Sensors and Actuators for ET

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Overview

- Payload local sensing
  - General Scheme
  - Sensitivity for different implementations
- Payload actuators
  - Proposed Implementation;
  - Actuator characterization;

Local Sensing

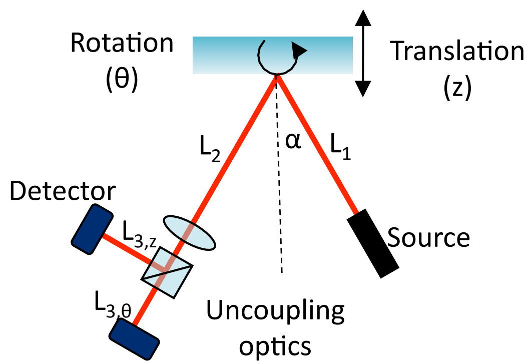
Definition and Motivation

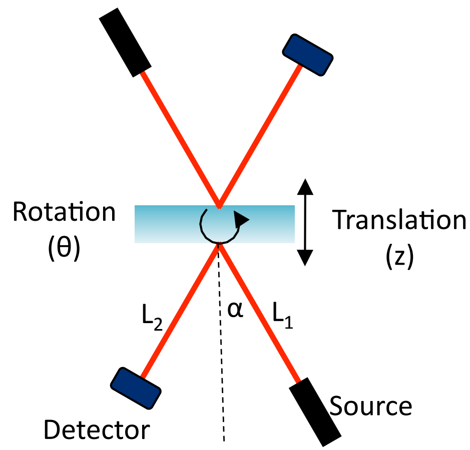
- The local sensing system is used to measure the payload position with respect to a local reference system
- It is used for different tasks:
  - Reduce the mirror motion amplitude to easily engage automatic controls;
  - Recover the angular position of the mirror and set it to the last "locked" condition;
- Since such sensing is performed with respect to the ground, the sensitivity is intrinsically limited by the seismic noise.

Local Sensing

General Scheme

- The proposed architecture is based upon the use of optical levers:
  - Probe beam;
  - Position detector (PSD or Quadrant photodiode);
- Same scheme on test mass and marionette
- A single beam mixes rotation and translation; then an uncoupling method must be applied:
  - Optical uncoupling or Geometrical uncoupling;





Local Sensing

Basic Relations

- The sensitivity depends on the detector but also on the uncoupling system;

- Optical/Geometrical gain:
  - z: mass translation, θ: mass rotation
  - $d_z = G_z z$, $d_\theta = G_\theta \theta$
  - d_q: beam displacement on the detector for the q degree of freedom;
- Detector sensitivity
  - $V_q = S_q q$
  - S_q is the sensitivity in V_n/m (V_n: normalized voltage)

Local Sensing

Basic Relations

- Comparison of different sensitivity:

Gain	**Opt.Uncoupling**	**Geom. Uncoupling**
G_z	$(2\ f \sin \alpha)/(L_2\text{-}f)$	$2 \sin \alpha$
G_θ	$2\ f$	$2\ L_2$
Sensitivity	**PSD**	**Quadrant**
S_q	$2/L$	$(8/\pi)^{1/2}/w$

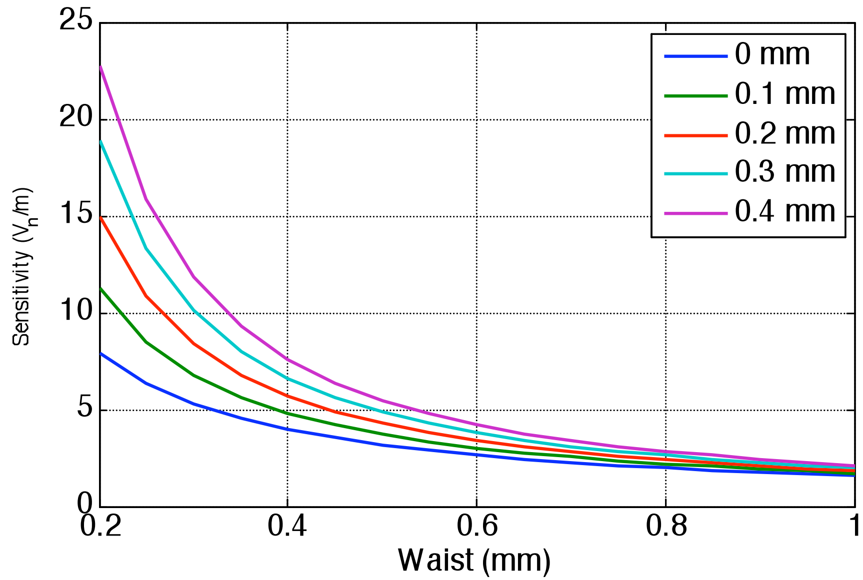
- In table:
  - L: full detector size;
  - w: beam waist on the detector
  - f: focal length (if optical uncoupling)

Local Sensing

Basic Relations

- The sensitivity for the quadrant detector was calculated for an “infinite” detector with no gap;
- More detailed calculations, taking into account these characters, show change in sensitivity;

Sensitivity of a quadrant photodiode with L=3 mm, for different values of gap and different waist on the detector



Local Sensing

Main limiting noises

- The fundamental limit is the shot noise:

  - $$q_{shot} = \sqrt{\frac{2h\nu}{\eta P}} \frac{1}{S_q G_q}$$

- The electronic noise mainly affects the lower frequency band (models depend on the electronic layout);

- The quantization noise is not considered since it can be easily lowered under the shot noise by using high resolution ADC and oversampling;

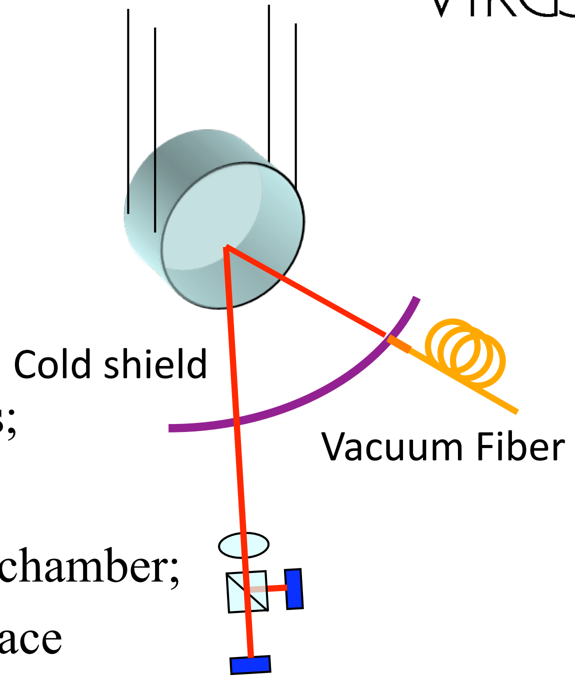
Local Sensing

Possible architecture for ET

- Three options have been presented as possible implementations for ET;
- They common constrains are:
  - Probe beam(s) guided into the vacuum chamber by optical fibers;
  - No active components inside the cold shields;
  - Beam(s) path(s) reduction;
- The solutions under investigations are:
  1. Internal uncoupling optics and detectors;
  2. Internal optical uncoupling and external detectors;
  3. Geometrical uncoupling and external detectors;

Local Sensing

Option 1



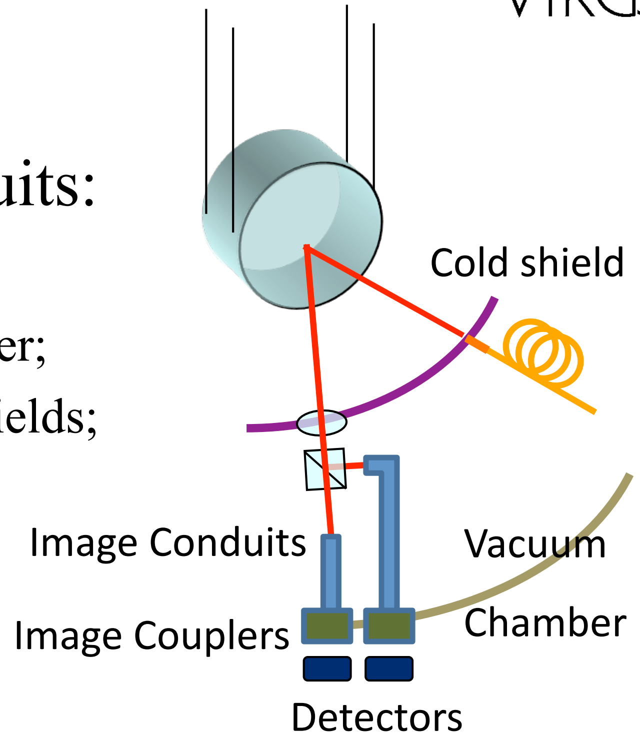
- The first option is the simplest:
  - Advantages:
    - Reduced number of beams inside the chamber;
    - Reduced number of apertures on the cold shields;
  - Disadvantages:
    - Space for uncoupling system inside the vacuum chamber;
    - Photodiodes need to stay at room temperature place

  - Sensitivity calculation for plausible geometrical values:
    - $\alpha=\pi/3$, $L_2=75$ cm, L=5mm, f=20 cm, P=1 mW, PSD detectors
  - Gives the following values:
    - $S=364/m$, $G_z=0.63$, $G_\theta=0.2m$, $L_{3,z}=0.27m$, $L_{3,\theta}= 0.2m$
    - $z_{shot}=2\cdot 10^{-10} m/Hz^{1/2}$, $\theta_{shot}=2\cdot 10^{-10} rad/Hz^{1/2}$

Local Sensing

Option 2

- The second option requires image conduits:
  - Advantages:
    - Reduced number of beams inside the chamber;
    - Reduced number of apertures on the cold shields;
    - Detectors outside the chamber;
  - Disadvantages:
    - Couplers to guide images outside;

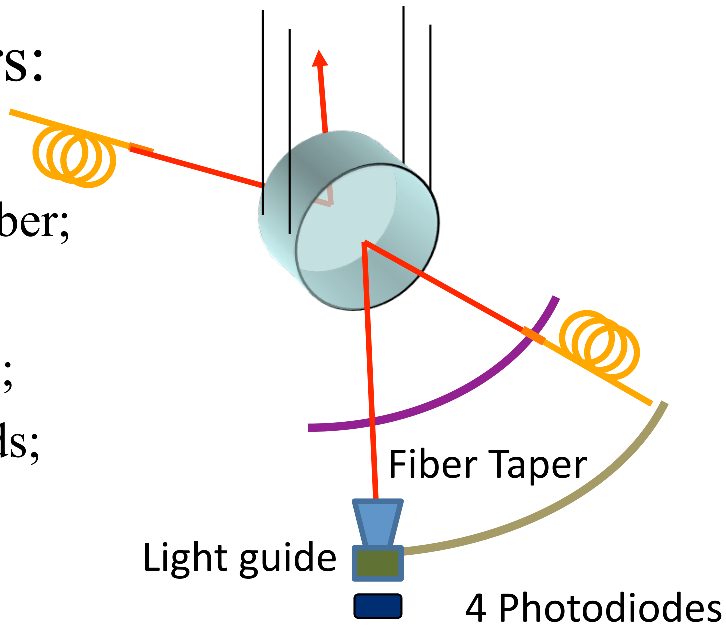


  - Sensitivity calculation for plausible geometrical values:
    - $\alpha=\pi/3$, $L_2=25$ cm, L=5mm, f=10 cm, P=1 mW, PSD detectors
  - Gives the following values:
    - $S=364/m$, $G_z=1.15$, $G_\theta=0.1m$, $L_{3,z}=0.17m$, $L_{3,\theta}= 0.1m$
    - $z_{shot}=1\cdot 10^{-10} m/Hz^{1/2}$, $\theta_{shot}=6.2\cdot 10^{-10} rad/Hz^{1/2}$

Local Sensing

Option 3

- The third option requires fiber tapers:
  - Advantages:
    - Simpler setup inside the vacuum chamber;
  - Disadvantages:
    - Double the number of the probe beams;
    - More (and larger) aperture in the shields;



  - Sensitivity calculation for plausible geometrical values:
    - $\alpha=\pi/3$, $L_2=75$ cm, $P=1$ mW
    - Tapers modeled as quadrant: L=5 cm, w=1 cm, Gap=1mm
  - Gives the following values:
    - $S=172/m$, $G_z=1.73$, $G_\theta=1.5m$
    - $z_{shot}=2.1\cdot10^{-10}m/Hz^{1/2}$, $\theta_{shot}=7.4\cdot10^{-10}rad/Hz^{1/2}$

Local Sensing

Options 2-3

- Technical solutions for options 2 and 3 exist;
- In the sensitivity calculation possible signal degradation due to the presence of image conduits or tapers was neglected (to be checked);

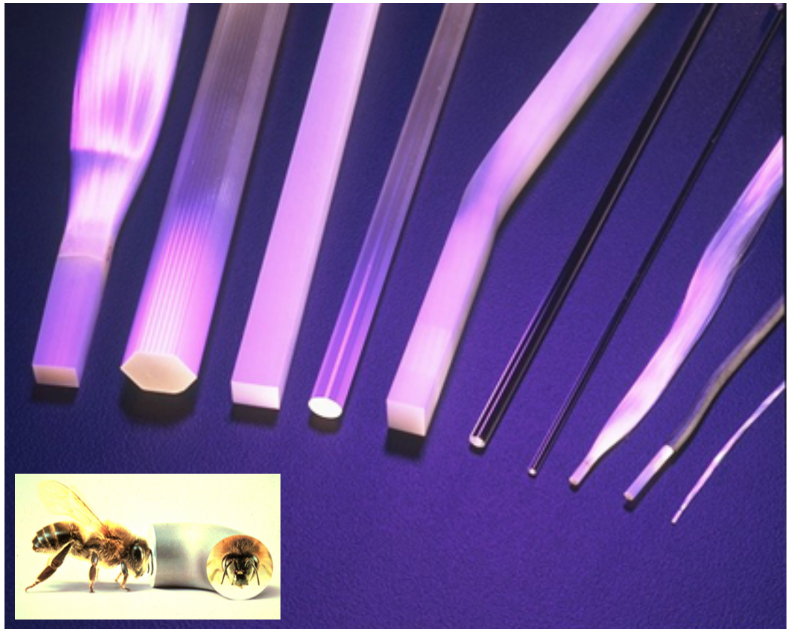


Image Conduits

Fiber Tapers

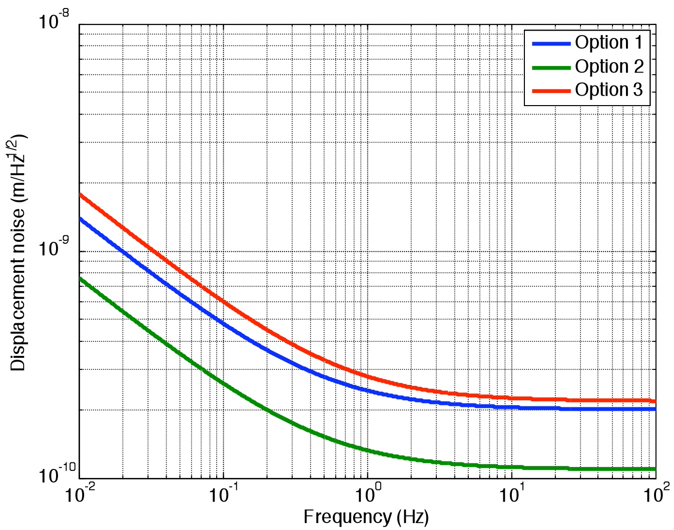
Local Sensing

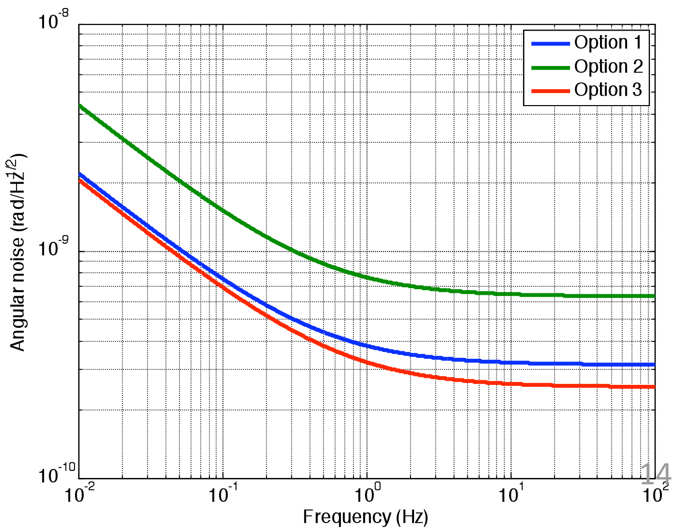
Noise Comparison

- Final sensitivity for both tilt and translation in the three configurations

Option	Z Sensitivity (1/m)	θ Sensitivity (1/rad)
1	229	145
2	420	73
3	298	258

- Electronic and shot noise for translations and rotation for all the options;
- Electronic noise calculated using standard "Virgo" electronics;





Local Sensing

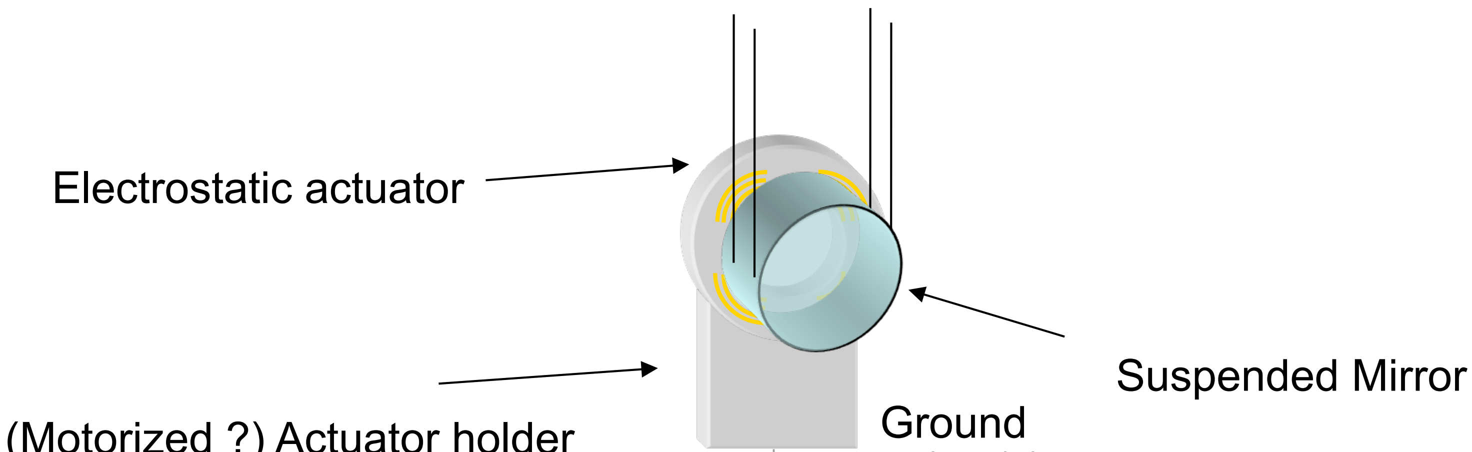
Remarks

- Sensitivity (and Noises) are not very different for different options: within a factor 3;
- Of course other solutions can be investigated, but no major changes are expected;
- Moreover, in any configuration, the limiting noise will be the seism acting on the sensing system. The design of each option must be updated according to the seismic level in underground sites.
- The thermal load of such sensing system are expected to be very low: most of the injected power is sent to the detectors through non conductive device close to the thermal shield.
- A small fraction of the optical lever power (< 1mW in this calculations) is expected to be absorbed by the test mass.

Actuation

A configuration proposal

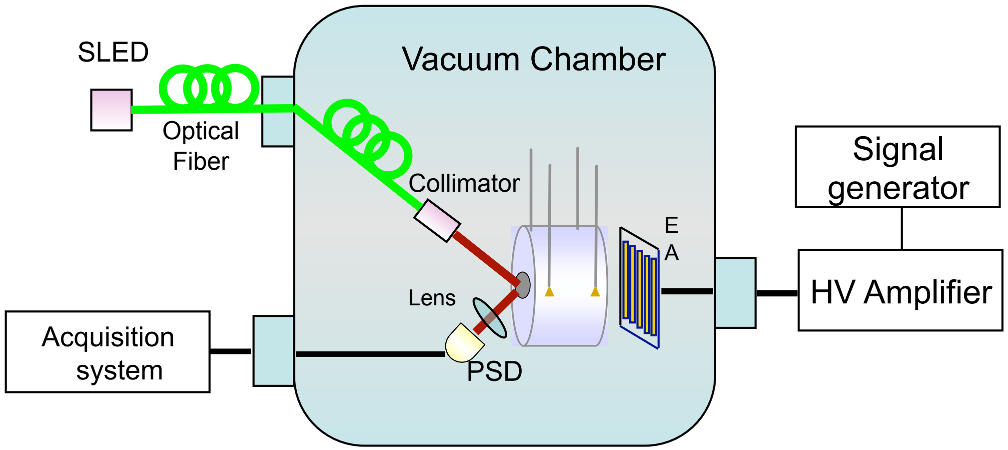
- The solution under investigation is:
  - Ground referenced electrostatic actuators for test mass damping and lock acquisition;
  - Standard coil magnets actuators at the marionette level for mirror steering and steady locking;
- The idea is to switch off completely the actuation on the test mass after the lock acquisition



Actuation

Actuator Characterization

- Mirror actuator design can be based on a numerical model developed in the past and recently confirmed by direct measurements.
- Experimental set-up:
  - Suspended dielectric mirror under vacuum
  - Optical lever for position monitor
  - Ground based actuator



Actuation

Actuator Characterization

- The actuation driving signal is in the form:

$$V = \sqrt{A_{DC} + A_{AC}\cos\omega t}\,\sin\omega_M t$$

- where ω_M is a modulation frequency
- The response of the actuator is:

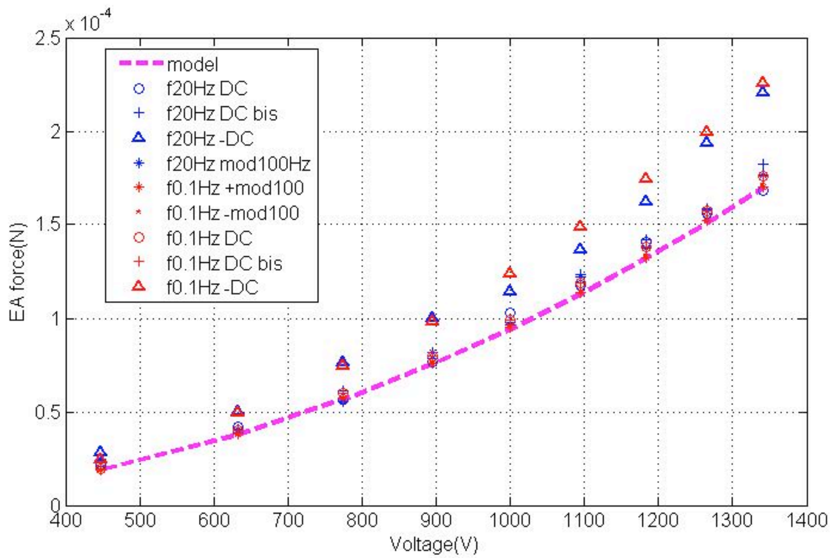
$$F = \alpha V^2 + \beta V$$

- where α is the electrostatic coupling and β is proportional to the stray charges present on the mirror;
- the presence of the modulation makes the last contribution to the force equal to zero

Actuation

Actuator Characterization

- Effectiveness of this technique experimentally checked.



- Only measurements performed with modulation are in agreement between them (and with the model) when repeated in different conditions.

Discussion

- A preliminary study of the thermal input through holes in the thermal shields, strongly integrated with the overall cryostat design, is mandatory and will be performed as a first step.
- A preliminary estimation of local sensor sensitivity and noise is available with reasonable (in terms of implementation) parameters.
- A detailed study will follow to characterize the effect of image conduits or fiber taper on transmitted beams in cryogenic environment.
- A working model to design the last stage actuators is available and tested on real data.
- A plan for systematic cryogenic tests on magnets is started.
- Electrostatic actuators and, refined by modulation driving technique, are effective and promising; actuator geometry is the next step.
- The thermal load of electrostatic actuation does not seem crucial since the actuator is used only during the lock acquisition.