A radiation-hardened μHz-range 24-bit 2.5-mW Digital-to-Analog Converter

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Contents

• introduction, requirements
• sigma-delta modulator
• switched-capacitor stage
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• measurement results
• conclusions
Introduction

• ESA Exomars mission
• Humboldt payload
• Seismic measurement system
• SHAMROC chip (by SRON)
• DAC (by Axiom IC)
## Key DAC requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
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</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>10 µHz – 50 Hz</td>
</tr>
<tr>
<td>SNR (0.1 Hz-50 Hz)</td>
<td>&gt; 110 dB (&gt;18 ENOB)</td>
</tr>
<tr>
<td>Temperature stability</td>
<td>&lt; 3 ppm/K (-55 – +35°C)</td>
</tr>
<tr>
<td>TID</td>
<td>6.2 krad</td>
</tr>
<tr>
<td>SEE</td>
<td>50 MeV·cm²/mg</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt; 6 mW</td>
</tr>
<tr>
<td>Technology</td>
<td>UMC 0.18 µm CMOS</td>
</tr>
</tbody>
</table>
DAC overview
Recursive $\Sigma\Delta$ modulator

- $\Sigma\Delta$: high resolution
- recursive modulator with weighted DAC elements:
  - low out-of-band noise
  - robust against mismatch
Recursive $\Sigma\Delta$ modulator (cont.)
Switched-capacitor DAC

- high temperature stability
- low 1/f noise
- radiation hard:
  - hardly any radiation effect on (metal) caps
  - parameter shift in switches has no effect (provided settling remains sufficient)
  - leakage around switches to be solved in layout
Radiation hardening: digital part

• use DARE kit
Radiation hardening: analog part

- Switched capacitor
  - robust against TID
  - no memory in analog part of circuit
- Guard rings to protect against latch-up
- STI avoids leakage, so ELT or H-shaped transistors not necessary
Chip photograph

area: 2.22 mm$^2$
Measurement results

- power consumption: 2.5 mW
- linearity well within spec
- output noise OK: 126 dB DR (0.1 – 50 Hz)
Measurement results (cont.)

- temperature coefficient: -1.5 ppm/K
Total ionizing dose (TID) test setup

• tested with $^{60}$Co source

• one reference device: 0 krad
• five devices: up to 16 krad
• five other devices: up to 409 krad

• measured all DACs after 0, 1, 3 and 9 days, and after annealing and accelerated ageing
Total ionizing dose (TID) test results

• low dose rate devices: no effects
• higher dose rate devices:
  • no effects up to 136 krad
  • at 409 krad:
    • higher offset (300 µV)
    • slightly higher noise
• DACs returned to normal behaviour after accelerated ageing (7 days @ 100°C)
Single-event effects (SEE) test setup

• preliminary CASE tests (with $^{252}$Cf source)

• no tests with particle accelerator
Single-event transient (SET) test results

- measured DAC output voltage
- 2 devices; 60 hours of testing each
- two transients detected (possibly SET)
- both occasions: spike < 5 µV (~2.5 ppm relative to full scale)
Single-event upset & latch-up (SEU & SEL)

- total testing: 13 days
- $144 \cdot 10^6$ digital values checked
- all correct $\Rightarrow$ no SEU
- $10^9$ measurements of supply current
- supply current always within limits $\Rightarrow$ no SEL
## Key measurement results

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Requirement</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>&gt; 110 dB (18 ENOB)</td>
<td>&gt; 126 dB</td>
</tr>
<tr>
<td>Temperature stability (-55 – 35°C)</td>
<td>&lt; 3 ppm/K</td>
<td>±1.5 ppm/K</td>
</tr>
<tr>
<td>TID</td>
<td>&gt;6.2 krad</td>
<td>no effects @133 krad</td>
</tr>
<tr>
<td>SEE</td>
<td>&gt;50 MeV·cm²/mg</td>
<td>&gt;43 MeV·cm²/mg</td>
</tr>
<tr>
<td>Power cons.</td>
<td>&lt; 6 mW</td>
<td>2.5 mW</td>
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Spin-off

Humboldt payload canceled, but DAC development continued:
• improvements:
  • added chopping (lower 1/f noise & offset)
  • temperature stability now even better
• wider application area
  • higher $f_s \rightarrow$ suitable for high-bandwidth instrumentation and control
Conclusions

High-resolution DAC
• new concepts demonstrated
• >20 ENOBs
• low temperature coefficient
• low 1/f noise
• robust against radiation
• scalable
• wide application area (low latency, low OOBN)