Catapult tests for microgravity characterization of the MICROSCOPE accelerometers

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On behalf ONERA & ZARM team

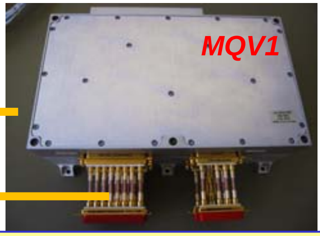
ONERA
THE FRENCH AEROSPACE LAB

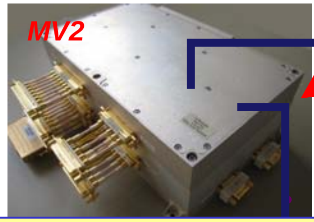
ZARM

retour sur innovation

Instrument Description

360 x 348 x 180 mm³ - 25kg





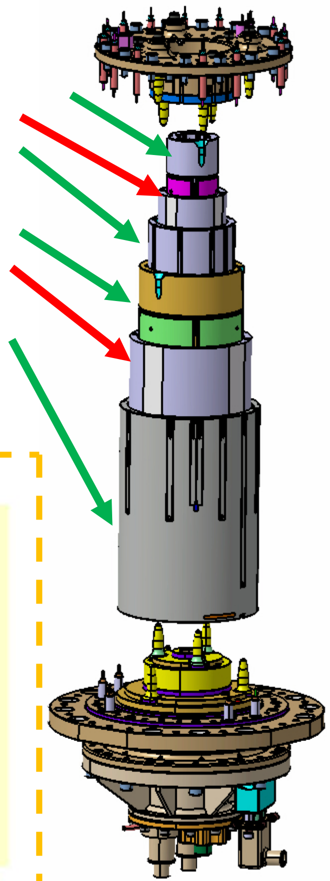
2 x { 28 cm x 17 cm x 9 cm - 3.5kg - 7W }

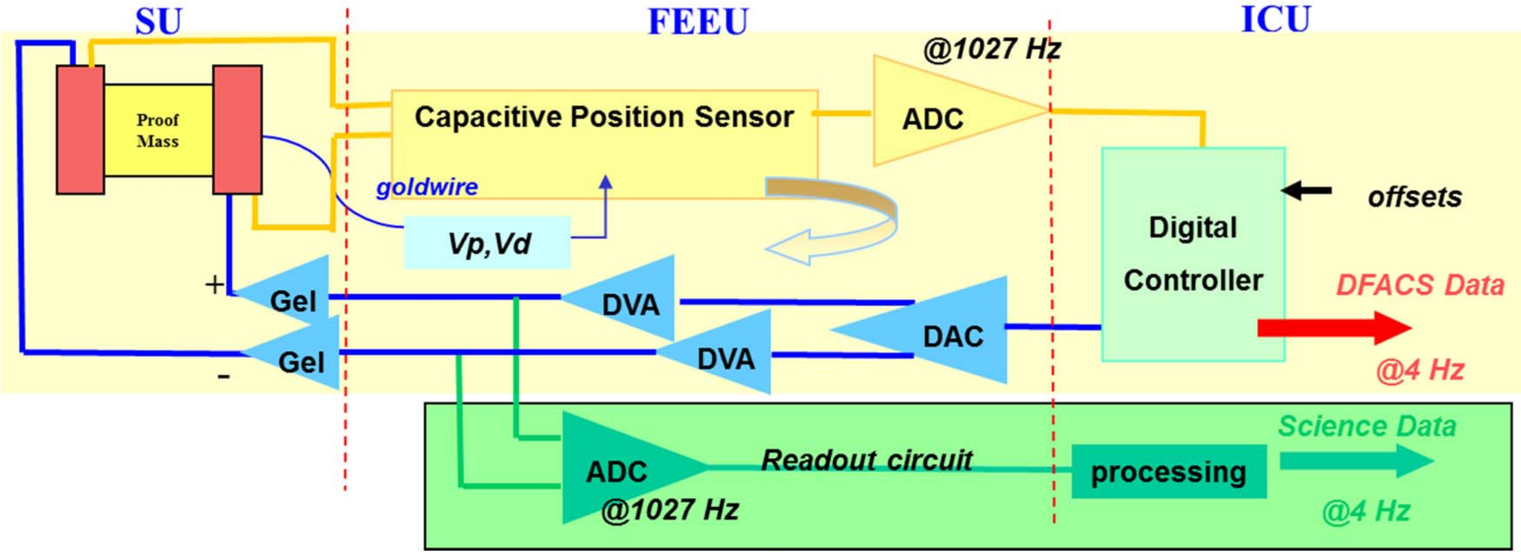
30 cm x 25 cm x 11 cm – 5kg – 2 x 11W

- Sensor Unit (SU) = differential accelerometer
  - **2 SU** on a Mechanics Interface (SUMI)
  - Each SU = 2 concentric Test-Masses (**Pt-Rh/Pt-Rh** or **Ti/Pt-Rh**)
  - Each mass = inertial sensor (defines measurement frame)
- Front End Electronics Unit (FEEU)
  - **Low noise analog electronic** with high stability
  - One FEEU for each SU
  - Each FEEU = measure + electrostatic control of 6 degrees of freedom
- Interface Control Unit (ICU)
  - 2 ICU stacked = ICUME
  - 1 ICU for each FEEU
  - Each ICU embarks 1 **DSP** + 1 **FPGA** for test-mass control and data conditioning for the On Board Computer
  - Each ICU embarks 2 **Power Control Unit** (1 nominal + 1 redundant) which converts the sat 28V in very stable secondary voltages (+/-48V, +/-15V,+5V,3.3V)

MICROSCOPE Differential accelerometer

- Each test-mass is surrounded by a set of electrodes to control 6 degrees of freedom
- Each degree of freedom is numerically controlled:
  - A high sensitive capacitive sensor
  - A 40V drive voltage amplifier
  - A digital "PID" controller delivering acc measurements (DFACS Data)
  - An out of loop measurement pick-up for X (Science Data)





- Stable DC voltage (Vp) and 100kHz voltage (Vd) applied to the TM

Operating range of the inertial sensor & test environment constraints

Worst case based on Pt-Rh heaviest mass	**HRM**	**FRM**	**FRM (Free-Fall)**
	Vp = 5V	Vp = 40V	Vp = 90V
	Vd = 5V	Vd = 1V	Vd = 1V
Electronics configuration	EM & FM	EM & FM	EM
Control acceleration range (X)	1 µm/s²	8 µm/s²	38 µm/s²
Control acceleration range (Y/Z)	6 µm/s²	94 µm/s²	450 µm/s²
Measurement acc range (X EP / DFACS)	0.4 / 1 µm/s²	4 / 8 µm/s²	8 / 38 µm/s²
Measurement acc range (Y/Z)	6 µm/s²	94 µm/s²	450 µm/s²
Capacitive sensor range (X)	27 µm	135 µm	135 µm
Capacitive sensor range (Y/Z)	23 µm	110 µm	110 µm
Evaluated bias (X DFACS)	5 nm/s²	55 nm/s²	240 nm/s²
Evaluated bias (Y/Z)	0.2 µm/s²	8.7 µm/s²	40 µm/s²

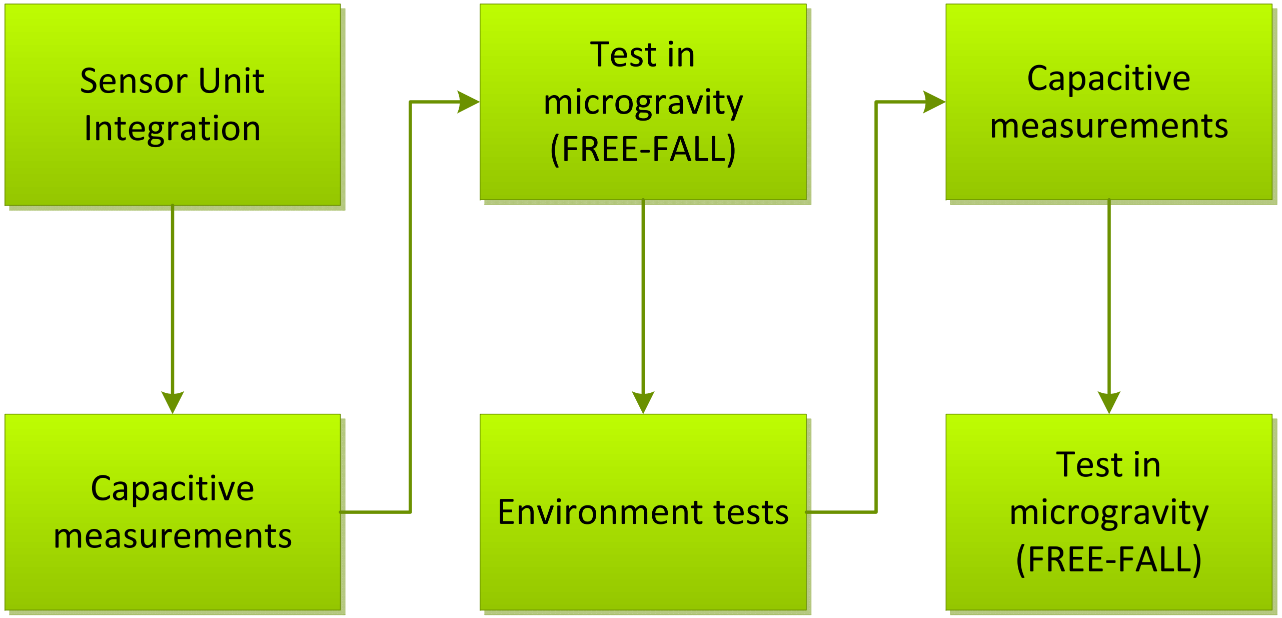
Science Mode in orbit	**Robust mode for commissionning phases or non drag free modes**	**Boost mode for free-fall**

FREE-FALL ENVIRONMENT:

- Standard capsule : along drag 100µm/s² to 200µm/s² _ horizont. axes <20µm/s² (4.7sec)
- Free-Flyer : along all axes <20µm/s² (4 sec)
- Catapult : along drag 100µm/s² to 200µm/s² _ horizont. axes <20µm/s² (9sec)

Philosophy of test

Qualification Model and Flight Model of the Sensor Units are tested in free-fall as ground operation is not possible



Capacitive measurements in laboratory
Determination of scale factors

MEASUREMENTS IN DIFFERENT PREDICTABLE POSITIONS

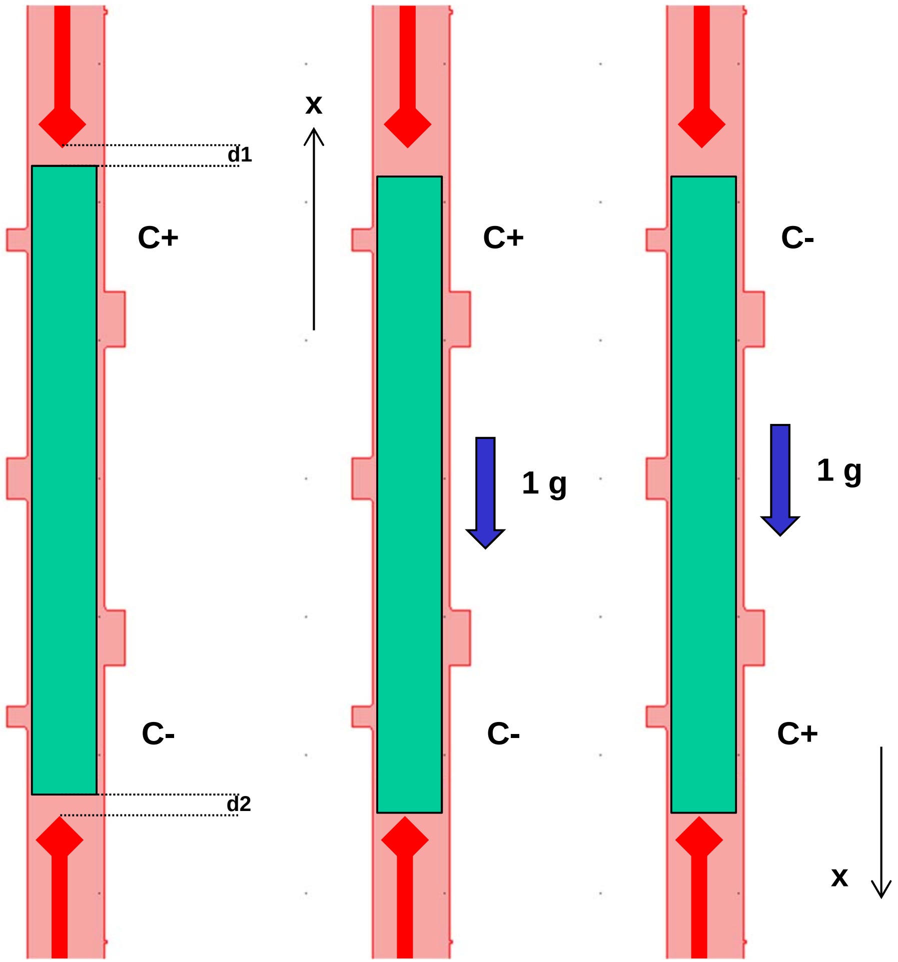
Capacitance sensitivity to displacement and geometry

SU	SU A		SU B	
Electrode	Capacitance in pF	Conductance in nS	Capacitance in pF	Conductance in nS
X1+	16.4047	-0.002	26.9024	-0.002
X1-	16.6455	-0.001	27.4345	0.001

Masse d'épreuve en x=–d2

SU	SU A		SU B	
Electrode	Capacitance in pF	Conductance in nS	Capacitance in pF	Conductance in nS
X1+	16.6607	-0.003	27.2809	-0.006
X1-	16.3856	-0.001	27.0205	-0.003

Masse d'épreuve en x=+d1



C+ = C- (x=0)
In orbit levitation

C+ & C-
For x=-d2
Under 1 G

C+ & C-
For x=d1
Under 1 G

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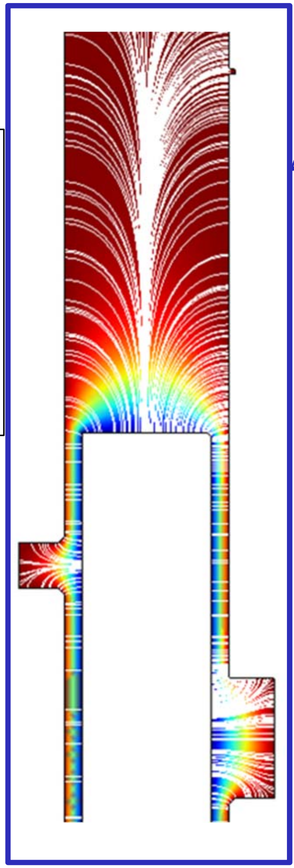
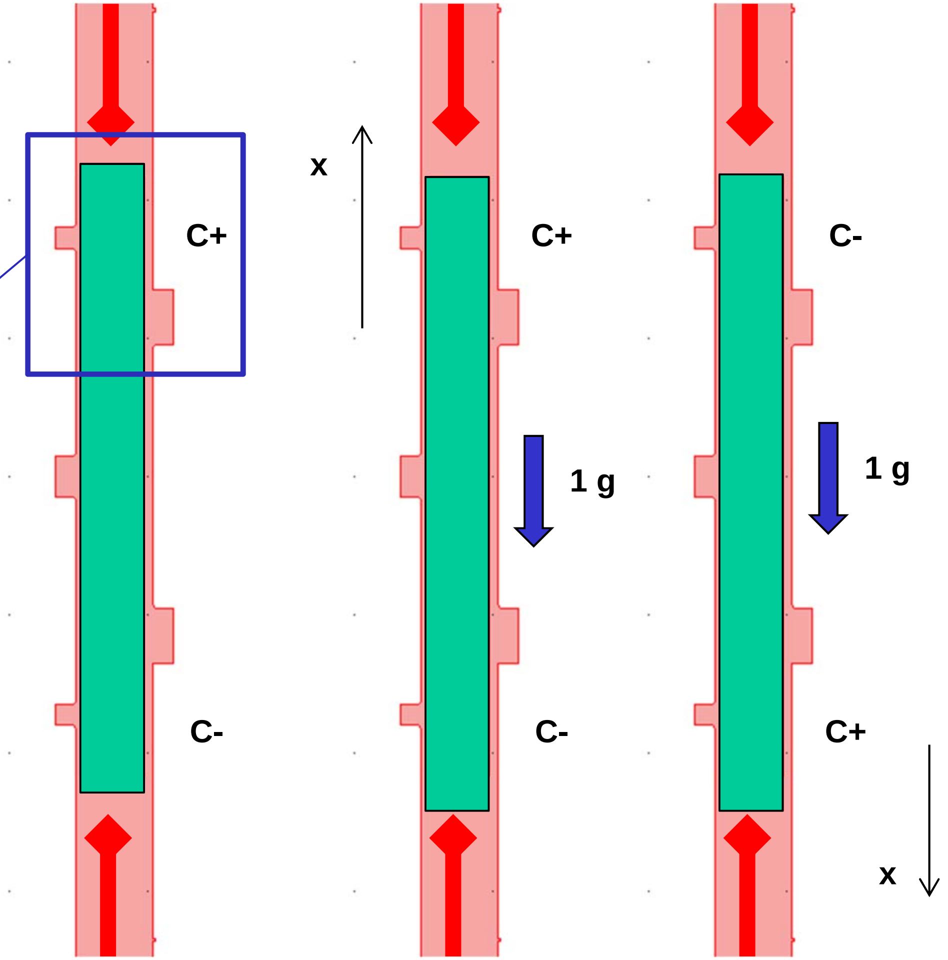
Capacitive measurements in laboratory
Determination of scale factors

A simplified analytic expression of the capacitance thanks to an electrostatic finite element model

$$\left(2\pi - 4(2\alpha)\right)\varepsilon_0 \frac{(L_x + x)}{ln\left(\frac{R_e}{R_m}\right)}$$
$$+4(2\alpha)\varepsilon_0 \frac{(L_x + x)}{ln\left(\frac{R_e}{R'_d}\right)}$$
$$+2\pi\varepsilon_0\left(\frac{R_e + R_m}{2}\right)\frac{2}{\pi} ln\left(1 + \frac{\pi}{4}\frac{1.2p_1}{R_e - R_m}\right)$$
$$+2\pi\epsilon_0\left(\frac{R_e + R_m}{2}\right)\frac{2}{\pi}\left[ln\left(1 + \frac{\pi}{2}\frac{2\beta_+ D_m}{R_e - R_m}\right)\right]$$

Analytic Model of Cx+



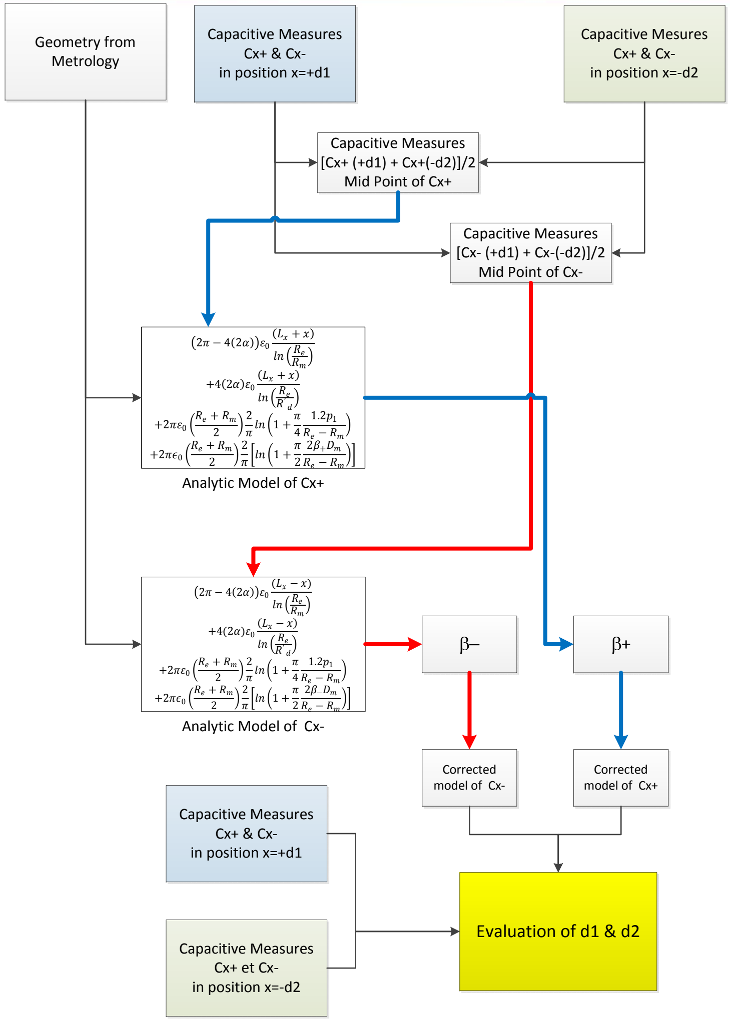


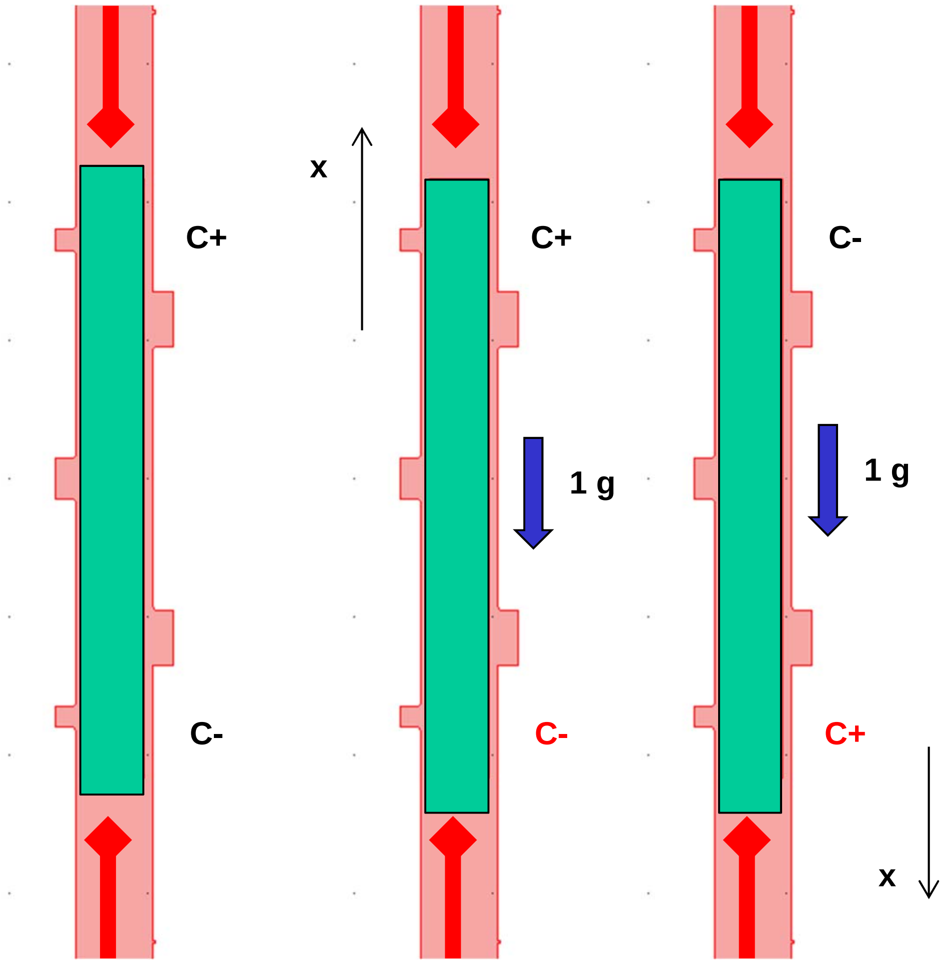
C+ = C- (x=0)
In orbit levitation

C+ & C-
For x=-d2
Under 1 G

C+ & C-
For x=d1
Under 1 G

Capacitive measurements in laboratory
Determination of scale factors





C+ = C- (x=0)
In orbit levitation

C+ & C-
For x=-d2
Under 1 G

C+ & C-
For x=d1
Under 1 G

Confirmation of the free motion of the test-masses

Capacitive data available

Sens Positif X

SU Electrode	SU Internal Capacitance in pF	SU Internal Conductance in nS	SU External Capacitance in pF	SU External Conductance in nS
X1+	16.4047	-0.002	26.9024	-0.002
X1-	16.6455	-0.001	27.4345	0.001
Y1+	5.0104	-0.002	21.246	0.008
Y1-	5.1175	-0.001	21.474	0.01
Y2+	5.0276	-0.001	21.1313	0.007
Y2-	5.1406	0.001	21.7052	0.007
Z1+	5.06	0.001	20.997	0.007
Z1-	5.1451	0.001	21.8979	0.008
Z2+	5.0547	0.004	20.7599	0.01
Z2-	5.2499	0.002	22.2356	0.01
Φ1+	4.1331	-0.002	20.952	-0.002
Φ2+	4.1501	-0.001	20.3568	-0.003
Φ1-	4.1363	0.001	20.6495	-0.005
Φ2-	4.1717	0.001	20.8444	0.001
Φ3+	4.0908	0.001	19.6025	0.003

Sens Positif Y

SU Electrode	C			
X1+				
X1-				
Y1+				
Y1-				
Y2+				
Y2-				
Z1+				
Z1-				
Z2+				
Z2-				
Φ1+				
Φ2+				
Φ1-				
Φ2-				
Φ3+				
Φ4+				
Φ3-	4.0438	-0.0007	19.4518	0.01
Φ4-	4.856	0.01	23.1809	0.06

Sens Positif Z

SU Electrode	SU Internal Capacitance in pF	SU Internal Conductance in nS	SU External Capacitance in pF	SU External Conductance in nS
X1+	16.6434	-0.003	27.3172	-0.002
X1-	16.6588	-0.002	27.3725	-0.001
Y1+	5.0621	-0.002	21.9458	0.004
Y1-	5.0893	-0.0004	20.8846	0.007
Y2+	5.1192	-0.01	22.4114	0.002
Y2-	5.0671	0.004	20.6314	0.005
Z1+	5.7432	-0.001	23.8329	0.008
Z1-	4.5908	-0.002	19.5126	0.008
Z2+	5.6879	0.002	24.6593	0.007
Z2-	4.7054	0.003	19.1055	0.008
Φ1+	3.6956	-0.0006	18.1433	-0.002
Φ2+	4.3097	-0.0009	20.8097	0.001
Φ1-	3.7162	0.001	18.5112	-0.004
Φ2-	3.9304	-0.001	18.916	0.001
Φ3+	4.6244	-0.0003	22.915	-0.002
Φ4+	3.9545	0.0007	19.8252	-0.001
Φ3-	4.7071	0.001	22.3998	0.001
Φ4-	4.5921	0.01	22.0152	0.01

Before closing the housing, all electrode signals are available

SU Electrode	SU Internal Capacitance in pF	SU Internal Conductance in nS	SU External Capacitance in pF	SU External Conductance in nS
X1+	16.6607	-0.003	27.2809	-0.006
X1-	16.3856	-0.001	27.0205	-0.003
Y1+	5.097	-0.0002	21.1025	-0.006
Y1-	5.0254	0.0001	21.6097	0.008
Y2+	5.0976	-0.001	21.4426	0.003
Y2-	5.0562	0.0003	21.3556	0.003
Z1+	5.0352	-0.0003	21.3466	0.002
Z1-	5.132	-0.001	21.5109	0.005
Z2+	5.0563	0.002	21.3065	0.008
Z2-	5.184	0.0001	21.6255	0.01
Φ1+	4.0929	-0.002	20.462	-0.001
Φ2+	4.0621	-0.001	20.463	-0.004
Φ1-	4.1469	-0.0005	20.2549	-0.002
Φ2-	4.0813	0.0003	20.5468	-0.002
Φ3+	4.1149	-0.0005	20.0177	0.002
Φ4+	4.1705	0.0002	20.104	0.001
Φ3-	4.163	0.0004	20.23	-0.003
Φ4-	4.3486	0.01	20.0428	0.008

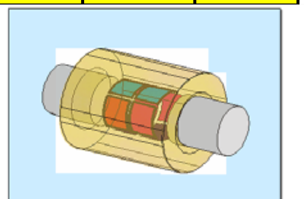
Sens Negatif Y

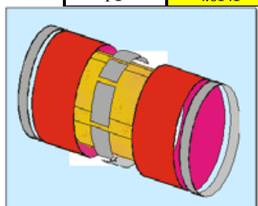
SU Electrode	SU Internal Capacitance in pF	SU Internal Conductance in nS	SU External Capacitance in pF	SU External Conductance in nS
X1+	16.6597	-0.004	27.302	0.001
X1-	16.6537	-0.001	27.4107	-0.005
Y1+	4.5194	0.004	19.2338	0.004
Y1-	5.7705	-0.0004	24.0425	0.01
Y2+	4.5604	-0.001	19.1593	0.009
Y2-	5.7465	0.0005	24.2954	0.01
Z1+	5.0441	0.0005	20.8584	0.007
Z1-	5.184	-0.0007	21.9064	0.008
Z2+	5.0644	0.003	21.1301	0.01
Z2-	5.2355	0.002	21.9361	0.01
Φ1+	4.3345	-0.001	21.7682	-0.002

Sens Negatif Z

SU Electrode	SU Internal Capacitance in pF	SU Internal Conductance in nS	SU External Capacitance in pF	SU External Conductance in nS
X1+	16.6635	-0.004	27.3899	-0.005
X1-	16.6454	-0.003	27.4488	-0.004
Y1+	5.1343	-0.002	21.3643	0.005
Y1-	5.0308	-0.001	21.4921	0.01
Y2+	5.1221	-0.002	21.1487	0.01
Y2-	5.0689	-0.002	21.8766	0.008
Z1+	4.4953	-0.002	19.0903	0.003
Z1-	5.8905	-0.004	24.4859	0.002
Z2+	4.5868	-0.002	18.7325	0.001
Z2-	5.8519	-0.002	25.2367	0.002
Φ1+	4.6141	-0.008	23.4127	-0.002
		-0.008	19.4734	-0.007
		-0.001	23.0109	-0.007
		-0.004	21.9131	0.002
		-0.003	17.8689	0.005
		-0.001	21.2259	0.003
		-0.001	18.1153	-0.002
		0.01	18.0229	0.01


Spin Electrodes


Radial Electrodes


Axial Electrodes

Phi **Y, Z, Theta, Psi** **X**

Capacitive data available

Sens Positif X

SU Electrode	SU Internal Capacitance in pF	SU Internal Conductance in nS	SU External Capacitance in pF	SU External Conductance in nS
X1+	16.16123	0.0065	26.8617	0.00116
X1-	16.585	-0.0011	27.6921	0.00127
Y1+	5.07035	-0.005	21.058	0.00175
Y1-	5.15061	-0.0989	21.7236	0.002
Y2+	5.077	-0.0212	21.42008	0.00191
Y2-	5.169	-0.00878	21.5883	0.002002
Z1+	4.9475	-0.00499	21.4394	0.00247
Z1-	5.3259	-0.00165	21.3891	-0.00266
Z2+	4.931	-0.00416	21.3883	0.0007
Z2-	5.447	-0.001	21.5912	-0.00139
Φ1+	8.2698	-0.0014	40.9467	0.00168

Sens Positif Y

SU Electrode	SU Internal Capacitance in pF	SU Internal Conductance in nS	SU External Capacitance in pF	SU External Conductance in nS
X1+	16.5544	-0.0032	27.8445	0.0003
X1-	16.6397	-0.0033	27.6586	-0.0001
Y1+	6.0665	-0.033	24.8549	0.0017
Y1-				
Y2+				
Y2-				
Z1+				
Z1-				
Z2+				
Z2-				
Φ1+				
Φ2+				
Φ1-				
Φ2-				
Φ3+				
Φ4+				
Φ3-				
Φ4-				

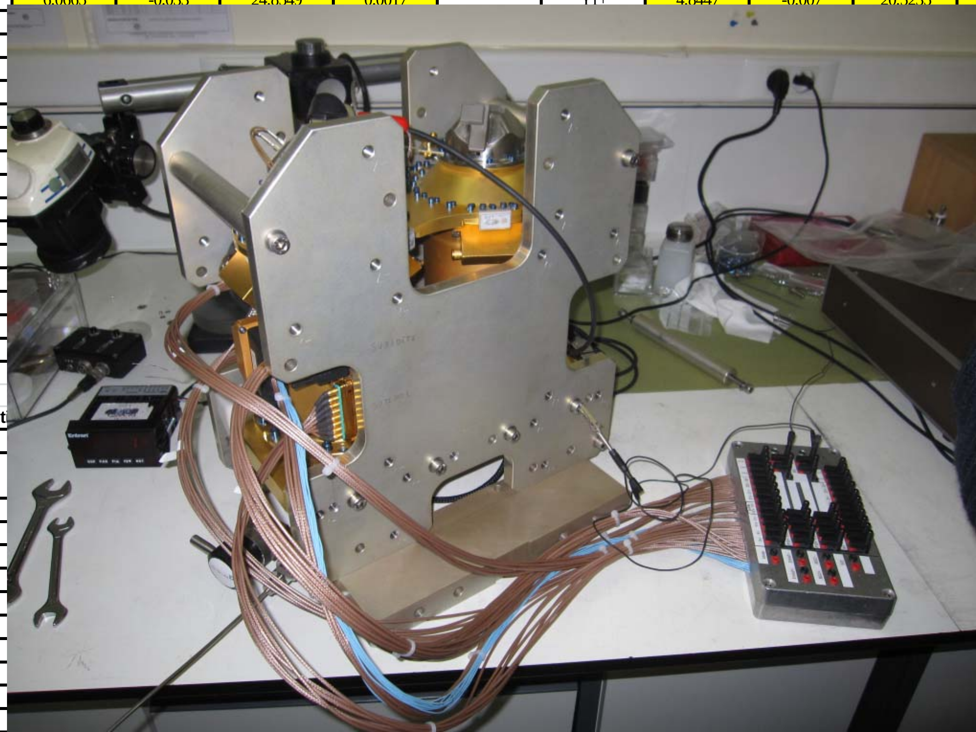
Sens Positif Z

SU Electrode	SU Internal Capacitance in pF	SU Internal Conductance in nS	SU External Capacitance in pF	SU External Conductance in nS
X1+	16.525	-0.00267	27.4658	0.0008
X1-	16.5975	-0.002	27.7034	0.0008
Y1+	4.8447	-0.007	20.5235	0.00128
				0.0018
				0.0014
				0.002
				0.0028
				0.0019
				0.0042
				0.0029
				0.004
				0.0004
				0.0051
				0.0062

After closing the housing,

Phi signal are mean value of pairs.

Post processing of capacitance measurements are in good agreement with analytic formulas to 1 to 2% error **for X, Y, Z**



SU Electrode	SU Internal Capacitance in pF	SU Internal Conductance in nS	SU External Capacitance in pF	SU External Conductance in nS
Z2+	5.209	0.0011	21.574	0.0045
Z2-	5.1845	0.00009	21.3515	0.0051
Φ1+	8.219	-0.0007	41.6178	0.0056
Φ2+				
Φ1-	8.1579	-0.0008	40.9516	0.0041
Φ2-				
Φ3+	8.0746	-0.0008	39.564	0.005
Φ4+				
Φ3-	8.1464	-0.00045	40.4059	0.0056
Φ4-				

Sens Negati…

SU Electrode	SU Internal Capacitance in pF	SU Internal Conductance in nS	SU External Capacitance in pF	SU External Conductance in nS
X1+				
X1-				
Y1+				
Y1-				
Y2+				
Y2-				
Z1+				
Z1-				
Z2+				
Z2-				
Φ1+	8.98745	-0.0005	43.5024	0.0078
Φ2+				
Φ1-	8.509	-0.007	42.054	0.0074
Φ2-				
Φ3+	7.48188	-0.0009	38.0607	0.00062
Φ4+				
Φ3-	7.9832	-0.0003	39.6898	0.0068
Φ4-				

SU Electrode	SU Internal Capacitance in pF	SU Internal Conductance in nS	SU External Capacitance in pF	SU External …nal …onductance in nS
				0.003
				0.002
				0.0024
				0.0031
				0.0026
				0.0032
				0.003
				0.005
				0.004
				0.007
Φ1+	8.5251	-0.002	43.9526	0.008
Φ2+				
Φ1-	9.0194	-0.0025	45.6832	0.008
Φ2-				
Φ3+	7.9395	-0.002	38.2848	0.006
Φ4+				
Φ3-	7.4601	-0.0028	36.6679	0.006
Φ4-				

Available data thru FEEU/ICUME (nominal conf)

- House Keeping @ 1Hz:
  - 4 Test Mass positions and attitudes (6 degrees of freedom)
  - Vp, Vd for each TM
  - 6 temperatures per SU, 5 temp per FEEU, 6 per ICUME
  - Force value of blocking system
  - Power supply voltages
  - Different status (memories, slew rates, latchups, control laws configuration,….)

- Science data @ 4Hz:
  - 6 acceleration (linear & angular) measurements per mass (6 degrees of freedom)
  - High resolution acceleration along X for each TM

DROP TEST CONFIGURATION

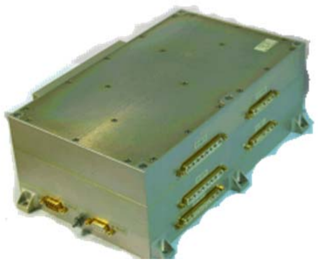
A challenge for getting a convergence within 4.7 seconds

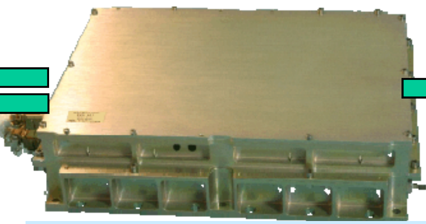
- Electrode control voltage boosted from 50V to 100V
- Optimized servo control (PID type)

- Data acquisition

Data, sampled at 1kHz, are acquired by the ICU from the FEEU via one bi-directional RS422 link at 1.25Mbaud. A spy line has been implemented from this link to an acquisition and storage system in order to collect data during the drop.

PXI spy
For data acquisition : 1 or 2 channels (SU+FEEU+ICU)





24 V

Batteries

FEEU:Control voltages boosted to 100V

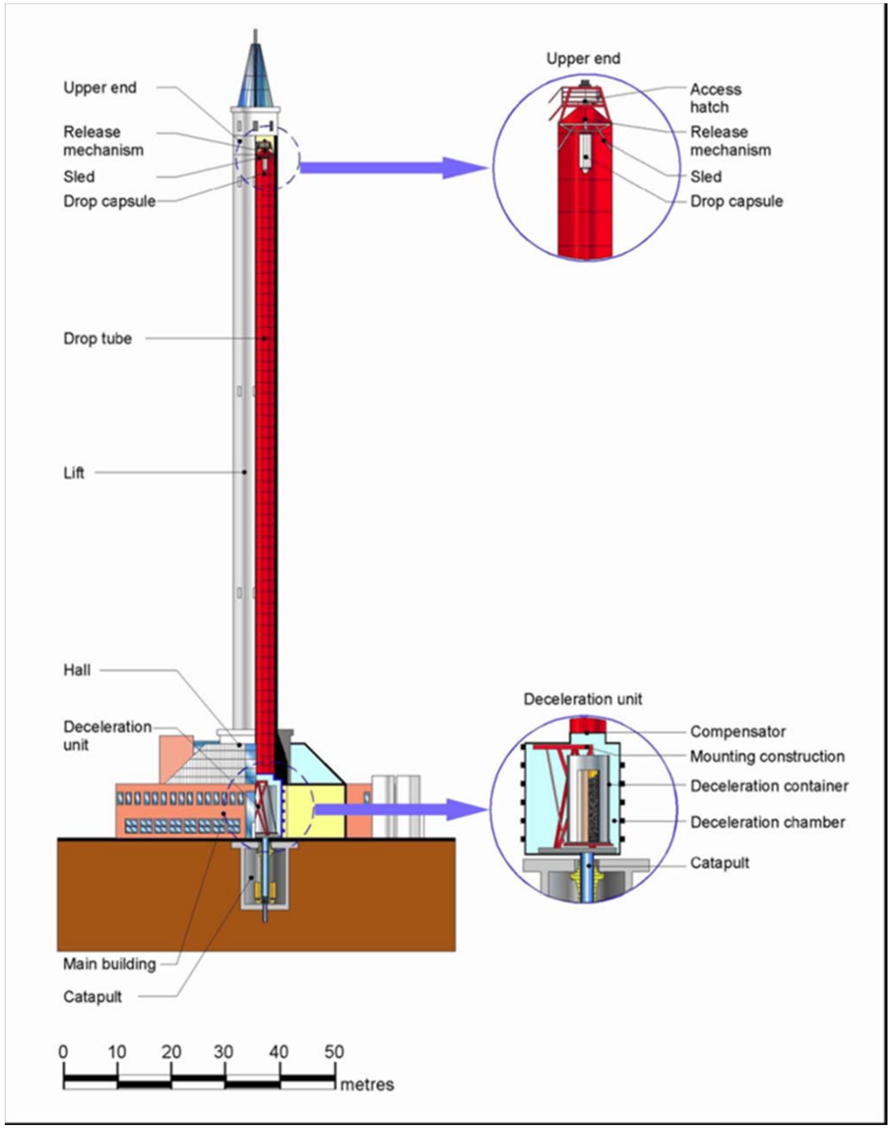
ICU:Servo Control laws Parameters patchable adjusted for the drop

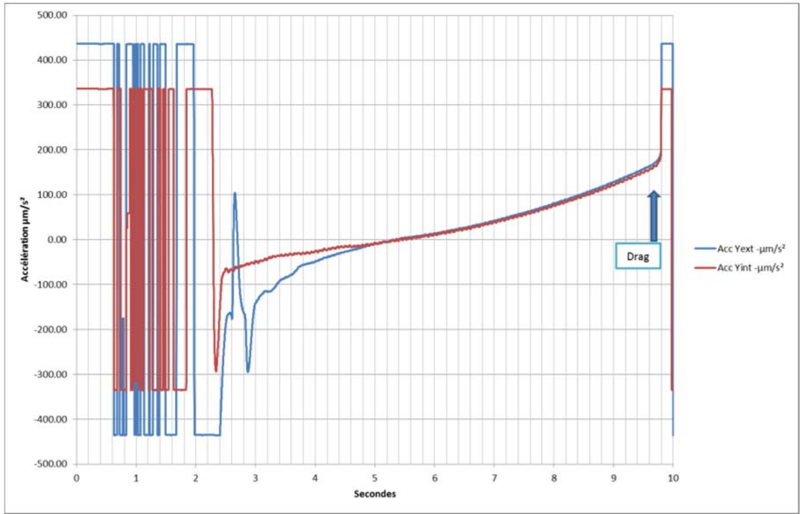
Available data thru ground specific link between FEEU & ICUME (FREE-FALL CONF)

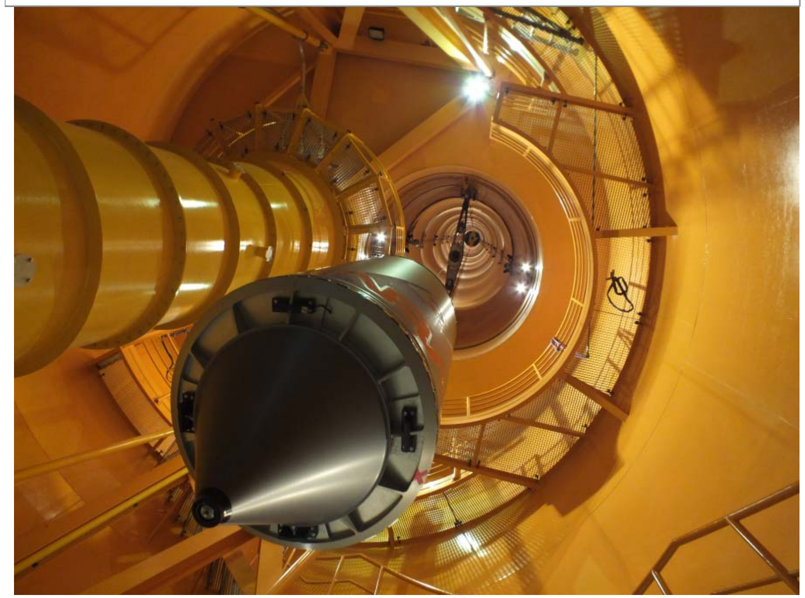
- **@ 1027 Hz:**
  - 4 Test Mass positions and attitudes (6 degrees of freedom)
  - Vp, Vd for each TM
  - 6 temperatures per SU, 5 temp per FEEU, 6 per ICUME
  - Force value of blocking system
  - Power supply voltages
  - Different status (memories, slew rates, latchups, control laws configuration,….)

  - 6 acceleration (linear & angular) measurements per mass (6 degrees of freedom)
  - High resolution acceleration along X for each TM

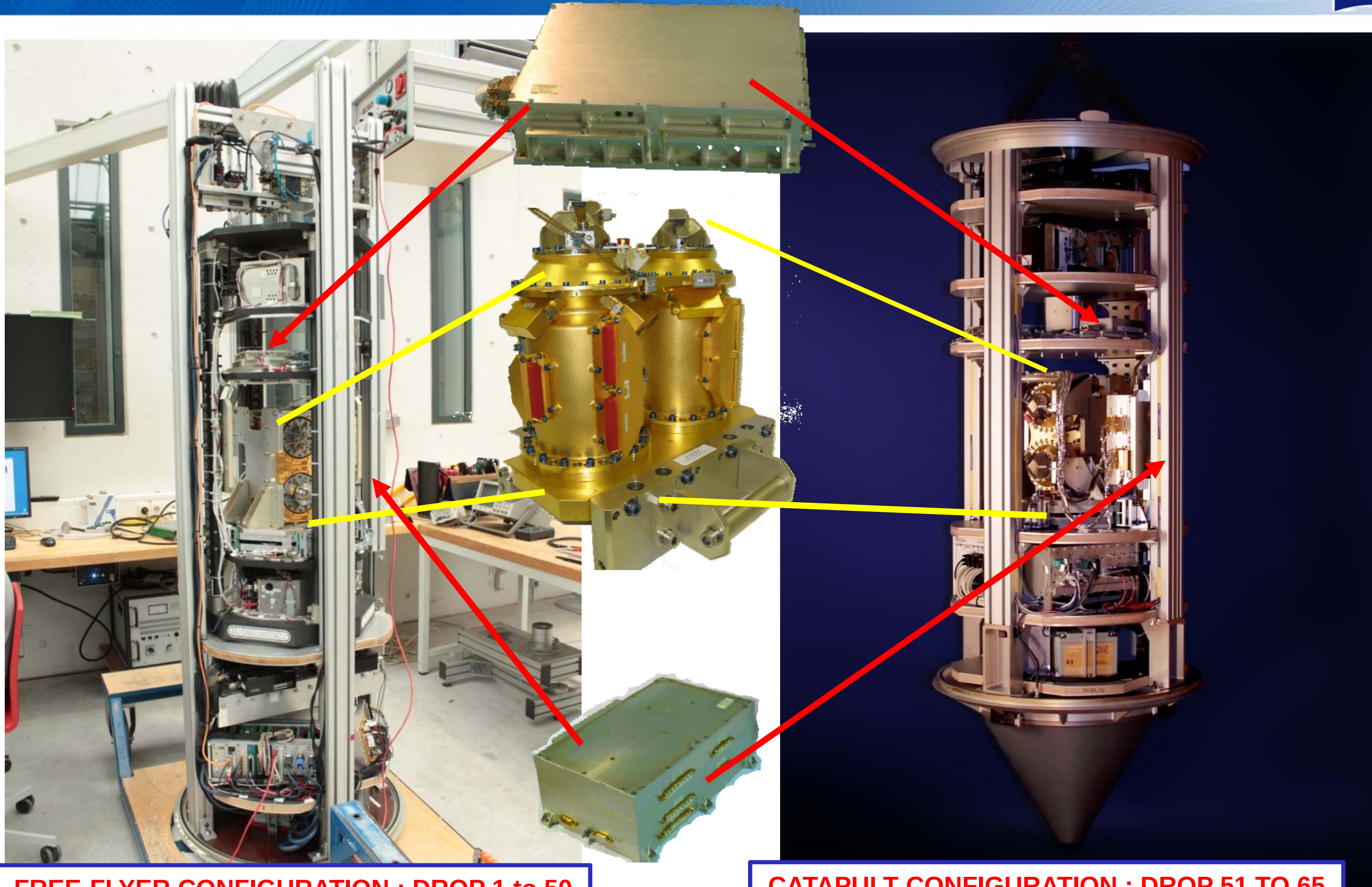
Catapult test of SUQM – drop n°55





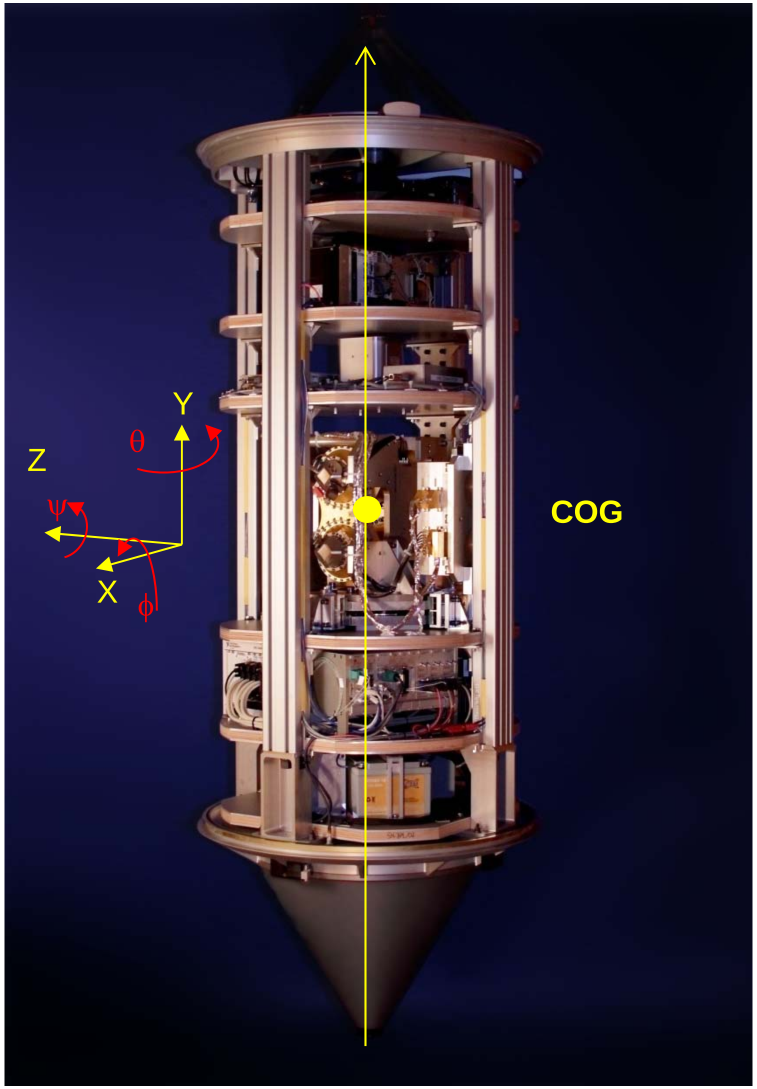


Free fall tests QM



FREE-FLYER CONFIGURATION : DROP 1 to 50

CATAPULT CONFIGURATION : DROP 51 TO 65



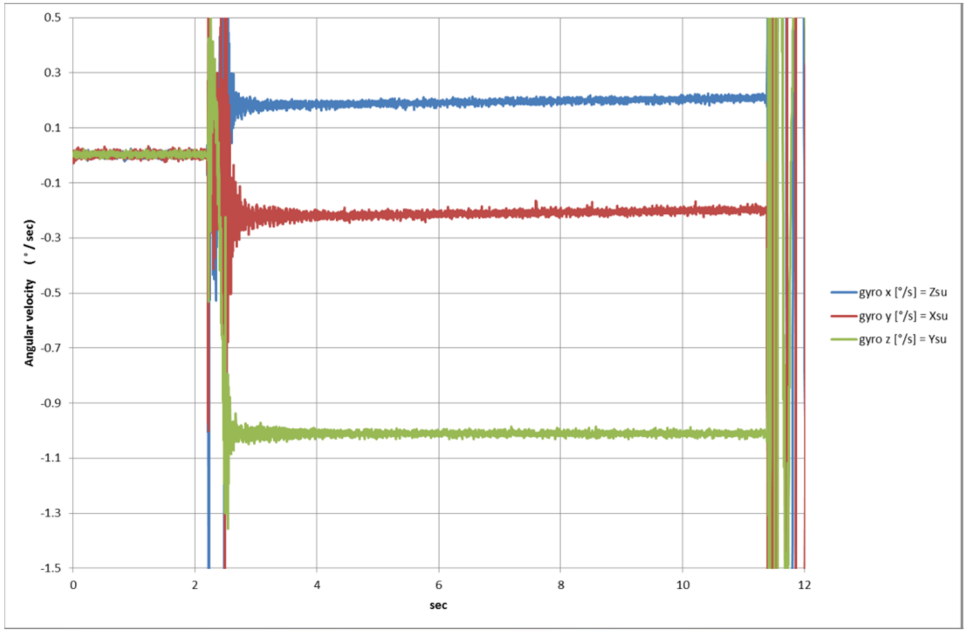
In SU ref. frame

Capsule Center of Gravity:

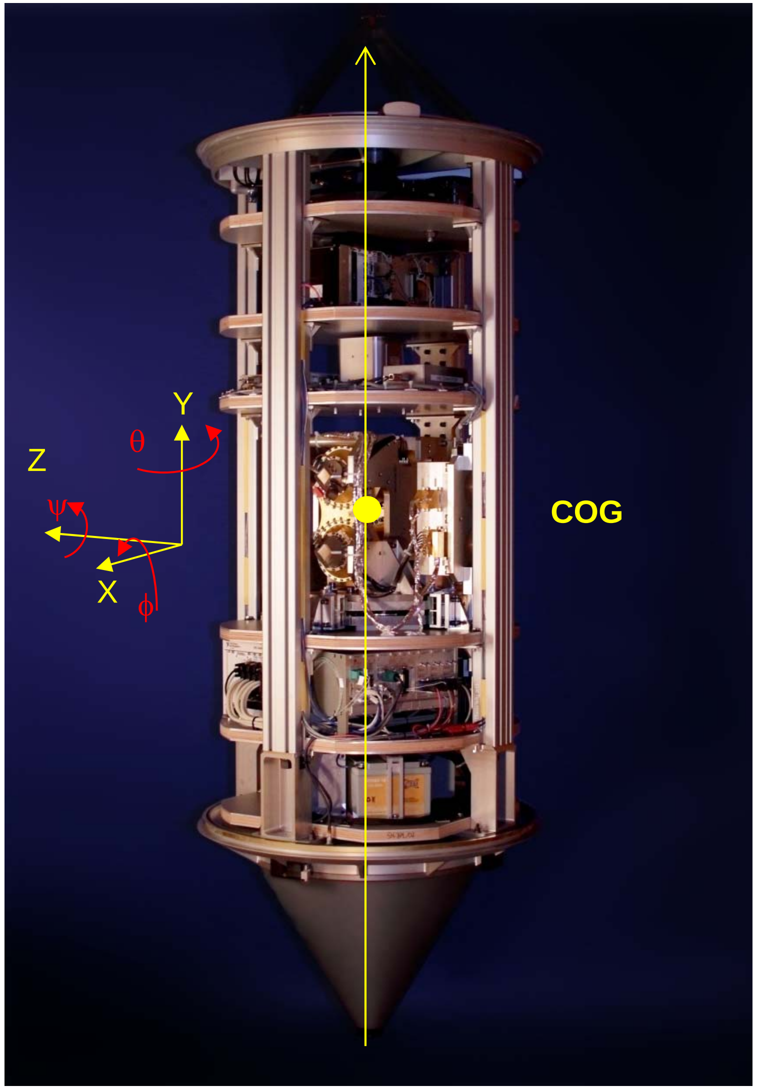
- Adjusted on ground before drop
- Test-Masses position wrt COG: (<1mm ; 85mm ; <1mm)

Angular velocity of the capsule (gyro typical meas.)

- $\Omega \sim (3\ 10^{-3}\ ; 17\ 10^{-3}\ ; 5\ 10^{-3})$ rad/s
- $\frac{d\Omega}{dt} \sim (5\ 10^{-5}\ ;\ 10^{-6}\ ; 5\ 10^{-5})$ rad/s²



Mechanical configuration and environment



In SU ref. frame

Induced centrifugal acceleration

- $\Omega \wedge (\Omega \wedge D) + \frac{d\Omega}{dt} \wedge D \sim (5\,;7\,;5)\mu\frac{m}{s^2} + (4;0;4)\mu\frac{m}{s^2}$

⇒ *Negligible along Y*

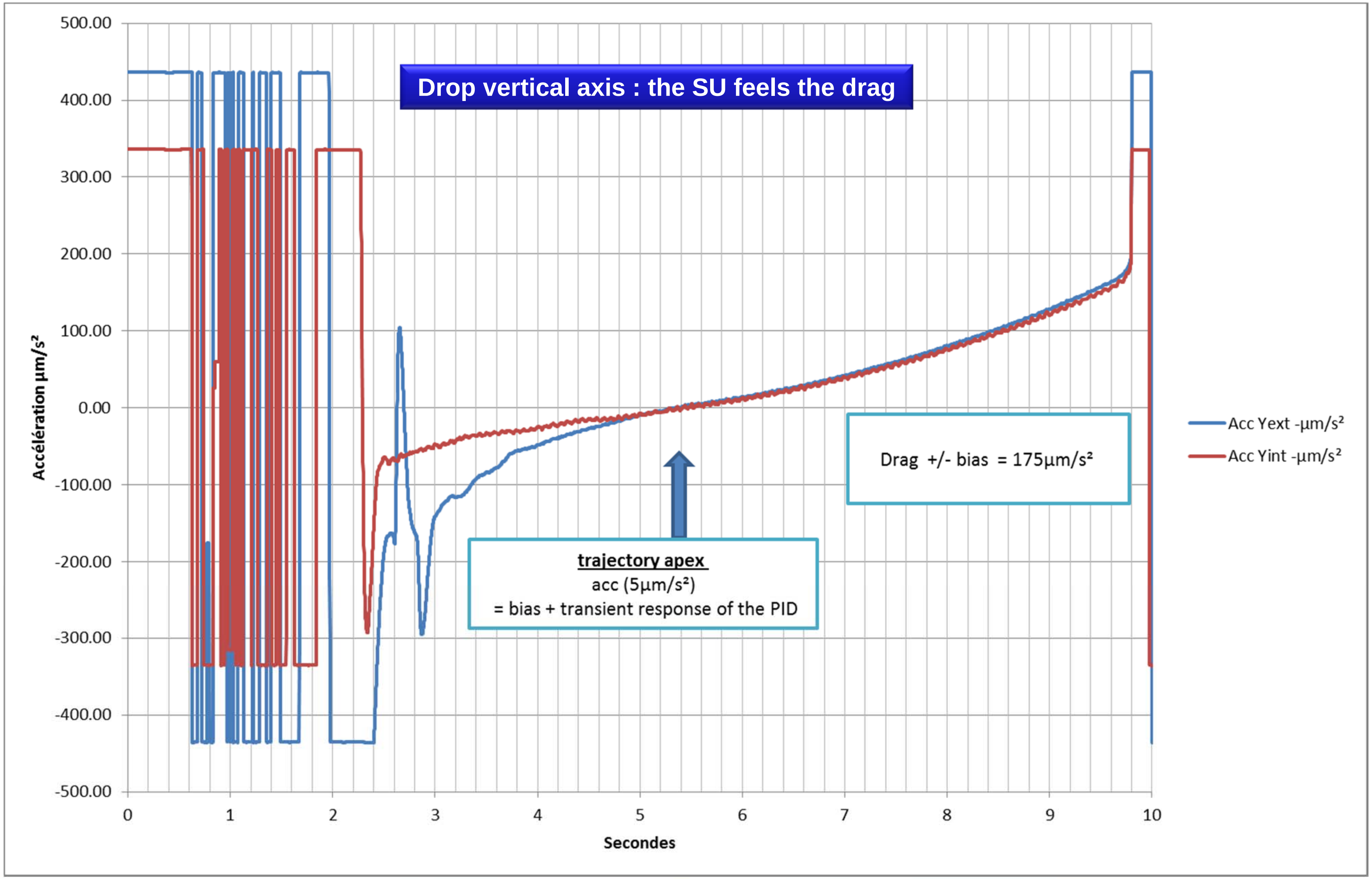
⇒ The Drag is proportional to the velocity along Y.

In addition, along X & Z, a small fraction of drag is seen due to the misalignment of the SU with vertical. It starts with 2 10^{-3}rad and finishes with a max **<u>40 10^{-3}rad</u>** by considering angular velocity:

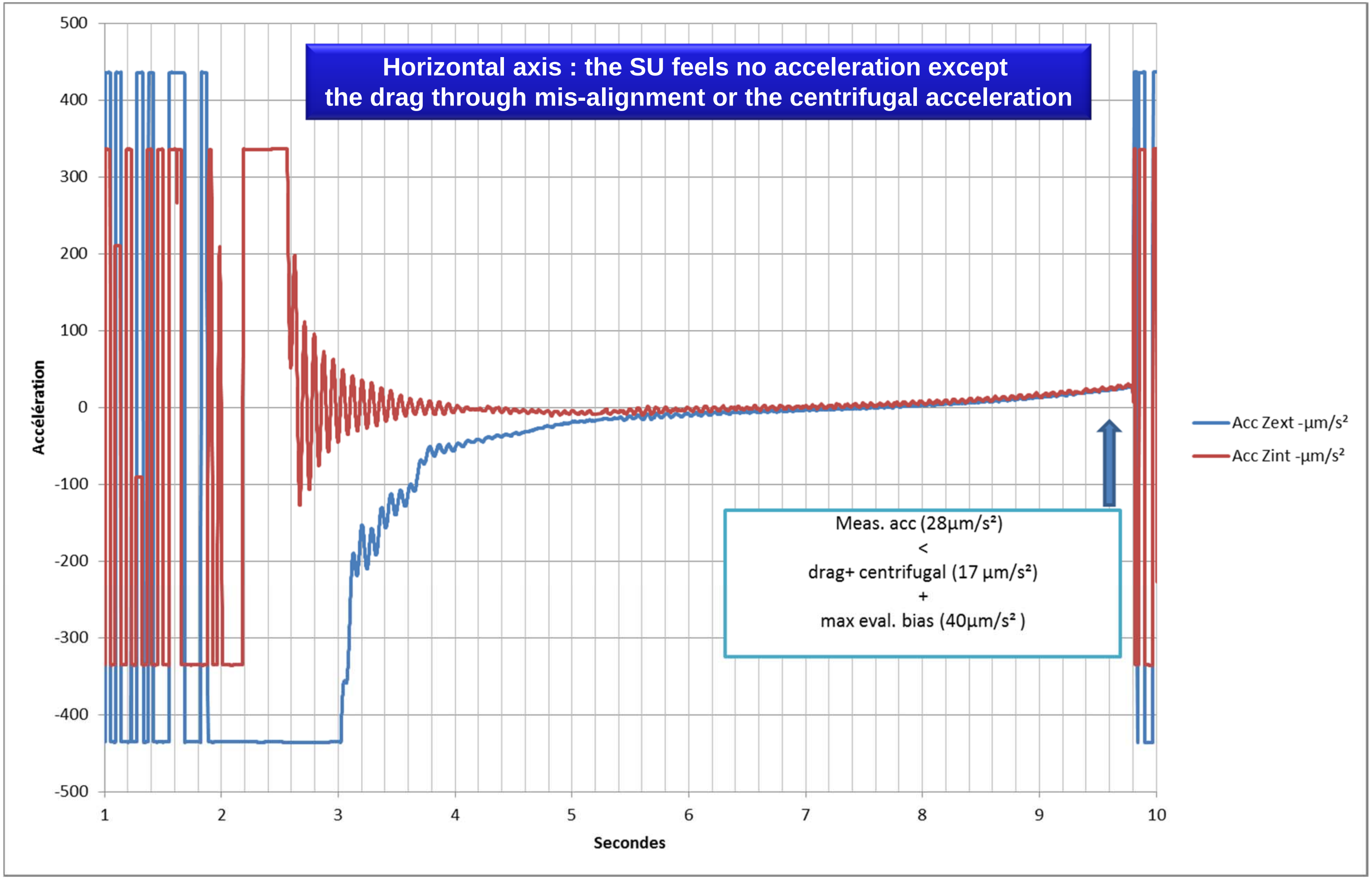
Max DRAG ~ (8 µm/s² ; 200 µm/s² ; 8µm/s²)

ACC BUDGET ~ (17 µm/s² ; 200 µm/s² ; 17 µm/s²)

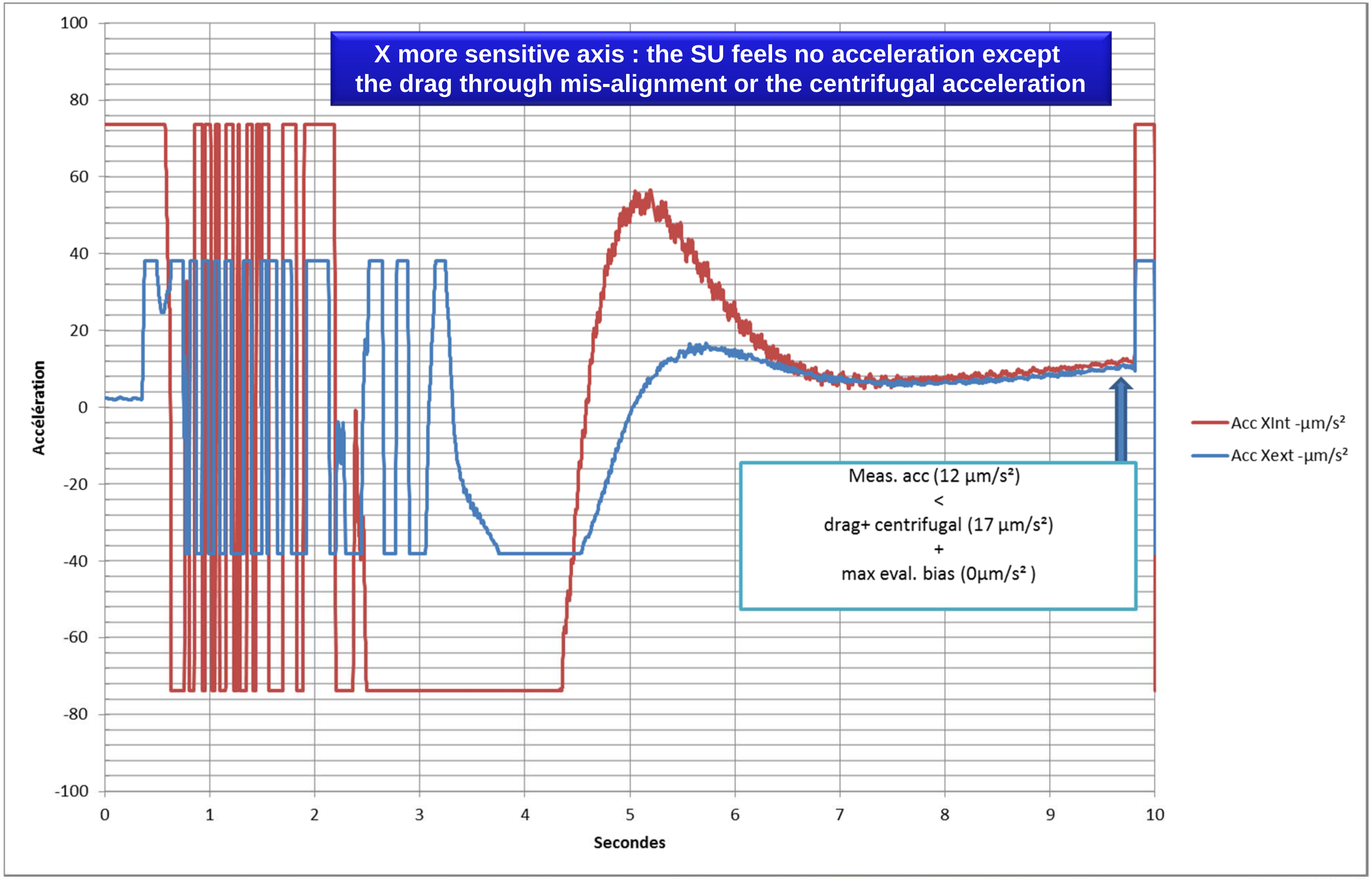
DROP 55 – April 2013 – SUQM – CATAPULT
Inner & Outer test-mass



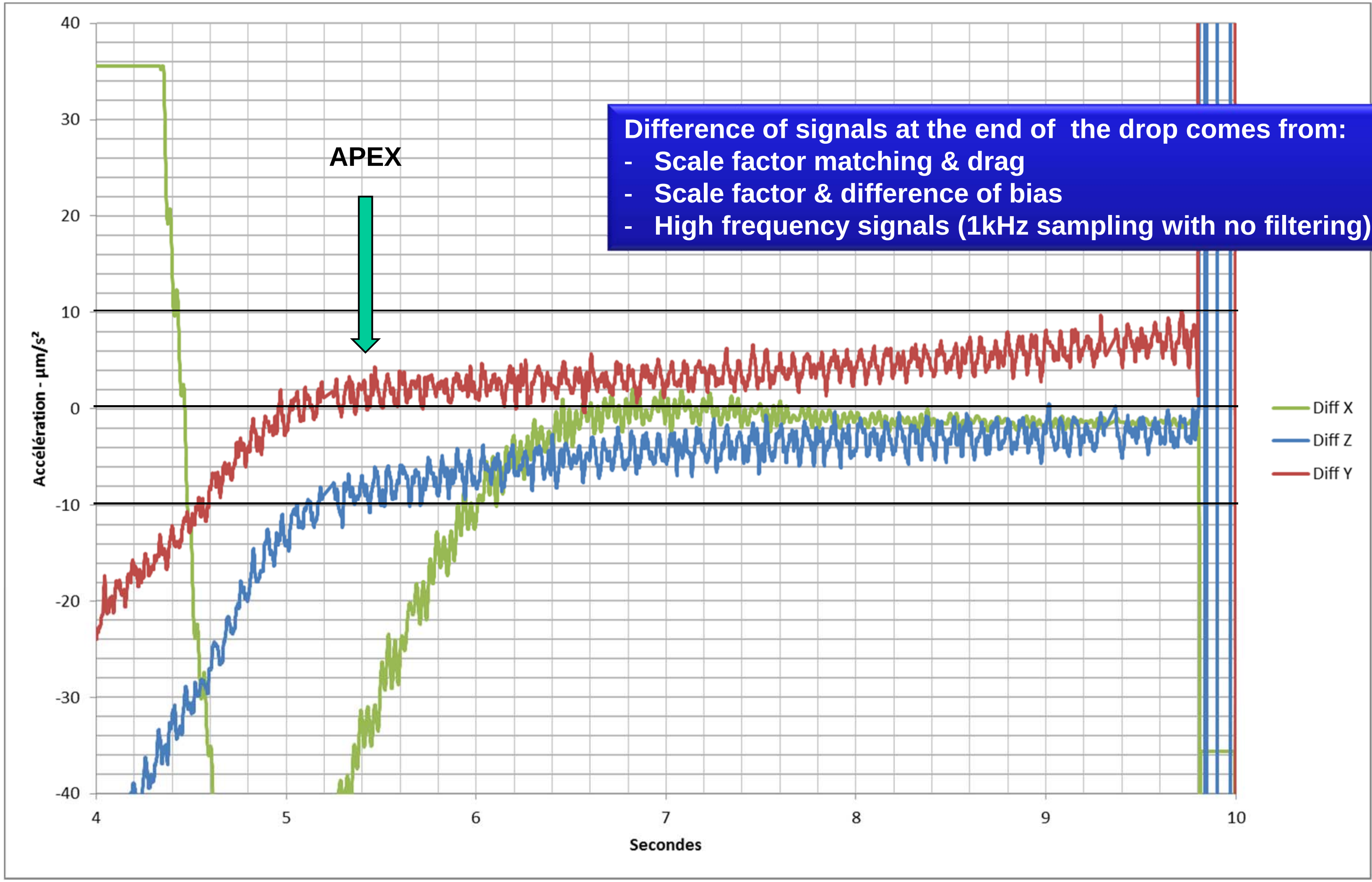
DROP 55 – April 2013 – SUQM – CATAPULT
Inner & Outer test-mass



DROP 55 – April 2013 – SUQM – CATAPULT
Inner & Outer test-mass



DROP 55 – April 2013 – SUQM – CATAPULT
Difference of acceleration



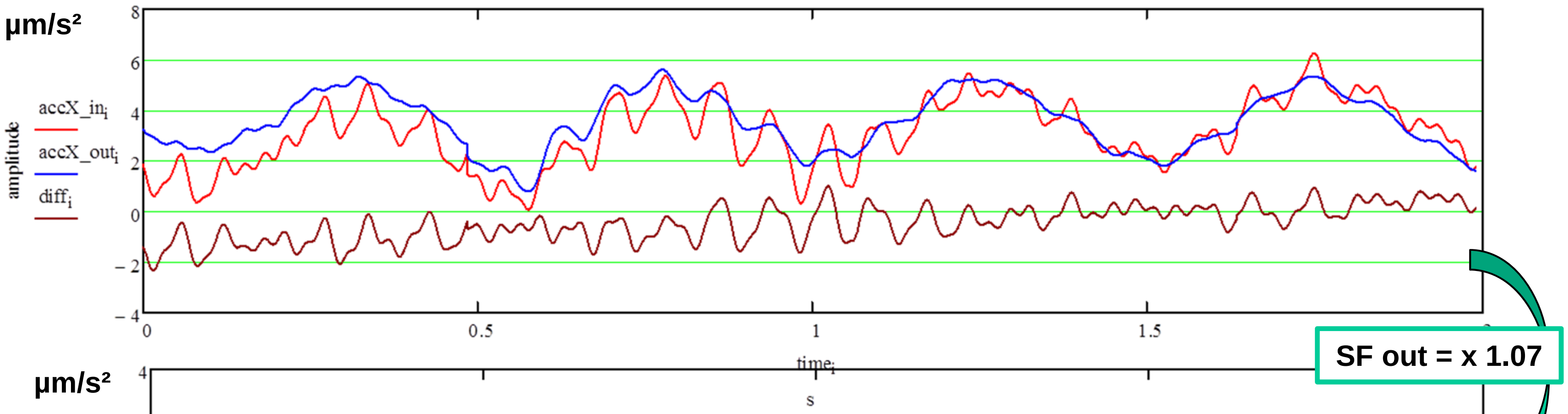
Difference of signals at the end of the drop comes from:

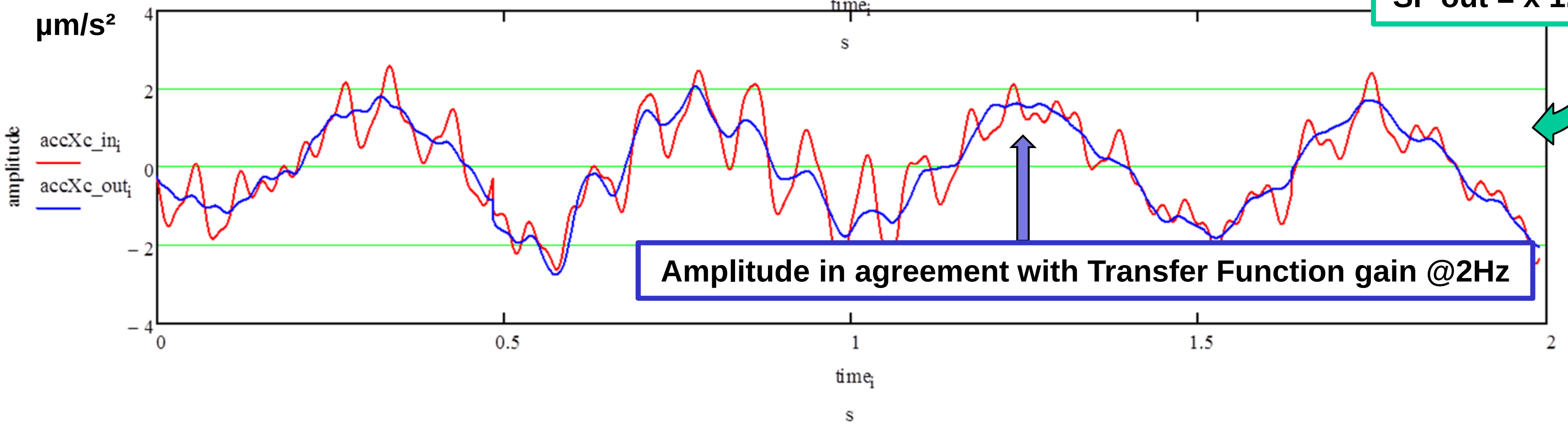
- **Scale factor matching & drag**
- **Scale factor & difference of bias**
- **High frequency signals (1kHz sampling with no filtering)**

DROP 61 – Sept. 2013 – SUQM – Catapult

Calibrated excitation along X of 5µm/s² (known with 5% accuracy) @ 2Hz

Signals measured at the last 2 sec of the drop (all axes acquired or at the end of the transient phase):
- **for practical purpose (9sec of experiment), the excitation is out of the accelerometer frequency band**
- **Different transient response to the environment conditions drops & vibrations**



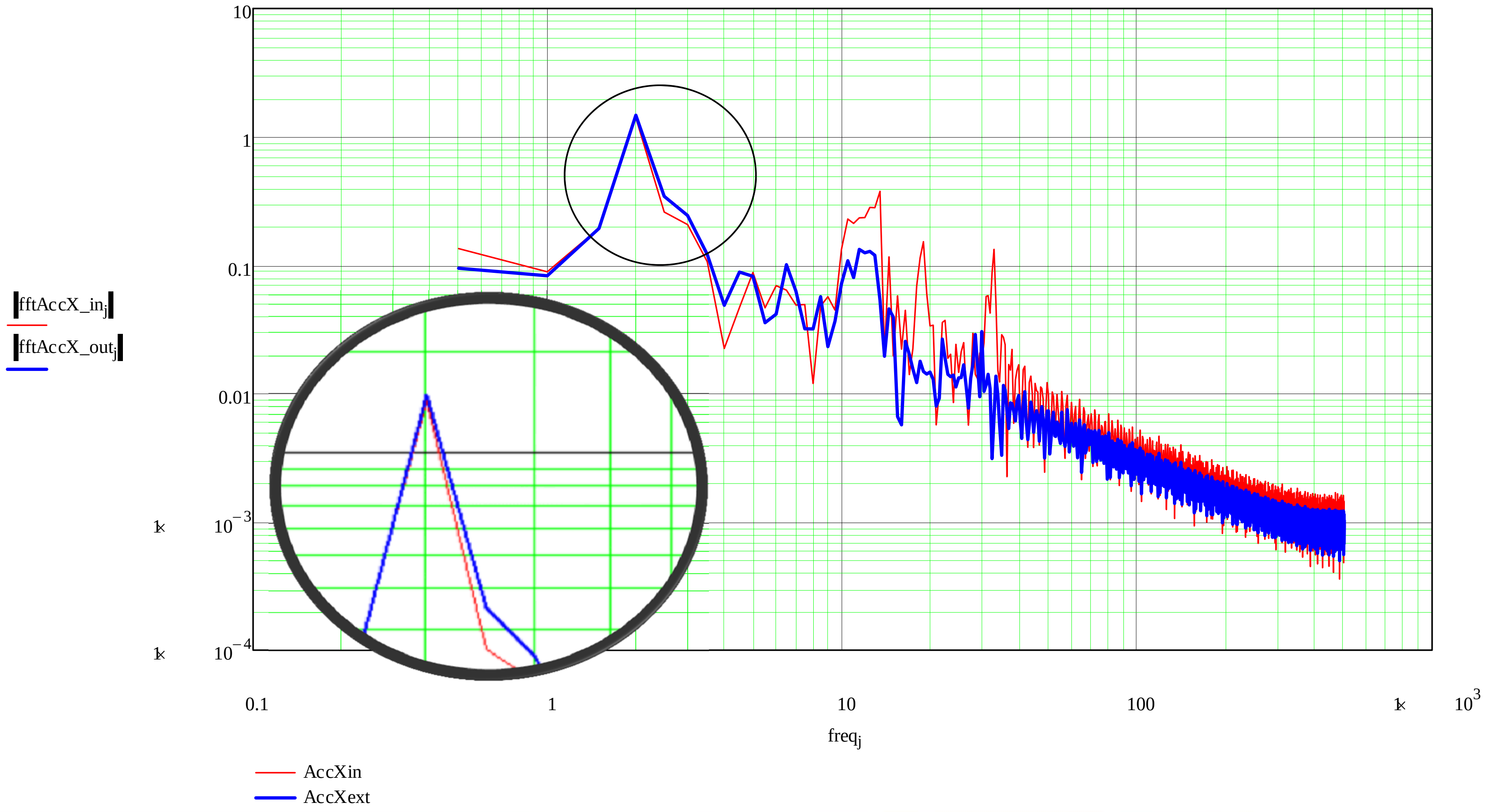


MAXIMUM SCALE FACTORS DIFFERENCES (outer/inner = 1.07)
Evaluation can be improved by taking into account the transfer function to better evaluate measurements

DROP 61 – Sept. 2013 – SUQM – Catapult

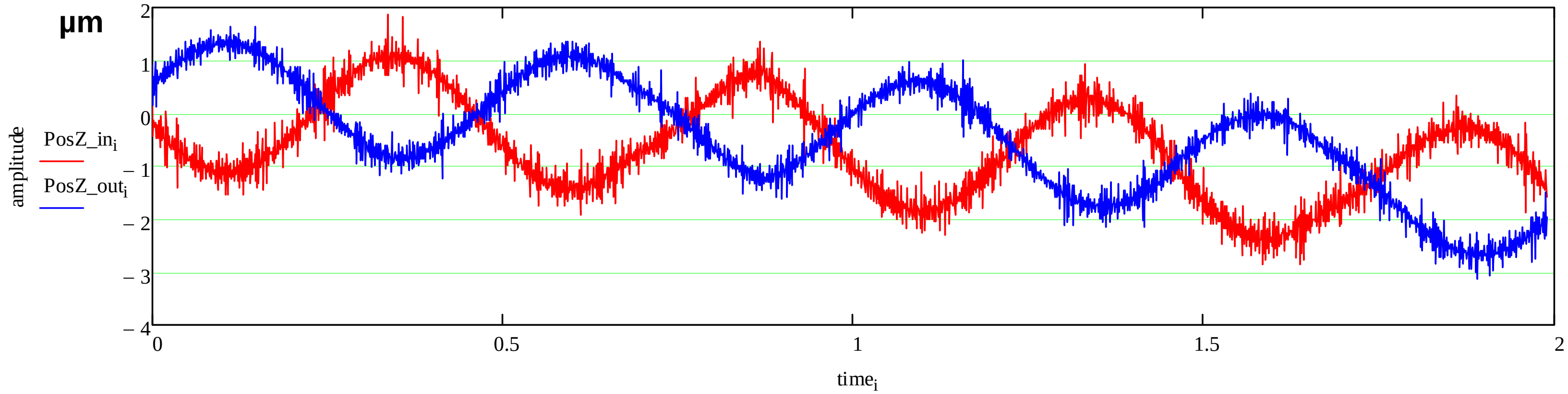
Calibrated excitation along X of 5µm/s² (known with 5% accuracy) @ 2Hz

Spectral analysis in signal (µm/s²)

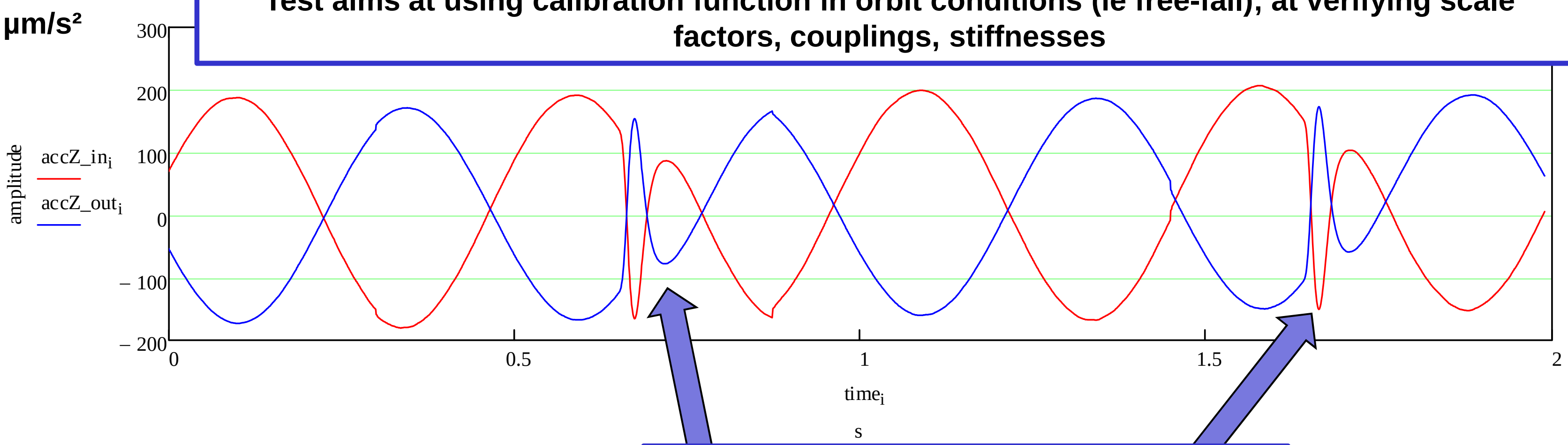


DROP 63 – Sept. 2013 – SUQM – Catapult
Under analysis

Calibrated excitation along X of 5µm/s² (5% accuracy) @ 4Hz
Biasing @ 2Hz of Z Channel at PID input = 1.67 µm (outer) ; -1.67µm (inner)



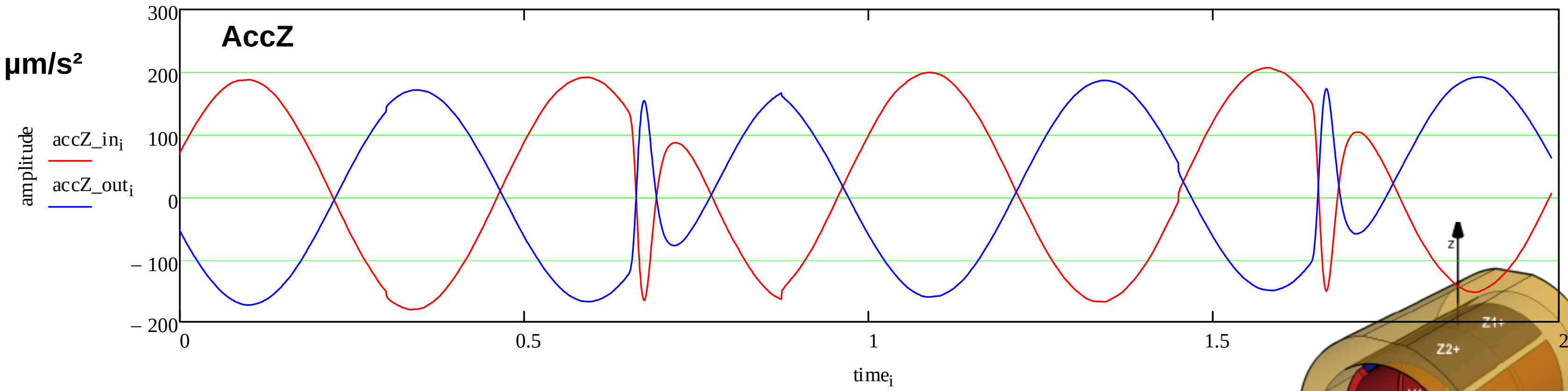
Test aims at using calibration function in orbit conditions (ie free-fall); at verifying scale factors, couplings, stiffnesses

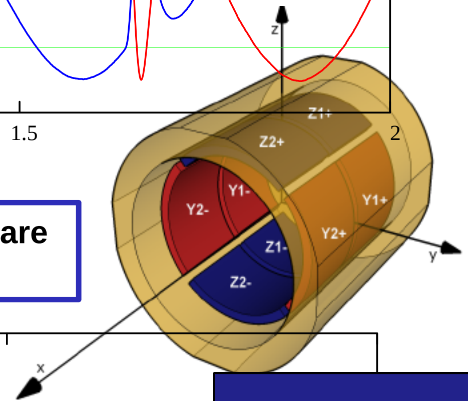


Soft bug in free-fall conf with no OBC

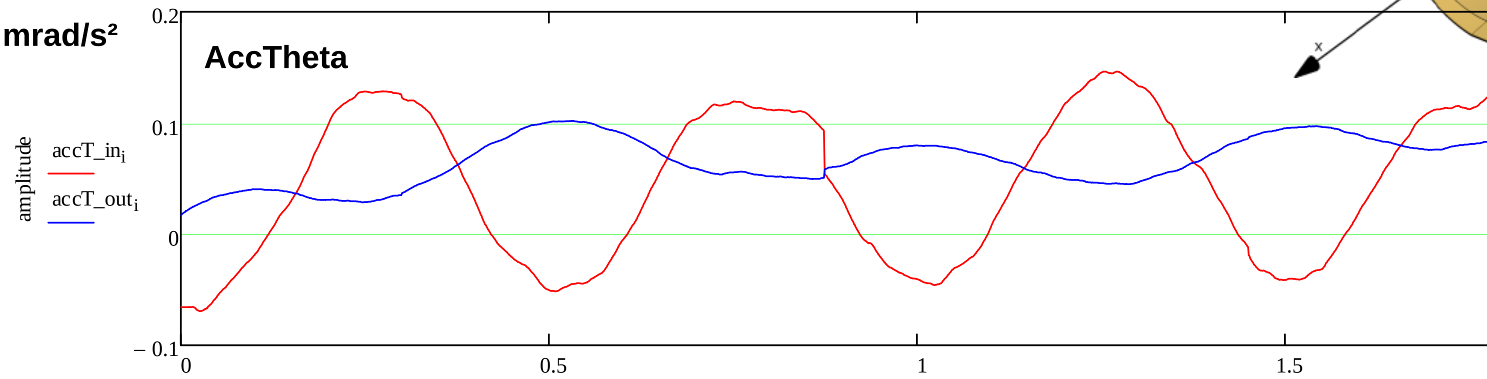
DROP 63 – Sept. 2013 – SUQM – Catapult
Under analysis

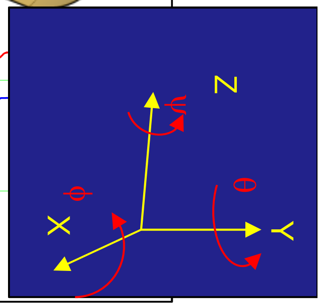
Calibrated excitation along X of 5µm/s² (5% accuracy) @ 4Hz
Biasing @ 2Hz of Z Channel at PID input = 1.67 µm (outer) ; -1.67µm (inner)





Theta is controlled by Z electrodes. Coupling occurs if detectors of channel Z1 & Z2 are note matched, if DVA gain not matched. Coupling with capsule motion TBD

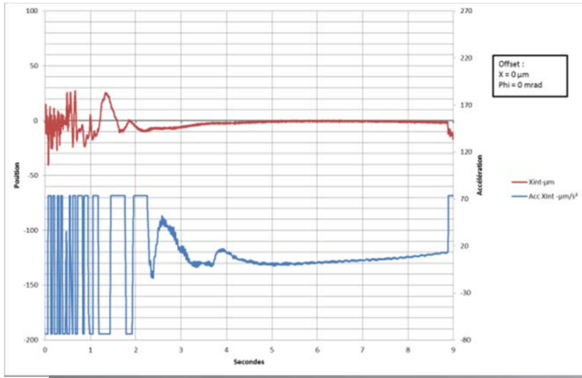




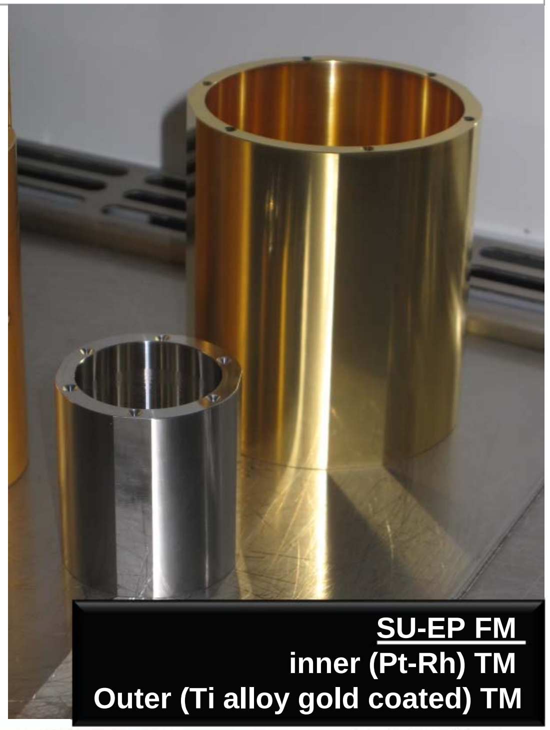
Coupling < 0.5 (rad/s²) / (m/s²) => within order of magnitude of spec
To be consolidated with loop gain & phase @ 4Hz

Conclusion

SU-EP FM Catapult test – X inner



- Qualification of SU is finished, the model is available for further tests in free-fall
- SU-EP FM have been integrated and tested in free-fall (end of September 2013):
  - Inner test-mass in Pt-Rh has identical response as QM one
  - Outer test-mass loop must be optimized
- Capacitive measurements must be more intensively exploited to evaluated free-motion (use of Phi electrodes), gradient of capacitances …..
- The catapult drops have the possibility of micro-gravity operation :
  - Optimization of PIDS
  - Sensitivity characterizations (scale factors, couplings, stiffness….)
  - Test of calibration function software
- Improvement of FM acceptance tests in free-fall
- TO BE DONE SOON:
  - FM acceptance
  - On QM: displacement along all axes, transfer functions correction, differential measurement and noises



SU-EP FM
inner (Pt-Rh) TM
Outer (Ti alloy gold coated) TM

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