Development status of the electrostatic accelerometer for the GRACE-FO mission

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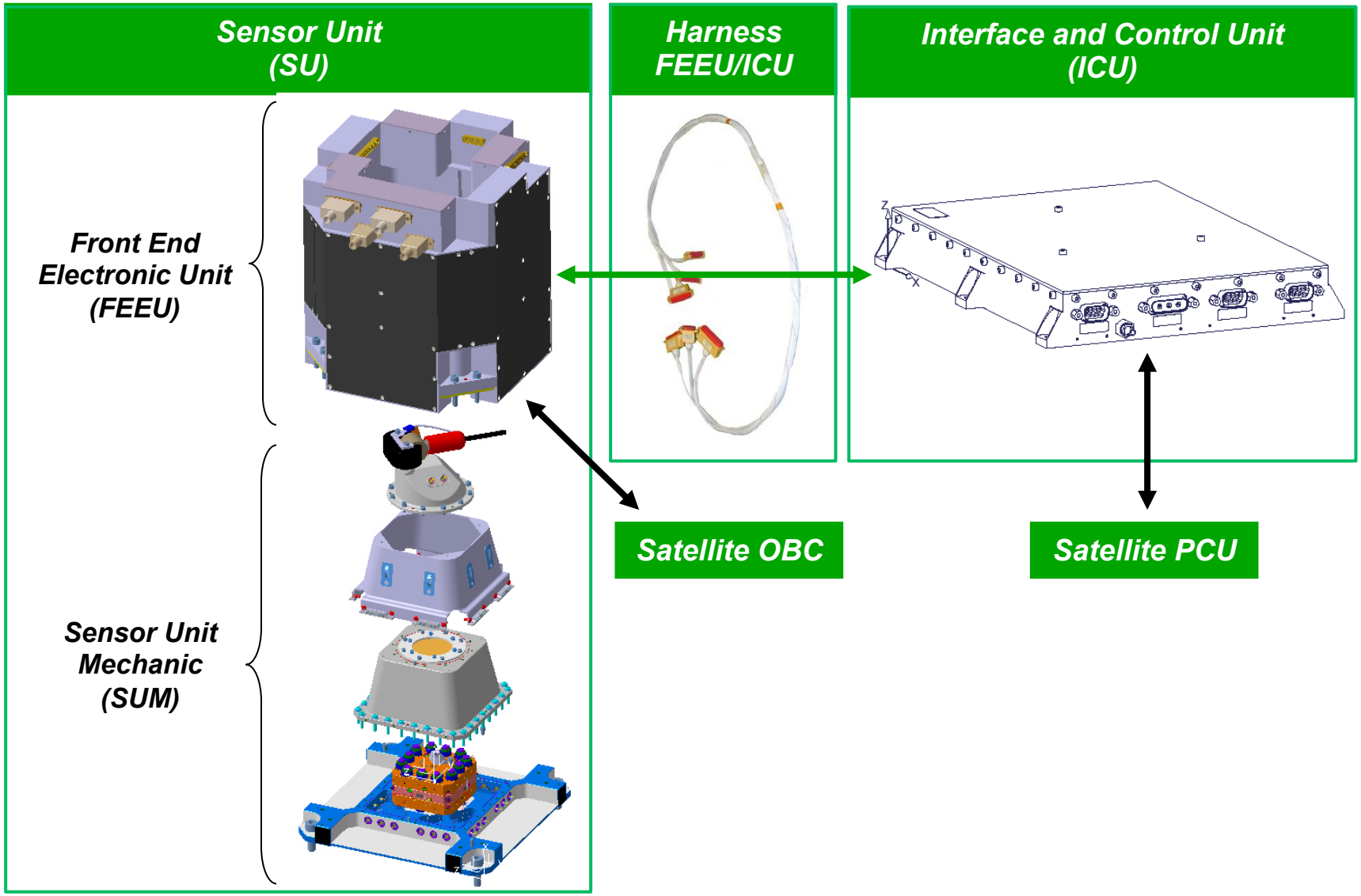
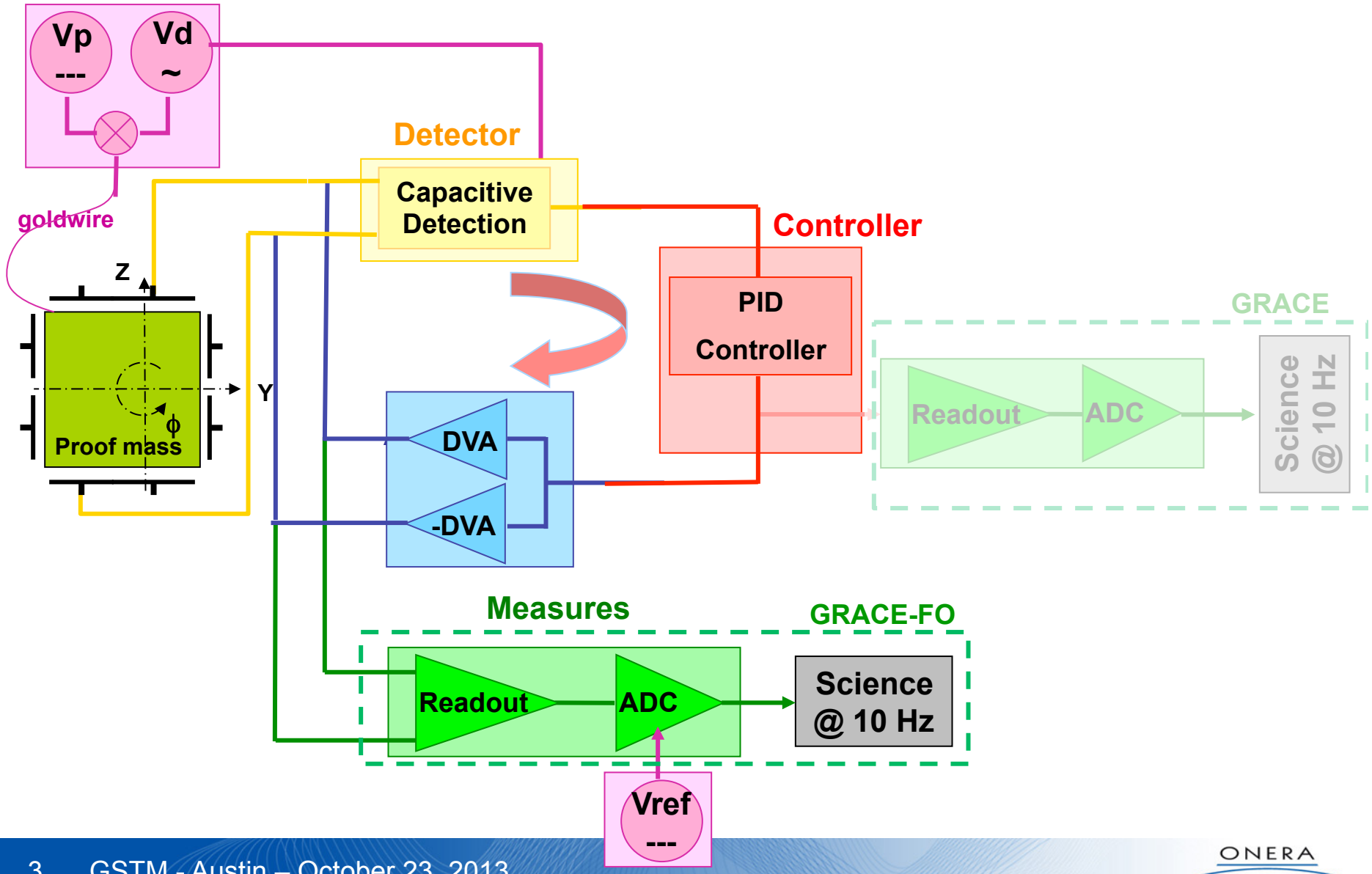
return on innovation

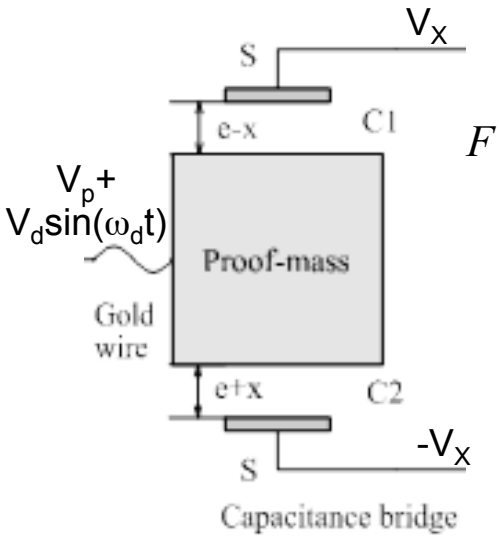
Accelerometer Description



Accelerometer principle of operation (1/2)



Accelerometer principle of operation (2/2)



Capacitive Detection

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

Electrostatic force

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

$$a_X = \frac{2\varepsilon S}{me^2}\left(V_p^2 + \frac{V_d^2}{2}\right)\frac{x}{e} - \frac{2\varepsilon S}{me^2} V_P V_X + \frac{2\varepsilon S}{me^2} V_X^2 \frac{x}{e}$$

- Electrostatic stiffness
- Electrostatic gain
- Cubic term
- The measurement

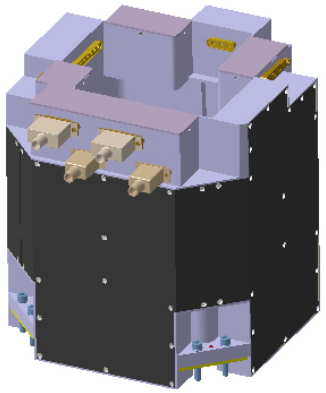
Accelerometer Mode

Large Range Mode (LRM) for acquisition : V_p= 40 V and V_d= 1,25 Vrms

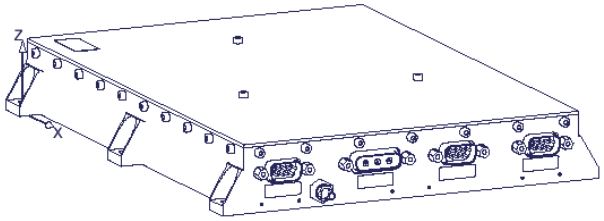
Nominal Range Mode (NRM) for science : V_d= 10 V and V_d= 5 Vrms

Electronics Description

FEEU



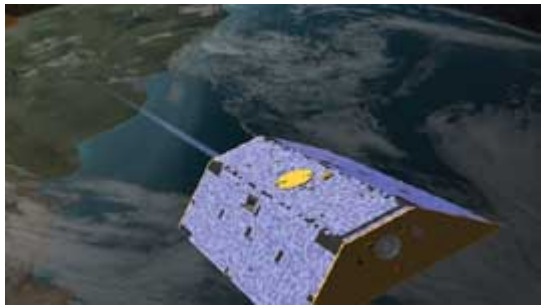
ICU



S/C

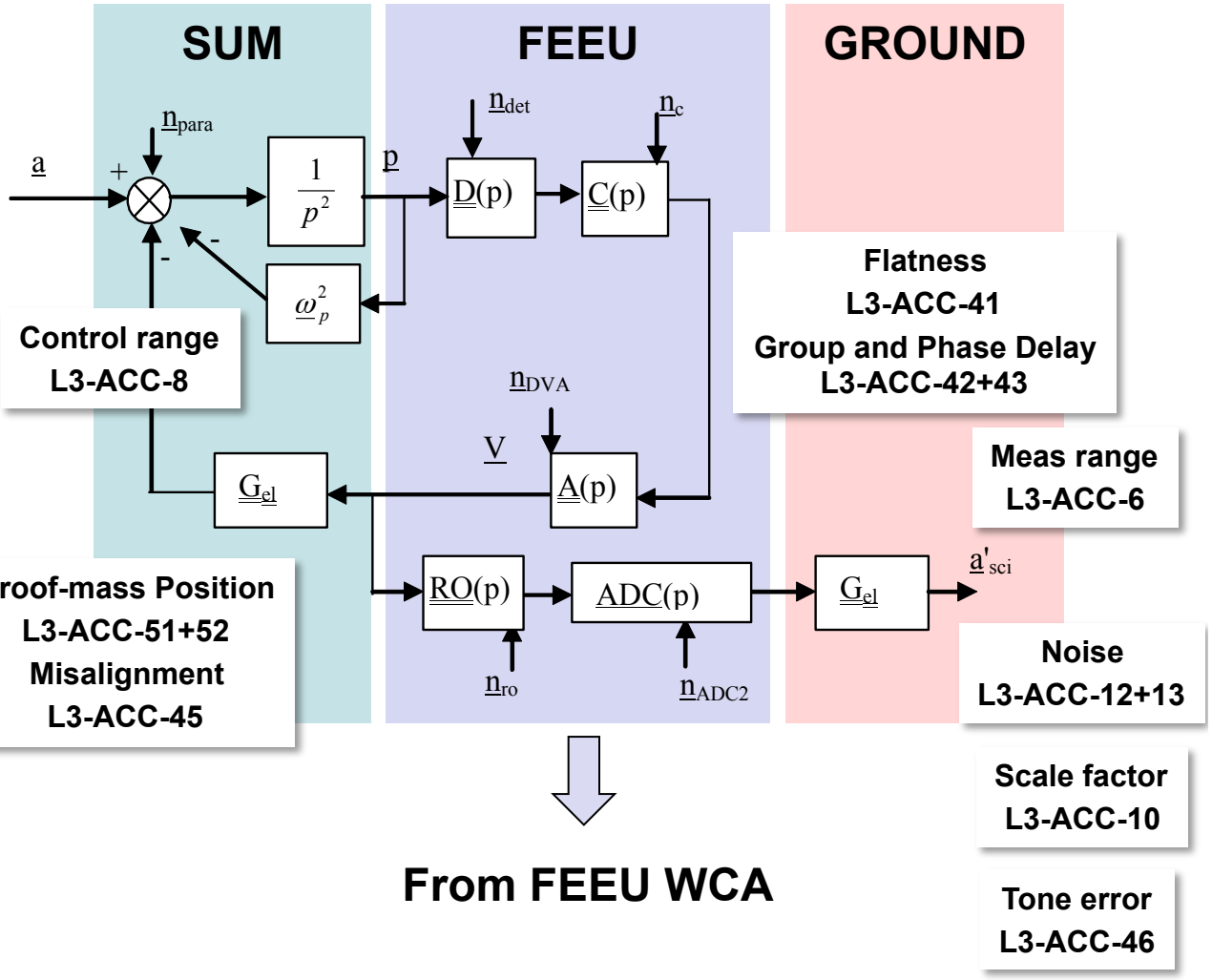
Requirements

Environment Drag

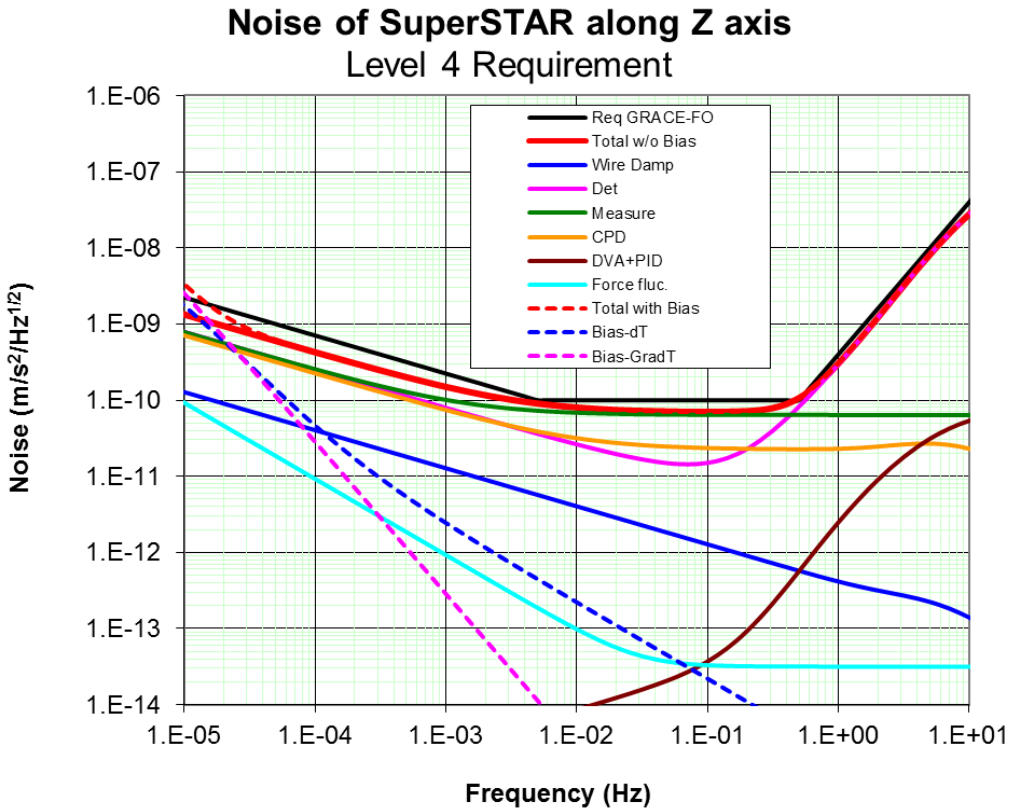


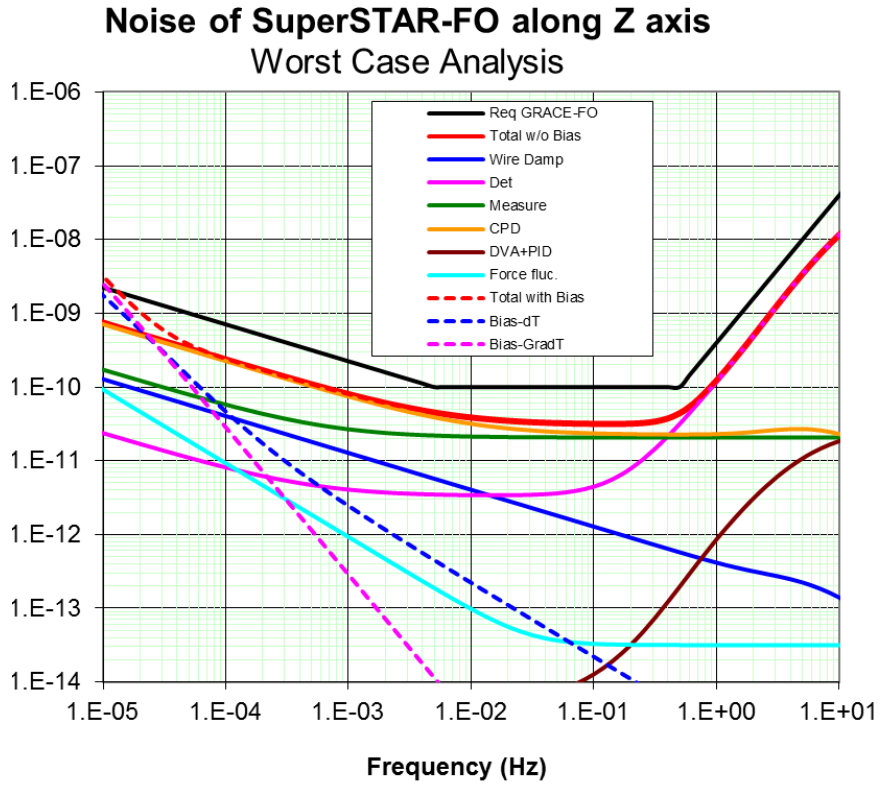
Y/Z± 5x10^{-5} m/s^2

X ± 5x10^{-4} m/s^2



Noise Performance





Requirement achieved

Scale factor knowledge

Level 4 Requirement

Knowledge on ground	At accelerometer level			At contributor level			
	X	Y	Z	X	Y	Z	unit
Gap knowledge	1.67%	1.14%	1.14%	0.5	1	1	µm
Mass knowledge	0.28%	0.28%	0.28%	0.2	0.2	0.2	g
Electrode surface knowledge	0.69%	1.41%	1.41%	0.05	0.07	0.07	mm
Polarization voltage knowledge	0.10%	0.10%	0.10%	0.100%	0.100%	0.100%	% of Vp
Reference voltage knowledge	0.10%	0.10%	0.10%	0.100%	0.100%	0.100%	% of Vref
Contact potential difference and patch effect	0.15%	0.15%	0.15%	0.015	0.015	0.015	V
DVA bias	0.02%	0.02%	0.02%	0.002	0.002	0.002	V
Read-out amplifier gain	0.50%	0.50%	0.50%	0.50%	0.50%	0.50%	%
ADC gain	0.05%	0.05%	0.05%	0.05%	0.05%	0.05%	%
Total	**1.90%**	**1.92%**	**1.92%**				
Requirement	**2%**	**2%**	**2%**				

WCA

Knowledge on ground	At accelerometer level			At contributor level			
	X	Y	Z	X	Y	Z	unit
Gap knowledge	1.67%	1.14%	1.14%	0.5	1	1	µm
Mass knowledge	0.28%	0.28%	0.28%	0.2	0.2	0.2	g
Electrode surface knowledge	0.69%	1.41%	1.41%	0.05	0.07	0.07	mm
Polarization voltage knowledge	0.02%	0.02%	0.02%	0.019%	0.019%	0.019%	% of Vp
Reference voltage knowledge	0.02%	0.02%	0.02%	0.019%	0.019%	0.019%	% of Vref
Contact potential difference and patch effect	0.15%	0.15%	0.15%	0.015	0.015	0.015	V
DVA bias	0.00%	0.00%	0.01%	2.89E-04	3.54E-04	5.00E-04	V
Read-out amplifier gain	0.43%	0.43%	0.24%	0.43%	0.43%	0.24%	%
ADC gain	0.05%	0.05%	0.05%	0.050%	0.050%	0.050%	%
Total	**1.88%**	**1.90%**	**1.86%**				
Requirement	**2%**	**2%**	**2%**				

Requirement achieved

Scale factor stability

Scale factor stability over 1 month (hypothesis)

Temperature range FA [5-40]°C : need a correction from ground characterisation

Stability over 1 month	At accelerometer level			At accelerometer level			At contributor level			
	X	Y	Z	X	Y	Z	X	Y	Z	unit
Variation between 0°C and 40°C, measured at 20°C	20 °C	corrected at	1 °C	20 °C	corrected at	1 °C				
Gap thermal variation	0.00172%	0.00172%	0.00172%	0.00172%	0.00172%	0.00172%	8.6	8.6	8.6	ppm/°C
Error on Gap thermal variation	0.00344%	0.00344%	0.00344%	0.00344%	0.00344%	0.00344%	0.86	0.86	0.86	ppm/°C
Electrode surface thermal variation	0.00006%	0.00006%	0.00006%	0.00006%	0.00006%	0.00006%	0.03	0.03	0.03	ppm /°C
Polarization voltage thermal variation	0.00050%	0.00050%	0.00050%	0.00042%	0.00042%	0.00042%	4.20	4.20	4.20	ppm/°C
Error on Polarization voltage thermal variation	0.00100%	0.00100%	0.00100%	0.00084%	0.00084%	0.00084%	0.42	0.42	0.42	ppm/°C
Reference voltage thermal variation	0.00050%	0.00050%	0.00050%	0.00043%	0.00043%	0.00043%	4.30	4.30	4.30	ppm/°C
Error on Reference voltage thermal variation	0.00100%	0.00100%	0.00100%	0.00086%	0.00086%	0.00086%	0.43	0.43	0.43	ppm/°C
Contact potential difference thermal variation	0.00400%	0.00400%	0.00400%	0.00400%	0.00400%	0.00400%	20	20	20	µV/°C
DVA bias thermal variation	0.00010%	0.00010%	0.00010%	0.00004%	0.00005%	0.00007%	3.83	4.69	6.64	µV/°C
Error on DVA bias thermal variation	0.00020%	0.00020%	0.00020%	0.00008%	0.00009%	0.00013%	0.383	0.469	0.664	µV/°C
Read-out amplifier gain thermal variation	0.00050%	0.00050%	0.00050%	0.00003%	0.00003%	0.00001%	0.26	0.26	0.14	ppm/°C
Error on Read-out amplifier gain thermal variation	0.00100%	0.00100%	0.00100%	0.00005%	0.00005%	0.00003%	0.026	0.026	0.014	ppm/°C
ADC gain thermal variation	0.00050%	0.00050%	0.00050%	0.00030%	0.00030%	0.00030%	3	3	3	ppm/°C
Error on ADC gain thermal variation	0.00100%	0.00100%	0.00100%	0.00060%	0.00060%	0.00060%	0.3	0.3	0.3	ppm/°C
Total thermal sensitivity	**0.006%**	**0.006%**	**0.006%**	**0.006%**	**0.006%**	**0.006%**				
Ageing over	1	month(s)		1	months					
Polarization voltage ageing	0.00400%	0.00400%	0.00400%	0.00320%	0.00320%	0.00320%	0.0032%	0.0032%	0.0032%	%/Month
Reference voltage ageing	0.00400%	0.00400%	0.00400%	0.00320%	0.00320%	0.00320%	0.0032%	0.0032%	0.0032%	%/Month
Contact potential difference ageing	0.00100%	0.00100%	0.00100%	0.00100%	0.00100%	0.00100%	100	100	100	µV/Month
DVA bias ageing	0.00010%	0.00010%	0.00010%	0.00000%	0.00000%	0.00001%	3.75E-01	4.60E-01	6.50E-01	µV/Month
Read-out amplifier gain ageing	0.00500%	0.00500%	0.00300%	0.00480%	0.00480%	0.00270%	48	48	27	ppm/Month
Total ageing	**0.008%**	**0.008%**	**0.006%**	**0.007%**	**0.007%**	**0.005%**				
Total	**0.010%**	**0.010%**	**0.009%**	**0.009%**	**0.009%**	**0.008%**				
Requirement	**1%**	**0.20%**	**0.01%**	**1%**	**0.20%**	**0.01%**				

Requirement achieved

For longer duration, ageing Vp, Vref and Readout Gain limit the performance

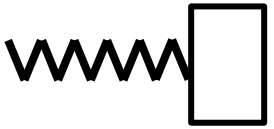
Tone error

Worst Case Analysis

Tone error	At accelerometer level			At contributor level			
	X	Y	Z	X	Y	Z	unit
Variation of temperature	0.1 °C	over one orbit					
Electronic bias							
Detector bias thermal variation	1.39E-10	2.38E-12	2.38E-12	30	30	30	µV/°C
Electrode surface thermal variation	8.49E-12	1.98E-13	1.98E-13	0.03	0.03	0.03	ppm/°C
Contact potential difference thermal variation	9.06E-11	2.11E-12	2.11E-12	2.00	2.00	2.00	µV/°C
Read-out amplifier bias thermal variation	2.08E-10	4.35E-12	2.38E-12	4.60	4.12	2.25	µV/°C
ADC bias thermal variation	1.43E-10	3.34E-12	3.34E-12	2.00	2.00	2.00	µV/°C
Total Electronic tone error	**3.02E-10**	**6.35E-12**	**5.19E-12**				
Parasitic acceleration							
Gold Wire stiffness thermal variation	3.87E-10	1.28E-11	1.28E-11	4.40E-04	4.40E-04	4.40E-04	ppm/°C
Radiometer Effect	1.20E-14	3.10E-15	3.10E-15	1.90E-13	4.90E-14	4.90E-14	$m/s^2/°C$
Radiation pressure	2.40E-15	6.01E-16	6.01E-16	3.80E-14	9.50E-15	9.50E-15	$m/s^2/°C$
Magnetism through thermal variation	2.70E-20	2.70E-20	2.70E-20	2.70E-19	2.70E-19	2.70E-19	$m/s^2/°C$
Magnetism through Earth magnetism variation	2.10E-13	2.10E-13	2.10E-13	2.10E-13	2.10E-13	2.10E-13	$m/s^2/°C$
Lorentz force	7.00E-15	9.70E-15	9.70E-15	7.00E-14	9.70E-14	9.70E-14	$m/s^2/°C$
Total Parasitic acceleration tone error	**3.87E-10**	**1.28E-11**	**1.28E-11**				
Total Tone error	**4.91E-10**	**1.43E-11**	**1.38E-11**				
Requirement	**4.00E-12**	**4.00E-12**	**4.00E-12**				

Resting point estimation of gold wire

1 mm / 25 mm



Requirement not fully achieved

Bias thermal sensitivity

GRACE

$$x : 2.7\times10^{-8}\,ms^{-2}/°C$$

$$y,z : 5.7\times10^{-9}\,ms^{-2}/°C$$

GRACE-FO

$$x : 4.9\times10^{-9}\,ms^{-2}/°C$$

$$y,z : 1.4\times10^{-10}\,ms^{-2}/°C$$

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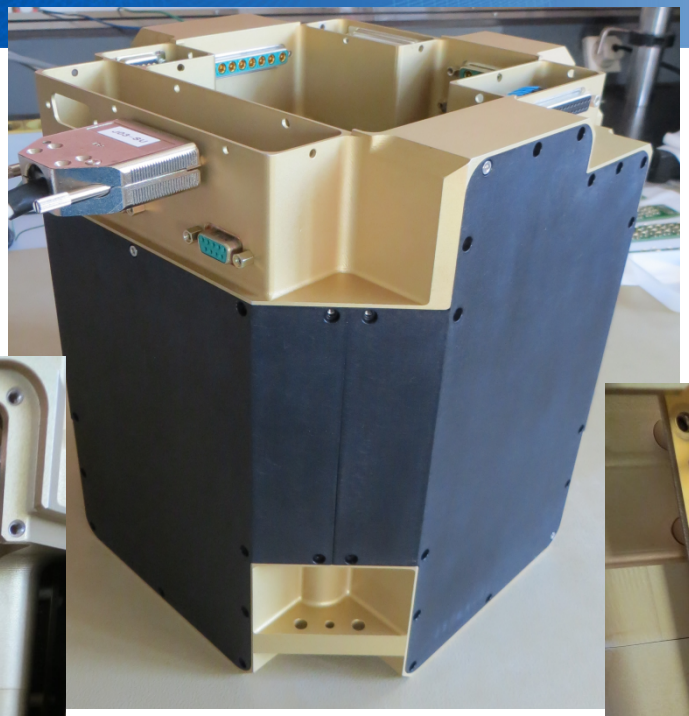
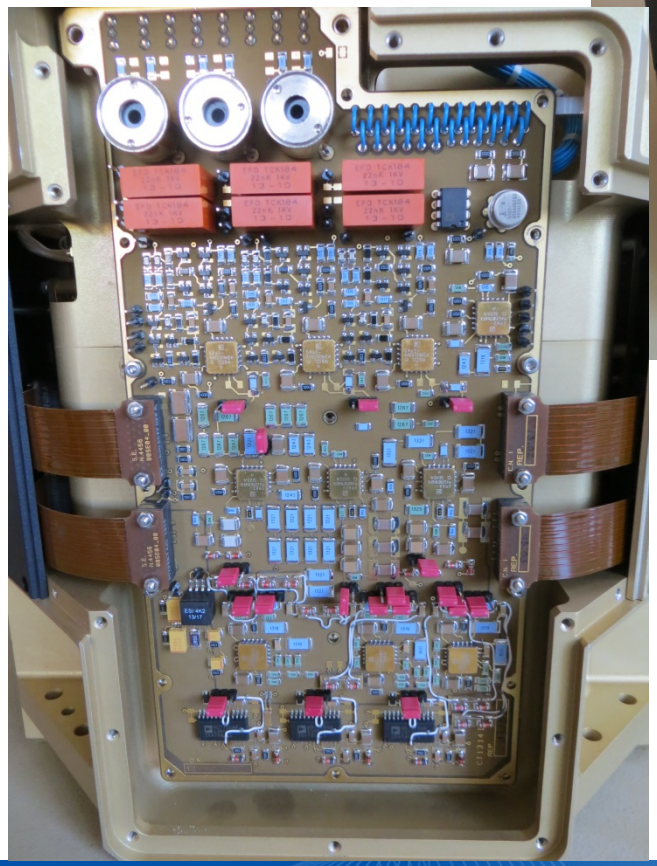
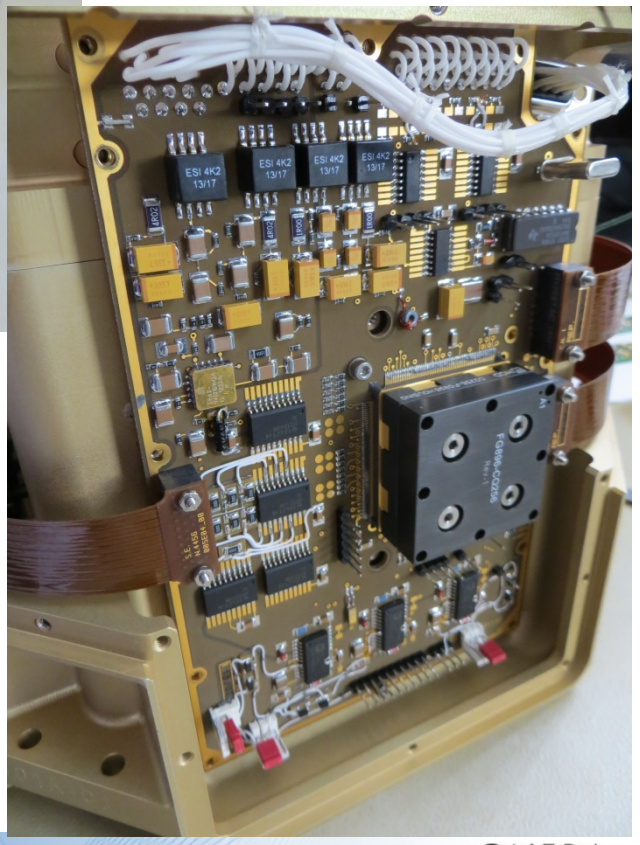
FEEU EM







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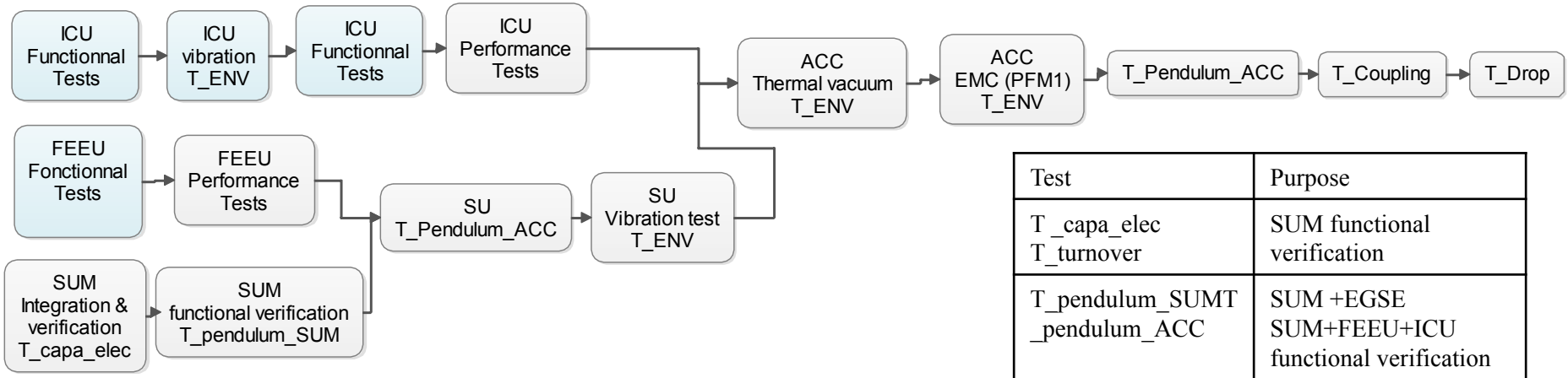
Assembly, Integration and ValidationTests

AIV Flow

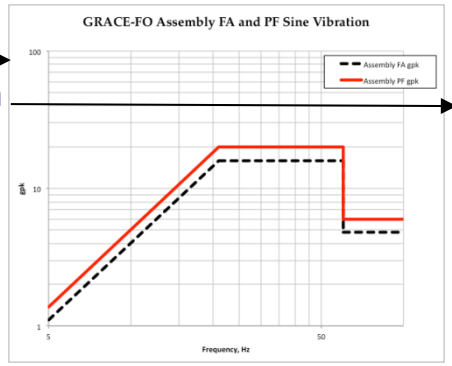


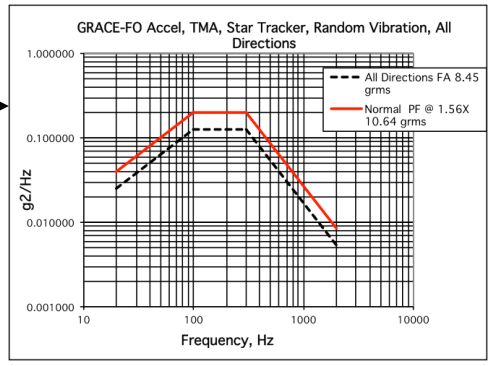
Test	Purpose
T _capa_elec T_turnover	SUM functional verification
T_pendulum_SUMT _pendulum_ACC	SUM +EGSE SUM+FEEU+ICU functional verification
T_ENV	Vibration, thermal cycling and EMC tests
T_coupling	Scale factor K calibration and Non linearity K2 verification
T_drop	Drop Tower test Flight configuration (X axis) Bias estimation

Environmental testing requirements → ERD

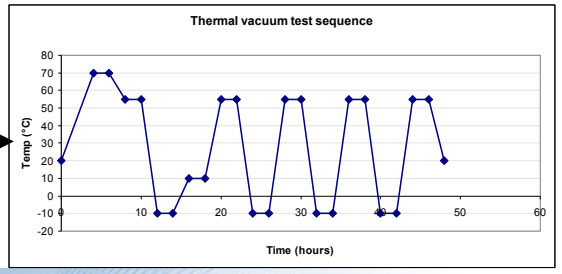
- Vibration

Sinus
Random
Shock





- Thermal vacuum



- EMC

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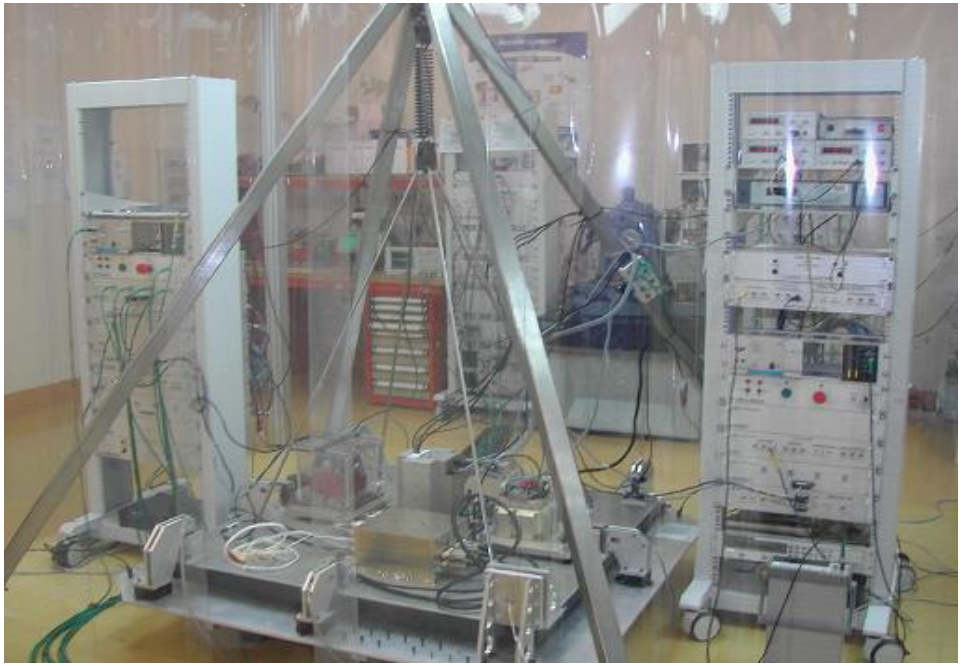
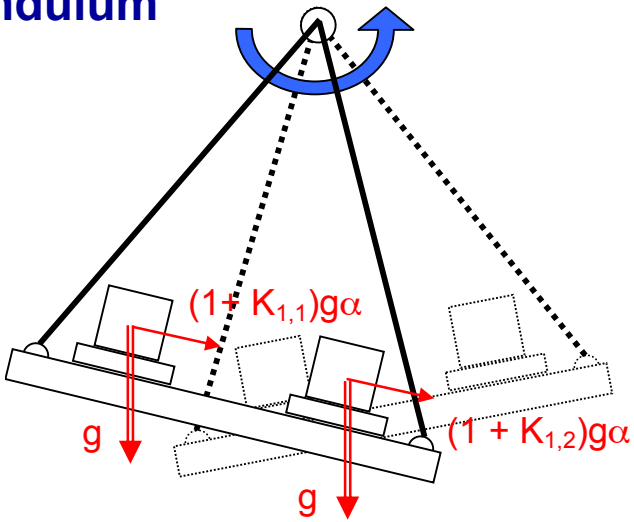
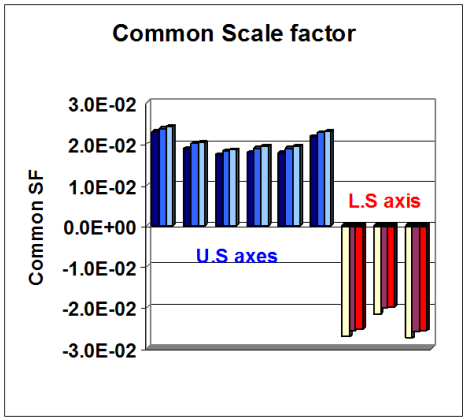
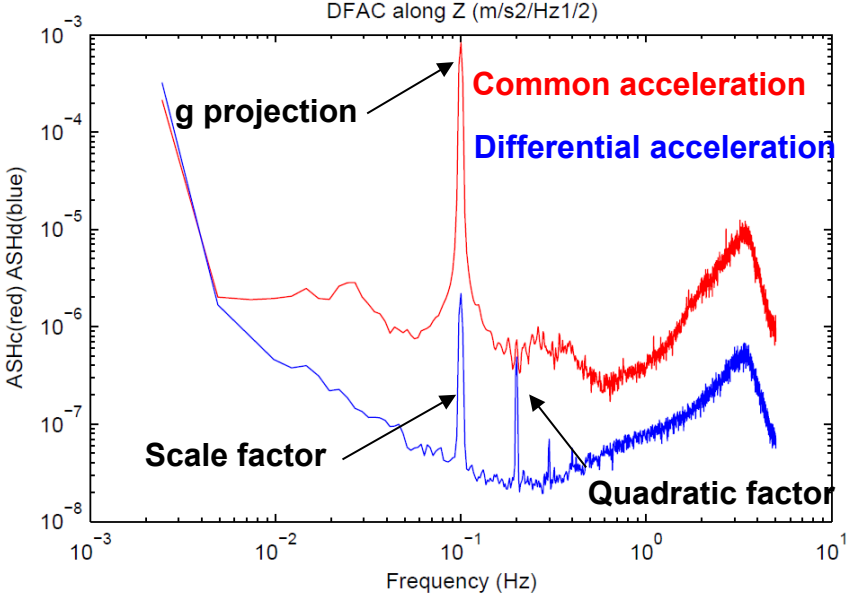
Electrostatic accelerometer – Testing : GOCE REX

Functional and performance verification on pendulum

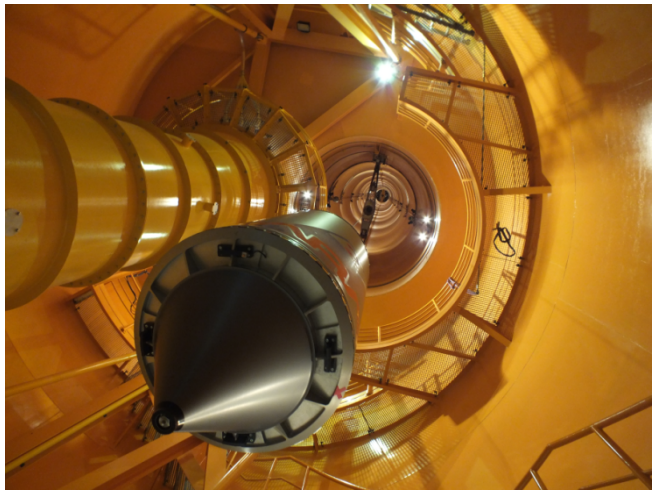


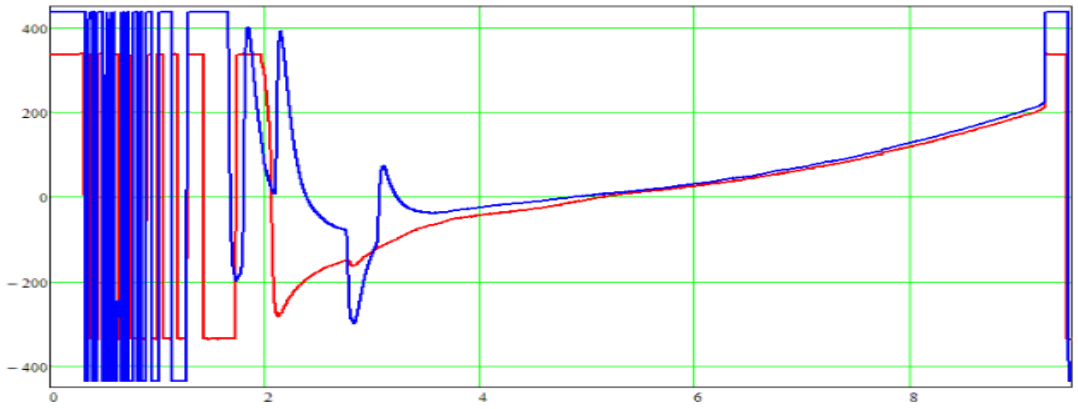




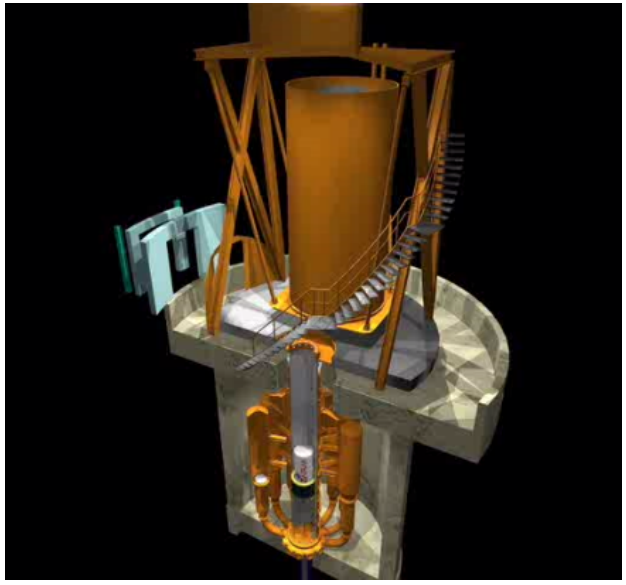


Catapult test of MICROSCOPE SUQM – drop n°61
Contribution from H. Selig (ZARM)

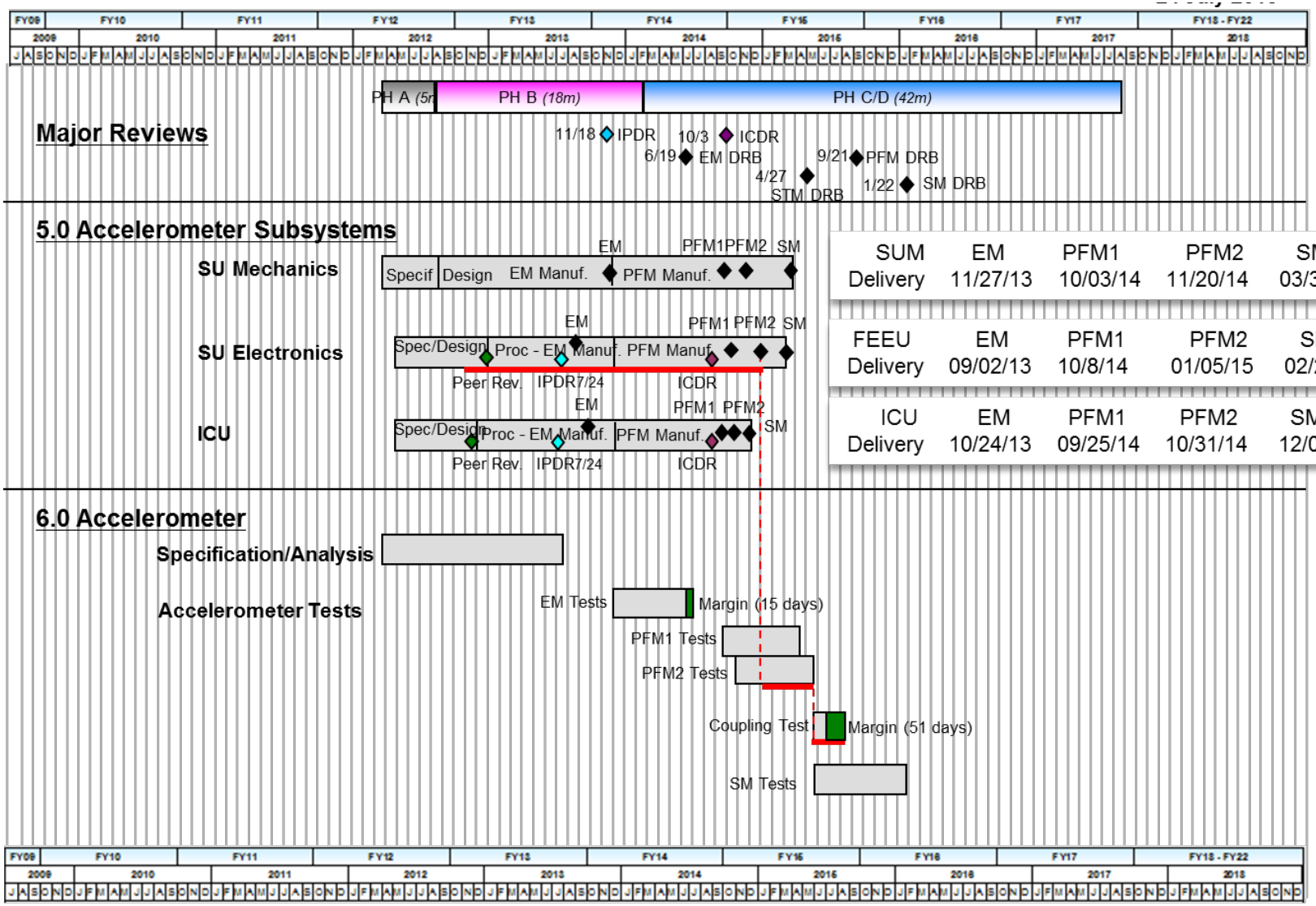




Slow motion (speed/2)



Schedule



SUM	EM	PFM1	PFM2	SM
Delivery	11/27/13	10/03/14	11/20/14	03/30/15

FEEU	EM	PFM1	PFM2	SM
Delivery	09/02/13	10/8/14	01/05/15	02/27/15

ICU	EM	PFM1	PFM2	SM
Delivery	10/24/13	09/25/14	10/31/14	12/09/14

35