In flight calibration plan for the instrument of the MICROSCOPE space mission

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ONERA
THE FRENCH AEROSPACE LAB

retour sur innovation

Origin and objectives

Expressed in 1911 by Einstein, the Equivalence Principle is:

- at the basis of the General Relativity
- only justified by experimental observations: specifically, universality of free fall → all bodies, independently of their mass or intrinsic composition, acquire the same acceleration in the same uniform gravity field

Recent Results:

- in laboratory (Adelberger, Phys. Rev. 1990 ; Su Y, Phys. Rev. 1994; S. Baessler et al, Phys. Rev. Let. 1999) 10^{-12} to 10^{-13}
- by Moon - Earth - Sun system observation (Williams et al., Int.J.Mod.Phys.D18:1129-1175,2009)→ 10^{-12}

Difficulties to merge:

- General Relativity & Quantum Theory
- Gravitational Interaction & Standard Model

→ equivalence principle violation below 10^{-14}
(T. Damour et al. Nucl. Phys. Rev D, 046007, 2002)

> The PE tests provide a more simple and direct check than the other tests of the General Relativity

The Equivalence Principle

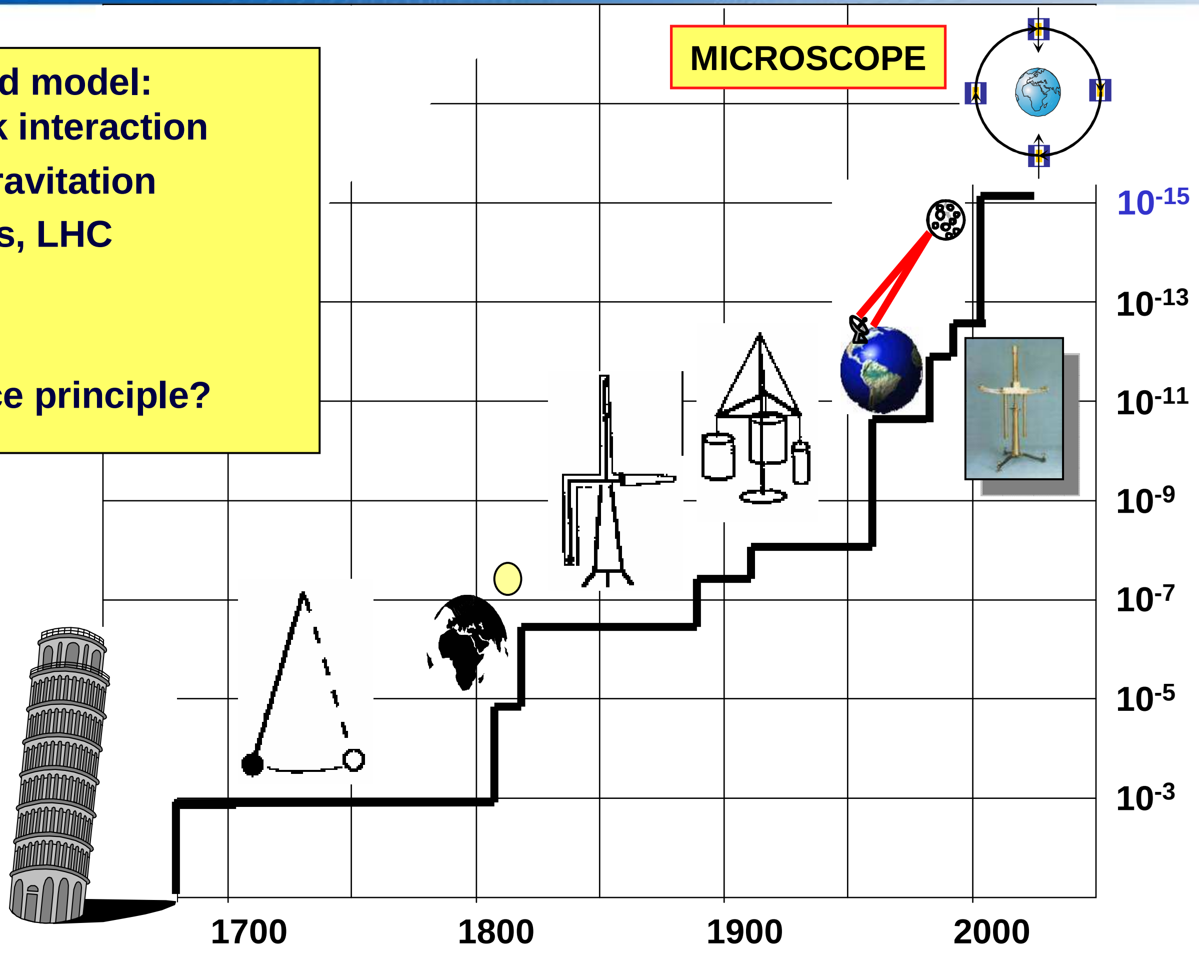
Quantum Mechanics, Standard model: electromagnetic, strong, weak interaction

≠ Geometrical theory of the gravitation

- **Super-symmetry: Sparticules, LHC**
- **String theory, Branes...**

=> New interaction?

=> Violation of the Equivalence principle?



Test with the highest accuracy and in various conditions the hypothesis and laws which rule the world

.

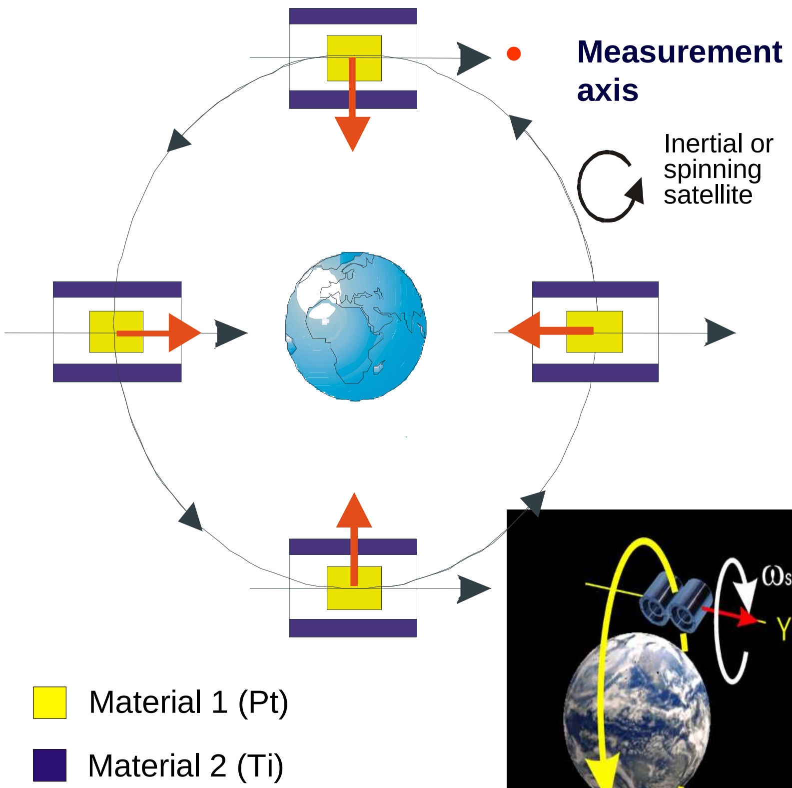
Accuracy of 10^{-15} → 10^{-15} g (Earth or Sun)

$$\frac{M_G}{M_I} = 1 + SEP + WEP = 1 + \eta \frac{E_G}{mc^2} + \omega$$

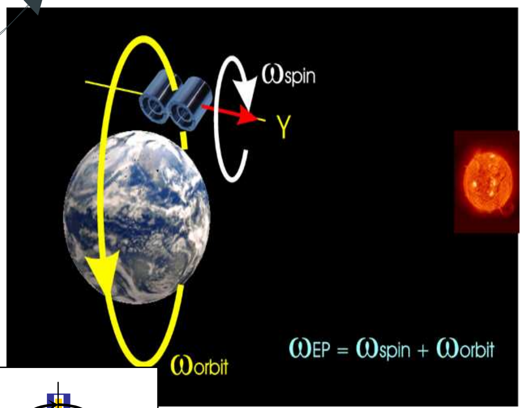
WEP: Effect of the composition of the body on the free fall

SEP: Coupling between internal energy and gravity

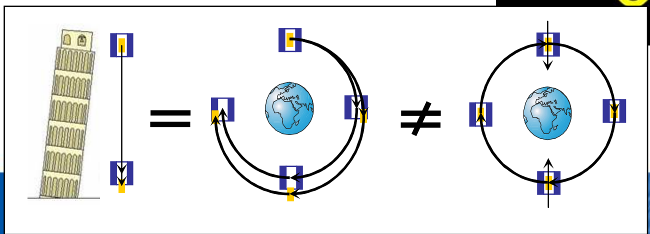
The principle of the MICROSCOPE space mission

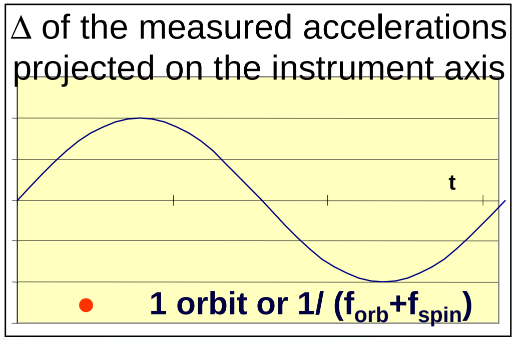


- Gravitational source: the Earth
- inertial acceleration: Orbital motion
- 2 masses of different composition:
- controlled on the same orbit (< 10^{-11}m) thanks to the measured electrostatic forces
- time span of the measurement:
  non limited by the free fall (> 20 orbits)
- Environment:
  Very controlled or avoiding perturbations, drag-free satellite
- Signal to be detected:
- phases & frequency are defined

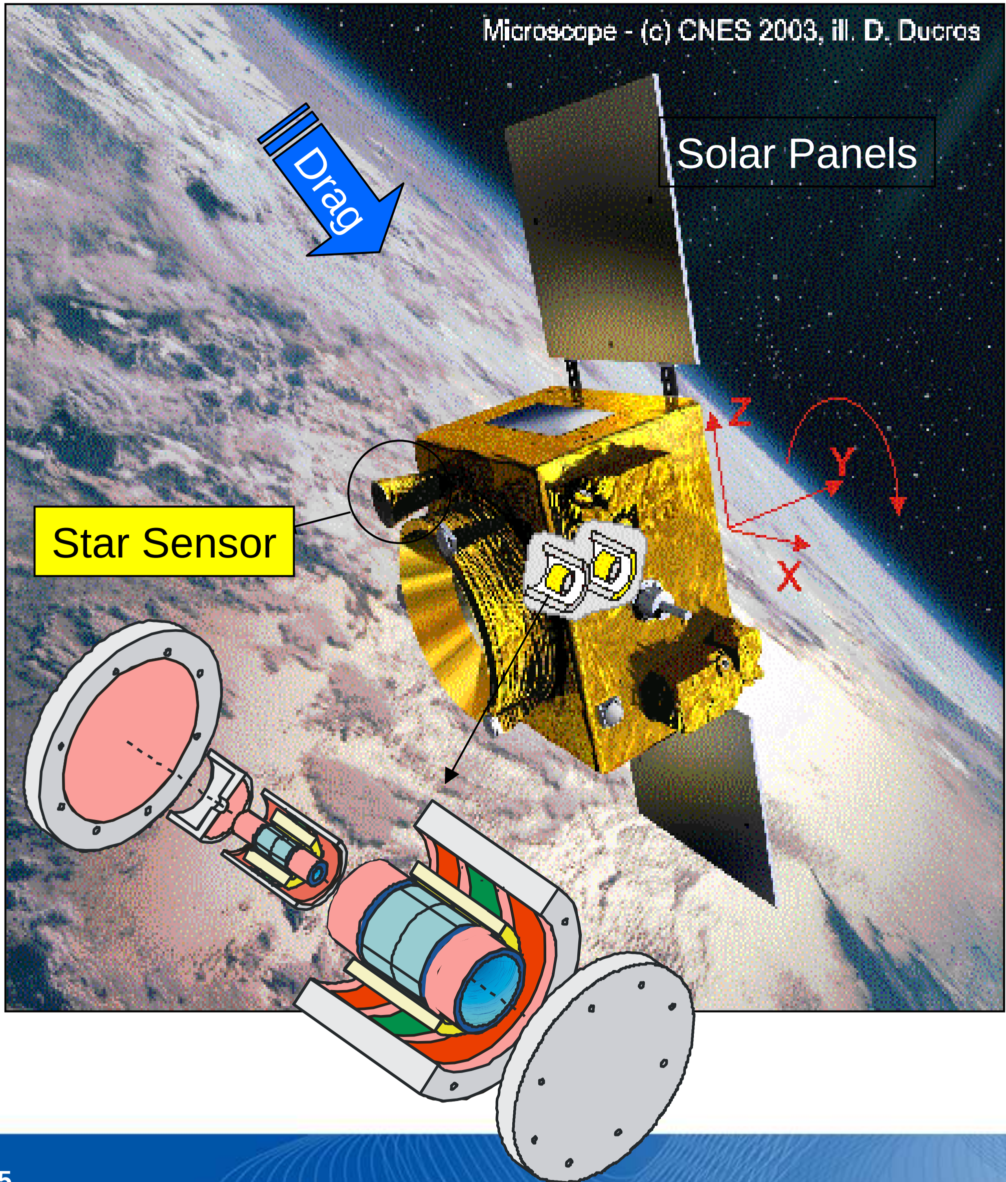


$f_{ep}=f_{orb}+f_{spin}$
Circular orbit
Earth ~ Monopole





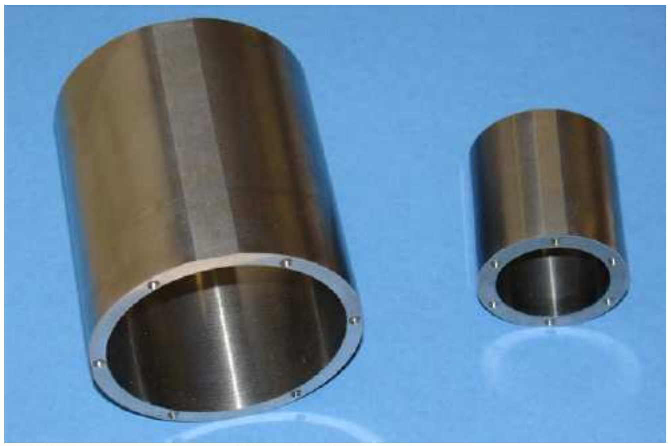
MICROSCOPE Mission Main Parameters



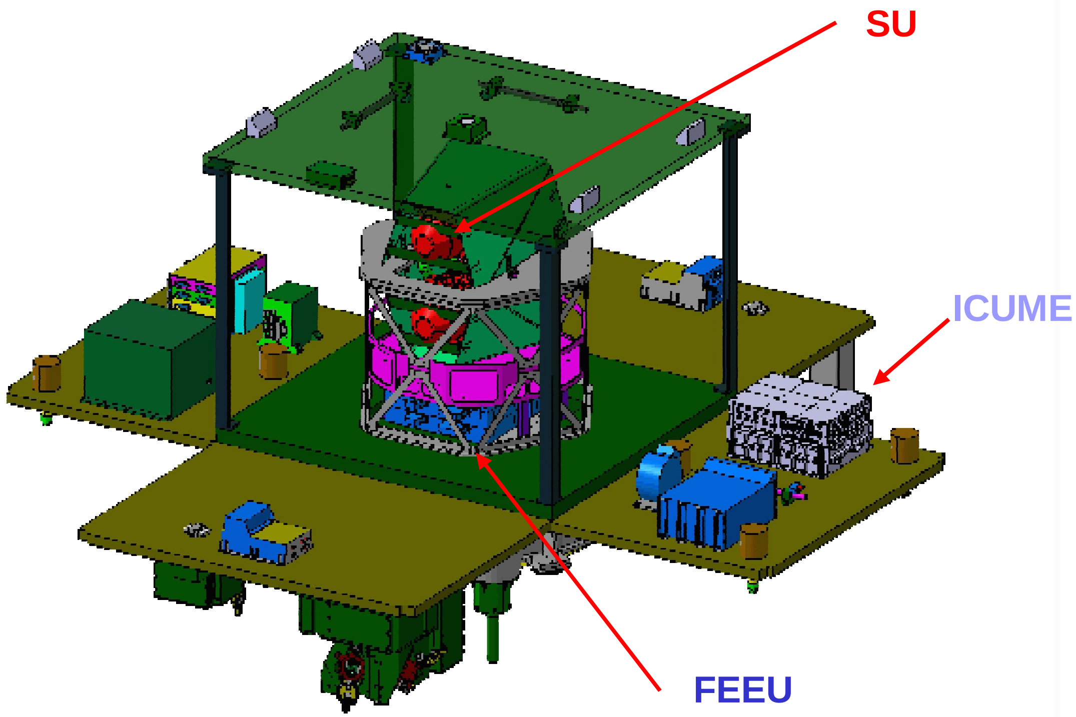
CNES MYRIADE Microsatellite

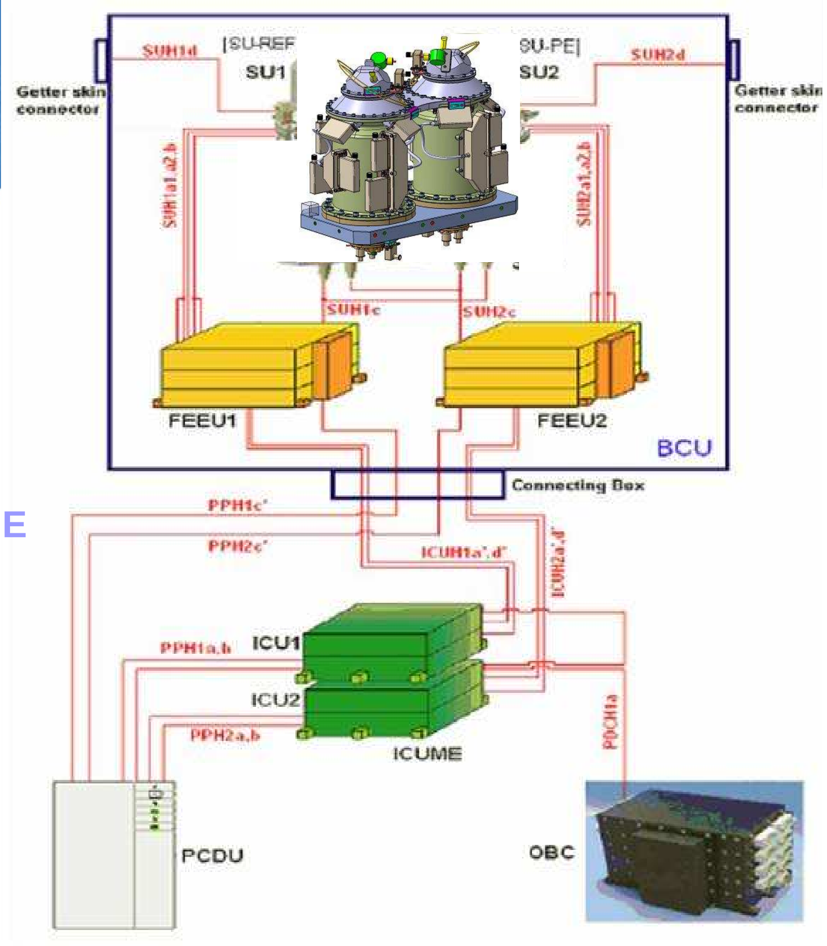
- Circular Orbit: 810 km, e < 5.10^{-3}
- Inertial or Rotating: 7.10^{-3} rd/s
- Mission duration: 12 months
- Mass of microsat: 200 kg
- Payload budgets: 35 kg, 40 Watts
- 2 differential electrostatic accelerometers

  (2 pairs of masses: Pt/Pt & Pt/Ti)
- Continuous drag compensation system



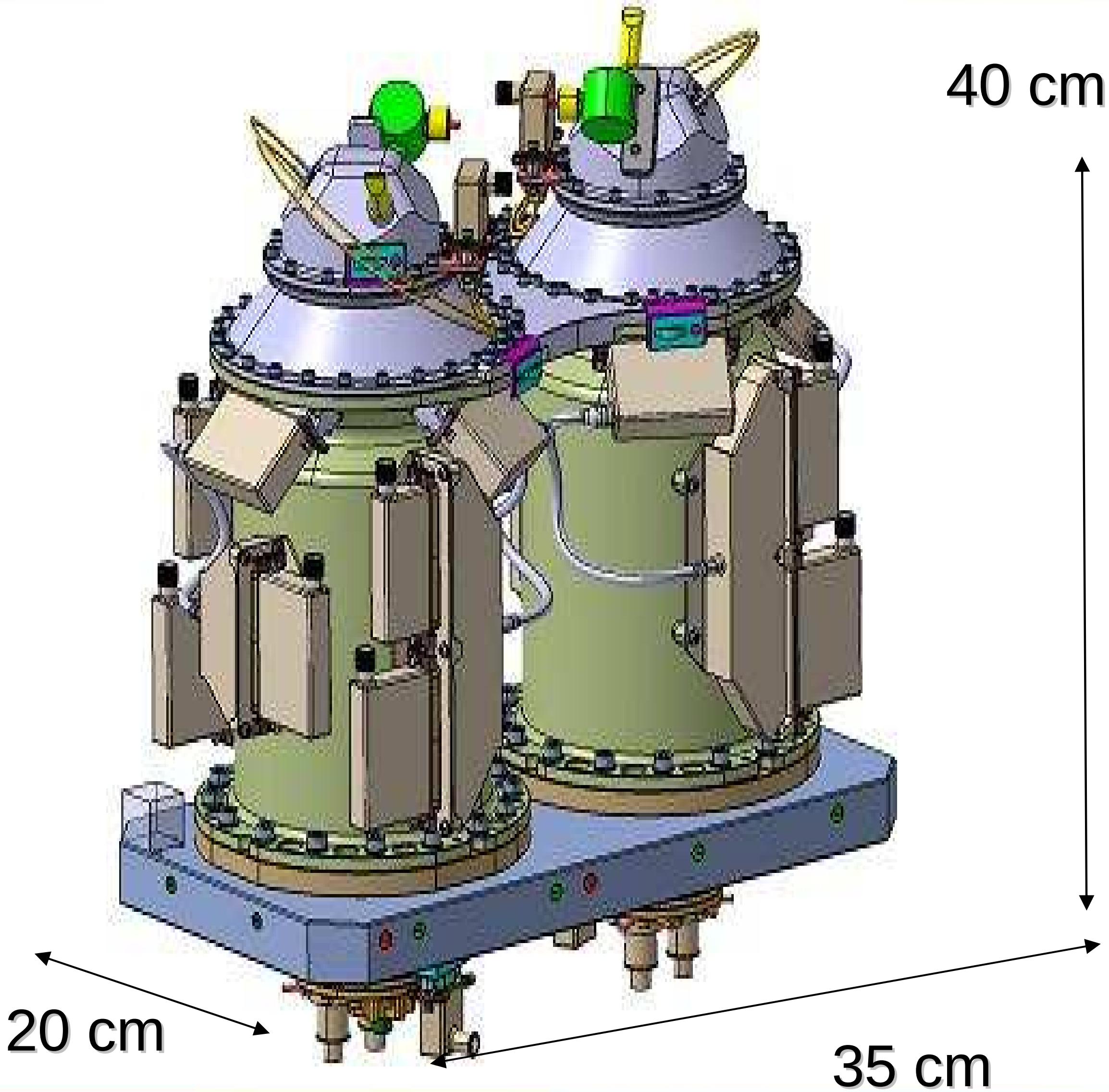
The payload: T-SAGE





- 2 Differential accelerometers (SU-EP and SU-Ref)
- 2 Front End Electronic Unit
- 2 Interface and Control Unit Mechanical Ensemble + software
- The harnesses

Sensor Unit

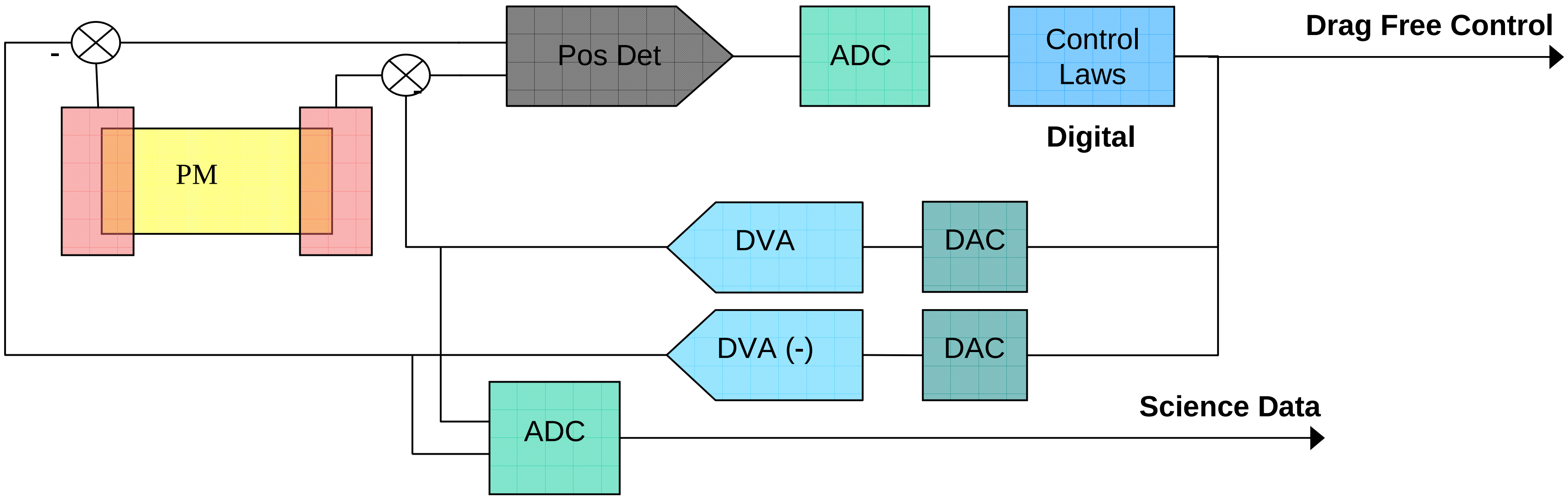


SU-Ref: 2 masses in platinum

SU-EP: 1 mass in platinum + 1 in titane

Total mass: 25kg

Control Electronics

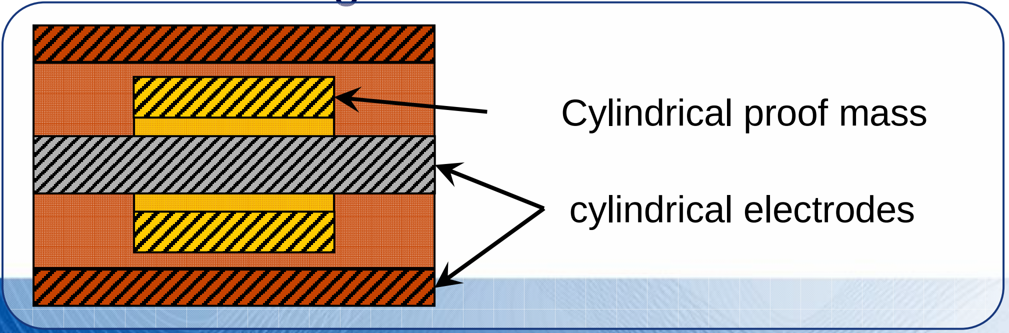


- Front End Electronic Unit:
  - Analog functions (Det, DVA)
  - Analog ↔ Digital converters
- Interface Control Unit:
  - Digital control laws
  - Satellite interface

- Scientific measurements along the cylinder axis, using surface variation electrodes
  - Linear, and lower parasitic stiffness
  - Depends on coaxiality and cylindricity
- Scientific data require noise lower than the SCAA data

Principle of an electrostatic accelerometer

- Proof mass
  - Physically ‘free’, except a gold wire of 5µm
  - Surounded by electrods (cylindrical configuration)
  - Electrostatic potential controled by the gold wire
    - Vd sine to detect the position
    - Vp constant to apply a certain force
  - Kept centered and motionless by control loop
- The electrods enable
  - The measurement of the position of the mass through variation of capacitance
  - The control of the electrostatic fields which control the mass
  - The control of its 6 degrees of freedom with electrostatic forces



Measurement principle

- Ideal measurement of of a proof mass (*k*):

$$\vec{\Gamma}_{App,k} = \frac{M_{gsat}}{M_{Isat}}\vec{g}(O_{sat}) - \frac{m_{gk}}{m_{Ik}}\vec{g}_k + \frac{\vec{F}_{NGsat}}{M_{Isat}} - \frac{\vec{F}_{Pak}}{m_{Ik}} + R_{In,Cor}(\overrightarrow{O_{sat}O_k})$$

$$\vec{\Gamma}_{App,k} = \underbrace{\left(\frac{M_{gsat}}{M_{Isat}} - \frac{m_{gk}}{m_{Ik}}\right)\vec{g}(O_{sat}) + (\mathrm{T}-\mathrm{I})\overrightarrow{O_kO_{sat}}}_{\vec{\Gamma}_{app,k}} - \cancel{2\Omega\dot{\overrightarrow{O_kO_{sat}}}} - \cancel{\ddot{\overrightarrow{O_kO_{sat}}}} + \frac{\vec{F}_{NGsat}}{M_{Isat}} - \frac{\vec{F}_{Pak}}{m_{Ik}}$$

$$\frac{\vec{F}_{NGsat}}{M_{Isat}} \rightarrow \frac{\vec{F}_{extsat}}{M_{Isat}}, \quad \frac{\vec{F}_{thsat}}{M_{Isat}}$$

- Half difference of acceleration of the two masses:

$$\vec{\Gamma}_d \approx \frac{1}{2}\left(\delta\vec{g}(O_{sat}) + (\mathbf{T}-\mathbf{I})\overrightarrow{O_1O_2}\right) \qquad \delta = \frac{m_{2g}}{m_{2I}} - \frac{m_{1g}}{m_{1I}}$$

Measurement limitation

- Real Measured acceleration of a proof mass (*k*):

$$\vec{\Gamma}_{meas,k} = \vec{B}_{o,k} + \mathbf{M}_k \vec{\Gamma}_k + \sum_{u=x,y,z} \left(\hat{u}^T \cdot \left(\mathbf{K}_{2,k} \cdot \vec{\Gamma}_k \cdot \vec{\Gamma}_k^T \right) \cdot \hat{u} \right) \cdot \hat{u} + \vec{\Gamma}_{n,k}$$

$$\begin{aligned}
\vec{\Gamma}_{mes,k} = & \underbrace{\vec{b}_{0k}}_{bias} + \left(\left[1 + \underbrace{dK_{1k}}_{scale} \right] + \underbrace{\left[\eta_k \right]}_{coupl.} \right) \cdot \underbrace{\left[\theta_k \right]}_{align.} \cdot \left(\vec{\Gamma}_{app,k/sat} + \frac{\vec{F}_{ext/sat}}{M_{Isat}} + \frac{\vec{F}_{th/sat}}{M_{Isat}} \right) \\
& + \left(\left[1 + \underbrace{dK_{1k}}_{scale} \right] + \underbrace{\left[\eta_k \right]}_{coupl.} \right) \cdot \left(- \frac{\vec{F}_{pa\,k/inst,k}}{m_{Ik}} - \frac{\vec{F}_{el,par\,k/inst,k}}{m_{Ik}} \right) \\
& + \underbrace{K_{2k}}_{quad} \Gamma_{App,k/sat}^{\;2}
\end{aligned}$$

Expression of the differential measurement

- The test is performed at f_{ep} → the bias can be neglected
- The common acceleration corresponds to the residual of the drag free system and its command
- The differential acceleration is composed of the violation signal + the Earth gravity gradient and inertia tensor terms due to the off-centring of the masses

$$\Gamma_{mes,dx} = \frac{1}{2}K_{1cx}\cdot\delta\cdot g_{x/sat} + \frac{1}{2}\begin{bmatrix}K_{1cx}\\ \eta_{cz}+\theta_{cz}\\ \eta_{cy}-\theta_{cy}\end{bmatrix}^t \cdot [T - In]\cdot \begin{bmatrix}\Delta_x\\ \Delta_y\\ \Delta_z\end{bmatrix}$$

$$+ \begin{bmatrix}K_{1dx}\\ \eta_{dz}+\theta_{dz}\\ \eta_{dy}-\theta_{dy}\end{bmatrix}^t \cdot (\vec{\Gamma}_{res_{df}} + C_x) + 2\cdot K_{2cxx}\cdot\left(\Gamma_{app,dx}+b_{1dx}\right)\cdot\left(\Gamma_{res_{df},x}+C_x-b_{0cx}\right)$$

$$+K_{2dxx}\cdot\left(\left(\Gamma_{res_{df},x}+C_x-b_{0cx}\right)^2 + \left(\Gamma_{app,dx}+b_{1dx}\right)^2\right)$$

Earth gravity gradient tensor

Inertia tensor

EP violation signal

Drag free residual

Drag free command

Objective of accuracy

- Global objective: 10^{-15}g → 8×10^{-15} ms^{-2}
- Objective for $\Gamma_{mes,dx}$: 4×10^{-15} ms^{-2}
- Source of errors: mechanical defects, gravity gradient, thermal and magnetic effects
  → 40 groups of contributors
- Specification for each group: 10^{-16} ms^{-2}
- 3 groups are explicit in the measurement equation

Budget before calibration

Group	Signal element	Parameter concerned	Contribution before calibration ($m \cdot s^{-2}$)
Defects between the instrument and the satellite	$K_{1cx} \cdot T_{xx} \cdot \Delta_x$	$K_{1cx} \cdot \Delta_x$ < 20.2 µm	8.4×10^{-14}
	$K_{1cx} \cdot T_{xz} \cdot \Delta_z$	$K_{1cx} \cdot \Delta_z$ < 20.2 µm	8.6×10^{-14}
	$K_{1cx} \cdot T_{xy} \cdot \Delta_y$	$K_{1cx} \cdot \Delta y$ < 20.2 µm	6×10^{-16}
	$(\eta_{cz} + \theta_{cz}) \cdot T_{yy} \cdot \Delta_y$	$\eta_{cz} + \theta_{cz}$ <2.6×10^{-3} rad Δ_y < 20 µm	8.6×10^{-16}
	$(\eta_{cy} - \theta_{cy}) \cdot T_{zz} \cdot \Delta_z$	$\eta_{cy} - \theta_{cy}$ <2.6×10^{-3} rad Δ_z < 20 µm	6.4×10^{-16}
Defects between the two sensors	$2 \cdot K_{1dx} \cdot \Gamma_{res_{df},x}$	K_{1dx} < 10^{-2}	2×10^{-14}
	$2 \cdot (\eta_{dz} + \theta_{dz}) \cdot \Gamma_{res_{df},y}$	$\eta_{dz} + \theta_{dz}$ < 1.6×10^{-3} rad	3.0×10^{-15}
	$2 \cdot (\eta_{dy} - \theta_{dy}) \cdot \Gamma_{res_{df},z}$	$\eta_{dy} - \theta_{dy}$ < 1.6×10^{-3} rad	3.0×10^{-15}
Quadratic non linearities	$4 \cdot K_{2,cxx} \cdot \Gamma_{app,dx} \cdot \Gamma_{res_{df},x}$	K_{2cxx} < 20000 s^2/m	8.0×10^{-16}
	$2 \cdot K_{2,dxx} \cdot (\Gamma^2_{res_{df},x} + \Gamma^2_{app,dx})$	K_{2dxx} < 20000 s^2/m	8.0×10^{-16}
	Total = $\sum \lvert \ \rvert$		2×10^{-13}

A posteriori correction is required

Overview of the calibration

- Objective of accuracy of the correction:

$$\Gamma_{mes,d} - \frac{1}{2}\delta g - \Sigma\hat{E}_i = \Sigma\delta E_i < 3\times10^{-16} ms^{-2}$$

- Each group is specified to be < $10^{-16} ms^{-2}$

- Calibration of some parameters to correct the measurement

  → Create a signal that amplifies the effect of the parameter to be calibrated in $\Gamma_{mes,d}$
- Reduction of the noise limiting the calibration through integration over several orbits
- Improvement of the calibration performance by reassessing the estimation of a parameter using the estimated value of others

Defects between the instrument and the satellite

$$\Gamma_{mes,dx} = \frac{1}{2} K_{1cx} \cdot \delta \cdot g_{x/sat} + \frac{1}{2} \begin{bmatrix} K_{1cx} \\ \eta_{cz} + \theta_{cz} \\ \eta_{cy} - \theta_{cy} \end{bmatrix}^t \cdot [T - In] \cdot \begin{bmatrix} \Delta_x \\ \Delta_y \\ \Delta_z \end{bmatrix} + \begin{bmatrix} K_{1dx} \\ \eta_{dz} + \theta_{dz} \\ \eta_{dy} - \theta_{dy} \end{bmatrix}^t \cdot \left(\vec{\Gamma}_{res_{df}} + \vec{C}\right) + 2 \cdot K_{2cxx} \cdot \left(\Gamma_{app,dx} + b_{1dx}\right) \cdot \left(\Gamma_{res_{df},x} + C_x - b_{0cx}\right)$$
$$+ K_{2dxx} \cdot \left(\left(\Gamma_{res_{df},x} + C_x - b_{0cx}\right)^2 + \left(\Gamma_{app,dx} + b_{1dx}\right)^2 \right)$$

Signal element
$K_{1cx} \cdot \Delta_x \cdot T_{xx}$
$K_{1cx} \cdot \Delta_z \cdot T_{xz}$
$K_{1cx} \cdot \Delta_y \cdot T_{xy}$
$\left(\eta_{cz} + \theta_{cz}\right) \cdot T_{yy} \cdot \Delta_y$
$\left(\eta_{cy} - \theta_{cy}\right) \cdot T_{zz} \cdot \Delta_z$

Use the important value of T_{xx} and T_{xz} at $2f_{orb}$. For $K_{1cx} \cdot \Delta_x$: $\Gamma_{calib1} = 2 \cdot \Gamma_{mes,dx/\cos}\left(2 f_{orb}\right) = \hat{T}_{xx}\left(2 f_{orb}\right) \cdot K_{1cx} \cdot \Delta_x$

T_{xy} is too weak → oscillate the satellite around Y_{sat}: $\Gamma_{calib1} = 2 \cdot \Gamma_{mes,dx}\left(f_{cal}\right) = \hat{\alpha}_0 \cdot \left[\hat{T}_{yy}(DC) - \hat{T}_{xx}(DC) - \omega_{cal}^2\right] \cdot K_{1cx} \Delta_y$

Oscillate the satellite around an axis and oscillate the mass along an other axis → Coriolis effect. For $\left(\eta_{cy} - \theta_{cy}\right)$:

$$\Gamma_{calib1} = 2 \cdot \Gamma_{mes,dx}\left(f_{cor}\right)$$
$$= \left(\eta_{cy} - \theta_{cy}\right) \cdot \frac{\overbrace{\Delta_{TM} \cdot (1 + g_{\det_y})}^{\wedge}}{2} \cdot \left(-2 \hat{\alpha}_0 \omega_{TM} \omega_{cal} + \hat{\alpha}_0 \left[\hat{T}_{zz}(DC) - \hat{T}_{yy}(DC) + \omega^2{}_{cal} \right] \right)$$

Δx, y, z cannot be reduced
T is very well known

- Parameter to be calibrated
- Signal amplifier

Defects between the two sensors

$$\Gamma_{mes,dx} = \frac{1}{2} K_{1cx} \cdot \delta \cdot g_{x/sat} + \frac{1}{2} \begin{bmatrix} K_{1cx} \\ \eta_{cz} + \theta_{cz} \\ \eta_{cy} - \theta_{cy} \end{bmatrix}^t \cdot [T - In] \cdot \begin{bmatrix} \Delta_x \\ \Delta_y \\ \Delta_z \end{bmatrix} + \begin{bmatrix} K_{1dx} \\ \eta_{dz} + \theta_{dz} \\ \eta_{dy} - \theta_{dy} \end{bmatrix}^t \cdot \left(\vec{\Gamma}_{res_{df}} + \vec{C} \right) + 2 \cdot K_{2cxx} \cdot \left(\Gamma_{app,dx} + b_{1dx} \right) \cdot \left(\Gamma_{res_{df},x} + C_x - b_{0cx} \right)$$

$$+ K_{2dxx} \cdot \left(\left(\Gamma_{res_{df},x} + C_x - b_{0cx} \right)^2 + \left(\Gamma_{app,dx} + b_{1dx} \right)^2 \right)$$

$$\Theta_{dz} = \frac{\eta_{dz} + \theta_{dz}}{K_{1cy}} - \frac{K_{1dx} \left(\eta_{cz} + \theta_{cz} \right)}{K_{1cx} \cdot K_{1cy}}$$

$$\Theta_{dy} = \frac{\eta_{dy} - \theta_{dy}}{K_{1cz}} - \frac{K_{1dx} \left(\eta_{cy} - \theta_{cy} \right)}{K_{1cx} \cdot K_{1cz}}$$

Signal element
$2 \cdot K_{1dx} \cdot \Gamma_{res_{df},x}$
$2 \cdot \left(\eta_{dy} - \theta_{dy} \right) \cdot \Gamma_{res_{df},z}$
$2 \cdot \left(\eta_{dz} + \theta_{dz} \right) \cdot \Gamma_{res_{df},y}$

Drag free limitation

Oscillate the satellite along each axis. The measured acceleration is controlled to follow a sine

Along X_{inst}: $\Gamma_{calib1} = \Gamma_{mes,dx}\left(f_{cal} \right) = \frac{K_{1dx}}{K_{1cx}} \cdot \Gamma_{mes,cx}\left(f_{cal} \right)$

Along Y_{inst}: $\Gamma_{calib1} = \Gamma_{mes,dx}\left(f_{cal} \right) = \Theta_{dy} \cdot \Gamma_{mes,cz}\left(f_{cal} \right)$

Along Z_{inst}: $\Gamma_{calib1} = \Gamma_{mes,dx}\left(f_{cal} \right) = \Theta_{dz} \cdot \Gamma_{mes,cy}\left(f_{cal} \right)$

Quadratic non linearities

$$\Gamma_{mes,1x} = \begin{bmatrix} K_{11x} \\ \eta_{1z} + \theta_{1z} \\ \eta_{1y} - \theta_{1y} \end{bmatrix}^t \cdot \Gamma_{app,1/sat} + K_{21xx} \cdot \vec{\Gamma}^2_{App,1x/sat}$$

Signal element
$2 \cdot K_{2,dxx} \cdot \left(\Gamma^2_{res_{df},x} + \Gamma^2_{app,dx}\right)$
$4 \cdot K_{2,cxx} \cdot \Gamma_{app,dx} \cdot \Gamma_{res_{df},x}$

Oscillate the satellite along X_{inst}. The measured acceleration is controlled to follow a sine

$$\Gamma_{calib1} = \Gamma_{mes,dx}(2 f_{cal}) = \frac{1}{2} \frac{K_{2dxx}}{K^2_{1cx}} \left(\Gamma_{mes,cx}(f_{cal})\right)^2$$

Calibrate K_{21} and K_{22}. For K_{21} (resp. K_{22}), drag compensation locked on the sensor 2 (resp. 1) and oscillation of the proof mass 1 (resp. 2) along X_{inst}

$$\Gamma_{calib1} = \Gamma_{mes,1x}(2 f'_{TM}) = \frac{1}{2} \frac{K_{21xx}}{K^2_{11x}} \Gamma^2{}_{mes,1x}(f'_{TM})$$

$$\Gamma_{calib1} = \Gamma_{mes,2x}(2 f'_{TM}) = \frac{1}{2} \frac{K_{22xx}}{K^2_{12x}} \Gamma^2{}_{mes,2x}(f'_{TM})$$

$$\rightarrow \frac{K_{2cxx}}{K^2_{1cx}}$$

Exemple of a calibration process: $K_{1cx}\Delta x$

- Global equation

$$2\cdot\Gamma_{mes,dx/\cos}(2f_{orb}) \approx \overbrace{T_{xx}(2f_{orb})\cdot K_{1cx}\cdot\Delta_x}^{\text{to be extracted}} + (\eta_{cy}-\theta_{cy})\cdot T_{zz}(2f_{orb})\cdot\Delta_z$$
$$+2\cdot K_{1dx}\cdot\Gamma_{res_{df},x}(2f_{orb}) + 2\cdot(\eta_{dz}+\theta_{dz})\cdot\Gamma_{res_{df},y}(2f_{orb}) + 2\cdot(\eta_{dy}-\theta_{dy})\cdot\Gamma_{res_{df},z}(2f_{orb})$$
$$+4\cdot K_{2cxx}\cdot\{(\Gamma_{app,dx}+b_{1dx})\cdot(\Gamma_{res_{df},x}+C_x-b_{0cx})\}(2f_{orb})$$
$$+2\cdot K_{2dxx}\cdot\{(\Gamma_{res_{df},x}+C_x-b_{0cx})^2+(\Gamma_{app,dx}+b_{1dx})^2\}(2f_{orb}) + 2\cdot\Gamma_{n,dx}$$

- The calibration equation is: $\Gamma_{calib1} = 2\cdot\Gamma_{mes,dx/\cos}(2f_{orb}) = \hat{T}_{xx}(2f_{orb})\cdot K_{1cx}\cdot\Delta_x$

- Some contributors lead to a systematic error and a stochastic error. The stochastic limitation is accounted for as: $3\frac{DSP_{noise}}{\sqrt{T_{cal}}}$

- The 2nd iteration calibration equation is:

$$\Gamma_{calib2} = 2\cdot\Gamma_{mes,dx/\cos}(2f_{orb}) - \widehat{(\eta_{cy}-\theta_{cy})}\cdot\hat{T}_{zz}(2f_{orb})\cdot\hat{\Delta}_z - 2\cdot\hat{K}_{1dx}\cdot\Gamma_{mes,cx}(2f_{orb})$$
$$-2\cdot\widehat{(\eta_{dz}+\theta_{dz})}\cdot\Gamma_{mes,cy}(2f_{orb}) - 2\cdot\widehat{(\eta_{dy}-\theta_{dy})}\cdot\Gamma_{mes,cz}(2f_{orb})$$
$$=\hat{T}_{xx}(2f_{orb})\cdot K_{1cx}\cdot\Delta_x$$

Evaluated calibration budget

T_{cal} = 10 orbits

Parameter to be calibrated	Perfo. After 1 round of calibration	Perfo. After 2 round of calibration	Specification
$K_{1cx} \cdot \Delta_x$	0.15 µm	0.08 µm	0.1 µm
$K_{1cx} \cdot \Delta_z$	0.16 µm	0.08 µm	0.1 µm
$K_{1cx} \cdot \Delta_y$	1.3 µm	1.3 µm	2 µm
$(\eta_{cz} + \theta_{cz})$	1.7×10^{-3} rad	1.1×10^{-3} rad	1.0×10^{-3} rad
$(\eta_{cy} - \theta_{cy})$	1.7×10^{-3} rad	1.0×10^{-3} rad	1.0×10^{-3} rad
K_{1dx} / K_{1cx}	2.3×10^{-3}	2.3×10^{-3}	1.5·10^{-4}
$\frac{\eta_{dz} + \theta_{dz}}{K_{1cy}}$	5.9×10^{-5} rad	1.7×10^{-5} rad	5·10^{-5} rad
$\frac{\eta_{dy} - \theta_{dy}}{K_{1cz}}$	5.9×10^{-5} rad	1.7×10^{-5} rad	5·10^{-5} rad
K_{2dxx} / K_{1cx}^2	1206.6 s²/m	188.7 s²/m	250 s²/m
K_{2cxx} / K_{1cx}^2	271.7 s²/m	271.7 s²/m	250 s²/m

Calibrated at 1st iteration → ($K_{1cx} \cdot \Delta_y$)

Unsufficiently calibrated → (K_{1dx} / K_{1cx})

To be corrected with non linear term: evaluate (K1+2K2b1)d the actual sensitivity about the b1 acceleration level

Conclusion (1/2)

- Payload:
  - Integration of the qualification model of the accelerometer realized
  - 06-09/2010: Free fall tests in Bremen
  - 10-11/2010: Qualification tests with the QM: vibrations, thermal vacuum, shock
  - 01-06/2011: flight model, tests
- Satellite:
  - Study of the cold gas propulsion
  - 2011: Preliminary definition of the flight model
  - 2012: Definition of the FM
  - 2013: Integration of the payload
  - 2014: launch

Conclusion (2/2)

- Calibration process definition
  - The budget of the measurement equation before calibration does not comply with the objective of the EP test accuracy
  - Several in flight calibrations are necessary during the space experiment
  - Parameters to be calibrated have been identified and appropriate methods of calibration have been proposed
  - The calibration accuracy has been analytically evaluated. All parameters are estimated with sufficient accuracy → differential scale factor to be more investigated taking into account non linearity
  - Next step: simulation of the calibration with satellite attitude and drag-free system

Sensor Unit (2/2)