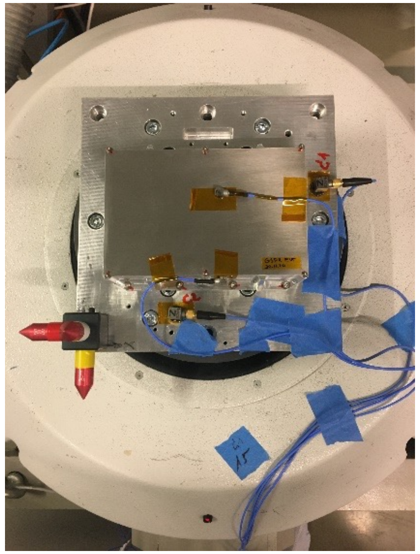


System-Level Verification

- Sinus and random vibration tests are applied to simulated the behavior during launch
- Based on the device structure it could be possible that resonance frequency can be achieved by the mechanical stress from the rocket that may lead to a destructive phenomena of the device (and can potentially destruct the rocket itself).

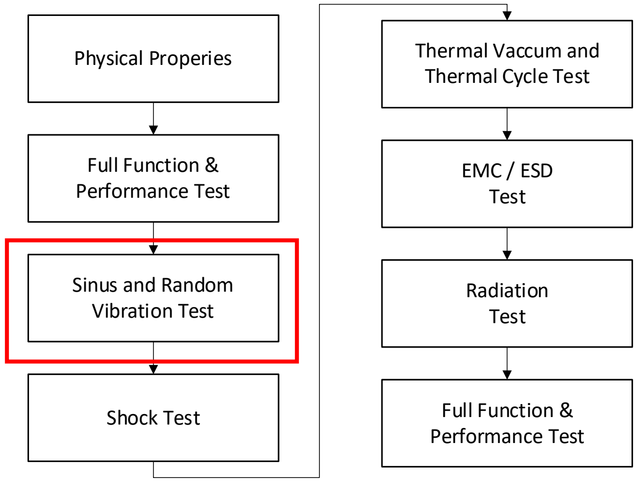


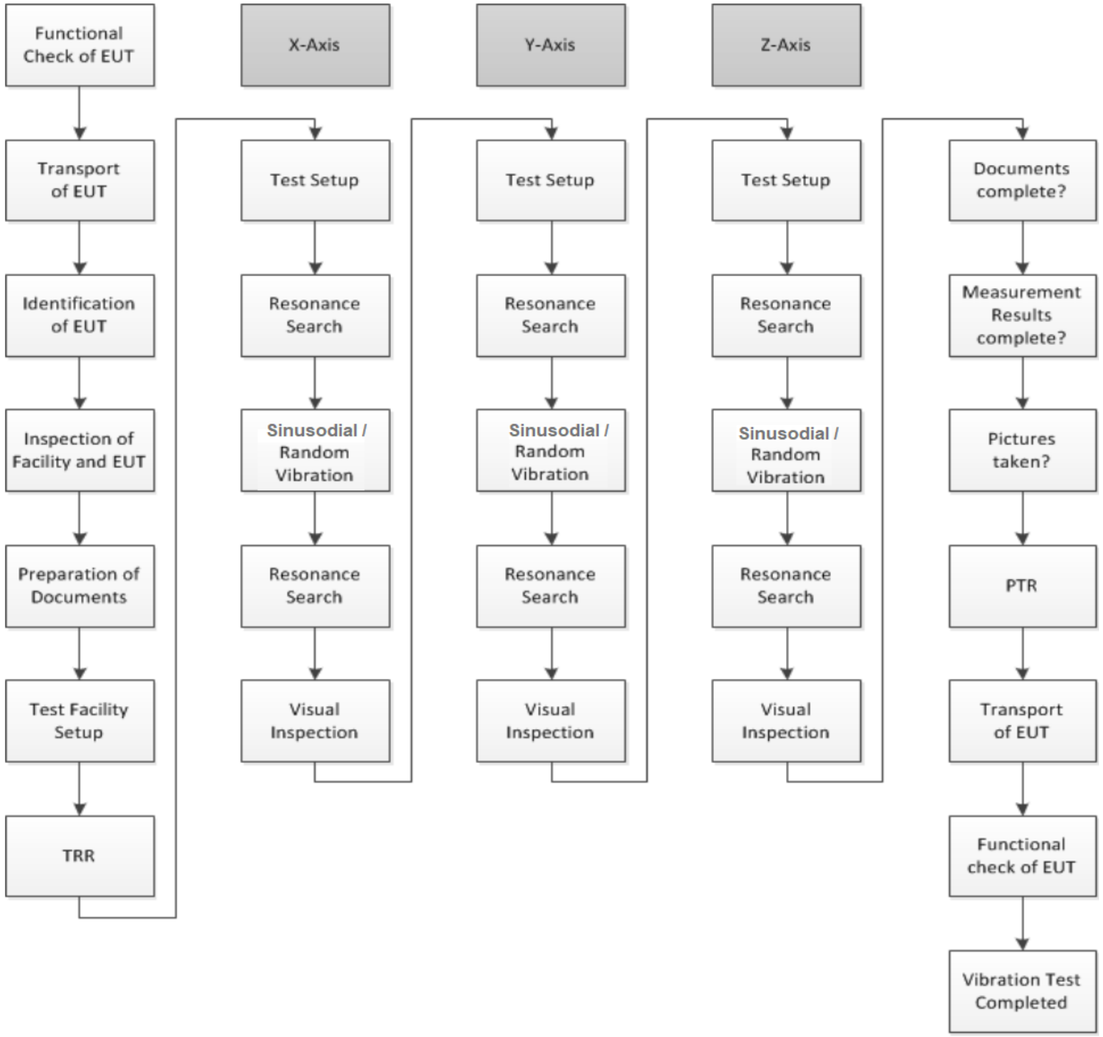




System-Level Verification

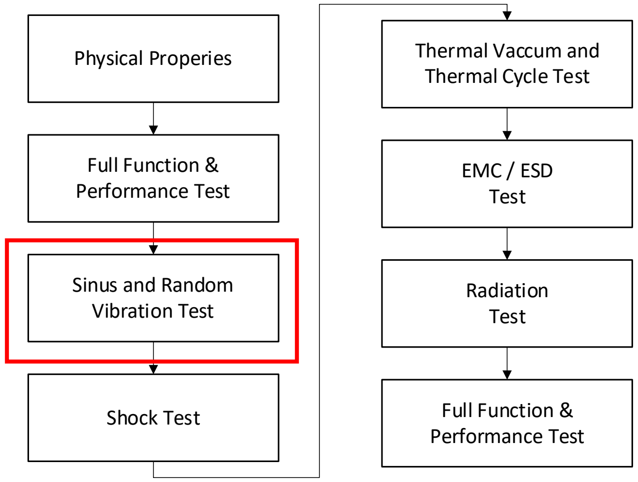
- Sinus and random vibration are tested an all the axis.
- To observed non-visible defects, a resonance survey is conducted after every run (2-2000Hz)

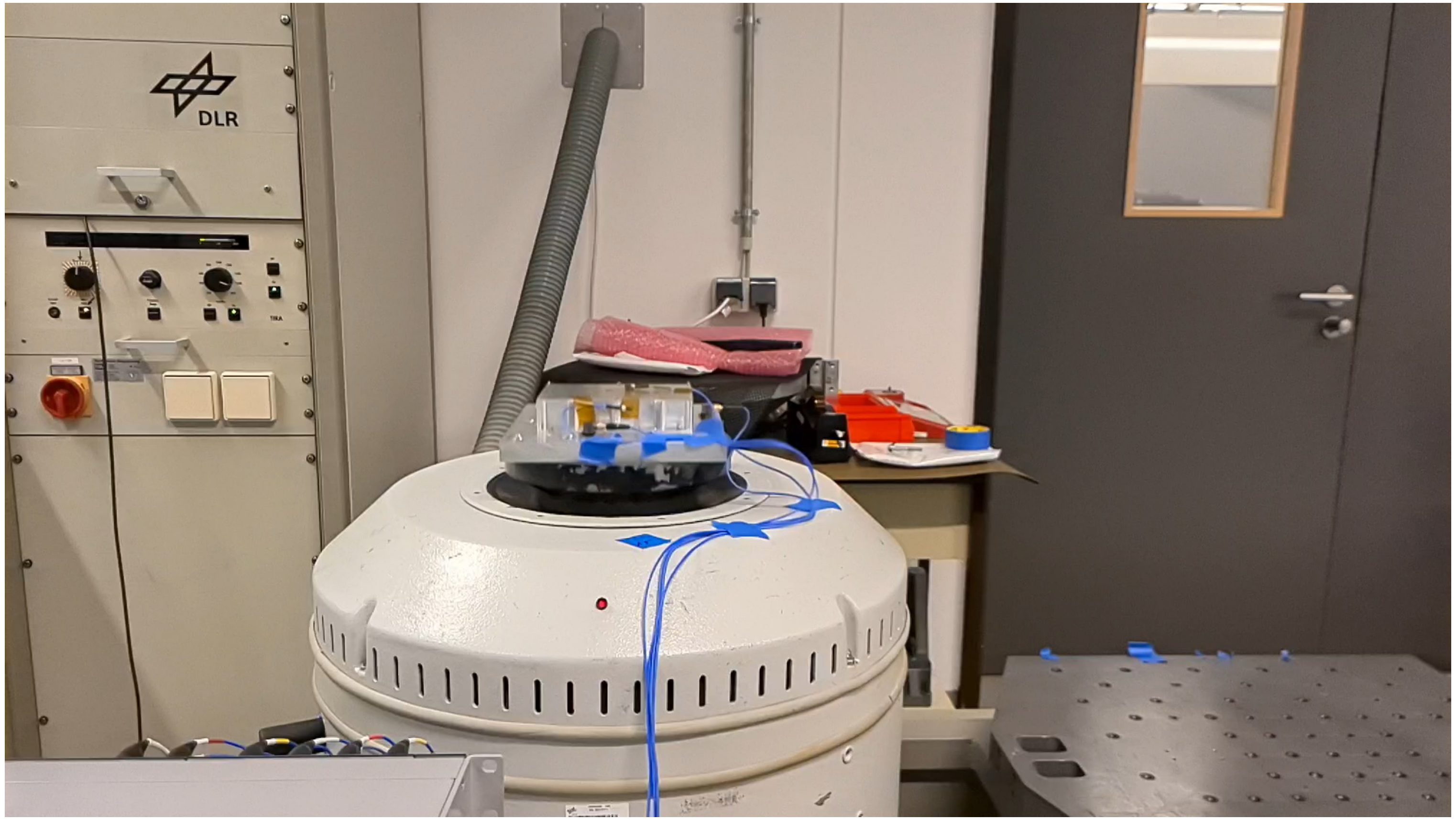




System-Level Verification

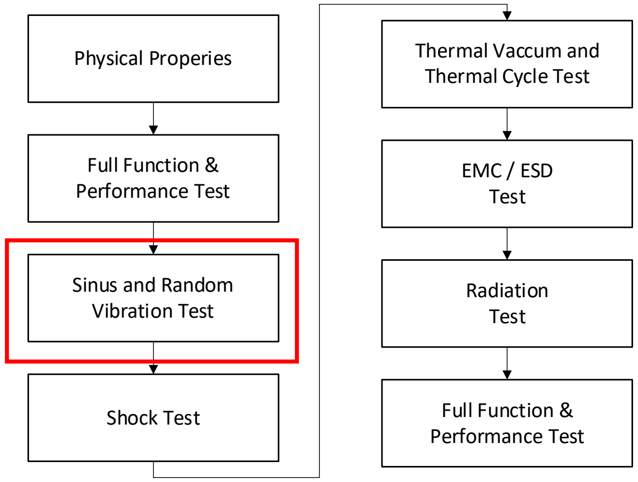
- Sinus test looks very stressful to the device but the smaller the EUT that less are sinusoidal stress critical (imagine a flat and long structure, e.g. solar panel)





System-Level Verification

- Random vibration is actually noise over the frequency spectrum from 20-2000Hz.
- The load that is integrated is 14.1 Grms
- ASD level is take von GEVS:



Frequency (Hz)	ASD Level (g^2/Hz)	
	Qualification	Acceptance
20	0.026	0.013
20-50	+6 dB/oct	+6 dB/oct
50-800	0.16	0.08
800-2000	-6 dB/oct	-6 dB/oct
2000	0.026	0.013
Overall	14.1 G_{rms}	10.0 G_{rms}

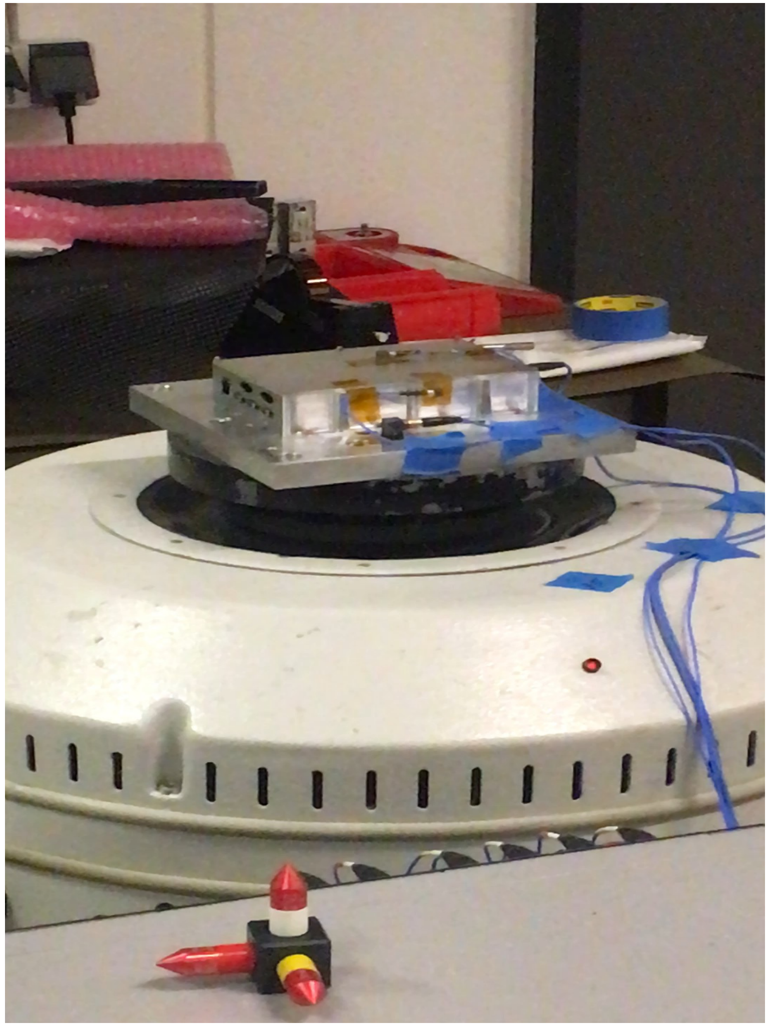
The acceleration spectral density level may be reduced for components weighing more than 22.7-kg (50 lb) according to:

	Weight in kg	Weight in lb	
dB reduction	= 10 log(W/22.7)	10 log(W/50)	
$ASD_{(50\text{-}800\ Hz)}$	= 0.16•(22.7/W)	0.16•(50/W)	for protoflight
$ASD_{(50\text{-}800\ Hz)}$	= 0.08•(22.7/W)	0.08•(50/W)	for acceptance

Where W = component weight.

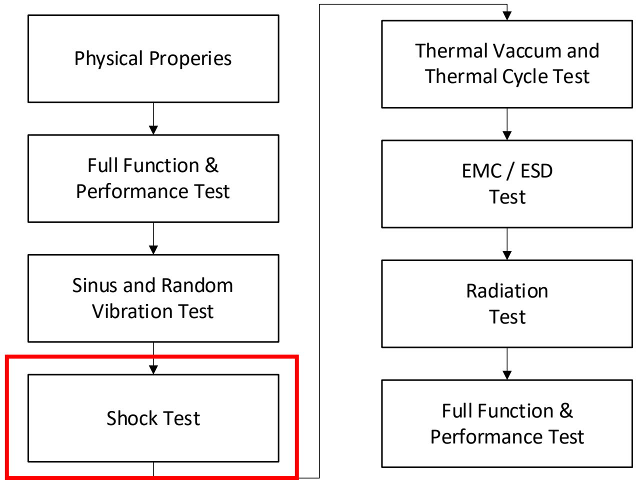
The slopes shall be maintained at + and - 6dB/oct for components weighing up to 59-kg (130-lb). Above that weight, the slopes shall be adjusted to maintain an ASD level of 0.01 g^2/Hz at 20 and 2000 Hz.

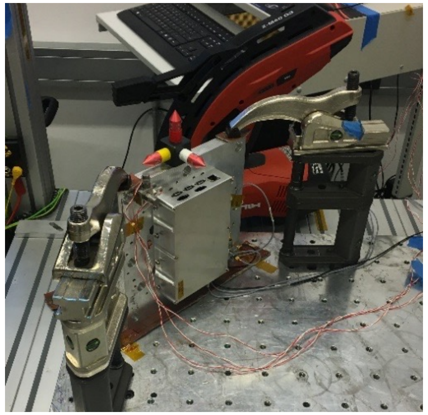
For components weighing over 182-kg (400-lb), the test specification will be maintained at the level for 182-kg (400 pounds).

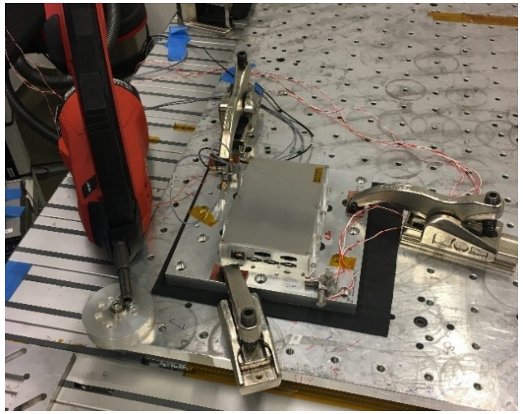


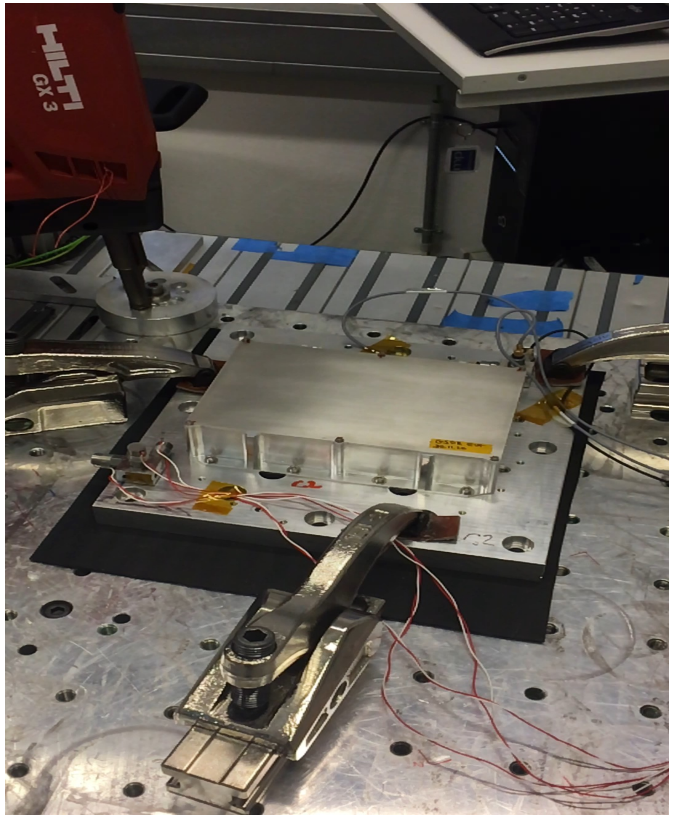
System-Level Verification

- Shocks apply during separation from the rocket and upper stage.
- Usually the separation mechanism from the upper stage is followed by a pyro injection.
- The shock can propagate through the structure and can cause critical damages.
- The loads are frequency depending and usually given by the launch provider.
- Best practice was applied for the SDR using loads of 40g at 100Hz and 1500g for frequency >1500Hz
- Shock tests needs to applied on all three axis

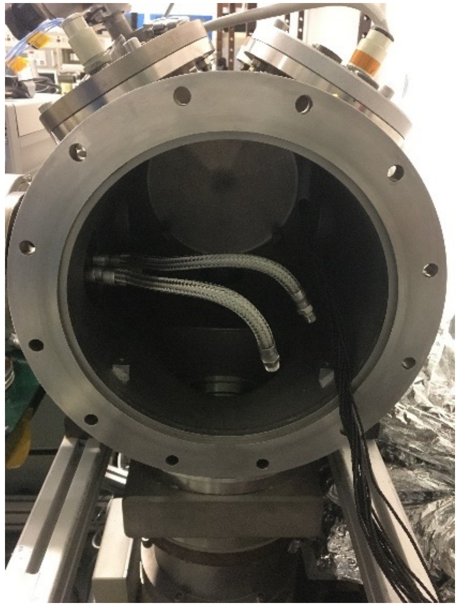




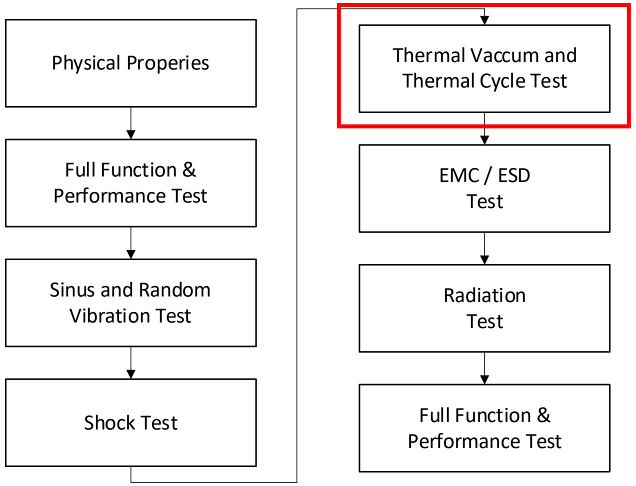


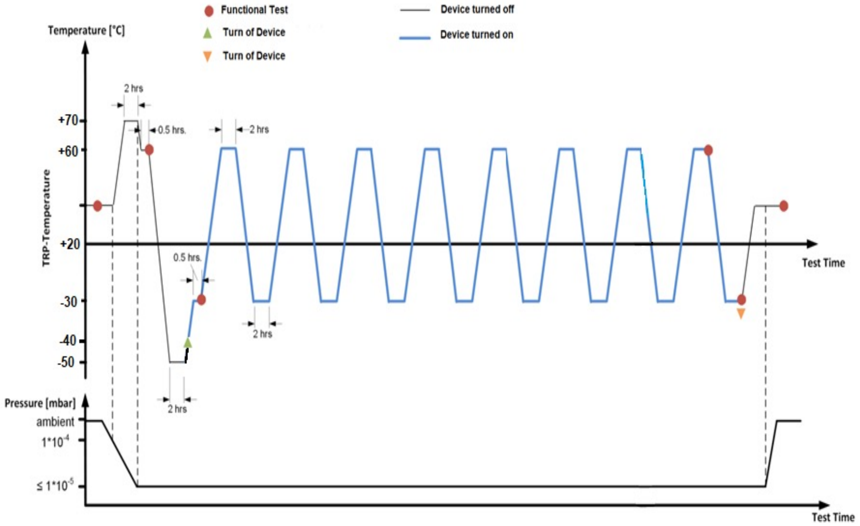


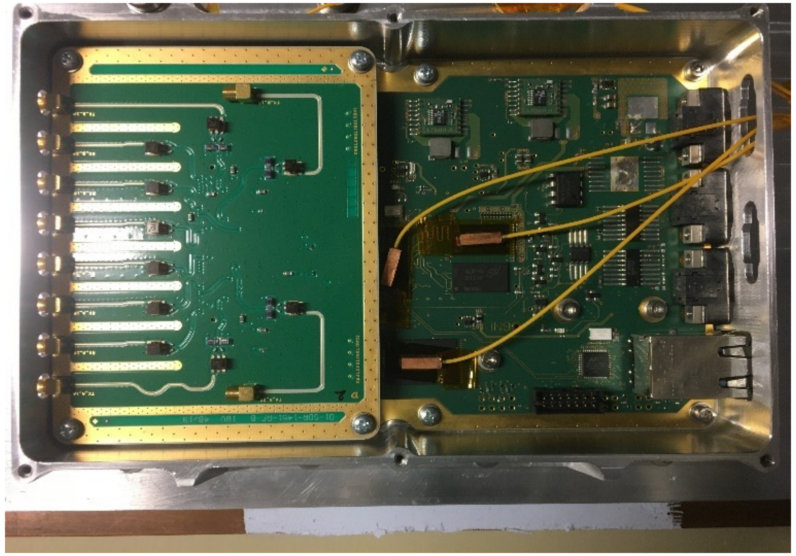
System-Level Verification



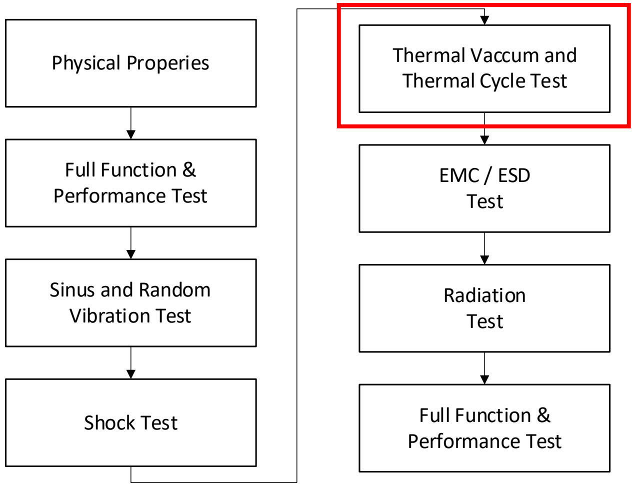
- According to ECSS-ST-10-03C
- Pressure: 1E-5 mbar
- 1x Non-Op Cycle ($T_{storage}$ +/- 10°C)
- 8x Op. Cycle ($T_{nominal}$ +/- 10°C)
- Tolerance: +/- 10% on voltage and current, +/- 5ppm on freq. and +/- 10% output power

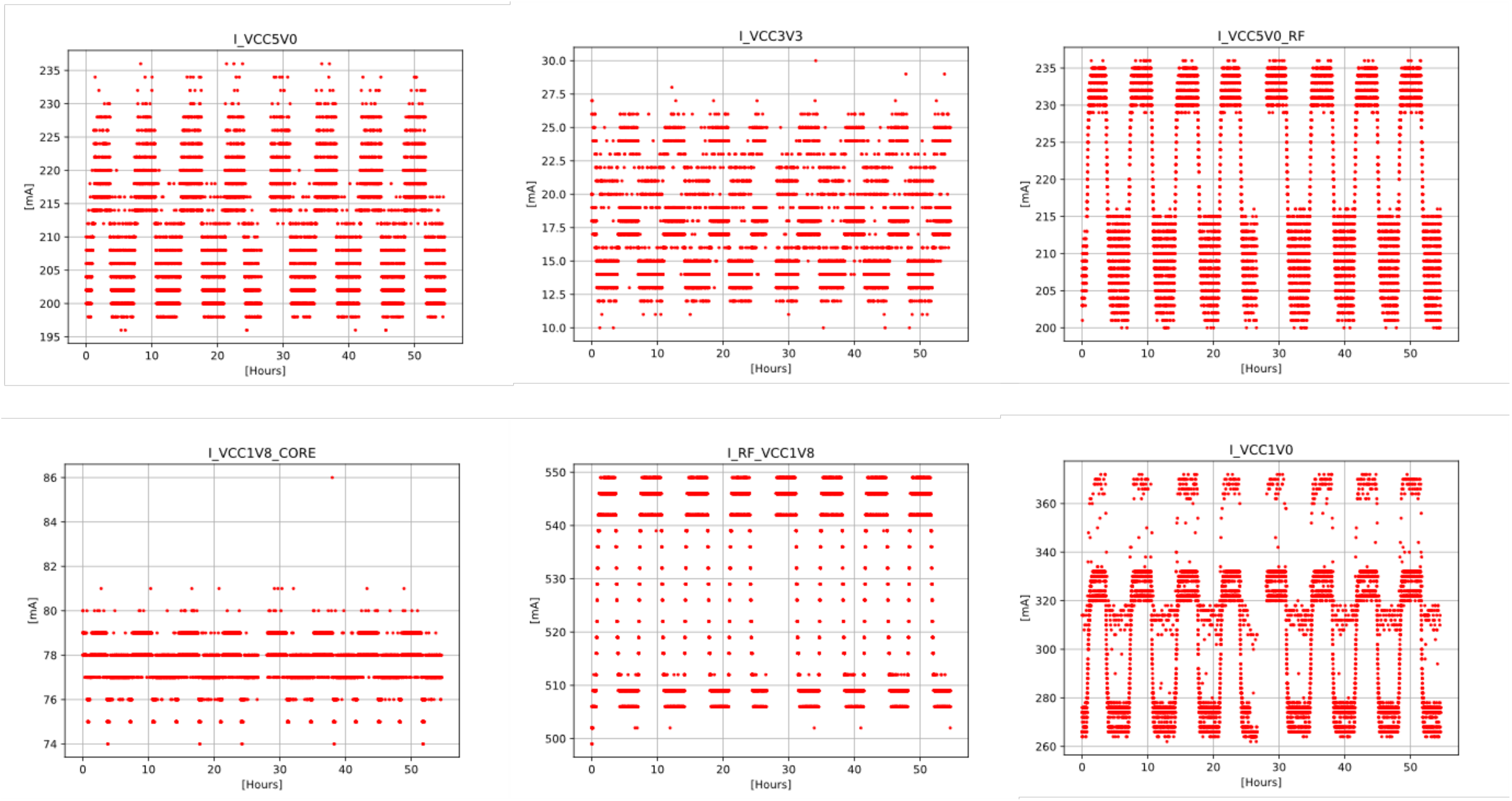






System-Level Verification





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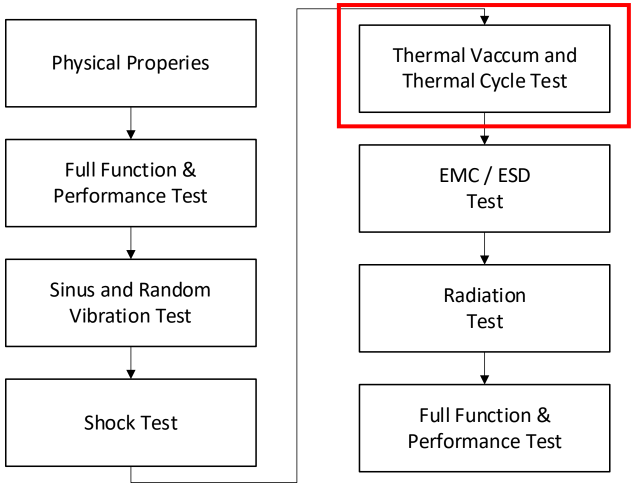

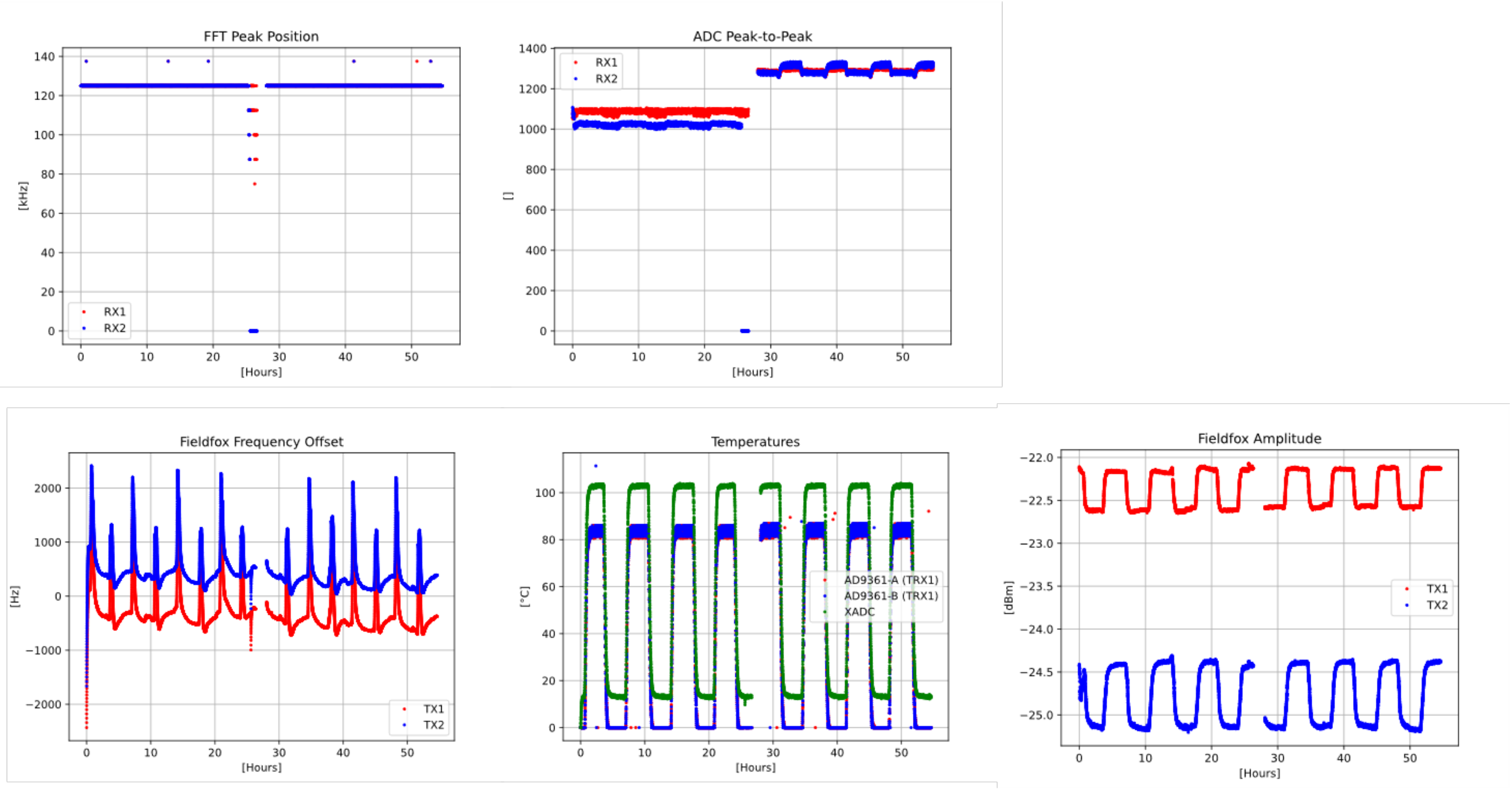

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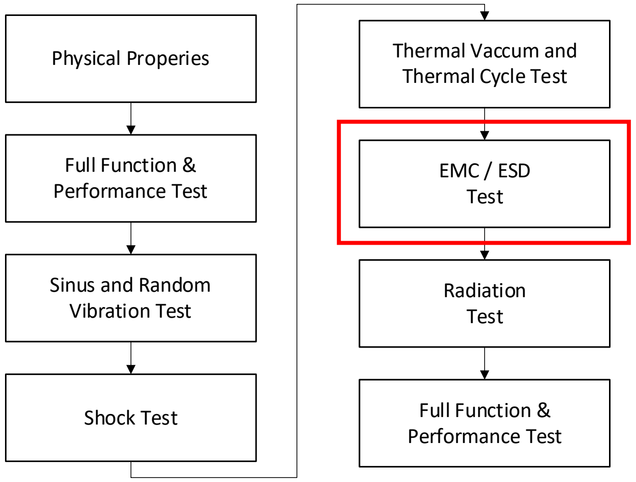
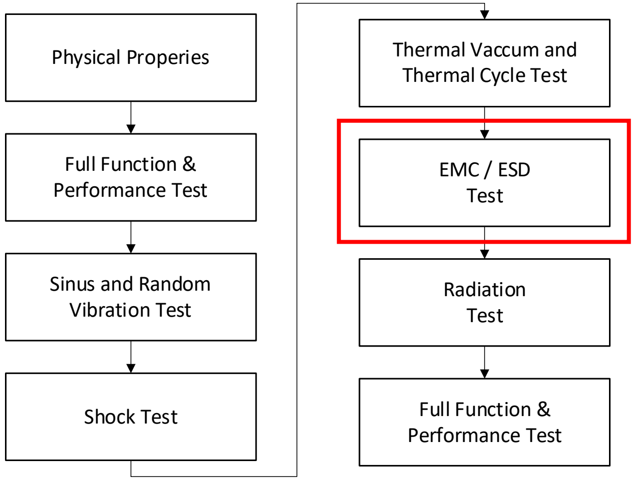
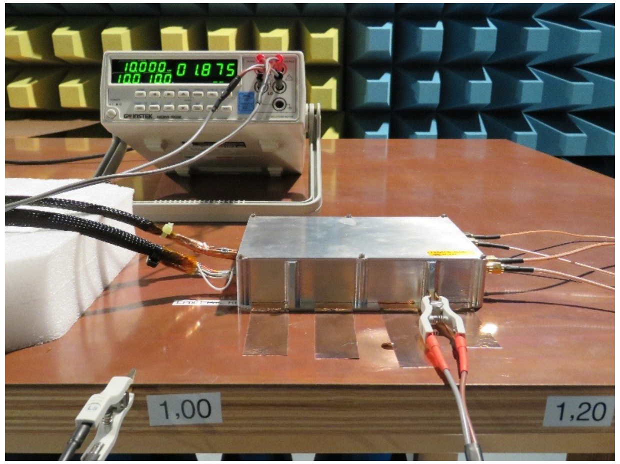


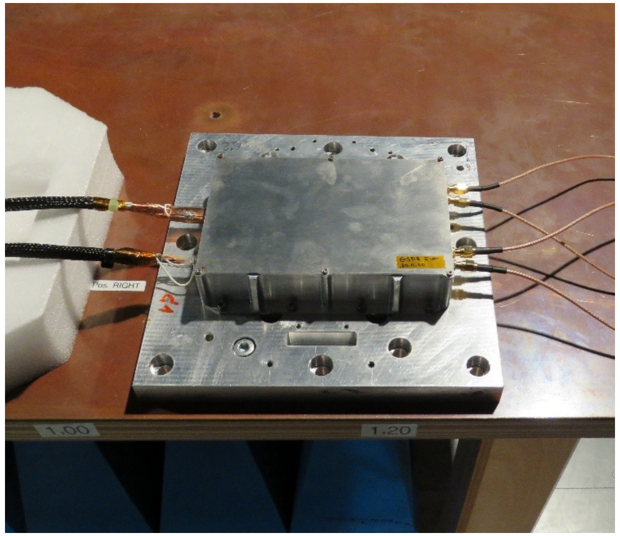
- The EMC test shall be performed in conformance with ECSS-E-ST-20-07 clause 5. For acceptance stage, the space segment equipment shall be subjected to the following tests, as per ECSS-E-ST-20-07:
  1. bonding verification;
  2. power lines isolation;
  3. inrush current;
  4. conducted emission time domain (ripple and spikes) on power lines in the operating mode, which produces maximum emissions;
  5. conducted emission frequency domain on power lines in the operating mode, which produces maximum emissions.

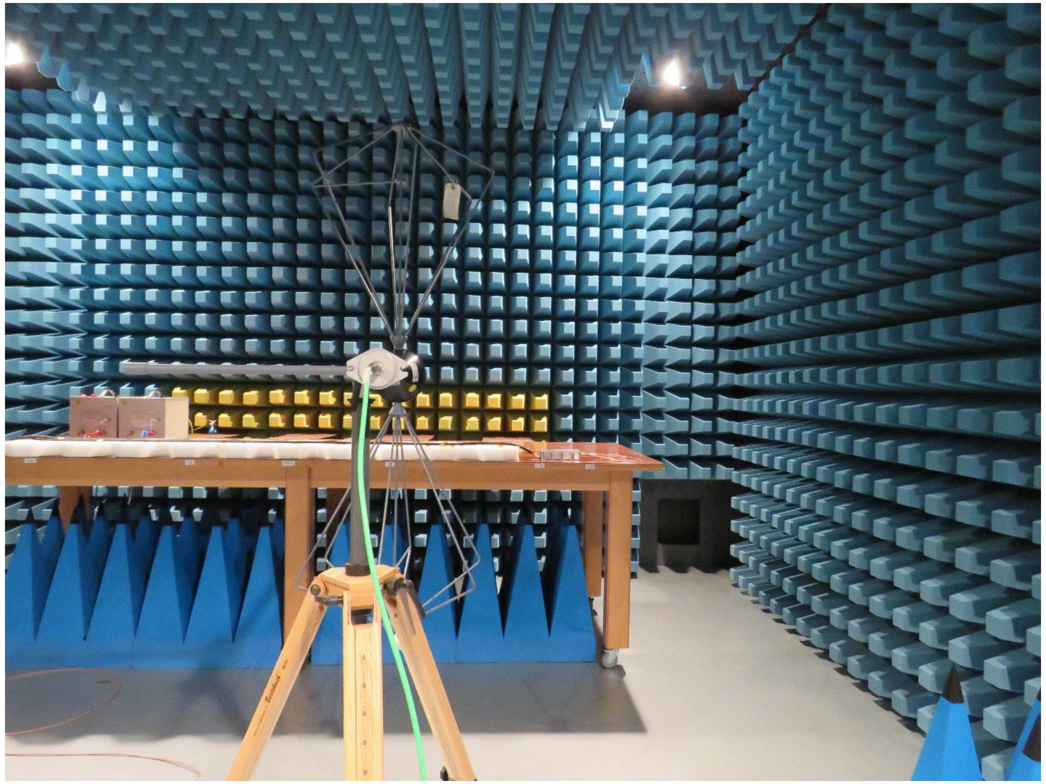
- For RF space segment equipment sniff or spray test shall be performed at one or several frequencies used by the space segment equipment under test or in mission critical receive bands. Sniff or spray test should be performed with a guide to coax transitions at a controlled distance.

System-Level Verification



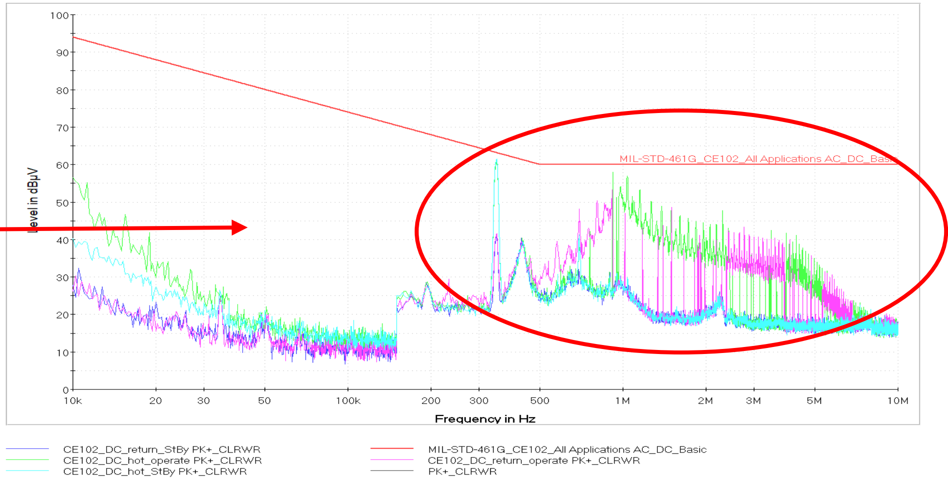




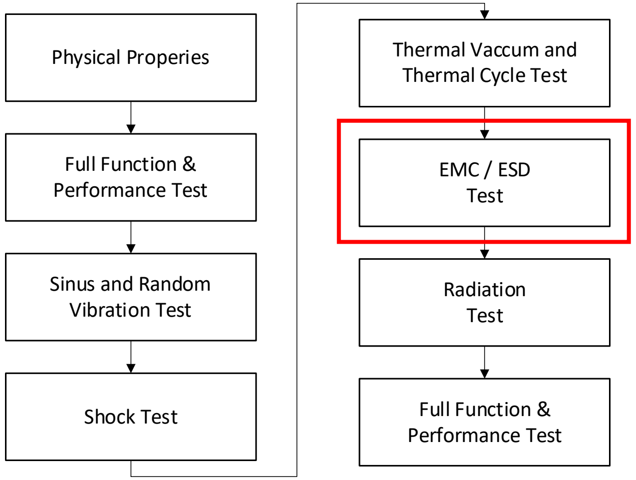


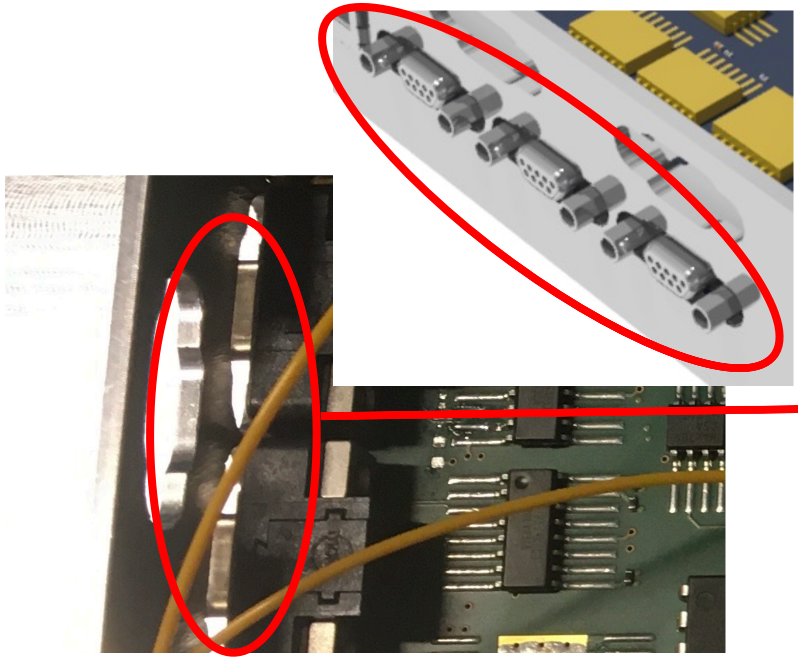
System-Level Verification

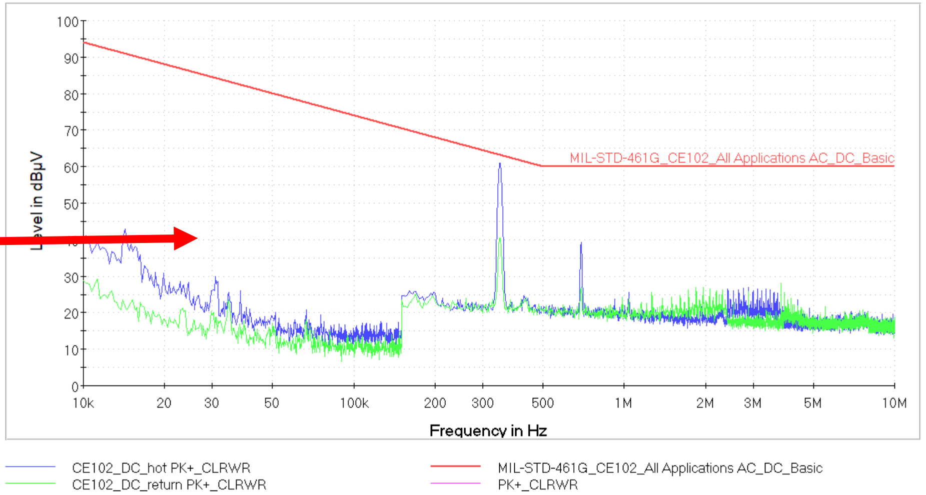
- Conducted emissions:
  - Measured on the power lines
  - Issues also observed by <u>non-ideal</u> grounding of connector/cable
  - Issues observed potentially due to problems with missing EMI Filter



Non-grounded measurement



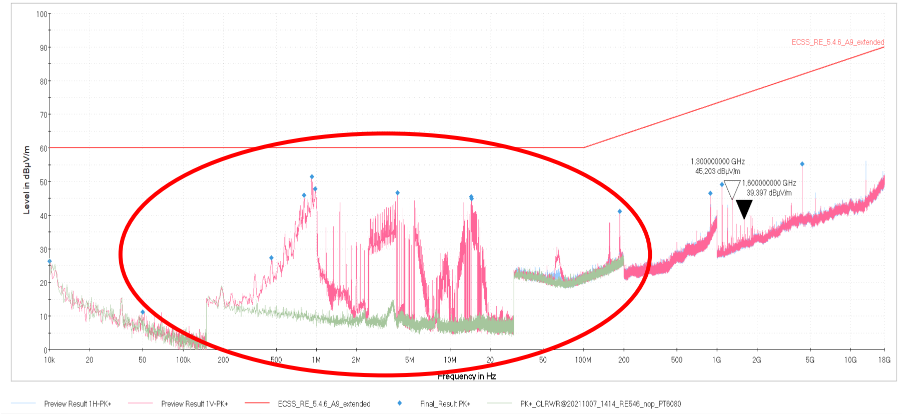




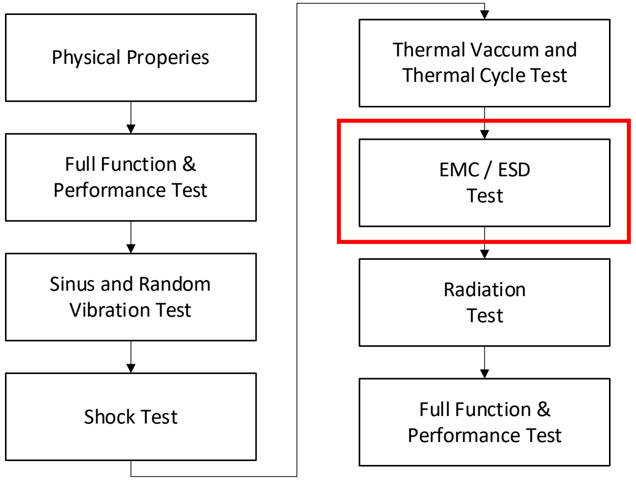
Grounded measurement

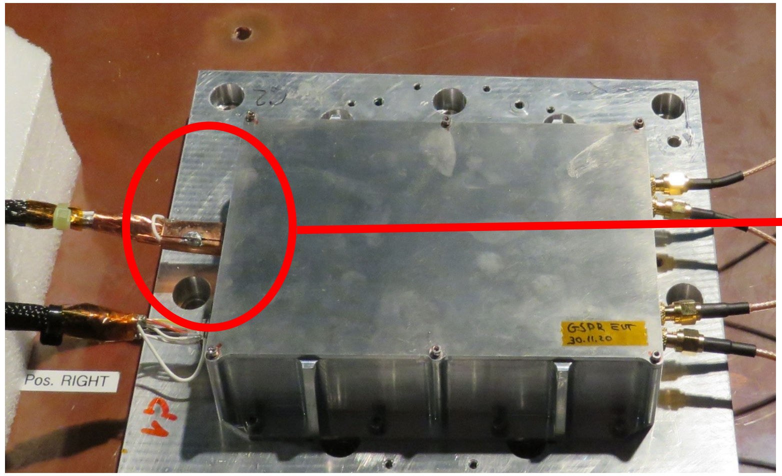
System-Level Verification

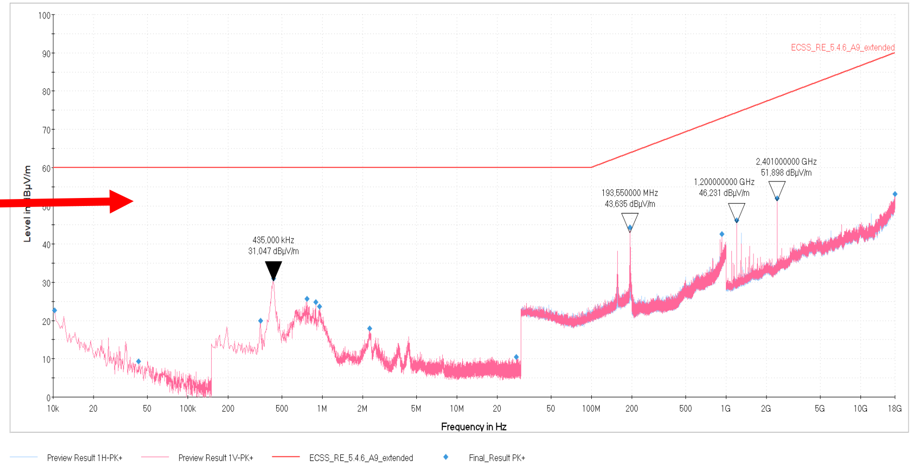
- Radiated emissions:
  - Issues observed due to problems with non-shielded cables / connectors
  - Issues mainly caused by data lines
  - Additional shielding and grounding fixed that issue



Non-shielded measurement







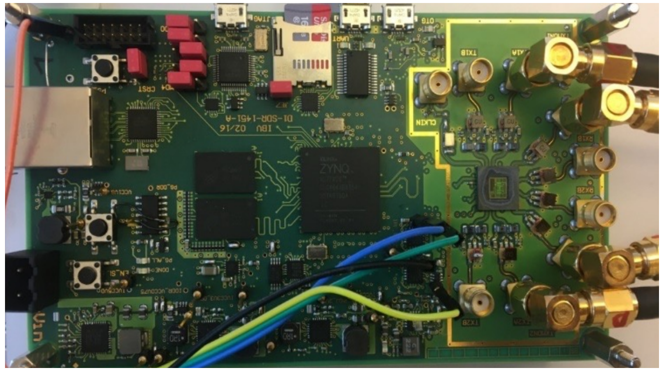
Shielded measurement

Conclusion

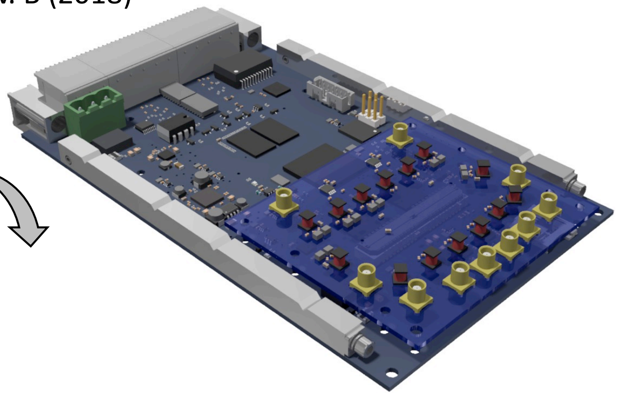
Conclusion

- Space environment is crucial for the use of COTS EEE parts, especially radiation
- Risk assessment is essential once COTS are intended or mandatory to be used
- Standards for testing and qualification are partly not a available or inconstant
- Design of a FMECA-based risk assessment approach has been presented
- Novel radiation characterization on the AD9361 RFIC (first of its kind)
- Hybrid design of using COTS and RadHard devices
- System validation at CHARM
- Satisfying error rates and test results (no heavy-ion):
    - ~1 self-recover event per day in GEO, ~8.5 days for LEO (worst case)
- Close cross-section saturation for self-recovery SEFIs for CHARM and KVI

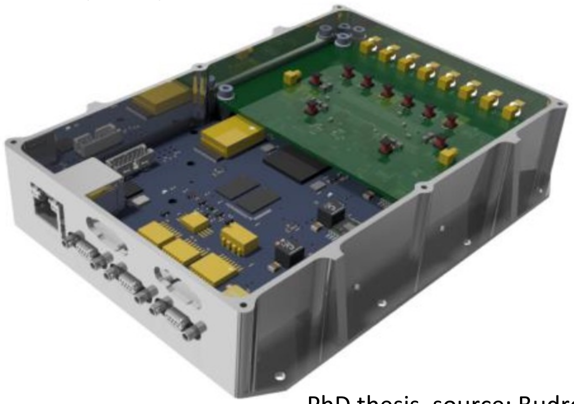
Rev. A (2015)



Rev. B (2018)



Rev. C (2019)



PhD thesis, source: Budroweit

Thanks for your attention

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