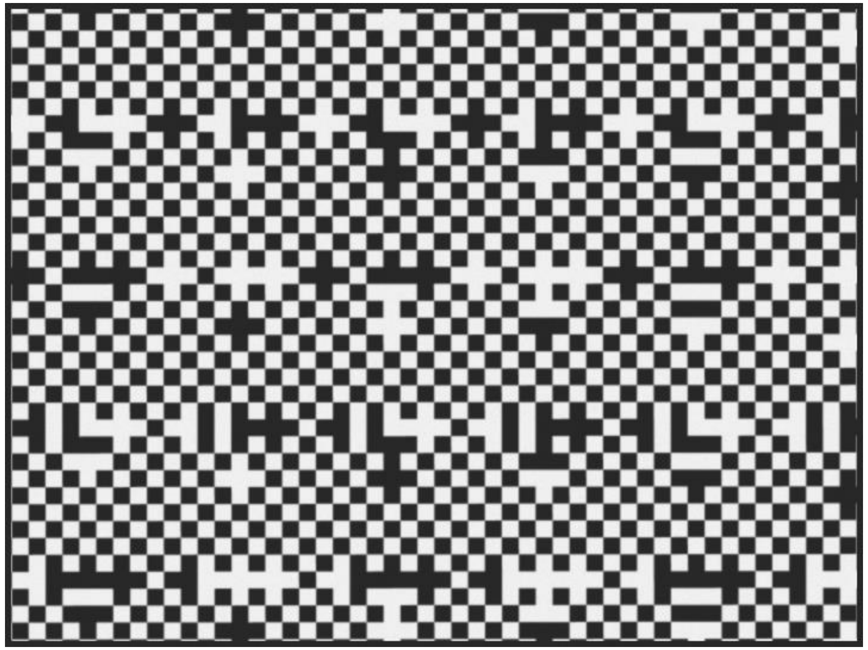
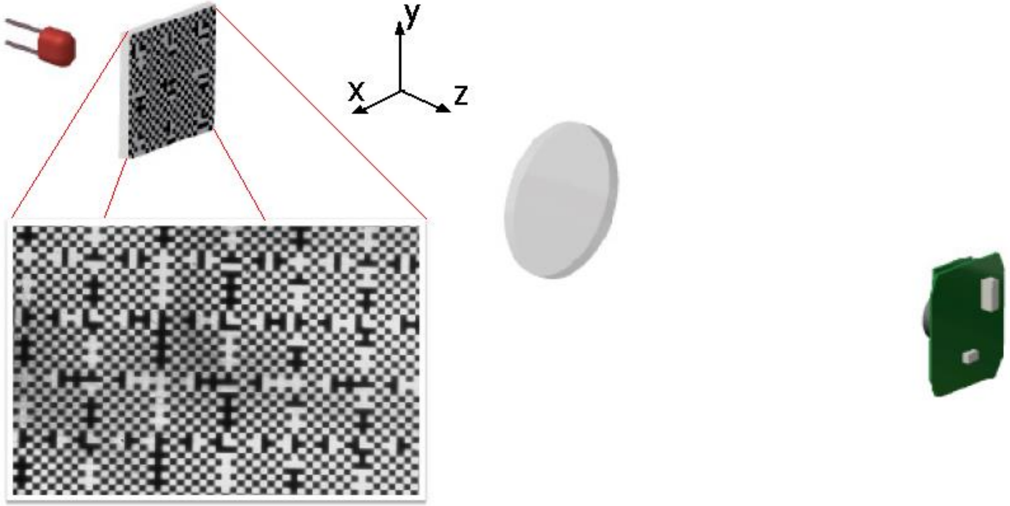


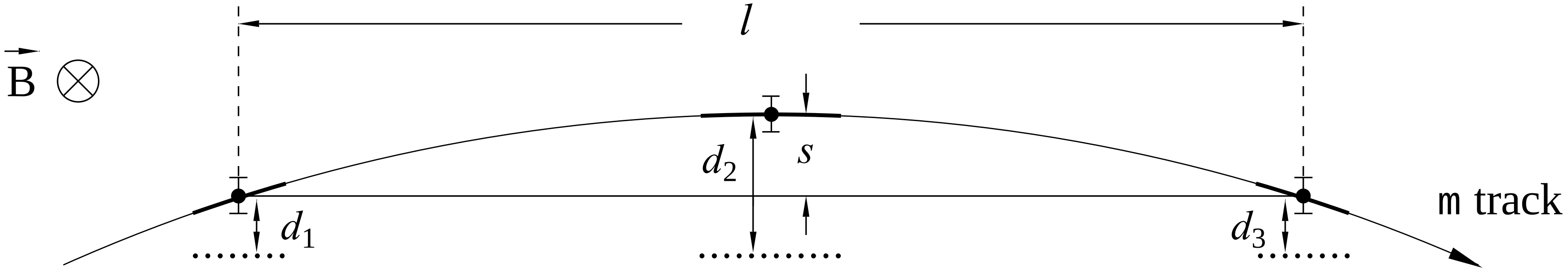
The application of the Rasnik 3-point alignment system in seismic instrumentation

Harry van der Graaf
Bram Bouwens
Alessandro Bertolini
Joris van Heijningen
Nelson de Gaay Fortman
Lennart Otemann



Nikhef

Muon chamber alignment for the L3 and ATLAS experiments at CERN



Muon momentum measurement: Radius of Curvature of track in magnetic field

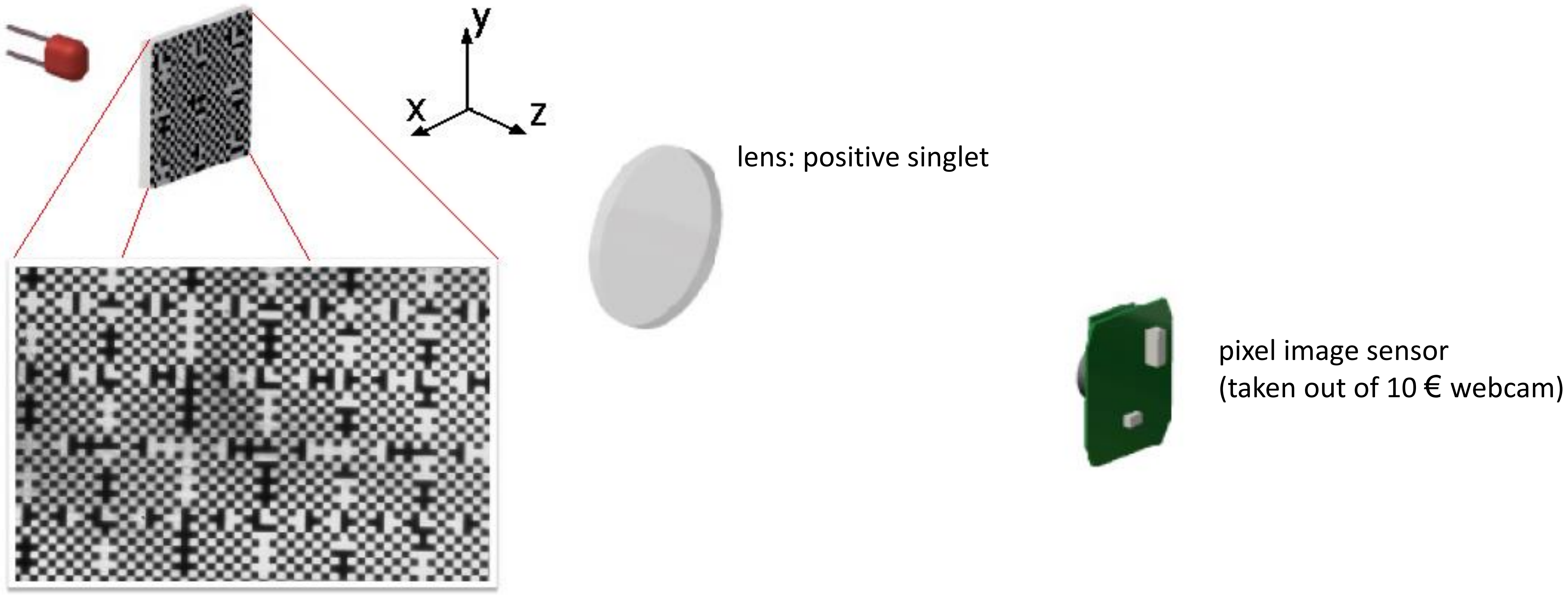
p = 0.2998 x B x R (GeV/c)

sagitta s = L^2 /8R

For this, the relative position of the central tracking detector with respect to the two outer chambers must be precisely (of order 10 μm) known

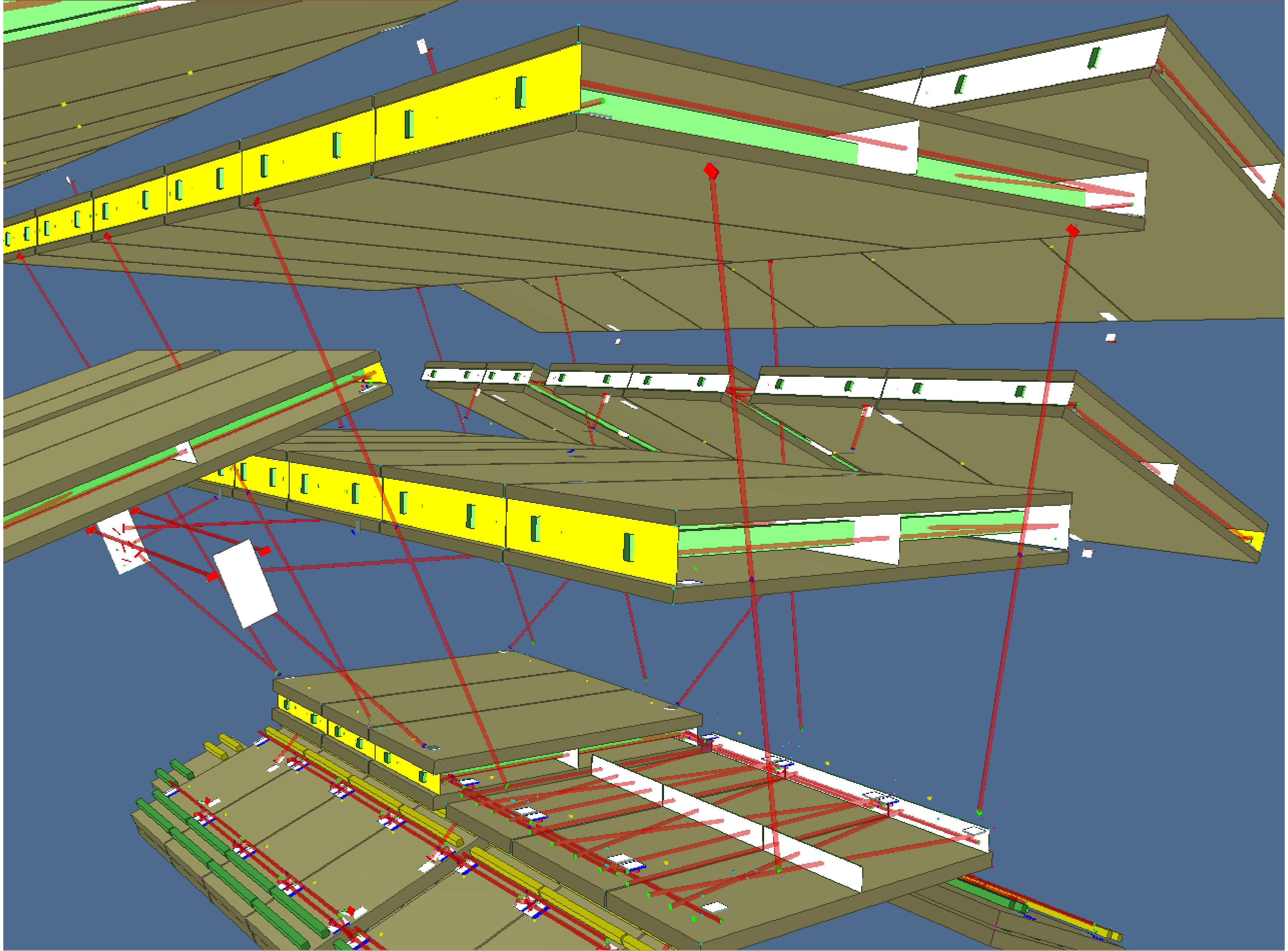
Mechanically this alignment is very hard to obtain, and even harder to maintain due to environment changes in temperature and on/off magnetic field

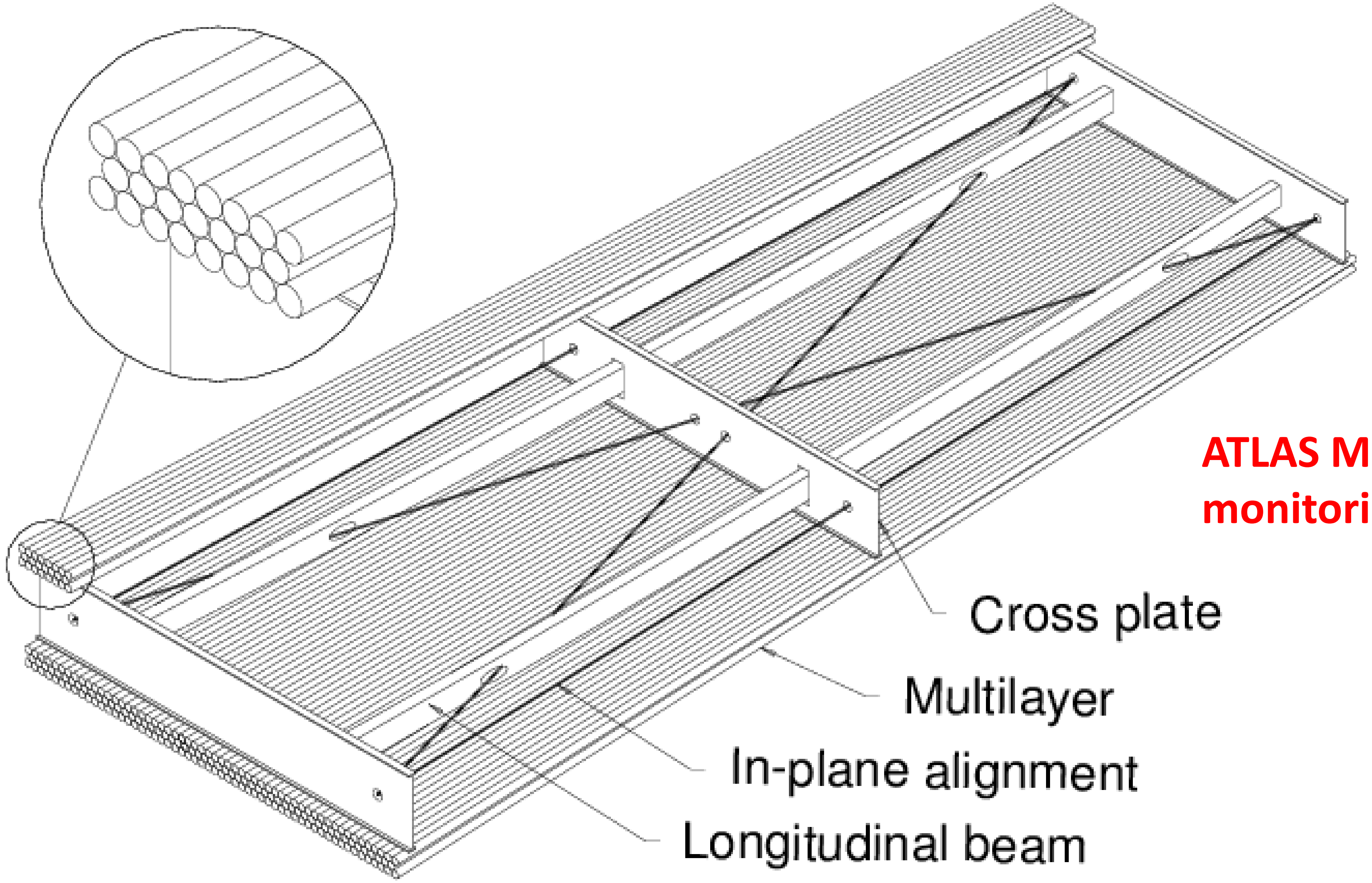
Therefore: monitoring of alignment



A relative shift of a mask, lens or image pixel sensor will cause:

- an image-shift-on-the-sensor in X
- an image-shift-on-the-sensor in y
- a change in the image scale S
- a rotation of the image around the optical (Z) axis



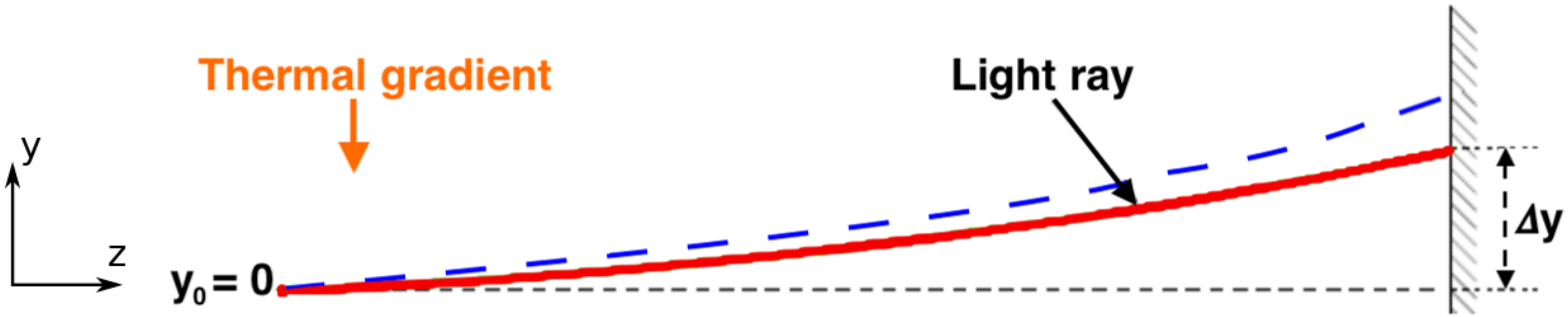


ATLAS Muon chambers: monitoring sag and torsion

In ATLAS, 8000 Rasnik systems are perfectly operational since 2005

The ATLAS Rasniks (6 m distance between mask and sensor) showed sub-um precision

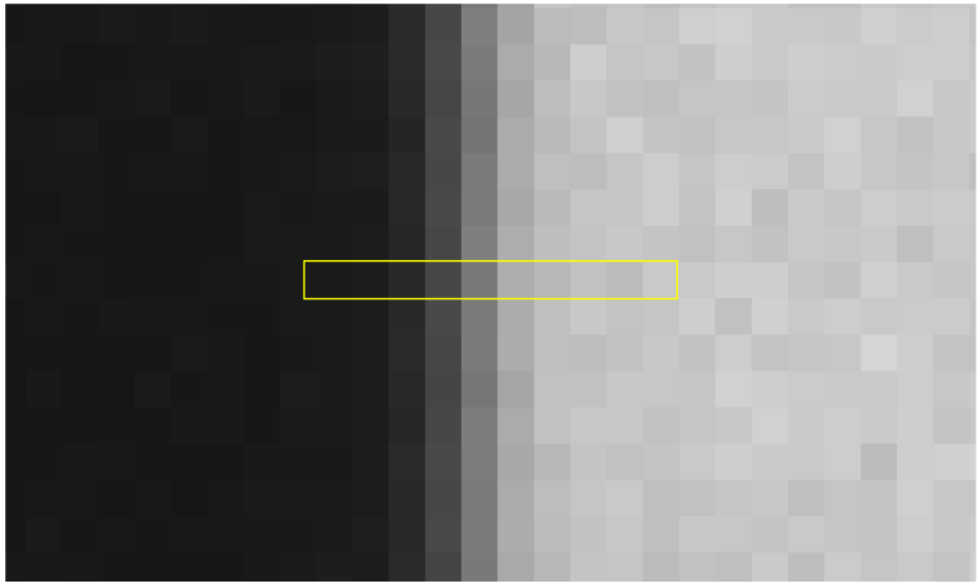
In practical systems, the largest error is due to gradients in air density:

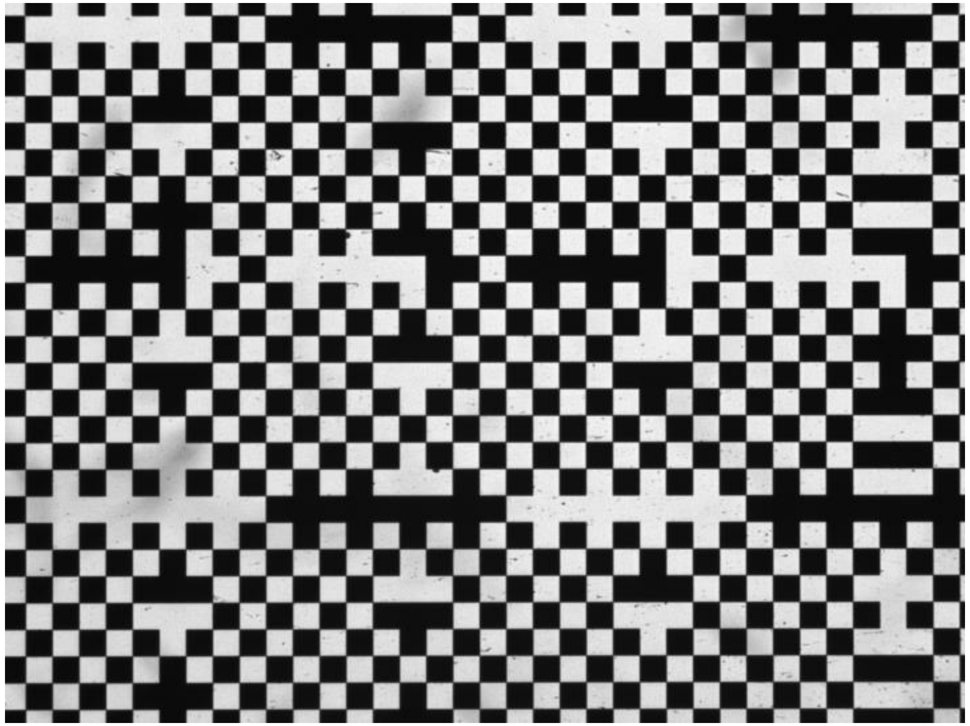


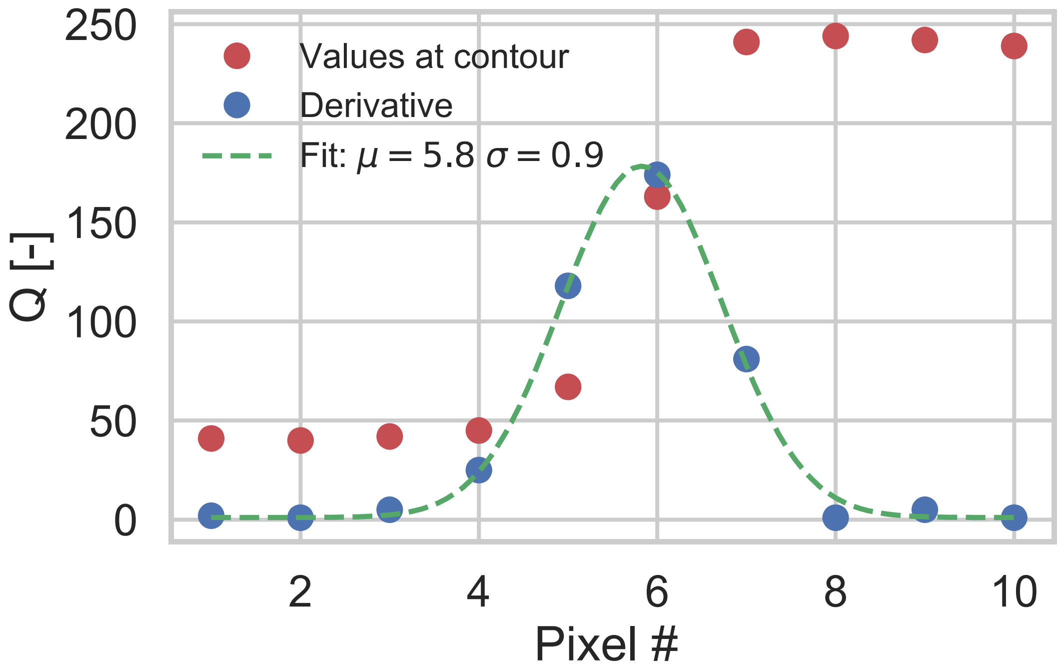
So, apply vacuum, or apply shielding of light path

Estimation of precision to be reached:
how well do we measure the image position on the sensor?

position measurement of contour (black-white transient)







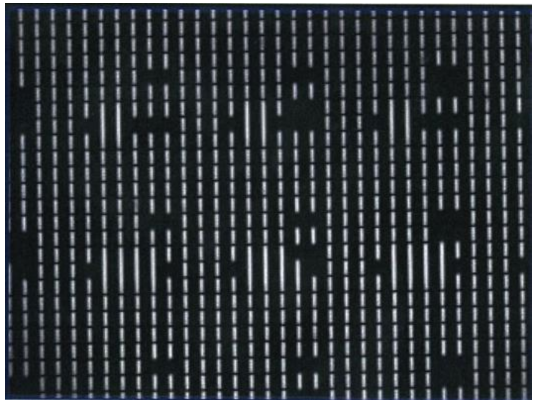
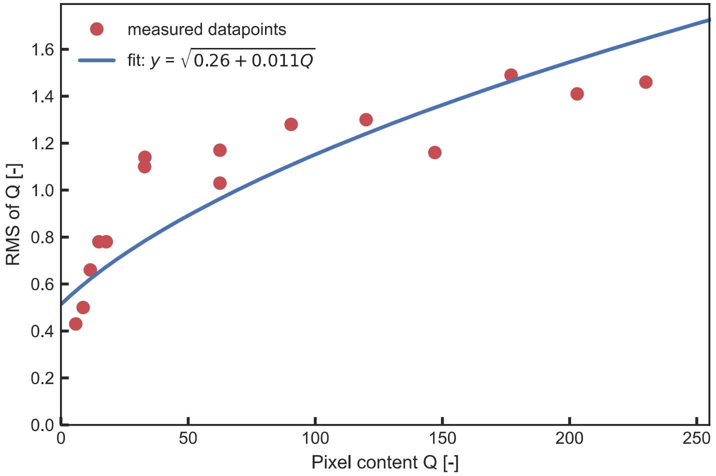


Image differentiated in X
Q(n) = Q(n+1) – Q(n-1)



Pixel noise:
mainly quantum fluctuations of light-on-pixel

Standard system:
Sensor: 4 mm x 3 mm
pixel size: 10 μm squares
ChessFiels size: 120 μm squares, optimized for diffraction limited image
Total contour length: 150 mm, both vertical and horizontal
Contour position is sampled each 10 μm, so position is measured 15 k times!

Given width of:

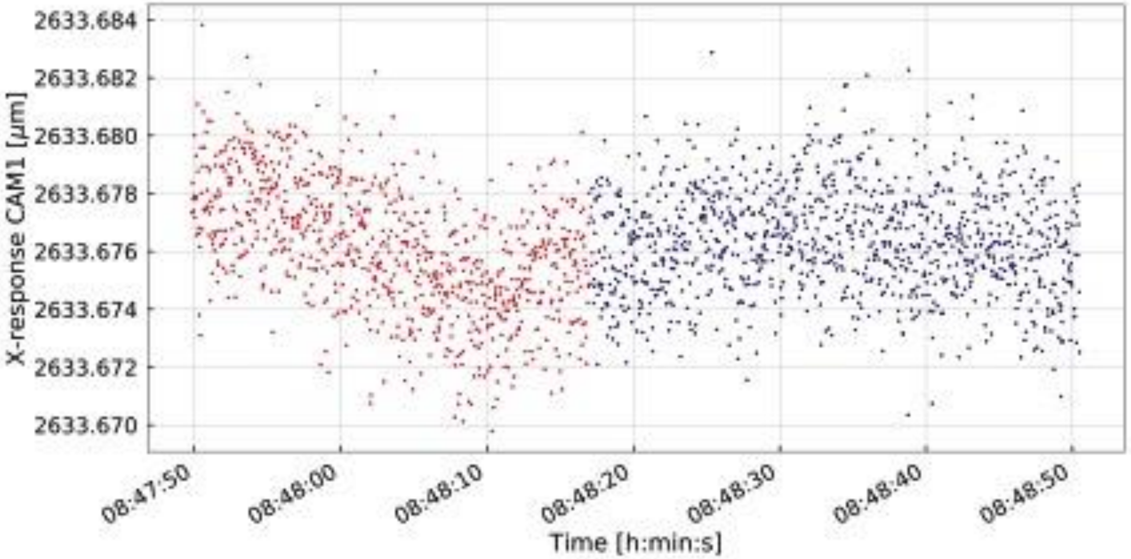
- Gaussian (diffraction) distribution and
- pixel noise

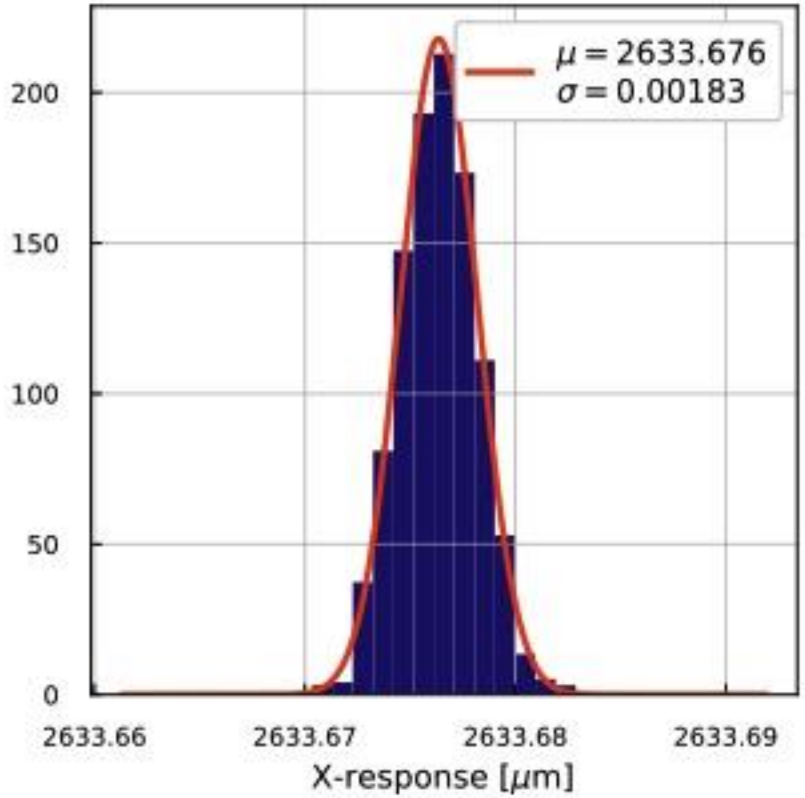
precision of each sample is 0.2 μm

Expected precision for complete image: 0.2 μm / √(15 k) = 1.5 nm

Quality of displacement sensor:

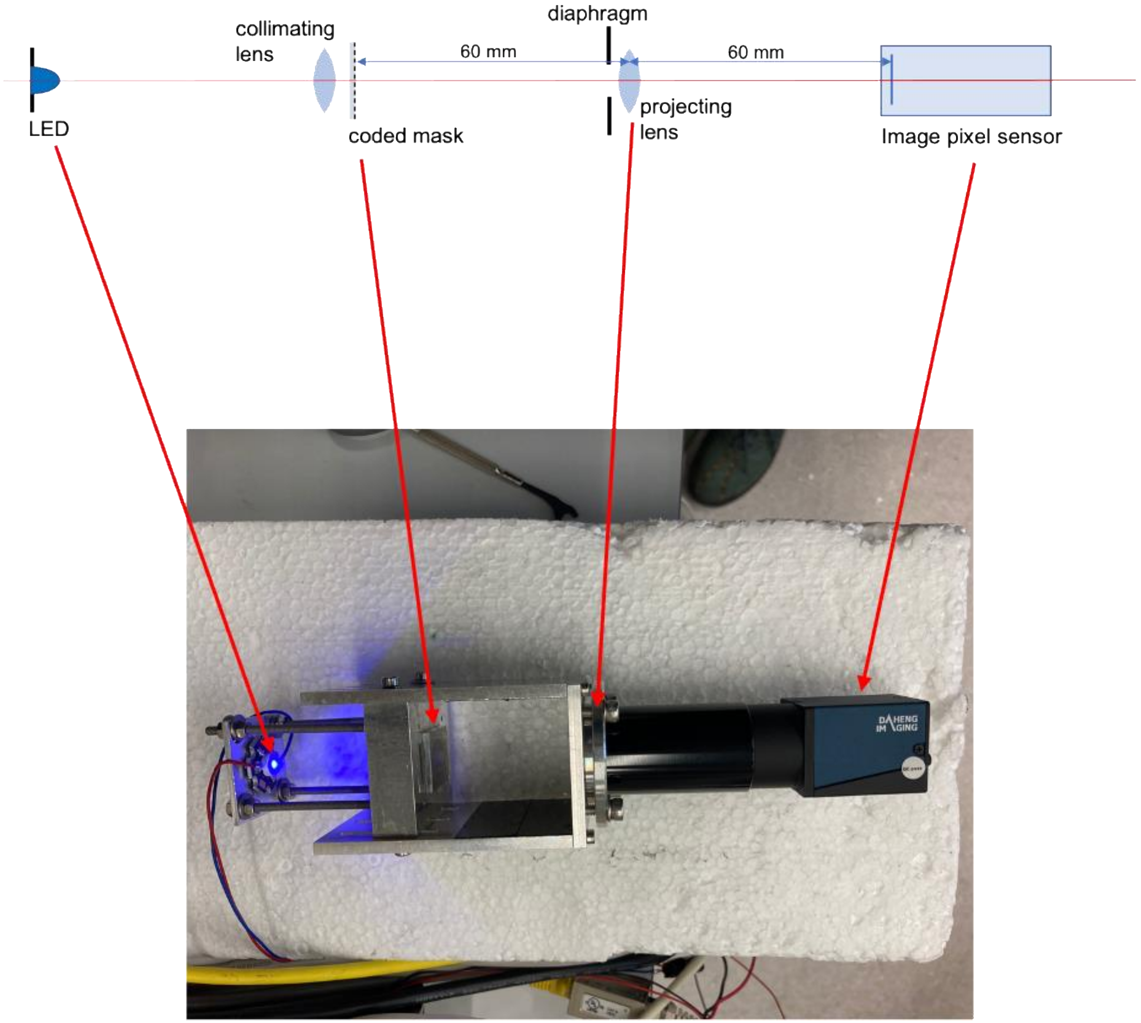
- **spatial resolution**
- **linearity**
- **how many measurements s^{-1} (resolution ‘power’)**


2633.684
2633.682
2633.680
2633.678
2633.676
2633.674
2633.672
2633.670
X-response CAM1 [μm]
08:47:50
08:48:00
08:48:10
08:48:20
08:48:30
08:48:40
08:48:50
Time [h:min:s]


μ = 2633.676
σ = 0.00183
200
150
100
50
0
2633.66
2633.67
2633.68
2633.69
X-response [μm]

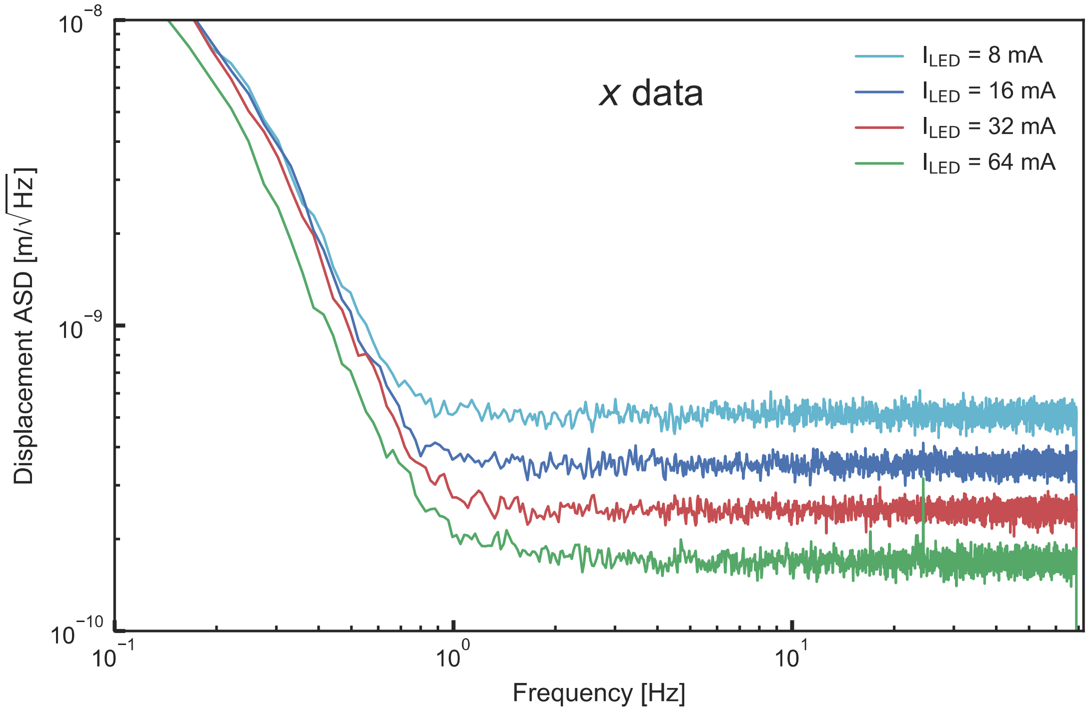
Measurement of spatial resolution

- solid fixation of relative position of mask, objective and sensor
- from multiple images at highest rate



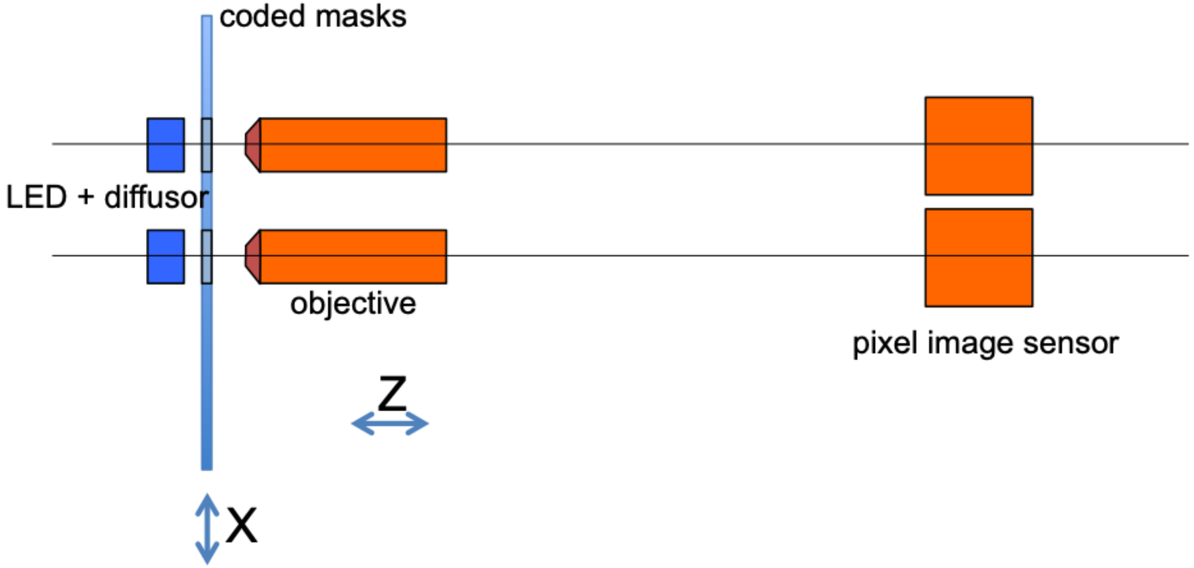
Welch plots, displaying Amplitude Spectral Density (ASD)

- includes ‘resolution power’ due to data rate
- filters (still present) thermal and mechanical displacements

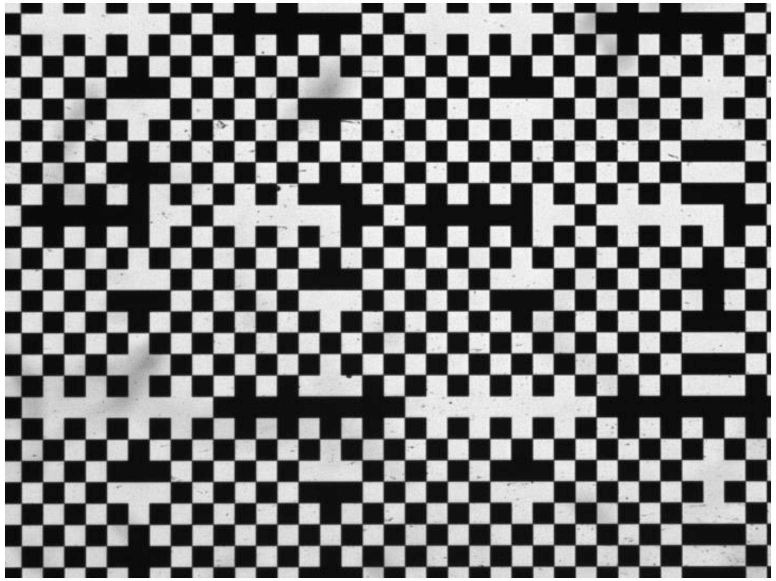


Welch plot of continues data (275 Hz), in open air

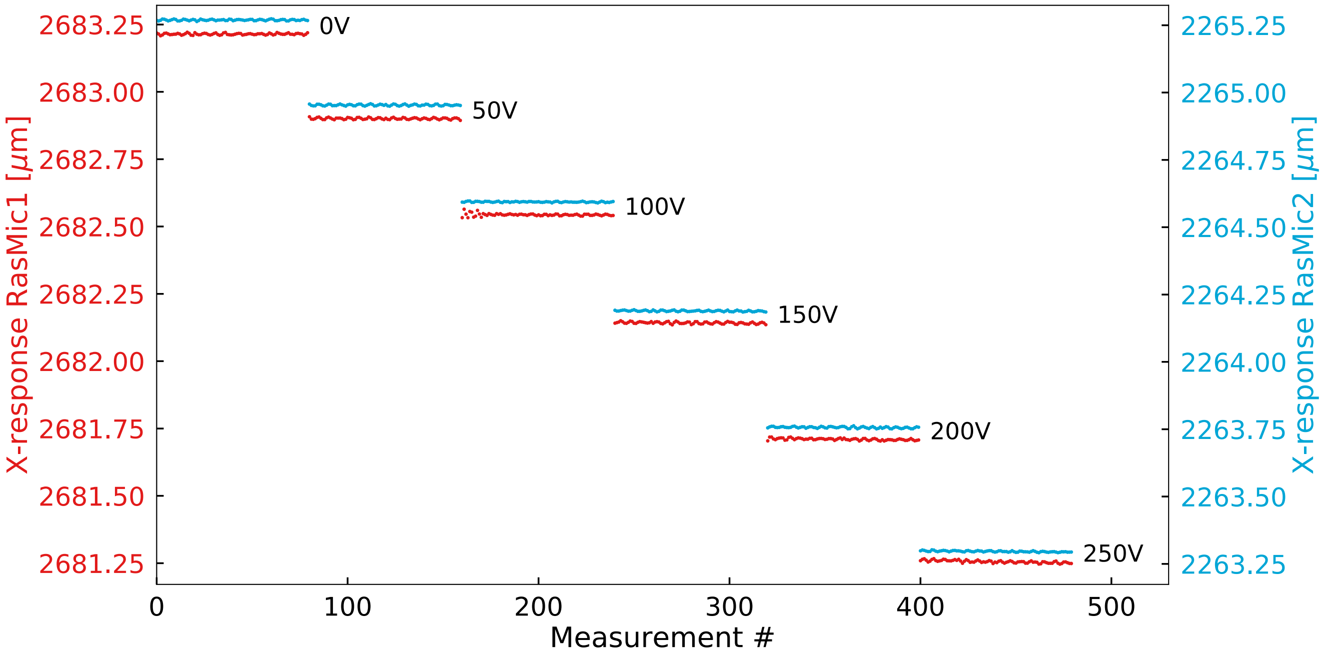
Replace positive lens by microscope objective:
image displacement increased by factor (magnification)

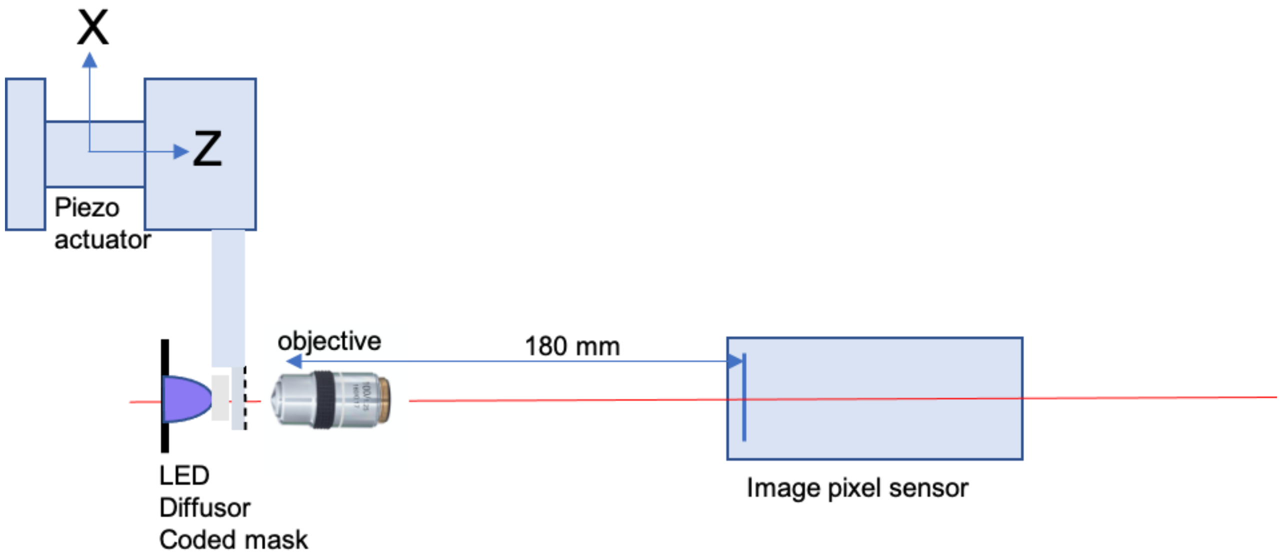


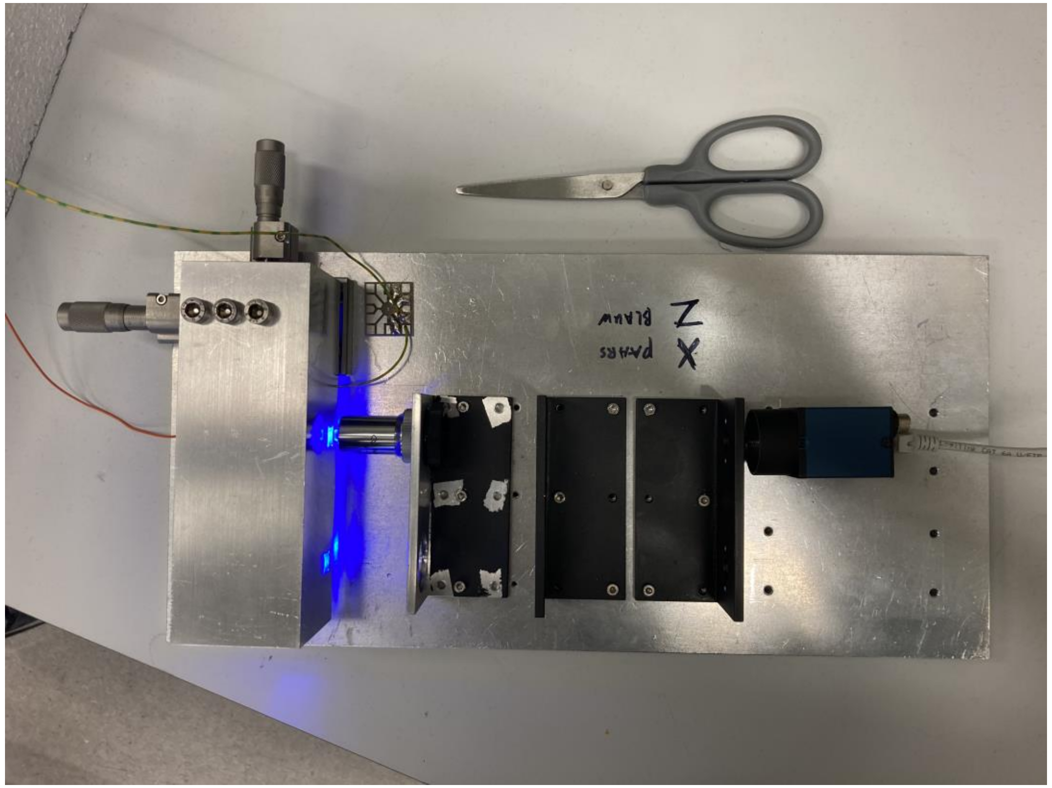
Measurement of spatial resolution and linearity:
take two (differential) Rasnik systems:
both masks are displaced equally by piezo actuator



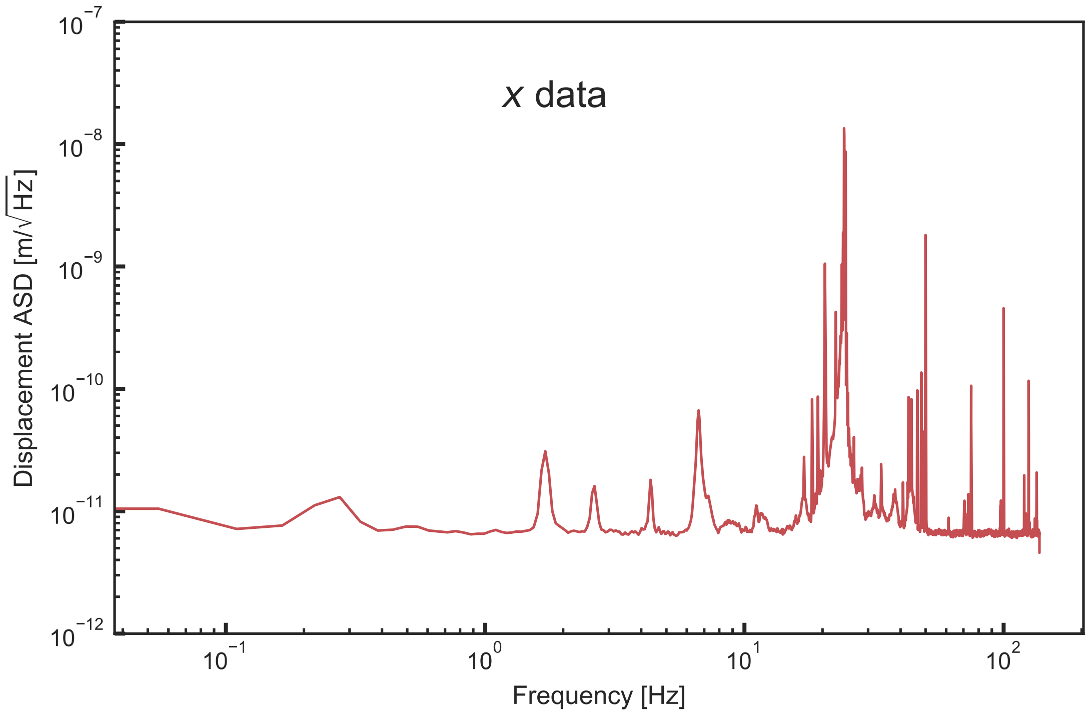
Linearity: determined by mask precision

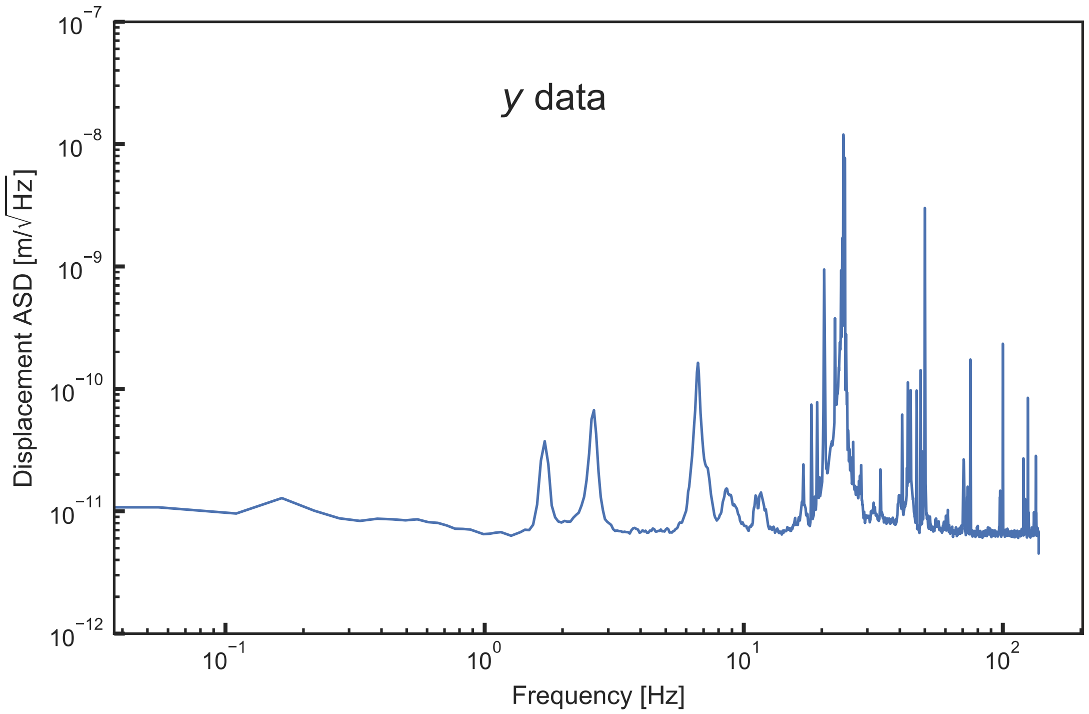




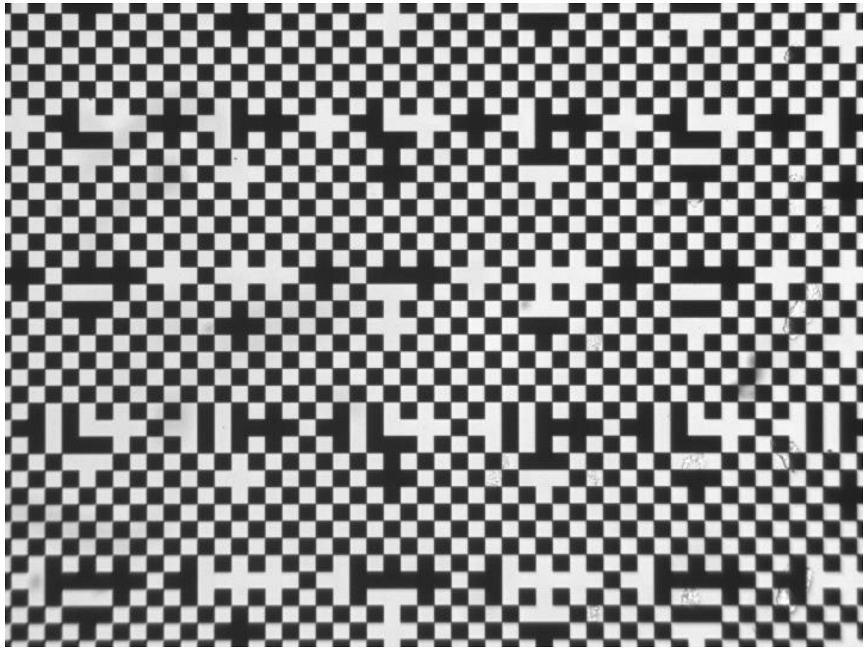


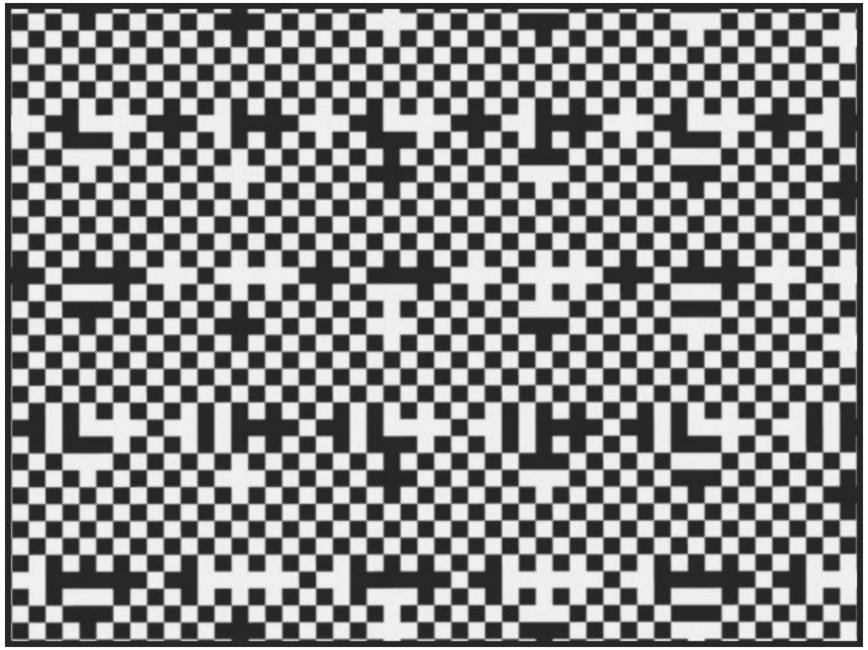
Complete unit was suspended by two thin wires in vacuum tank

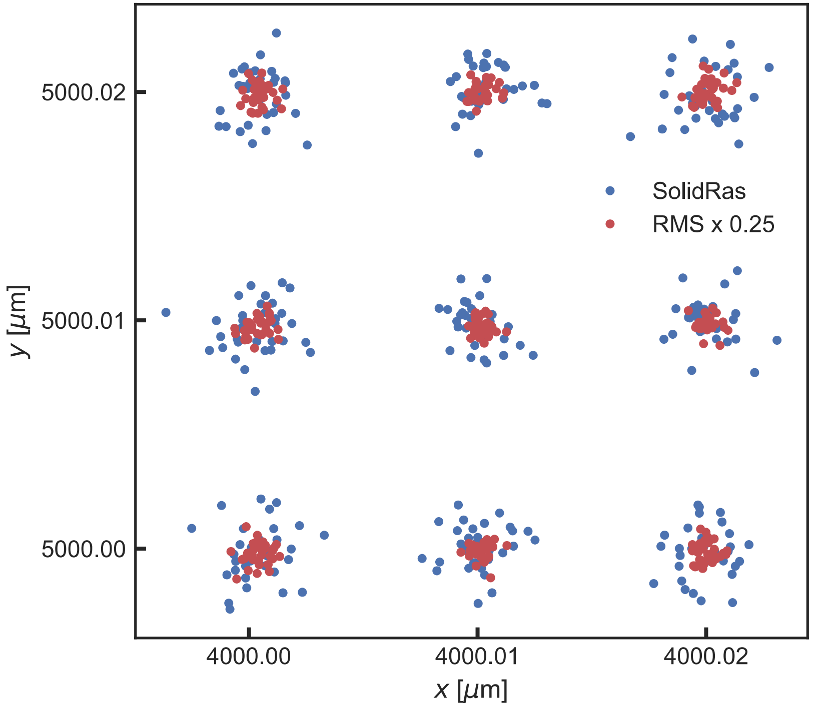




Noise floor level at 7 pm / √ Hz

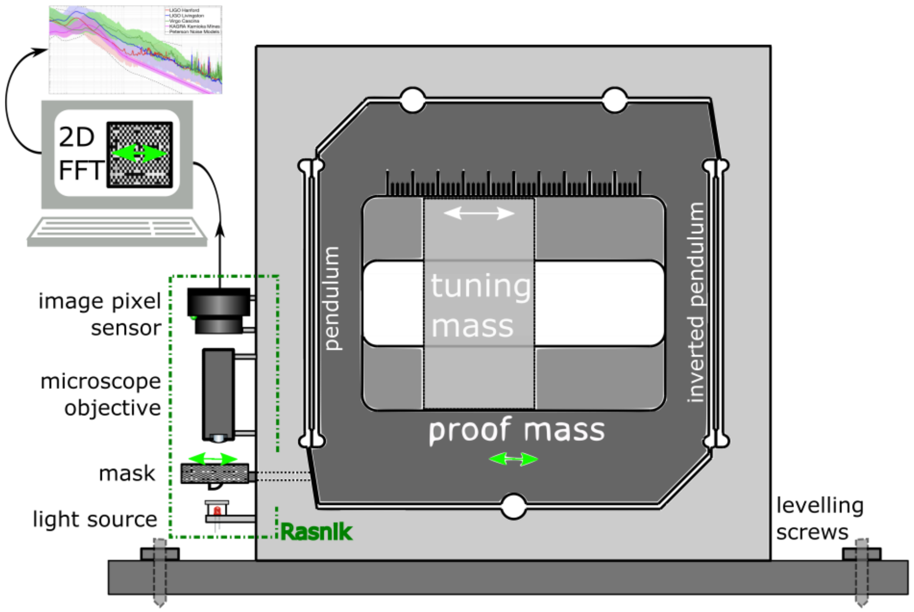






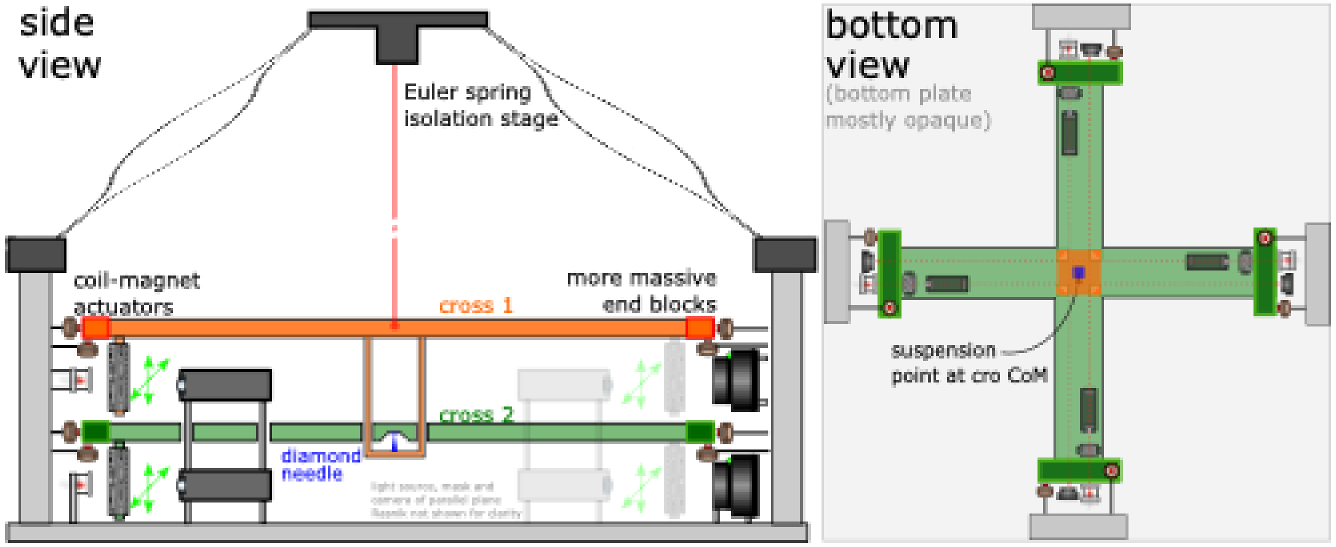
Simulations: revealed non-linearities within a mask period

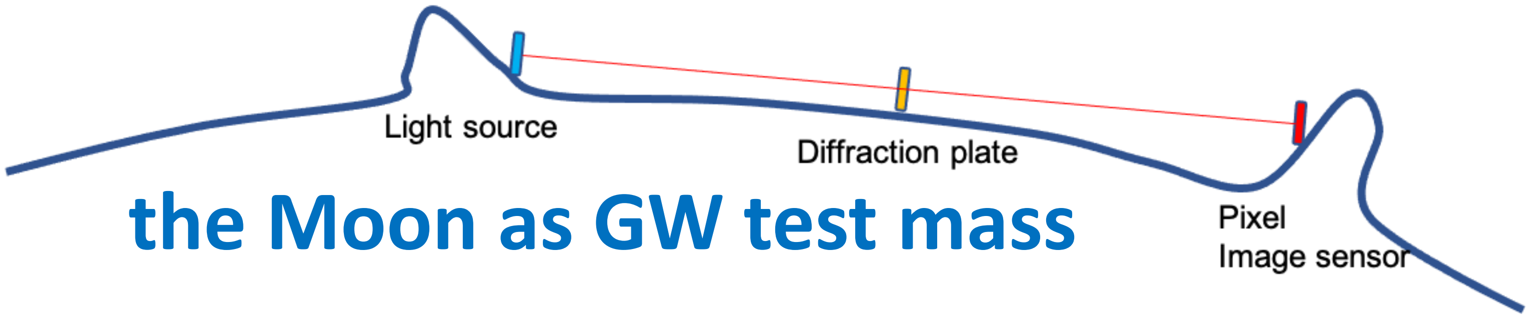
Applications



(inertial) seismic sensor

(inertial) seismic **tilt** sensor





the Moon as GW test mass

Conclusions

- Rasnik measures a 2D displacement in the plane of the mask with respect to the optical axis, perpendicular to the mask plane. The optical axis is defined by the fixed-together lens and optical image sensor unit

- systematical linearity error 50 pm or smaller over arbitrarily large dynamic range, in x and y

- only one precision element: the coded mask, available at low cost thanks to MEMS and IC industry

- no cross coupling between output parameters x, y, S and θ_z; perpendicularity between x and y only defined by the mask

- no calibration required

- straight, analog/digital linear measurement system: no ‘lock’ control and feedback systems required

- arbitrarily large range of measurement (determined by mask size)

- extremely low $1/f$ noise, and absence of drift; only 3rd order temperature effects

- no special electronics required: a system can be composed of only commercially available CMOS pixel image sensors, CPUs and USB or Ethernet3 networking, and COTS optical components

- (very) low cost: 300 - 3000 € excl. network and CPUs

- light pressure onto the mask acts perpendicular to the directions of interest

- system can operate in air, or in vacuum, and in cryogenic environments if case-specific precautions are taken.

The proven spatial resolution in x and y of Rasnik:	7	pm/ √Hz
is not as good as can be obtained with interferometers	4	fm/ √ Hz,
and SQUIDs	0.1 to 3	fm/ √ Hz