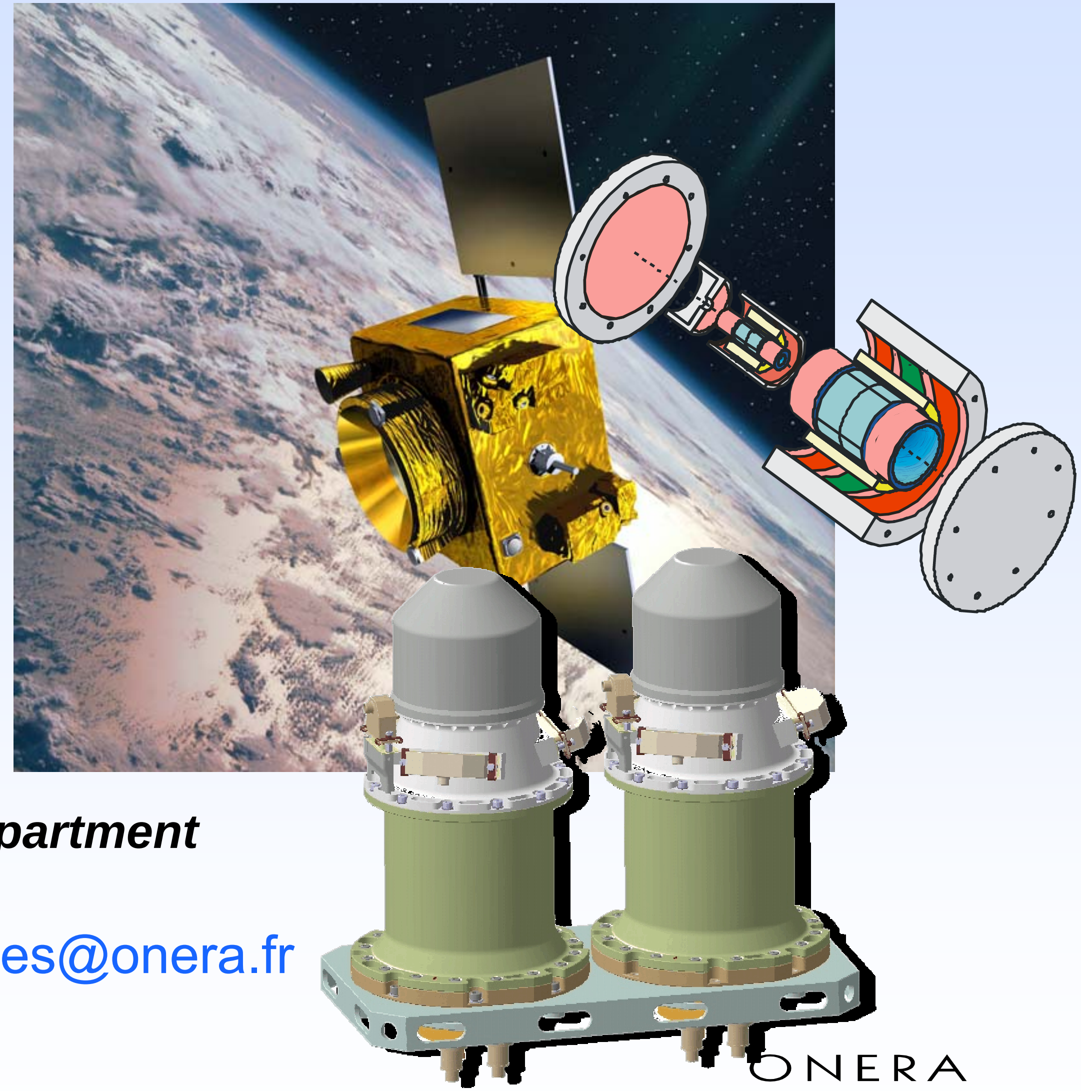
GREX 2004 : NICE 27 - 29 octobre 2004

MICROSCOPE

MISSION & INSTRUMENT



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ZARM Bremen	**H. Dittus (Co-I), H. Selig, S. Theil**
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ESA	**D. Nicolini**

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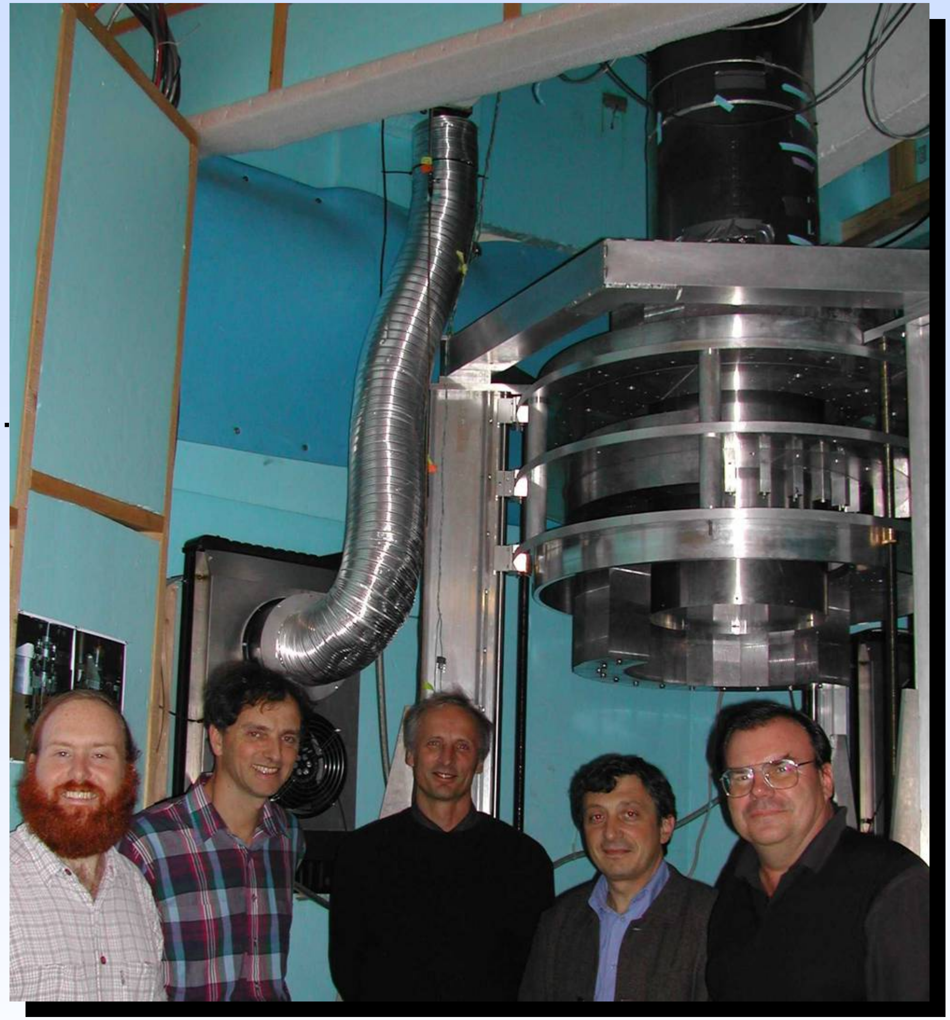
Testing the EP on ground



From Eötvös Experiment To:

- **In laboratory:**
  - Baessler S., Heckel B. , Alderberger E., Gundlach J.,…
  - Eotwash project : Torsion pendulum
  - *Washington State University*

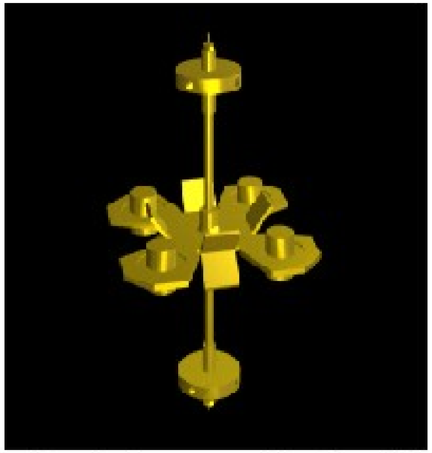
$$\left\langle \left[\frac{M_G}{M_I}\right]_E - \left[\frac{M_G}{M_I}\right]_M \right\rangle_{wep} = (0.1 \pm 4.4)\times 10^{-13}$$

$$\left[a_{Earth} + a_{Moon}\right]/2 = 5.93\times 10^{-3}\,ms^{-2} \quad \text{(toward the Sun)}$$

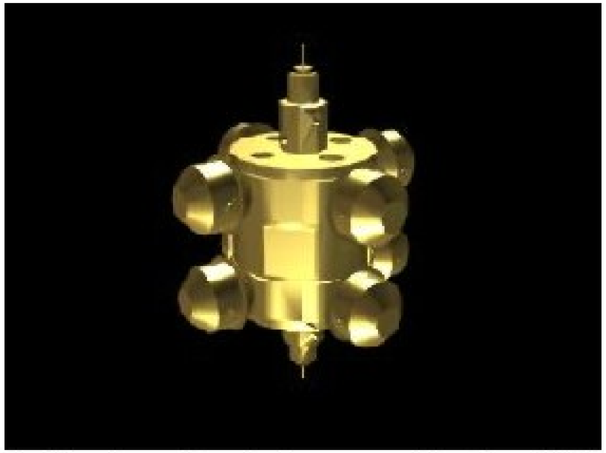
Ref:
Short-range tests of the equivalence principle
G. L. Smith, C. D. Hoyle, J. H. Gundlach, E. G. Adelberger, B. R. Heckel, and H. E. Swanson
Department of Physics, University of Washington, Seattle, Washington 98195
PHYSICAL REVIEW D, VOLUME 61, 022001

Testing the EP on ground

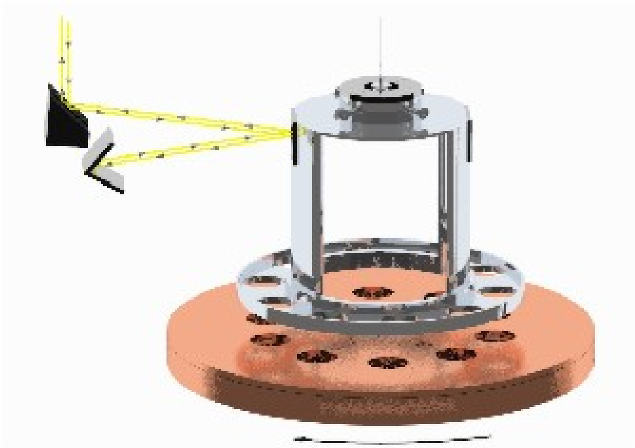
- Eotwash project : Torsion pendulum - *Washington State University*



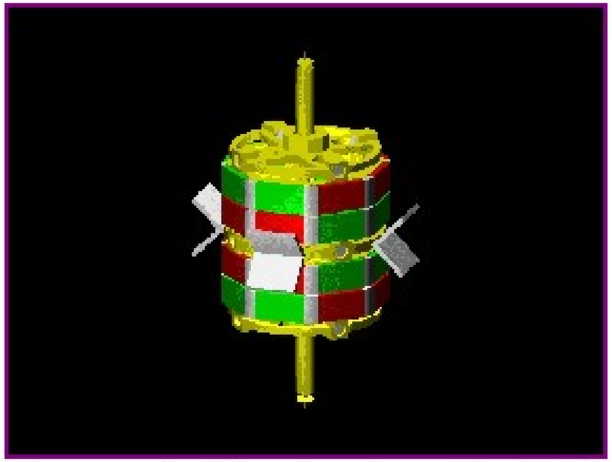
Torsion Pendulum used in the Rot-Wash Instrument



8-Body Torsion Pendulum used in the Eöt-Wash III Instrument

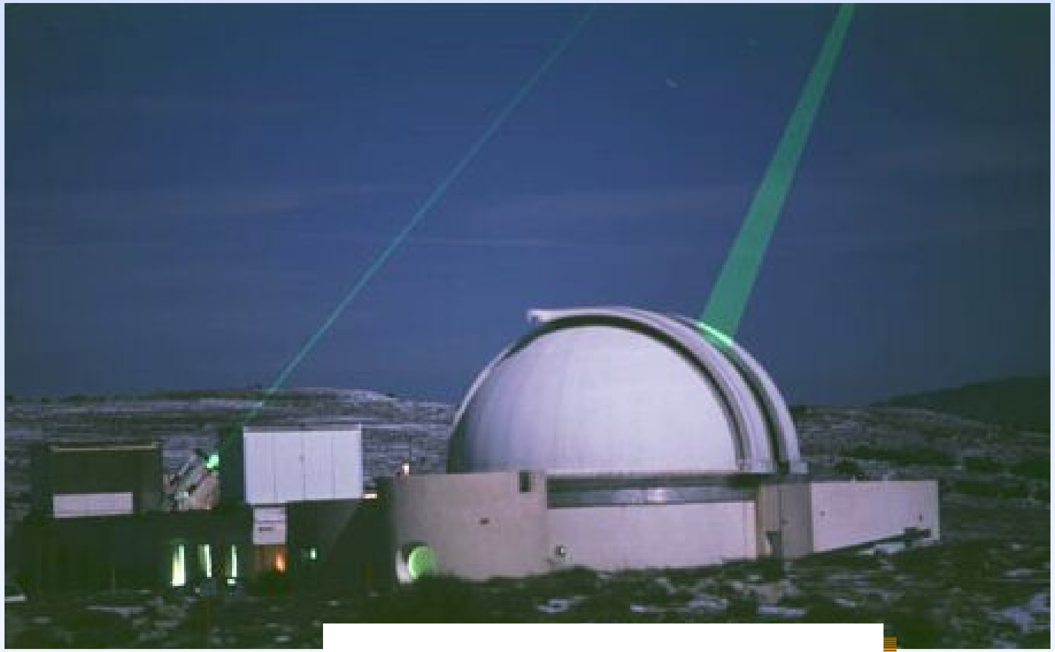


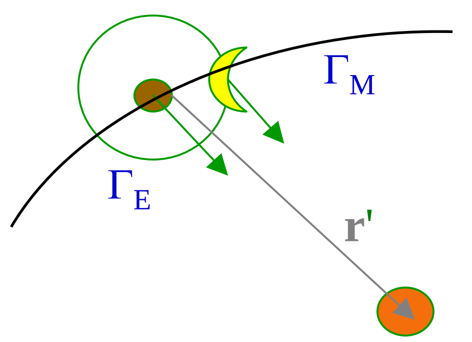
Torsion pendulum and attractor used in the short-range experiments



Pendulum, containing about a mole of polarized electrons, used to search for spin-coupled forces

EP Test by Moon Laser Telemetry





From Mercury perihelion advance to :

Parameters of the experiment

- Laser pulse 100ps
- 1 photon back out of 10^{20} emitted
- 1 photon back every 100 pulses

Results

Post-Newtonian parameters:

$$\beta - 1 = -0.001 \pm 0.004$$

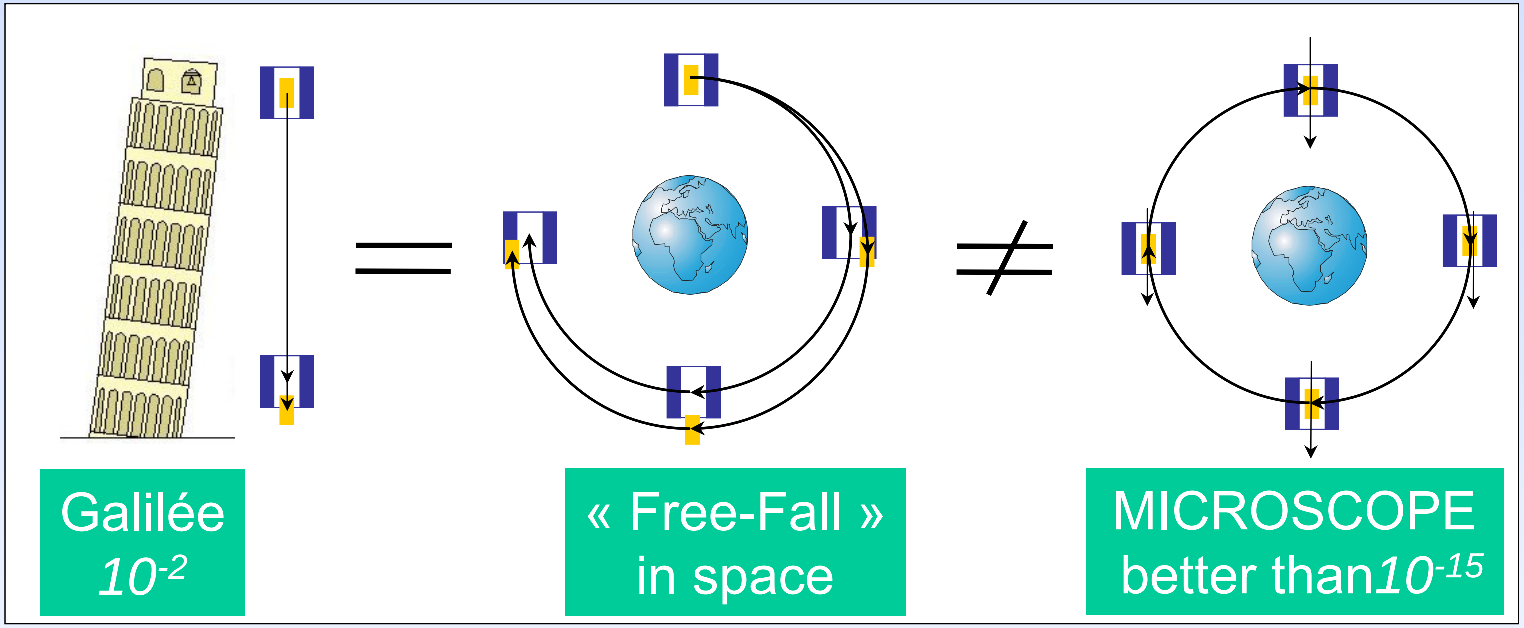
$$\gamma - 1 = \quad 0.002 \pm 0.004$$

- EP test from 20 years measurements:

$$\delta = \left[\frac{M_G}{M_I}\right]_{Earth} - \left[\frac{M_G}{M_I}\right]_{Moon} = (-1 \pm 2) \times 10^{-13}$$

- Expected accuracy in 2010: $5\ 10^{-14}$

Testing EP in space



Space Laboratory = S/C in orbital motion, “quite” in free fall

- Drag free system and fine attitude control demanded
- S/C : to protect from radiation pressures and residual drag the masses & to carry the measuring device and facilities

Difference of orbital trajectory :

- Measured by ultrasensitive detectors (SQUIDS, capacitive, optical …)
- Necessary « weak » springs to S/C (electrostatic, magnetic, mechanic)
- Non steady configuration

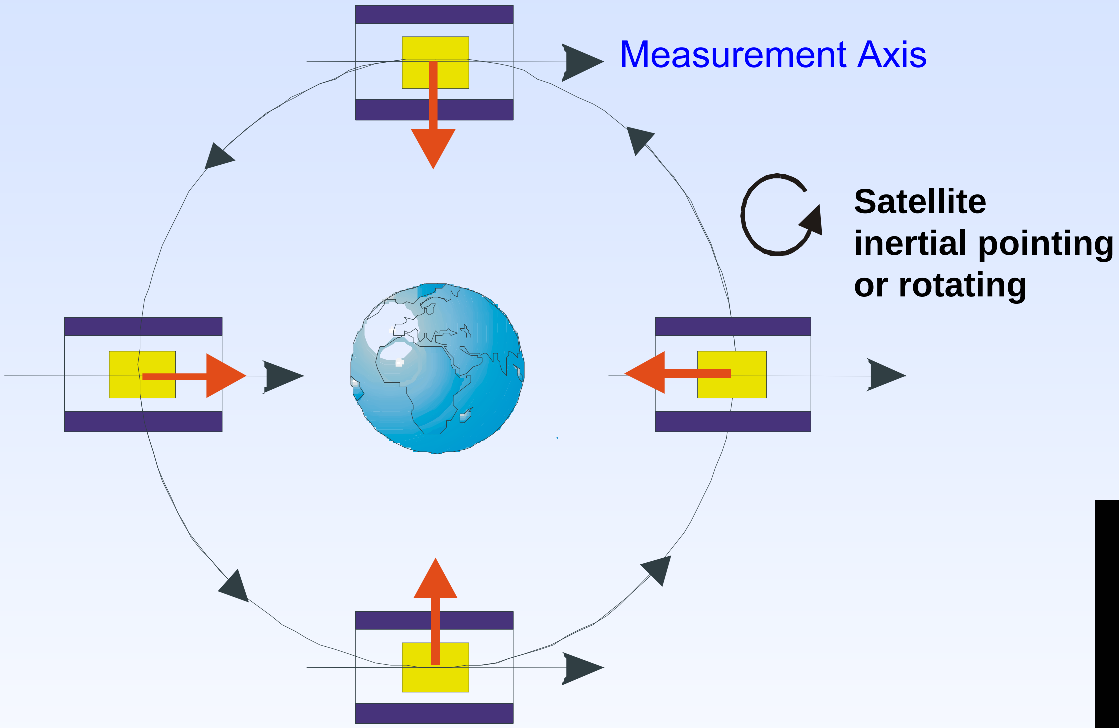
Difference of necessary force to equalize the trajectories

- Electrostatic servo-controlled system to maintain motionless the masses
- Stable and symmetric configuration => defect of symmetry = EP violation

Equivalence Principle Test in Space

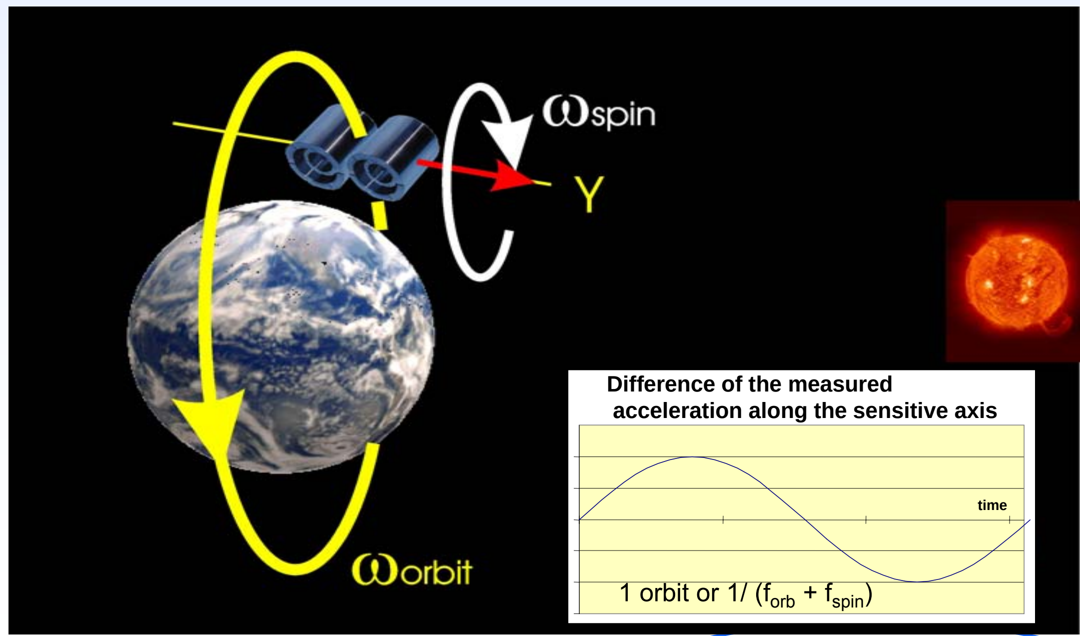
MICROSCOPE

- Gravitational Source : The Earth
- Inertiel Acceleration : Orbital Motion
- Control of the 2 masses on the same orbit with electrostatic pressure (< 10^{-11}m)
- Test duration : not limited by free-fall duration (> n times 20 orbits ~1.2 10^{5}s)
- Spatial environment : reduced or controled disturbances, drag free satellite
- Signal to be detected : well known phase and frequency signal



Material 1 (Pt)

Material 2 (Ti)



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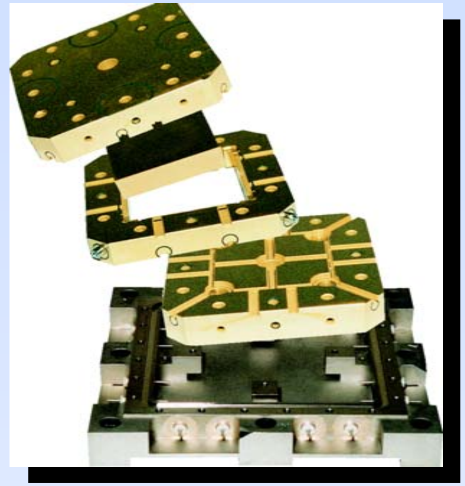
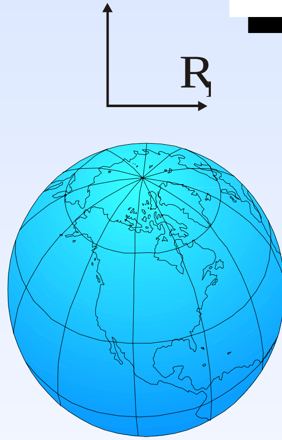
MICROSCOPE APPROACH

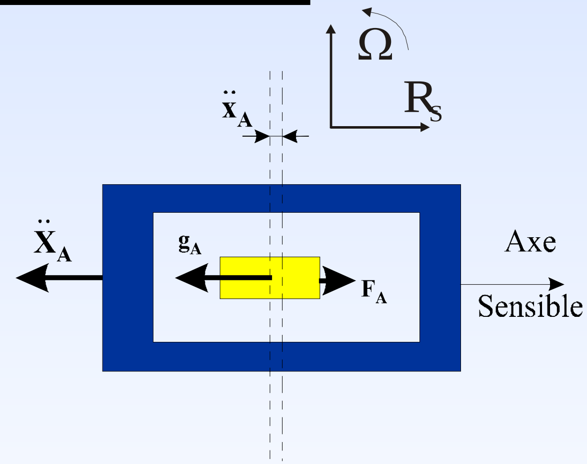
- Opportunity of Micro satellite (100- 200 kg) mission
- Necessity of limited development & cost



→ **Payload case : < 40 kg, 40 W**
Room temperature operation

→ **Take advantage of existing space electrostatic accelerometers : configuration to be optimized**





EP Test-mass =	Cylindric Proof-mass of electrostatic inertial sensor

One Differential accelerometer = 2 inertial sensors with 2 concentric test-masses

When the 2 masses have different composition	=	EP Test
When the 2 masses have same composition	=	Test accuracy verification

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EP Test Mission Principle

Accelerometer A Output:

$$\frac{\hat{F}_A}{m_{I_A}} = (I + K_A)F_A + E(F_A) + E_{n_A}$$

Difference of 2 inertial sensor measurements:

$$
\begin{aligned}
\frac{\hat{F}_A}{m_{I_A}} - \frac{\hat{F}_B}{m_{I_B}} \approx\ & (K_A - K_B)\frac{\ddot{X}_A + \ddot{X}_B}{2} \\
& + \left(\mathring{\mathring{X}}_A + \mathring{\mathring{x}}_A - \mathring{\mathring{X}}_B - \mathring{\mathring{x}}_B\right) + 2\Omega\left(\mathring{X}_A + \mathring{x}_A - \mathring{X}_B - \mathring{x}_B\right) \\
& + \left(\Omega \times \Omega + \dot{\Omega}\right)\left(X_A + x_A - X_B - x_B\right) \\
& - \left(\frac{m_{g_A}}{m_{I_A}} + \frac{m_{g_B}}{m_{I_B}}\right)\left(\frac{g_A - g_B}{2}\right)\left(I + \frac{K_A + K_B}{2}\right) \\
& + \left(\frac{F_{p_A}}{m_{I_A}} - \frac{F_{p_B}}{m_{I_B}}\right) \\
& + \left(\frac{m_{g_A}}{m_{I_A}} - \frac{m_{g_B}}{m_{I_B}}\right)\left(\frac{g_A + g_B}{2}\right)\left(I + \frac{K_A + K_B}{2}\right) \\
& + E(F_A) - E(F_B) + E_{n_A} - E_{n_B}
\end{aligned}
$$

- ***(1) Common mode acceleration***
  Scale factor matching ~ 3×10^{-4}, Satellite drag-free control $3\ 10^{-10}\ ms^{-2}\ Hz^{-1/2}$
  Instrument structure stability (silica), Thermal control
- ***(2) Proof-mass relative motion structure stability & electrostatic control***
  Servo-loop control : electronics performance,
  Structural & Thermal Stability, Attitude Control
- ***(3) Satellite attitude motion***
  Attitude control / proof-mass positioning 20 µm ⇒ 0.1 µm
- ***(4) Difference of Gravity field effects***
  S/C stiffness and thermo-elastic behavior, Earth gravity gradient filtered out
- ***(5) Non gravitational acceleration***
  Mass motion disturbances & forces on the mass,
  Actuator noise & sensing back-action
- ***Signal representative of EP violation***
- ***(6) Instrument (non-linearity & noise)***
  Non linearity & Measurement electronics noise

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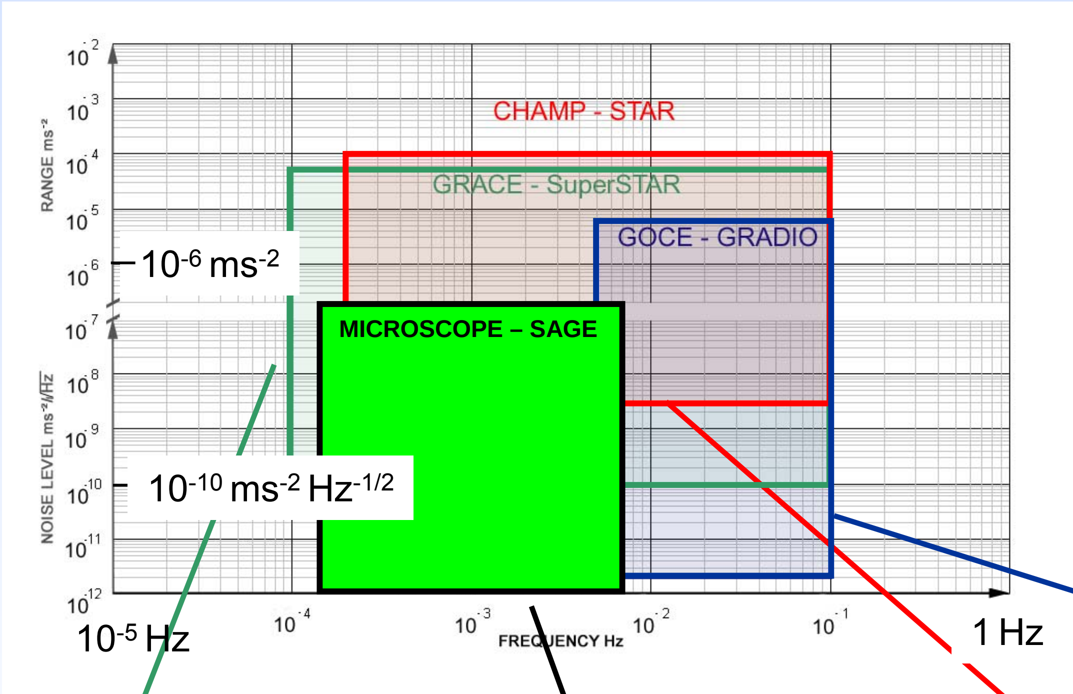
Differences between Accelerometers from STAR, SuperSTAR, GRADIO to SAGE



SAGE

Space Accelerometer for Gravitation Experience

Same concept & technology but
- Optimised core design
- Digital control loop
- Better control of the environment
- Frequency bandwidth

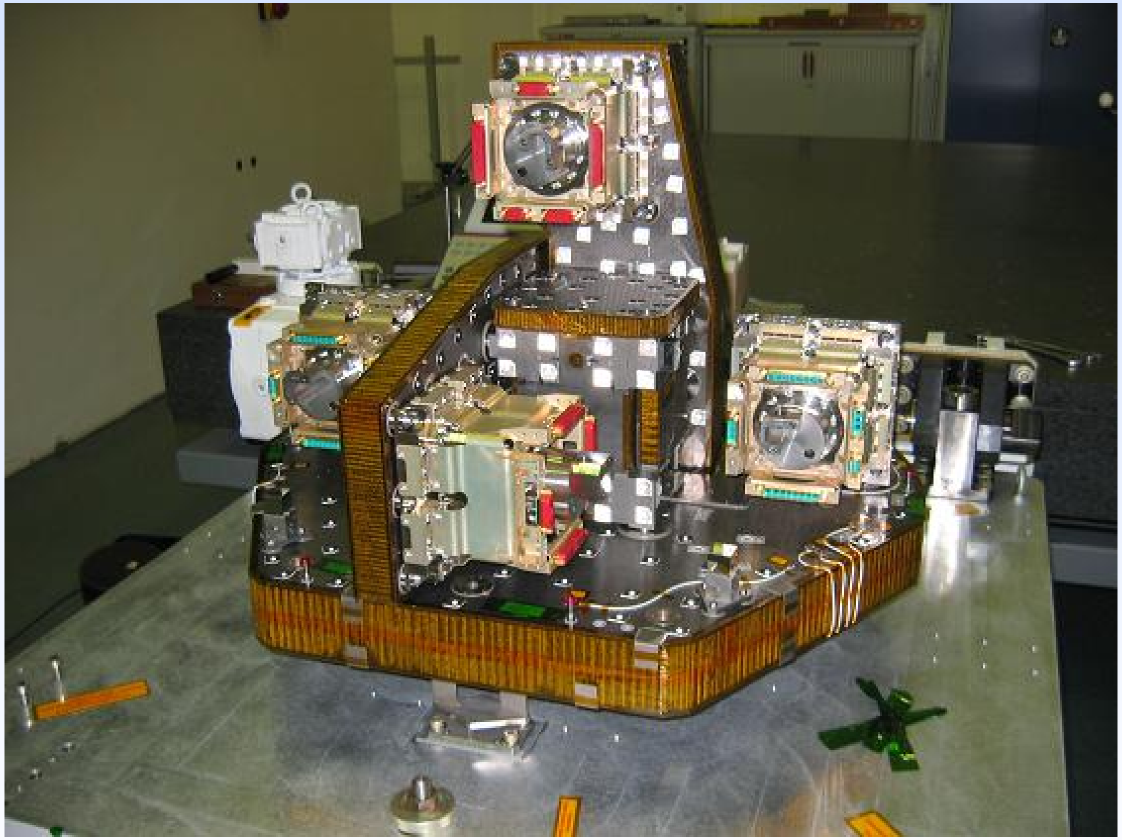
- Γ_n : $3 \cdot 10^{-9}$ ms^{-2} /Hz$^{1/2}$
- Γ_{max} : 10^{-4} ms^{-2}
- [$2 \cdot 10^{-4}$; 10^{-1}]Hz

- Γ_n : 10^{-12} ms^{-2} /Hz$^{1/2}$
- Γ_{max} : $2.5\ 10^{-7}$ ms^{-2}
- [10^{-4}; $5\ 10^{-3}$]Hz

- Γ_n : 10^{-10} ms^{-2} /Hz$^{1/2}$
- Γ_{max} : $5 \cdot 10^{-5}$ ms^{-2}
- [10^{-4}; 10^{-1}]Hz

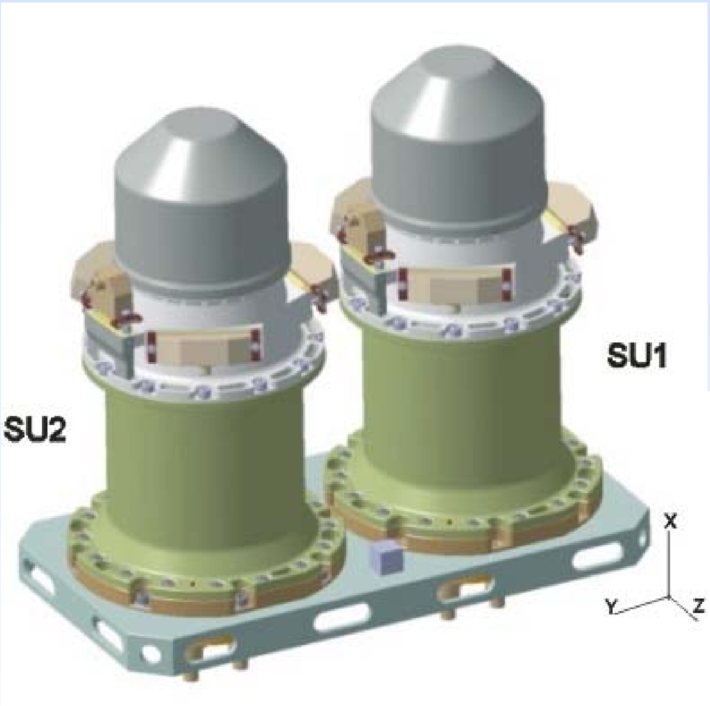
- Γ_n : $2 \cdot 10^{-12}$ ms^{-2} /Hz$^{1/2}$
- Γ_{max} : $6 \cdot 10^{-6}$ ms^{-2}
- [$5 \cdot 10^{-3}$; 10^{-1}]Hz

GOCE Gradiometer

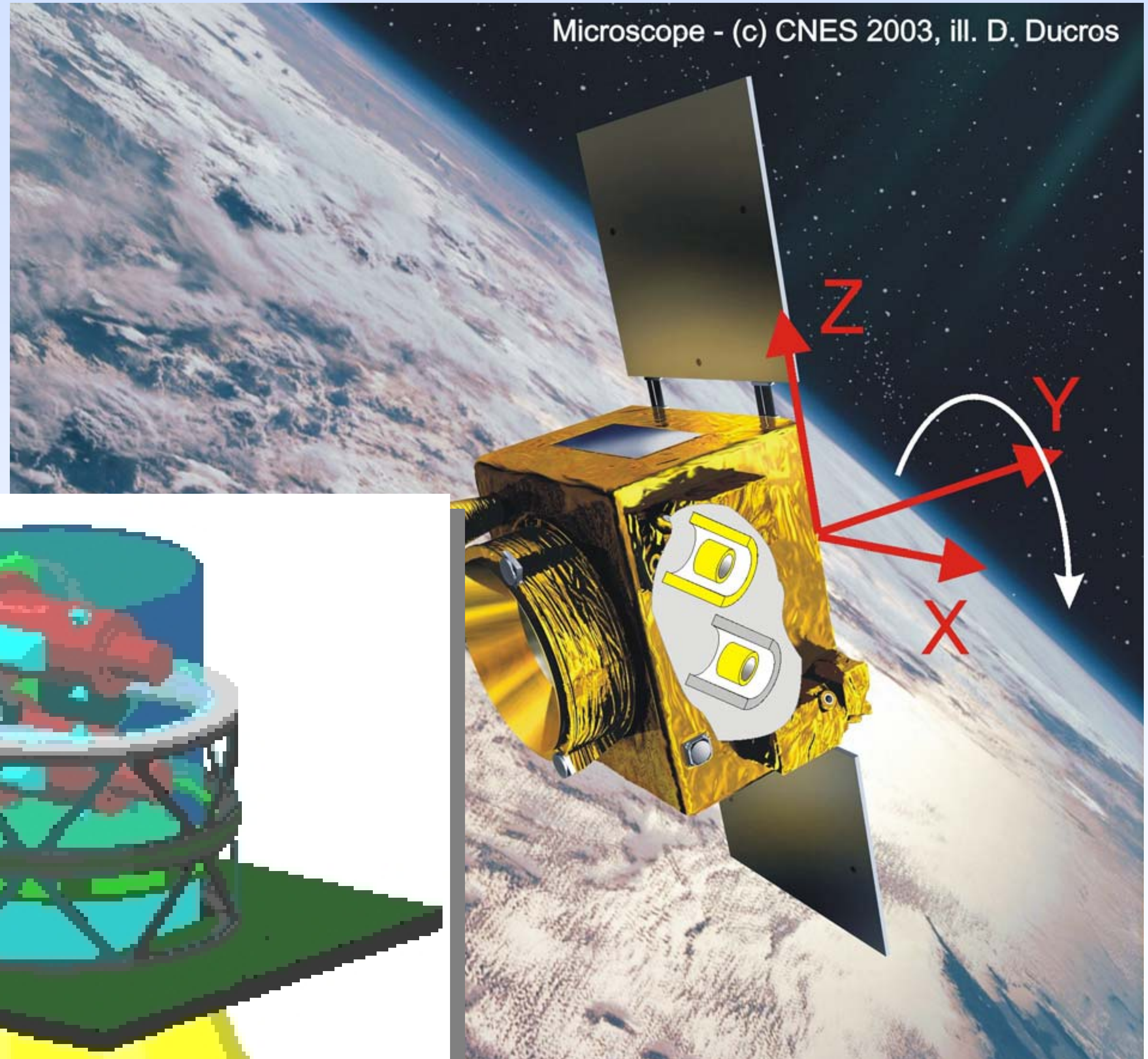


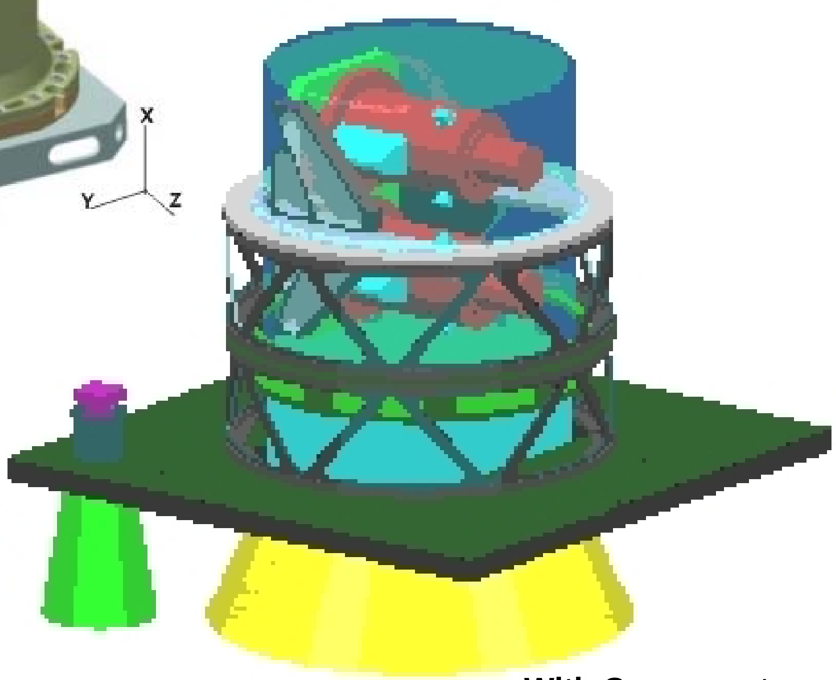
STM GRADIOMETER

MICROSCOPE PAYLOAD



2 similar differential accelerometers





With Cnes courtesy

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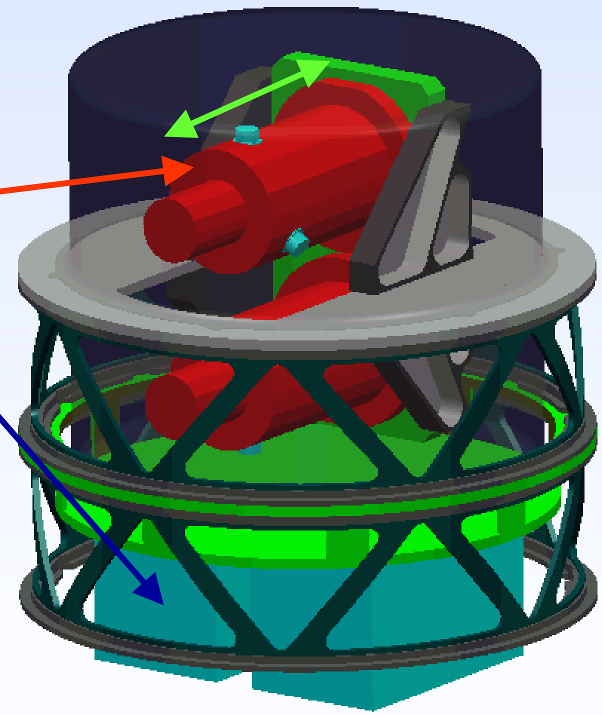
THERMAL Environment to be provided by the S/C

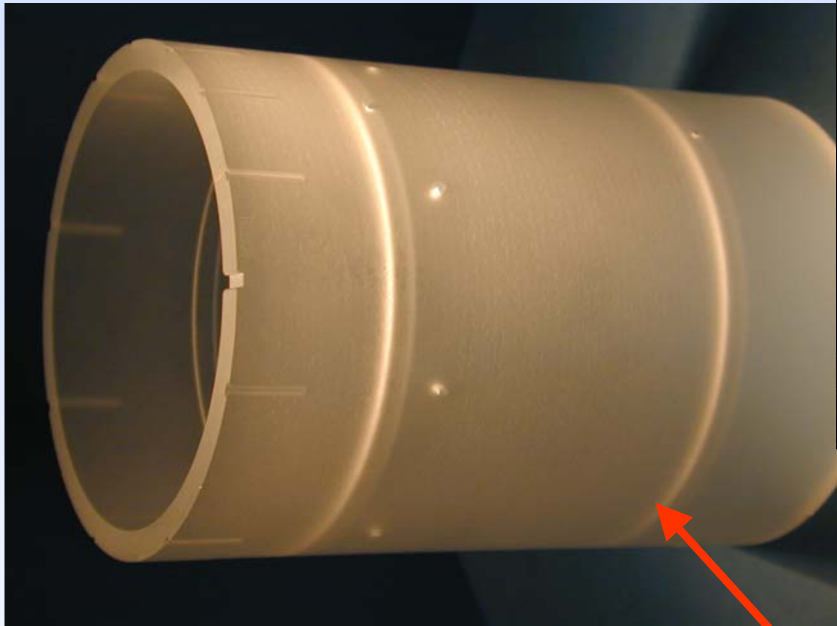
Thermal specifications :

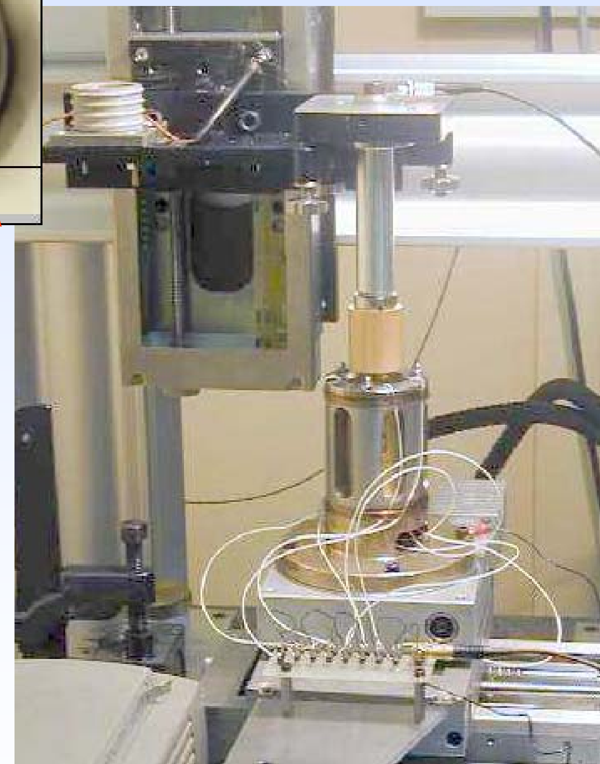
Sensor (SU) Core thermal behavior
Parasitic forces (Radiometer effect, Radiation pressure, bias fluctuation)
Sensor Electronics (FEEU) sensitivity
Sensor interface electronics (ICU) sensitivity

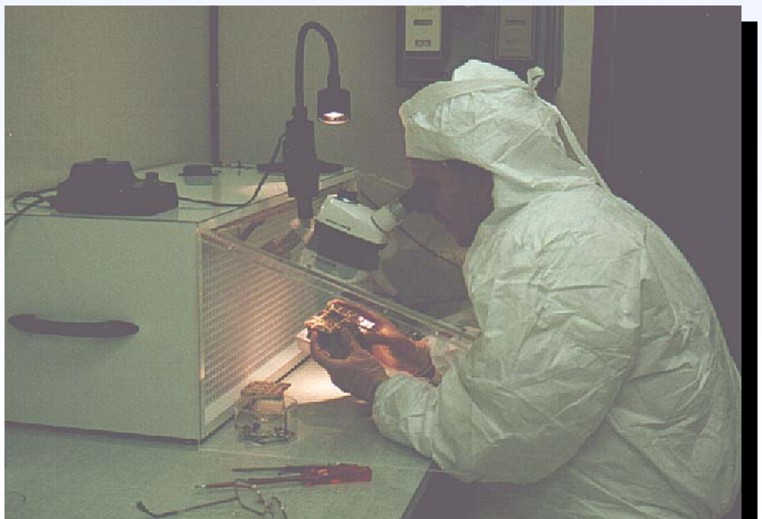
Location	Value
On SU skin	- 0.3K $Hz^{-1/2}$ between 0.1mHz and 0.1Hz - 1 mK @ fep - 10 mK @ 2 fep et 4 fep
On FEEU skin	- 3K $Hz^{-1/2}$ between 0.1mHz and 0.1Hz - 10 mK @ fep - 100 mK @ 2 fep et 4fep
Thermal gradients on SU (axial)	- 1K/m at DC - 3 K/m $Hz^{-1/2}$ between 0.1mHz and 0.1Hz - 10 mK/m @ fep - 100 mK/m @ 2 fep et 4 fep
At ICU interface	- 10 K $Hz^{-1/2}$ between 0.1mHz and 0.1Hz - 2.5 K @ fep



Sensor Core

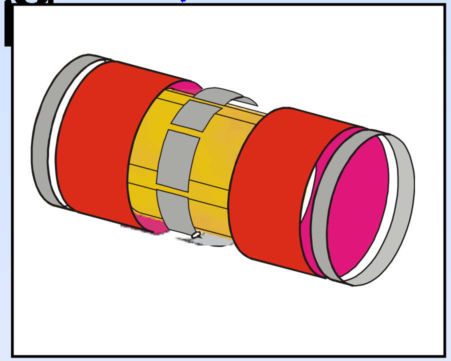




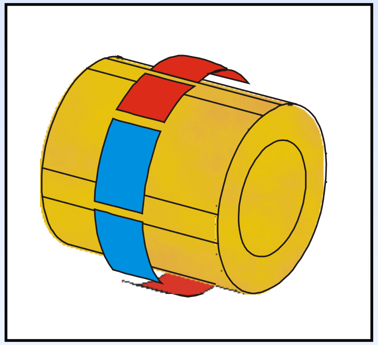


- Low CTE material : Silica
- Ultrasonic machining
- Gold coating (sputtering)
- Accurate metrology
- Clean room integration
- → micromys, arcsecond

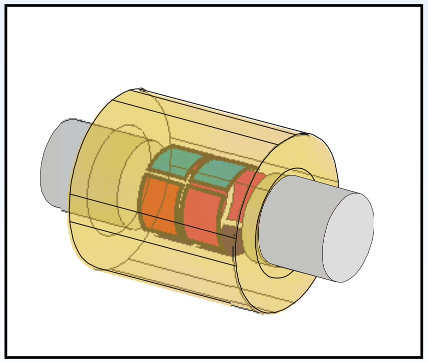
Electrostatic Inertial Sensor Configuration



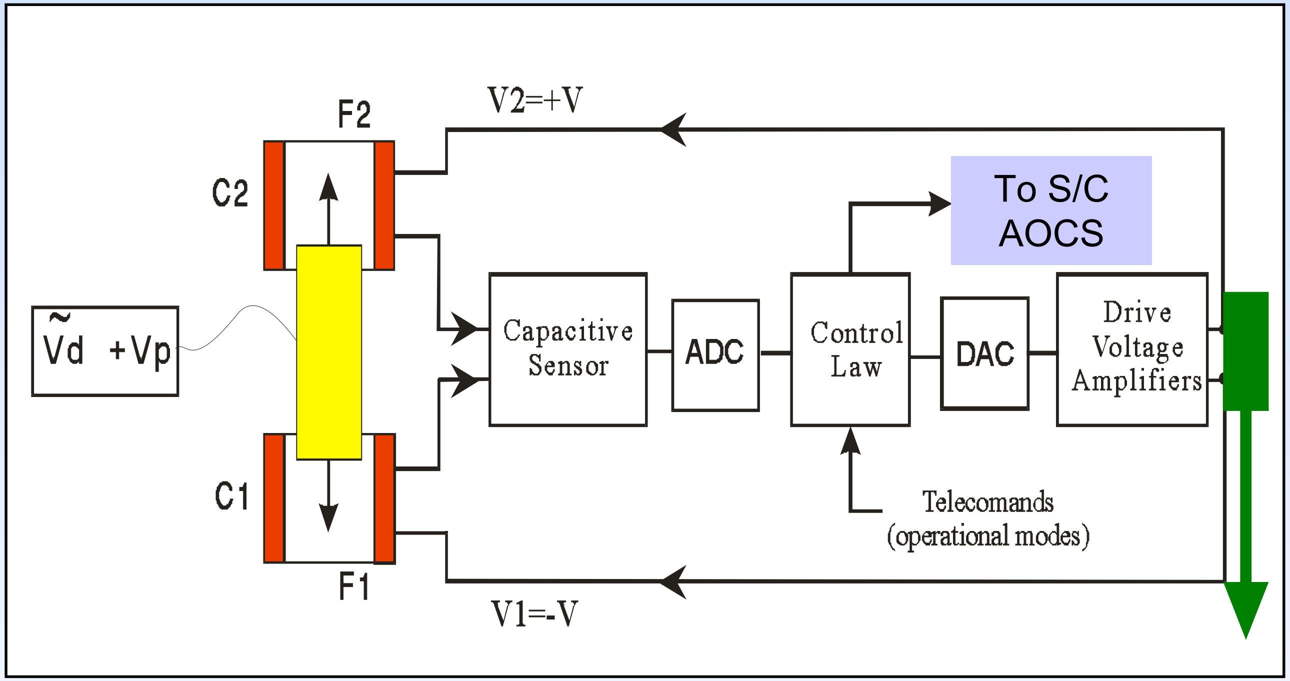
Axial electrodes



Spin electrodes

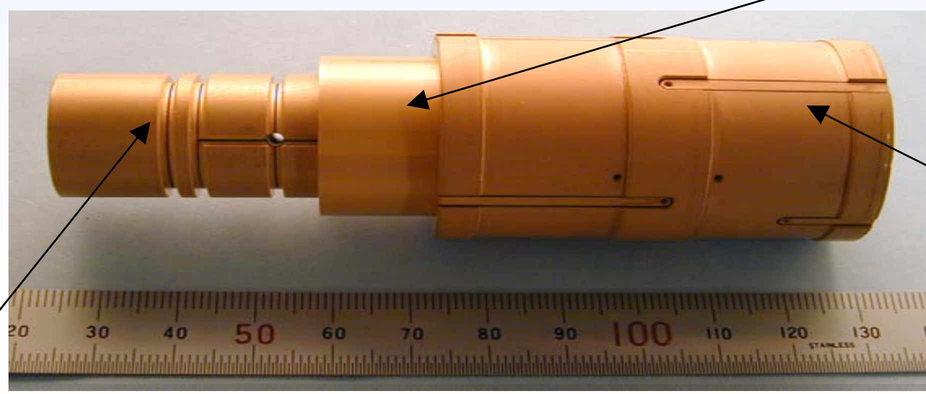


Radial electrodes



EP Test data

Test-mass



External electrode cylinder

Internal electrode cylinder

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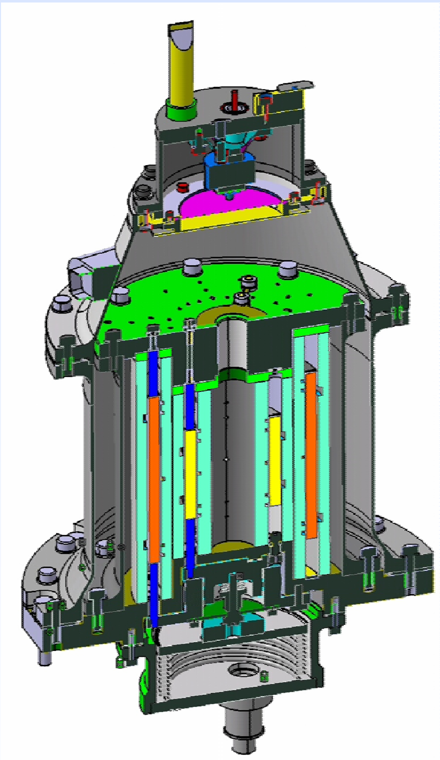
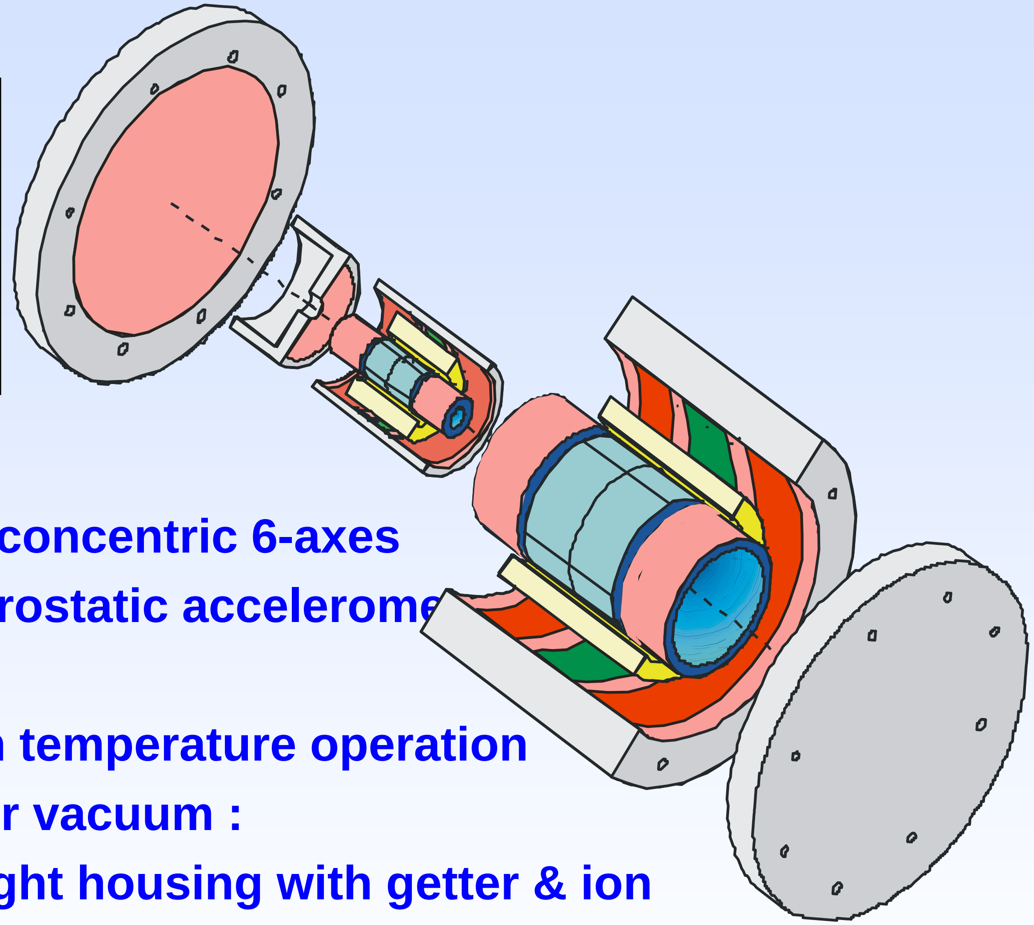
SAGE instrument : Differential Accelerometer Core Configuration



- Test masses
- Axial electrodes
- Spinl electrodes
- Radial electrodes
- Elect. Shield



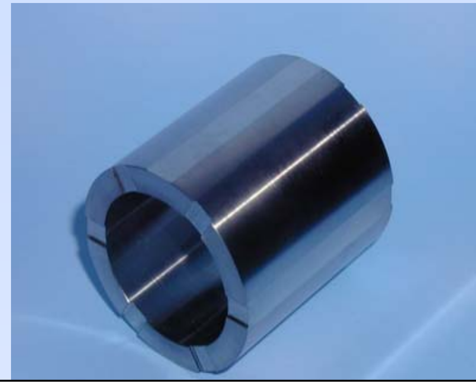
- Two concentric 6-axes
- electrostatic accelerome
- room temperature operation
- under vacuum :
- --> tight housing with getter & ion
- blocking mechanism for launch
- specific alignment and positionning rods

Material selection

On the basis of an eventual violation dependancy on:

- E/M T. Damour et al. (2002)
- With $E = Z(Z-1)/(N+Z)^{1/3}$ & $M = m/u$
- (atomic mass m and u = 931.49432 MeV)

Mat i	Mat j	(E/M)i – (E/M)j
Pt	**Ti**	**2.67**
Pt	**Cu**	**2.11**
Pt	**Pt**	**0 (whatever the mass)**



***PTB** (Braunschweig)*
machining of titanium alloy mass

Ra = 0.2 µm

Flat areas C, D, E, F

- **Planeity < 0.5µm**
- **Perpendicularity 2 by 2 < 4 arc sec**
- **Parallelism / dG < 4 arc sec**
- **Parallelism 2 by 2 < 4 arc sec**

Pt/Ti larger signal but lower instrument resolution

	B mean	Z	M mean	ρ (kg m^{-3})	χ(CGS)10^{-6}	CTE (K^{-1})	λ (W/m/K)
Pt	**195.11626**	**78**	**193.56593**	**21.45**	**1.1**	**9.1 10^{-6}**	**71.6**
Ti	**47.93050**	**22**	**47.50717**	**4.5**	**3.43**	**8.5 10^{-6}**	**21.6**
Cu	**62.61652**	**29**	**63.05216**	**8.96**	**-0.086**	**16.4 10^{-6}**	**401**

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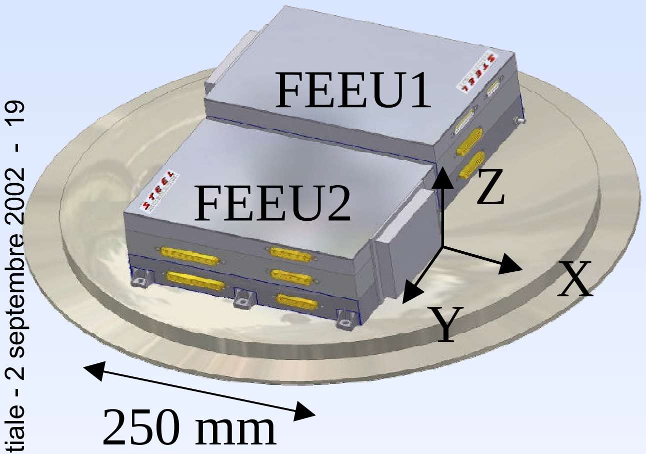
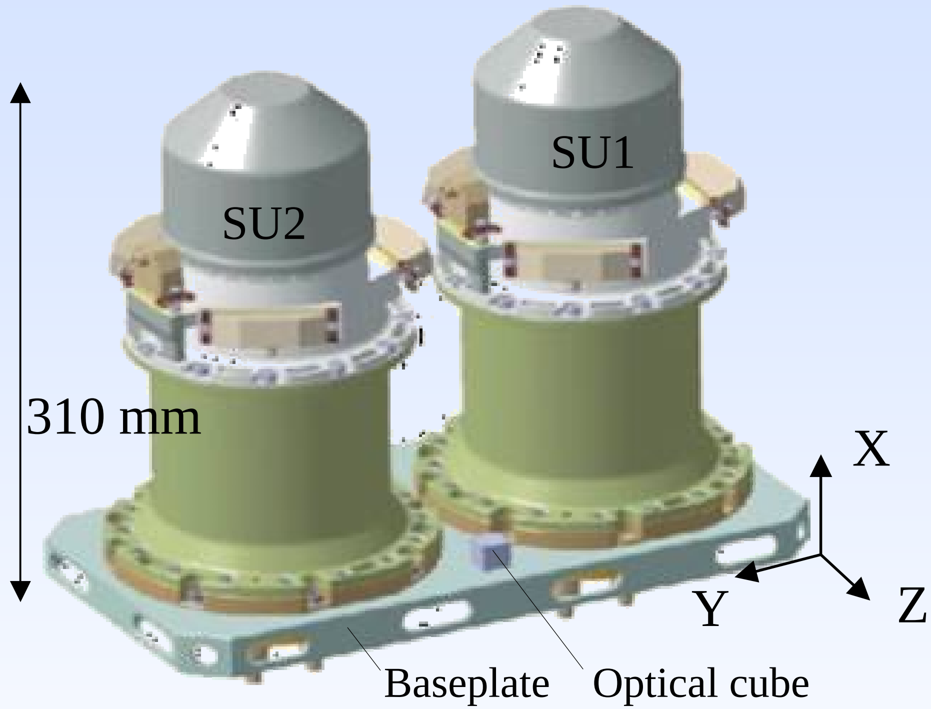
CylDoree.wmv

Instrument Components

Front End Electronics Unit



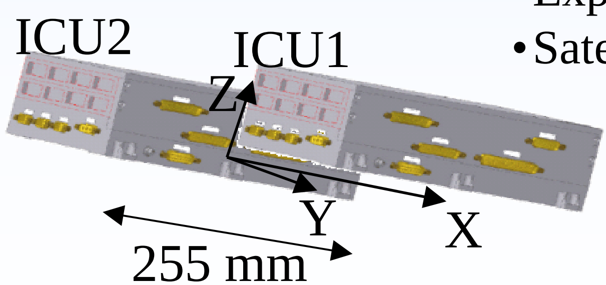
- Low noise electronics
    - Capacitive detectors
    - DACs/ADCs
- Requires temperature stability



Sensor Unit

- Low power operation
- Requires precise alignment with star camera

Interface Control Unit



- SU operation
- Experiment control
- Satellite interface

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Instrument resolution

Test-mass motion disturbances

- Stiffnesses
- Damping
- Bias force fluctuations:
  - electrical & magnetic
  - residual gas
  - radiation pressure
  - gravitational

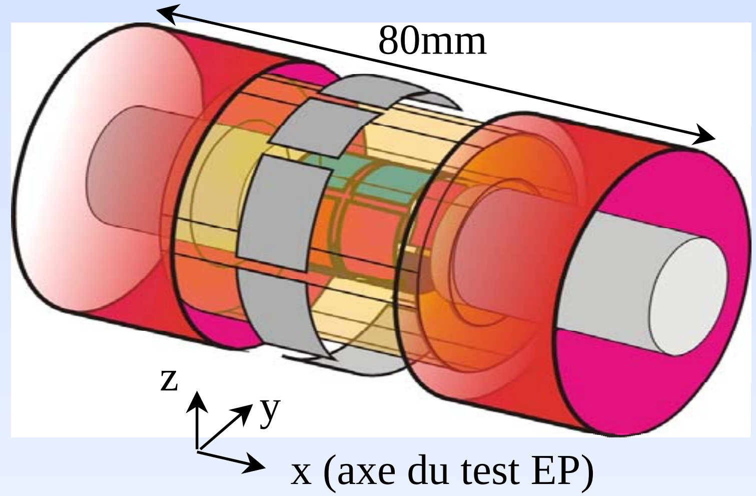
Electrostatic loop Noise

- Capacitive position sensing
- Electrostatic actuators
- Pick-up measurement

⇒ Back Actions

Thermal sensitivities

Alignments & scale factor matching



amplitude	X	Y/Z
Biais (K_0) (m/s²)	0,54 10^{-7}	8,0 10^{-7}
Fact d'échelle (K_1)	1 ± 10^{-2}	1 ± 1.10^{-2}
Alignements (α,β,γ)	$\pm 10^{-2}$	$\pm 10^{-3}$
Couplages (ε,η,μ)	$\pm 10^{-4}$	$\pm 10^{-4}$
Résolution (Γ_n) (m/s²/√Hz)	10^{-12}	8.10^{-11}

Analog Electronics test results

Obtained with Electronics realised for LISA Pathfinder inertial sensor

- ***Capacitive position sensor noise***

10^{-19} F/Hz$^{1/2}$ (Sensitivity ~ 20V/pF)

corresponding to :

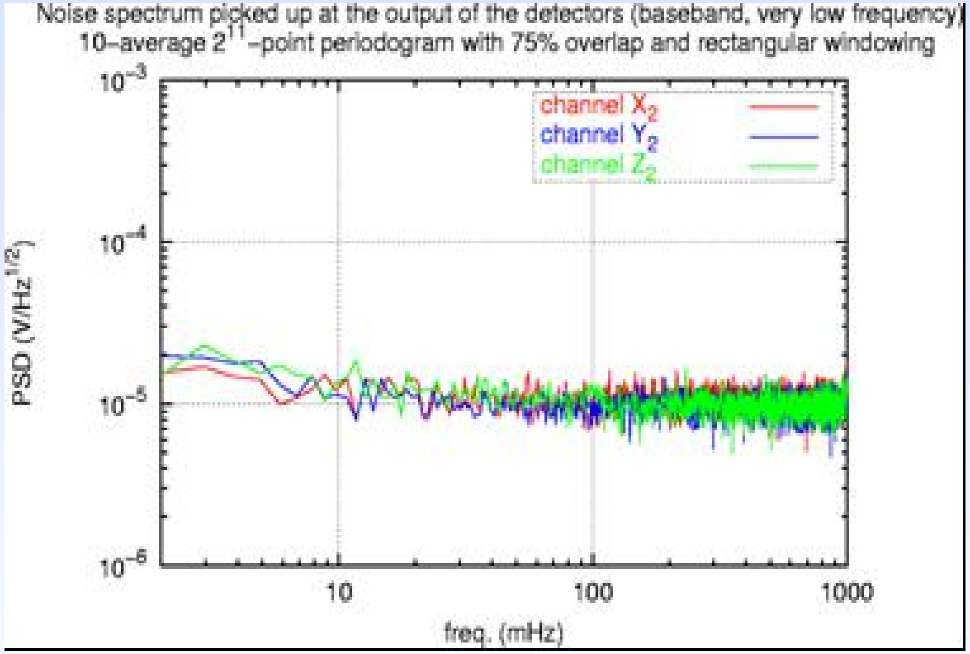
- 10^{-9} m /Hz$^{1/2}$ @ 4 mm

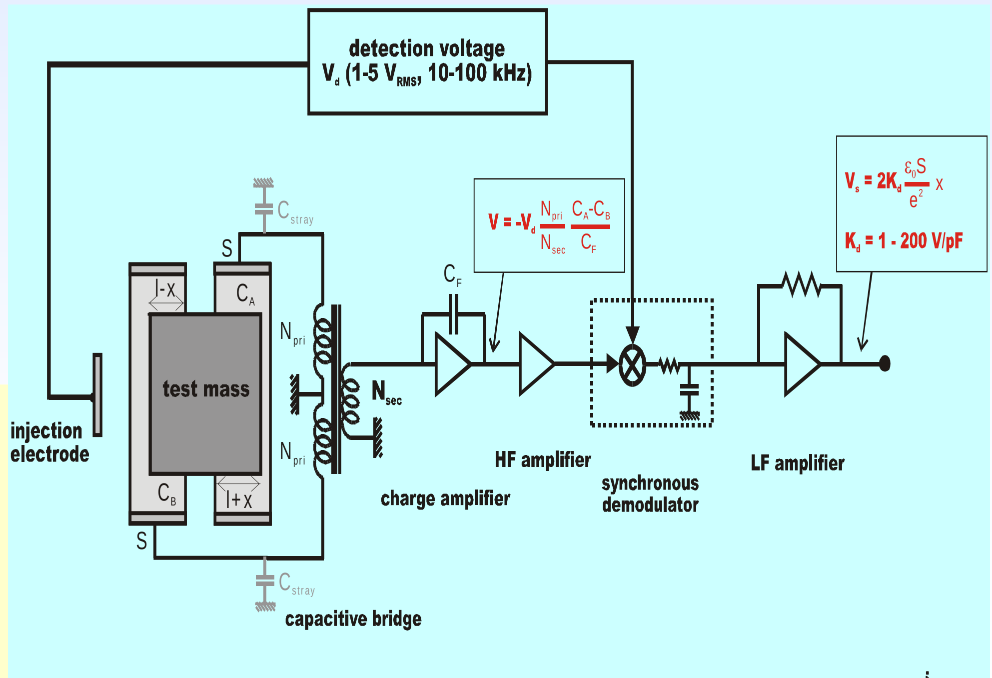
LTP configuration with large gaps

- 10^{-10} m /Hz$^{1/2}$ @ 400 µm

MICROSCOPE configuration

leading to at least 3.10^{-12}m @ f_{EP}





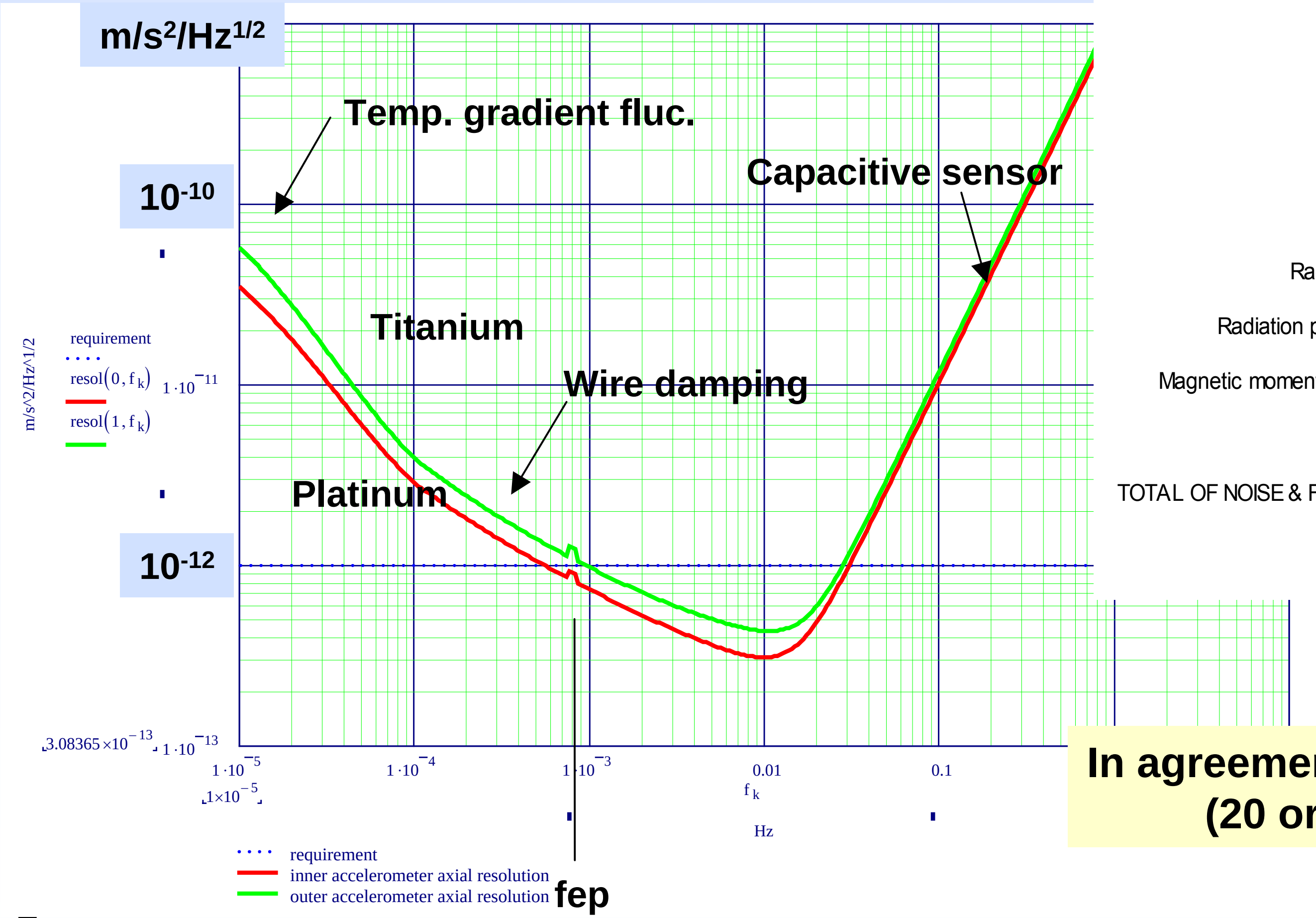
Electrostatic actuator noise :

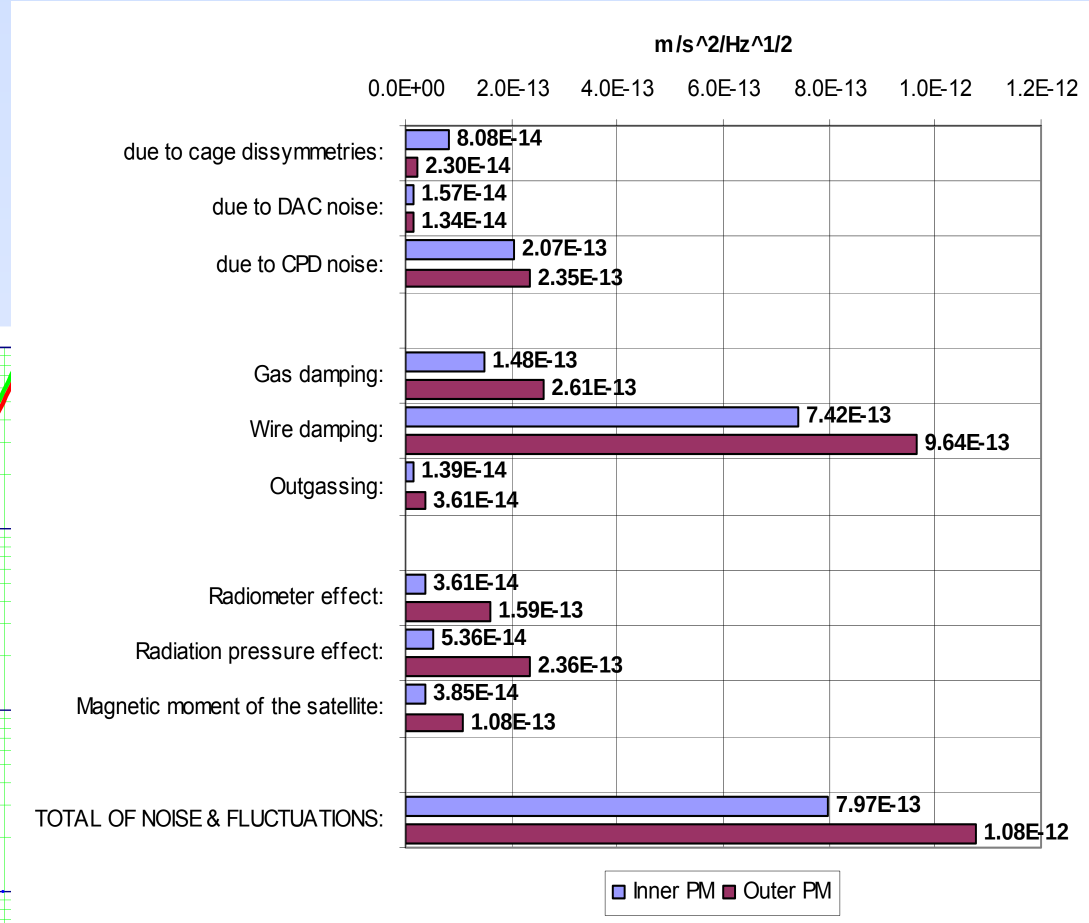
- **Drive Voltage Amplifier noise : 100 nV/Hz$^{1/2}$**

(input noise with Amp. gain 16)

- **Corresponding to : 10^{-10} N/Hz$^{1/2}$ to 10^{-13}N/Hz$^{1/2}$ according to accelerometer conf. and axis**

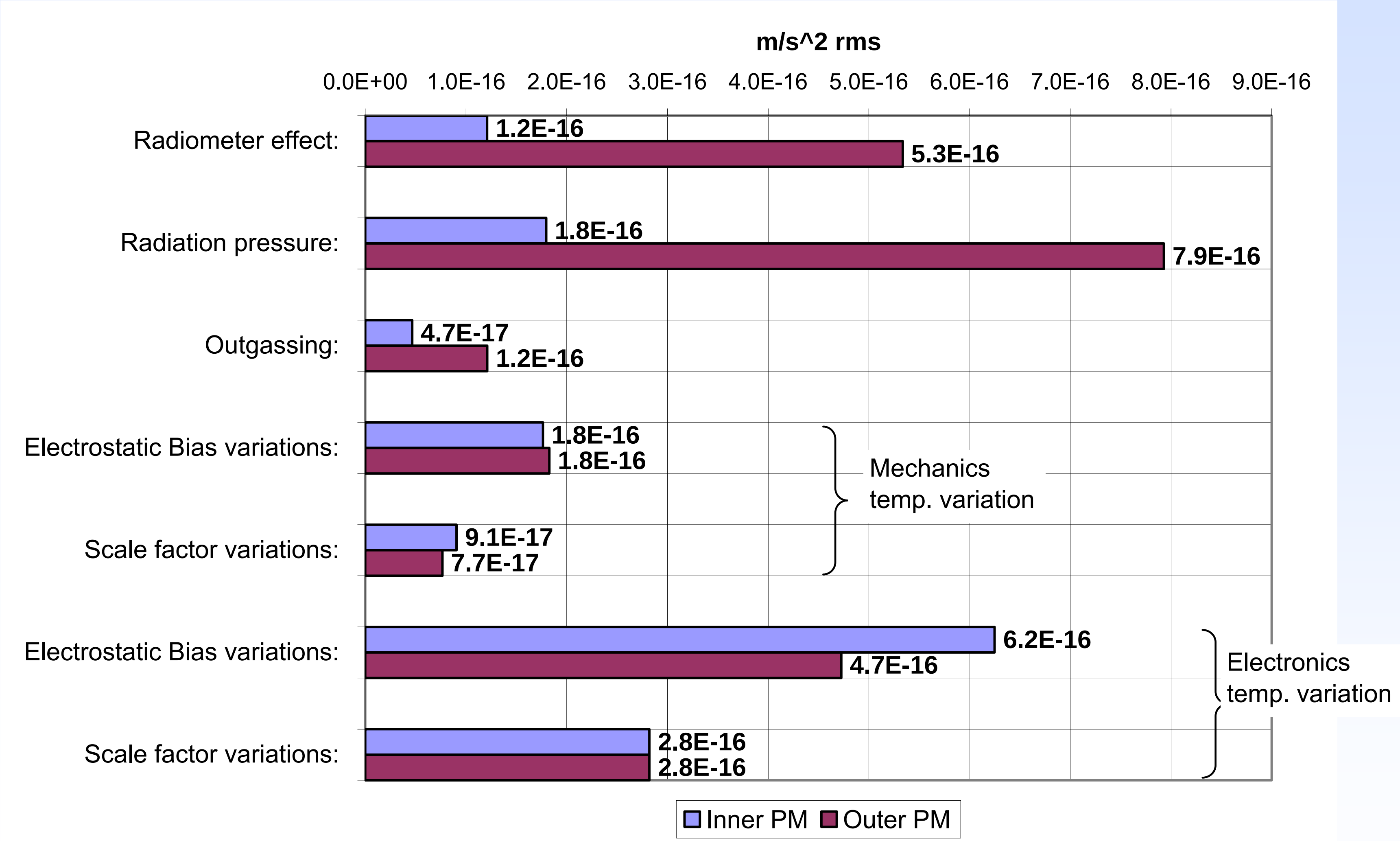
Random noise





In agreement with 10^{-15} EP test accuracy (20 orbits integration period)

Systematic Errors



Quadratic sum ~ 1.5 E-15 (non correlated source and distributed phase)

without considering rejection in the difference

Instrument Calibration : sensitivity matix

$$\begin{pmatrix}\Gamma_{mes,x}\\ \Gamma_{mes,y}\\ \Gamma_{mes,z}\end{pmatrix} \approx \begin{pmatrix}K_{0,x}\\ K_{0,y}\\ K_{0,z}\end{pmatrix} + \begin{pmatrix}K_{1x} & \varepsilon+\theta_z & \eta-\theta_y\\ \varepsilon-\theta_z & K_{1y} & \mu+\theta_x\\ \eta+\theta_y & \mu-\theta_x & K_{1z}\end{pmatrix} . \begin{pmatrix}\Gamma_{réel,x}\\ \Gamma_{réel,y}\\ \Gamma_{réel,z}\end{pmatrix} + \begin{pmatrix}\Gamma_{n,x}\\ \Gamma_{n,y}\\ \Gamma_{n,z}\end{pmatrix}$$

Measure — Bias — Sensitivity Matrix — Actual Mass Acc. — Noise

One Inertial Sensor Linear Model

Instrument data ouputs from 2 Sensors

$$\Gamma_{mes,1} = K_{0,1} + M_1.\Gamma_{réel,1} + \Gamma_{n,1}$$

$$\Gamma_{mes,2} = K_{0,2} + M_2.\Gamma_{réel,2} + \Gamma_{n,2}$$

<u>Differential mode</u>

$$\Gamma_{mes,diff} = \frac{\Gamma_{mes,1} - \Gamma_{mes,2}}{2}$$

<u>Common mode</u>

$$\Gamma_{mes,com} = \frac{\Gamma_{mes,1} + \Gamma_{mes,2}}{2}$$

⇨

$$\Gamma_{mes,diff} = K_{0,diff} + M_{com}.\Gamma_{réel,diff} + M_{diff}.\Gamma_{réel,com} + \Gamma_{n,diff}$$

$$\frac{\Gamma_{réel,1} - \Gamma_{réel,2}}{2} = \frac{1}{2}.\delta g + ([T]-[I]).\frac{\Delta}{2}$$

$$\frac{\Gamma_{réel,1} + \Gamma_{réel,2}}{2} \approx \Gamma_{surface}$$

$$\delta = \left(\frac{m_{g1}}{m_{i1}} - \frac{m_{g2}}{m_{i2}}\right)$$

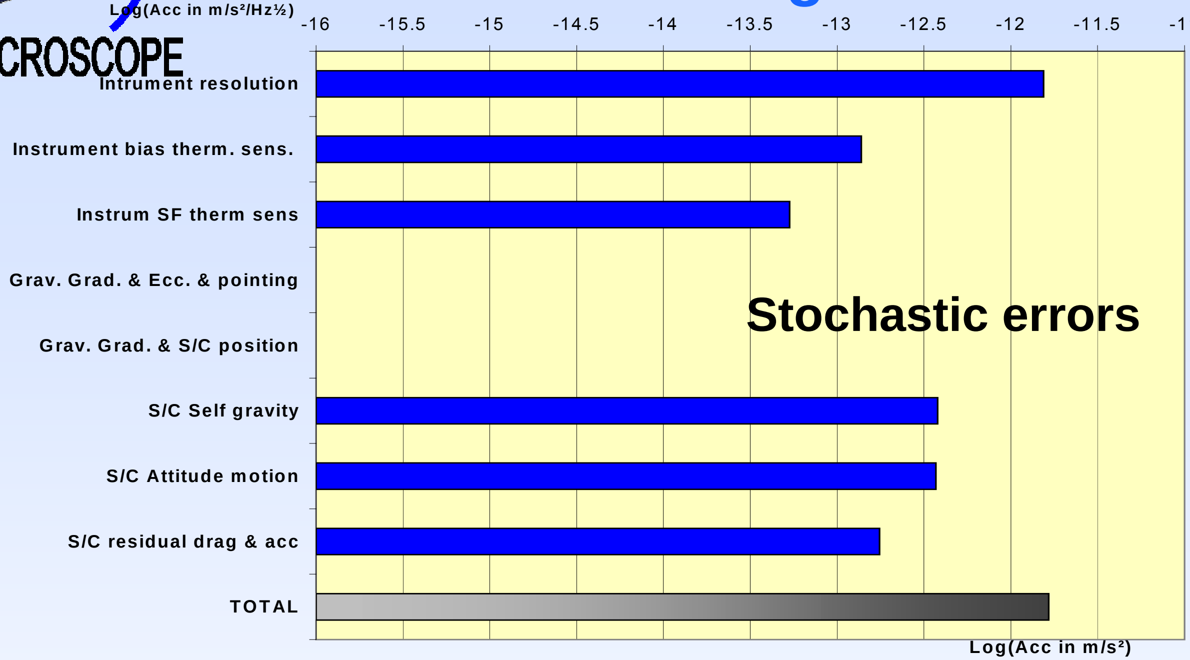
Δ : 2 mass offcentring ($< 20\mu m$)

Calibration: calibrated parameters (summary)

Parameters	Maximum value by construction	Impact before calibration	Spec for $e=5\cdot10^{-3}$	Impact after calibration
θ_{cy} and θ_{cz} for $\Delta \leq 20\mu m$	$1.5\cdot10^{-3}$ rad	$3.4\cdot10^{-16} m\cdot s^{-2}$	10^{-3} rad	$2.4\cdot10^{-16} m\cdot s^{-2}$
$K_{cx}\cdot\Delta_x$ and $K_{cx}\cdot\Delta_z$ ($K_{cx}\leq10^{-2}$ rad)	20,2 µm	$8\cdot10^{-14}$ $m\cdot s^{-2}$	0,1 µm	10^{-17} $m\cdot s^{-2}$
Δ_y	20 µm	$3.4\cdot10^{-16} m\cdot s^{-2}$	0,4 µm	$7\cdot10^{-18} m\cdot s^{-2}$
K_{dx}	10^{-2}	$6\cdot10^{-13}$ $m\cdot s^{-2}$	$1,5\cdot10^{-4}$	$6\cdot10^{-17}$ $m\cdot s^{-2}$
θ_{dy} and θ_{dz}	10^{-3} rad	$1.2\cdot10^{-12} m\cdot s^{-2}$	$5\cdot10^{-5}$ rad	$1.2\cdot10^{-16} m\cdot s^{-2}$

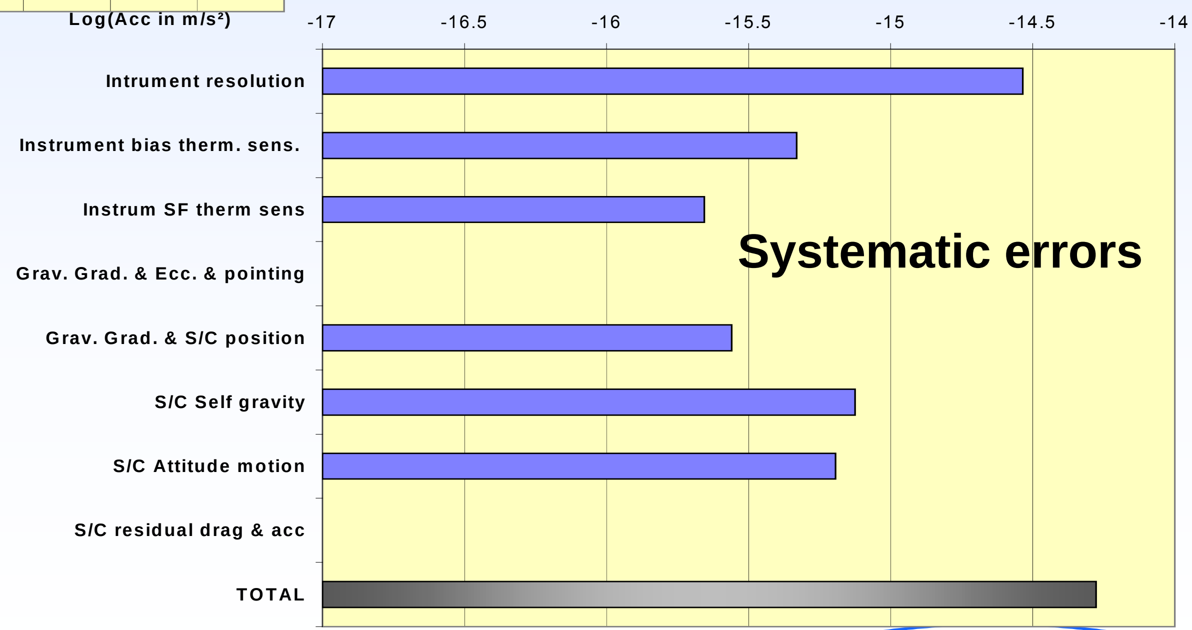
e: orbit excentricity in MICROSCOPE nominal configuration

Mission Error Budget: in rotating mode



EP test @ 7.8 10^{-4}Hz
Sensor limits :
-1.7 10^{-12} ms^{-2} $Hz^{-1/2}$
-- 4.7 10^{-15} ms^{-2} when direct sum of any source tone disturbance
(1.5 10^{-15} ms^{-2} when quadratic sum, rejection in the difference : ?)

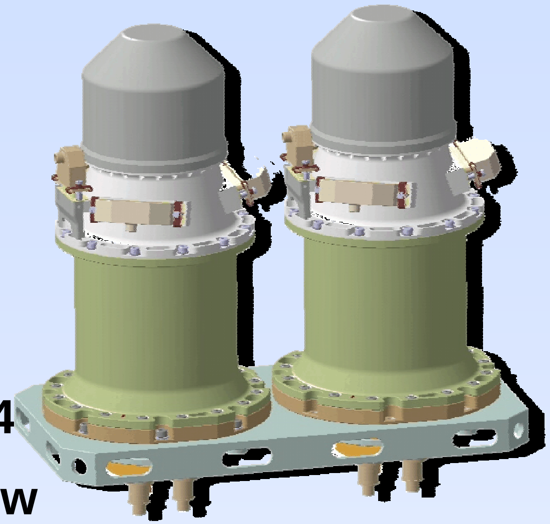
Mission minimum performance : 6.9 $10^{-15}$$ms^{-2}$



EP TEST 0.9x10^{-15}

DMPH

MICROSCOPE : PLANNING



- nov. 03: Phase A Review : Mission & Satellite

- jan. 04 - juin 04 : Phase B1, Review successful on 17/06/04
- juin 04 - avr. 05 : Phase B2, --> Preliminar Definition Review

- mai 05 - juin 06 : Phase C, --> Critical Definition Review
- mars 06 - mars 07: Phase D Instrument, --> Test & Acceptance Review for integ.
- juil. 07 - déc.07 : Satellite Intégration, --> Flight Acceptance Review

Launch in March 08