Quartz Inertial Sensors for Space

Jean Guérard, Stève Masson, Denis Janiaud, Rachid Taïbi, Raphaël Lévy, Vincent Gaudineau, Claude Chartier, Marc Pernice, Olivier Le Traon

Sensors and Microtechnologies research unit
Physics and Instrumentation Department

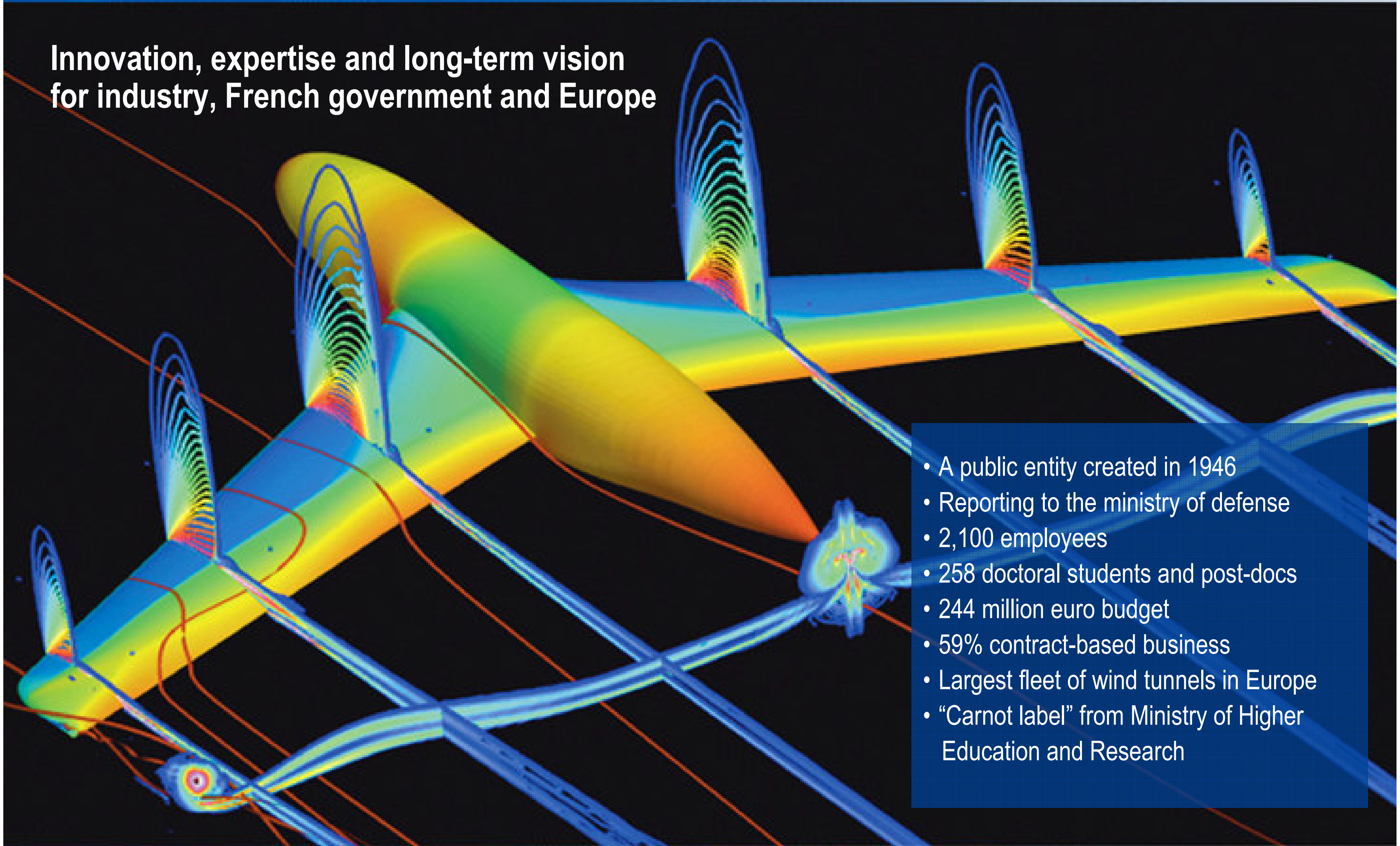
ONERA
THE FRENCH AEROSPACE LAB

Contact :
jean.guerard@onera.fr

return on innovation

8th ESA round table on MNT, 15-18 october 2012

The French Aerospace Lab



Innovation, expertise and long-term vision for industry, French government and Europe

- A public entity created in 1946
- Reporting to the ministry of defense
- 2,100 employees
- 258 doctoral students and post-docs
- 244 million euro budget
- 59% contract-based business
- Largest fleet of wind tunnels in Europe
- “Carnot label” from Ministry of Higher Education and Research

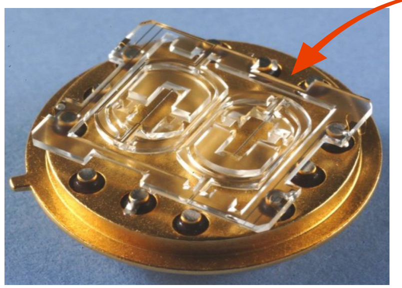
Outline

- Piezoelectric vibrating inertial sensors at ONERA
- Accelerometers
- Angular rate Gyros
- Assembly and Electronics

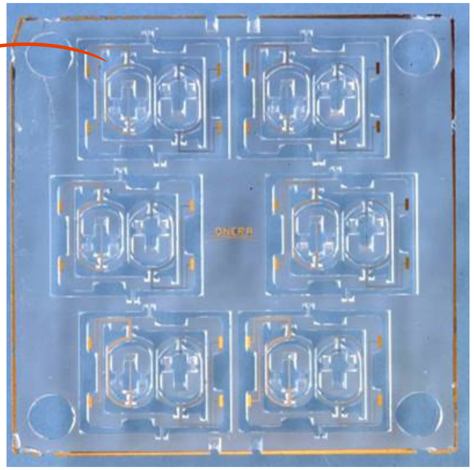
Piezoelectric vibrating inertial sensors at ONERA

- **Flat monolithic sensors compatible with collective etching process**
- **High quality piezoelectric crystal : Quartz**

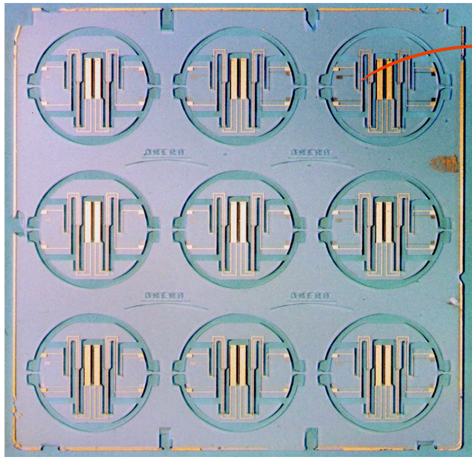
→ Performances
(no assembling, chemical etching to preserve material quality, high stability of parameters)
→ Miniaturization, mass product
→ Easiness of vibration excitation/detection systems by piezoelectricity



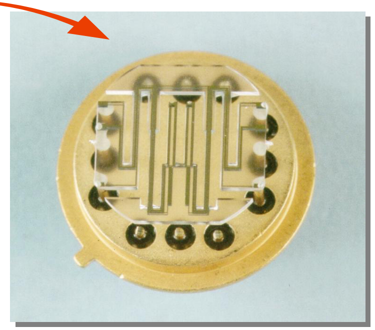
DIVA accelerometer



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



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



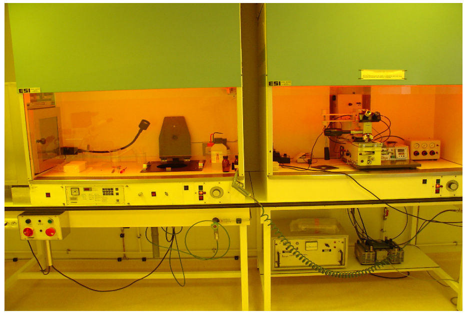
VIG Gyro

PLATINE clean room

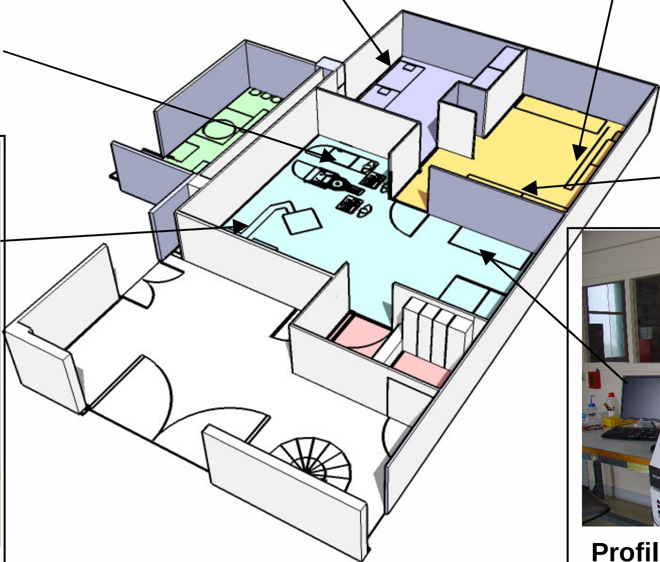
80 m², class 10 000
(including 20 m² class 100)

DRIE for hard/dielectric materials
(quartz, GaPO4, SiC, ..)

Surface preparation and Quartz Etching Hoods

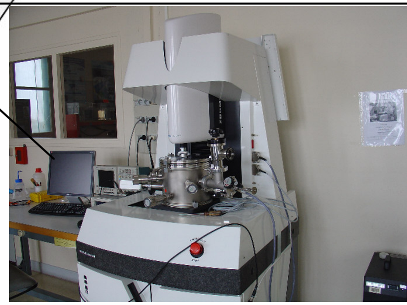


- Spinner KARL SUSS RC5 GYRSET
- KARL SUSS Aligner MJB3



Back / Front side Aligner EVG AL-6

Metallic thin film deposition by evaporation (Ti, Cr, Au,..)

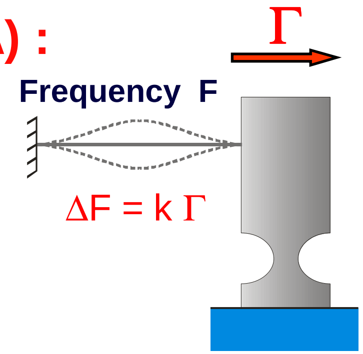


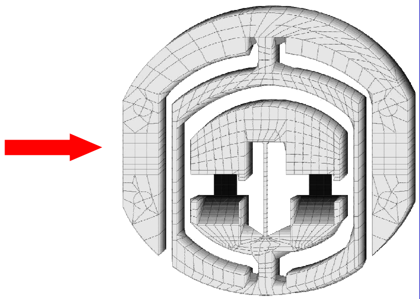
Profilometer/vibrometer
Fogale nanotech Zoomsurf3D

Vibrating Inertial Sensors: physical principles

⇒ **Vibrating Beam Accelerometer (VBA) :**
Vibrating Inertial Accelerometer

→ **Use the high sensitivity of vibrating beam frequency to axial forces. The output is a frequency and its variations are proportional to the input acceleration**

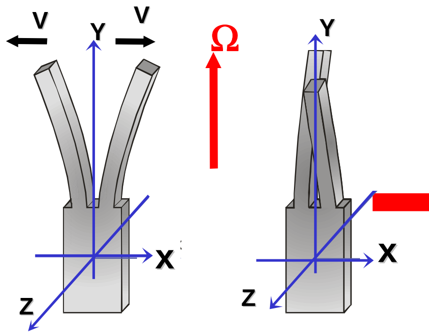




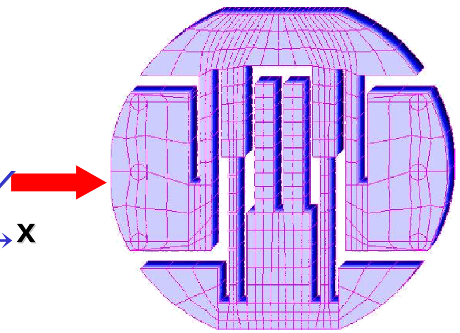
VIA accelerometer
(Onera patent)

⇒ **Coriolis Vibrating Gyro (CVG) :**
Vibrating Integrated Gyrometer

→Detection of an alternative displacement generated by Coriolis acceleration when a resonator, moving at an alternative velocity V, is submitted to an input angular rate Ω.



$$\vec{\Gamma}_c = 2\,\vec{\Omega} \wedge \vec{V} \Rightarrow Z = \frac{X}{(\omega_x - \omega_z)}\Omega$$

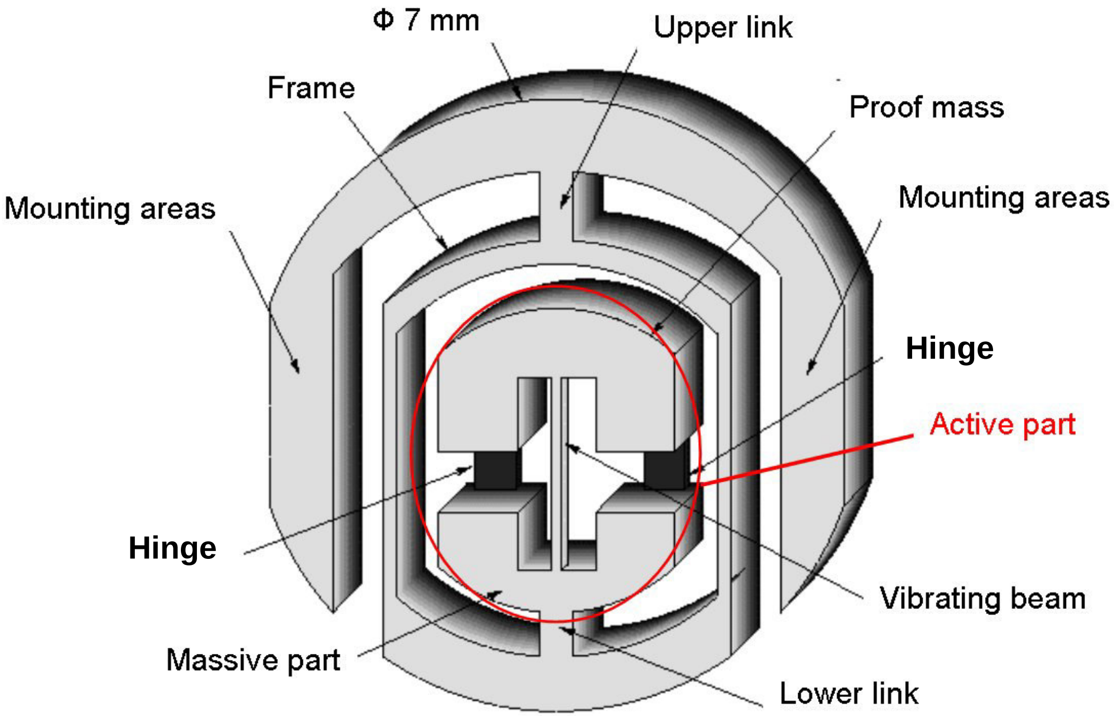


VIG gyro
(Onera patent)

Outline

- Piezoelectric vibrating inertial sensors at ONERA
- Accelerometers
- Angular rate Gyros
- Assembly and Electronics

VIA accelerometer : configuration



Beam Frequency	**~ 60 kHz**
Scale Factor	**~ 12 Hz / g**

Main originality :

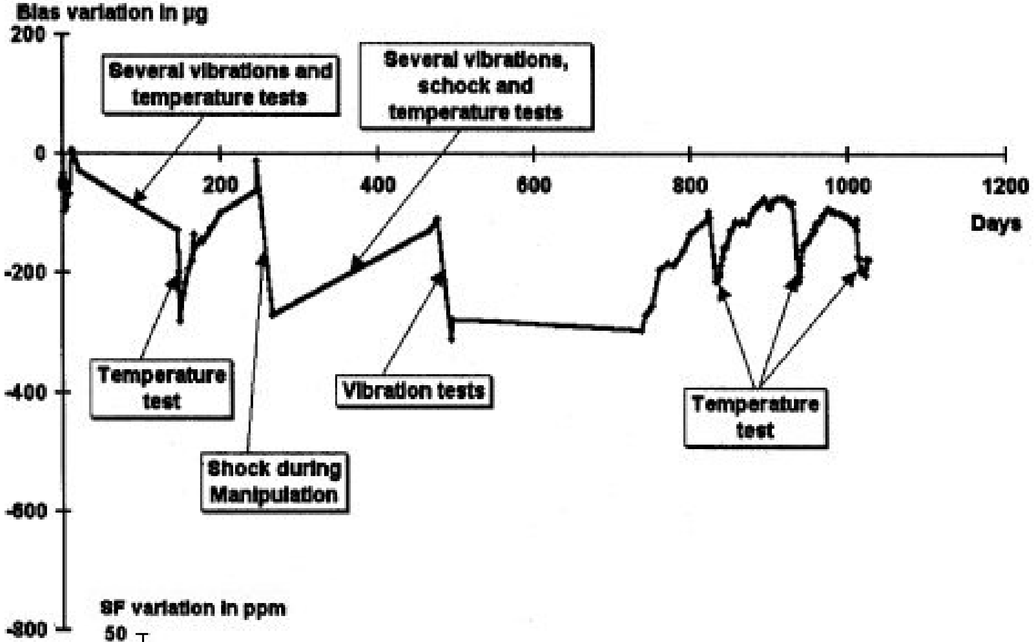
Decoupling system (frame + links) connecting the active part to the mounting areas :
- decoupling of the beam vibration
- insulation of the beam against thermal stresses

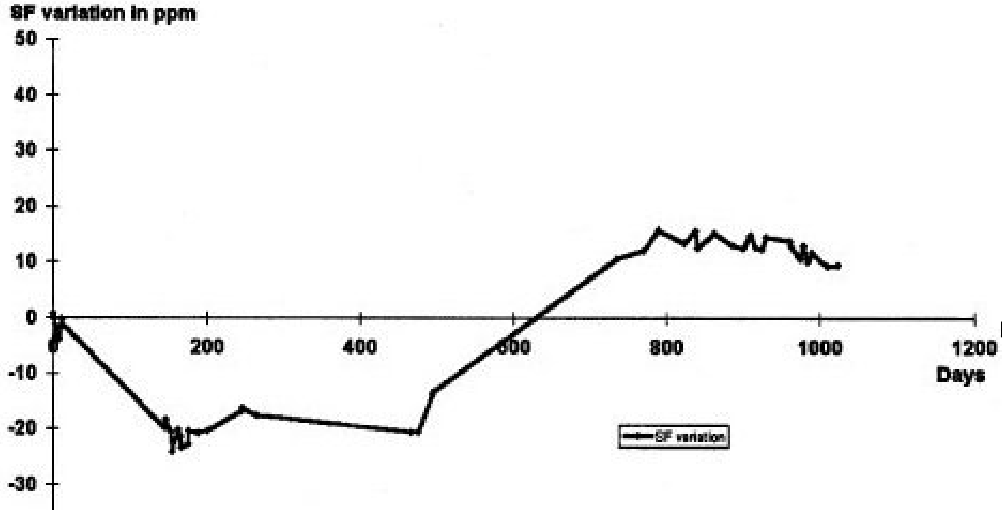
⇒excellent frequency stability (bias) and excellent temperature behavior (low hysteresis)

→ Patented in 21 countries
⇒ 3 industrial transfers

VIA evaluation

Long term behavior





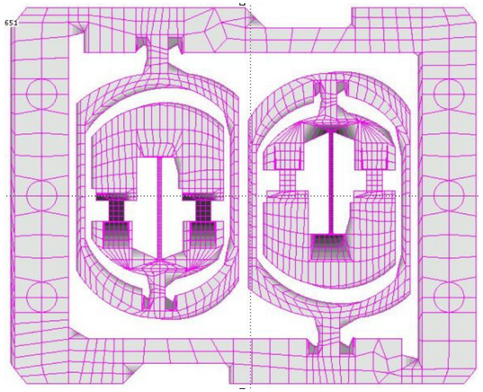
Time interval	≃ 3 years
Variation of bias:	
peak	350 µg
standard deviation	70 µg

Measurement range	±100 g
Bandwidth	1000 Hz
Acceleration behavior (**±100 g**) :	
Scale factor	**30 Hz/g**
Non-linearity K2	**2 µg/g²**
Non-linearity K3	**0,02 µg/g³**
Residual error	**150 µg**
Thermal behavior **(- 40 °C to + 80 °C)** :	
Bias sensitivity	**~100 µg/°C**
Bias residual	**80 µg**
Scale factor sensitivity	**2 ppm/°C**
Scale factor residual	**8 ppm**
Long term behavior :	
Bias (std dev.)	**~70 µg**
Scale factor	**15 ppm**

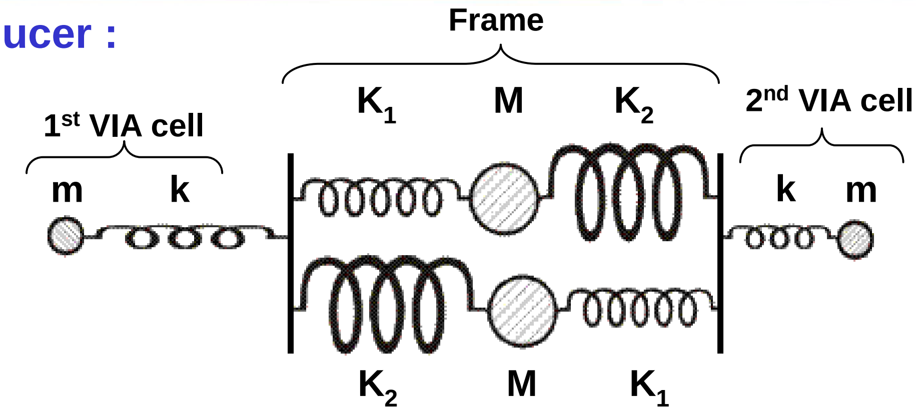
Variation of scale factor:	
peak	25 ppm
standard deviation	15 ppm

DIVA accelerometer

- Role of the frame around the 2 VIA tansducer :



⇔

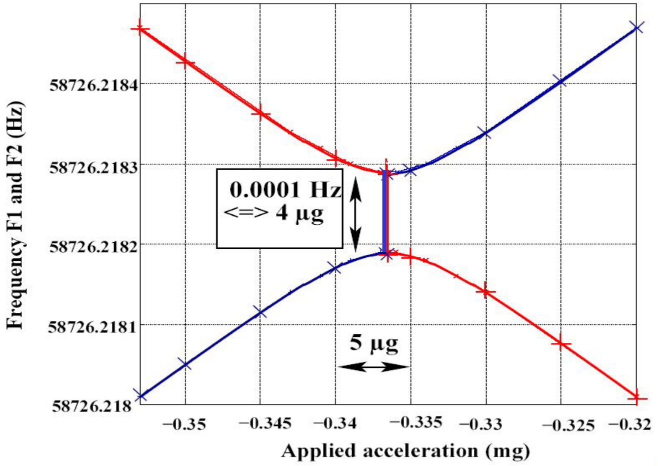


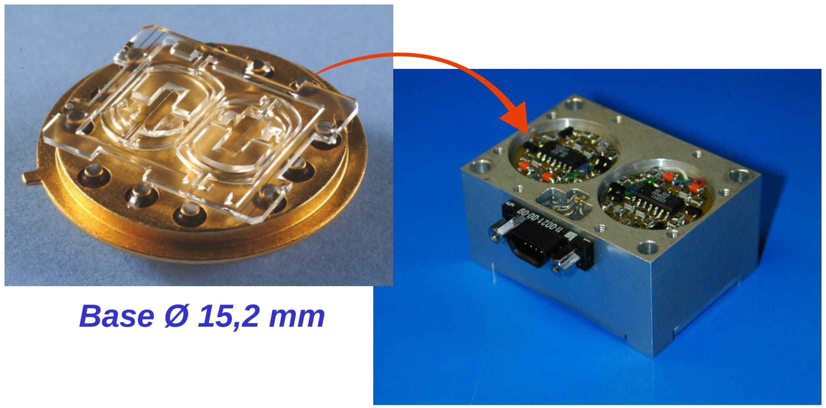
One dimension analytic model of the frame

- Specific tuning conditions of the frame frequencies give a null lock-in zone.

➡ **Patent + 2 industrial transfers**

- F.E.M of mechanical coupling:





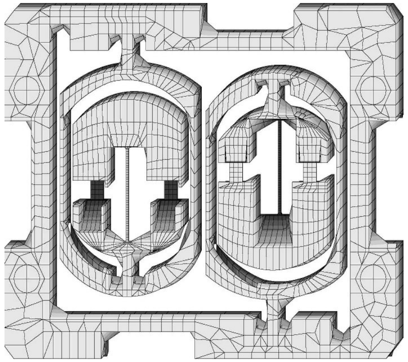
Base Ø 15,2 mm

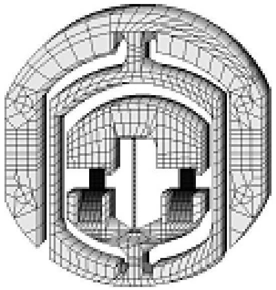
Prototype (45 x 32 x 24 mm)

Vibrating beam accelerometers developed at ONERA

Under development

"Tactical grade"





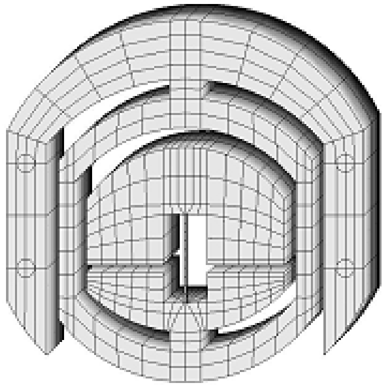
DIVA

Range 100 g
precision ~ 300 µg
Noise : 1 µg @ 1 Hz
(12mmx10mm)

VIA

Range 100 g
precision ~300 µg
Noise : 1 µg @ 1 Hz
(Ø 6 mm)

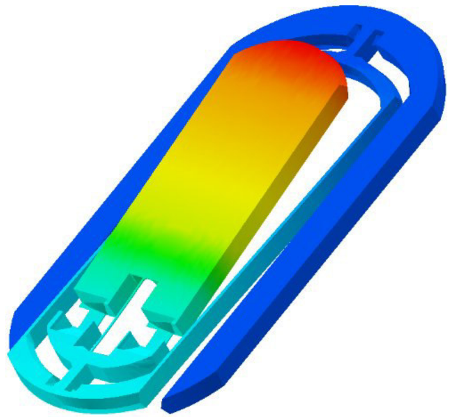
"Navigation grade"



VIA HP

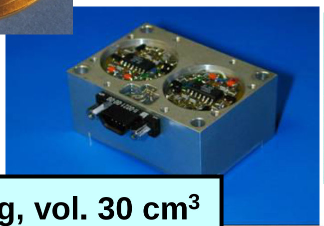
Range 50 g
Targeted precision < 50 µg
Targeted Noise : 0.5 µg @ 1 Hz
(Ø < 11 mm)

"High resolution"

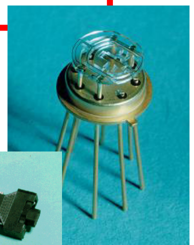


AVAS

Range : 5 g
Targeted Precision : 5 µg
Targeted Noise:
50 nano-g @ 1 Hz
(9 mm x 15 mm)



Mass 60 g, vol. 30 cm^3
Consumption < 0,2 W
Onera's packaging



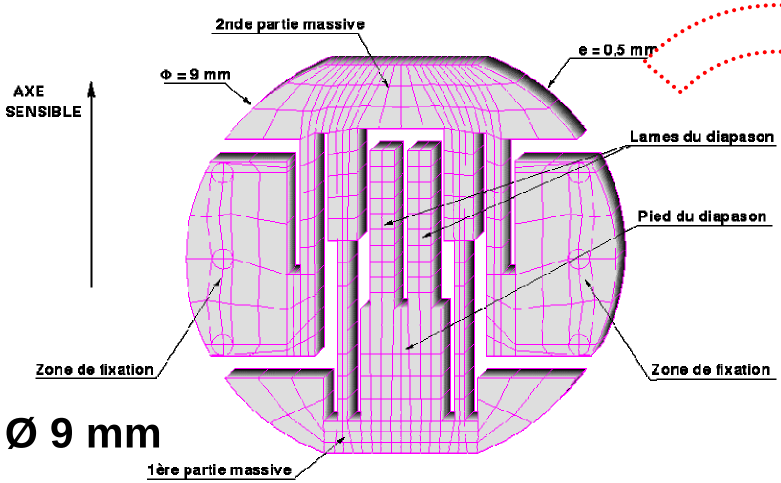
Mass : 30 g, vol. 10 cm^3
Consumption < 0,2 W
Onera's packaging

- **Current state of art**
  - *Conventional analog/digital electronics.*
  - *TO5-8 socket + copper case under vacuum.*

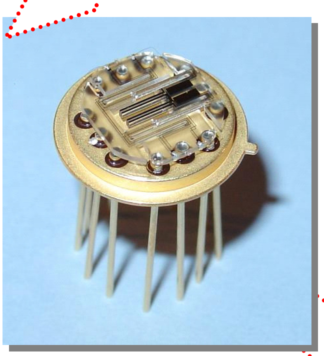
Outline

- Piezoelectric vibrating inertial sensors at ONERA
- Accelerometers
- Angular rate Gyros
- Assembly and Electronics

Vibrating Integrated Gyro (VIG)



Monolithic structure

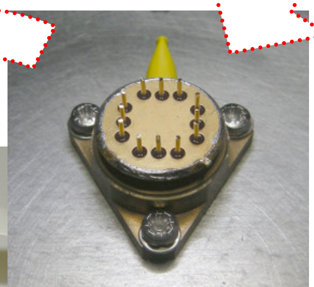


Current prototype

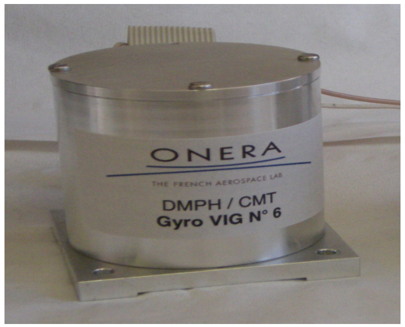
- 10 g Copper case
- 10 g local electronics

- 40 mm diameter
- 20 mm height

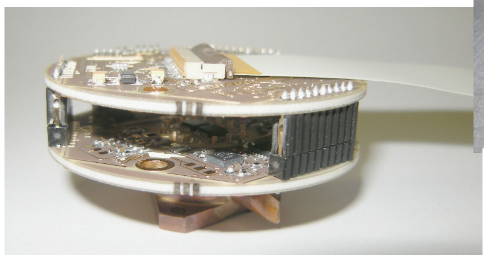
- Single 3.3 V supply
- Digital link with host (SPI)



Vacuum packaging



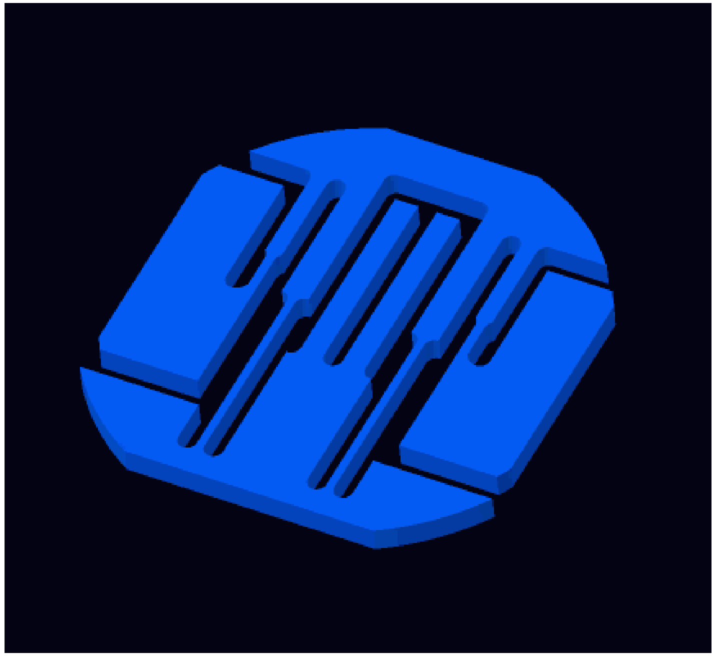
Lab prototype



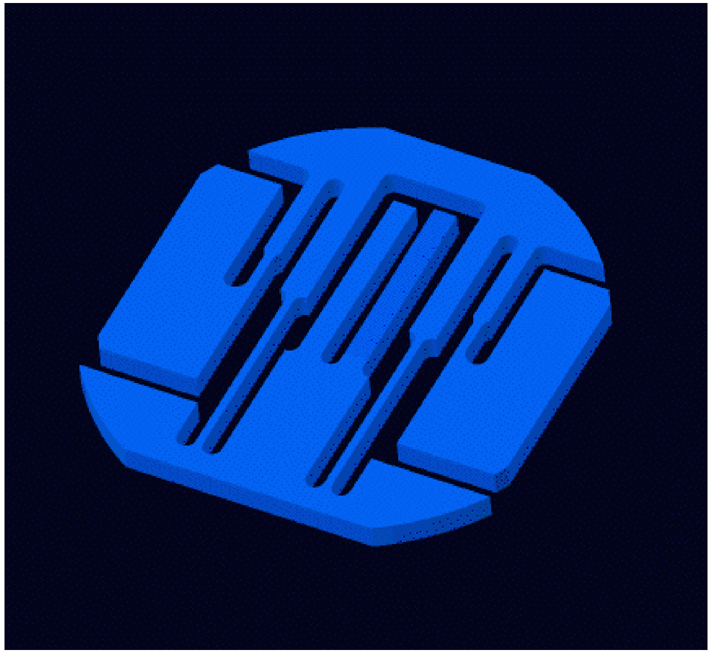
Electronics

Choice of the resonator: Q decoupling

$$Q = 2\pi \frac{\text{stored energy}}{\text{dissipated energy per period}} \Rightarrow \frac{1}{Q} = \frac{1}{Q_{\text{viscosity}}} + \frac{1}{Q_{\text{thermoelastic}}} + \frac{1}{Q_{\text{surface}}} + \frac{1}{Q_{\text{decoupling}}}$$

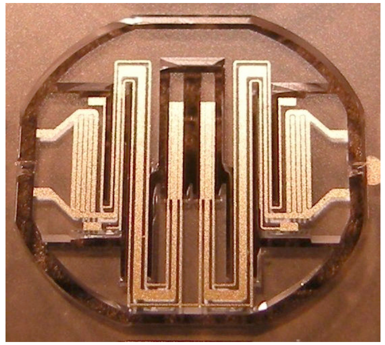


DRIVE



SENSE

$$Q_{\text{decoupling}} \cong Q_{\text{support}} \frac{\text{Strain energy}}{\text{Support strain energy}}$$

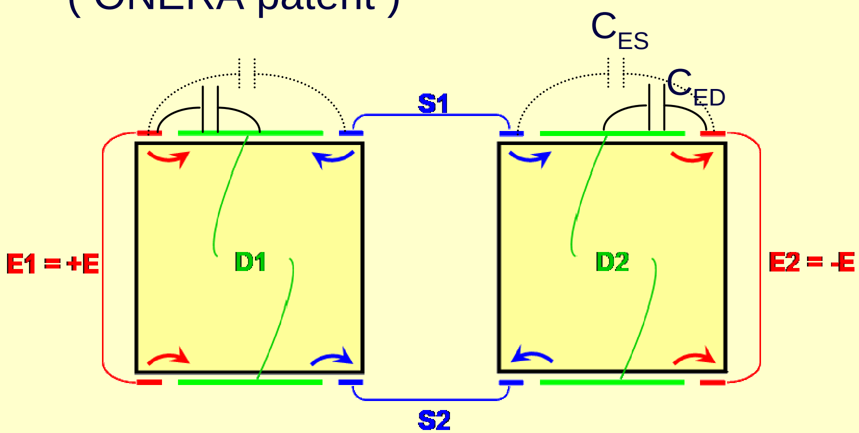


Benefit of the VIG structure: 2 decoupling modes ($Q_{decoupling}$ > 10^8)

Measured quality factor ~ 150 000 for the 2 modes @ 22kHz

Vibrating Structure

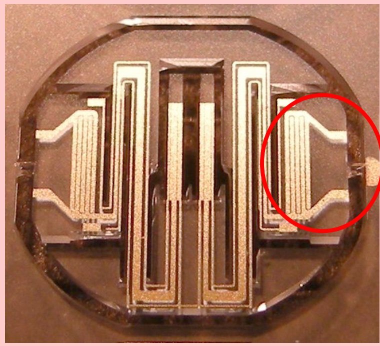
- Electrodes configuration
  (ONERA patent)

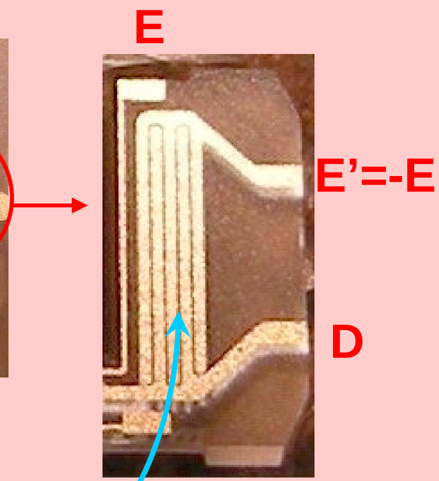


Excitation Drive Sense

- Drive between E and S ➡ Ground shield
  ➡ Reduce C_{ES}
  ➡ C_{ES} balance (+E, -E)
- Nominal residual capacitance C_{ES} < 10 fF
- Not C_{ED}

- Capacitive balance

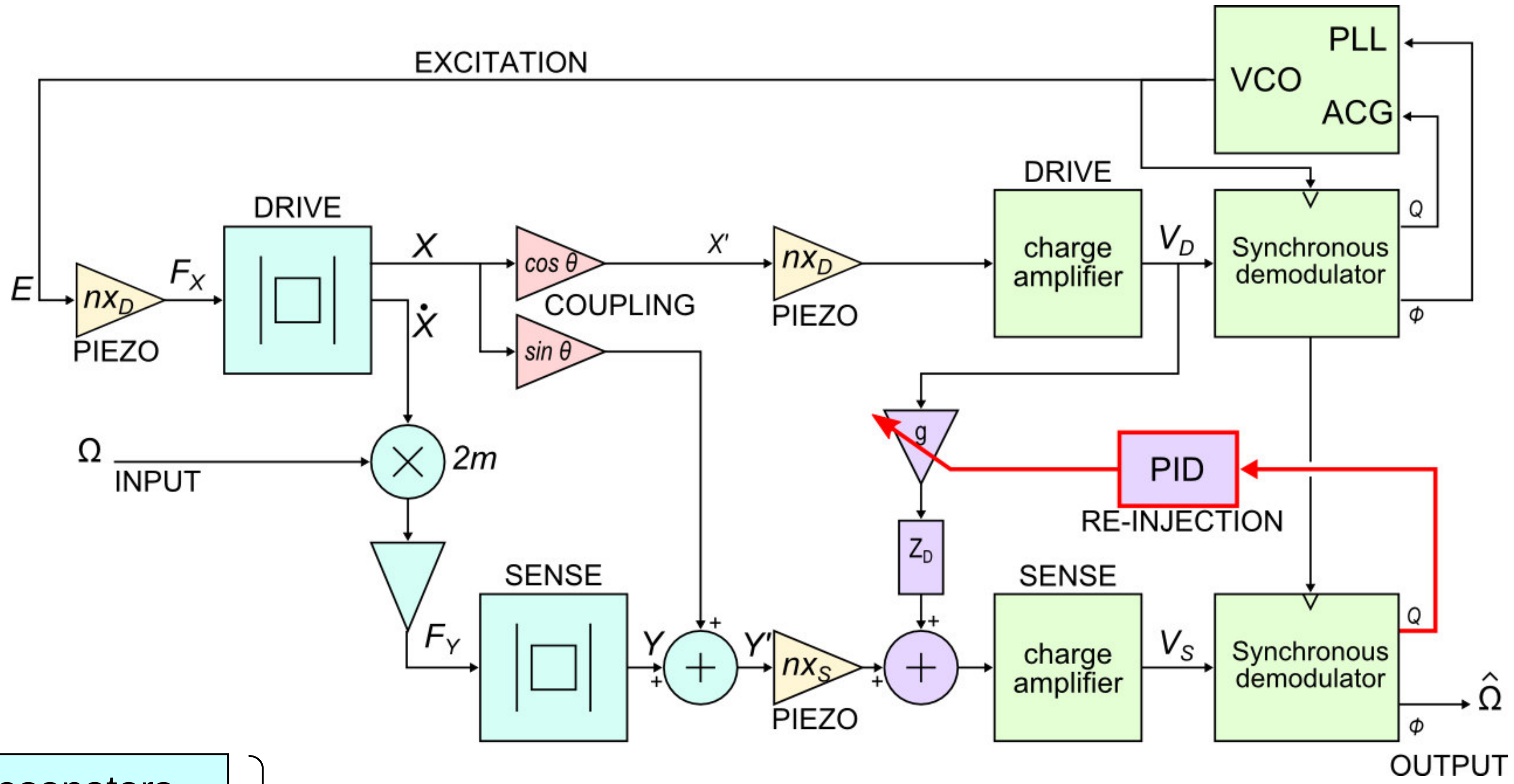




- C_{ED} : ~1 pF
- (electrodes on beam)
- Electrostatic comb
- $C_{COMB} = C_{ED}$ (same physics, same T)
- Excitation E cos ωt on **E**
- Compensation -E cos ωt on **E'**
- -E from true symmetric DAC
- → compensation residue < 1 fF

Global efficient capacitive compensation at quartz level

Coriolis Vibrating Gyro architecture



Resonators

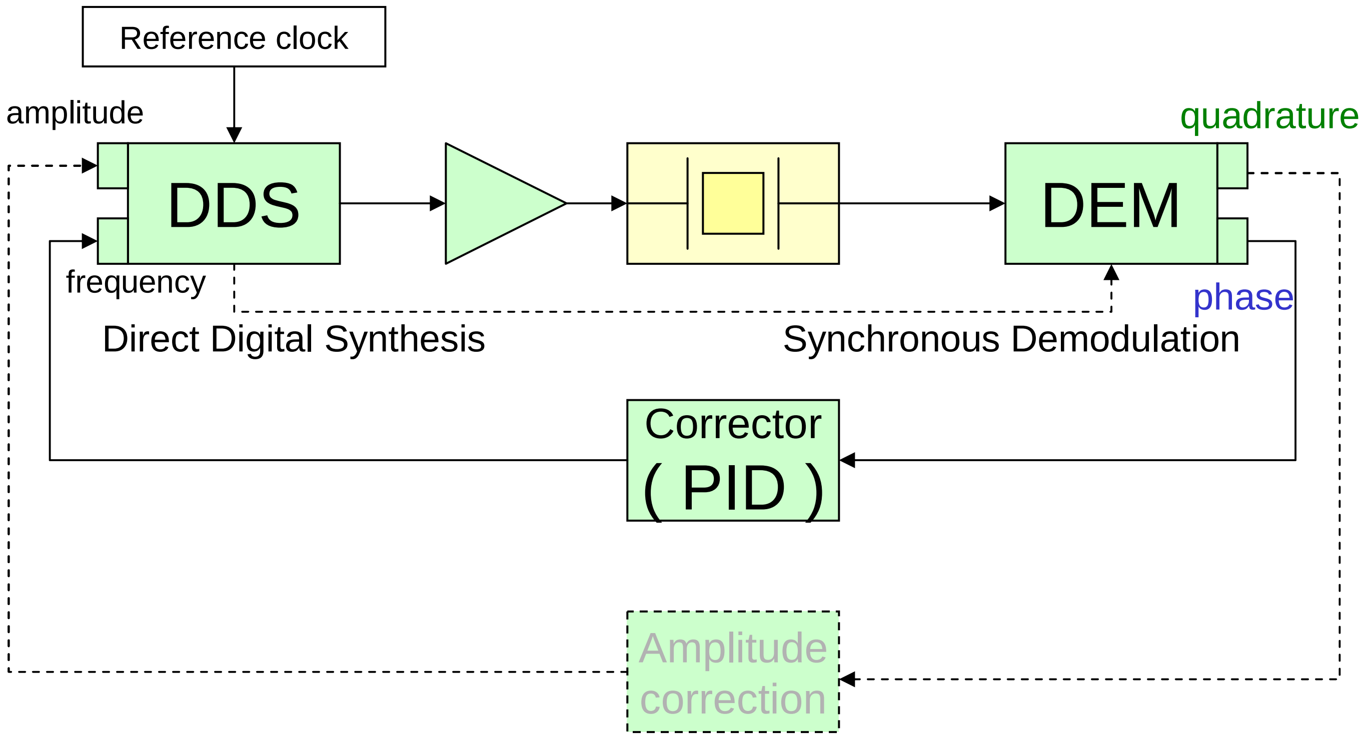
Piezoelectricity

Electronics

} Quartz cell

- Quadrature error compensated with electronics
- No trimming on quartz

Digital Drive Loop

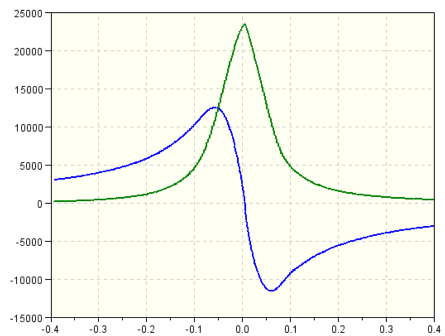


No need for amplitude regulation

$\Omega = K\, V_{SNS} \,/\, A_{DRV}$

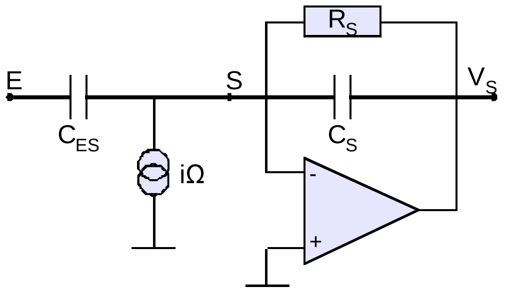
normalisation

- Excitation reduced by 2 (single supply +3.3 V)
- Standard Reference clock 10 MHz (from host)



- Phase noise : 1 µrd / √Hz
- Phase jitter : 30 µrd
- Frequency resolution : 20 µHz
- Mostly digital functions

Charge Detection



Charge amplifier ≡ Capacitive Detector

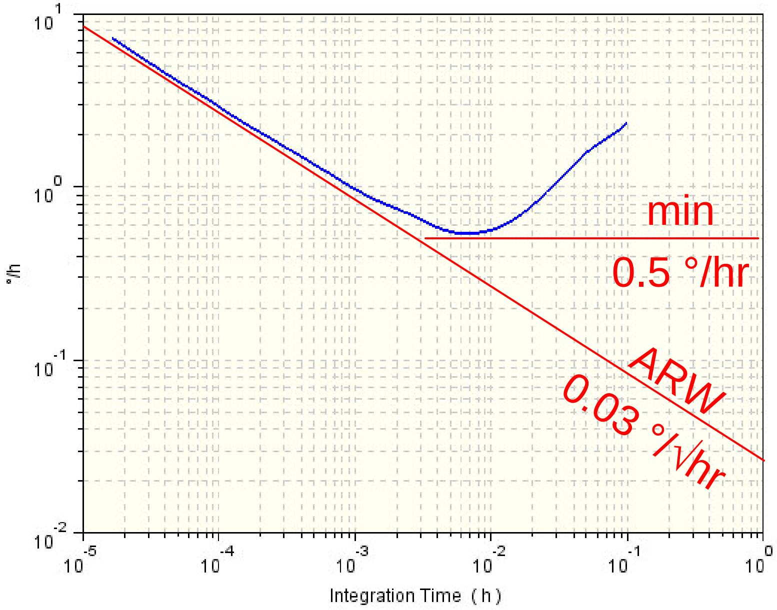
- Sensitivity : … V / C
  55 V / pF
- Noise : 0.3 aF / √Hz
- Thermal sensitivity : 2 aF / K
- Single supply : 3.3 V
- 40 mW per axis
  (including ADC)

State of Art of ONERA capacitive detectors
for the Ultra-Sensitive accelerometers
(GRACE, GOCE, MICROSCOPE)

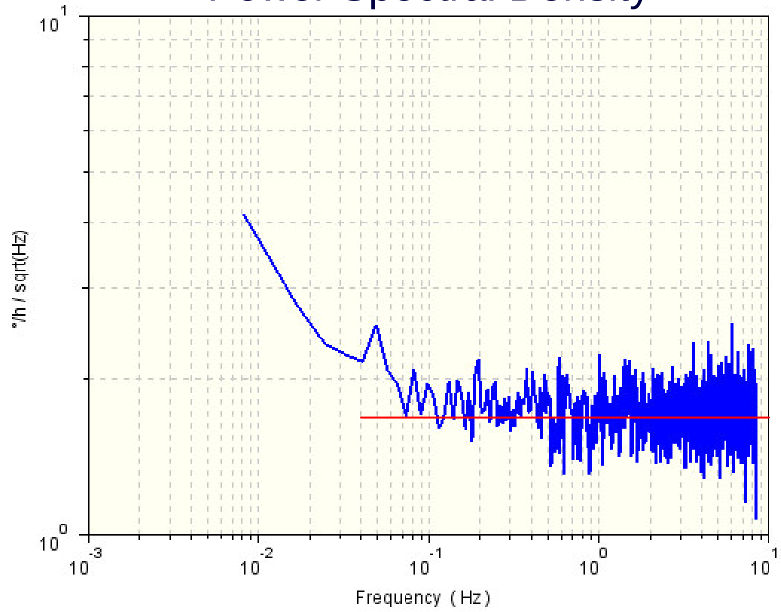
1 – 10 V / pF
0.2 – 4 aF / √Hz
6 – 30 aF / K
50 mW per axis, ± 15 V, not including ADC

Noise performance

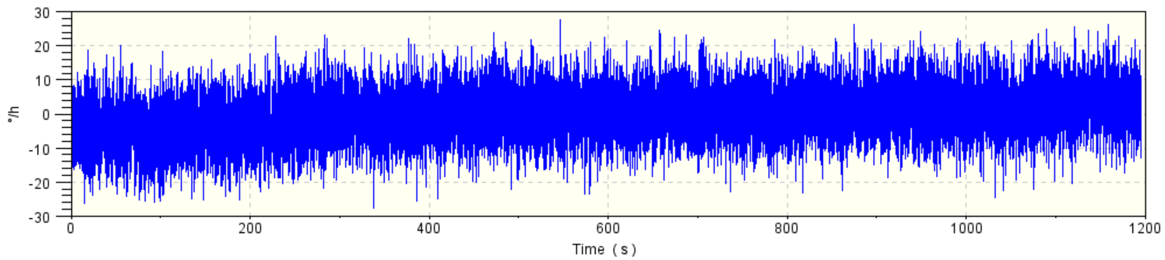
Allan variance



Power Spectral Density

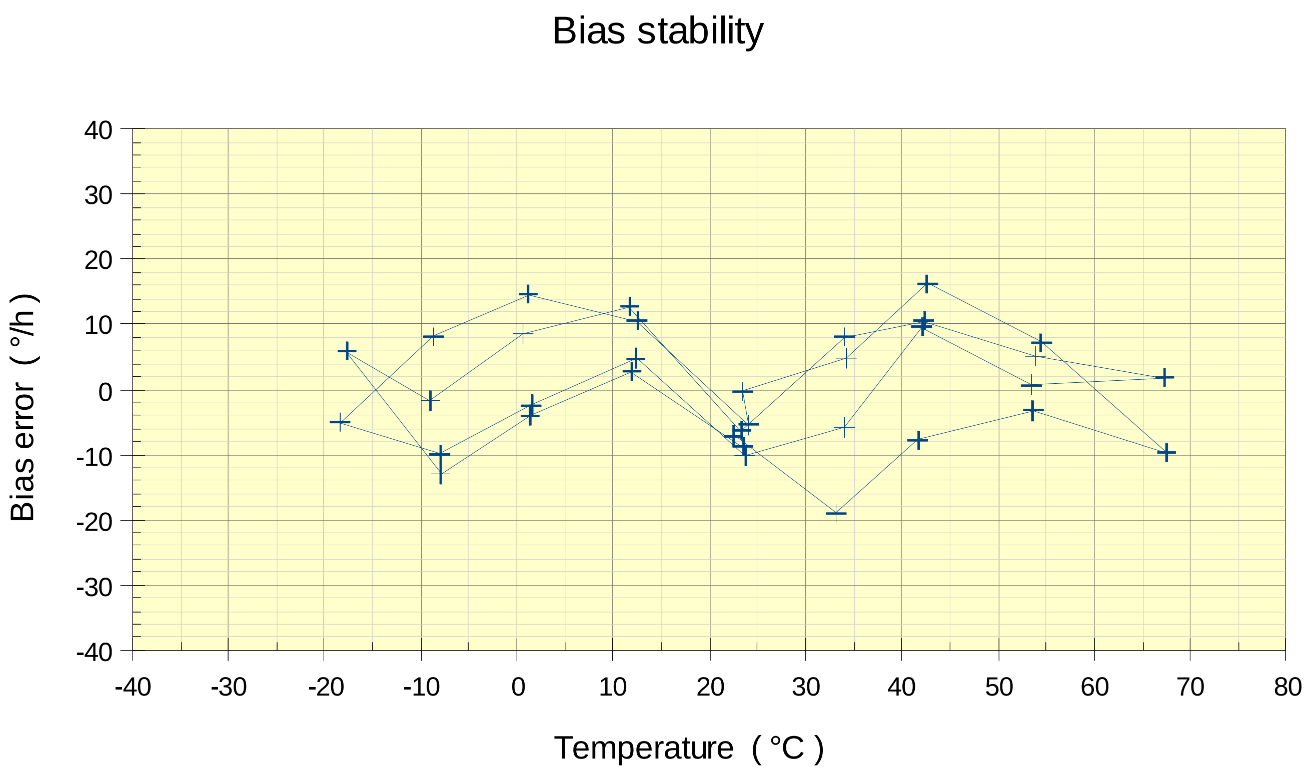


0.03 °/√hr ≡ 1.8 °/h / √Hz



ONERA

Bias performance



Standard deviation

9°/h rms

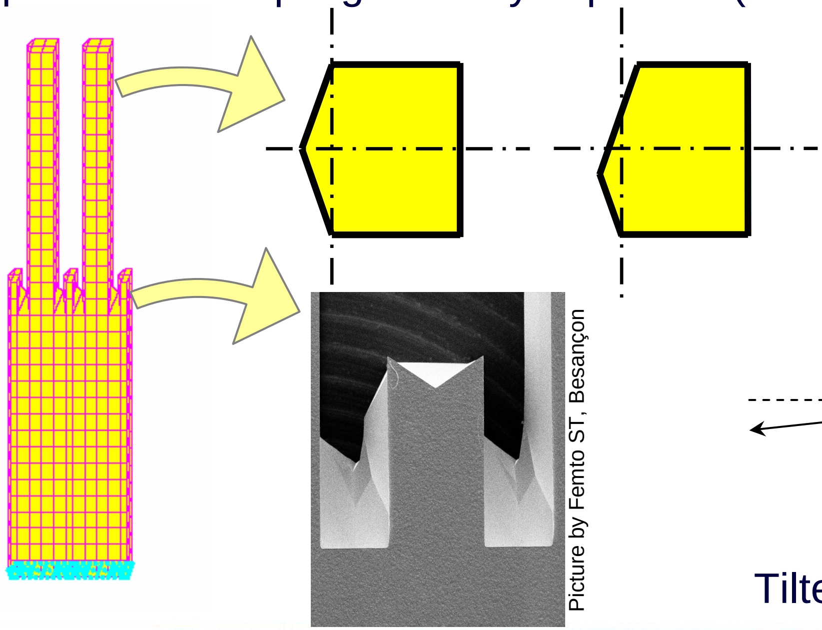
Thermal cycling : -20 -- +70 °C
2 last cycles

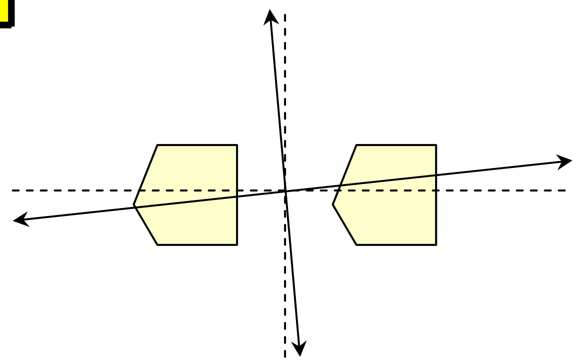
Stabilised points at ambient (more time) → encouraging

Conclusion

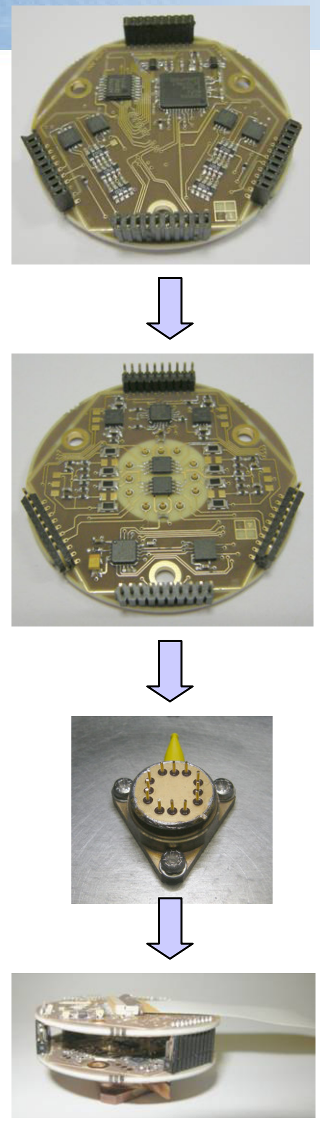
- Progress on integration, power supply, size and mass
- Electronic is mainly digital and deliverable as IP
- Performance not as good as expected from the previous generation projection, but :

→ Still Open Loop gyro
→ quadrature coupling still very important (→ high re-injection level)





Tilted modes → coupling



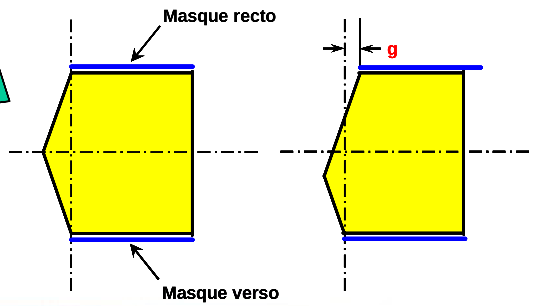
Ø 40 mm

Short term Perspectives

→ reduce by 10 the quadrature error is possible with better control of quartz structure etching :

- 2 phases :
- Obtain repeatable distribution of quadrature error on wafers
- Determine better configurations of quartz structure through Mask shift control in the Photolithography step
- → mask optimization

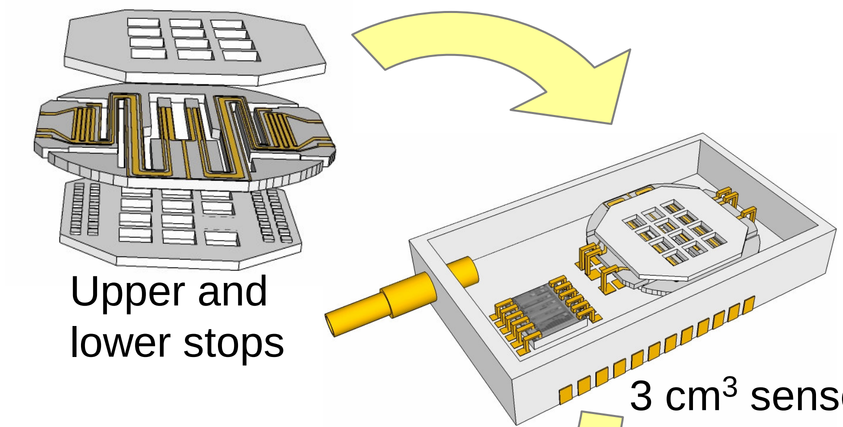
New double side aligner in clean room



Outline

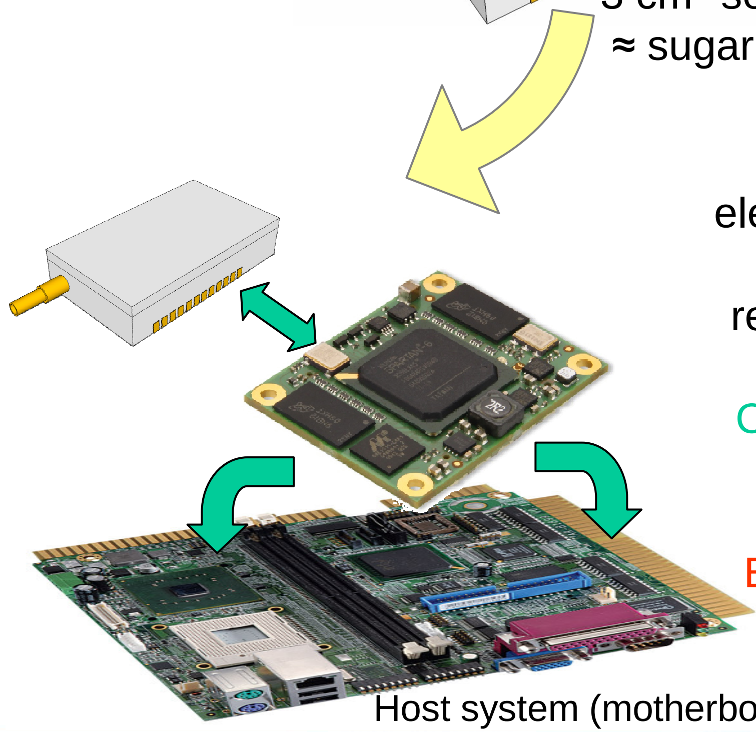
- Piezoelectric vibrating inertial sensors at ONERA
- Accelerometers
- Angular rate Gyros
- Assembly and Electronics

Sensor Head assembly and Electronics



Upper and lower stops

3 cm³ sensor head
≈ sugar cube



Spread electronics on local resources…
=
Component vision
≠
Equipment vision

Host system (motherboard)

- FPGA or ASIC : ~ 50k gates

DARE RHBD library from imec

0.18 µW / gate / MHz
→ 100 mW @ 10 MHz

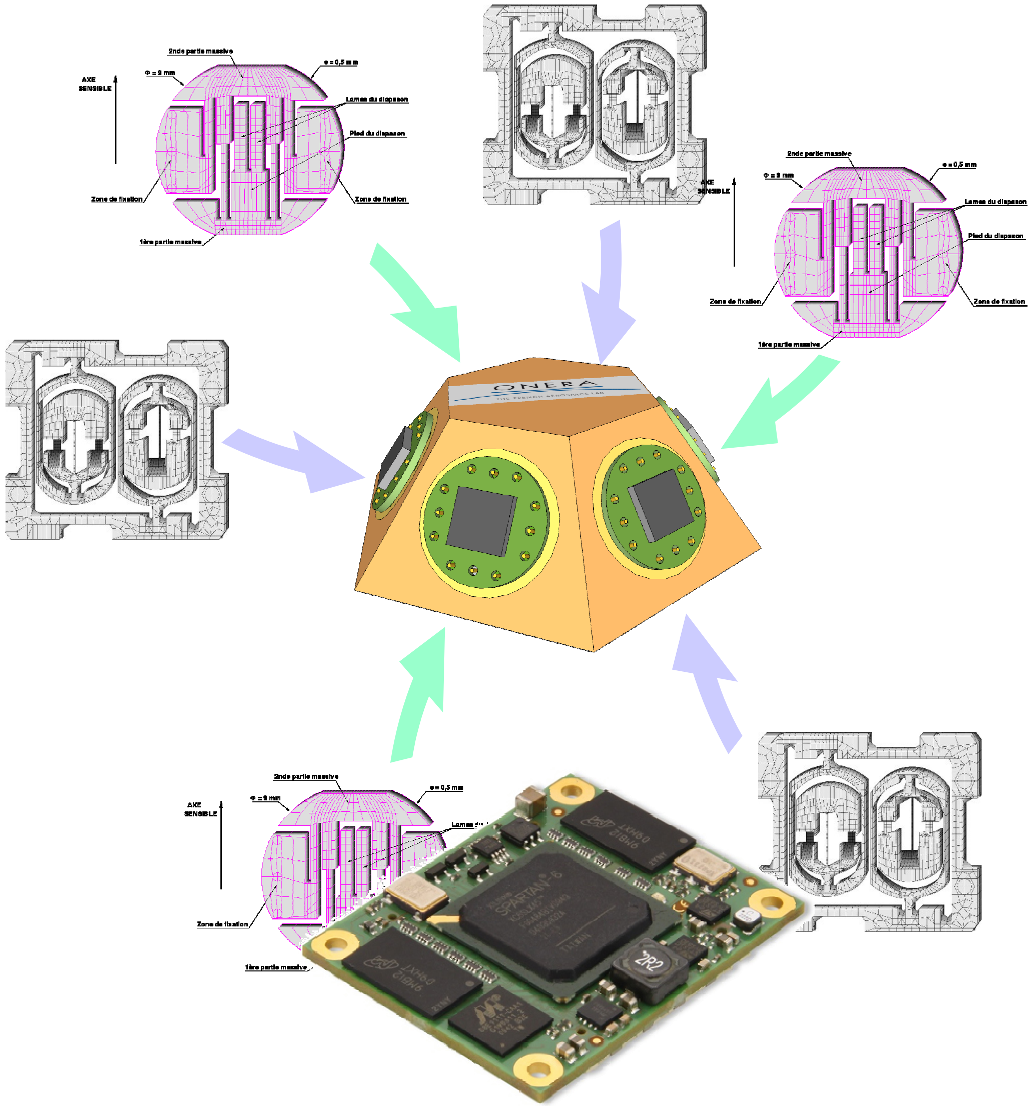
- 44 µm² / gate
≡ 23000 gates / mm² → 2 mm²

- Computer need
  - Hard wired Frequency synthesizer
  - But raw ADC data to be processed
  - With Fs ≈ 10 Hz,
    computer power need is 30 KIPS,
    one interrupt @ 300 Hz
- Host example : SPARC LEON ATMEL AT697F
  - 85 MIPS @ 100 MHz
  - → ONERA gyro = 0.1 % of the CPU
- Delivery of source code

Quartz IMU development

- Development of 6-axis IMU
  - 3 accelerometers : DIVA
  - 3 gyros : VIG
  - Integrated electronics :
    - ASIC
    - FPGA

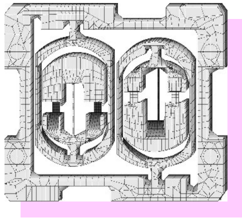
- Expected performances :
  - Acceleration :
    - Range : 100 g
    - Precision ~100 µg
  - Rotation rate :
    - Range : 100 °/s
    - Precision : 2 °/hr
    - ARW : 0.02 °/ √hr
  - Mass : 300 g
  - Size : Φ 50 mm x 30 mm
  - Consumption : 2 W



Inertial Sensors: Design versus space applications

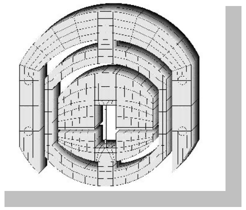
Accelerometer Applications	Range	Precision
FDIR/Anomaly detection	50 mg	800 µg
Rover navigation	400 mg	300 µg
Launcher	10 g	100 µg
Entry, Descent, Landing	10 g	50 µg
Aerobraking	600 µg	50 µg
∆V (0.1 to 10 m/s)	3 mg	10 µg
Fine Orbit Control	3 mg	10 µg
Formation Flying	100 µg	100 ng
Electric Propulsion	500 µg	50 ng
Geodesy	< 1 µg	< 1 pg

DIVA



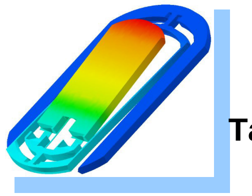
Range 100 g
precision ~ 300 µg
Noise : 10 µg / √Hz
(12mmx10mm)

VIA HP



Range 50 g
Targeted precision < 50 µg
Targeted Noise : 0.5 µg / √Hz
(Φ <11mm)

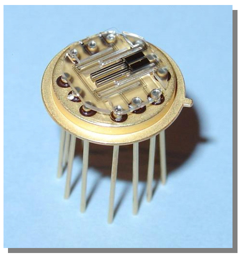
AVAS

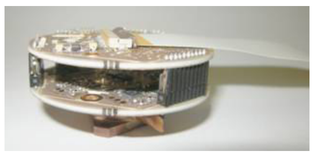


Range : 5 g
Target Precision : 5 µg
Target Noise: 50 nano-g / √Hz
(9 mm x 15 mm)

Multipurpose space mems gyro

Range : 100 °/s
Bandwith : 30 Hz
Bias stability: 2°/h
ARW: 0.02 °/ √hr
Consumption < 0.5 W





VIG

Gyro Applications	Range	ARW
Anomaly Detection	10 °/s	0.2 °/√hr
Rover Navigation	20 °/s	0.15 °/√hr
Safe Mode	20 °/s	0.1 °/√hr
Attitude acquisition	20 °/s	0.1 °/√hr
Transfer	-	0.04 °/√hr
Orbit Control	-	0.002 °/√hr
Normal Mode	-	0.001 °/√hr

Thank you for your attention