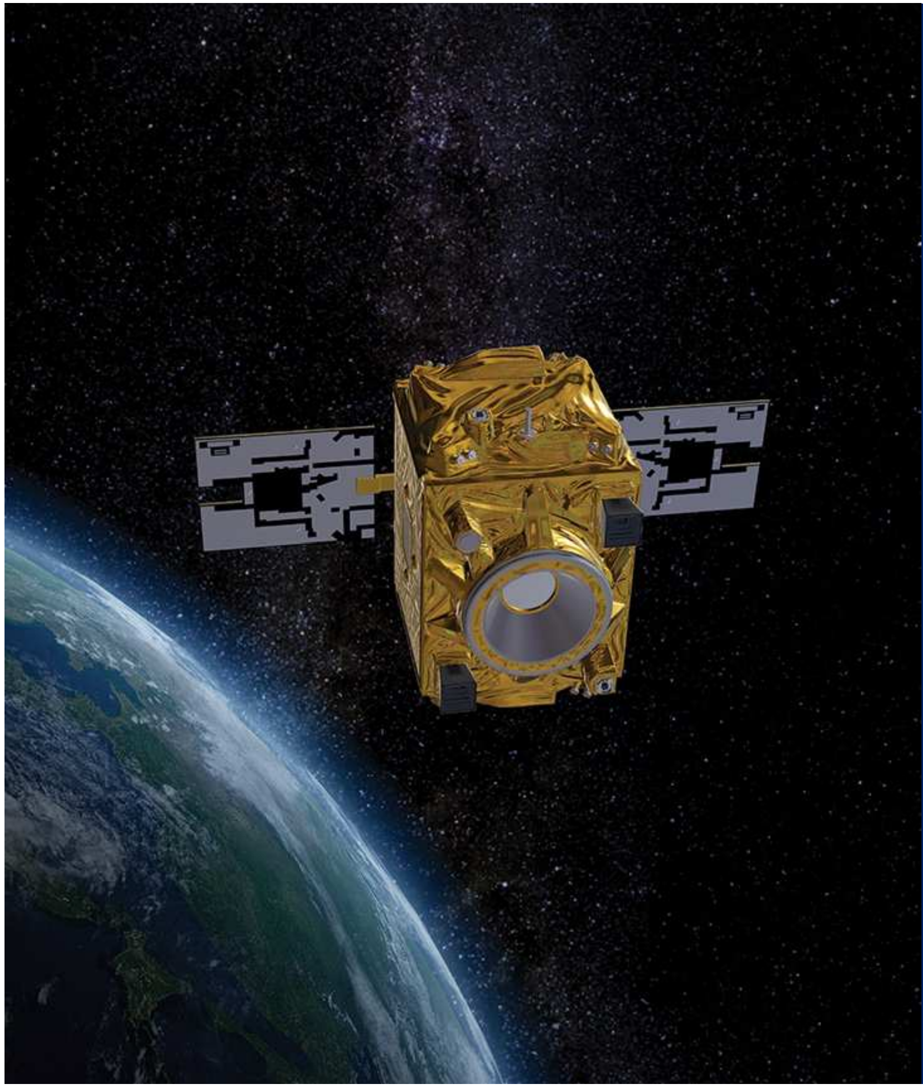


1st results of the MICROSCOPE test of the equivalence principle in space.

Manuel RODRIGUES

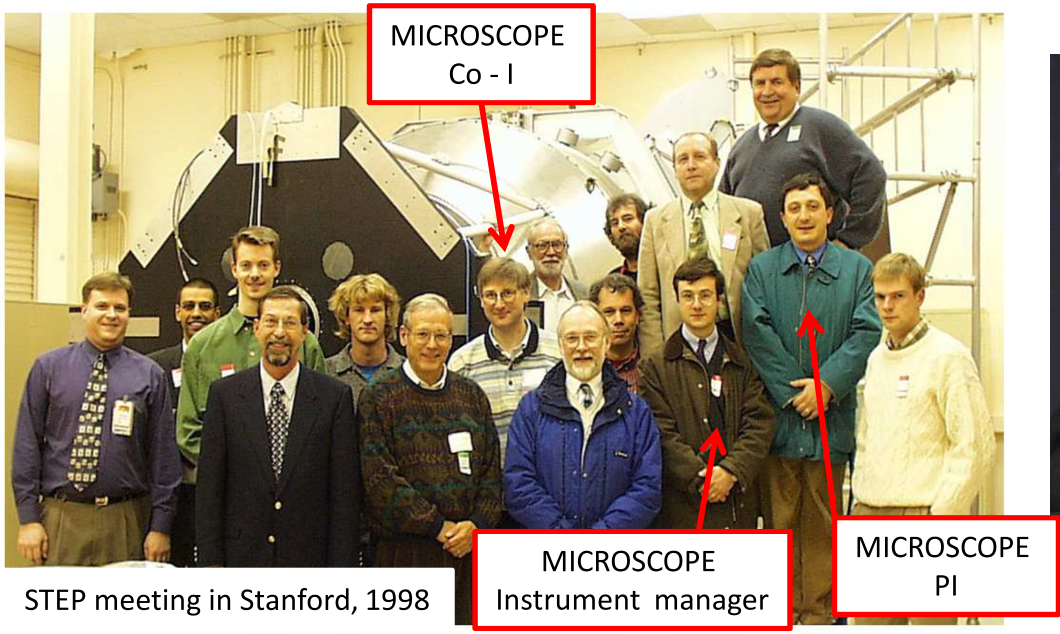
On behalf of the MICROSCOPE team

ONERA

THE FRENCH AEROSPACE LAB

STEP : THE MICROSCOPE ORIGINS

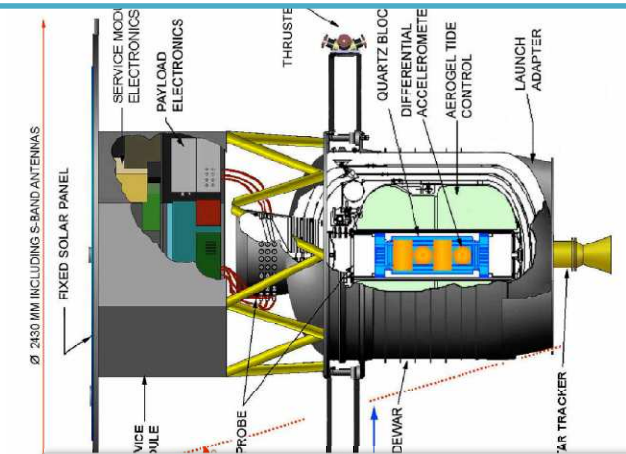
- Pr. Francis Everitt : PI of GPB & STEP had been gathering US & European teams in the late 90's => but no mission came up in NASA nor in ESA
- Stanford University : test of EP with 10^{-18} accuracy based on GPB technology

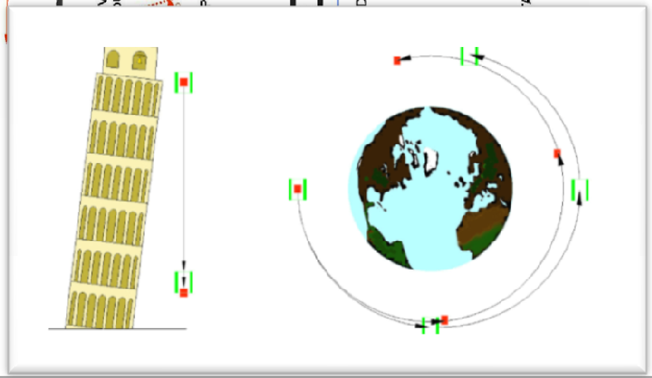


STEP meeting in Stanford, 1998

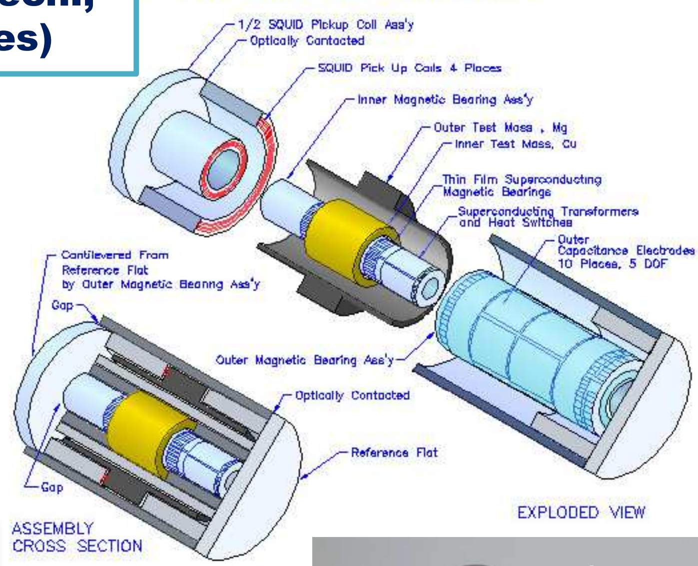
Pr. Francis Everitt

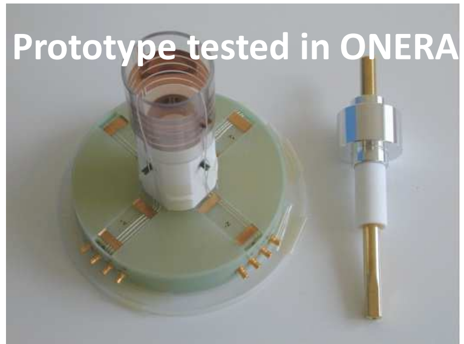
STEP MISSION AND ACCELEROMETER (Cryogenic tech., SQUIDS, Superfluid He, supraconducting test-masses)





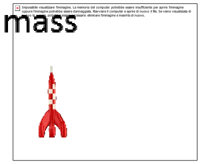
STEP ACCELEROMETER CONCEPT

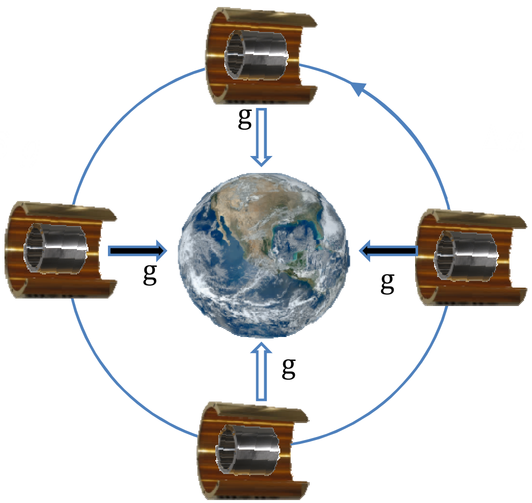




The « free-fall » test in space with MICROSCOPE resolution objective on δ : 10^{-15}

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

m_g = gravitational mass  m_i = inertial mass 



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

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

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

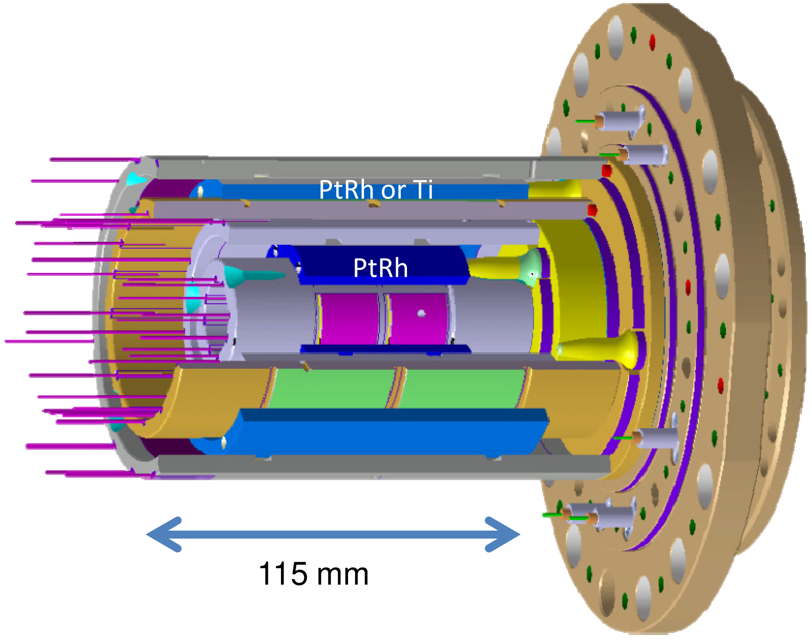
If $\boldsymbol{\delta} = \mathbf{0}$: $\Delta \boldsymbol{a} = \mathbf{0}$

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

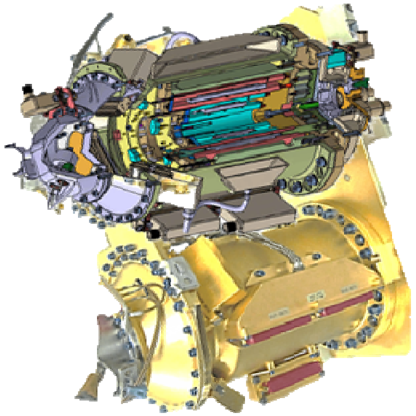
2 double accelerometers for the test

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



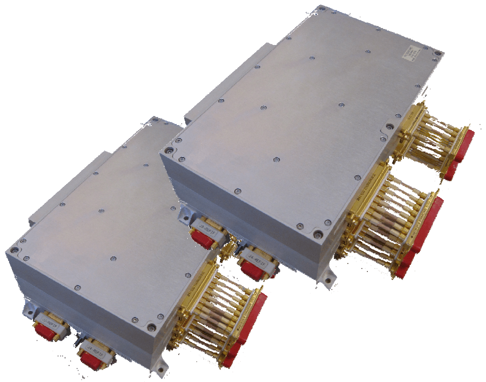
T-SAGE (Twin Space Accelerometer for Gravitation Experiment) – micrometer & microvolt accuracy inherited from GOCE, GRACE ONERA know how



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
$0.2\mu V\ Hz^{-1/2}$

Low noise measurement
pick-up $<1\mu V\ Hz^{-1/2}$

Digital Interface Electronics:
2 stacked **ICU**

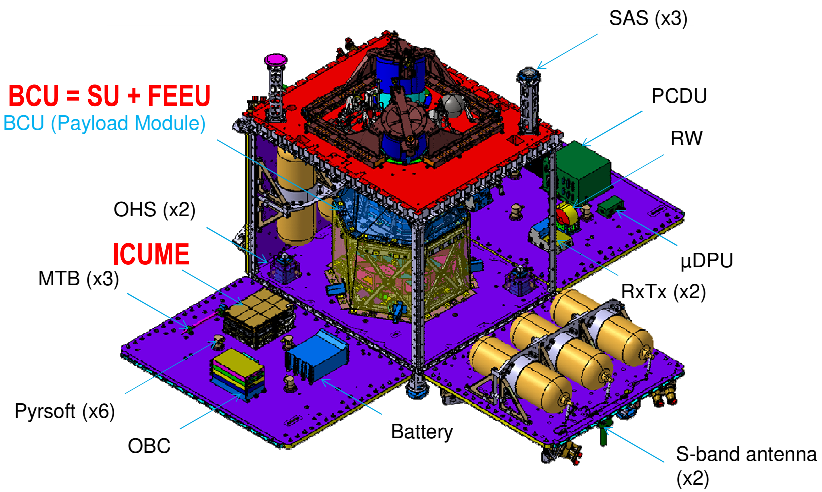
DSP + FPGA
Control loop handling
2x 24 x 40bits signals @ 1kHz

Science TM = 24bits @ 4Hz

The MICROSCOPE satellite

- **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

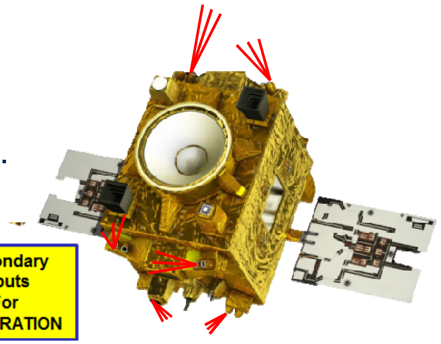
- **Cold Gaz propulsion**
- **A space laboratory of 300kg**
- **1,4 m x 1 m x 1,5 m**
- **Instrument in the BCU (Payload Thermal Cocoon Case) at the center of the satellite**



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).



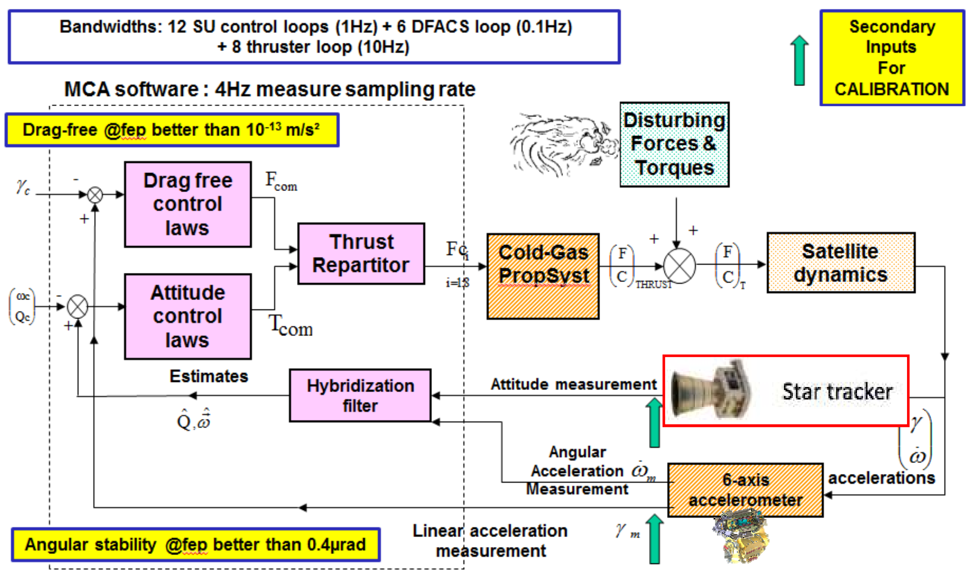
Performance of drag-free

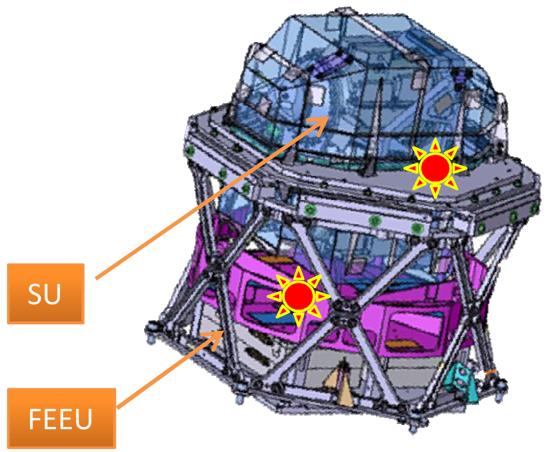
$\Gamma(f_{EP}) < 3\times10^{-13}$ m/s²

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

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

$\int \Omega < 1\mu rd$





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

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

+ noise

g = 7,9 ms^{-2}

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

$\dot{\Delta}$ *and* $\ddot{\Delta}$ are negligible in the bandwidth of the test-mass servo loops

estimated by calibration
observed or/and computed
negligible at *Fep*

FIRST RESULTS PUBLISHED IN PRL BASED ON 2 SESSIONS

SUEP

	dateDebut	nomFiche	Num Orb	contrainte Environnement	crit.	duree	etat	conso GazZp	conso GazZm	capacite GazZp	capacite GazZm	
	-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	[illegible]	[illegible]	
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	[illegible]	6604.9	
210	2017-02-14T15:10:44.141758	EPR_V3DFIS2_01_SUEP	4					6	151.3	6392.6	6453.3	
211	2017-02-18T01:45:43.539435		4						4.2	6386.9	6448.7	
212	2017-02-18T04:15:53.554441	EPR_V3DFIS2_01_SUEP	4					.5	235.1	6123.1	6213.3	
213	2017-02-23T09:55:00.000000		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	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	
	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	[illegible]	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	
221	2017-03-09T01:57:46.642557		4663	NO_ECLIPSE_NO_LUNE	2	1.01295	E	0.8	1.4	5712.1	5766.8	
222	2017-03-09T03:38:09.628548	CAL_tetadYDFIS2_01_SUEP	4664	NO_ECLIPSE_NO_LUNE	2	5.07000	E	3.6	8.3	5708.3	[illegible]	
223	2017-03-09T12:00:35.776718		4669	NO_ECLIPSE_NO_LUNE	2	1.18063	E	2.9	4	5705	5754	
224	2017-03-09T13:5											
225	2017-03-09T22:2											
226	2017-03-10T00:1											

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

From mean square fit

Over 120 orbits

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

Phys. Rev. Letts. 119 231101 (2017) : No evidence of violation > $1{,}9\times10^{-14}$

SUREF

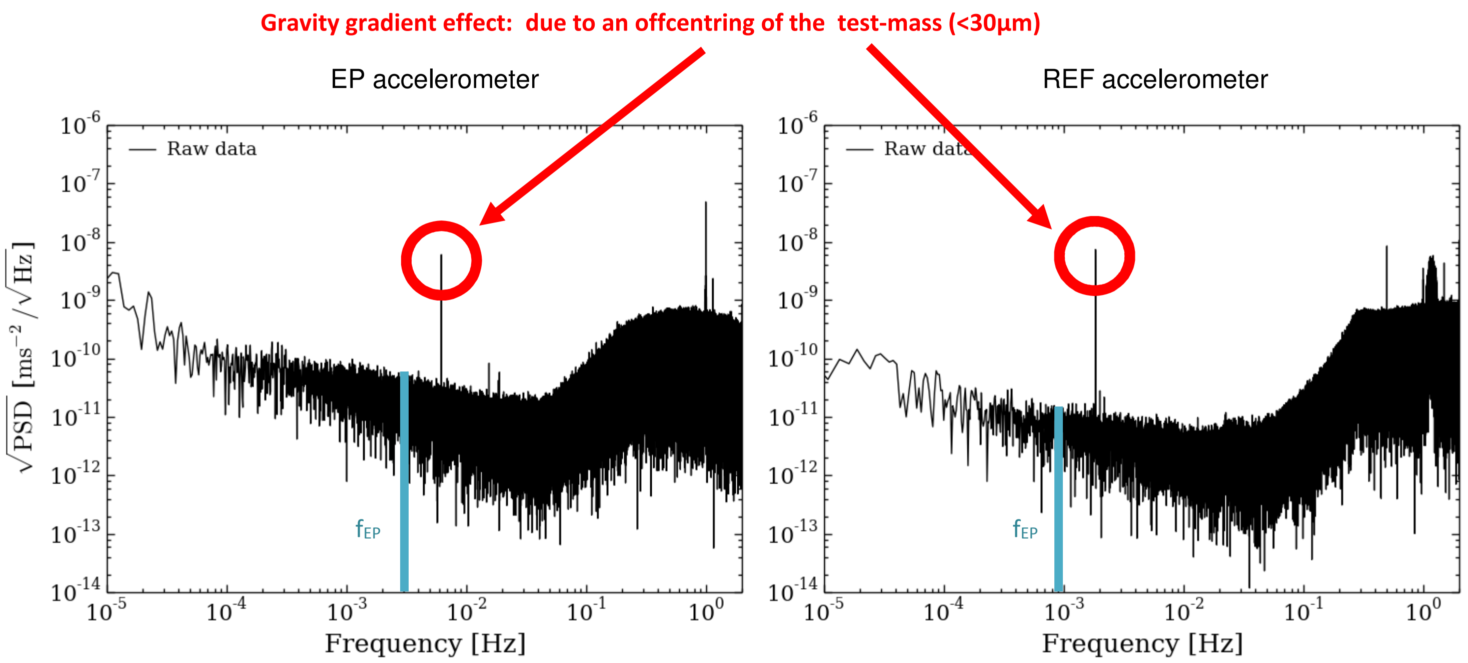
	dateDebut	nomFiche	Num Orb	contrainte Environnement	crit.	duree	etat	conso GazZp	conso GazZm	capacite GazZp	capacite GazZm
	-18T14:22:59.978006		3944	NO_ECLIPSE_NO_LUNE	1	1.01295	E	0.9	0.9	6808.7	682
	-18T16:03:22.968294	CAL_K1dxDFIS2_01_SUREF	3945	NO_ECLIPSE_NO_LUNE	1	5.07000	E	4.7	5.6	6804	682
173	2017-01-19T00:25:49.137973		3950	NO_ECLIPSE_NO_LUNE	1	3.07939	E	2.5	2.5	6801.2	6818
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
	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
	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
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

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

Over 62 orbits

- Statistical noise integrated
- Systematics evaluated after PRL (TBC) with a majoring of SU temperature variations (30µK @ f_{EP})

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

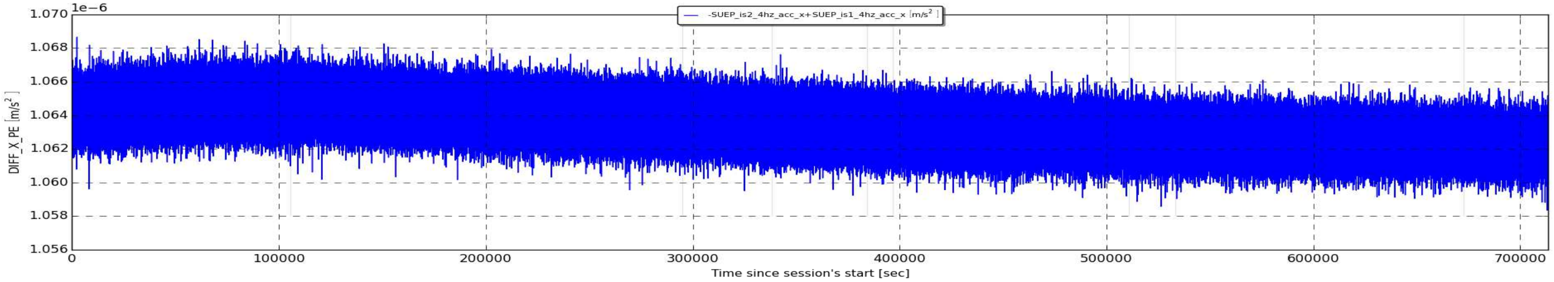


$f_{\mathrm{EP}} = 3.11 \times 10^{-3}$ Hz

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

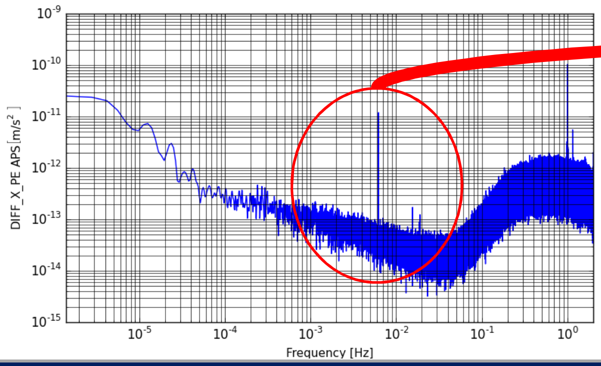
Effect of in-flight calibration on session 218 (SUEP)

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



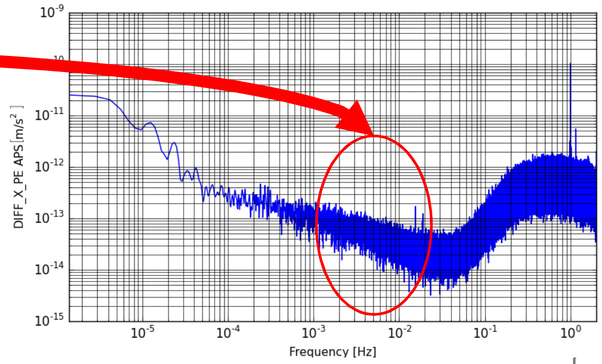
- Test-mass off-centering estimated through the Earth's gravity effect at $2f_{EP}$

=> 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



Calibration of scale factor matching

- **Scale factor matching**

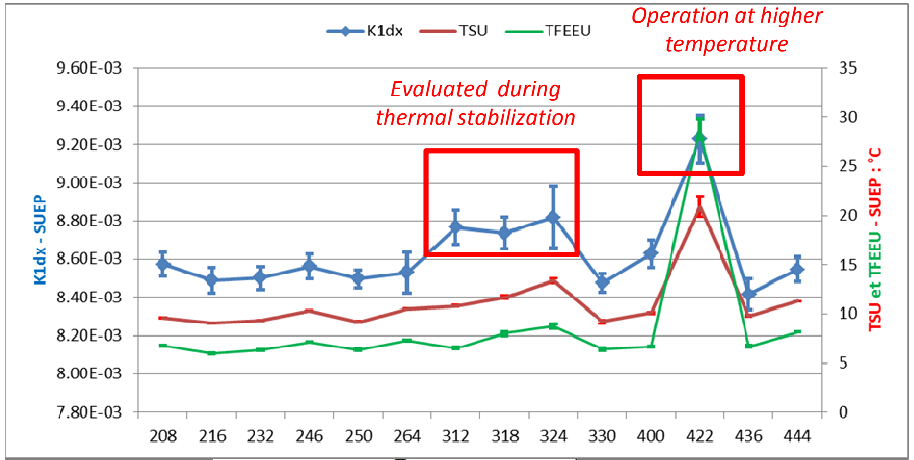
- **Evaluated by biasing the X mean acceleration measure output to the DFACS: $5\times10^{-8}m/s^2$ at 1.23×10^{-3}Hz**

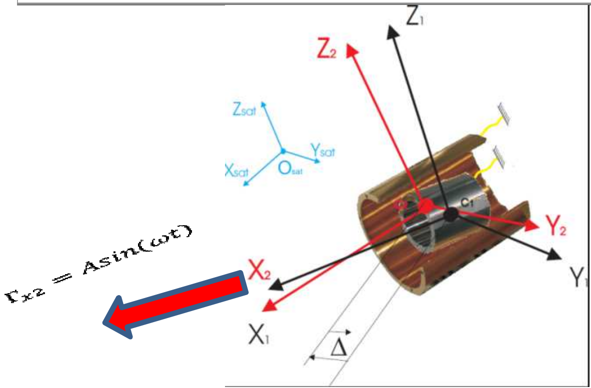
- **Differential measure along X gives the scale factor matching error**

- **Level of DFACS residual disturbances @f_{EP}:**

  $K_{1dx}\Gamma_{cx}(f_{EP}) < 3\times10^{-15}m/s^2$

  Gives a limit of 0.5×10^{-15} on δ





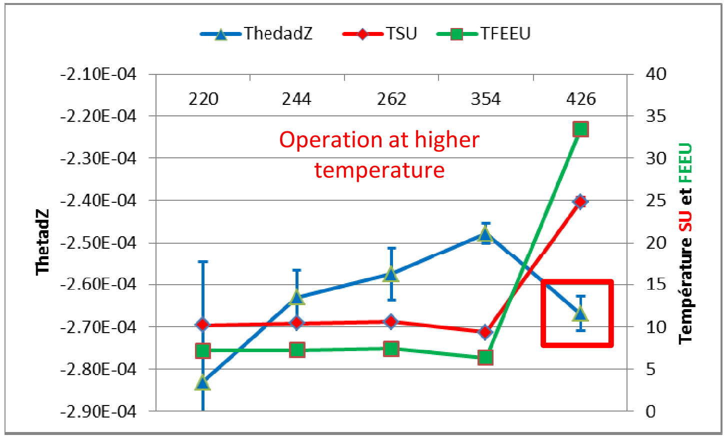
$A_{d11} \sim K_{1dx}$

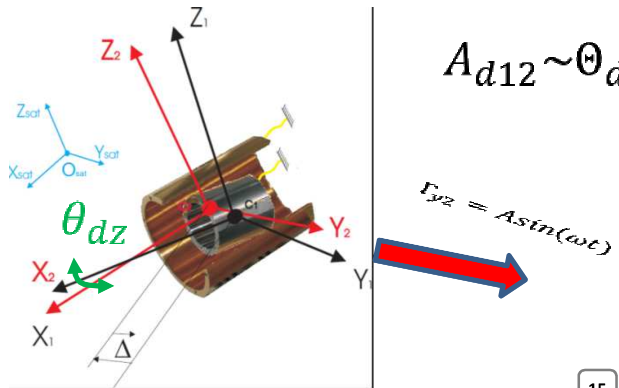
- Correction useful at 10^{-15} level
- Temperature effect correction not needed

Calibration of misalignment matching

Misalignment of the 2 concentric test-masses

- **Evaluated by biasing the Y mean acceleration measure output to the DFACS: 5×10^{-8}m/s² at 1.23×10^{-3}Hz**
- **Differential measure along X gives the misalignment about Z**
- **Level of DFACS residual disturbances @f_{EP}:**



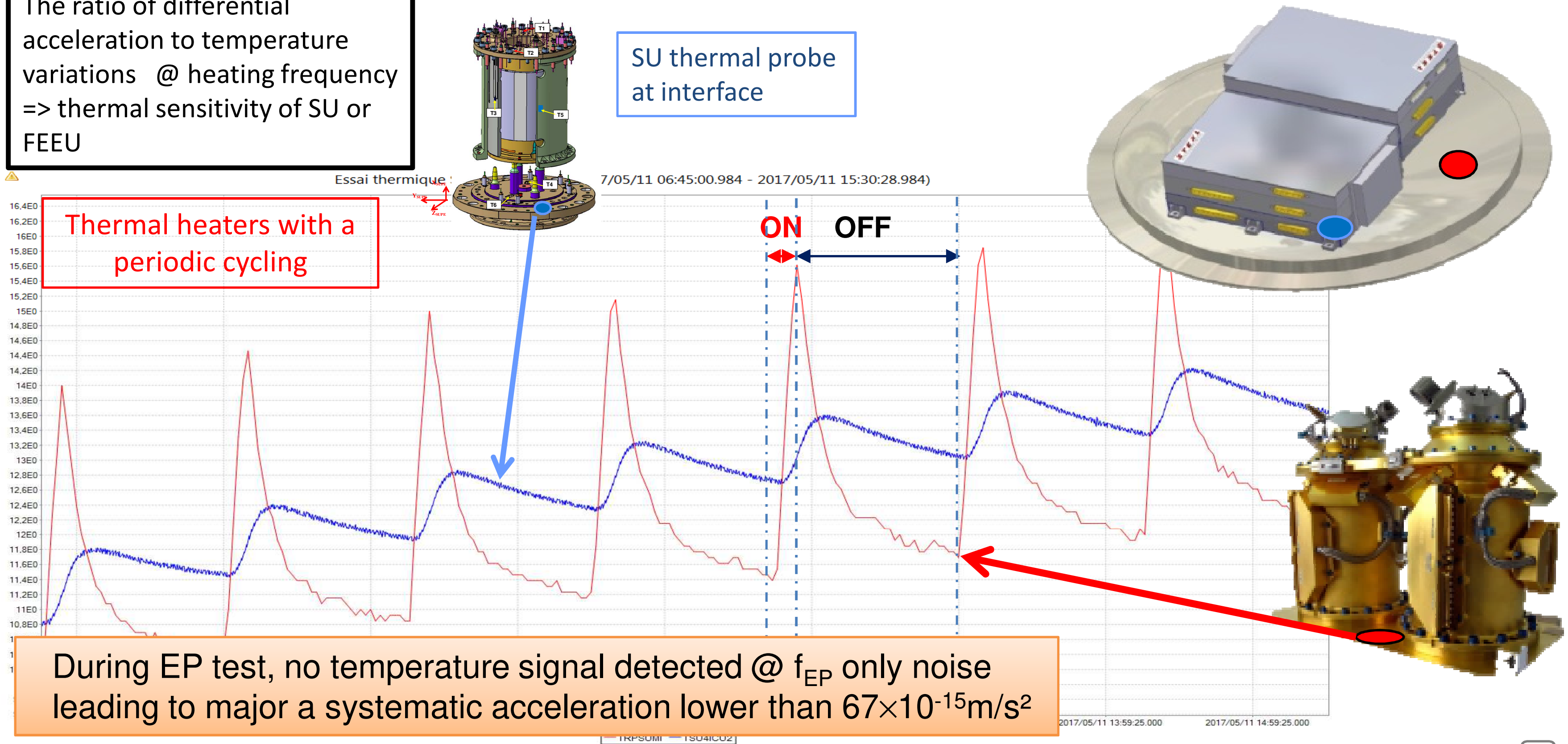


- Correction NOT manadatory for a test at 10^{-15} level
- Temperature effect negligible

Thermal sensitivity measured in flight by local thermal stimuli

The ratio of differential acceleration to temperature variations @ heating frequency => thermal sensitivity of SU or FEEU

SU thermal probe at interface



Thermal heaters with a periodic cycling

During EP test, no temperature signal detected @ f_{EP} only noise leading to major a systematic acceleration lower than $67 \times 10^{-15} m/s^2$

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CURENT STATUS : in 2018 less science more sensitivity tests & technological tests

- 750 orbits dedicated to sensor thermic behavior and systematic check have been successfully performed => very promising

- From March to August 2018: SUEP is to be continuously measuring without switch off (for technological experiment purposes)
- In 2018 : 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.

- End of mission : 16th of October 2018

CONCLUSION

- **The satellite & the instrument have worked during more than 2 years in very good symbiosis, with outstanding performances.**

- **Analysis of less than 7% of the available data shows**
  - a factor 10 improvement on EP test experiments (PRL paper December 2017)
  - no violation at level of 1.9×10^{-14}

- **A lot of work remains:**
  - Effect of satellite cracks in the measurement : wavelet or shapelet modeling could improve the result
  - Thermal behavior of the SU core is being consolidated (improved analysis from PRL)
  - Better characterization of accelerometer along all axes (couplings, non linearity): better confidence on instrument physics modelisation
  - Process of all EP sessions to get a final result
  - **Publication of the final result foreseen at end of 2019**

- **Objective of the data process: get closer to the primary objective of 10^{-15} accuracy.**

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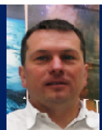
TSAGE PAYLOAD TEAM - ONERA

S/C OPERATION – CNES ONERA

CENTER OF MICROSCOPE SCIENCE MISSION (CMSM) – ONERA+OCA

THANK YOU

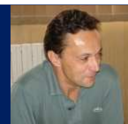
Pierre Touboul (ONERA)
Prime Investigator



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