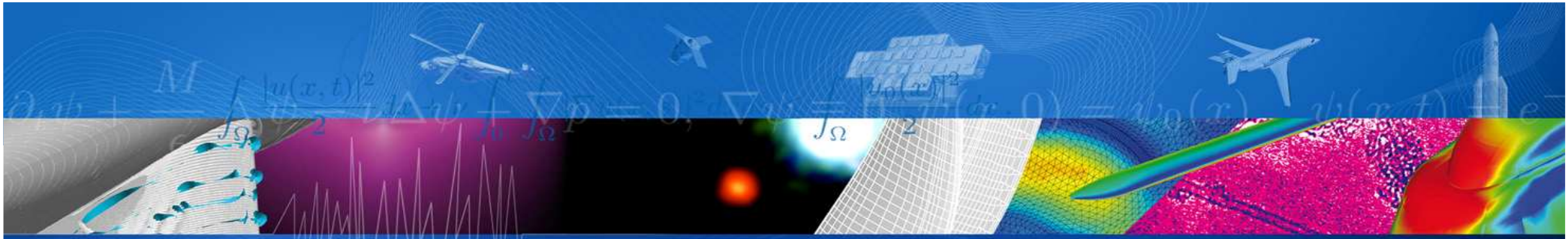

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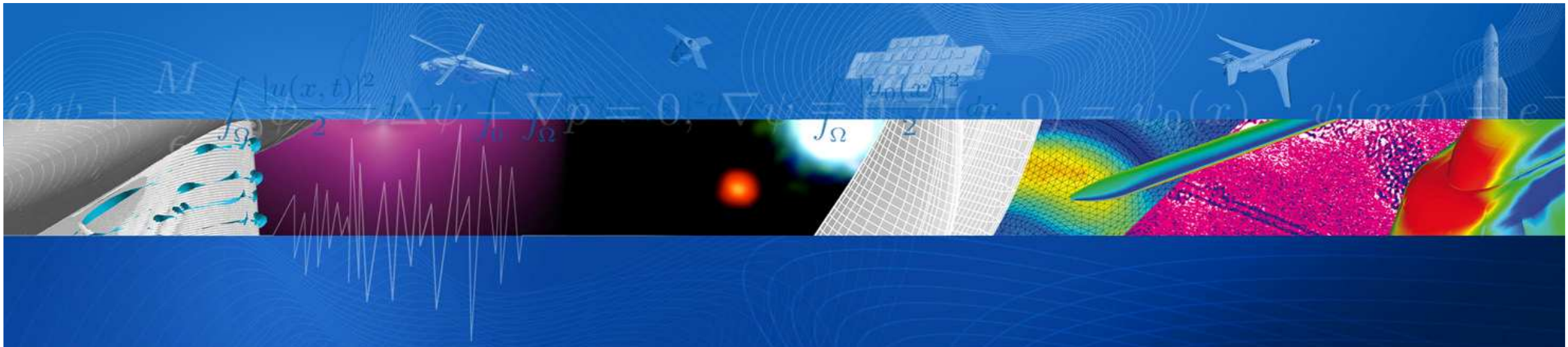

MicroSTAR accelerometer

Bernard Foulon,
Bruno Christophe, Françoise Liorzou & Vincent Lebat
Bernard.foulon@onera.fr

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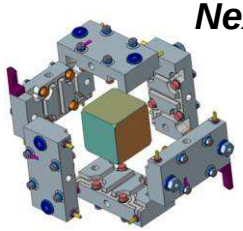
Electrostatic space accelerometer at Onera

Cubic Proof-mass

3 linear accelerations

3 angular accelerations



Next missions 2020 - 2030

Geodesy NGGM (ESA) – GRACE-2 (NASA)

-Smaller, less consumption

-3 sensitives axis

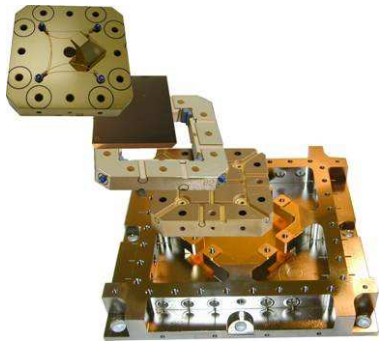
-comparable noise and thermal performances

Parallelipipedic Proof-mass

2+1 linear accelerations

1+2 angular accelerations

On-ground levitation



Accelerometer for Gravity missions:

CNES – CHAMP – 2000 – 10^{-9} m/s²/Hz$^{1/2}$

JPL – GRACE – 2002 – 10^{-10} m/s²/Hz$^{1/2}$

ESA – GOCE – 2009 – 10^{-12} m/s²/Hz$^{1/2}$

JPL – GRACE-FO – Launch foreseen in 2017- 10^{-10} m/s²/Hz$^{1/2}$

Accelerometer for fondamental physics:

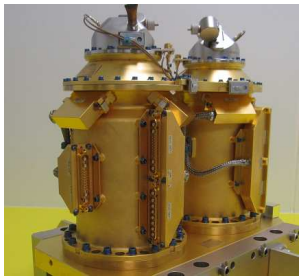
CNES – MICROSCOPE –10^{-12} m/s²/Hz$^{1/2}$

Launch foreseen in 2016

Cylindrical Proof-mass

3 linear accelerations

3 angular accelerations



Spherical Proof-mass

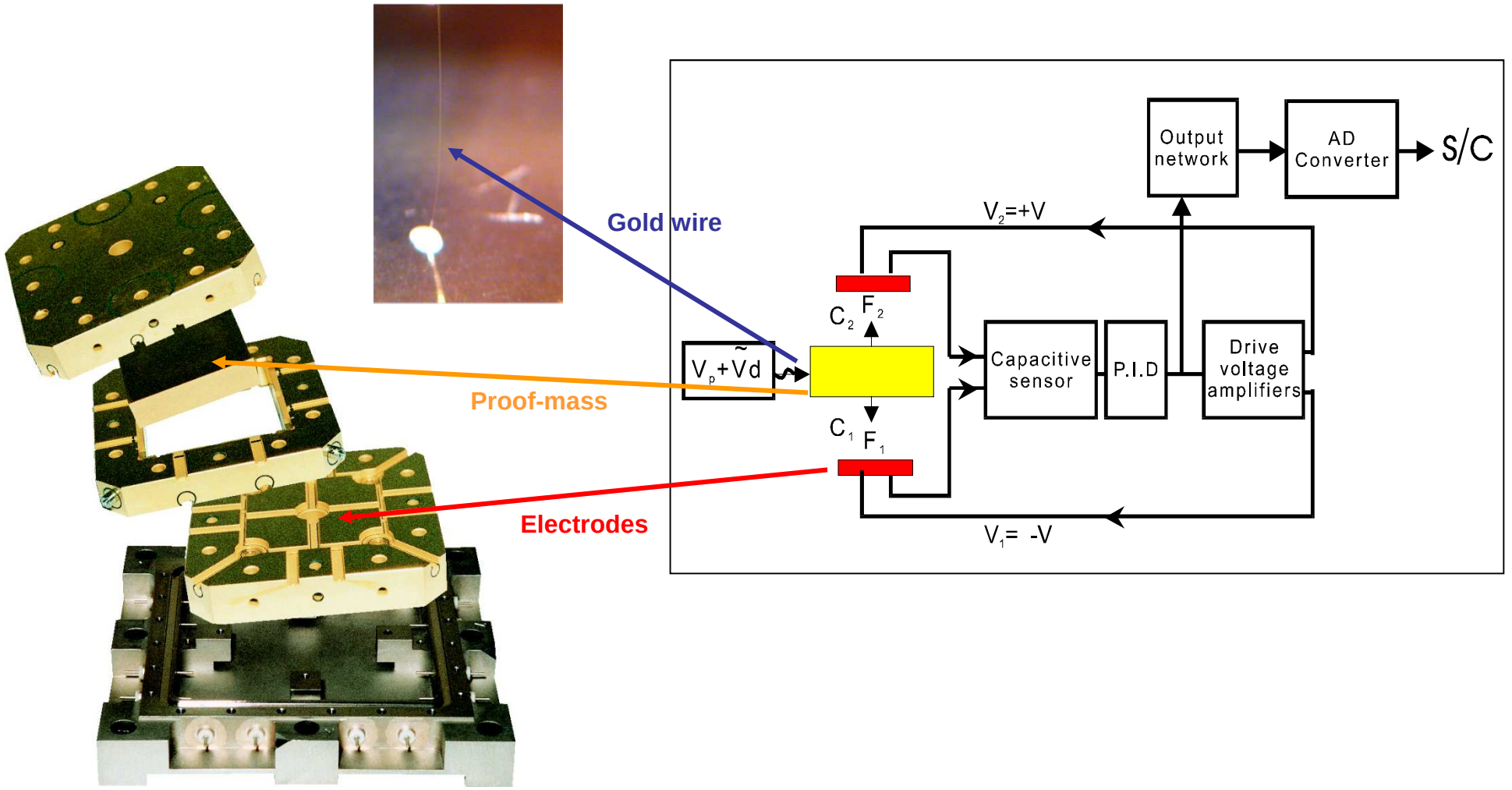
3 linear accelerations

CNES – CACTUS Accelerometer

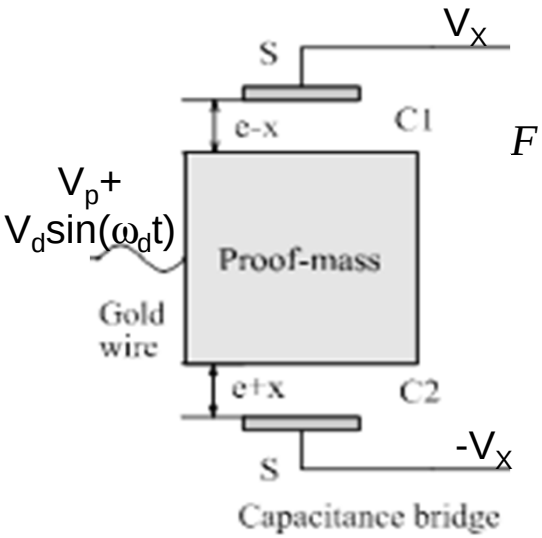
Lanch on the 15th May 1975 (Diamant BP4)

Electrostatic accelerometer - Principle

Capacitive detection and electrostatic action



Accelerometer principle of operation



Electrostatic force

$$F = F_1 - F_2 = \frac{1}{2}\left[\frac{\partial C_2}{\partial x}\left(V_X - V_p - V_d \sin(\omega_d t)\right)^2\right] - \frac{1}{2}\left[\frac{\partial C_1}{\partial x}\left(V_X + V_p + V_d \sin(\omega_d t)\right)^2\right]$$

$$a_X = \frac{2\varepsilon S}{me^2}\left(V_p^2 + \frac{V_d^2}{2}\right)\frac{x}{e} - \frac{2\varepsilon S}{me^2} V_P V_X + \frac{2\varepsilon S}{me^2} V_X^2 \frac{x}{e}$$

- $\frac{2\varepsilon S}{me^2}\left(V_p^2 + \frac{V_d^2}{2}\right)\frac{x}{e}$: Electrostatic stiffness
- $\frac{2\varepsilon S}{me^2} V_P V_X$: Electrostatic gain
- $\frac{2\varepsilon S}{me^2} V_X^2 \frac{x}{e}$: Non linear term
- V_X : The measurement

Capacitive Detection

$$\Delta C = \frac{2\varepsilon S}{e} x$$

Accelerometer Modes

Large Range Mode (LRM) for acquisition : V_p= 40 V and V_d= 1,25 Vrms

Nominal Range Mode (NRM) for science : V_d= 10 V and V_d= 5 Vrms

Electrostatic accelerometers for Earth Gravity Missions

GRACE (NASA-JPL), March 2002

Microwave K-Band
Inter satellite Ranging System

+

Electrostatic Accelerometer

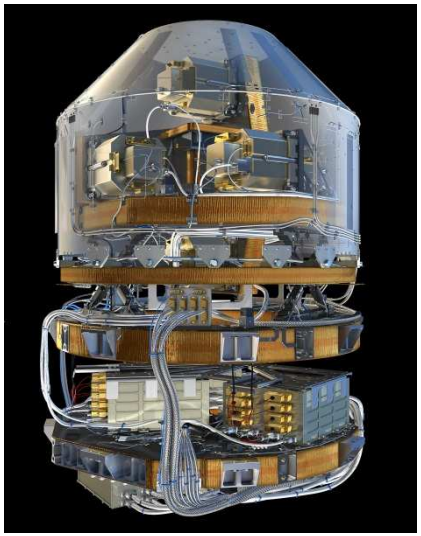
GOCE (ESA), March 2009

Drag Free System
with Electric Propulsion

+

Gradiometer (EGG)
with 6 Accelerometers

+



The common mode the accelerometers of each Gradio arm provides the NG acceleration to feed @10Hz the Drag Free System

The accelerometers provide the NG acceleration to correct the inter S/C range from NG contribution in order to retrieve the pure gravitational effect.

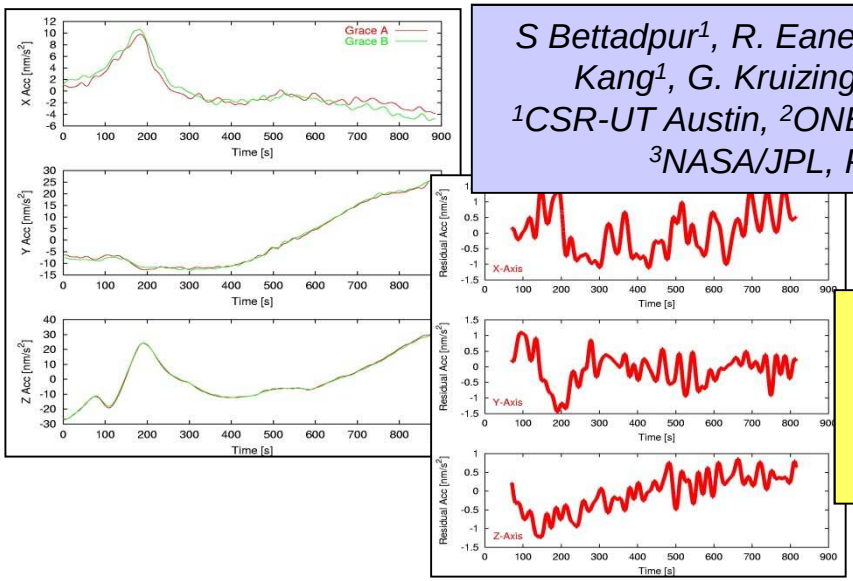
- Γ_n: $1.0 \cdot 10^{-10}$ ms^{-2} /$Hz^{1/2}$
- Γ_{max}: 5.10^{-5} ms^{-2}
- $[0.1 \cdot 10^{-3} ; 10^{-1}]$ Hz

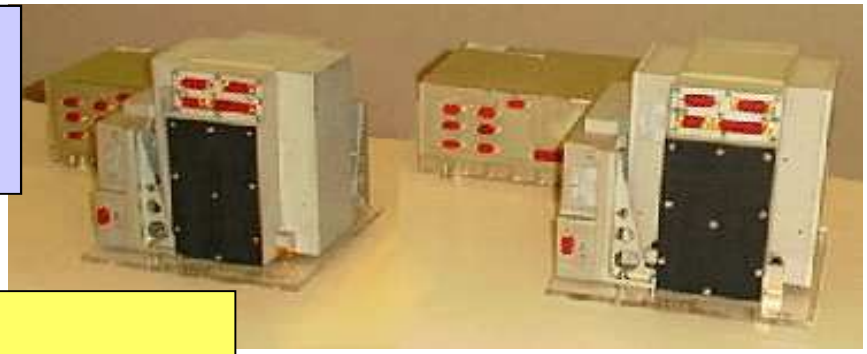
Differential accelerometer measurements are used to retrieve the GGT components

- Γ_n: $2.0 \cdot 10^{-12}$ ms^{-2} /$Hz^{1/2}$
- Γ_{max}: 6.10^{-6} ms^{-2}
- $[5 \cdot 10^{-3} ; 10^{-1}]$ Hz

GRACE Accelerometer : Performance & Lessons

S Bettadpur[1], R. Eanes[1], D. Hudson[2], Z. Kang[1], G. Kruizinga[3] & P. Nagel[1]
[1]CSR-UT Austin, [2]ONERA-DMPH, Paris, [3]NASA/JPL, Pasadena





RMS maxi error :
X (cross-track) = 0.44 nm/s^2
Y (radial) = 0.50 nm/s^2
Z (along-track) = 0.40 nm/s^2

Acc. noise at 35–200 mHz, 10^{-10} m/s^2.Hz$^{-1/2}$

Satellite	Date	X_{ARF}	Y_{ARF}	Z_{ARF}
GRACE A	2007-01-17	5.4 - 7.7	0.6 - 1.2	0.5 - 1.3
GRACE B	2004-12-09	4.8 - 7.5	0.6 - 1.5	0.4 - 1.0

J. Flury, S. Bettadpur, B.D.Tapley, Precise accelerometry on board the GRACE gravity field satellite mission, Adv. Space Res., 42, 2008.

SuperSTAR specifications

Full Scale Range Y,Z : 5.10^{-5} ms^{-2}

Frequency Bandwidth : 5.10^{-5}Hz - 4.10^{-2}Hz

(in fact from DC to a few Hz)

Noise PSD : S(f) = 10^{-20} (1+5 10^{-3}/ f) m^{2}s^{-4}Hz^{-1}

Biais C_0 Y, Z < 2 10^{-6} ms^{-2}

Scale factor C_1 = 1.0 +/- 2%

Non linearity C_2 < 20 m^{-1}s^2

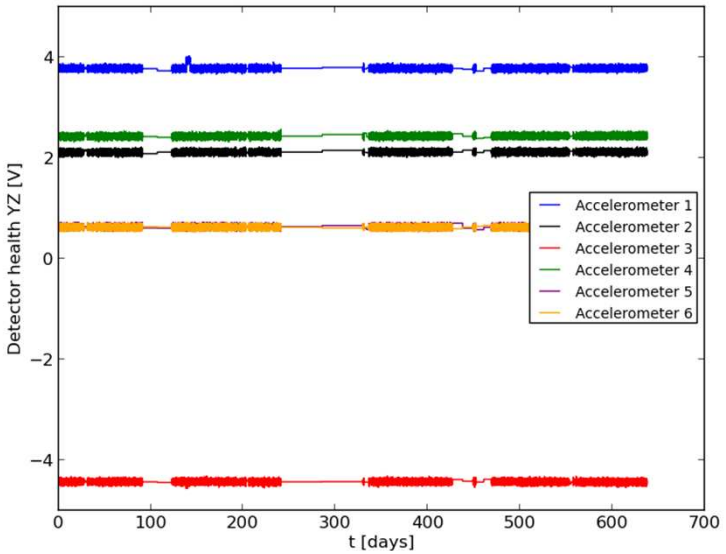
C_3 < 10^4 m^{-2}s^4

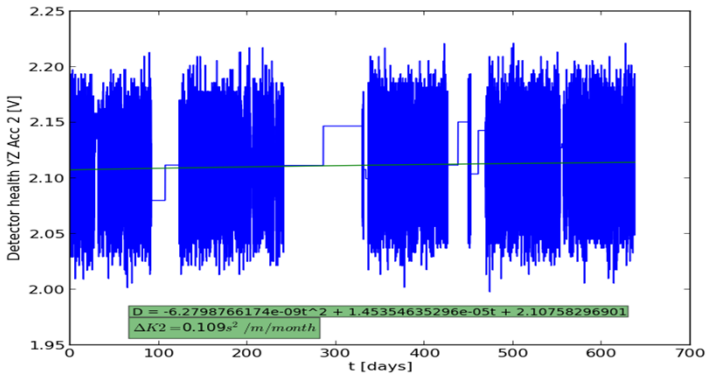
Bias : in orbit estimate → X: 9.214 Y: 0.566 Z: 0.786 10^{-6} ms^{-2}

T.Van Helleputte, E.Doornbos, P.Visser, CHAMP and GRACE accelerometer calibration by GPS-based orbit determination, Adv. Space Res., 43, 2009.

GOCE accelerometer performance & lessons

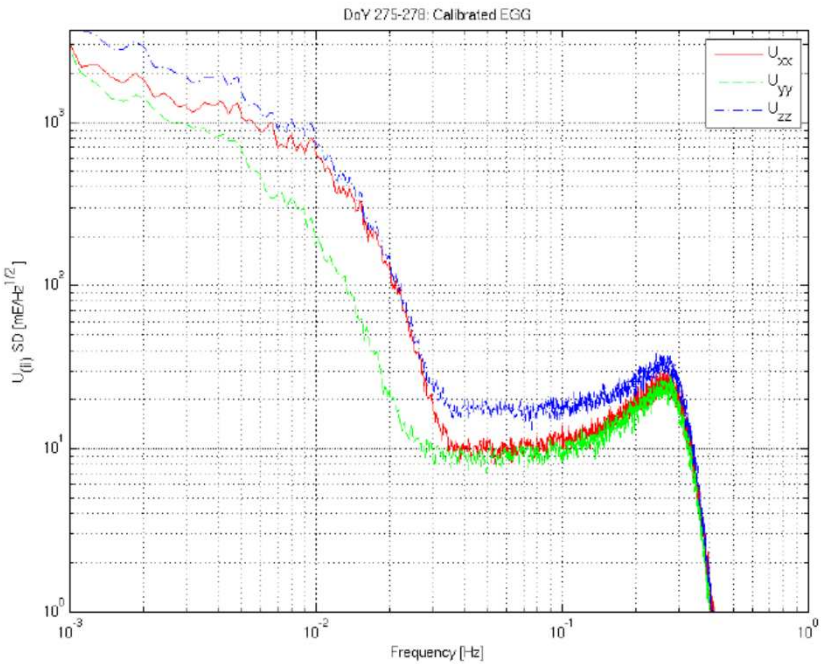
Good health test of the position sensors





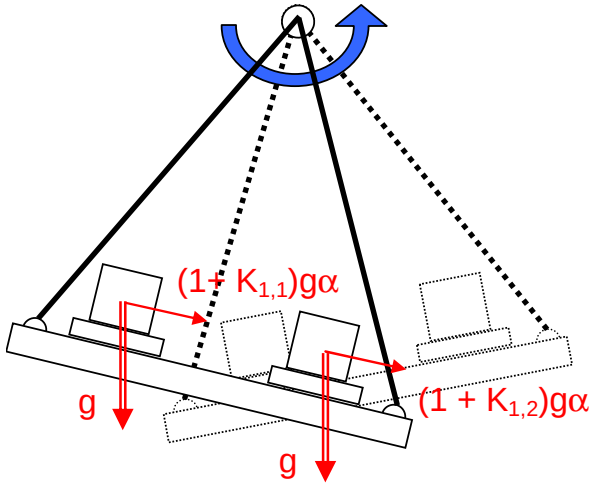
Bias evolution of the position sensors
ASH2 accelerometer example : 1.45 x 10^{-5} V/Day

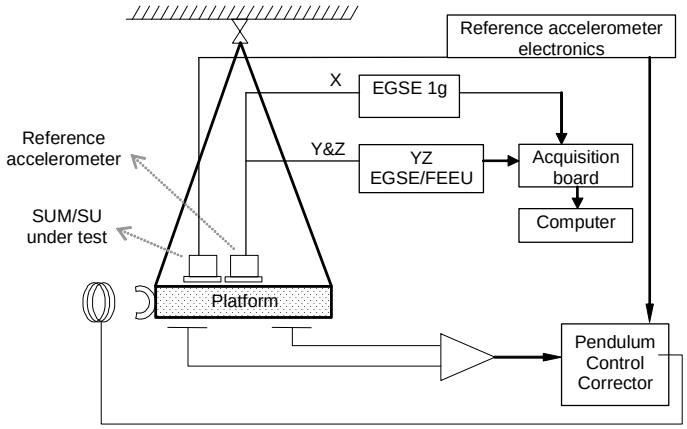
PSD noise of the GOCE accelerometer (by arm pair)

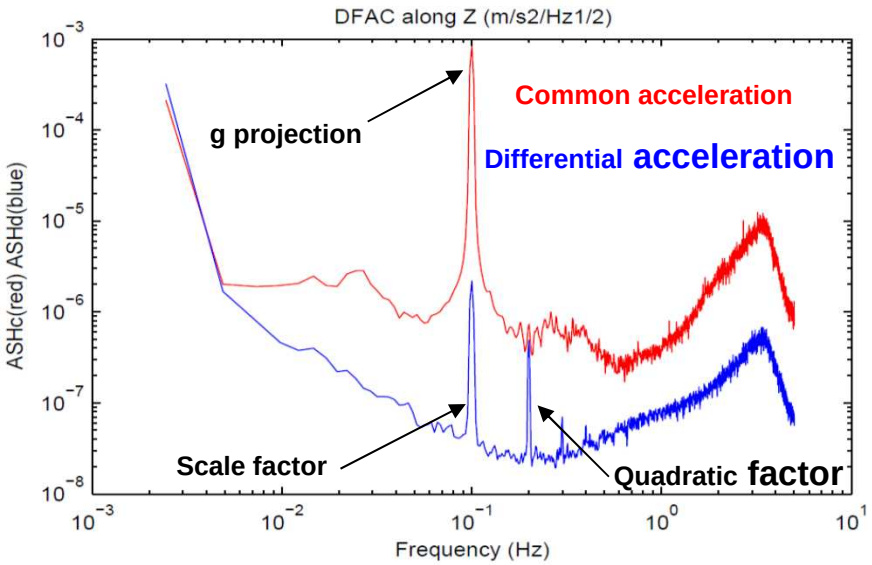


Accelerometer performance (40-100 mHz),
ASH_{14} noise: 3.9 10^{-12} m/s²/Hz$^{1/2}$
ASH_{25} noise: 3.1 10^{-12} m/s²/Hz$^{1/2}$
ASH_{36} noise: 6.7 10^{-12} m/s²/Hz$^{1/2}$
Expected: 2.0 10^{-12} m/s²/Hz$^{1/2}$

Functional and performance verification on pendulum bench

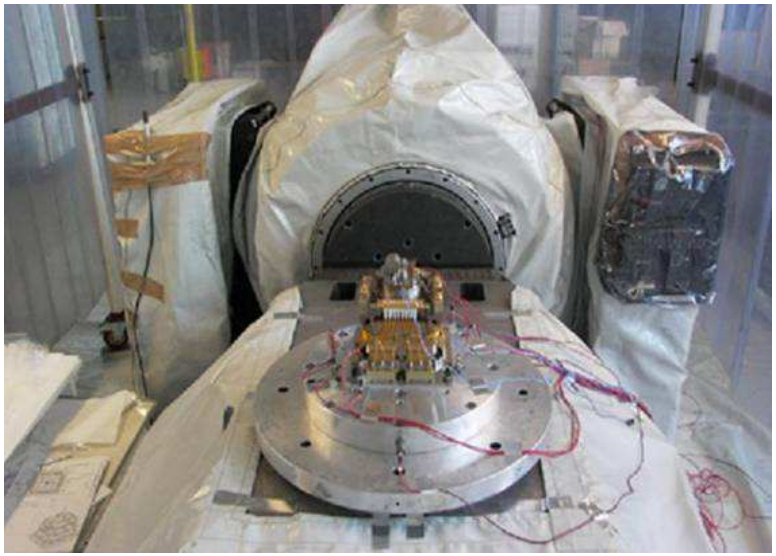


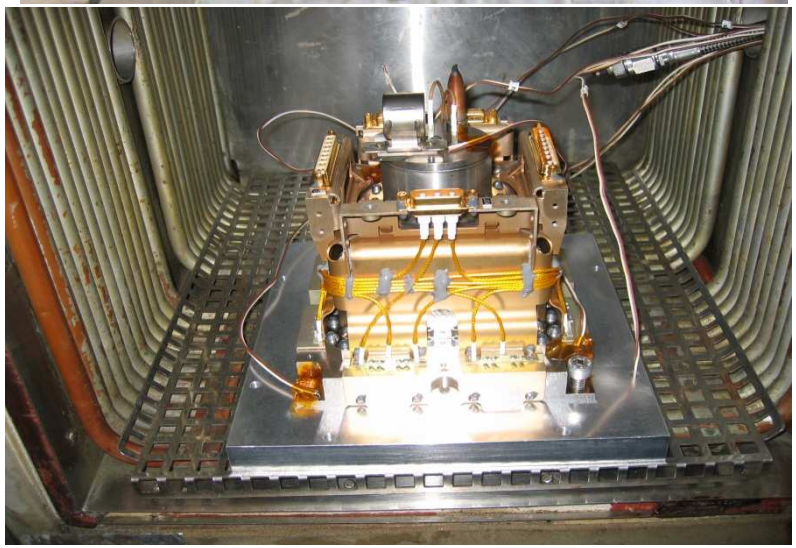




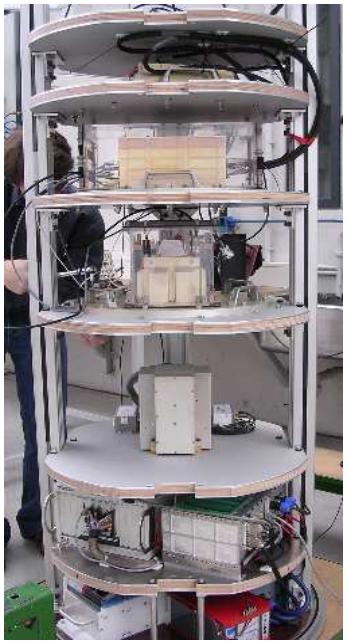
Qualification / Acceptance Tests

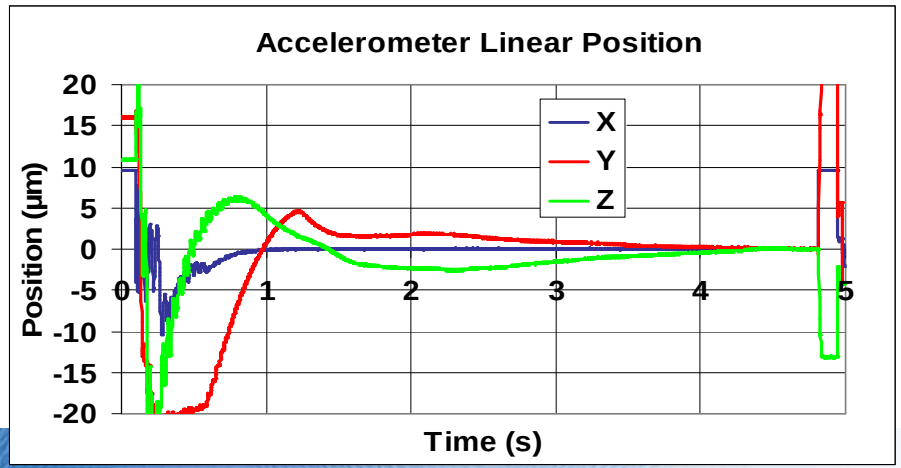
2. Vibration and thermal cycling





3. Free fall in Bremen Zarm drop tower





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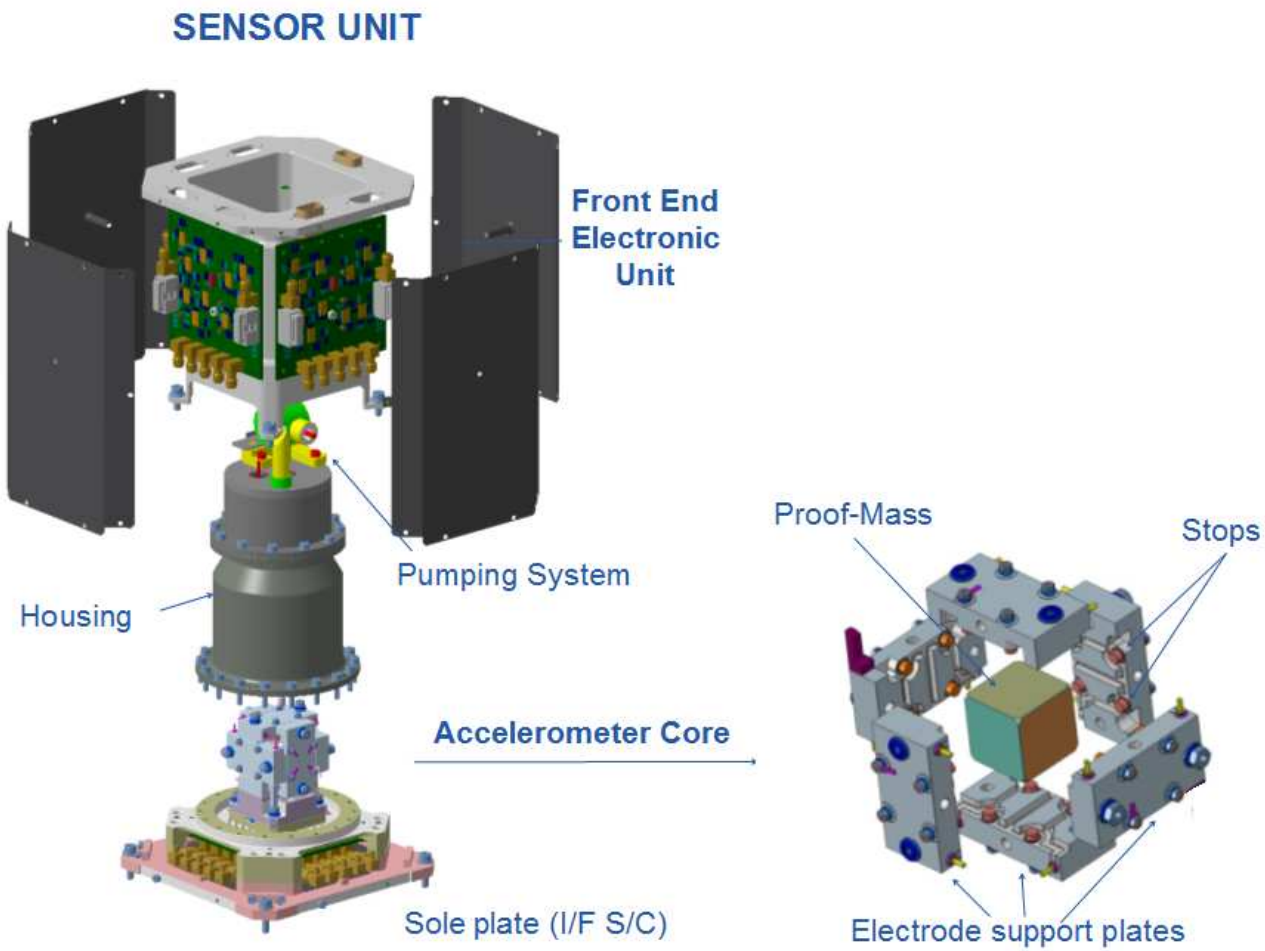
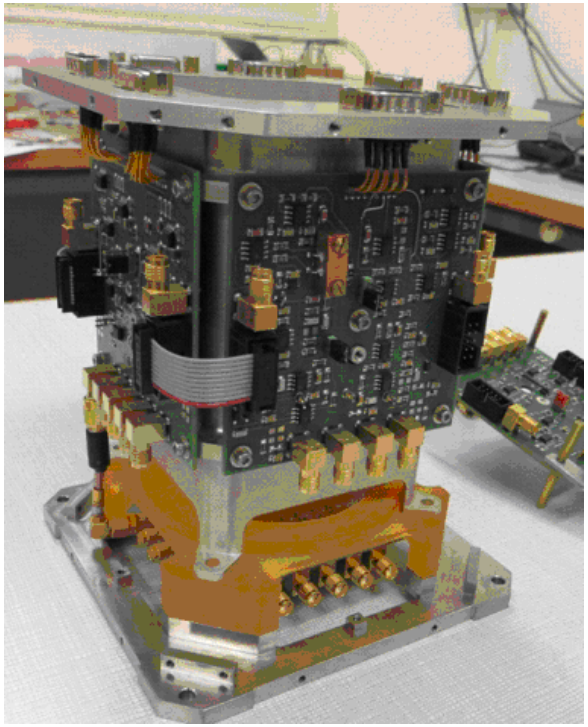
MicroSTAR Accelerometer : prototype description

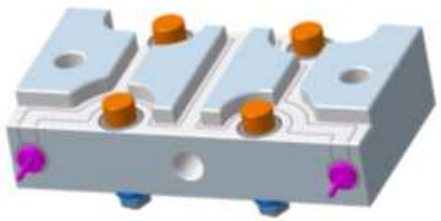




MicroSTAR Accelerometer : technology

dimension

Proof-mass dimension:	**30×30×30 mm³**
Mass:	**238 g**
Inertia:	**3.564×10⁻⁵ kg.m²**
Gap:	**300 µm**
Free motion:	**± 60 µm**
Electrode area:	**2.114 cm²**
Electrode capacitance:	**4 pF**
Gold wire	**L 22 mm Φ 7.5 µm**



Electrode plate design

Electrode plate after US machining

- Glass material (ULE)
- Optical polishing
- High accuracy of the final plate in accordance with the peformance budget

ULTRA-SONIC MACHINING OF THE CORE PLATES

→Specific Process developed by ONERA

Gold coating

ULE plate on ultra-sonic machine (ONERA patent)

Control

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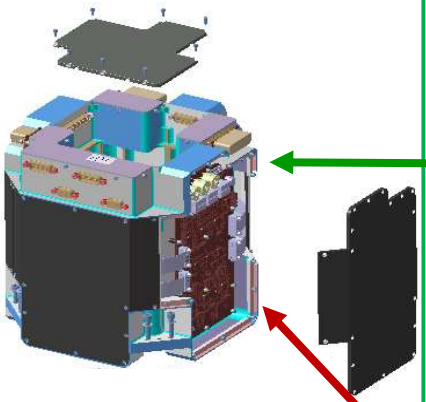
MicroSTAR Accelerometer packaging

Sensor Unit (SU)

Front End Electronic Unit (FEEU)

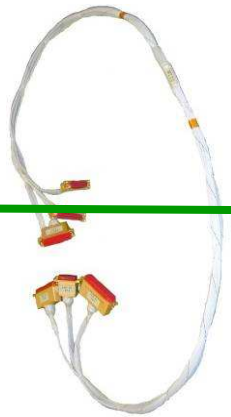


Vol : 200x200x200 mm²

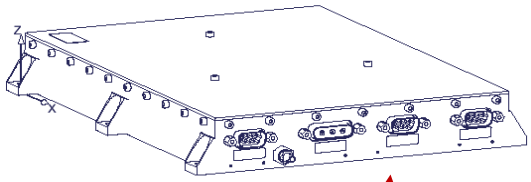
Mass : 8 kg

Sensor Unit Mechanic (SUM)

Harness FEEU/ICU



Interface and Control Unit (ICU)



Vol : 250x200x35 mm²

Mass : 1.5 kg

Data, PPS

28 V

Satellite

PCU

Power : 10 W

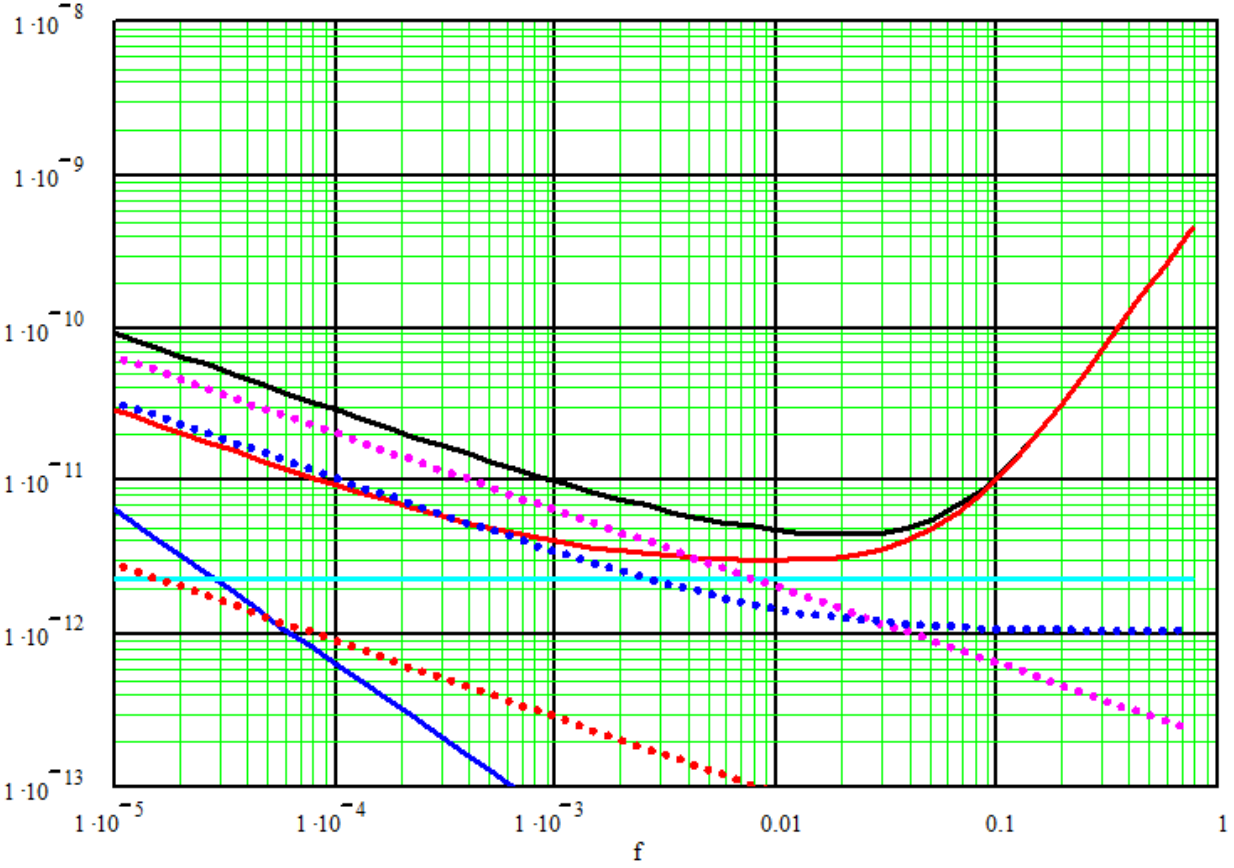
OBC

Science data : 6 accelerations + Vp + 1 HK = 8 x 24 bit @ 10 Hz

HK data : 6 position sensors + Vd + 5 power lines + n temperatures

MicroSTAR Accelerometer : Measurement noise

Square-root of the noise PSD



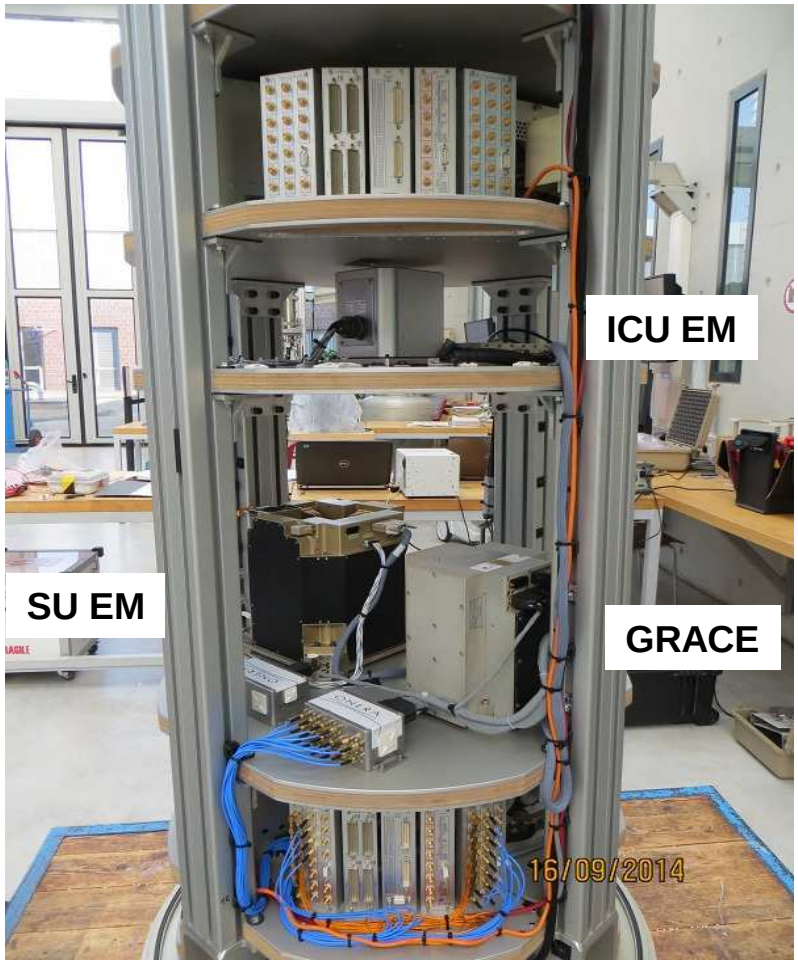
Measurement range = 7×10^{-6} ms^{-2}

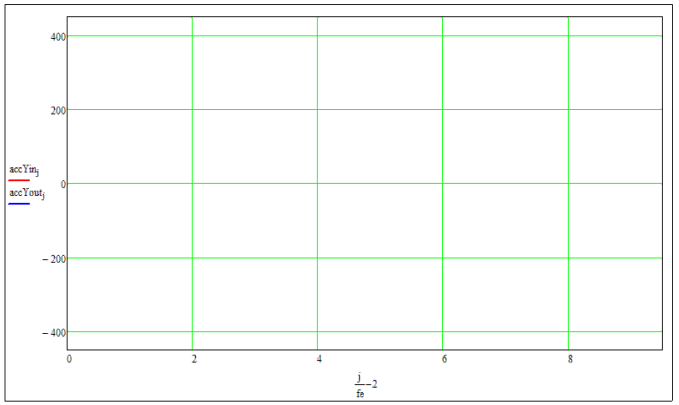
- Total noise
- Position sensor
- Pressure + thermal
- ADC
- Dissymmetry + electrical noise
- Wire
- CPD

$$\sqrt{Sn(f)} = K\sqrt{1+\left(\frac{f}{5\,\mathrm{mHz}}\right)^{-1}+\left(\frac{f}{0.07\ \mathrm{Hz}}\right)^{4}} \quad \text{with} \quad k = 4\times10^{-12}\ \mathrm{m.s^{-2}.Hz^{-1/2}}$$

Drop Tower test

Catapult





Slow motion (speed/2)

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Catapult Test : GRACE-FO EM / GRACE Comparison

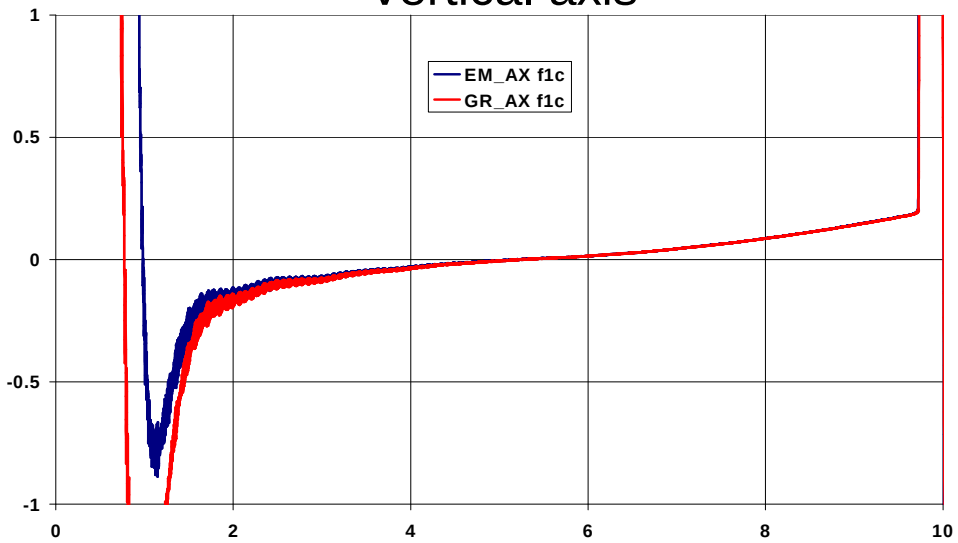
GFO EM in LRM : Vp = 40 V and Vd = 1.25 Vrms

GRACE in LRM : Vp = 40 V and Vd = 5 Vrms

Measurement filtered with 1st order at 10 Hz

Equivalent to the ΣΔ ADC averaging

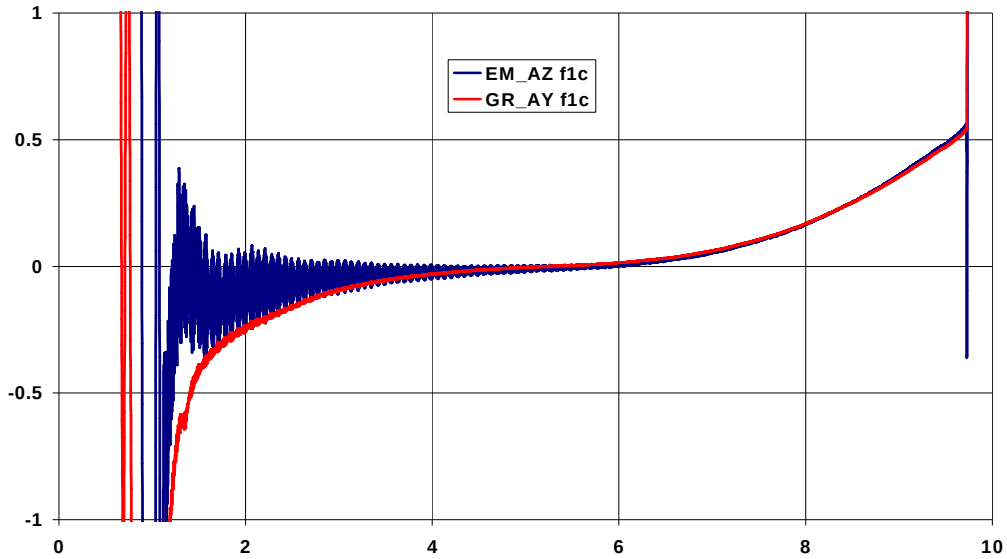
$\times 10^{-3}$ m.s^{-2} Vertical axis



Bias correction :

- GFO EM AX → 18.6×10^{-3} m.s^{-2}
- GRACE AX → -8.7×10^{-3} m.s^{-2}

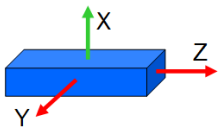
$\times 10^{-4}$ m.s^{-2} Horizontal axis

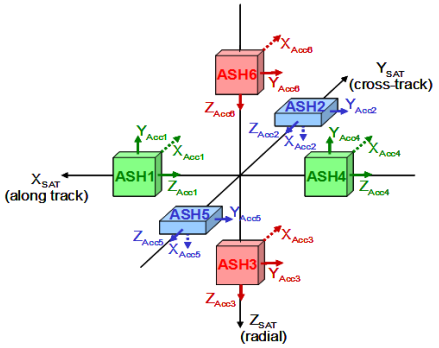


Bias correction :

- GFO EM AY → 5.2×10^{-5} m.s^{-2}
- GRACE AY → -4.7×10^{-5} m.s^{-2}
- GFO EM AZ → 6.2×10^{-6} m.s^{-2}
- GRACE AZ → 5.7×10^{-6} m.s^{-2}

GOCE : Comparison between Angular Accelerations from Linear and Angular outputs





in accelerometer reference frame

$$US : \dot{\omega}_{X,el} = \dot{\omega}_X + \frac{I_Z - I_Y}{I_X}\omega_Y\omega_Z \approx \dot{\omega}_X$$

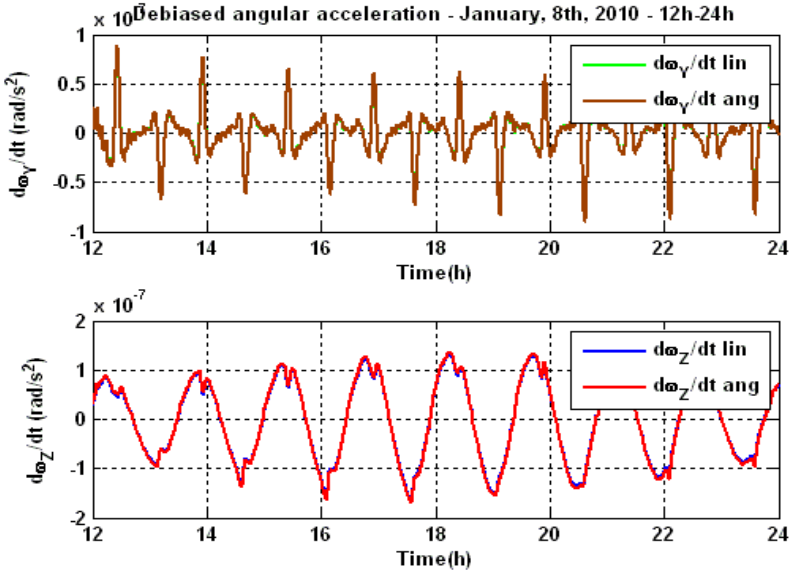
$$LS : \dot{\omega}_{Y,el} = \dot{\omega}_Y + \frac{I_X - I_Y}{I_Y}\omega_X\omega_Z \approx \dot{\omega}_Y - \omega_X\omega_Z$$

$$LS : \dot{\omega}_{Z,el} = \dot{\omega}_Z + \frac{I_Y - I_X}{I_Z}\omega_X\omega_Y \approx \dot{\omega}_Z + \omega_X\omega_Y$$

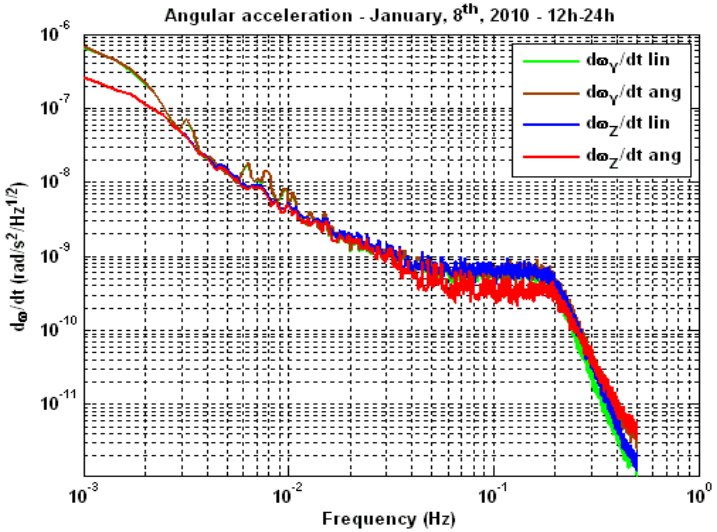
in spacecraft reference frame

$$\dot{\omega}_Y = \frac{\dot{\omega}'_{1,US} + \dot{\omega}'_{4,US} + \dot{\omega}'_{3,US} + \dot{\omega}'_{6,US}}{4}$$

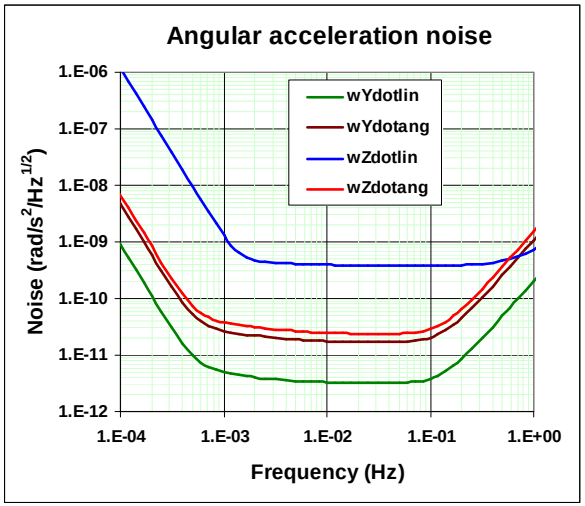
$$\dot{\omega}_Z = \frac{\dot{\omega}'_{2,US} + \dot{\omega}'_{5,US}}{2}$$



Angular acceleration noise (uncalibrated data)

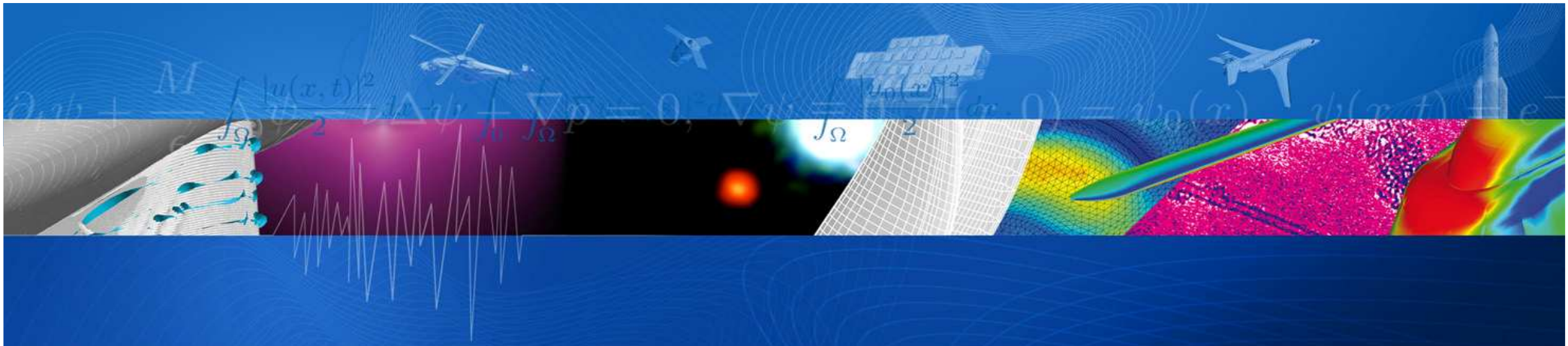


Expected noise



Conclusion

- **MicroSTAR proposed for GRASP Project with 3x3x3 cm^2 cubic proof-mass**
- **Same technologies inherited from previous GRACE, GOCE, GFO and MICROSCOPE missions**
- **No more on-ground levitation but inhanced drop tower testing thanks to the catapult facility as for MICROSCOPE**
- **Non-Gravitational forces measurement to improve POD**
- **3 linear accelerations measurements**
- **PSD noise < 10^{-11} $ms^2/Hz^{1/2}$ in [10^{-3} Hz – 0.1 Hz] MBW**
- **3 angular acceleration measurements to improve attitude control and determination by hybridation with Star Trackers measurement as in GOCE**



Thank you for your attention

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