GReAT: General Relativity Accuracy Test
EP test balloon experiment

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GReAT experiment

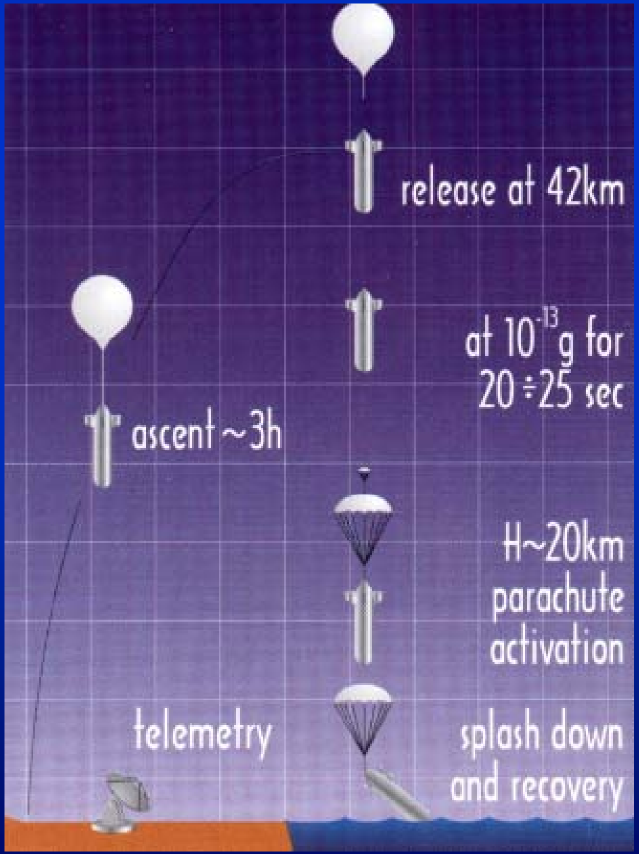
GReAT compared to the other proposed flying experiments to test the WEP:

STEP:	10^{-18}	(drag–free satellite)	NASA;
GG:	10^{-17}	(drag–free satellite)	INFN/ASI;
MicroScope:	10^{-15}	(drag–free satellite)	CNES/ESA;
GReAT:	$5*10^{-15}$	(drag–shielded capsule)	ASI/NASA;

GReAT experiment

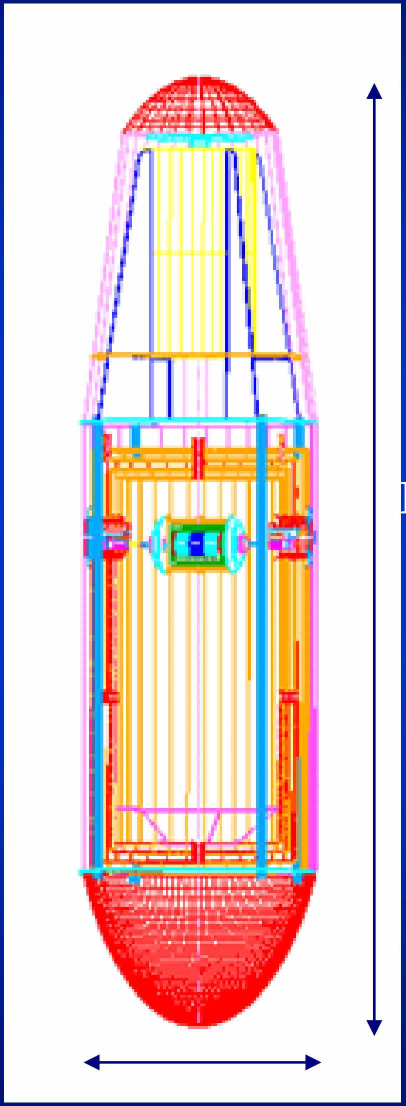
The goal of the **GReAT** experiment is to test the Weak–Equivalence–Principle (**WEP**) with an accuracy of a few parts in 10^{15} , i.e., 2 orders–of–magnitude better than the actual ground–based measurements:

- The differential accelerometer composed of two test masses of different material free falls inside a 3 m long cryostat dropped from a 40 km altitude balloon;
- the FF duration is about 30 s inside an evacuated capsule;
- the falling masses are part of a high–sensitivity differential accelerometer with a sensitivity in detecting differential accelerations of about $10^{-15} g_{\oplus}/\sqrt{Hz}$ at the liquid–helium temperature (4.2 K);



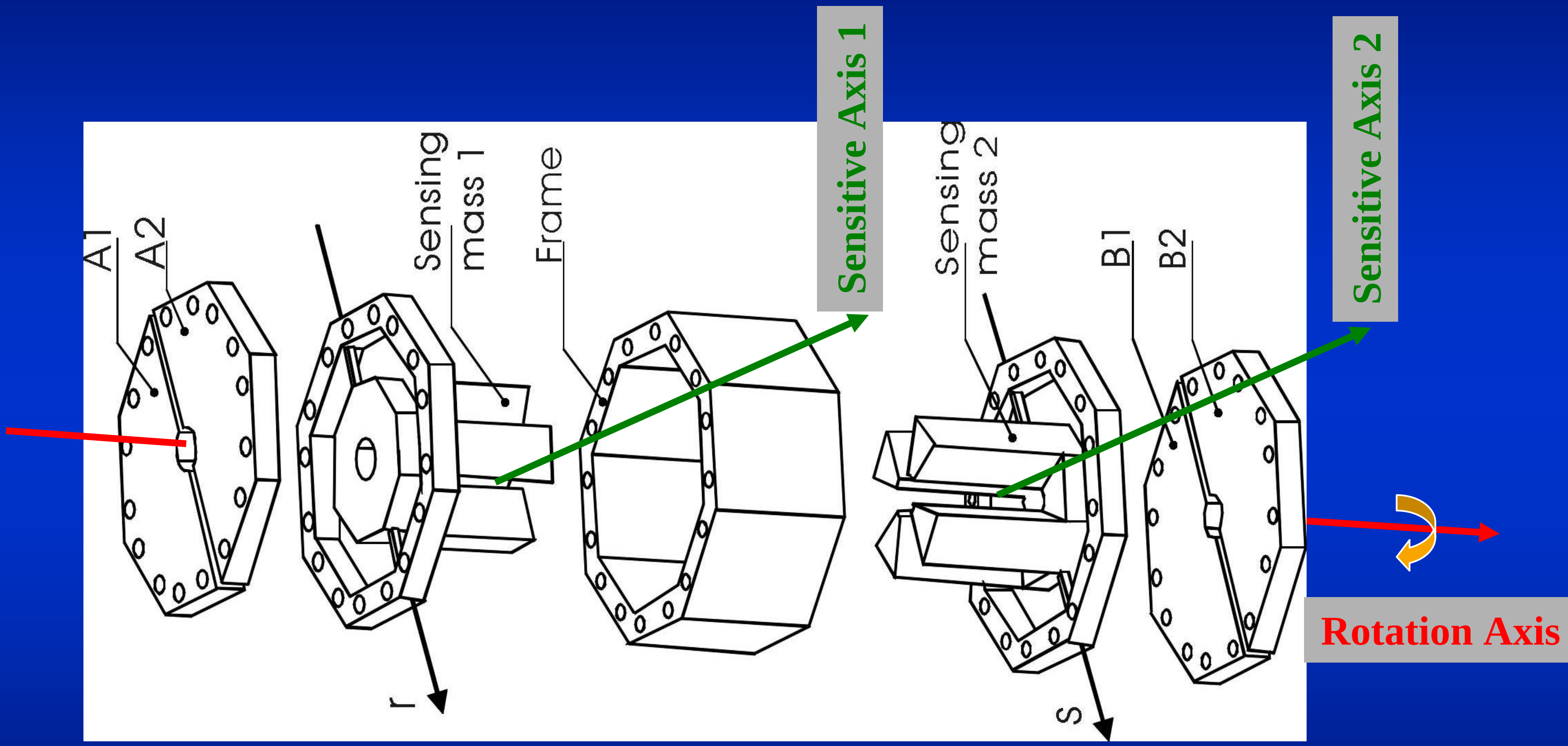
GReAT experiment

- the differential accelerometer apparatus is spun about an horizontal axis at a frequency of 1 Hz (1ω) in order to modulate the signal during free fall;
- the experiment is isolated from external noise sources acting on the capsule, such as air drag;
- a non–zero differential acceleration appearing at the rotation frequency will indicate a violation of the Equivalence Principle;
- once the instrument package reaches the capsule's floor, the capsule is decelerated by a parachute for retrieval and re-flight;



M = 1300 kg

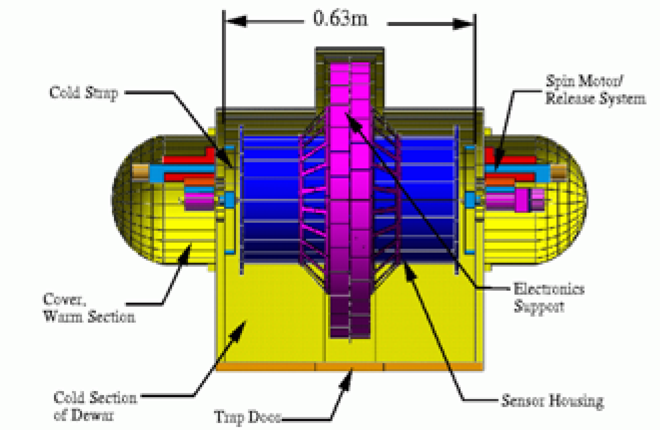
Differential accelerometer



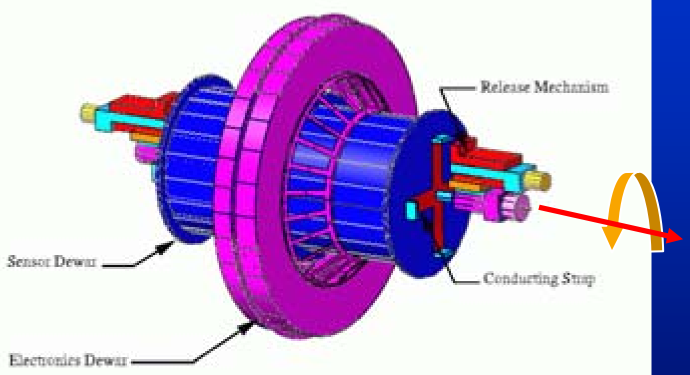
GReAT experiment

The liquid–helium refrigeration is important to provide:

- low thermal noise;
- high thermal stability;
- low thermal gradients;
- high Q–factors of the differential accelerometer detector;



Equivalence Principle Sensor Assembly
Dewar Shown Sectioned



Equivalence Principle Sensor
Assembly Exposed

- Small cryostat to refrigerate the instrument package (blue/purple);
- Open doors at bottom of cryostat;
- Instrument package span at ≤ 1 Hz before release into room–temperature capsule;

GReAT experiment

GReAT has several advantages with respect to other ground–based experiments:

- full Earth's gravity signal: $1g_\oplus$; → $$\eta = \frac{\Delta a}{g}$$
- acceleration noise of the FF detector $\leq 10^{-12} g_\oplus$ for a residual pressure of 10^{-6}mbar;
- drag–shielded vertical FF;
- longer integration time;

GReAT experiment

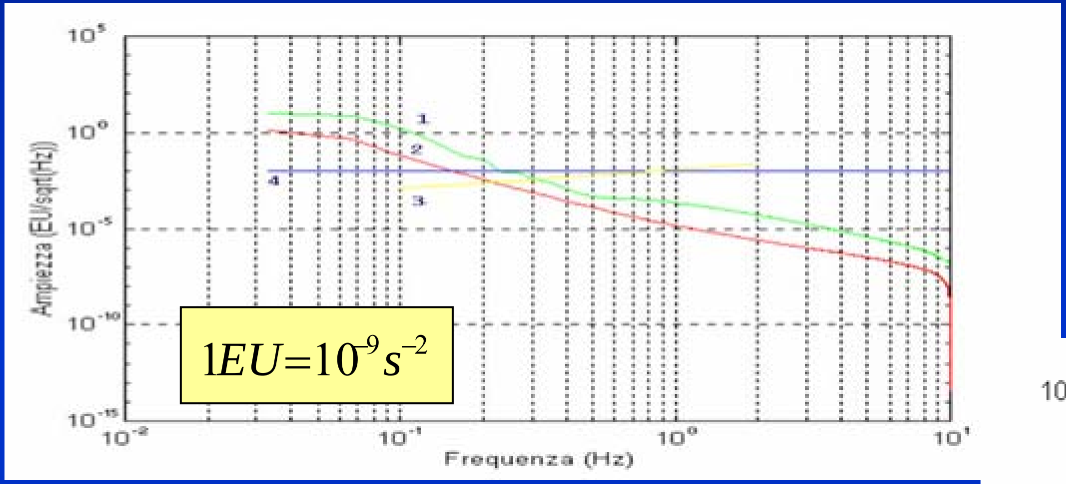
The work of the teams involved in the **GReAT** experiment to test the WEP has been subdivided in the following main aspects:

- Free–Fall system (SAO):
  - cryogenic system (with Janis Research);
  - release mechanism (cooling and clean release);
  - room temperature electronics and detector power source;

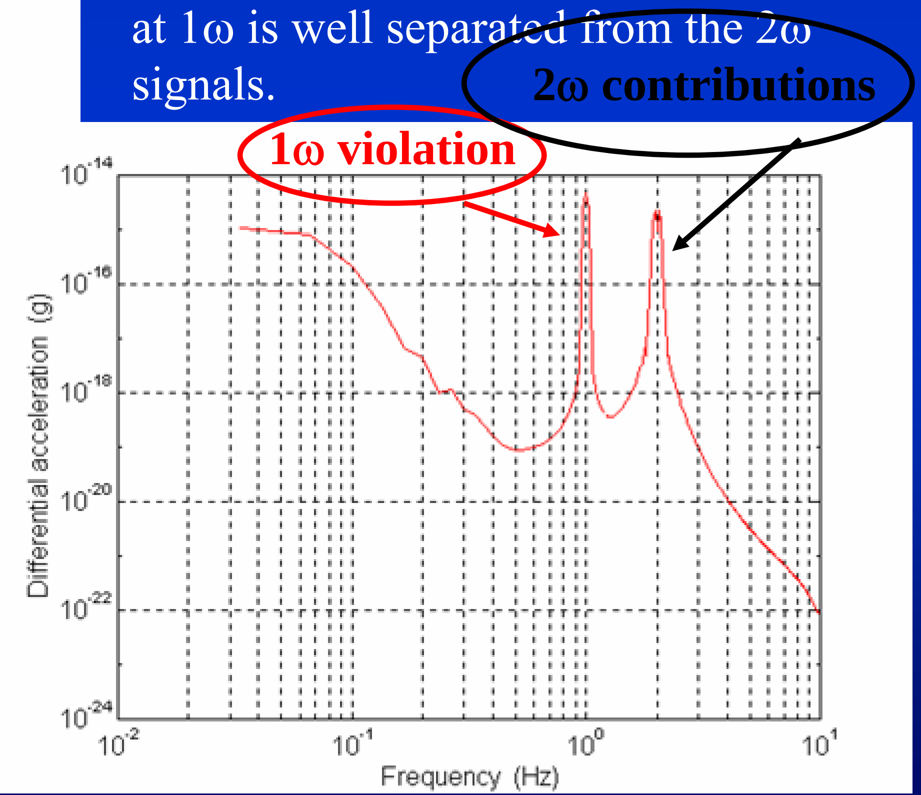
- Detector (IFSI/CNR):
  - achieving the required values (e.g., Q–factor);
  - attenuating initial transients;
  - common–mode rejection;

GReAT experiment

Numerical simulations.



FF simulation with the instrument package spun at 1 Hz including a possible violation of the WEP at the level of $10^{-15} g_{\oplus}$. The violation signal at 1ω is well separated from the 2ω signals.



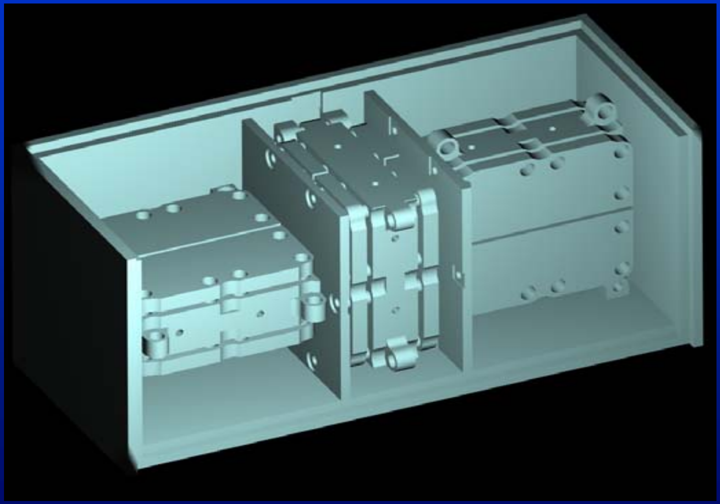
Spectral densities:

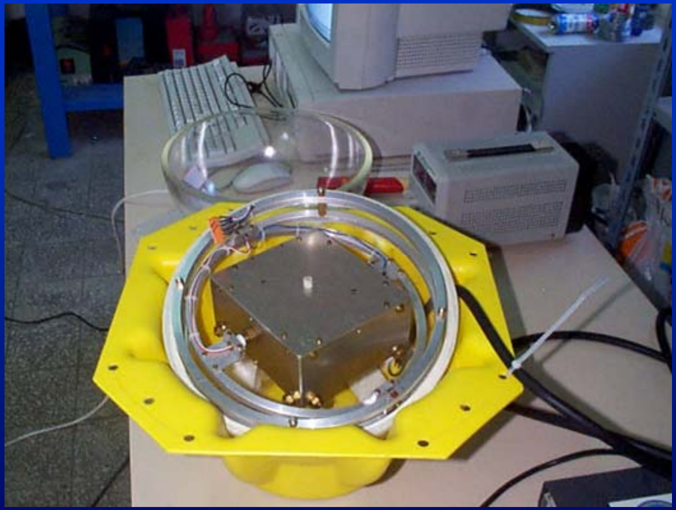
- Capsule gravity gradients;
- Earth's gravity gradients;
- Inertial gradients due to the vibrations of the capsule walls and to the platform, via the residual gas in the capsule;
- Reference gravity gradient: $10^{-2}\ EU/\sqrt{Hz}$;

The ISA accelerometer

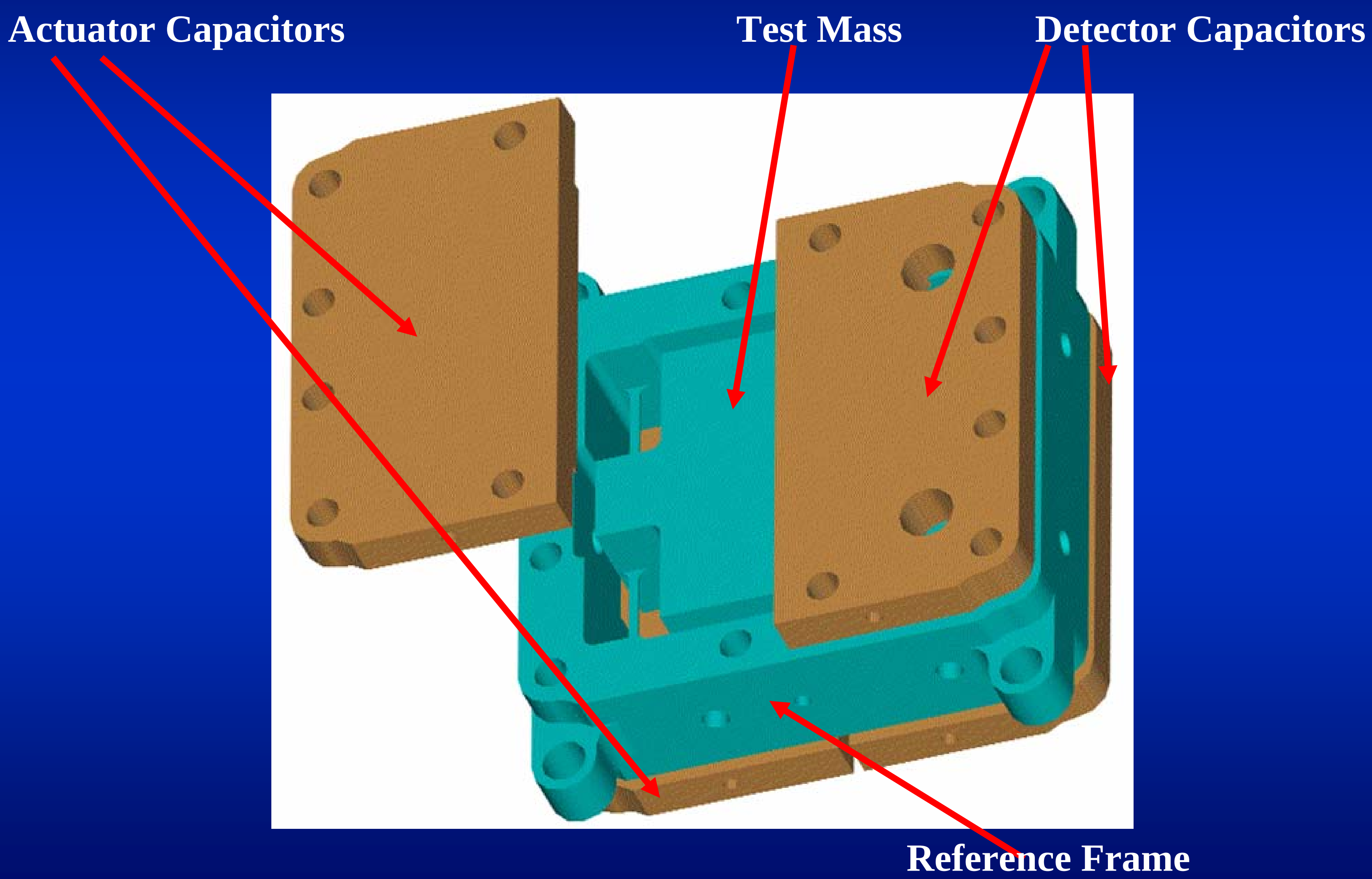
BepiColombo

GEOSTAR

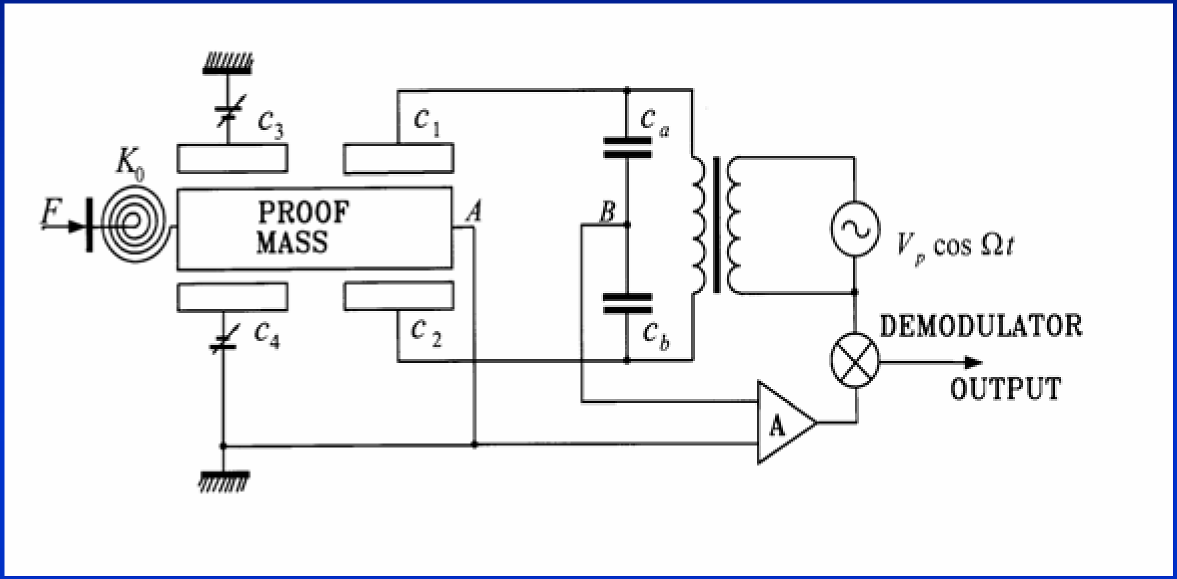




The ISA accelerometer



Base concept of the accelerometer



$$\beta = \frac{\alpha^2 C}{m_r \omega_o^{\ 2}}$$

$$\frac{1}{Q_e} = \left(4 \frac{\omega_o}{\Omega_p} \frac{tg\delta}{\beta} \right)$$

$$\frac{1}{Q} = \left(\frac{1}{Q_m} + \frac{1}{Q_{de}} \right)$$

$$a_t^{\ 2}(\omega) \approx \frac{4 k_b \omega_o}{m_r} \left[\frac{T}{Q} + T_n \frac{2 Z_n C \omega_o}{\beta} \right] \Delta f$$

no matching

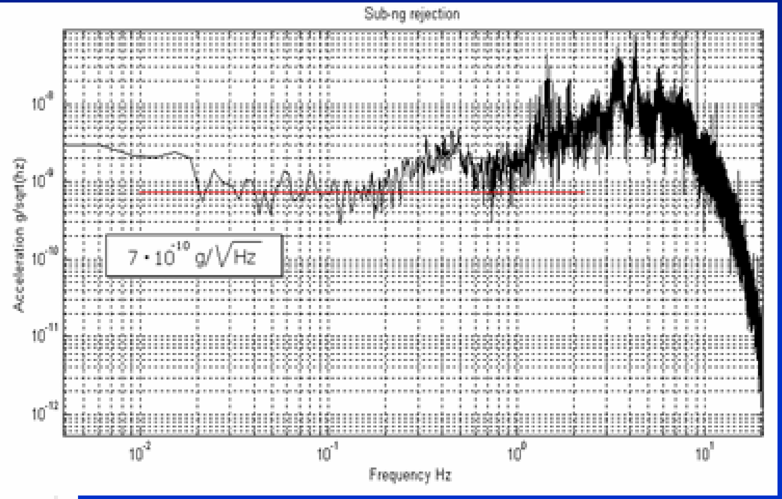
$$a_{bW} = \left(\frac{4 k_b T \omega_o}{m_r Q} \right)^{1/2}$$

$$a_t^{\ 2}(\omega) \approx \frac{4 k_b \omega_o}{m_r} \left[\frac{T}{Q} + T_n \frac{2}{\beta} \frac{\omega_o}{\Omega_p} \right] \Delta f$$

matching

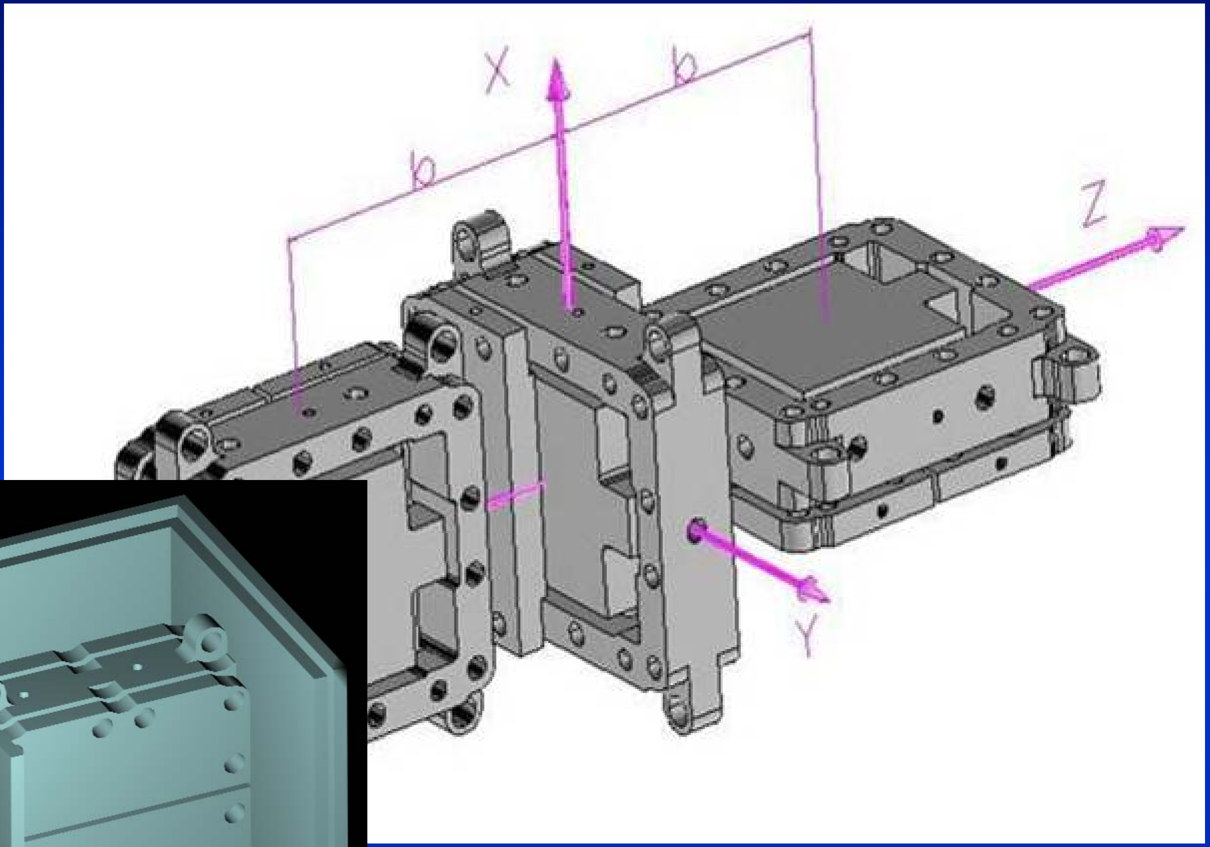
Accelerometer for space use

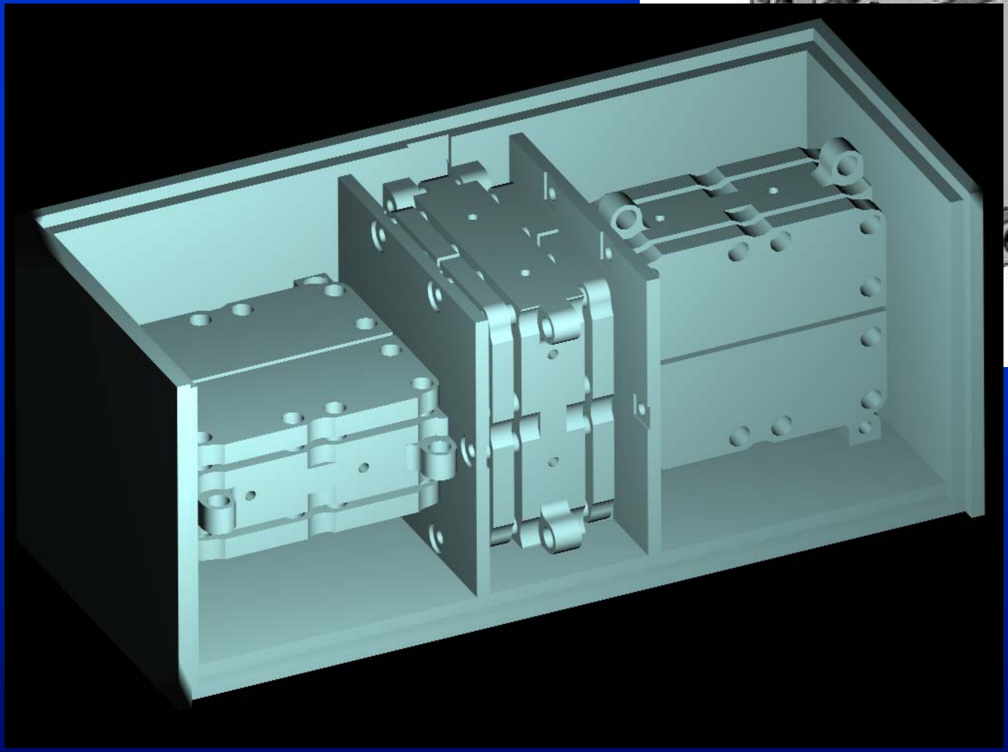
		Actual value	Possible value	Cryogenic
a_{min}	Sensitivity $g/\sqrt{Hz}$	$3.3*10^{-12}$	$4*10^{-14}$	$5.7*10^{-15}$
m_r	Proof mass (Kg)	0.22	10	10
f_o	Frequency of resonance (Hz)	3.5	1	1
f_p	Polarisation frequency (KHz)	10	10	10
P	Pressure condition ($mbar$)	10^{-4}	10^{-6}	10^{-6}
C_1	Sensing capacity (pF)	300	300	300
$tg\delta_{C1}$	Angle of loss of C_1 condenser	$4*10^{-4}$	$4*10^{-4}$	$4*10^{-4}$
C_a	External fixed capacity (pF)	300	300	300
$tg\delta_{Ca}$	Angle of loss of C_a condenser	$3*10^{-4}$	$3*10^{-4}$	$3*10^{-4}$
	Electronic device	AD743/AD	OPA128	OPA128
v_n	Voltage noise of amplifier ($V/\sqrt{Hz}$)	$3*10^{-9}$	$15*10^{-9}$	$15*10^{-9}$
i_n	Current noise of amplifier ($A/\sqrt{Hz}$)	$7*10^{-15}$	$0.1*10^{-15}$	$0.1*10^{-15}$
T_n	Temperature noise of amplifier (K)	0.76	0.06	0.06
α	Transducer factor (V/m)	10^5	10^5	$5*10^5$
β	Electromechanical transducer factor	$2.8*10^{-2}$	$7.6*10^{-3}$	$1.9*10^{-1}$
Q_e	Electric merit factor	$6.6*10^4$	$6.3*10^4$	$1.5*10^6$
Q_m	Mechanical merit factor	$5.7*10^3$	10^5	10^5
Q	Total merit factor	$5.7*10^3$	$6.3*10^4$	10^5
$a_{bw}{}^2$	Brownian noise $(m/\sec^2)^2/Hz$	$2.9*10^{-22}$	$1.6*10^{-25}$	1.410^{-27}
$a_{el}{}^2$	Electronic noise $(m/\sec^2)^2/Hz$	$8.4*10^{-22}$	$4.9*10^{-26}$	$1.9*10^{-27}$



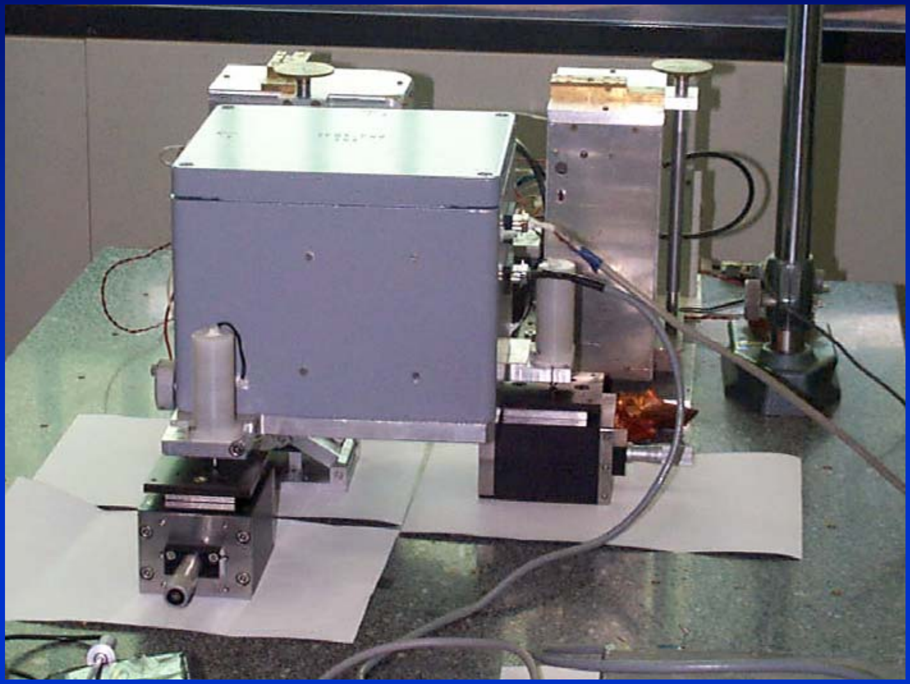
Differential measurement in order to eliminate the seismic noise in the laboratory performed with two accelerometers with sensitive axes parallel. The residual flat noise is due to the electronics. The setup electronic (that used for the geophysics) was not the best one in order to reach the actual sensitivity of $3.3{\cdot}10^{-12}$ $g_{\oplus}/\sqrt{Hz}$. Anyway the level of the mechanical rejection is quite good.

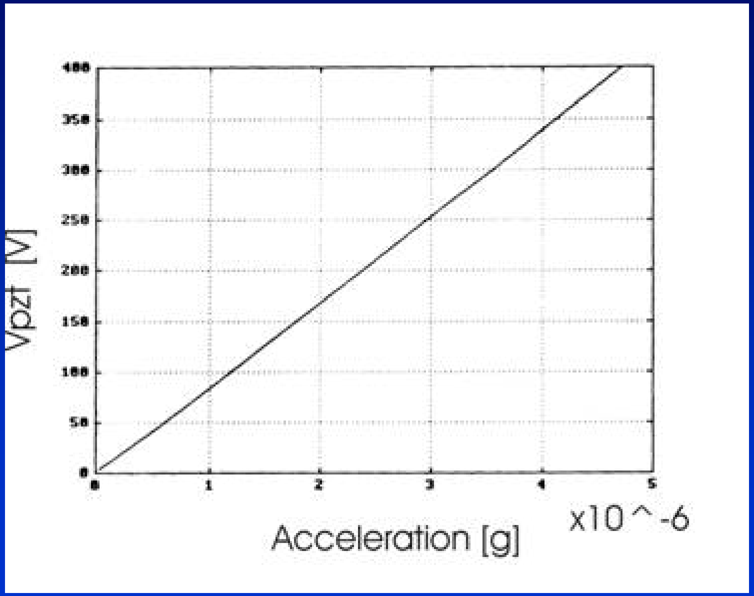
ISA (Italian Spring Accelerometer)
Three-axis

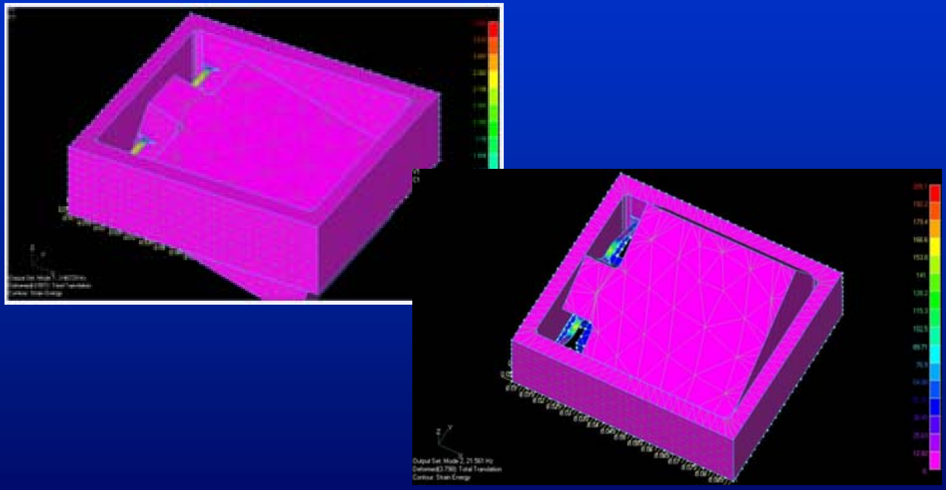


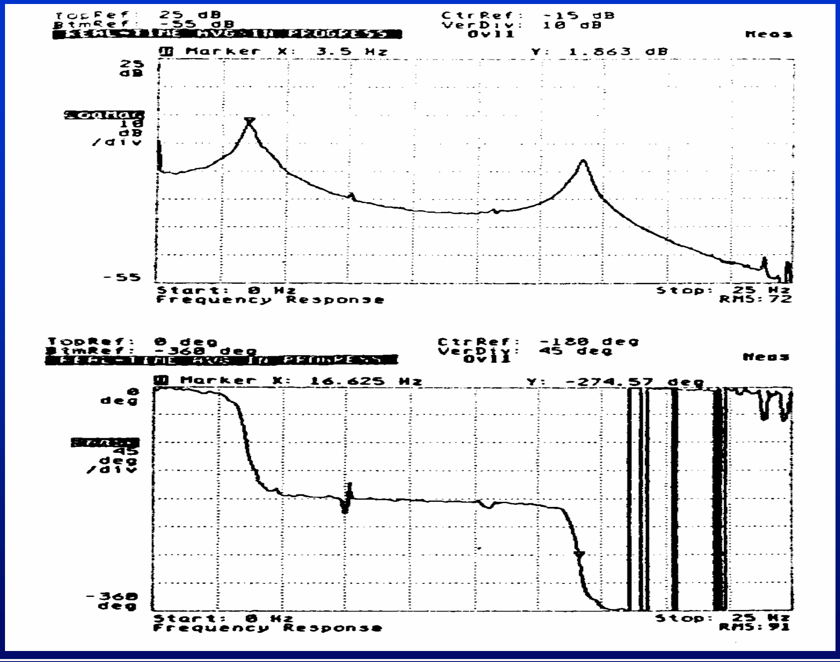


ISA laboratory calibrations



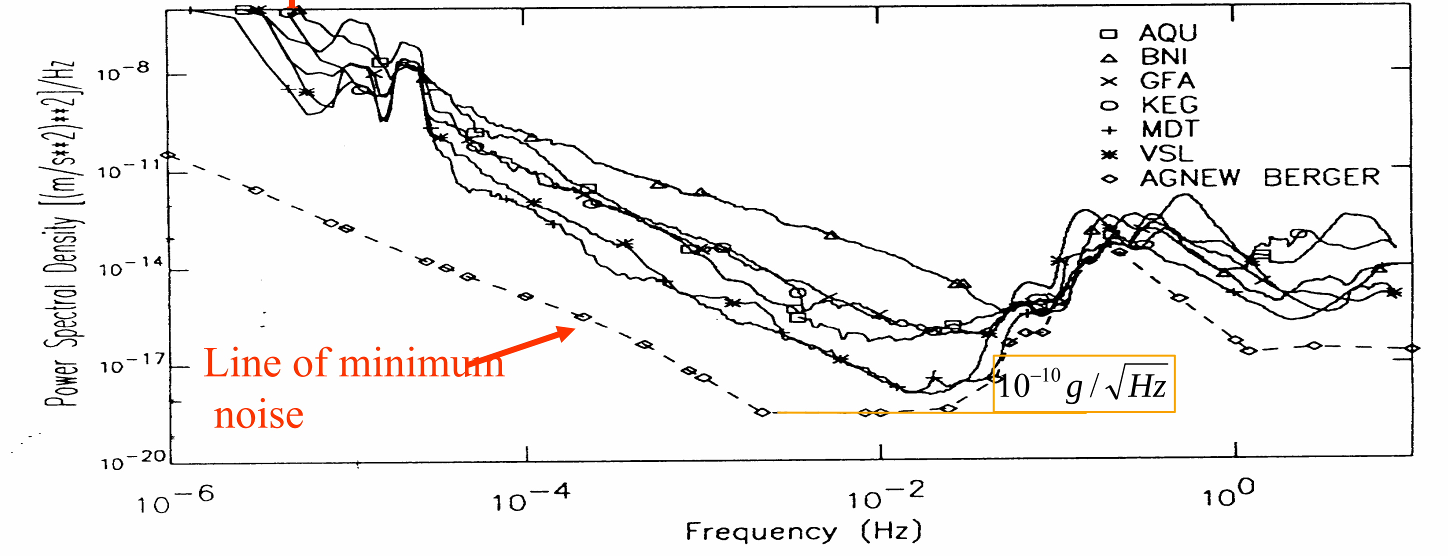




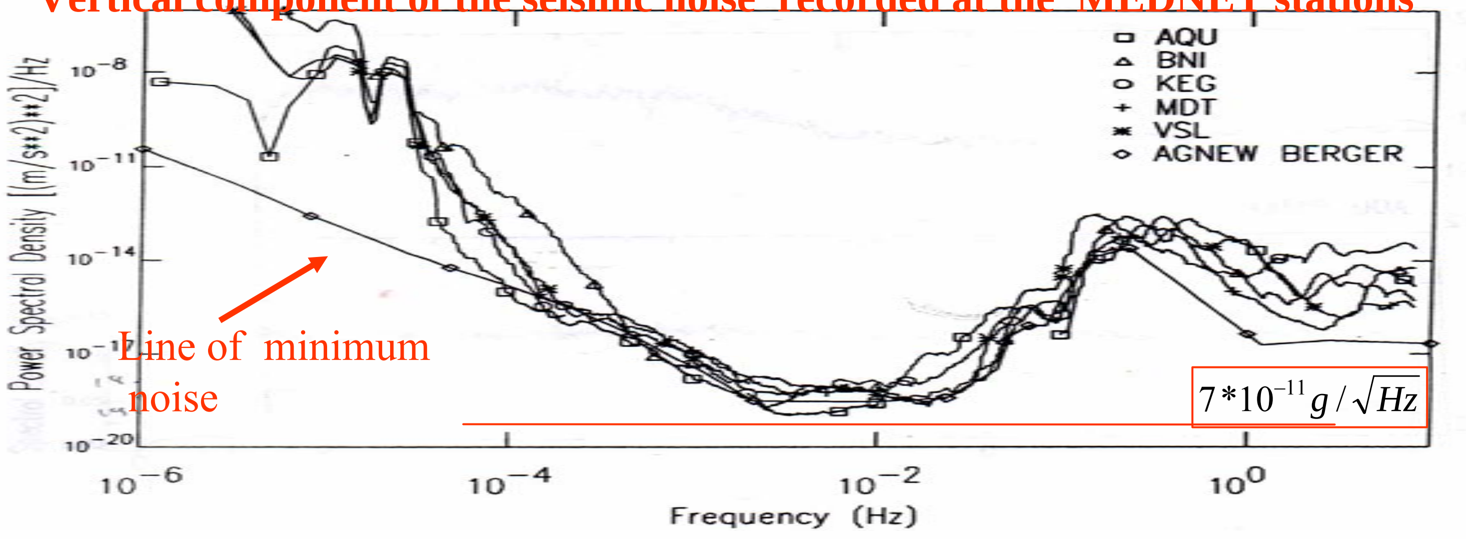


Geophysical Measurements

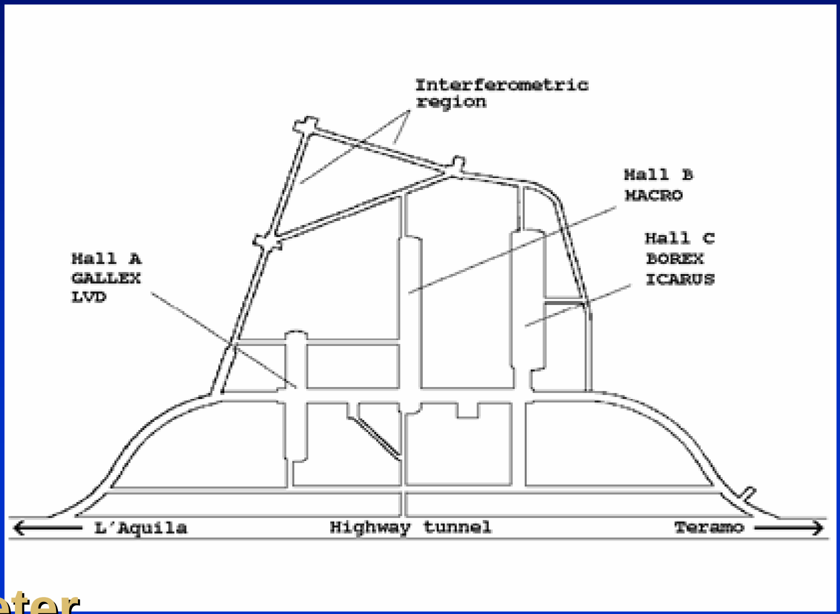
Horizontal component of the seismic noise recorded at the MEDNET stations



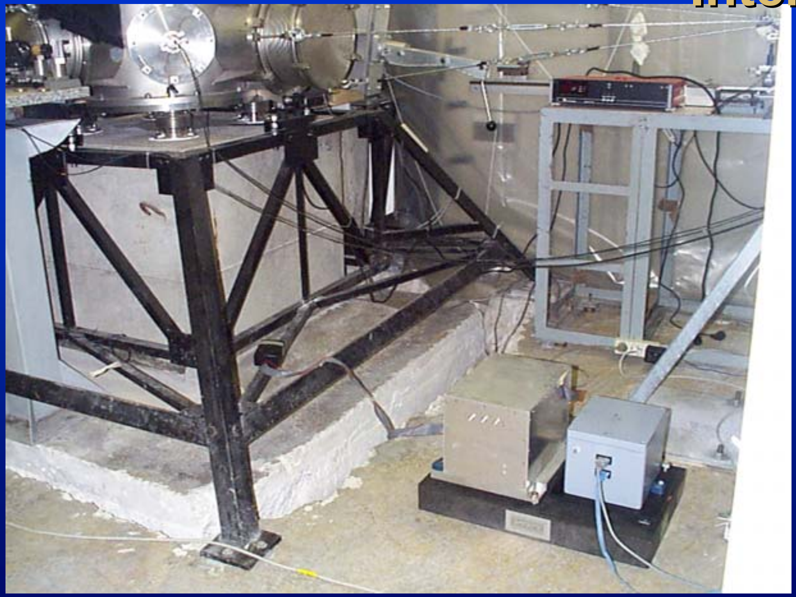
Vertical component of the seismic noise recorded at the MEDNET stations



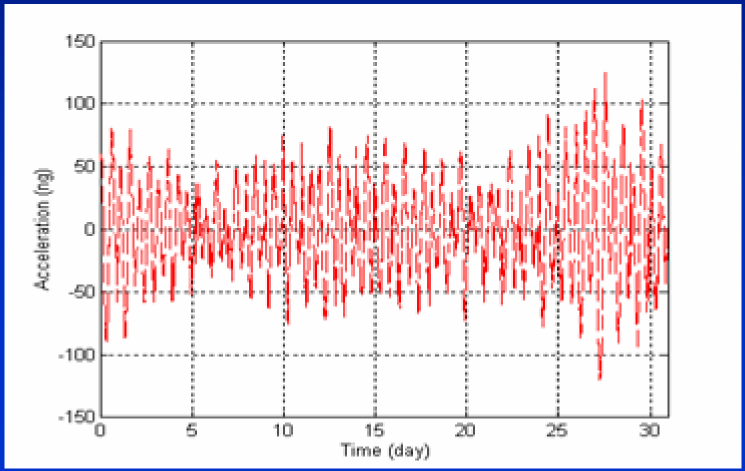
Istituto Nazionale di Fisica Nucleare (INFN)
Gran Sasso

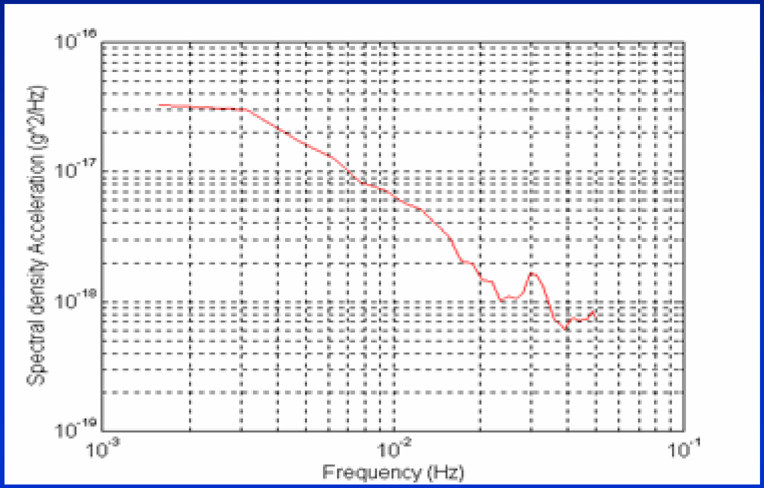


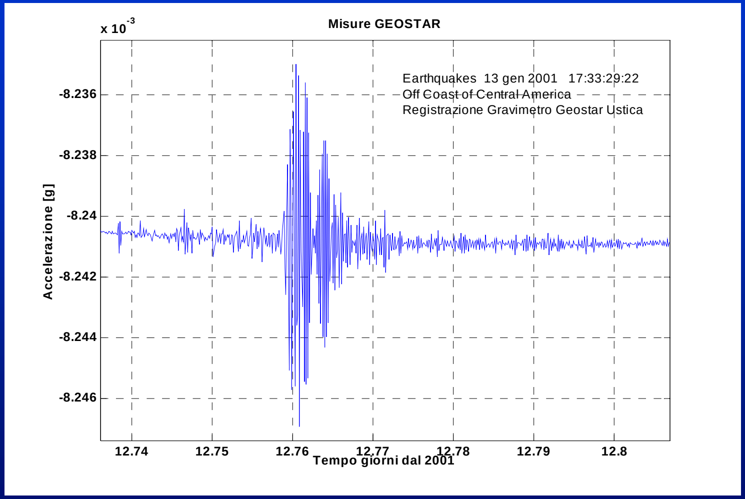
Interferometer

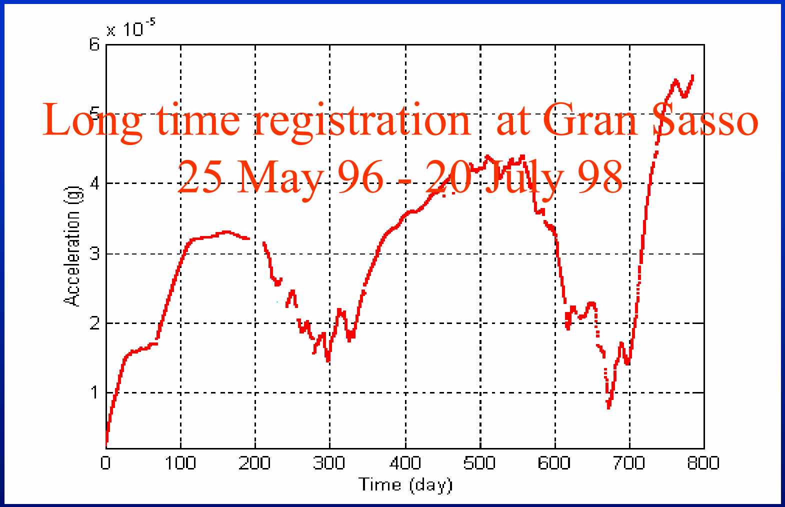


Geophysical Measurements



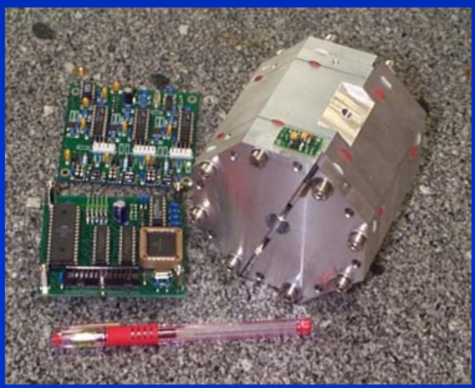


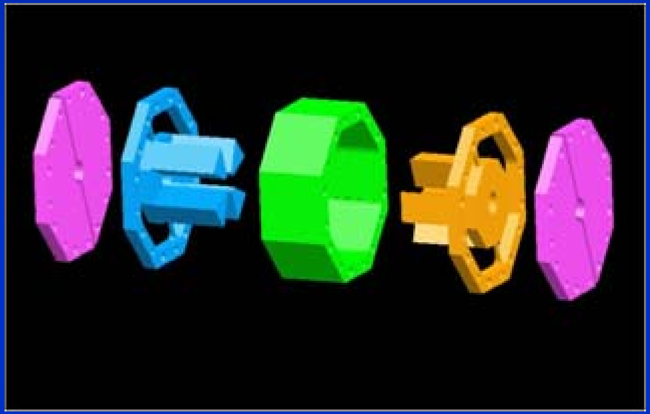




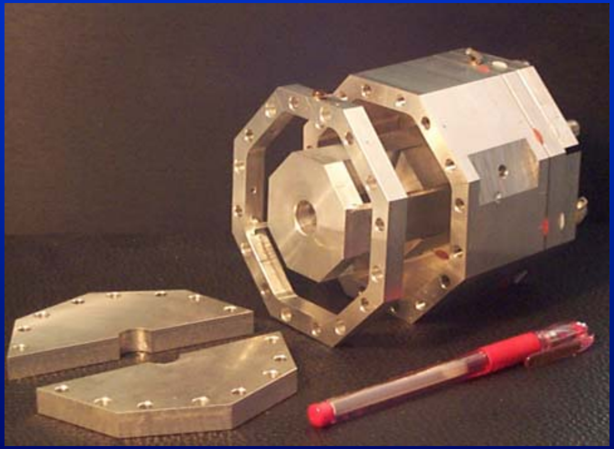
Experimental results with a differential accelerometer prototype

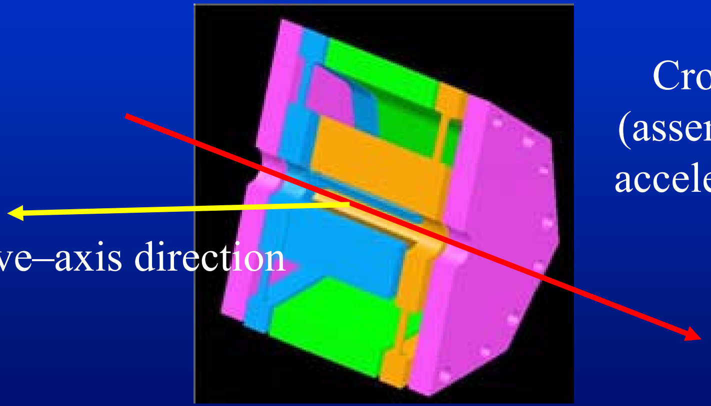
The first differential accelerometer prototype built at IFSI/CNR:





Exploded view of the differential accelerometer prototype



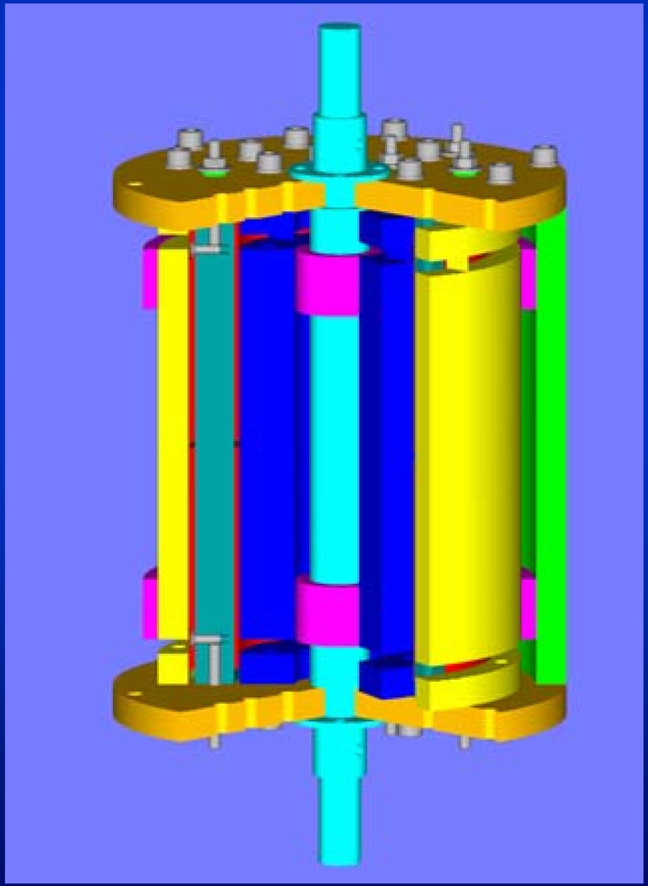


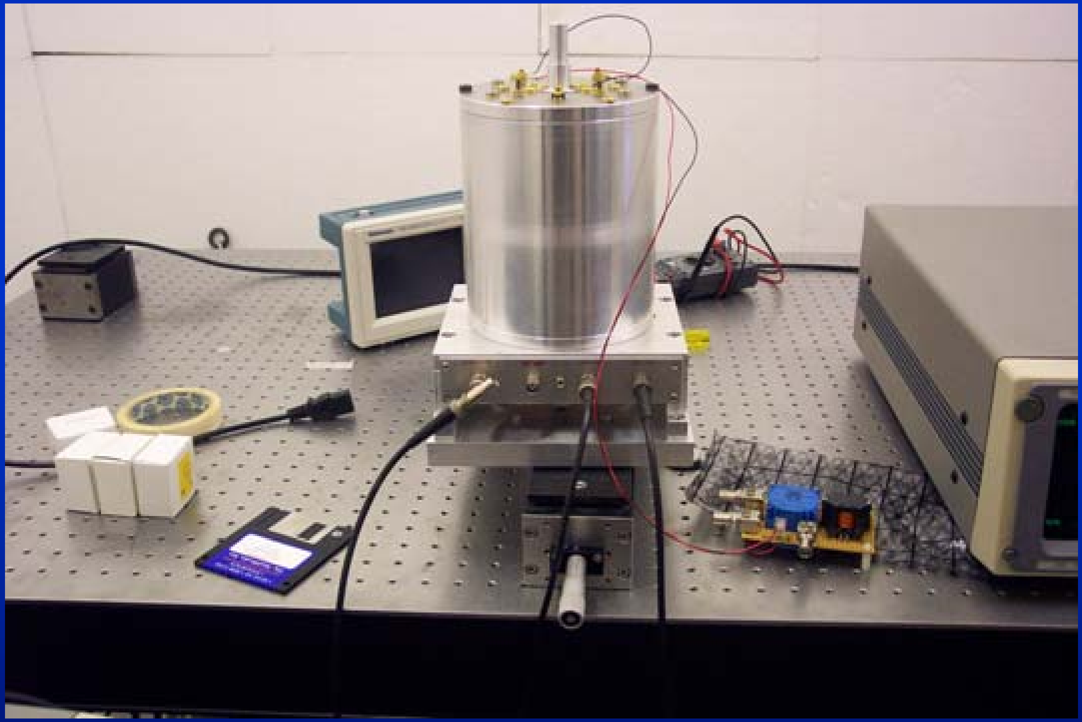
Cross section of the (assembled) differential accelerometer prototype

Each sensing mass has to fixed capacitors plates for the signal pickup.

New configuration of the differential accelerometer

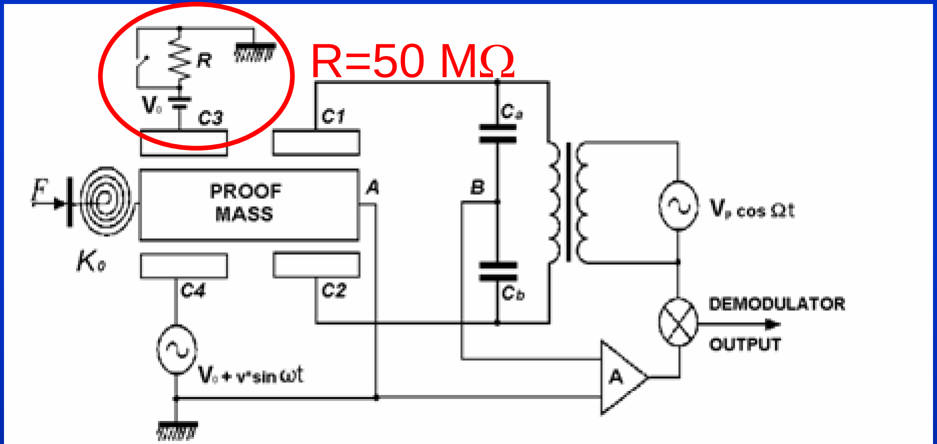
The second differential accelerometer prototype built at IFSI/CNR.





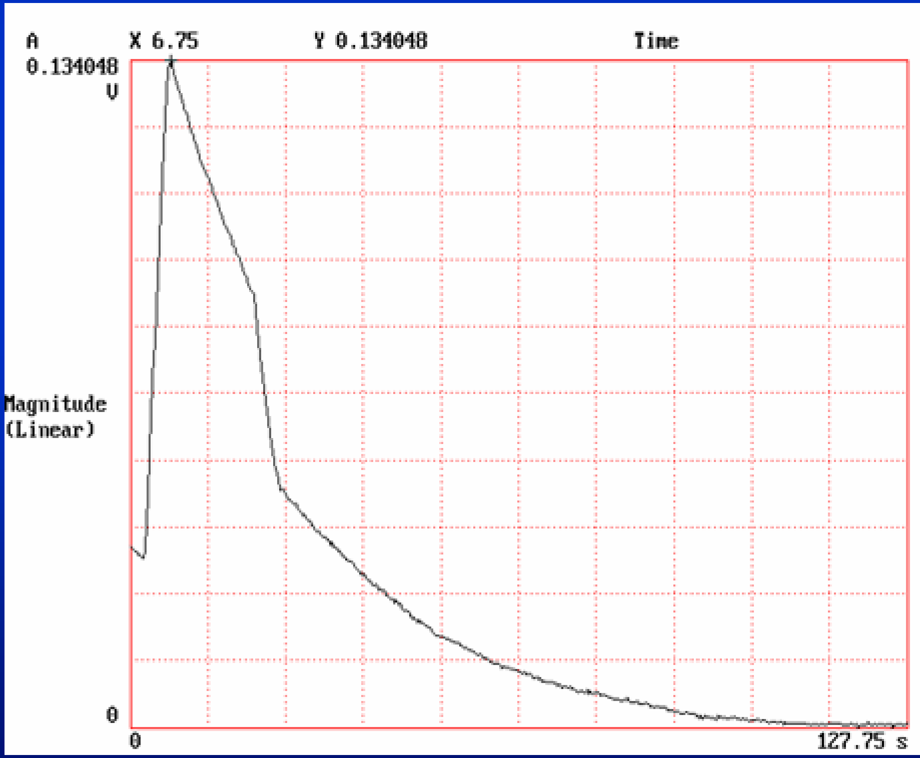
Experimental results with a differential accelerometer prototype

Abatement of the natural dynamics excited by the instrument release into the capsule.



Electrical scheme with resistance added to the feedback loop

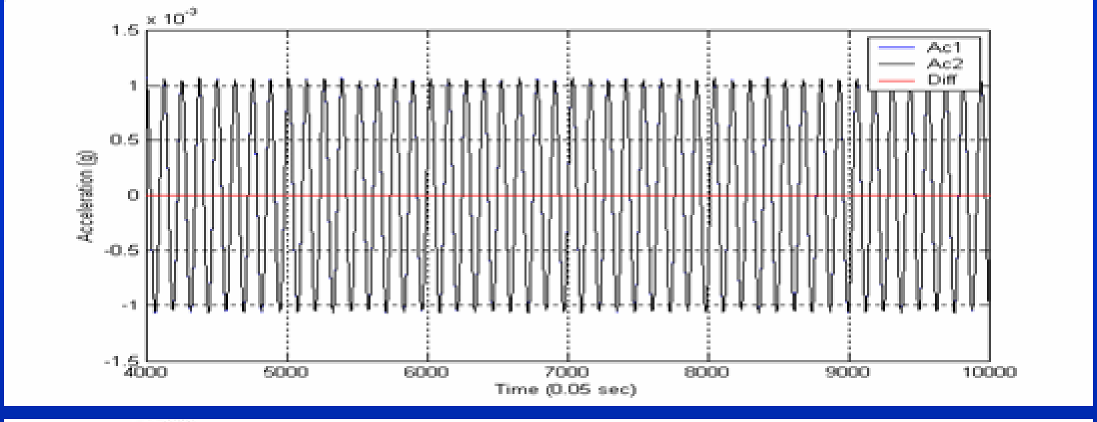
$$\frac{1}{Qt} = \frac{1}{Qm} + \frac{1}{Qe} \qquad \frac{1}{Qe} = \beta \frac{\omega_o RC}{1+(\omega_o RC)^2} \qquad \beta = \frac{C \cdot E^2}{M \cdot \omega_0^2}$$

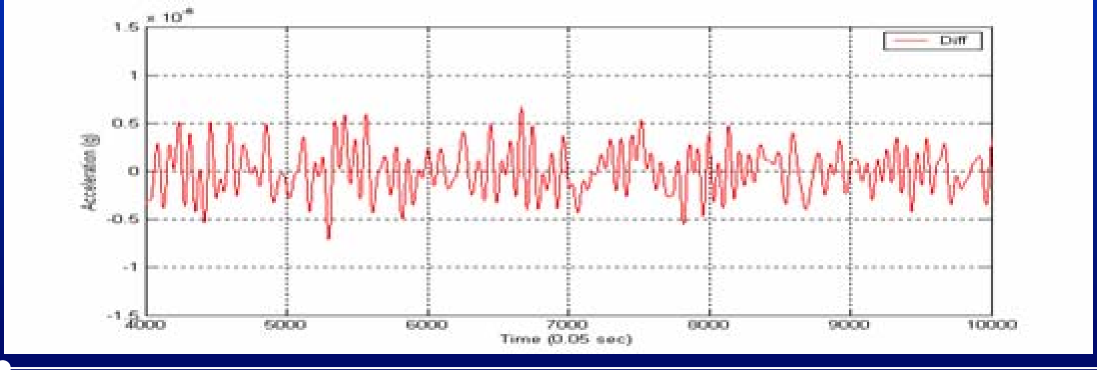


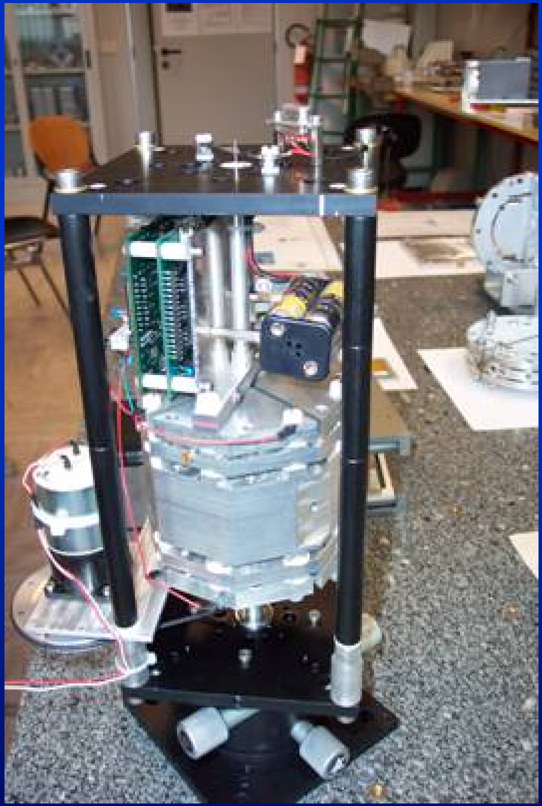
Experimental results with a differential accelerometer prototype

<u>Rejection of the common–mode signals.</u>

One important characteristic of a differential accelerometer is its ability to reject perturbations that are not differential, i.e., common–mode disturbances. This ability is quantified by the common–mode rejection factor (CMRF).



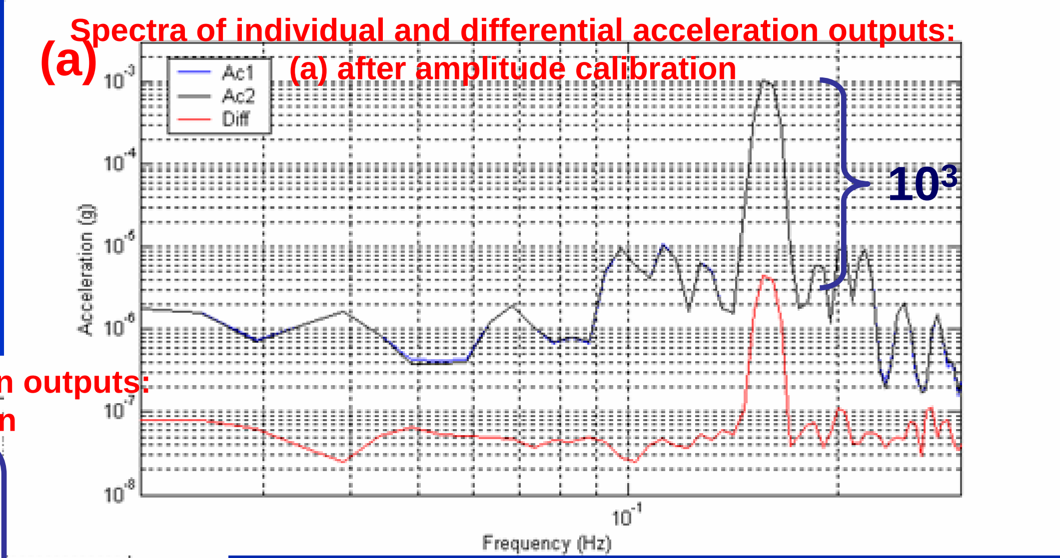


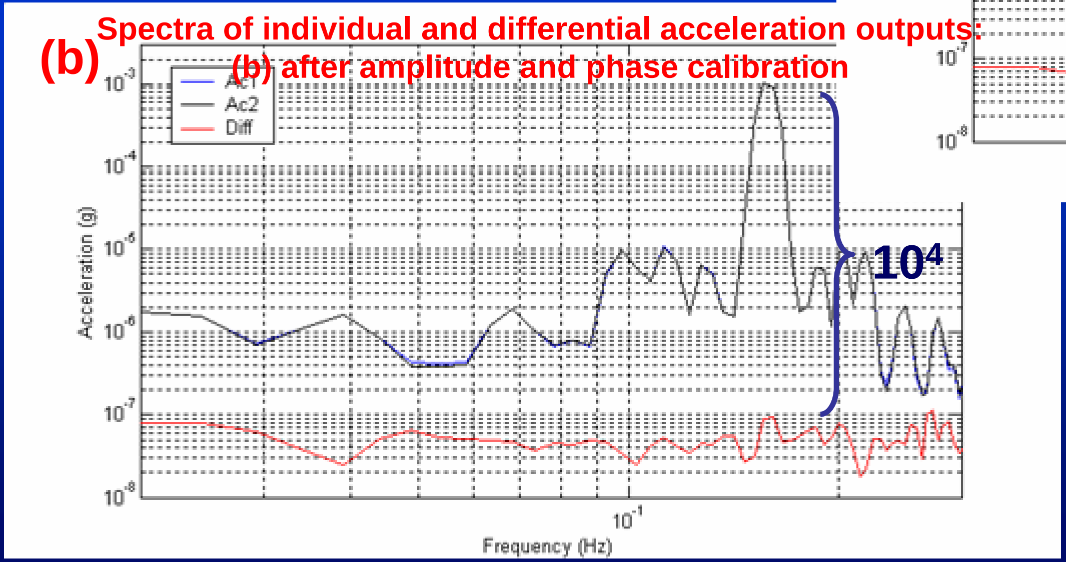


Experimental results with a differential accelerometer prototype

Rejection of the common–mode signals.

Figure (b) shows that after calibrating for amplitude and phase a 10^4 attenuation is readily obtained for the differential signal. This level of attenuation is effective not only at the perturbation frequency of 0.15 Hz but also over a larger frequency band.





An attenuation of 10^4 or equivalently a common–mode rejection factor of 10^{-4} meets the present requirement on the CMRF for the proposed tests of the WEP.

Conclusions

- **Advantages**
  – Reusability and easy access to experiment
  – Low cost
  – Strong gravity signal (i.e., 1 g)
  – Noise level comparable to drag-free satellites

- **Disadvantages**
  – Short integration time

- **In summary**
  – Estimated accuracy in testing the WEP several parts in 10^{-15} with 95% confidence level
  – Potential accuracy improvement of 2 orders of magnitude with respect to the state of the art

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