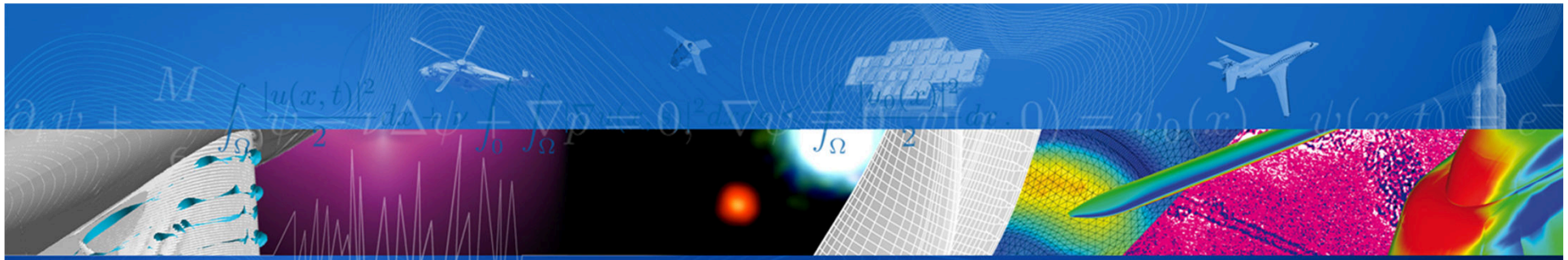

Towards Space Qualification for Quartz MEMS inertial sensors

Jean Guérard, Raphaël Lévy, Béatrice Bourgeteau, Pierre Lavenus, Denis Janiaud, Olivier Le Traon

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Physics and Instrumentation Department

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ONERA
THE FRENCH AEROSPACE LAB

return on innovation

9th ESA Round Table on Micro and Nano Technologies for Space Applications
10-13 June 2014, Lausanne

Outline

- Coriolis Vibrating Gyros
- Piezoelectric CVG at ONERA
- VIG generation, State of Art
- Start of qualification in NEOSAT program
- Next generations of vibrating structures

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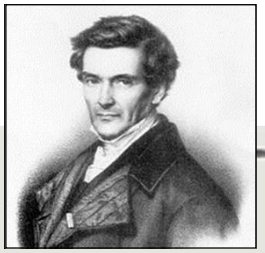
Coriolis effect (1835)

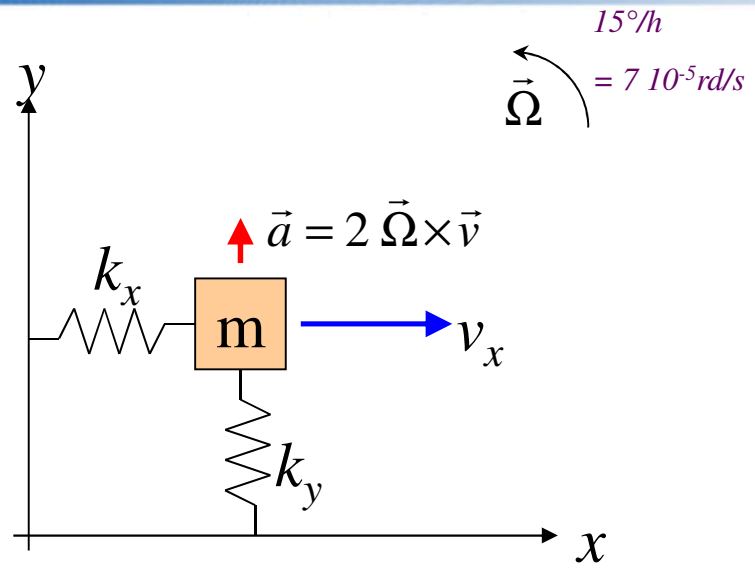


MÉMOIRE

Sur les équations du mouvement relatif des systèmes de corps;

PAR G. CORIOLIS.

Dans un Mémoire qui fait partie du XXI^e Cahier du *Journal de l'École Polytechnique*, j'ai montré que pour appliquer le principe des forces vives aux mouvemens relatifs des systèmes entraînés avec



$$\begin{cases} \ddot{x} + \dfrac{\omega_{0x}}{Q_x}\dot{x} + \omega_{0x}{}^2 x - 2\Omega\dot{y} = \dfrac{F_x}{m} \\ \ddot{y} + \dfrac{\omega_{0y}}{Q_y}\dot{y} + \omega_{0y}{}^2 y + 2\Omega\dot{x} = \dfrac{F_y}{m} \end{cases}$$

Use of resonators

- Along x : Drive

  confine the motion locally
  isolate the system from external perturbation

- Along y : Sense

  amplify the detection

→ sensor

CVG Coriolis Vibrating Gyro

Resonator configuration

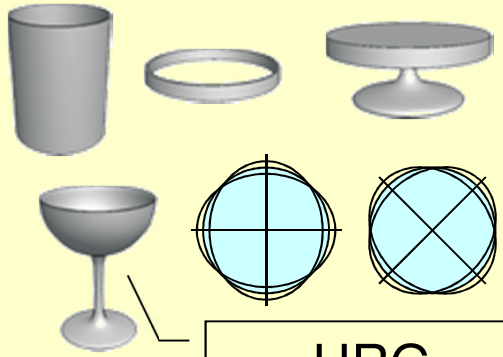
$$\begin{cases} \ddot{x} + \frac{\omega_{0x}}{Q_x}\dot{x} + {\omega_{0x}}^2 x - 2\Omega\dot{y} = \frac{F_x}{m} \\ \ddot{y} + \frac{\omega_{0y}}{Q_y}\dot{y} + {\omega_{0y}}^2 y + 2\Omega\dot{x} = \frac{F_y}{m} \end{cases}$$

Type I

Revolution Symmetry

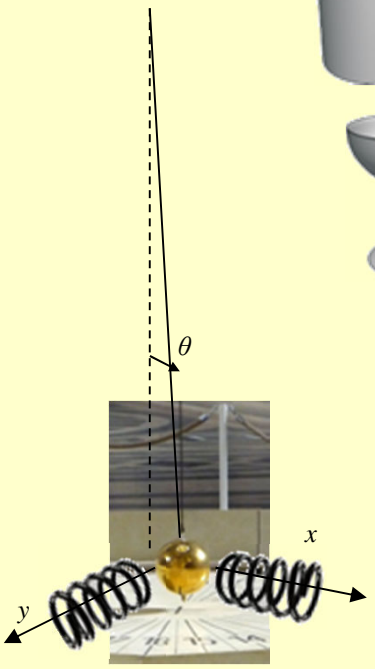
→ Identical modes $F_{0x} = F_{0y}$ (and $Q_x = Q_y$)

→ Whole angle mode



HRG

G.H. Bryan, 1890

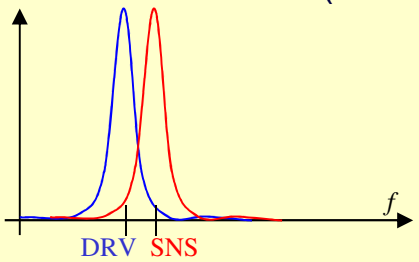


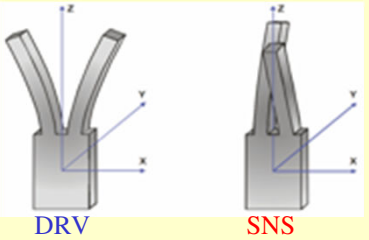
[Foucault 1851]

SAGEM REGYS 20

Type II

2 different modes (or more)

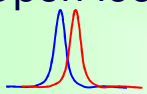




- Excitation at F_{DRV}
  → X high
  Y does not amplify
  Y small

Excitation at F_{SNS}
→ X small
Y amplifies
Y small

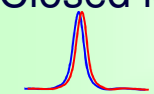
Open loop



$$\frac{Y}{X} = \frac{1}{\Delta\omega}\Omega$$

- Limited BW
- Reduced gain

Closed loop



$$\frac{F_y}{F_x} = \frac{2Q}{\omega_0}\Omega$$

- BW OK
- Gain ++
- ⚠ $\omega_{0x} = \omega_{0y}$ with T

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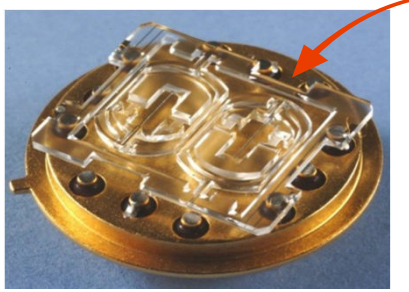
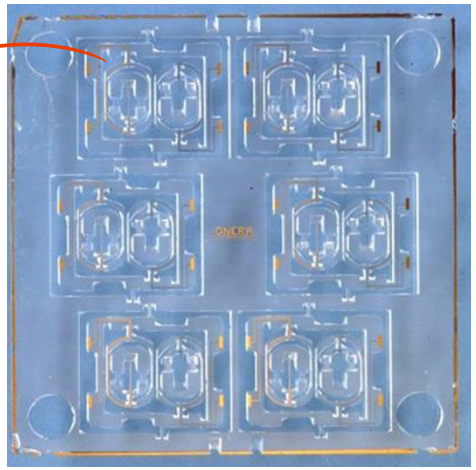
Piezoelectric vibrating inertial sensors at ONERA

- **Flat monolithic sensors manufactured by collective etching**
- **High quality piezoelectric crystal : Quartz**

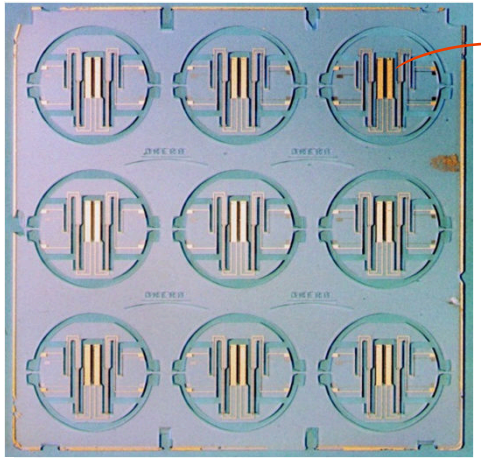
→ Performances : high stability of crystalline structures
→ Non dependence (watch industry)
→ Piezoelectric action & detection



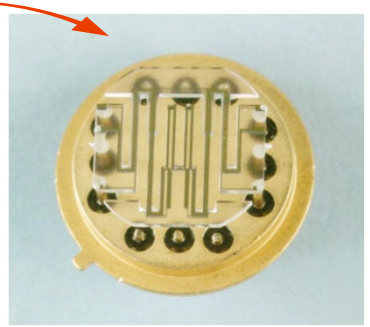
DIVA accelerometer



Quartz Wafer (1,5"x1,5") with 6 DIVA accelerometers

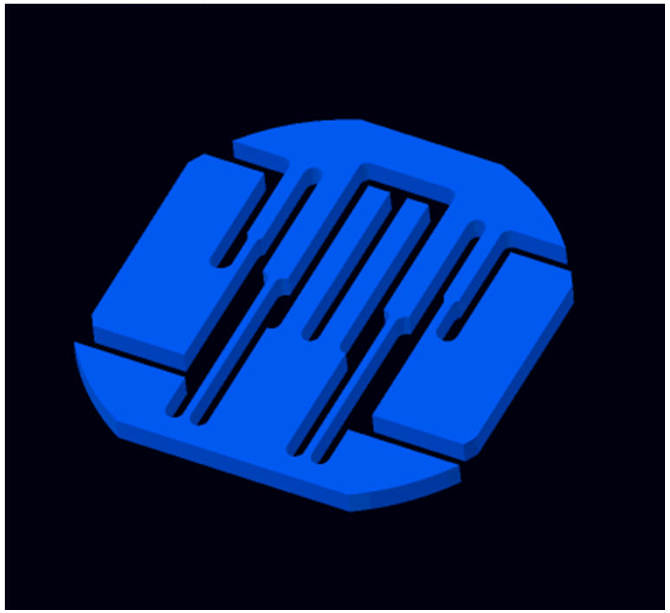


Quartz Wafer (1,5"x1,5") with 9 VIG Gyros

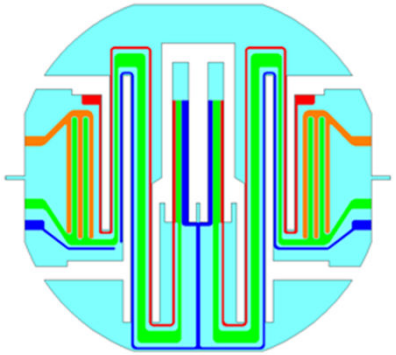


VIG Gyro

VIG Quartz cell

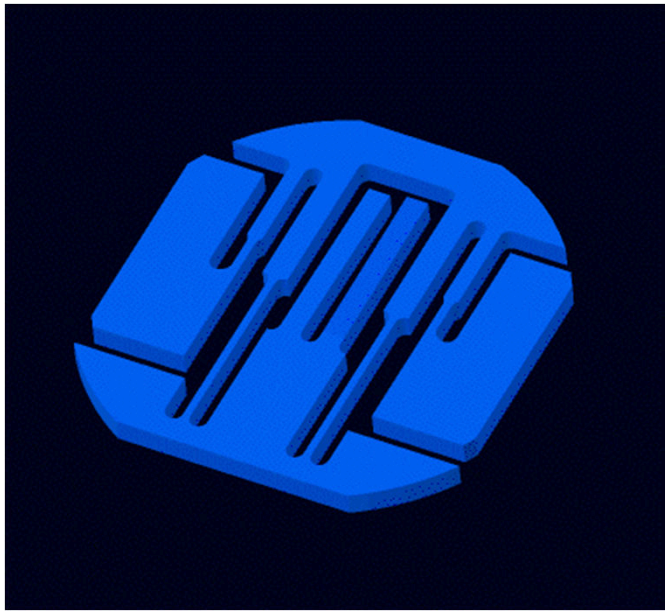


Vibrating Integrated Gyro



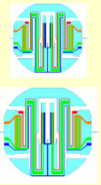
Patent 1999

DRIVE SENSE



F.E. simulations with OOFELIE from Open Engineering

- Integrated decoupling frame
  - Q = 150000 scale 1, Ø 10 mm
  - Q = 200000 scale 4/3, Ø 13 mm



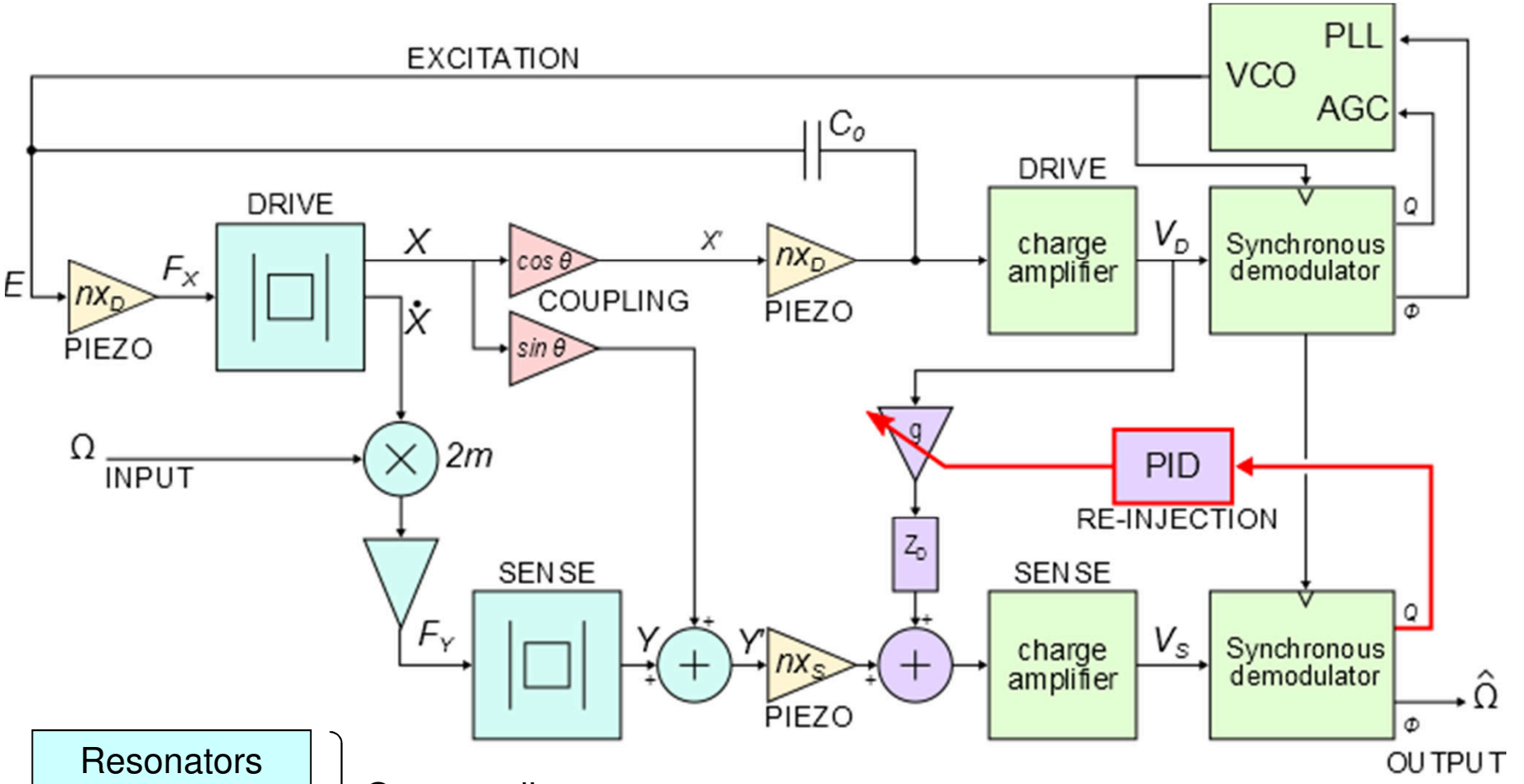
- Electrodes pattern
  - Full differential EXC, DRV, SNS
  - Capacitive coupling reduction

Patent 2009

- Electrostatic combs
  - Compensate for Excitation capacitive coupling
  - Drive phase accuracy at resonance

- **Performances limited by mechanical coupling**
  - Slanted Drive vibration
  - ➔ projection of Drive in the Coriolis Detection

Associated Electronic Architecture



Resonators

Piezoelectricity

Electronics

} Quartz cell

- Quadrature error (mechanical coupling) compensated by electronics
- No trimming on quartz

Outline

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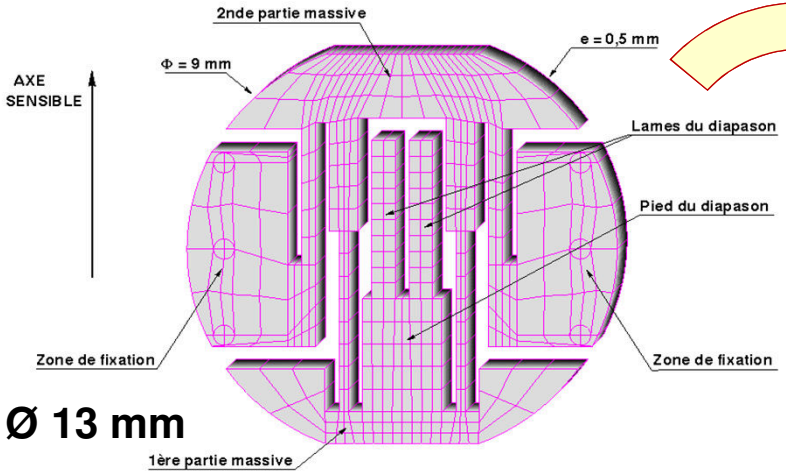
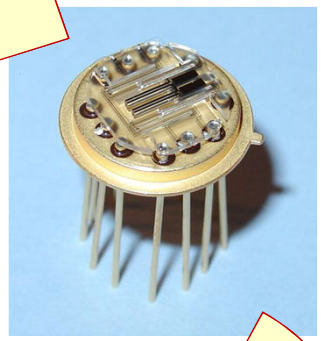
VIG integration

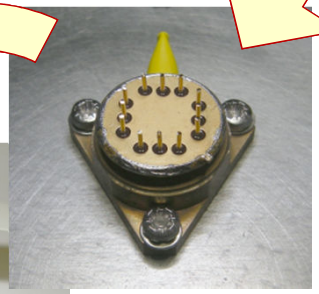


Monolithic structure

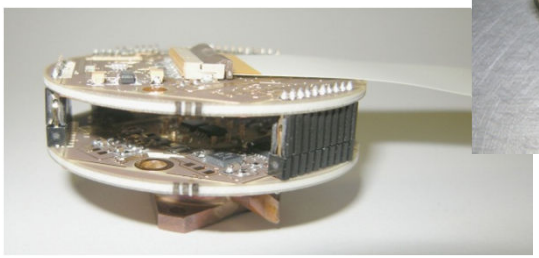


Current prototype

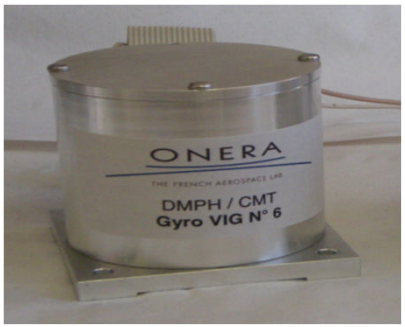
- 16 g Cell + Copper case
- 10 g local electronics
- 40 mm diameter
- 20 mm height
- Single 3.3 V supply
- Digital link with host (UART)



Vacuum packaging



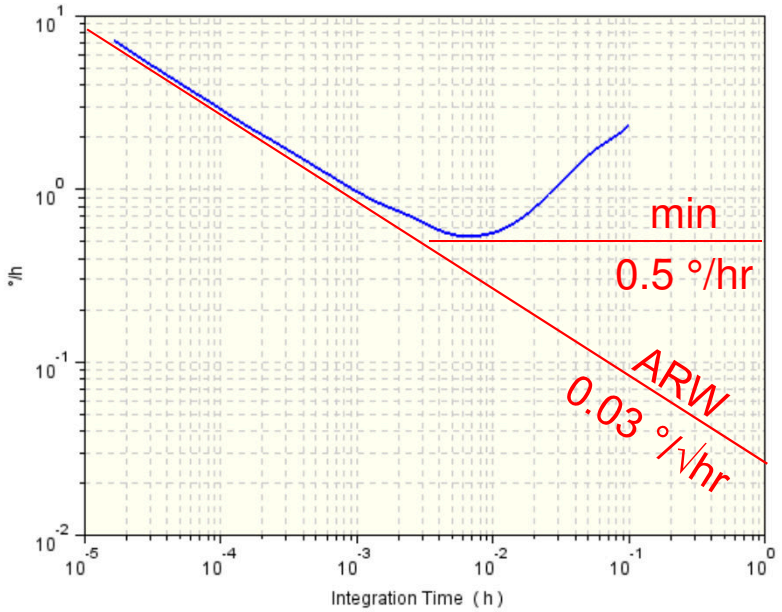
Electronics



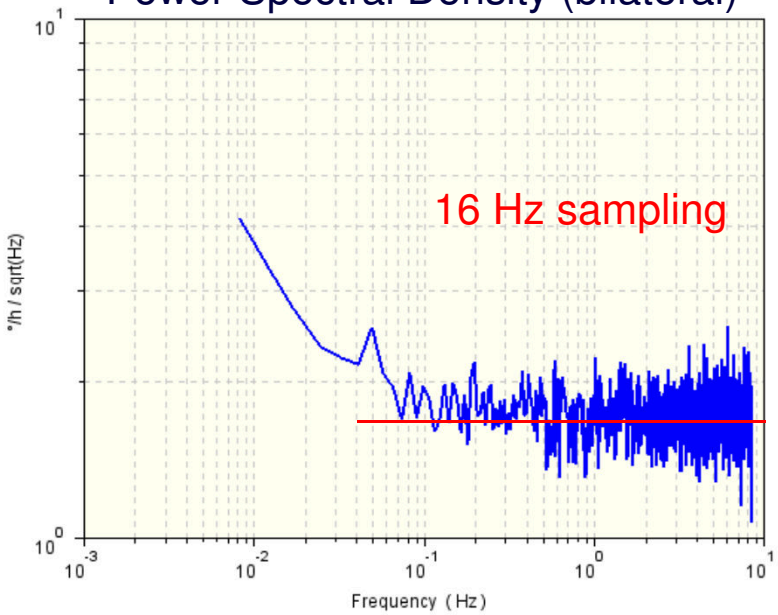
Lab prototype

Noise performance

Allan variance

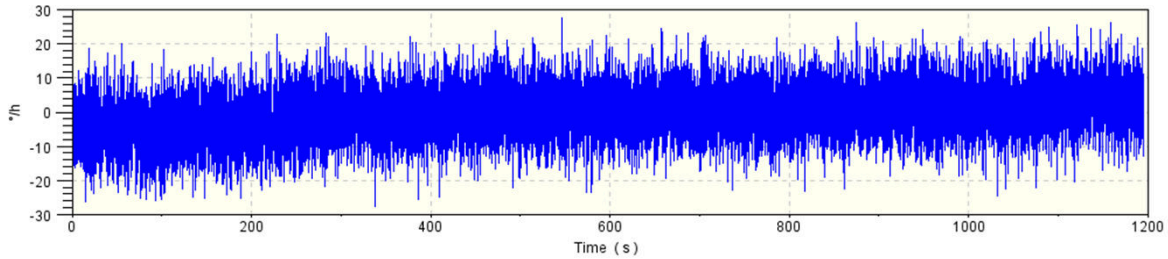


Power Spectral Density (bilateral)

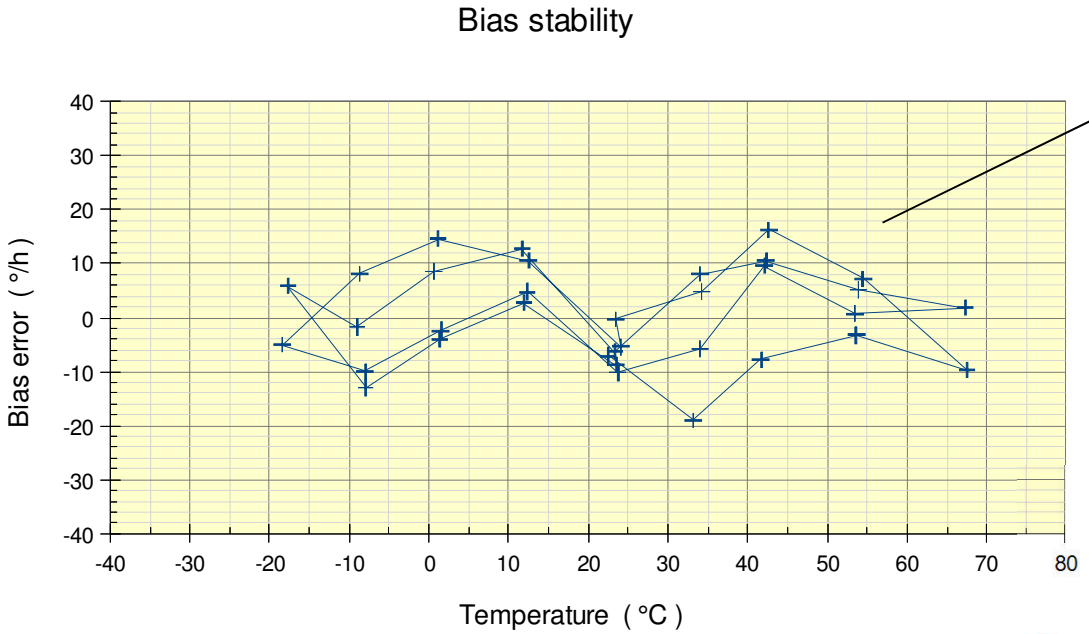


0.03 °/√hr ≡ 1.8 °/h / √Hz (bilateral)

≡ 2.5 °/h / √Hz (unilateral)



Bias performance



Standard deviation

9°/h rms

After thermal model

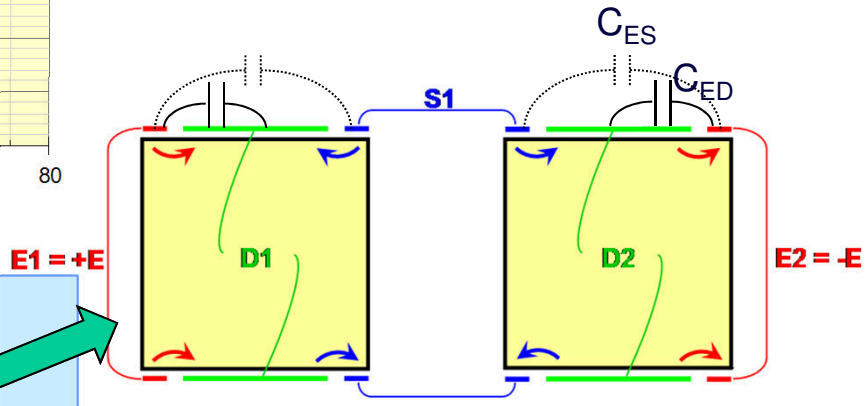
Thermal cycling : -20 -- +70 °C
2 last cycles

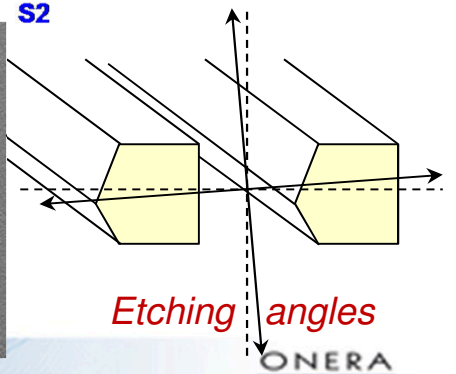
- Cleaned circuits
- Vacuum pumped electronics

In order to reduce capacitive coupling residuals

- Fine tuned re-injection

In order to reduce Mechanical coupling residuals





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- VIG generation, State of Art
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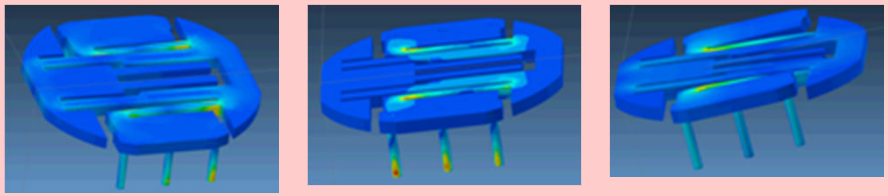
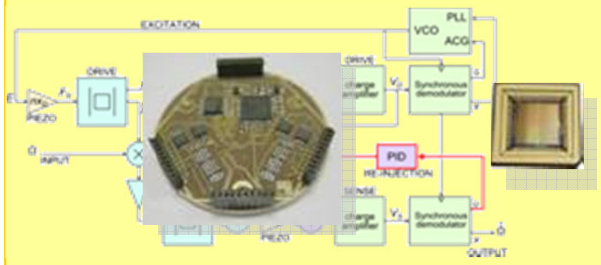
GEOGYRO : 2013 - … NEOSAT program
ASTRIUM & TAS prime

Application : low cost gyro (NEOSAT is… cost-driven)
assistance to Star Tracker, de-tumbling

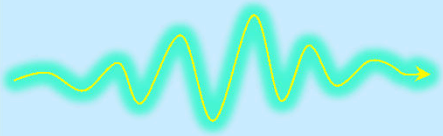
Evaluate the mechanical robustness of the cell (vibration and shocks)

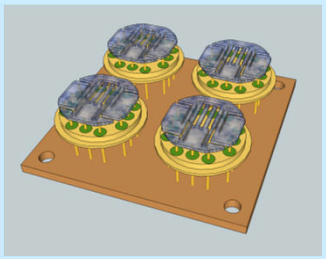


Silicon technologies and qualified ASIC design and realization



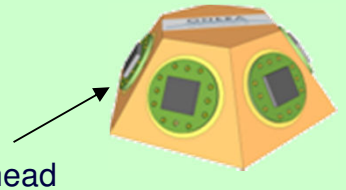
Radiation test (dose) on the quartz cell





Implementation of the gyro application (software) in the OBC

Single 3.3 V
SpaceWire link
3 gyros together in a single sensor head
Embedded software



➔ *Pre-development, Phase I executed*

Stress experimental determination

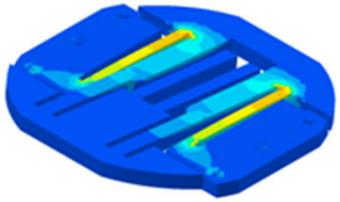
- Measure suspension modes accurately

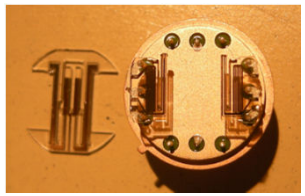
1743 Hz, 3047 Hz

OK OK

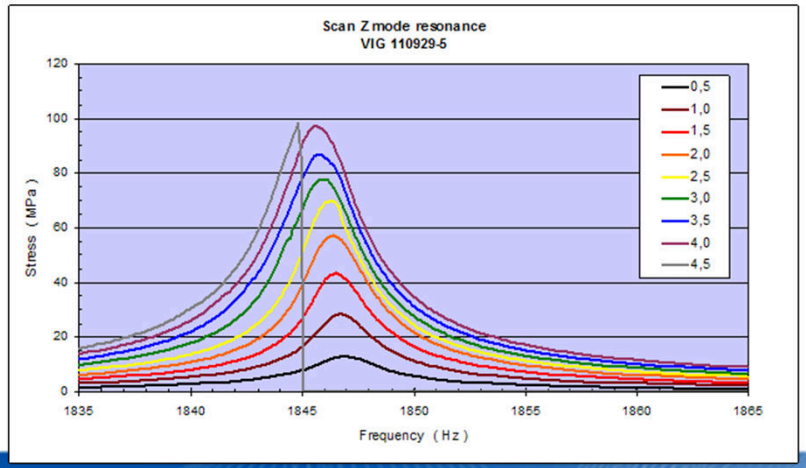
- Install on shaker

Finite Elements Prediction





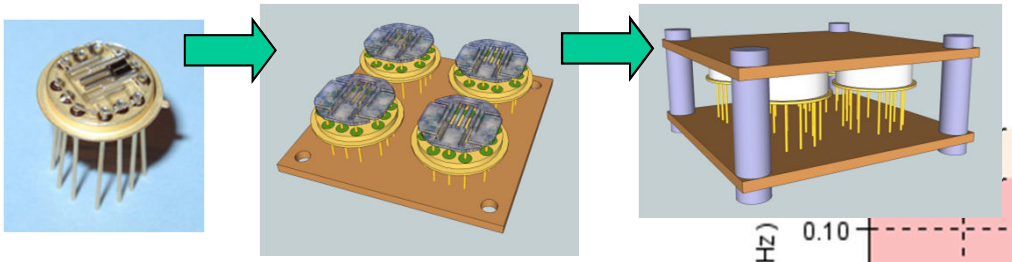
- Scan resonance, increasing amplitude

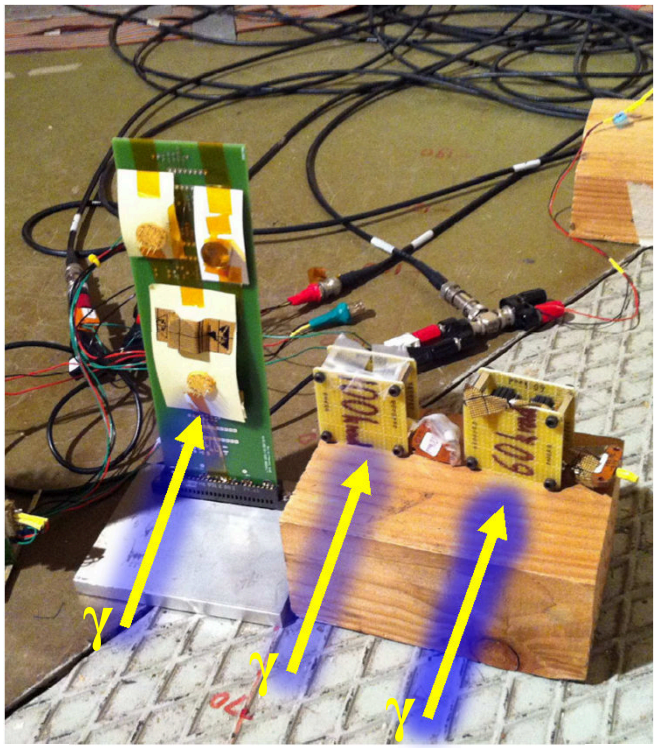


Test result just below specifications :
Sine : 1000 g, 22-100 Hz
Noise : 360 g rms
Shock : 500 g, 180µs

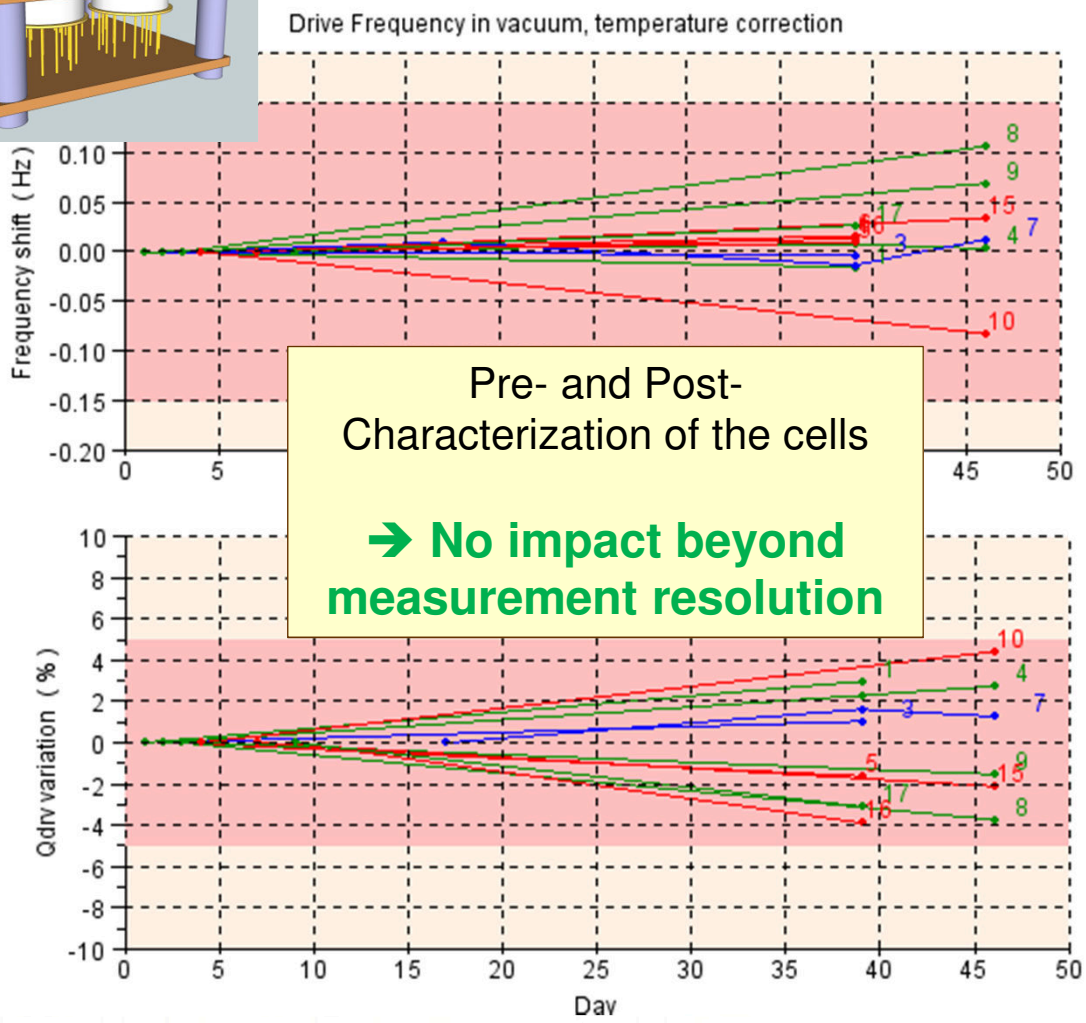
➔ **OK with Elastomer absorber (Smactane™)**

Radiations, up to 100 krad





Co60 source from Université Catholique de Louvain la Neuve UCL (Belgique)



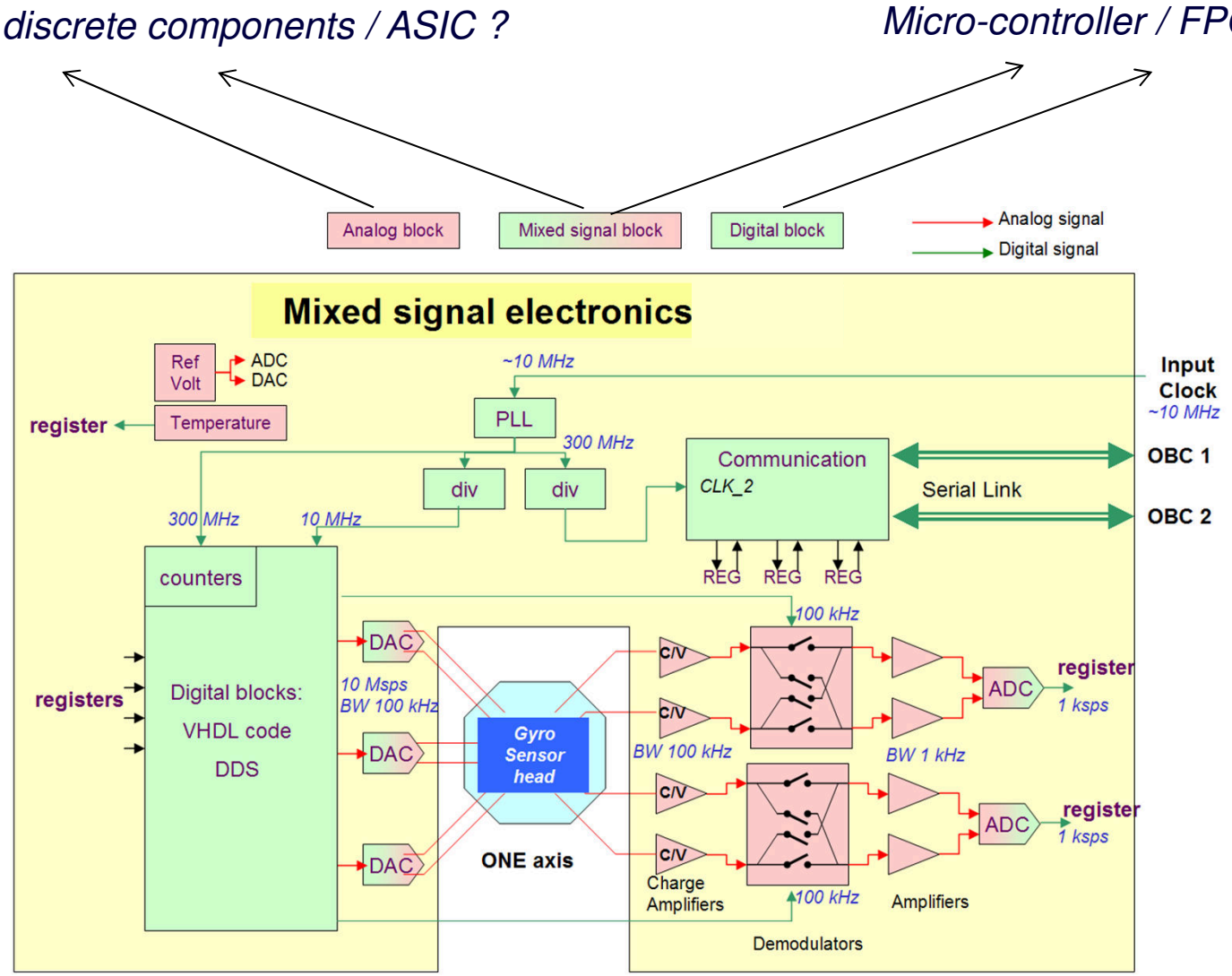
Pre- and Post-Characterization of the cells

➔ **No impact beyond measurement resolution**

Electronic description (low level)

discrete components / ASIC ?

Micro-controller / FPGA ?

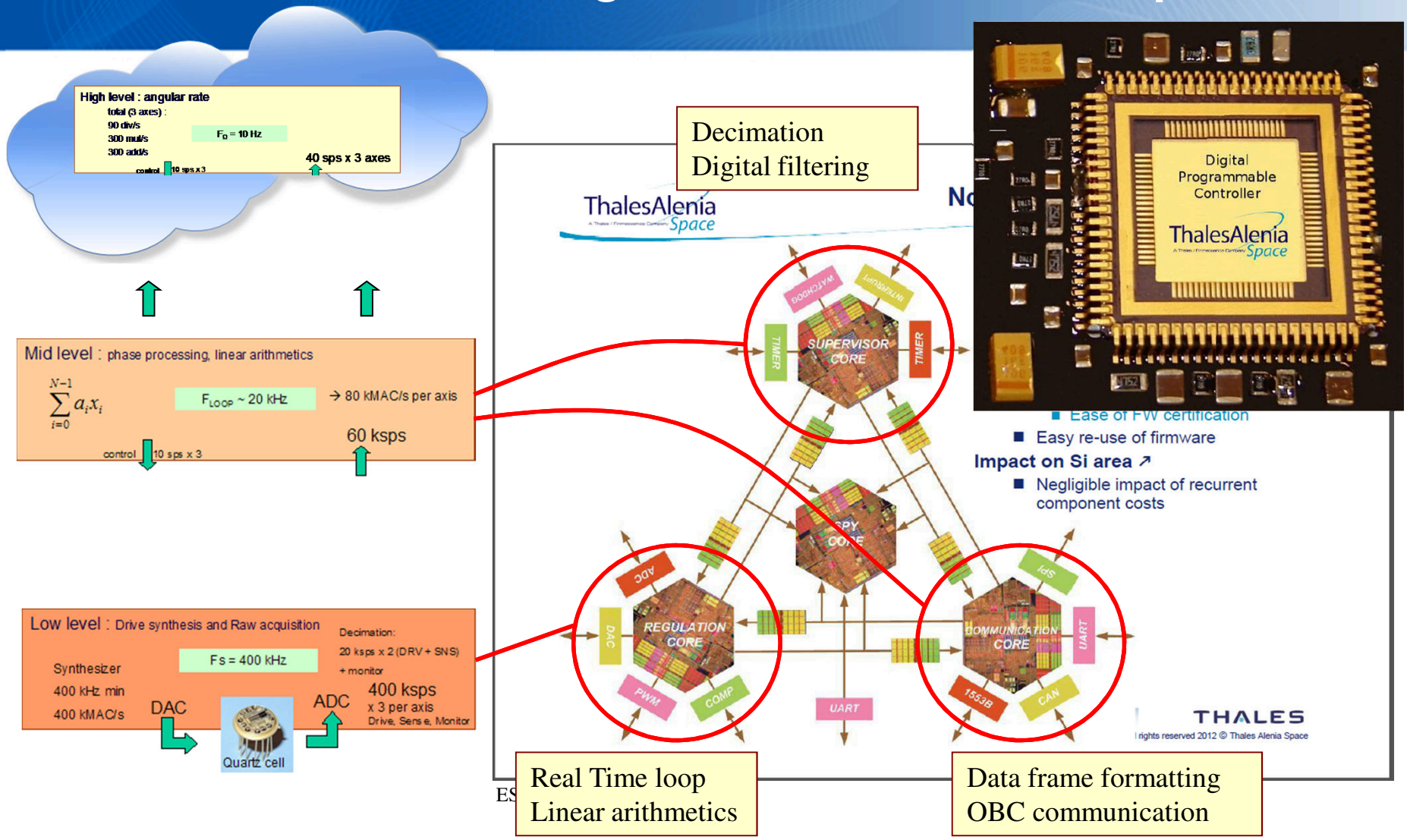


Charge amplifiers are challenging in an ASIC

Little analog circuits if external discrete components

ASIC expensive, not worth the size reduction

Micro-controller investigations : ThalesAlenia Space DPC



Current Status : build a demonstrator

(Backup with FPGA)

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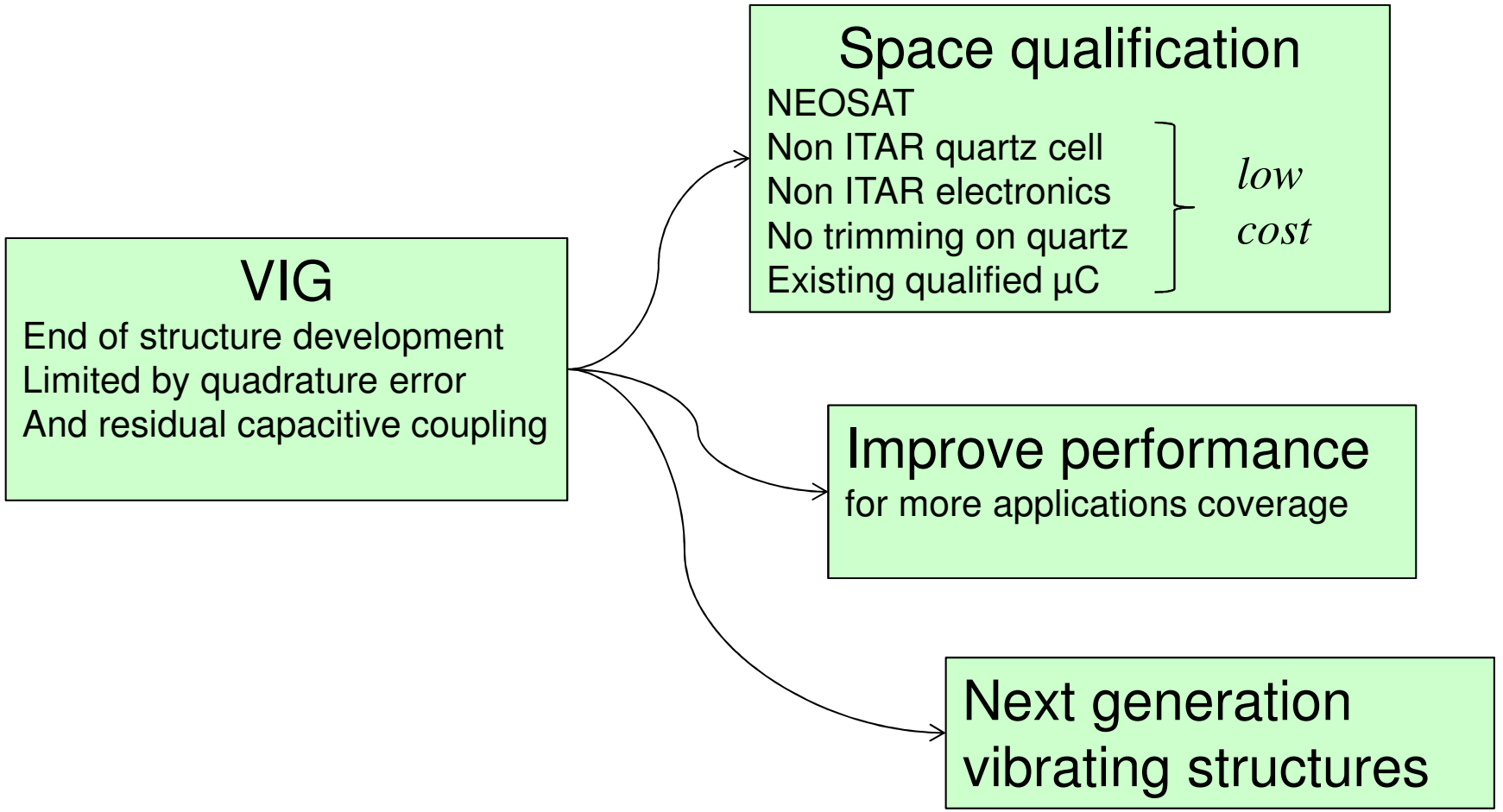
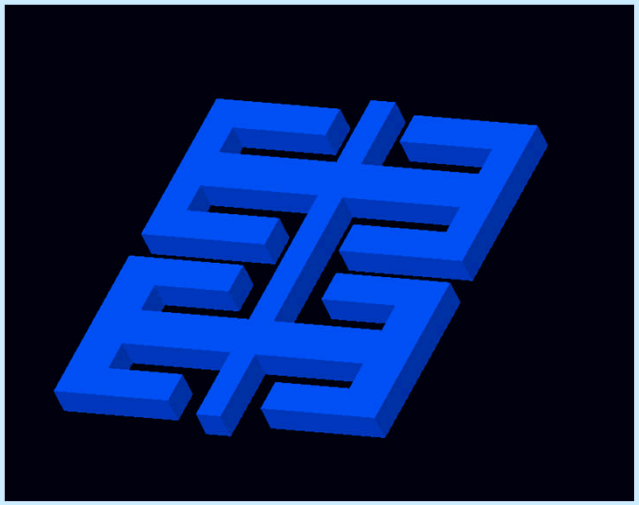
ONERA Roadmap

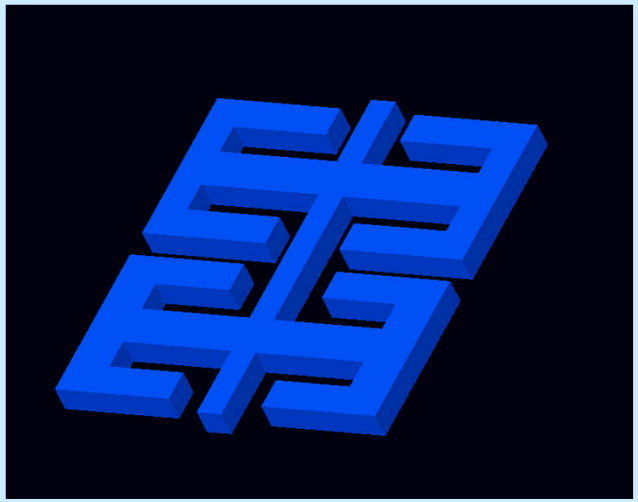


New Vibrating Structure : VIGTOR

- Next generation of vibrating structures (ONERA patent) :
  Designed without (nominal) quadrature error



DRIVE



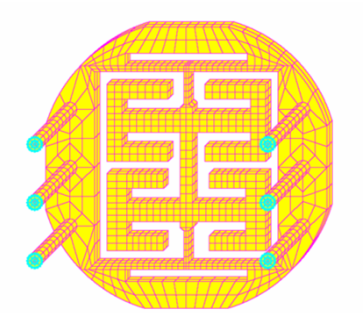
SENSE

Use of a torsion mode

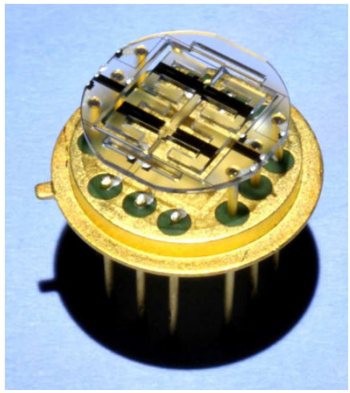
Intrinsic mechanical isolation of the 2 useful modes

Simulations by OOFELIE

- Simplified decoupling frame
- Q = 385 000 scale 1, Ø 10 mm
- Improved electrodes pattern
  - Full differential EXC, DRV, SNS
  - Capacitive coupling reduction

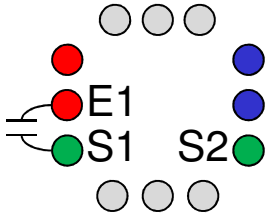


Finite Elements model



Mounted on socket

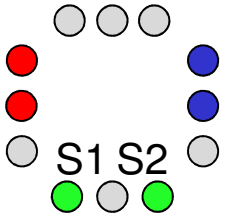
VIGTOR cell : final Capacitive coupling reduction

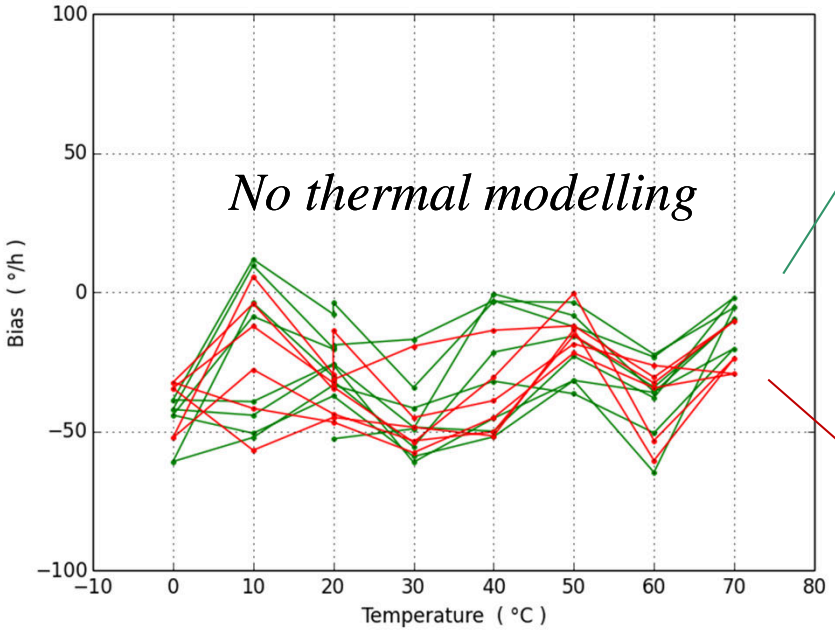


Initial layout of socket :
Residual capacitance between Excitation and Sense

400°/h variation with Temperature

New routing just released



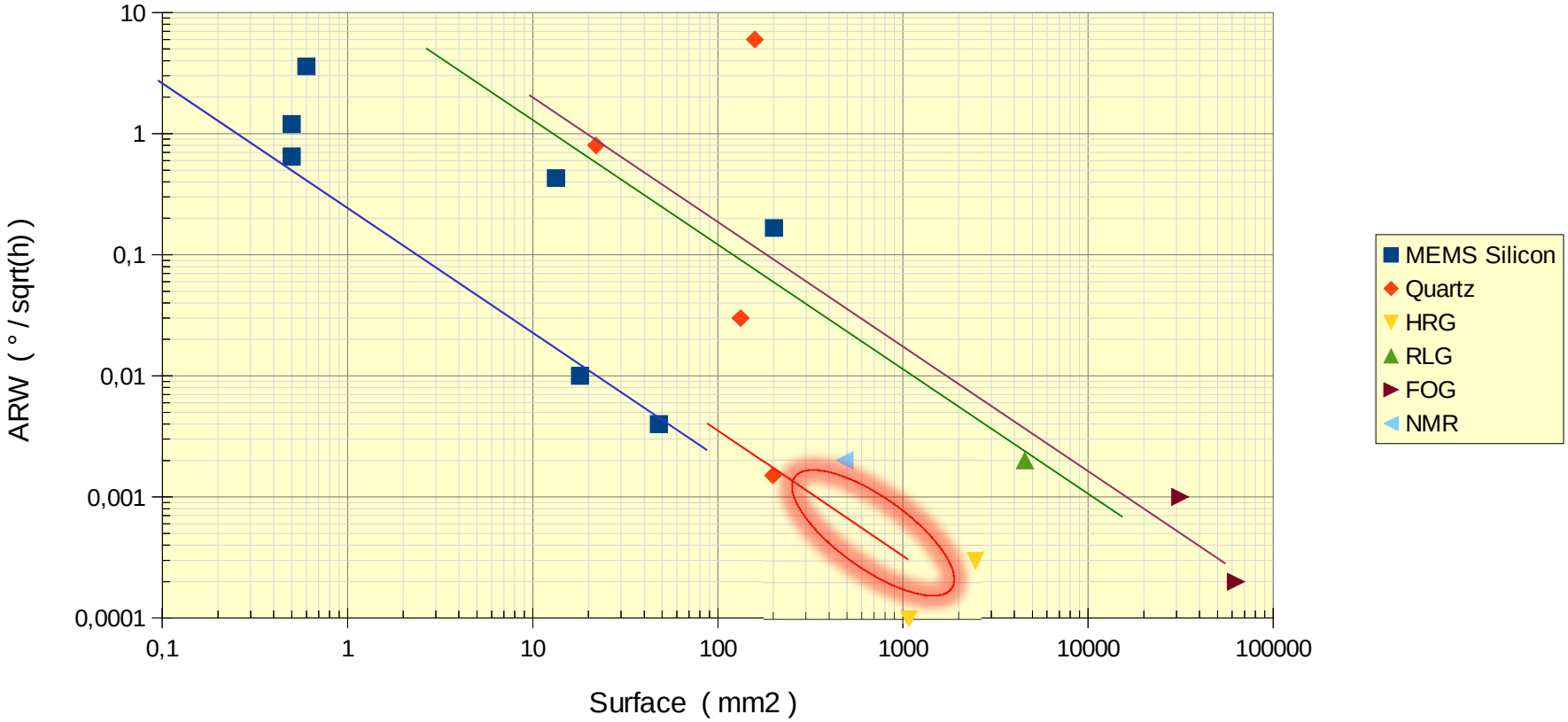


New thermal cycle :
Bias repeatability ~ 10°/h rms

Not even packaged
(10 cm wires with amplifiers)
Raw vacuum (~ mbar)
No offgassing

Back to air
re-pumped into raw vacuum

Performance vs Scale : physical limits



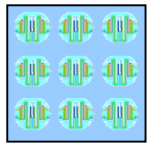
some scale rules… noise depends on sensor head surface
(RLG, FOG, capacitive detection)
Also quartz : piezoelectric charges increase with scale^2

Projection on performances of Size Increase

- Main effect : increase the Scale Factor before charge amplifier
- No extra cost : same process, same electronic (size and power)

Performance	VIG 2012	Gain on SF	Gain on Q	Gain on Excitation	Gain on ΔF	Projection on VIGx4
Bias	9 °/h	/ 9	/ 5		/ 2	0.1 °/h
Résolution	0.5 °/h	/ 9		/ 2	/ 2	0.01°/h
ARW	0.03 °/√h	/ 9		/ 2	/ 2	0.001 °/√h

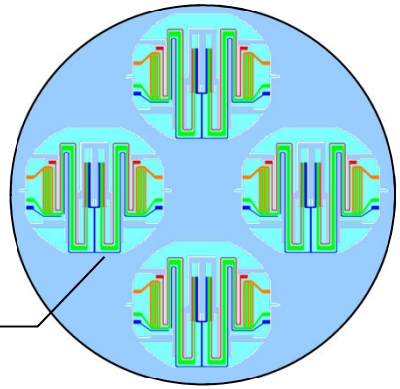
- Associated technology : wet etching of 2 mm thick, 4in wide wafers



→ 2012

Thickness 666 µm

Ø cell 13 mm



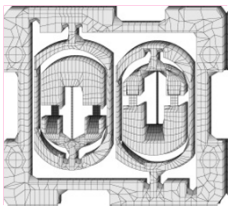
Ø cell 39 mm

Thickness 2000 µm

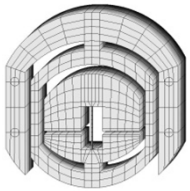
- ✓ Set up etching process
- ✓ Procure wafers
- ✓ Scaled socket & mask
- ✓ Realize cells
- → Characterize

First step on size increase : the AVAS accelerometer

VIA
Ø 6 mm

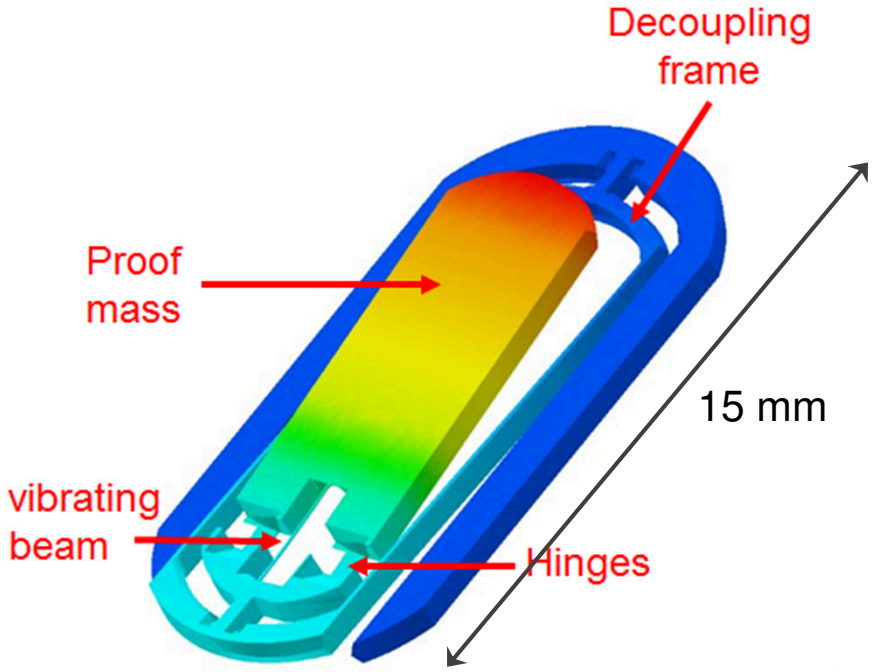


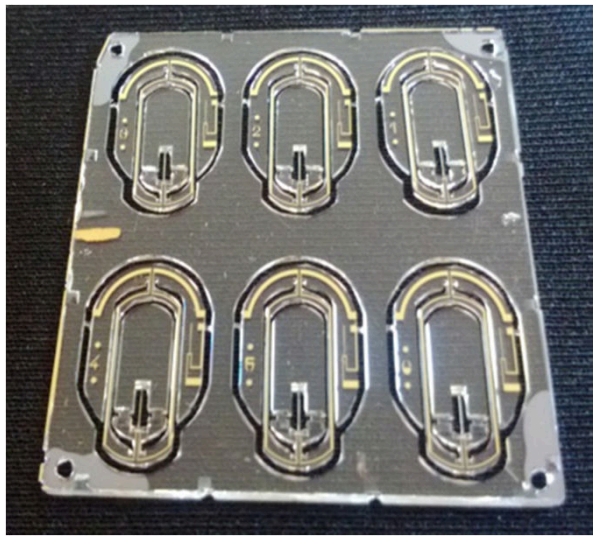
DIVA
12×10 mm



VIA HP
Ø 11 mm

AVAS
9 ×15 mm





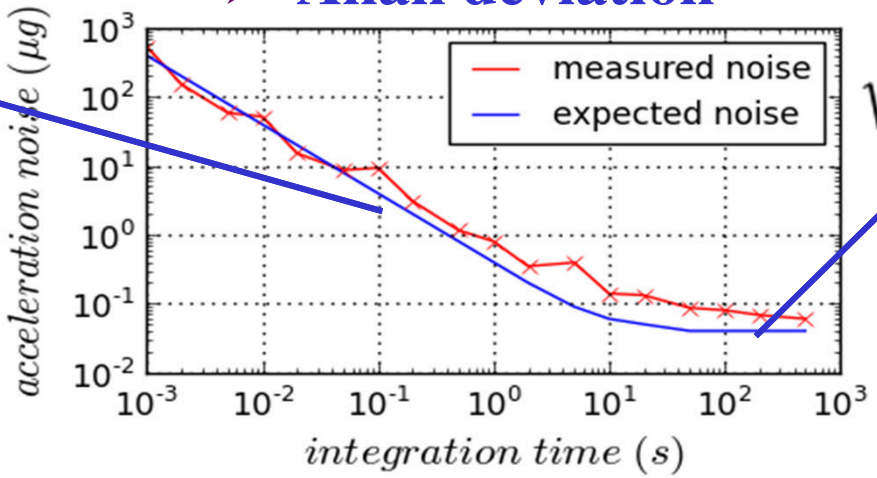
High resolution VBA

➢ Allan deviation

$$\frac{\sqrt{3FkTf_H}}{\sqrt{P_0}\,2\pi.SF}\frac{1}{\tau}$$

= 500ng @ τ=1s

- F : Amplifier noise factor
- P_0 : Carrier power
- SF: Accelerometer scale factor



$$\sqrt{\frac{\ln(2)b_{-1}}{2}}\frac{f_0}{Q.SF}$$ **= 50ng**

- b_{-1} : Amplifier Flicker phase noise
- Q : Q factor of the beam
- f_0 : Eigen frequency of the beam

No detection electronics - Frequency output – digital sensor

Applications

Fine Orbit Control	3 mg	10 µg
Formation Flying	100 µg	100 ng
Electric Propulsion	500 µg	50 ng
Drag in Thermosphere		50 ng
Seismology		30 ng

Together with the gyroscope:
A high performance Quartz IMU
sub µg, sub °/h

ONERA

Conclusion

- (old) VIG generation has been proposed as low cost european gyro for NEOSAT
  - No dependence on quartz
  - Use of an existing micro-controller
  - No trimming on quartz
  - Build a demonstrator ?

- Increase the size of the cell is possible at no extra cost
  - Performances → scale^2
  - Already tested, same quartz grade
  - Larger application field :
    - better than 0.1 °/h (bias drift), 0.01 °/h (Allan min), 0.001 °/√h ARW
    - Navigation grade
    - Gyro-compass, north-finding
    - star-tracker hybridation

- Next generation of vibrating structures

- gyroscopes
  - Lower capacitances (20 times less)
  - Lower quadrature error (10 times less)

- Accelerometers
  - Increased sensitivity (30 times)

Thank you for your attention