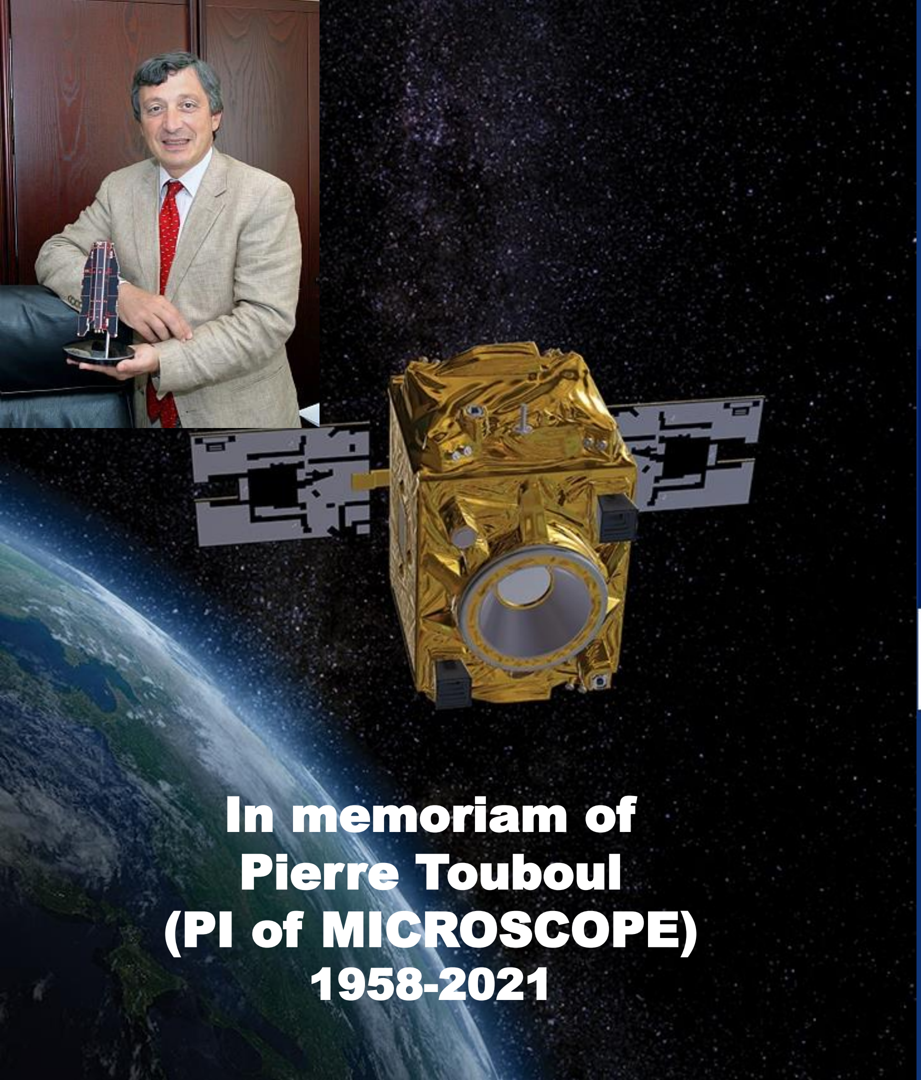
RÉPUBLIQUE
FRANÇAISE

Liberté
Égalité
Fraternité

ONERA

THE FRENCH AEROSPACE LAB

www.onera.fr



MICROSCOPE: Final Results of the Test of the Equivalence Principle

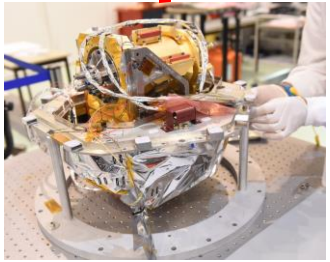
Manuel RODRIGUES
On behalf of MICROSCOPE team

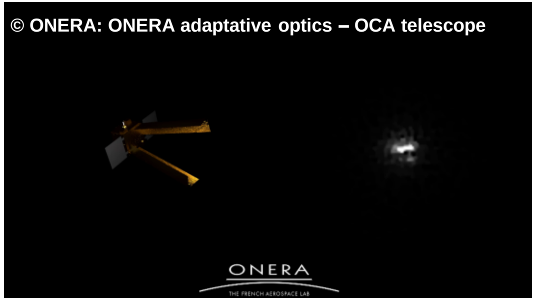
ACES Workshop - October 2022

MICROSCOPE LONG PATH TO THE FINAL RESULT

- Objective : EP test at 10^{-15} sensitivity,
- Project started in 2000,

- S/c integration : 2014 – 2016,
- S/c launched in 2016,
- in orbit operations stopped in 2018.





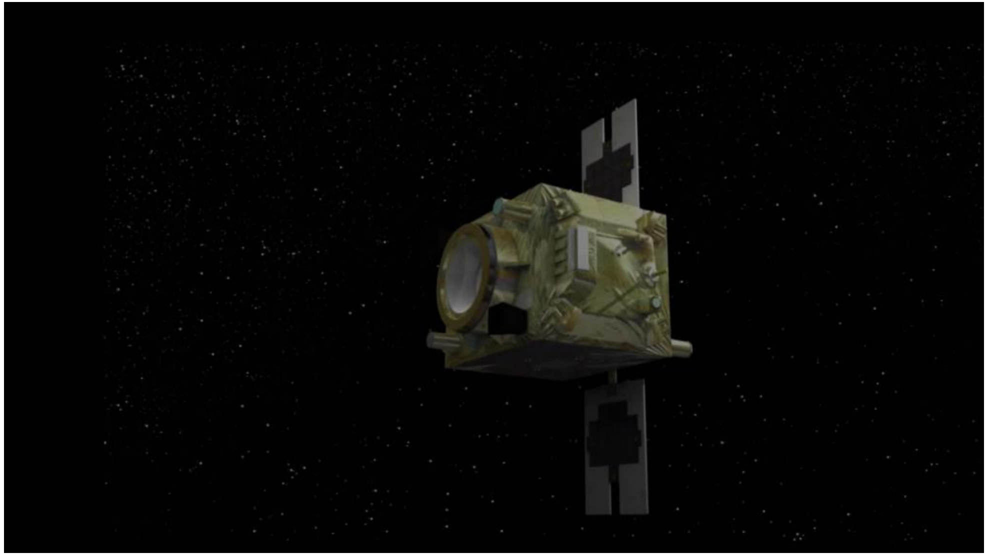
MICROSCOPE PRINCIPLE

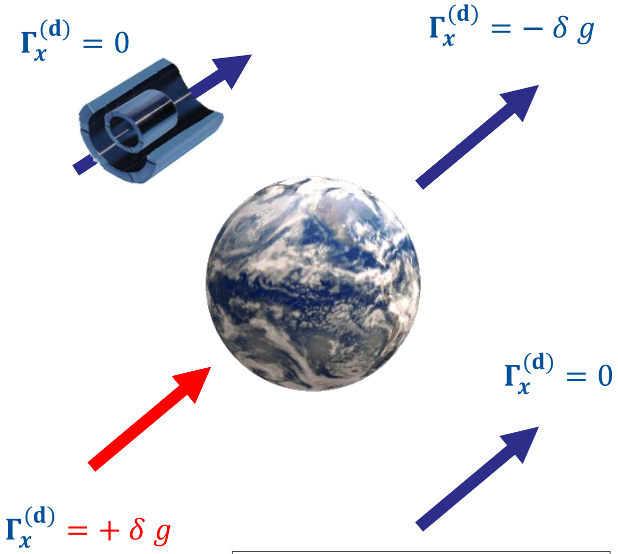
$$\boldsymbol{\Gamma}_x^{(d)} = \boldsymbol{\Gamma}_x^{(1)} - \boldsymbol{\Gamma}_x^{(2)}$$

Eötvös Parameter $\delta = \dfrac{\boldsymbol{\Gamma}_x^{(1)} - \boldsymbol{\Gamma}_x^{(2)}}{\frac{1}{2}\left(\boldsymbol{\Gamma}_x^{(1)} + \boldsymbol{\Gamma}_x^{(2)}\right)} = \dfrac{\frac{mg1}{mi1} - \frac{mg2}{mi2}}{\frac{1}{2}\left(\frac{mg1}{mi1} + \frac{mg2}{mi2}\right)}$

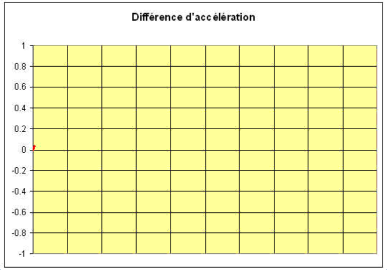
in ideal world : $\boldsymbol{\Gamma}_x^{(d)} = \boldsymbol{\delta g_x}$

Potential EP signal at same frequency of g modulation

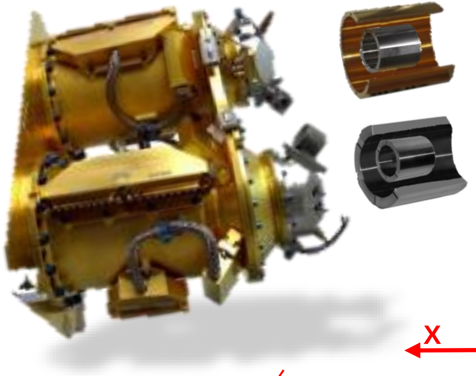




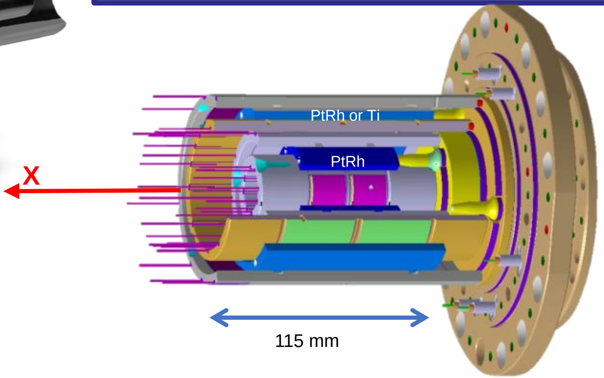
Variation of signal
At orbital frequency
$f_{EP} = f_{orbital}$

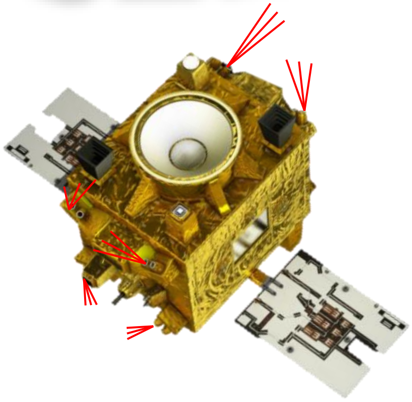


MICROSCOPE : a test of the Equivalence Principle in space

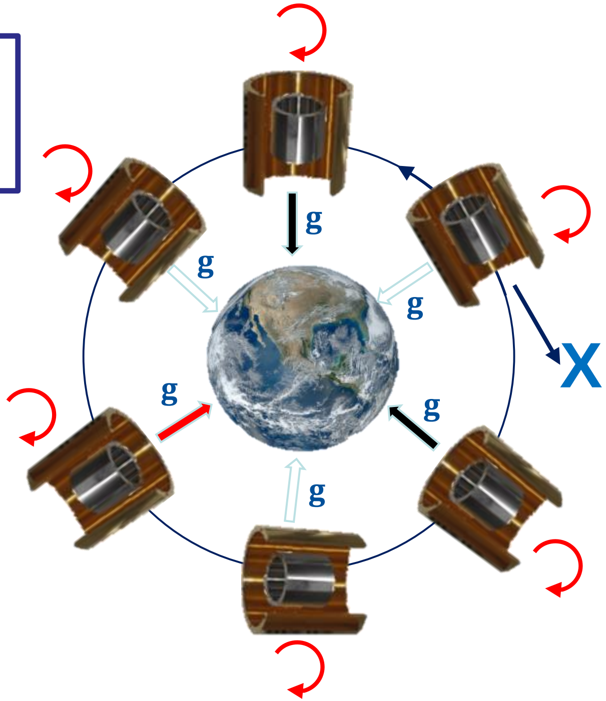


2 Pairs of concentric accelerometers
SUREF : PtRh10 / PtRh10
SUEP : PtRh10/Ti (TA6V)





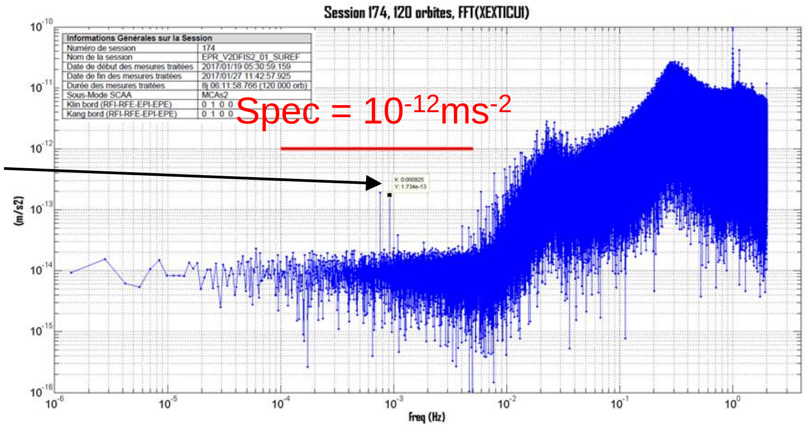
Micro-satellite at 710 km
Sun-synchronous
Circular orbit



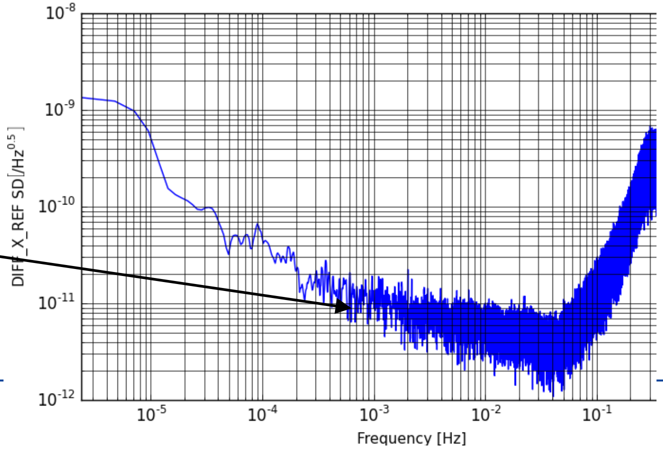
$$f_{EP} = f_o + f_{spin}$$

Performance of the satellite and T-SAGE

- **Drag-Free and Attitude Control System (DFACS)**
  - Linear acceleration controlled at 3×10^{-13} m/s²
  - Angular motion controlled by hybridizing the star sensor and the accelerometer : better than 3×10^{-10} rad/s



- **T-SAGE: reference accelerometer for the DFACS & scientific instrument**
  - At the heart of the satellite and the data process
  - Instantaneous resolution: $10^{-11} ms^{-2} Hz^{-1/2}$
  - Integrated accuracy over the scientific selected duration: 8.7×10^{-15} m/s²



The measurement equation

But in reality:

$$
\begin{aligned}
\Gamma_x^{(d)} \approx\; & B_{0x}^{(d)} \\
& + \bar{a}_{c11} b_{1x}^{(d)} + \bar{a}_{c12} b_{1y}^{(d)} + \bar{a}_{c13} b_{1z}^{(d)} \\
& + \bar{a}_{c11}\,\delta g_x + \bar{a}_{c12}\,\delta g_y + \bar{a}_{c13}\,\delta g_z \\
& + (T_{xx} - \mathrm{In}_{xx})\,\bar{a}_{c11}\Delta_x + (T_{xy} - \mathrm{In}_{xy})\,\bar{a}_{c11}\Delta_y + (T_{xz} - \mathrm{In}_{xz})\,\bar{a}_{c11}\Delta_z \\
& + (T_{yx} - \mathrm{In}_{yx})\,\bar{a}_{c12}\Delta_x + (T_{yy} - \mathrm{In}_{yy})\,\bar{a}_{c12}\Delta_y + (T_{yz} - \mathrm{In}_{yz})\,\bar{a}_{c12}\Delta_z \\
& + (T_{zx} - \mathrm{In}_{zx})\,\bar{a}_{c13}\Delta_x + (T_{zy} - \mathrm{In}_{zy})\,\bar{a}_{c13}\Delta_y + (T_{zz} - \mathrm{In}_{zz})\,\bar{a}_{c13}\Delta_z \\
& + 2\left(\frac{a_{d11}}{a_{c11}}\Gamma_x^{(c)} + \frac{a_{d12}}{a_{c22}}\Gamma_y^{(c)} + \frac{a_{d13}}{a_{c33}}\Gamma_z^{(c)}\right) \\
& - 2\left[\bar{a}_{c11}\left(-\Omega_z\dot{\Delta}_y + \Omega_y\dot{\Delta}_z\right) + \bar{a}_{c12}\left(\Omega_z\dot{\Delta}_x - \Omega_x\dot{\Delta}_z\right) + \bar{a}_{c13}\left(-\Omega_y\dot{\Delta}_x + \Omega_x\dot{\Delta}_y\right)\right] \\
& - \bar{a}_{c11}\ddot{\Delta}_x - \bar{a}_{c12}\ddot{\Delta}_y - \bar{a}_{c13}\ddot{\Delta}_z \\
& + 2\left(c'_{d11}\dot{\Omega}_x + c'_{d12}\dot{\Omega}_y + c'_{d13}\dot{\Omega}_z\right) \\
& + n_x^{(d)} - 2\left(\frac{a_{d11}}{a_{c11}} n_x^{(c)} + \frac{a_{d12}}{a_{c22}} n_y^{(c)} + \frac{a_{d13}}{a_{c33}} n_z^{(c)}\right) \\
& + \Gamma_{q,x}^{(d)},
\end{aligned}
$$

Offsets, drifts and systematics

Potential EP signal

Gravity & Inertia Gradients

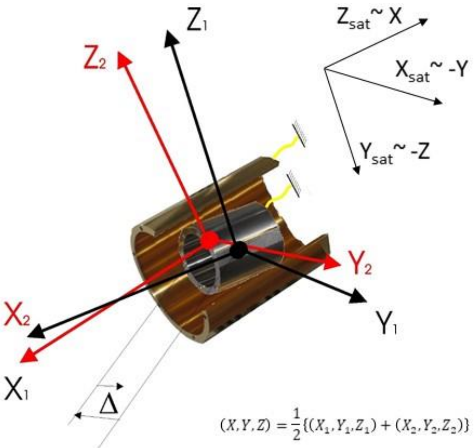
Common mode projection

Null thanks to Servo-loop

Angular to linear couplings

noise

Quadratic term



$$(X,Y,Z) = \frac{1}{2}\{(X_1,Y_1,Z_1) + (X_2,Y_2,Z_2)\}$$

First results in 2017 and 2019 based on 7% of available data

SUEP

	dateDebut	nomFiche	Num Orb	contrainte Environnement	crit.	duree	etat	conso GazZp	conso GazZm	capacite GazZp	capacite GazZm	
	…T13:59:55.846867		4321	NO_ECLIPSE_NO_LUNE	2	1.01295	E	0.7	1.1			
206	2017-02-13T15:40:18.833216	CAL_K1dxDFIS1_01_SUEP	4322	NO_ECLIPSE_NO_LUNE	2	5.07000	E	4	3.7			
207	2017-02-14T00:02:44.983178		4327	NO_ECLIPSE_NO_LUNE	2	1.01295	E	0.5	0.6			
208	2017-02-14T01:43:07.970959	CAL_K1dxDFIS2_01_SUEP	4328	NO_ECLIPSE_NO_LUNE	2	5.07000	E	2.9	3.3	6579.4	6614.3	
209	2017-02-14T10:05:34.128091		4333	NO_ECLIPSE_NO_LUNE	2	3.07939	E	10	9.3	6569.7	6604.9	
210	2017-02-14T15:10:44.141758	EPR_V3DFIS2_01_SUEP	4337	NO_ECLIPSE_NO_L…					151.3	6392.6	6453.3	
211	2017-02-18T01:45:43.539435		4387	NO_ECLIPSE_NO_L…					4.2	6386.9	6448.7	
212	2017-02-18T04:15:53.554441	EPR_V3DFIS2_01_SUEP	4388	NO_ECLIPSE_NO_L…					235.1	6123.1	6213.3	
213	2017-02-23T09:55:00.000000		4464	NO_ECLIPSE_NO_LUNE	0	0.00000	E	0	0	6123.1	6213.3	
214	2017-02-23T09:55:00.000000	TSNA	4464	NO_ECLIPSE_NO_LUNE	0	61.80639	E	0	3.3	6122.9	6209.7	Rep
215	2017-02-27T16:00:00.028541		4526	NO_ECLIPSE_NO_LUNE	2	1.01295	E	1.3	1.1	6121.7	6207.8	
216	2017-02-27T17:40:23.014532	CAL_K1dxDFIS2_01_SUEP	4527	NO_ECLIPSE_NO_LUNE	2	5.07000	E	4.9	8.3	6116.9	6199.3	
217	2017-02-28T02:02:49.160909		4532	NO_ECLIPSE_NO_LUNE	2	3.07939	E	10.4	11	6106.4	6187.8	
218	2017-02-28T07:07:59.169132	EPR_V3DFIS2_01_SUEP	4535	NO_ECLIPSE_NO_LUNE	2	120.00000	E	384.8	405.8	5721	5781.7	
219	2017-03-08T13:19:57.511429		4655	NO_ECLIPSE_NO_LUNE	2	2.57703	E	3.7	4.9	5716.8	5776.4	
220	2017-03-08T17:35:20.494387	CAL_tetadZDFIS2_01_SUEP	4658	NO_ECLIPSE_NO_LUNE	2	5.07000	E	3.9	7.9	5712.9	5768.3	
225	2017-03-09T22:20:01.933724		4675	NO_ECLIPSE_NO_LUNE	2	1.18366	E	0.4	1.6	5691.9	5735.9	
226	2017-03-10T00:17:19.958477	CAL_K21xx_02_SUEP	4676	NO_ECLIPSE_NO_LUNE	2	5.07000	E	3.3	7.3	5688.3	5728.3	

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

From least square fit

Phys. Rev. Letts. 119 231101 (2017) : No evidence of violation > 1,9 × 10^{-14}

Over 120 orbits

- Statistical noise integrated over 120 orbits
- Systematics = SU temperature probe noise integrated over 120 orbits (15µK @ f_{EP})
- *90% of systematics come from upper bound limit on temperature variations*

SUREF

	dateDebut	nomFiche	Num Orb	contrainte Environnement	crit.	duree	etat	conso GazZp	conso GazZm	capacite GazZp	capacite GazZm
	…8T14:22:59.978006		3944	NO_ECLIPSE_NO_LUNE	1	1.01295	E	0.9			
	…8T16:03:22.968294	CAL_K1dxDFIS2_01_SUREF	3945	NO_ECLIPSE_NO_LUNE	1	5.07000	E	4.7			
173	2017-01-19T00:25:49.137973		3950	NO_ECLIPSE_NO_LUNE	1	3.07939	E	2.5			
174	2017-01-19T05:30:59.159261	EPR_V2DFIS2_01_SUREF	3953	NO_ECLIPSE_NO_LUNE	1	120.00000	E	81.1	67.5	6720	6750.3
175	2017-01-27T11:42:57.925815		4073	NO_ECLIPSE_NO_LUNE	1	1.51531	E	1	0.6	6719	6749.6
176	2017-01-27T14:13:07.942964	EPR_V2DFIS2_01_SUREF	4074	NO_ECLIPSE_NO_LUNE	1	82.00000	E	56	48.4	6662.9	6701
177	2017-02-02T05:39:19.100109		4156	NO_ECLIPSE_NO_LUNE	1	2.57703	E	1.8	2	6661	6699
178	2017-02-02T09:54:42.094912	CAL_tetadZDFIS2_01_SUREF	4159	NO_ECLIPSE_NO_LUNE	1	5.07000	E	3.1	2.8	6657.8	6696.2
179	2017-02-02T18:17:08.262799		4164	NO_ECLIPSE_NO_LUNE	1	1.01295	E	0.6	0.7	6657.2	6695.5
180	2017-02-02T19:57:31.253445	CAL_tetadYDFIS2_01_SUREF	4165	NO_ECLIPSE_NO_LUNE	1	5.07000	E	2.6	3.1	6654.6	6692.4
			4170	NO_ECLIPSE_NO_LUNE	1	1.18063	E	3.9	3.6	6650.5	6688.3
		…F	4171	NO_ECLIPSE_NO_LUNE	1	5.07000	E	13.2	13.5	6637.1	6674.5
			4176	NO_ECLIPSE_NO_LUNE	1	1.18365	E	0.4	0.6	6636.6	6673.8
184	2017-02-03T16:36:41.576425	CAL_K21xx_02_SUREF	4178	NO_ECLIPSE_NO_LUNE	1	10.00000	E	5.1	5.3	6631.4	6668.5

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

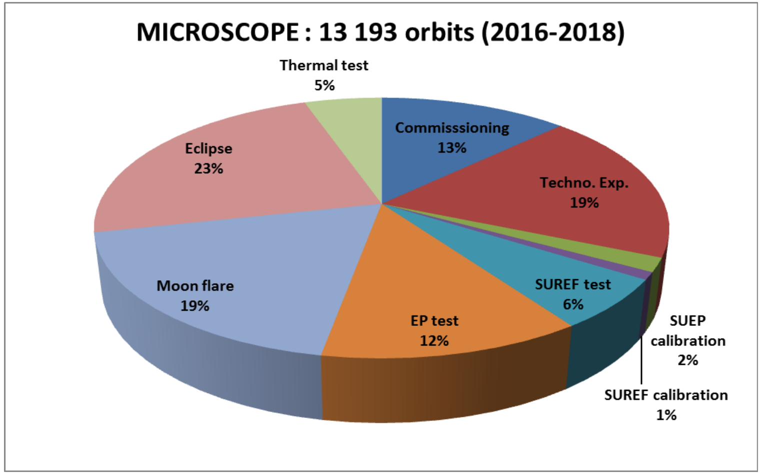
CQG. Vol. 36.N22 Oct. 2019

Over 62 orbits

- Statistical noise integrated
- Systematics evaluated with temperature measurements and evaluation of sensitivity

Improvements performed since 2017

- More than 2500 orbits of science data have been cumulated
- Analysis of systematics:
  - Thermal analysis thanks to more than dedicated 600 orbits
  - Satellite cracking led to glitches in data and to a necessary new reprocessing of all the mission
  - Test with fake signals to asses new reprocessing procedure

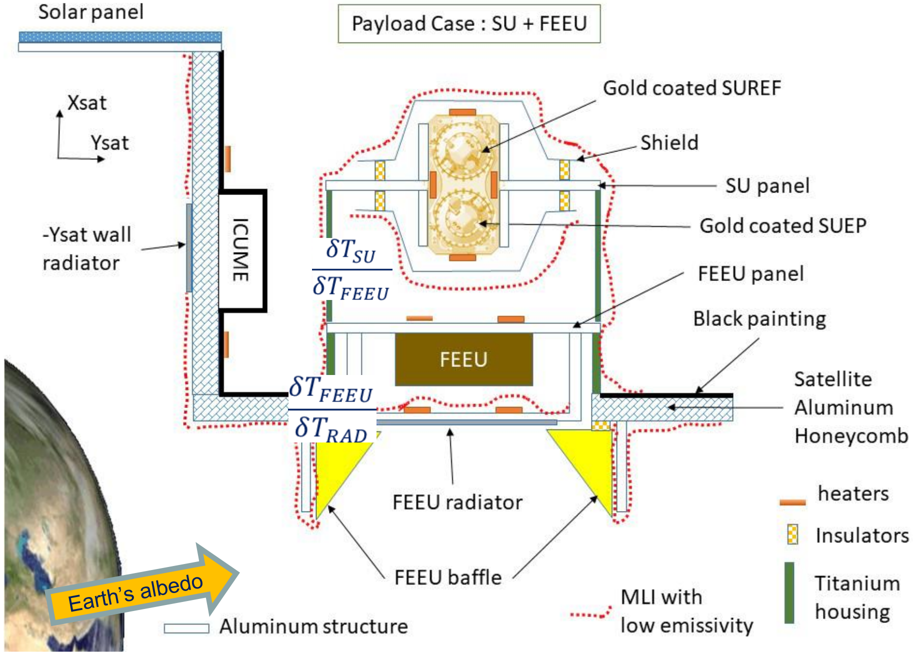


Systematic error analysis of thermal variation effects on the bias at f_{EP}

$$\frac{\partial \Gamma_x^d}{\partial T_{SU}} \delta T_{SU}(f_{EP}) + \frac{\partial \Gamma_x^d}{\partial T_{FEEU}} \delta T_{FEEU}(f_{EP})$$

Dedicated sessions performed :

- To evaluate the measurement sensitivity to temperature
- To demonstrate that the main sensitivity is due to Earth's albedo arriving on FEEU radiator
- AND thus to evaluate the thermal filtering of this process : $\frac{\delta T_{SU}}{\delta T_{FEEU}}$ and $\frac{\delta T_{FEEU}}{\delta T_{RAD}}$



Systematic errors due to thermal variations on SUEP :

- SU Temperature variations at f_{EP} < 0.1µK
- Systematic acceleration < 9.3×10^{-15}ms^{-2}
- Reduction by a factor 7 with respect to PRL2017

MICROSCOPE systematic error analysis, Rodrigues et al, CQG 2022 Vol.39 N. 20

Glitches due to satellite cracking

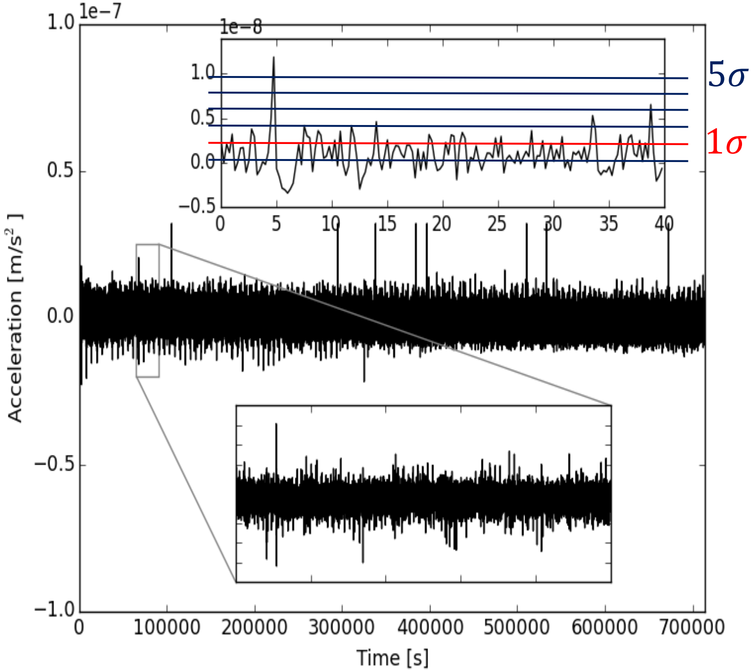
Satellite cracking:

- Transient << 1s seen as a damped pulse because of accelerometer transfer functions
- Transients have a periodic pattern @f_{EP} ! ! !
- Performance killer

Data Process:

- Detection along X, Y, Z of glitches > 4.5 σ
- Data masked with "0" in [T_{glitch}-5sec;T_{glitch}+10sec]
- Iterative method to estimate and to reconstruct the missing signal (M-ECM) in the masked data (with the best estimation of noise) *https://doi.org/10.1103/PhysRevD.93.122007*

=> Process validated on a fake violation signal of **<u>3.4x10^{-15} and 34x10^{-15} added to the real data</u>**



Fake signal estimated at 6% accuracy with SUREF and 0.1% withSUEP

Worst case error = 0.06x10^{-15}

Systematic error analysis

$$\Gamma_k^{(d)} = \frac{1}{\sum_l \frac{1}{\sigma_l^2}} \sum_l \frac{1}{\sigma_l^2} \Gamma_{k,l}^{(d)}$$

Temperature variations : the higher sensitivity of the instrument than expected is the major limitation

Non linearity:

- The differential quadratic parameter ($K_{2d,xx}$) is calibrated before each session
- The common quadratic parameter ($K_{2c,xx}$) is not calibrated and because of large variations of K_{2dxx} => $K_{2c,xx}$ fixed to the max estimated ground value

Error in the final result: $\sqrt{\sum_k (\Gamma_k^{(d)})^2}$

Table 15: Budget of systematic error analysis compared to specification analysis [5].

	Systematic error sources	SUEP $m\,s^{-2}$	SUREF $m\,s^{-2}$	Specification $m\,s^{-2}$
$\Gamma_1^{(d)}$	Earth gravity gradients	0.0×10^{-15}	0.0×10^{-15}	0.0×10^{-15}
$\Gamma_2^{(d)}$	Instrument gravity	0.0×10^{-15}	0.0×10^{-15}	0.2×10^{-15}
$\Gamma_3^{(d)}$	Satellite gravity gradients	0.1×10^{-15}	0.1×10^{-15}	0.3×10^{-15}
$\Gamma_4^{(d)}$	Angular motions	0.1×10^{-15}	0.1×10^{-15}	1.1×10^{-15}
$\Gamma_5^{(d)}$	Instrument parameters	0.2×10^{-15}	0.1×10^{-15}	0.8×10^{-15}
$\Gamma_6^{(d)}$	Temperature variations	9.3×10^{-15}	17.9×10^{-15}	0.9×10^{-15}
$\Gamma_7^{(d)}$	Drag-Free residuals	0.0×10^{-15}	0.0×10^{-15}	0.5×10^{-15}
$\Gamma_8^{(d)}$	Magnetic sensitivity	0.0×10^{-15}	0.0×10^{-15}	0.4×10^{-15}
$\Gamma_9^{(d)}$	Non linearity	6.0×10^{-15}	3.1×10^{-15}	0.8×10^{-15}
	Total quadratic sum ($m\,s^{-2}$)	11.5×10^{-15}	18.3×10^{-15}	
	Total systematic errors for the Eötvös δ estimation with $g = 7.9\,m/s^2$			
	Quadratic sum of errors	1.5×10^{-15}	2.3×10^{-15}	

Einstein's GR theory has resisted to the more accurate experiment ever realised

No violation > 2.7×10^{-15}

- SUEP :

$$\delta(Ti, Pt) = [-1.5 \pm 2.3(stat) \pm 1.5(sys)] \times 10^{-15} \sim 2.7 \times 10^{-15}$$

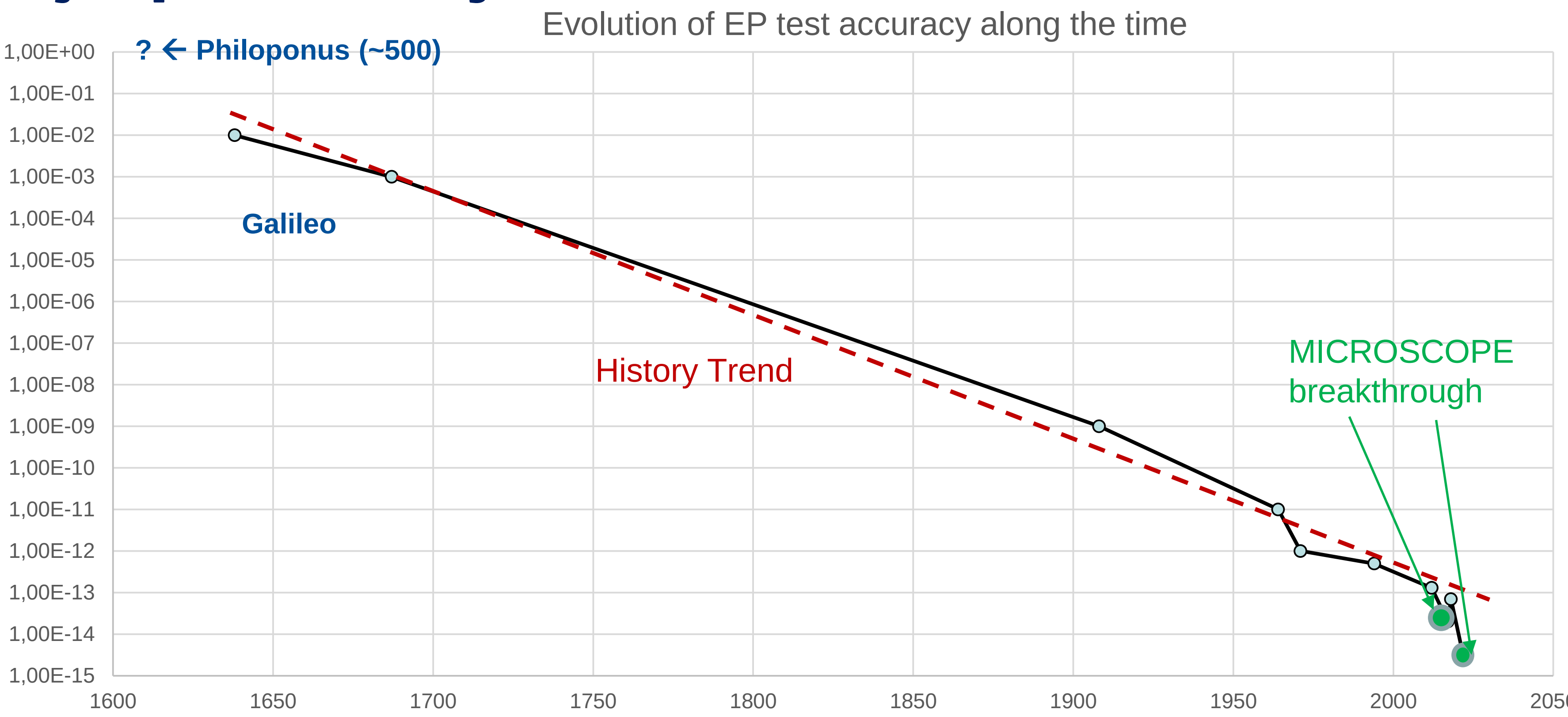
- SUREF :

$$\delta(Pt, Pt) = [0.0 \pm 1.1(stat) \pm 2.3(sys)] \times 10^{-15} \sim 2.5 \times 10^{-15}$$

- **Physical Review Letters (American Physics Society): Phys. Rev. Lett. 129, 121102**
- **Classical Quantum Gravity (IOP Publishing): An special edition of 11 papers, CQG Vol 39, N.20, 2022**

- **DATA AVAILABLE ON : https://cmsm-ds.onera.fr/**

A jump in accuracy



This outstanding accuracy results from a long and hard collaborative work

- **Experts in very different technology and scientific areas**
  - Performance Group (CNES, ONERA, OCA, ZARM)
  - Science Working Group (IHES, Imp. Col., Delf Un., ZARM, DLR, ENS, LKB, IGN)
  - Numerous of out of project experts in CNES, ONERA et sub-contractors
- **It is the first experiment in space dedicated to EP test: one shot success !! And 100 better than any other ground experiement since 4 century**
- **There is a lot of reasons to violated the EP => testing with better accuracy is still a major topic in Physics**
- **The experience return of MICROSCOPE lets imagine even more accurate experiment in space in the future.**


cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES
MICROSCOPE


À
10-15 près,
j'ai toujours
raison !