MICROSCOPE mission
A test of the Equivalence principle in space

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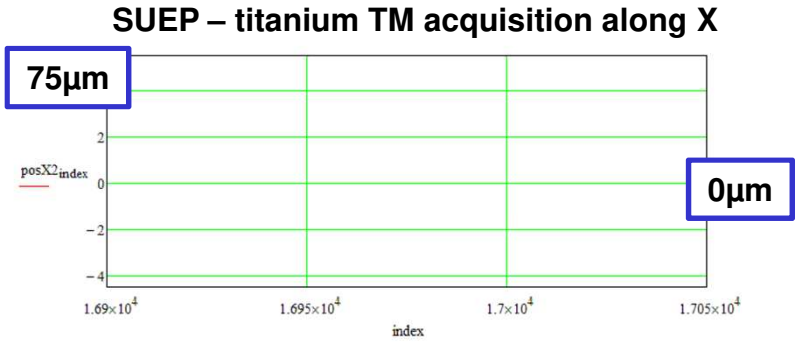
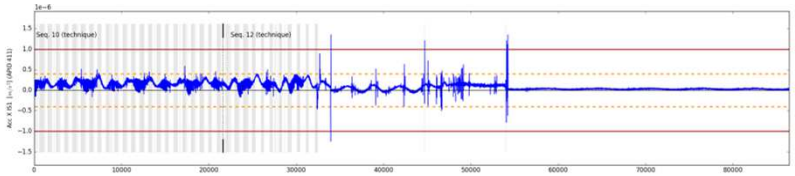
on behalf of MICROSCOPE team

Launched on the 25th of April 2016

- 25th of April 2016: satellite launch as piggy bag of Sentinel 1B by Soyutz

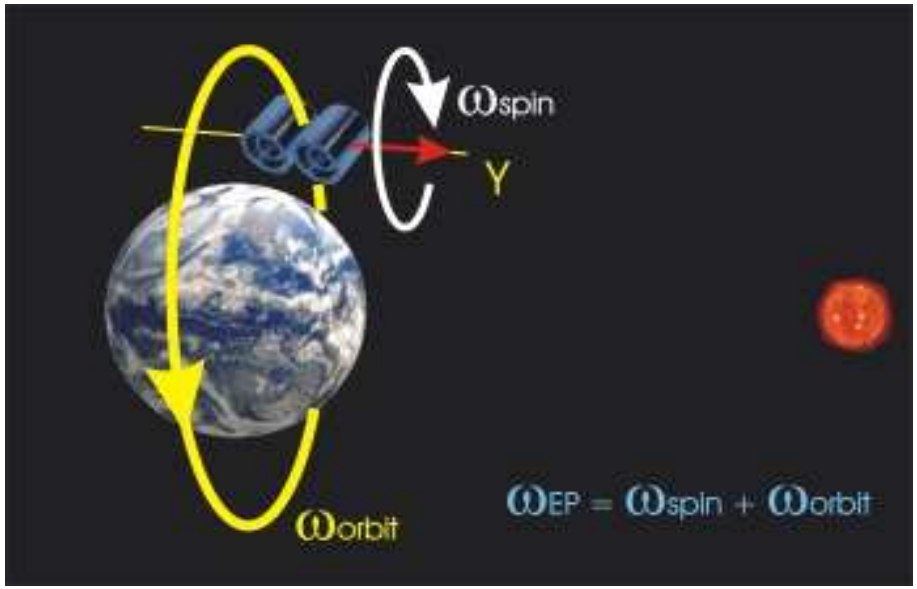


- 2nd of May 2016 : test-masses release and electrostatic control in robust mode
- 11th May : 1st test of Payload science mode



- 7th of June 2016: 1st Attitude control with hybridization of the Star Sensor & the Payload angular accelerometer
- 9th of June 2016 : 1st “drag-free” above 6 axes on Earth’s low orbit

Principle of the test in space



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

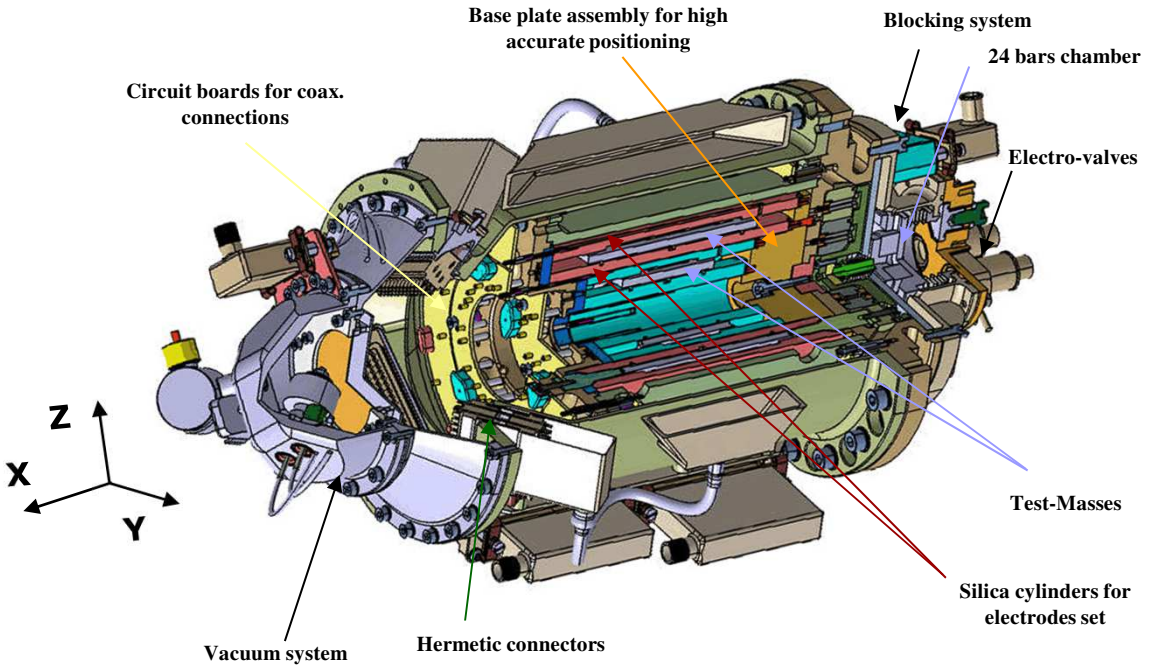
evaluated @ 10^{-15} level

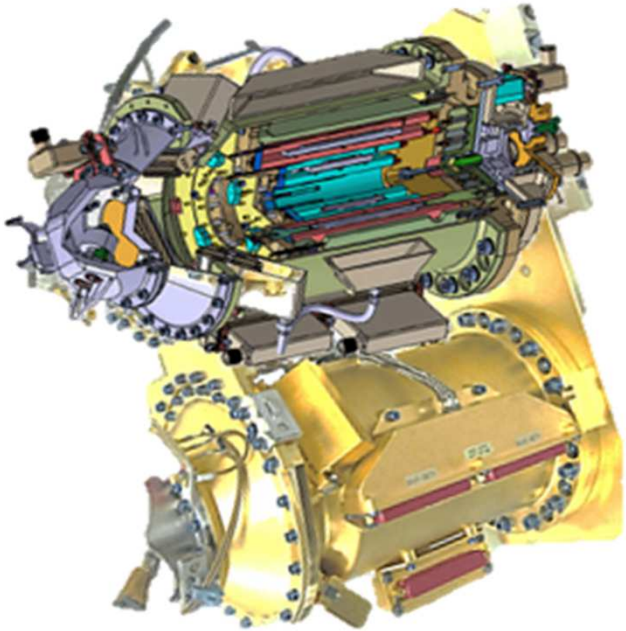
The eventual violation signal frequency is at orbital frequency + s/c rotation rate (spin mode)

- 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 (7,92m/s² @ 717km)
- 2 test bodies in Pt(Rh10%) for systematic error evaluation
- 2 test bodies in Pt(Rh10%) vs Ti(Al6%) for the EP test
- The measurement axis, X, is in the orbital plane = cylinder axis

The instrument

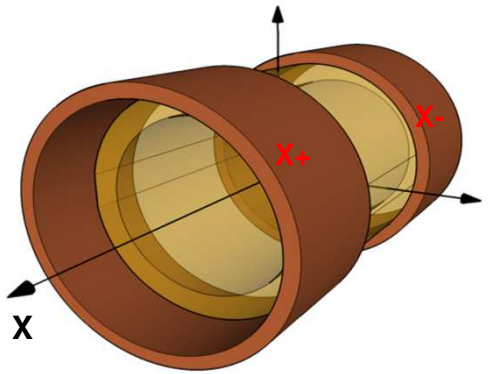
ICU : digital control laws, data conditioning





SU: 2 Sensor units REF + EP

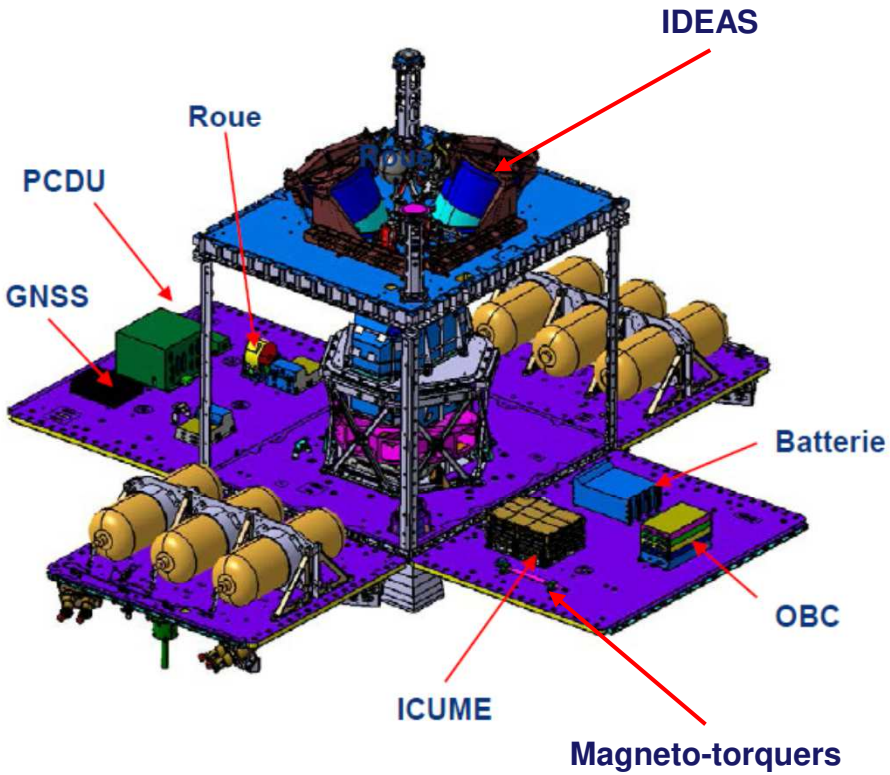
FEEU : 2 low noise Electronics units



The payload inside the satellite

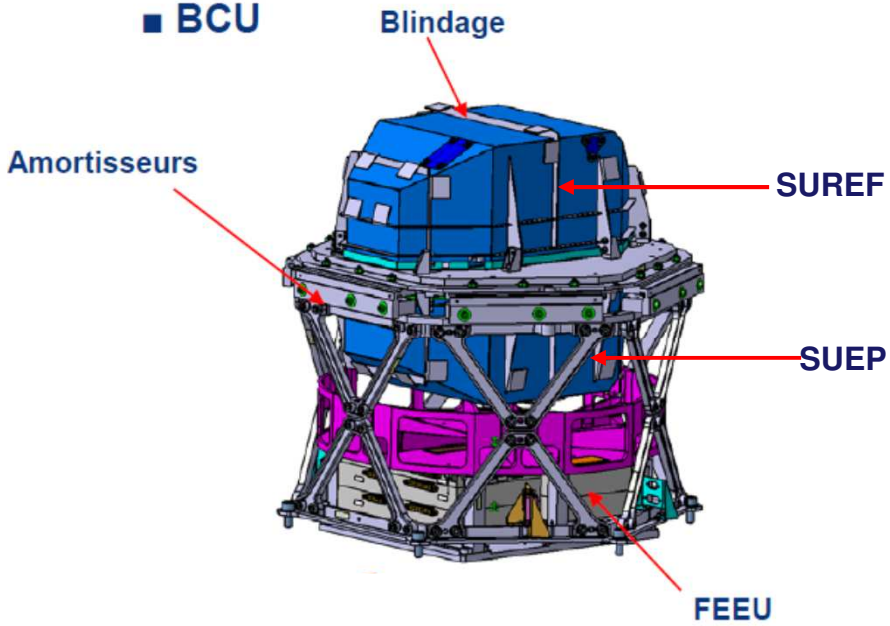
■ Satellite panneaux ouverts

Concept panneaux identiques Myriade



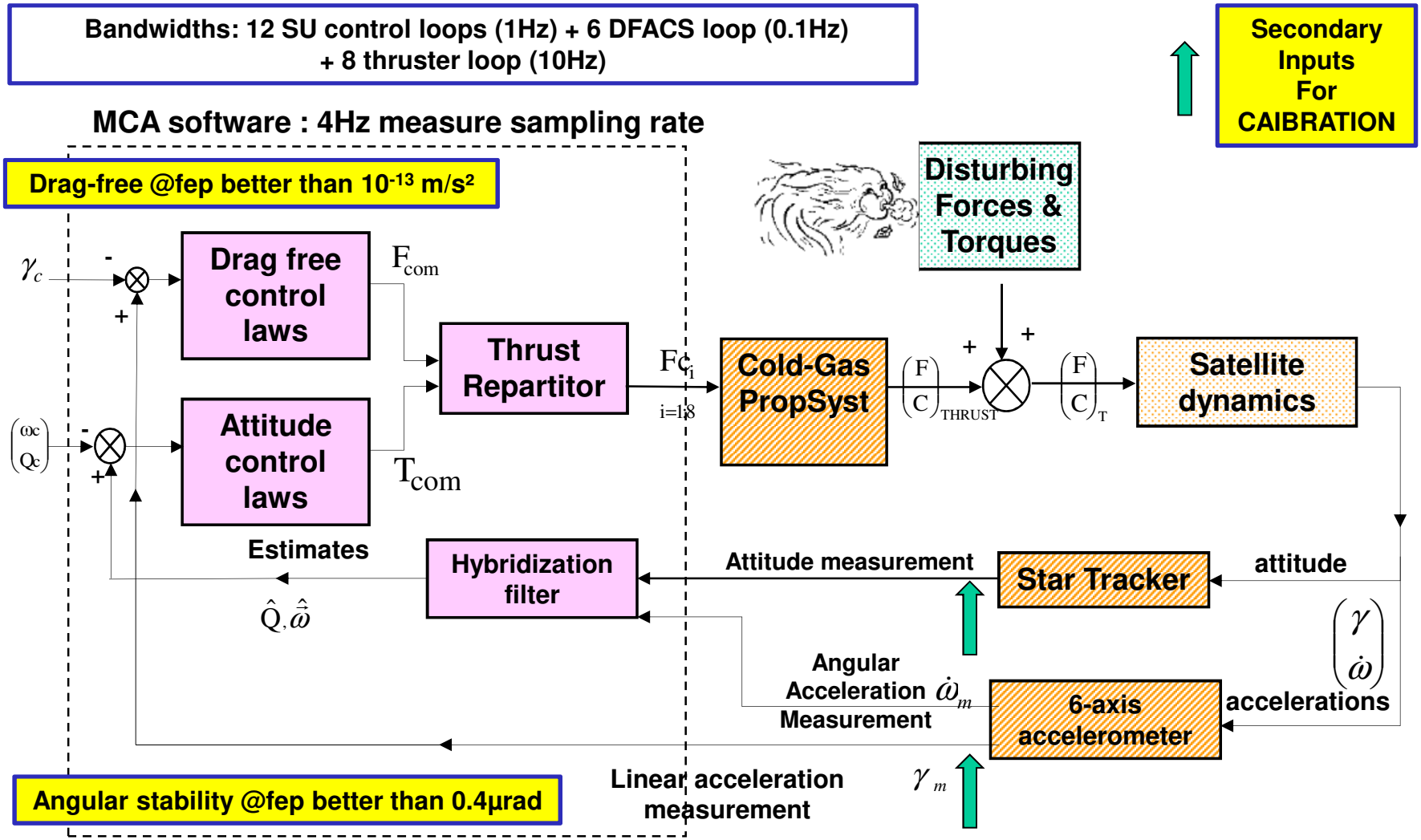
6 CDR Satellite – Toulouse : 27/03/2014 – B-1 : AMT

■ BCU



- **The Sensor (SU) and the Low noise electronics (FEEU) is accommodated inside a passive thermal cocoon.**
- **The SU is accommodated inside a magnetic shield.**

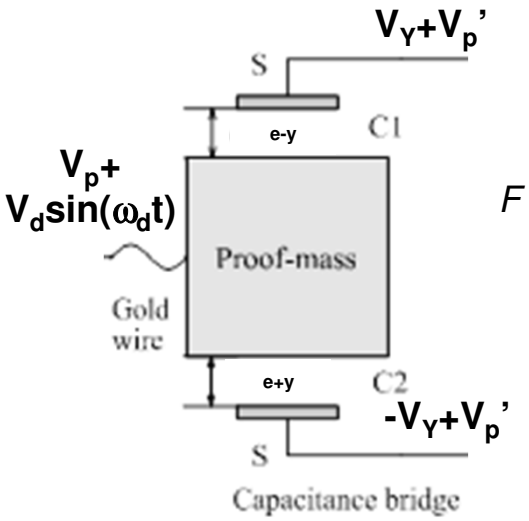
DFACS : Drag Free & Attitude Control System of the 6 degrees of freedom



Observatoire de la CÔTE d'AZUR

ONERA THE FRENCH AEROSPACE LAB

Accelerometer principle of operation



Capacitive Detection

$$\Delta C = \frac{2\varepsilon S}{e} y$$

Electrostatic force

$$F = F_1 - F_2 = \frac{1}{2}\left[\frac{\partial C_2}{\partial y}\left(V_Y + V_p' - V_p - V_d \sin(\omega_d t)\right)^2\right] - \frac{1}{2}\left[\frac{\partial C_1}{\partial y}\left(V_Y + V_p' + V_p + V_d \sin(\omega_d t)\right)^2\right]$$

THE MEASUREMENT in N0 level of data

$$a_Y = \frac{2\varepsilon S}{me^3}\left(\left(V_p' - V_p\right)^2 + \frac{V_d^2}{2}\right) y - \frac{2\varepsilon S}{me^2}(V_p - V_p') V_Y + \frac{2\varepsilon S}{me^2} V_Y^2 \frac{y}{e}$$

Electrostatic stiffness

Electrostatic gain

Non linear term

The real observable

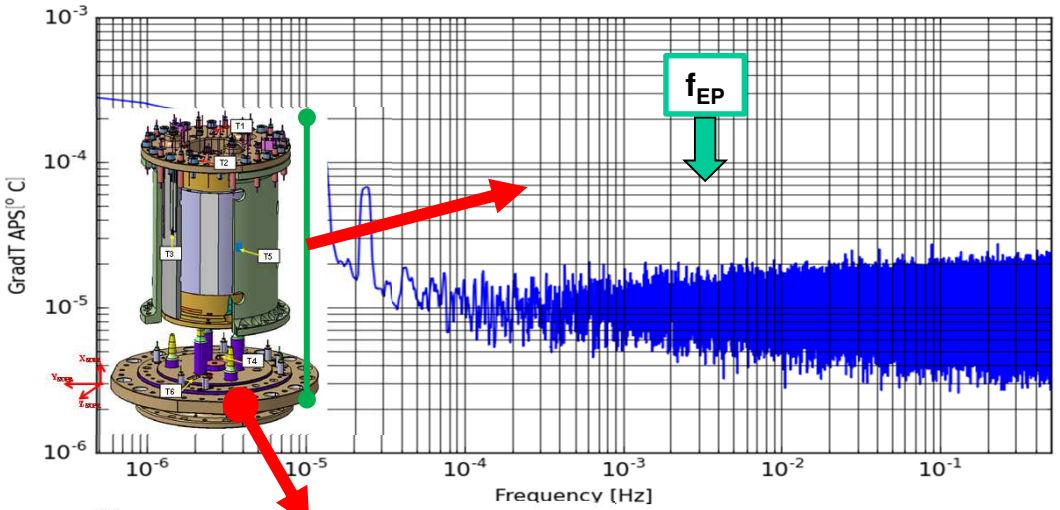
In FRM : V_p~ 40 V and V_d ~ 1 Vrms
In HRM : V_p = 5 V and V_d= 5 Vrms

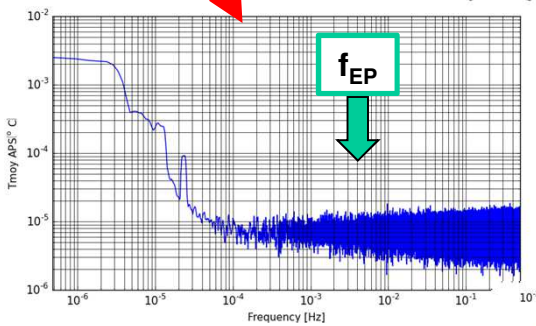
Commissioning phase main events and results

- April – Nov 2016: ***hard work, rich of unexpected events***
  - Accelerometer : 2 short circuits in FEEU capacitance (SUREF). No impact on performance, still operating, with time to time need to reset the TM levitation.
  - Star sensor: some Earth's albedo light on border of images corrected by software (masks)
  - Cold Gaz thruster : minor anomalies corrected by software but bias is stable, noise < $0.3\mu NHz^{-1/2}$
- **The satellite, with help of the accelerometer, of the star sensor, of the thermal passive control and of the GPS, exhibits a very quiet environment at least 10 times better than expected**
  - Star sensor:
    - DFACS Performance : 0.03 – 0.3µrd stability @fep
    - With SU hybridization: 0.5 – 5 $10^{-12}rd/s^2$ @fep
  - DFACS : Acceleration control over 120 orbits; 0.3 – 4 $10^{-14}m/s^2$ @fep
  - GPS + Doppler orbit determination : 0.1-0.3 m @fep

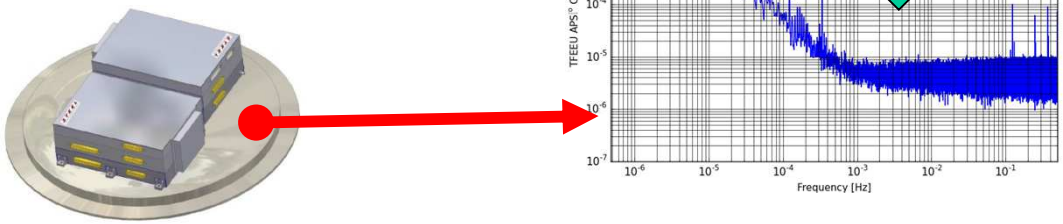
The commissioning phase results: Variations of Temperatures in the SU & in the FEEU

1 to 2 orders of magnitude better than specified





FFT of temperature probes



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}m/s²**

$\Gamma = \frac{1}{2m} S \frac{16\Delta T}{3c} \sigma T^3$ **< 10^{-15}m/s²**

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

The equation of measure

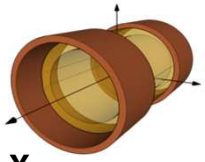
Measurement of the accelerations applied to the test masses to keep them centered and concentric	
d: differential mode (half difference) → contains the EP violation term	c: common mode (half sum) → command of the drag-free system

EP violation parameter :

$$\delta = \frac{m_{2\,g}}{m_{2\,I}} - \frac{m_{1\,g}}{m_{1\,I}}$$

Gravity gradient **Inertia gradient**

$$\Gamma_{mes,dx} = \frac{1}{2}(\Gamma_{mes,1} - \Gamma_{mes,2}) = \frac{1}{2}K_{1cx}\cdot\delta\cdot g_{x/sat} + \frac{1}{2}\begin{bmatrix} K_{1cx} \\ \eta_{cz} + \theta_{cz} \\ \eta_{cy} - \theta_{cy} \end{bmatrix}^t \cdot [T - In] \cdot \begin{bmatrix} \Delta_x \\ \Delta_y \\ \Delta_z \end{bmatrix}$$



$$+ \begin{bmatrix} K_{1dx} \\ \eta_{dz} + \theta_{dz} \\ \eta_{dy} - \theta_{dy} \end{bmatrix}^t \cdot (\vec{\Gamma}_{res_{df}} + C_x) + 2\cdot K_{2cxx}\cdot(\Gamma_{app,dx} + b_{1dx})\cdot(\Gamma_{res_{df},x} + C_x - b_{0cx})$$

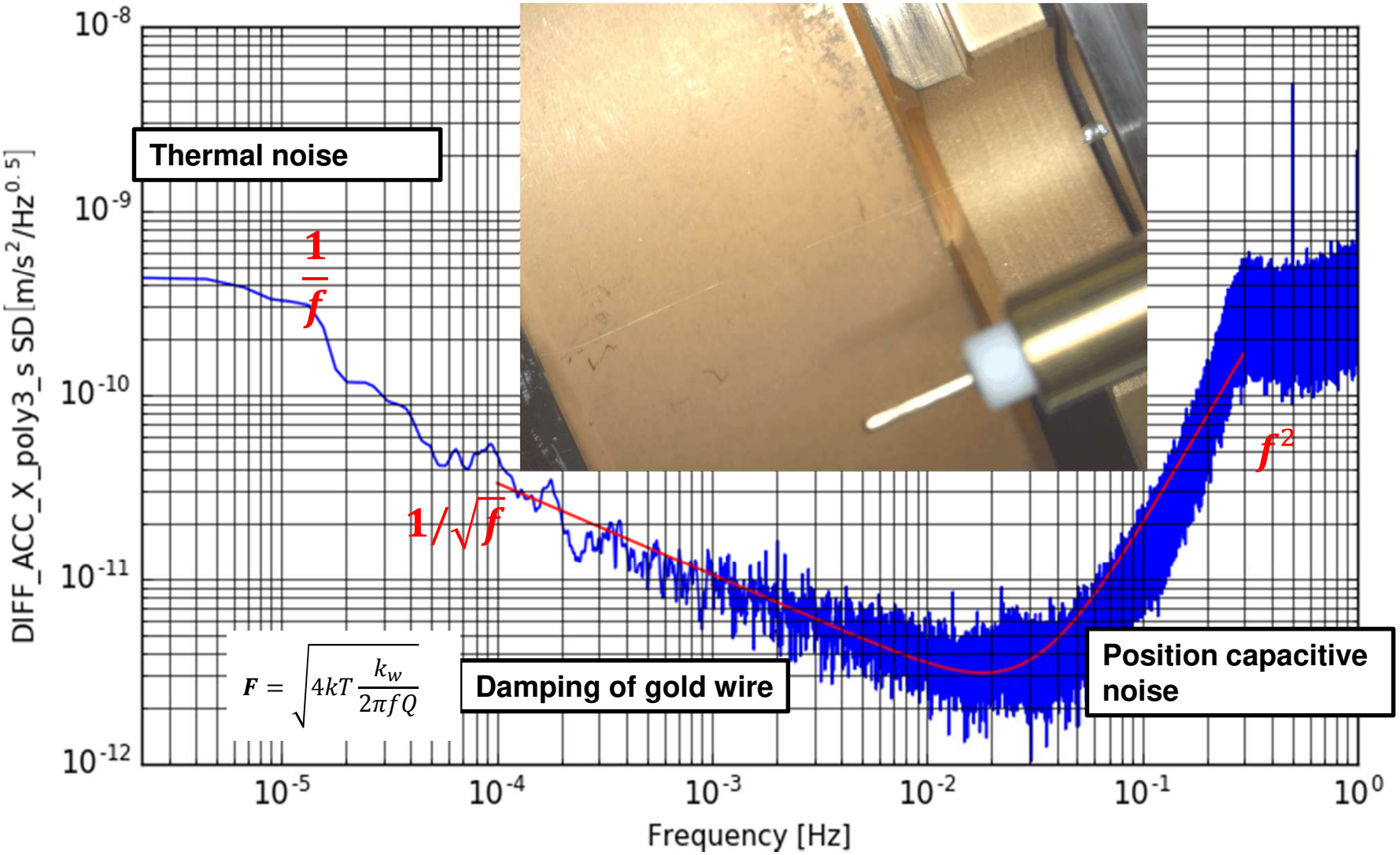
$$+ K_{2dxx}\cdot\left((\Gamma_{res_{df},x} + C_x - b_{0cx})^2 + (\Gamma_{app,dx} + b_{1dx})^2\right)$$

b_0 : bias
b_1 : parasitic forces
$\Gamma_{res,df}$: drag-free residual
C : drag-free command

Δ : off-centering
K_1 : scale factor
η : coupling

θ : misalignement
K_2 : quadratic term

In orbit SUREF half difference of the acceleration spectrum noise (All tone signals are subtracted from the plot)



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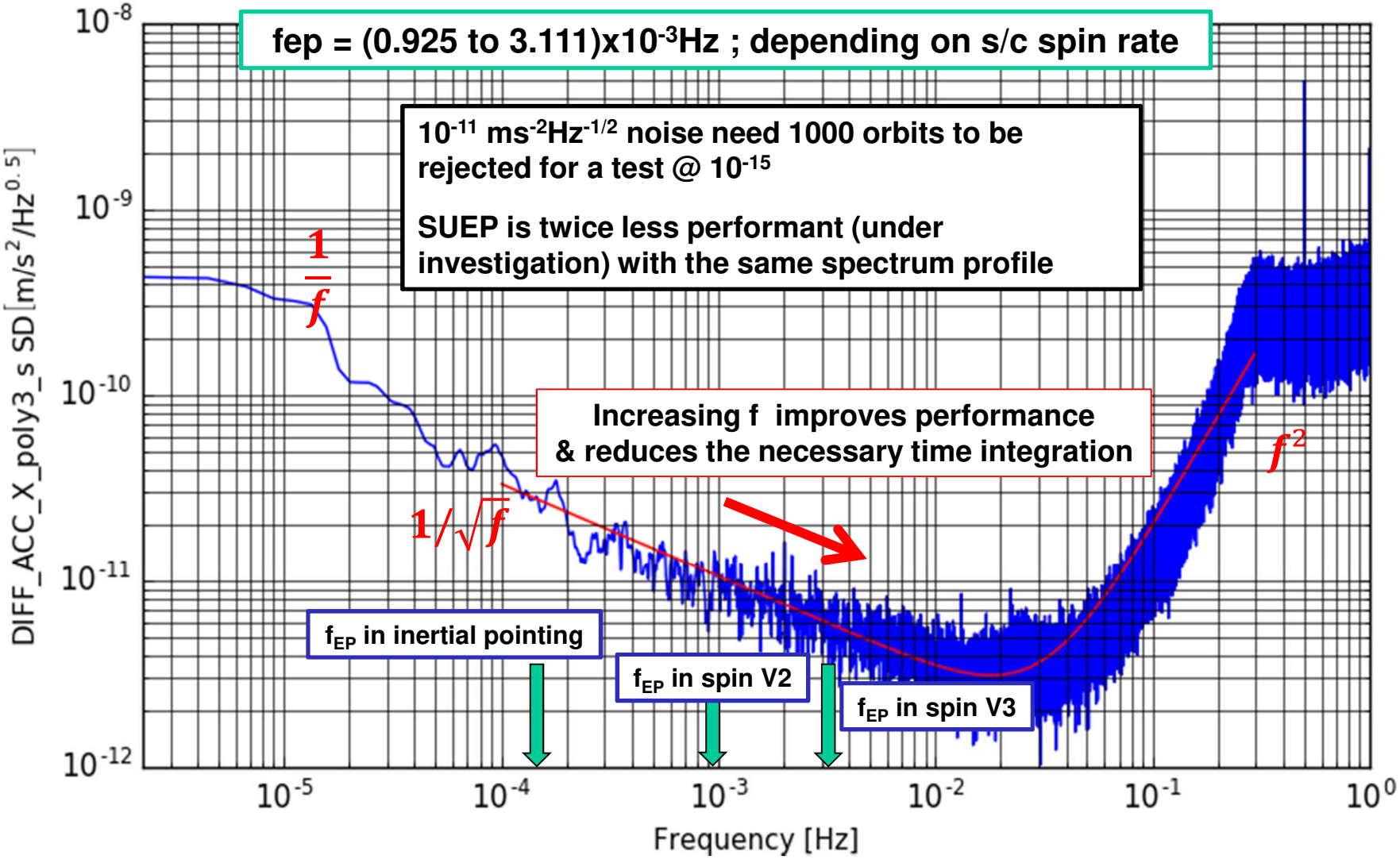
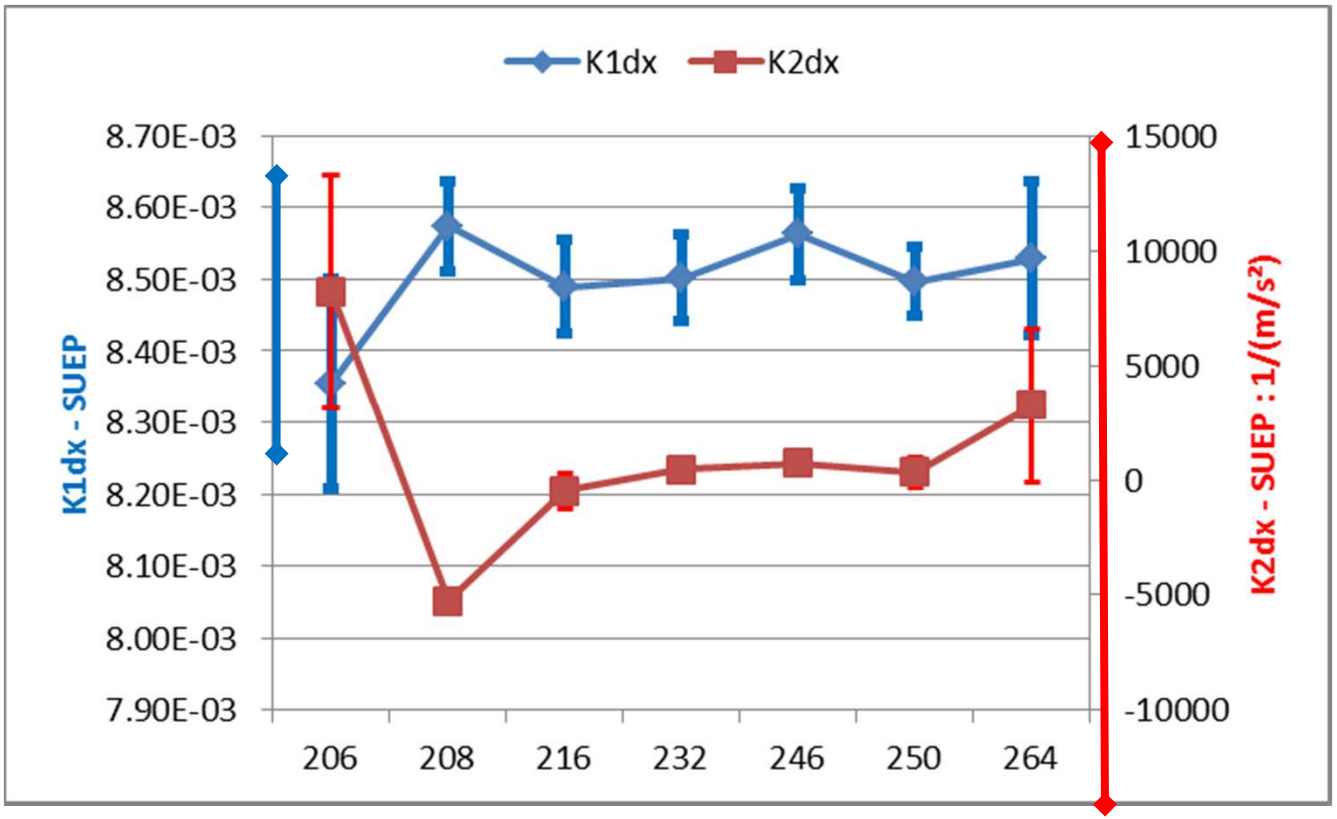


Scale factor matching (K1dx)
& Quadratic non linear term matching (K2dx)

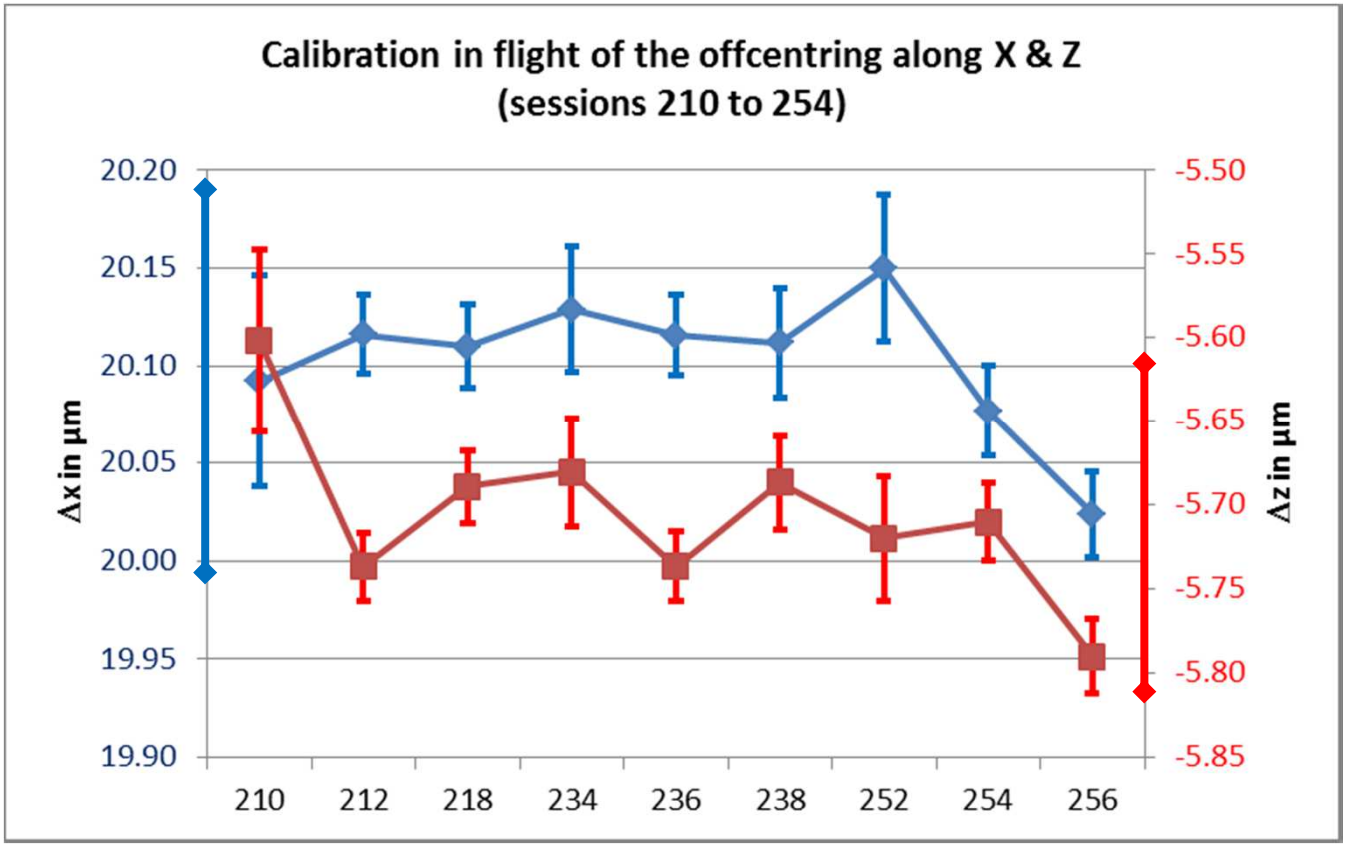


Spec domain on K2dx
< 15000 $(m/s^2)^{-1}$

Uncertainty domain spec for estimation of K1dx
± 2 10^{-4}

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

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



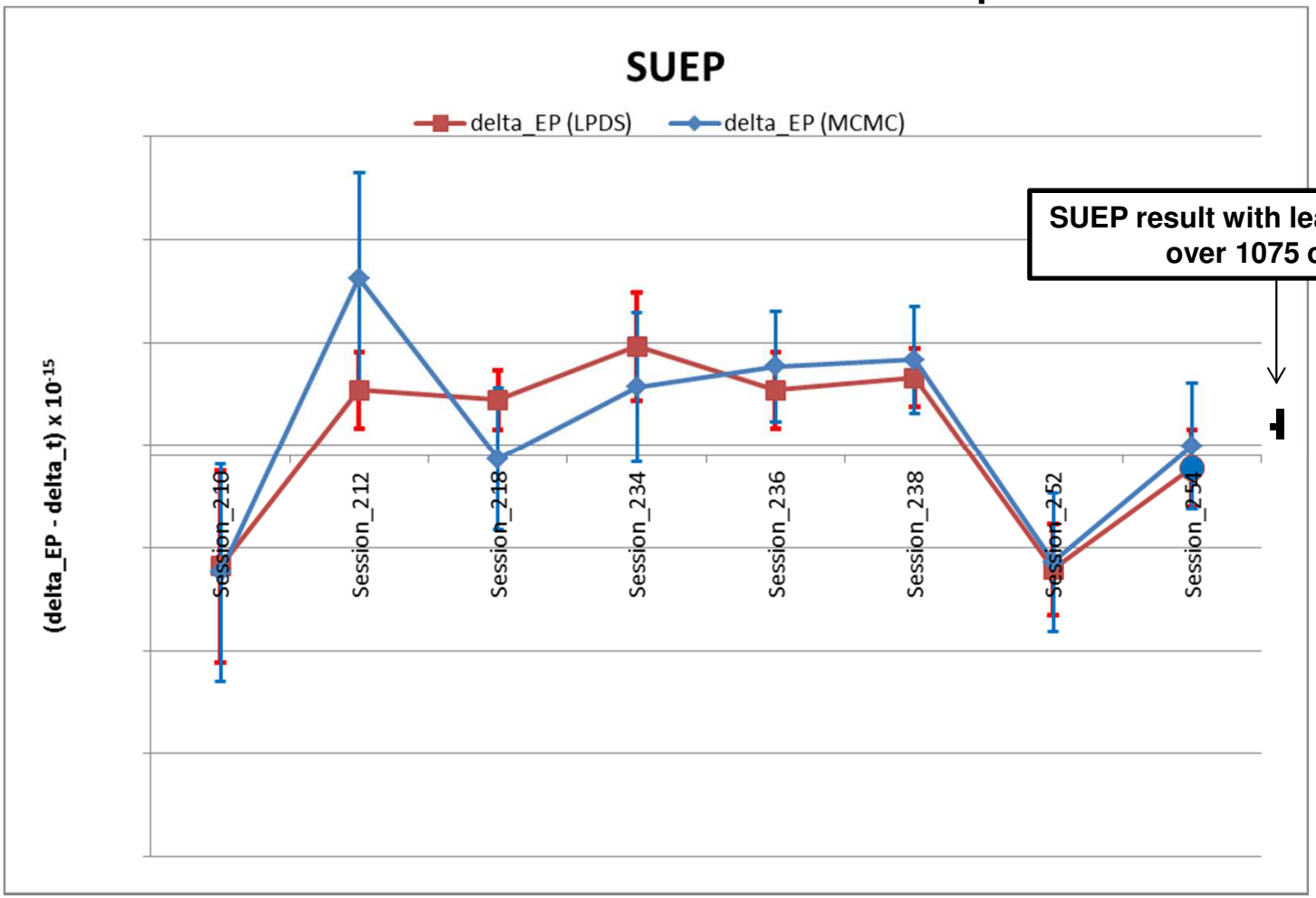
Uncertainty domain spec for estimation of Δz ± 0.1µm

Uncertainty domain spec for estimation of Δx ± 0.1µm

- The offcentrings are extracted at the same time as the Eotvos parameter
- Dispersion on session 210 could come from non linearity at the limit of specs (session 206 & 208 performed just before)

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**
- **The science session will be resumed in September 2017**
- **With the remaining gas, we should cumulated another 480 orbits for SUEP and 424 orbits for SUREF dedicated to EP test :**

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

Science data process and preliminary results

- 3 methods have been used and give quite the same result:
  - Monte-Carlo Markov Chains Hammer (H. Inchauspe – Post-doc ONERA)
  - Kalman Auto-Regressive Model Analysis (Q. Baghi thesis ONERA/OCA)
  - Least-square fit in the frequency domain (OCA/ONERA)
- The stochastic noise reduces with time integration and have been verified over the 1075 usable orbits
- Systematics comes principally from thermal sensitivity: at the moment an upper limit have been established and should compete the stochastic noise over 1075 orbits….. More work on going to better quantify the upper limit of the systematics

Conclusion

- Despite the first fears of the commissioning phase, the satellite & all subsystems are now working very well for the best detection of the Equivalence Principle 'violation or not' for an objective of 10^{-15}
- A paper is under review to give the first & preliminary scientific results on the test of EP for Pt/Ti
- The end of the mission is foreseen by mid 2018
- An announcement of distribution of data will be released after publication of the last results (2019)

TANK YOU FOR YOUR ATTENTION

& Stay tune for very exciting results coming soon …
https://microscope.onera.fr