AdV OpLev concept*

VIR-0070A-16

Inspired by
Virgo experience
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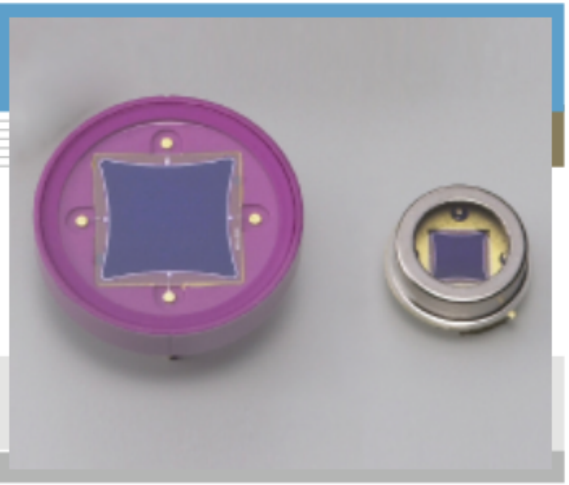
(crucial contributors L. Di Fiore and P. Ruggi)

ezuce with NAOJ 28/04/16

Two-dimensional PSD
S1880, S2044



Non-discrete position sensor utilizing photodiode surface resistance

PSD (Position Sensitive Detector) is an optoelectronic position sensor utilizing photodiode surface resistance. Unlike discrete element detectors such as CCD, PSD provides continuous position data and features high position resolution and high-speed response.

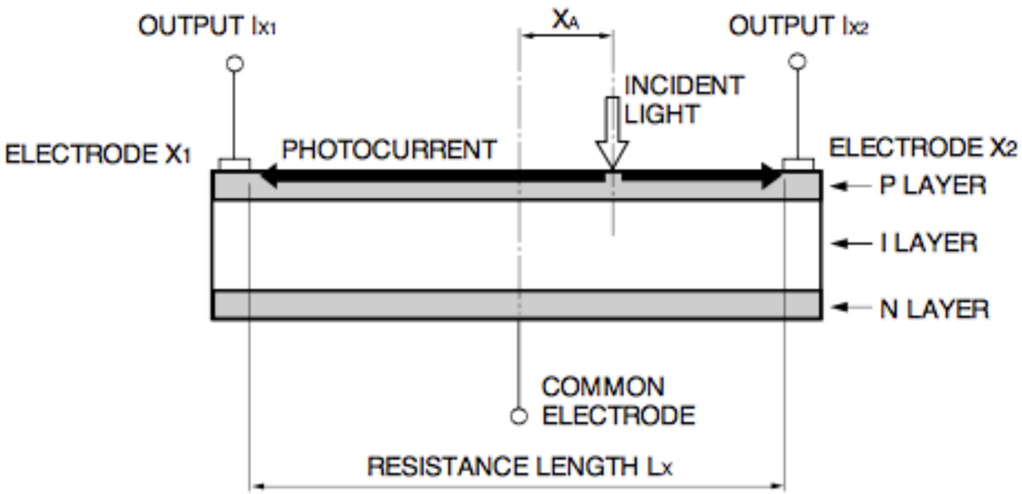
Features

- High position resolution
- Wide spectral response range
- High-speed response
- Simultaneous measurements of position and intensity
- Position is measured independent of light-spot size
- High reliability

Applications

- Optical position and angle sensing
- Remote optical control systems
- Automatic range finder systems
- Displacement and vibration monitors
- Laser beam alignment
- Medical equipment

One-dimensional PSD sectional view

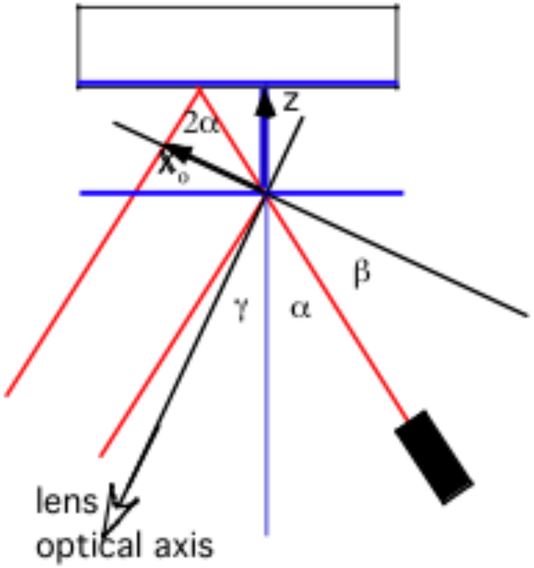


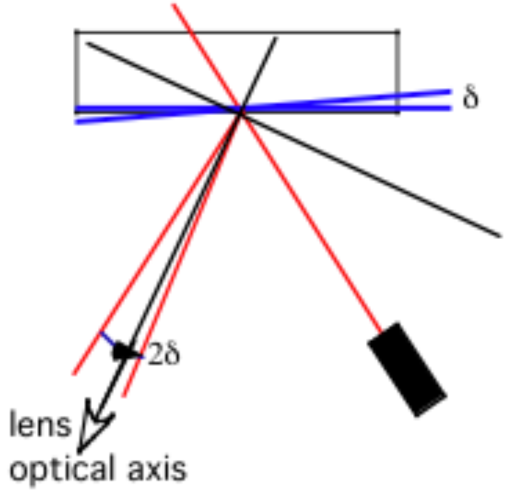
Position conversion formula

$$\frac{I_{X2} - I_{X1}}{I_{X1} + I_{X2}} = \frac{2X_A}{L_X}$$

Mirror displacements causing reflected beam displacements (in the simple 2D case)

z = pure translation





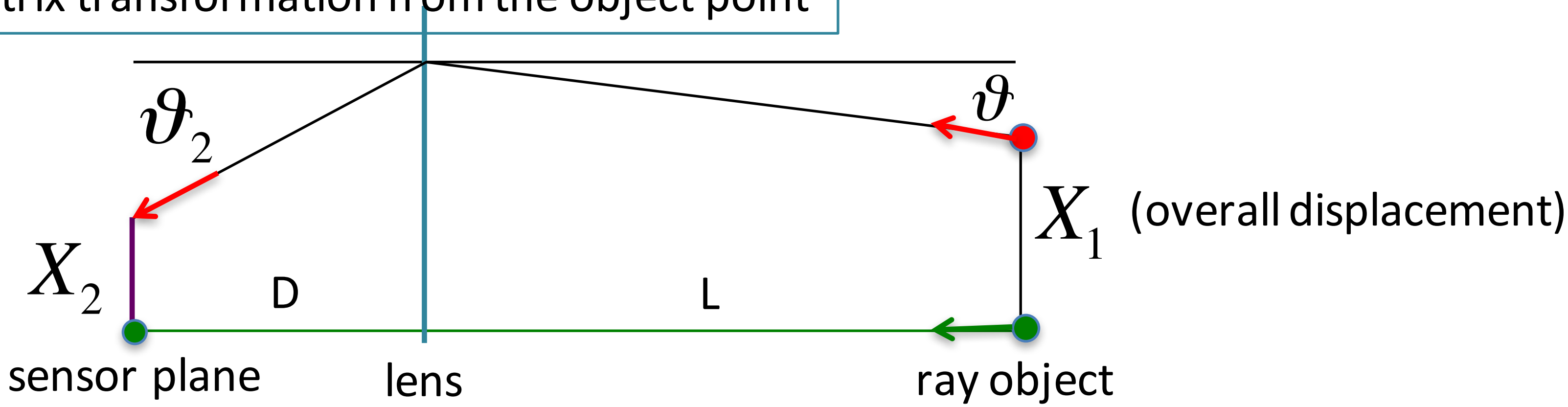
δ = pure rotation

$$X_1 = 2 \cdot z \frac{\sin\alpha}{\cos(\alpha - \gamma)}$$

$$\vartheta = 2\delta$$

(paraxial beam $\alpha = \gamma$)

Using matrix transformation from the object point

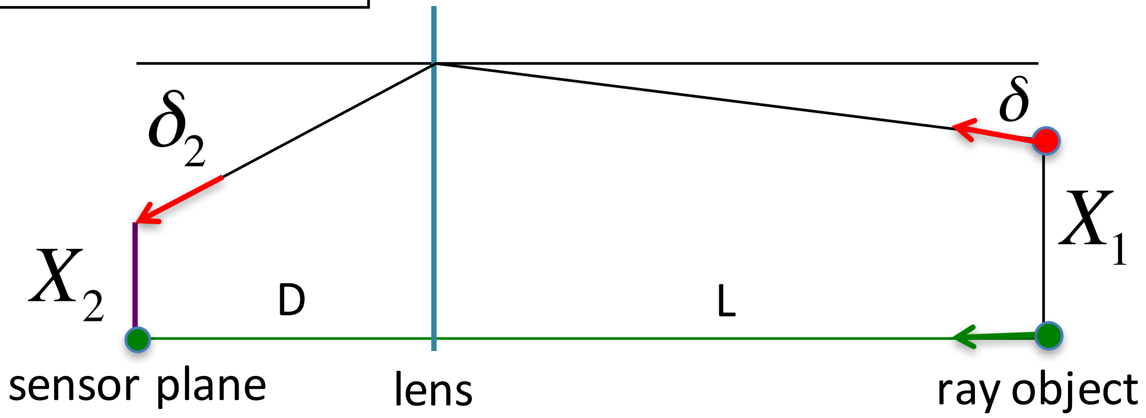


$$\begin{pmatrix} X_2 \\ \vartheta_2 \end{pmatrix} = \begin{pmatrix} 1 & D \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} X_1 \\ \vartheta \end{pmatrix}$$

$$\begin{pmatrix} X_2 \\ \vartheta_2 \end{pmatrix} = \begin{pmatrix} 1-\frac{D}{f} & D + L(1-\frac{D}{f}) \\ -\frac{1}{f} & 1-\frac{L}{f} \end{pmatrix} \cdot \begin{pmatrix} X_1 \\ \vartheta \end{pmatrix}$$

$$\Rightarrow \quad X_2 = \left(1-\frac{D}{f}\right) \cdot X_1 + \left(L(1-\frac{D}{f}) + D\right) \cdot \vartheta$$

Two plains: image and focal



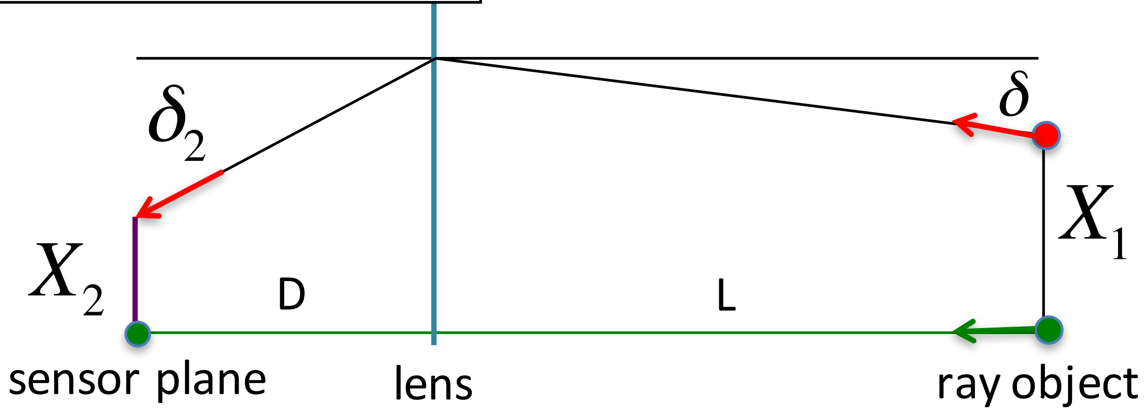
$$\frac{\partial X_2}{\partial X_1} = 1 - \frac{\mathrm{D}}{\mathrm{f}} \qquad \frac{\partial X_2}{\partial \vartheta} = \mathrm{L}\left(1 - \frac{\mathrm{D}}{\mathrm{f}}\right) + \mathrm{D}$$

If $D = D_f = f$ (focal plane) ➔ the spot on the sensor moves only upon rotations

If $D = D_0 = \dfrac{Lf}{L-f}$ (image plane) $\quad \dfrac{\partial X_2}{\partial X_1} = -\dfrac{\mathrm{D}}{\mathrm{L}} \qquad \dfrac{\partial X_2}{\partial \vartheta} = 0$

➔ the spot moves only upon translations

Image plane detection example :



If L = 1.3 m and f = 200 mm

$$\Delta D = D_0 - f = \frac{f^2}{L - f} = 3.6 \ cm$$

The coupling is (magnification)

$$\frac{\partial X_2}{\partial X_1} = -0.18$$

Accuracy in positioning the PSD example with L=1.3m and f=0.2m

Close to focal plane

$$D = f + \delta D$$

$$\begin{pmatrix} x_2 \\ \vartheta_2 \end{pmatrix} = \begin{pmatrix} \frac{\delta D}{f} & f + \delta D \left(1 - \frac{L}{f}\right) \\ -\frac{1}{f} & 1 - \frac{L}{f} \end{pmatrix} \cdot \begin{pmatrix} X_1 \\ \vartheta \end{pmatrix}$$

Close to image plane

$$D = \frac{Lf}{L - f} + \delta D$$

$$\begin{pmatrix} x_2 \\ \vartheta_2 \end{pmatrix} = \begin{pmatrix} -\frac{D + \delta D}{L} & \delta D \left(1 - \frac{L}{f}\right) \\ -\frac{1}{f} & 1 - \frac{L}{f} \end{pmatrix} \cdot \begin{pmatrix} X_1 \\ \vartheta \end{pmatrix}$$

If the sensor position is wrong by δD = 1 mm we get

In the focal plane :

$$\frac{\partial X_2}{\partial X_1} = 0.005$$

$$\frac{\partial X_2}{\partial \vartheta} = 0.2075$$

In the image plane :

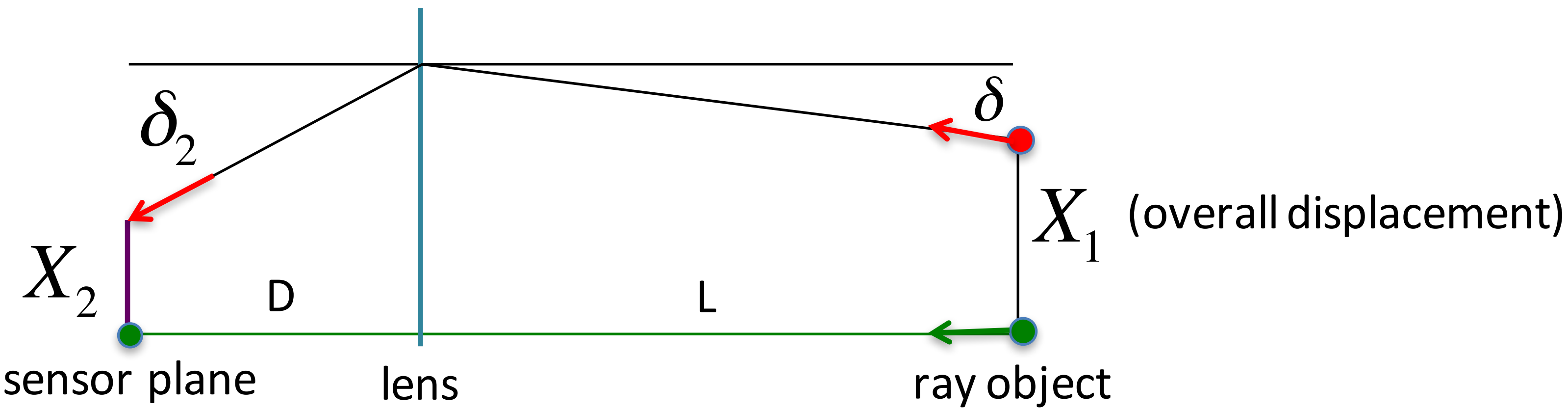
$$\frac{\partial X_2}{\partial X_1} = -0.185$$

$$\frac{\partial X_2}{\partial \vartheta} = 0.064$$

The coupling would be ~ 20% ➔ To allow optical decoupling ≤ 0.2 % one needs micrometric slide steps $\leq 10 \mu m$

In practice a slide with 10 um tick adjustment OK

Range



if the lens radius is R=2.5 cm, the maximum measurable angle is θ_{max}=R/L= 19 mrad yielding a spot displacement on the sensor of 3.8 mm

The angular range is then da = $\theta_{max}/2$ ~ 10 mrad.

In practice ± 6-8 mrad is the spot dynamics allowed by suitable mechanical stops of the suspension system

In conclusion :

in the image plane ➔ DX_2 = -2(D/L) X_1 = - 0.36 z (OL @ 30 deg)

in the focal plane ➔ $DX_2 = 2 \cdot f \cdot \delta =$ 0.4 δ

With the parameters used (L,D,α) the mirror displacements are sensed with 40% coupling (the sensors are referenced to seismic noise)

$$\tilde{X}_2(1\ \mathrm{Hz}) \approx 10^{-9}\, m/\sqrt{Hz}$$

$$\tilde{X}_2(10\ \mathrm{Hz}) \approx 10^{-11}\, m/\sqrt{Hz}$$

$$\tilde{Z}\,(1\mathrm{Hz}) = \frac{\tilde{X}_2}{0.36} \approx 3\cdot 10^{-9}\, m/\sqrt{Hz}$$

$$\tilde{\delta}(10\ \mathrm{Hz}) = \frac{\tilde{X}_2}{0.4} \approx 2.5\cdot 10^{-10}\, rad/\sqrt{Hz}$$

3D model developed in Python, useful if the incidence plane is not horizontal

Purpose of OL local control in Virgo

GENERAL:

1. **No sensors onboard on the payload,**
2. **Last filter of single-point suspension system sensed and damped WRT ground**
3. **Payload sensed from ground and actuated through suspension chain**
4. **OL very useful provided the soft modes of the suspended payload (pitch,roll @120-140 mHz, yaw @ 20 mHz)**
5. **The setup must be rather accurate (E.g. 4-stage micrometric stages for PSD are needed)**

6. **REMARK:**
   the DC position of the payload must be ensured easily, at low cost and from outside

PRE-ALIGNMENT of the payload (and mirror) with respect to the ground.
In Virgo OL are used preliminary even during the suspension assembly phases (once we used CCD cameras, OL are much simpler to use.

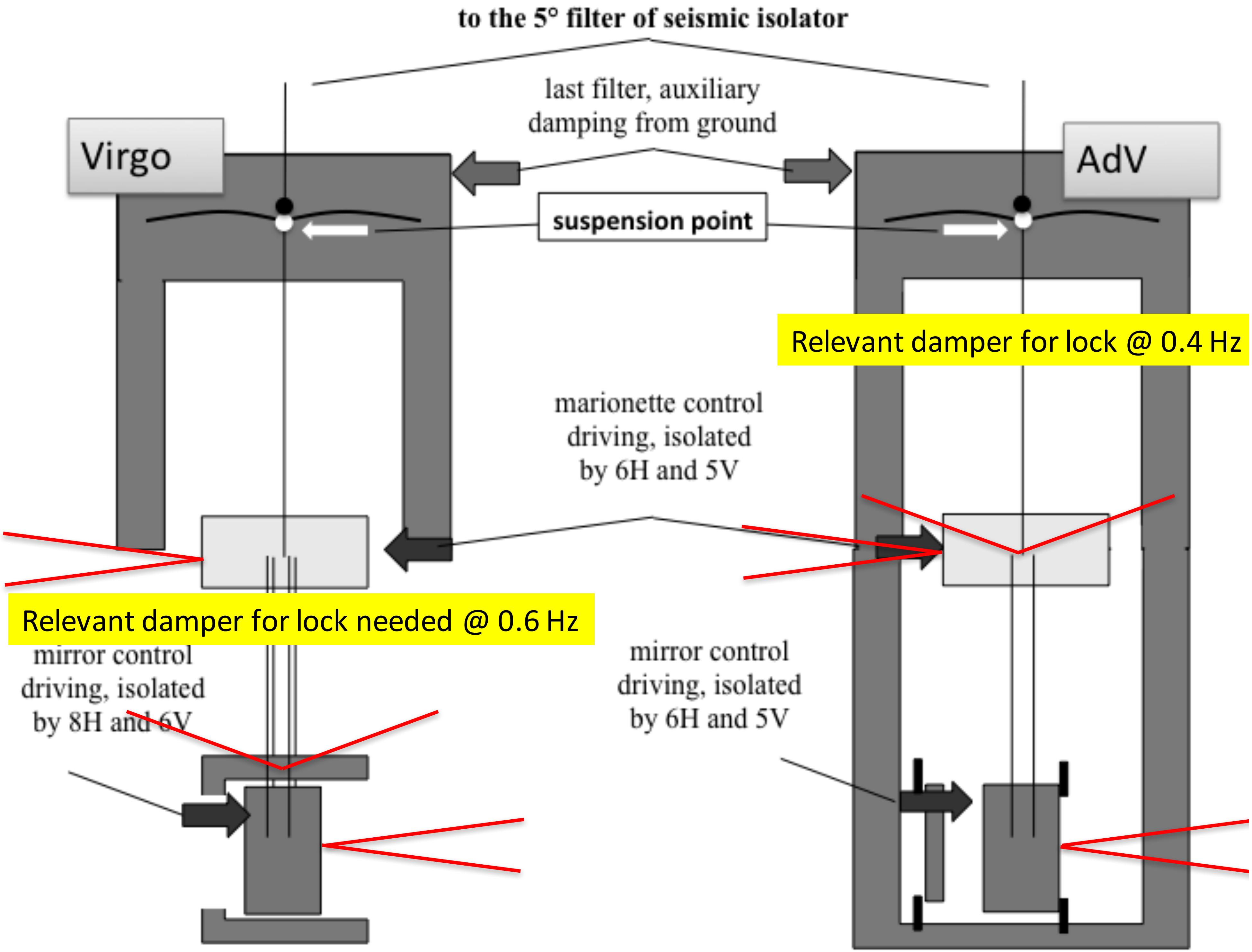
ANGULAR CONTROL of payload (few Hz BW)
(essentially from the marionette, it allows to significantly reduce the correction).
Very relevant until automatic alignment control signals are set in operation

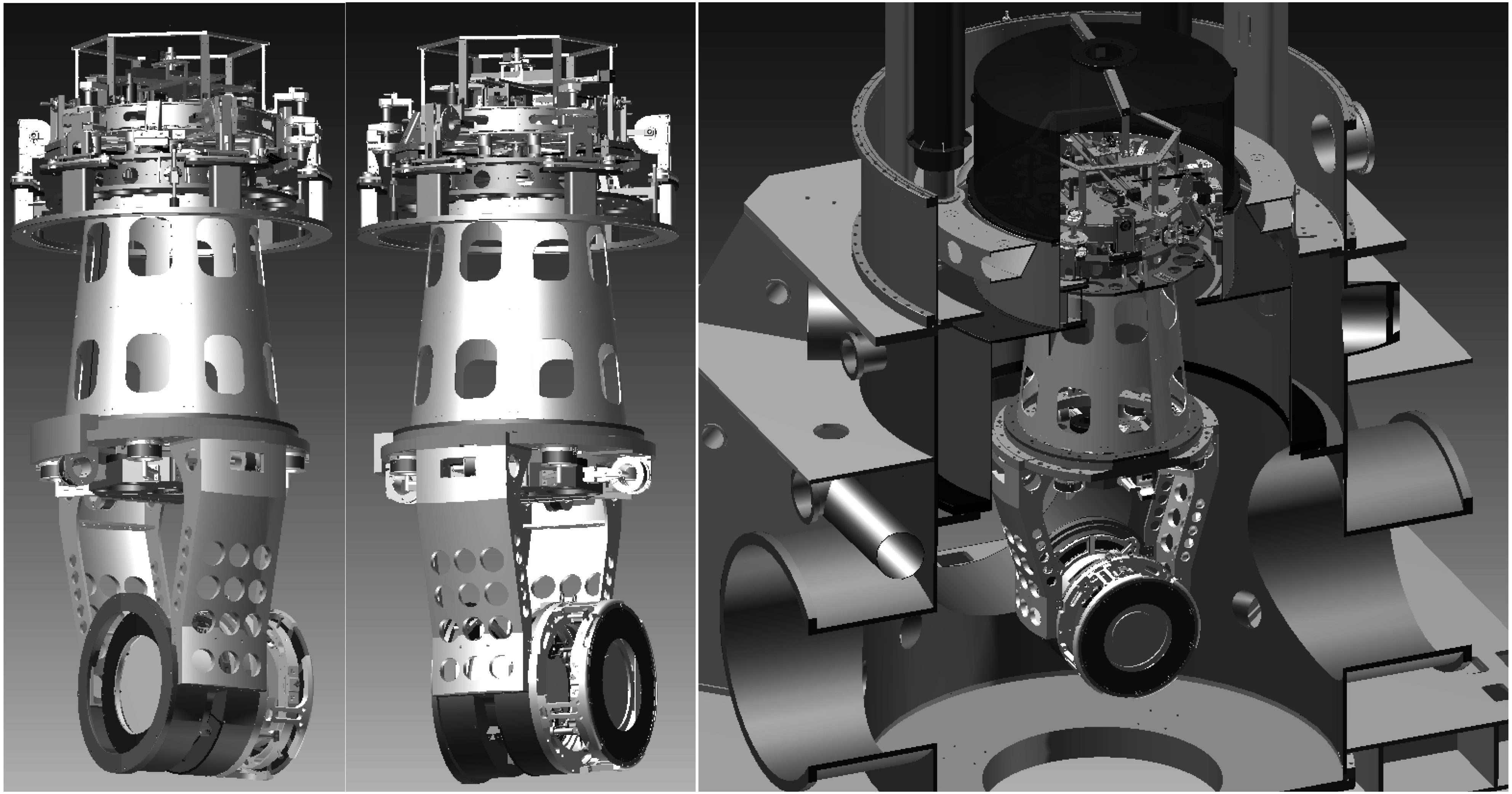
LOCKING using longitudinal signal, to slow down mirror speed.

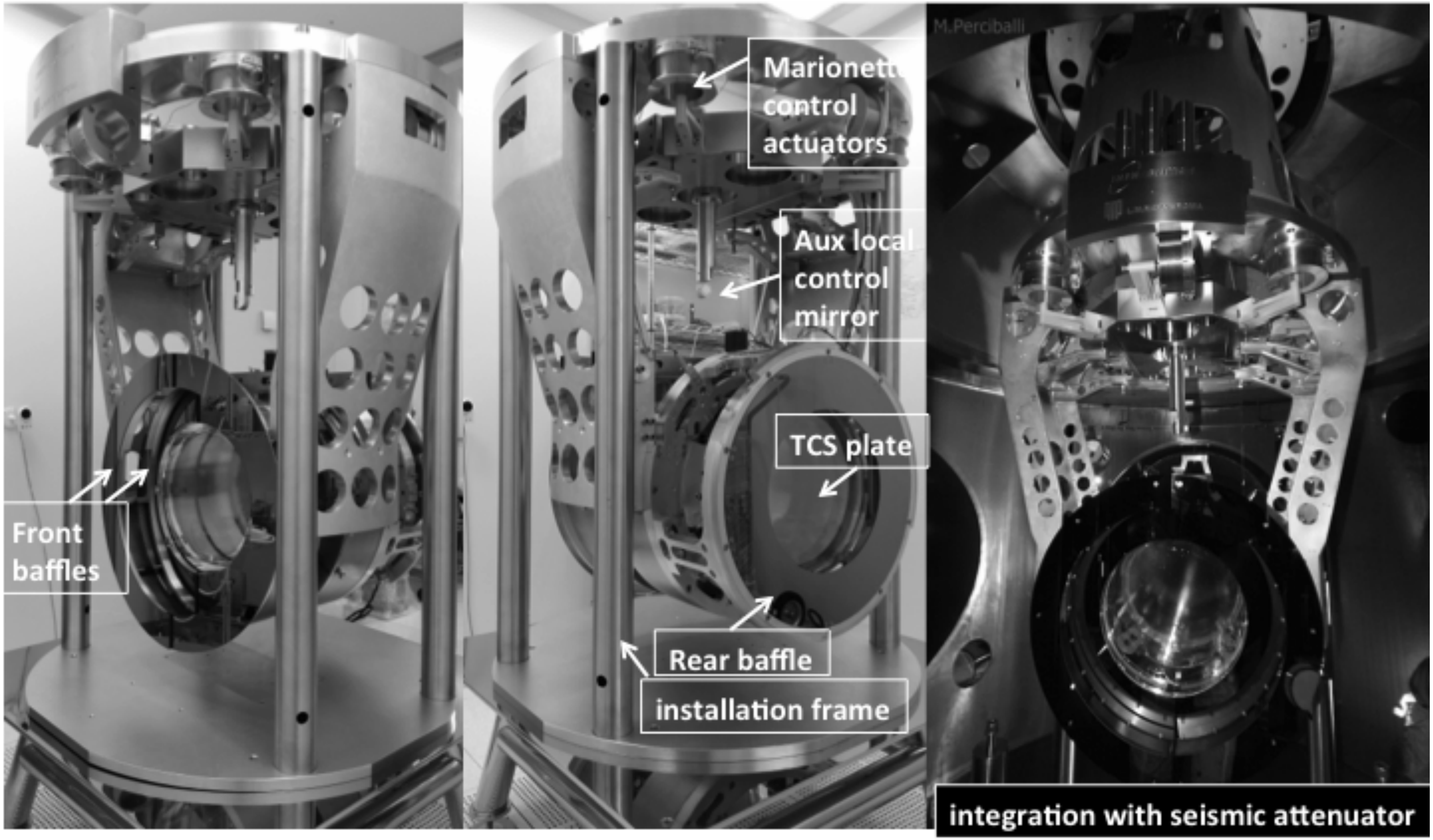
Questions for KAGRA

- How will the payload be referenced and driven to the IFO beam directions ?
  (only using the last filter handles ? Having all the DoF of the last filter controlled from ground in principle OK, but it seems not so easy)

- Isn't it useful to have some redundancy in position signals ?

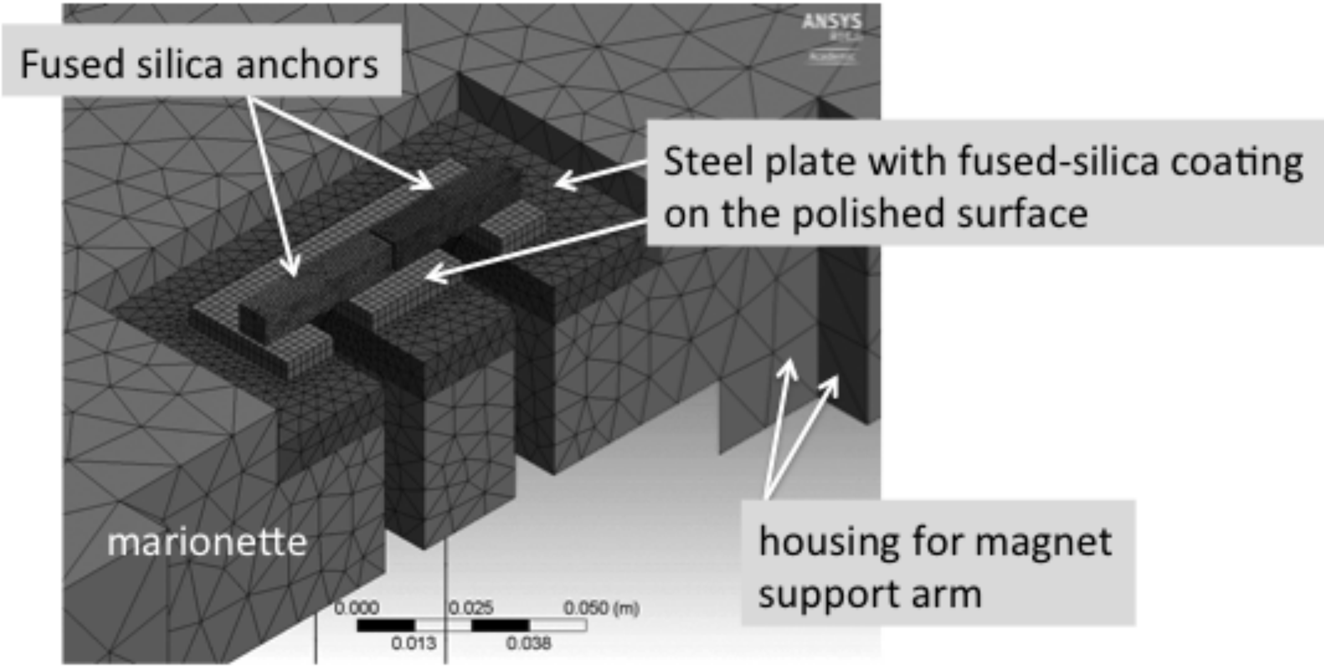

to the 5° filter of seismic isolator
last filter, auxiliary
damping from ground
Virgo
AdV
suspension point
Relevant damper for lock @ 0.4 Hz
marionette control
driving, isolated
by 6H and 5V
Relevant damper for lock needed @ 0.6 Hz
mirror control
driving, isolated
by 8H and 6V
mirror control
driving, isolated
by 6H and 5V

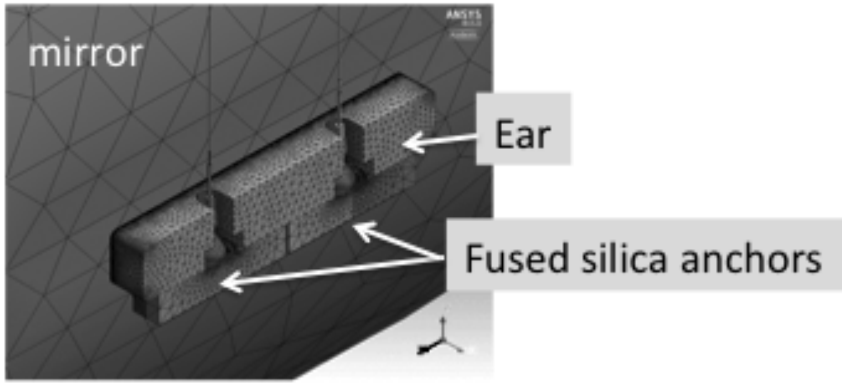




Front
baffles
Marionett
control
actuators
Aux local
control
mirror
TCS plate
Rear baffle
installation frame
M.Perciballi
integration with seismic attenuator

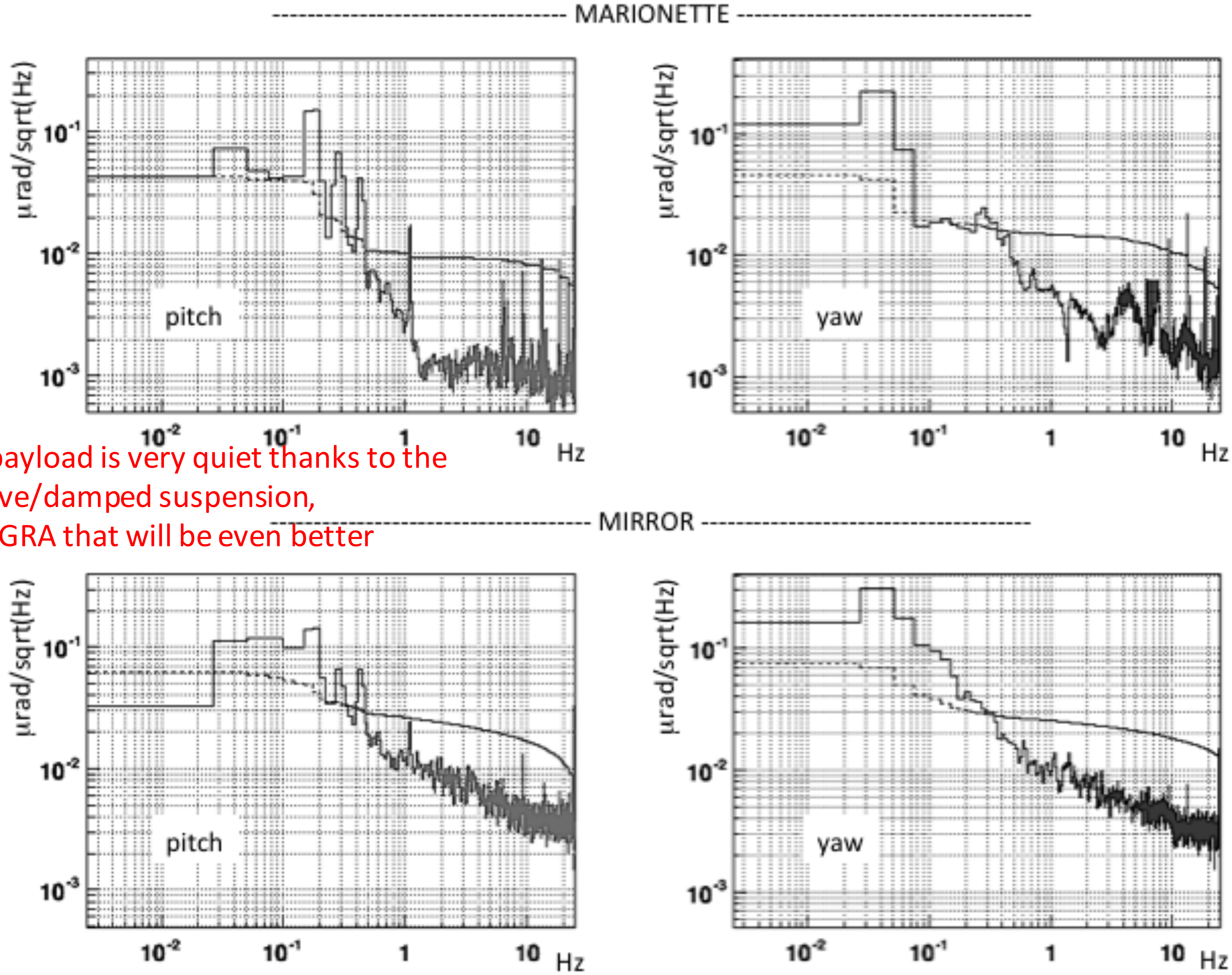
A curiosity (…fiber hooking)





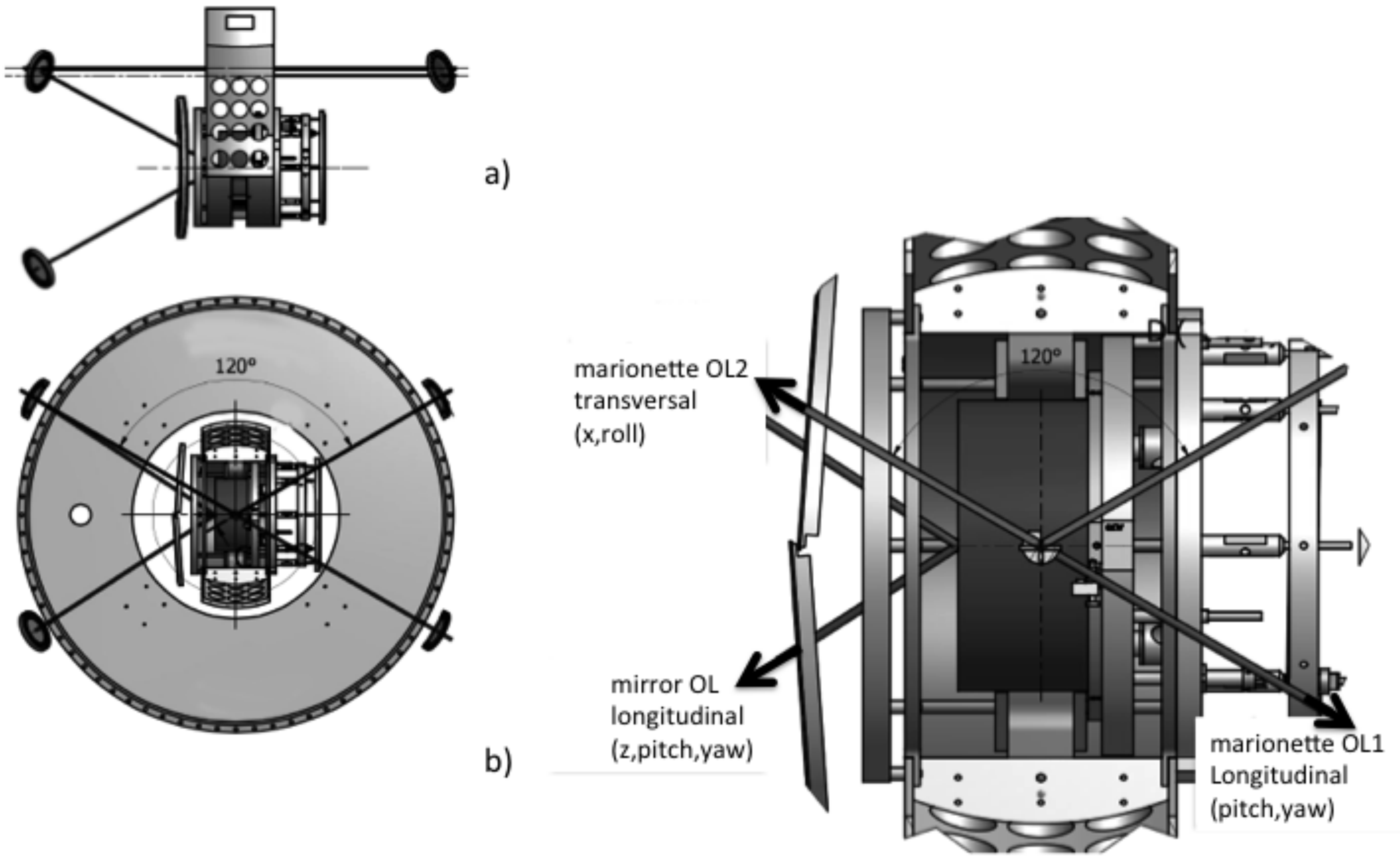
performance essay 1:

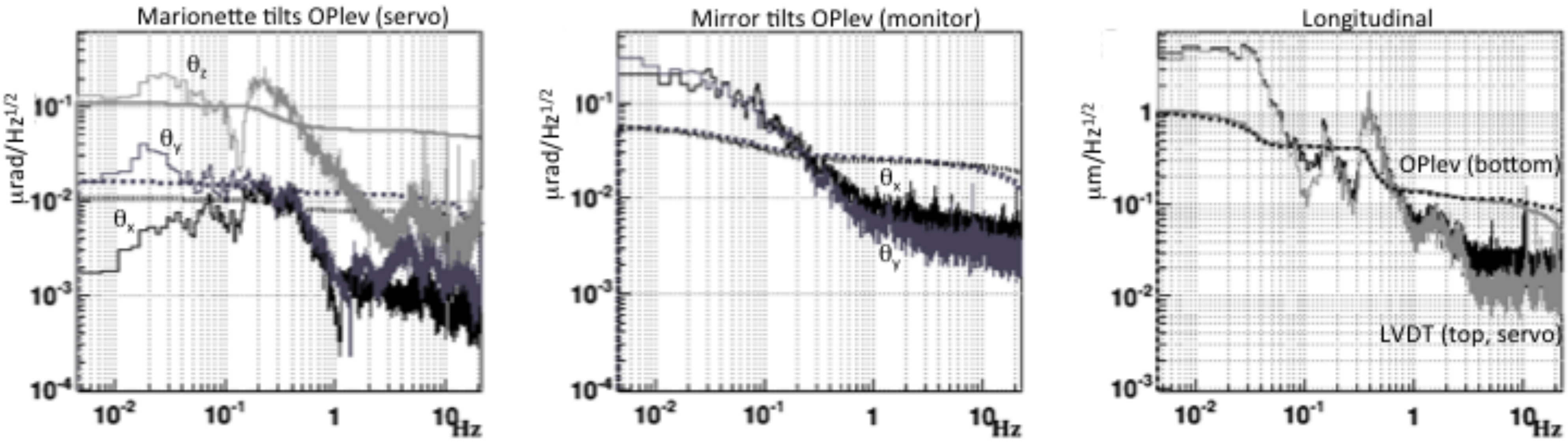
displacement RMS in Virgo payload with inertial damping ON (top stage) and LC OFF



The payload is very quiet thanks to the passive/damped suspension, in KAGRA that will be even better

OL optical layout (…constrained by viewports and by payload actuation cage)





Typical linear spectral density and cumulative RMS using marionette optical levers to control the payload. **Left**: tilt control through yaw, pitch and roll error signals provided by two optical levers. The error signal to roll tilt in this case (beam splitter payload) is smaller by a factor 4 with respect to pitch; this feature is not a critical issue. **Centre**: the pitch and yaw are also monitored by the third optical lever, (here neither the electronics nor the optical layout (in air) is optimized. **Right**: the image plane of the third lever provides the longitudinal position of the mirror, expectedly it monitors the accuracy of the seismic suspension top-stage.

θ_x = PITCH
θ_y = YAW
θ_z = ROLL
z = long translation

- **9 suspended objects**
- **34 PSD sensors**
- **51 (60) D.o.F.**

T= transversal
(n) available (redundant)

N Lever	Suspension	Reflection	PSD location	D.o.F.	N D.o.F.	N sensors
1	INJ	Bench	Focal, Image	$\theta_x\ \theta_y$ z	3	2
2	INJ	MarioT	Focal	$\theta_y\ \theta_z$	1 (2)	1
3	MC	Mirror	Focal, Image	$\theta_x\ \theta_y$ z	3	2
4	MC	RmT	Focal	$\theta_y\ \theta_z$ x	2 (3)	1
5	PR	Mario	Focal	$\theta_x\ \theta_y$	2	1
6	PR	MarioT	Focal	$\theta_y\ \theta_z$	1 (2)	1
7	PR	Mirror	Focal, Image	$\theta_x\ \theta_y$ z	3	2
8	BS	Mario	Focal	$\theta_x\ \theta_y$	2	1
9	BS	MarioT	Focal	$\theta_y\ \theta_z$	1 (2)	1
10	BS	Mirror	Focal, Image	$\theta_x\ \theta_y$ z	3	2
11	NI	Mario	Focal	$\theta_x\ \theta_y$	2	1
12	NI	MarioT	Focal	$\theta_y\ \theta_z$	1 (2)	1
13	NI	Mirror	Focal, Image	$\theta_x\ \theta_y$ z	3	2
14	NE	Mario	Focal	$\theta_x\ \theta_y$	2	1
15	NE	MarioT	Focal	$\theta_y\ \theta_z$	1 (2)	1
16	NE	Mirror	Focal, Image	$\theta_x\ \theta_y$ z	3	2
17	WI	Mario	Focal	$\theta_x\ \theta_y$	2	1
18	WI	MarioT	Focal	$\theta_y\ \theta_z$	1 (2)	1
19	WI	Mirror	Focal, Image	$\theta_x\ \theta_y$ z	3	2
20	WE	Mario	Focal	$\theta_x\ \theta_y$	2	1
21	WE	MarioT	Focal	$\theta_y\ \theta_z$	1 (2)	1
22	WE	Mirror	Focal, Image	$\theta_x\ \theta_y$ z	3	2
23	PR	Mario	Focal	$\theta_x\ \theta_y$	2	1
24	PR	MarioT	Focal	$\theta_y\ \theta_z$	1 (2)	1
25	PR	Mirror	Focal, Image	$\theta_x\ \theta_y$ z	3	2