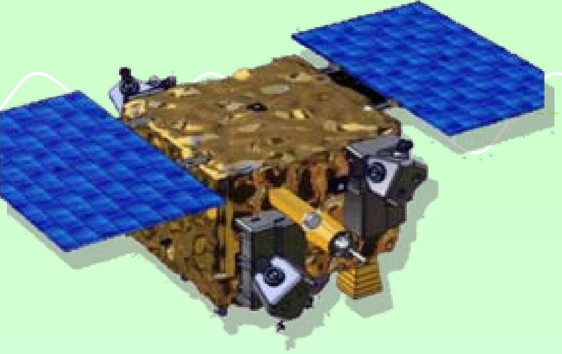


ONERA

MICROSCOPE status, mission definition and recent instrument development

P. Touboul

pierre.touboul@onera.fr

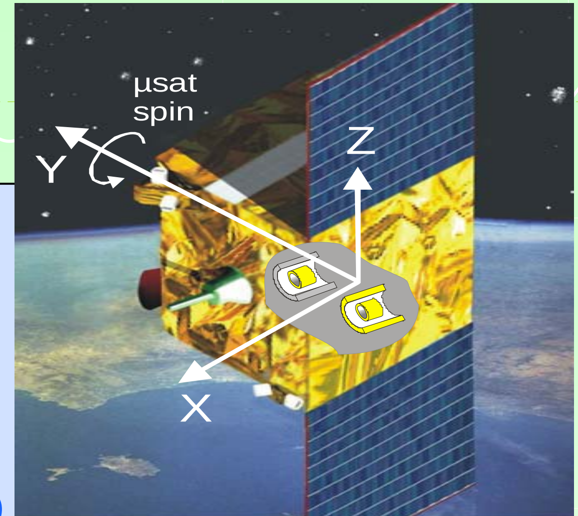
"The ratio of the masses of two bodies is defined in two ways which differ from each other fundamentally,…, as the reciprocal ratio of the accelerations which the same motive force imparts to them (inert mass),…, as the ratio of the forces which act upon them in the same gravitational field (gravitational mass). The equality of these two masses, so differently defined, is a fact which is confirmed by experiments…

The possibility of explaining the numerical equality of inertia and gravitation by the unity of their nature, gives to the general theory of relativity, according to my conviction, such a superiority over the conception of classical mechanics…"

A. EINSTEIN The Meaning of Relativity, Princeton,

MICROSCOPE

THE MICROSCOPE MISSION



Courtesy CNES

SELECTED IN CNES NATIONAL SCIENTIFIC PROGRAM
with ESA COOPERATION

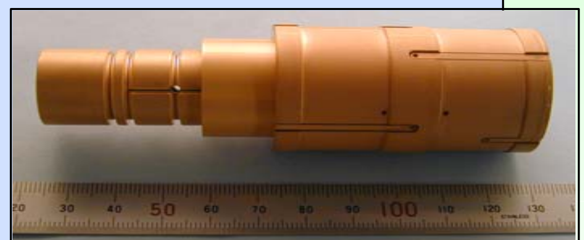
CNES SMALL SATELLITE MISSION

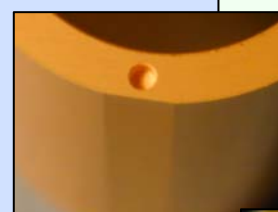
ESA THRUSTERS

MISSION PROPOSED BY ONERA (Pi) & OCA (Co-Pi) with ZARM (Co-I)

Jan – April 2006 :
Preliminary Design Review of the Instrument,
the Satellite, the Mission (End of Phase B)

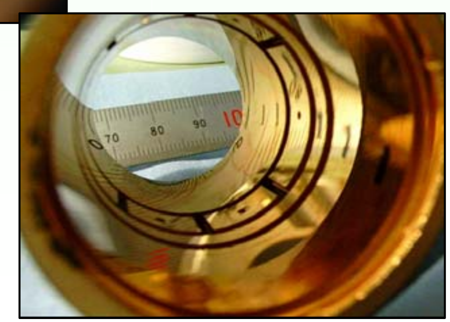
Launch expected in 09-10 depending on Feeps.





Thanks to Gilles Métris and his team (OCA),
to Hans Dittus and his team (ZARM),
to Jean Bernard Dubois and his team (CNES),
to Davide Nicolini and his team (ESA)
to GREX for scientific supports, exchanges and emulations

Activities supports and Funding from CNES and Institutes



"The ratio of the masses of two bodies is defined in two ways which differ from each other fundamentally,…, as the reciprocal ratio of the accelerations which the same motive force imparts to them (inert mass),…, as the ratio of the forces which act upon them in the same gravitational field (gravitational mass). The equality of these two masses, so differently defined, is a fact which is confirmed by experiments…

Equivalence Principle

- Quantum Theory, Standard Model
  Electromagnetism, Strong & Weak Nuclear Force
- Geometric Theory of Gravitation, GR

→ Super Symmetry requires new particles...
→ Super String Theory, Branes… requires new field…

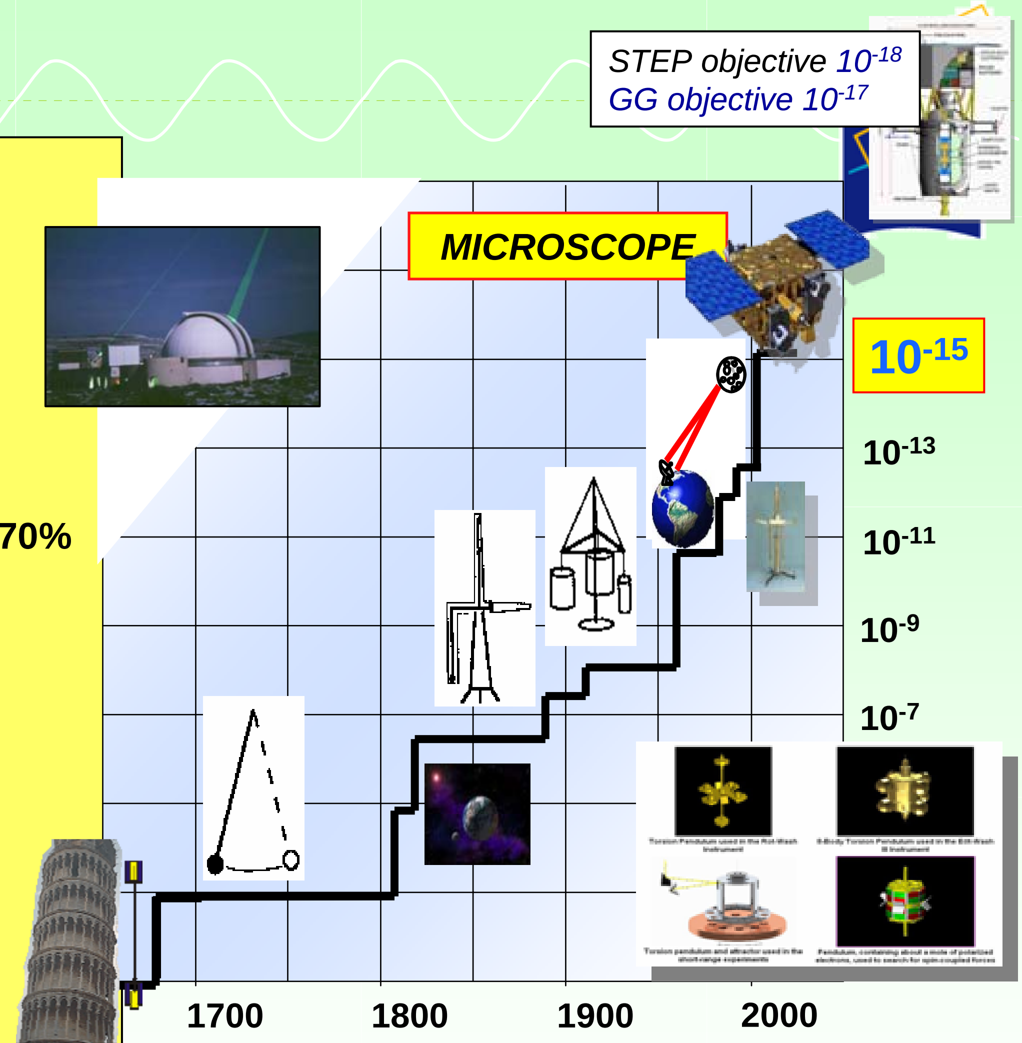
⇒ Galaxy rotation → Dark matter ? 25%

⇒ Universe Expansion acceleration → Dark Energy ? 70%

Domain of validity for current theories to be always confirmed more accurately

Many proposed space experiments:

- *Lorentz Invariance test :PHARAO, LATOR,…*
- *Post-Newtonian Parameters accurate determination : GPB, PHARAO,...*
- *Determination and observation of relativistic effects : GPB, LISA, ASTROD, …*
- *Stability of 'Constants'*



Equivalence Principle Tests (by UFF test) directly verify a fundamental basis of our present Gravity knowledge & may confirm dilaton existence

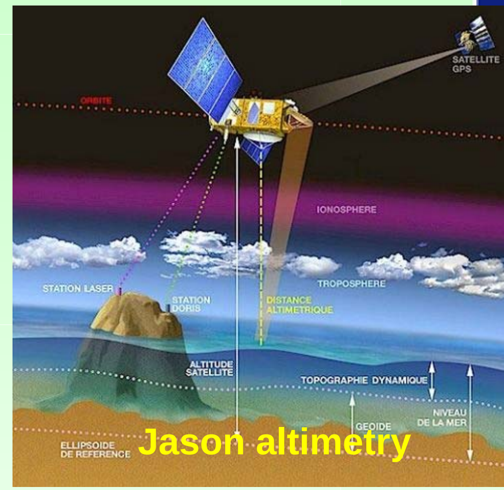
$$\delta = \frac{m_{g2}}{m_{I2}} - \frac{m_{g1}}{m_{I1}}$$

The possibility of explaining the numerical equality of inertia and gravitation by the unity of their nature, gives to the general theory of relativity, according to my conviction, such a superiority over the conception of classical mechanics…"
A. EINSTEIN The Meaning of Relativity, Princeton,

A Mission concept relying on best current technologies and models

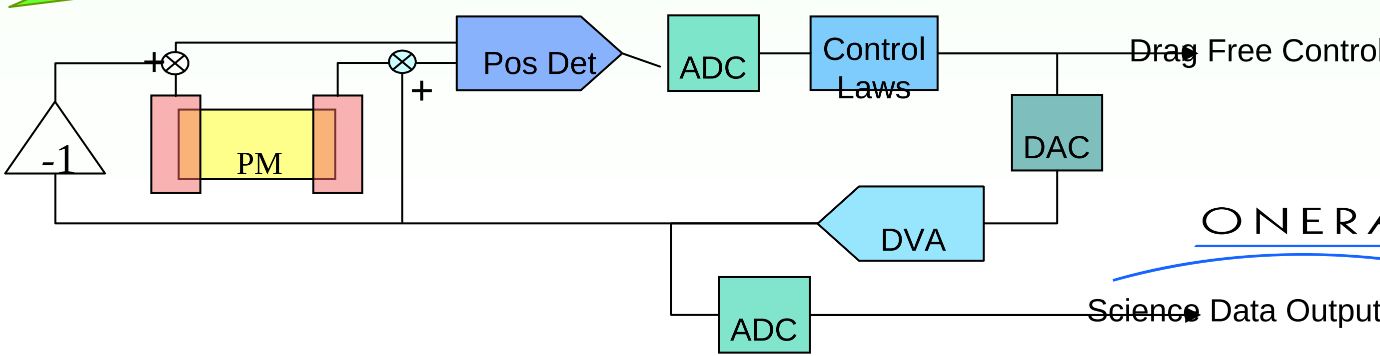
CNES micro satellite

ONERA Accelerometer

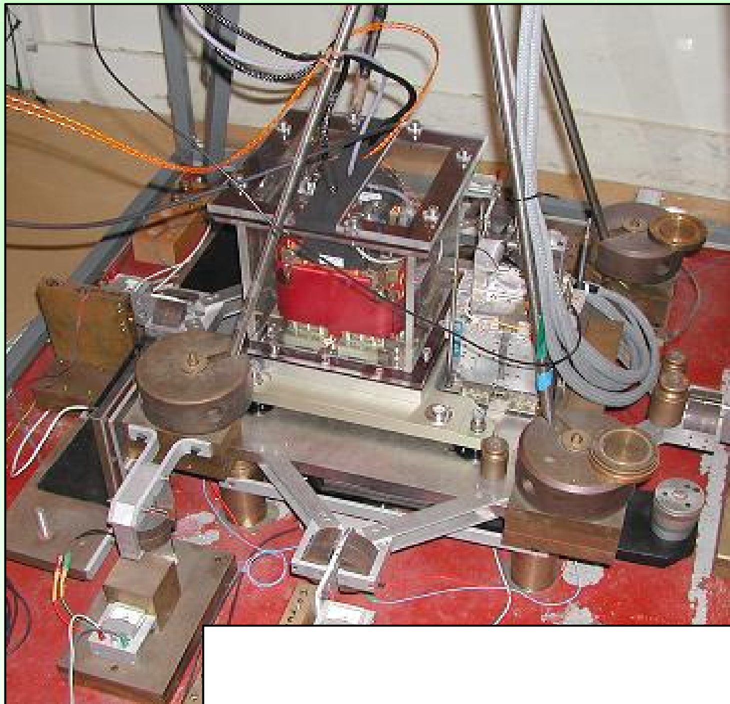


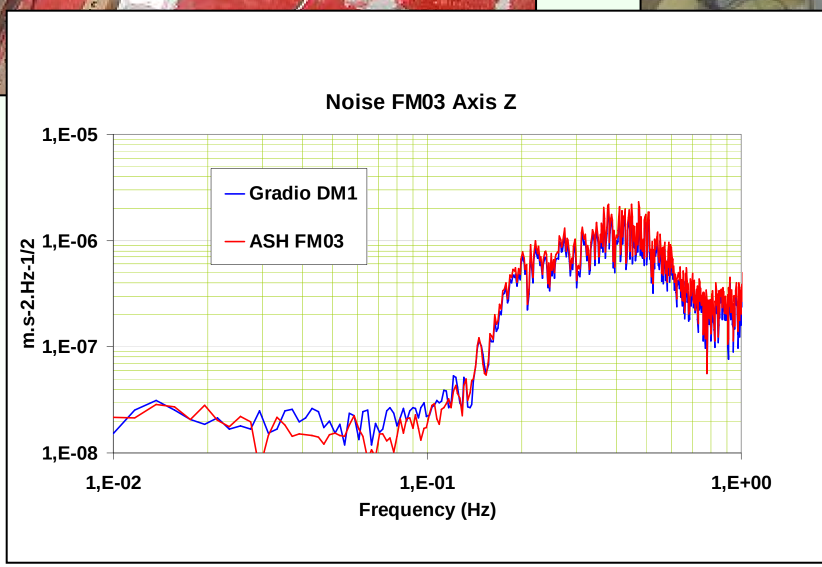
OCA Space Geodesy & Astrometry

ESA FEEP



GOCE FM tests in lab. (Jul 06)





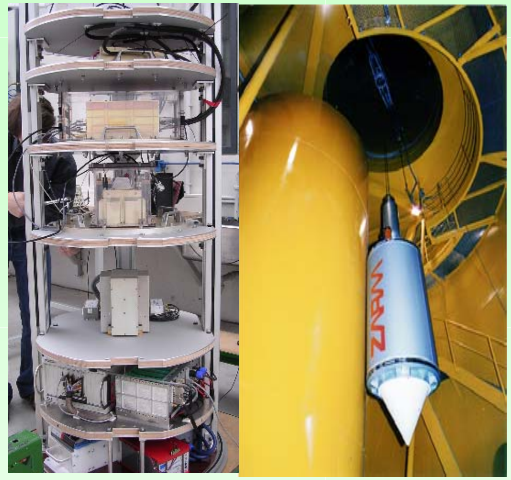
GOCE ESA mission :

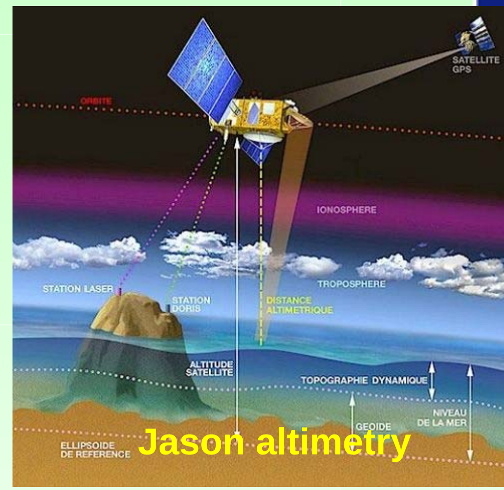
• 6 Electrostatic accelerometers for the full tensor gravity gradiometer

Tests on horizontally controlled table

ONERA

A Mission concept relying on best current technologies and models



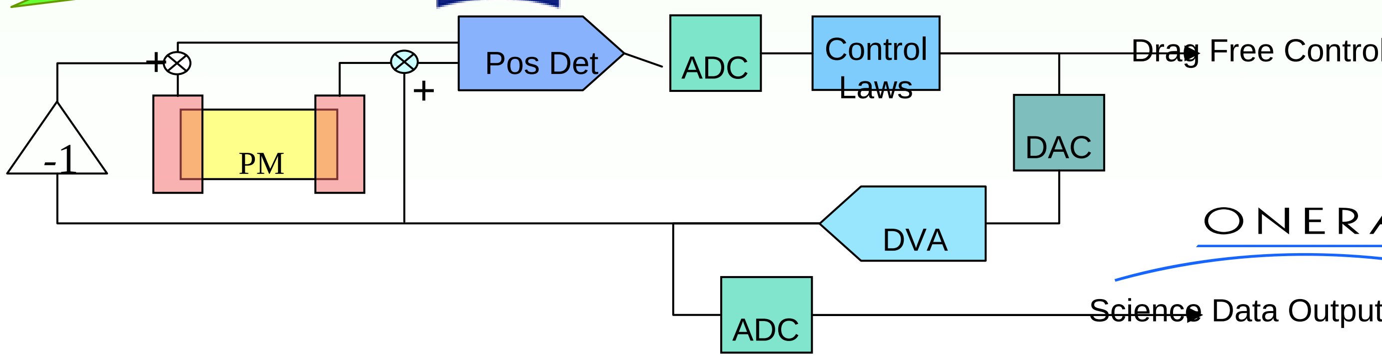


CNES micro satellite

ONERA Accelerometer
ZARM drop tower

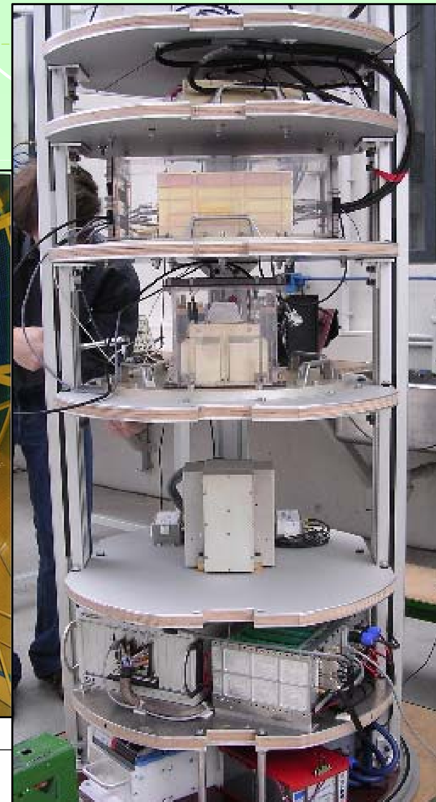
OCA Space Geodesy & Astrometry

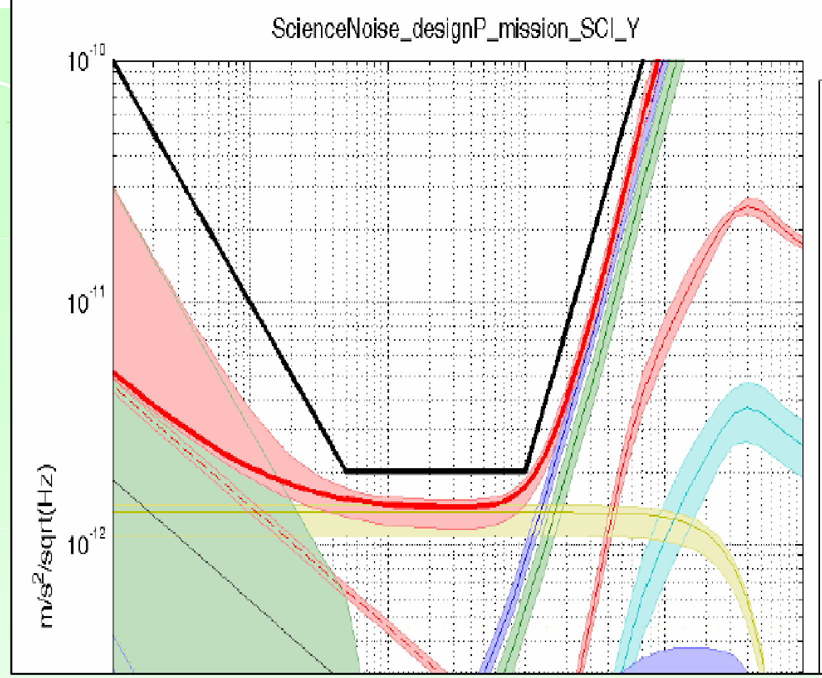
ESA FEEP



ONERA

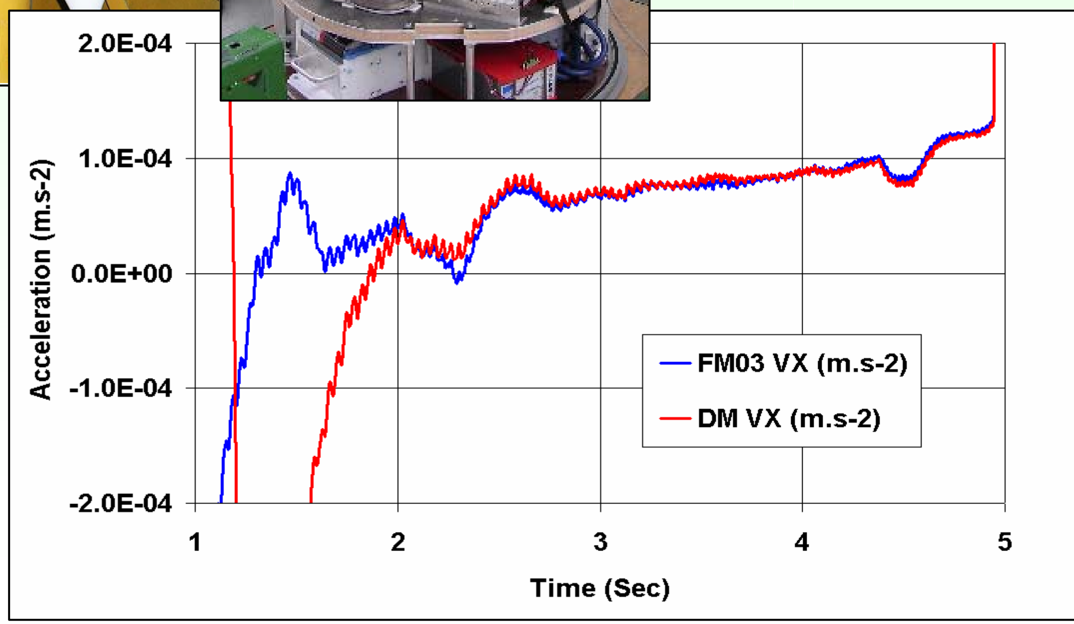
Free fall tests in ZARM





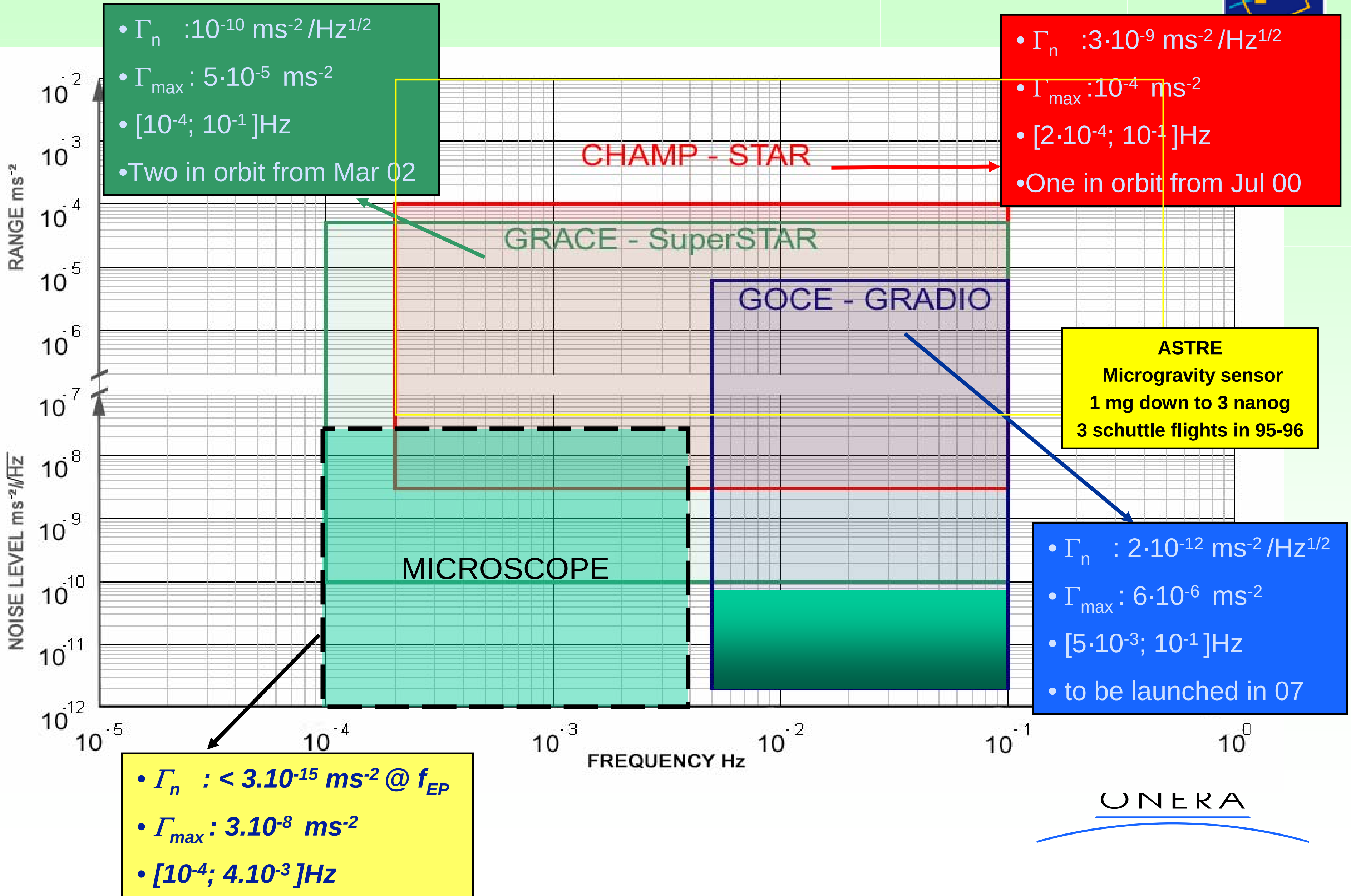
2.10^{-12} ms^{-2}/Hz$^{1/2}$ from 5 to 100 mHz

ZARM drop tower



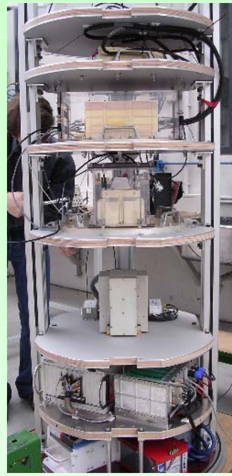
Comparison between GRACE and GOCE inst. along vertical

A family of space accelerometers

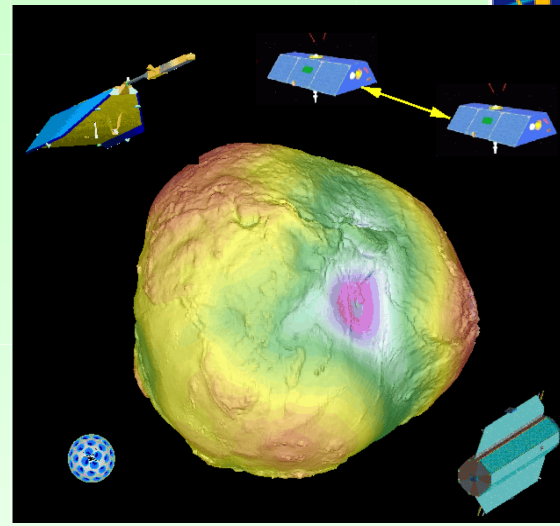


A Mission concept relying on best current technologies and models

CNES micro satellite



ONERA Accelerometer
ZARM drop tower

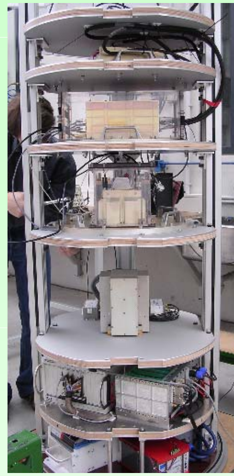


OCA Space Geodesy & Astrometry

ESA FEEP

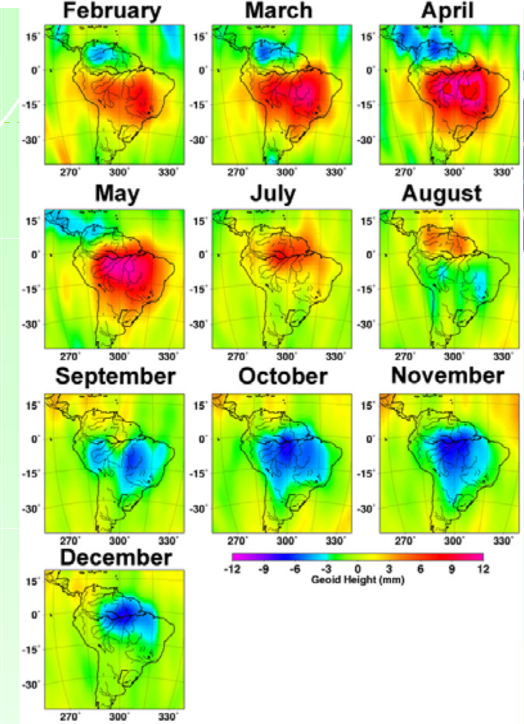
A Mission concept relying on best current technologies and models

CNES micro satellite



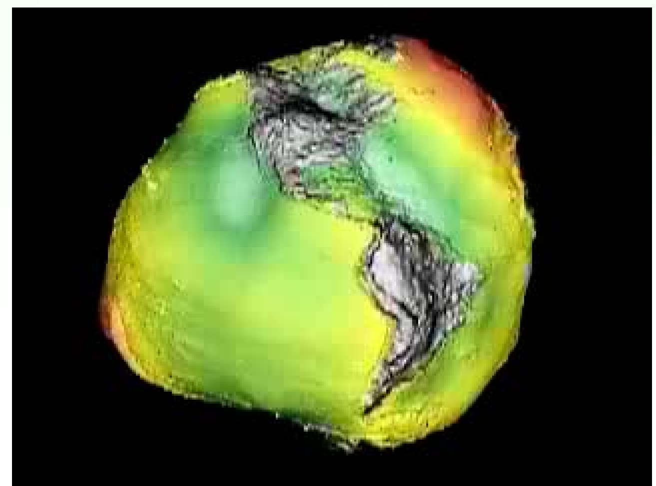
ONERA Accelerometer

ZARM drop tower



OCA Space Geodesy & Astrometry

ESA FEEP



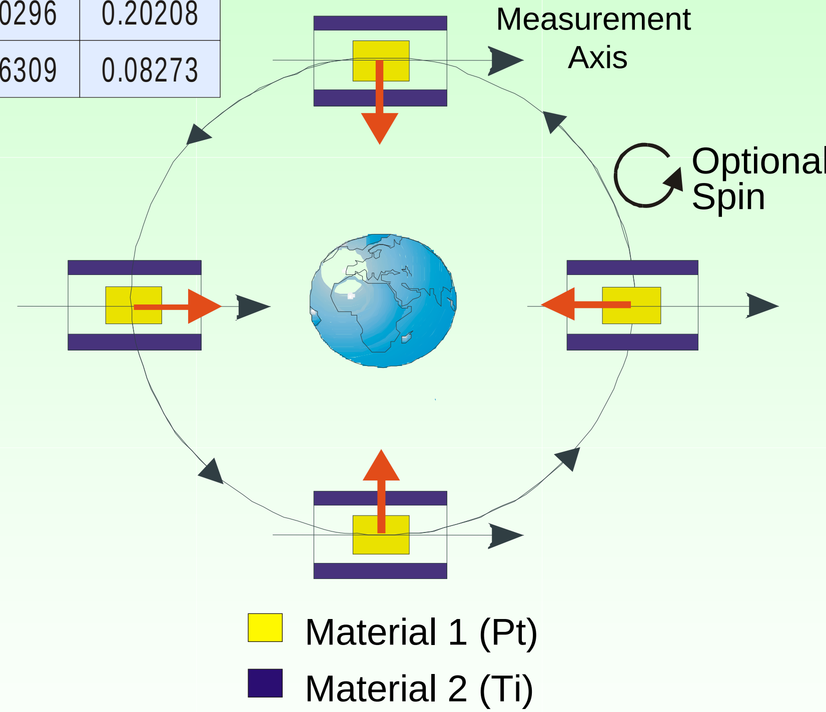
MICROSCOPE Test Principle

Test accuracy : $\delta = 10^{-15}$
Specified per session of 1 day to 1 week
Mission duration : 1 year

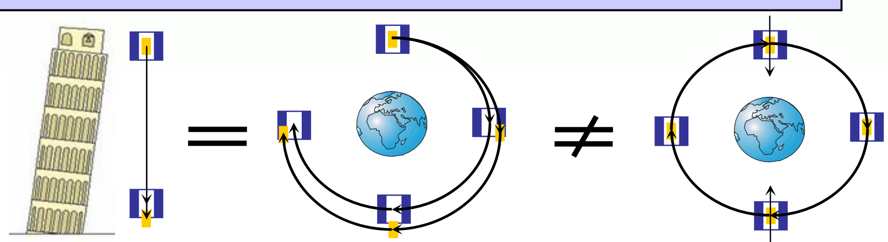
- **Earth : Gravity Source**
- **Two pairs of masses made of different composition in free fall**
  - *Test: Pt/Ti*
  - *Reference : Pt/Pt*

	B/μ	Z/μ	$(N-Z)/\mu$
Pt	1.008009	0.40296	0.20208
Ti	1.008911	0.46309	0.08273

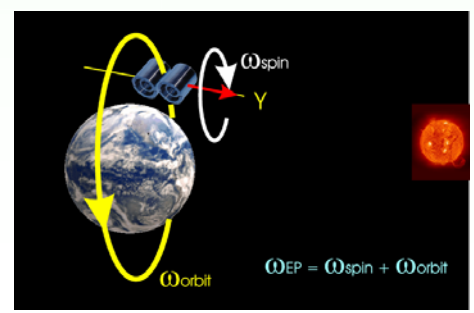
- **Maintained on the same orbit ($<10^{-11}$m) by electrostatic forces**
  - *→Test measurement*
- **Low noise:**
  - *Long duration integration (>20 orbits) & numerous measures*
  - *Drag compensated satellite*
  - *Very clean thermal environment*
- **EP violation signal well defined**
  - *Phase: attitude wrt position in orbit*
  - *Frequency: $f_{orb} + f_{spin}$*



PIERRE TOUBOU



$$f_{ep} = f_o + f_s$$



The Orbit

<u>HELIOSYNCHRONOUS</u>

- *Thermal stability*
- *Maxi power with less solar panels*

(stiff S/C : high frequency modes)

- *No eclipse during measurement phase*

<u>QUASI-CIRCULAR & POLAR</u>

- *Eccentricity < 5.10^{-3}*

To limit Earth gravity gradient (Egg) @ f_{EP}

- *Known better than $5.\ 10^{-5}$*

To correct measurements from Egg effects

<u>Pointing</u>

•Inertial or rotating satellite :

2 spin freq. : $(\pi + 1/2)\ f_{orb}$ & $(\pi + 3/2)\ f_{orb}$

•Finely controlled requiring

Attitude Estimator from SST &

Instrument data, up to a few 0.1 µrad :

sensitive to S/C thermal behavior

<u>Satellite altitude</u>

• 730 or 790 km : Larger signal

Less radiation (electronics)

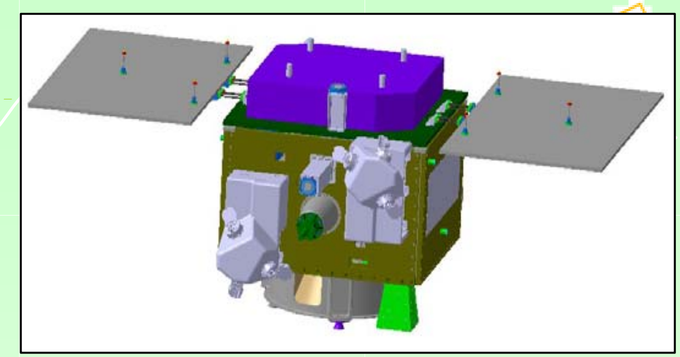
Higher f_{orb}

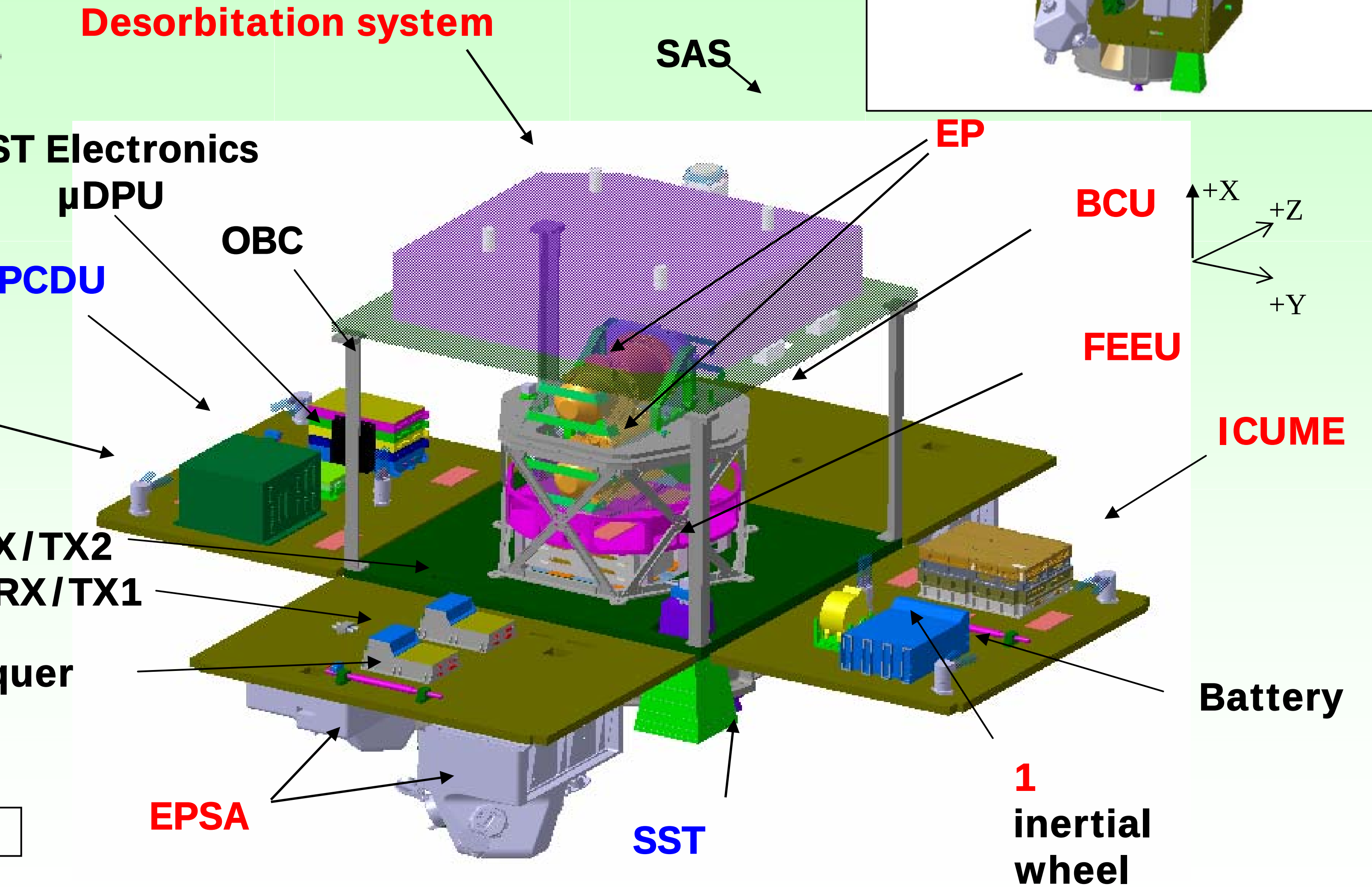
(to 1400 km : No eclipse,

Less thermal disturbance)

•Position to be known from 7 m, 14 m to 100m (for Earth gravity gradient corrections)

A satellite coming from MYRIADE line

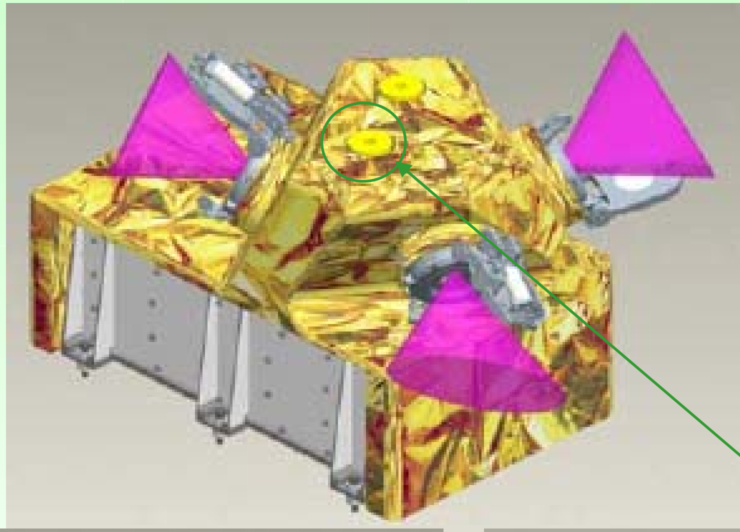




No gyros

With Cnes Courtesy

Electric Propulsion System : Baseline Configuration for the drag-free control

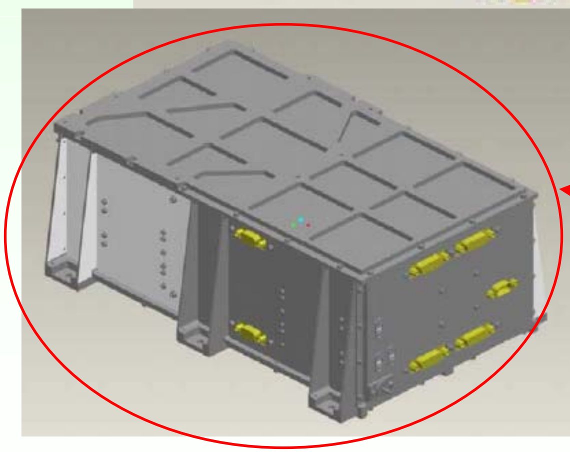


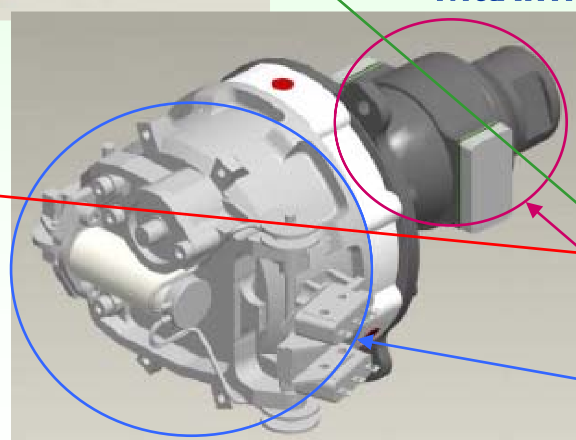
4 Electric Propulsion Subsystem Assembly, Cluster of 3 FEEP thrusters

Cesium FEEP

=> Specific constraints & Electrostatic Discharge risk

- *EPS total mass = 41 kg*
- *Average power ~100 W (@ 30 µN)*
- *Maximum power = 4 x 53 W = 212 W*





EPS:	ESA
EPSA:	ALTA (prime)
PPCU:	Galileo Avionica
NA:	AAS Proel
PMD:	Astrium SAS
LOM:	Contraves Space

Drag free system specs : $3.10^{-10}\ ms^{-2}Hz^{-1/2}$ along 3 axes

$10^{-12}\ ms^{-2}$ @ f_{EP}

Alternate Solutions

Indium FEEP :

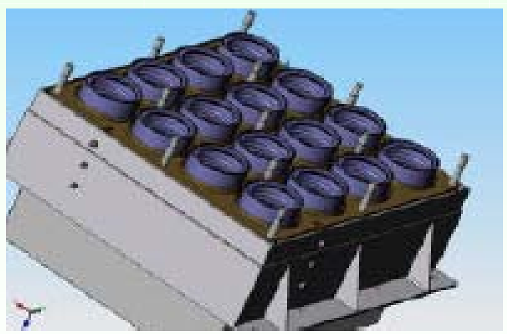
Interest:

- *low interaction with water vapor*
- *tested*

Drawbacks:

limited thrust (50 µN) ⇒ clusters

⇒ weight and power very high for microsatellite



back-up with double solar panels

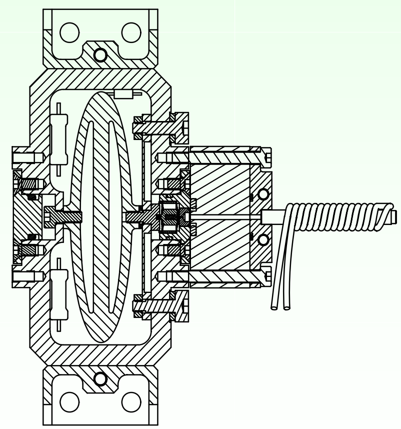
Proportional cold gas thruster :

Interest :

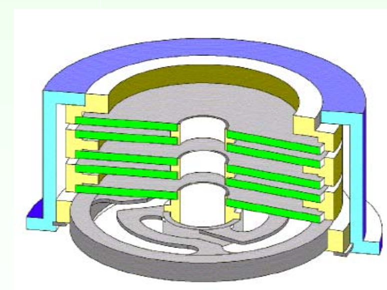
- *relatively simple ⇒ reliability*
- *reduced power consumption 50 W (reduced solar panel area : x 0.6)*

Drawbacks:

small Isp ⇒ mass increase : + 20kg



Marotta UK



AAS (Laben)

Possible back-up

Instrument Description

2 identical instruments cores, Sensor Units (SU) =

2 Electrostatic Differential Accelerometers

Each = 2 Inertial sensors with two concentric masses

2 identical Front End Electronics Units (FEEU)

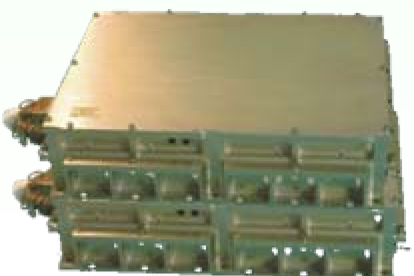
- ***Low noise/ High stability Analog Electronics***
- ***2 X 6 electrostatic channels + measurements***

2 Interface Control Unit (ICU) stacked

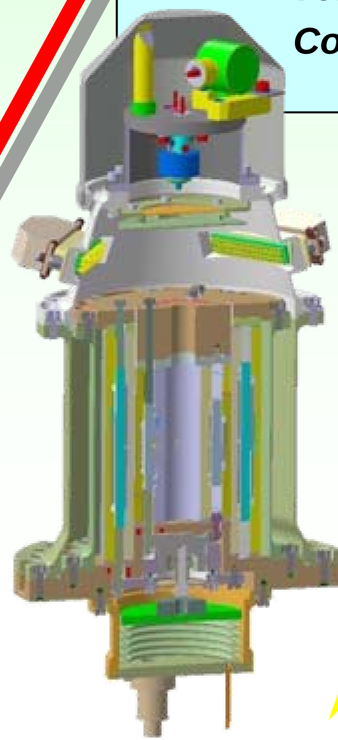
- ***Digital Logics and Electronics 1 DSP + 2 FPGA***
- ***Power Control Unit with very stable secondary voltages (+/-45V, +/-15V,+5V, + 3.3V)***
  Control laws, S/C data bus interfaces

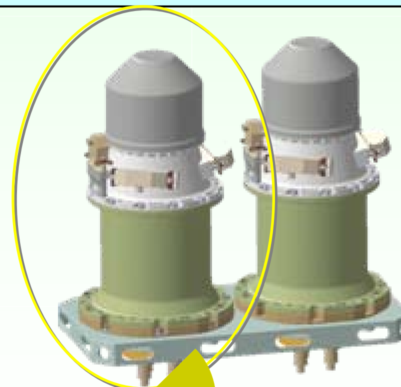
360 x 348 x 180 mm³ x 20kg

274×171×90 mm³ x 3.5kg x 2



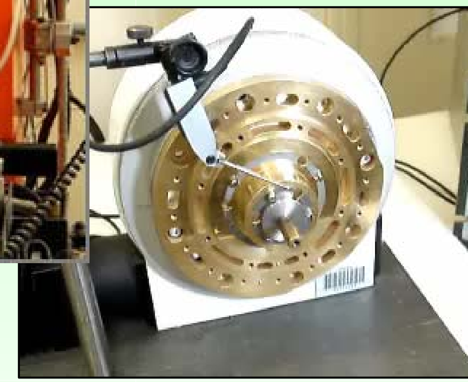
255 x 200 x 110 mm³ x 7kg

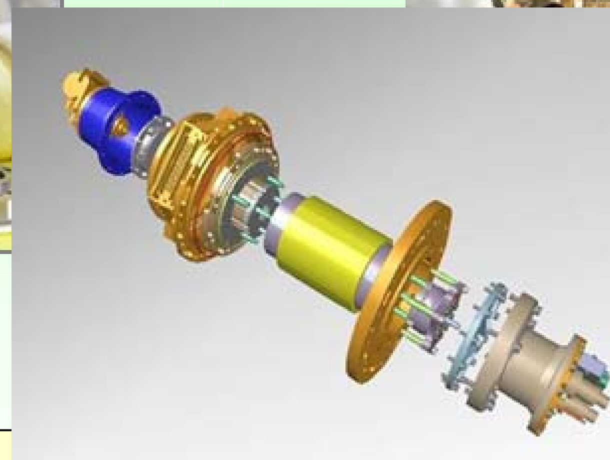




ONERA

Sensor Head Technology

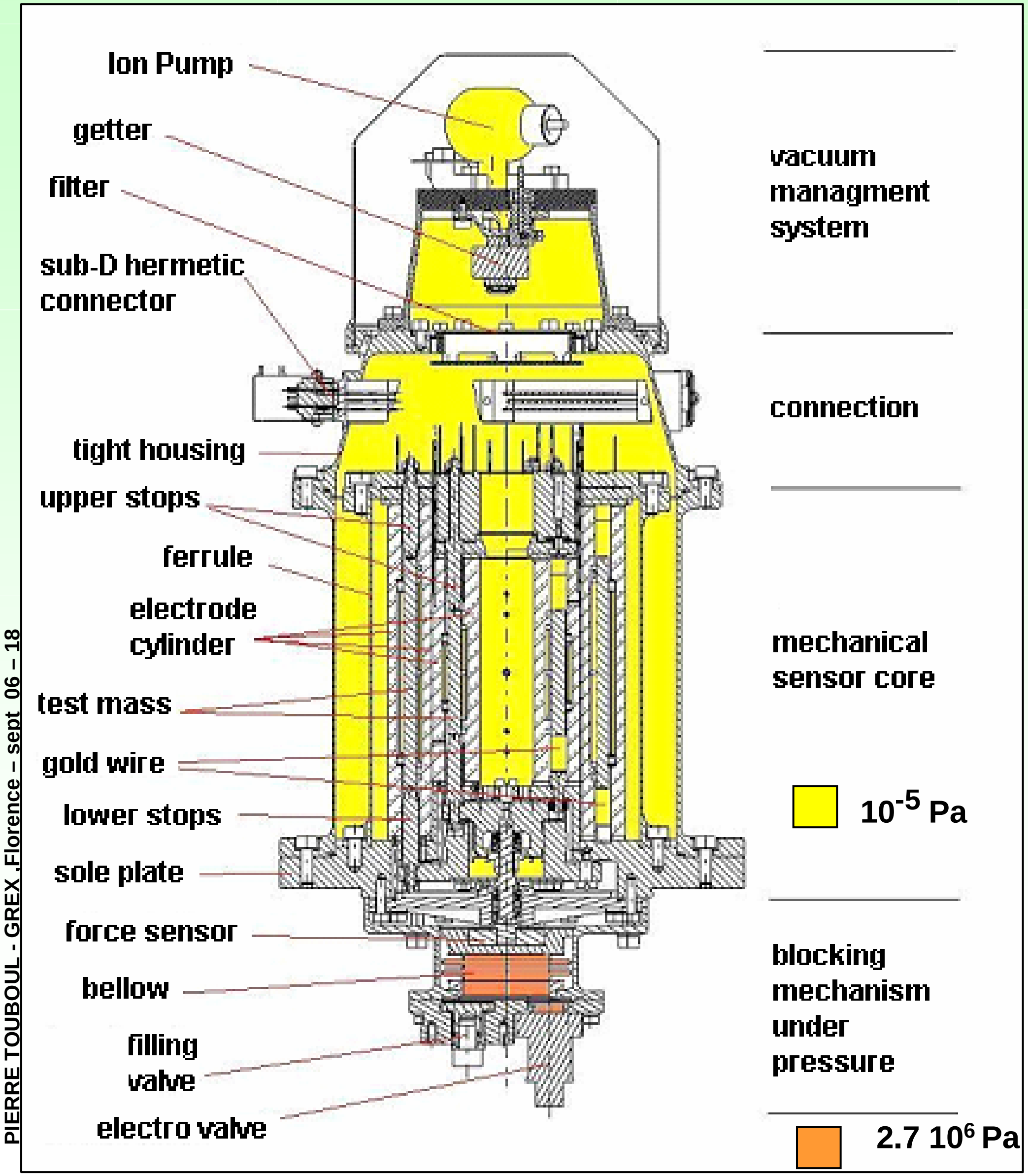




- *SIO_2 material*
- *Optical grinding*
- *Ultrasonic machining*
- *Gold coating by RF diode sputtering*
- *Clean room integration*
- *High vacuum housing and magnetic shielding*

micrometer, arc second accuracies

Sensor Unit



Challenging new technology :

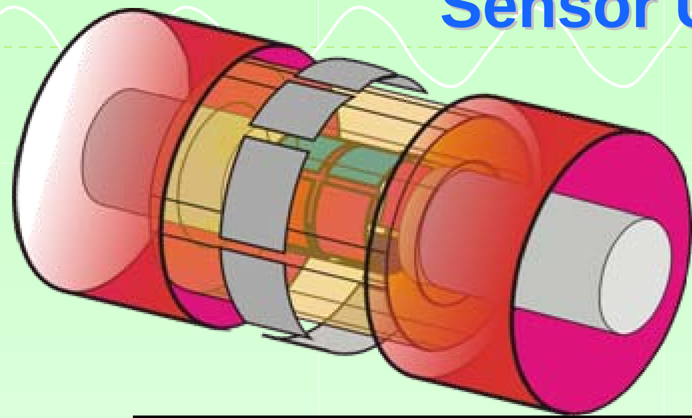
- *Cylindrical Shapes (mass, electrodes)*
- *Accuracy of mass and electrode cylinder geometries*
- *2 concentric sensors & Relative positioning and centering*
- *Ultra-vacuum technology for connectors and gaskets*
- *Blocking mechanism*
- *Integration procedures*

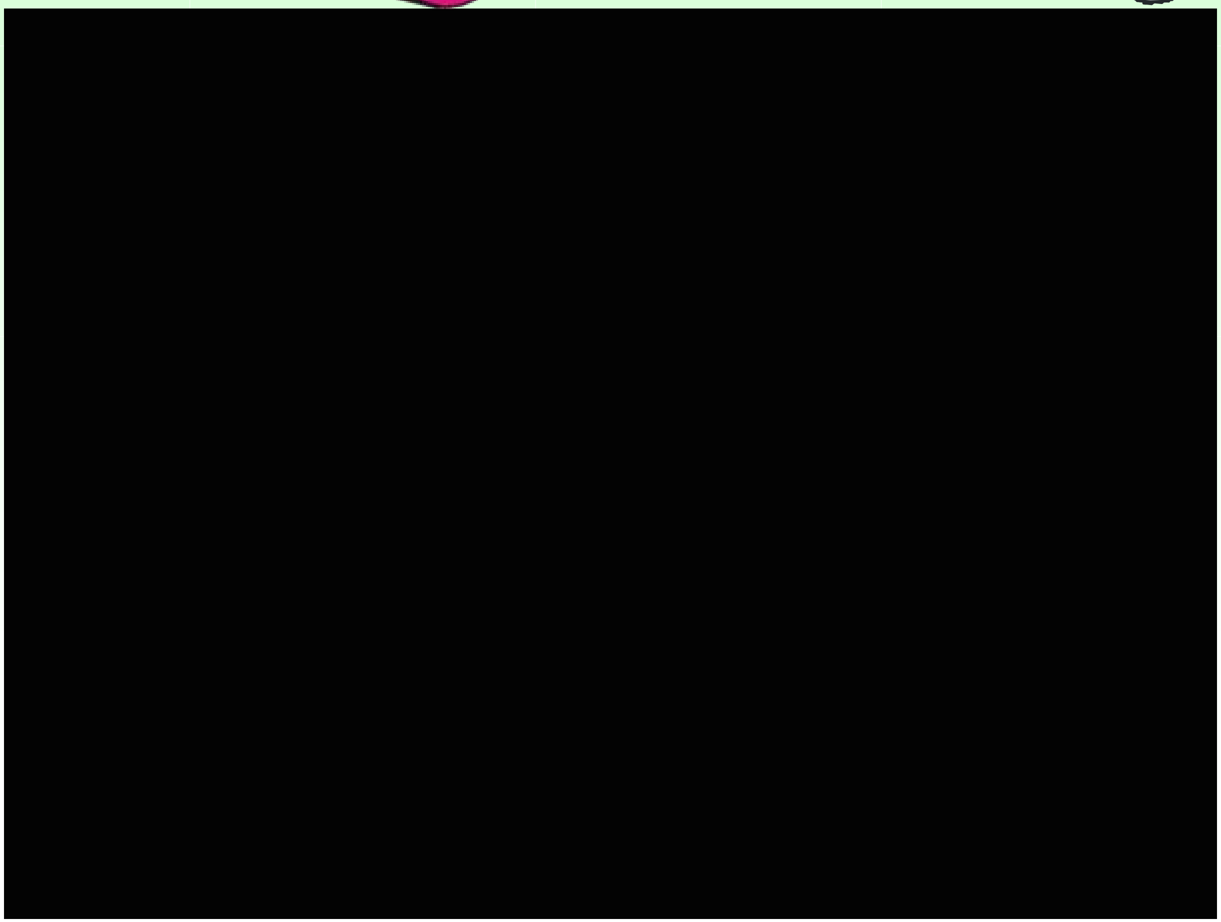
36 x 35 x 18 cm^3

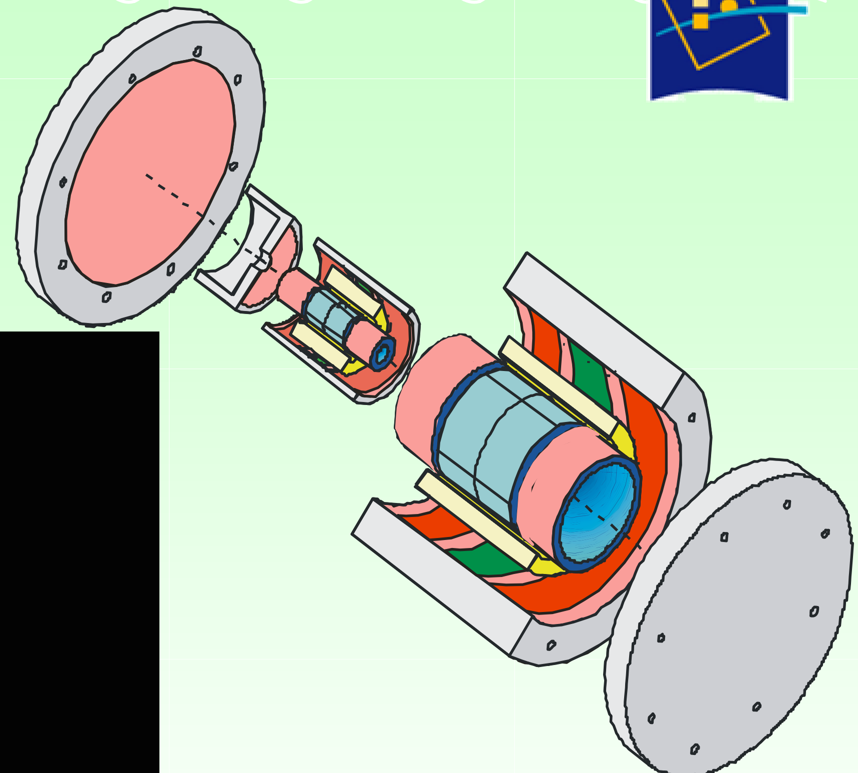
ONERA

PIERRE TOUBOUL - GREX, Florence – sept 06 – 18

Sensor Unit Mechanical Assembly





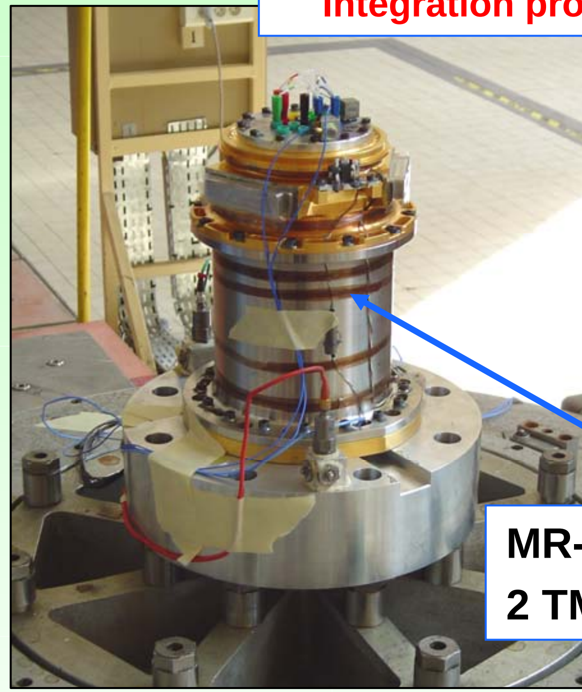


Instrument Development

Vibration tests for design assessment
Integration process development

Lab model : Electronics
- Analog sensing and control
- 300 V to 800 V for 1g levitation

2006

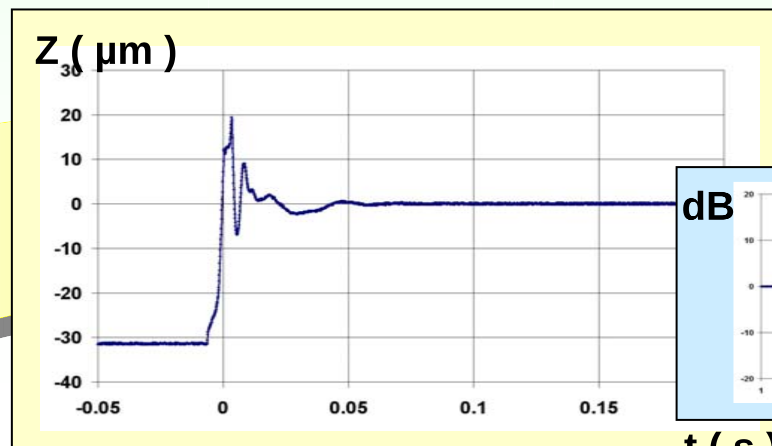


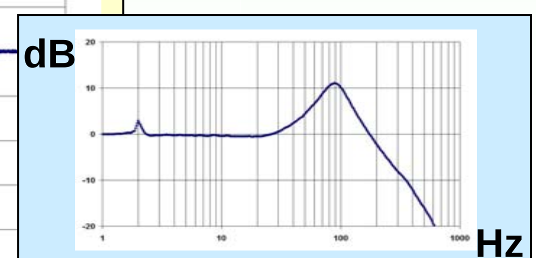
MR-VIB : Sensor core
2 TM in W alloy

Lab model : Sensor core
- 1 test-mass in silica (15g)

Electrostatic control loop for
coupling and stiffness assessment

2004-2008





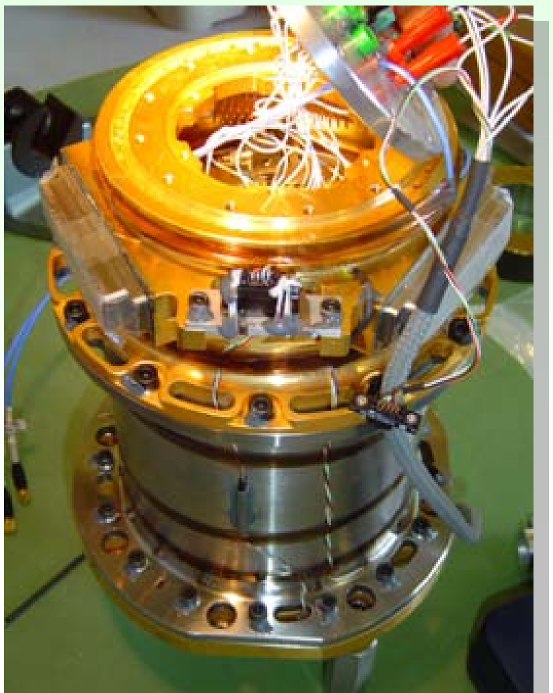
SU Prototype, production

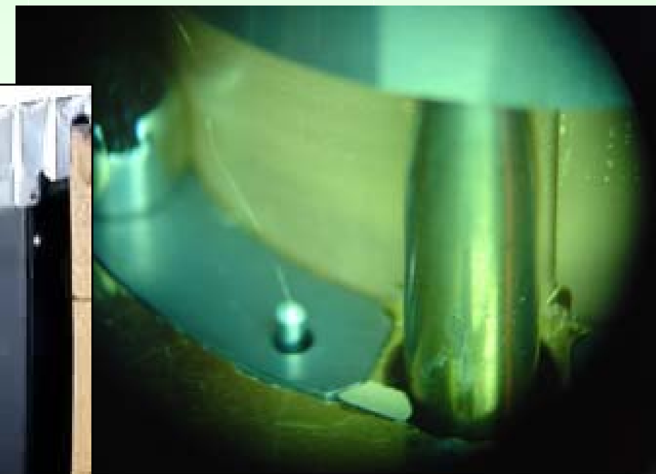
Integration procedures

- *5µm diameter gold wires, implementation.*
- *Silica parts, positioning and alignment.*
- *Blocking forces, adequate.*

Vibrations

- *Resonances identified at specific vibration frequencies (≈ 700 Hz)*
- *Blocking mechanism compatible with the up- dated vibration levels*
- *Blocking mechanism tank successfully tested with over- pressure of 100bars*





ONERA

Front End Electronics Unit

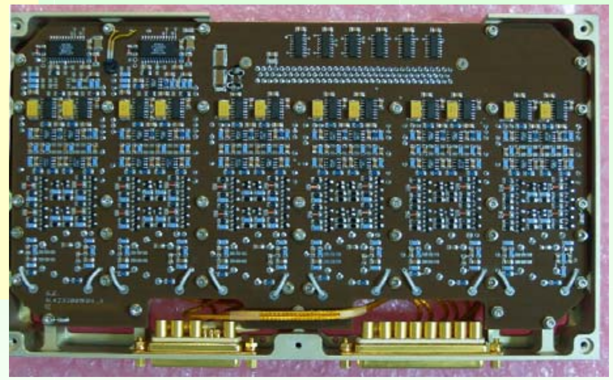
FEEU: accurate analog electronics functions

- ***test mass position sensing***
- ***actuations***
- ***reference voltages generation***
- ***HK data measurement***

Budget :

- ***Volume : 274×171×89.50 mm³***
- ***Mass (EM) : 3.045 kg***
- ***Power : 6.4 W***

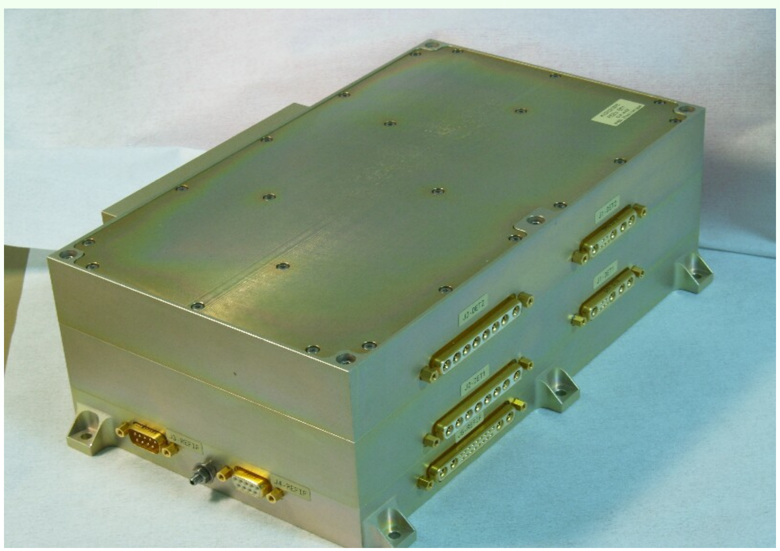
6 capacitive position sensors 5×10^{-19} F/Hz$^{1/2}$



6 pairs of Drive Voltage Amplifiers 2×10^{-7} V/Hz$^{1/2}$

-Reference voltage sources (Vp, Vd)
- Housekeeping data

-Digital interface with ICU (FPGA, drivers)



Performance drivers (1/3)

$$\vec{\Gamma}_{app,k} \approx \frac{\vec{F}_{ng}}{M_I} + \frac{M_g}{M_I}\cdot\vec{g}(O_{sat}) - \frac{m_{gk}}{m_{Ik}}\cdot\vec{g}(O_{sat}) + ([T]-[In])\cdot\overrightarrow{O_k O_{sat}}$$

sensor

$$\vec{\Gamma}_{app,d} = 1/2\cdot\left(\vec{\Gamma}_{app,1} - \vec{\Gamma}_{app,2}\right)$$

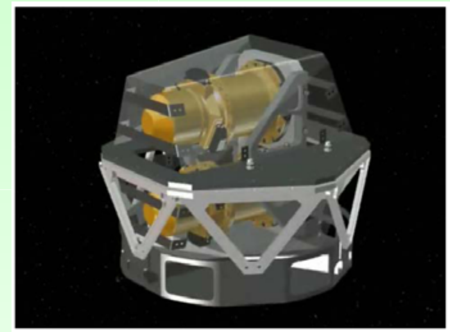
Differential sensor

Gravity gradient

$$\vec{\Gamma}_{app,d} \approx 1/2\cdot\left(\delta\cdot\vec{g}(O_{sat}) + ([T]-[In])\cdot\vec{\Delta}\right)$$

Instrument model

$$\vec{\Gamma}_{meas,k} \approx \vec{K}_{0,k} + M_k\cdot\vec{\Gamma}_{app,k} + \sum_{l=x,y,z}\left(u_l\cdot\left(K_2\cdot\vec{\Gamma}_{app,k}\cdot\vec{\Gamma}^{t}_{app,k}\right)\cdot u_l\right)\cdot u_l + \vec{\Gamma}_{n,k}$$



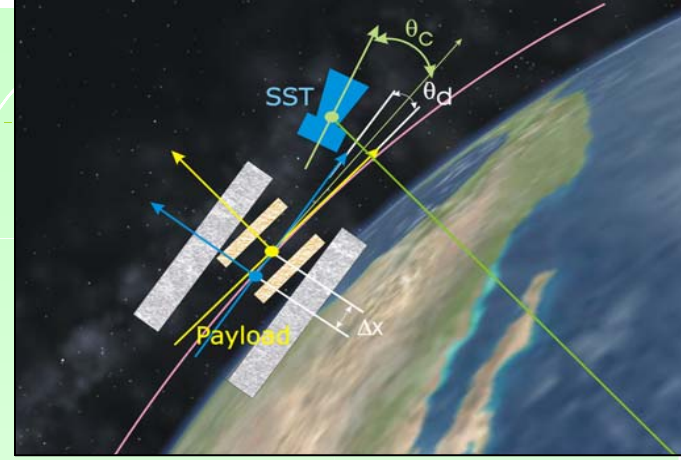
- ***S/C position tracking (Doppler) : < 23m, < 23m, 100m accuracy @ fep***

- ***Attitude Control :***
  - ***Pointing : 10^{-3} rad with variations*** — ***< 24 µrad (inertiel) & 0.4 µrad (spin) @ fep***
  - ***Angular velocity variations*** — ***< 2.5 10^{-9} rad/s (spin) @ fep***
  - ***Angular accelerations variations*** — ***< 2.3 10^{-11} rad/s² (inertial) &1.5 10^{-11} rad/s² (spin) @ fep***

- ***Drag-Free Control : < 3.10^{-10} $ms^{-2}Hz^{-1/2}$ noise and < 10^{-12} ms^{-2} variations @ fep***

Results from definitions and simulations presented at Cnes satellite PDR

Performance drivers (2/3)



$$\vec{\Gamma}_{app,k} \approx \frac{\vec{F}_{ng}}{M_I} + \frac{M_g}{M_I}\cdot\vec{g}(O_{sat}) - \frac{m_{gk}}{m_{Ik}}\cdot\vec{g}(O_{sat}) + ([T]-[In])\cdot\overrightarrow{O_k O_{sat}}$$

$$\vec{\Gamma}_{app,d} = 1/2\cdot\left(\vec{\Gamma}_{app,1} - \vec{\Gamma}_{app,2}\right)$$

$$\Gamma_1 - \Gamma_2 \approx \underbrace{\eta_{EP}\, g}_{\text{EP violation signal}} + \underbrace{\left[\frac{\partial g_k}{\partial x_j}\Delta x_j\right]}_{\text{gravity gradient disturbing terms}} - \underbrace{\left[\Omega\wedge(\Omega\wedge\Delta x) + \dot{\Omega}\wedge\Delta x\right]}_{\text{Attitude motion control}} + \underbrace{[M_d]\Gamma_c}_{\substack{\text{Scale factor matching}\\ \text{TM Alignment matching}\\ \otimes\ \text{Drag Free Control}}} - \underbrace{[I+\theta_c]}_{\substack{\text{Instrument}\\ \text{mis-alignment}\\ \text{wrt SST frame}}}\underbrace{\left[\frac{\partial \hat{g}_k}{\partial x_j}\Delta\hat{x}_j\right]}_{\substack{\text{Earth's gravity gradient and}\\ \text{mis-centring correction}\\ \text{in SST frame}}} \begin{matrix} + bias & + noise \\ + nonlin. & + dynamics \end{matrix}$$

Instrument characteristics and in-orbit calibration :

- ***Resolution :*** ***< 10^{-12}ms^{-2}Hz$^{-1/2}$ and 10^{-9}rads^{-2}Hz$^{-1/2}$***
- ***Stability of sensitivity :*** ***< 6.8 10^{-8} sine (FEEU thermal effect) and 1.2 10^{-5} Hz$^{-1/2}$ @ fep***
- ***SF matching :*** ***< 1.5 10^{-4}***

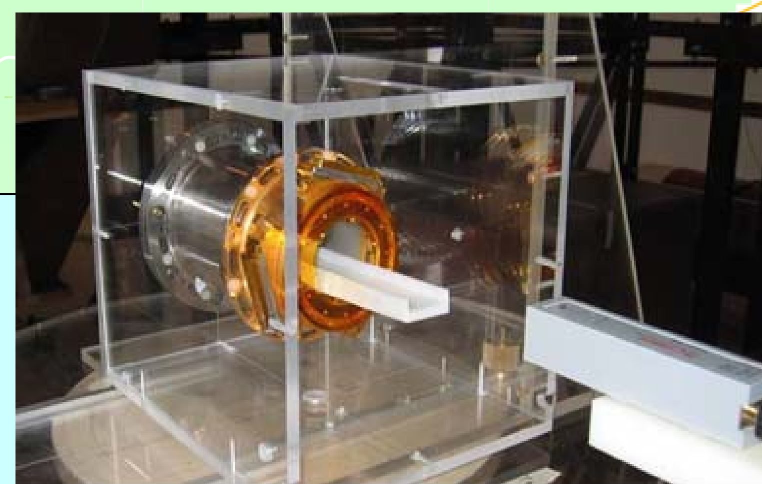
with stability : ***< 0.3 10^{-8} sine (SU thermal effect) and 3.10^{-6} Hz$^{-1/2}$ @ fep***

- ***Alignment matching :*** ***< 5.10^{-5} rad***

with stability : ***<1.5 10^{-9} rad sine (SU thermal effect) and 3.10^{-7}rad Hz$^{-1/2}$ @ fep***

Results from instrument & satellite definitions and simulations presented during instrument & mission PDR

Performance drivers (3/3)



Magnetic property characterized in Cnes lab

Experiment Environment

Magnetic :

- *< 10^{-4} Am² variations @ fep to 0.3 m*
- *Test-mass magnetic susceptibility :*

$$X_{Pt\ alloy} = 2.8\ 10^{-4}\ ;\ X_{Ti\ alloy} = 7.1\ 10^{-5}$$

- *Shield from magnetic field and gradients,*

Obtained through Supranister case & INVAR SU tight housing (Tests realized in CNES and in ONERA lab.)

Self-gravity :

- *Variations of the self-gravity gradient specified < $10^{-11} s^{-2}$*
- *Thermo-mechanics Finite Element Models*

+ Temperature fluctuations → 10 less gradients on the masses

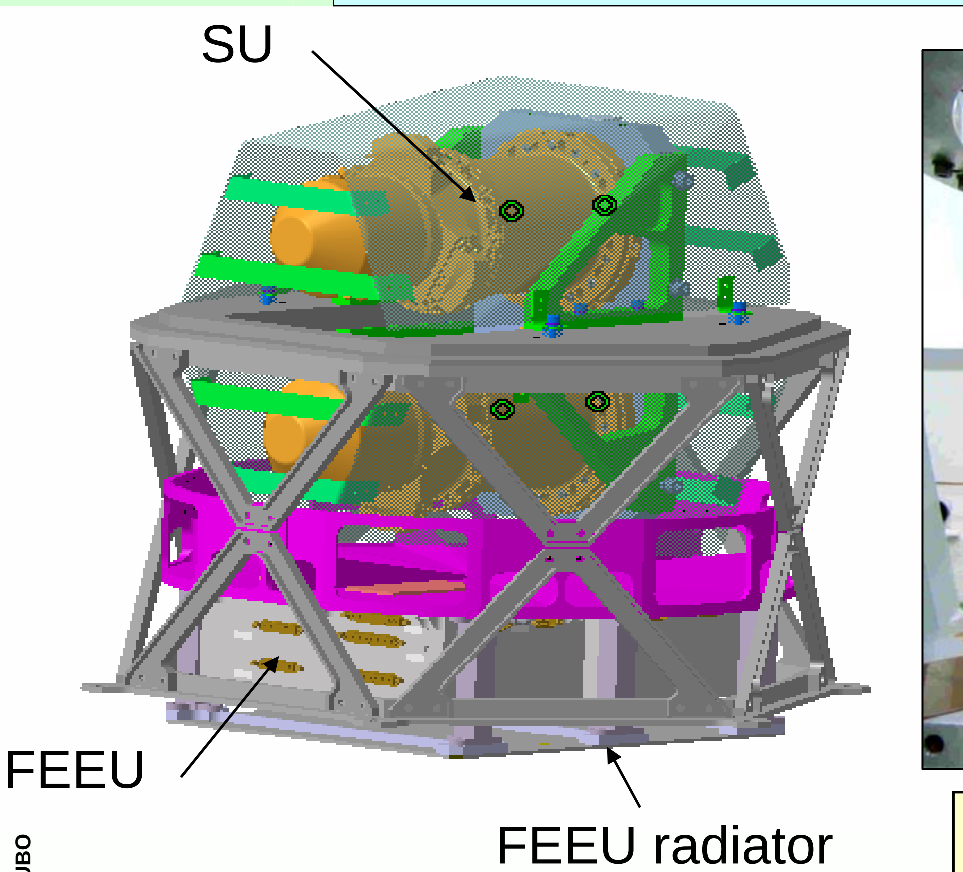
Thermal accommodation :

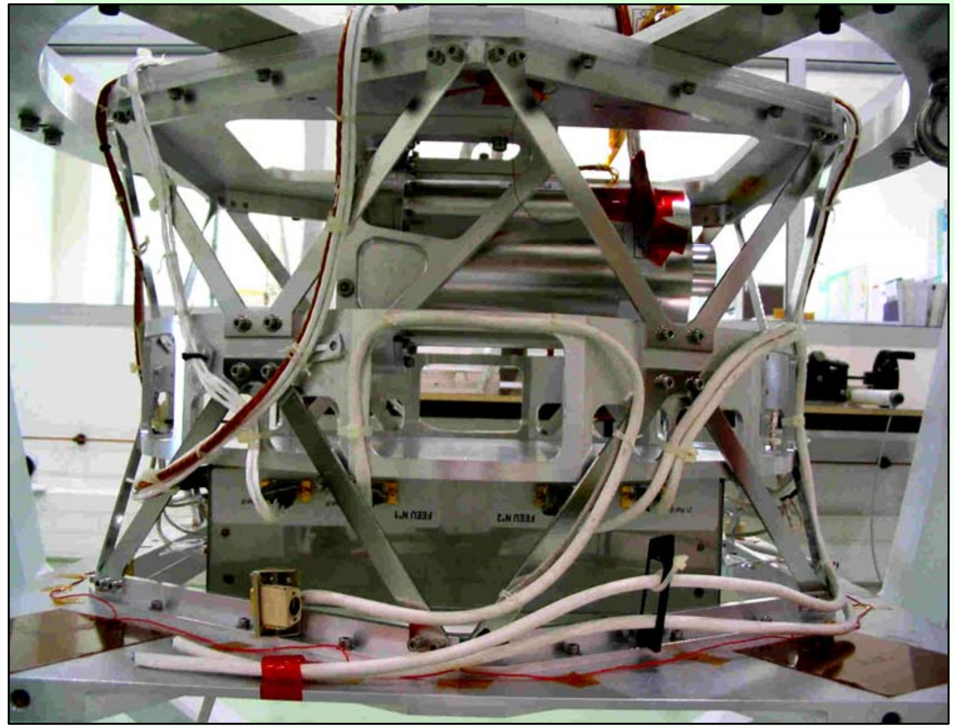
- *1mK @ fep on SU at the unit interface*
- *10mK/m @ fep on SU at the unit interface*
- *10 mK @ fep on FEEU at the unit interface*
- *1 K @ fep on ICU at the unit interface*

Cnes specific facility

Specific double insulation Payload Case for integration in the satellite

Thermal stability of SU & FEEU with passive insulation and anti-Sun radiator





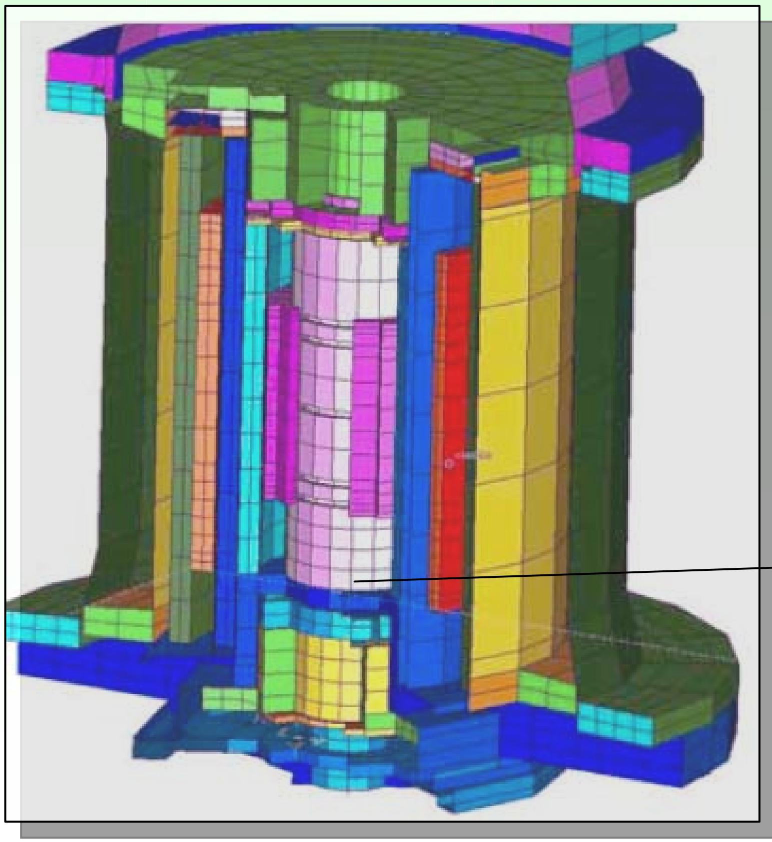
CNES Thermal model being integrated before tests

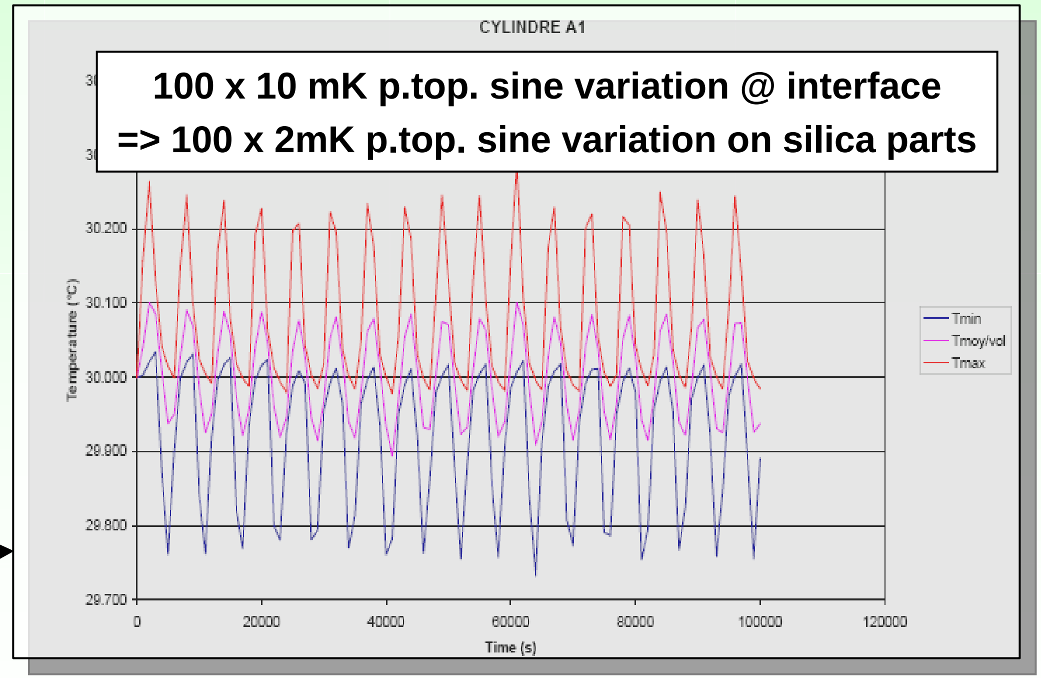
Instrument Thermal Model

From interface Temperature to relevant Temperature :

Photons/Molecules therrmalized on gold coated silica surrounding masses

Temperature filtered out @ f_{EP} by a factor 5





3D finite elements Thermal model

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Temperature fluctuation Impact (SU)

Radiation pressure : **< 3.2 10^{-16} ms^{-2} (worst case* @ fep)**

Difference of forces exerted on each test-mass by photons pressure when temperature difference varies on each side in regards to mass (ΔT_{Si})

$$Pr = \frac{4\sigma}{3c} T^4 \qquad \Gamma_n = \frac{1}{m}\left(P_r \frac{4\Delta T_{Si}}{T}\right)S$$

Radiometer effect : **< 2.2 10^{-16} ms^{-2} (worst case* @ fep)**

Difference of forces exerted on each test-mass by residual gas pressure Pg when temperature difference varies on each side in regards to mass (ΔT_{Si})

$$\Gamma_n = \frac{1}{m}\left(P_g \frac{\Delta T_{Si}}{T}\right)S$$

Outgassing : **< 2.5 10^{-17} ms^{-2} (worst case* @ fep)**

Difference of forces exerted on each test-mass by variation of gaz pressure ΔPg induced by the outgassing of the gold coated silica parts

$$\Delta P_g \propto \frac{\Delta \mathrm{grad}T_{Si}}{T^2} \qquad \Gamma_n = \frac{1}{m}\Delta P_g S$$

Gold Wire stiffness : **thermal stability < 1.7 10^{-15} ms^{-2} (worst case @ fep)**

Electrical link between mass and Voltage Reference : 5µm ϕ wire when temperature varies, Young Modulus varies

$$\Gamma_n = \frac{1}{m} k_{wire}\, x_0 \left(\frac{1}{E}\frac{\partial E}{\partial T}\right)\Delta T_{Si}$$

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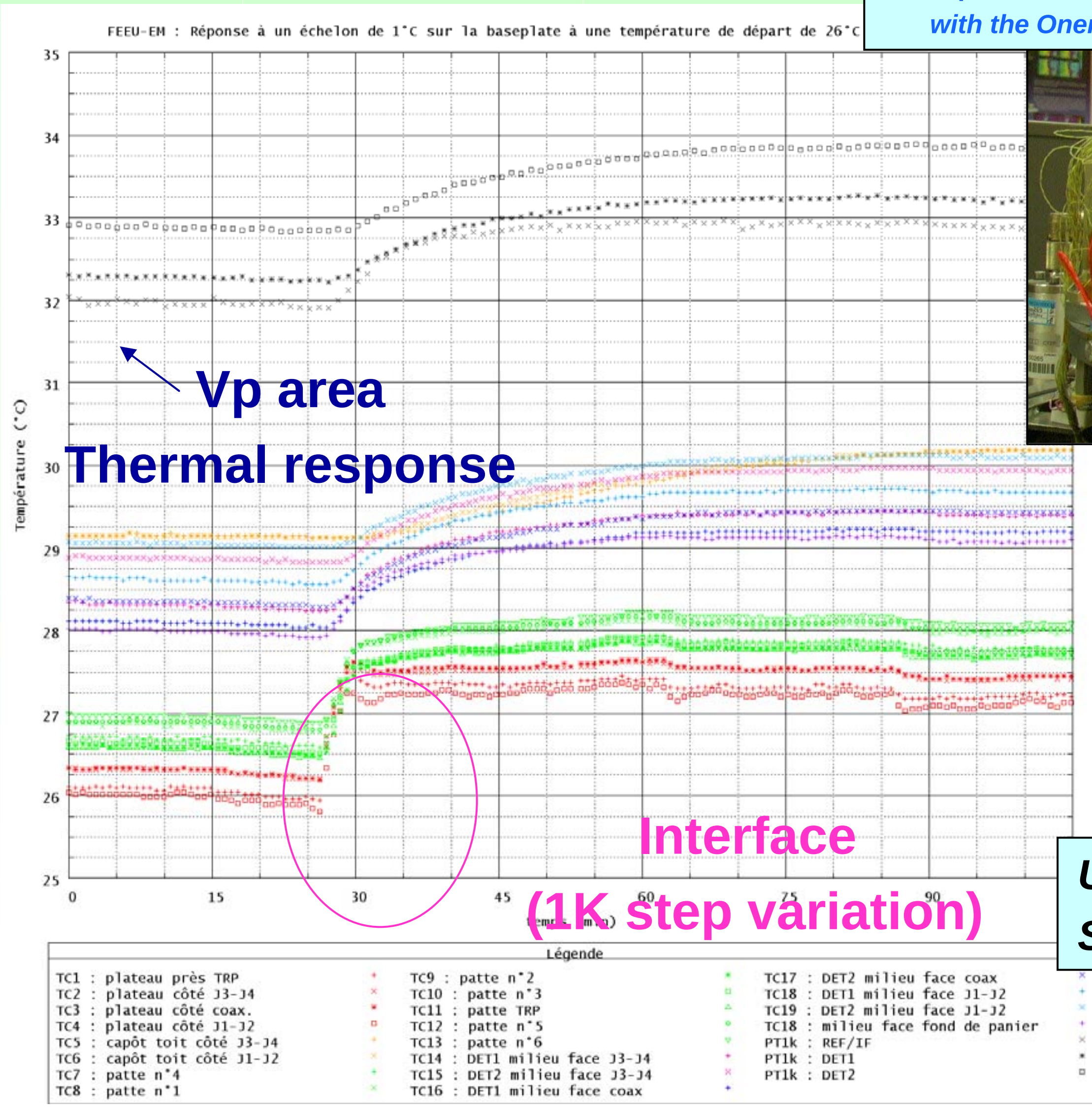
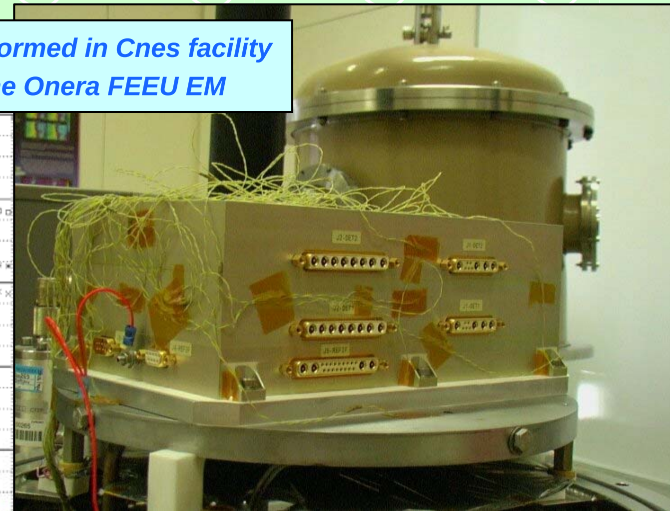
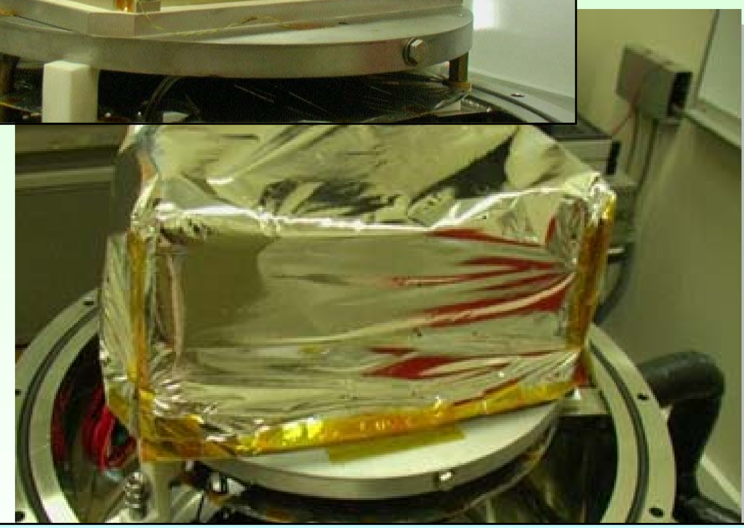
*Worst case *: lower density mass & inertial pointing (lower f_{EP}, thus less thermal filtering)*

FEEU THERMAL VACUUM TESTS



Tests performed in Cnes facility with the Onera FEEU EM





Unit Power consumption fluctuations
Spec : < 5 mW @ fep ; Verified : <3 mW

Thermal Filtering focused on Vp reference voltage: factor 2 expected

Temperature Fluctuation Impact :major effects

Electrostatic stiffness & bias force :

Thermal stability < 1.8 10^{-15} + 1.10^{-15} ms^{-2} (worst case @ fep)

- ***Bias due to geometrical dissymetry (Cylindricity, electrode geometry,…) or to electrical dissymmetry (capacitive sensor position offset $\Delta_{CSoffset}$, …)***

$$\Delta Bias \approx A_{geometry}\left[\frac{\Delta_{cylind}}{gap}\right]\frac{\partial\left(V_p^2+V_d^2\right)}{\partial T}\Delta T_{FEEU}$$

$$\Delta Bias \approx \underbrace{\left(\frac{\partial\omega_{elec}^2}{\partial T}\right)\Delta T_{FEEU}}_{\text{Electrostatic stiffness variations}}\Delta_{CSoffset}$$

Scale factor stability :

< 6.5 10^{-6} K^{-1} , effect depending on S/C drag compensation system performance

- ***Due to Vp stability (40µV/K) and to ADC reference source stability (30µV/K)***
- ***Interest of thermal insulation of these circuits wrt unit interface***
- ***Interest of regulated power line and steady power consumption***

$$\left(\frac{\partial V_p}{\partial T}\right) = 40\mu V / K$$

Thermal variations mainly due to Reference Voltage source :

being improved by an expected factor 4 with up-dated components

Mission Performances :

Rotating satellite session : $f_{EP} = (\Pi+3/2)\, f_{orb} \sim 8 . 10^{-4} Hz$

- ***More than 70 error terms taken into account :***
  - *Bias : 18, noise : 17, sf : 1*
  - *Temperature sensitivity : 30 + 3 ; thermal gradient sensitivity : 3*
  - *Magnetism : 2*
- **Major terms**

Random	$ms^{-2}/Hz^{1/2}$
Coriolis (differential mode)	5.12 E-13
PM Motion (differential mode)	3.11 E-13
Accelerometer measurement noise	1.34 E-12
Bias sensitivity to thermal gradient variation	3.75 E-13

Invar thermal fluctuations
Positioning Instabilities
Mass Damping
Radiation & Radiometer

Tone @ fep	ms^{-2}
Coriolis (differential mode)	1.71 E-15
PM motion (differential mode)	1.04 E-15
PM position (differential mode)	8.68 E-16
Bias sensitivity to thermal gradient variation	1.25 E-15

Invar thermal fluctuations
Positioning Instabilities
$[T-\Omega^2]$
Radiation & Radiometer

- ***Budget***

Total random errors : $B = 1.6\ 10^{-12}\ ms^{-2}/Hz^{-1/2}$
integration duration : T_i = 20 orbits @ h = 730km
4 major tone errors : $D = 4.9\ 10^{-15}\ ms^{-2}$
($D = 2.5\ 10^{-15}\ ms^{-2}$ with quad. sum)

$$\eta = \frac{\sqrt{D^2 + \frac{B^2}{T_i}}}{g(H)} = 0.9\times10^{-15}$$

Value compatible with the specification : 1×10^{-15} per session
At least 50 sessions during the 1 year mission

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Conclusion

Payload & Satellite definition achieved

PDRs conclude with no mission stopping items
but 6-12 months needed more to assess FEEP or other solution,

Instrument :

SU definition can be still optimized :

for resistance to vibration : ***according to selected launcher requirements***

for thermal stability : ***SU Temp. gradient can be improved***
& ref. voltage source can be more thermally insulated

Error analysis to be completed with experimental results
and correlation analysis

End 2006 : Payload key point before QM production

2007 : QM production & tests

2008 : FM production & tests

2009 : FM qualification & delivery

End 2006 : Mission Performance key point

Mid 07 : Propulsion System Review

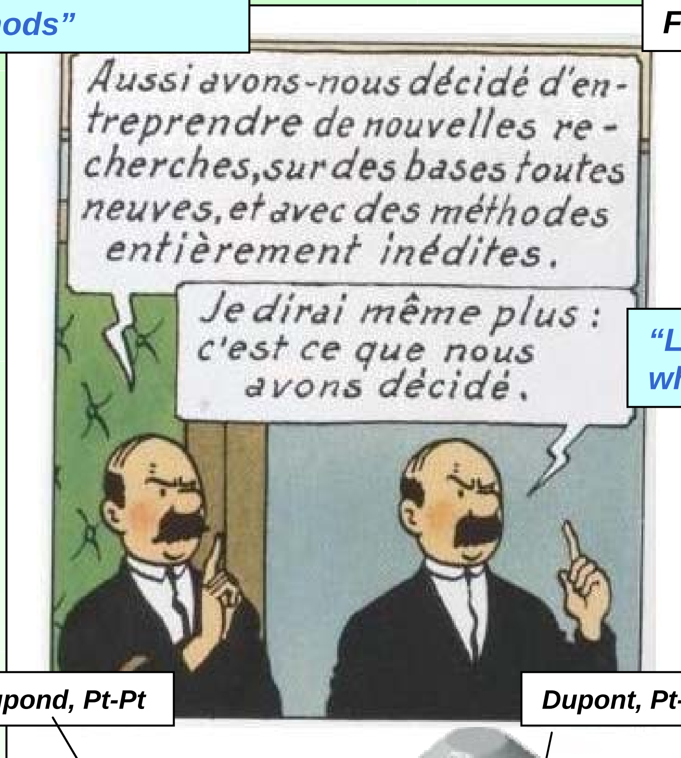
2007, 2009 : satellite development

Launch date :

2009-2010 depending on Propulsion System delivery

“So, we have decided to undertake new researches, on new basis and with original methods”

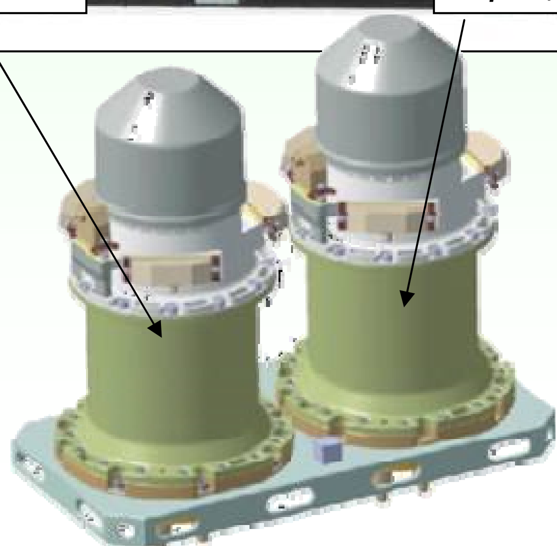
From Hergé



“Let me add more : this is what we have decided”

Dupond, Pt-Pt

Dupont, Pt-Ti



Thanks,

Questions ?

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Acknowledgments to Cnes, OCA, ZARM and Onera teams

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