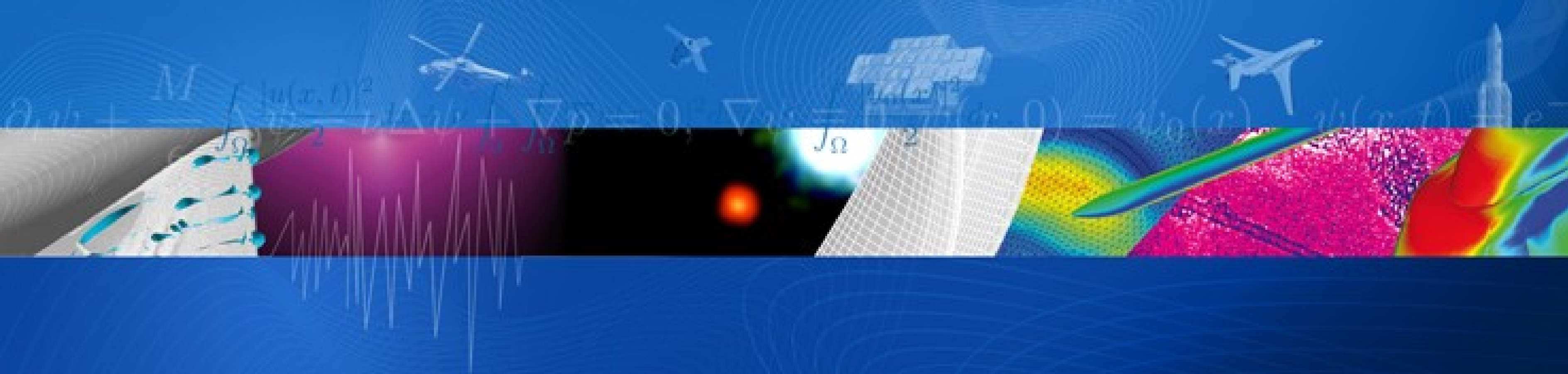

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The ultra sensitive GOCE Accelerometers and their future developments

J.P. MARQUE, B.CHRISTOPHE, B.FOULON, P.TOUBOUL

Towards a Roadmap for Future Satellite Gravity Missions

GRAZ –AUSTRIA – September 30- October 02 2009

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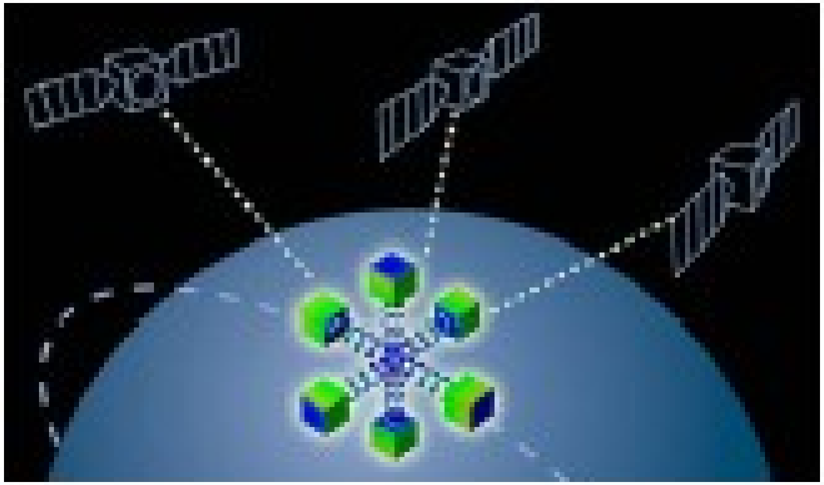
The realization of the accelerometers of the esa GOCE mission was carried out under contract with ThalesAlenia Space acting as Prime Contractor of the Satellite.



Acquisition Mode:

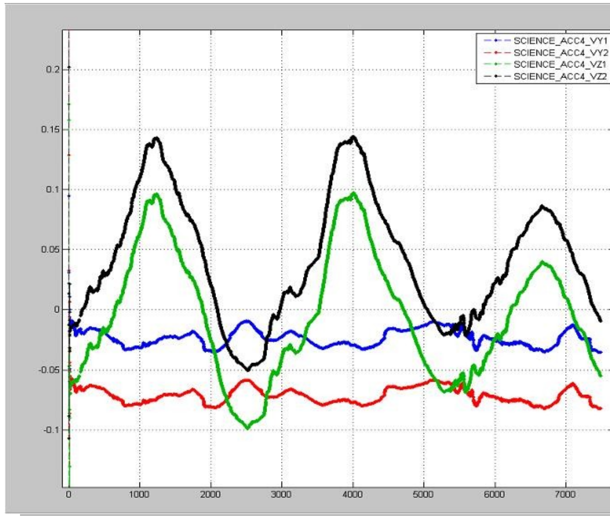
April 7th ,9h06 UTC

6 Proof masses in levitation

Science Mode:

April 8th, 8h02 UTC

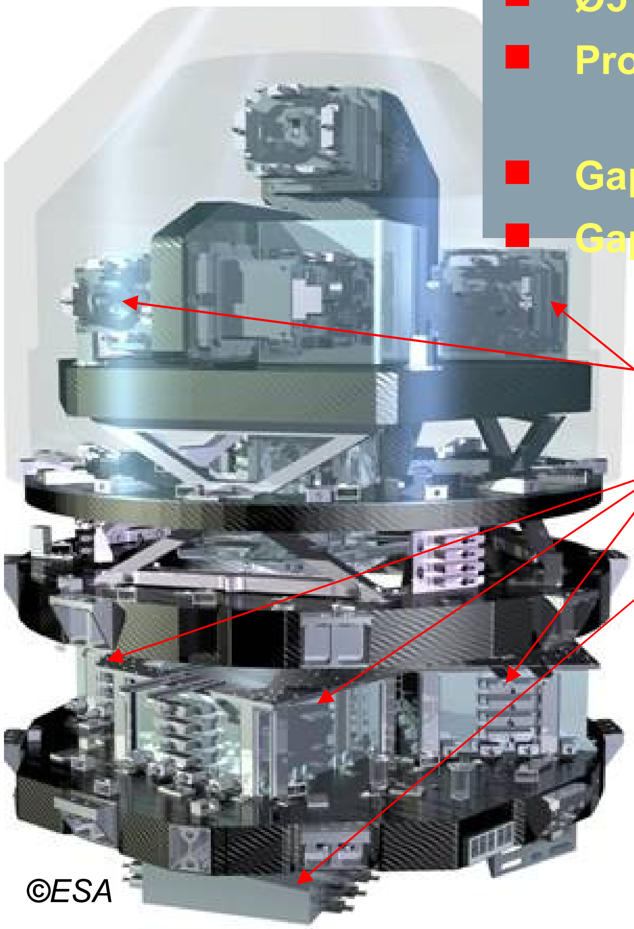
©ESA



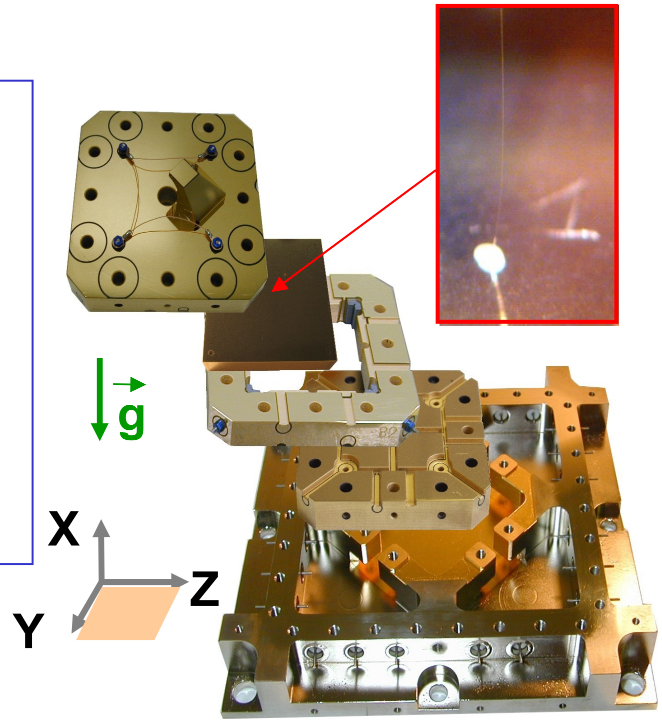
Before to come to such a signal …….

GRADIOMETER / ACCELEROMETER CONFIGURATION

- Ø5 µm Goldwire for PM DC voltage bias
- Proof mass : 320g platinum-rhodium alloy (40 x 40 x 9.992 mm)
- Gap X : proof mass - the 4 x electrode pairs = 32 µm
- Gap YZ : proof mass - the 4 (Y and Z) electrode pairs = 299 µm



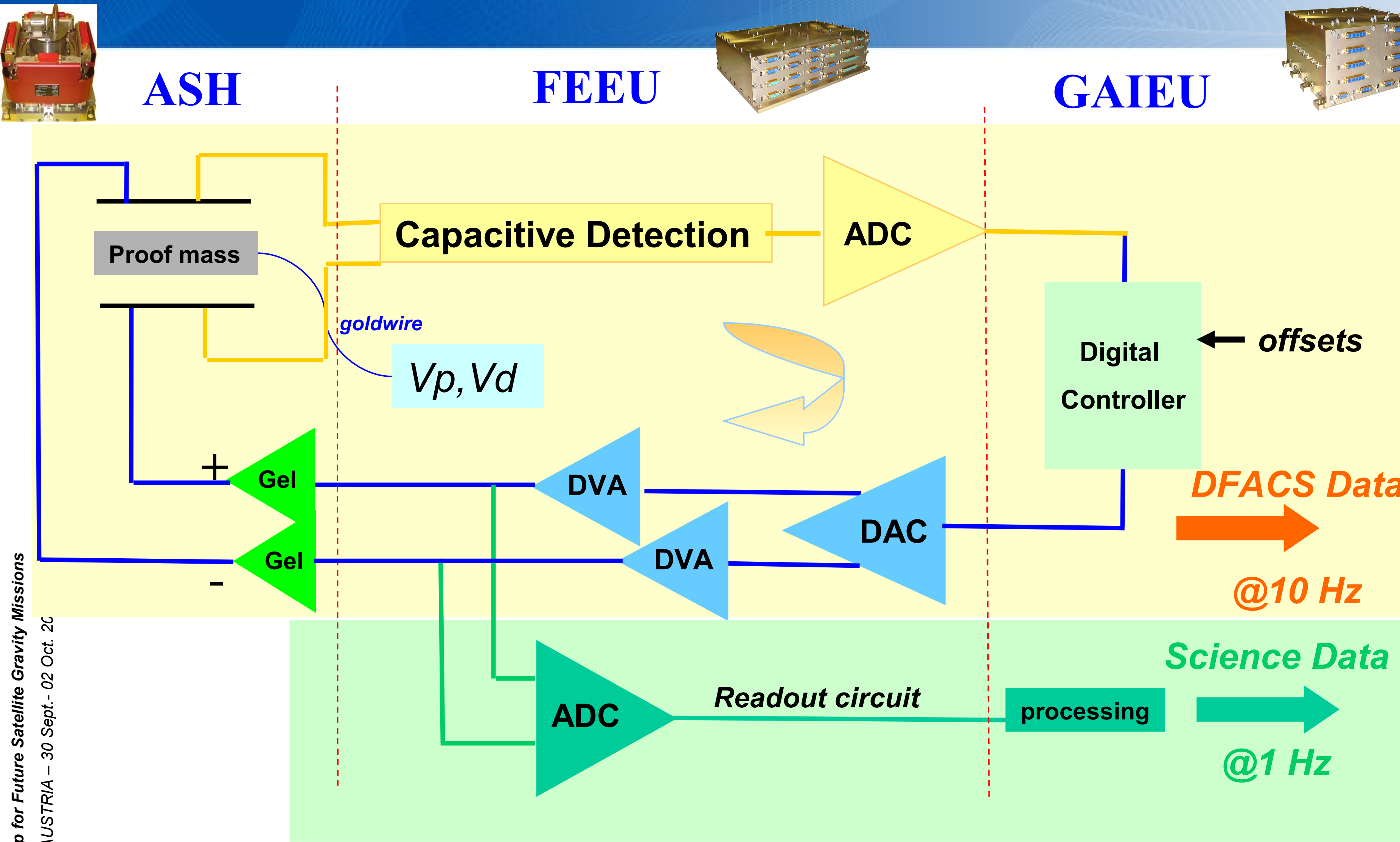
- 3 pairs of Accelerometer Sensor Head (ASH)
- 3 Front End Electronics Unit
- 1 Gradiometer Interface Unit
- 1 Carbon-Carbon stable structure
- 3 stages accurate thermal control



GOCE Gradiometer

ASH mechanical core

CONTROL LOOP AND DATA PROCESSING



$$\Gamma(V_{sc}) = bias + G(1+K_1)\,V_{sc} + K_2 G^2 V_{sc}^{\,2} + noise$$

ACCELEROMETER PERFORMANCES *(Science mode)*

PM Polarisation Voltage

Vp = 7.5 V

PM Detection Voltage

Vd = 7.6 V @ 100 KHz

Detector gain ***1.7 mV / nano-m***

Scale factor

Science data	***100 nano-g/V***
DFACS data	***1.7 micro-g/V***

Resolution $< 2\ 10^{-12}\ ms^{-2}\ Hz^{-1/2}$

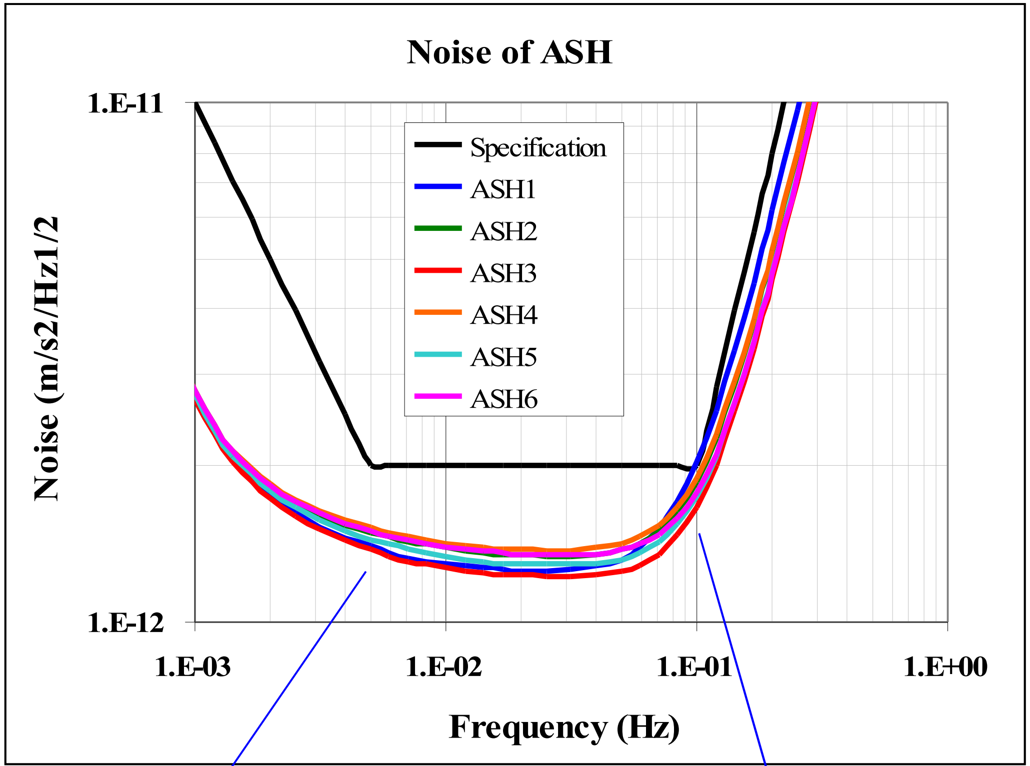
Range $\pm\ 6.5\ 10^{-6}\ ms^{-2}$

Main contributors in MBW

Upper Part : Detector-ADC1, ADC 2

Lower Part : ADC2, Goldwire damping

Bias thermal sensitivity



1.38 - 1.52 $\times 10^{-12}\ ms^{-2}\ Hz^{-1/2}$ ***@ 5 mHz***

1.67 – 2.02 $\times 10^{-12}\ ms^{-2} Hz^{-1/2}$ ***@ 100 mHz***

Roadmap for Future Satellite Gravity Missions

GRAZ –AUSTRIA – 30 Sept.- 02 Oct. 2009

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TEST PLAN : from parts to Unit

<u>At Parts level:</u>

- *Dedicated Physics experiments : tribology, CPD, stiffness...*
- *Accurate geometrical control: down to 1µm for core parts*
- *Test bench for Electronics performance and thermal sensitivity : down to 0.1µV and 10^{-15} F*

<u>At Unit level, on ground tests need:</u>

- *to levitate the PM against gravity*
- *a low acceleration environment to not saturate electronics*

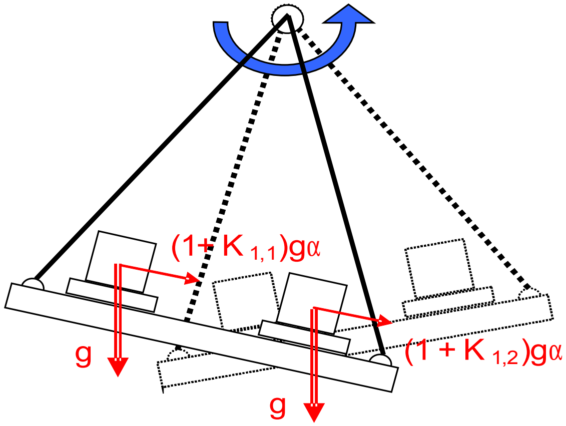
- ❑ *ASH X axis dedicated to 1 g levitation of the PM*
- ❑ *Pendulum bench controlled in horizontality better than 1 µrad*
- ❑ *Free Fall test in low gravity conditions*

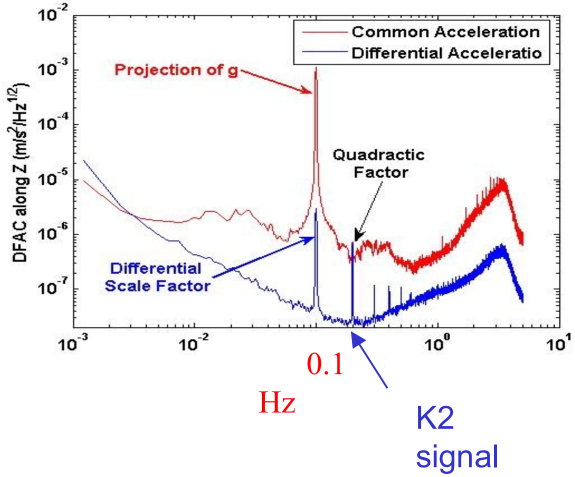
<u>Application to:</u>

- *Functional test and transfer function, linearity, range, stiffness verification,…*
- *Scale factor and Quadratic factor verification,*
- *FDIR software verification,*

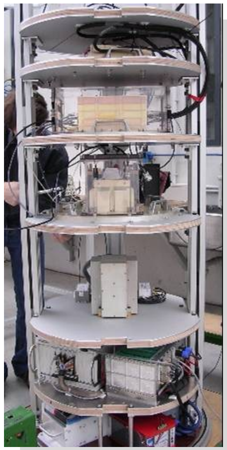
ON GROUND TESTS

Creation of a controlled in-plane acceleration by tilting the pendulum





Free Fall Test in ZARm drop tower



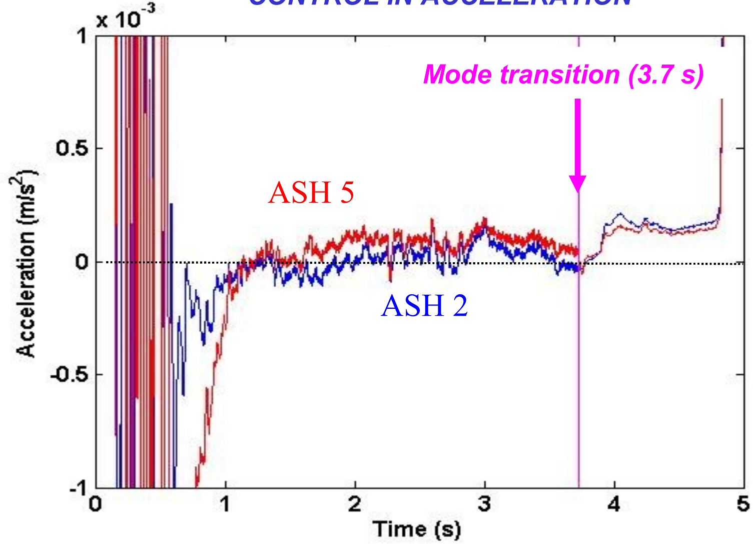
FEEU

ASH Pair

Super STAR Accelerometer

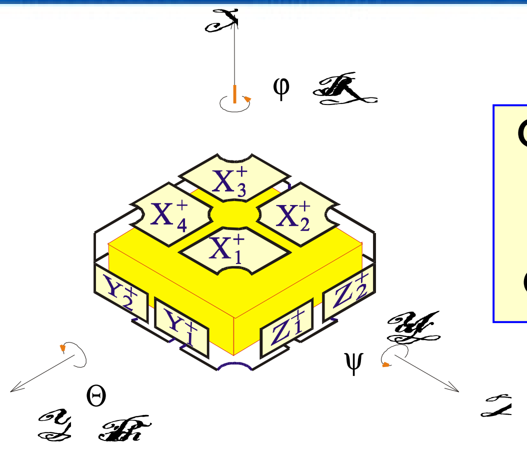
Capsule computer & batteries

X AXIS (g axis) : CONTROL IN ACCELERATION



IN FLIGHT PRELIMINARY RESULTS

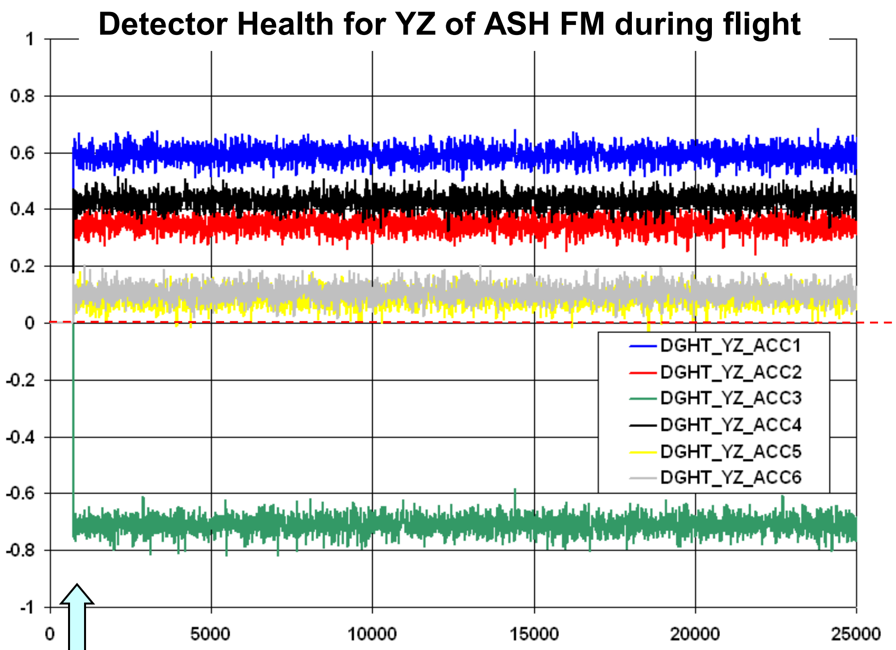
FLIGHT versus DROP TOWER TEST



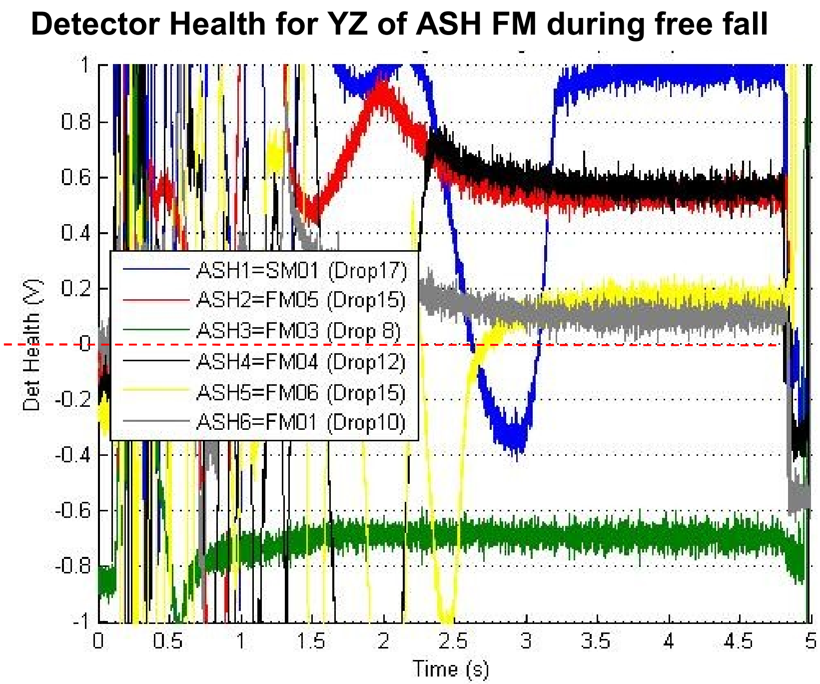
$\Phi \propto (Y2\text{-}Y1)$
or
$\Phi \propto (Z2\text{-}Z1)$

Detector_Health Test:
IY2-Y1 – Z1-Z2I < Threshold

1volt ⇒ 0.6 µm **30mV$_{rms}$ ⇒ 2 nm$_{rms}$**



06/04/2009 9h26'40"



Roadmap for Future Satellite Gravity Missions

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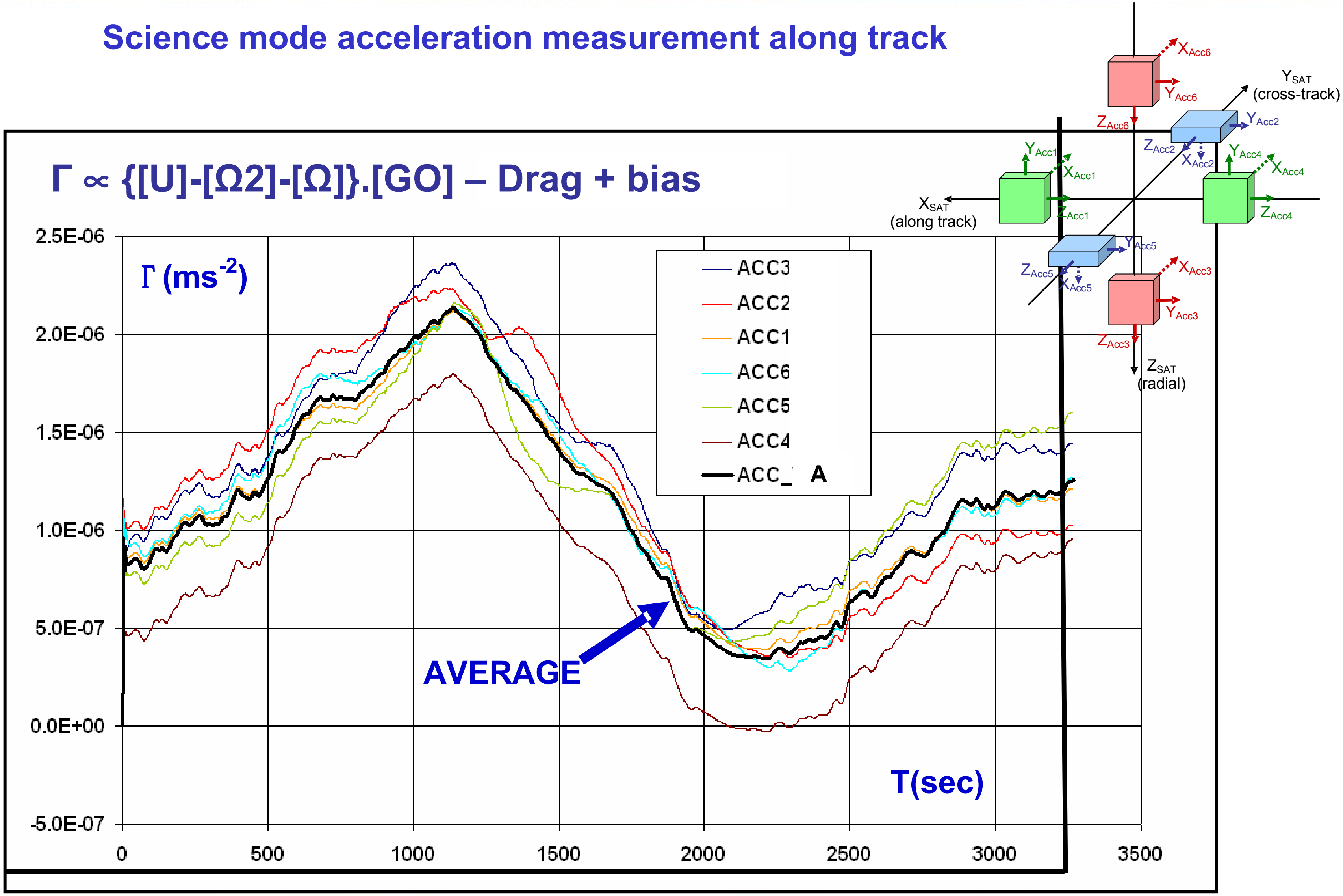
IN FLIGHT PRELIMINARY RESULTS

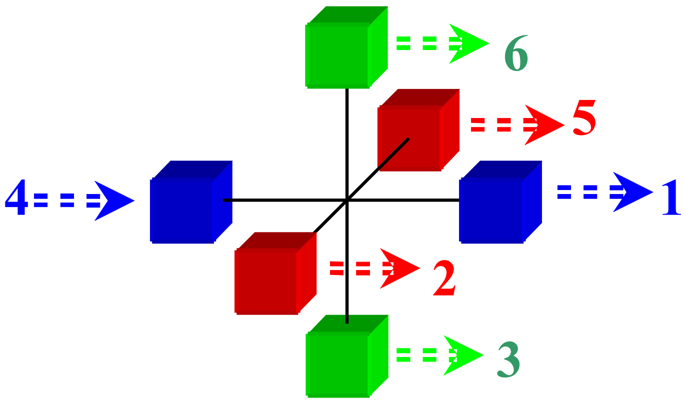
Science mode acceleration measurement along track



GOCE DRAG FREE PERFORMANCE

GOCE drag free performance, verified in commissioning phase (June 09) *@270km*

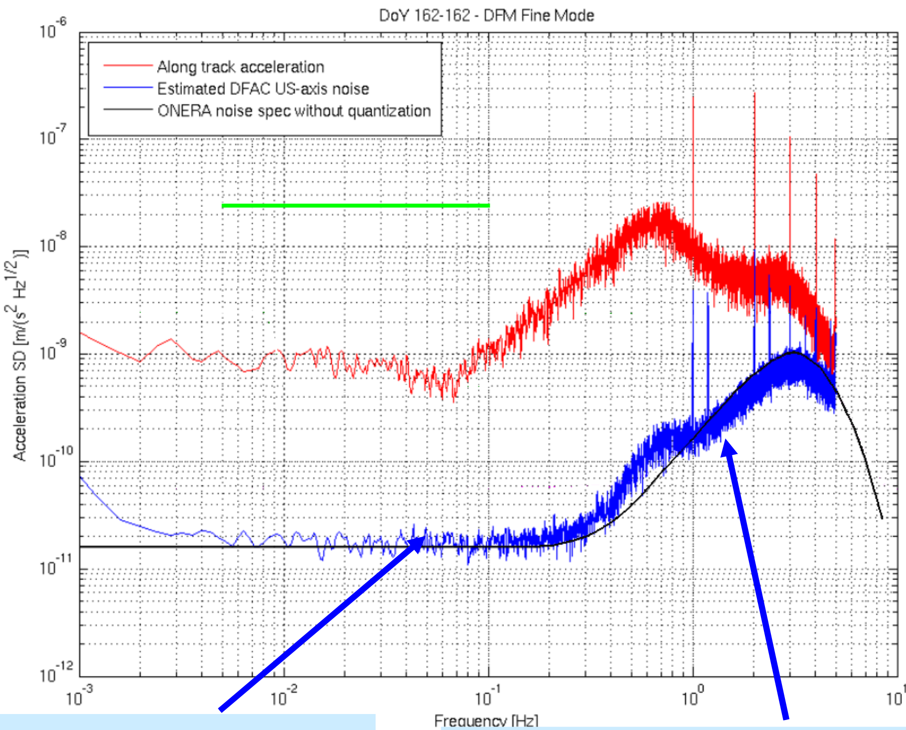
GOCE: Space technology for the reference Earth gravity field determination,
A.Allasio, D.Muzi, B.Vinai, S.Cesare,G.Catastini, M.Bard, J.P. Marque, EUCASS 2009, Versailles France.



The common mode of the two accelerometers voltages measures the non gravitational forces at the middle of their axis, located at the center of gravity of the satellite.

DFAC noise estimated through redundant acceleration measurements

N = 2/sqrt(3) [acc14x – (acc25x +acc36x)/2]



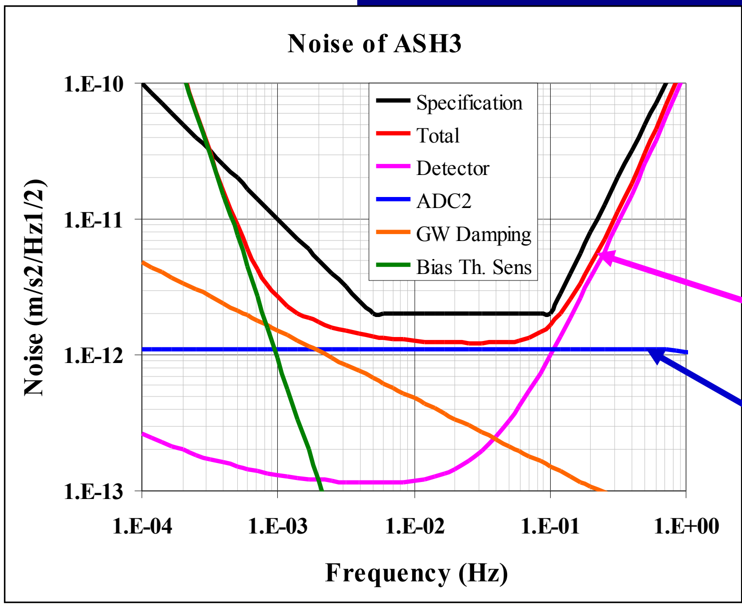
Actuation noise (DAC + DVA) main contributor in [10 mHz – 100 mHz] MBW

Detection noise (detector + ADC1) main contributor in [0.5 Hz – 5 Hz] MBW

PRESENT IN FLIGHT STATUS

Agreement between the in-orbit noise and the predicted error budget of the DFAC channel

- ***6 accelerometers nominally operating***
- ***Same behaviour of the 6 accelerometers***
- ***Accelerometer control loops ⇨ OK***
- ***W.r.t. foreseen Science channel Error Budget :***
  - ***Detection noise ⇨ OK***
  - ***Electrostatic actuation noise ⇨ OK***



Validated by DFAC data

In flight test validation

GOCE ACCELEROMETER STATUS

- Mature Technology of the Mechanical sensor optimised in terms of design, manufacturing and integration processes to reach the necessary resistance and the stability *(< 8 µm over instrument life)* of the Accelerometer Reference Frame during the launch phase,

- Space quality electronics designed to reach an acceleration resolution better than 2.0×10^{-12} ms^{-2} / $Hz^{1/2}$ with a large measurement range of 6.5×10^{-6} ms^{-2},

- Flexibility in the retrieval of the 6 Degrees of Freedom and redundancy with 8 electrode pairs organised in 6 digital control loops per accelerometer,

- On Ground test ability thanks to ASH geometrical configuration and dedicated EGSE with high voltage electronics and Complete test plan to assess reliability.

- As inertial sensor of the DFAC system, it provides highly accurate data to measure the 3 D acceleration of the gradiometer centre which is also the S/C CoG and it participates to fine attitude estimation.

1. **PAST and PRESENT**

STAR for CHAMP

- Γn: $3\cdot10^{-9}$ ms^{-2} $/Hz^{1/2}$
- Γmax: 10^{-4} ms^{-2}

SuperSTAR for GRACE

- **Γn: $1.0\cdot10^{-10}$ ms^{-2} $/Hz^{1/2}$**
- **Γmax:510^{-5} ms^{-2}**

GRADIO for GOCE

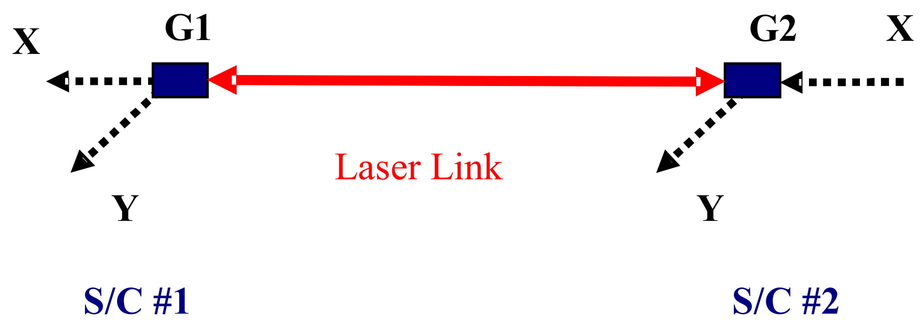
- Γn: $2.0\cdot10^{-12}$ ms^{-2} $/Hz^{1/2}$
- Γmax: 610^{-6} ms^{-2}

Adjustability of the design w.r.t. performances:

PM weight
gaps value
number of electrodes
loop design

Adaptability to the Satellite Configuration →

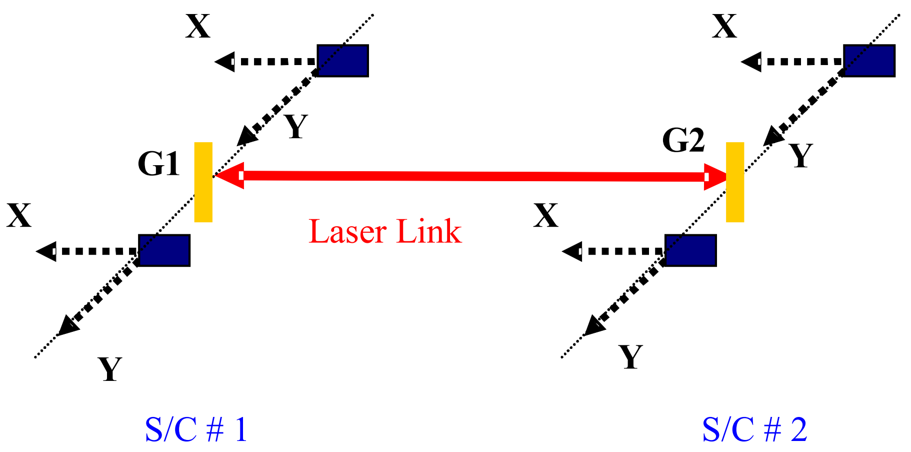
Case #1 Accelerometer at Center of Gravity as in CHAMP & GRACE



- Laser link better than microwave link
- To reflect link on proof-mass or not ?
- Drag free satellite without acceleration measurement :
  - → optimized configuration of the inertial sensor:
    - larger gaps → reduced disturbances
    - but S/C motion w.r.t. mass : fluctuation of self gravity & CPD (GPB...)
    - other axes : coupling between axes ? linear and angular...

Return of Experience and towards next Gravity mission

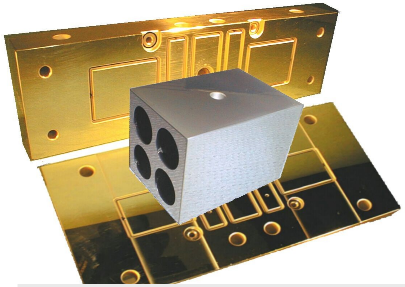
Case #2 Accelerometer off-centered with Gradio pair at Center of Gravity (GOCE)



- S/C acceleration from common mode of each Gradio pair
- Accelerometers and no inertial sensors:

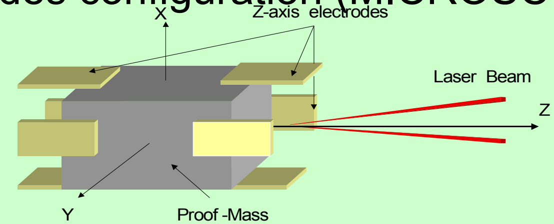
  = drag free sensor + gradiometer sensor + accelerometer sensor for laser link
- S/C drag free satellite in all directions ?

Improvements for accurate future gravity mission

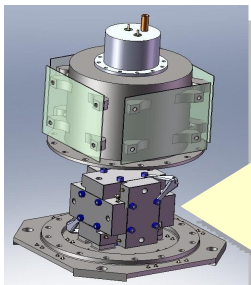


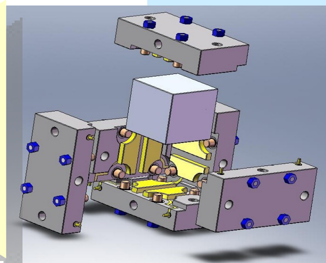
In the case of laser link between the SST satellites possibility to use the proof-mass itself as mirror for the interferometer.

Linear actuation (and capacitive sensing) through surface variation electrodes configuration (MICROSCOPE Conf.)



Optical position sensing using fiber laser interferometry techniques:
off-loop detection, very low back-action



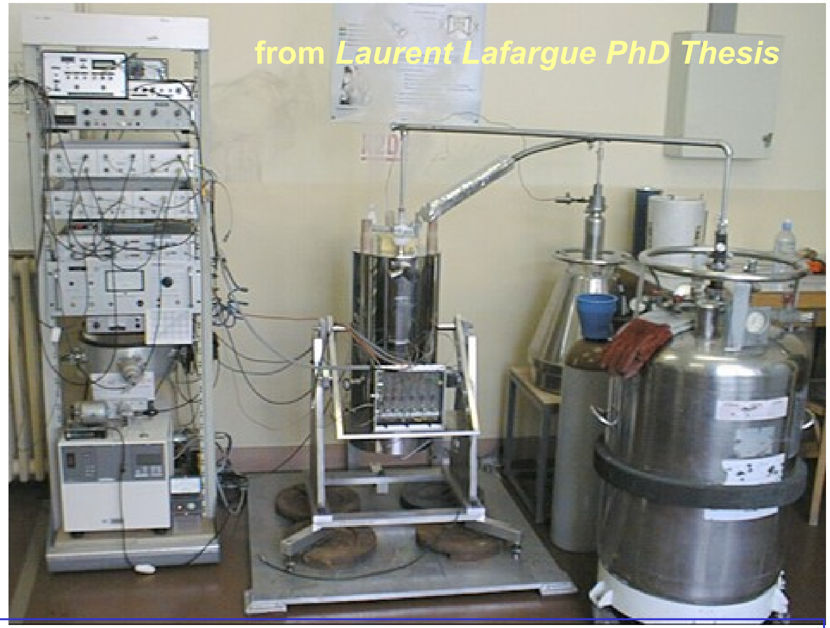


Mass, volume and power budgets reduction:
MICROSTAR model
~1kg – 1 l – 1 W)

Cryogenic temperature instrument : operation verified (*Laurent Laffargue PhD Thesis*), thermodynamic noise reduced by one order of magnitude, improvement of thermal and mechanical stabilities

Atomic Interferometry based accelerometer (ICE Project)

Cryogenics accelerometers



Operation verified at Low Temperature:

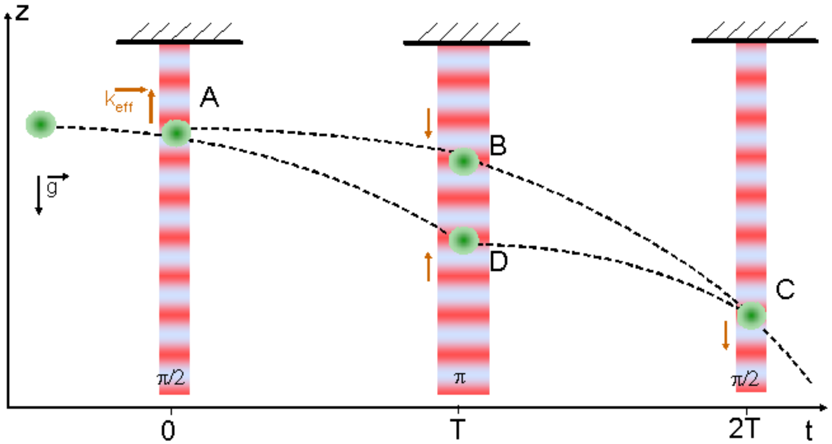
- **Thermodynamic noise reduced by one order of magnitude,**
- **Improvement of thermal and mechanical stabilities**

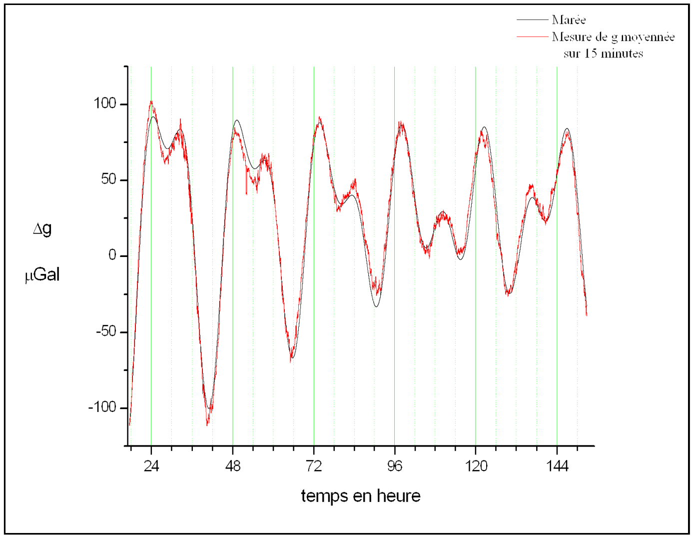
Superconductive :

- **SQUID + Magnetic suspension :**
  - **no servo-control**
  - **necessity of electrostatic control and damping in addition**
- **Electrostatic:**
  - **easy operation with room temperature electronics**
  - **reduced thermodynamic noise to be associated to active charge control**

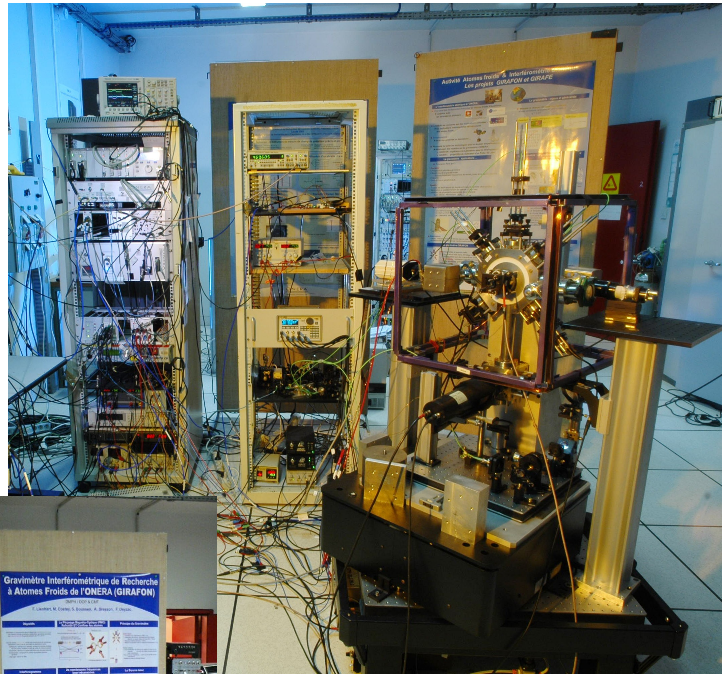
→expected gain in resolution up to 100 w.r.t. GOCE accelerometer range to be adapted

Atomic gravimeters also exist at Onera/DMPH !





Daily gravity field variation



Laboratory Setup

CONCLUSION

The 6 GOCE accelerometers are flight operational

9 Electrostatic Accelerometers are presently working in orbit (CHAMP,GRACE,GOCE)

Robustness and Flexibility of the Design

Adjustability of the design w.r.t. performances

(PM weight, gaps value, number of electrodes,loop design….)

Demonstration of drag compensation at low altitude
(ultra sensitive electrostatic accelerometer + ion propulsion)

Possibility to combine LL-SST with Gradiometry from applications of accelerometers in GRACE and GOCE

Thank you for your attention

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