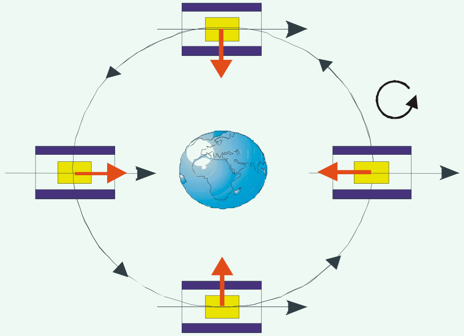
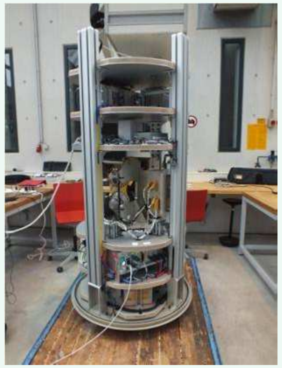


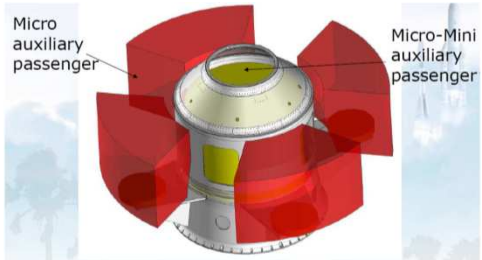
THE MICROSCOPE MISSION : TWO YEARS BEFORE THE LAUNCH

Pierre Touboul,
on behalf of the MICROSCOPE Team

ONERA, The French Aerospace Lab, BP 80100, F- 91123 Palaiseau
pierre.touboul@onera.fr



ESA Copernicus programme’s Sentinel satellites !



ASAP SOYUZ configuration

- ✓ **Copernicus programme : Global Monitoring for Environnent (EC with ESA partnership)**
- ✓ **Five families of Sentinel satellites**
- ✓ **Sentinel-1 is a two satellites constellation with prime objectives of Land and Ocean monitoring : C-Band SAR data (accurate imaging in all weathers) following ERS-2 and Envisat.**
- ✓ **Sentinel 1a ready for launch in spring 2014 : heliosynchronous orbit at 786 km**
- ✓ ***Sentinel 1b to be ready for launch as soon as sept. 2015 with Soyouz (object: end of 2015)***

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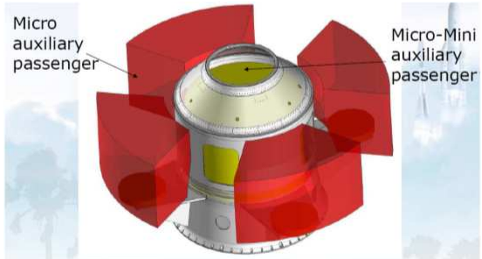
MICROSCOPE, PASSENGER FOR THE LAUNCH !



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MICROSCOPE UFF TEST RATIONALE

- ✓ ***Physics is not completely understood → new Physics***
  → New experiments
  → New type of results
- ✓ **UFF violation → one of the invariance of the EEP (UFF, LPI, LLI) violated!**

$$\delta_{12} = 2\,\frac{\dfrac{m_{g1}}{m_{i1}} - \dfrac{m_{g2}}{m_{i2}}}{\dfrac{m_{g1}}{m_{i1}} + \dfrac{m_{g2}}{m_{i2}}} \approx \frac{m_{g1}}{m_{i1}} - \frac{m_{g2}}{m_{i2}} = 0\,? \quad ?$$

- ✓ **MICROSCOPE Objective : 10^{-15} accuracy**
- ✓ ***MICROSCOPE is the first accurate UFF test in space***
- ✓ ***Scientific results + Return on Space technology limitations***
  - ***Thermal, magnetic, structural, acceleration stabilities @ picometer/s^2***
  - ***On board calibration with satellite control***
  - ***Accurate pointing with SST and Angular Accelerometer***
  - ***Scientific Mission Center with Mission Scenario Management***

MISSION SCENARIO

- **Reference scenario** is established before the launch : list of sequences (transition or scientific session or technical session):
  - *Commissionning step 1: 29 days, operation of all sub-systems & payload verified*
  - *Commissionning step 2: 20 days, drag free and calibration operation validated*
  - *Preliminary tests and Performance tests : 25 + 29 days*
  - *EP tests : 92 + 52 days*

    (Calibrations + 2 spins + 2 inertial orientations+ 2 test mass centring) x (EP + REF)
  - *Complementary EP tests : 71 days*

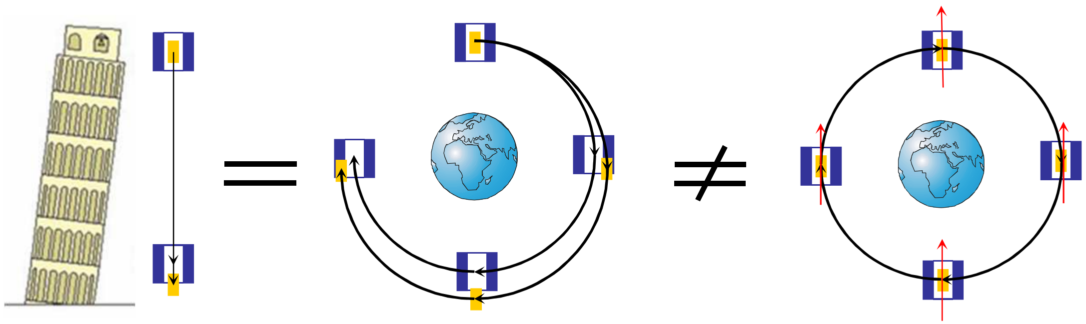
  Breaks periods with satellite in operating mode without thrusters & gas consumption are scheduled and can be added (used to take advantage of the obtained results).

- **Working scenario** to be executed:
  - Cover 1 month
  - Is up-dated every weak and validated through Drag-free Expertise and Control Center
  - Sequences mentionned as :

  AE = to be Executed (Q = qualified or AQ= to be qualified) → AC = to be confirmed → C=confirmed → EC = Running → E = Execuded or EI = Executed but non successful,

- Executed scenario updates the reference scenario of the whole mission to compute the whole gas consumption and predict the offered possibilities.

UFF and MICROSCOPE space experiment...



Galileo Galilei · « Free fall » in space · **Microscope**

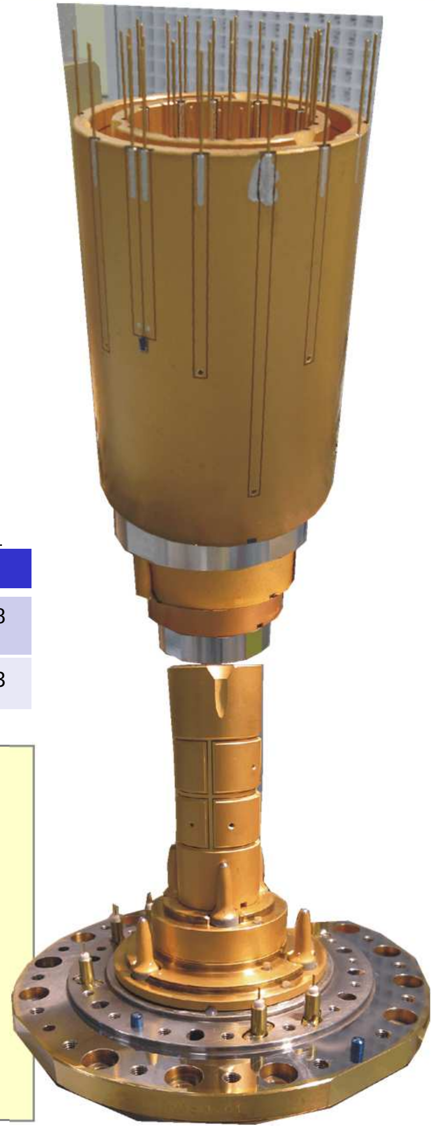
- **2 test masses made of different composition**
- **Gravitational Source : the Earth**
- **Kinematic Acceleration : the orbital motion**
- **Identical initial conditions of motion**

	B/µ	Z/µ	(N-Z)/µ
Pt	1,008009	0,40286	0,20208
Ti	1,008911	0,46309	0,08273

- **Permanent pico-meter control of the 2 masses**
- **Measurement = Necessary forces to control the same orbital motion**
- **No fluctuations of the mass environment due to relative motion**
- **Centring : 20 µm when the mass are levitated**

→ Gravity Gradients corrected or centring controlled @ 0.1 µm in orbital plane (X,Z)

- **Satellite imposes the common motion : reduced → instrument better operation**



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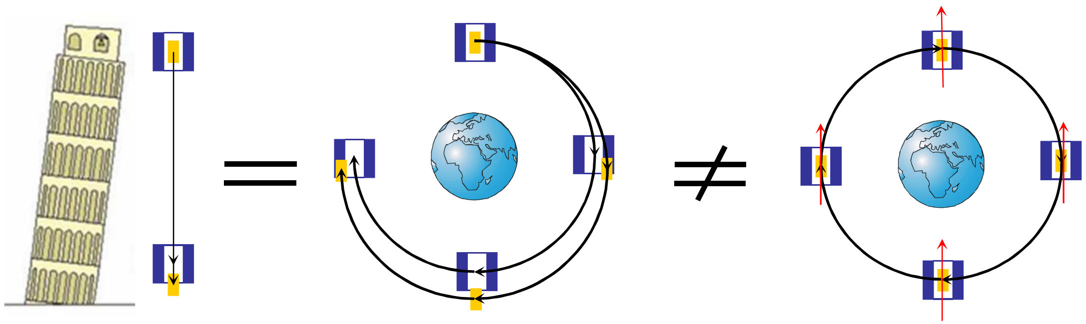

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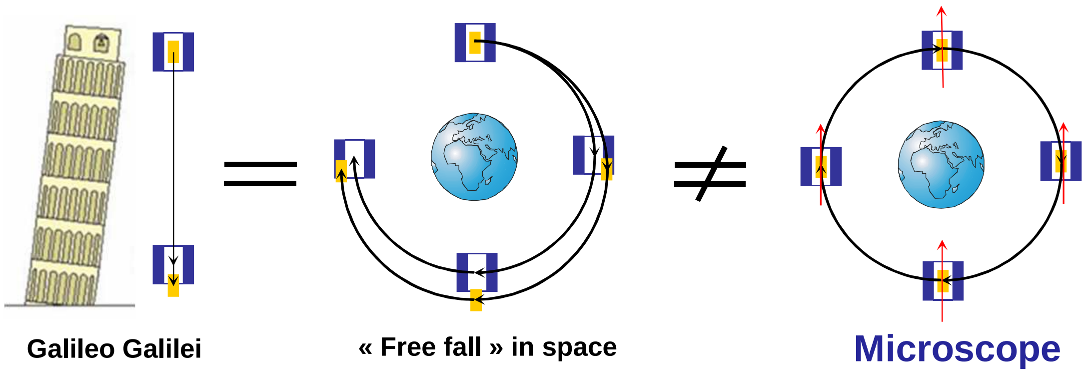

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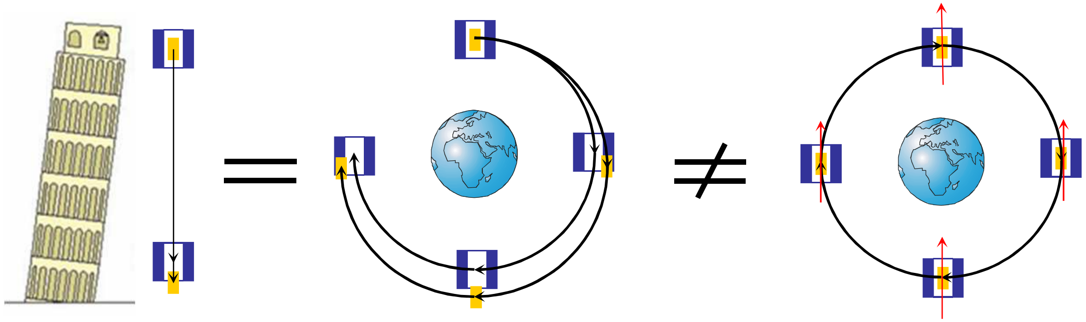

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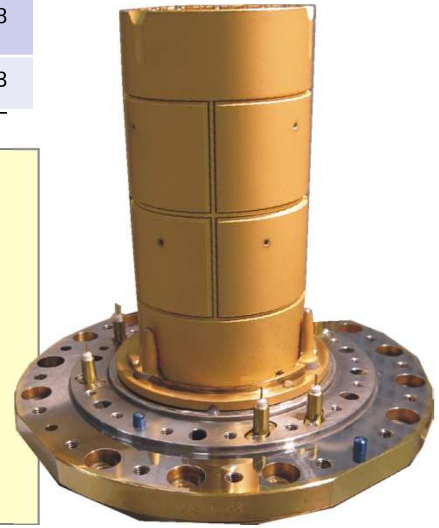

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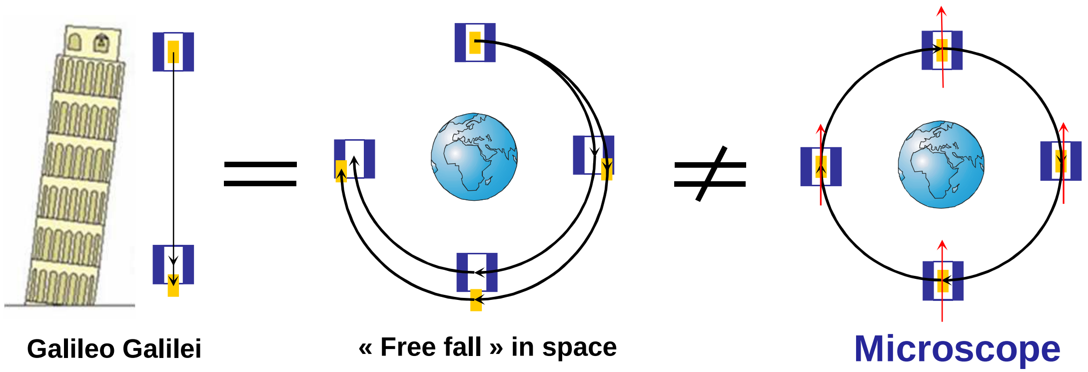

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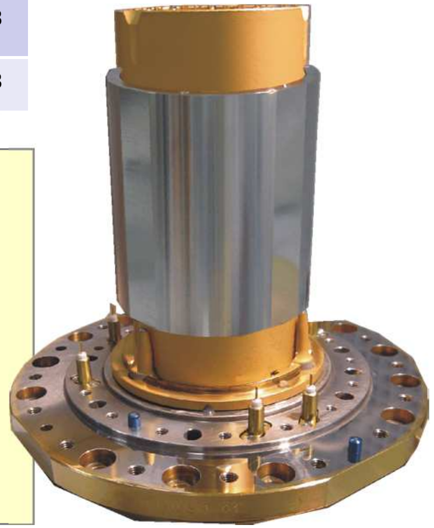

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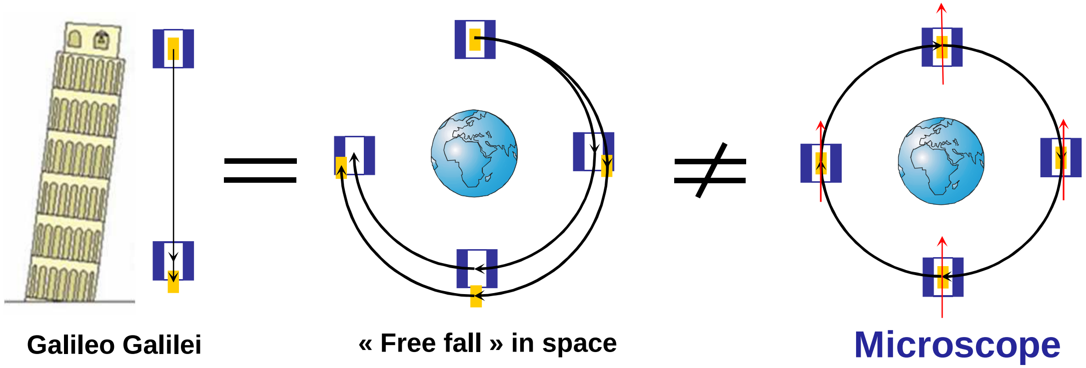

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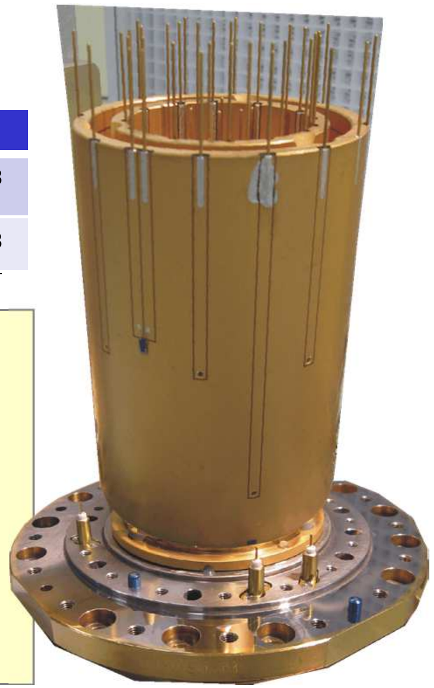

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MICROSCOPE PROVIDED MEASUREMENTS

$$\frac{\vec{F}el_i}{m_{Ii}} - \frac{\vec{F}el_j}{m_{Ij}} = (\delta_j - \delta_i)\vec{g}(O_j) + (1+\delta_i)[T]\overrightarrow{O_iO_j} - R_{In,COR}\left(\overrightarrow{O_iO_j}\right) - \frac{\vec{F}pa_i}{m_{Ii}} + \frac{\vec{F}pa_j}{m_{Ij}}$$

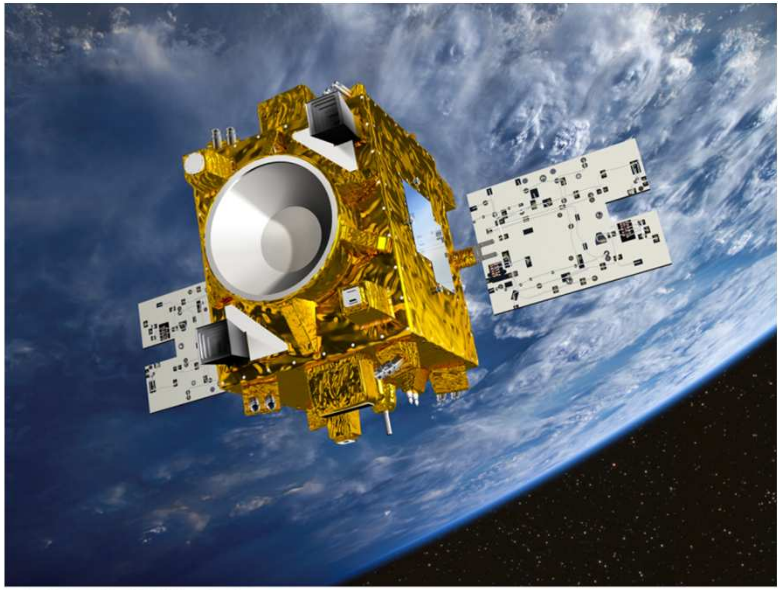
$$\vec{g}(O_j) - \vec{g}(O_i) = [T]\overrightarrow{O_iO_j} + O(T2)$$

$$R_{In,COR}\left(\overrightarrow{O_{sat}O_k}\right) = \dot{\vec{\Omega}} \wedge \overrightarrow{O_{sat}O_k} + \vec{\Omega} \wedge (\vec{\Omega} \wedge \overrightarrow{O_{sat}O_k}) + 2[\Omega]\dot{\overrightarrow{O_{sat}O_k}} + \ddot{\overrightarrow{O_{sat}O_k}}$$

- *centering*
- *shape : spherical inertia, multipoles*
- *material density homogeneity*

- *Angular acceleration & centrifugal acceleration : to be controlled*
- *Coriolis & Cinematic relative acceleration*

→ stability of the ULE configuration and electrostatic servo-conrol



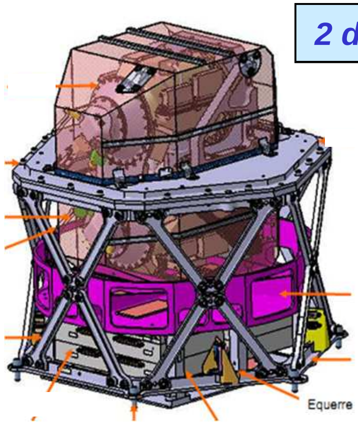
2 years mission duration : fine survey of gas consumption
Heliosynchronous orbit ~ 710 km → 1,7 10^{-4} Hz
Passive temperature stabilities

Compensation of the drag by GAIA type thrusters
Attitude control without gyro. and wheels
Inertial and rotating pointing → 1 mHz

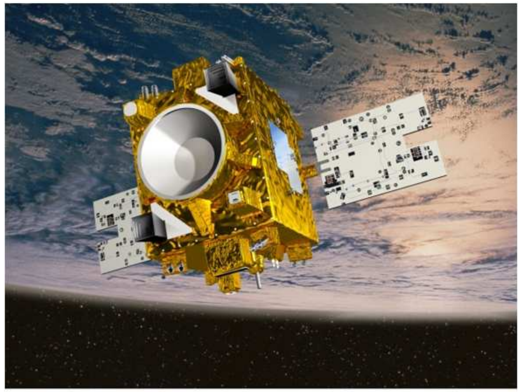
No moving masses and structural motions @ f_{EP}
Position and attitude sufficiently well known

Payload contributes to s/c motion control
S/C contributes to Payload outputs

MICROSCOPE Satellite : a space lab.



2 differential electrostatic accelerometers in thermal cocoon



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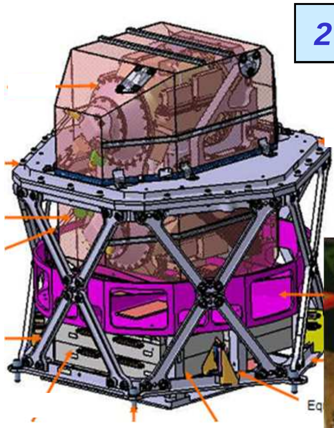
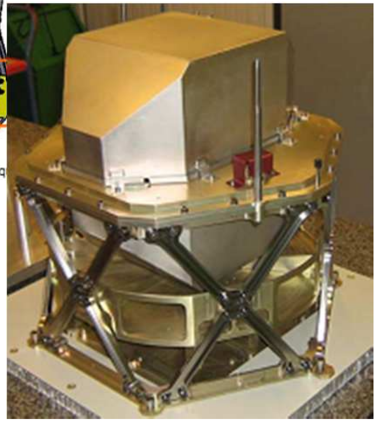
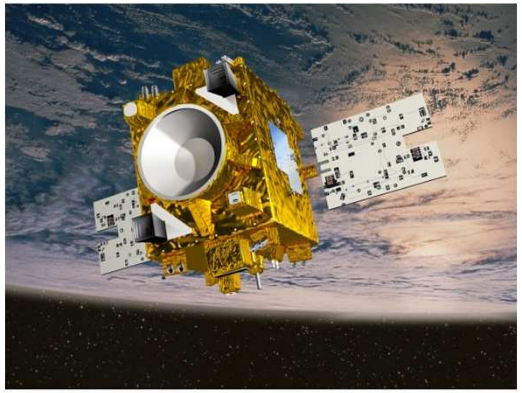


2 differential electrostatic accelerometers in thermal cocoon

magnetic cocoon



payload at the center of the satellite :
-for thermal stability
-for spin mode
-for self gravity



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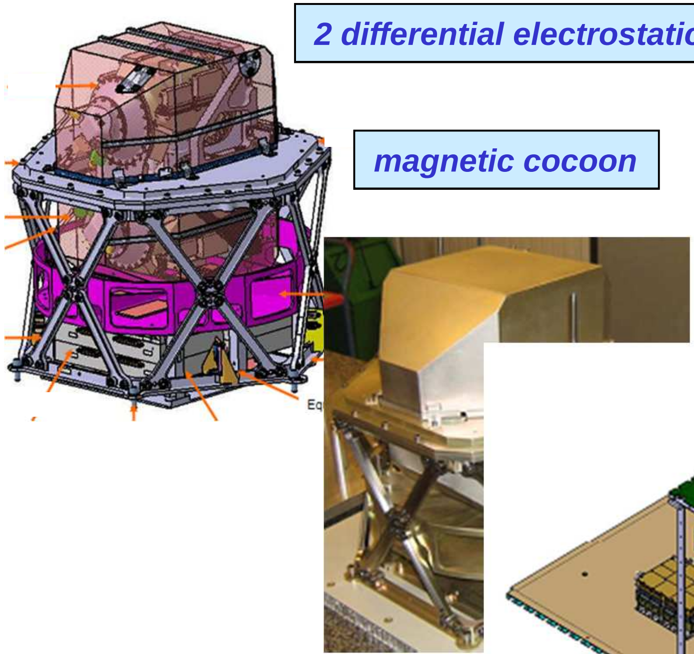

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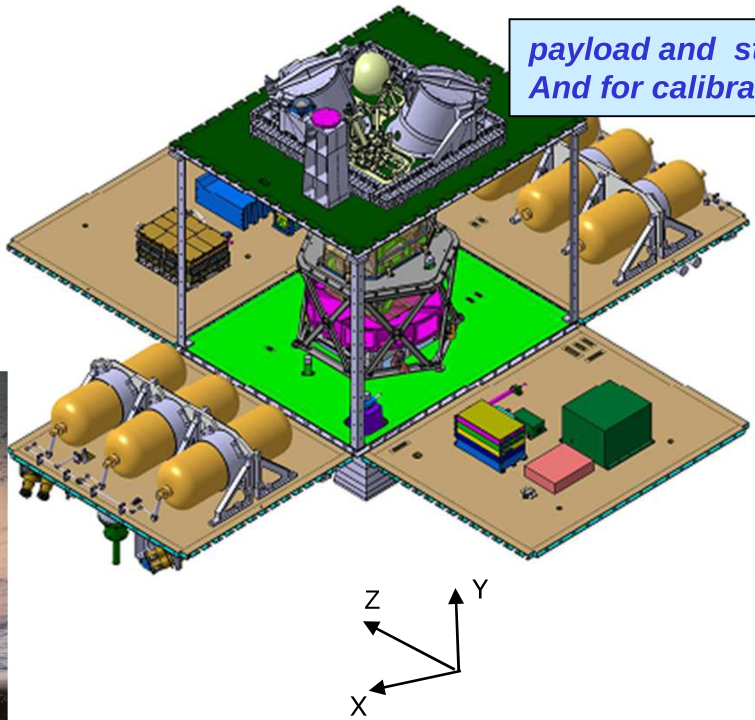
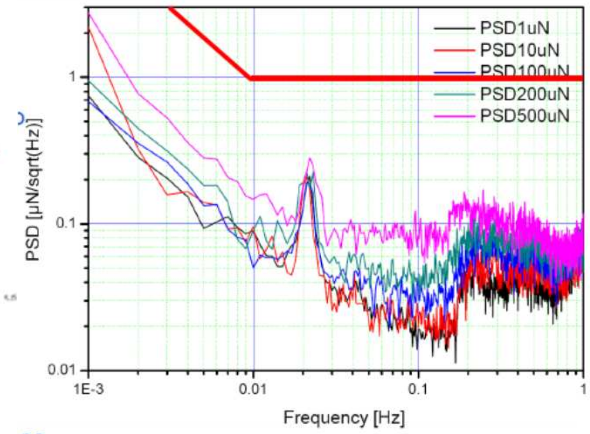
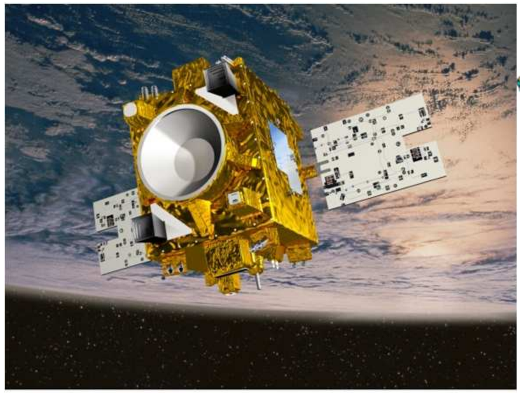
payload and star sensor for attitude & orbit control
And for calibration







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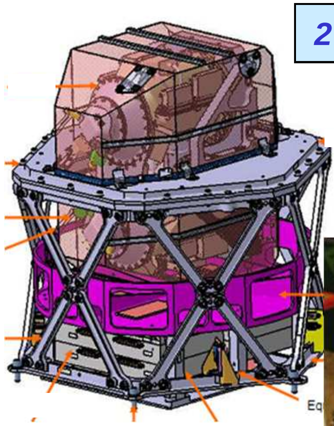

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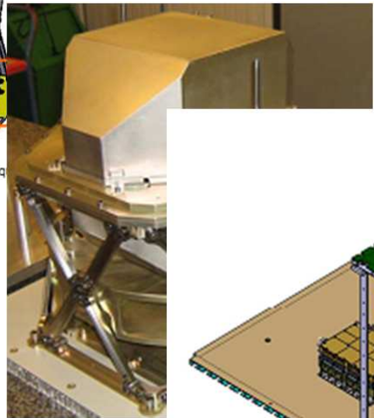

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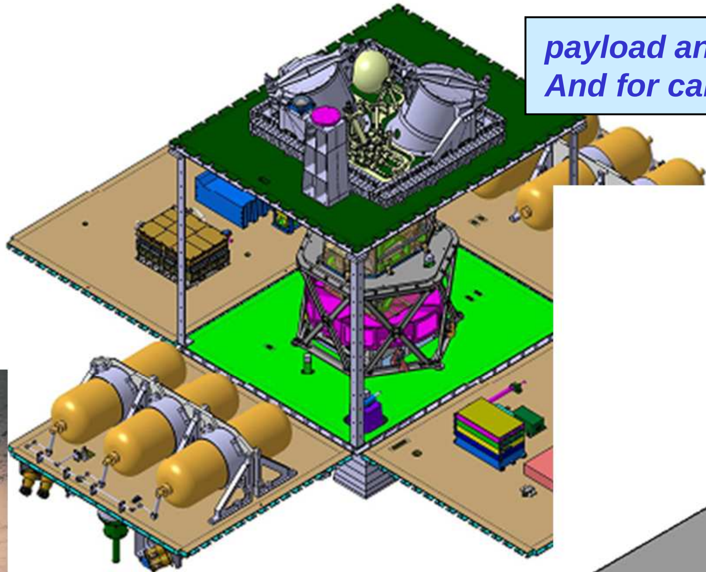

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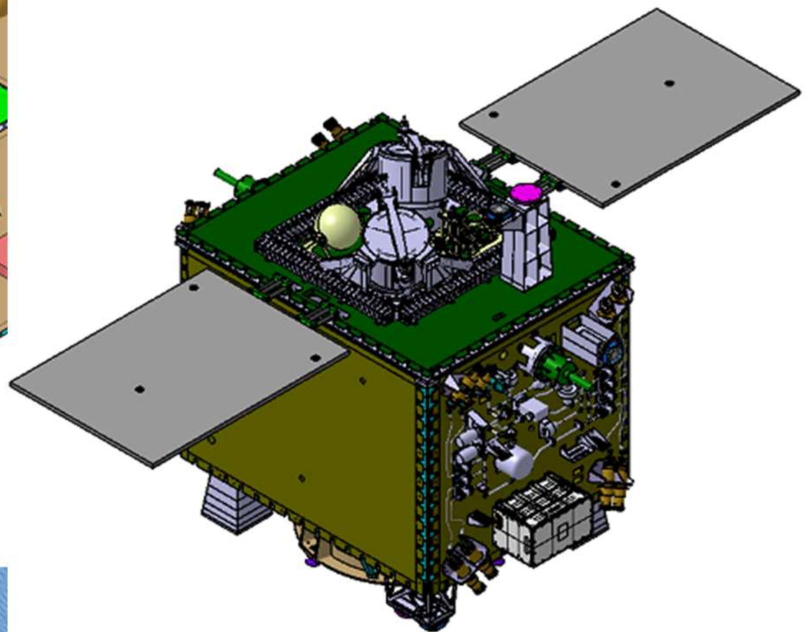
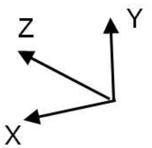
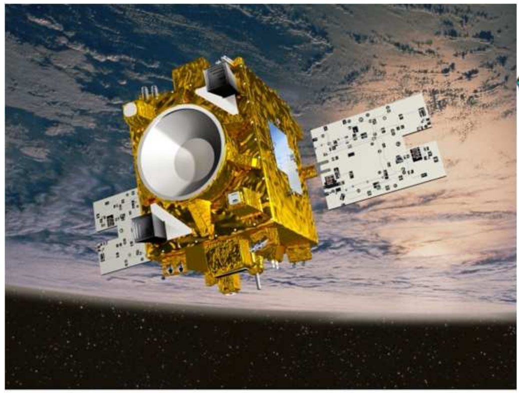
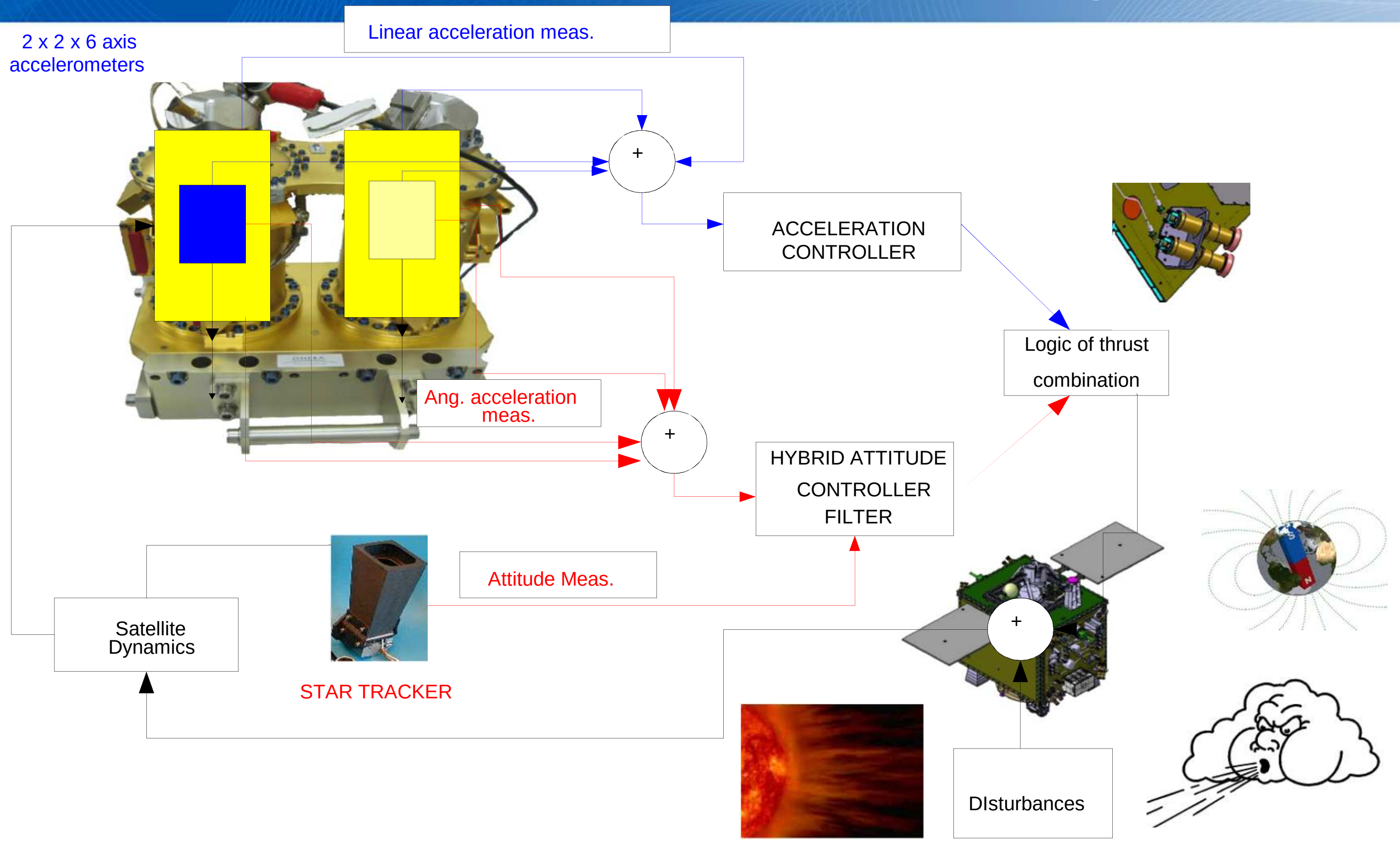






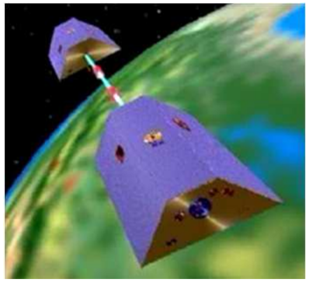
MICROSCOPE Space Lab. with 6 DoF Controlled to the benefit of the environment stability



Earth Gravity Gradient	→	***eccentricity < 5.10^{-3}***	
		S/C position tracking (Doppler) :	*< 7m, < 14m, 100m @ fep*
		Pointing : 10^{-3} rad with variations	*< 10 µrad (inertial) & 10 µrad (spin) @ fep*
Mass Off-Centering	→	***Angular velocity variations***	*< 10^{-9} rad/s (spin) @ fep*
		Angular accelerations variations	*< 10^{-11} rad/s² (inertial) & 5.10^{-12} rad/s² (spin) @ fep*
Sensitivity Matching	→	***Drag-Free Control***	*< 3.10^{-10} ms^{-2}Hz$^{-1/2}$ and < 10^{-12}ms^{-2} @ fep*

Space Electrostatic accelerometers
for Earth gravity field recovery

GRACE (NASA-JPL), March 2002 – 2015 ?



altitude~500km

- Γn: $1.0 \cdot 10^{-10}$ ms^{-2} $/Hz^{1/2}$
- Γmax: 510^{-5} ms^{-2}
- $[0.1 \cdot 10^{-3}; 10^{-1}]$ Hz

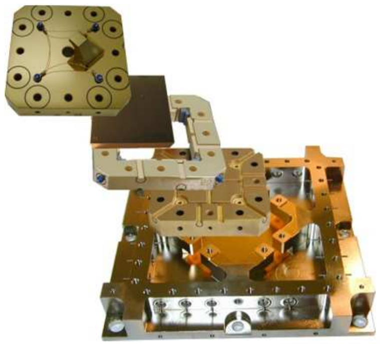
Today : 3971 days in orbit

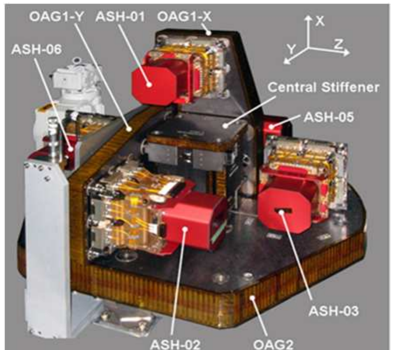
GOCE (ESA), March 2009 – October 2013 ?

altitude~260km

- Γn: $2.0 \cdot 10^{-12}$ ms^{-2} $/Hz^{1/2}$
- Γmax: 610^{-6} ms^{-2}
- $[5 \cdot 10^{-3}; 10^{-1}]$ Hz

g





Courtesy TAS-F

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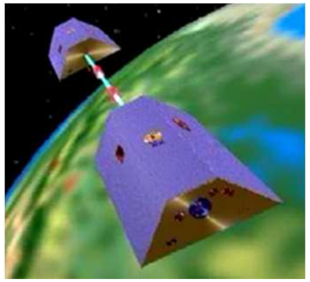

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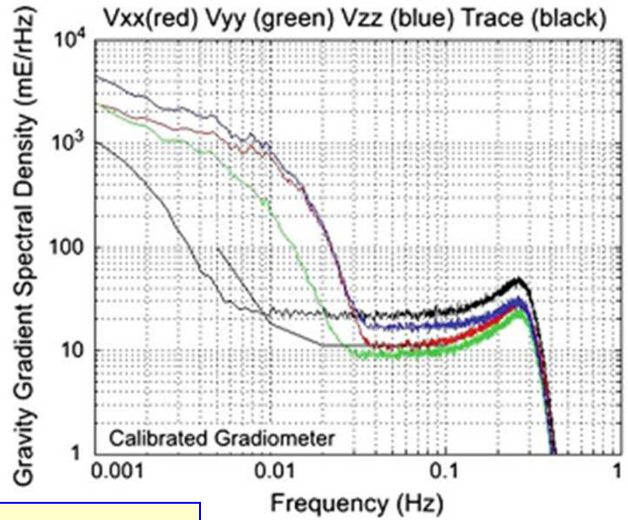


) and individual diagonal gravity gradient (*red*, ormance for calibrated gradiometer (with non- plied). Note that <30 mHz the noise is not visible gradient curves, since signal dominates

GOCE (ESA), March 2009 – October 2013 ?

altitude~260km

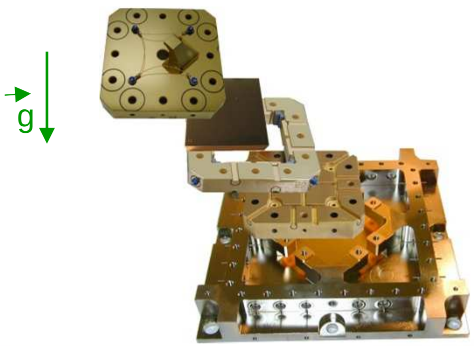
- Γn: $2.0 \cdot 10^{-12}$ ms^{-2} /$Hz^{1/2}$
- Γmax: $6 10^{-6}$ ms^{-2}
- [$5 \cdot 10^{-3}$; 10^{-1}] Hz

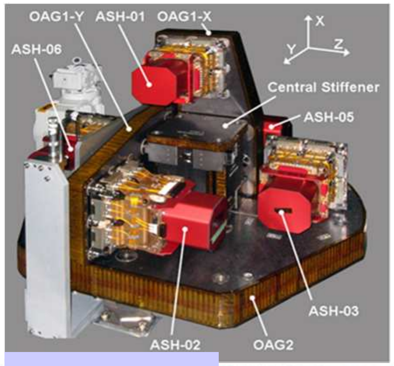
Accelerometer PSD in 40-100 mHz

$ASH_{3,6}$: 6.7 10^{-12} $m/s^2/Hz^{1/2}$

$ASH_{1,4}$: 3.9 10^{-12} $m/s^2/Hz^{1/2}$

$ASH_{2,5}$: 3.1 10^{-12} $m/s^2/Hz^{1/2}$

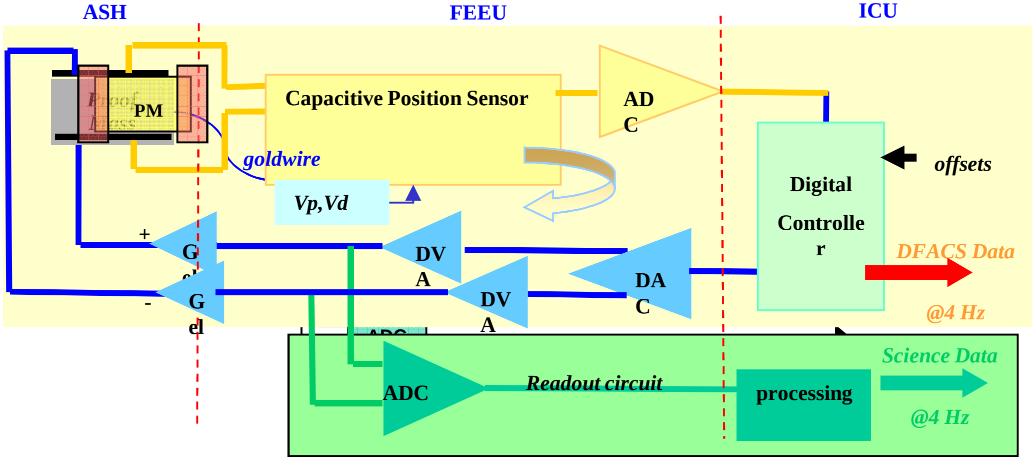




Courtesy TAS-F

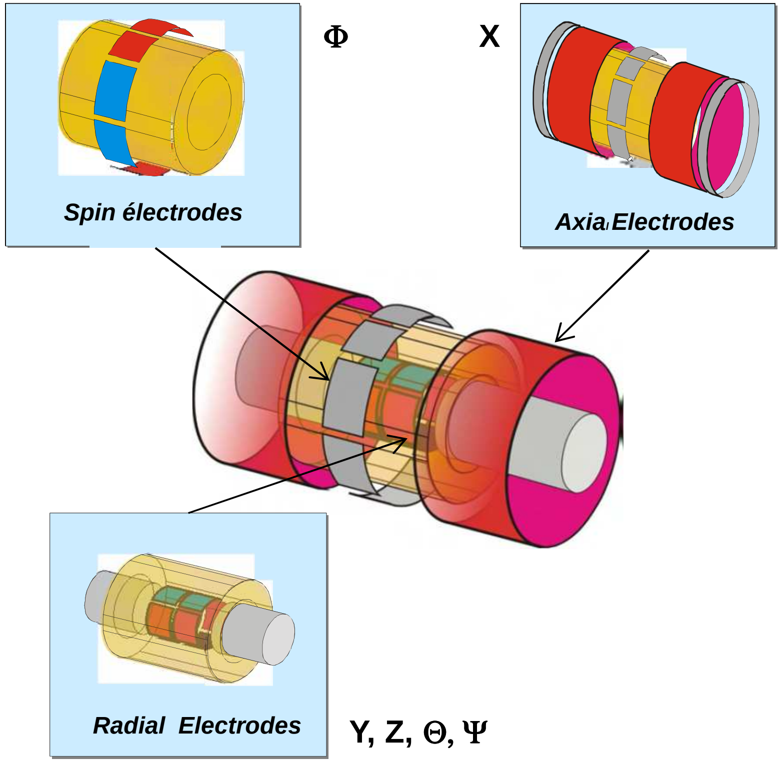
	GOCE	MICROSCOPE
Gold wire :	Ø= 5 µm	Ø=7.5 µm
PT-Rh Proof mass :	m= 320g	m=1400 - 307 g
Gap Y,Z :	e = 299 µm	e= 600 µm
PM Polarisation :	Vp = 7.5 V	Vp =5 V
Detection :	Vd = 7.6 V @ 100 KHz	Vd = 7.07 V @ 100 KHz
Detector gain	1.7 mV / nano-m	0.3 - 0.26 mV / nano-m
Scale factor :		
Science data	1. 10^{-7} ms^{-2}/V	1.8 - 2.1 10^{-7} ms^{-2}/V
DFACS data	17. 10^{-6} ms^{-2}/V	0.7- 1.7 10^{-6} ms^{-2}/V
Range	± 6.5 10^{-6} ms^{-2}	± 4.8 - 4.6 10^{-7} ms^{-2}
Expected Res.	< 2 10^{-12} ms^{-2} $Hz^{-1/2}$	< 2 10^{-12} ms^{-2} $Hz^{-1/2}$

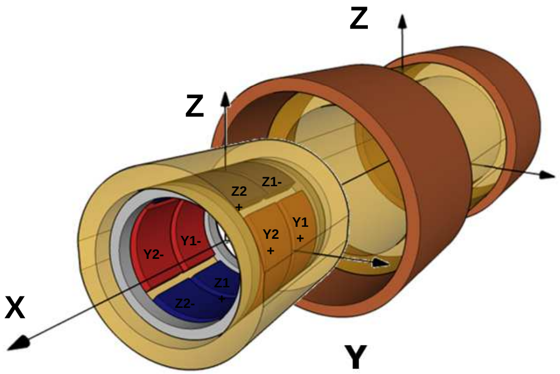
MICROSCOPE : A dedicated instrument



- •6 servo-channels and associated electrode sets → Sensing and actuations
- •Very steady and accurate configuration
- •Cylindrical configuration
- →Concentric masses
- →Overlapping electrodes along X → Linearity

One differential accelerometer = 2 inertial sensors
Each inertial sensors exploits :
Electrostatic concept & Technology similar to GOCE



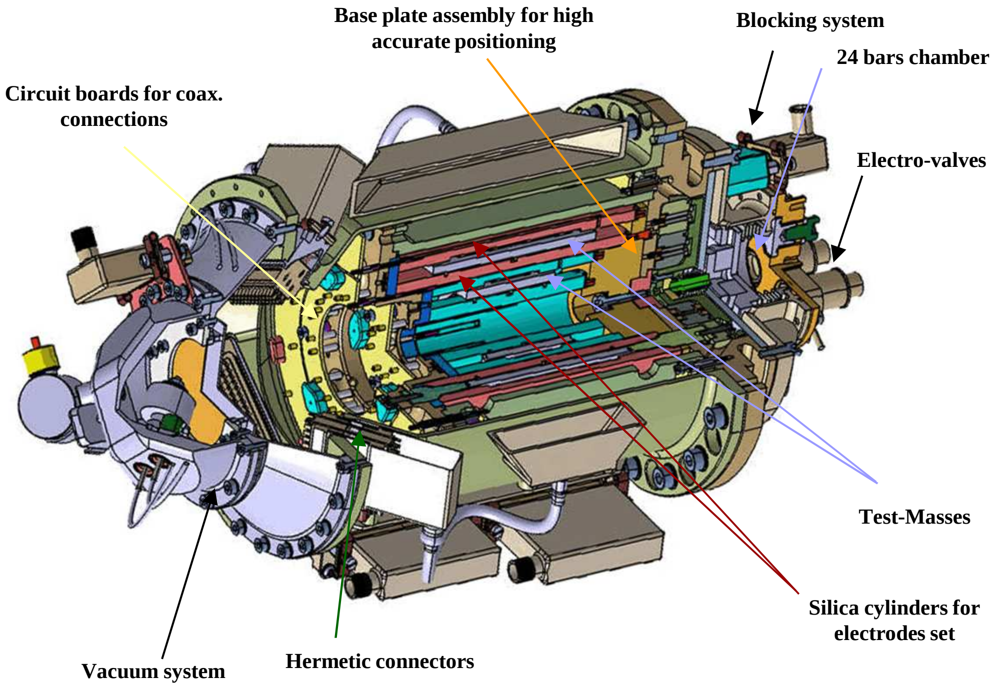


Instrument Design

36 cm x 34.8 cm x 18 cm -25kg

2 Sensor Units mounted on reference plate

(2 concentric Test-Masses Pt-Rh / Pt-Rh or Ti / Pt-Rh)



30 cm x 25 cm x 11 cm – 5.5kg – 2 x 11W

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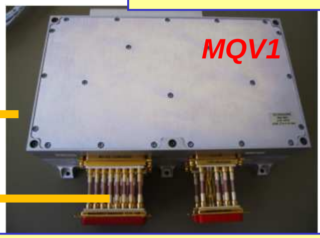
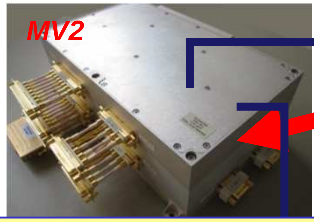
Instrument Design

36 cm x 34.8 cm x 18 cm -25kg



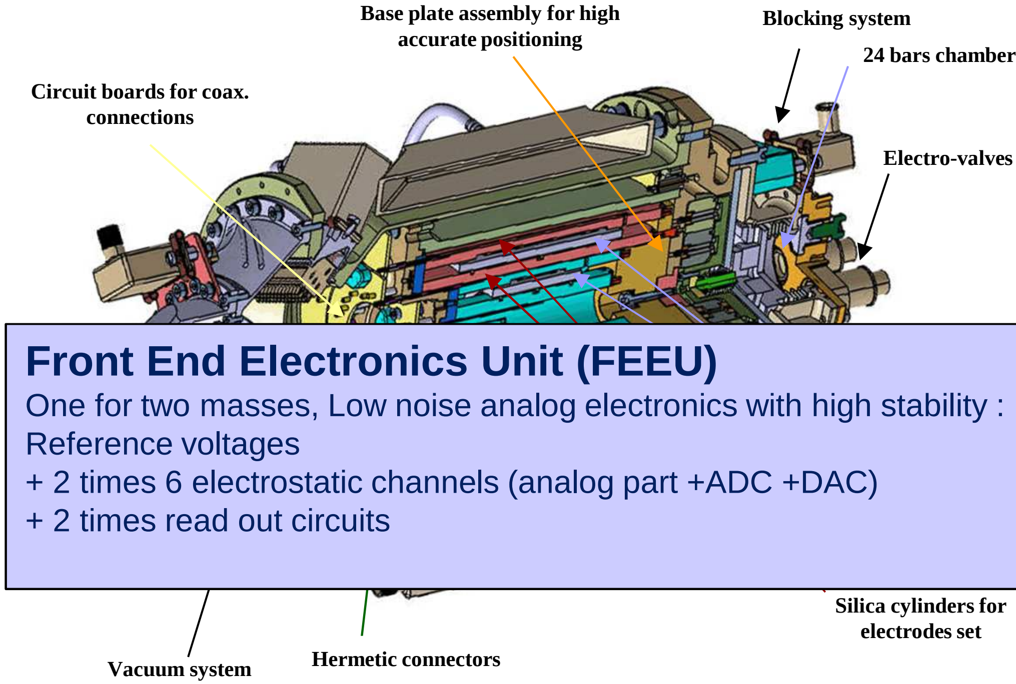


2 x { 28 cm x 17 cm x 9 cm - 3.5kg - 7W }

30 cm x 25 cm x 11 cm – 5.5kg – 2 x 11W

2 Sensor Units mounted on reference plate

(2 concentric Test-Masses Pt-Rh / Pt-Rh or Ti / Pt-Rh)



Front End Electronics Unit (FEEU)

One for two masses, Low noise analog electronics with high stability :

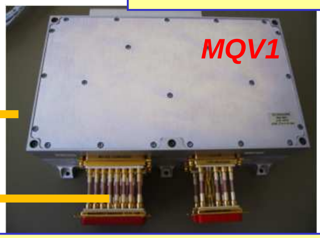
Reference voltages

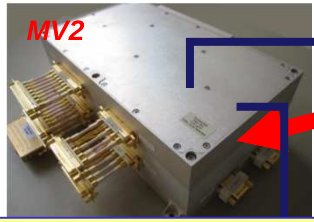
+ 2 times 6 electrostatic channels (analog part +ADC +DAC)

+ 2 times read out circuits

Instrument Design

36 cm x 34.8 cm x 18 cm -25kg





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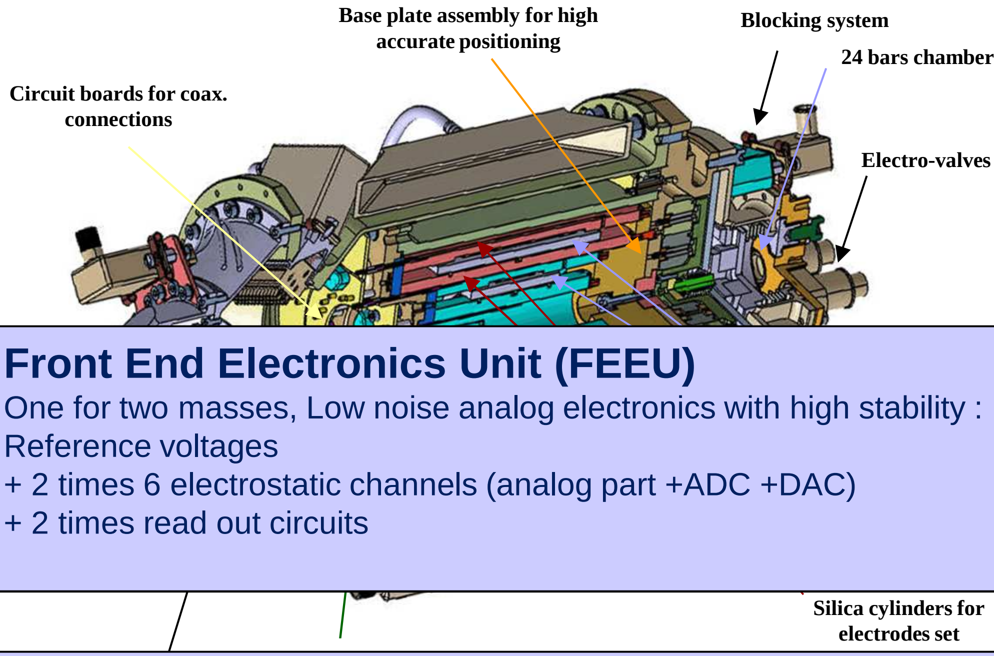

Front End Electronics Unit (FEEU)

One for two masses, Low noise analog electronics with high stability :
Reference voltages
+ 2 times 6 electrostatic channels (analog part +ADC +DAC)
+ 2 times read out circuits

Interface Control Unit (ICU)

2 stacked ICU (1 per FEEU), including each :
1 DSP + 1 FPGA for test-mass control and data conditioning/interfaces,
2 Power Control Units (1 nominal + 1 redundant): very stable secondary voltages (+/-48V, +/-15V,+5V,+3.3V)

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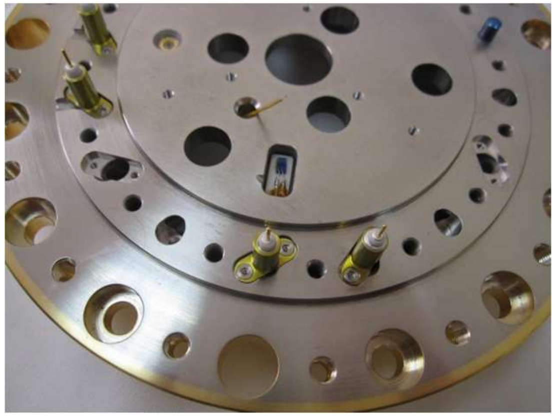
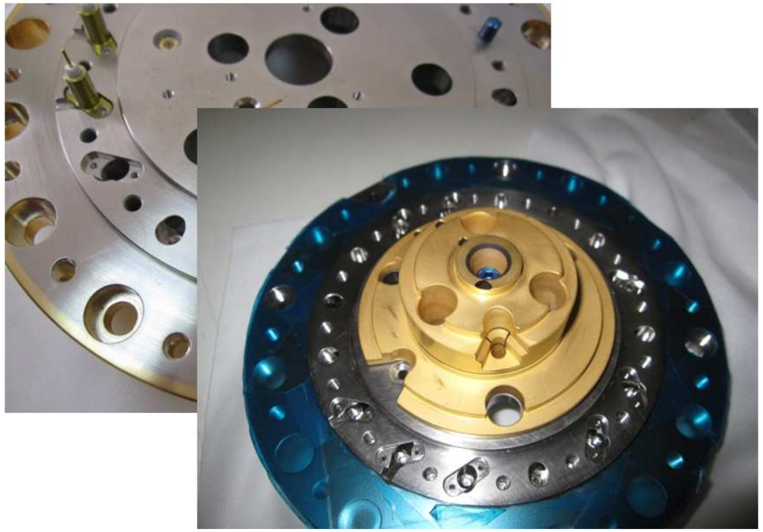
INTEGRATION FM 2 : Platinum / Titanium (1/4)



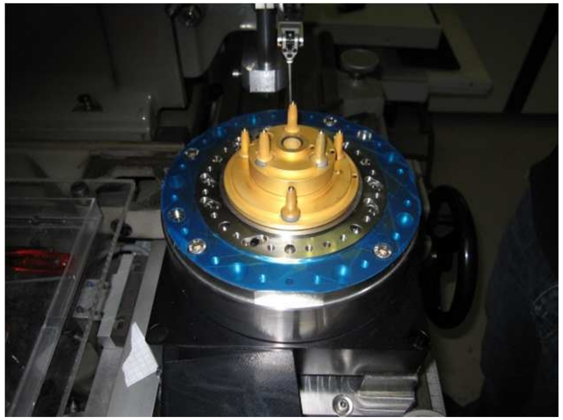
INTEGRATION FM 2 : Platinum / Titanium (1/4)



INTEGRATION FM 2 : Platinum / Titanium (1/4)

INTEGRATION FM 2 : Platinum / Titanium (1/4)

Reference plate with silica top hat and fingers



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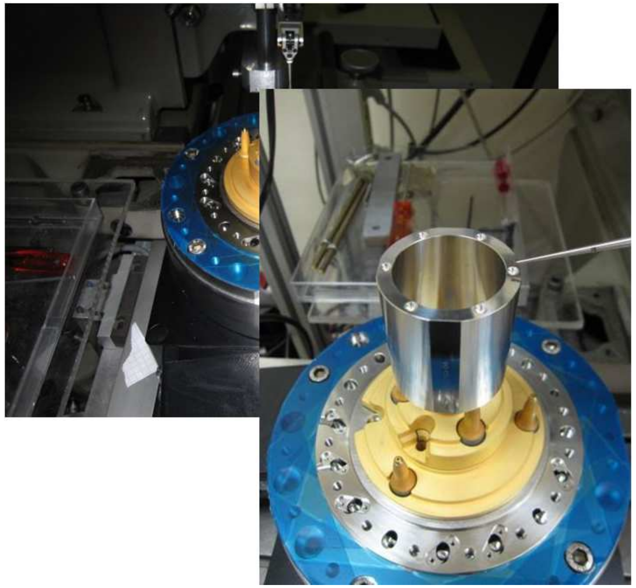

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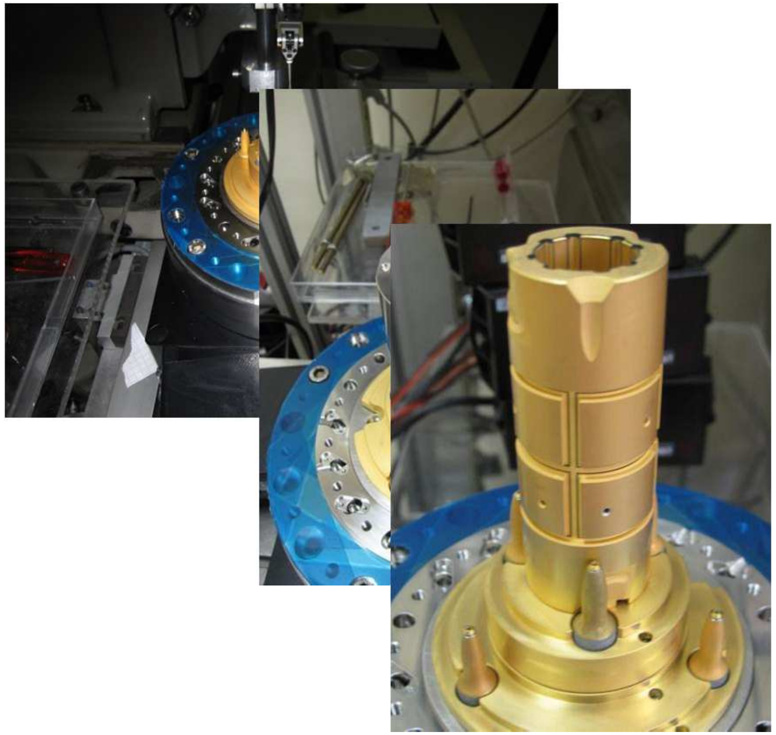

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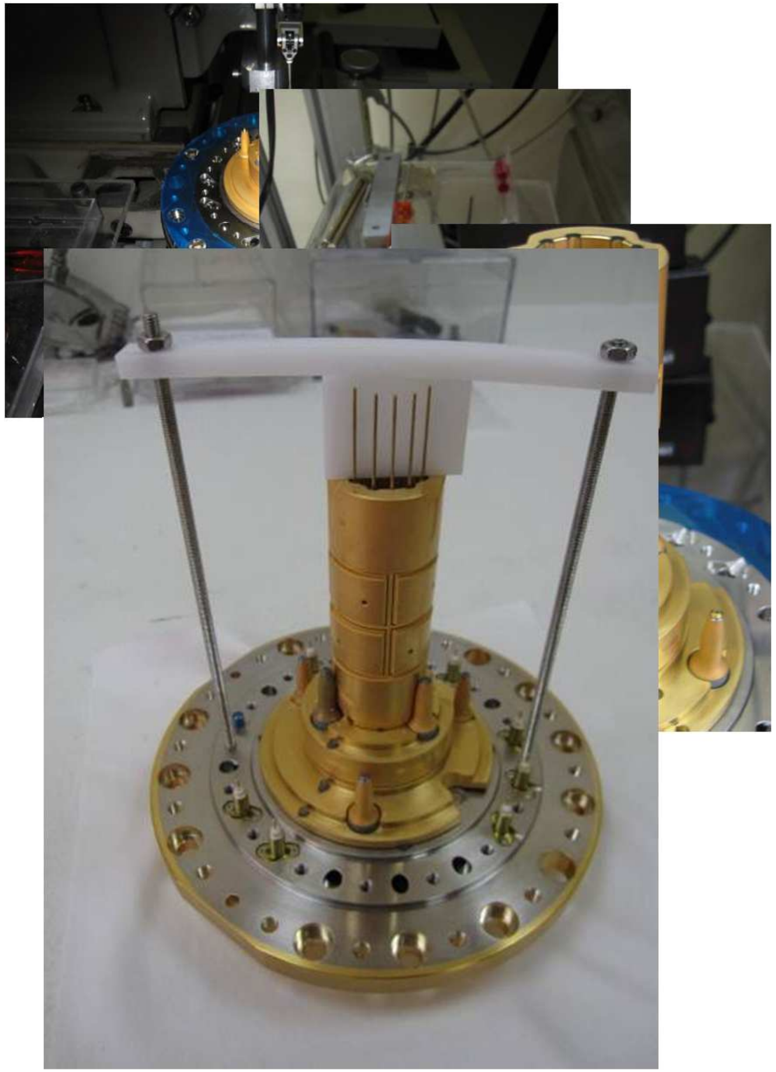
INTEGRATION FM 2 : Platinum / Titanium (1/4)

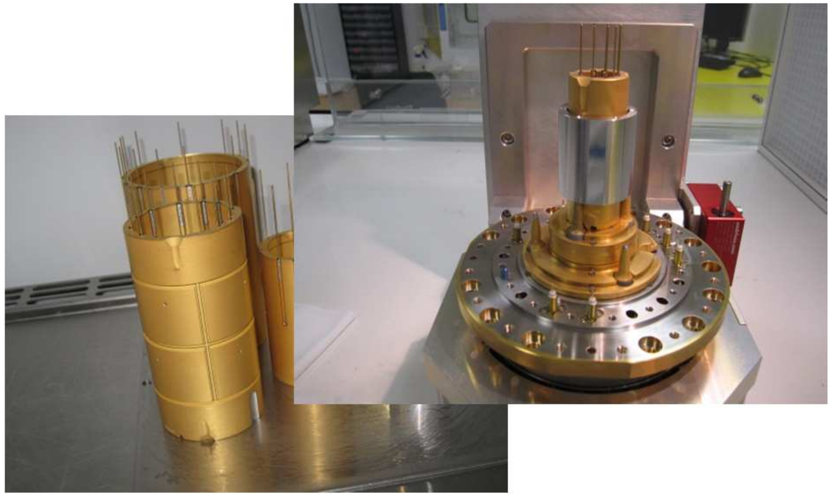
Reference plate with silica top hat and fingers



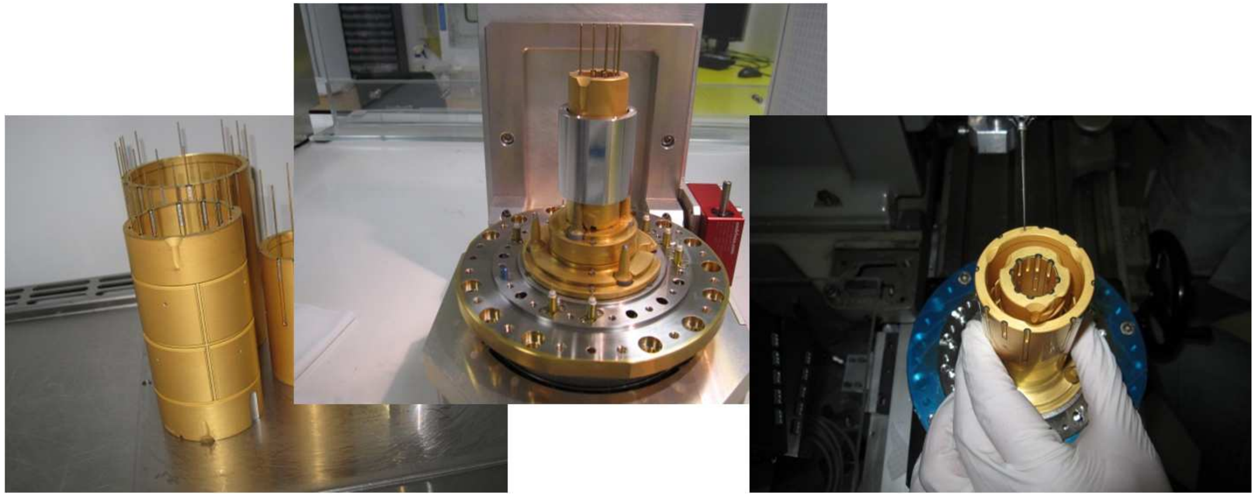
Reference plate with inner radial electrode rod

INTEGRATION FM 2 : Platinum / Titanium (2/4)

INTEGRATION FM 2 : Platinum / Titanium (2/4)



INTEGRATION FM 2 : Platinum / Titanium (2/4)



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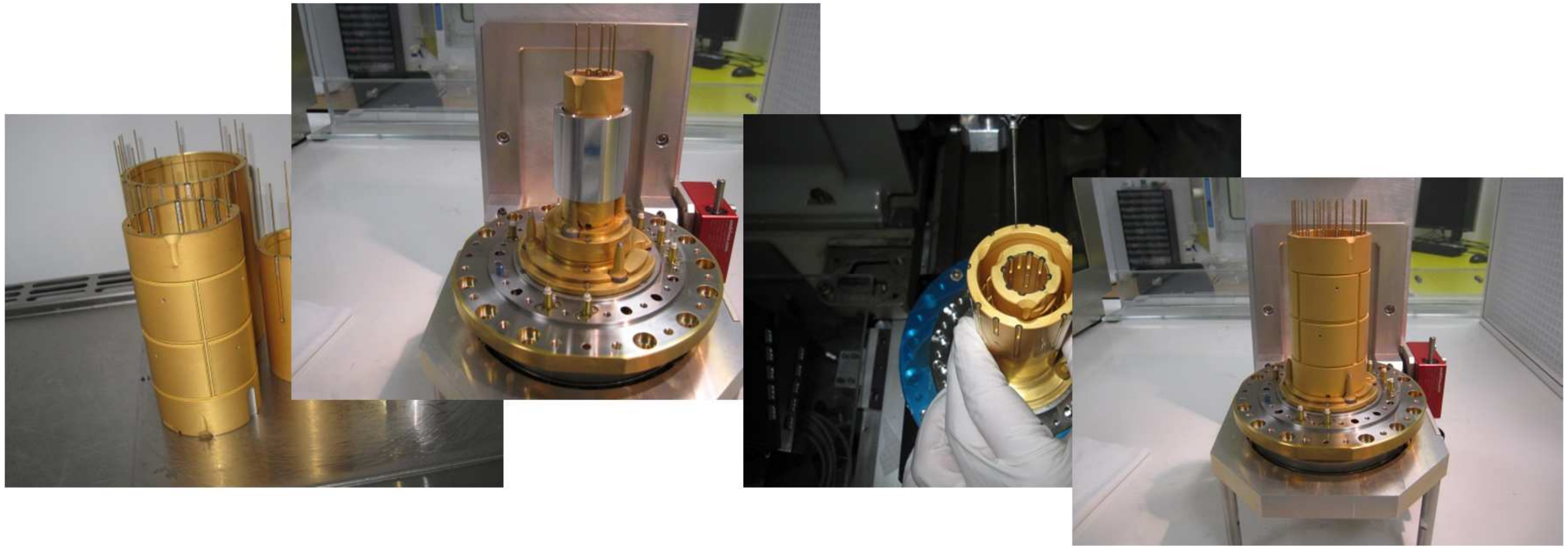
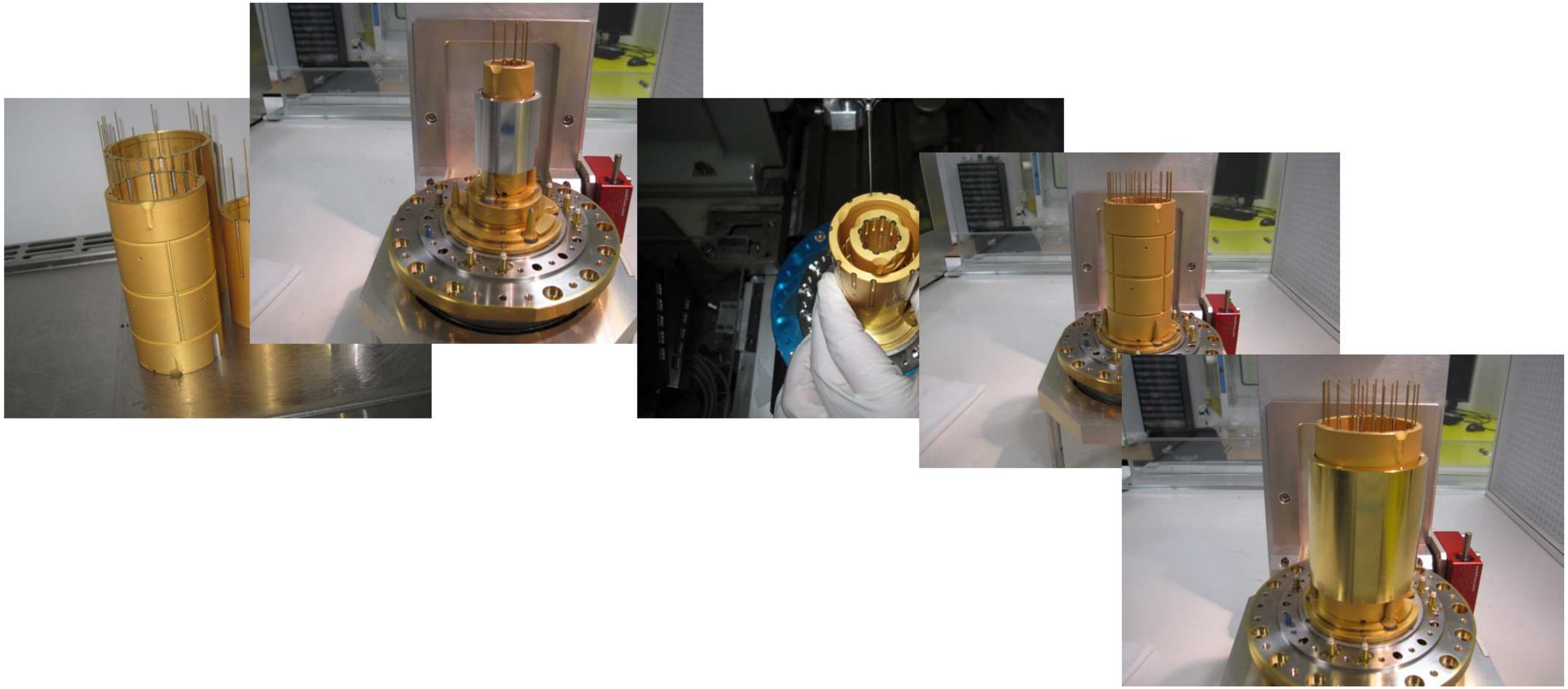
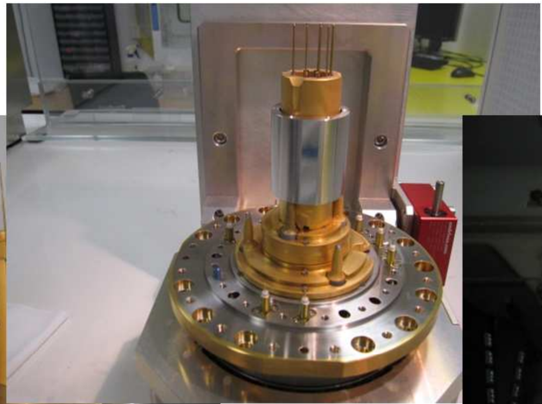
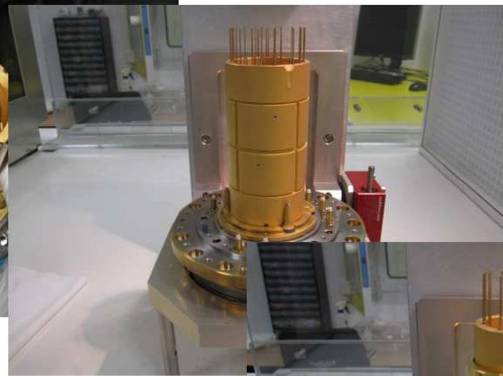


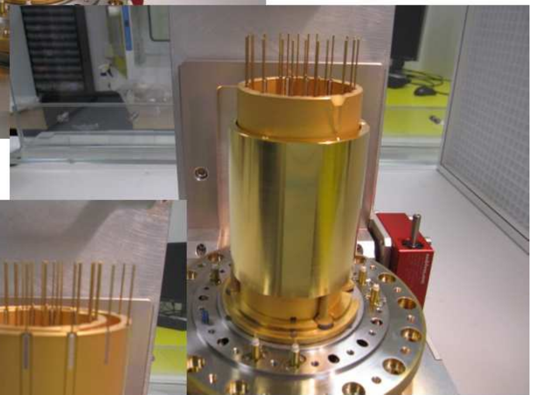
INTEGRATION FM 2 : Platinum / Titanium (2/4)

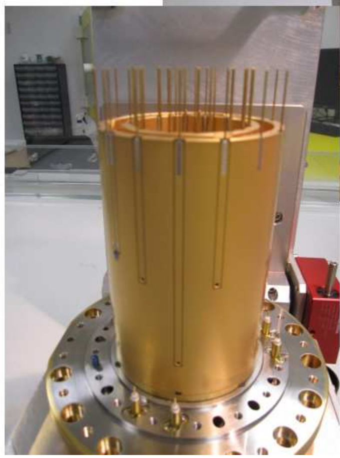


INTEGRATION FM 2 : Platinum / Titanium (2/4)









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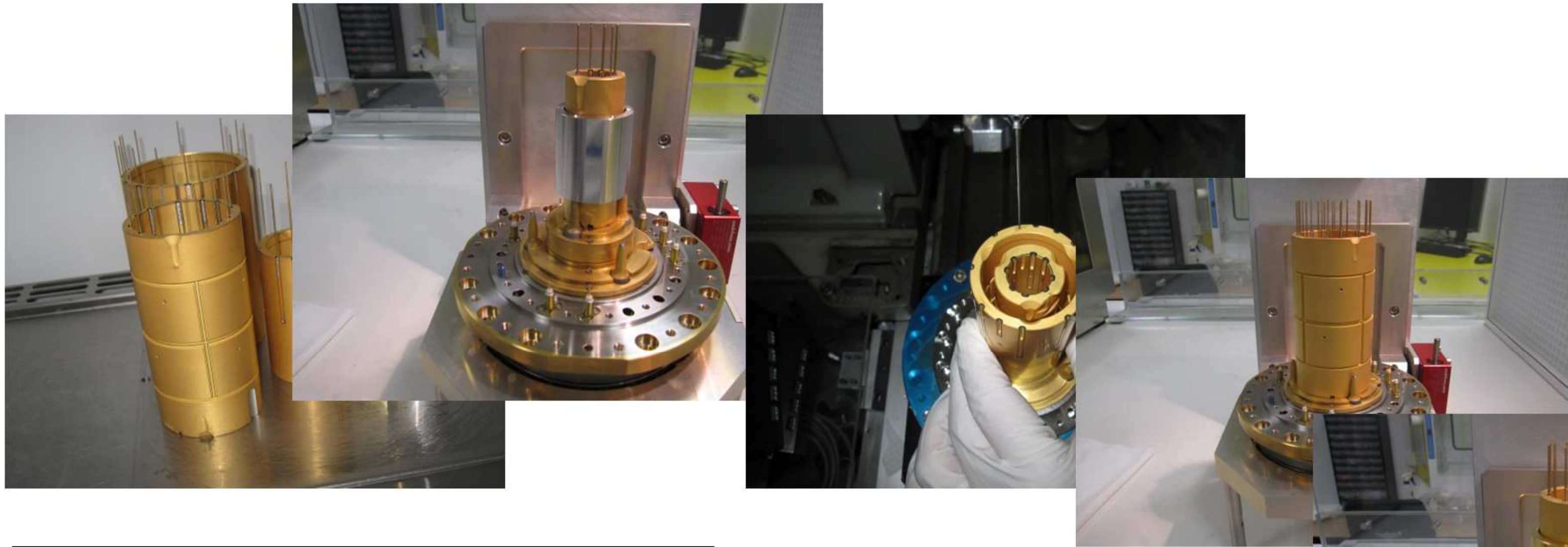
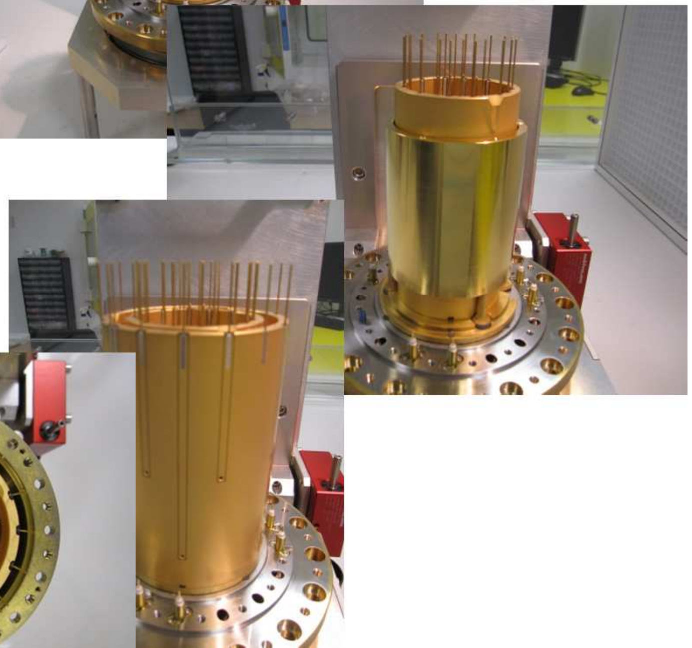
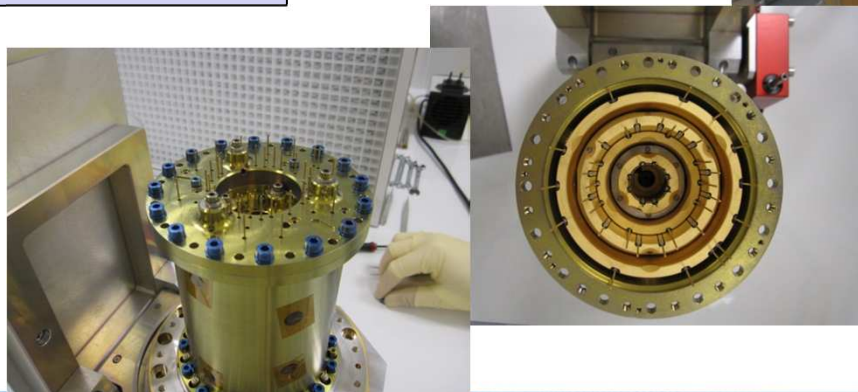
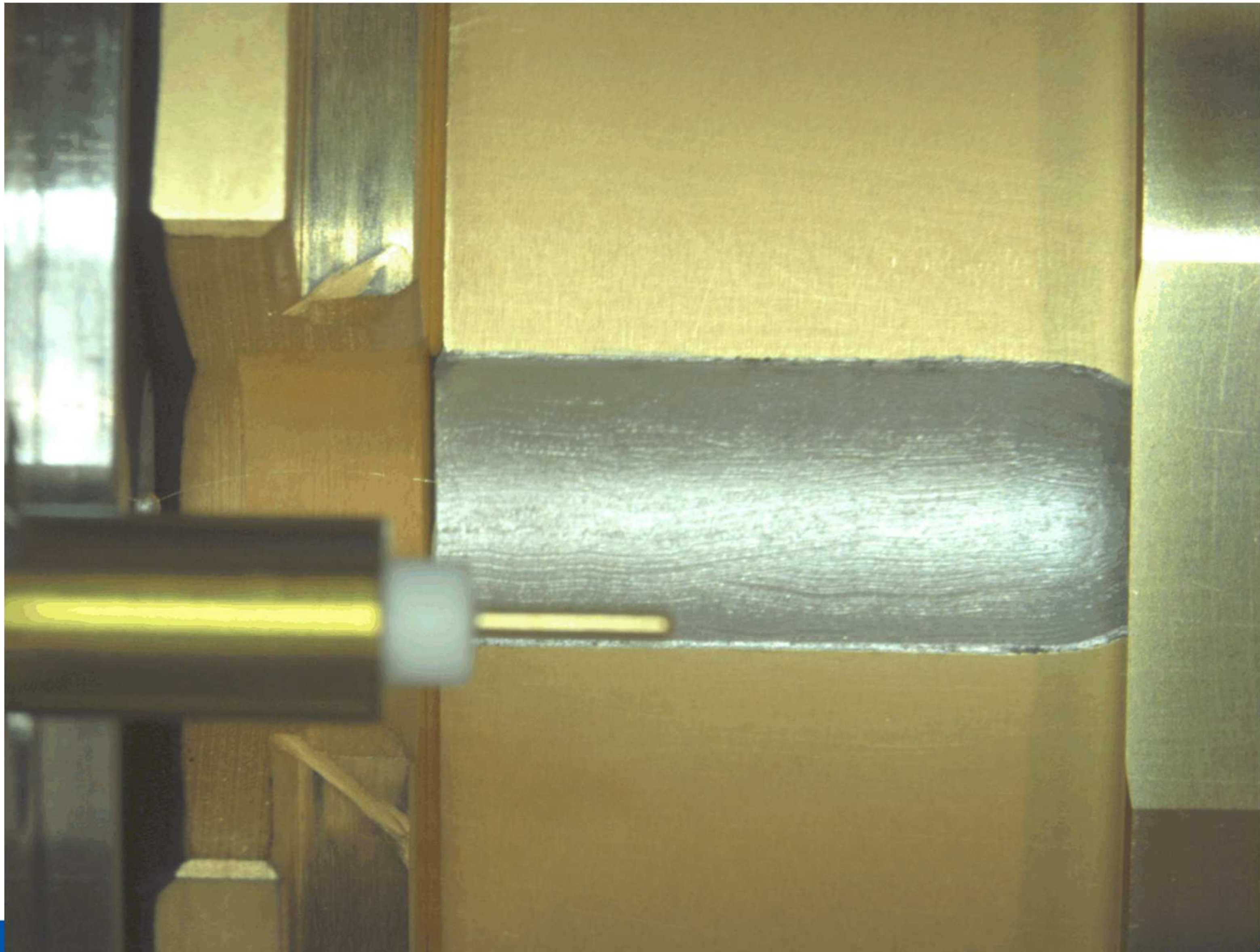


- ✓ The two masses are integrated inside their electrode rods;
- ✓ Geomefric control have been performed
- ✓ Electrical board with connectors and getter pumping element to be mounted

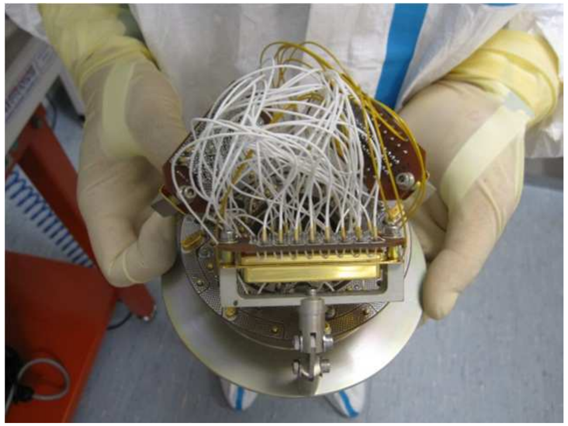




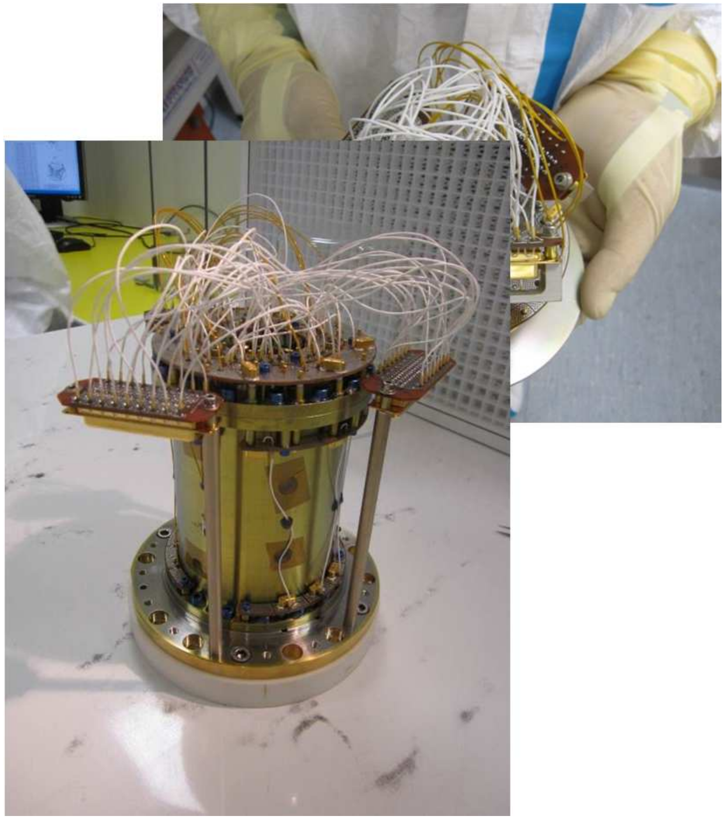
INTEGRATION FM 2 : Platinum / Titanium (3/4)



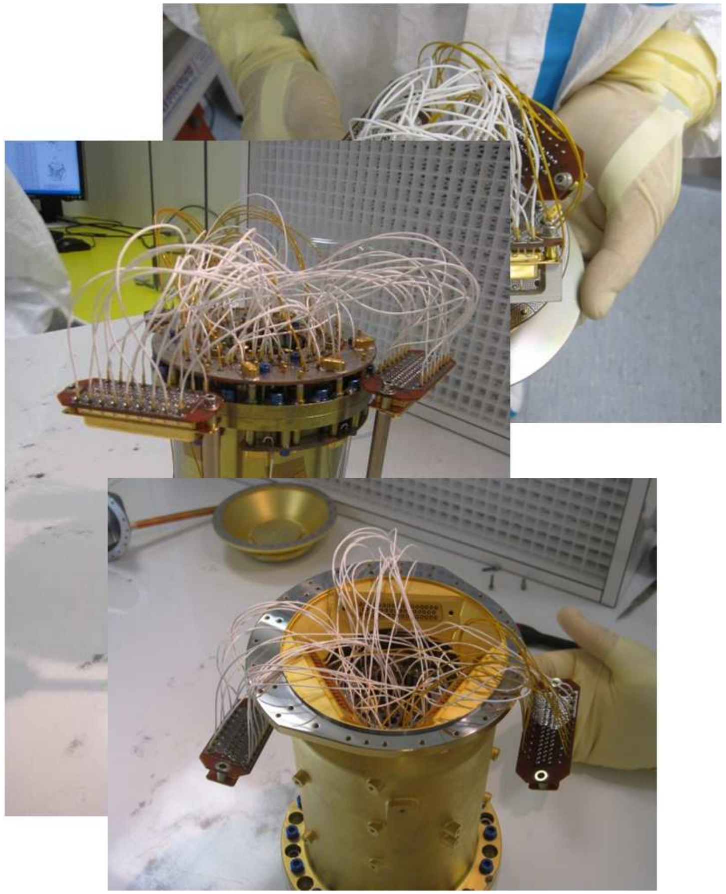
INTEGRATION FM 2 : Platinum / Titanium (4/4)



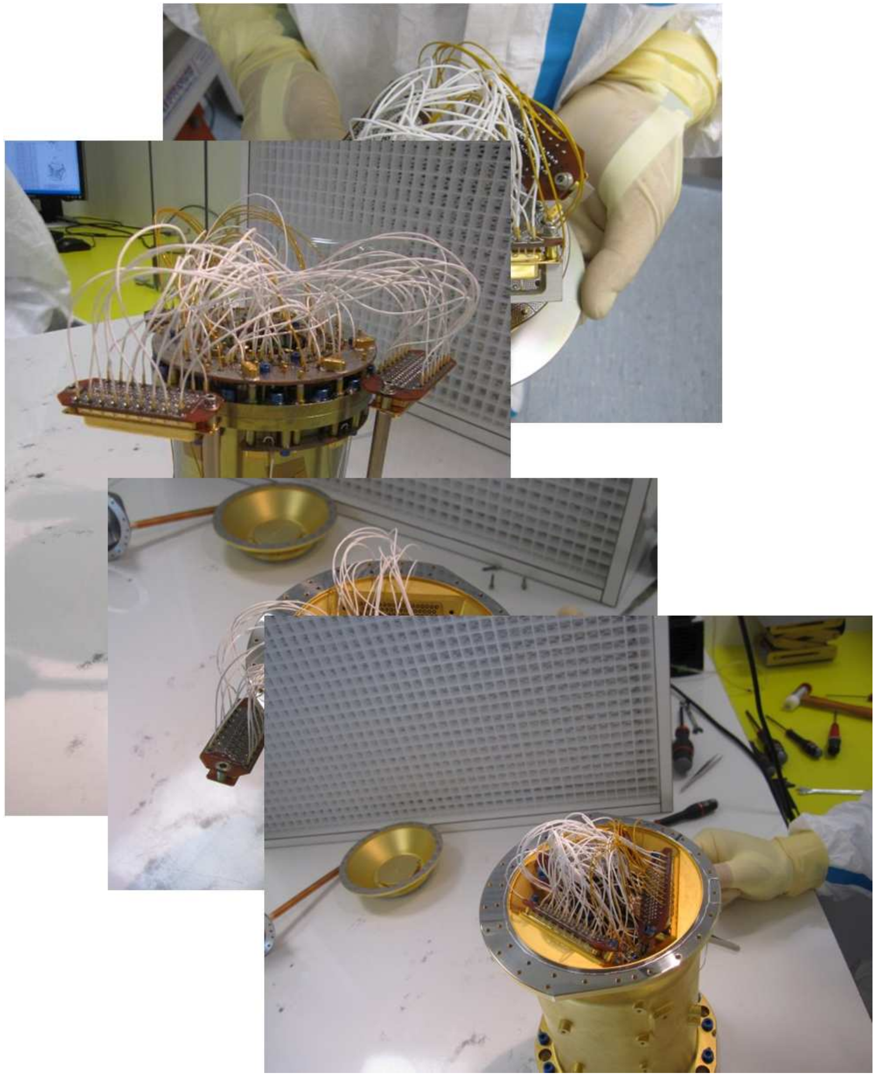
INTEGRATION FM 2 : Platinum / Titanium (4/4)

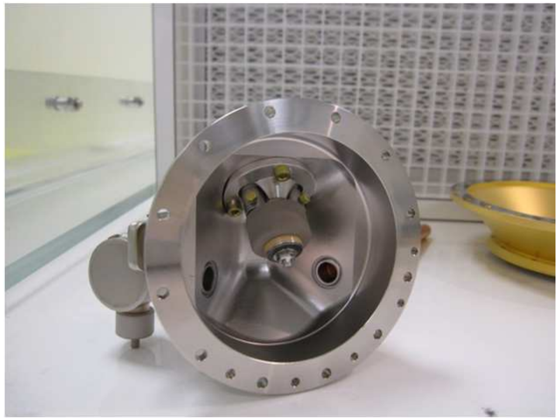


INTEGRATION FM 2 : Platinum / Titanium (4/4)

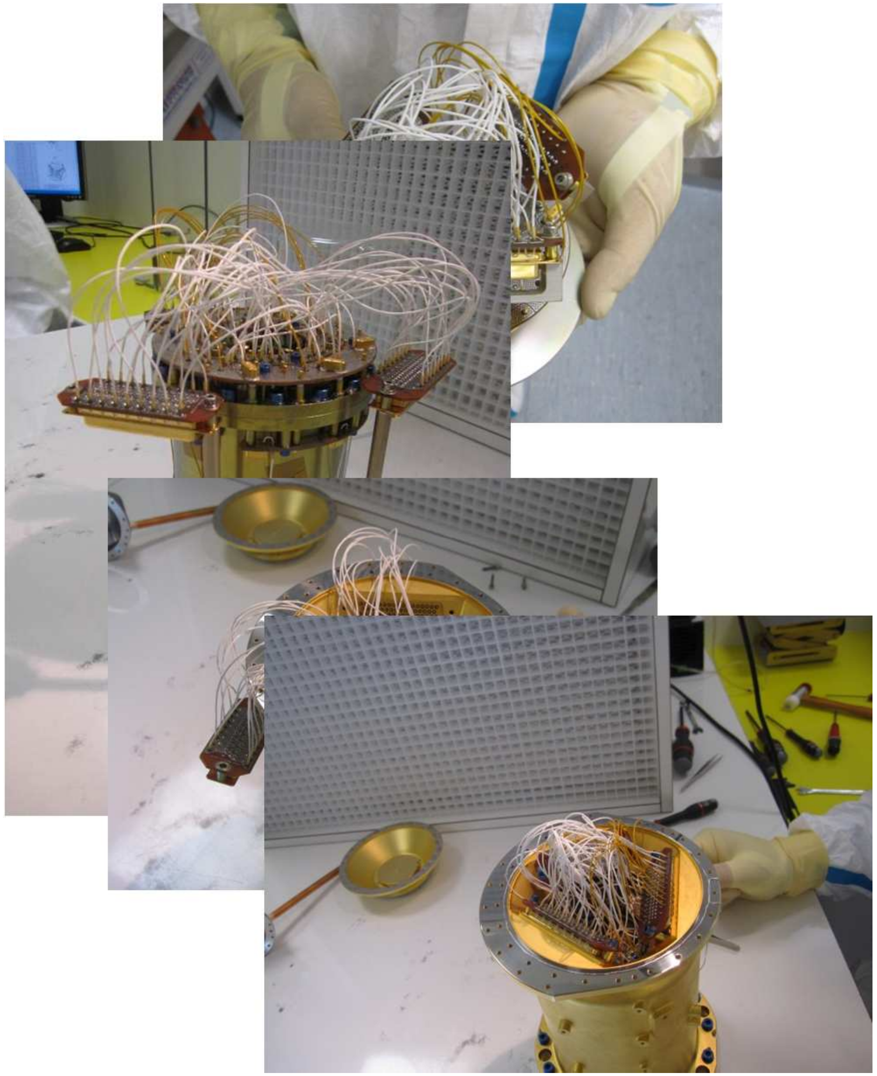


INTEGRATION FM 2 : Platinum / Titanium (4/4)

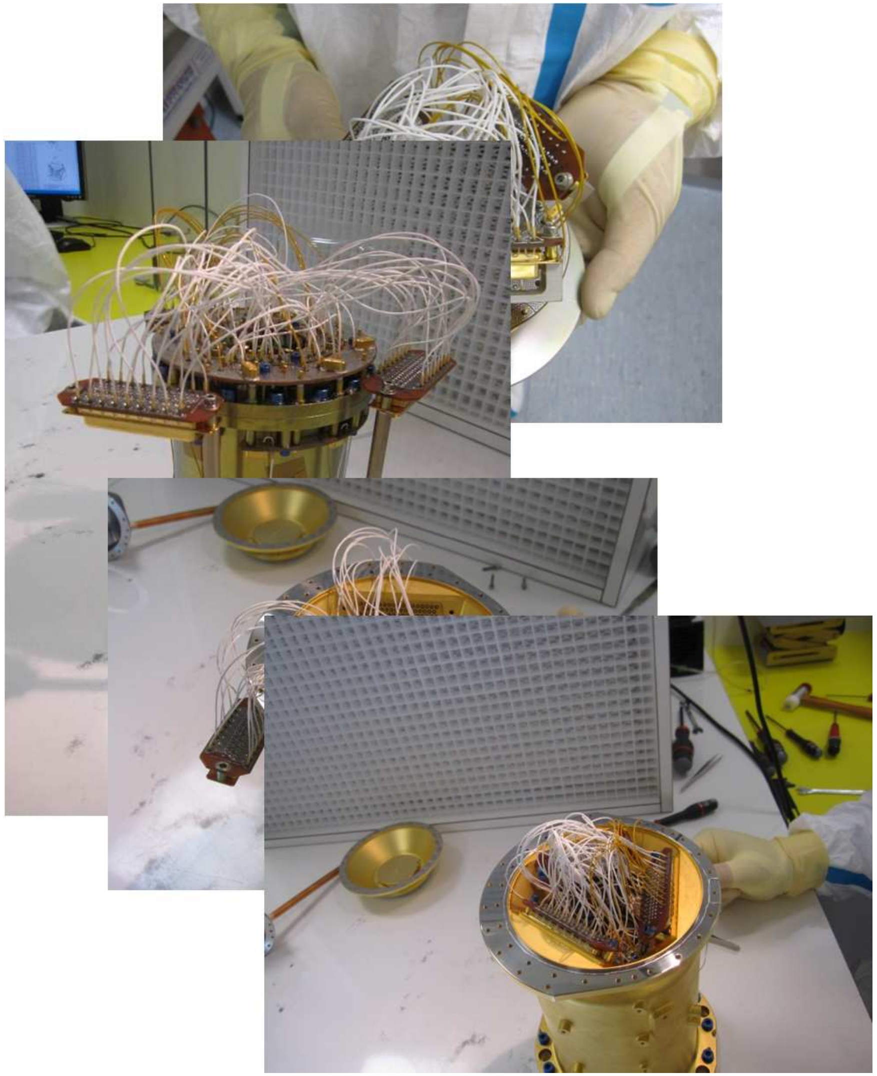




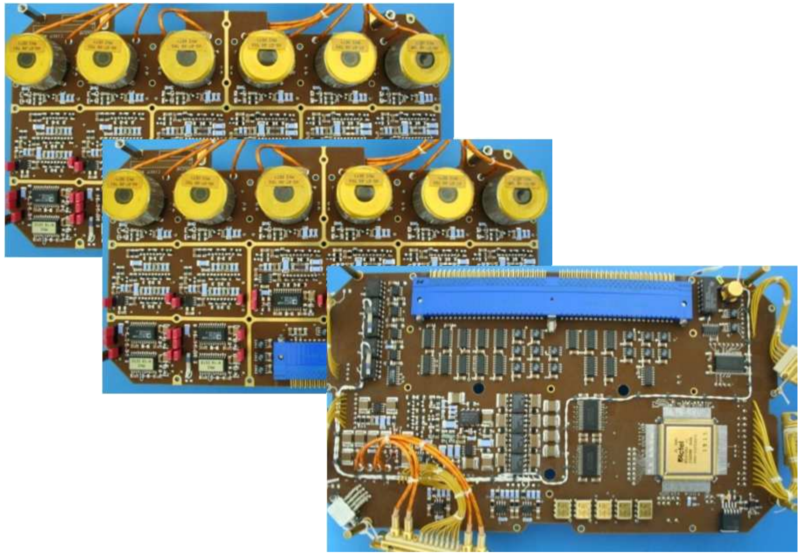
INTEGRATION FM 2 : Platinum / Titanium (4/4)



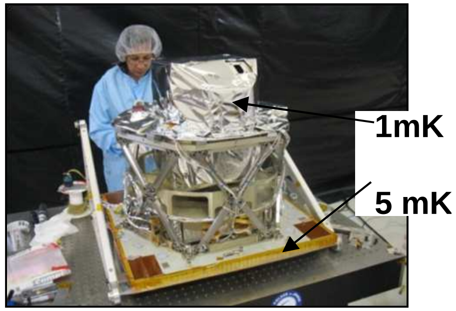
INTEGRATION FM 2 : Platinum / Titanium (4/4)

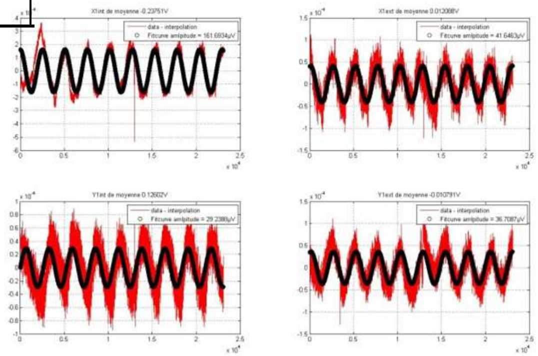


FEEU and ICU qualification



Axe	Résultat [µV/℃]	Spécification
X1i	64.68	<300µV/C
X1e	16.66	<300µV/C
Y1i	11.70	<20µV/C
Y1e	14.68	<20µV/C
Y2i	8.40	<20µV/C
Y2e	9.34	<20µV/C
X2i	36.56	<300µV/C
X2e	130.93	<1800µV/C
Z1i	12.15	<20µV/C
Z1e	37.63	<20µV/C
Z2i	16.37	<20µV/C
Z2e	13.26	<20µV/C



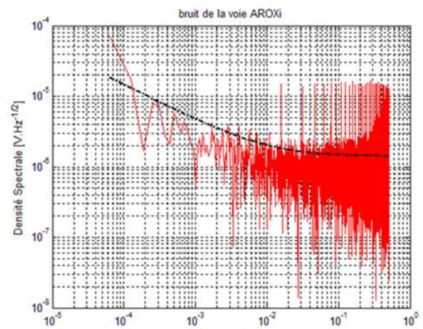


X inner: 2.6 10^5 V/m → <10µV.Hz$^{1/2}$ = 3.8 10^{-11}m.Hz$^{1/2}$
X outer: 3.0 10^5 V/m → < 6µV.Hz$^{1/2}$ = 2.0 10^{-11} m.Hz$^{1/2}$

Y,Z inner: 2.3 10^5 V/m → < 6µV.Hz$^{1/2}$ = 2.6 10^{-11}m.Hz$^{1/2}$
Y,Z outer: 3.1 10^5 V/m → < 4µV.Hz$^{1/2}$ = 1.3 10^{-11}m.Hz$^{1/2}$

The 3 FEEU FM, successfully tested in performance :
- ***noise + bias + linearity + bandwidth + thermal sensitivity***
- ***Interface with FM ICUs***

Now, under potting after increase of the read-out range, Qualification under vibrations and thermal cycles are scheduled in Dec. 2013.



Read out noise (red) vs spec. (black) :
1µV.Hz$^{1/2}$ = 9.2 10^{-14}ms^{-2}.Hz$^{1/2}$

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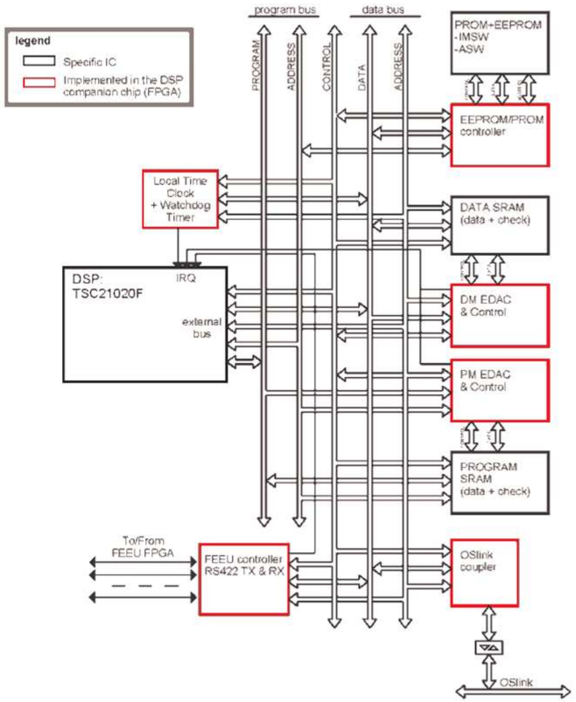
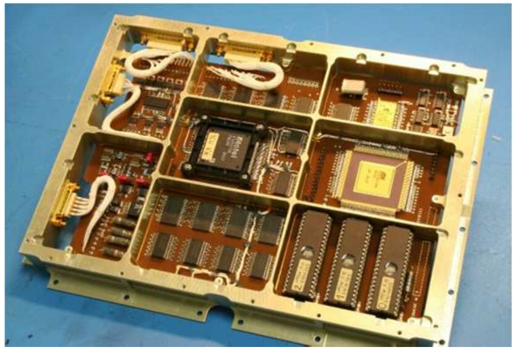
FM Interface Control Unit :DSP Hardware

1 DSP board per differential accelerometer (No redundancy) :
1 DSP → 1 SU → 12 servo-loops channels
1 DSP = 1 Oslink customer

Architecture on TSC21020F:
- *Rad-tolerant FPGA*
- *SEL immune SRAM (SEU protected by EDAC)*
- *PROM containing the master (Boot) software (IMSW)*
- *EEPROM containing the application software (ASW) and the parameter tables.*

Software and Hardware tested, accuracy verified.





- ***DSP hardware now compliant (more robust chronogram) :***
  - ***With the whole range of operating temperature***
  - ***And with the 2 years duration of the mission***
- ***Tests have been successfully performed***
- ***Software 2.6 to be delivered at end of November.***

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Instrument status and performance verification

- ***Sensors:***

  Qualification, now performed with demonstration of resistance to launch vibrations, chocks, aging (gold wire);

  FM 2, integrated and under tests;

  FM 1, integration running;

  To be delivered in March 2014

- ***Analog electronics:***

  FM Tested and being potted after full range adjustment;

  To be delivered in Feb. 2014

- ***Digital electronics:***

  Robustness to increase of temperature now insured;

  Software to be up-dated;

  To be delivered in Feb. 2014

- ***Documentation:***

  In progress

- ***Error budget***

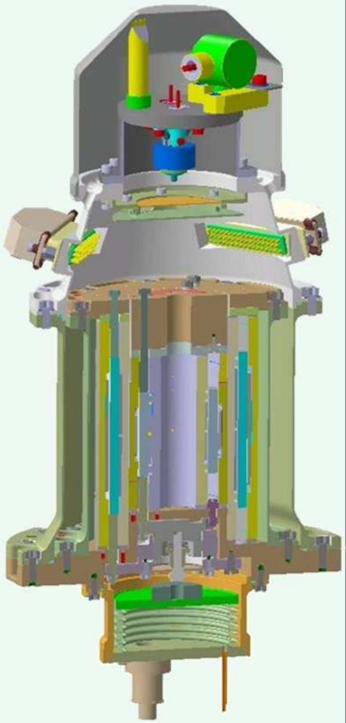
  Now performed with QM actual values and satellite expected environment

  Spin mode : 1,12 10^{-15} over 20 orbits and 0,66 10^{-15} over 120 orbits

  Inertial mode : 1,42 10^{-15} over 120 orbits

  Both limited by the sensor noise, the SU gradients of temperature variations,

  the SU and FEEU temperature variations.



Instrument status and performance verification

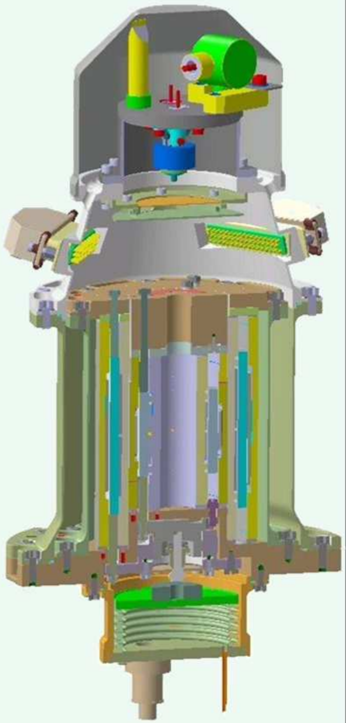
<u>***Performance test session : 29 days***</u>

- ✓ *Verification of acceleration output linearity*
- ✓ *Sensibility of output linearity to static TM position (along the 3 axes)*
- ✓ *Variation of the electrostatic configuration*
  - ✓ *through test mass DC potential*
    - → *observation of bias and noise*
  - ✓ *through test-mass sine motion : change of geometry*
  - ✓ *through S/C sine motion : change of electrode voltages*
- ✓ *Evaluation of couplings and TM self gravity*
- ✓ *Evaluation of Magnetic sensitivity through magneto-torquer actuations*
- ✓ *Evaluation of thermal sensitivity of SU and FEEU with dedicated thermistances*

<u>***Calibration : 3 phases of 14 days***</u>

- ✓ *Before and after*
- ✓ *EP and REF*

ons, chocks, aging (gold wire);



➢ <u>***Error budget***</u>

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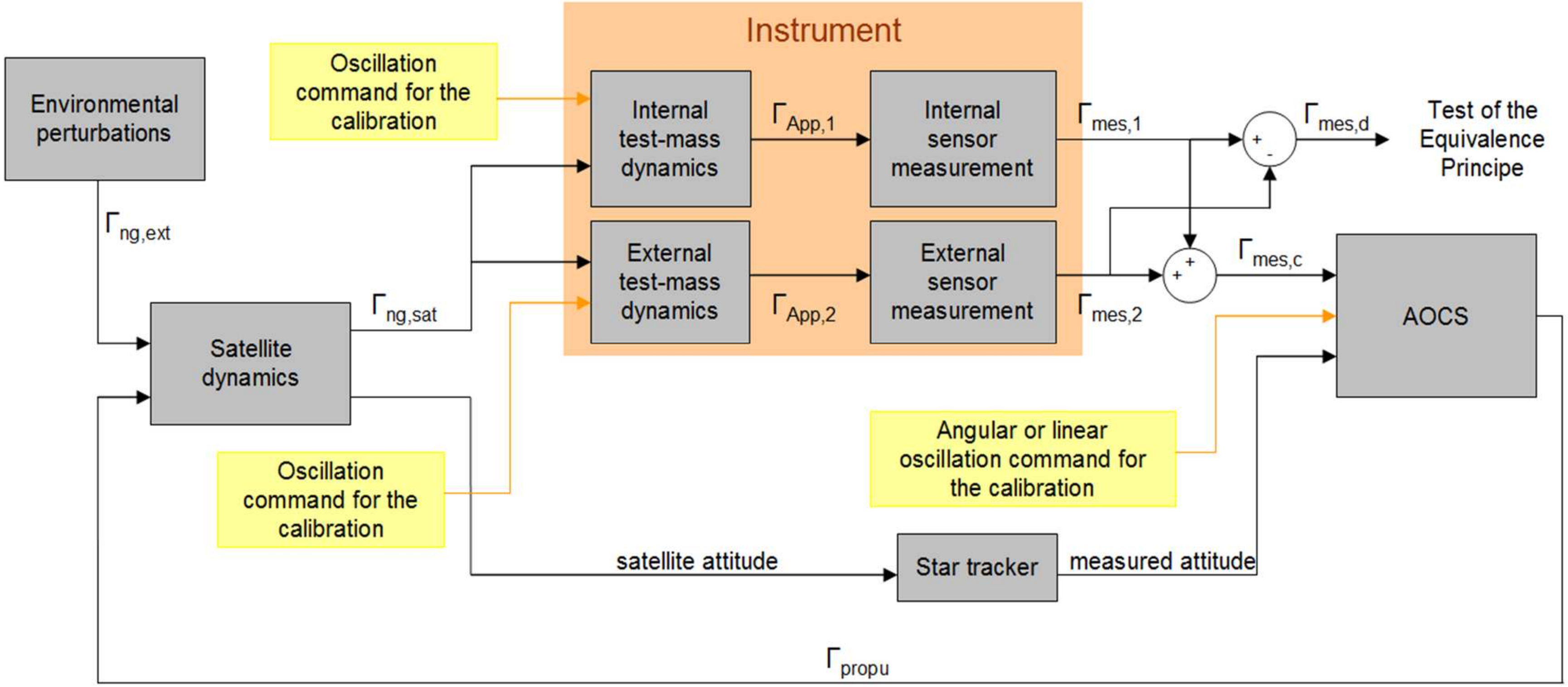
Inertial mode : 1,42 10^{-15} over 120 orbits

Both limited by the sensor noise, the SU gradients of temperature variations, the SU and FEEU temperature variations.

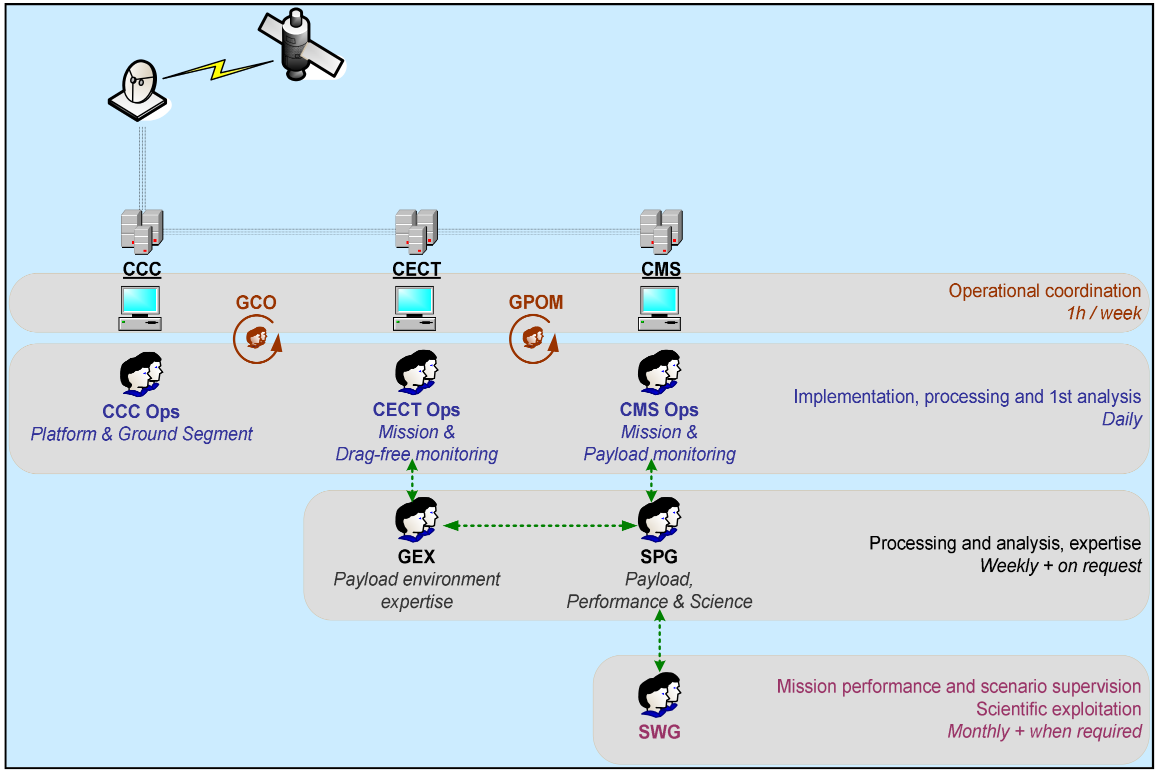
CALIBRATION : 2 servo-loops to generate well known acceleration outputs



- ✓ Drag compensation loop → To excite the linear satellite motion
  → Common excitation → Differential outputs vs drag-free point
- ✓ Attitude S/C control through SST and angular accelerometer
  → To oscillate the S/C → Differential outputs vs eccentricity or instrument attitude vs SST
- ✓ Proof- mass oscillation → Elect. Conf. modif. Or Corriolis effects

Operational & scientific organization

3 levels



- **permanent activity for data processing**
- **monthly meetings**
- **weekly potential request for mission scenario & operation**

- **biannual meetings or quarterly for data processing organization and validation**
- **monthly potential requests for mission scenario**

The MICROSCOPE Science Working Group promotes the exploitation of the data & is responsible in particular for:

- **Supervising and approving the evaluation and the validation of the performance**
- **Approving the final scientific data products to be distributed to the community,**
- **Promoting the exploitation of the data and the diffusion of the information (colloquia…).**

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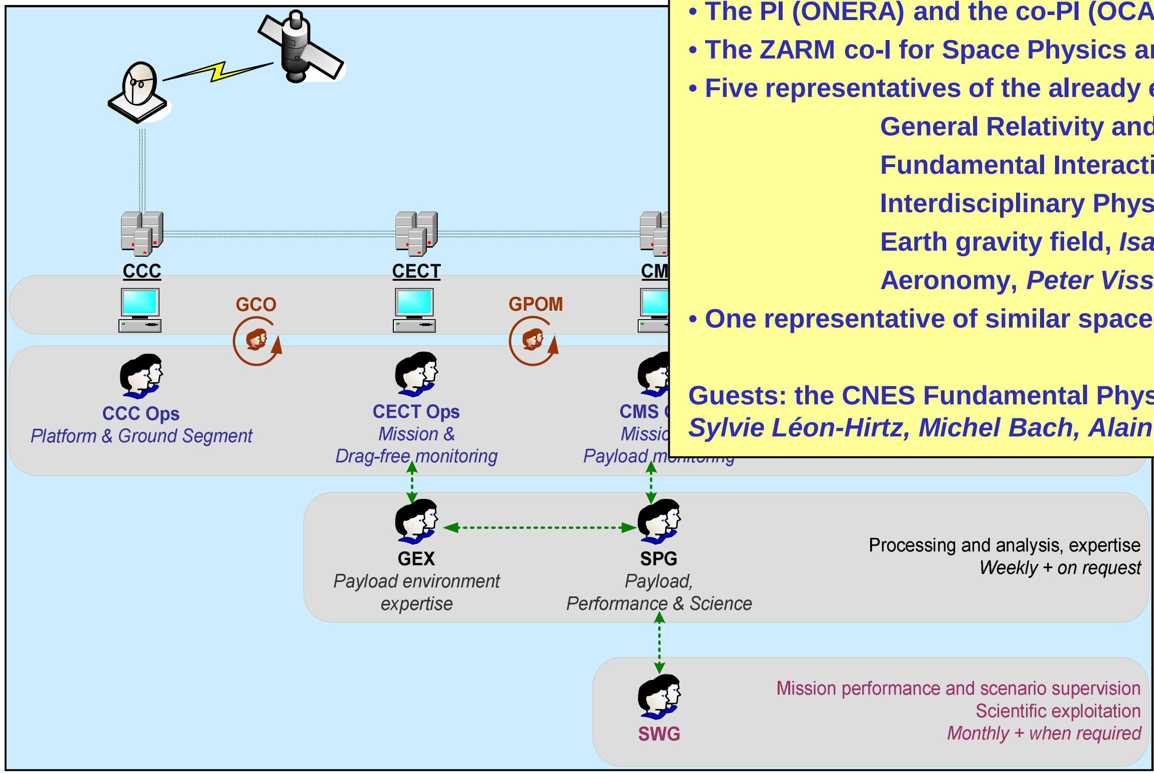
Operational & scientific organization

3 levels



Members of the SWG :

- **The PI (ONERA) and the co-PI (OCA), *Pierre Touboul , Gilles Métris,***
- **The ZARM co-I for Space Physics and the DLR co-I, *Claus Lämmerzhal , Hans Dittus,***
- **Five representatives of the already envisaged scientific themes, i.e.:**
  - **General Relativity and Gravitation, *Thibault Damour,***
  - **Fundamental Interactions, *Pierre Fayet,***
  - **Interdisciplinary Physics, *Serge Reynaud,***
  - **Earth gravity field, *Isabelle Planet,***
  - **Aeronomy, *Peter Visser,***
- **One representative of similar space missions, *Tim Sumner,***

Guests: the CNES Fundamental Physics coordinator, *Project manager, CECT chairman, Sylvie Léon-Hirtz, Michel Bach, Alain Robert* and the CMS manager, *Manuel Rodrigues.*

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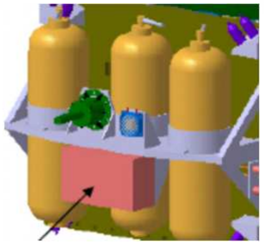
Thanks to MICROSCOPE present partners

MICROSCOPE



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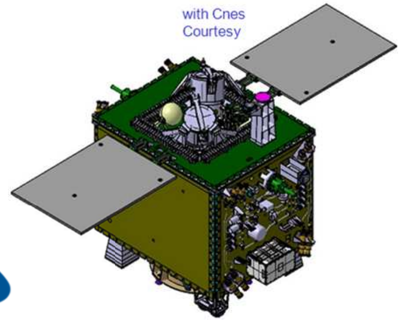

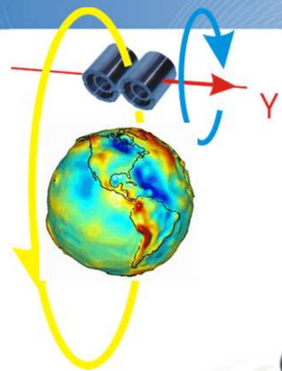

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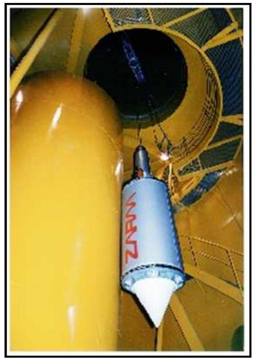
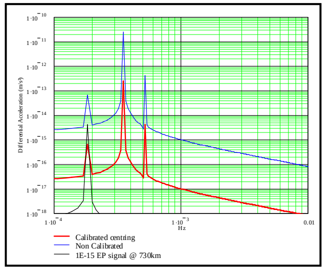
CENTRE NATIONAL D'ÉTUDES SPATIALES

Géo Azur

ASTROGÉO

Observatoire de la Côte d'Azur





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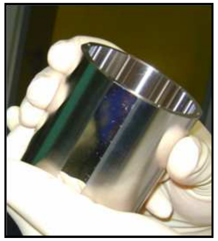

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THANK YOU FOR YOUR ATTENTION

QUESTIONS ?