MICROSCOPE: Firsts results of the Equivalence Principle test in space…before last release

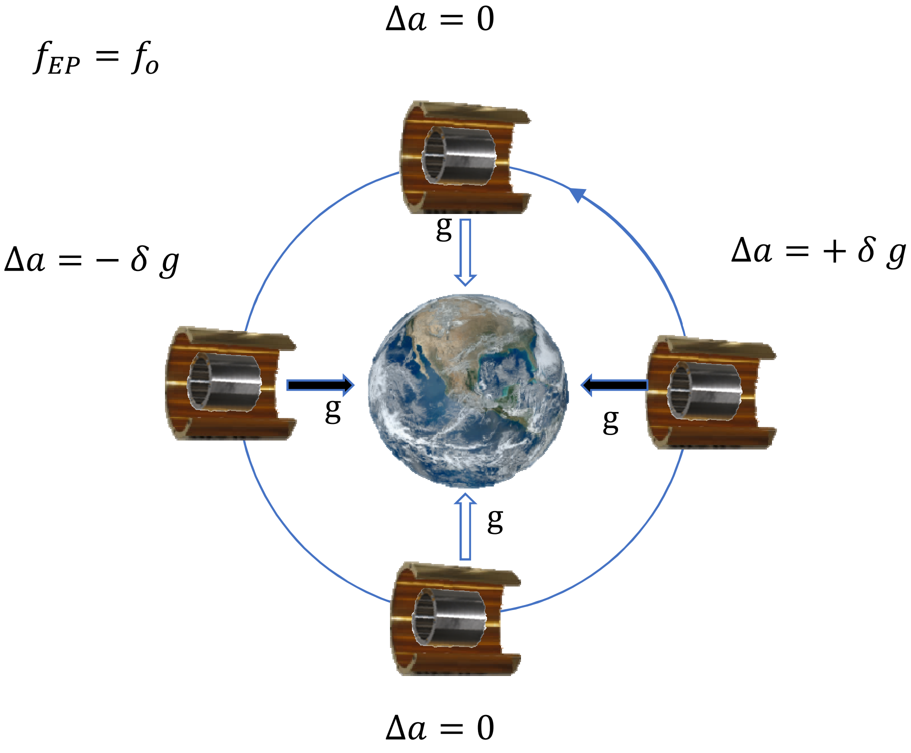
PARIS 2019 – ACES Workshop

Manuel RODRIGUES,

on behalf of the MICROSCOPE team

The « free-fall » test in space with MICROSCOPE resolution objective on WEP parameter: δ @ 10^{-15}

$$\Delta \boldsymbol{a} = \boldsymbol{a1} - \boldsymbol{a2} = \left(\frac{m_{g1}}{m_{i1}} - \frac{m_{g2}}{m_{i2}}\right) g$$



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

m_g= gravitational mass

m_i= inertial mass

Comparison of the acceleration of 2 bodies constrained to fall in the same gravity field:

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

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

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

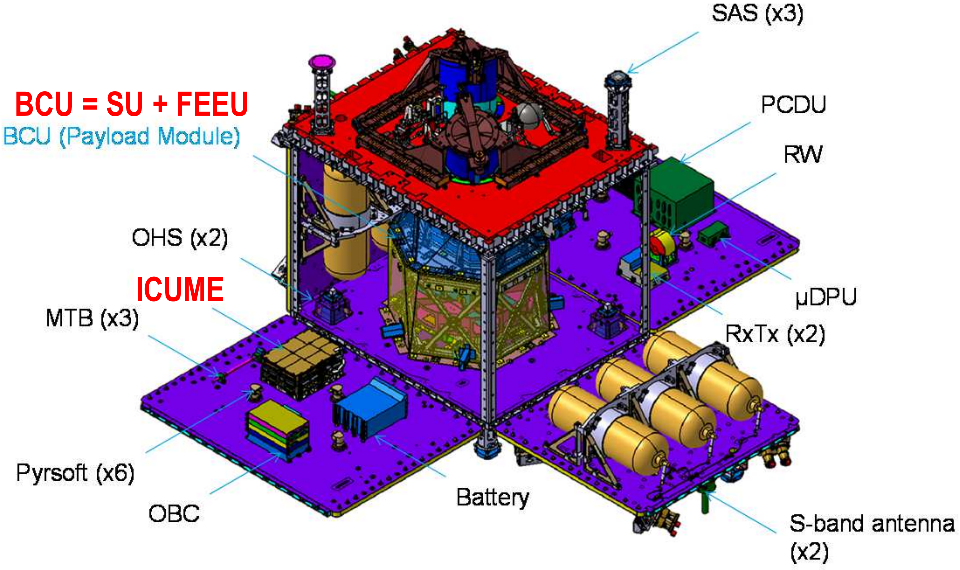
The MICROSCOPE satellite

- **Sun-synchronous 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

© CNES / Virtual-IT 2017+ Onera 2017

- **Cold Gas propulsion**
- **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**

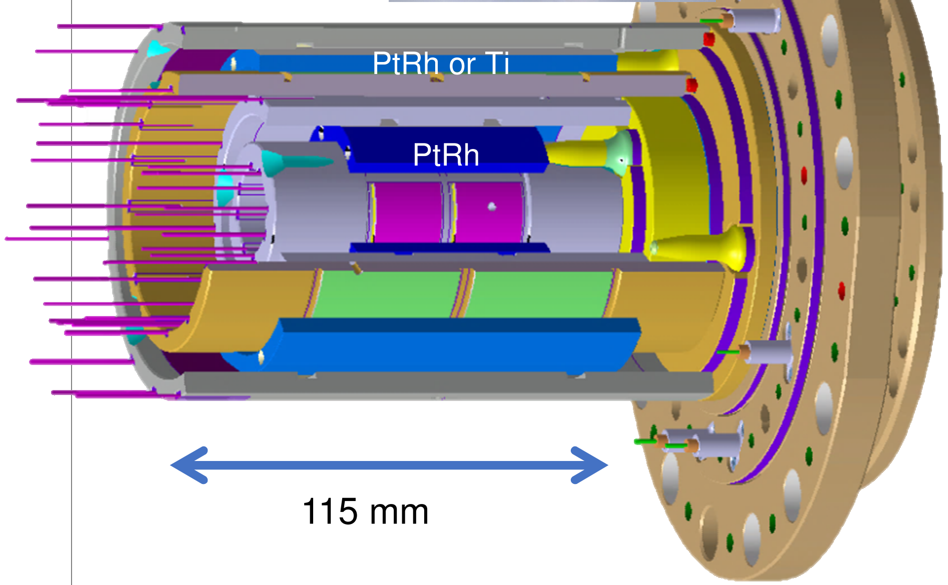


Instrument : 2 double accelerometers for the test

<u>2 Sensor Units on board which comprise each 2 concentric test-masses</u>

SUEP : Sensor Unit with Ti / PtRh

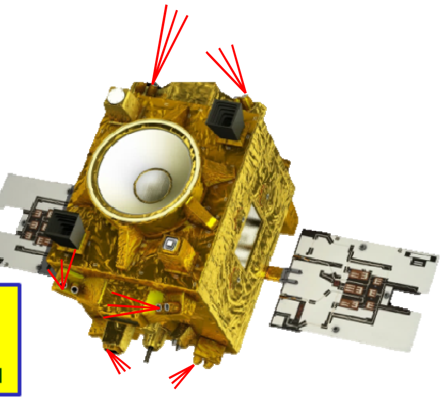
SUREF : Sensor Unit with PtRh / PtRh, helps to get confidence on the overall performance and data process

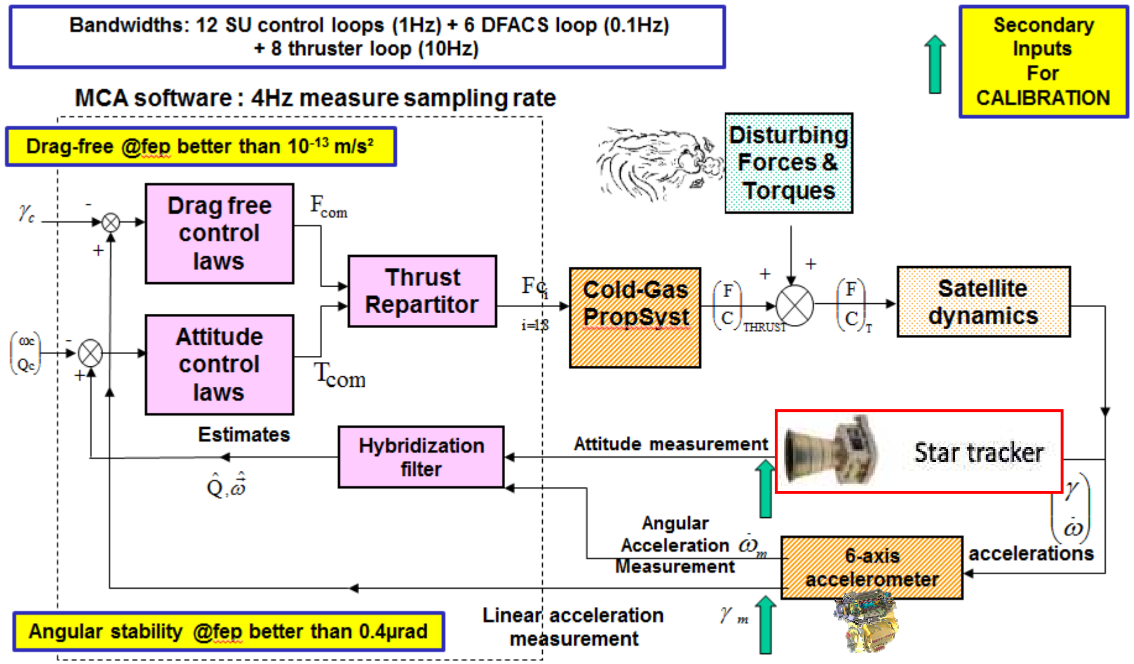


DRAG-FREE SATELLITE LABORATORY OF PHYSICS

With capabilities of stimuli production:

- linear or angular sine accelerations,
- Test-masses displacements,
- controlled thermal heaters (Off in science mode).





Secondary Inputs For CALIBRATION

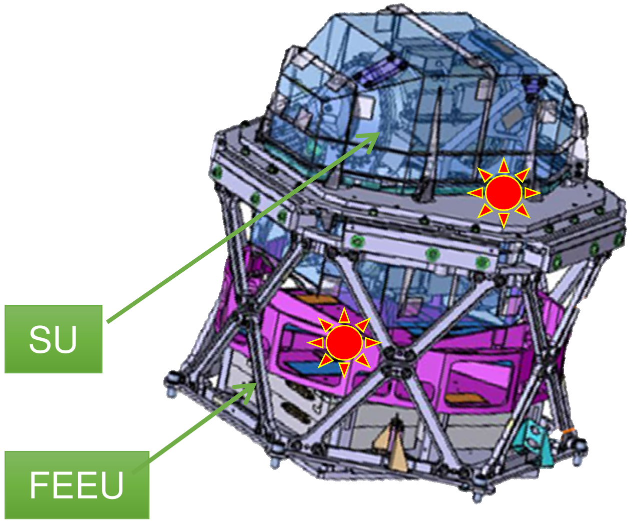
Performance of drag-free

$\Gamma(f_{EP}) < 3\times10^{-13}$ m/s²

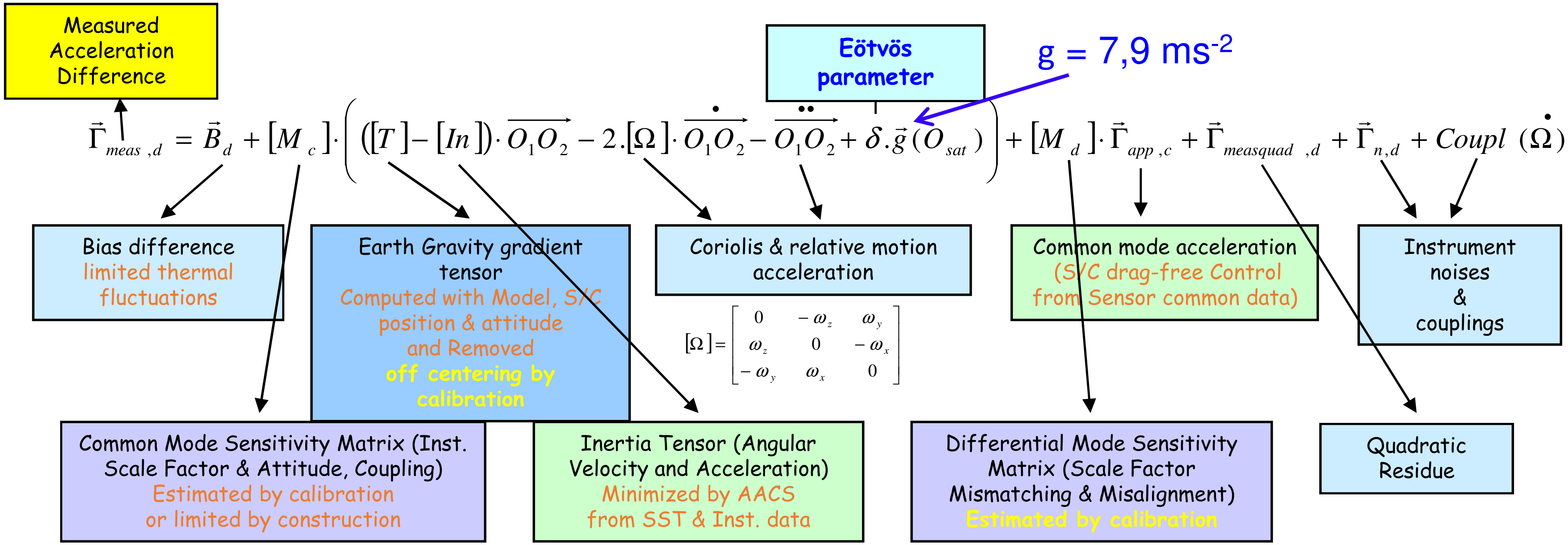
$\dot{\Omega}(f_{EP}) < 4\times10^{-12}$ rd/s²

$\Omega(f_{EP}) < 3\times10^{-10}$ rd/s

$\int \Omega < 1$µrd



The measurement: Earth, satellite, instrument and Physics contributions



Measured Acceleration Difference

Eötvös parameter

g = 7,9 ms^{-2}

$$\vec{\Gamma}_{meas,d} = \vec{B}_d + [M_c]\cdot\left(([T]-[In])\cdot\overrightarrow{O_1O_2} - 2.[\Omega]\cdot\dot{\overrightarrow{O_1O_2}} - \ddot{\overrightarrow{O_1O_2}} + \delta.\vec{g}(O_{sat})\right) + [M_d]\cdot\vec{\Gamma}_{app,c} + \vec{\Gamma}_{measquad,d} + \vec{\Gamma}_{n,d} + Coupl(\dot{\Omega})$$

Bias difference
limited thermal fluctuations

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

Coriolis & relative motion acceleration

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

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 AACS from SST & Inst. data

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

Quadratic Residue

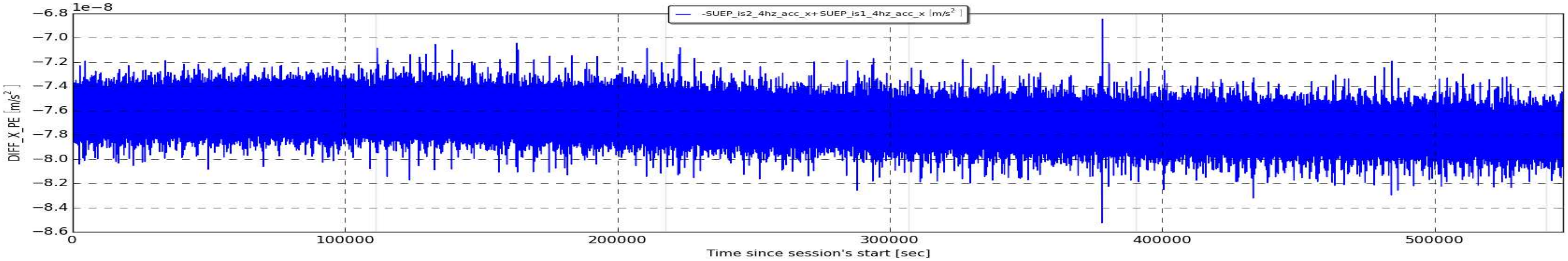
$$\begin{bmatrix} K_{cx} & \eta_{cz}+\theta_{cz} & \eta_{cy}-\theta_{cy} \\ \eta_{cz}-\theta_{cz} & K_{cy} & \eta_{cx}+\theta_{cx} \\ \eta_{cy}+\theta_{cy} & \eta_{cx}-\theta_{cx} & K_{cz} \end{bmatrix}$$

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

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

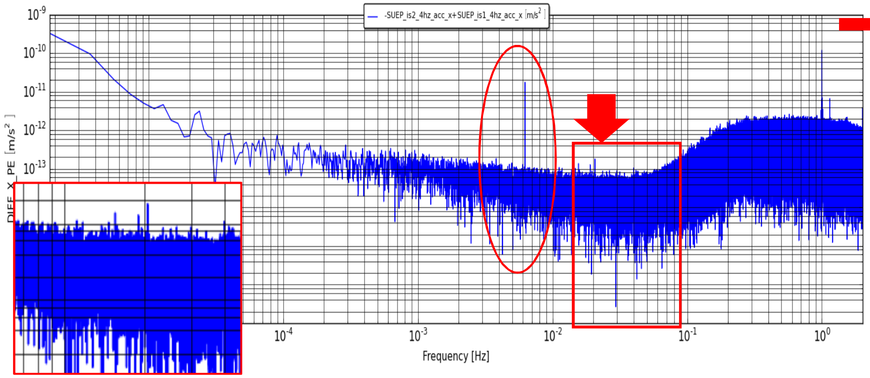
The measurement along the cylinder axis (X) = the main measurement

Measured time series and effect of in-flight calibration (session 234)

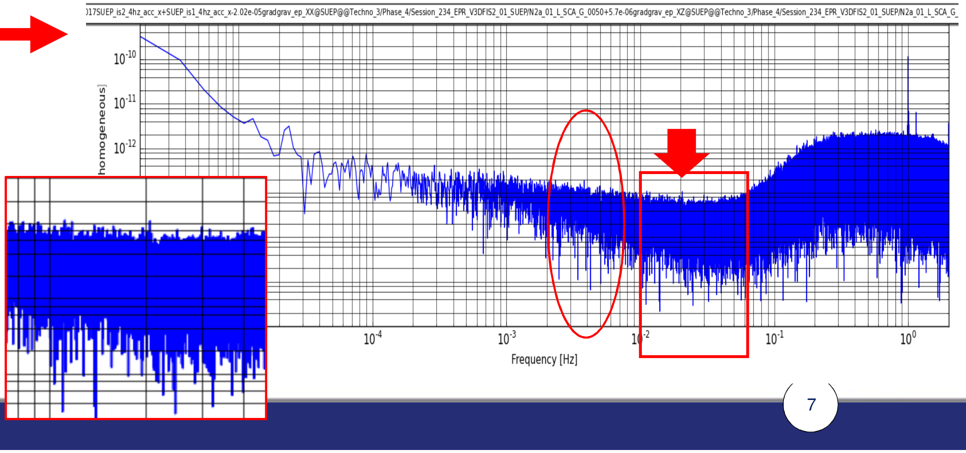


- Scale factor matching through a dedicated session before the EP session
- Test-mass off-centering estimated through the Earth's gravity effect at $2f_{EP}$ => Correction of off-centering effects at all frequencies (f_{EP} and $2f_{EP}$ included)

K_{dx} = 0.0085 +/- 6 10^{-5}
Δx = (20.2 +/- 0.03) µm
Δz=(-5.7 +/- 0.03) µm

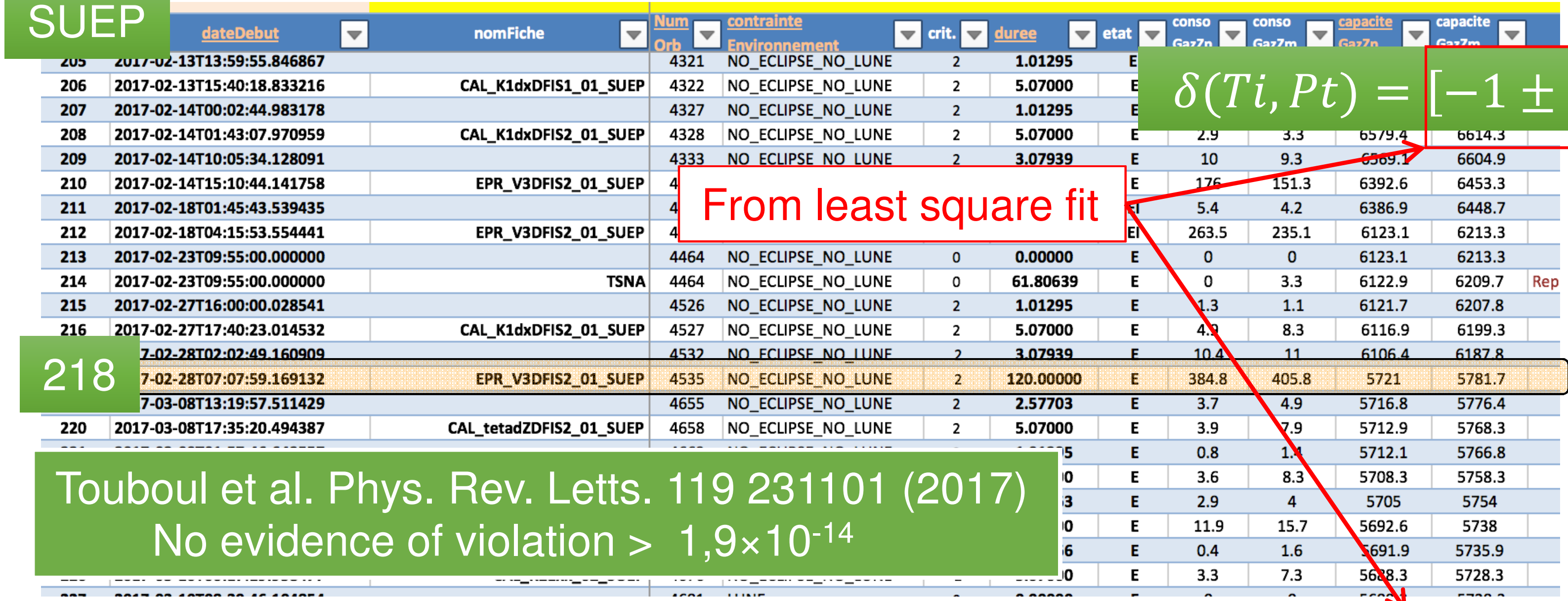


Correction



FIRST RESULTS PUBLISHED BASED ON 2 SESSIONS

SUEP



	dateDebut	nomFiche	Num Orb	contrainte Environnement	crit.	duree	etat	conso GazZp	conso GazZm	capacite GazZp	capacite GazZm	
205	2017-02-13T13:59:55.846867		4321	NO_ECLIPSE_NO_LUNE	2	1.01295	E					
206	2017-02-13T15:40:18.833216	CAL_K1dxDFIS1_01_SUEP	4322	NO_ECLIPSE_NO_LUNE	2	5.07000	E					
207	2017-02-14T00:02:44.983178		4327	NO_ECLIPSE_NO_LUNE	2	1.01295	E					
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	6569.1	6604.9	
210	2017-02-14T15:10:44.141758	EPR_V3DFIS2_01_SUEP					E	176	151.3	6392.6	6453.3	
211	2017-02-18T01:45:43.539435						E	5.4	4.2	6386.9	6448.7	
212	2017-02-18T04:15:53.554441	EPR_V3DFIS2_01_SUEP					E	263.5	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	
	7-02-28T02:02:49.160909		4532	NO_ECLIPSE_NO_LUNE	2	3.07939	E	10.4	11	6106.4	6187.8	
	7-02-28T07:07:59.169132	EPR_V3DFIS2_01_SUEP	4535	NO_ECLIPSE_NO_LUNE	2	120.00000	E	384.8	405.8	5721	5781.7	
	7-03-08T13:19:57.511429		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	
							E	0.8	1.4	5712.1	5766.8	
							E	3.6	8.3	5708.3	5758.3	
							E	2.9	4	5705	5754	
							E	11.9	15.7	5692.6	5738	
							E	0.4	1.6	5691.9	5735.9	
							E	3.3	7.3	5688.3	5728.3	

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From least square fit

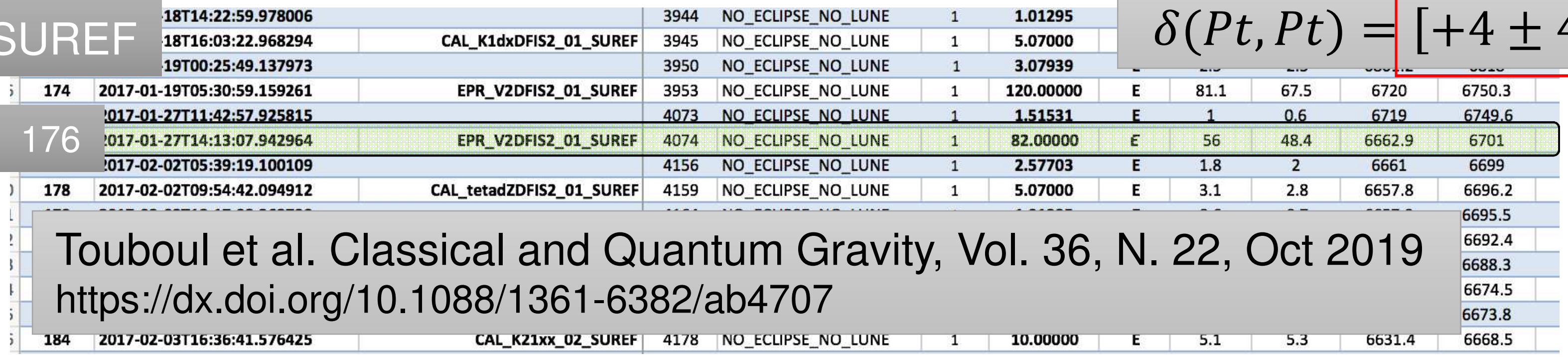
$$\delta(Ti, Pt) = \boxed{[-1 \pm 9(stat)} \pm 9(syst)] \times 10^{-15}$$

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

Over 120 orbits

- Statistical noise integrated over 120 orbits
- **Systematics evaluated with a majoring of SU temperature** variations (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
	18T14:22:59.978006		3944	NO_ECLIPSE_NO_LUNE	1	1.01295					
	18T16:03:22.968294	CAL_K1dxDFIS2_01_SUREF	3945	NO_ECLIPSE_NO_LUNE	1	5.07000					
	19T00:25:49.137973		3950	NO_ECLIPSE_NO_LUNE	1	3.07939					
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
	017-01-27T11:42:57.925815		4073	NO_ECLIPSE_NO_LUNE	1	1.51531	E	1	0.6	6719	6749.6
	017-01-27T14:13:07.942964	EPR_V2DFIS2_01_SUREF	4074	NO_ECLIPSE_NO_LUNE	1	82.00000	E	56	48.4	6662.9	6701
	017-02-02T05:39:19.100109		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
											6695.5
											6692.4
											6688.3
											6674.5
											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

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

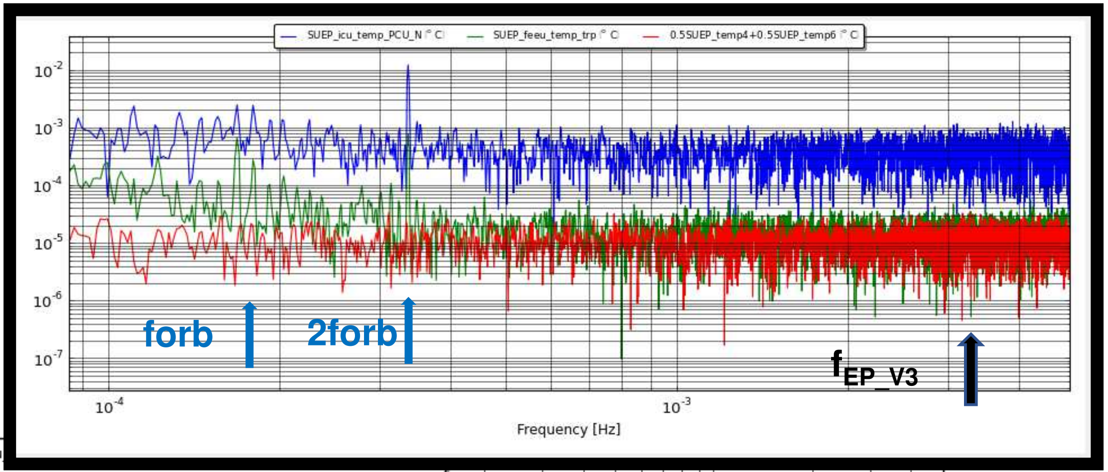
Touboul et al. Classical and Quantum Gravity, Vol. 36, N. 22, Oct 2019
https://dx.doi.org/10.1088/1361-6382/ab4707

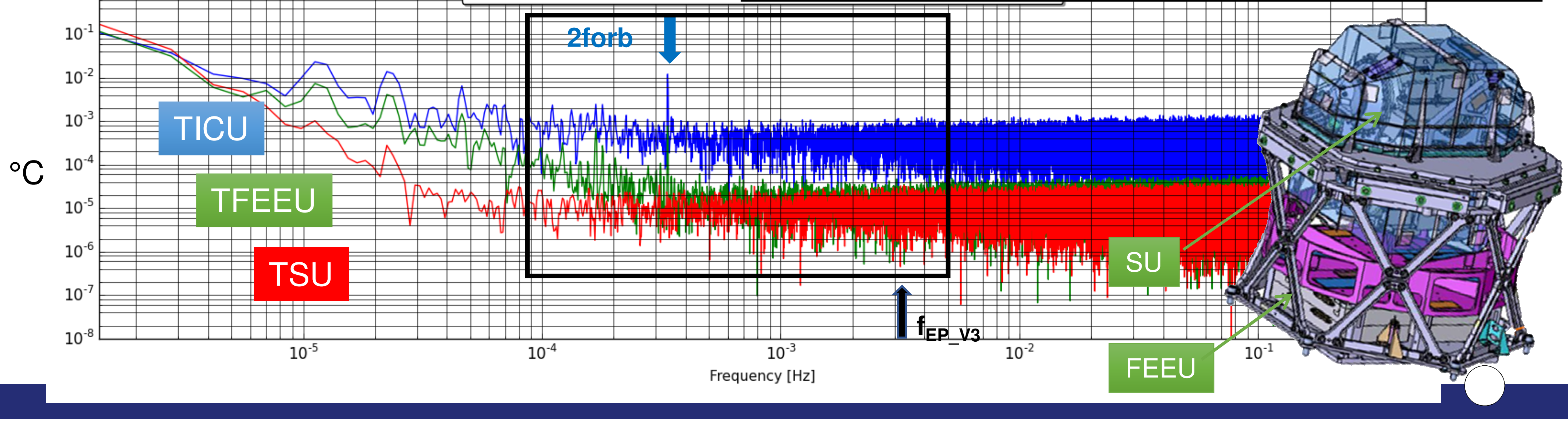
Over 62 orbits

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

Session 218 – SUEP EPRV3- Typical FFT of the temperatures (SU, FEEU, ICU)

- **The disturbances are mainly at forb & 2 forb in the FEEU. No signal at f_{EP}**
- **No peak at forb in the ICU (only 2forb): the ICU is not in the BCU**
- **No significant temperature signal in the SU at all for f > forb**

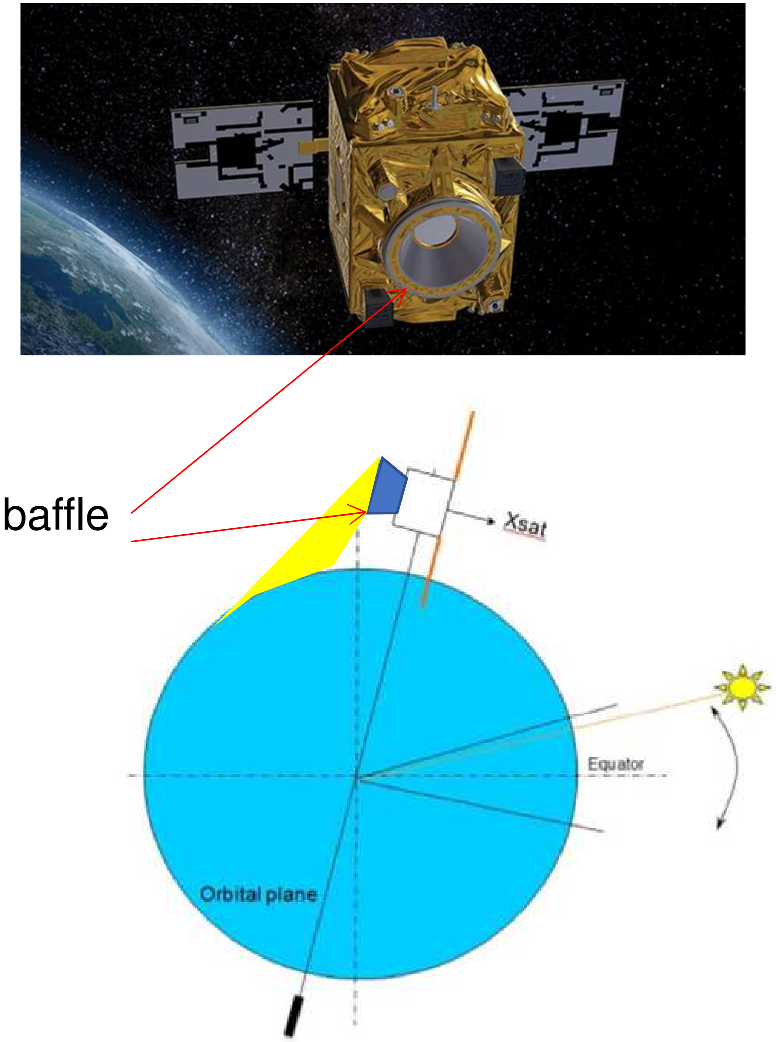


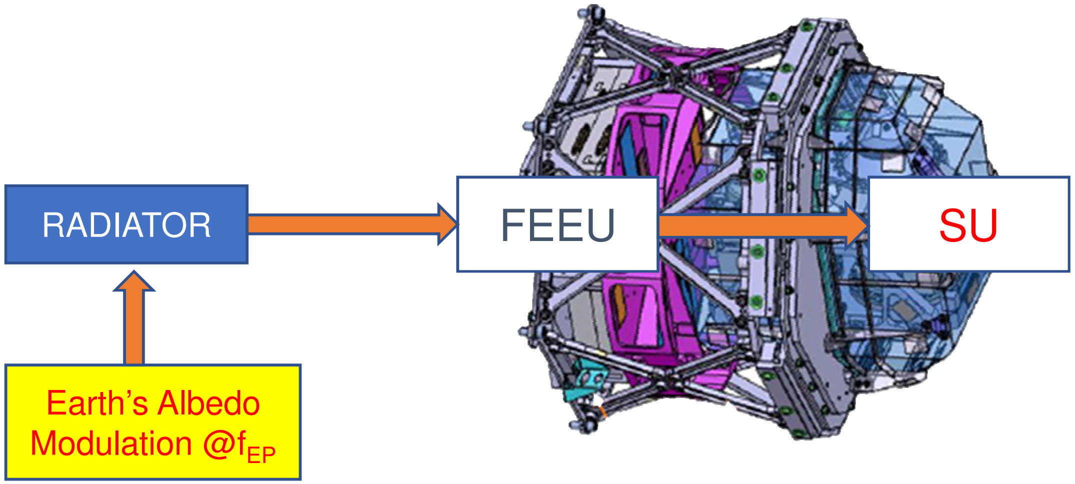


THERMAL TESTS IN FLIGHT

OBJECTIVE:

- **To confirm the thermal model : temperature variations in the sensor (SU) is dominated by thermal conduction coming from the radiator through the FEEU plate**
- **To evaluate the thermal filtering from Radiator to FEEU and from FEEU to SU**


baffle


RADIATOR

FEEU

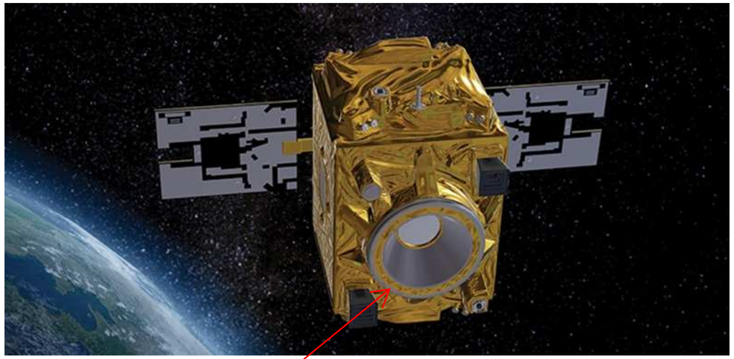
SU

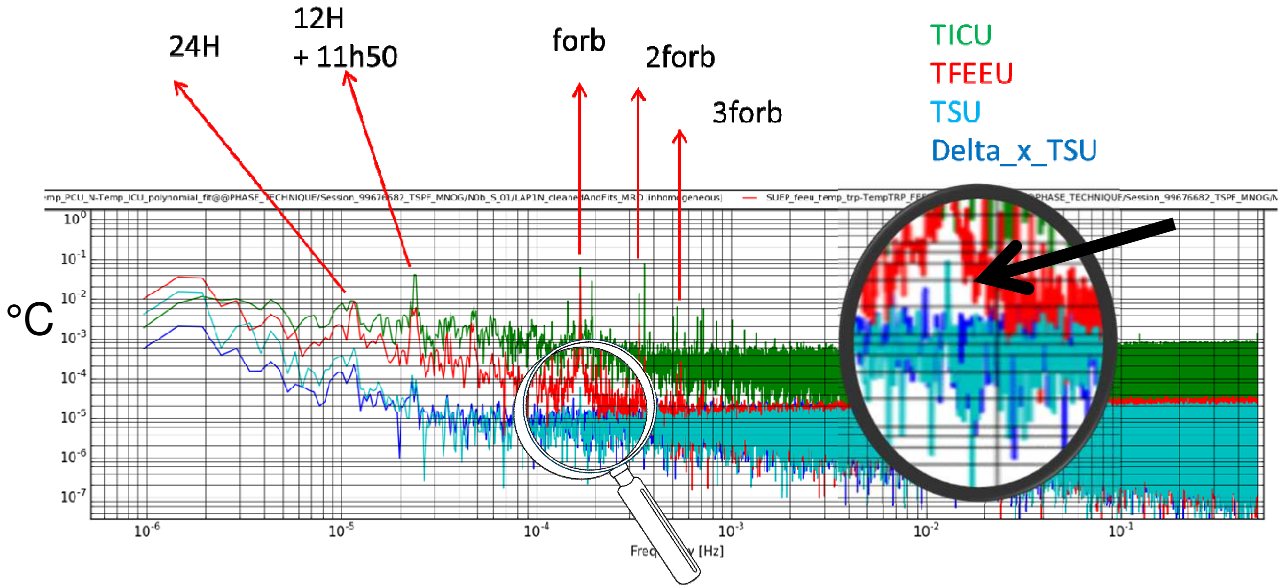
Earth's Albedo Modulation @f_{EP}

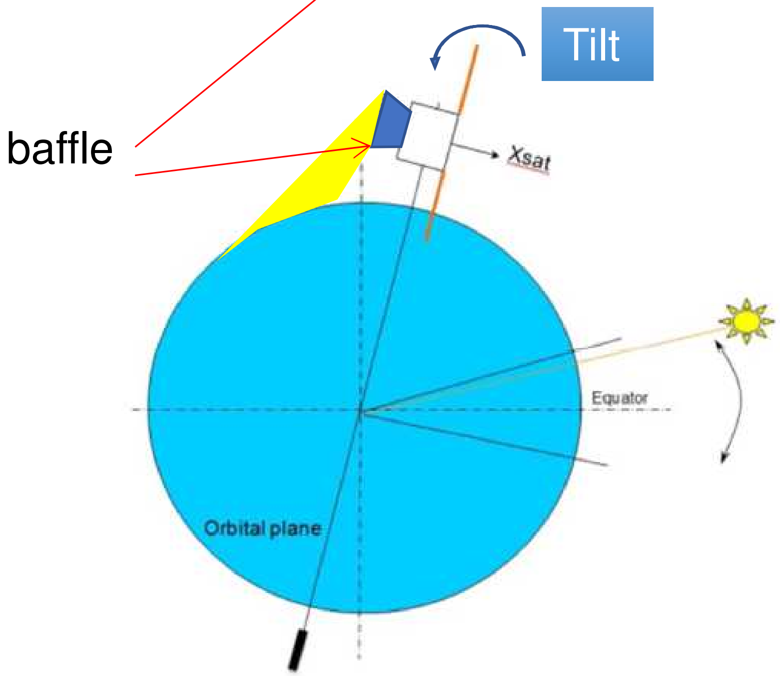
THERMAL FILTERING CHARACTERISATION

A specific session (*SPICHO*) of 460 continuous orbits was performed to amplify the Earth's thermal flux at orbital frequency by tilting the satellite

The result is awesome : $$\left(\frac{\Delta T_{FEEU}}{\Delta T_{SU}}\right)_{1.7\times10^{-4}Hz} = 500$$







Thermal sensitivity & systematics

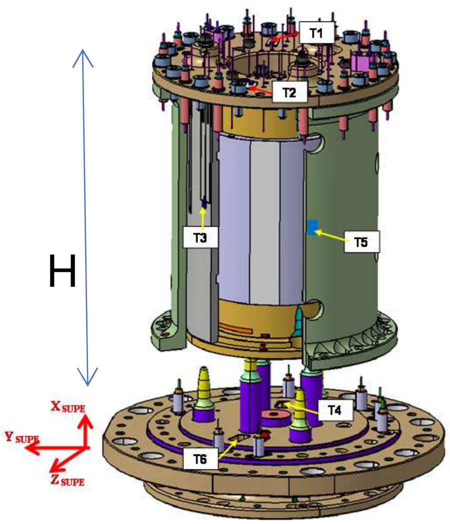
	SUREF	SUEP
Sensitivity to T_{SU} at f_{EP} [ms^{-2}K^{-1}]	3.9×10^{-9}	4.3×10^{-9}
Sensitivity to T_{FEEU}, at f_{EP} [ms^{-2}K^{-1}]	5×10^{-11}	7×10^{-11}

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

$|\Delta\nabla T_{SU}|.H < |\Delta T_{SU}| \ll |\Delta T_{FEEU}|$ in all sessions

In all science sessions : $|\Delta T_{SU}|$ is dominated by the probe noise but thanks to The thermal characterization :

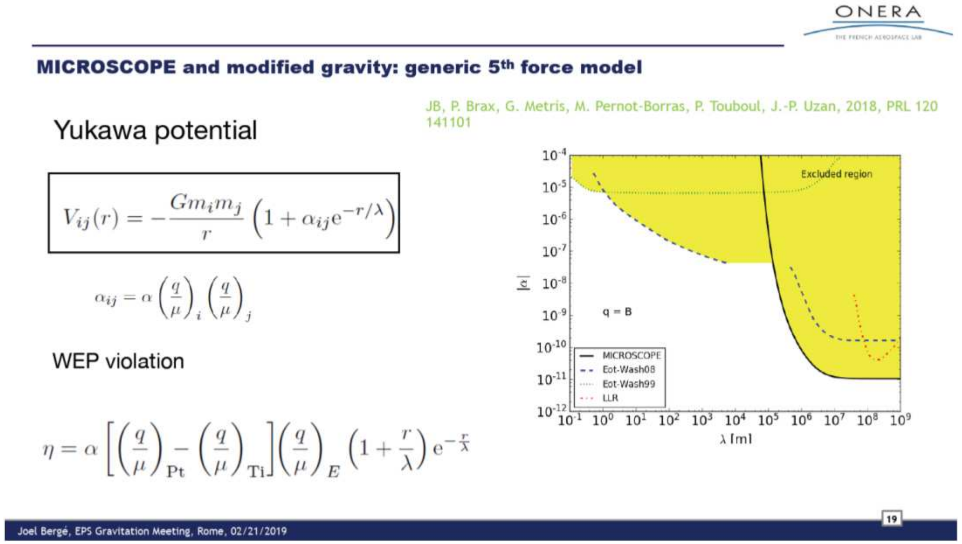
ΔT_{SU} < 0.1µK (instead of 15µK of the upper limit in PRL)



$$\nabla T_{SU}.H = \frac{1}{2}(T1 + T2 - T6 - T4)$$

$$T_{SU} = \frac{1}{2}(T6 + T4)$$

Some first resulting physics from 2017/2019 papers



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

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

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

WEP violation

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

Joel Bergé, EPS Gravitation Meeting, Rome, 02/21/2019

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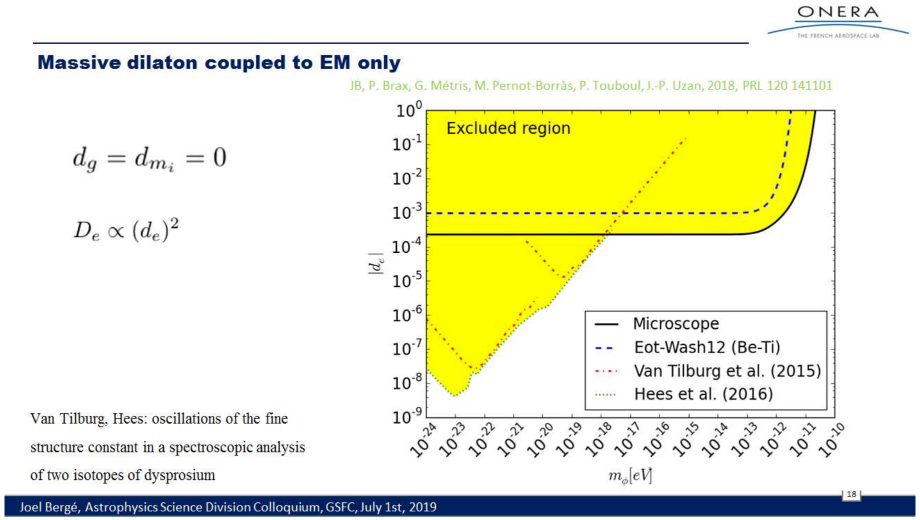

Massive dilaton coupled to EM only

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

$$d_g = d_{m_i} = 0$$

$$D_e \propto (d_e)^2$$

Van Tilburg, Hees: oscillations of the fine structure constant in a spectroscopic analysis of two isotopes of dysprosium

Joel Bergé, Astrophysics Science Division Colloquium, GSFC, July 1st, 2019

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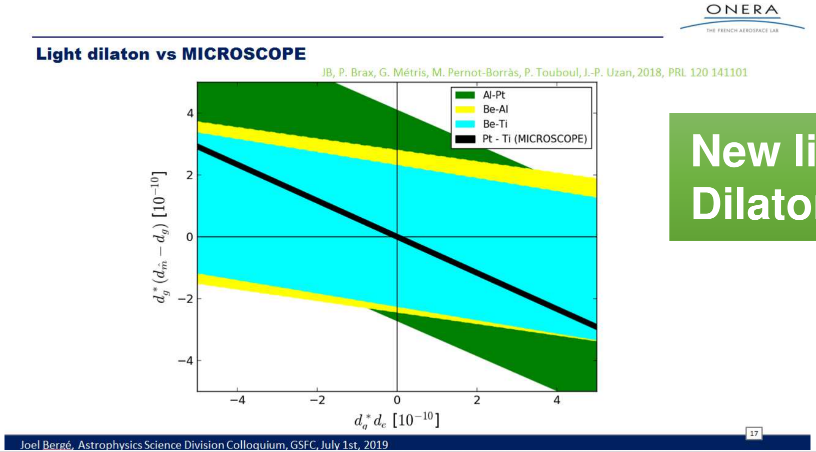

Light dilaton vs MICROSCOPE

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

Joel Bergé, Astrophysics Science Division Colloquium, GSFC, July 1st, 2019

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New limits on Dilaton & Yukawa

MICROSCOPE Mission: First Constraints on the Violation of the Weak Equivalence Principle by a Light Scalar Dilaton
Bergé et al. PRL 120, 141101

Some first resulting physics from 2017/2019 papers

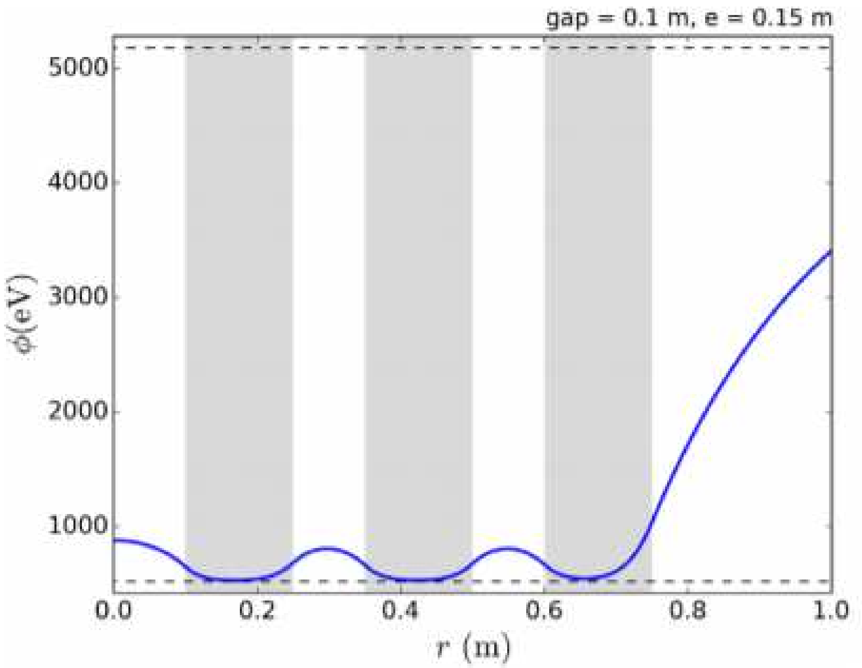
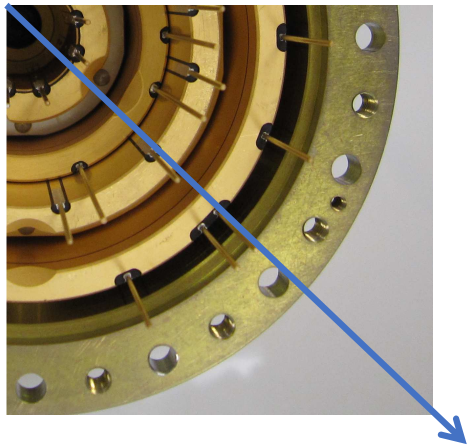


FIG. 20. Radial profile for three nested cylinders of thickness e with the same matter density. Cylinders are delimited by the shaded regions and separated by a distance *gap*. The $\phi_{\min}$ values are represented by the horizontal segments.

MICROSCOPE & Chameleonic forces:
Screening effects of local mater modelling

General study of chameleon fifth force in gravity space experiments
Pernot-Borràs et al. PRD 100, 084006 (2019)



Some first resulting physics from 2017/2019 papers

MICROSCOPE limits on the strength of a new force with comparisons to gravity and electromagnetism
Pierre Fayet, Phys. Rev. D **99**, 055043 – Published 28 March 2019

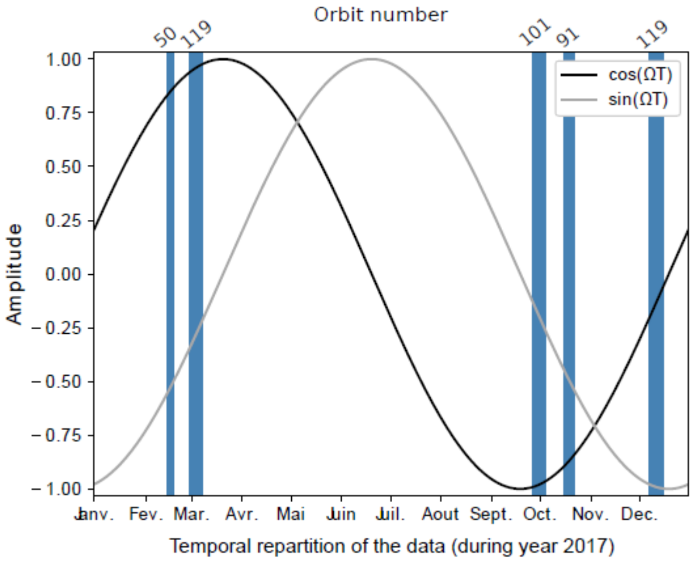
Improved limits on the strength of a new long-range force by one order of magnitude

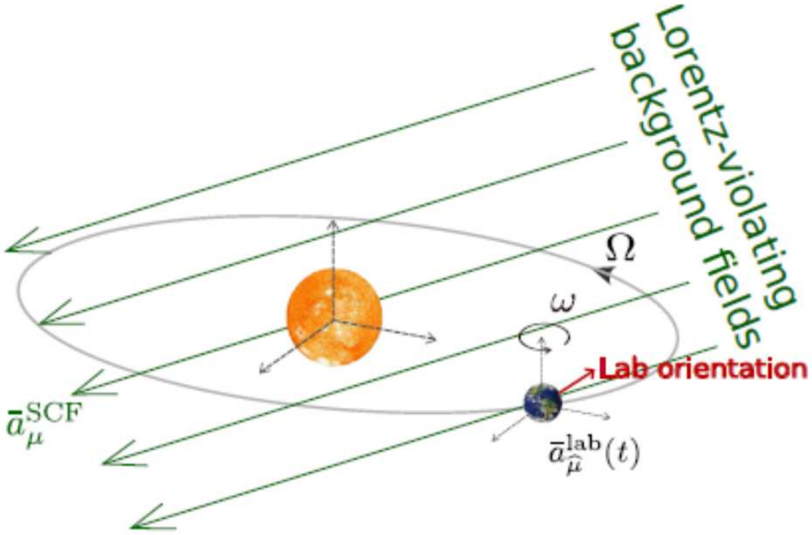
MICROSCOPE limits for new long-range forces and implications for unified theories
Pierre Fayet, Phys. Rev. D **97**, 055039 – Published 26 March 2018

Some first resulting physics from 2017/2019 papers

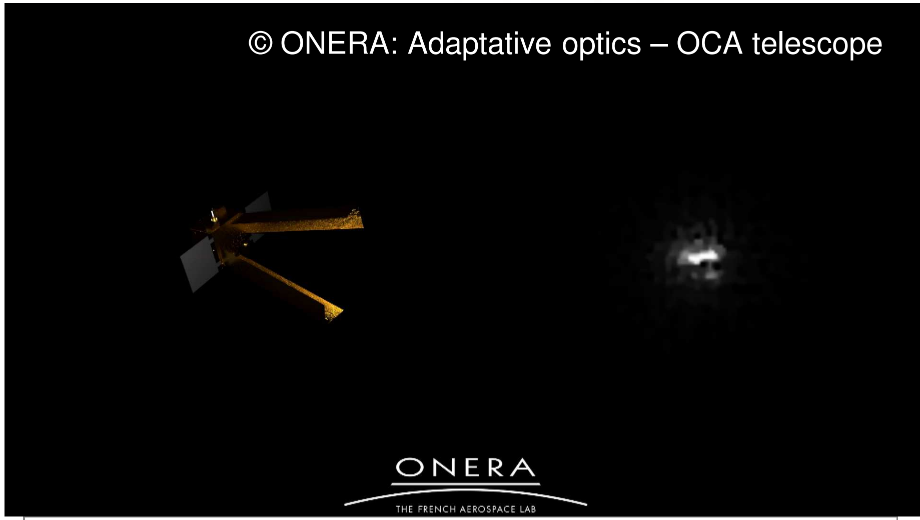
New test of Lorentz invariance using the MICROSCOPE space mission
Phys. Rev. Lett.
Pihan-le Bars et al, October 2019 accepted

5 sessions analyzed
New constraints on SME coefficients
SEE NEXT PRESENTATION





SUMMARY OF MICROSCOPE FLIGHT



© ONERA: Adaptative optics – OCA telescope

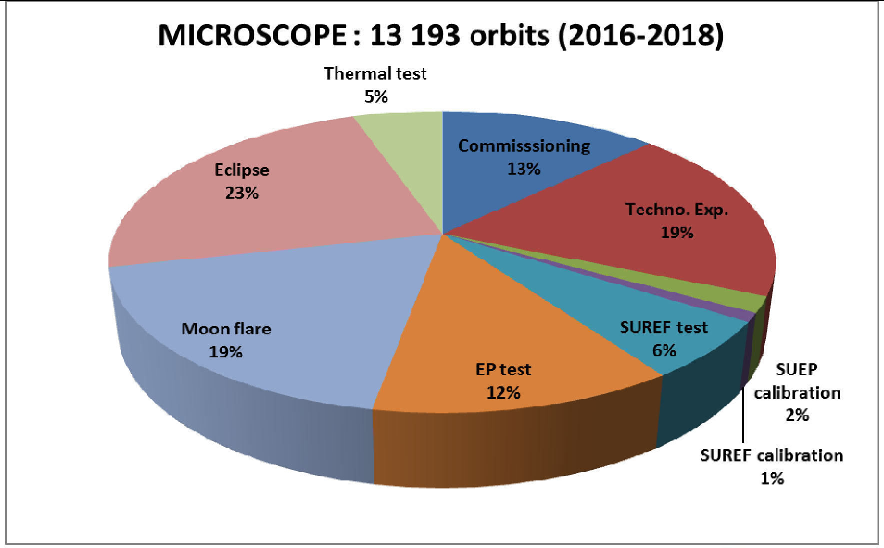
Launched on the 25th of April 2016, switched off on the 16th of October 2018 : 2.5 year

20% (2768 orbits) dedicated to science

5% of thermal tests

19% of technological experiment

1 orbit = 6000 sec



10 papers under preparation with the final consolidated result: submission by end of 2019

⇒ Release by mid 2020

⇒ Data opened to public after release

OCTOBER 17th – SWICHT OFF SAT FEST

THANK YOU FOR YOUR ATTENTION

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