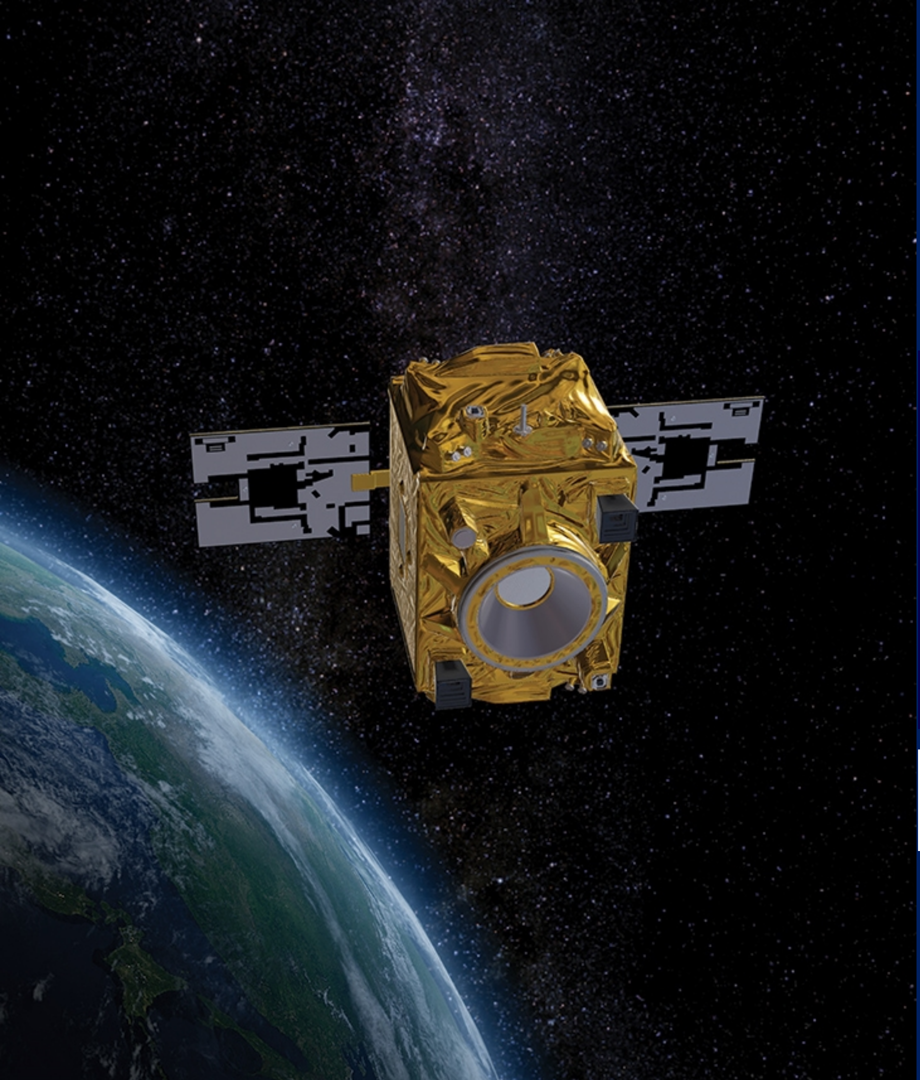


MICROSCOPE: while waiting for the final results…

Joel Bergé

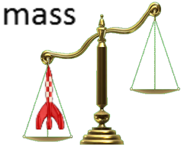
On behalf of the MICROSCOPE consortium

And with P. Brax, M. Pernot-Borràs & J.-P. Uzan

Goal: test the Weak Equivalence Principle (WEP) down to 10^{-15}

Test universality of free-fall

m_g = gravitational mass



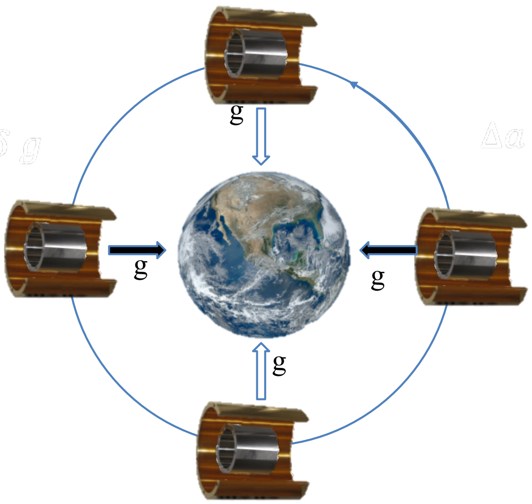
m_i = inertial mass

Comparison of the 2 body free-fall ⇔ comparison of their acceleration:

$$\boxed{\boldsymbol{\delta} = \frac{\boldsymbol{a1} - \boldsymbol{a2}}{\frac{1}{2}(a1 + a2)} = \frac{\frac{mg1}{mi1} - \frac{mg2}{mi2}}{\frac{1}{2}\left(\frac{mg1}{mi1} + \frac{mg2}{mi2}\right)}}$$

If $\boldsymbol{\delta} = \mathbf{0}$: $\Delta \boldsymbol{a} = \mathbf{0}$

If $\boldsymbol{\delta} \neq \mathbf{0}$: $\Delta a \neq 0$ detection of a signal collinear to g (same phase, same frequency)

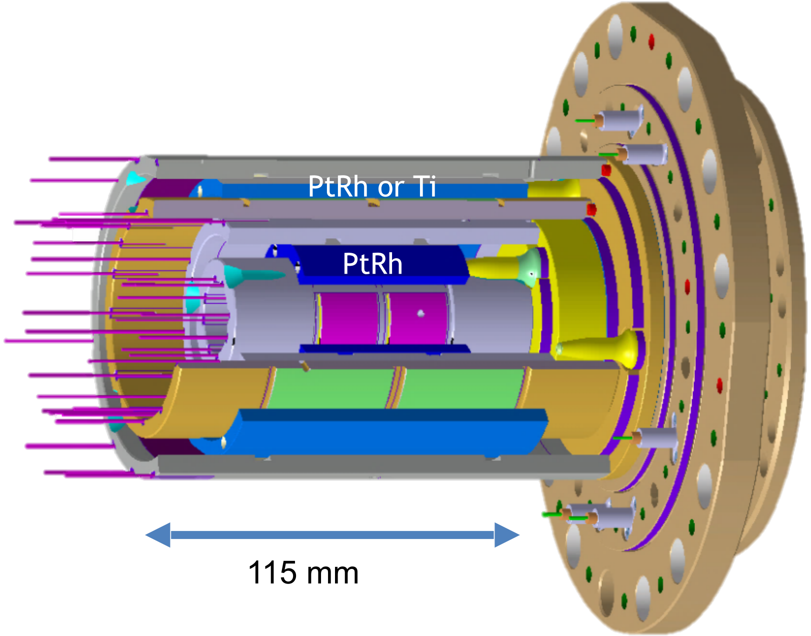


$$g(@710km) = 7.9 m/s^2$$

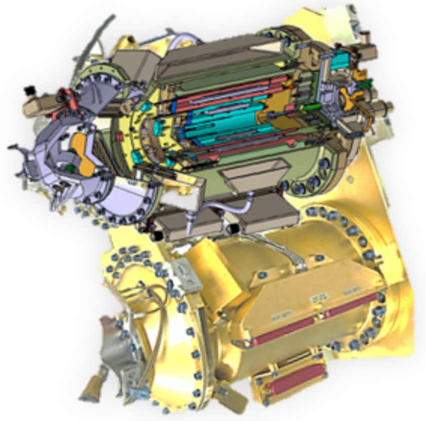
2 double accelerometers for the test

2 similar instruments on board which comprise each 2 concentric test-masses
SUEP :   Sensor Unit with Ti / PtRh
SUREF : Sensor Unit with PtRh / PtRh

Silica part realized by ultrasonic machining (ONERA patent). Accuracy is 2 to 5µm



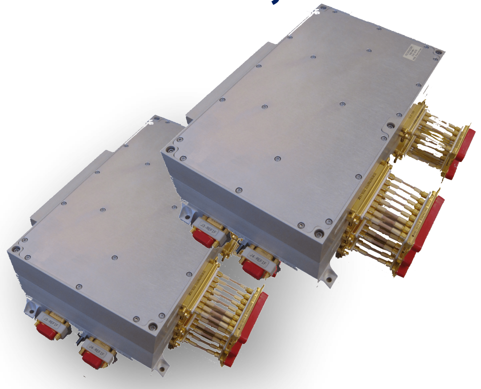
T-SAGE (Twin Space Accelerometer for Gravitation Experiment) – micrometer & microvolt accuracy inherited from GOCE, GRACE ONERA know how



Sensors: **SU PE + SU REF**

2 double-accelerometers

Each SU gives a TM difference of acceleration to femto-g level



Analog Front End Electronics :
1 FEEU for each SU

Low Noise voltage references
0.2µV $Hz^{-1/2}$

Low noise measurement
pick-up <1µV $Hz^{-1/2}$

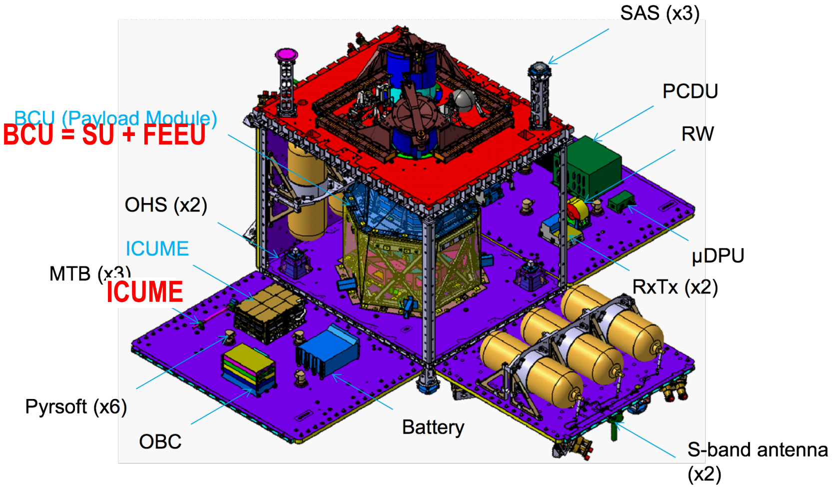
Digital Interface Electronics:
2 stacked **ICU**

DSP + FPGA
Control loop handling
2x 24 x 40bits signals @ 1kHz

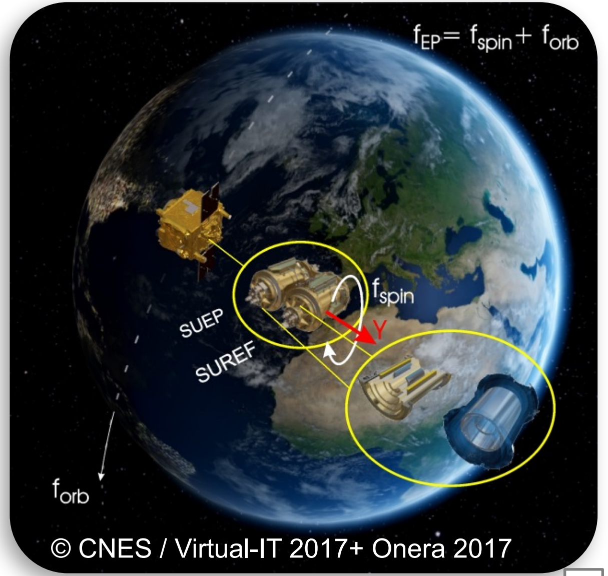
Science TM = 24bits @ 4Hz

The MICROSCOPE satellite

- Cold Gaz propulsion / Drag-free, Attitude control
- A space laboratory of 300kg
- 1,4 m x 1 m x 1,5 m
- Instrument in the BCU (Payload Thermal Cocoon Case) at the center of the satellite



- Sun-synchronous polar orbit @ 710 km
- Several modes :
  - Inertial f_{EP} = orbital frequency = 1.7×10^{-4} Hz
  - 2 rotation rates of S/C $f_{EP} = 0.9\times10^{-3}$Hz & $f_{EP} = 3.1\times10^{-3}$Hz



ACCELEROMETER MEASUREMENT

- sensor (test mass) k
- theoretical acceleration (input): $\vec{\gamma}^{(k)}$

Contains the Eötvös parameter

- measured acceleration (output): $\vec{\Gamma}^{(k)}$

$$\vec{\Gamma}^{(k)} = \vec{B}^{(k)} + [\mathbf{M}]^{(k)} [\mathbf{\Theta}]^{(k)} \vec{\gamma}^{(k)} + \vec{Q}^{(k)} + \left[\mathbf{N}^{(\mathbf{k})}\right] \dot{\vec{\Omega}}^{(k)} + \vec{\Gamma}_n^{(k)}$$

Biais

Scale factors
+ axis coupling
(symmetric matrix)

Test mass rotation

Quadratic terms

Angular to linear acceleration coupling

Noise
(not white!)

The measure along the cylinder axis (X) = the main measure

g = 7,9 ms^{-2}

$$
\begin{aligned}
2\Gamma_x^{(d)} &= 2B_x^{(d)} \\
&+ \delta_x g_x \\
&+ \boxed{\Delta_x S_{xx} + \Delta_y S_{xy} + \Delta_z S_{xz} + (ac_{13}\Delta_y + ac_{12}\Delta_z) S_{yz} + ac_{12}\Delta_y S_{yy} + ac_{13}\Delta_z S_{zz}} \\
&+ (-ac_{13}\Delta_y + ac_{12}\Delta_z + 2nd_{11})\,\dot{\Omega}_x - (\Delta_z - 2ac_{13}\Delta_x + 2nd_{12})\,\dot{\Omega}_y + (\Delta_y - 2ac_{12}\Delta_x + 2nd_{13})\,\dot{\Omega}_z \\
&+ 2\left(-ac_{13}\dot{\Delta}_y + ac_{12}\dot{\Delta}_z\right)\Omega_x - 2\left(\dot{\Delta}_z - 2ac_{13}\dot{\Delta}_x\right)\Omega_y + 2\left(\dot{\Delta}_y - 2ac_{12}\dot{\Delta}_x\right)\Omega_z \\
&- mc_{11}\ddot{\Delta}_{x,inst} - mc_{12}\ddot{\Delta}_{y,inst} - mc_{13}\ddot{\Delta}_{z,inst} \\
&+ 2\left(ad_{11}\Gamma_x^{(c)} + ad_{12}\Gamma_y^{(c)} + ad_{13}\Gamma_z^{(c)}\right) \\
&+ K_{2xx}^{(1)}\left(\frac{\Gamma_x^{(1)} - b_{0x}^{(1)}}{K_{1x}^{(1)}}\right)^2 - K_{2xx}^{(2)}\left(\frac{\Gamma_x^{(2)} - b_{0x}^{(2)}}{K_{1x}^{(2)}}\right)^2
\end{aligned}
$$

+ noise

Eötvös parameter

Earth's gravity gradients with test-mass off-centering Δ

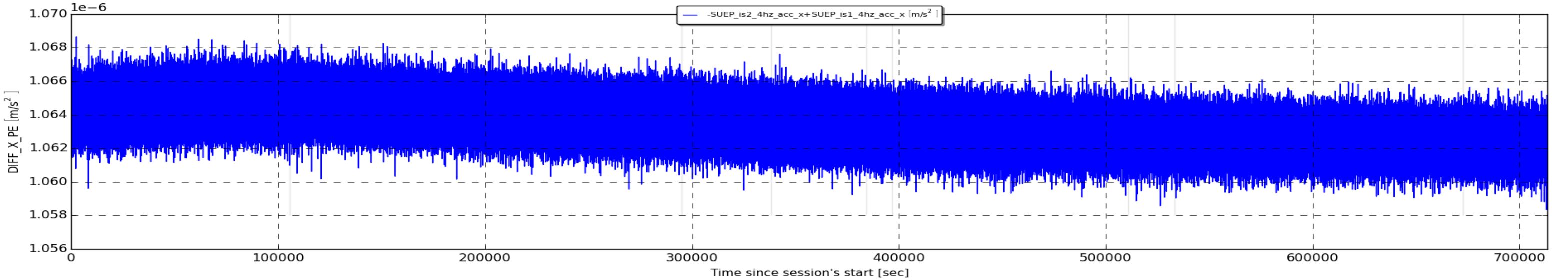
ad$_{11}$: Scale factor matching
Ad$_{12 \text{ or } 13}$: Misalignment of 2 test-masses

are negligible in the bandwidth of the test-mass servo loops

estimated by calibration
observed or/and computed
negligible at Fep

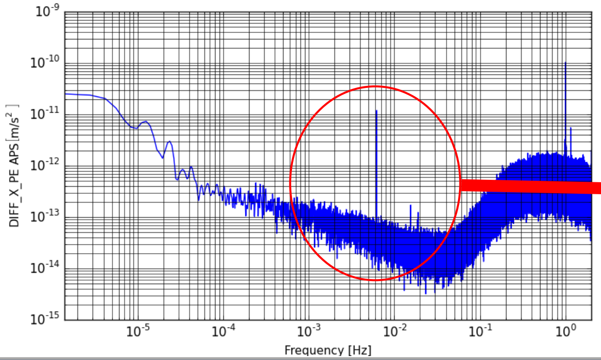
Effect of in-flight calibration on session 218 (SUEP)

- Time evolution of measured difference of acceleration on SUEP along X



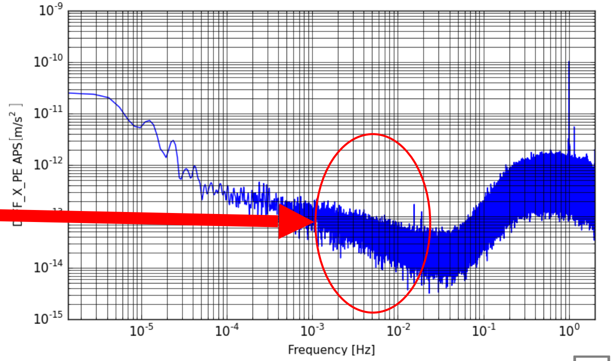
- Test-mass off-centering estimated through the Earth's gravity effect at $2f_{EP}$

=> Correction of off-centering effects at f_{EP} and $2f_{EP}$



Δx = (20.15 +/- 0.03) µm
Δz=(-5.69 +/- 0.03) µm

Level of acceleration to be corrected @f_{EP} < 3×10^{-17} m/s²
NEGLIGIBLE for a rotating satellite



The new upper bound on the WEP

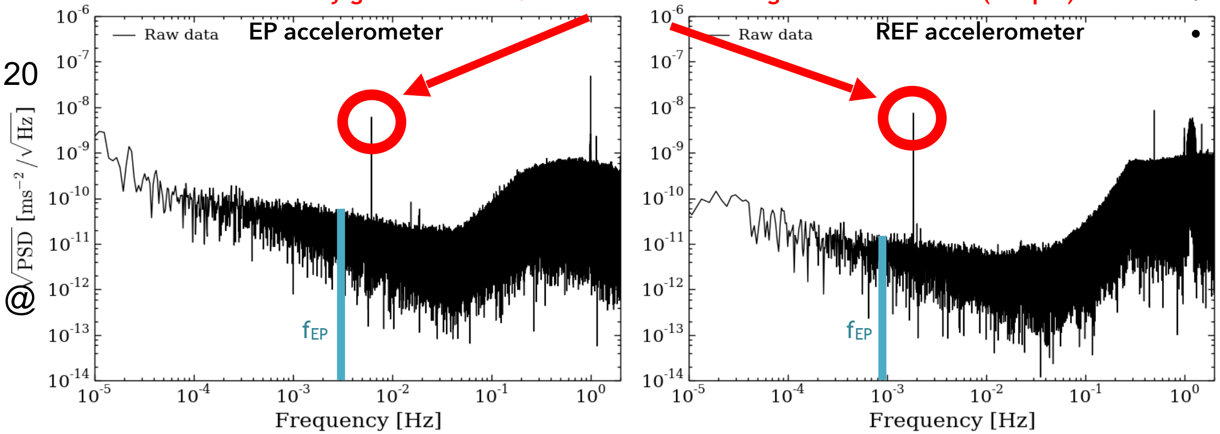
Touboul+ 2017, PRL 119 231101

From 2 sessions representing 7% of available data for the EP test :
We detect the Earth's gravity gradient effect but no WEP violation…

Over 120 orbits

- Statistical noise integrated over 120 orbits
- Systematics evaluated with a majoring of SU temperature variations (15µK @ f_{EP})

Gravity gradient effect: due to an offcentring of the test-mass (<30µm)



$f_{\mathrm{EP}} = 3.11 \times 10^{-3}$ Hz

$f_{\mathrm{EP}} = 0.93 \times 10^{-3}$ Hz

Over 62 orbits

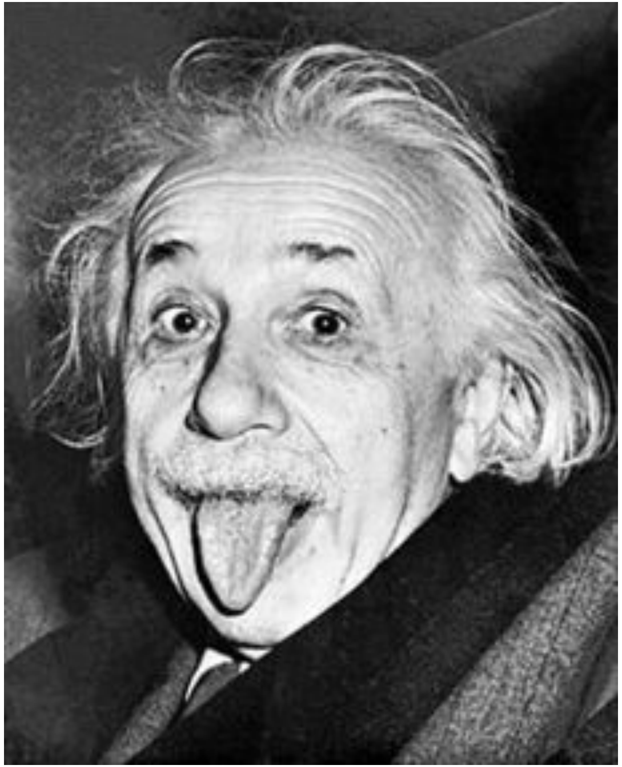
- Statistical noise integrated
- Systematics evaluated after publication, see next slides

$$\boxed{\delta(\mathrm{Ti},\mathrm{Pt}) = [-1 \pm 9(\mathrm{stat}) \pm 9(\mathrm{syst})] \times 10^{-15}}$$

$$\boxed{\delta(\mathrm{Pt},\mathrm{Pt}) = [+4 \pm 4(\mathrm{stat}) \pm 8(\mathrm{syst})] \times 10^{-15}}$$

Intermission: as of early 2018

- No WEP violation seen at $>2\times10^{-14}$



MICROSCOPE 2018: less science and more sensitivity tests & technological tests

- 750 orbits dedicated to sensor thermic behavior and systematics check have been successfully performed => next slides

- March to August 2018: SUEP continuously measuring without switch off (for technological experiment purposes)
- More than 5 months of experiment dedicated to aeronomy (Drag Free Off)

- EP test data available from the beginning : 1882 orbits for SUEP and 932 orbits for SUREF (including different temperature conditions & test-mass displacements) ; 300 orbits for calibration.

Systematic errors

Table 11. Evaluation of systematic errors in the differential acceleration measurement for SUEP @f_{EP}=3.1113×10^{-3} Hz.

Term in the Eq. (1) projected on $\vec{x}$ in phase with g_x at f_{EP}	Amplitude or upper bound	Method of estimation
Gravity gradient effect $[T]\vec{\Delta}$ in $\mathrm{m\,s^{-2}}$		
$(T_{xx}\Delta x;\ T_{xy}\Delta y;\ T_{xz}\Delta z)$	$< (10^{-18};10^{-19};10^{-17})$	Earth's gravity model.
Gradient of inertia matrix $[In]$ effect along X in $\mathrm{m\,s^{-2}}$		
$\dot{\Omega}_y\Delta z - \dot{\Omega}_z\Delta y$	5×10^{-17}	DFACS performances and calibration.
$\Omega_x\Omega_y\Delta y - \Omega_x\Omega_z\Delta z - (\Omega_y^2+\Omega_z^2)\,\Delta x$	1.3×10^{-17}	DFACS performances and calibration.
Drag-free control in $\mathrm{m\,s^{-2}}$		
$([M_d]\,\vec{\Gamma}_c^{app}).\vec{x}$	1.7×10^{-15}	DFACS performances and calibration.
Instrument systematics and defects in $\mathrm{m\,s^{-2}}$		
$(\vec{\Gamma}_d^{quad}).\vec{x}$	5×10^{-17}	DFACS performances and calibration.
$([Coupl_d]\vec{\Omega}).\vec{x}$	$< 2\times10^{-15}$	Couplings observed during commissioning phase.
Thermal systematics	$< 67\times10^{-15}$	Thermal sensitivity in-orbit evaluation.
Magnetic systematics	$< 2.5\times10^{-16}$	Finite elements calculation.
Total of systematics in Γ_{dx}^{meas}	$< 71\times10^{-15}\ \mathrm{m\,s^{-2}}$	
Total of systematics in δ	$< 9\times10^{-15}$	

Touboul+ CQG-submitted

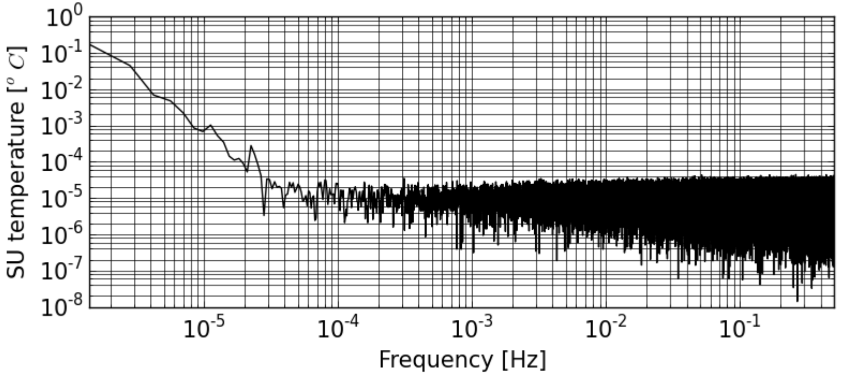
Max value on session 218 (sign is not considered, all terms added).
Perf. of DFACS evaluated from measurement (Acc+SST)

Quadratic terms evaluated from calibration & maximised on 2fep, fep and DC terms

Couplings evaluated from commissioning sessions

Magnetism : maximised from CNES model and analysis

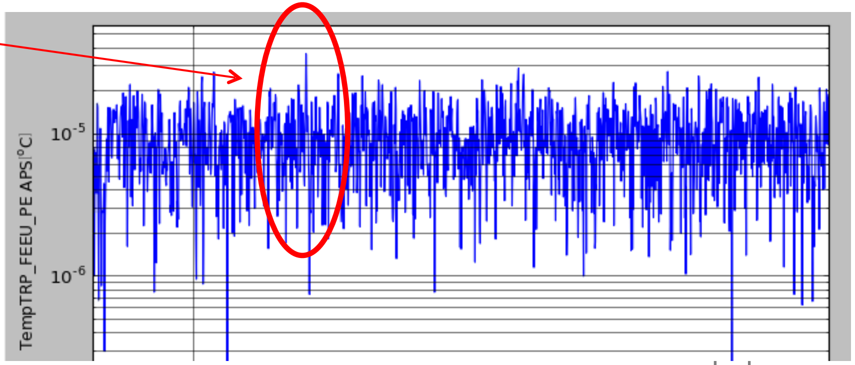
Thermal variations during EP sessions



➢ Cumulating sessions 234 to 238 (332 orbits with SUEP @ Spin V3) :

signal detected (?) on $\Delta T_{FEEU} = 72\mu K @ f_{ep}$

No signal on $\Delta T_{SU} < 13\mu K$ (1σ noise)@f_{ep}



❖ Additional experiments to better estimate the SU thermal filtering

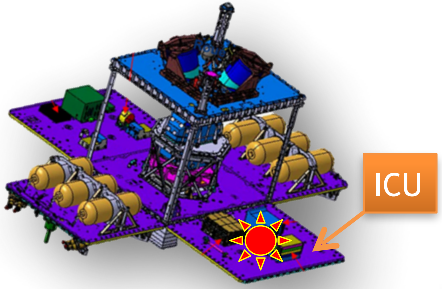
WHAT IS THE REAL SU TEMPERATURE VARIATION AT f_{EP}?

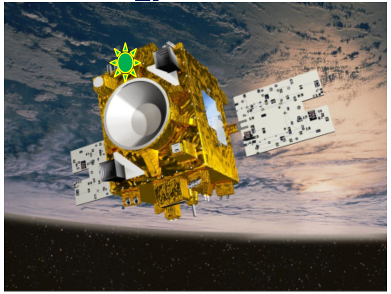
Thermal error source = the Earth at same frequency as gravity modulation (f_{EP})

- **The thermal flux can enter into the satellite through the walls or from the bottom baffle**

- **Thermal sessions:**

  Amplification of the thermal flux
  - On the wall
  - On FEEU plate
  - On the baffle radiator





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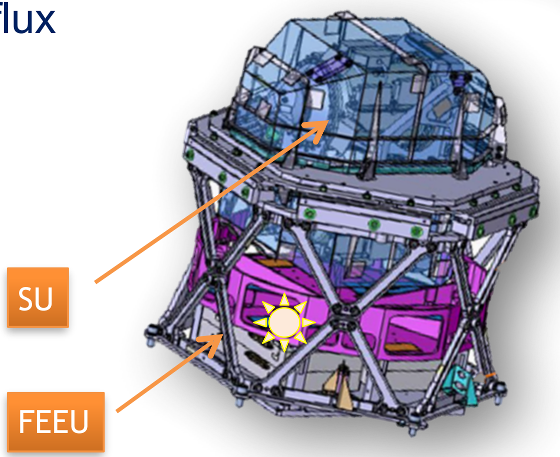
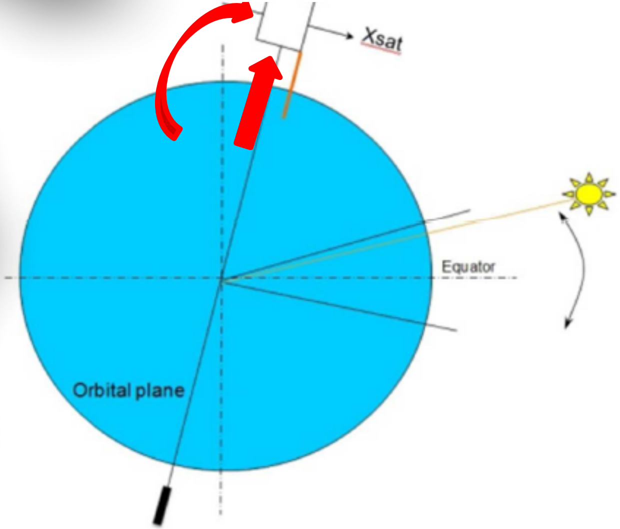
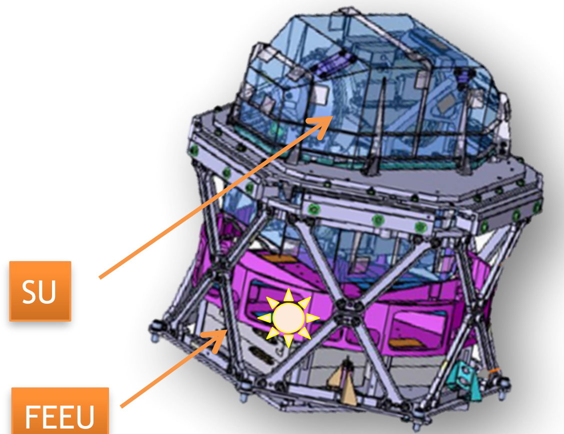
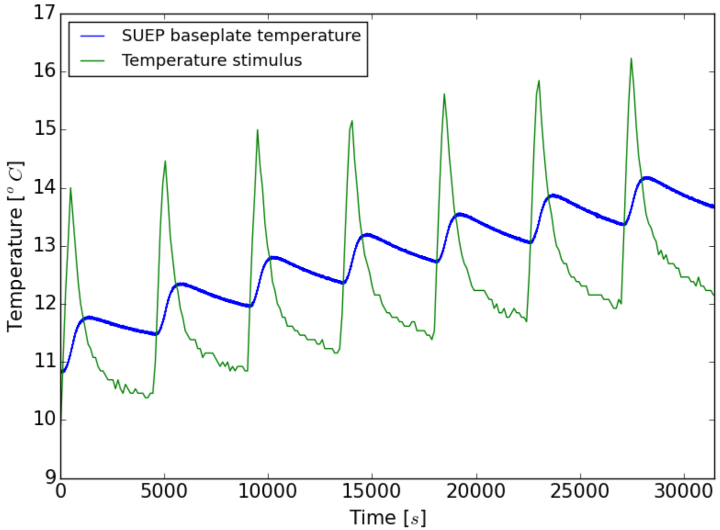




Thermal sensitivity estimation

Touboul+ CQG-submitted





$$\Gamma_{dx}(syst_{therm}) = \left|\frac{\partial\Gamma}{\partial T_{SU}}\Delta T_{SU}\right| + \left|\frac{\partial\Gamma}{\partial T_{FEEU}}\Delta T_{FEEU}\right|$$

Table 9. Differential acceleration thermal sensitivity at f_{EP}

	SUREF	SUEP
Linear drift due to T_{SU} variation [$\mathrm{ms}^{-2}\mathrm{K}^{-1}$]	0.3×10^{-9}	12×10^{-9}
Sensitivity to T_{SU} at f_{EP} [$\mathrm{ms}^{-2}\mathrm{K}^{-1}$]	3.9×10^{-9}	4.3×10^{-9}
Sensitivity to T_{FEEU}, at f_{EP} [$\mathrm{ms}^{-2}\mathrm{K}^{-1}$]	5×10^{-11}	7×10^{-11}

Systematic errors

Table 11. Evaluation of systematic errors in the differential acceleration measurement for SUEP @f_{EP}=3.1113×10^{-3} Hz.

Term in the Eq. (1) projected on $\vec{x}$ in phase with g_x at f_{EP}	Amplitude or upper bound	Method of estimation
Gravity gradient effect $[T]\vec{\Delta}$ **in** $\mathrm{m\,s^{-2}}$		
$(T_{xx}\Delta x;\ T_{xy}\Delta y;\ T_{xz}\Delta z)$	$<(10^{-18};10^{-19};10^{-17})$	Earth's gravity model.
Gradient of inertia matrix $[In]$ **effect along** X **in** $\mathrm{m\,s^{-2}}$		
$\dot{\Omega}_y\Delta z - \dot{\Omega}_z\Delta y$	5×10^{-17}	DFACS performances and calibration.
$\Omega_x\Omega_y\Delta y - \Omega_x\Omega_z\Delta z - (\Omega_y^2+\Omega_z^2)\,\Delta x$	1.3×10^{-17}	DFACS performances and calibration.
Drag-free control in $\mathrm{m\,s^{-2}}$		
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Instrument systematics and defects in $\mathrm{m\,s^{-2}}$		
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$([Coupl_d]\vec{\Omega}).\vec{x}$	$<2\times10^{-15}$	Couplings observed during commissioning phase.
Thermal systematics	$<67\times10^{-15}$	Thermal sensitivity in-orbit evaluation.
Magnetic systematics	$<2.5\times10^{-16}$	Finite elements calculation.
Total of systematics in Γ_{dx}^{meas}	$<71\times10^{-15}\ \mathrm{m\,s^{-2}}$	
Total of systematics in δ	$<9\times10^{-15}$	

SUEP - EPRV3 (120 orbits):
$\Delta T_{FEEU}<30\mu K@f_{ep}$ & $\Delta T_{SU}<20\mu K@f_{ep}$:mean valu
1σ noise

SUREF – EPRV2 (120 orbits):
$\Delta T_{FEEU}<400\mu K@f_{ep}$ & $\Delta T_{SU}<28\mu K$ (1σ noise)@f$_{ep}$

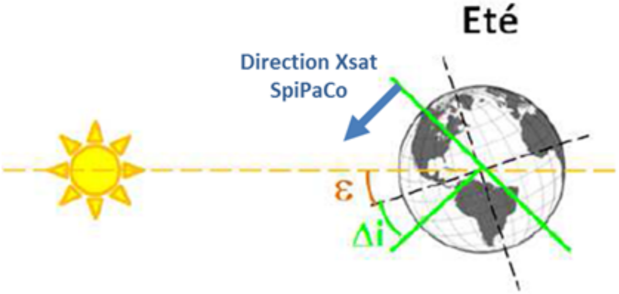
Thermal sensitivity

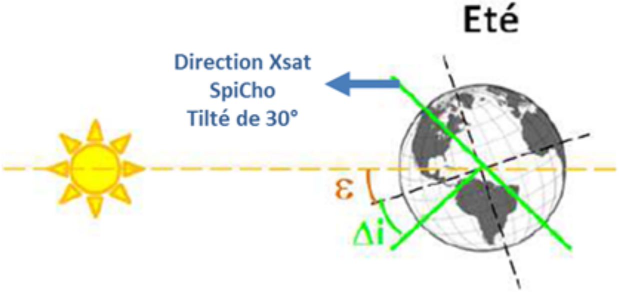
Touboul+ CQG-submitted

Complementary experimentations : SPICHO CONF

- Pointing : tilt of 30° of s/c spin axis
- FEEU radiator pointed to the Earth at the north pole and to the space at the south pole
- Temperature variations amplified at forb
- Spin rate = π . forb

- Objective: measure a thermal signal at FEEU and SU interface and estimate the temperature filtering between radiator to FEEU and then to SU
- Analysis in progress





MICROSCOPE and modified gravity: generic 5th force model

JB, P. Brax, G. Metris, M. Pernot-Borras, P. Touboul, J.-P. Uzan, 2018, PRL 120 141101

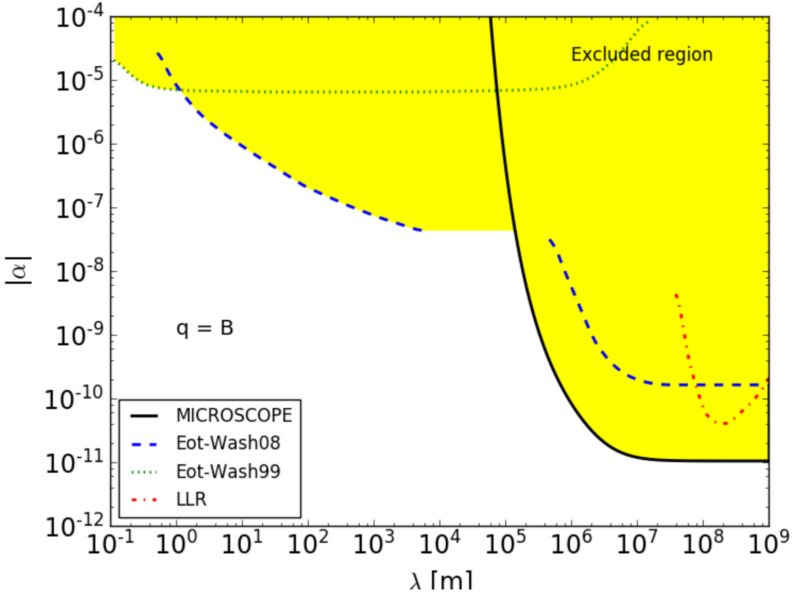
Yukawa potential

$$\boxed{V_{ij}(r) = -\frac{G m_i m_j}{r}\left(1 + \alpha_{ij} \mathrm{e}^{-r/\lambda}\right)}$$

$$\alpha_{ij} = \alpha \left(\frac{q}{\mu}\right)_i \left(\frac{q}{\mu}\right)_j$$

WEP violation

$$\eta = \alpha \left[\left(\frac{q}{\mu}\right)_{\mathrm{Pt}} - \left(\frac{q}{\mu}\right)_{\mathrm{Ti}}\right]\left(\frac{q}{\mu}\right)_E \left(1 + \frac{r}{\lambda}\right)\mathrm{e}^{-\frac{r}{\lambda}}$$



MICROSCOPE and modified gravity: high expectations (chameleon)…

VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

Chameleon Fields: Awaiting Surprises for Tests of Gravity in Space

Justin Khoury and Amanda Weltman
ISCAP, Columbia University, New York, New York 10027, USA
(Received 10 September 2003; published 22 October 2004)

We present a novel scenario where a scalar field acquires a mass which depends on the local matter density: the field is massive on Earth, where the density is high, but is essentially free in the solar system, where the density is low. All existing tests of gravity are satisfied. We predict that near-future satellite experiments could measure an effective Newton's constant in space different from that on Earth, as well as violations of the equivalence principle stronger than currently allowed by laboratory experiments.

DOI: 10.1103/PhysRevLett.93.171104 PACS numbers: 04.50.+h, 04.80.Cc, 98.80.–k

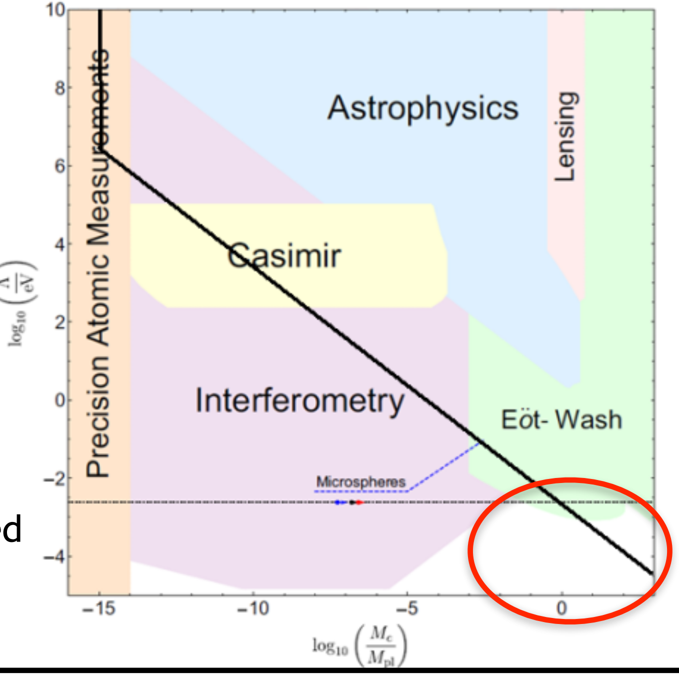
$$\boxed{\beta^2 \times 10^{-19} < \eta < \beta^2 \times 10^{-11}}$$

MICROSCOPE can see a significant chameleon-induced WEP violation if it is not itself screened

...but real life is tougher than theory

- Test-masses are not in vacuum… but surrounded by a satellite
- Still some atmosphere @700km

Burrage & Sakstein 2018, LRR 21:1
Pernot-Borras+ in prep



Above the line, MICROSCOPE is not screened: possible WEP violation

Below the line, MICROSCOPE is screened: no WEP violation expected

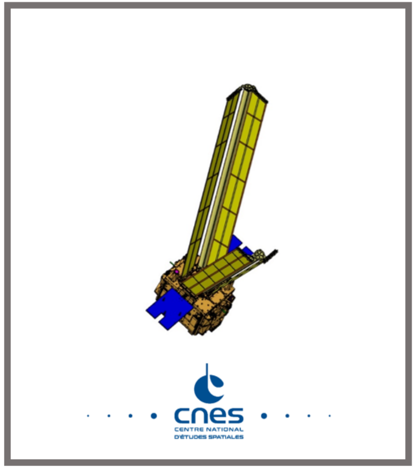
Region of interest

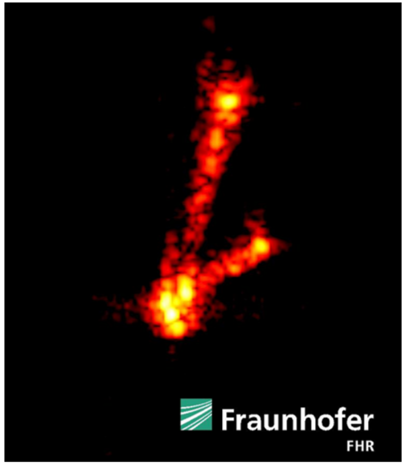
Don't take theorists' ballpark numbers for granted, real life is much more complicated

Conclusion

- No WEP violation seen at $>2\times10^{-14}$
- A lot of work done to better understand systematics… Expect improvements!
- New constraints on 5th force and modified gravity
- Final results end of 2019… Stay tuned

- MICROSCOPE was successfully passivated October 16, 2018. Back to Earth in 25 years





<u>Satellite MICROSCOPE du CNES avec ses 2 ailes de désorbitation déployées</u> (17/10/2018)
Modèle CAO (à gauche) et image radar capturée par le système TIRA du Fraunhofer Institute (à droite)

ONERA
THE FRENCH AEROSPACE LAB


TSAGE PAYLOAD TEAM - ONERA


S/C OPERATION – CNES ONERA


MICROSCOPE MISSION SCIENCE CENTER (CMSM) – ONERA+OCA

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES · ONERA THE FRENCH AEROSPACE LAB · Géo Azur · Observatoire de la Côte d'Azur · cnrs · esa · DLR · ZARM · PTB


Pierre Touboul (ONERA)
Prime Investigator


Gilles Metris (CNRS-UCA-OCA-Géoazur)
Co PI - Data analysis


Manuel Rodrigues (ONERA)
Co-I - Instrument + CMSM


Pierre-Yves Guidotti (CNES)
MICROSCOPE Proj. Manager


Alain Robert (CNES)
Perf. Group