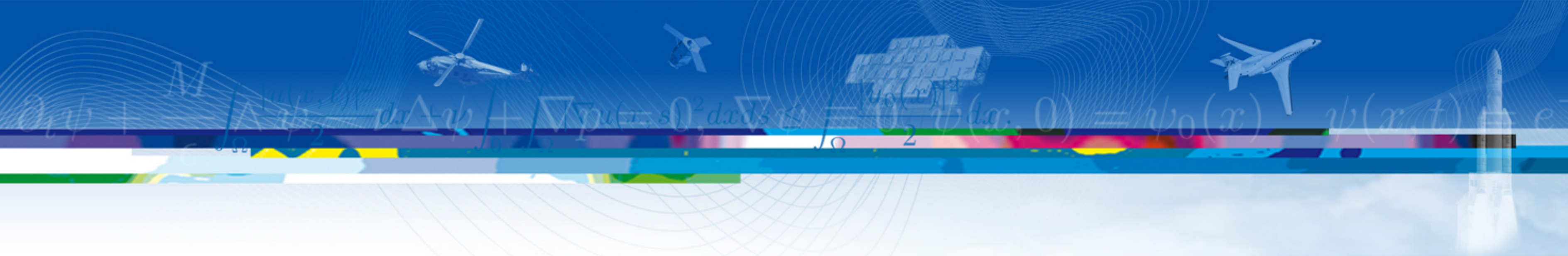


MICROSCOPE – Testing the weak Equivalence Principle in Space

P. Touboul on behalf of the MICROSCOPE team

Team in Onera:

Y. Alonso, D. Boulanger, R. Blum, R. Chhun, Y. Durand, B. Foulon, E. Hardy, P.D. Maigret, P. Flinoise, C. Gageant, P. Kayser, V. Lebat, P. Leseur, J. Bergé, PA Huynh, F. Liorzou, M. Pernice, E. Perrot, M. Rodrigues, A. Rebray, N. Tanguy. P. Touboul

Team in CNRS-OCA, Gilles Métris , L. Serron et al.

Team in PTB, Franck Löffler, D. Hagedorn et al.

Team in ZARM, Claus Lammerzahl, Hanns Selig et al.

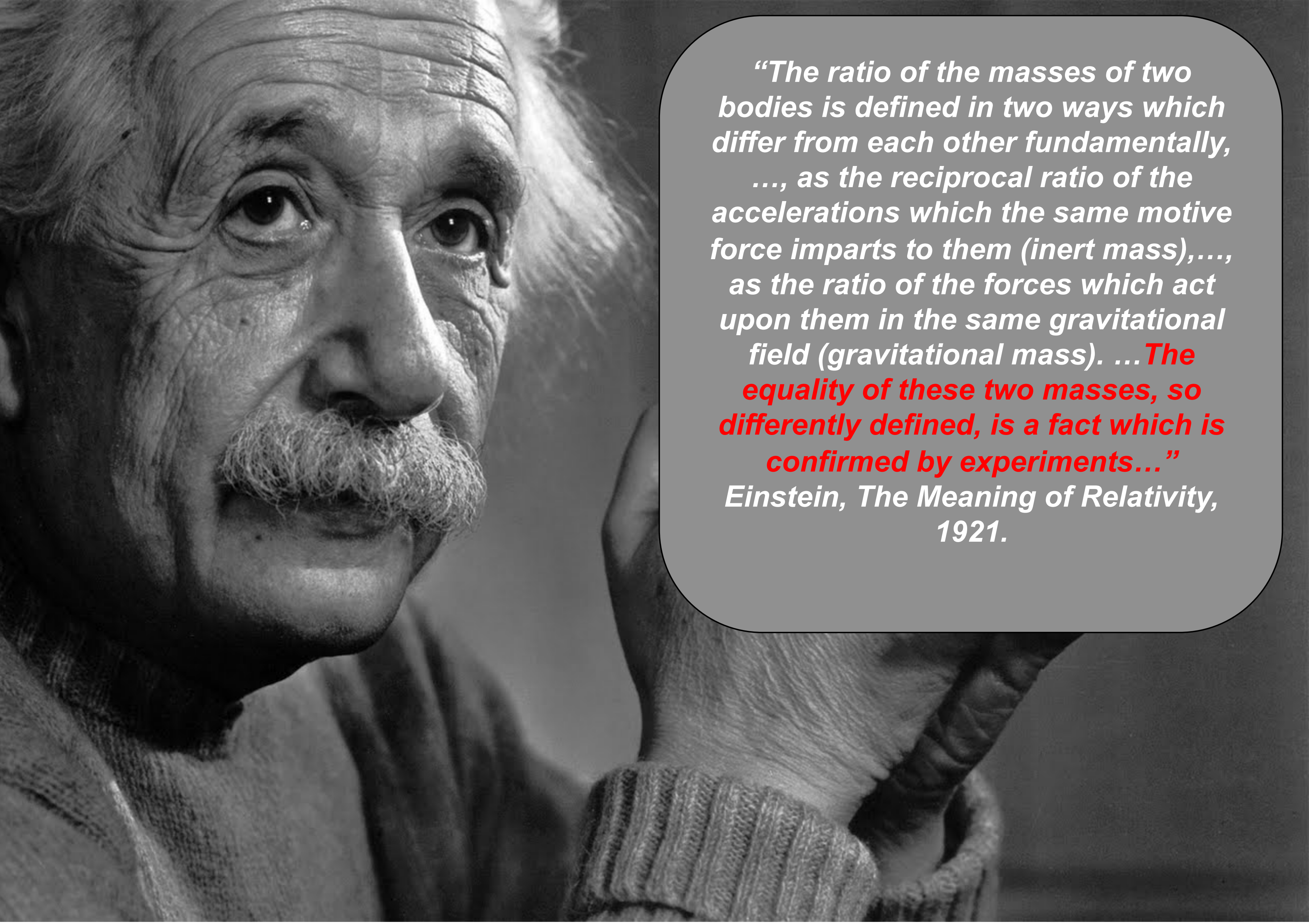
Team in DLR, Hansjoerg Dittus et al.

Team in Cnes, Sylvie Léon Hirtz, Y. André, Alain Robert et al.

Observatoire de la Côte d'Azur

Physikalisch-Technische Bundesanstalt

retour sur innovation



"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…"

Einstein, The Meaning of Relativity, 1921.

The Equivalence Principle

General Relativity

Weak EP → Universality of free fall : all bodies, independently of their mass or intrinsic composition, acquire the same acceleration in the same uniform gravity field

$$\frac{M_G}{M_I} = 1$$

Quantum mechanics & General Relativity

Unification of the 4 interactions

Alternative theories

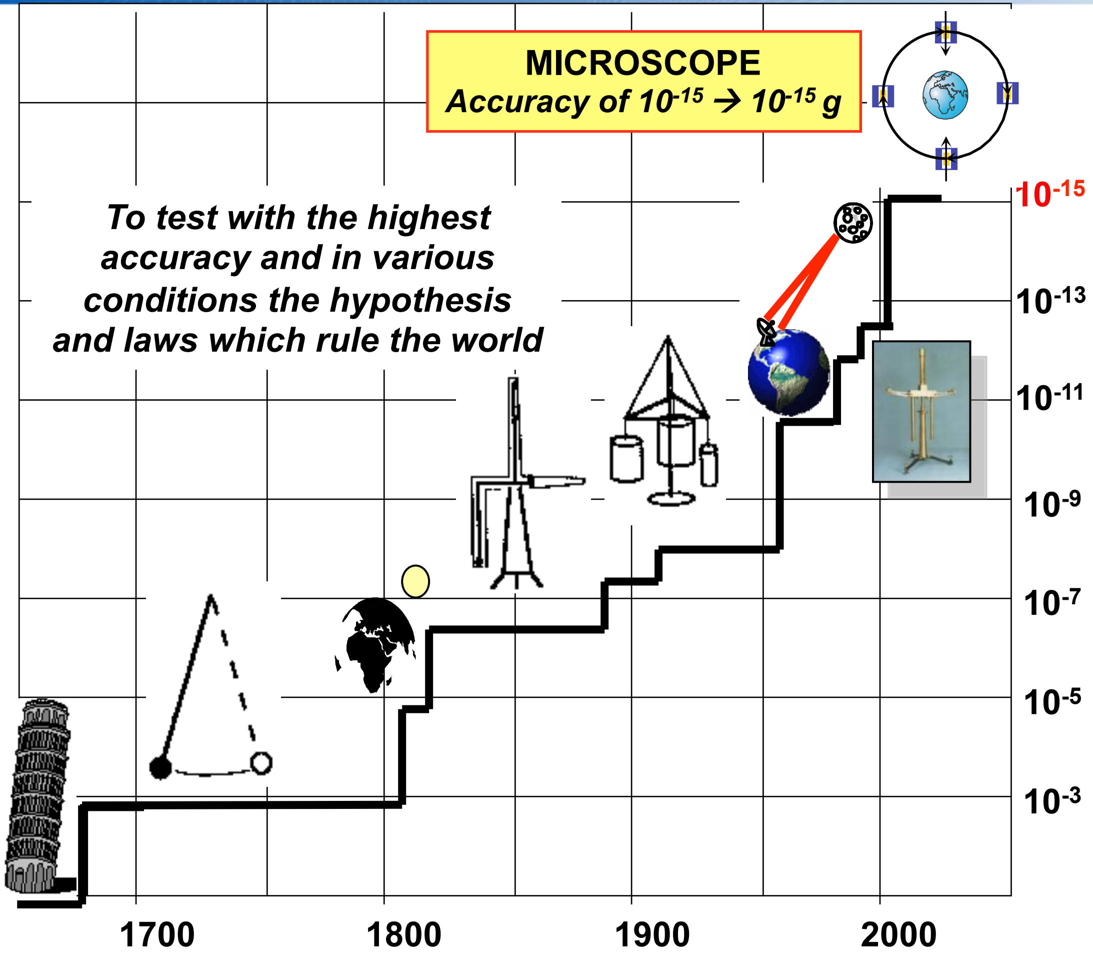
þ New interaction?

þNew particles ?

Dark mass

Dark energy

þ Equivalence Principle violation?



MICROSCOPE

Accuracy of 10^{-15} → 10^{-15} g

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

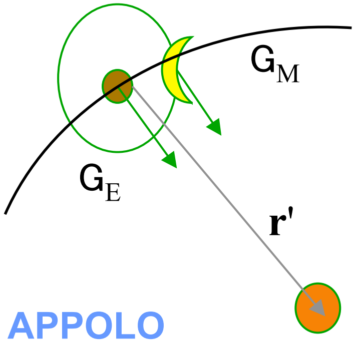
MICROSCOPE space experiment: test of the Equivalence Principle with an accuracy of 10^{-15}

Best present EP tests

Laser Ranging

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

- **laser impulse 100ps (10^{20} emitted photons)**
- **1 photon detected back for every 100 pulses**
- **EP Test from 20 years' ranging**



J. G. Williams, X. X. Newhall, and J. O. Dickey, Phys.Rev. D 53, 6730 (1996).

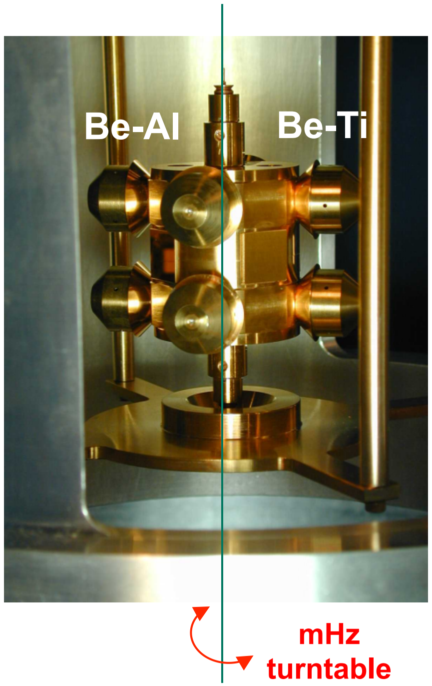
APPOLO

(Apache Point Observatory Lunar Laser-ranging Operation)

APOLLO : Lunar laser Tracking Millimeter range precision, APOLLO will in particular test:
- **first, the Strong Equivalence Principle (SEP) to 10^{-5}**
- **de Sitter relativistic precession to a few parts in 10^4**
- **the time variation of the gravitational constant G to 1 / 10^{13} per year.**

arXiv:0710.0890v2 [astro-ph] 8 Nov 2007, T.W. Murphy, Jr., E.G. Adelberger, et al.

Eötwash group (2012)

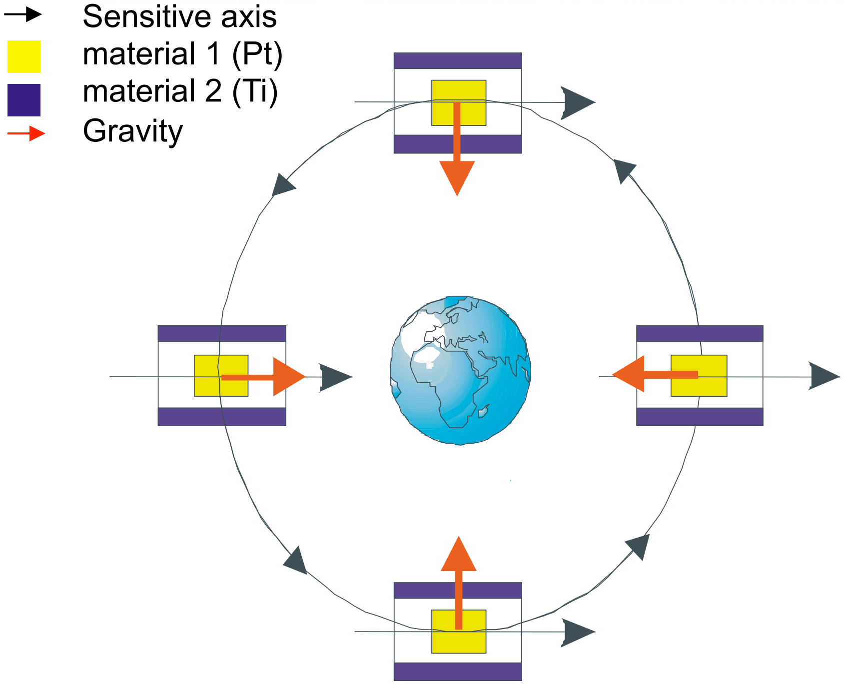


Earth's Horizontal gravity In Seatle 1.68cm s^{-2}

$d \sim 10^{-13}$

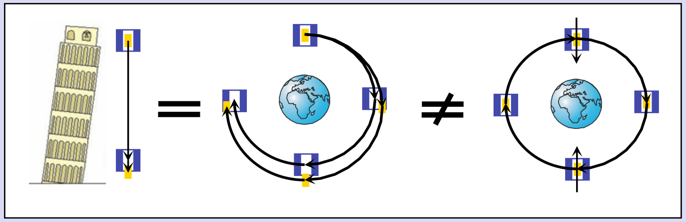
aN(Be) − aN(Ti) = (+0.6 ± 3.1) × 10^{-15} m/s^2
aW(Be) − aW(Ti) = (−2.5 ± 3.5) × 10^{-15} m/s^2
→ η (Be,Ti) = (+0.3 ± 1.8) × 10^{-13} in 75 days of data
aN(Be) − aN(Al) = (−2.6 ± 2.5) × 10^{-15} m/s^2
aW(Be) − aW(Al) = (+0.7 ± 2.5) × 10^{-15} m/s^2
→η (Be,Al) = (−1.5 ± 1.5) × 10^{-13} in 96 days of data

The principle of the MICROSCOPE space mission


→ Sensitive axis
🟨 material 1 (Pt)
🟪 material 2 (Ti)
→ Gravity

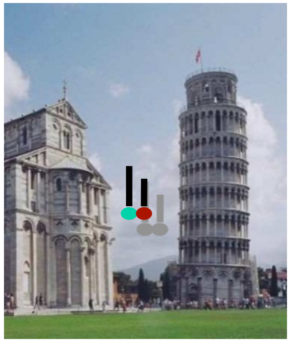
- Gravitational source: the Earth
- inertial acceleration: orbital motion
- 2 masses of different composition: controlled on the same orbit (< 10^{-11}m) by electrostatic pressures

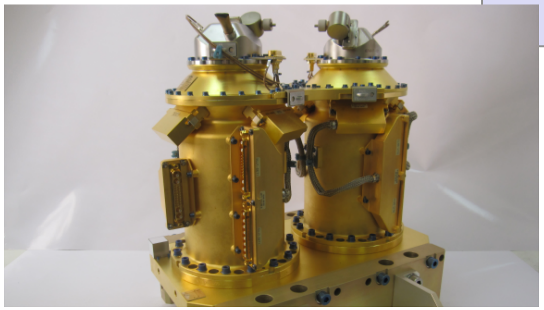
→ Steady configuration, control of the satellite



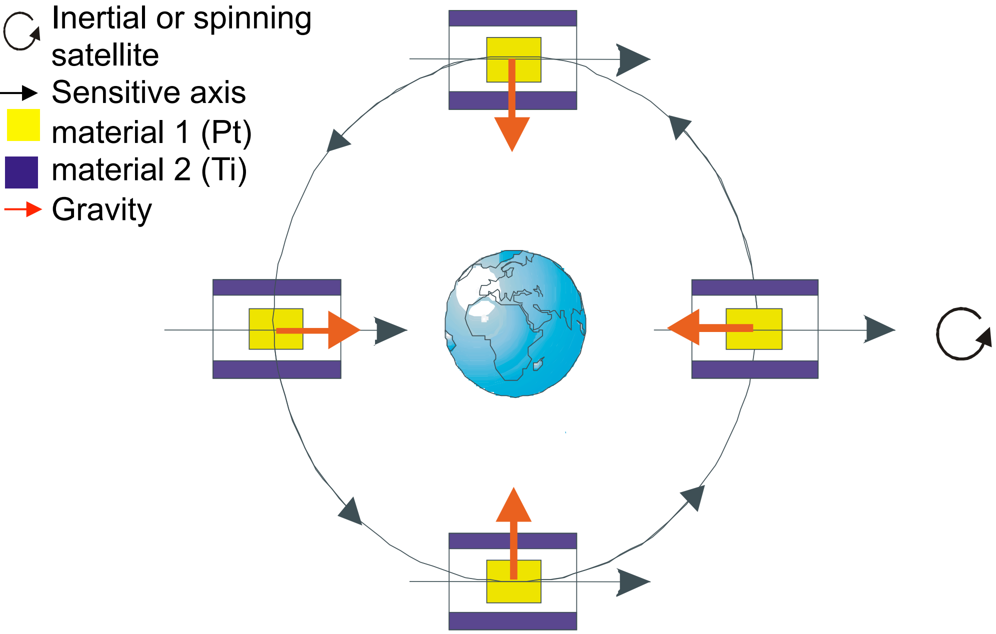
- Time span of the measurement: non limited by the free fall (> 20 orbits)
- Environment: limited and controlled perturbations, drag-free satellite
- Signal along Earth monopole direction: well defined phase & frequency

Galilée (1590)





The principle of the MICROSCOPE space mission



- ↻ Inertial or spinning satellite
- → Sensitive axis
- 🟨 material 1 (Pt)
- 🟪 material 2 (Ti)
- → Gravity

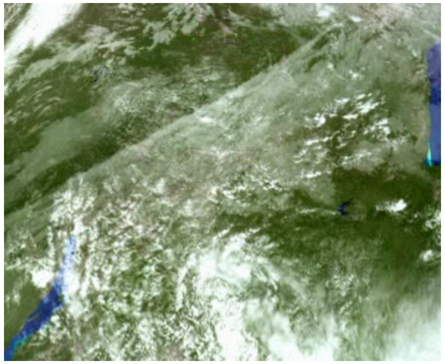
CNES MYRIADE Microsatellite

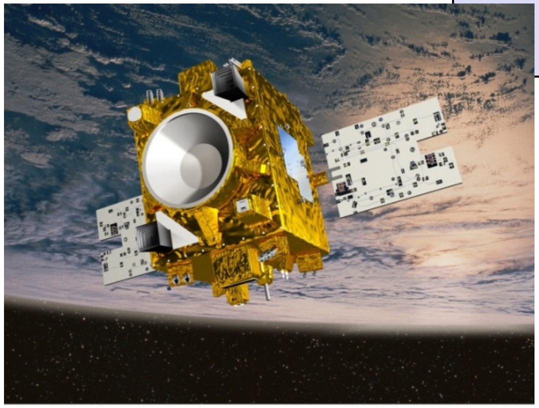
- Circular Orbit: 700 km, e < 5.10^{-3}

  Control of the gravity gradient
- Inertial or Rotating: 7.10^{-3} rd/s

  Control of the kinetic acceleration
- Mission duration: 2 years depending of thrust gas
- Mass of microsatellite : 320 kg
- Payload budgets: 35 kg, 40 Watts
- 2 differential electrostatic accelerometers

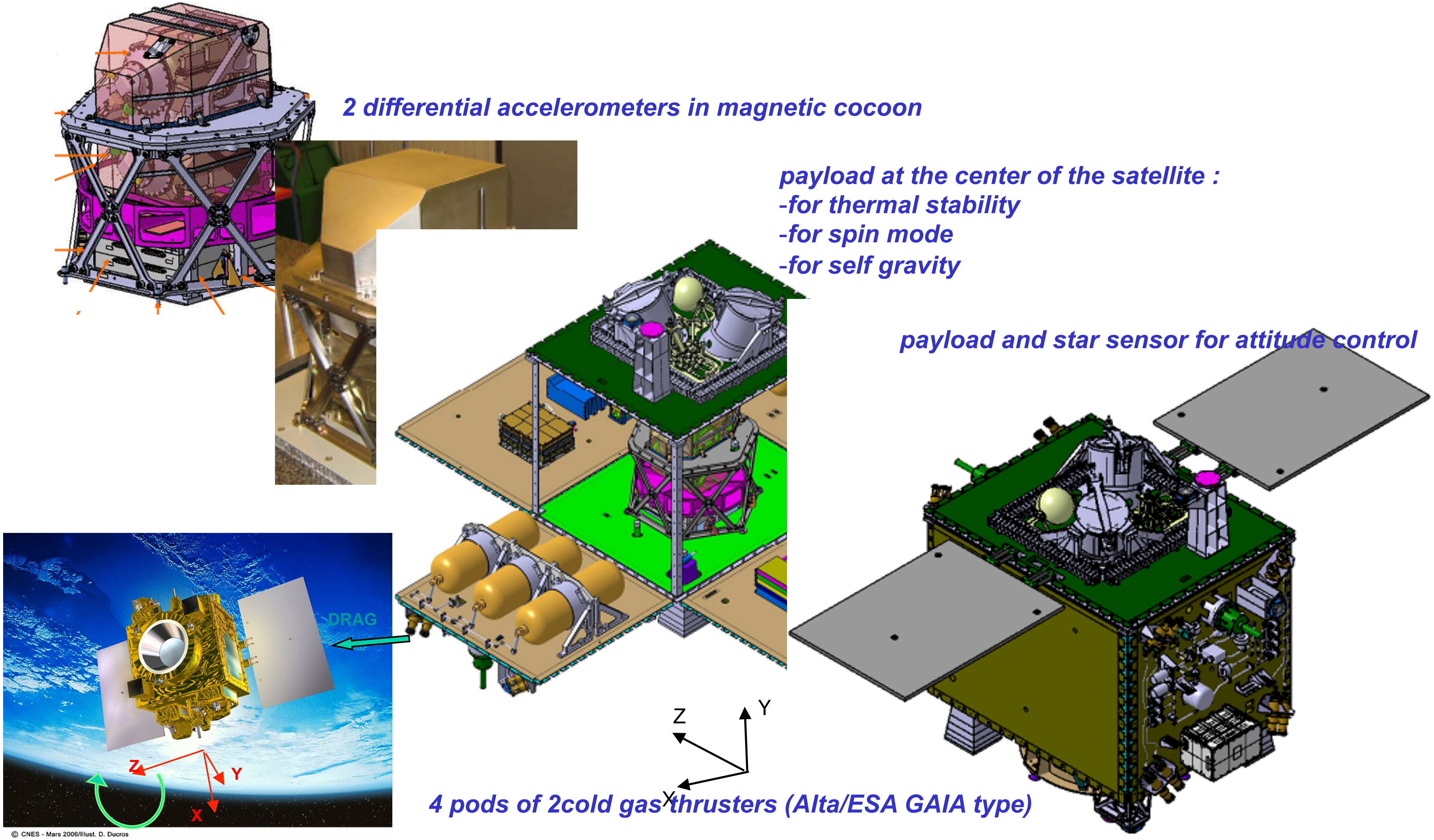
  (2 pairs of masses: Pt/Pt & Pt/Ti)
- $f_{ep} = f_{orb} + f_{spin}$
  - ➢ Inertial mode: $f_{spin} = 0$
  - ➢ Spinning mode: $f_{spin} = 7/2$ or $9/2\ f_{orb}$





© CNES - Juillet 2012 / Illust. D. Ducros

MICROSCOPE Satellite



© CNES - Mars 2006/Illust. D. Ducros

2 differential accelerometers in thermal cocoon

2 differential accelerometers in magnetic cocoon

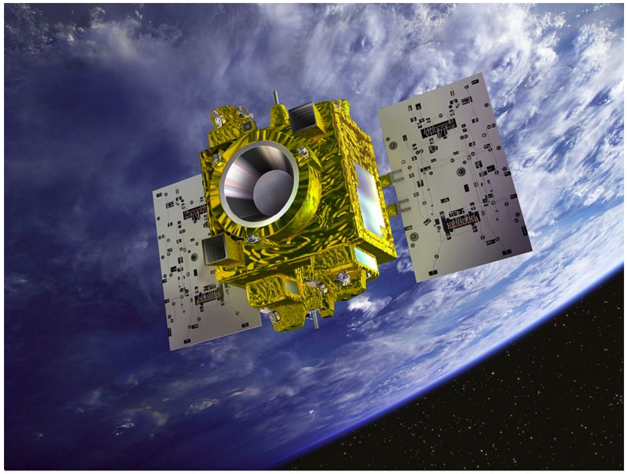
payload at the center of the satellite :
-for thermal stability
-for spin mode
-for self gravity

payload and star sensor for attitude control

4 pods of 2cold gas thrusters (Alta/ESA GAIA type)

Instrument accomodation : a dedicated passive thermal control

- ☐ *Heliosynchronous orbit : steady external configuration*
- ☐ *3 locations for the payload units versus thermal requirements*
- ☐ *Fine passive decoupling and well protected radiator from Earth radiations*
- ☐ *Models and dedicated Tests performed in 09-10 confirm :*
- ✓ *the thermal case fine insulation*
- ✓ *the instrument low sensitivities of mechanical core & Electronics*
- ✓ *the low power consumption and fluctuations*



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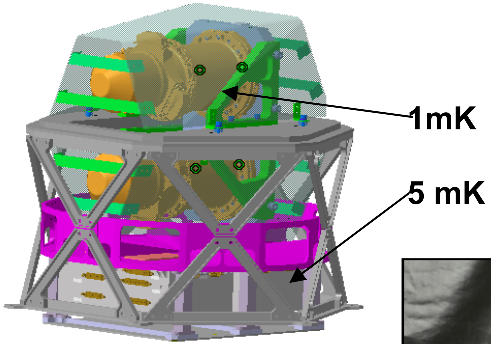
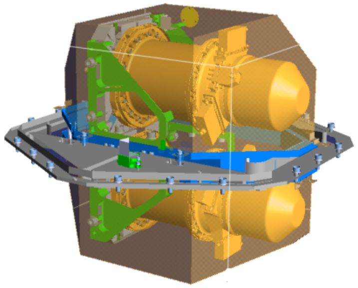
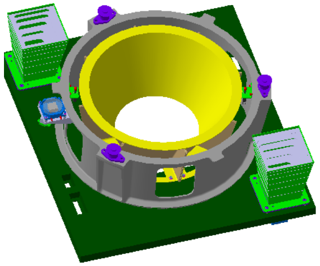
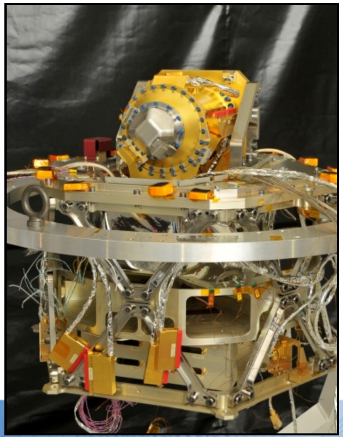
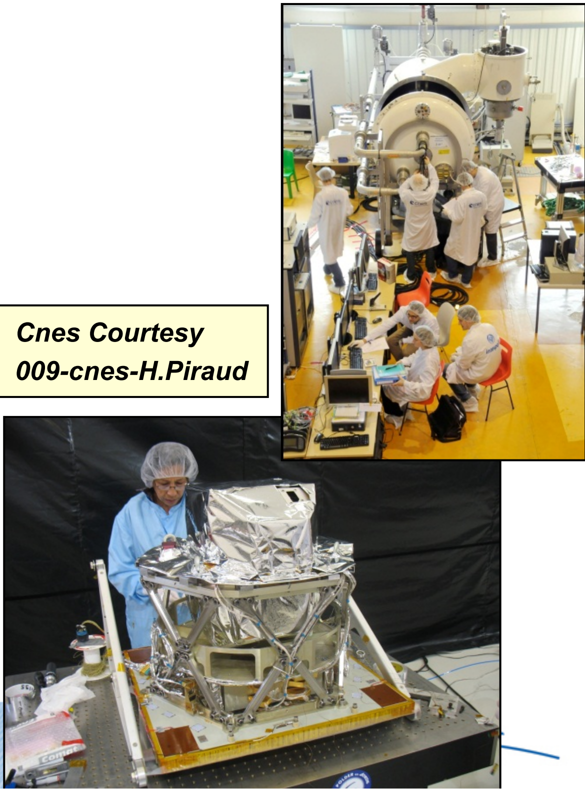










Cnes Courtesy
009-cnes-H.Piraud

KP Perfo, CDR Propulsion, CDR satellite

- ☐ Reviews : 25-27 mars 2014
- ☐ Director Comitee : 15 mai 2014

=> Design & Sub-system procurement compatible with mission specs

Integration with launch objective as soon as Feb. 2016 with Sentinel 1B / Soyouz

PK Performances MICROSCOPE
Introduction

Michel BACH - PO/EU

CNES MICROSCOPE Project Manager

25 mars 2014

PK Performances– Toulouse : 25/03/2014 – Michel Bach

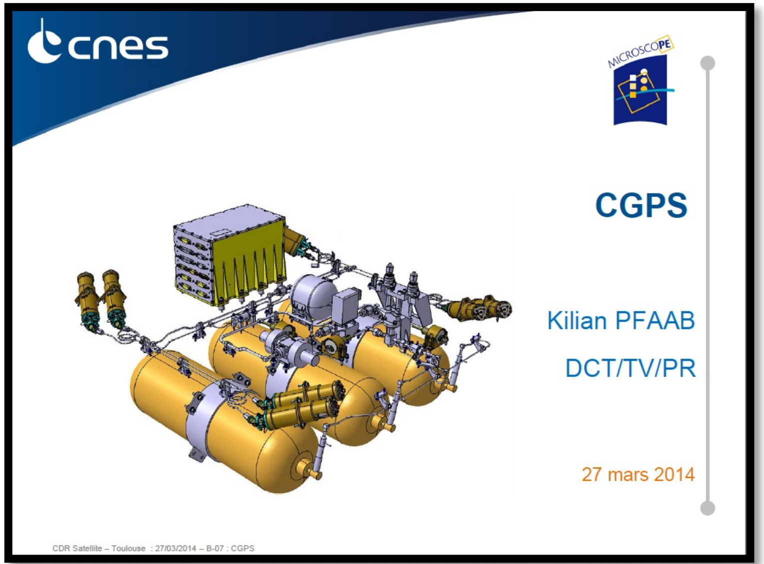
RCD Satellite MICROSCOPE
Introduction

Michel BACH - PO/EU

CNES MICROSCOPE Project Manager

27 mars 2014

CDR Satellite – Toulouse : 27/03/2014 – Michel Bach



CGPS

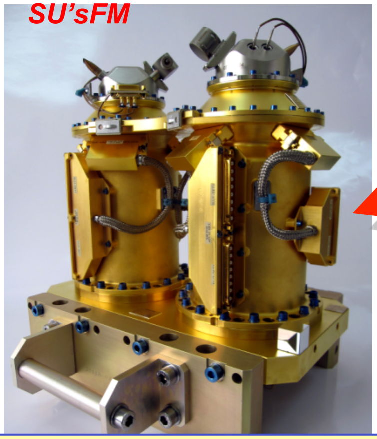
Kilian PFAAB

DCT/TV/PR

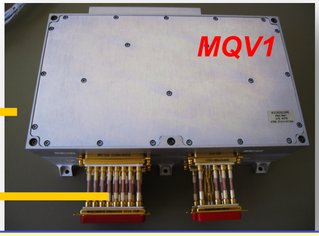
27 mars 2014

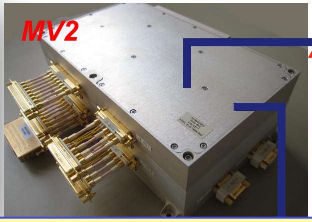
CDR Satellite – Toulouse : 27/03/2014 – B-07 : CGPS

The instrument



360 x 348 x 180 mm^3 - 25kg





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

30 cm x 25 cm x 11 cm – 5kg – 2 x 11W

- 2 identic sensor Unit = differential accelerometers

Each with 2 concentric Test-Masses (Pt-Rh/Pt-Rh or Ti/Pt-Rh)
Each mass controlled independently → inertial sensor

- 2 Low noise Electronics Units : one per couple of masses

For each test mass :
Capacitive sensing
Control of Proof-mas with electrode charges
Digital interface with computer and then s/c data bus

- 2 Digital Control Units
  - Each Unit embarks :

- 1 (DSP + FPGA) for 2 test-mass control and data conditioning for the On Board Computer

- 2 Power Control Unit (nominal + redundant)
  - converts the sat 28V in very stable secondary voltages (+/-48V, +/-15V,+5V,3.3V)

MICROSCOPE instrument configuration

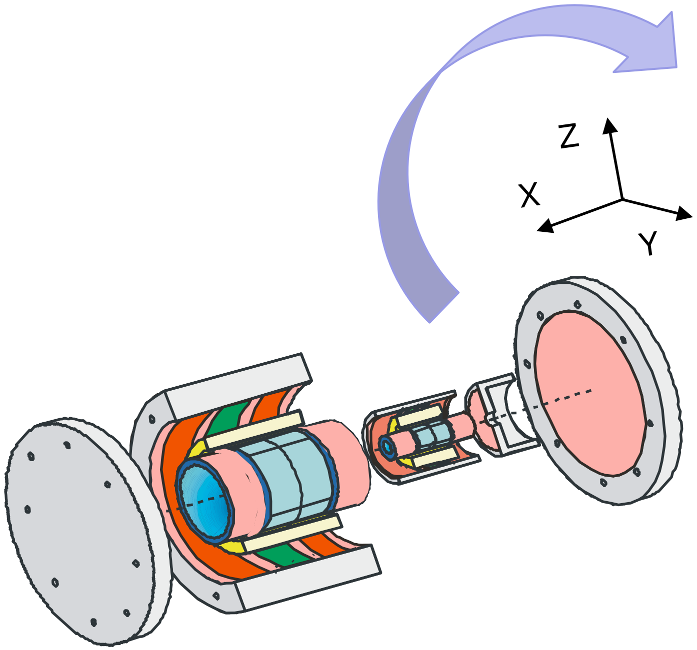
- **2 identic instruments, each including one pair of masses :**

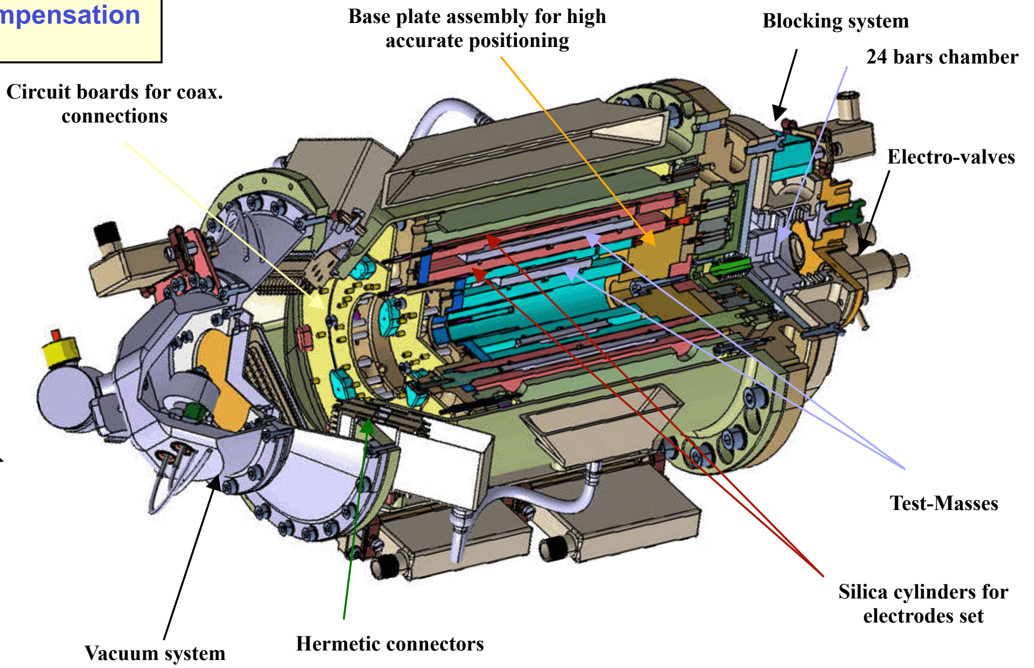
→ 2 pairs of masses : Pt / Pt & Pt / Ti

→ Double difference of four inertial sensor outputs

→ Scientific data &

→ AOCS data for pointing and continuous drag compensation

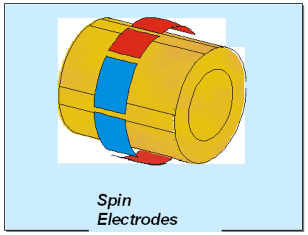


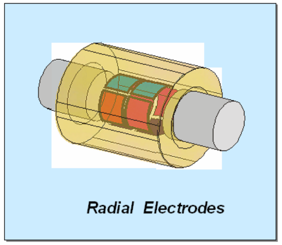


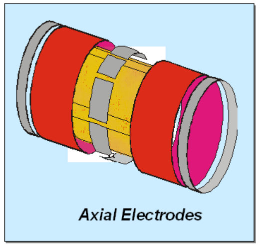
Precise test-mass servo positioning thanks to

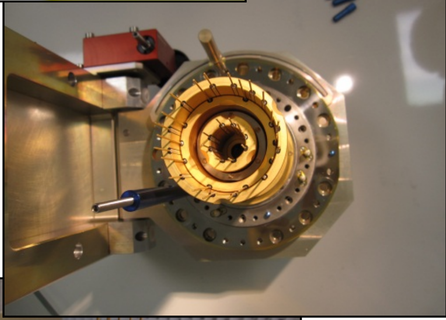
- **accurate machining**
- **accurate metrology and integration**
- **low noise electronics**
- **thermal stability**

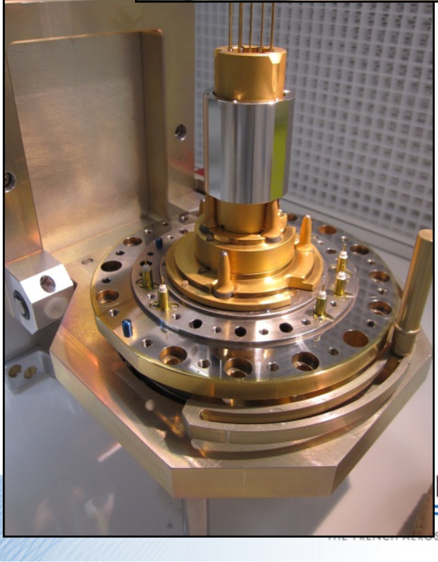
Instrument Measurement


Spin Electrodes


Radial Electrodes


Axial Electrodes



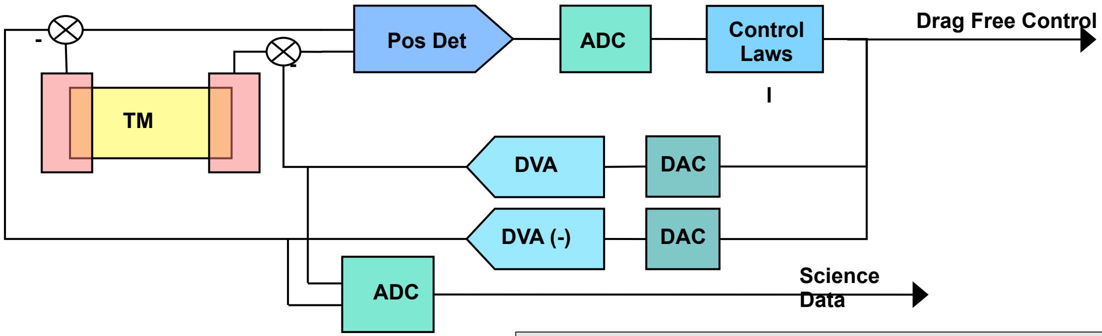


For each mass :

3 types of electrodes to control all six degrees of freedom

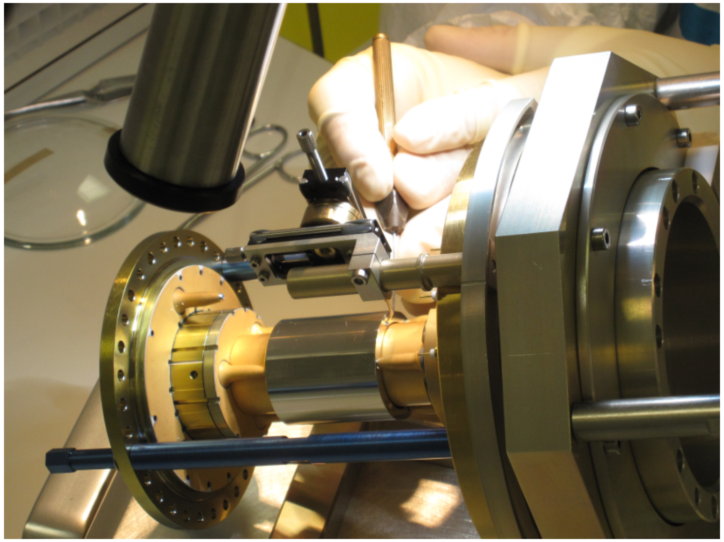
→ 6 servo-loop channels :

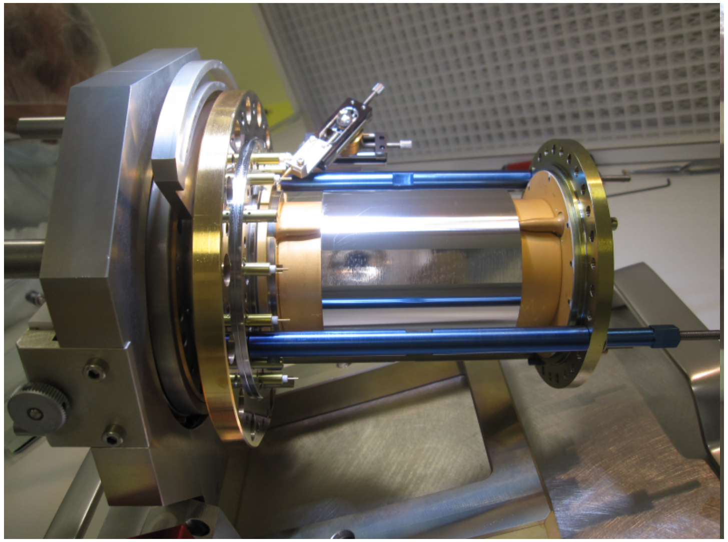
- **Axial x, position = ring electrodes**
- **Rotation about x = 4 pairs of electrodes in regard to the mass flat areas**
- **Radial y and z, position and rotation = quadrant electrodes**



- ✓ Steady configuration
  - → *Patch effect*
- ✓ Cold damping + Thin gold wire
  - → *Niquist fluctuations*
- ✓ Operation at switch on
- ✓ Same electrodes for actuation and action

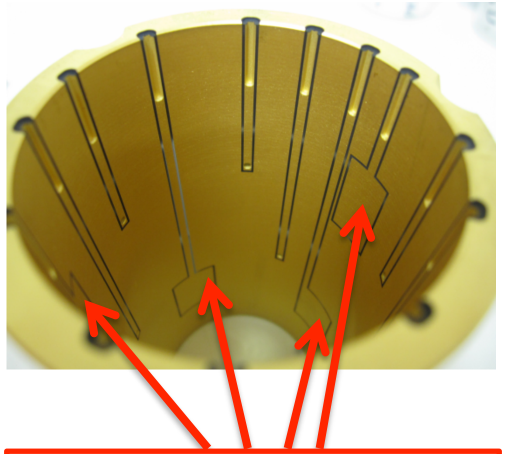
Integration of the Core is a challenging task accuracy, robustness, repeatability



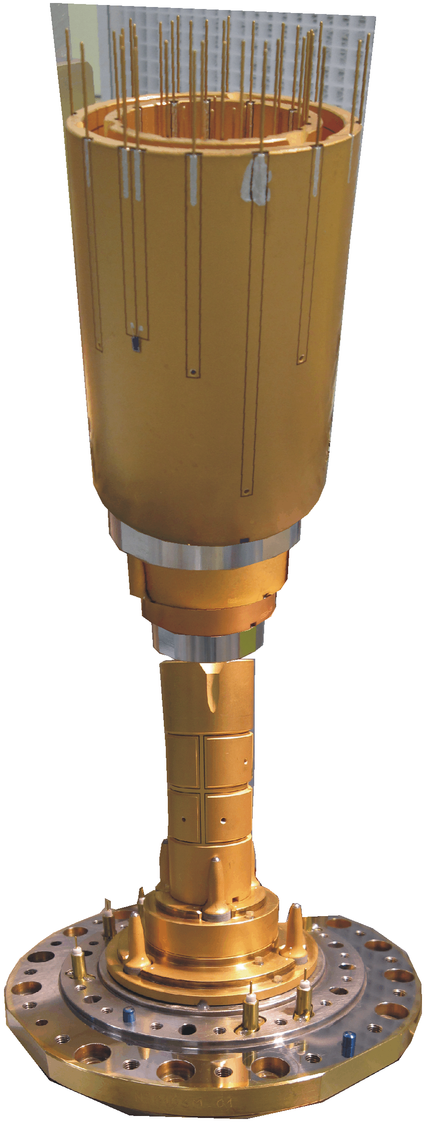


__7 µm gold wire :__

- *To maintain a stable voltage on test-masses*
- *To apply a 100kHz voltage for capacitive detection*



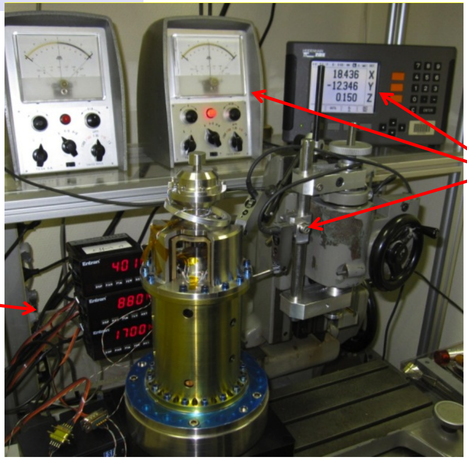
Electrodes to control inertial sensor alignment & centering during ground operations



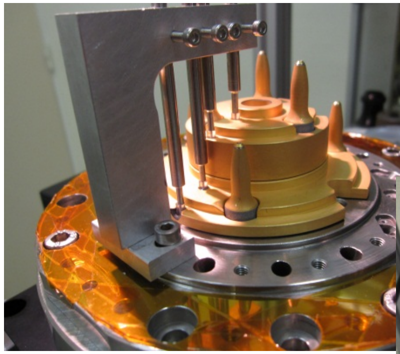
Electrostatic configuration geometry

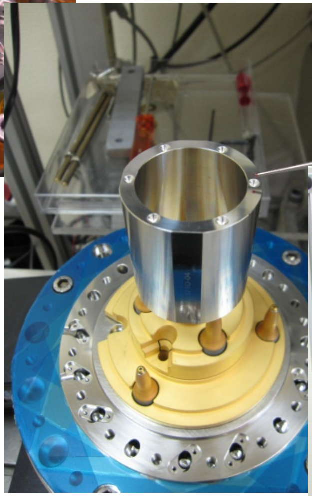
Integration of T-SAGE instrument FM : 1 year

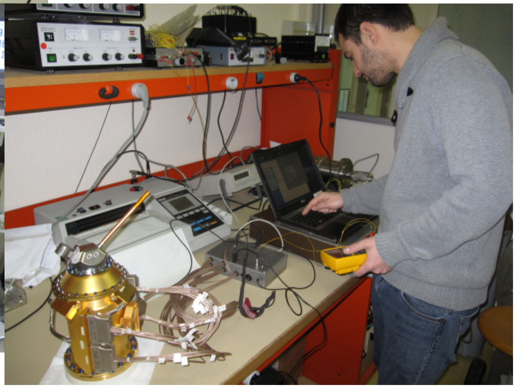
200 points of control per sensor
Adjustment of the centering of the two masses of the same accelerometer
Adjustment of the mass free motion
Adjustment of the clamping mechanism


Contrôle du déplacement des masses

Efforts de blocage

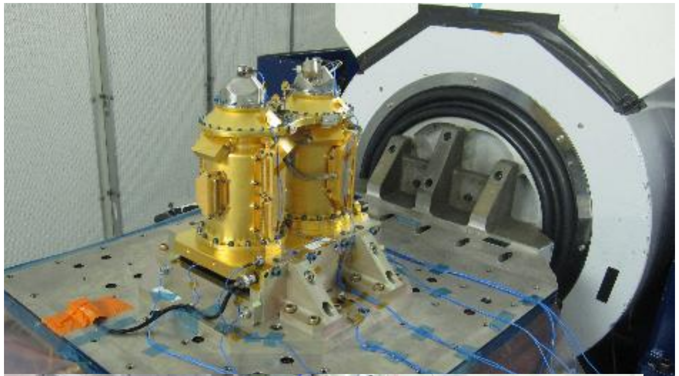


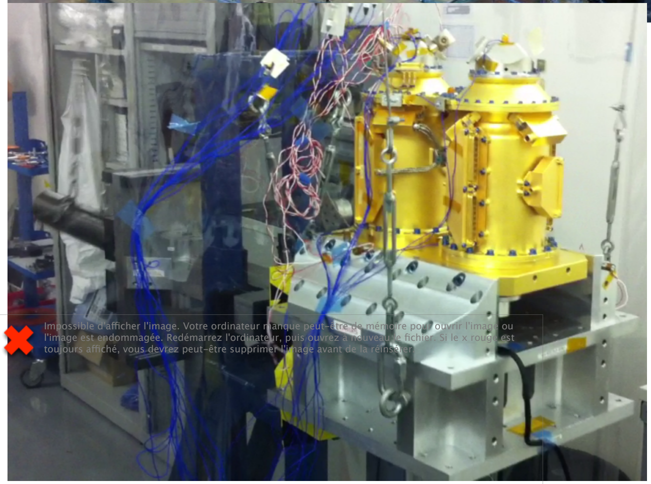




The sensor core is in accordance with the performance requirements. Delivered to CNES on Sept 17th of 2014

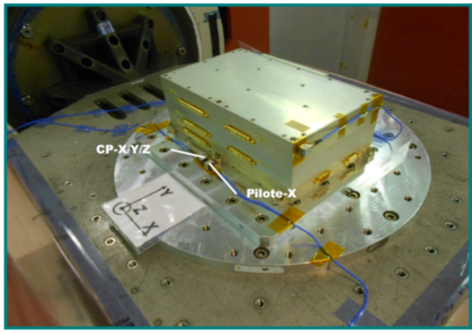
Successful Qualification and Acceptance tests performed in the time frame 2012-2014





Qualification, QM: 2012-2013

vibrations, shocks, thermal cycling



Acceptance, Sensor FM: 2014

vibrations, thermal cycling

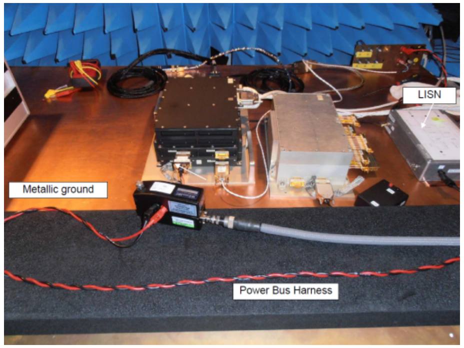
Acceptance of Electornics FEEU FM: 2014

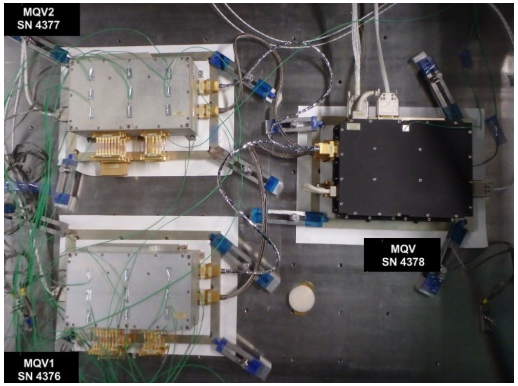
vibrations, schocks, thermal vacuum cycling, CEM

Acceptance of Digital Electronics FM:

To be done in early 2015

Firsts tests of thermal vacuum cycling with FEEU passed in 2014





Developement status of SU's

SU'sFM : Sensors

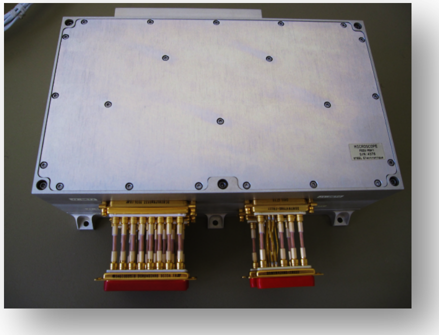
- The sensor core is in accordance with the performance requirements.
- Delivered to CNES on Sept 17th of 2014
- → integration in S/C cocoon

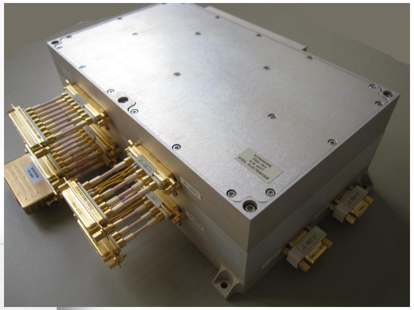
FEEU QFM1 + FM2 : Low noise Electronics U.

- Qualified in July 2014.
- Final performance tests in summer
- Delivered to CNES on 15th October
- → integration in S/C cocoon

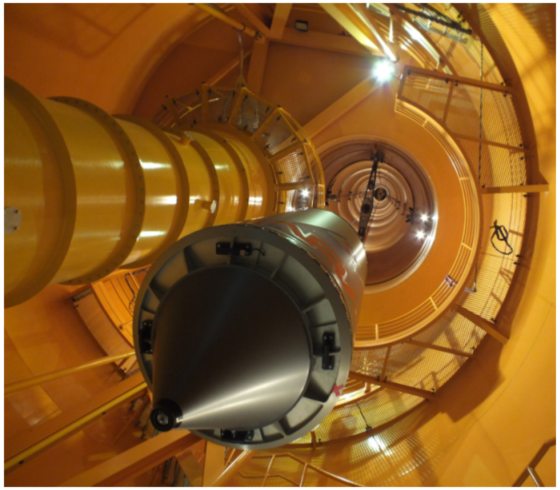
ICUME QFM : Digital Electronics U.

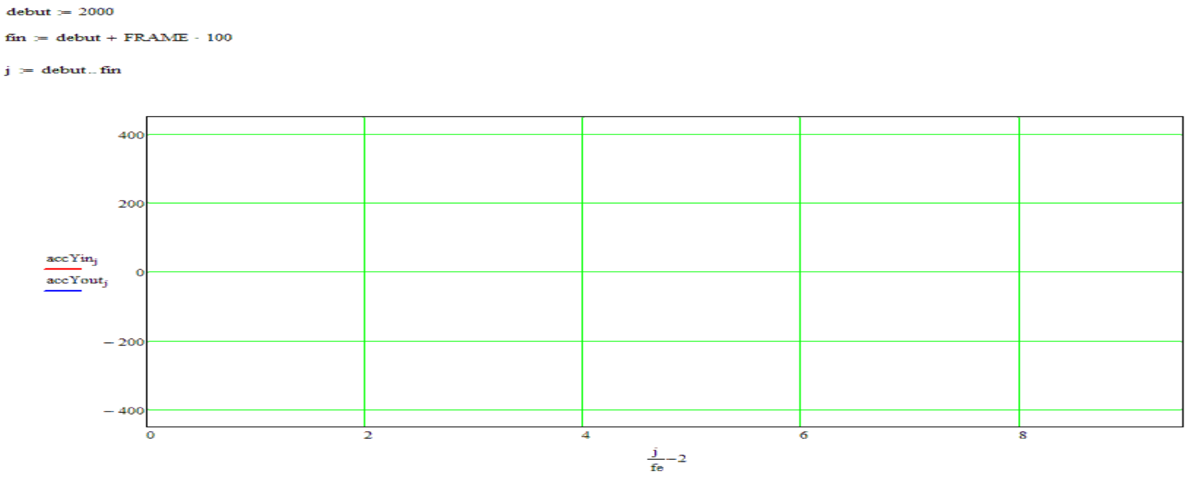
- Partial thermal tests in July 2014.
- FPGA under final coding
- Qualification and delivery end of March 2015





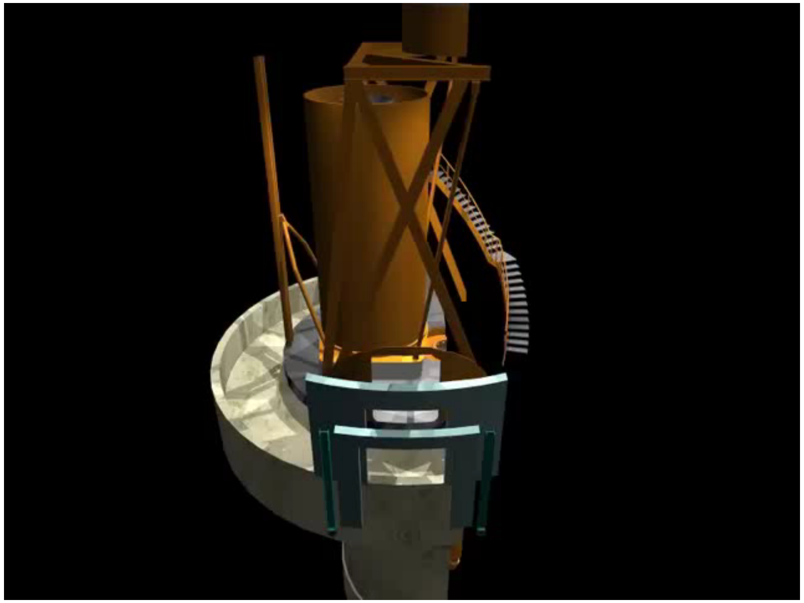
Catapulte test to validate the qualification or the acceptante (Drop n°61 with QM inZARM)

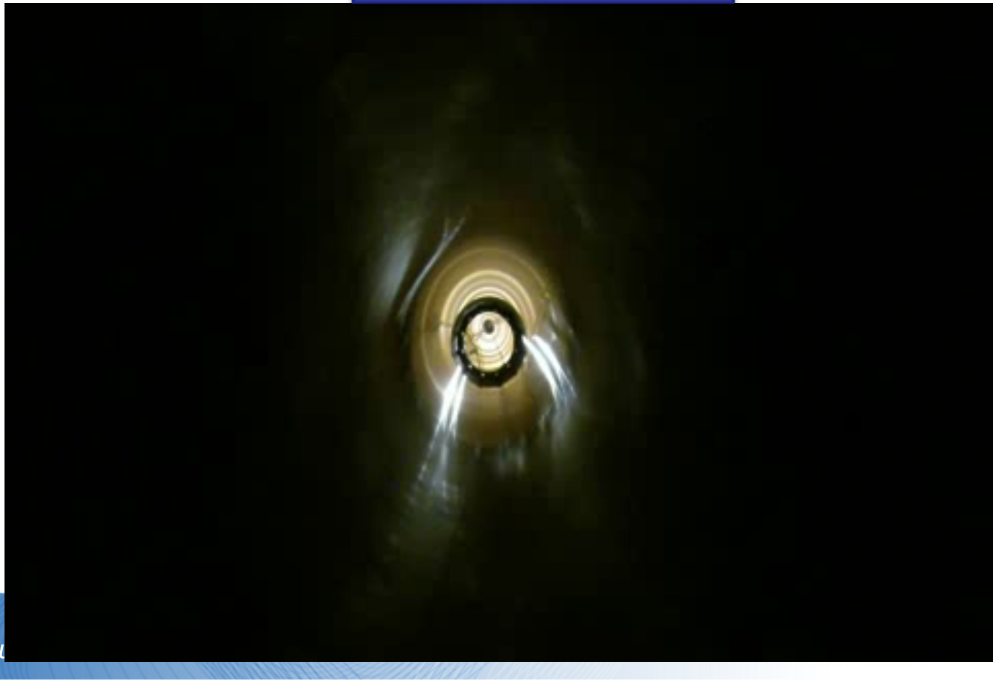




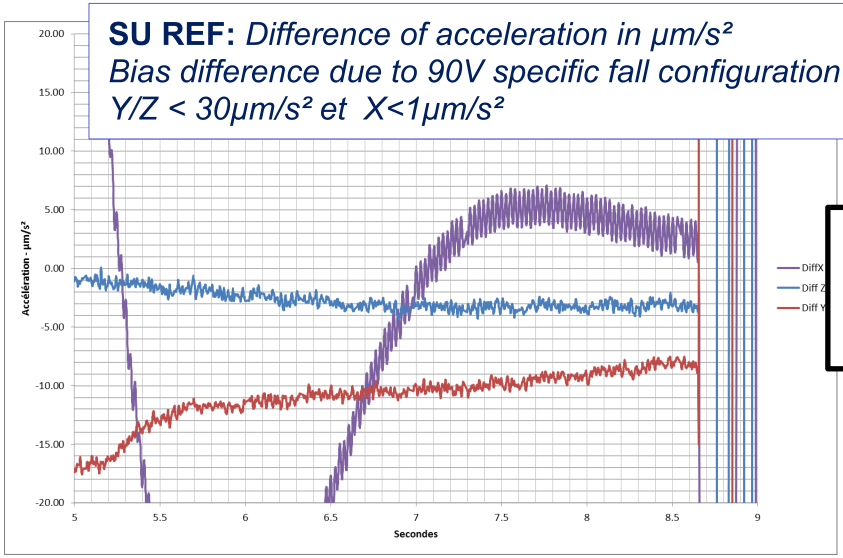
```
debut := 2000
fin := debut + FRAME · 100
j := debut .. fin
```

Slow motion (speed/2)



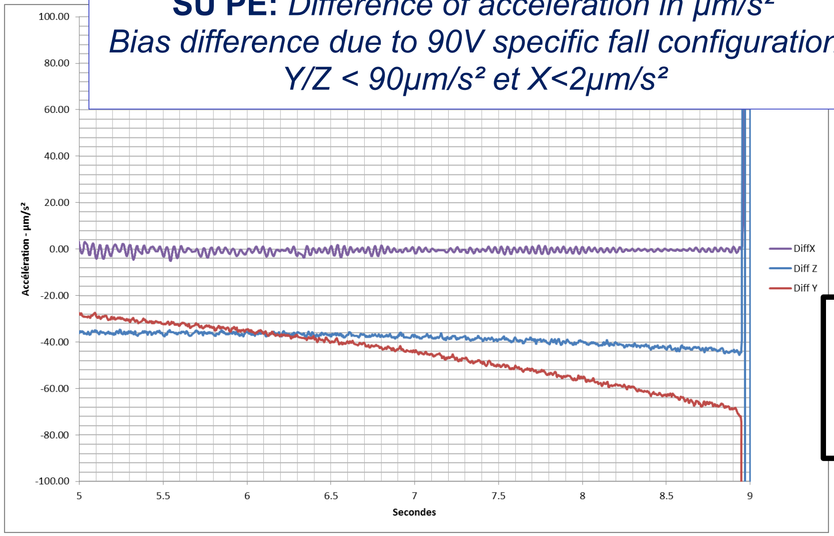


FM Drop 05 et 06 : 20th March of 2014
1st results



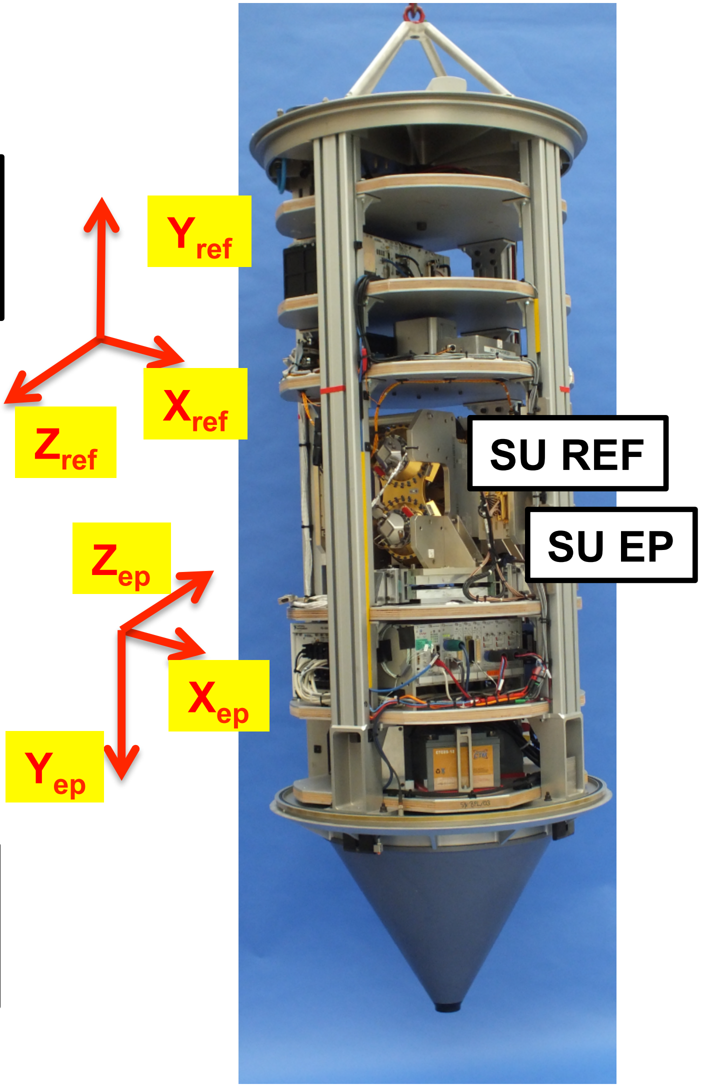
SU REF: *Difference of acceleration in $\mu m/s^2$*
Bias difference due to 90V specific fall configuration
$Y/Z < 30\mu m/s^2$ et $X<1\mu m/s^2$

Bias + Scale Factor
$X < 3\ \mu m/s^2$
$Z < 3\ \mu m/s^2$
$Y < 8\ \mu m/s$



SU PE: *Difference of acceleration in $\mu m/s^2$*
Bias difference due to 90V specific fall configuration
$Y/Z < 90\mu m/s^2$ et $X<2\mu m/s^2$

Bias + Scale Factor
$X < 1\mu m/s^2$
$Z < 40\mu m/s^2$
$Y < 67\mu m/s$



Electronics performance

Capacitive sensing :

	Internal Mass	External Mass
X	12 $\mu VHz^{-1/2}$ = 0.4 10^{-10} $mHz^{-1/2}$	6 $\mu VHz^{-1/2}$ = 0.25 10^{-10} $mHz^{-1/2}$
Y,Z	6 $\mu VHz^{-1/2}$ = 0.25 10^{-10} $mHz^{-1/2}$	3 $\mu VHz^{-1/2}$ = 0.1 10^{-10} $mHz^{-1/2}$

Electrostatic control & measurement :

	Internal Mass	External Mass
X	1.1 $\mu VHz^{-1/2}$ = 20 10^{-15} $NHz^{-1/2}$	1.6 $\mu VHz^{-1/2}$ = 52 10^{-15} $NHz^{-1/2}$
Y,Z	2.3 $\mu VHz^{-1/2}$ = 160 10^{-15} $NHz^{-1/2}$	2.3 $\mu VHz^{-1/2}$ = 710 10^{-15} $NHz^{-1/2}$

Proof mass charge :

- **Vp : 5V ; 0.22 $\mu VHz^{-1/2}$; 13 ppm/°C**

+ stability compatible with 5mK fluctuations

Power supply :

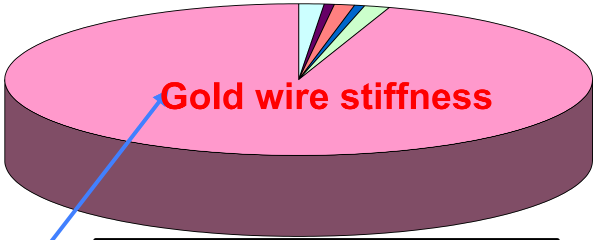
- **0,1 mV for 1 V satellite power bus variation & 2mV/°C**

Disturbing source of the instrument

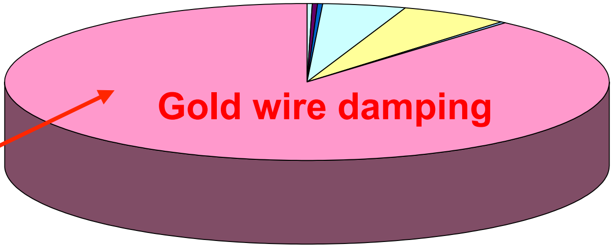
Ex.: X SCI / SU-EPI

Radial electrode dissymmetries due to machining
Front wall along X: due to defect of symmetry of the axial electrodes
Front wall along X: Conicité de la PM vis-à-vis des surfaces en bout
Cylindricity defect of the silica external cylinder wrt cylindrical PM /m\
Cylindricity defect of the PM wrt silica external cylinder c/ \c
Cylindricity defect of the silica internal cylinder wrt cylindrical PM m/ \m
Cylindricity defect of the PM wrt silica internal cylinder /c\
Lever arm error: Centring of X electrodes wrt YZ electrodes (for $\theta\psi$)
Lever arm error: Axial capacitive sensor bias (for $\theta\psi$)
Lever arm error: PM conicity (for $\theta\psi$)
Lever arm error: Electrode cylinder conicity (for $\theta\psi$)
YZ bias error: DAC+DVA distribution over 4 electrodes (for $\theta\psi$)
YZ bias error: CPD (for $\theta\psi$)
YZ bias error: Radial electrode dissymmetries (for $\theta\psi$) all in 0
Concentricity of the two cages
Detection: Capacitive sensor + ADC, electronic noise
Detection: Capacitive sensor + ADC, position noise
Read-Out
Actuation: DAC+DVA
CPD
Wire stiffness/torsion constant
Wire damping
Gas damping
TOTAL (quadratic sum)

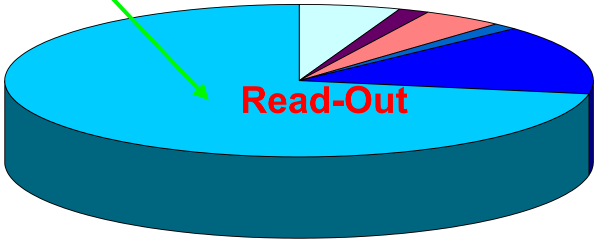
Bias



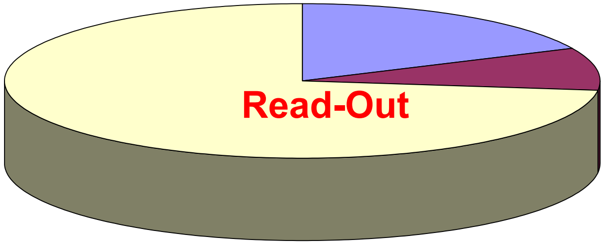
Noise- bias fluctuations



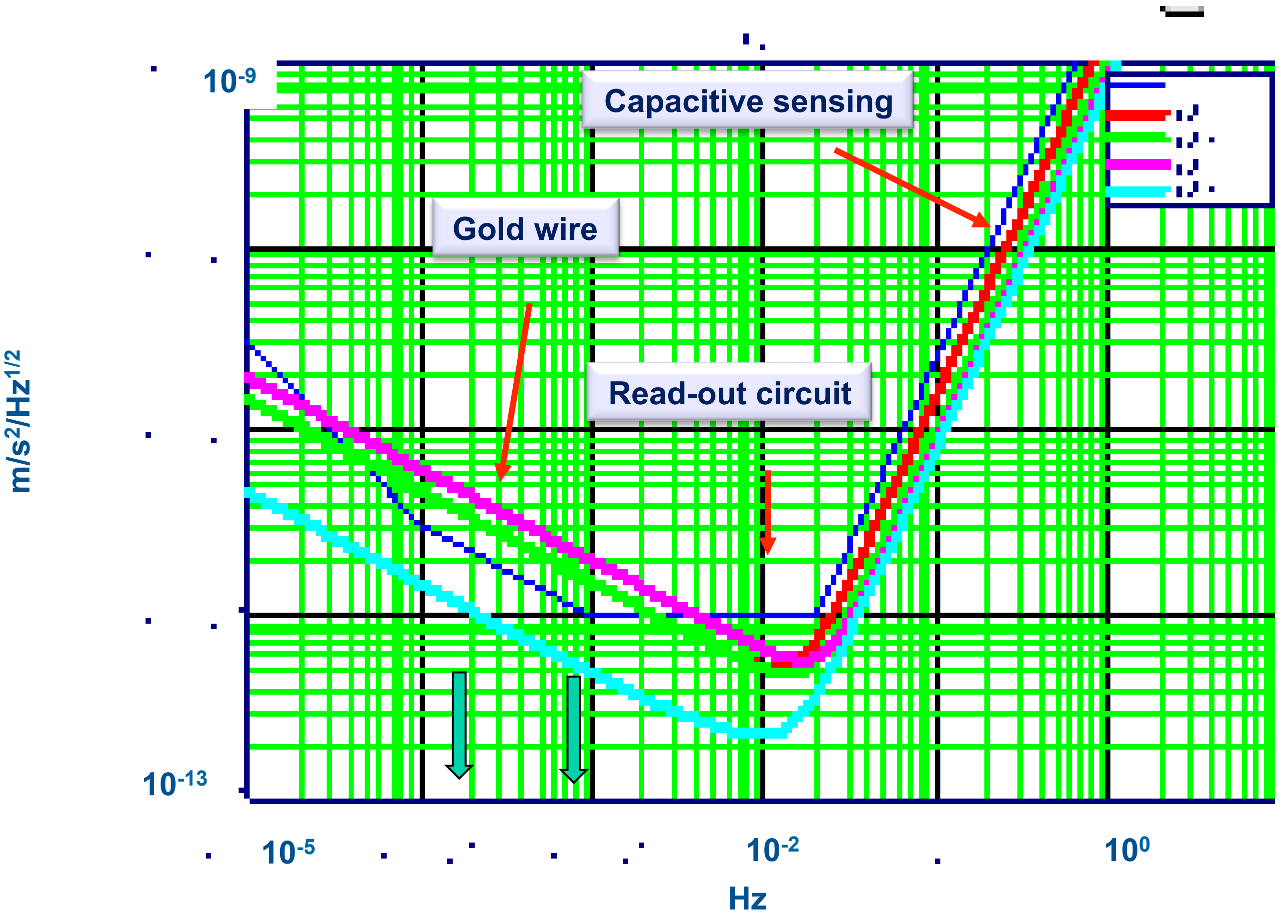
electronics thermal sensitivity: bias



electronics thermal sensitivity: gain



FM instrument noise: axial (X SCI)



Similar to GOCE noise performance, at least demonstrated by a factor 2 in orbit
Interest in lower frequency and longer integrating period but smaller bandwidth

EP test expected accuracy :
with FM SU-EP validated characteristics

Inertial pointing : one session of 120 orbits

	noise (m/s²/Hz^1/2) in $2\Gamma_{mesd}$		tone @fep (m/s²) in $2\Gamma_{mesd}$	
TOTAL (direct sum)/3			**7,58E-15**	**135,3%**
TOTAL (quadratic sum)	**6,64E-12**	**140,4%**	▨	▨
SPEC	**4,73E-12**		**5,60E-15**	
			ΔEP	**1,38E-15**

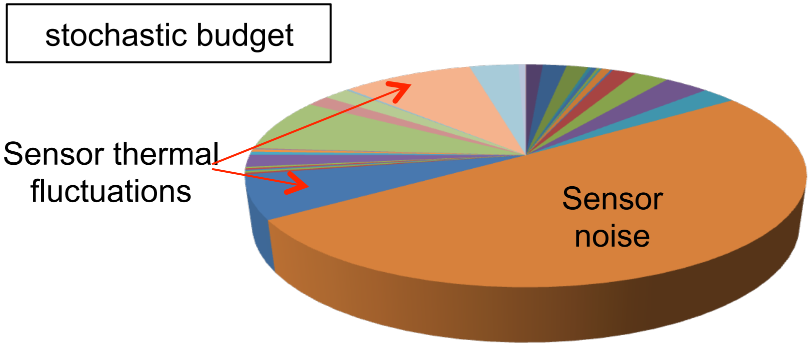
$1{,}19\ 10^{-15}$ **Over 240 orbits**

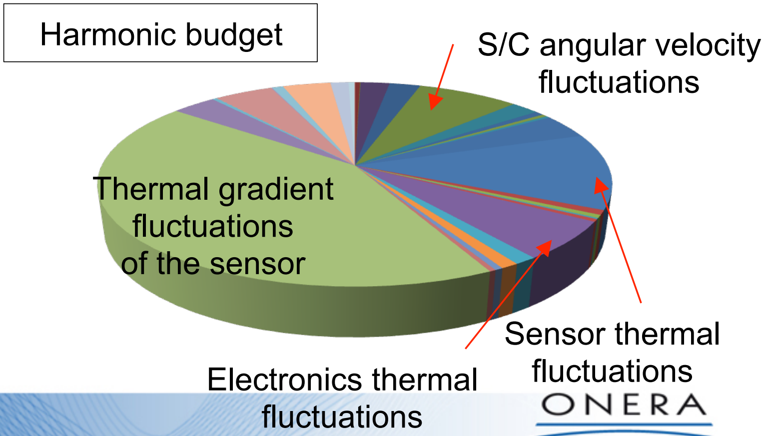
rotating pointing : one session of 120 orbits

	noise (m/s²/Hz^1/2) in $2\Gamma_{mesd}$		tone @fep (m/s²) in $2\Gamma_{mesd}$	
TOTAL (direct sum)/3			**3,05E-15**	**54,5%**
TOTAL (quadratic sum)	**2,73E-12**	**57,6%**	▨	▨
SPEC	**4,73E-12**		**5,60E-15**	
			ΔEP	**5,61E-16**

$0{,}48\ 10^{-15}$ **Over 240 orbits**

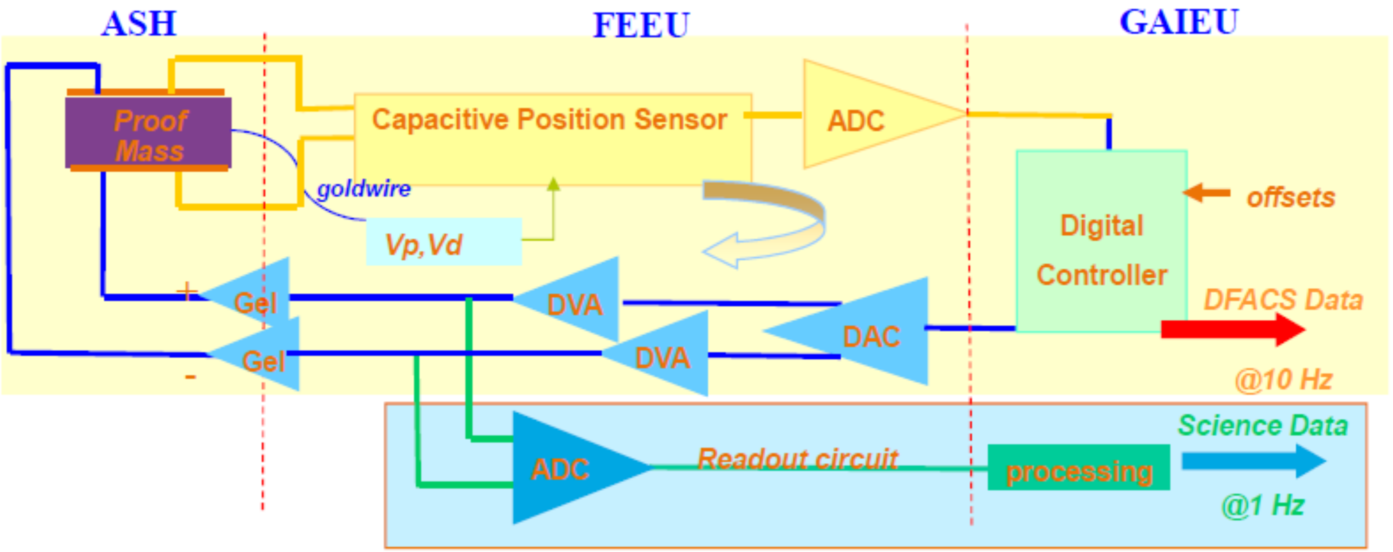
$0{,}45\ 10^{-15}$ **Over 360 orbits**





Measurement principle

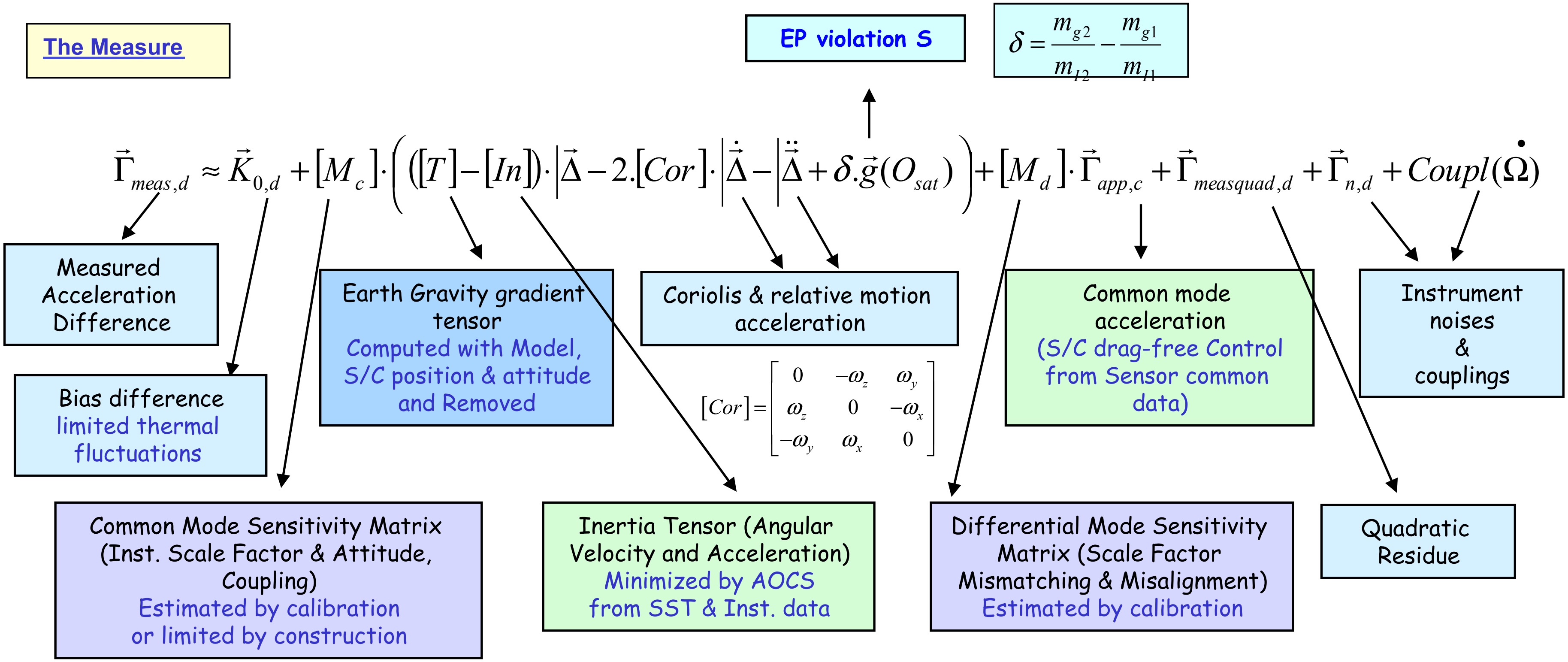
1 masse = 1 senseur inertiel = 6 mesures AOCS + 1 mesure scientif.



$$m_I \ddot{x} = F_{el} + F_{pa} + m_G g \qquad \Rightarrow \qquad F_{el} / m_I = (\ddot{x}_{\text{inst}} + \ddot{x}_{cap}) - F_{pa} / m_I - (m_G / m_I) g$$

$$\frac{m_{Gk}}{m_{Ik}} = 1 + \delta_k \qquad \overrightarrow{\Gamma_{App,k}} = \frac{\vec{F}el_k}{m_{Ik}} = \frac{M_{Gsat}}{M_{Isat}} \vec{g}(O_{sat}) - (1+\delta_k)\vec{g}(O_k) + R_{In,COR}\left(\overrightarrow{O_{sat}O_k}\right) - \frac{\vec{F}pa_k}{m_{Ik}} + \frac{\vec{F}ext}{M_{Isat}} + \frac{\vec{F}th}{M_{Isat}}$$

What do we measure ? Earth's, satellite, instrument, physics contributions



The Measure

EP violation δ

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

$$\vec{\Gamma}_{meas,d} \approx \vec{K}_{0,d} + [M_c]\cdot\Big(([T]-[In])\cdot\big|\vec{\Delta} - 2.[Cor]\cdot\big|\dot{\vec{\Delta}} - \big|\ddot{\vec{\Delta}} + \delta.\vec{g}(O_{sat})\Big) + [M_d]\cdot\vec{\Gamma}_{app,c} + \vec{\Gamma}_{measquad,d} + \vec{\Gamma}_{n,d} + Coupl(\dot{\Omega})$$

Measured Acceleration Difference

Bias difference
limited thermal fluctuations

Earth Gravity gradient tensor
Computed with Model, S/C position & attitude and Removed

Coriolis & relative motion acceleration

$$[Cor] = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix}$$

Common mode acceleration
(S/C drag-free Control from Sensor common data)

Instrument noises & couplings

Common Mode Sensitivity Matrix (Inst. Scale Factor & Attitude, Coupling)
Estimated by calibration
or limited by construction

Inertia Tensor (Angular Velocity and Acceleration)
Minimized by AOCS
from SST & Inst. data

Differential Mode Sensitivity Matrix (Scale Factor Mismatching & Misalignment)
Estimated by calibration

Quadratic Residue

$$\begin{bmatrix} K_{cx} & \eta_{cz}+\theta_{cz} & \eta_{cy}-\theta_{cy} \\ \eta_{cz}-\theta_{cz} & K_{cy} & \eta_{cx}+\theta_{cx} \\ \eta_{cy}+\theta_{cy} & \eta_{cx}-\theta_{cx} & K_{cz} \end{bmatrix}$$

$$[In] = \begin{bmatrix} -\omega_y^2-\omega_z^2 & \omega_x\cdot\omega_y-\dot{\omega}_z & \omega_x\cdot\omega_z+\dot{\omega}_y \\ \omega_x\cdot\omega_y+\dot{\omega}_z & -\omega_x^2-\omega_z^2 & \omega_y\cdot\omega_z-\dot{\omega}_x \\ \omega_x\cdot\omega_z-\dot{\omega}_y & \omega_y\cdot\omega_z+\dot{\omega}_x & -\omega_x^2-\omega_y^2 \end{bmatrix}$$

$$\begin{bmatrix} K_{dx} & \eta_{dz}+\theta_{dz} & \eta_{dy}-\theta_{dy} \\ \eta_{dz}-\theta_{dz} & K_{dy} & \eta_{dx}+\theta_{dx} \\ \eta_{dy}+\theta_{dy} & \eta_{dx}-\theta_{dx} & K_{dz} \end{bmatrix}$$

Stochastic and Tone Signals to be considered with a limited observation period and some lacks of data
→ Detailed Specifications for S/C Sub-Systems, Instrument Environment & Instrument Performances
→ Accurate in orbit calibration
→ A posteriori estimation and corrections

Calibrations

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

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

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

b_0 : bias *b_1 : parasitic forces*
$\Gamma_{res,df}$: drag-free residual acceleration
C : drag-free command

Δ : off-centering
K_1 : scale factor
η : coupling

θ : misalignement
K_2 : quadratic term

Error budget before calibration: 1.10^{-13} m.s^{-2}

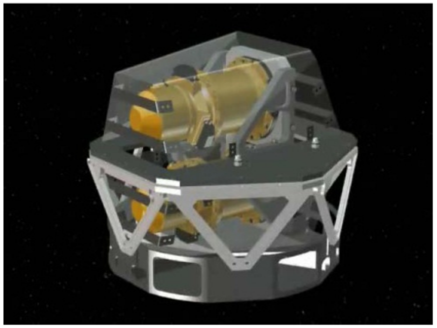
→ an in-orbit calibration is necessary

1. **$K_{1cx}\Delta_x$** and **$K_{1cx}\Delta_z$**: use the important value of T_{xx} and T_{xz} at $2f_{orb}$
2. **$K_{1cx}\Delta_y$** : T_{xy} too weak → oscillate the satellite around Y_{sat}
3. ***Parameters of the common sensitivity matrix ($\eta_{cz} + \theta_{cz}$, $\eta_{cy} - \theta_{cy}$):*** *oscillation of the test masses along Y and Z at f_{TM}+ modulation of the Earth gravity gradient at $2f_{orb}$ → calibration signal at f_{TM}+ $2f_{orb}$*
4. ***Parameters of the differential sensitivity matrix (K_{1dx}, $\eta_{dz} + \theta_{dz}$,$\eta_{dy} - \theta_{dy}$):*** *oscillation of the satellite along X, Y or Z through the drag-free command C*
5. ***Differential quadratic factor K_{2dxx}:*** *oscillation of the satellite along X through the drag-free command C → calibration signal at $2f_{cal/lin}$*
6. ***Common quadratic factor K_{2cxx}:***

- *- K2ixx: oscillation of the test mass i along X, drag-free locked on the sensor j → calibration signal at $2f_{TM}$; same with j and i*

MICROSCOPE Major mission specifications
Instrument/Satellite dynamics

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



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* $< 10^{-12} ms^{-2}$ *variations @ fep*

Instrument characteristics and in-orbit calibration :

- ***Resolution :*** $< 2.3\ 10^{-12} ms^{-2}Hz^{-1/2}$ *and* $2.6\ 10^{-9} rads^{-2}Hz^{-1/2}$
- ***Sensitivity stability*** $< 6.8\ 10^{-8}$ *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*

P. Touboul, Space Sci Rev, 2009.

MISSION SCENARIO

- ***Mission duration driven by gas consumption***
- ***Mission scenario takes into account transition phase***
- ***Assessment sessions of the satellite, the instrument, the propulsion system, the drag-free and attitude control***
- ***But also performance sessions with magnetic, thermal excitations***
- ***Margin for lack of data :***
  - ***Inertial pointing : 123 orbits***
  - ***Rotating pointing : 7 x 20 orbits***
- ***Calibration sessions before and after the test sessions***
- ***Possibility to perform an actual centering of the mass***
- ***Foreseen scenario can be rescheduled according to obtained results***

system guaranteed scenario:
99.8% confidence
→3155 orbits

scientific objectives scenario :
80% confidence
→ 4921 orbits

SPACE EXPERIMENT SCENARIO :
being implemented in details wrt S/C & Ground Segment Rqts

S/C & payload Operation Verification & Adjustment

Preliminary Tests and EP Inertial sensor calibration

Calibration of both EP and REF Instruments

EP Tests with and without mass centering

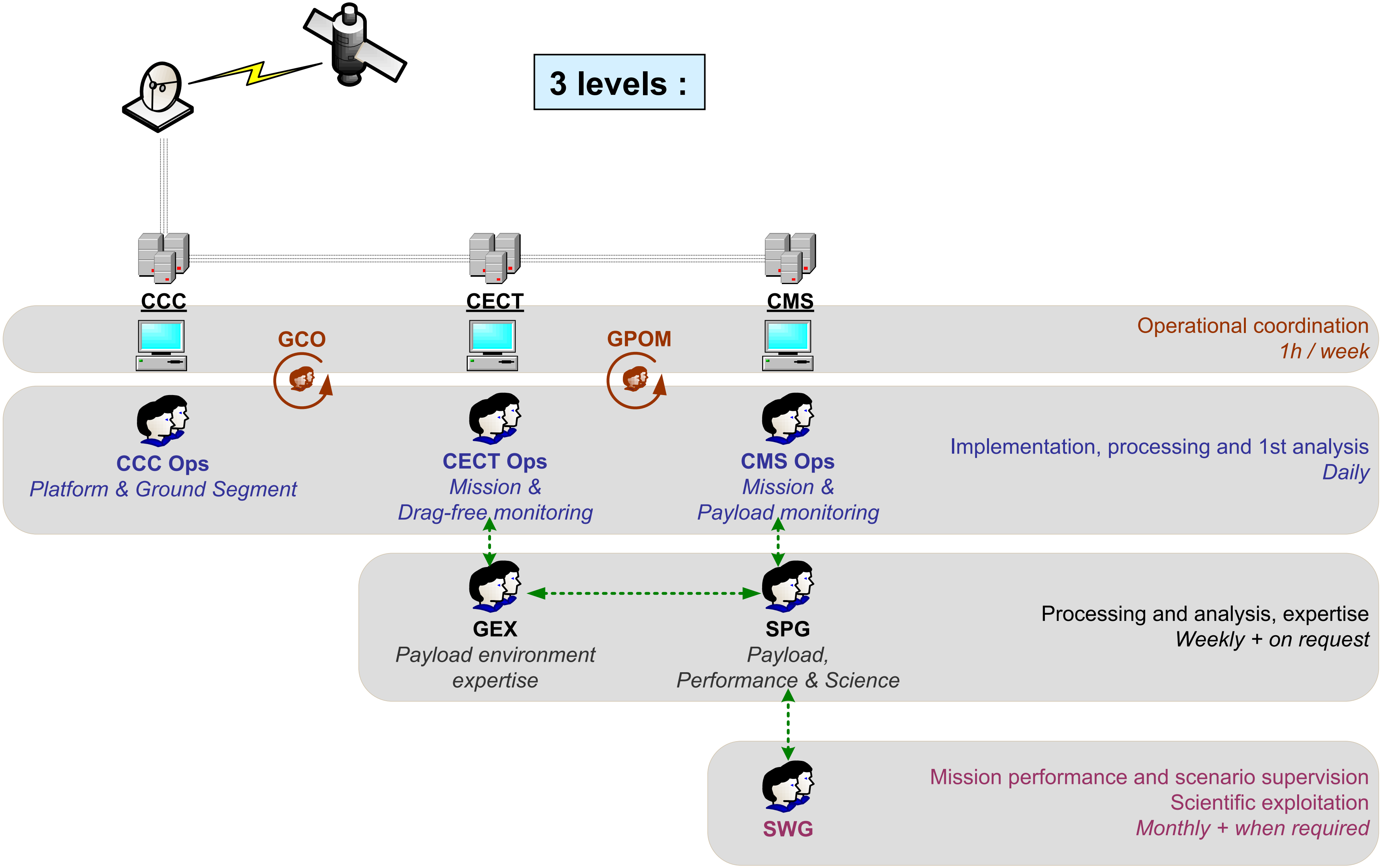
2nd calibration of both instruments for stability verifation.

Tests with mass centering

Additional EP Tests & calibration

Phases (successive sequences)	orbits	days	months	orbits with propu ON
S/C Assessment	51	3	0,1	0
TSAGE Assessment	87	6	0,2	0
Propulsion system Assessment	73	5	0,2	20
AOCS laws Assessment	143	10	0,3	143
AOCS including T-SAGE	15	1	0,0	15
Thruster calibration	15	1	0,0	15
Drag free operation	44	3	0,1	44
Total Commisioning step 1	425	29	1	235
Break	200	14	0,5	0
Drag-free assessment	106	7	0,2	106
T-SAGE Calibration Assessment	44	3	0,1	44
Margin	145	10	0,3	145
Total Commisioning step 2	295	20	1	295
Break	200	14	0,5	0
Preliminary Test EPI SUEP & SUREF	250	17	0,6	250
Preliminary Test EPR SUEP & SUREF	110	8	0,2	110
Performance Test	418	29	0,9	418
Total (Preliminary EP Tests)	778	54	2	778
Break	200	14	0,5	0
Calibration SUEP	132	9	0,3	132
Calibration SUREF	132	9	0,3	132
Test EPI-SUEP, phase 0° and 90°	250	17	0,6	250
Test EPI-SUREF, phase 0° and 90°	250	17	0,6	250
Test EPR-SUREF, spin 1 and 2	284	20	0,6	284
Test EPR-SUEP, spin 1 and 2	284	20	0,6	284
Total (SUEP-SUREF EP Tests)	1332	92	3,0	1332
Calibration SUEP	108	7	0,2	108
Calibration SUREF	108	7	0,2	108
Test EPI-SUEP centered TM, phase 0°	125	9	0,3	125
Test EPI-SUREF centered TM, phase 0°	125	9	0,3	125
Test EPR-SUREF centered TM, spin 1	142	10	0,3	142
Test EPR-SUEP centered TM, spin 1	142	10	0,3	142
Total(SUREP-SUREF centered TM)	750	52	1,7	750
Test EPR-EP Complement, spin 1 and 2	284	20	0,6	284
Test EPR-SUREF Complement, spin 1 and 2	284	20	0,6	284
Calibration SUEP	108	7	0,2	108
Calibration SUREF	108	7	0,2	108
Test EPI SUEP complement, phase 90°	125	9	0,3	125
Test EPI SUREF complement, phase 90°	125	9	0,3	125
Total consolidation tests	1034	71	2,3	1034
Total not including unavailabilities	**5214**	**359**	**12**	**4424**

Scientific and operational organisation



3 levels :

CCC **CECT** **CMS**

GCO **GPOM**

Operational coordination
1h / week

CCC Ops
Platform & Ground Segment

CECT Ops
Mission &
Drag-free monitoring

CMS Ops
Mission &
Payload monitoring

Implementation, processing and 1st analysis
Daily

GEX
Payload environment expertise

SPG
Payload,
Performance & Science

Processing and analysis, expertise
Weekly + on request

SWG

Mission performance and scenario supervision
Scientific exploitation
Monthly + when required

Scientific organization : Science Working Group

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

- **Supervising and approving** the **evaluation** and the **validation** of the **performance** and of the calibration analysis of the instrument both on ground and in orbit,
- **Selecting the proposals for the data processing** in response to the calls, with new Co-Is when needed,
- **Reviewing the scientific goals of the mission** at regular intervals in the light of the results,
- **Approving the final scientific data products** to be distributed to the community,
- **Reviewing the organisation of the data archive,**
- **Promoting the exploitation of the data and the diffusion of the information** (colloquia…).

Scientific organization : Science Working Group

PI (ONERA) who is the Chairperson	Pierre Touboul
co-PI (OCA)	Gilles Metris
ZARM co-I for Space Physics	Claus Lämmerzhal
DLR co-I	Hansjoerg Dittus
General Relativity and Gravitation	Thibault Damour
Fundamental Interactions	Pierre Fayet
Interdisciplinary Physics	Serge Reynaud
Earth gravity field	Isabelle Planet
Aeronomy	Pieter Visser
European scientist representative of similar space missions	Tim Sumner
CNES Fundamental Physics coordinator	Sylvie Léon-Hirtz
CMS manager	Manuel Rodrigues
CNES project manager	Yves André
Payload manager	Manuel Rodrigues
CECT chairman	Alain Robert

Mission Core Team

Scientific Experts Per domain

Invited Permanent

Invited when needed

New Investigators and data policy

- Validation Period:
  - Start: reception of the first data
  - End: when the first data set is calibrated and validated (decision of SWG)
  - Status: not released data outside SPG and SWG ;
  - Possible publication in agreement with the PI, SWG and Cnes Document (1)

- Diffusion Period:
  - Begins at the end of the validation period
  - Status: data dissemination to the whole community; no restriction on publication.

- New investigators can be selected after the call for ideas and for proposals, for the use of data during the property (development + validation) period
- Proposals can address the main objective of MICROSCOPE or other objectives in fundamental physics or other themes
- Proposals and applicants are selected by SWG
- The new investigators can have access to the data during the validation period in the framework described in the document (1)

(1) " MICROSCOPE Science Cooperation Rules " CNES/DSP/SME-2013/20946 on 2013/12/06

Conclusion

- The instrument is being integrated in its satellite cocoon
- The satellite integration with two panels is being performed

- **Launch foreseen on Soyouz in April 2016 as a secondary passenger with Sentinel 1B.**

  Cnes contract in July 2014

- The satellite control center and CECT is being developed in Cnes
- The Science Mission Center is being developed in Onera
- 5th of September 2014: 1st tests of interface and exchanges of representative data with CNES

END

Thanks

Questions

T-SAGE ONERA TEAM