MICROSCOPE: Ready to test the Equivalence Principle in space

Joel Bergé (ONERA)
on behalf of the Microscope team

Micro-Satellite à traînée Compensée pour l'Observation du Principe d'Equivalence

Drag-free microsatellite for the observation of the Equivalence Principle

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return on innovation

Weak Equivalence Principle

a.k.a the universality of free fall

All test bodies follow the same universal trajectory in a gravitational field, independently of their mass, detailed internal structure and composition.

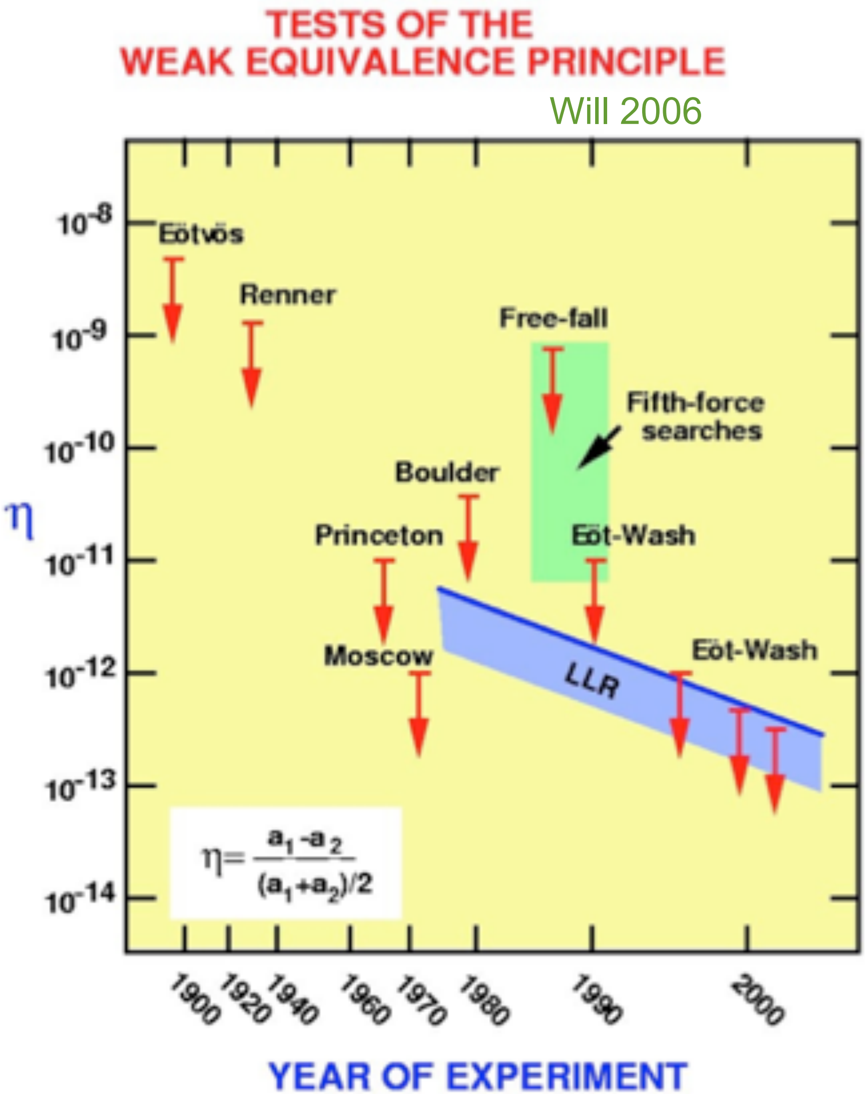
For all test bodies, the inertial mass and the gravitational mass are equal: $m_i = m_g$

$$F = m_i\, a$$
$$F_g = m_g\, g$$

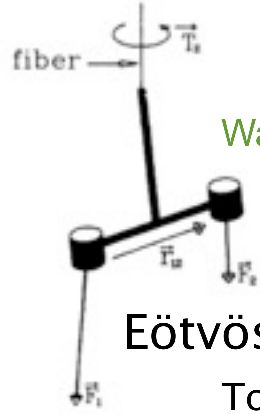
Precision measured in terms of the Eötvös ratio

$$\eta_{1,2} = \frac{a_1 - a_2}{(a_1 + a_2)/2} = \frac{(m_g/m_i)_1 - (m_g/m_i)_2}{[(m_g/m_i)_1 + (m_g/m_i)_2\,]/2}$$

WEP tests up to now



Will 2006



Wagner+ 2012

Eötvös, Eöt-Wash

Torsion balance

Lunar Laser Range Williams+ 1996

Probes fall of Earth and Moon towards the Sun

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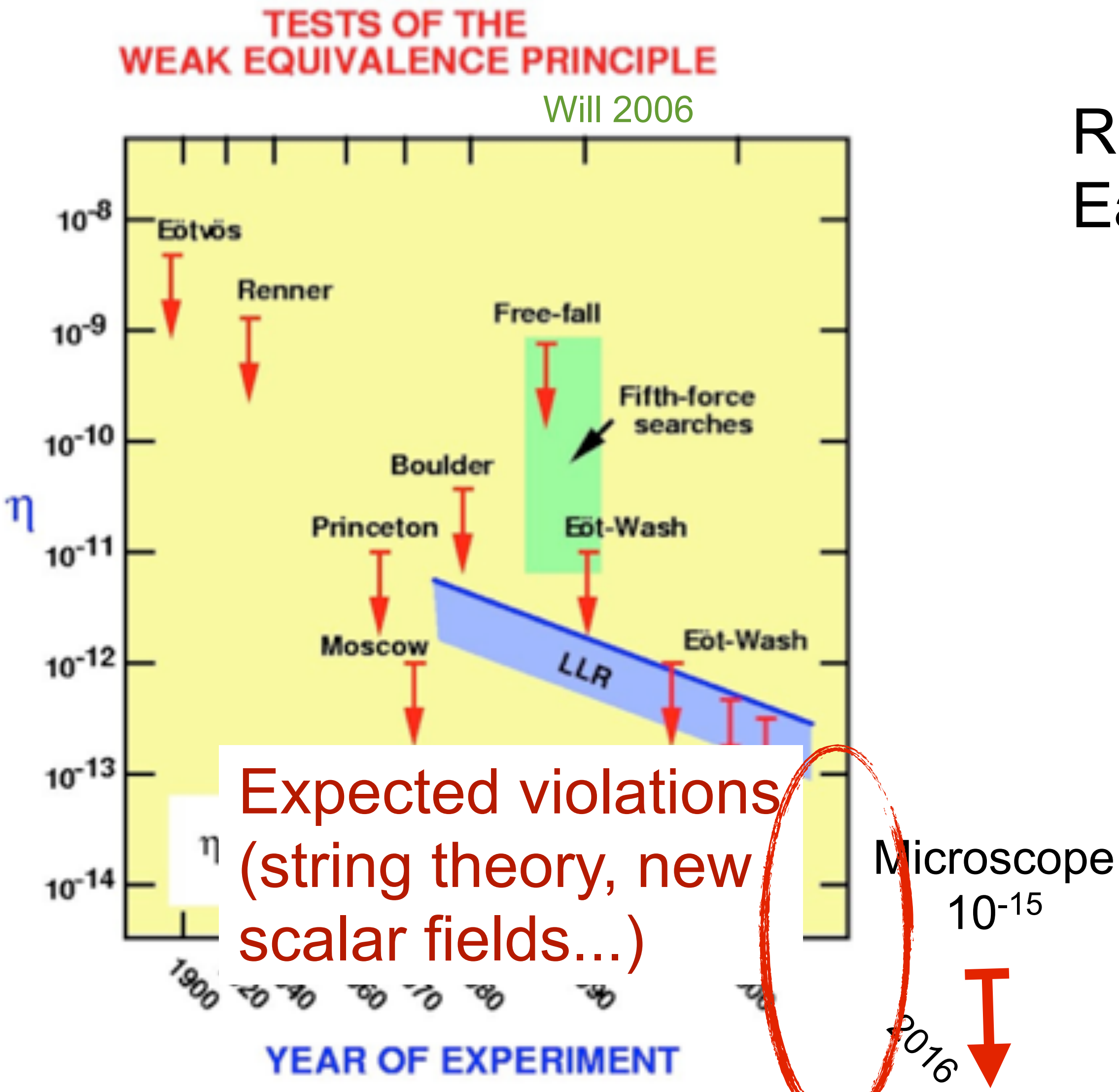
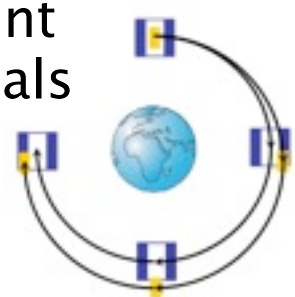
The near future, what to expect?



Reaching the limits on Earth => go to space

Free fall of different materials



Both masses do not have the same orbit

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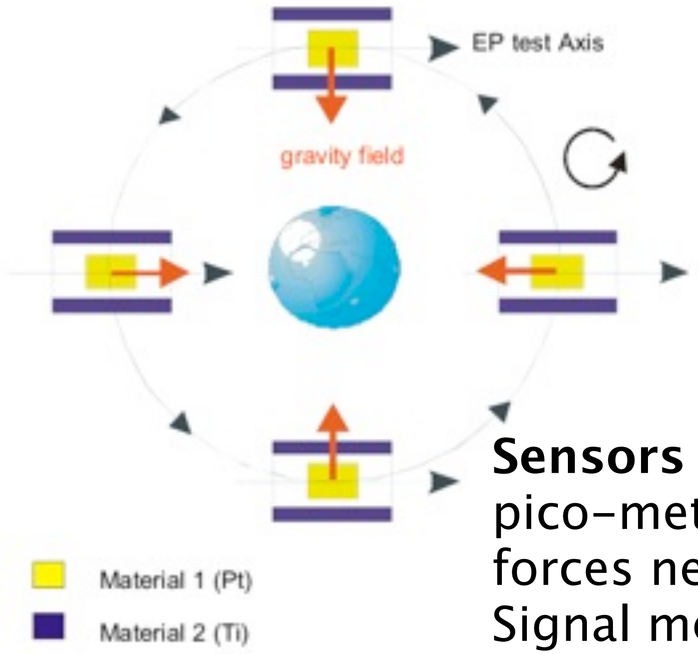
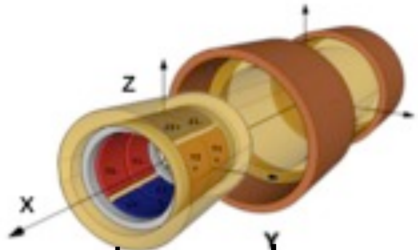


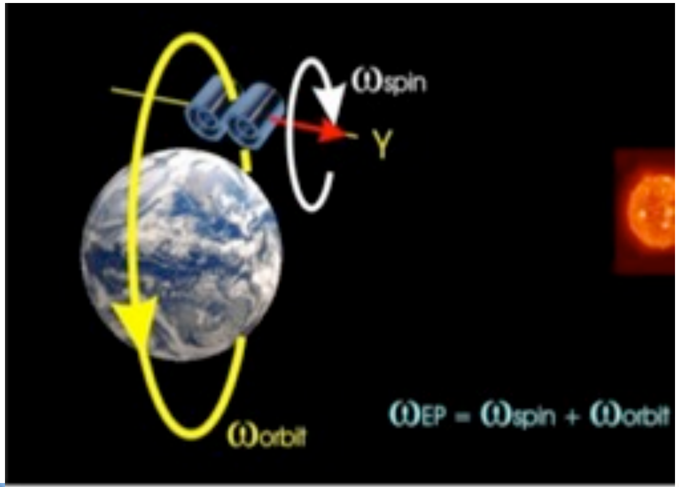


Differential electrostatic accelerometer:
2 coaxial cylindrical inertial sensors

Sensors forced to follow the same orbit (permanent pico-meter control) => we measure the electrostatic forces needed to keep the sensors centered.
Signal measured along an ultra-sensitive axis.

Source: gravity field modulated by satellite's motion around the Earth => sine of known frequency f_{EP} that can be varied by either:

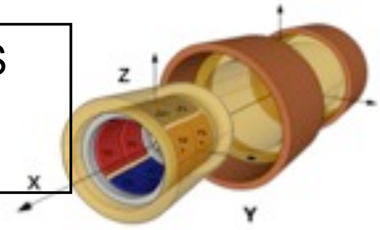
- Keeping the satellite in inertial motion
- Or spinning it



MICROSCOPE in a nutshell

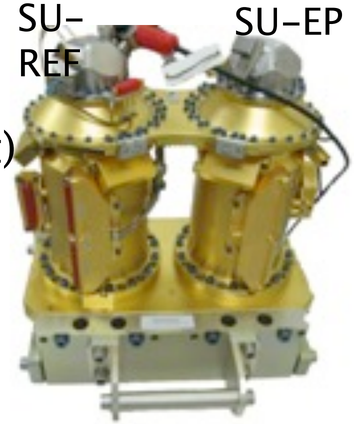
Dedicated space instrument for EP violation tests

PI: Pierre Touboul (ONERA), in collaboration with OCA Nice and CNES
Instrument + Data processing and analysis: ONERA / OCA Nice
Satellite: CNES



Satellite

- drag compensation (residual< 10^{-12} ms^{-2} @ f_{EP}) and fine attitude control (angular stability < 7µrad, velocity < 10^{-9} rad/s + acceleration < 10^{-11} rad/s^2 @ f_{EP}) => very sensitive 6-axis sensor and very fine actuators
- fine passive thermal control (~mK @ f_{EP}) and soft electromagnetic environment
- satellite position on orbit known at < 7 m
- no mechanism (minimize micro-disturbances eg changes in self-gravity)
- magnetic shield for the payload

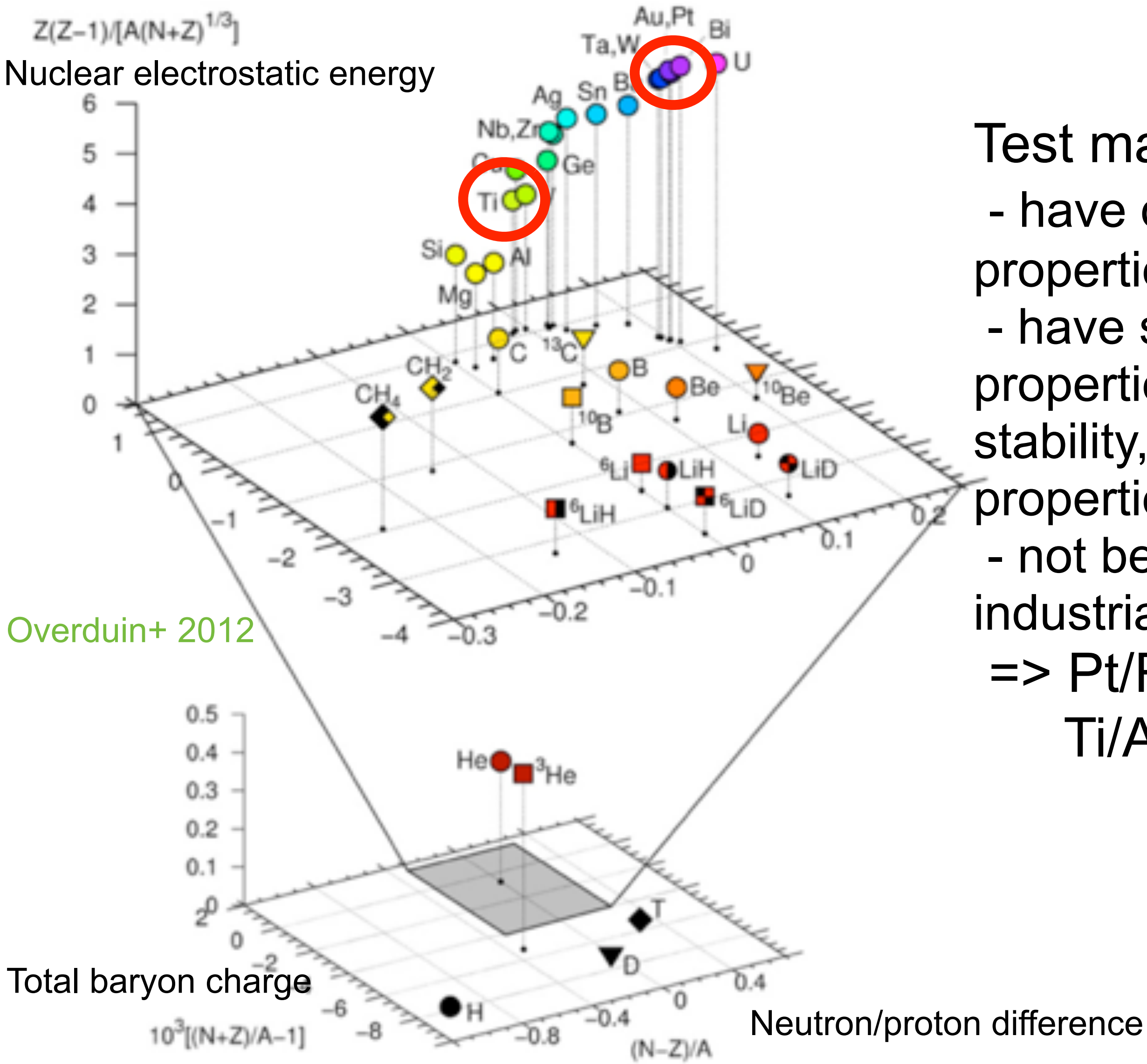


Payload: T-SAGE (Twin Space Accelerometer for Gravitation Experiment)

Two differential electrostatic accelerometers (Sensor Units):

- Each accelerometer made of 2 coaxial cylindrical accurate test masses (relative dissymmetry of moments of inertia < 7×10^{-4}, inhomogeneity ~ 10^{-4})
- One with test masses of same composition (Pt/Rh) for reference
- The other one with test masses of different composition (Pt/Rh – Ti) for EP test

Why Pt/Rh and Ti test masses?

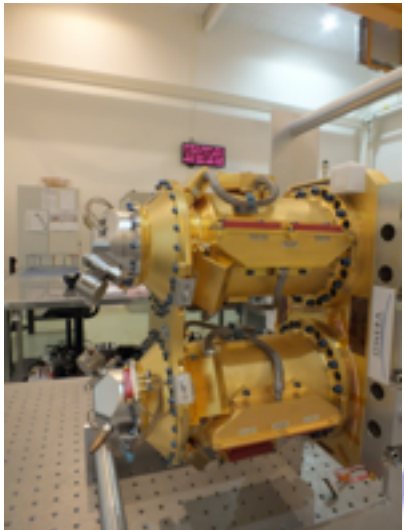


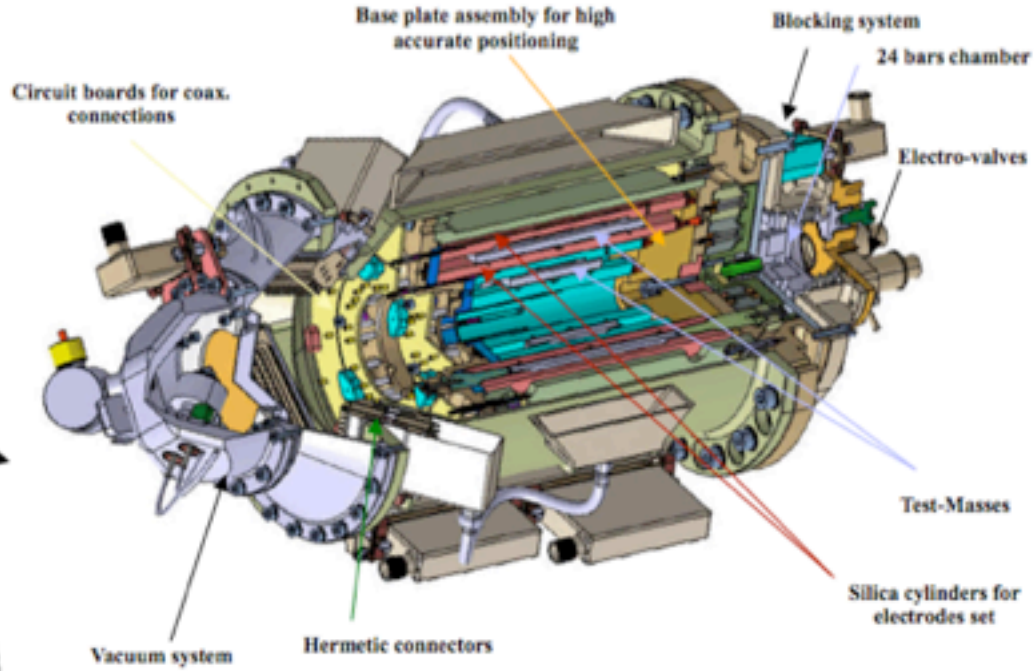
Test masses should:

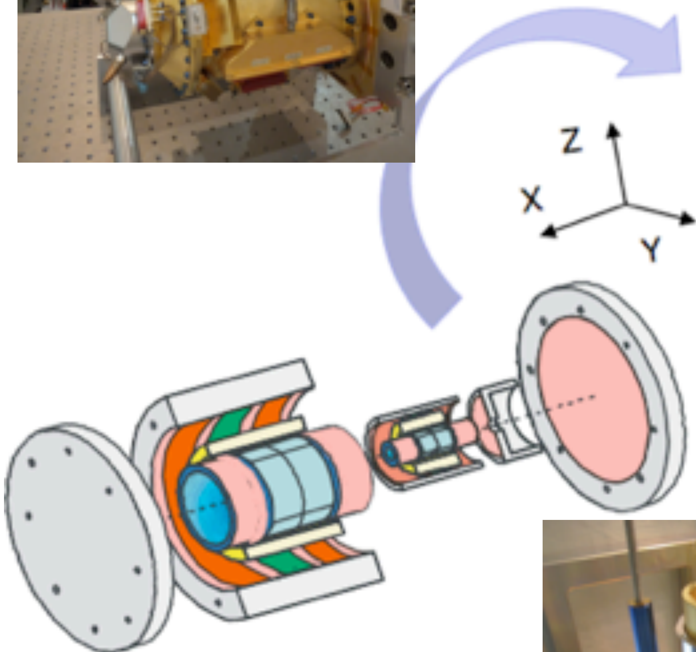
- have different nuclear properties to maximize signal
- have special macroscopic properties (homogeneity, chemical stability, electrical and magnetic properties)
- not be too difficult to machine industrially

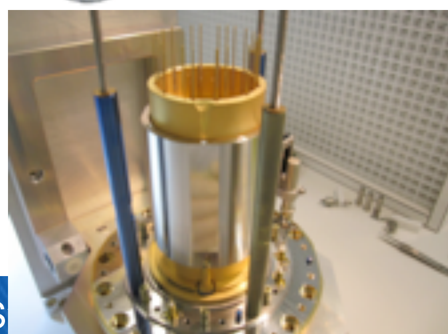
=> Pt/Rh alloy (90%, 10%)
Ti/Al/V alloy (90%, 6%, 4%)

T-Sage Sensor Unit







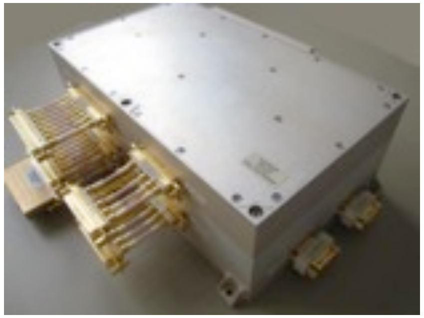


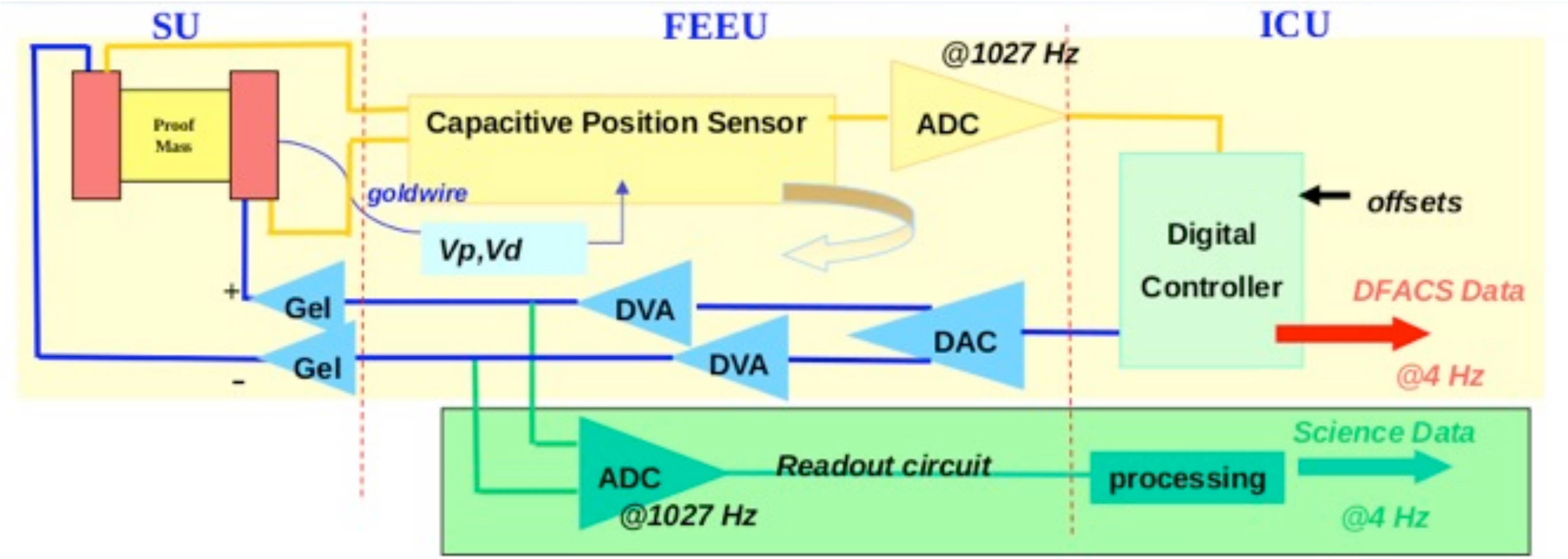
Precise test-mass servo positioning thanks to

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

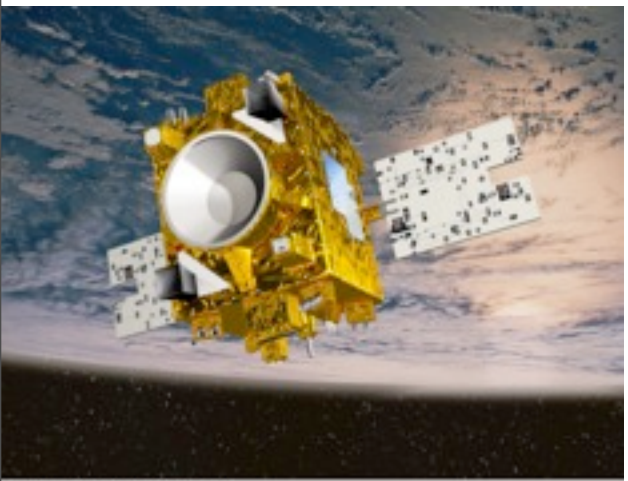
Servo-loop control

Electronics control test mass' position.

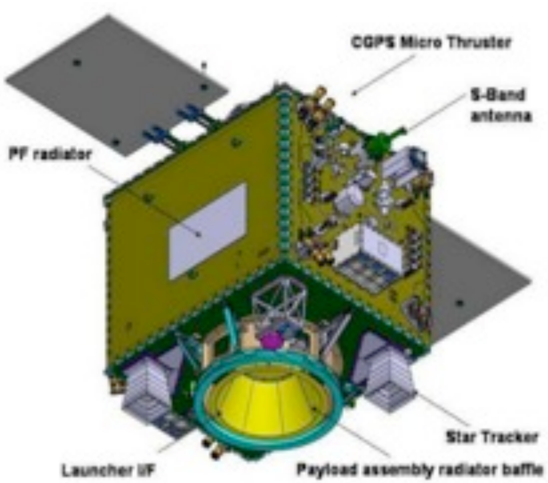




Satellite



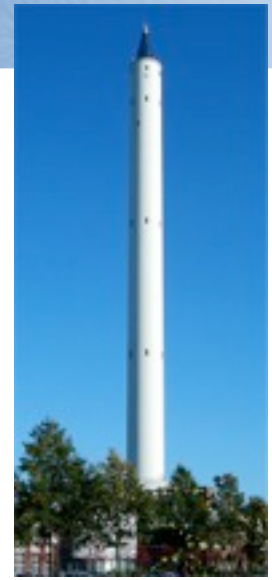
CNES Myriade satellite
- almost “Off-the-shelf”modular micro-satellite
- series of satellite (Demeter, Parasol, Picard)
- mass: 325 kg
- dimensions: 1380 mm x 1040 mm x 1580 mm
- Cold Gas propulsion system -> developed by CNES with major ESA contribution

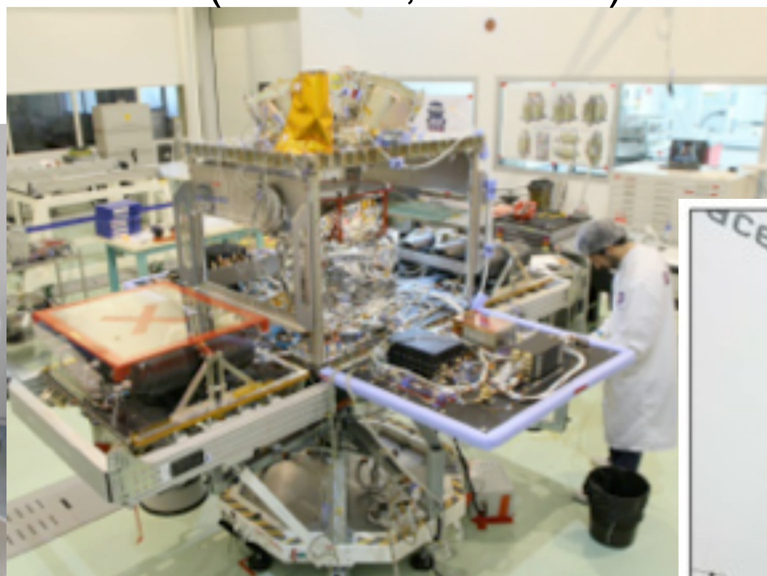


Payload Assembly System:
- thermally insulates SU and FEEU from the satellite (autonomous passive thermal control)
- magnetically shields SU

Status

- Free fall tests (ZARM tower): Feb. / Mar. 2014
- Sensor cores delivered Sept. 2014
- Electronics qualified and delivered Oct. 2014 / Mar. 2015
- Satellite’s physical properties measurements (mass, center of gravity tuning and location) Nov. 2015
- Satellite’s mechanical (vibration, acoustic) tests Nov/Dec 2015

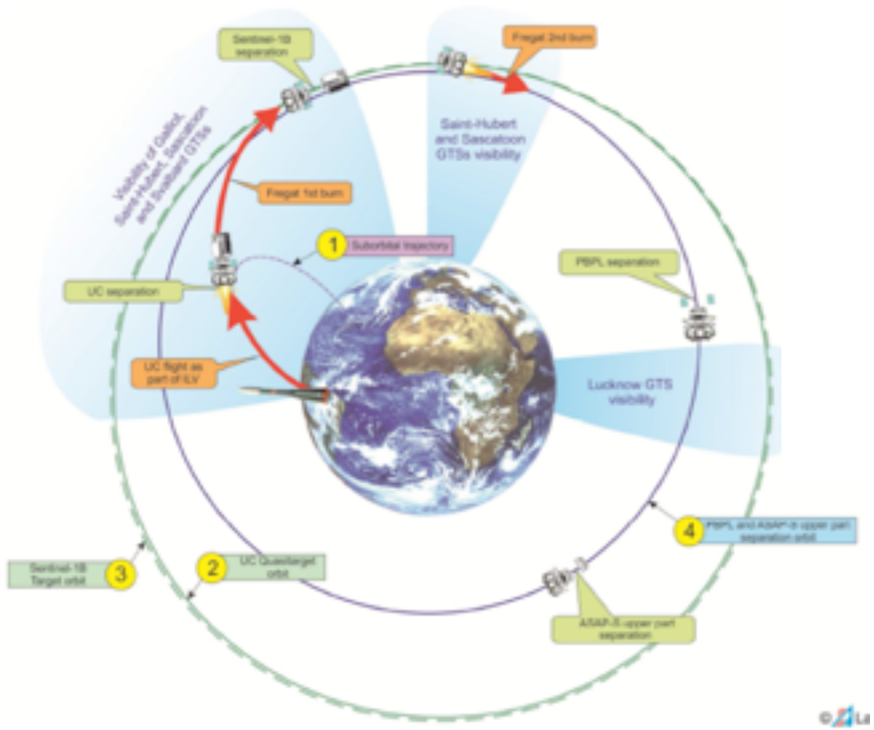




Steps to the launch

- Final reference and performance tests: January 2016
- Final satellite configuration setting: early February 2016
- Transport to Kourou February 19, 2016

- Launch April 2016



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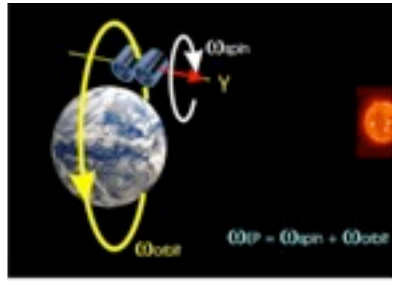
Exploitation phase

What must be done...

- accurate measurements of the WEP test in various configurations
    - inertial pointing with 2 orientations at ascending node
    - spinning pointing at 2 different frequencies
    - modify test masses off-centering
- validate the performance
    - accurate in-flight calibration of the major driving parameters
    - accurate characterization of the instrument thermal behavior and sensitivity to other parameters

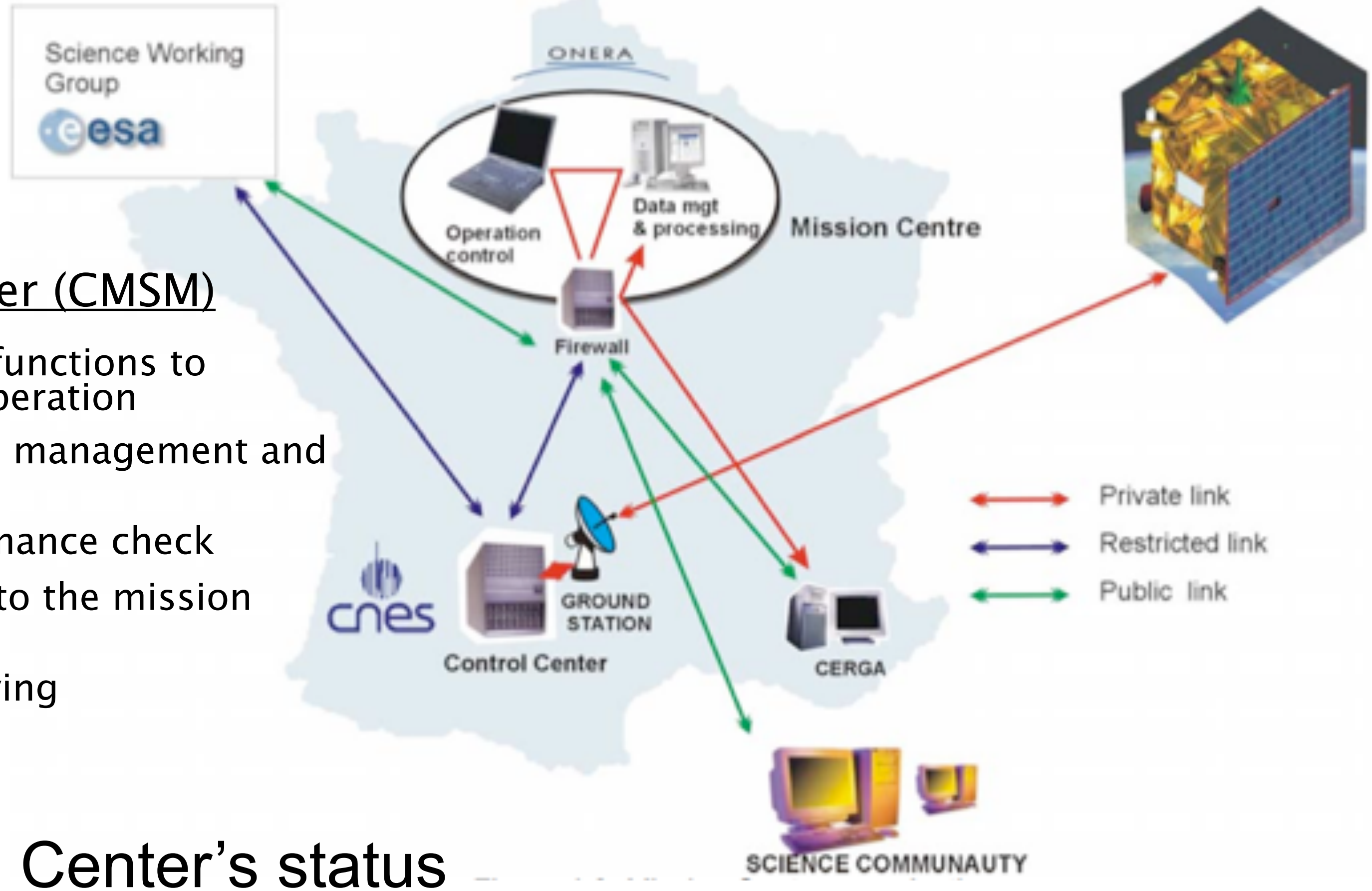


... under some constraints

- limited gas quantity for the thrusters => priorities established, no improvisation during the mission
- operational security => need of planning in advance what to do and how

Nominal mission duration: 2 years

Ground segment / Science Mission Center



Science Mission Center (CMSM)

- Ensure all operational functions to maximize instrument's operation
- Day-to-day instrument management and monitoring
- Weekly mission performance check
- Propose modifications to the mission scenario
- Data release and archiving

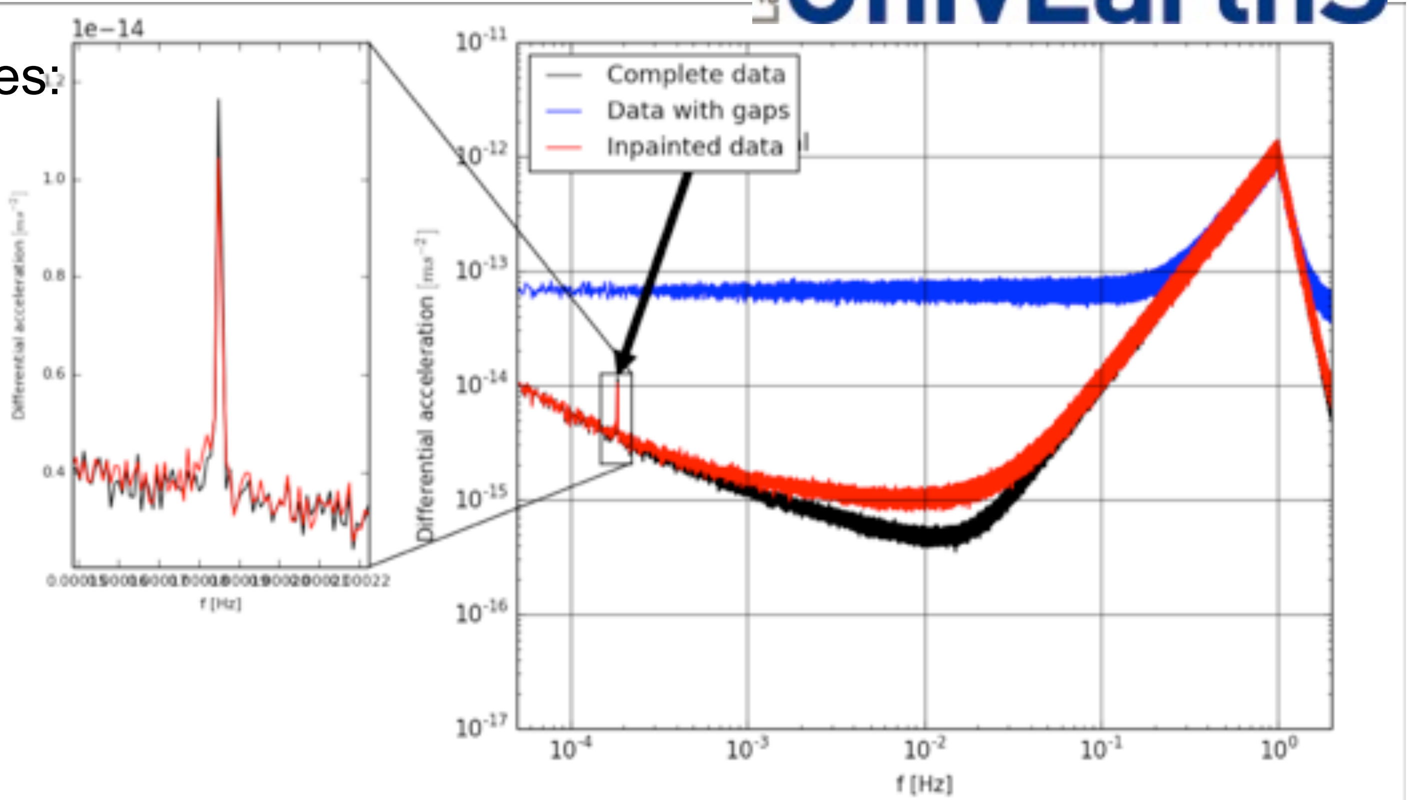
Science Mission Center's status

- Instrument's monitoring softwares developed, under tests
- Development of data processing software in progress
- Technical/Operation qualification with CNES underway

Data analysis: the curse of missing data

Missing data causes:

- telemetry loss
- micrometeorite impacts
- crackles due to tankers, coating



Only ~2% missing data, but spectral leakage of high frequency into lower frequency

- Development of the KARMA method: optimal Least-Square fit with missing data (Baghi+ 2015)
- Adaptation of the *inpainting* method (Bergé+ 2015, Pires+ 2016) to fill in gaps with statistically similar signal: extrapolation of missing data using a sparsity prior.

Conclusions

- MICROSCOPE will test the Weak Equivalence Principle in space down to an accuracy of 10^{-15} (2 orders of magnitude better than current constraints)
- Test of fundamental physics, may rule out new theories that predict an EP violation around 10^{-14}, or even GR
- Will show that the technology is ready for extremely fine satellite attitude control and precise drag-free system
- Launch expected in April 2016
- Results in 2017

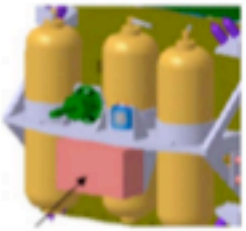
Take away ballpark number: 10^{-15}, what does that mean?

In orbit, at 710 km, g=8 ms^{-2} => WEP: 8×10^{-15} ms^{-2}

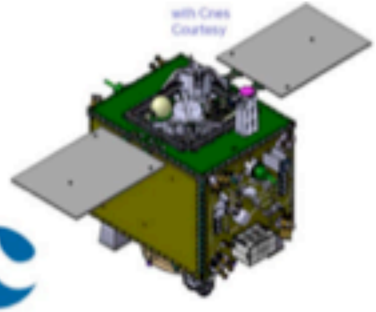
➡ At 8×10^{-15} ms^{-2}, a pedestrian walking at a speed of 5 km/h will take more than 5.5×10^{6} years to stop and will go 3×10^{6} times around the Earth

➡ Difference of weight of a 400 meter-long, 500000 ton-supertanker, with or without of 0.5 mg drosophilia on board

Partners



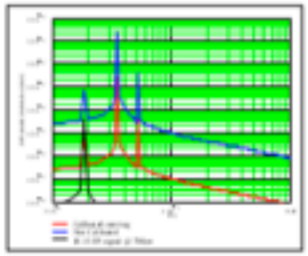
esa



cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

Geo Azur

Observatoire de la Côte d'Azur



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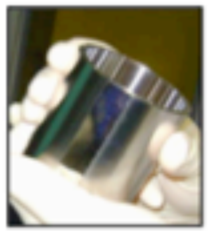
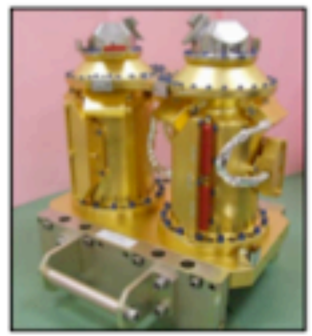
DLR





ZARM

PTB
Physikalisch-Technische Bundesanstalt

What we measure: differential acceleration

EP violation signal

$$\delta = \frac{m_{g2}}{m_{i2}} - \frac{m_{g1}}{m_{i1}}$$

$$\vec{\Gamma}_{\text{meas,d}} = [\mathcal{M}_c]\left(\delta\vec{g} + ([\mathcal{T}] - [\mathcal{I}n])\vec{\Delta} - 2[\Omega]\dot{\vec{\Delta}} - \ddot{\vec{\Delta}}\right) + \overrightarrow{K_{0,d}} + [\mathcal{M}_d]\left(\vec{\Gamma}_{\text{app,c}} + \frac{\vec{F}_{ext}}{M_{Isat}} + \frac{\vec{F}_{th}}{M_{Isat}}\right) + \frac{1}{2}K_{2,i}\Gamma^2_{App,i} - \frac{1}{2}K_{2,j}\Gamma^2_{App,j} + \vec{\Gamma}_{\text{n,d}} + [\mathcal{C}_d]\dot{\vec{\Omega}}$$

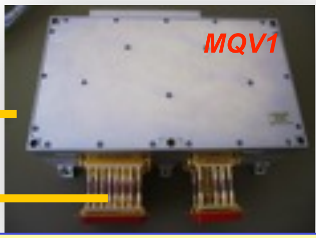
- $\delta \vec{g}$: EP violation signal
- $[\mathcal{T}]$: Earth gravity gradient tensor: *model, S/C position and attitude*
- $[\mathcal{I}n]$: Instrument's moments of inertia: *minimized by AOCS from SST and instr. data*
- $\vec{\Delta}$: Separation between test masses' centers: *minimized by instrument design*
- $2[\Omega]\dot{\vec{\Delta}}$: Coriolis acceleration
- $\ddot{\vec{\Delta}}$: Relative acceleration
- $\frac{\vec{F}_{ext}}{M_{Isat}} + \frac{\vec{F}_{th}}{M_{Isat}}$: Non-gravitational accelerations => *drag-free system*
- $[\mathcal{M}_c]$: Common mode sensitivity matrix: *estimated by in-flight calibration, limited by design*
- $\overrightarrow{K_{0,d}}$: Bias difference: *limited thermal fluctuations*
- $[\mathcal{M}_d]$: Differential mode sensitivity matrix: *estimated by in-flight calibration*
- $K_{2,i}$: Quadratic factor
- $\Gamma_{App,i}$: Total acceleration applied to proof-mass
- $\vec{\Gamma}_{\text{n,d}}$: Instrument noise
- $[\mathcal{C}_d]$: Angular-linear couplings

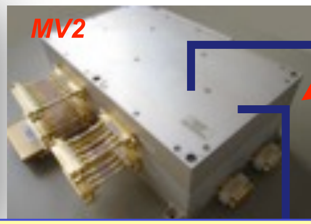
$$\begin{pmatrix} K_{cx} & \eta_{cz} + \theta_{cz} & \eta_{cy} - \theta_{cy} \\ \eta_{cz} - \theta_{cz} & K_{cy} & \eta_{cx} + \theta_{cx} \\ \eta_{cy} + \theta_{cy} & \eta_{cx} - \theta_{cx} & K_{cz} \end{pmatrix}$$

- K_{cx}: Scale factor
- η: Coupling between instrument's axes
- θ: Instrument's axes / satellite reference frame alignment

Full instrument

360 x 348 x 180 mm3 - 25kg



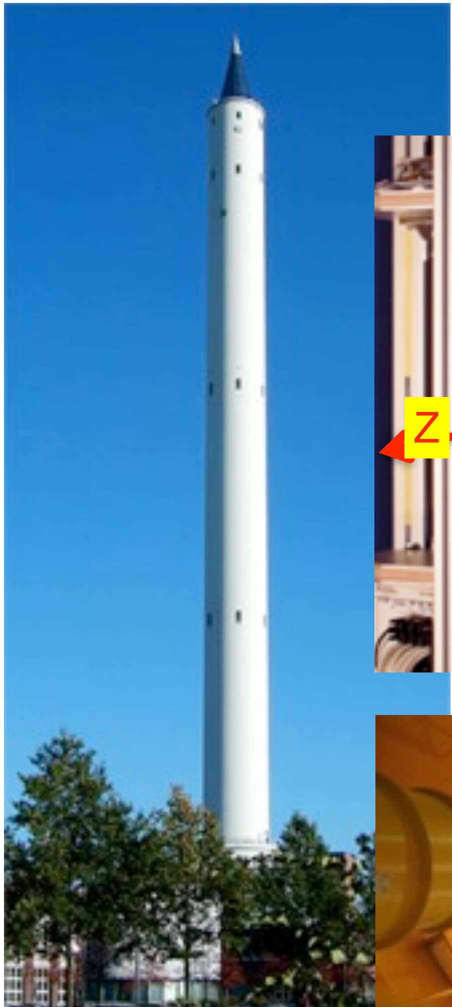


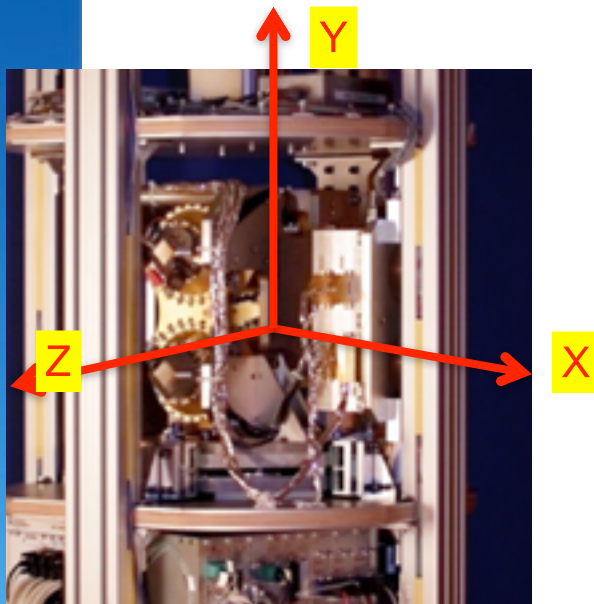
2 x { 28 cm x 17 cm x 9 cm - 3.5kg - 7W }

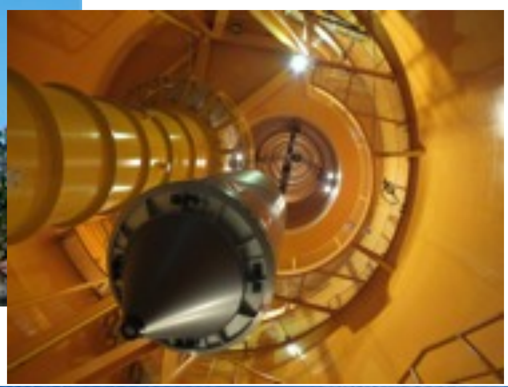
30 cm x 25 cm x 11 cm – 5kg – 2 x 11W

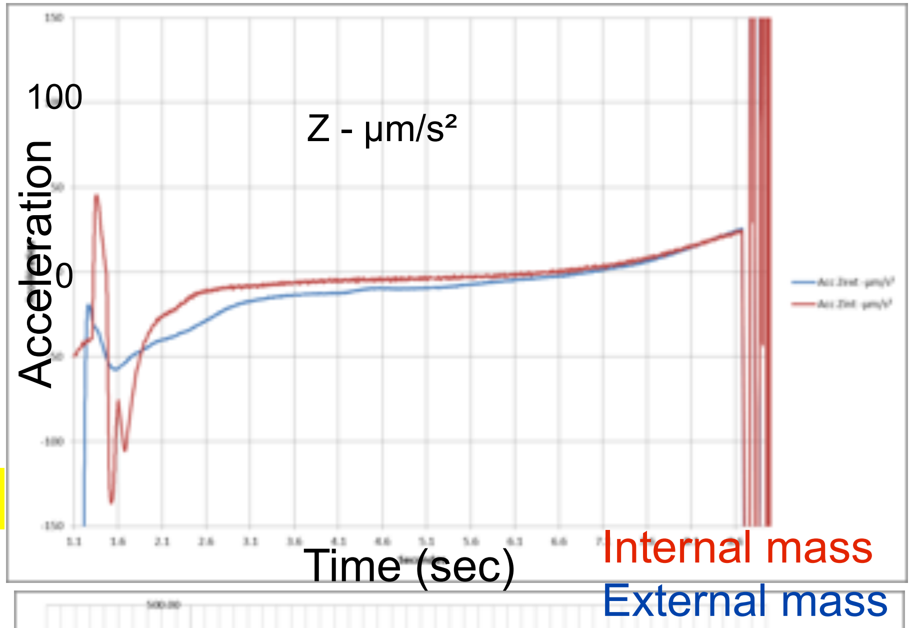
- Sensor Unit (SU) = differential accelerometer
  - **2 SU** on a Mechanics Interface (SUMI)
  - Each SU = 2 concentric Test-Masses (**Pt-Rh/Pt-Rh** or **Ti/Pt-Rh**)
  - Each mass = inertial sensor (defines measurement frame)
- Front End Electronics Unit (FEEU)
  - **Low noise analog electronic** with high stability
  - One FEEU for each SU
  - Each FEEU = measure + electrostatic control of 6 degrees of freedom
- Interface Control Unit (ICU)
  - 2 ICU stacked = ICUME
  - 1 ICU for each FEEU
  - Each ICU embarks 1 **DSP** + 1 **FPGA** for test-mass control and data conditioning for the On Board Computer
  - Each ICU embarks 2 **Power Control Unit** (1 nominal + 1 redundant) which converts the sat 28V in very stable secondary voltages (+/-48V, +/-15V,+5V,3.3V)

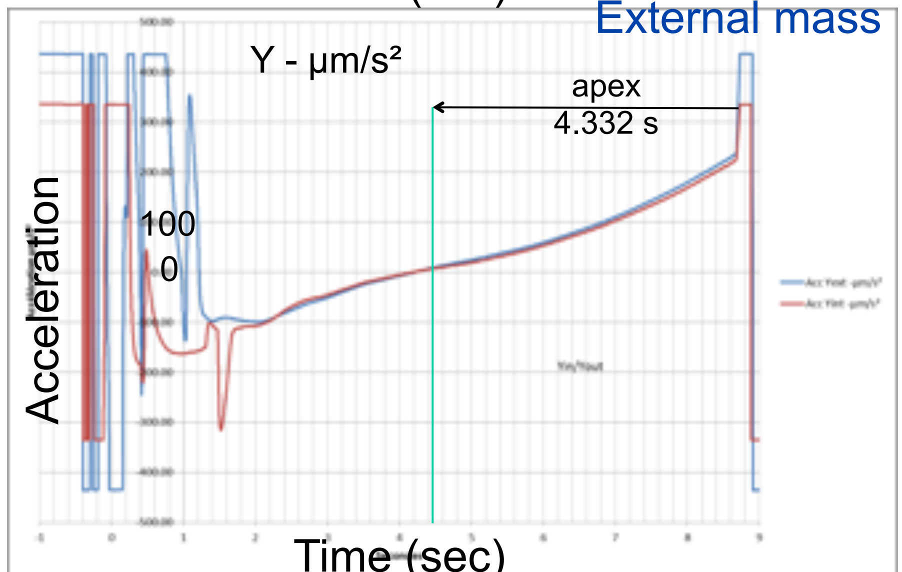
Catapult tests at ZARM drop tower (February - March 2014)











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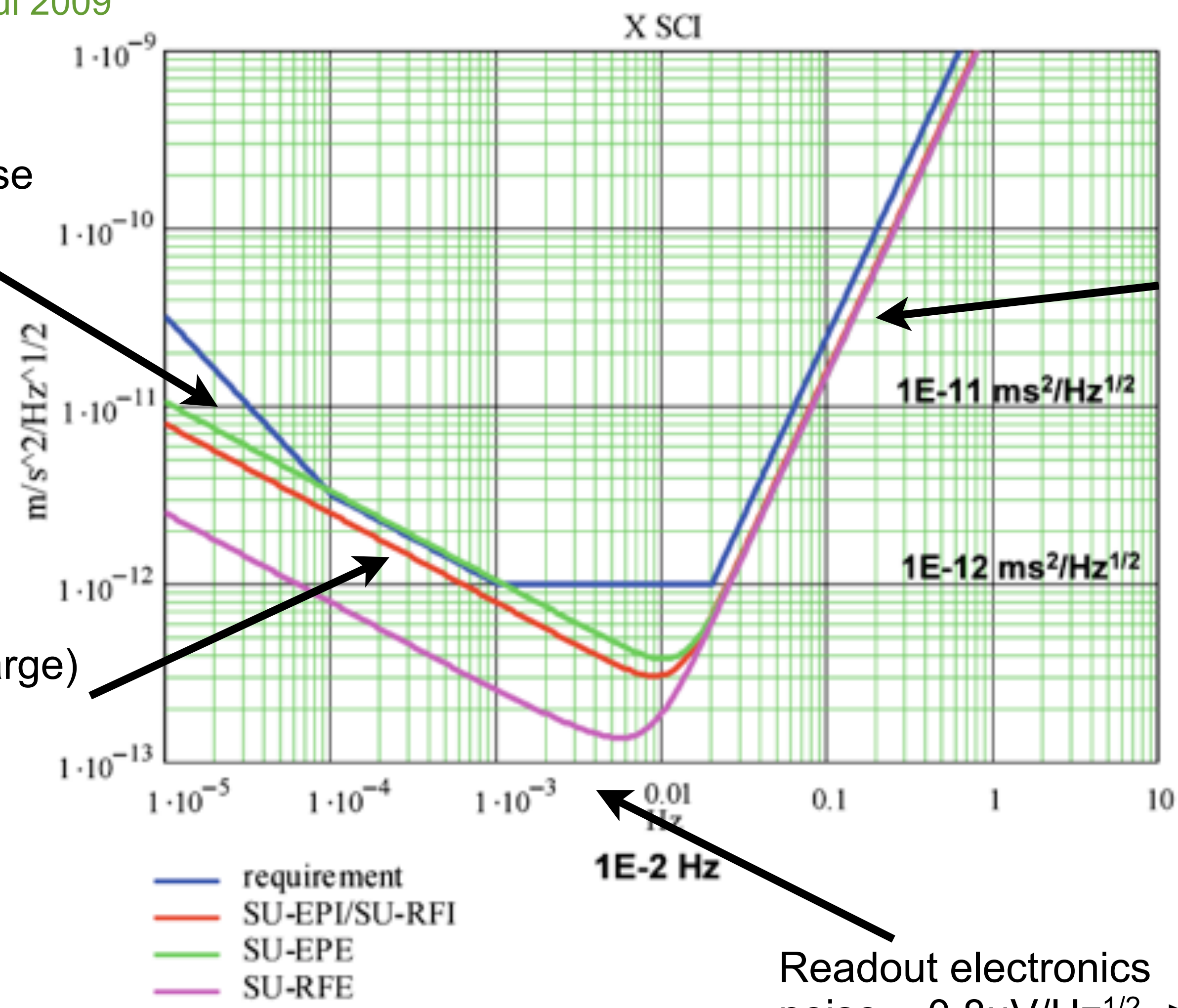
Noise budget

Touboul 2009

Thermal noise



Capacitive position sensing noise

Gold (discharge) wire noise

Readout electronics noise ~ 0.8μV/Hz$^{1/2}$ -> 10^{-13} ms^{-2}/Hz$^{1/2}$

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specs

- Drag-free system
  - Needs a sensitive 6 axis sensor and fine actuator
  - Drag-free < 10^{-12} ms^{-2} at f_{EP}
  - Angular stability: velocity < 10^{-9} rad/s + acceleration < 10^{-11} rad/s^2 at f_{EP}

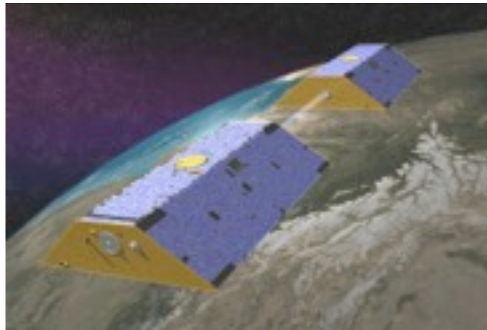
- Thermal control
  - Thermal stability of SU < 1 mK at f_{EP}
  - Thermal stability of FEEU < 3 mK at f_{EP}
  - Thermal stability of ICU < 1 K at f_{EP}

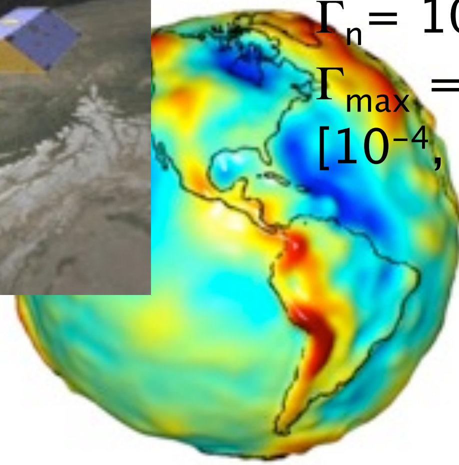
- Minimize micro-perturbations
  - Displacement inside the satellite
  - Change of the induced gravity gradient
  - Magnetic forces
  - No mechanism
  - No active thermal control

Technology: drag-free nano-g accelerometry

ONERA's long experience (30 years) in ultra-sensitive accelerometers: ASTRE, CHAMP, GOCE, GRACE…

GRACE (NASA-JPL): Gravity Recovery and Climate Experiment, 2002-2015(?)





$\Gamma_n = 10^{-10} ms^{-2}/Hz^{1/2}$
$\Gamma_{max} = 5x10^{-5} ms^{-2}$
$[10^{-4}, 10^{-1}]$ Hz

GOCE (ESA)
Gravity Field and Steady State Ocean Circulation Explorer, 2009-2013

$\Gamma_n = 2x10^{-12} ms^{-2}/Hz^{1/2}$
$\Gamma_{max} = 6x10^{-6} ms^{-2}$
$[5x10^{-3}, 10^{-1}]$ Hz

Coming up:
GRACE Follow-On (JPL)