

MICROSCOPE

Gilles METRIS

For the MICROSCOPE consortium



What?

- ❖ **Testing the WEP with a targeted accuracy of 10^{-15} for the Eötvös parameter**

$$\eta = \frac{a_1 - a_2}{\frac{1}{2}(a_1 + a_2)} = \frac{\frac{mg_1}{m_{i1}} - \frac{mg_2}{m_{i2}}}{\frac{1}{2}\left(\frac{mg_1}{m_{i1}} + \frac{mg_2}{m_{i2}}\right)}$$

approximated by

$$\delta = \frac{mg_1}{m_{i1}} - \frac{mg_2}{m_{i2}}$$

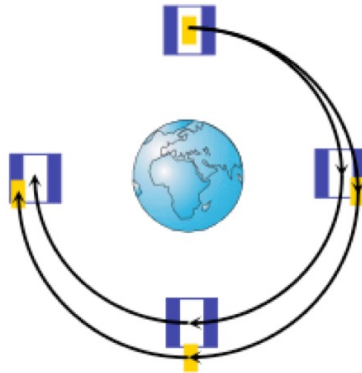
- ❖ **Test masses composition: trade-off between theoretical advantages for the test (distance in the A-Z space), ease of machining, physical characteristics (magnetism...) →**
 - Test mass 1 : platinum-rhodium alloy
 - Test mass 2 : titanium

How?

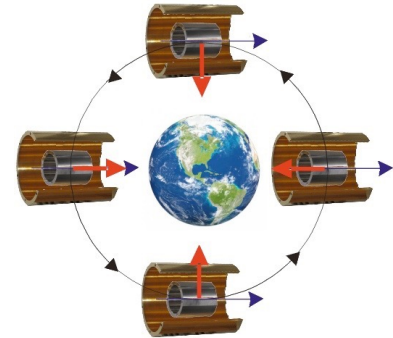
❖ Comparison of “free falls” in Earth’s orbit



Free fall on the earth's surface



Free fall in orbit

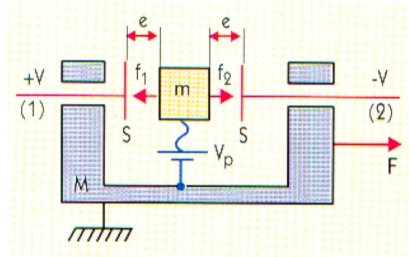


“Controlled” free fall in orbit

Electrostatic accelerometers (ONERA)

- ❖ Test masses are not free in the satellite but they are enclosed in the instrument which:
 - Detects variations of position of the test-masses by capacitive detection
 - Forces the masses to stay at rest w.r.t the instrument (and thus w.r.t. the satellite) thanks to a control loop with electrostatic forces for the actuation.

Servo controlled
electrostatic accelerometer

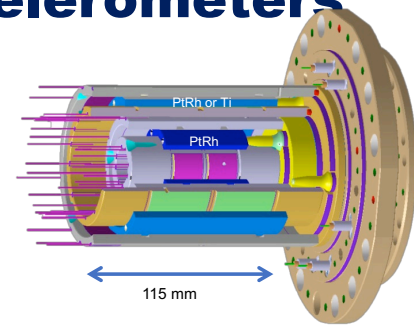


$$\Gamma = \frac{F}{m} = \left(\frac{2\epsilon_0 S}{me^2} V_p \right) V$$

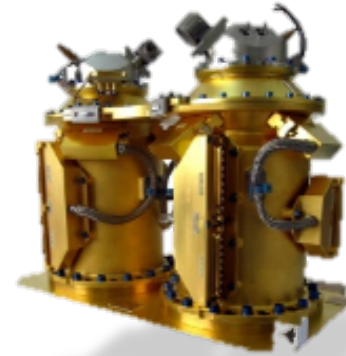
- ❖ The electrostatic force (**which is measured**) equilibrates all other “natural” forces (difference of gravity, non gravitational effects, inertial acceleration) acting on the test masses
- ❖ Dividing this electrostatic force by the mass of test mass yields what we name “measured acceleration” and is the fundamental measurement in MICROSCOPE

The T-SAGE payload: 2 differential accelerometers

- ❖ 2 co-axial, concentric, cylindrical test masses
- ❖ The measurements are done independently for the 2 masses (no direct measurement of the differential acceleration)
- ❖ The MICROSCOPE payload, T-SAGE is composed by 2 such differential accelerometers :
 - SUEP : Sensor Unit with Ti / PtRh (to test the EP)
 - SUREF : Sensor Unit with PtRh / PtRh (no violation expected)

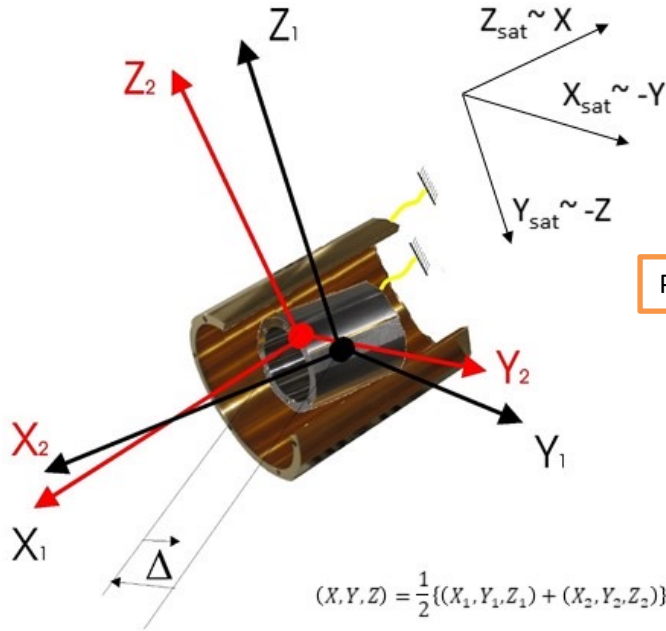


ONERA



ONERA

The measurement model



Potential EP signal

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

Offsets, drifts and systematics
Gravity & Inertia Gradients
Common mode projection
Angular to linear couplings
noise
Quadratic term

Null thanks to Servo-loop

The satellite

- ❖ **1.4m x 1m (2.8 with solar panels deployed) x 1.3m ; \approx 300 kg**
- ❖ **Payload at the center of the satellite in a thermal and magnetic cocoon**
- ❖ **No moving masses**
- ❖ **Cold gas thrusters micro propulsion to ensure attitude and acceleration control**



- ❖ **Sun synchronous orbit @ 710 km**
- ❖ **Several modes :**
 - (quasi) inertial pointing $f_{EP} = f_{orb} = 1.7 \times 10^{-4}$ Hz
 - 2 spin rates: $f_{EP} = f_{orb} + f_{spin}$
 - ➔ $f_{EP} = 0.9 \times 10^{-3}$ Hz & $f_{EP} = 3.1 \times 10^{-3}$ Hz



CNES

Attitude and Orbit Control System (AOCS)

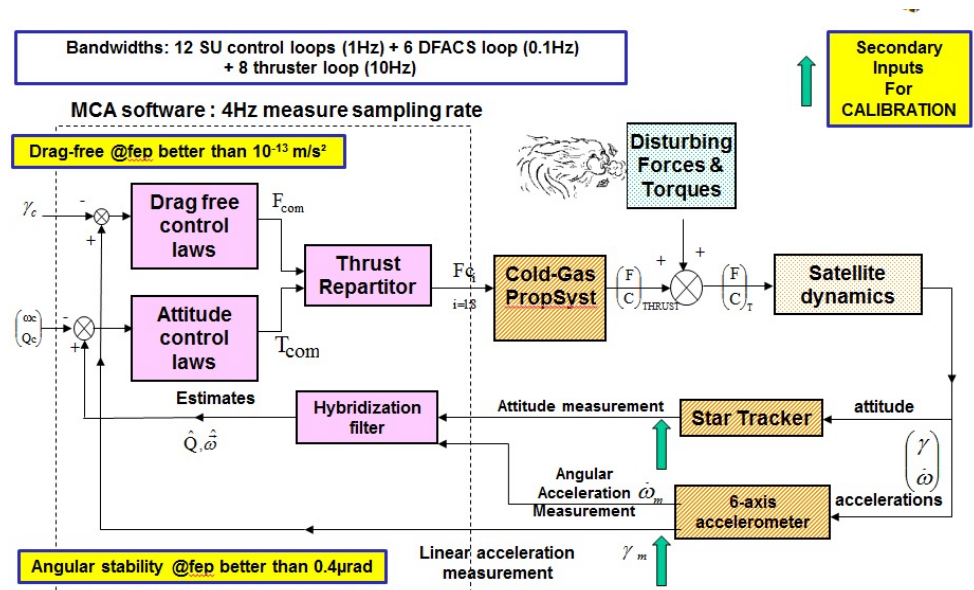
Allows to:

- Cancel any combination of the 4 measured acceleration (in a certain bandwidth): “drag-free”;
- Apply additional sinusoidal accelerations for calibration purpose;
- Ensure a very stable attitude.

❖ Detectors:

- Linear acceleration measured by the 4 accelerometers along their 3 axes;
- Star trackers + angular acceleration measured by the 4 accelerometers about their 3 axes.

❖ Actuators: 8 micro-thrusters

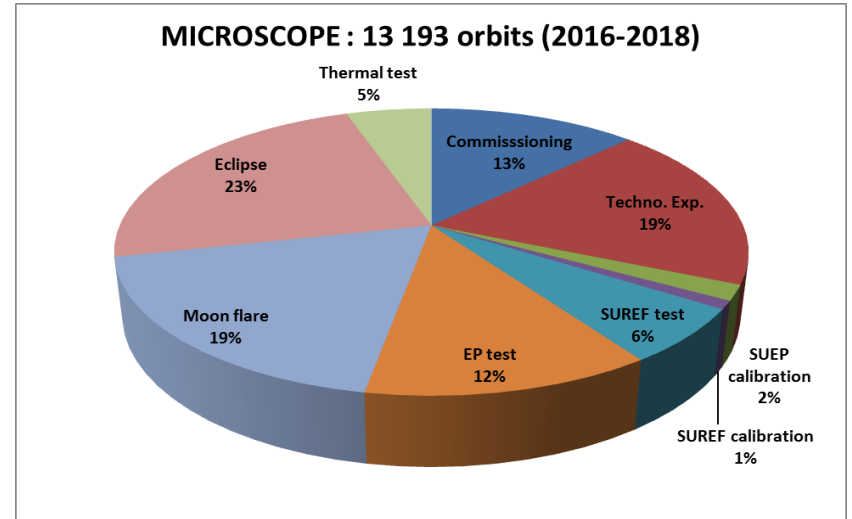


When?

- ❖ Launched on the 25th of April 2016
- ❖ switched off on the 16th of October 2018
- ❖ 20% of the 2.5 years (2768 orbits) dedicated to science

Configuration	Number of cumulated orbits	
	SUREF	SUEP
EPR _{V2}	563	240
EPR _{V3}	214	1402
	53 days	113 days

Orbital period: $T = 5946 \text{ s} = 1.65 \text{ h}$



FIRST RESULTS PUBLISHED in 2017 and 2019 BASED ON 2 SESSIONS

SUEP

	dateDebut	nomFiche	Num Orb	contrainte	crit.	duree	etat	conso GazZp	conso GazZm	capacite GazZp	capacite GazZm
	02-13T13:59:55.846867		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	4341	NO_ECLIPSE_NO_LUNE	2	120.00000	E	176	151.3	6392.6	6453.3
211	2017-02-18T01:45:43.539435		4344	NO_ECLIPSE_NO_LUNE	2	1.01295	E	5.4	4.2	6386.9	6448.7
212	2017-02-18T04:15:53.554441	EPR_V3DFIS2_01_SUEP	4345	NO_ECLIPSE_NO_LUNE	2	1.01295	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
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
	17-02-28T02:02:49.160909		4532	NO_ECLIPSE_NO_LUNE	2	3.07939	E	10.4	11	6106.4	6187.8
218	17-02-28T07:07:59.169132	EPR_V3DFIS2_01_SUEP	4535	NO_ECLIPSE_NO_LUNE	2	120.00000	E	384.8	405.8	5721	5781.7
	17-03-08T13:19:57.511429		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

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

From mean square fit

- Over 120 orbits
- Statistical noise integrated over 120 orbits (≈ 8.2 days)
 - Systematics evaluated with a majoring of SU temperature variations ($15\mu\text{K}$ @ f_{EP})
 - **90% of systematics come from upper bound limit on temperature variations**

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

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

SUREF

	dateDebut	nomFiche	Num Orb	contrainte	crit.	duree	etat	conso GazZp	conso GazZm	capacite GazZp	capacite GazZm
	01-18T14:22:59.978006		4073	NO_ECLIPSE_NO_LUNE	1	1.51531	E	1.1	0.6	6719	6749.6
	01-18T16:03:22.968294	CAL_K1dxDFIS2_01_SUREF	4074	NO_ECLIPSE_NO_LUNE	1	82.00000	E	56	48.4	6662.9	6701
	01-19T00:25:49.137973		4156	NO_ECLIPSE_NO_LUNE	1	2.57703	E	1.8	2	6661	6699
174	2017-01-19T05:30:59.159261	EPR_V2DFIS2_01_SUREF	4073	NO_ECLIPSE_NO_LUNE	1	1.51531	E	81.1	67.5	6720	6750.3
176	2017-01-27T11:42:57.925815	EPR_V2DFIS2_01_SUREF	4074	NO_ECLIPSE_NO_LUNE	1	82.00000	E	56	48.4	6662.9	6701
	2017-01-27T14:13:07.942964		4156	NO_ECLIPSE_NO_LUNE	1	2.57703	E	1.8	2	6661	6699
	2017-02-02T05:39:19.100109		4159	NO_ECLIPSE_NO_LUNE	1	5.07000	E	3.1	2.8	6657.8	6696.2
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
181	2017-02-03T04:19:57.421332		4170	NO_ECLIPSE_NO_LUNE	1	1.18063	E	3.9	3.6	6650.5	6688.3
182	2017-02-03T06:16:57.435594	CAL_deltaYDFIS2_01_SUREF	4171	NO_ECLIPSE_NO_LUNE	1	5.07000	E	13.2	13.5	6637.1	6674.5
183	2017-02-03T14:39:23.605273		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

CQG. Vol. 36.N22 Oct. 2019

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

- Over 62 orbits
- Statistical noise integrated
 - Systematics evaluated with temperature measurements and evaluation of sensitivity

Since:

❖ Operations:

- Numerous additional EP sessions
- Improvement of the characterisation of systematic thermal effects

❖ Analyses:

- Meticulous editing of the data
- Numerous tests and simulations to find the most robust strategy to detect glitches and to avoid leakage effects
- Processing of all sessions cumulated in a global analysis
 - 1642 orbits for SUEP
 - 777 orbits for SUREF

❖ Publications:

- The final result is to be published in a special edition of Classical Quantum Gravity (11 papers, 10 already accepted) + 1 paper in PRL (accepted)

A few lessons from MICROSCOPE: general philosophy

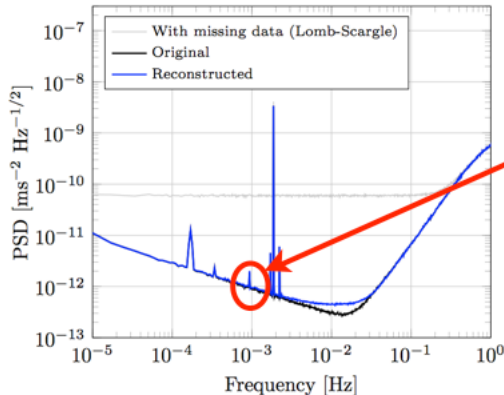
- ❖ **During the design of the experiment, we establish specifications related to obvious limiting factors but we can forget conditions implicitly assumed**
 - (potential) example: gravity gradient deeply analysed but specification of the regularity of the sampling forgot
 - Hopefully, it seems that no essential thing was forgot for MICROSCOPE
- ❖ **Plan the measurement all what you can with margins in the accuracy**
 - e.g. in MICROSCOPE we would have appreciated more accurate temperature measurements due to unexpected thermal sensitivity
- ❖ **Characterise all what you can by applying amplified stimuli during dedicated sessions**
 - e.g, apply large temperature variations
 - e.g shake and oscillate the satellite
 - AOCS of MICROSCOPE (thrusters loop controlled with accelerometers and SST) was an invaluable tool

A few lessons from MICROSCOPE: specific points

- ❖ **Not only avoid any mass motion inside the satellite but also limit the MLI crackles:**
 - The crackles are sensitive to temperature/insulating variations
 - ➔ they are modulated non only by apparent direction of the Sun, but also by the direction of the Earth (albedo) exactly as Earth gravity
- ❖ **Be vigilant about regular data sampling (limit data gaps) ➔ leakage**

Simulation from
Baghi et al.,
Phys. Rev. D 93, 2016

2% of missing data



**Simulated Equivalence
Principle Violation
(3×10^{-15})**

A few lessons from MICROSCOPE: mission organisation

- ❖ **Plan a nominal scenario for the mission but also prepared to be very flexible according to the events**
 - Plan numerous configurations
 - Be ready to analyse (even if not in an optimal way) the data almost online to possibly modify the nominal configuration
 - To achieve this:
 - Training before the launch is important: numerical simulations using the actual format of the data + test bench including the maximum of instrumentation
 - During the mission, scientists must be included in the operational loop

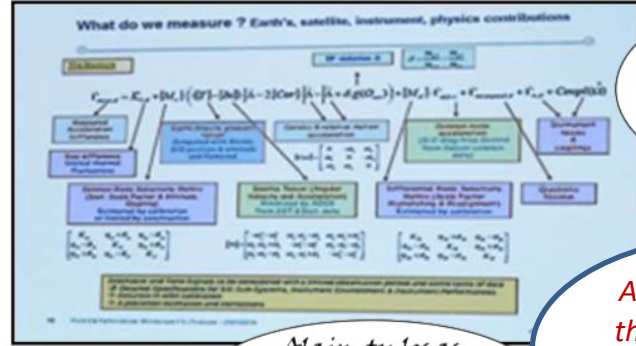
- ❖ **To end up, a saying from my colleague Manuel Rodrigues:**

“Planned failures never happen but what was not planned does happen.”

Pierre Touboul (1958-2021)



Pierre Touboul
The right man at the right place

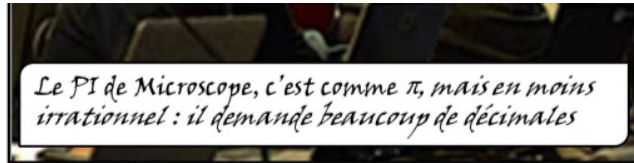


Alain, tu les as prévenus? Ils sont qualifiés.

Alain, did you warn them? Do they have the "perfo" diploma?

$P^* \xi + \tilde{\alpha}_{ij}$.
Ah ouai, quand même!

The PI of MICROSCOPE is like π : he requires many decimals; hopefully he is less irrational!



Le PI de Microscope, c'est comme π , mais en moins irrationnel : il demande beaucoup de décimales

CR Pierre-Yves Guidotti (CNES)
MICROSCOPE project manager

THANK YOU