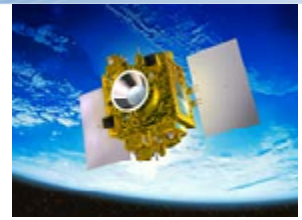
MICROSCOPE : 6 months before the launch

P. Touboul on behalf of the MICROSCOPE team

AKNOWLEDGEMENTS



Observatoire de la Côte d'Azur

Physikalisch-Technische Bundesanstalt

Constant in their effort since…

Team in Onera : Y. Alonso, D. Boulanger, 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

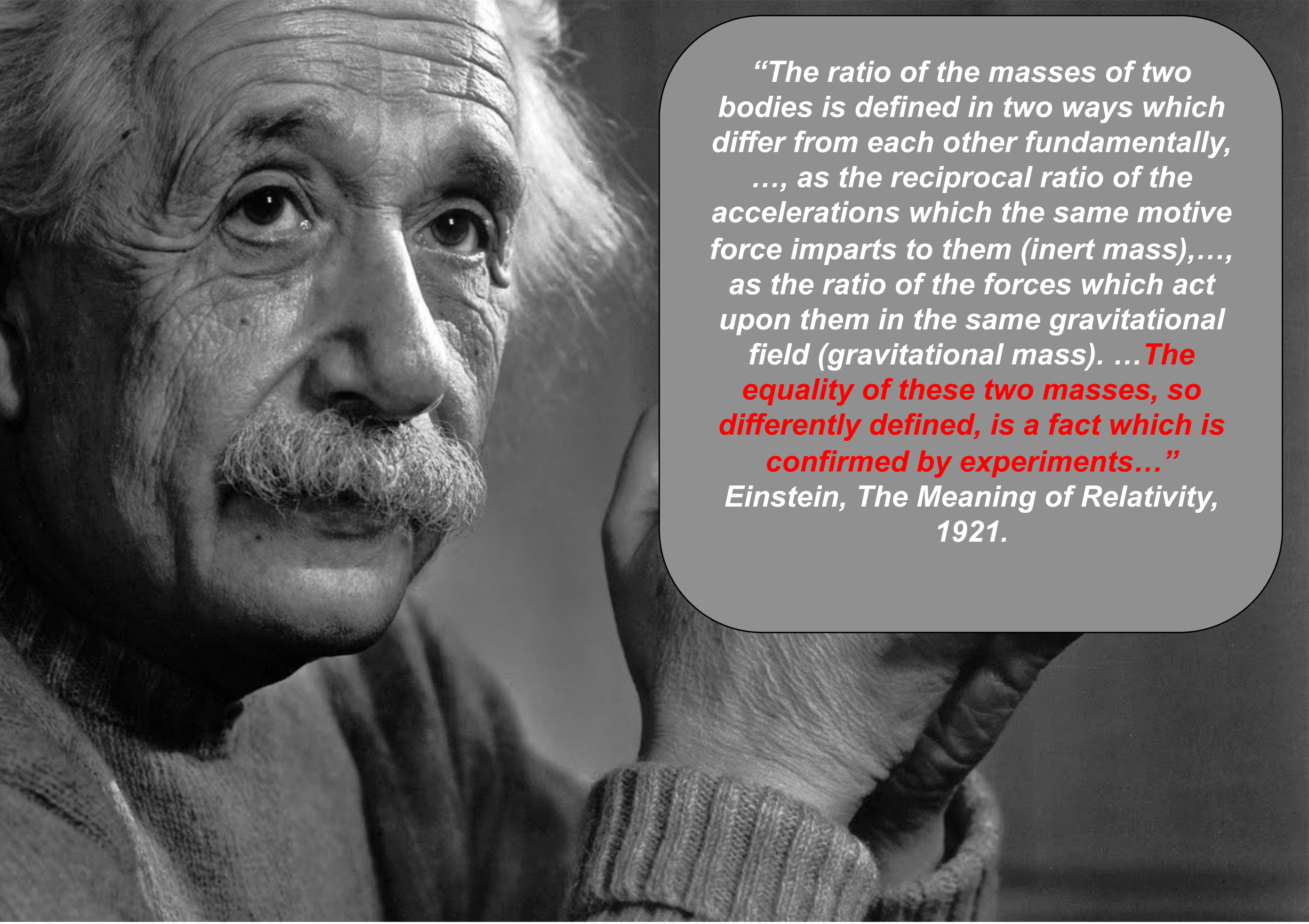
Team in OCA, Gilles Métris et al.

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

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

Team in DLR, Hansjorg Dittus et al.

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



"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…"

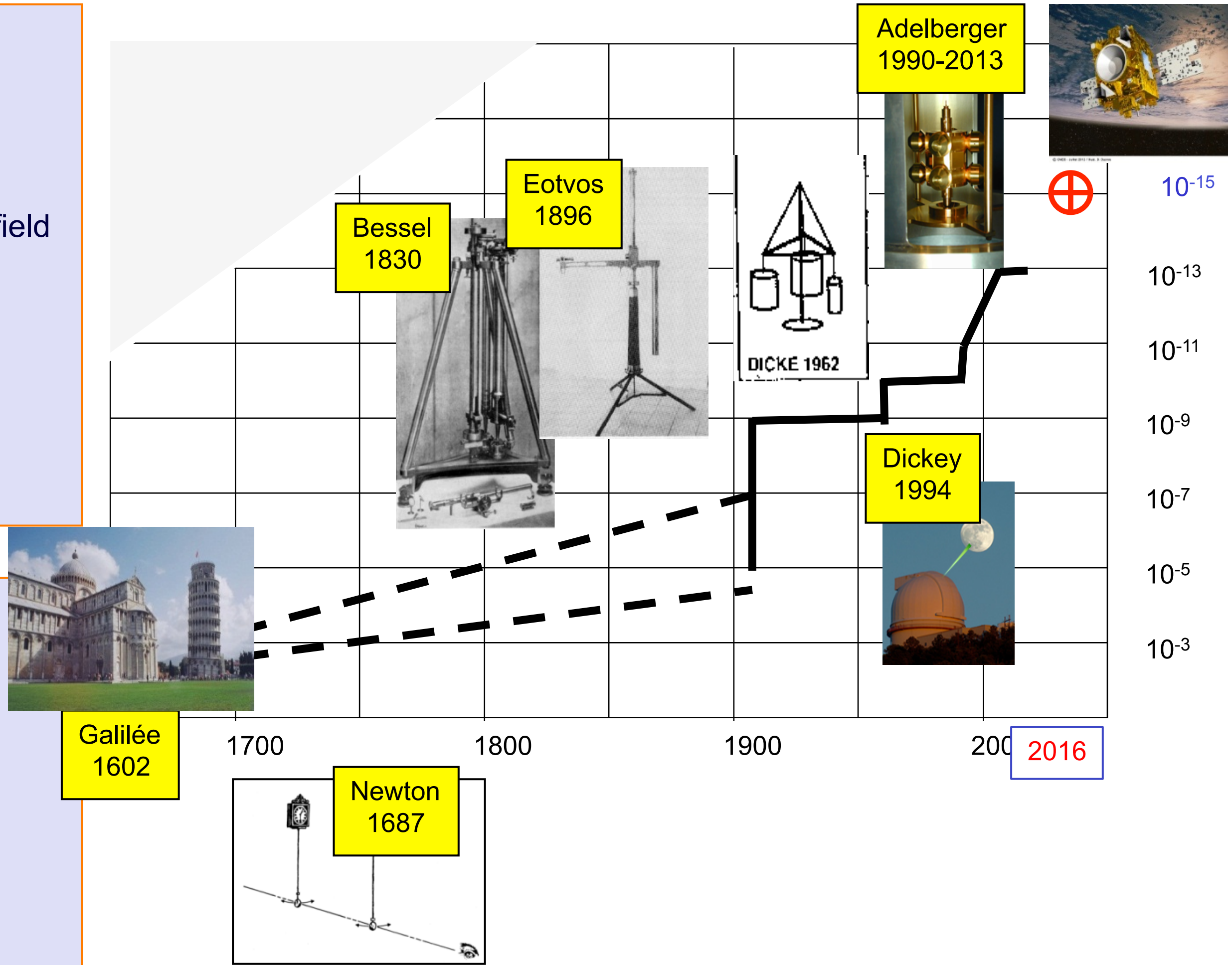
Einstein, The Meaning of Relativity, 1921.

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
- Lorentz invariance
- Local invariance

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



Quantum mechanics
& General Relativity

Unification of the 4 interactions

Alternative theories
⇒ New interaction?
⇒New particles ?

Dark mass

Dark energy

⇒ Equivalence Principle violation?

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

10^{-15} EP Test

In orbit, at 710 km, g (9,81 ms^{-2})→ 8. ms^{-2}
WEP @ 10-15 → $8x10^{-15}$ ms^{-2}

- ✓ A pedestrian walking at a speed of 5km/h stops with this acceleration in more than 5.5 million years and traveled more than 3 million rounds of the Earth.

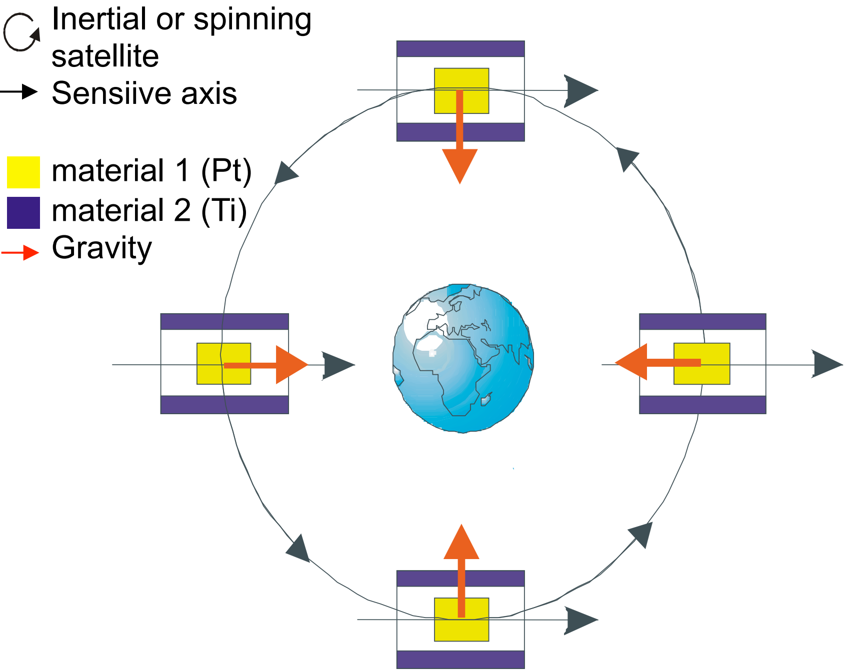
- ✓ Difference of weight of a supertanker 400 m long, 500 000 tones, with or without a Drosophila 0.5 mg on board.

Increase by 100 factor with respect to present accuracy :

- ✓ Distance Earth to Moon: **a few cm** @ lunar month (29.53 days) **X 1%**

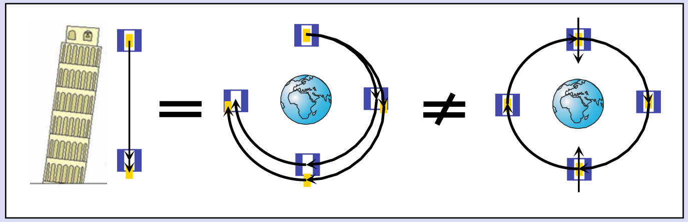
- ✓ Torsion pendulum sensitive to changes in the differential attraction due for instance to gravity gradient of the hill before or after rain **X 1%**

The principle of the MICROSCOPE space mission



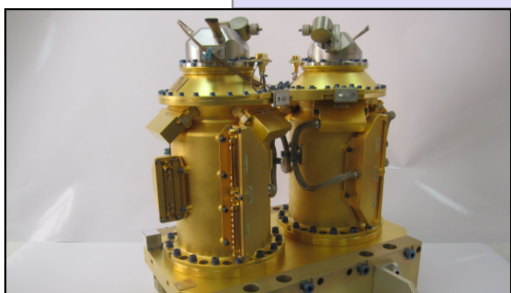
- Gravitational source: the Earth
- inertial acceleration: orbital motion
- 2 masses of different composition: controlled on the same orbit (< 10^{-11}m) by electrostatic pressures

→ Steady configuration, control of the satellite

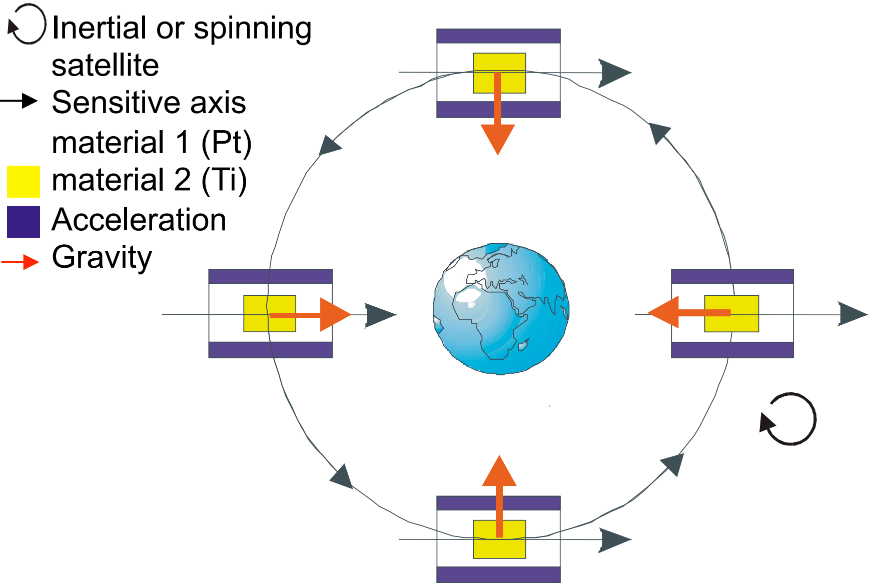


- Time span of the measurement: non limited by the free fall (> 20 orbits)
- Environment: limited and controlled perturbations, drag-free satellite
- Signal along Earth monopole direction: well defined phase & frequency

Galilée (1590)

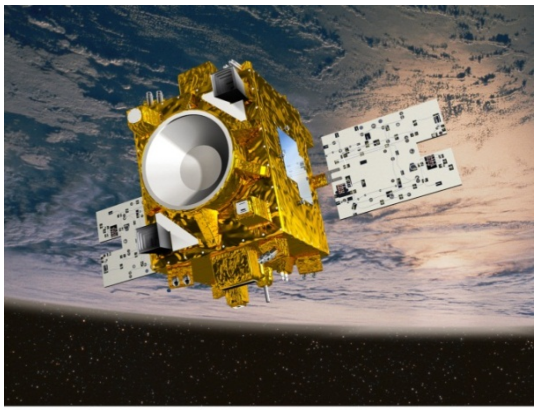


The principle of the MICROSCOPE space mission



CNES MYRIADE Microsatellite

- Circular Orbit: 710 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 with 2 pairs of mass : Pt-Pt and Pt-Ti
- 2 differential electrostatic accelerometers
  (2 pairs of masses: Pt/Pt & Pt/Ti)
- f_{ep} =
  - Inertial mode: f_{orb}
  - Spinning mode: $f_{orb} + f_{spin}$



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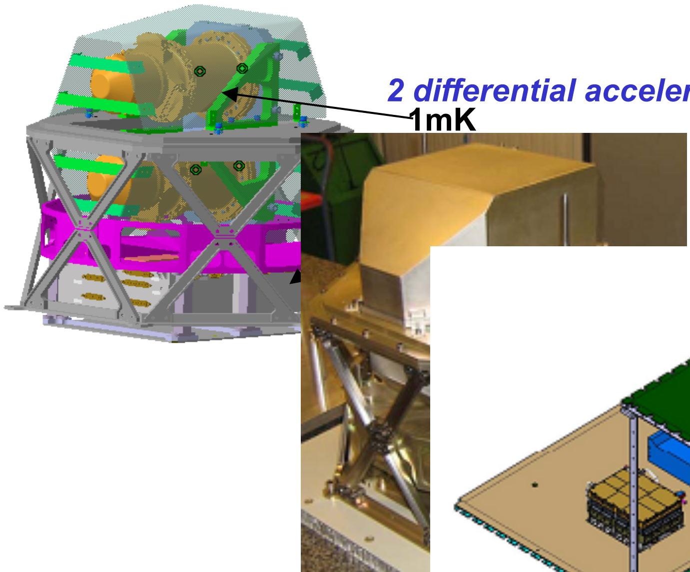
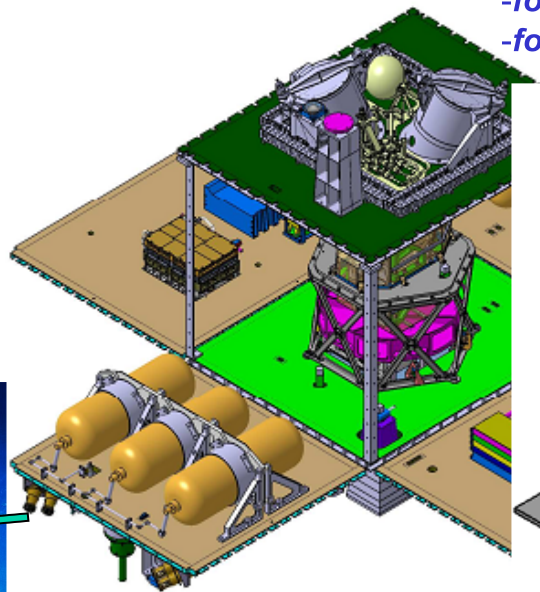
MICROSCOPE Satellite design

2 differential accelerometers in thermal cocoon

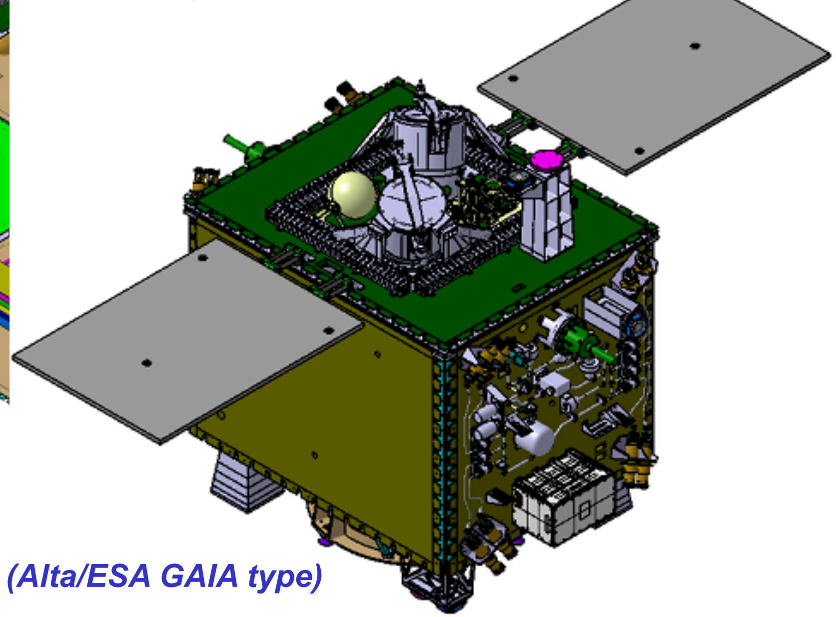
2 differential accelerometers in magnetic cocoon

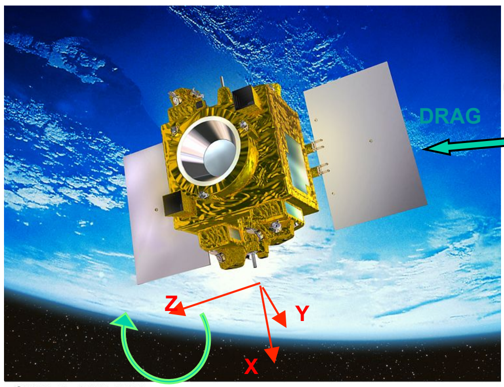


payload at the center of the satellite :
-for thermal stability
-for spin mode
-for self gravity



payload and star sensor for attitude control





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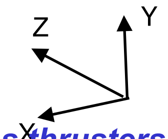

4 pods of 2cold gas thrusters (Alta/ESA GAIA type)

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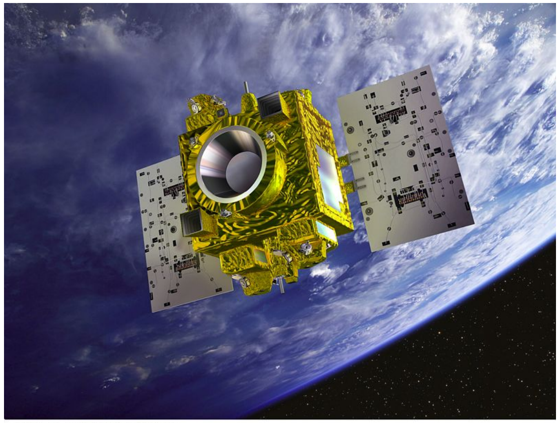
MICROSCOPE satellite thermal stability & in orbit configuration



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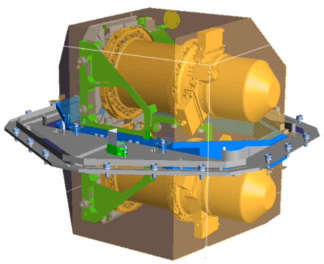
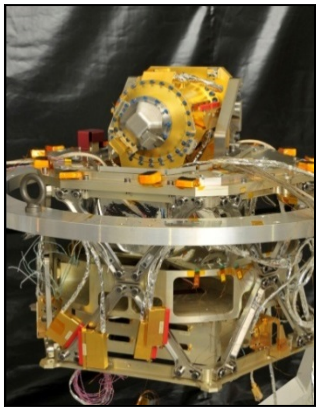
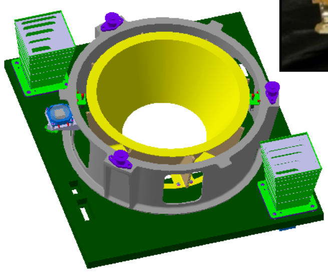
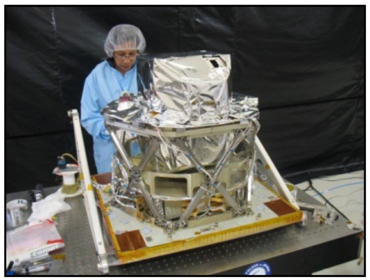
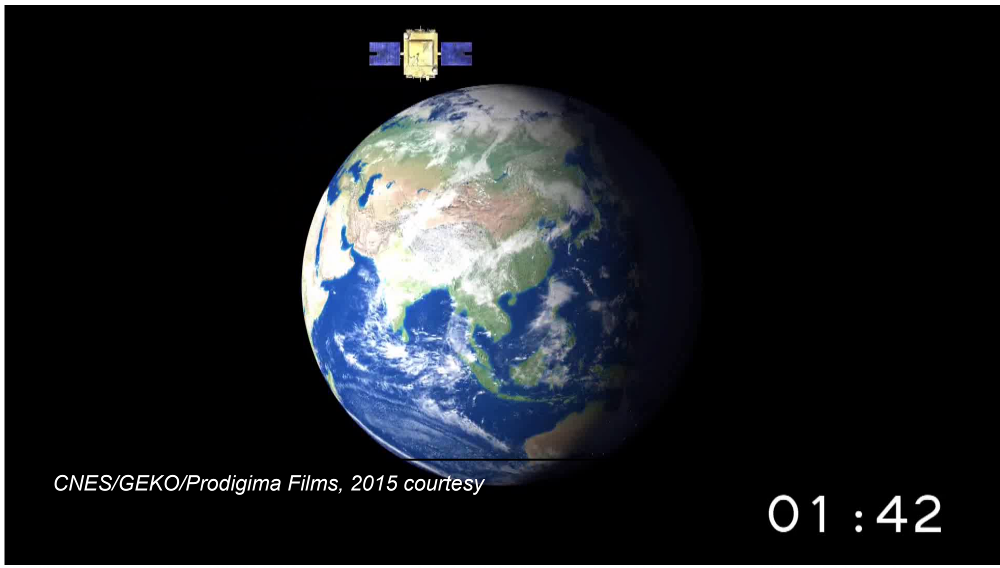
- ❑ *Heliosynchronous orbit : steady external configuration*
- ❑ *3 locations for the payload units versus thermal requirements*
- ❑ *Fine passive decoupling and well protected radiator from Earth radiations*
- ❑ *Models and dedicated tests, performed in 09-10, confirm :*
- ✓ *the thermal case fine insulation*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











CNES/GEKO/Prodigima Films, 2015 courtesy

MICROSCOPE instrument configuration

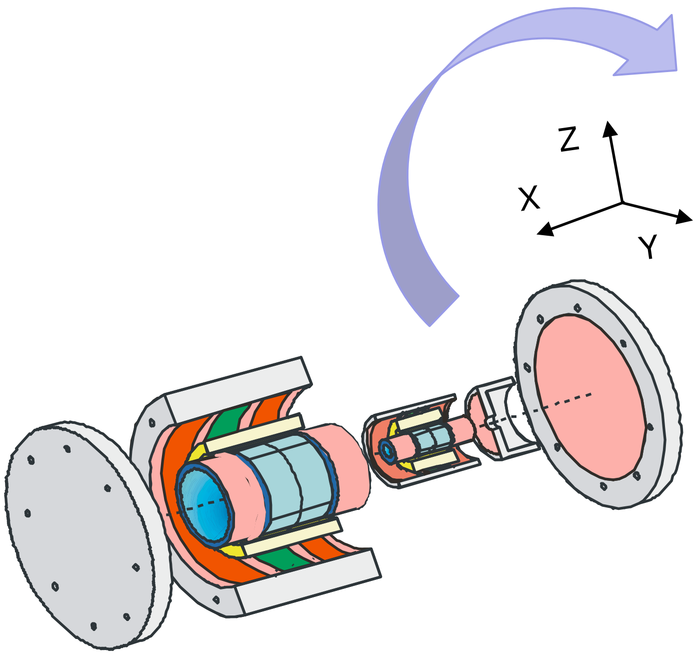
- 2 similar instruments, each including one pair of masses :

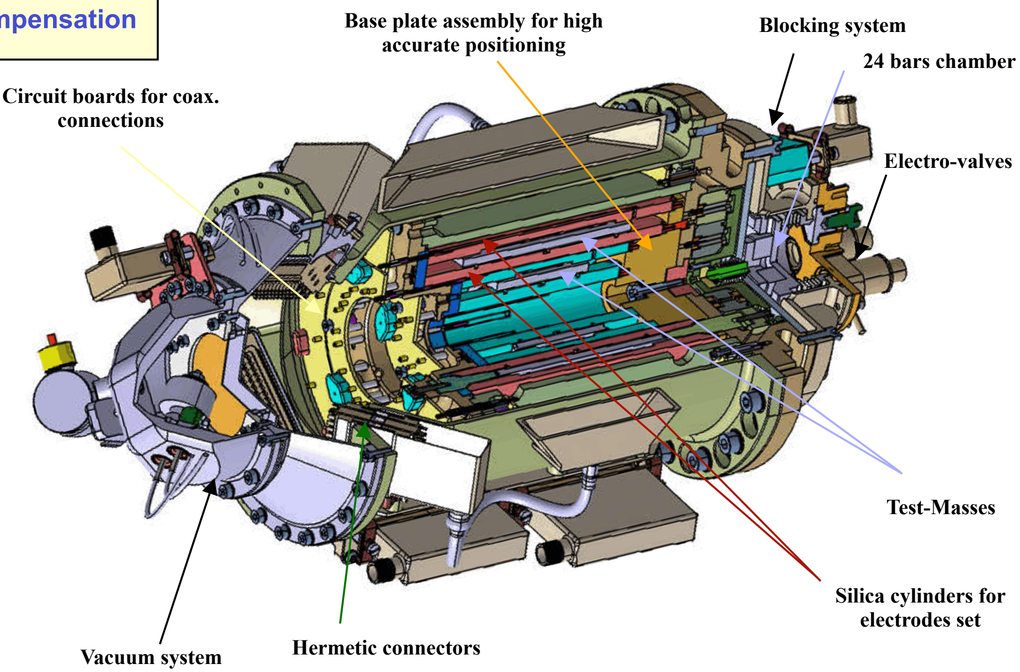
→ 2 pairs of masses : Pt / Pt & Pt / Ti

→ Double difference of four inertial sensor outputs

→ Scientific data &

→ AOCS data for pointing and continuous drag compensation

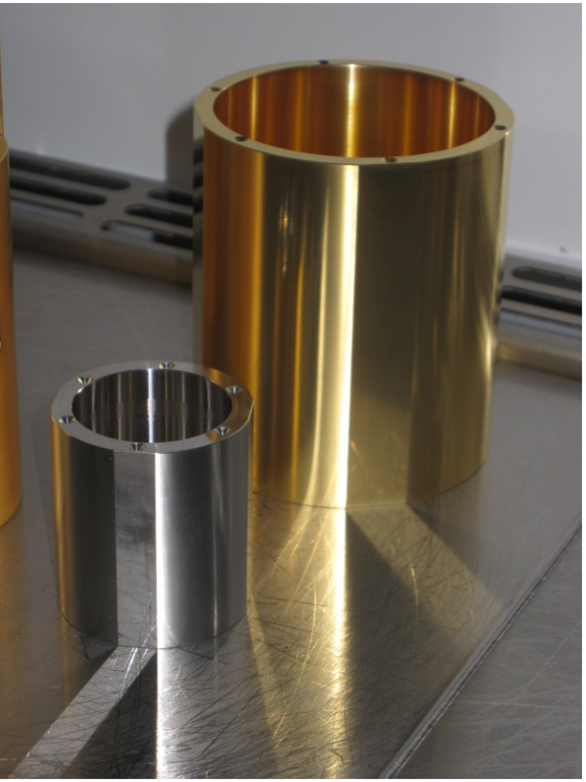


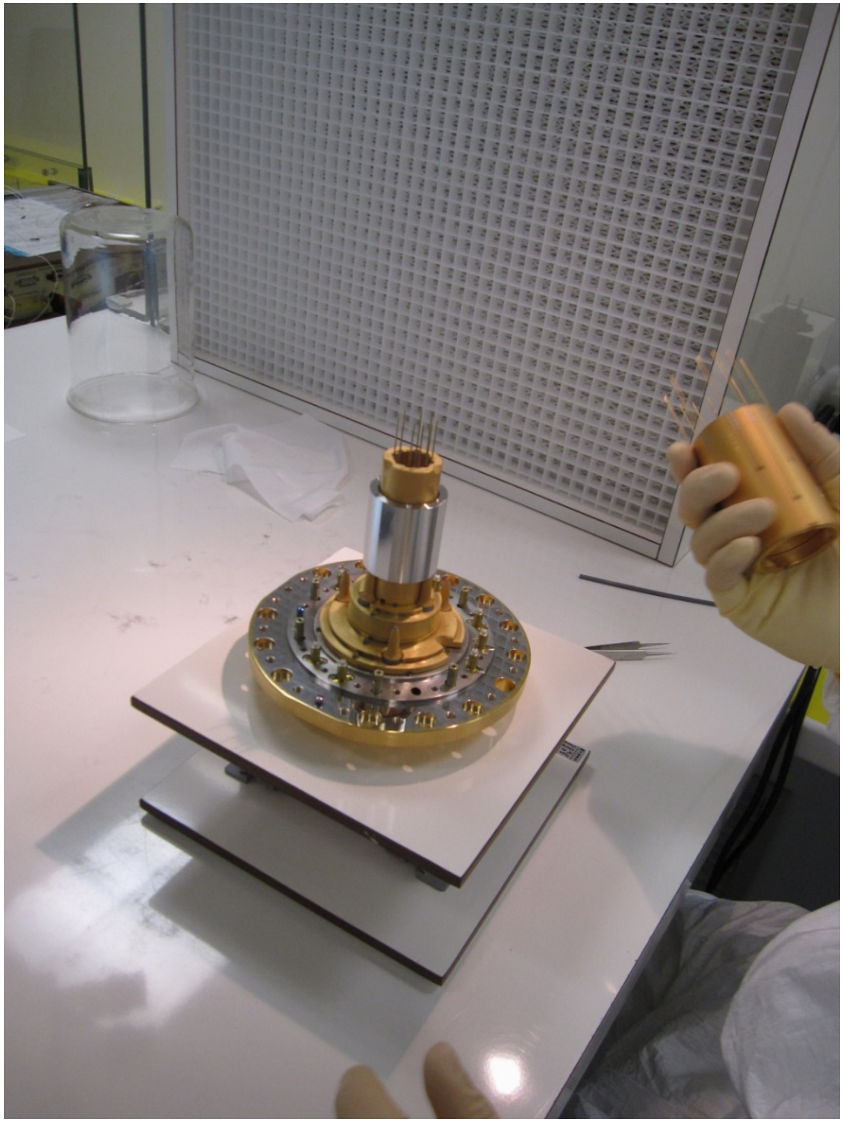


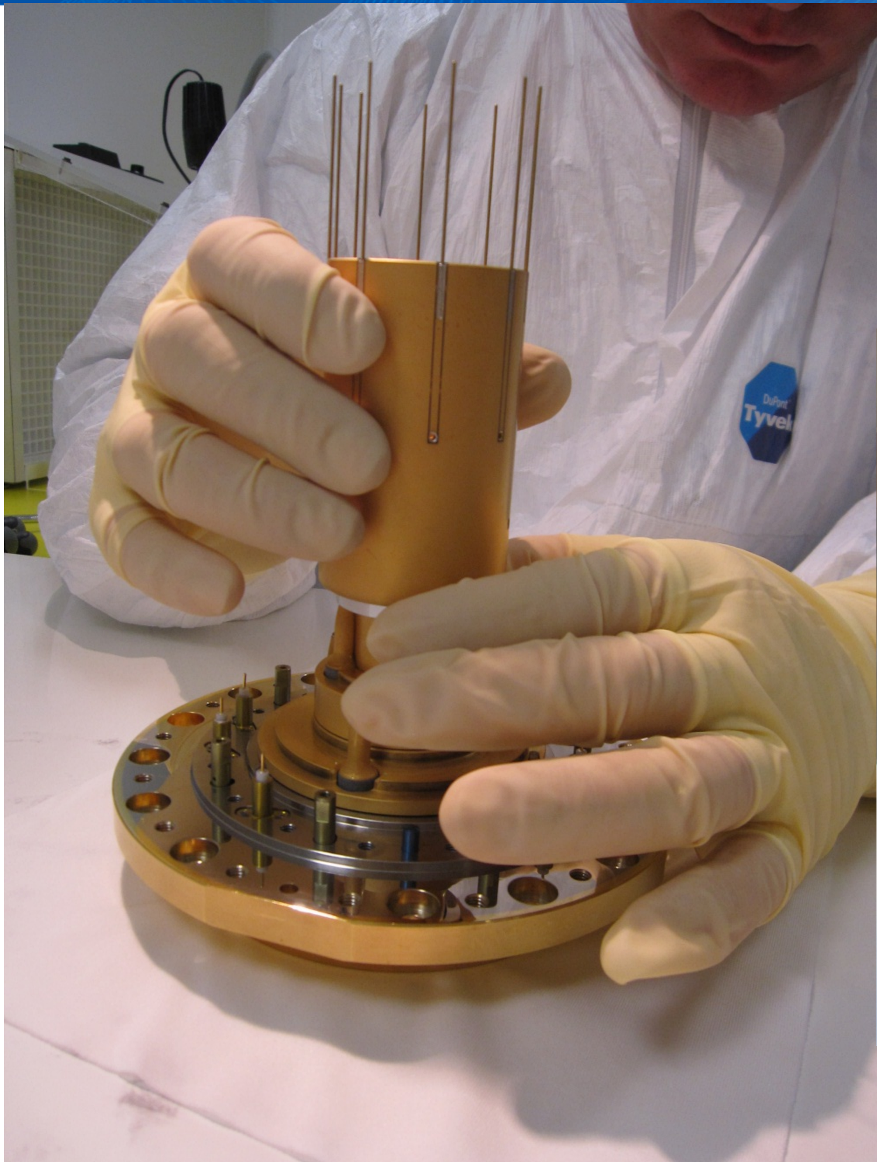
Precise test-mass servo positioning thanks to

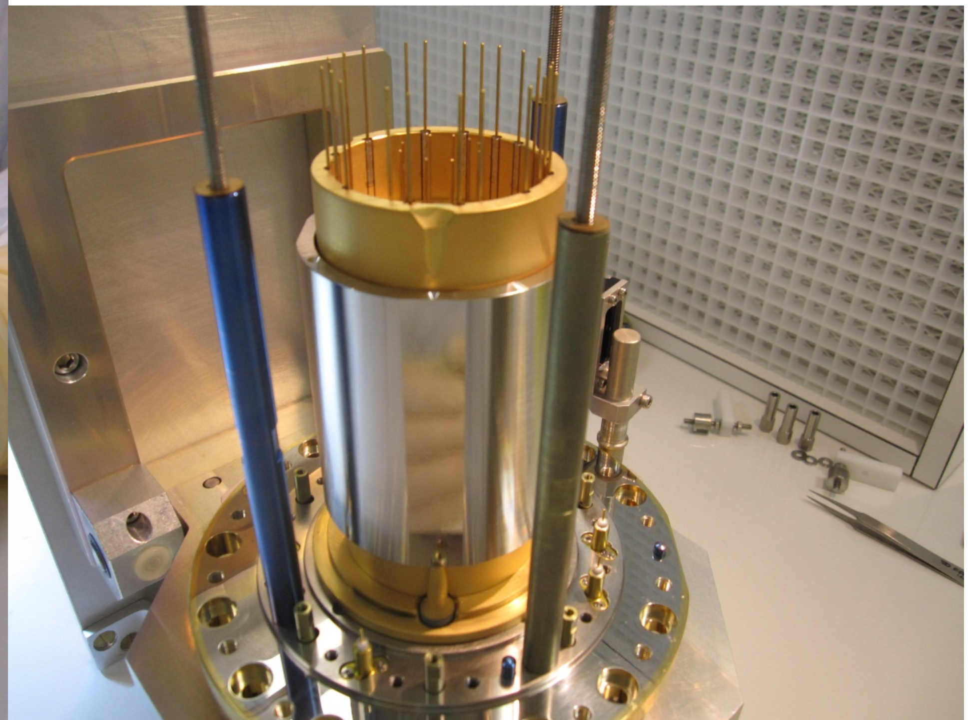
- accurate machining
- accurate metrology and integration
- low noise electronics
- thermal stability

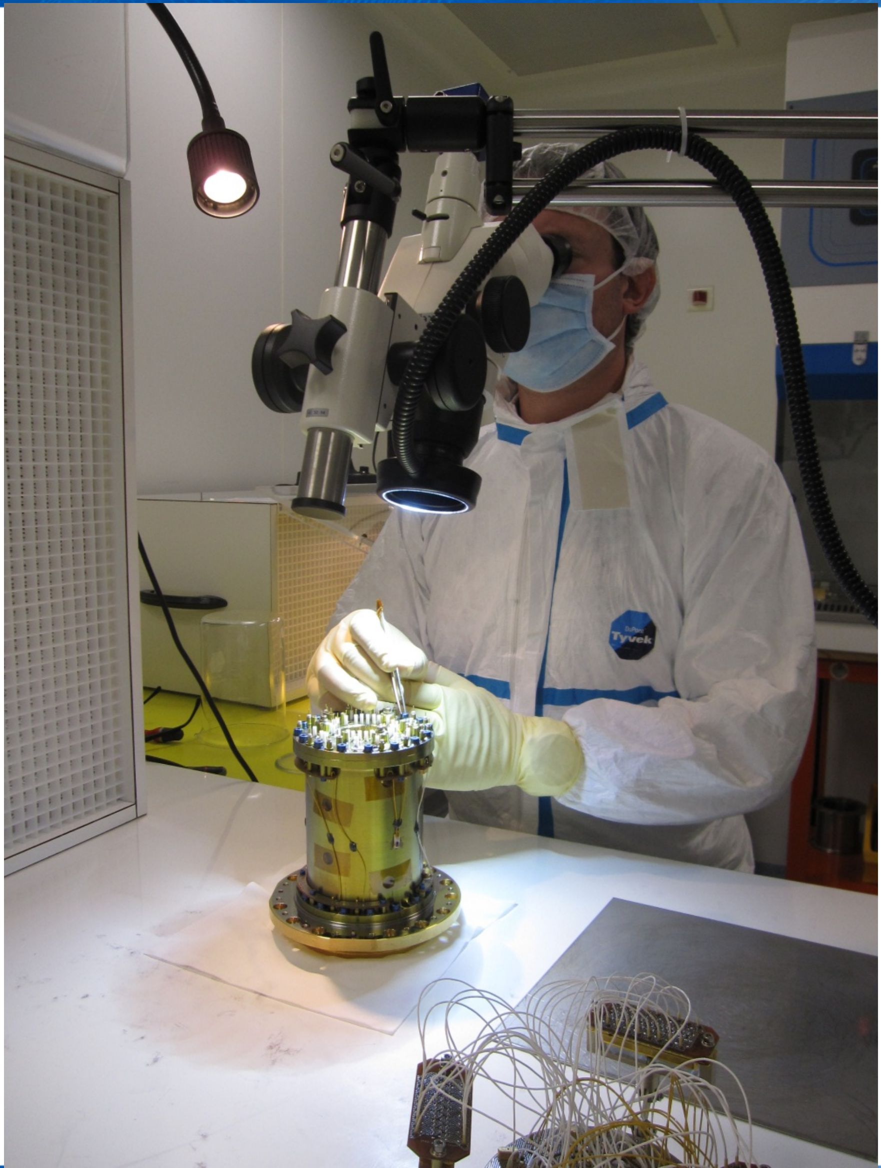
INTEGRATION

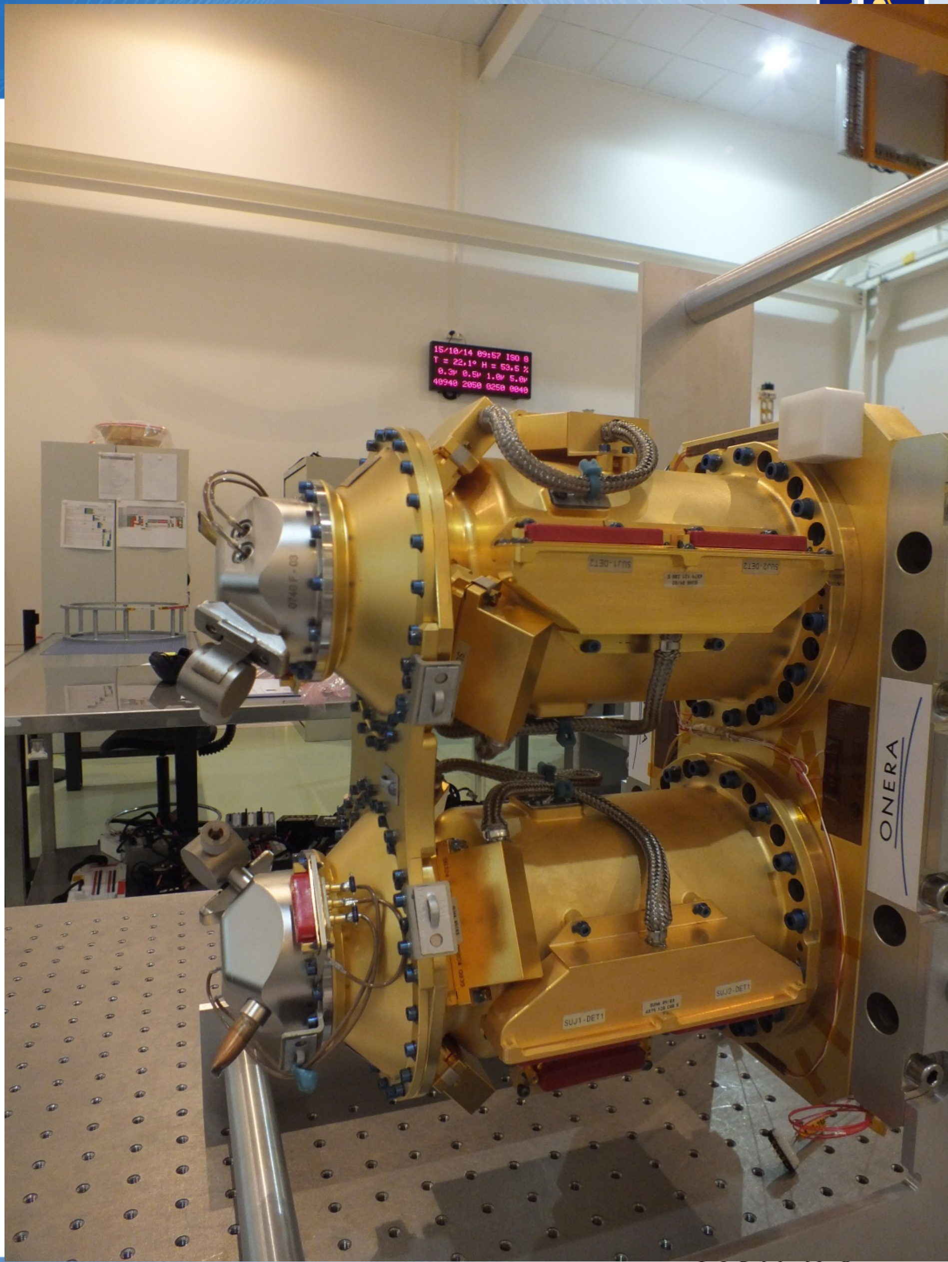








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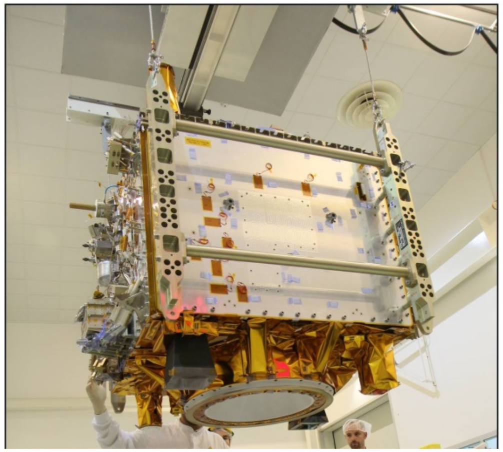
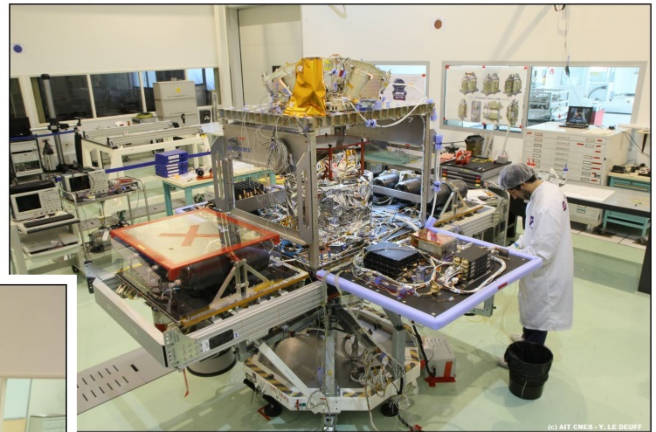
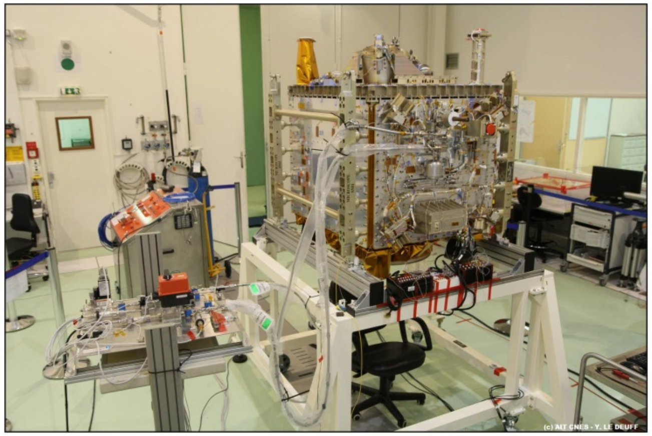
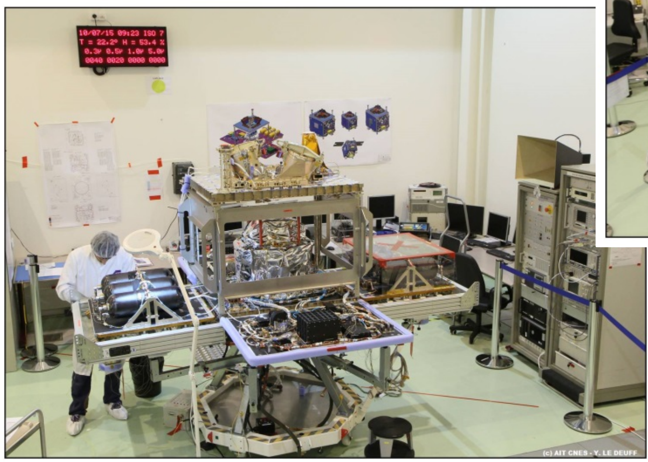
Satellite integration

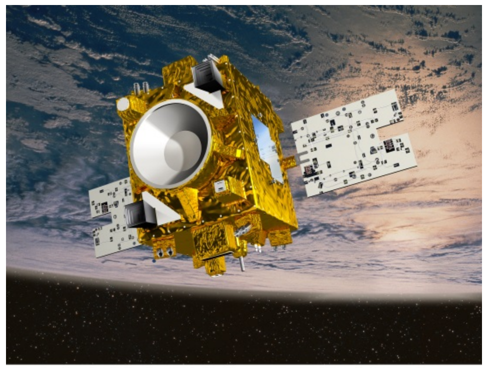








CNES Courtesy



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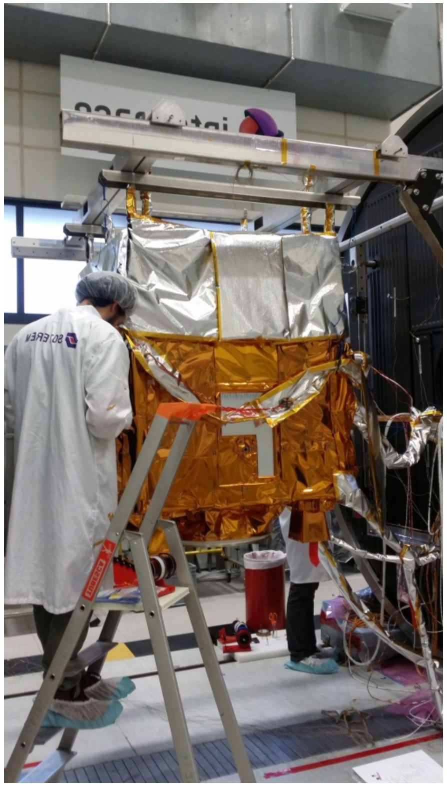
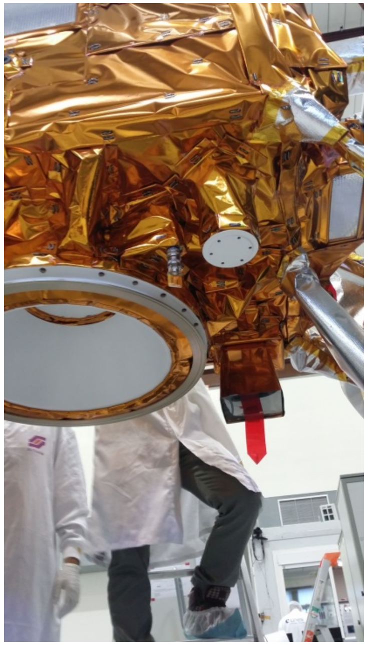




CNES courtesy

SU + FEEU + ICU

SU'sFM : Sensors

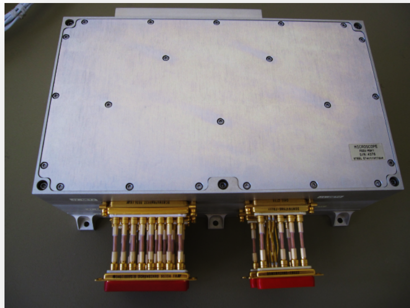
- The sensor core is in accordance with the performance requirements.
- Delivered to CNES on Sept 17th of 2014
- → integration in S/C cocoon

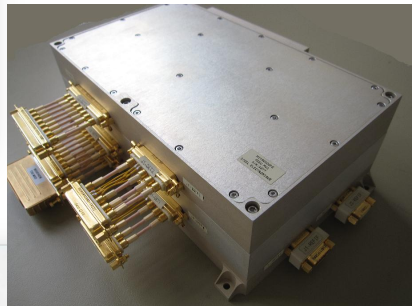
FEEU QFM1 + FM2 : Low noise Electronics U.

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

ICUME QFM : Digital Electronics U.

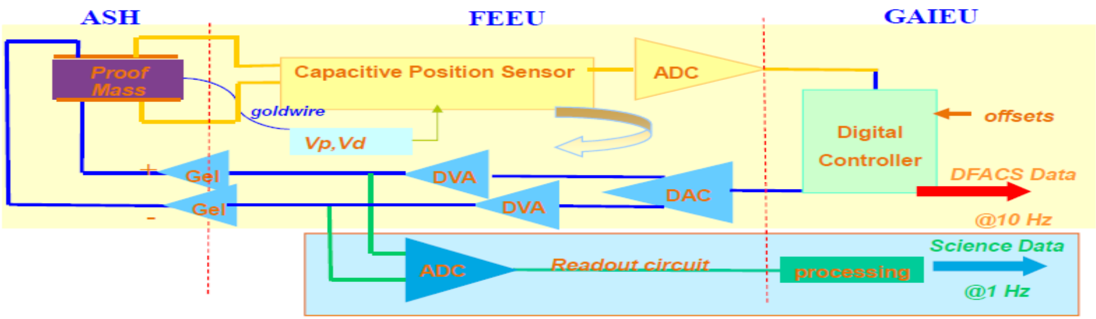
- Qualification and delivery end of March 2015
- Interface test with S/C : OK
- EMC test of the S/C: OK





Measurement principle

1 inertial sensor = 1 mass with reference voltages + 6 servo-channels + 1 read-out circuit



Same orbital motion at better than 10^{-11}m wrt stabilized same reference

Measured applied accelleration at better than $10^{-15}ms^{-2}$

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

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

Capacitive sensing :

	Internal Mass (1,4 kg)	External Mass (0,4kg)
X	12 μV$Hz^{-1/2}$ = 4 10^{-11} m$Hz^{-1/2}$	6 μV$Hz^{-1/2}$ = 2.5 10^{-11} m$Hz^{-1/2}$
Y,Z	6 μV$Hz^{-1/2}$ = 2.5 10^{-11} m$Hz^{-1/2}$	3 μV$Hz^{-1/2}$ = 1 10^{-11} m$Hz^{-1/2}$

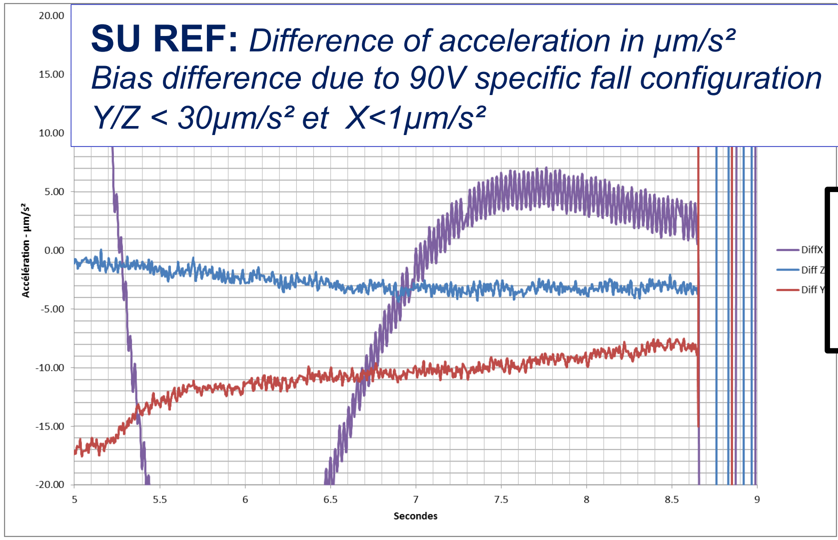
Electrostatic control & measurement :

	Internal Mass	External Mass
X	1.1 μV$Hz^{-1/2}$ = 20 10^{-15} N$Hz^{-1/2}$	1.6 μV$Hz^{-1/2}$ = 52 10^{-15} N$Hz^{-1/2}$
Y,Z	2.3 μV$Hz^{-1/2}$ = 160 10^{-15} N$Hz^{-1/2}$	2.3 μV$Hz^{-1/2}$ = 710 10^{-15} N$Hz^{-1/2}$

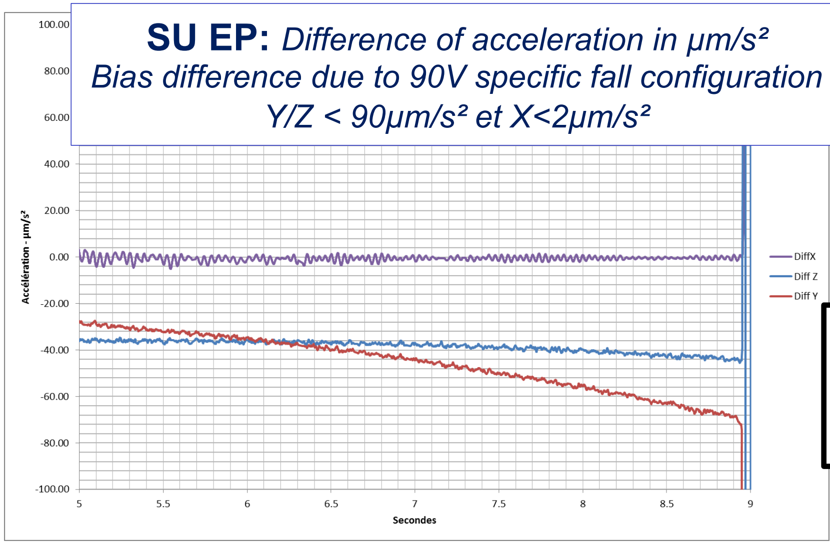
Proof mass reference voltage : Vp = 5V ; 0.22 μV$Hz^{-1/2}$; 13 ppm/°C + stability compatible with 5mK fluctuations

Power supply : 0,1 mV for 1 V satellite power bus variation & 2mV/°C

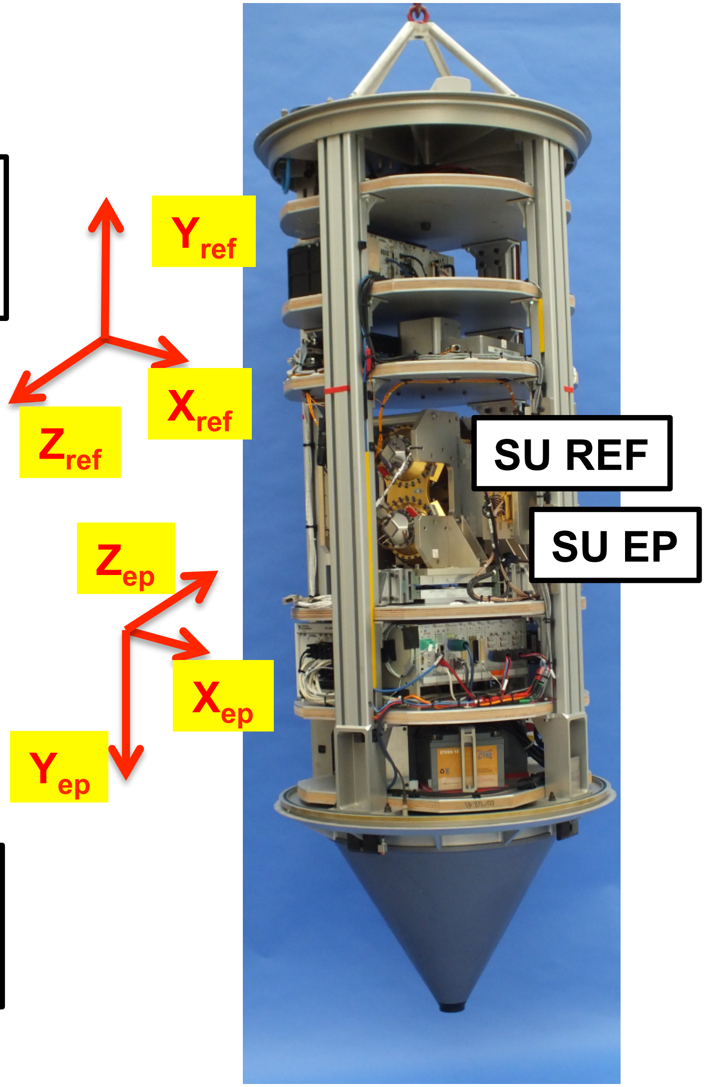
FM Drop 05 et 06 : 20th March of 2014
1st results



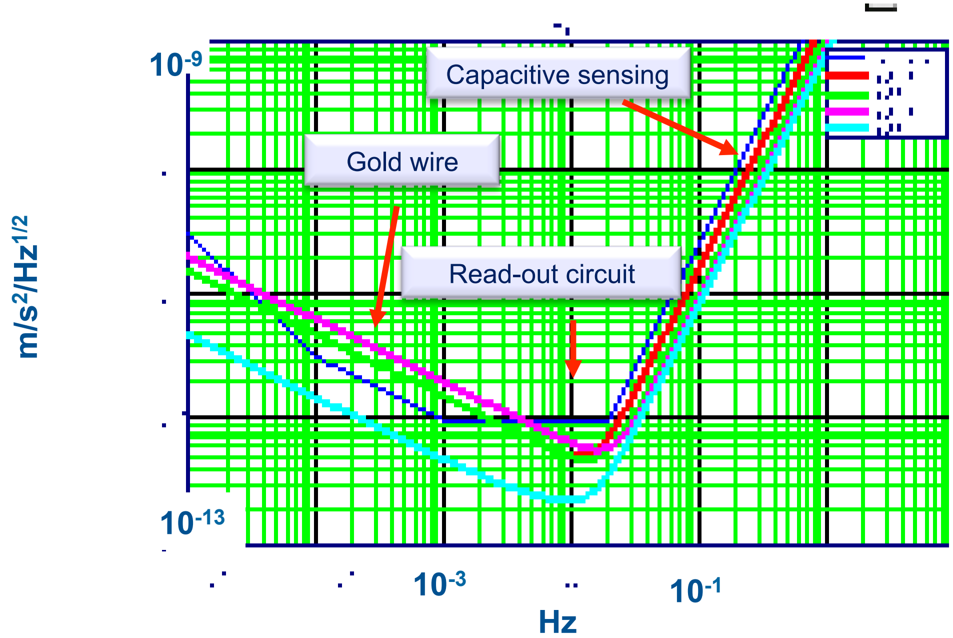
Bias + Scale Factor
X < 3 μm/s²
Z < 3 μm/s²
Y < 8 μm/s



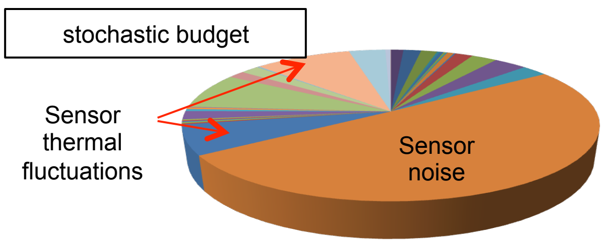
Bias + Scale Factor
X < 1μm/s²
Z < 40μm/s²
Y < 67μm/s



FM error budgets



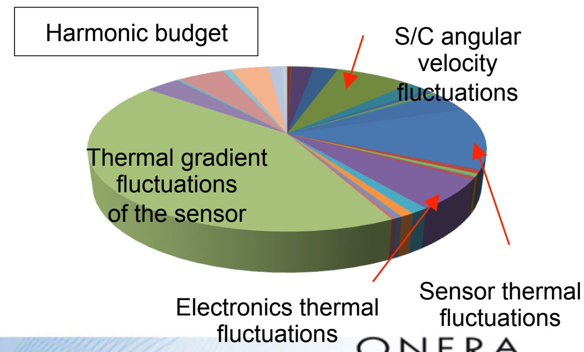
Similar to GOCE sensor noise performance : demonstrated in orbit by a factor 2 at least in the [5,10^{-3}; 10^{-1}] bandwidth
MICROSCOPE at lower frequency, smaller bandwidth and longer integrating period



Overall mission error budget :

- ***59 disturbing sources evaluation stochastic & tone***
- ***Instrument : more than 100 contributions***
- ***Taking into account verified instrument and satellite charcteristics***

	stochastic disturbing source	tone disturbing source	EP (120 orbits)	EP (240 orbits)	EP (360 orbits)
	$ms^{-2}/Hz^{1/2}$ quadratic sum	ms^{-2} direct sum/3			
Inertial satellite pointing (f_{EP}= f_{orb}= 1,7 10^{-4}Hz)	6,64 10^{-11}	7,58 10^{-15}	1,38 10^{-15}	1,19$10^{-15}$	
Rotating satellite attitude (f_{EP}= 11/2 or 11/2 f_{orb}= 7,7 or 9,4 10^{-4}Hz)	6,64 10^{-12}	6,64 10^{-13}	0,58 10^{-15}	0,48 10^{-16}	0,45 10^{-17}



MICROSCOPE

The Measure

EP violation δ

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

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

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
→ Estimate of the mass off-centering and Earth gravity gradient corrections
→ Difference of sensitivity & alignment corrections
→ Non linearities verifications

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MICROSCOPE Major mission specifications Instrument/Satellite dynamics

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

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*
- *Assessment sessions of the satellite, the instrument, the propulsion system, the drag-free and attitude control*
- *But also performance sessions with mass displacement, accelerometric, magnetic, thermal excitations*
- *Measurement session (with margin for lack of data)*
  - *Inertial pointing : 123 orbits*
  - *Rotating pointing : 6 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 the obtained results :*
  - *Each possible sequence is precisely defined, argued and tested*
  - *CMS with autonomous software to evaluate operating conditions*
  - *Dedicated every week procedures*

system guaranteed scenario:
99.8% confidence
→3155 orbits

scientific objectives scenario :
80% confidence
→ 4921 orbits

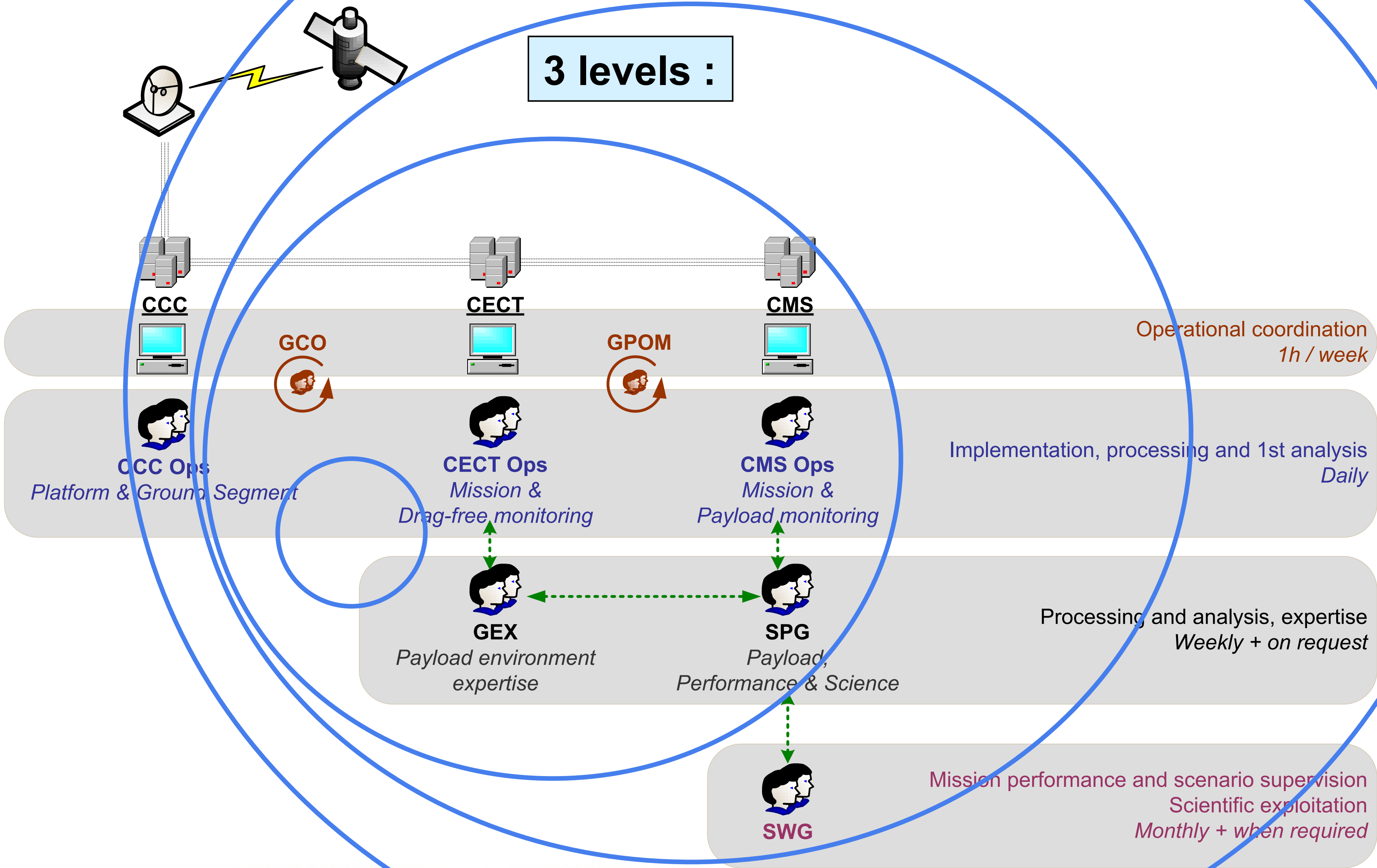
A PRIORI SCENARIO

	orbits	days	propulsion ON
S/C, T-SAGE, Propulsion system, AOCS laws with & without T-SAGE Assessments	369	25	178
Thruster calibration, drag-free operation	59	4	59
Total Commissionning step 1	428	29	237
Drag-free & calibration assessment	150	10	128
Margin	145	10	145
Total Commissionning step 2	295	20	273
Limited Test EP & REF inertial and spinned attitude	360	25	360
Performance Test	898	62	898
Total Preliminry EP Test	1258	87	1258
Break	200	14	0
Calibration EP & REF	300	21	300
Full Test EP & REF	1068	73	1068
Total EP Test	1568	108	1368
Calibration EP & REF	192	13	192
Half Test EP & REF with centered test mass	534	37	534
Total EP Test with centered test-mass	726	50	726
Spinned Test EP & REF Complement	568	39	568
Calibration EP & REF	192	13	192
Inertial Test EP & REF Complement	250	17	250
Total complement EP Test	1010	70	1010
TOTAL	5285	364	4872

Performance tests :

1. *Response to Heavyside in acceleration and in position*
2. *Relative orientation of star tracker (Gravity Model & S/C attitude) & instrument axis (mass motion) : $\eta c + \theta c$*
3. *Sensitivity to S/C acceleration along each axis → difference of sensitivity and non linearity + alignments*
4. *Sensitivity to Test-mass motion along each axis → stiffness, non linearity, self gravity*
5. *Sensitivity to high frequency acceleration signal in the loop along each axis → individual non linearities*
6. *Sensitivity to 3 in the band acceleration signal along the 3 axes → coupling*
7. *Sensitivity to magnetic field*
8. *Sensitivity to thermal fluctuations of the SU, th FEEU*
9. *Sensitiy of 3,4,5 to mass potential and position*

Scientific and operational organisation



Scientific organization : Science Working Group

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

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 call for proposals for the use of data
- 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 (delivered one year ago) is integrated in its satellite cocoon.
- The satellite is integrated with its payload and is under environment tests : present agenda is in agreement with the launch date
- **Launch scheduled on Soyouz in April 2016 as a secondary passenger with Sentinel 1B.**
- The satellite control center and CECT has been developed by Cnes and are under operation tests
- The Science Mission Center has been developed by Onera and is under tests : - Operational software : data exchanges with Cnes, validation and completion, achieving, quick-look, easy analysis : ready
  - Scientific analysis : under optimization

"I never worry about the future. It comes soon enough." —Albert Einstein --- Aphorism, 1945–1946. AEA 36–570
« I, too» Pierre T., November 2015

END

Thanks

Questions