Radiation challenges and perspectives for the ESA JUICE mission

Marco Pinto
Outline

- JUICE
- Jupiter and its moons
- Jovian Radiation Environment
- RADEM
- Radiation Hardness Assurance for RADEM and JUICE
Jupiter Icy Moons Explorer

Cosmic Vision
L-class Mission

Launch in 2022

What are the conditions for planet formation and emergence of life?
- Emergence of habitable worlds around gas giants

How does the Solar System work?
- Jupiter system as an archetype for gas giants

Radiation challenges and perspectives for the ESA JUICE mission
Exploration

Galileo
1610

Pioneer 11
11/1974 – 01/1975

Voyager 2
07/1979 – 07/1979

Galileo Spacecraft
1995-2003

New Horizons
01/2007-06/2007

JUICE
2030-2033

Pioneer 10
12/1973 – 01/1974

Voyager 1
03/1979-04/1979

Ulysses
02/1992

Cassini
12/2000

Juno
07/2016-07/2021

04-Jul-19, Lisbon (PT)
JUICE S/C

- Dry mass ~1900 kg, propellant mass ~2900 kg
- High $\Delta v$ required: 2600 m/s
- Payload ~105 kg, ~150 W
- 3-axis stabilized s/c
- Power: solar array ~80 m$^2$, ~800 W
- HGA: >3 m, fixed to body, X & Ka-band
- Data return >1.4 Gb per day
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JUICE Interplanetary Cruise

7.5 years

Earth flybys (3)

Venus flyby

Mars flyby
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Jovian tour

1. Jupiter Orbit Insertion 01.2030
2. Jupiter equatorial phase #1 ~11 mon
3. Two Europa flybys 36 days
4. Jupiter high-latitude phase 260 days
including Callisto flybys
5. Jupiter equatorial phase #2 ~11 mon

Ganymede Orbit

6. Elliptic #1 30 days
7. High altitude (5000 km) 90 days
8. Elliptic #2 30 days
9. Circular (500 km) 102 days
10. Circular (200 km) 30 days

Perijoves

Callisto

Ganymede

Europa

JUICE phase

Year

2030
2031
2032
2033

...
Jupiter

Largest planet on the Solar System
Mass: $10^{27}$ kg

Large influence over the dynamics and evolution of the Solar System

79 known moons (12 found in 2018)
1 larger than Mercury
1 with a magnetosphere
3 with liquid water oceans (possibly)
And more...

Strong magnetic field
extends past the orbit of Saturn
giant accelerator (10h rotation)
Icy moons - Ganymede

Larger than Mercury:
Mass: $1.48 \times 10^{23}$ kg
Radius: 2634.1 km
Orbital distance: 1 070 400 km
Orbital Period: 7.15 days

Ice shell + ocean
Unknown thickness
Difficult to separate intrinsic and induced magnetic field

Atmosphere + ionosphere
H, O, Si, Na, H$_2$O

Dipole-like magnetic field - magnetosphere
Icy moons - Europa

Properties
Mass: $0.48 \times 10^{23}$ kg
Radius: 1560.8 km
Orbital distance: 670.800 km
Orbital period: 3.51 days

Ice shell + ocean
Induced field

Atmosphere + ionosphere + exosphere
H, O, Si, Na, H$_2$O

Sink and possible source of radiation
Icy moons - Callisto

Properties
Mass: $1.076 \times 10^{23}$ kg
Radius: 2 410.3 km
Orbital distance: 1 882 700 km
Orbital period: 16.69 days

Ice shell+Ocean
Not in orbital resonance
Induced field

Surface composition
No spatial resolution so far

Heavily cratered
Old impacts
Window to the primordial Solar System
Challenges

Power

Communication

Distance from the Sun/Earth

Temperature

Radiation

Total Ionizing Dose (TID)

Displacement Damage Dose (DDD)

Single Event Effects (SEE)

Noise
Radiation Environment

- Galactic Cosmic Rays (GCR) → Constant low flux high energy ions
- Solar Energetic Particles (SEP) → Sporadic high flux p, e- and ions
- Trapped Particles → Complex variable flux e-, p and ions
Cosmic Rays

- Constant high energy omni-directional flux
  - Low energy modulated by Solar activity
- Can cause Single Event Effects on electronics
  - Linear Energy Transfer is the Figure Of Merit

![Graph showing integral flux and dN/dE vs LET and Kinetic Energy Per Nucleus](image)
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Trapped Particles

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Jovian Magnetosphere

Radiation challenges and perspectives for the ESA JUICE mission
Radiation challenges and perspectives for the ESA JUICE mission
Trapped Particles - Models

- Models have evolved based on new data:
  - Only long-term measurements made by Galileo
  - Short-term Pioneer, Voyagers, Ulysses

- JOSE Model
  - Semi-empirical
  - Average fluxes
  - Used for the JUICE mission

Credit: S. Bourdarie @ 2014 NSREC course

>10 MeV e^-

>100 MeV protons

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Angular Variability

Butterfly profile

Sin profile

Beam profile

LPA - Local Pitch Angle
Requirements:

- **Electron detector**
  - Spectral range 300 keV – 40 MeV
  - Peak Flux $10^9 \text{ e/cm}^2/\text{s}$

- **Proton Detector**
  - Spectral range 5 MeV– 250 MeV
  - Peak Flux $10^8 \text{ p/cm}^2/\text{s}$

- **Particle Separation**
  - From Helium to Oxygen

- **Dose determination**

- **Low mass** (~3 kg currently)

- **Low power**
Stack Detector Heads

Traditional Stack Detectors
SREM, MFS, BERM...

Copper Collimator
Al/Ta Absorbers
Silicon PIN-diodes

Energy bins (MeV)

<table>
<thead>
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<th>PDH</th>
<th>EDH</th>
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<td>4-7</td>
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<td>20-35</td>
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<td>35-50</td>
<td>4-7</td>
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<td>50-80</td>
<td>7-17.5</td>
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<td>80-125</td>
<td>17.5-35</td>
<td></td>
</tr>
<tr>
<td>&gt;125</td>
<td>&gt;35</td>
<td></td>
</tr>
</tbody>
</table>

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LIP concept

Copper Collimator
- 28 holes (directions)
  - Diameter: 1mm
  - Length: 8mm

Single 505 µm Kapton absorber
- Different energy thresholds

Detection Plane (instrumented PIN diode):
- 31 sensors
  - Si Diodes
  - 4 zenithal directions
  - 9 azimuthal directions
  - 3 blind sensors
3x ASIC VATA 466 – developed specifically for RADEM

- 36 channels:
  - 4 Low-Gain
  - 32 High-Gain

- 1 MHz count rate / channel

- Programable Low and High Thresholds

- Programable Gain

- Programable Integration Time

- Coincidence Logic

- Radiation Hard
  - Based on same technology results
DDH – Proof of Concept

Geant4 simulations

- Design optimization
- Directional response
- Maximum count rate assessment
- Background removal
- Electron/proton discrimination
- Radiation Analysis (of the full instrument)

Beam Tests

- Validation of new parts functionality and coupling ASIC VATA466 + Silicon plane sensor
- Detection of electrons and protons
- Count rate
- Charge collection
Geant4 Simulations

Full geometry imported as tessellated solids via GDML with GUIMesh

(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)

Spacecraft described as Aluminum shielding equivalent

(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)
Mechanical geometries can be rather complex:
- Complicated geometries
- Large number of solids
- CAD format (STEP)

Difficult to implement via Geant4 C++ geometry classes:
- Great number of volumes
- Volumes with different complexities
- No open-source free tool to convert STEP to Geant4

FreeCAD
- General purpose 3D CAD modeler
- Open-source
- Imports CAD formats (STEP)
- Exports Mesh formats (STL, PLY)
- Supports Python

STL (STereoLithography) – Mesh format
Describes solids as series of triangles adjacent to each other enclosing the full volume. Equivalent to Geant4 tessellated solids.

GUIMesh
1. Open STEP file
2. Assign material (database + custom materials)
3. Mesh geometry (User defined precision)
4. Writes GDML

Fully developed at LIP!
Application extends to other relevant fields
Open source
(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)
DDH – Count rate

- Count rate < 1 MHz / channel
  - True even for worst-case

- Phase dependent
  - Spatial resolution
  - Direction resolution
  - Background removal

- # Proton << # electrons
  - Contamination very low

(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)
DDH – Baseline Directional Response

Directional Response depends on electron spectrum

(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)

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DDH – Background

(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)

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DDH – Beam tests

ASIC + Sensor Plane

Tests with protons and electrons @PSI
2 proton energies (PiM1)
2 electron energies (PiM1, EMC)

(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)
RADEM Development

Breadboard → Engineering Model → Engineering Qualification Model → Flight Model

- Hardware (HW)
- Software (SW)

Detectors
- Working principle
  - Energy bins
  - Directionality

- ASIC
  - Noise
  - Thresholds
  - Coincidences
  - Linearity

Same ASIC for all detectors

HG channels -> EDH and DDH

LG channels -> IDH
RADEM EM – Thresholds

Tests done at PIF (protons)

High Gain channels

100 MeV proton beam

Low Gain channels

(M. Pinto et al, submitted for publication)
Tests performed with 200 MeV protons

All pixels were analysed

Linear response on all pixels

Tests need to be extended to higher fluxes

(M. Pinto et al, submitted for publication)
RADEM EM - Coincidences

Tests done with 200 MeV protons with th EDH

Experiment

Simulation

Coincidence logic shown to work

Discrepancy due to energy cut

(M. Pinto et al, submitted for publication)
Preliminary setup
- Sr90 source
- In air
- X-Y table

Only 2 diodes measured
- Mechanical constraints

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RADEM EM - Conclusions

- Concept is validated

- Full instrument functional
  - H/W ✓
  - S/W ✓

- Detector Heads
  - Energy response ✓
  - Alignment (preliminary)

- ASIC
  - Coupling to diodes ✓
  - Trigger ✓
  - Logic ✓
  - Linearity ✓

Noise issues
From a variety of sources
Must be solved in the next models!
Radiation Hardness Assurance

Mission Radiation Environment Specification → Part Selection

Mitigation Strategy → Radiation levels estimation

Risk Assessment → Accept

Testing
Particularly problematic in Jupiter

Typical hardened component sensitivity

1 Gy = 100 rad
TID Effects

- MOSFETs
  - $V_G = V_{gd}$
  - $V_D$
  - $V_S$
  - Parasitic Path
  - Cross talk
  - $\Delta V_G_{th}$

- Bipolar Transistors
  - Electrons
  - Holes
  - n++
  - p
  - n
  - Parasitic Path
  - Cross talk
  - Parametric and Functional Failures

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TID mechanism - MOSFETs

Credit @ T. Oldham
TID mechanism - Recombination

- Calculated with several assumptions
- Empirically shown only for a small subset of cases
- Depends on bias/temperature/technology/dose rate...
- Recent indications that it might not always be true
- Extremely important for the Jovian environment

Credit @ T. Oldham

Radiation challenges and perspectives for the ESA JUICE mission
Eco60 - Components

Extensive test campaign to compare effects on different technologies
LIP - ESA Contract No: RFQ/3-13975/13/NL/PA

<table>
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<tr>
<th>Component Type</th>
<th>Reference</th>
<th>Manufacturer</th>
<th># of Parameters</th>
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<td>STRH100N10</td>
<td>STMicroelectronics</td>
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<tr>
<td>B FLASH-NAND Memory (MOS/CMOS IC)</td>
<td>MT29F32G08ABAAAWP-ITZ</td>
<td>Micron</td>
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<tr>
<td>C Transistor (Bipolar)</td>
<td>2N2222</td>
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<tr>
<td>D Analog ICs non ELDRS</td>
<td>LM124</td>
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<tr>
<td>E Analog ICs displaying ELDRS</td>
<td>LM4050WG5.0-MPR</td>
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</tr>
</tbody>
</table>

(M. Pinto et al, DOI: 10.1109/NSREC.2017.8115475)
Eco60 – Test Campaign

4 Facilities

- Campus Tecnológico e Nuclear (CTN)
- Hospital Santa Maria (HSM)
- ESA-ESTEC
- RADEF

5 irradiation campaigns

- **Co2**
  - Co60 at HDR (24 krad/hour)

- **Eb1**
  - 12 MeV $e^-$ at HDR (24 krad/hour)

- **Co1**
  - Co60 at LDR (~280 rad/hour)

- **Eb2**
  - 12 MeV $e^-$ at HDR (24 krad/hour)

- **Eb3**
  - 20 MeV $e^-$ at HDR (24 krad/hour)

Irradiation

20* krad steps irradiations up to 100 krad
Components measured before and between irradiation steps
Reference measured at several points for comparison

<table>
<thead>
<tr>
<th>Component</th>
<th>Co1</th>
<th>Co2</th>
<th>Eb1</th>
<th>Eb2</th>
<th>Eb3</th>
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<td>D</td>
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<tr>
<td>E</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

*A factor had to be applied for electron dosimetry purposes*
Eco60 – Results

Radiation challenges and perspectives for the ESA JUICE mission

(M. Pinto et al, DOI: 10.1109/NSREC.2017.8115475)
Eco60 – Results

- Clear enhanced effect in electron irradiation
- Strong evidence for DDD contribution
- Results compared to TID + DDD tests on the same component
  - DDD in ECo60 much lower
  - Different test lot
  - Same trends!
- Known presence of neutrons in LINACs

Component D: LM 124

(D. Pinto et al, DOI: 10.1109/NSREC.2017.8115475)
Eco60 – Conclusions

- 5 component types were selected for irradiation:
  - Power MOSFET (MOS)
  - Flash-NAND Memory (MOS IC)
  - Bipolar Transistor (Bipolar)
  - OPAMP (Analogue IC)
  - Reference Voltage (Analogue IC ELDRS)

- Components showed similar sensitivity to Co60 than to 12 MeV and 20 MeV electron beams

- LM 124 showed increased sensitivity to electrons
  - Electron NIEL
  - Neutrons

- Co60 is representative of worst-case scenario damage to components flown in the missions to the Jovian system
Radiation levels

TID and DDD
- Ray-tracing
  - Fast
  - Conservative
- Monte Carlo
  - Includes Physics
  - Accurate
  - Slow

Level < Sensitive*RDM
Several shielding options

SEE
- LET based calculations
- GCR LET spectrum
- Proton belts/solar (same as TID) + LET spectrum

Impact is application dependent
No shielding

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129 sensitive components

Total shielding mass ~2kg

SpaceWire Transceiver
- Responsible for communication
- 100 krad sensitivity
- TID level = 112.39 ± 1.03 krad
- RDM=2
- Only at the end of the mission
- Redundant!
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SRAM is the weakest link

Average error rate: 29.3 (bit.day)$^{-1}$
(worst-case trapped protons)

EDAC and scrubbing

Data flow from ASIC to S/C

- ASIC data size full at max rate in 5s
- Data is stored in SRAM
- S/C receives data every 30s
- Bits must be read or written for EDAC to correct errors

$P(k, t) = e^{-rt} \frac{rt^k}{k!}$

- $P$ is the probability of exactly $k$ errors occurring in time $t$
- $r$ is the average error rate
- $t$ is the time in days
- $k$ is the number of errors
Conclusion

- RADEM is being developed and is now moving on to the EQM

- It fulfills all requirements

- Although there are some delays it is still within mission schedule

- Main concern are the ASIC radiation sensitivity

- And the noise...
Interplanetary radiation environment
- Jupiter is the main source of electrons in quiet times!
- SEPs at different A.U. with multiple instruments
- Forbush decrease during ICME

Extend Jovian system radiation models to higher energies with actual data
- Better engineering models (dynamical)
- Better understanding of the acceleration processes

Study Ganymede radiation belts
- First long-term modelling
- Coupling to the Jovian radiation belts

Interaction of radiation with the moons
- Sputtering
- Exchange of materials between surface and the environment

Synergy between plasmas and high energy particles with RADEM and PEP... and also JMAG
Future Work

- EQM and FM calibration
- ASIC testing
- Development of flux reconstruction algorithms
- In-flight data analysis
- Cross-calibration in Earth flybys
- SEP analysis during cruise phase
- Jovian Radiation environment data analysis and model construction
- And more for over a decade of time
- ECo60 and GUIMesh can also benefit from more exploration
Thank you

Questions?
dN/dE=k

(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)
DDH – Baseline Directional Response

\[ dN/dE = k \]

(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)