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

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- sigma-delta modulator
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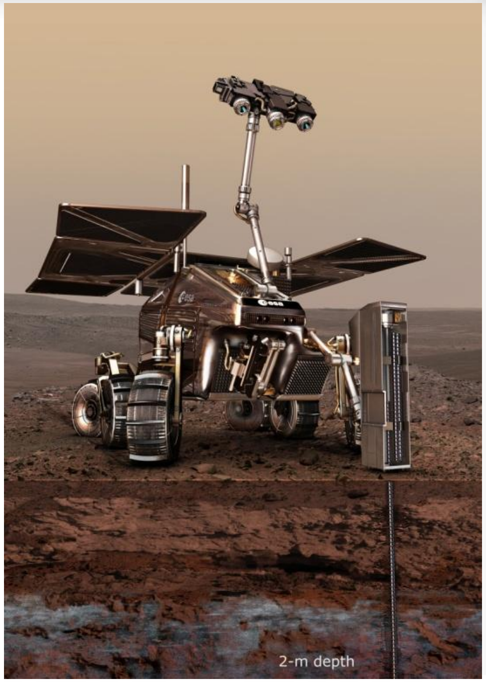
Introduction

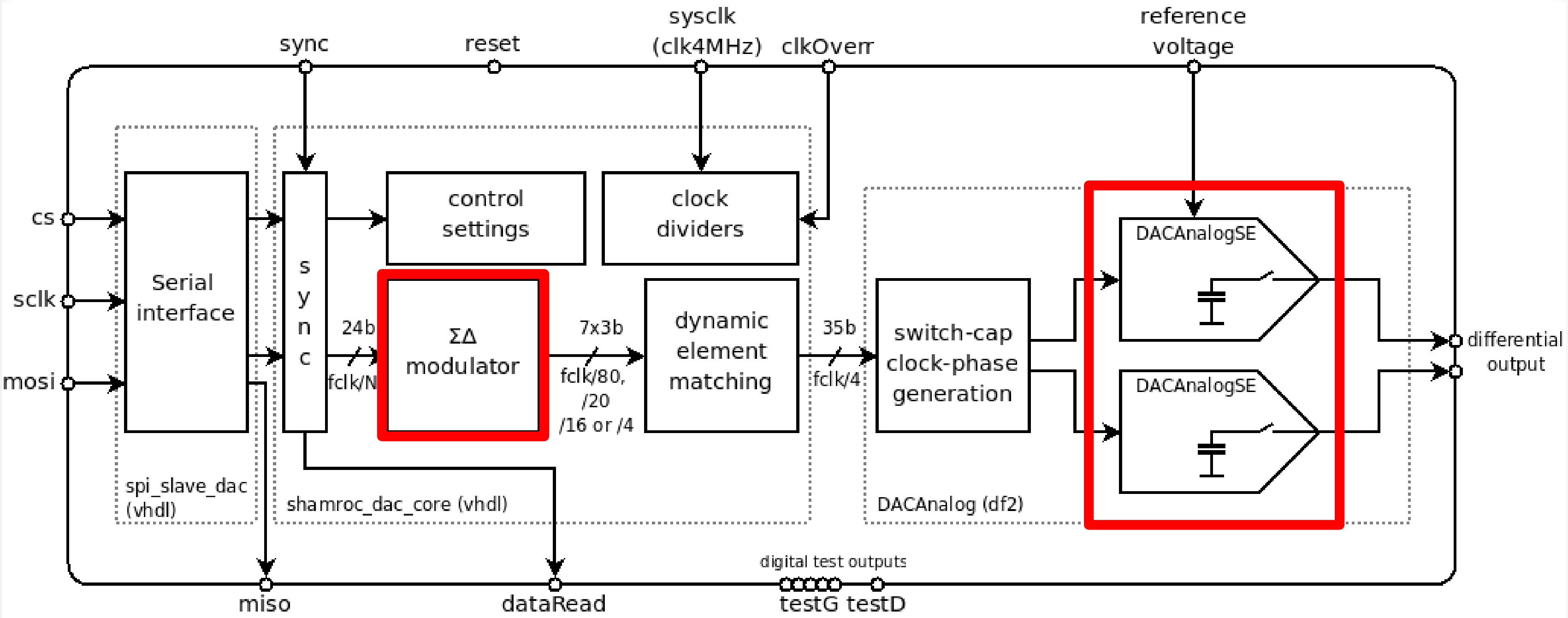
- ESA Exomars mission
  - Humboldt payload
    - Seismic measurement system
      - SHAMROC chip (by SRON)
        - DAC (by Axiom IC)



Key DAC requirements

Frequency range	10 µHz – 50 Hz
SNR (0.1 Hz-50 Hz)	> 110 dB (>18 ENOB)
Temperature stability	< 3 ppm/K (-55 – +35°C)
TID	6.2 krad
SEE	50 MeV·cm^2/mg
Power consumption	< 6 mW
Technology	UMC 0.18 µm CMOS

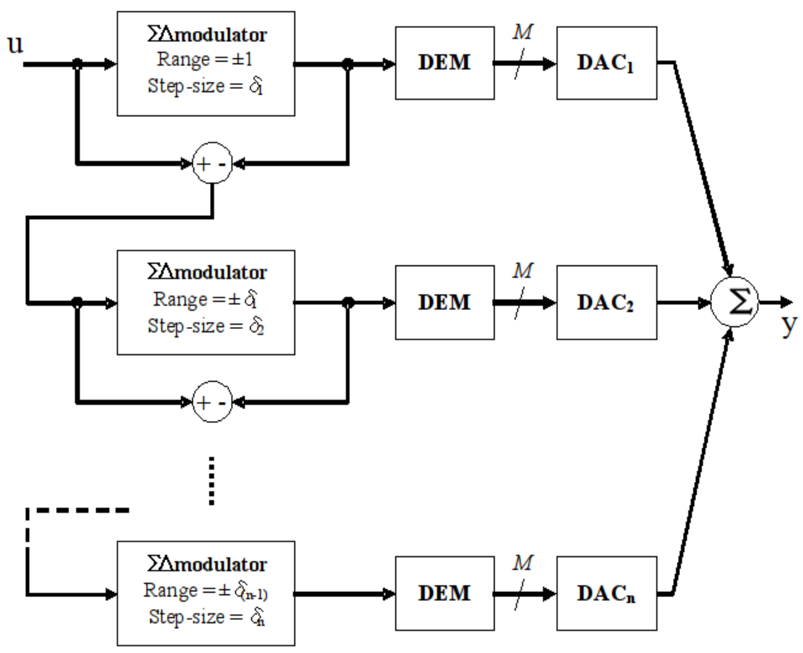
DAC overview

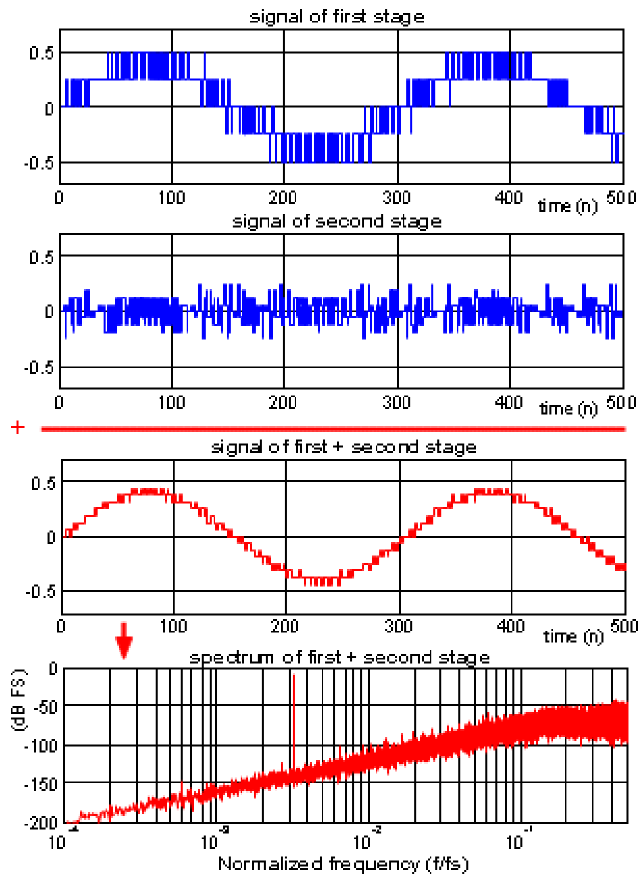


Recursive ΣΔ modulator

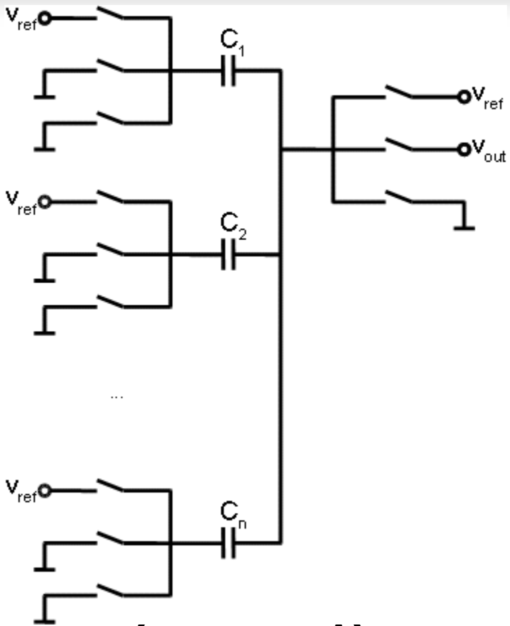
- ΣΔ: high resolution
- recursive modulator with weighted DAC elements:
    - low out-of-band noise
    - robust against mismatch

Recursive ΣΔ modulator (cont.)





Switched-capacitor DAC

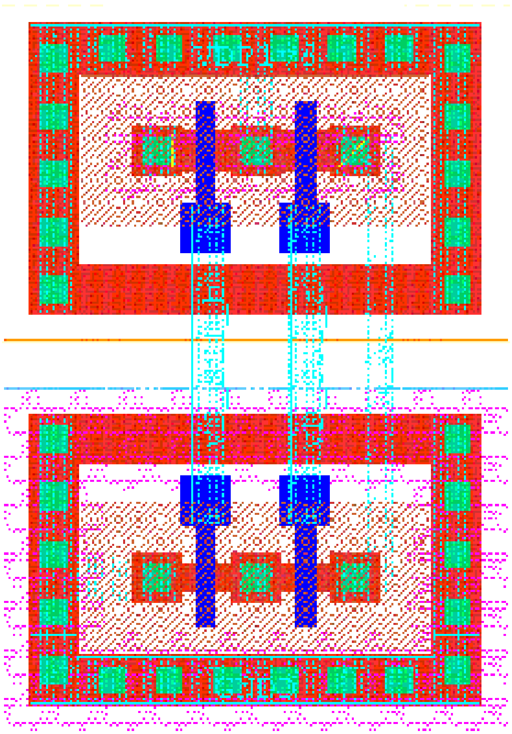


- high temperature stability
- low 1/f noise
- radiation hard:
  - hardly any radiation effect on (metal) caps
  - parameter shift in switches has no effect (provided settling remains sufficient)
  - leakage around switches to be solved in layout

Radiation hardening: digital part

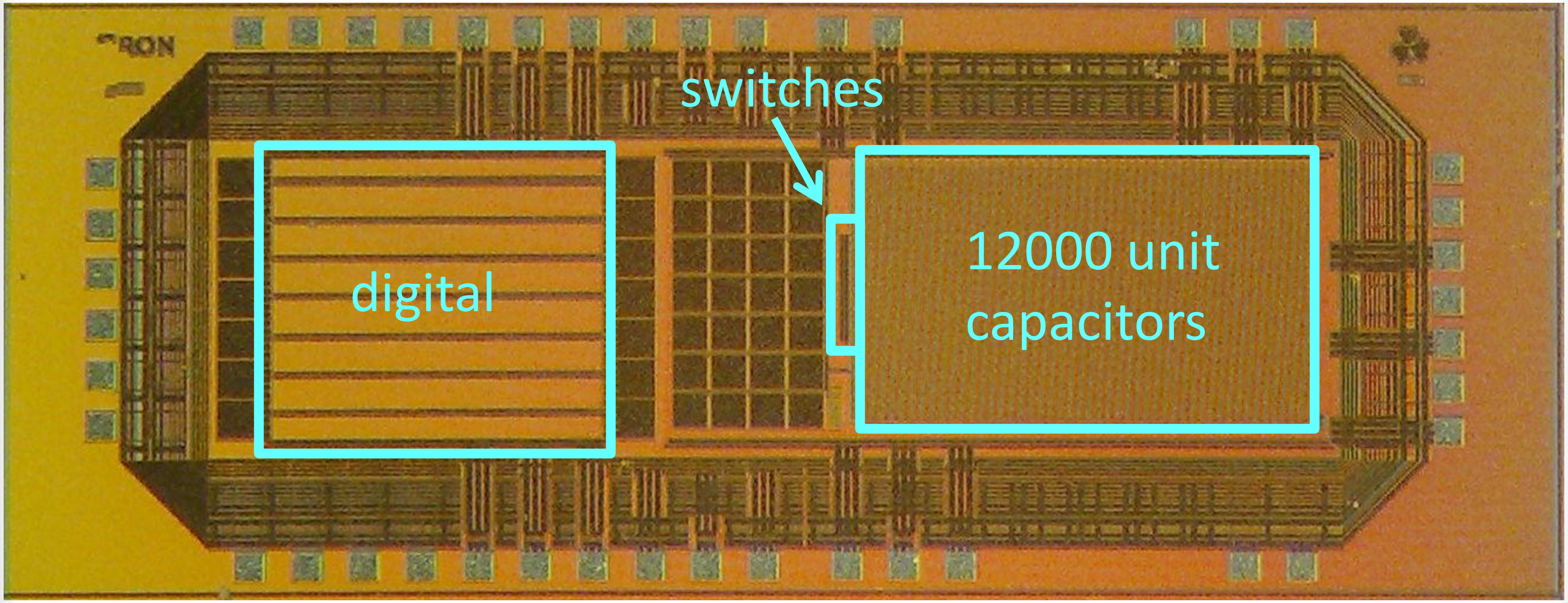
- use DARE kit

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

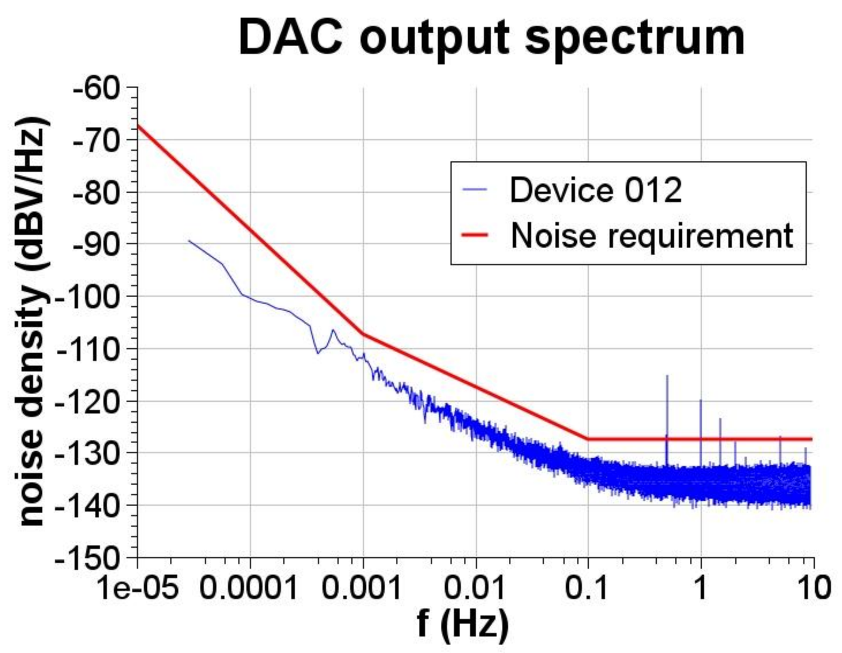
Chip photograph



area: 2.22 mm^2

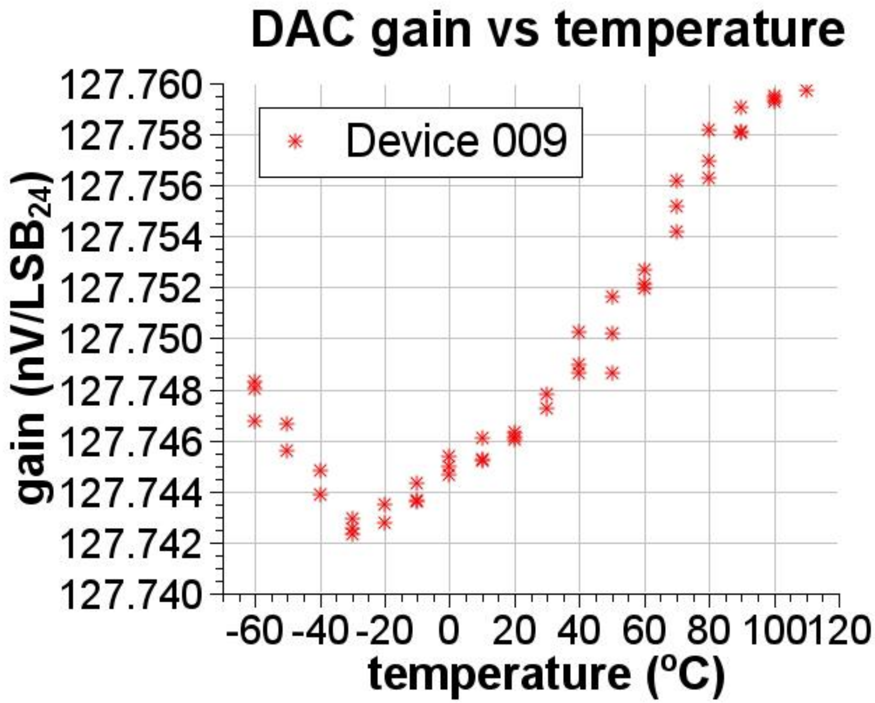
Measurement results

- 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

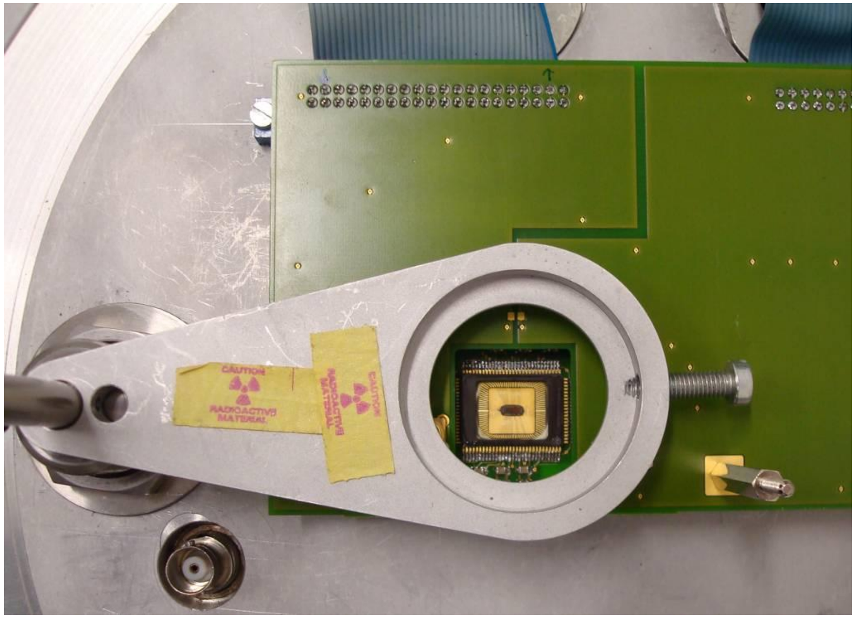
- measured all DACs after 0, 1, 3 and 9 days, and after annealing and accelerated ageing

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 → no SEU

- 10^9 measurements of supply current
- supply current always within limits
  → no SEL

Key measurement results

	Requirement	Result
SNR	> 110 dB (18 ENOB)	> 126 dB
Temperature stability (-55 – 35°C)	< 3 ppm/K	±1.5 ppm/K
TID	>6.2 krad	no effects @133 krad
SEE	>50 MeV·cm²/mg	>43 MeV·cm²/mg (preliminary CASE)
Power cons.	< 6 mW	2.5 mW

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 → 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)

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