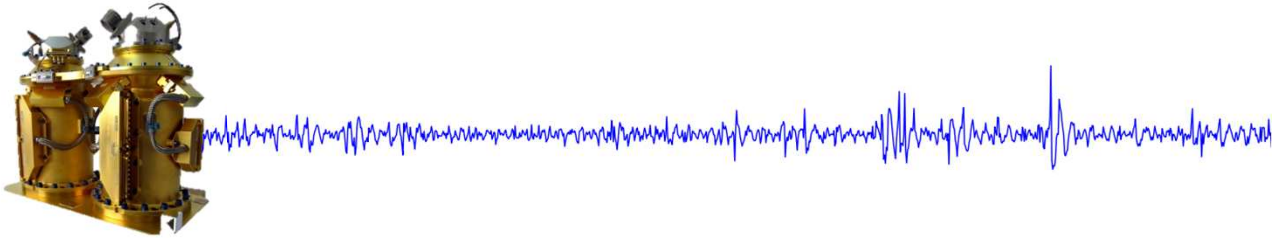
MICROSCOPE mission
A test of the Equivalence principle in space



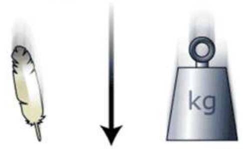
<u>Manuel Rodrigues</u>, Pierre Touboul

on behalf of MICROSCOPE team

SCIENCE OBJECTIVES

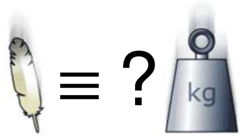
Newton Law

$$F = \frac{GM_T}{r^2} m_g = m_g\ g$$



$$\boxed{F = m_i a}$$

Do a feather and a weight fall the same way?



$$a = g\ ?$$

Eötvös parameter

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

Einstein Weak Equivalence Principle $m_g = m_i \quad \Longrightarrow \quad \eta = \mathbf{0}$

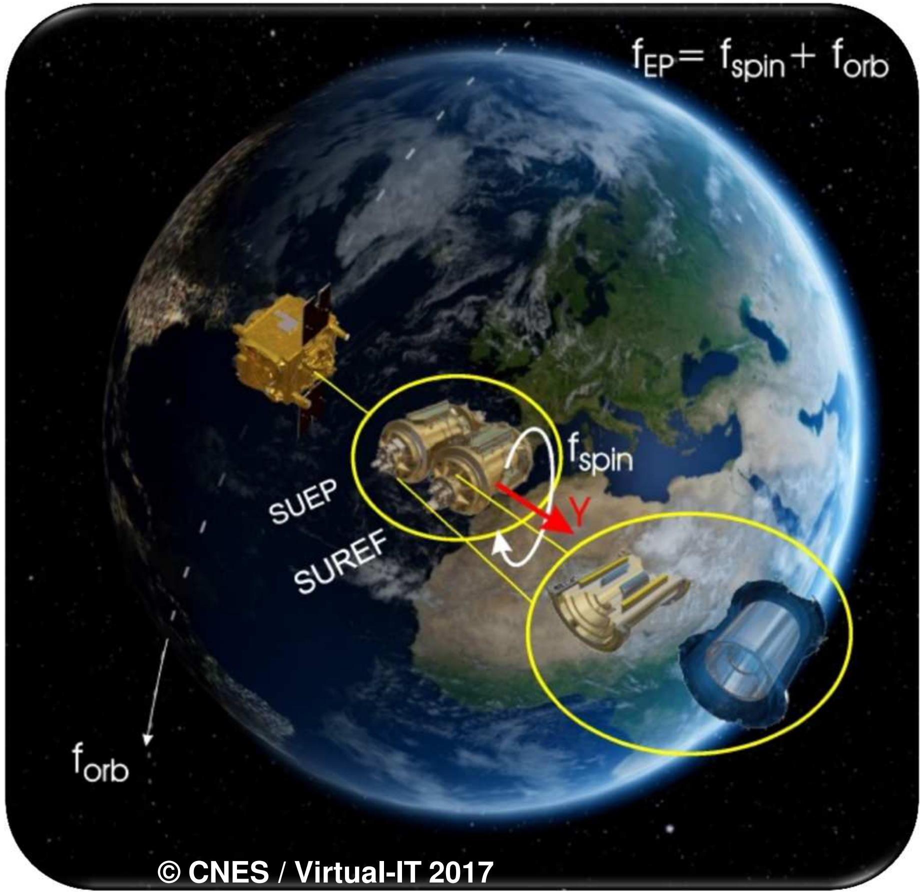
$$\eta_{\text{Earth,Be-Ti}} = (0.3 \pm 1.8) \times 10^{-13}$$

S. Schlamminger *et al* 2008

$$\eta_{\boldsymbol{Earth,Pt-Ti}} = ?\ \pm\ \boldsymbol{\varepsilon}$$

MICROSCOPE Objective : $\varepsilon < 10^{-15}$

Principle of the test in space



$$\eta = \frac{a1 - a2}{\frac{1}{2}(a1 + a2)} = \frac{\left(\frac{mg}{mi}\right)_1 - \left(\frac{mg}{mi}\right)_2}{\frac{1}{2}\left[\left(\frac{mg}{mi}\right)_1 + \left(\frac{mg}{mi}\right)_2\right]}$$

Comparison of the measured accelerations (a1 & a2) applied on a pair of test-masses when orbiting on the same orbit in the Earth's gravity field ($7,92 m/s^2$ @ 710km)

SUREF = 2 test bodies in Pt(Rh10%) :

η should be

$$0 + (systematics) + (statistics)$$

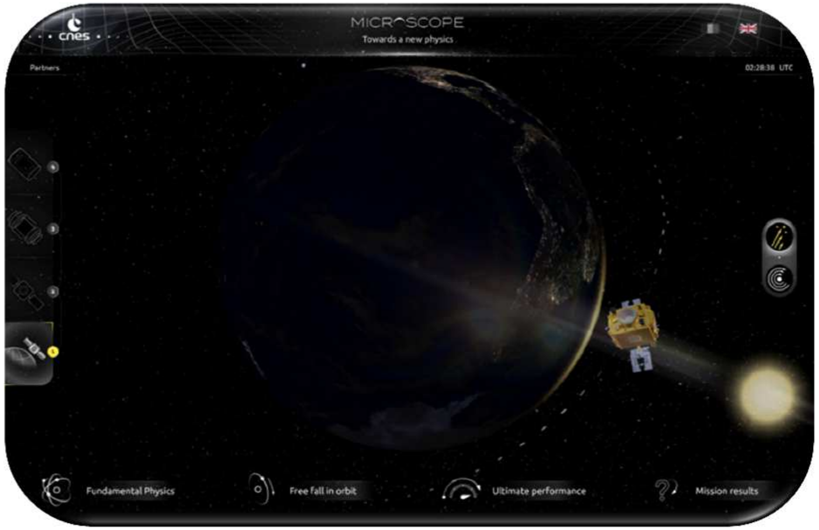
SUEP = 2 test bodies in Pt(Rh10%) vs Ti(Al6%V1%) for the EP test

The measurement axis, X, is in the orbital plane = cylinder axis

$\vec{g}$ is the direction of interest for the measurement of acceleration:

Relative motion of Earth around TM is at f_{EP} = measurement frequency

THE SATELLITE



© CNES / Virtual-IT 2017

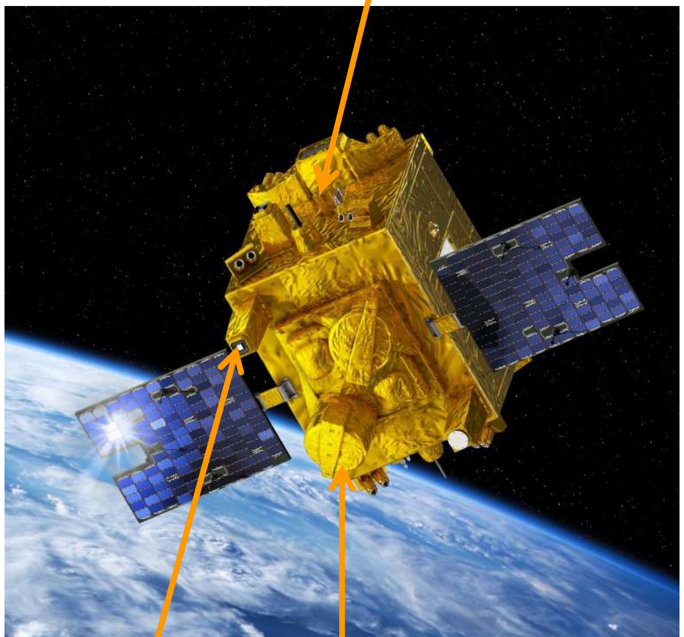
Launch on 25th of April 2016 in sun synchronous 18h orbit @ 710km with an eccentricity < 1.5×10^{-3}

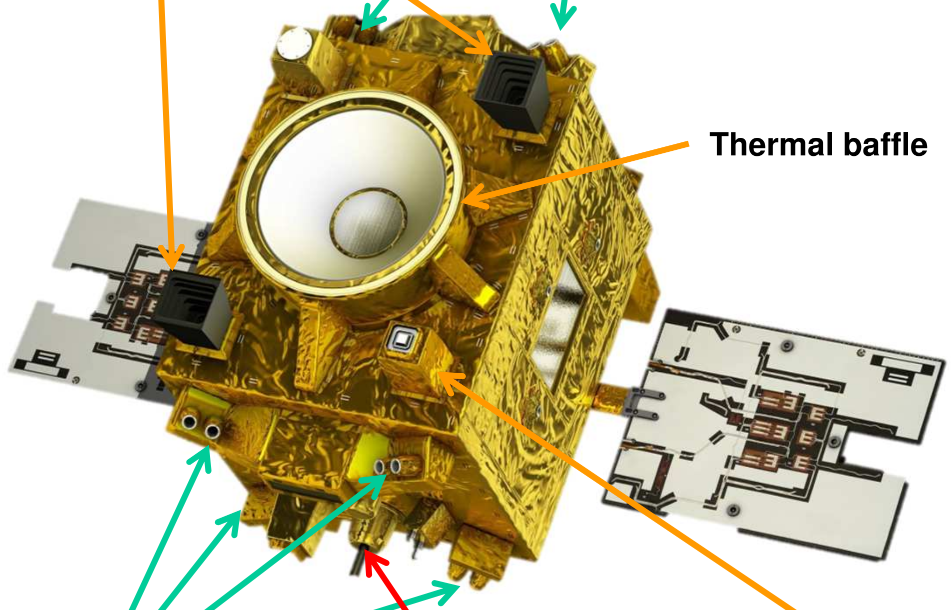
Orbit accuracy determination : 1m (hybridization of Doppler effect & GPS)

Satellite of 301.4 kg based on MYRIADE microsatellite family

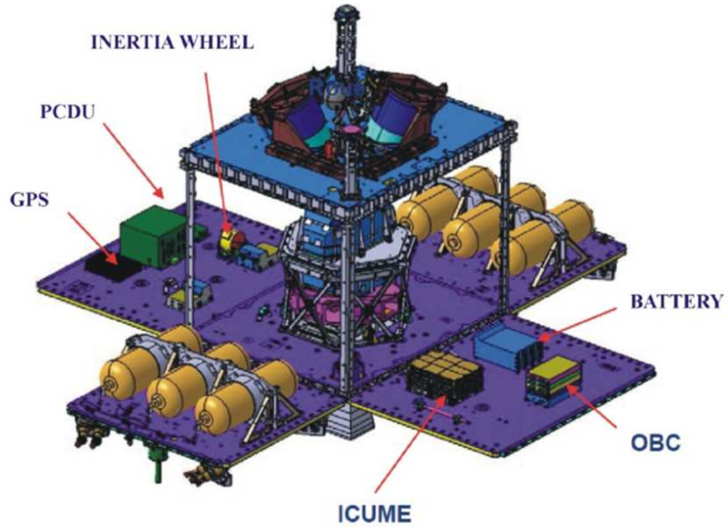
210 W including 40W for the payload (both sensor units ON)

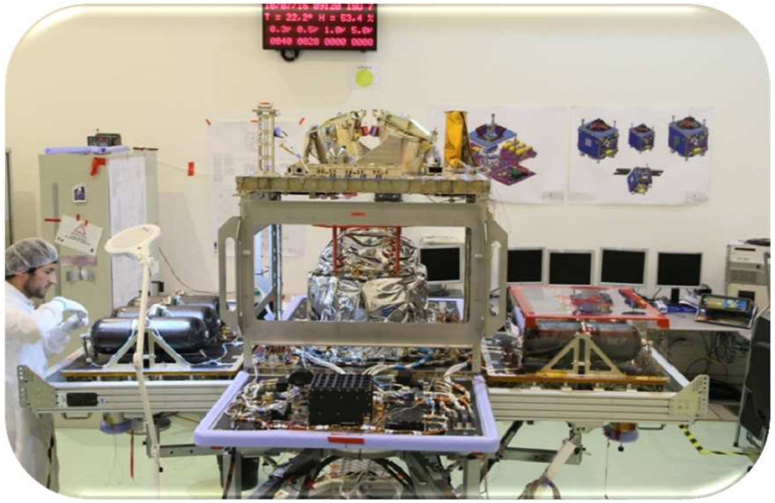
THE SATELLITE





THE SATELLITE



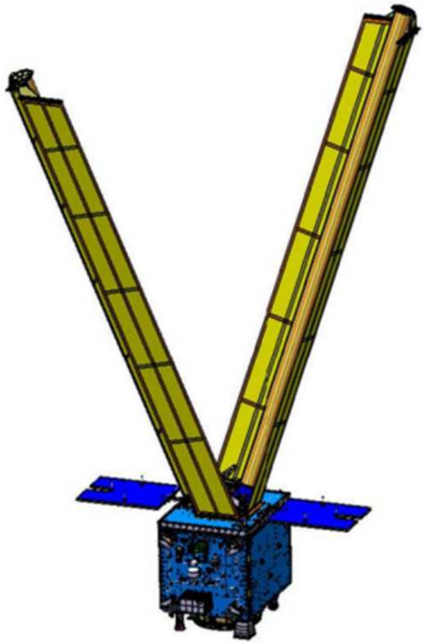


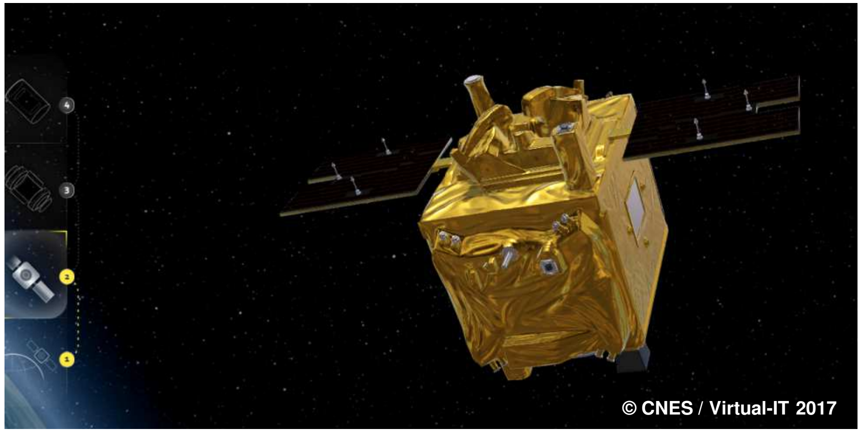
The Payload at the core of the satellite in a thermal cocoon and a magnetic shield

The reservoirs of cold gas are distributed on 2 walls of the satellite

All electronics are on the walls except payload high resolution front end electronics

THE SATELLITE





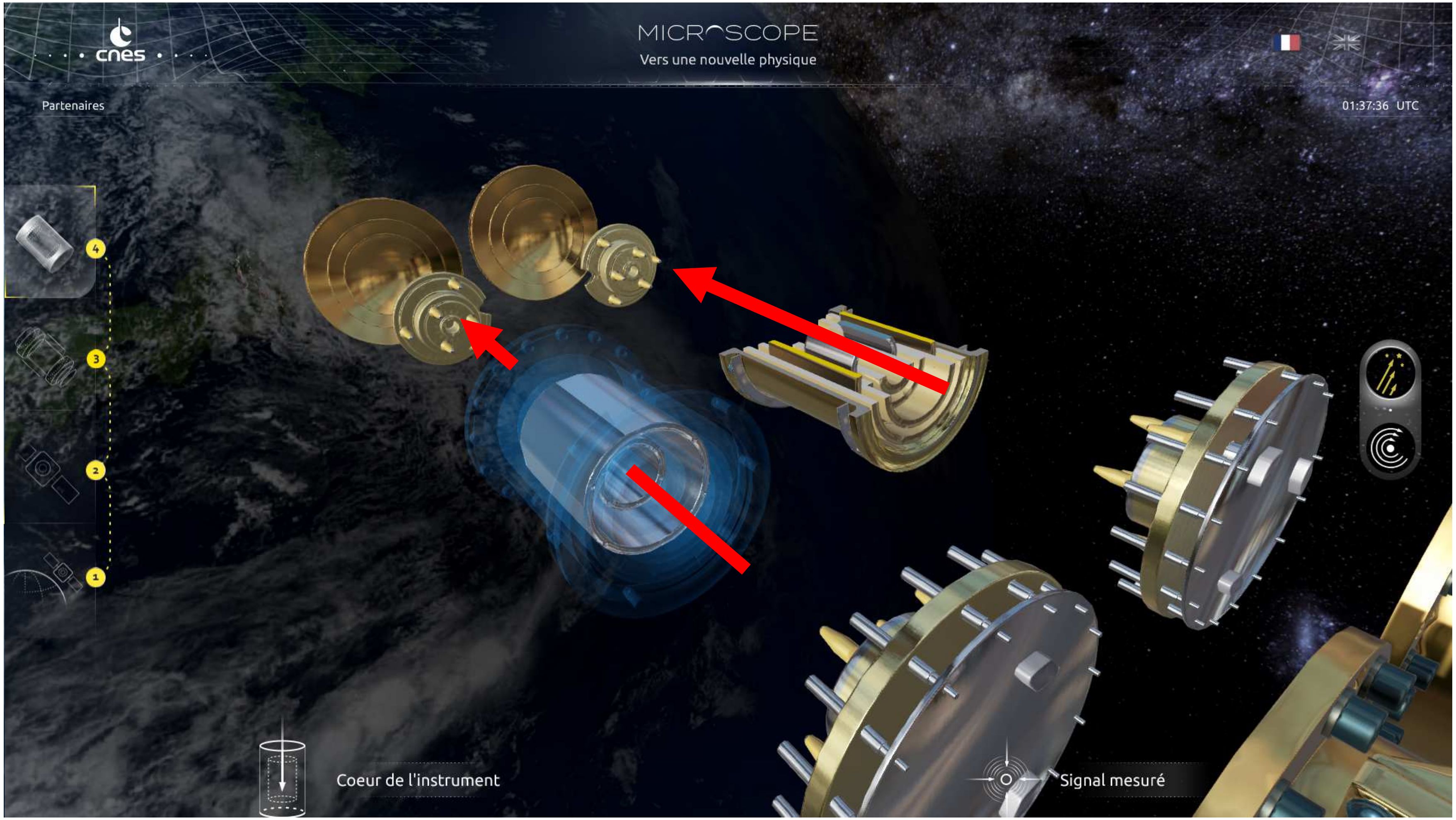
The Payload at the core of the satellite in a thermal cocoon and a magnetic shield

The reservoirs of cold gas are distributed on 2 walls of the satellite

All electronics are on the walls except payload high resolution front end electronics

A de-orbitation system is placed on the solar panel side : 2 wings will deploy at the end of the mission to make the s/c fall in 25 years (instead of 75 years).

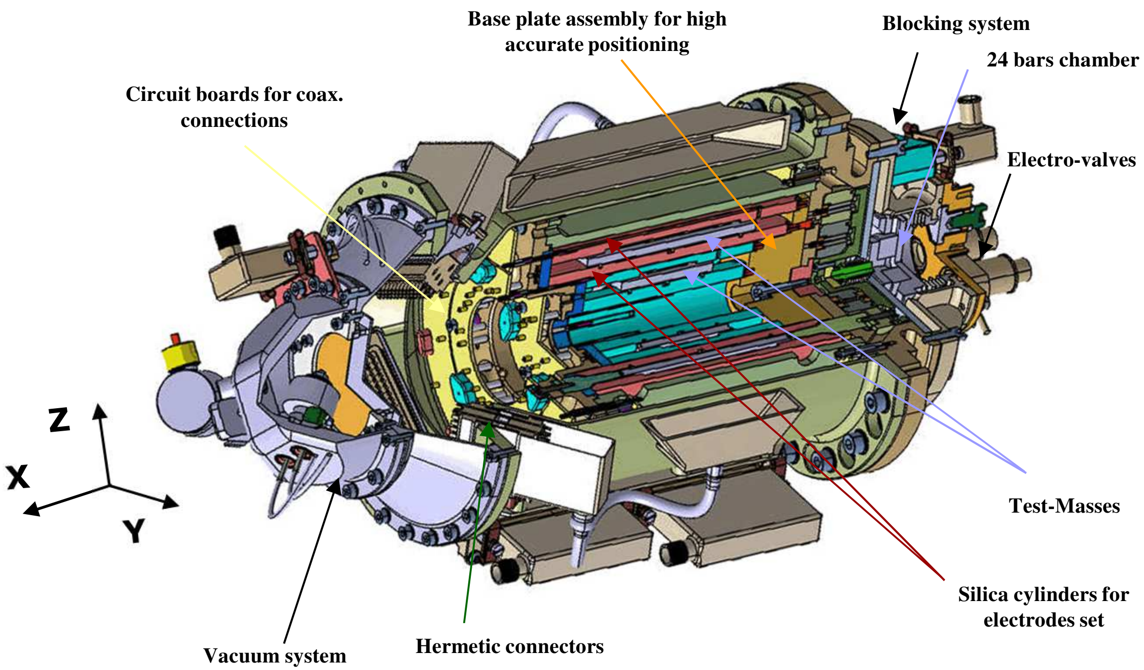
THE PAYLOAD

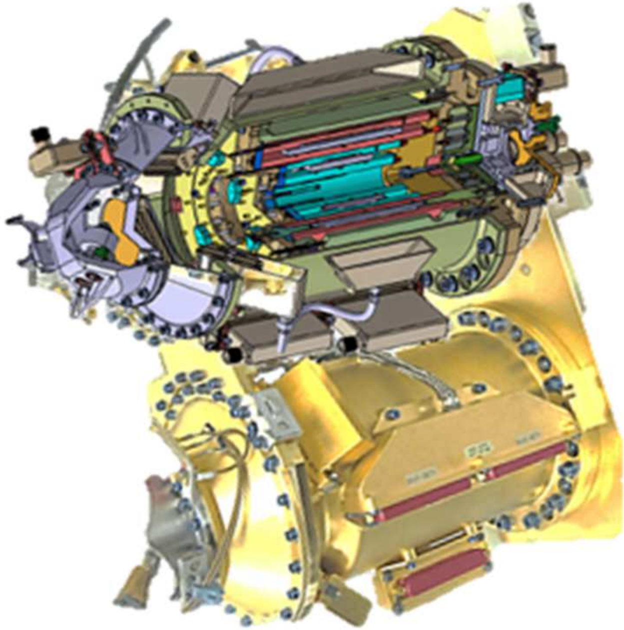


cnes
MICROSCOPE
Vers une nouvelle physique
Partenaires
01:37:36 UTC
Coeur de l'instrument
Signal mesuré

THE PAYLOAD

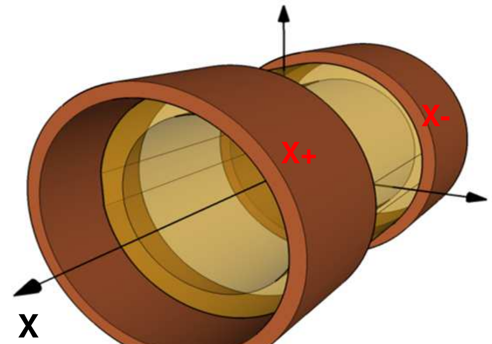
ICU : digital control laws, data conditioning





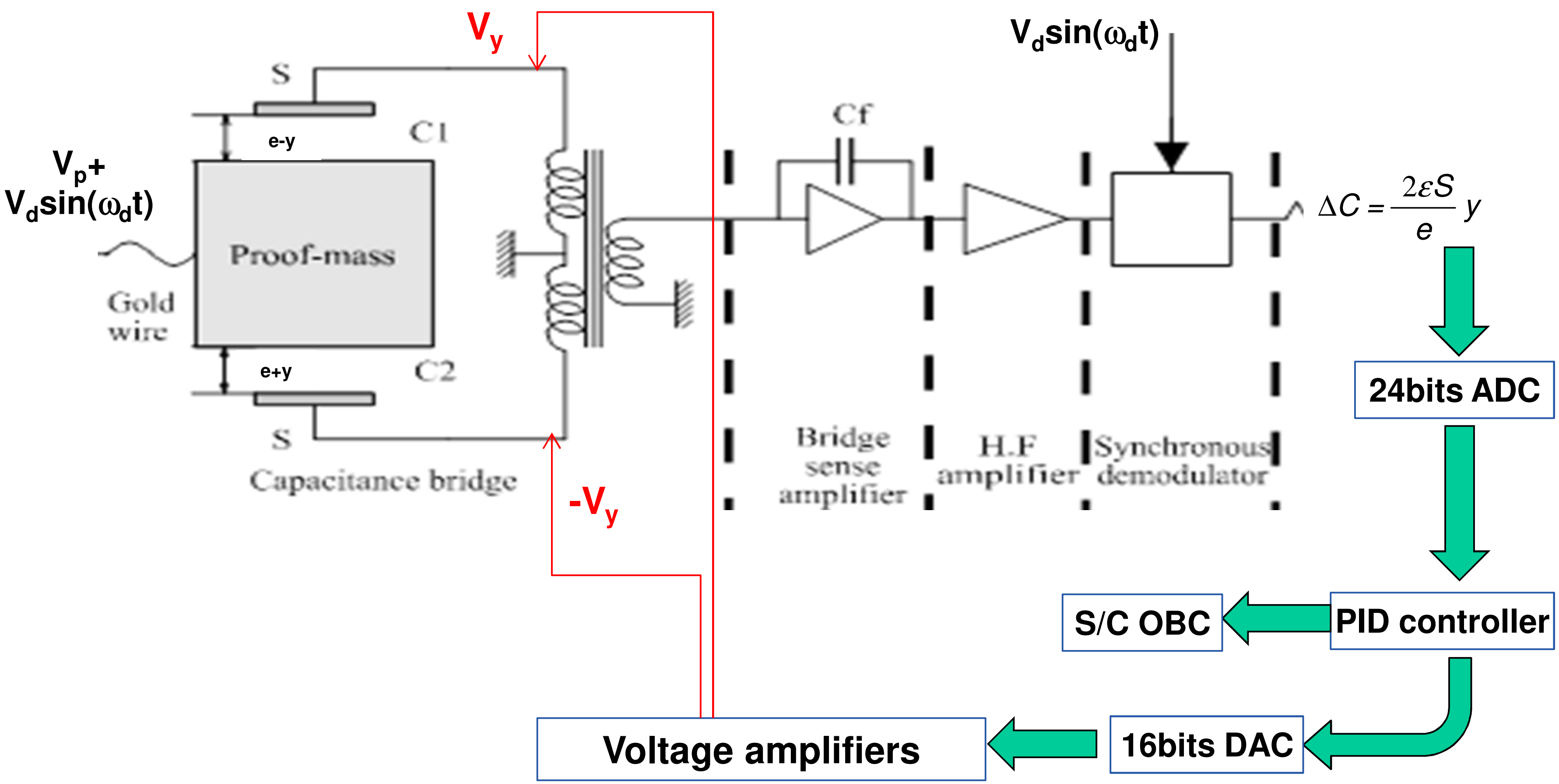
SU: 2 Sensor units REF + EP

FEEU : 2 low noise Electronics units



Accelerometer Servo-loop Principle

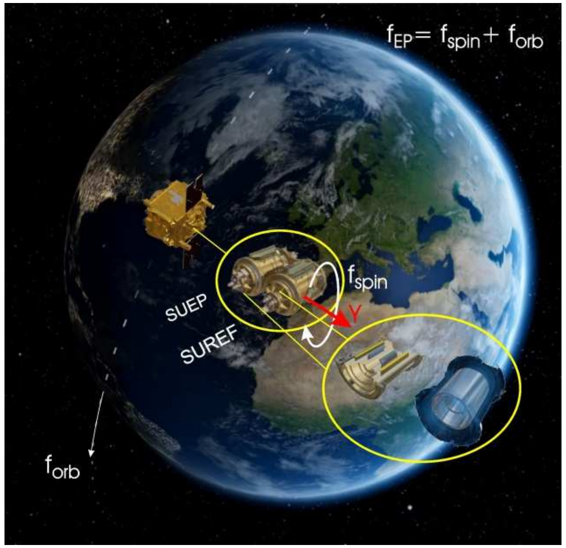
Capacitive Detection



$$F = F_1 - F_2 = \frac{1}{2}\left[\frac{\partial C_2}{\partial y}\left(V_y - V_p - V_d \sin\left(\omega_d t\right)\right)^2\right] - \frac{1}{2}\left[\frac{\partial C_1}{\partial y}\left(V_y + V_p + V_d \sin\left(\omega_d t\right)\right)^2\right]$$

Electrostatic forces and acceleration measurement

$$F = F_1 - F_2 = \frac{1}{2}\left[\frac{\partial C_2}{\partial y}\left(V_y - V_p - V_d \sin(\omega_d t)\right)^2\right] - \frac{1}{2}\left[\frac{\partial C_1}{\partial y}\left(V_y + V_p + V_d \sin(\omega_d t)\right)^2\right]$$



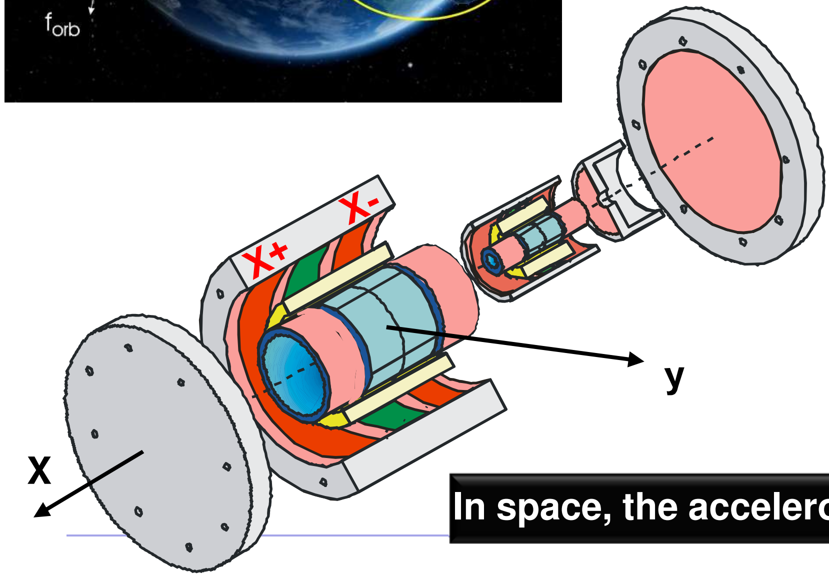
$$a_y = \frac{2\varepsilon S_y}{me^3}\left(V_p^2 + \frac{V_d^2}{2}\right) y - \frac{2\varepsilon S_y}{me^2} V_p V_y + \frac{2\varepsilon S_y}{me^2} V_y^2 \frac{y}{e}$$

Measurement: V_y

Electrostatic stiffness: $\frac{2\varepsilon S_y}{me^3}\left(V_p^2 + \frac{V_d^2}{2}\right)$

Electrostatic gain: $\frac{2\varepsilon S_y}{me^2} V_p$

Non linear term: $\frac{2\varepsilon S_y}{me^2} V_y^2 \frac{y}{e}$

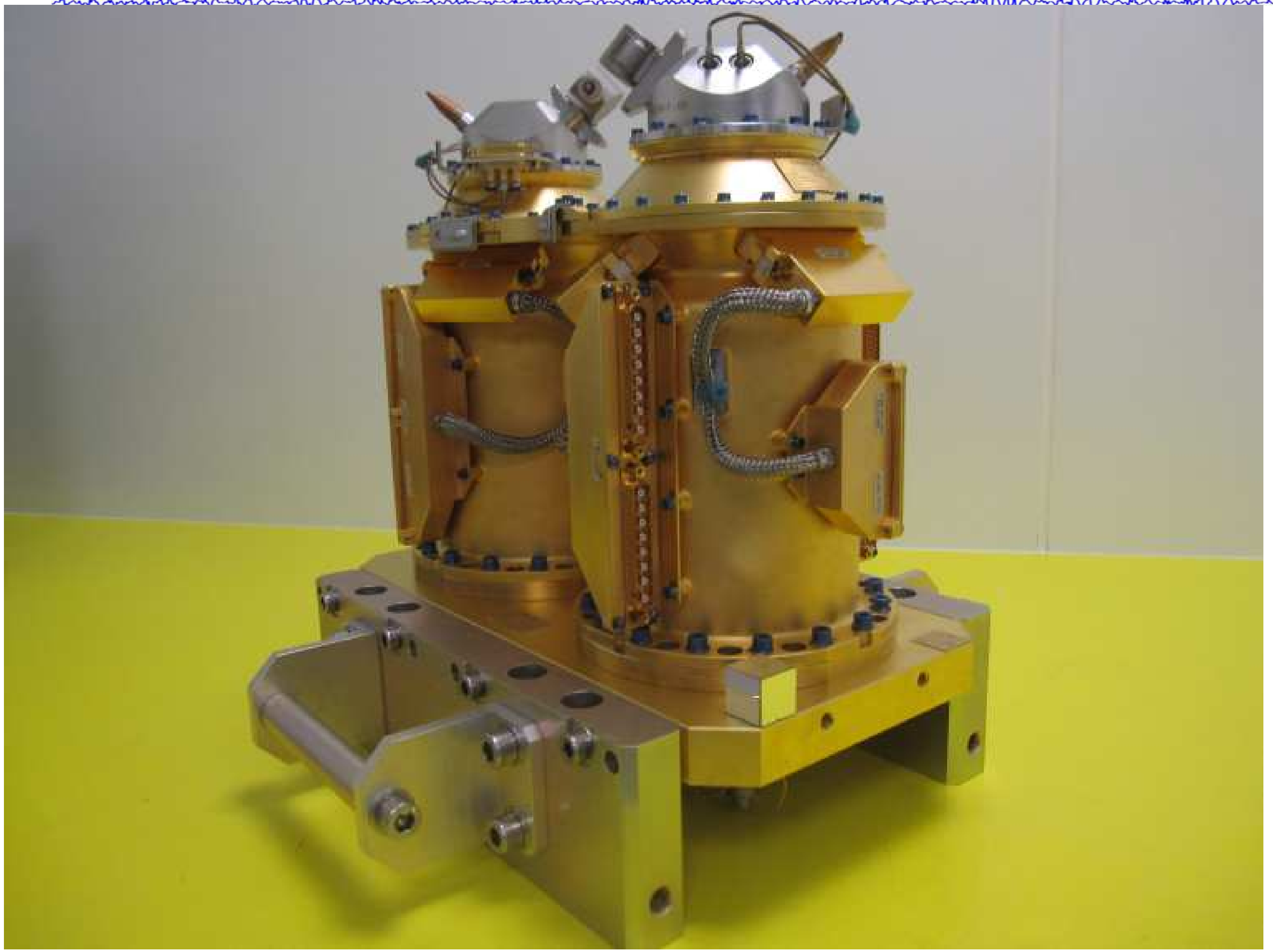


$$a_x = -\frac{2\pi\varepsilon R}{me} V_p V_x$$

Along X
No theoretical stiffnesses or nonlinearities

In space, the accelerometer measures: $(\Gamma_{s/c} - g)$

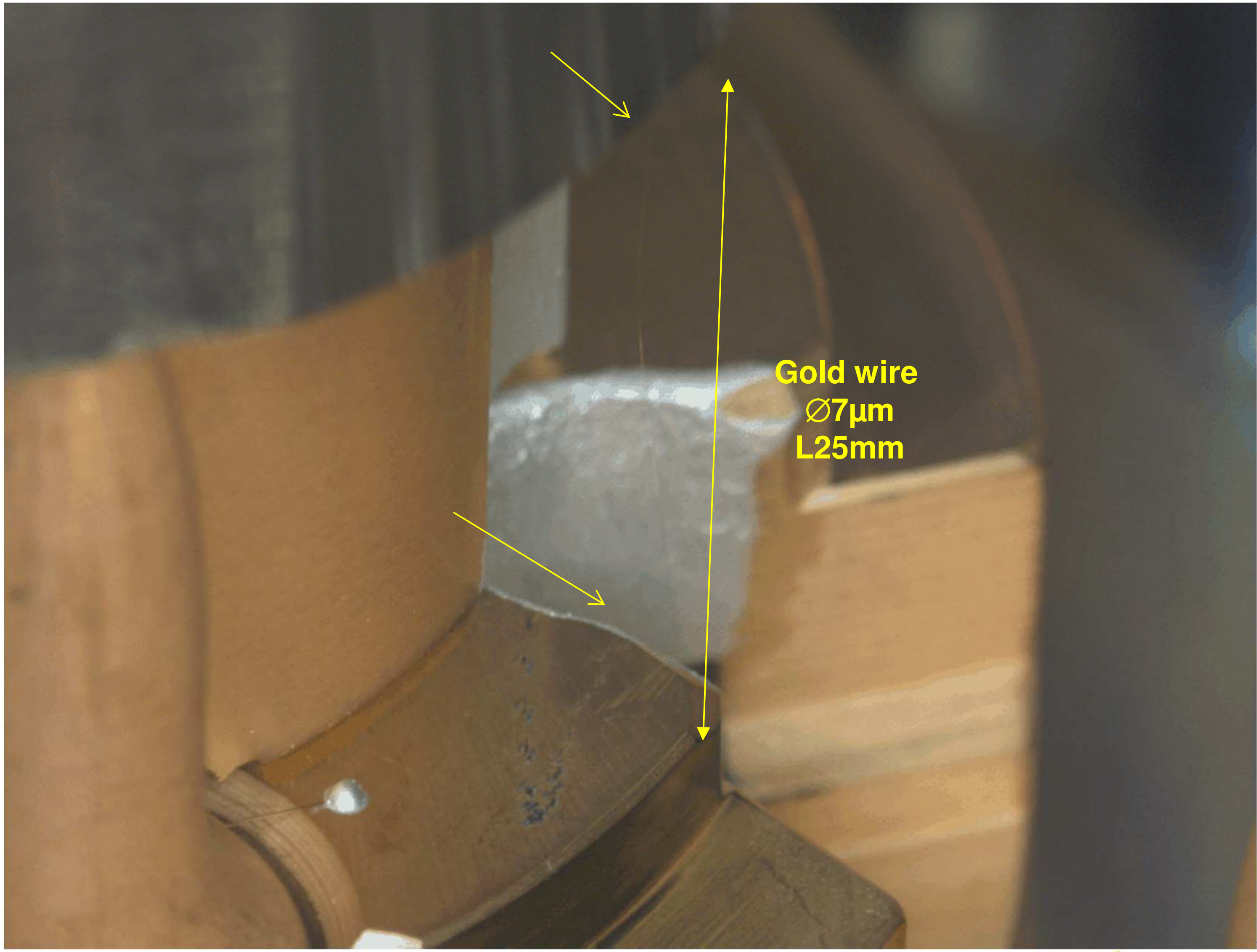
ACCELEROMETER = pair of concentric test masses



PTB:
-TM development

ONERA:
-US machining of electrode sets
-Gold Coatings
-Inner connections
-Integration
-110°C outgassing

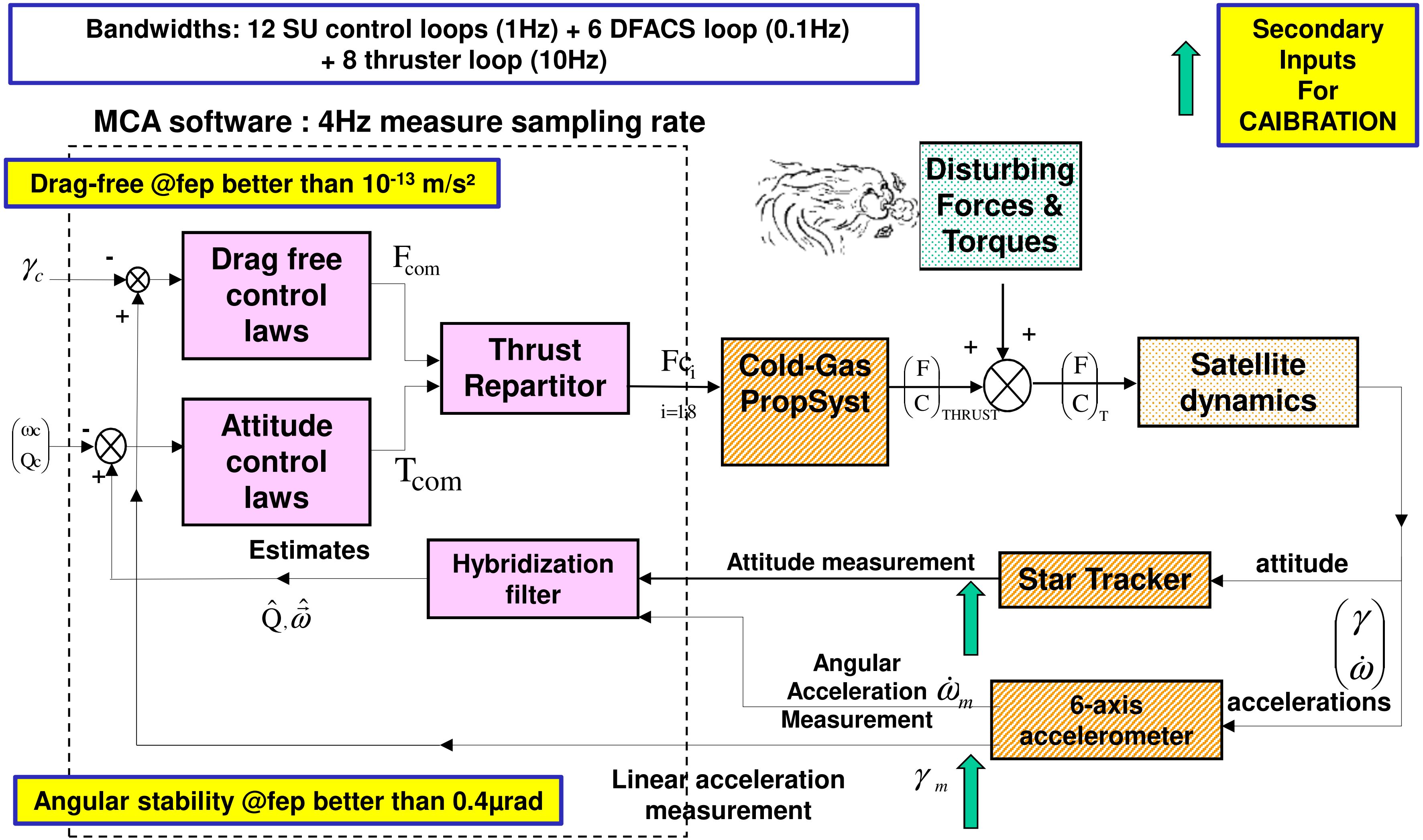
THE FAMOUS GOLD WIRE



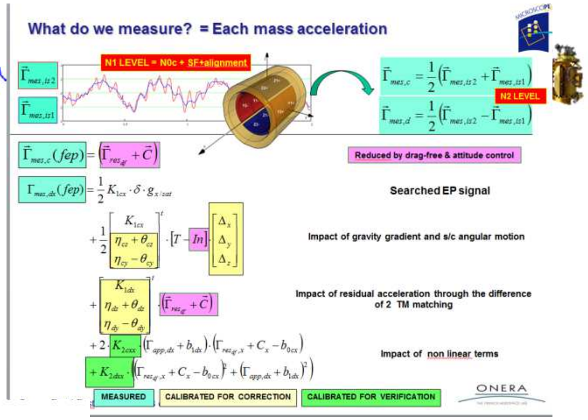
**Electrical test:
250 V applied
on electrodes
to move gold wire
and check no contact
with electrodes**

**Gold wire generates
Stiffness & Damping**

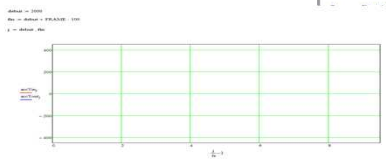
DFACS : control loop of 6 degrees of freedom



ROLE OF ONERA



- Mission design, definition & analysis + in-flight calibration development…(with Perf. Group)

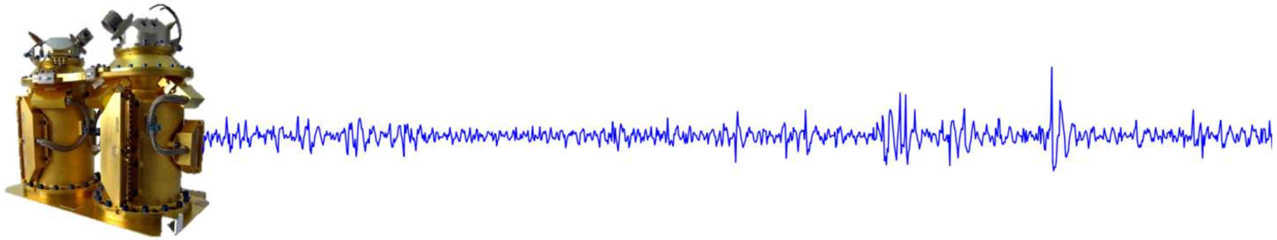


- Performance (mission, instrument), ground tests, free-falls…

- Instrument development, production, integration, qualification, test, delivery, s/c integration

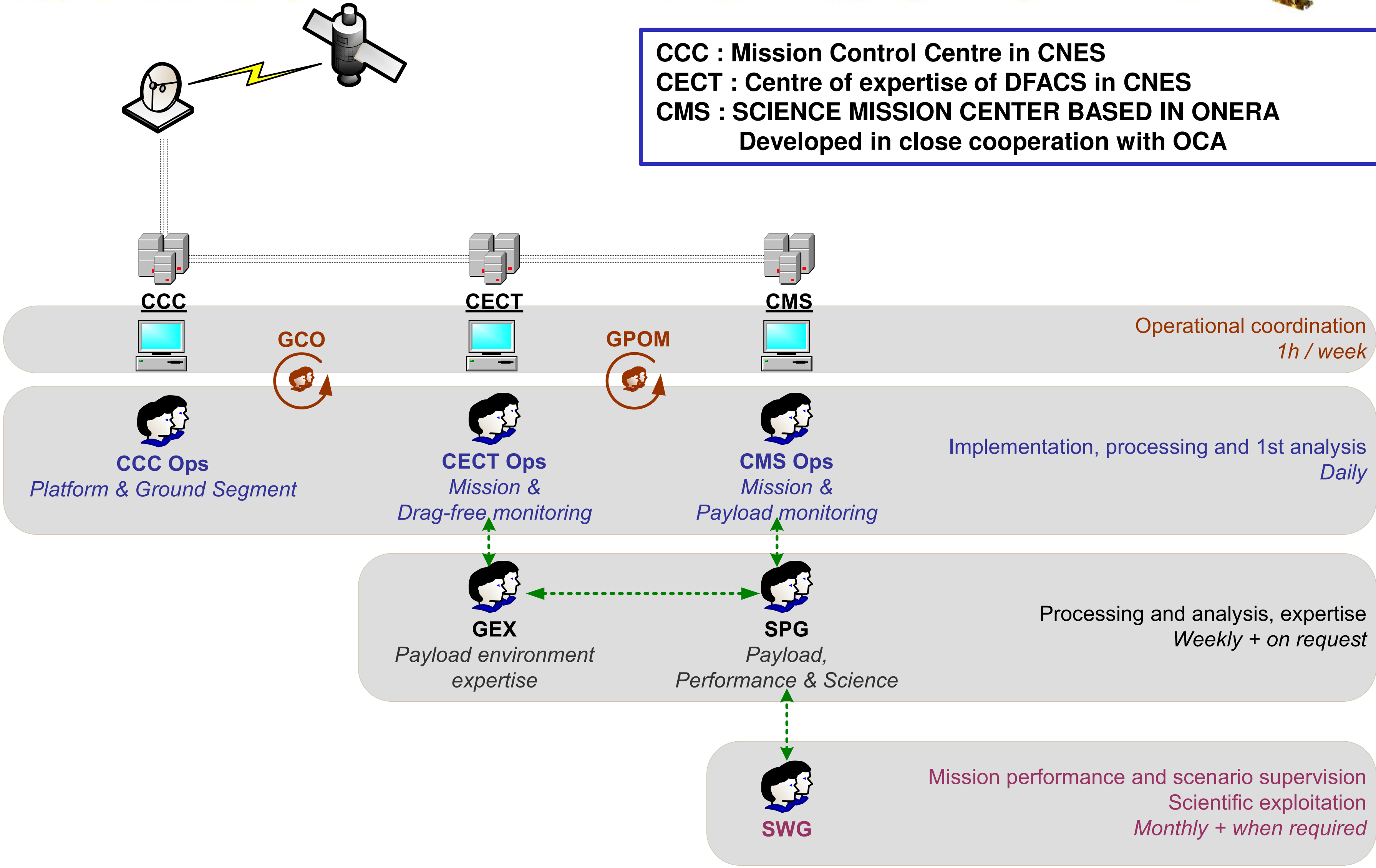
- Science Mission Center

In-flight measurements



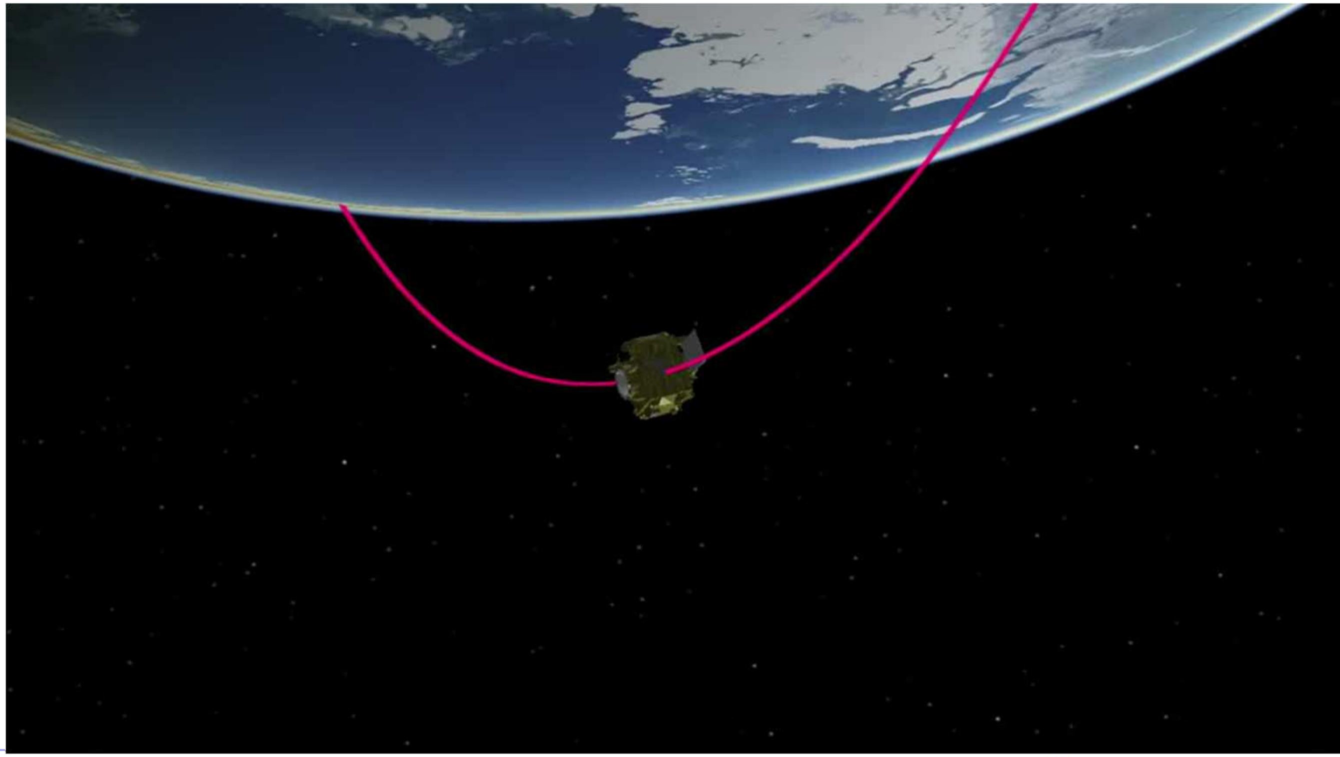
Scientific and operational organization

CCC : Mission Control Centre in CNES
CECT : Centre of expertise of DFACS in CNES
CMS : SCIENCE MISSION CENTER BASED IN ONERA
Developed in close cooperation with OCA

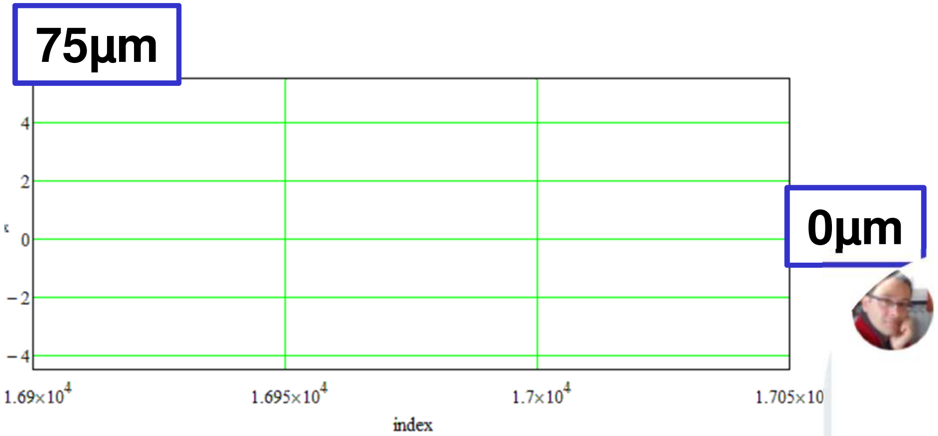


Commissioning phase: functional test of all subsystems and performance evaluation

- April – June 2016: ***hard work, life is rich of unexpected events***
  - Cold Gaz thruster : minor anomalies corrected by software but bias is stable, noise < $0.3 \mu N Hz^{-1/2}$
  - Star sensor: some Earth's albedo light on border of images corrected by software (masks)

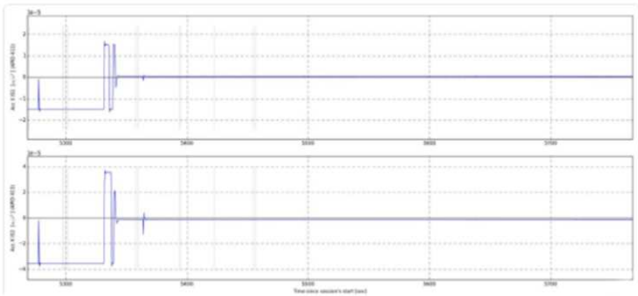


2nd of May 2016 : TM release & 1st operation

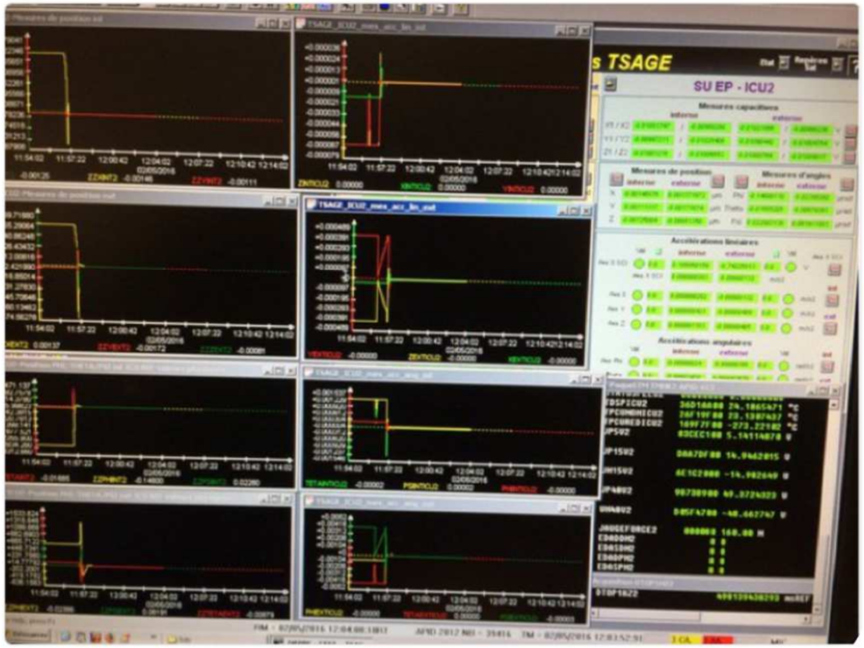


SUEP – titanium TM acquisition along X

Manuel Rodrigues @ManuelSantosRod · 2 mai 2016
The first acceleration measurement of #TSAGE @onera_fr in @CNES CECT.
À l'origine en anglais



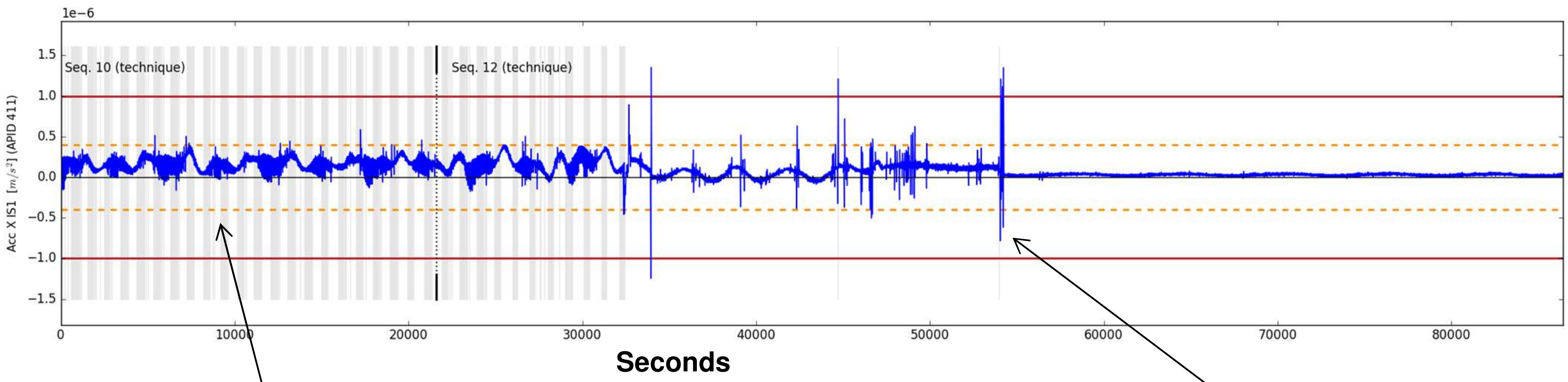
Manuel Rodrigues @ManuelSantosRod · 2 mai 2016
#TSAGE @onera_fr is on. The test masses have been released and servo looped !!!! Great all green
À l'origine en anglais



2 6 6

11th of May 2016 : Switch from Full Range Mode to High Resolution Mode (HRM)

Acceleration of Xinner of SUEP

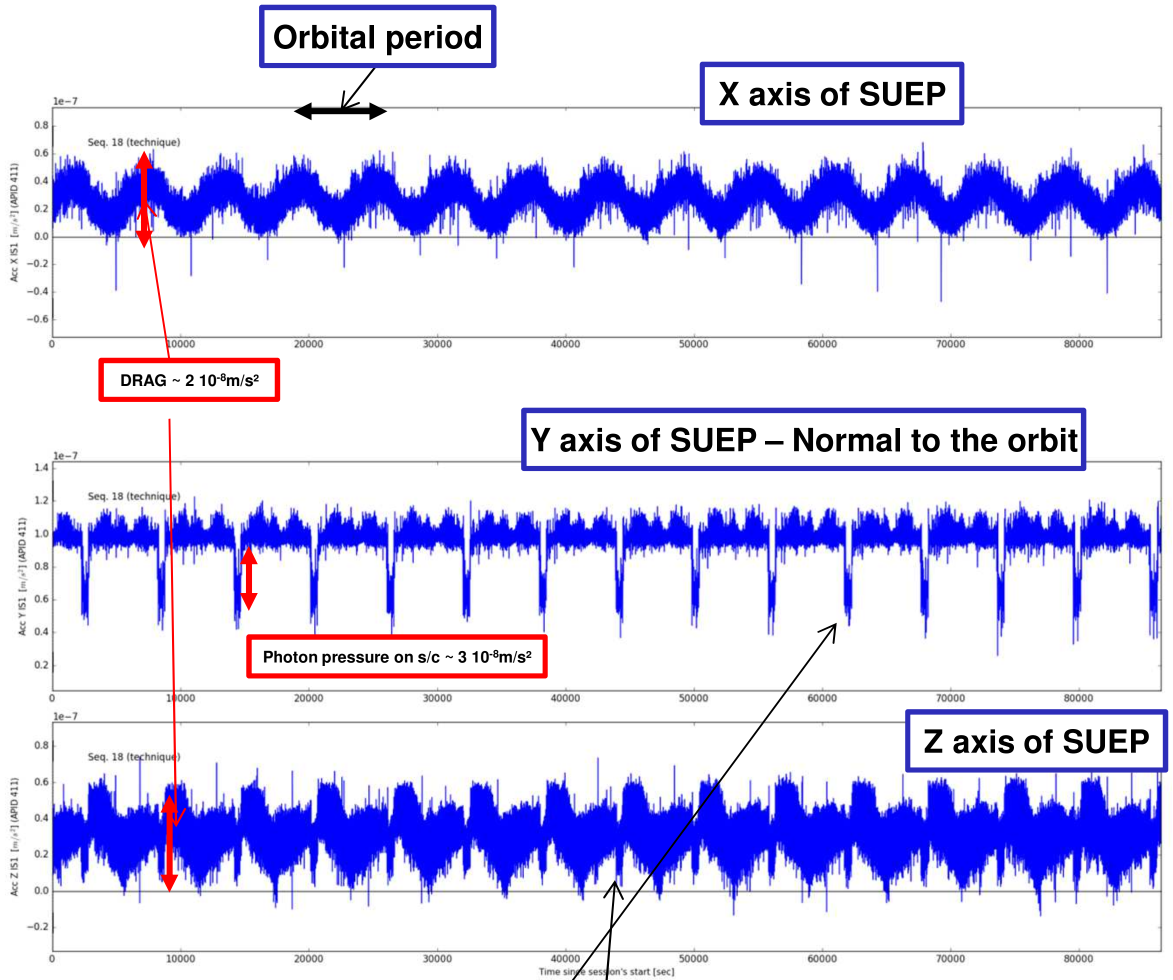


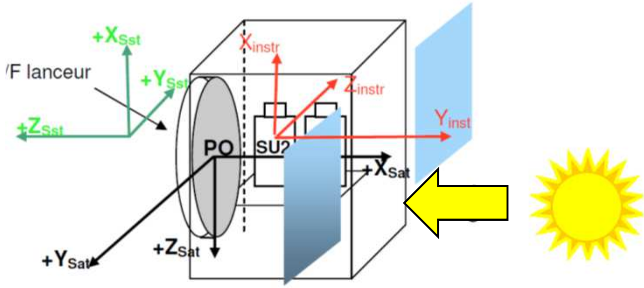
S/C is in MNOG Magnetotorquer Control Of the Attitude

Cold Gaz Thrusters used in combination with SST to Finely control the attitude of S/C.

First Swith on of HRM (science mode). S/C is rotating with a small conic motion

Inertial pointing during 1 day

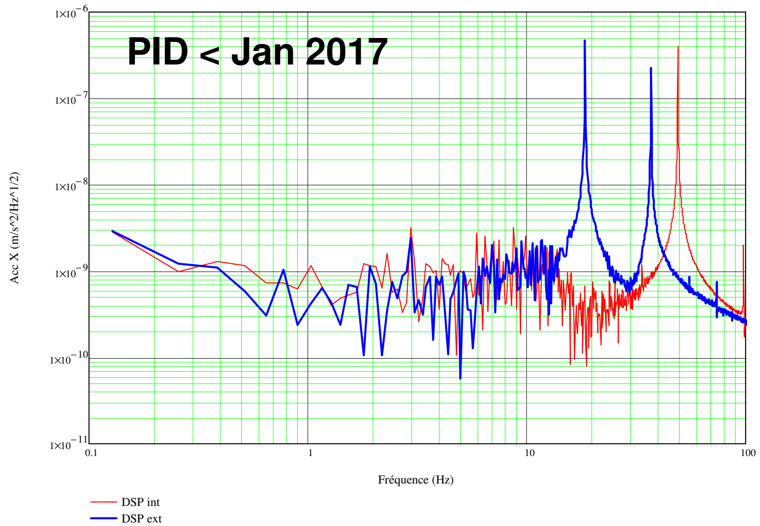


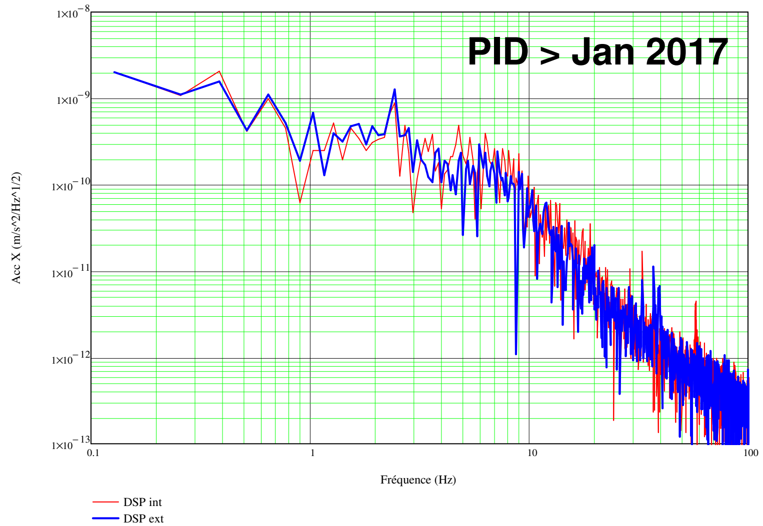


Effect of Earth's eclipse: the Sun radiation is no more pushing on the satellite => ~3 10^{-8}m/s² is the acceleration due to photons Pressure on satellite

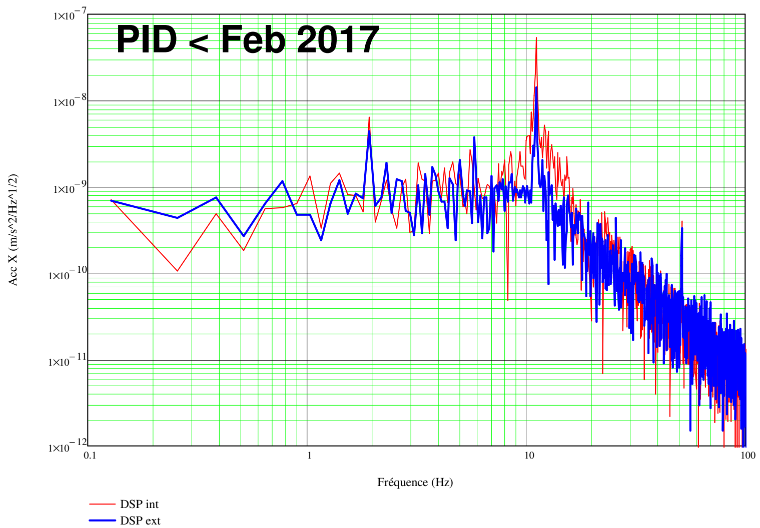
Optimization of PID in flight thanks to 1kHz measurement capture during 8sec
=> improves linearity response during calibration

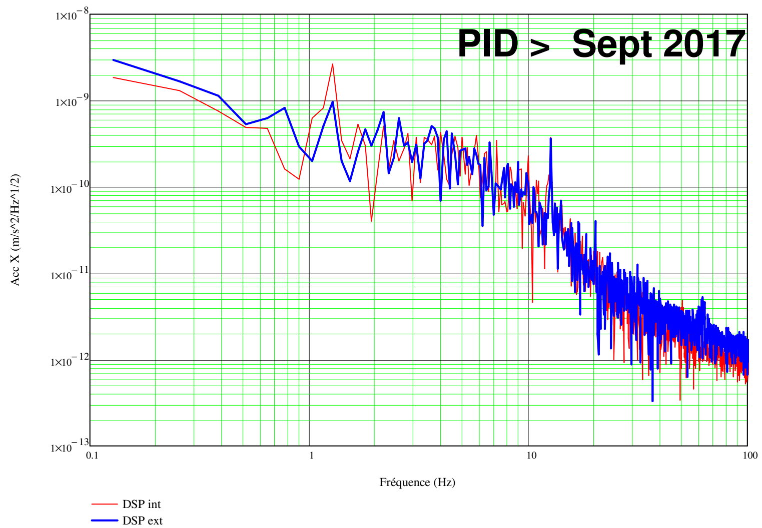
SUEP



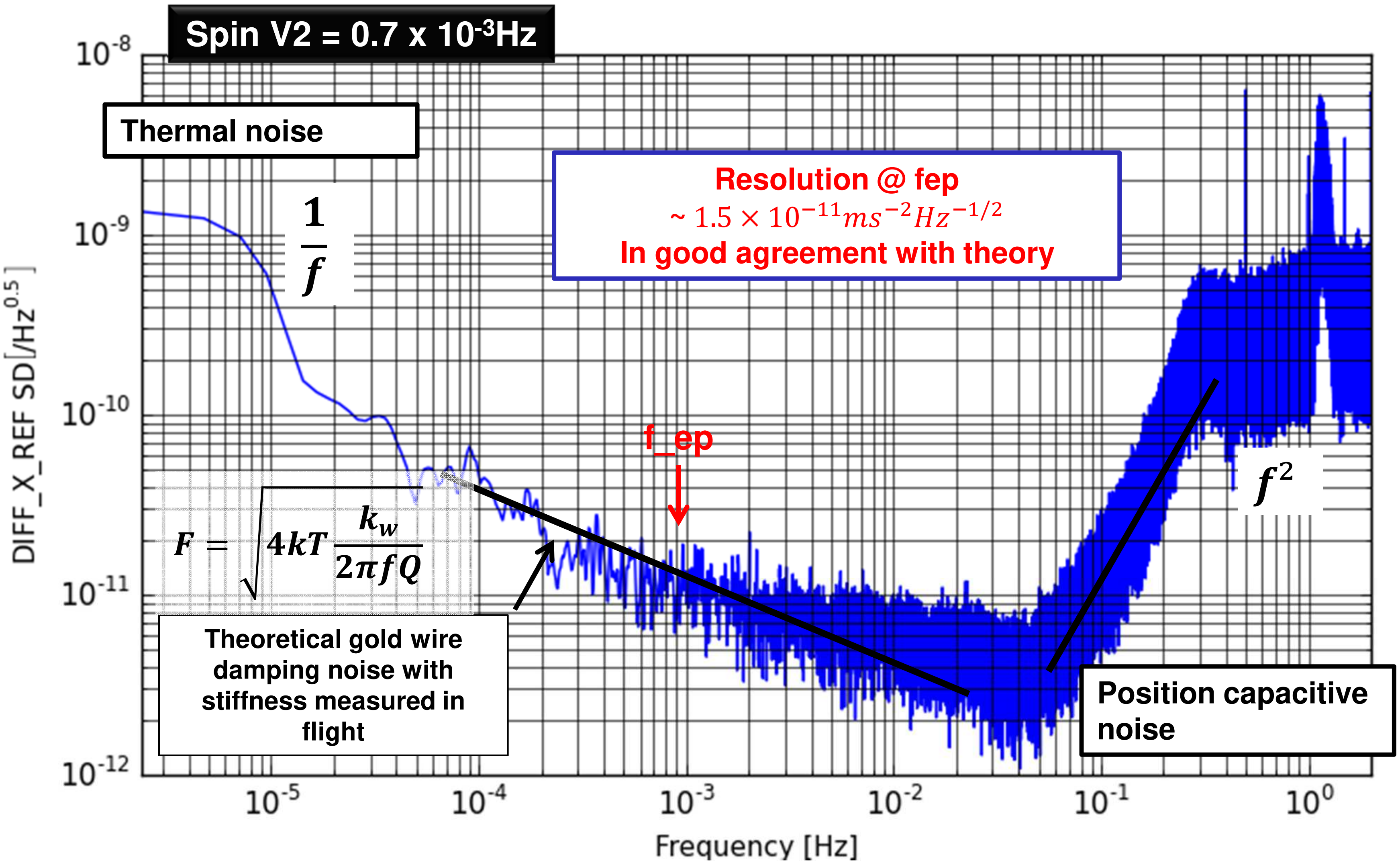


SUREF



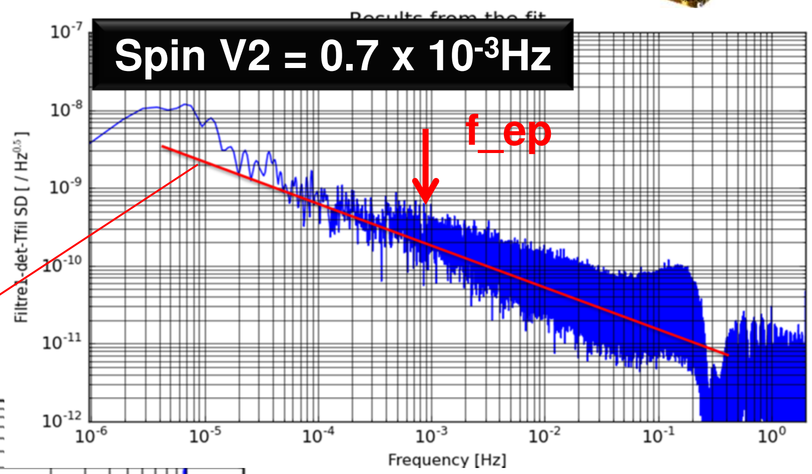


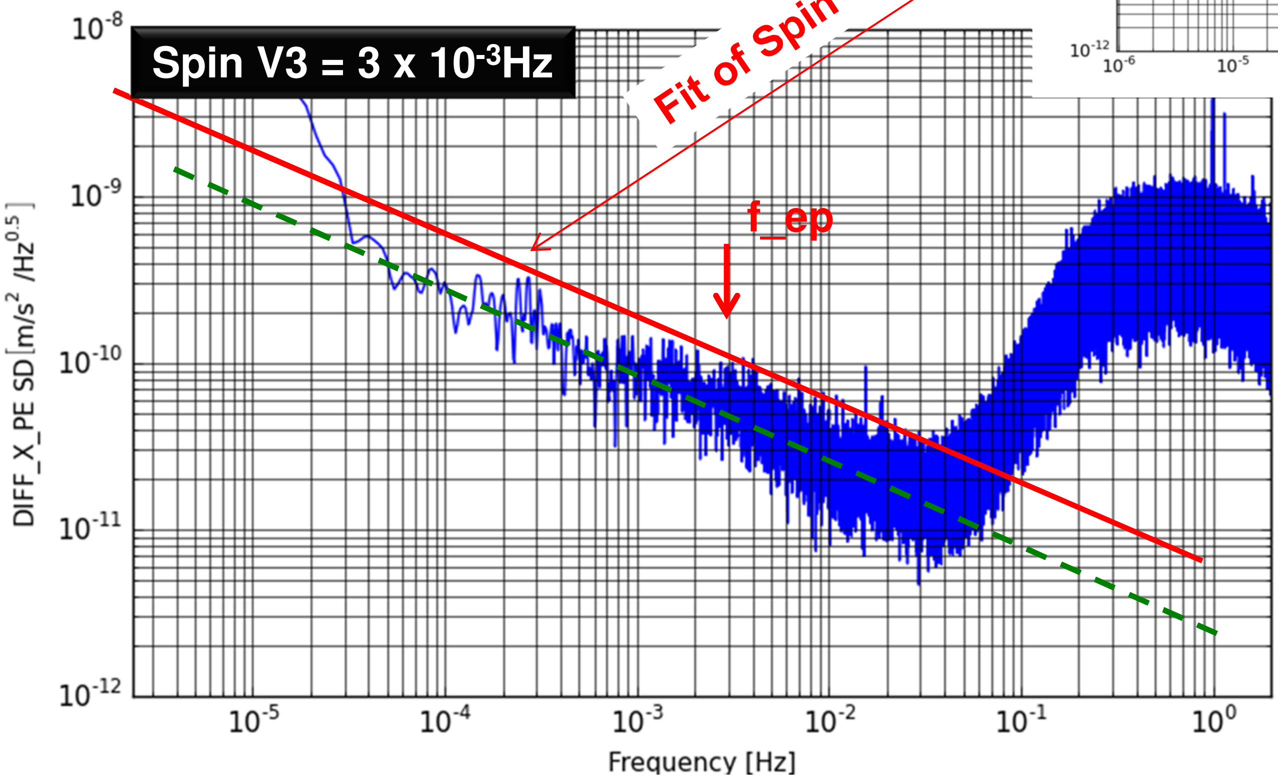
Session in spin V2 – SUREF – Earth's gravity effect subtracted



Session in spin V3 – SUEP – Earth's gravity effect subtracted

Increase of frequency from 0.9 to 3.1 x10^{-3}Hz
=> Theoretical gain of 1.8 on the noise
But in orbit gain of 4 (not explained)
=> Needs 16 less time to reach the same perfo





$\sim 2 \times 10^{-10} ms^{-2} Hz^{-1/2}$

With 1000 orbits, statistical error rejected to 80x10^{-15}m/s²

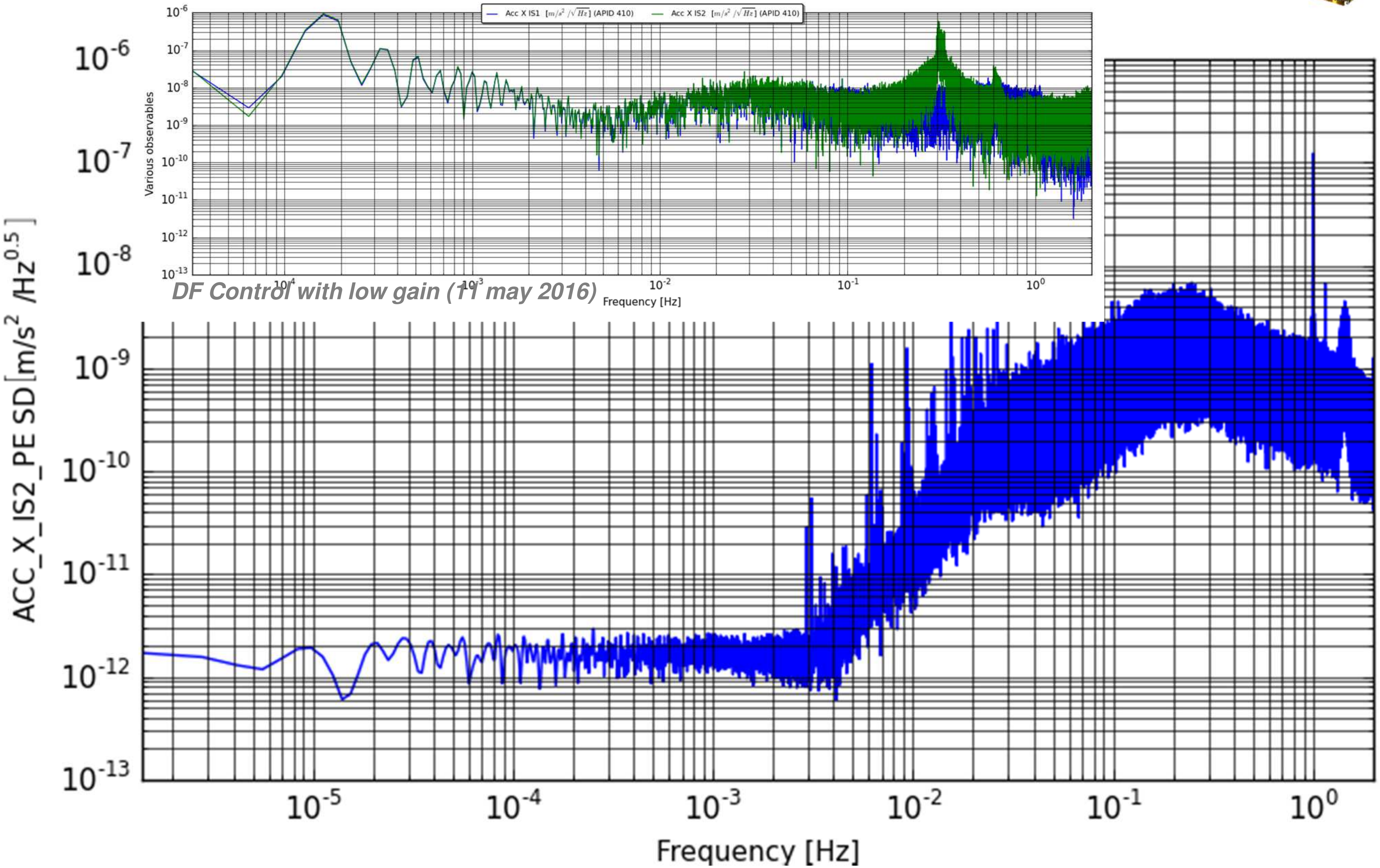
Spin V2

Spin V3

$\sim 5 \times 10^{-11} ms^{-2} Hz^{-1/2}$

With 1000 orbits, statistical error rejected to 20x10^{-15}m/s²

DRAG-FREE residues on SUEP IS2 (outer TM)

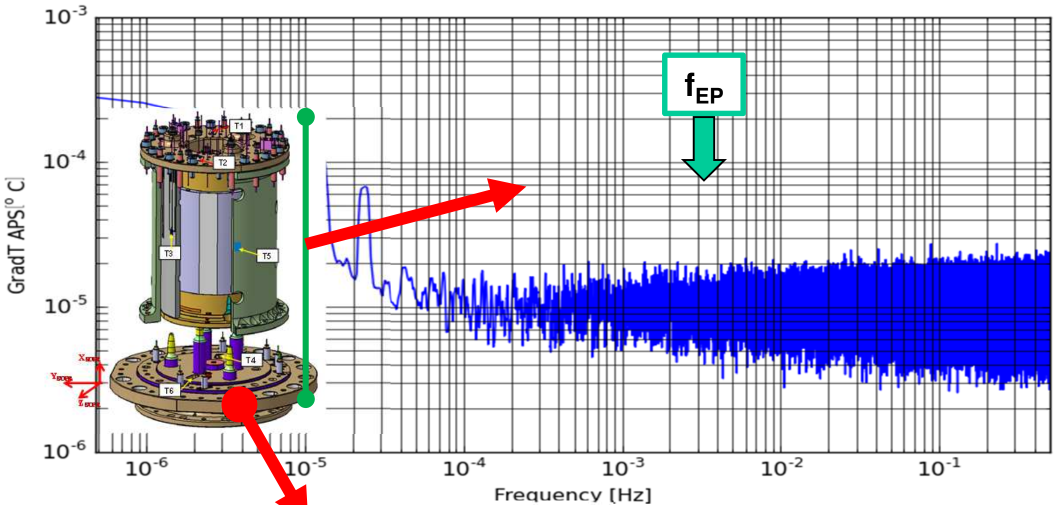


Observatoire de la CÔTE d'AZUR

ONERA THE FRENCH AEROSPACE LAB

The commissioning phase results: Variations of Temperatures in the SU & in the FEEU

1 to 2 orders of magnitude better than specified

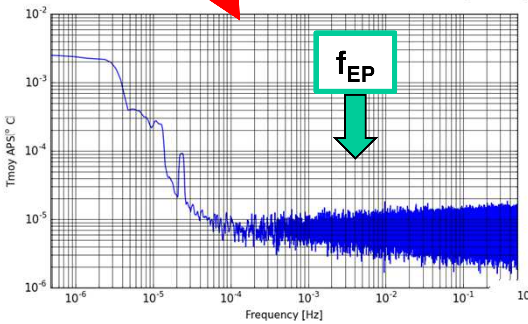


No signal @ 15µK level between each end of the test-masses

Radiometer or radiation pressure effect

$\Gamma = \frac{1}{2m} PS \frac{\Delta T}{T} < 5\ 10^{-16}\,\text{m/s}^2$

$\Gamma = \frac{1}{2m} S \frac{16\Delta T}{3c} \sigma T^3 < 10^{-15}\,\text{m/s}^2$

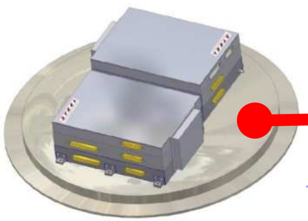


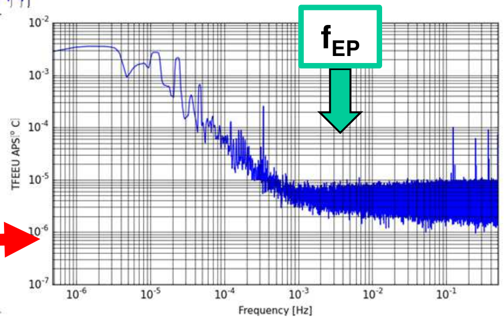
FFT of temperature probes

No signal @ 10µK level

Thermal stability of parasitic forces

Sensitivity tests performed on May 2017, under analysis



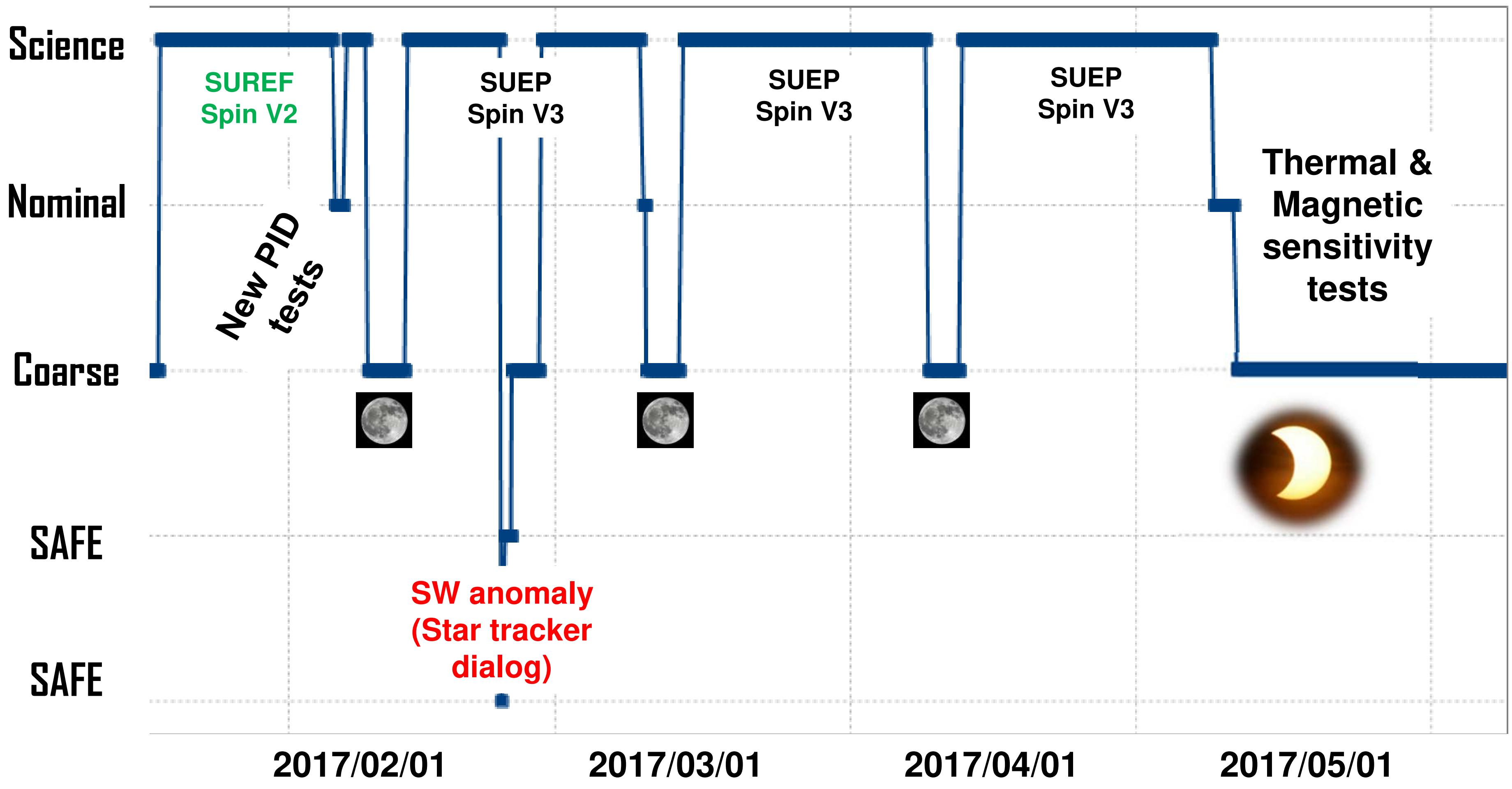


No signal @ 10µK level

Thermal stability of electronics biases

Sensitivity tests performed on May 2017 => systematics of 0.7x10^{-15} m/s²

Science phase in one plot
Jan-2017 to June-2017



THE SCENARIO OF APRIL 2017 : one of the typical science phase = 1 month

Scénario MICROSCOPE : mic_cmsm_scenarioTravail ⟨ : 4903 ⟩

Nom :	mic_cmsm_scenarioTravail	RevisionSvnXsd :	4487	RevisionSvn :	: 4903

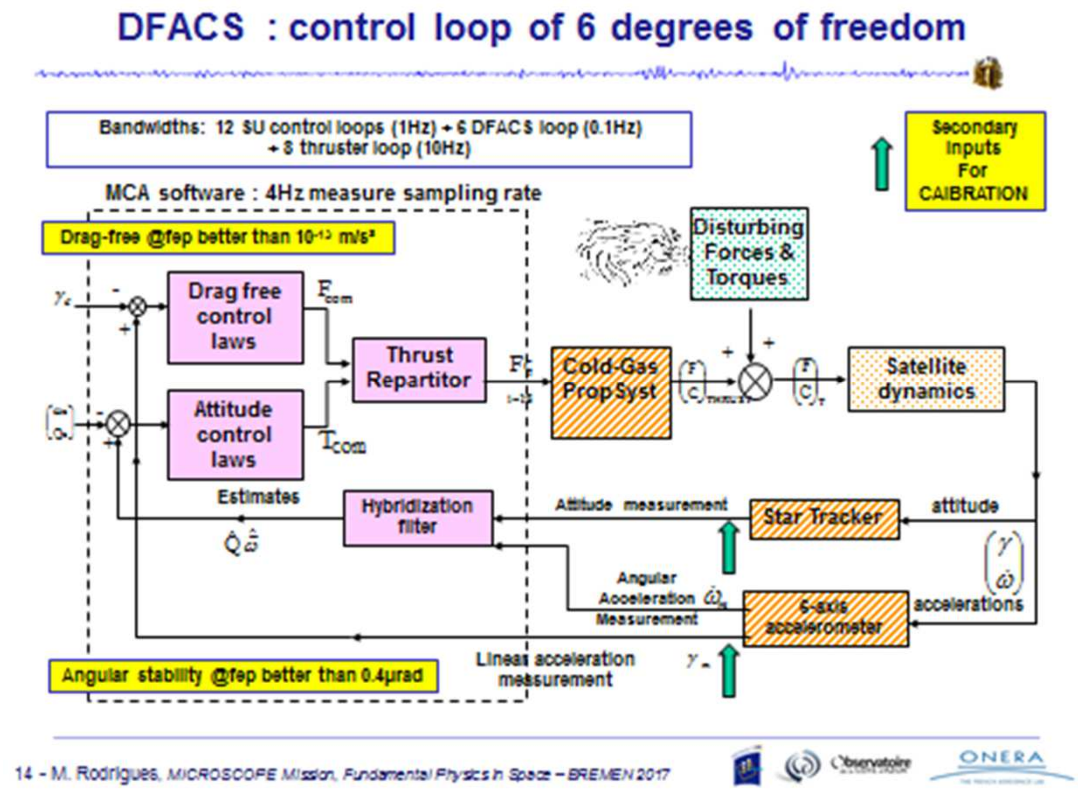
Scale factor matching

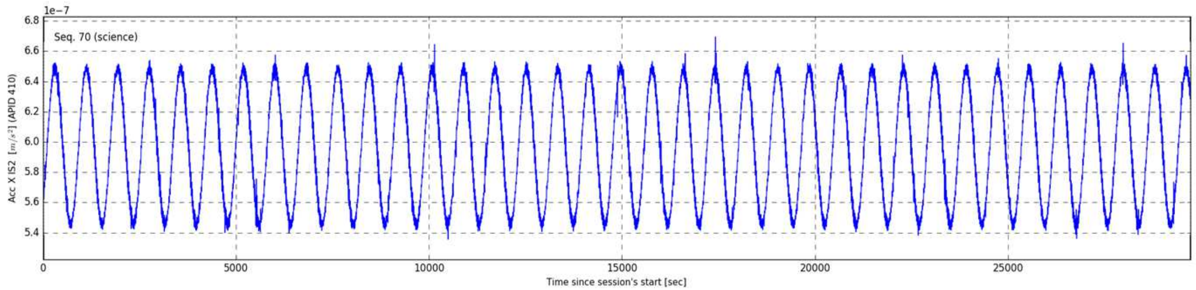
340 orbits of EP test

Alignment, Y centring

Num	Fiche Session	Phase Mission	Date Début	Fréquence Orbitale	Numéro Orbite Début	Contrainte Environnement	Criticité	Durée Effective	État	Commentaire	Capacité Gaz ZP	Conso Gaz ZP	Capacité Gaz ZM	Conso Gaz ZM
248	TSNA_Oper_1		2017-04-09T00:19:14.348944	1.6818076e-04 Hz	5112.18311	LUNE	0	55.40000 Forb	AC	Lune d'avril	4560.6 g	0.0 g	4519.9 g	0.0 g
249			2017-04-12T19:49:21.826946	1.6818079e-04 Hz	5167.58311	NO_ECLIPSE_NO_LUNE	0	1.01295 Forb	AC		4552.8 g	7.8 g	4511.6 g	8.3 g
250	CAL_K1dxDFIS2_01_SUEP_Oper_1	Phase_5	2017-04-12T21:29:44.809714	1.6818080e-04 Hz	5168.59606	NO_ECLIPSE_NO_LUNE	0	5.07000 Forb	AC		4548.6 g	4.2 g	4503.2 g	8.4 g
251			2017-04-13T05:52:10.938166	1.6818079e-04 Hz	5173.66606	NO_ECLIPSE_NO_LUNE	0	3.07939 Forb	AC	EPR courte au debut pour stab thermiq	4543.4 g	5.2 g	4498.1 g	5.1 g
252	EPR_V3DFIS2_01_SUEP_Oper_1	Phase_5	2017-04-13T10:57:20.936591	1.6818078e-04 Hz	5176.74545	NO_ECLIPSE_NO_LUNE	0	106.00000 Forb	AC	A ajuster en fonction de la Lune	4203.5 g	339.9 g	4139.7 g	358.4 g
253			2017-04-20T18:01:55.097527	1.6818078e-04 Hz	5282.74545	NO_ECLIPSE_NO_LUNE	0	1.51531 Forb	AC		4202.2 g	1.3 g	4138.5 g	1.2 g
254	EPR_V3DFIS2_01_SUEP_Oper_1	Phase_5	2017-04-20T20:32:05.104497	1.6818078e-04 Hz	5284.26076	NO_ECLIPSE_NO_LUNE	0	120.00000 Forb	AC		3817.4 g	384.8 g	3732.7 g	405.8 g
255			2017-04-29T02:44:03.022537	1.6818078e-04 Hz	5404.26076	NO_ECLIPSE_NO_LUNE	0	1.51531 Forb	AC		3816.1 g	1.3 g	3731.5 g	1.2 g
256	EPR_V3DFIS2_01_SUEP_Oper_1	Phase_5	2017-04-29T05:14:13.029507	1.6818078e-04 Hz	5405.77607	NO_ECLIPSE_NO_LUNE	0	120.00000 Forb	AC		3431.3 g	384.8 g	3325.7 g	405.8 g
257			2017-05-07T11:26:10.947547	1.6818078e-04 Hz	5525.77607	NO_ECLIPSE_NO_LUNE	0	2.57703 Forb	AC		3426.9 g	4.4 g	3321.5 g	4.2 g
258	CAL_tetadYDFIS2_01_SUEP_Oper_1	Phase_5	2017-05-07T15:41:33.923216	1.6818078e-04 Hz	5528.35310	NO_ECLIPSE_NO_LUNE	0	5.07000 Forb	AC		3422.7 g	4.2 g	3313.1 g	8.4 g
259			2017-05-08T00:04:00.055253	1.6818078e-04 Hz	5533.42310	NO_ECLIPSE_NO_LUNE	0	1.18063 Forb	AC		3420.7 g	2.0 g	3311.2 g	1.9 g
260	CAL_deltaYDFIS2_01_SUEP_Oper_1	Phase_5	2017-05-08T02:01:00.060749	1.6818078e-04 Hz	5534.60373	NO_ECLIPSE_NO_LUNE	0	5.07000 Forb	AC		3408.8 g	11.9 g	3295.5 g	15.7 g
261			2017-05-08T10:23:26.192786	1.6818078e-04 Hz	5539.67373	NO_ECLIPSE_NO_LUNE	0	1.18282 Forb	AE		3406.8 g	2.0 g	3293.6 g	1.9 g
262	CAL_tetadZDFIS2_01_SUEP_Oper_1	Phase_5	2017-05-08T12:20:39.219984	1.6818078e-04 Hz	5540.85655	NO_ECLIPSE_NO_LUNE	0	5.07000 Forb	AE		3402.6 g	4.2 g	3285.2 g	8.4 g
263			2017-05-08T20:43:05.352021	1.6818078e-04 Hz	5545.92655	NO_ECLIPSE_NO_LUNE	0	1.01295 Forb	AE		3401.7 g	0.9 g	3284.4 g	0.8 g
264	CAL_K1dxDFIS2_01_SUEP_Oper_1	Phase_5	2017-05-08T22:23:28.335147	1.6818078e-04 Hz	5546.93950	NO_ECLIPSE_NO_LUNE	0	5.07000 Forb	AE		3397.5 g	4.2 g	3276.0 g	8.4 g
265			2017-05-09T06:45:54.467184	1.6818078e-04 Hz	5552.00950	ECLIPSE	0	0.00000 Forb	AE		3397.5 g	0.0 g	3276.0 g	0.0 g

Scale Factor matching session





2

The drag-free operates on IS1

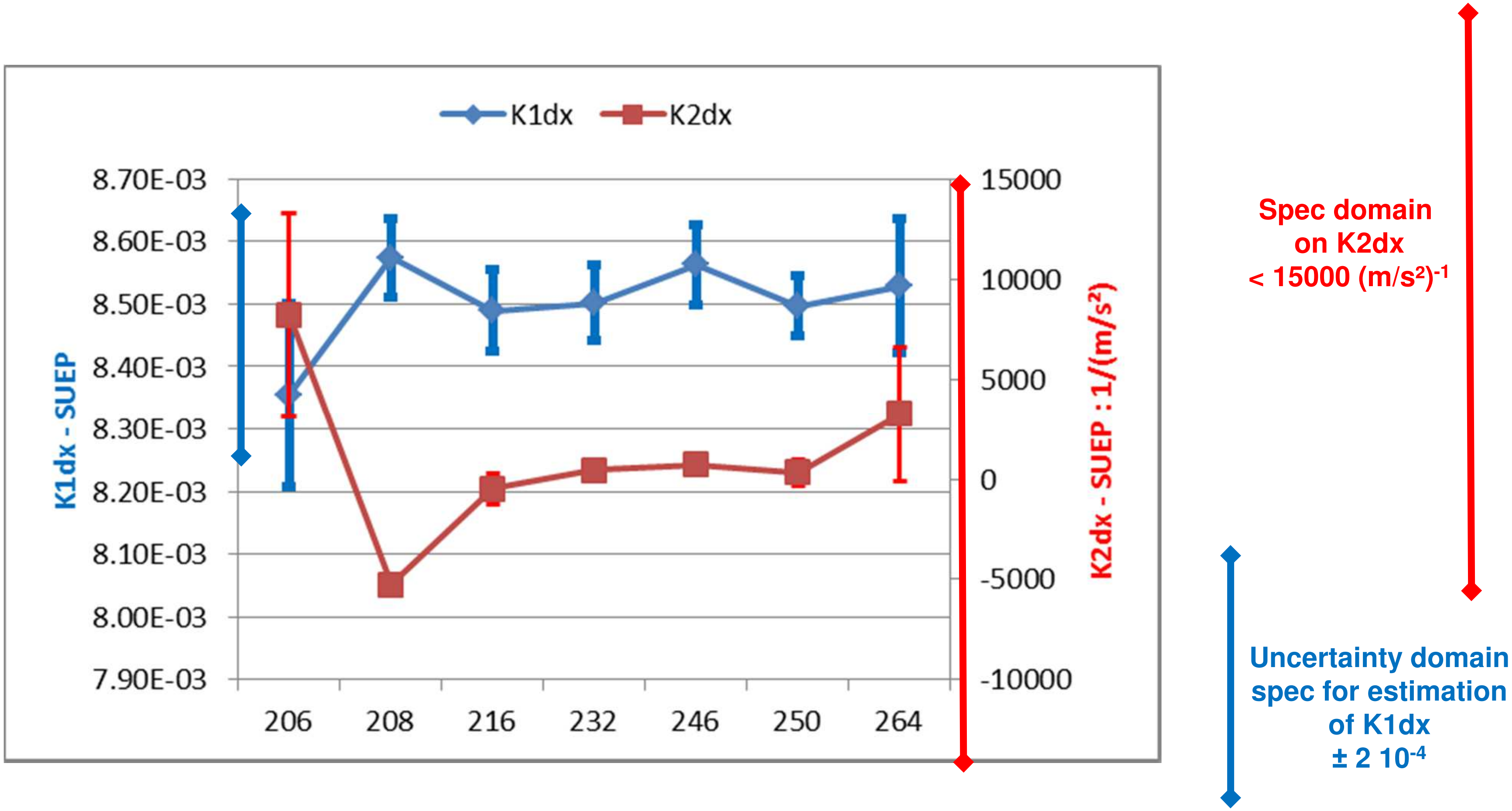
The measurement is biased by a sine of 5×10^{-8} m/s² @ fcal=1.25×10^{-3}Hz

THEN IS2 measures the sine with a factor (ratio of the scale factor of IS2 and IS1) @ fcal & non linear terms @ 2fcal

$K1_{is2}/K1_{is1} \cdot 5 \times 10^{-8}$ m/s²

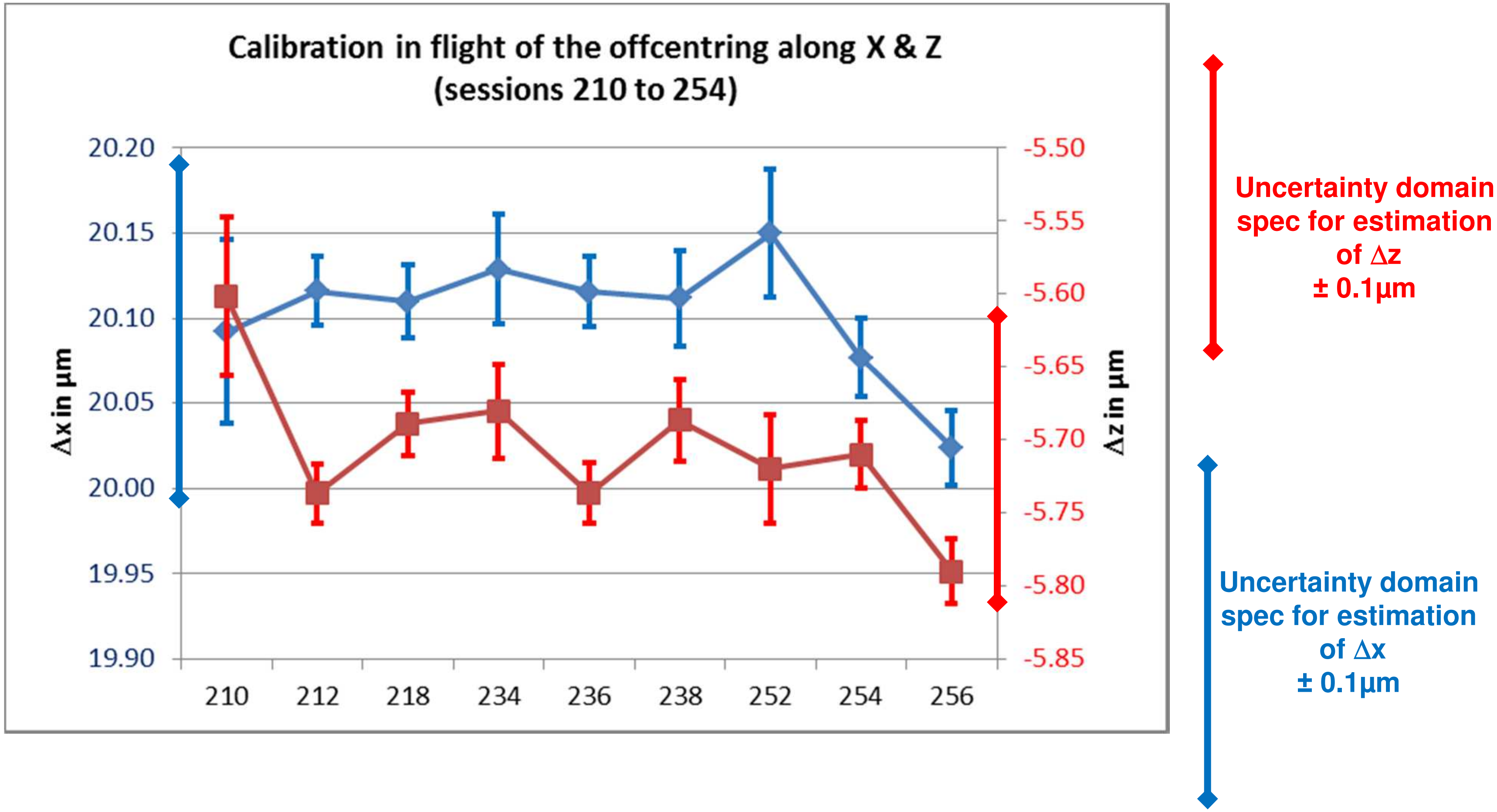
$K2d_{is2}/K1^2_{is1} \cdot (5 \times 10^{-8}$ m/s²$)^2$

Scale factor matching (K1dx)
& Quadratic non linear term matching (K2dx)



- **Sessions 206 & 208 have larger non-linearities (under investigations)**

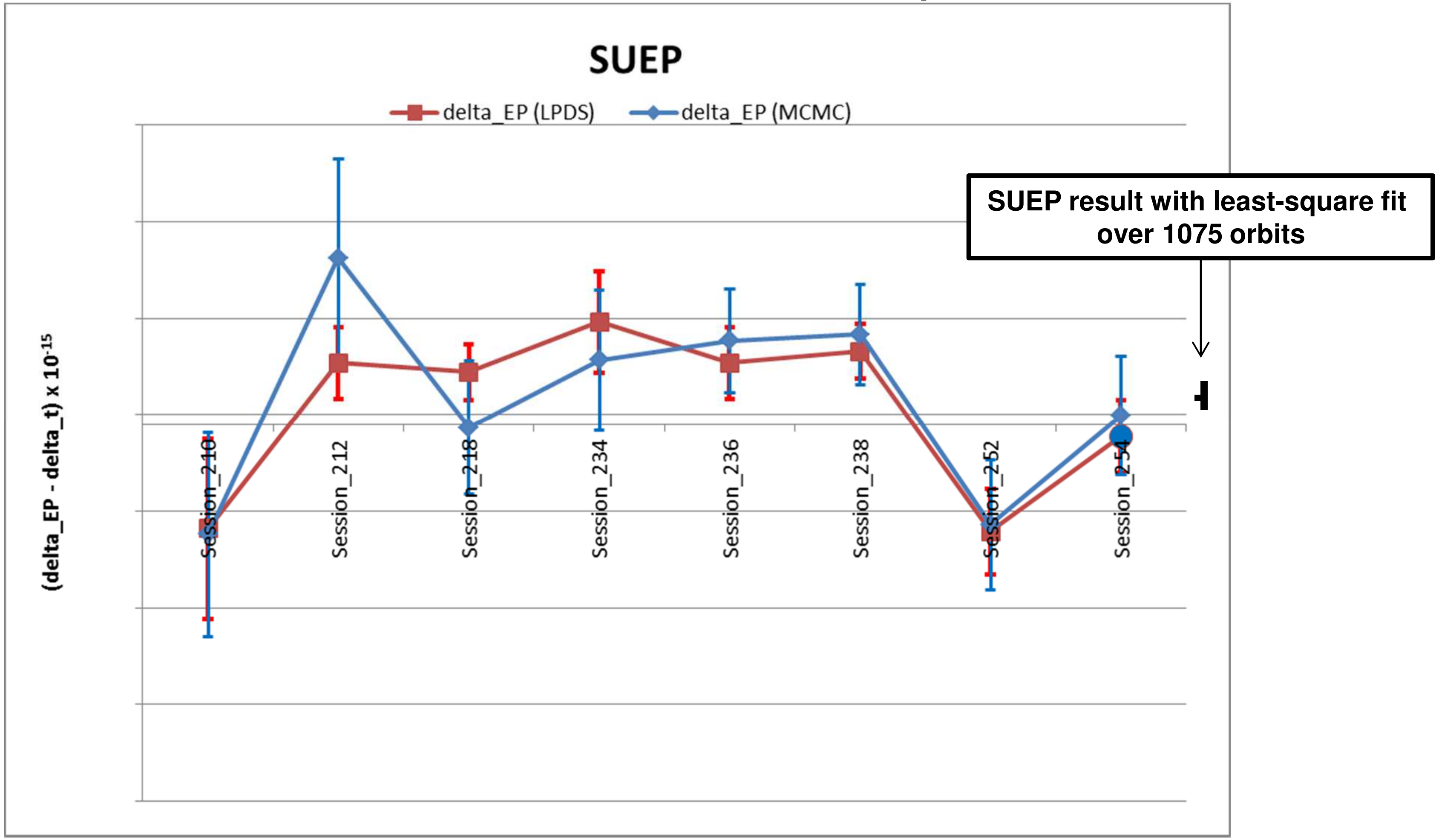
Offcentring estimation from Earth's gravity gradient effect at 2 f_{EP}



- **The offcentrings are extracted at the same time as the Eotvos parameter**
- **No corrections of scale factors or of non linear terms**
- **Dispersion on session 210 could come from non linearity at the limit of specs**

δ_{EP_i} with least-square fit in frequency domain & MCMC Hammer

The scale of Eotvos parameter is hinted and biased until publication validation (on going)
Performed without correction of calibrated parameters



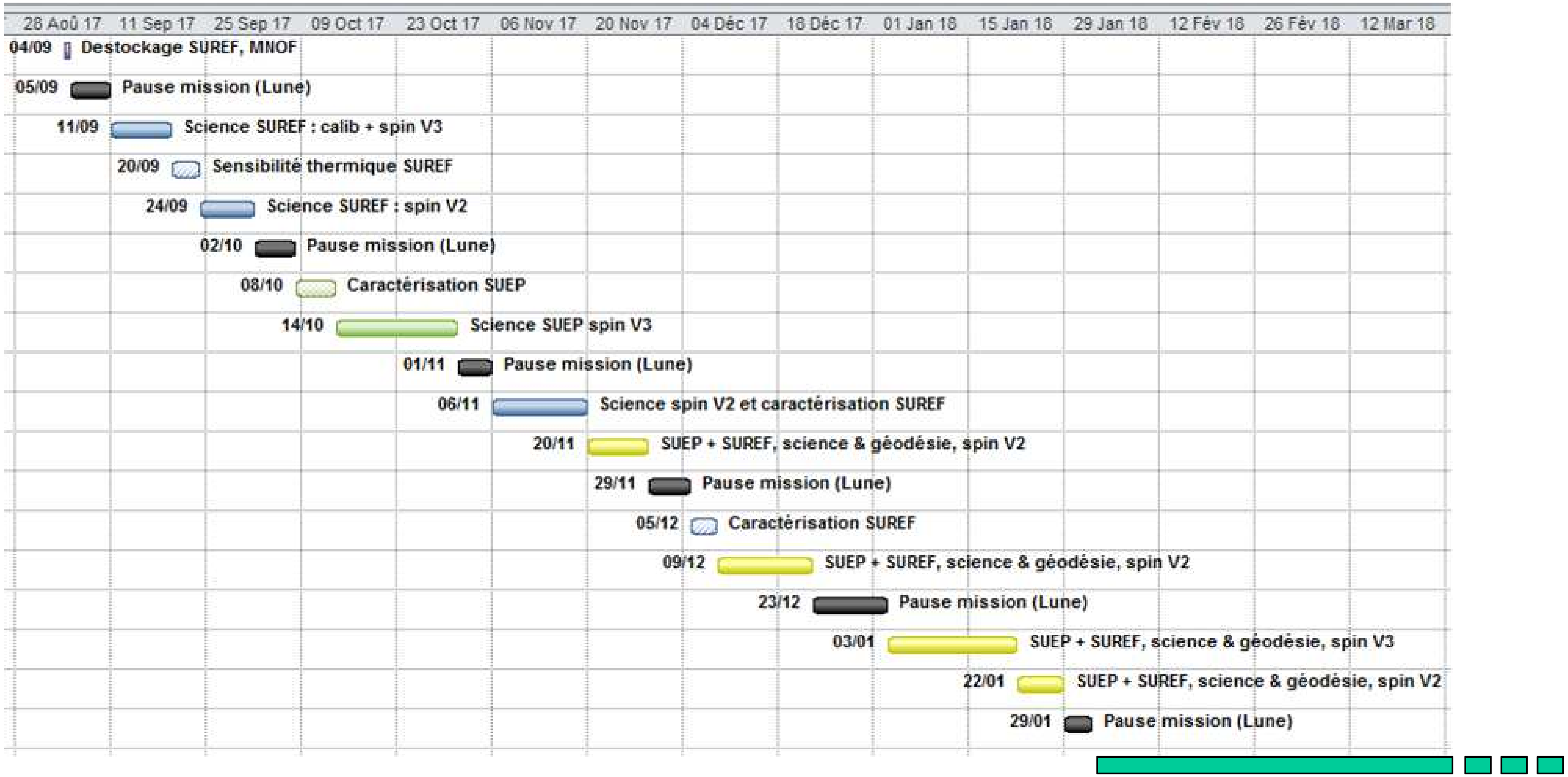
The status of the mission scenario

Orbits nb.	11/05/2017	SUEP	SUREF	*Total*	
Technical	Commissionning Phase			*829*	15%
	Moon, Eclipse (TSAGE OFF)			*2177*	39%
	Others			*609*	11%
Transitions	Transitions			*112*	2%
Science	EP test	1205	368	*1574*	28%
	Calibration	196	103	*300*	5%

- **Propulsion : 60% of the available cold gas has been consumed**
- **PAUSE from May 2017 to August 2017**
- **The science sessions start again in September 2017**
- **With the remaining gas, we will cumulate another 480 orbits for SUEP and 424 orbits for SUREF dedicated to EP test until end of February 2018:**

=> Concerning stochastic noise, we should gain 10% in performance for SUEP and 30% for SUREF

Mission scenario



Technological tests to be end in Fall 2017

CONCLUSION

- MICROSCOPE has flown 8000 orbits (equivalent to 2 times distance Earth vs Sun)
- About 25% are used for Science. The satellite delivered a lot of valuable and outstanding data
- End of mission foreseen within one year
- Some data have been distributed to selected labs by SWG
- Firsts results are under reviewed in PRL, we hope to get a green light soon and communicate more in details

The MICROSCOPE mission: first results of a space test of the Equivalence Principle

Pierre Touboul,[1,*] Gilles Métris,[2,†] Manuel Rodrigues,[1,‡] Yves André,[3] Quentin Baghi,[2] Joël Bergé,[1] Damien Boulanger,[1] Stefanie Bremer,[4] Patrice Carle,[1] Ratana Chhun,[1] Bruno Christophe,[1] Valerio Cipolla,[3] Thibault Damour,[5] Pascale Danto,[3] Hansjoerg Dittus,[6] Pierre Fayet,[7] Bernard Foulon,[1] Claude Gageant,[1] Pierre-Yves Guidotti,[3] Daniel Hagedorn,[8] Emilie Hardy,[1] Phuong-Anh Huynh,[1] Henri Inchauspe,[1] Patrick Kayser,[1] Stéphanie Lala,[1] Claus Lämmerzahl,[4] Vincent Lebat,[1] Pierre Leseur,[1] Françoise Liorzou,[1] Meike List,[4] Frank Löffler,[8] Isabelle Panet,[9] Benjamin Pouilloux,[3] Pascal Prieur,[3] Alexandre Rebray,[1] Serge Reynaud,[10] Benny Rievers,[4] Alain Robert,[3] Hanns Selig,[4] Laura Serron,[2] Timothy Sumner,[11] Nicolas Tanguy,[1] and Pieter Visser[12]

[1]ONERA, chemin de la Hunière, BP 80100, F-91123 Palaiseau Cedex, France
[2]Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur, 250 avenue Albert Einstein, F-06560 Valbonne, France
[3]CNES, 18 avenue Edouard Belin, F-31401 Toulouse, France
[4]ZARM, Center of Applied Space Technology and Microgravity, University of Bremen, Am Fallturm, D-28359 Bremen, Germany
[5]IHES, Institut des Hautes Études Scientifiques, 35 route de Chartres, F-91440 Bures-sur-Yvette, France
[6]DLR, Köln headquarters, Linder Höhe, 51147 Köln, Germany
[7]LPTENS, École Normale Supérieure (PSL Research University), 24 rue Lhomond, 75231 Paris Cedex 05, France
[8]PTB, Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[9]IGN, Institut géographique national, 73 avenue de Paris, F-94160 Saint Mandé, France
[10]Laboratoire Kastler Brossel, UPMC-Sorbonne Université, CNRS, ENS-PSL Research University, Collège de France, F-75005 Paris, France
[11]Blackett Laboratory, Imperial College London, United Kingdom
[12]Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands

(Dated: September 20, 2017)

According to the Weak Equivalence Principle, all bodies should fall at the same rate in a gravitational field. The MICROSCOPE satellite, launched in April 2016, aims to test its validity at the 10^{-15} precision level, by measuring the force required to maintain two test masses (of titanium and platinum alloys) exactly in the same orbit. A non-vanishing result would correspond to a violation of the Equivalence Principle, or to the discovery of a new long range force. Analysis of the first data

- The final paper release is expected to 2019 with a large distribution of the data

MICROSCOPE : the success of a team

CNES / OCA / ZARM / ONERA

Performance meeting (since 2004 : 126)

CNES / ONERA

Commissioning phase in Toulouse control center