Tiltmeters for Terrestrial Gravitational Wave Detectors

Satoru Takano

22/11/2019 Ando Lab Seminar

Contents

- Motivation
- Tiltmeter in the world
- Application to KAGRA
- Summary

Tiltmeter

- Tiltmeter = sensors for tilt motion
- Many types of tilt meter

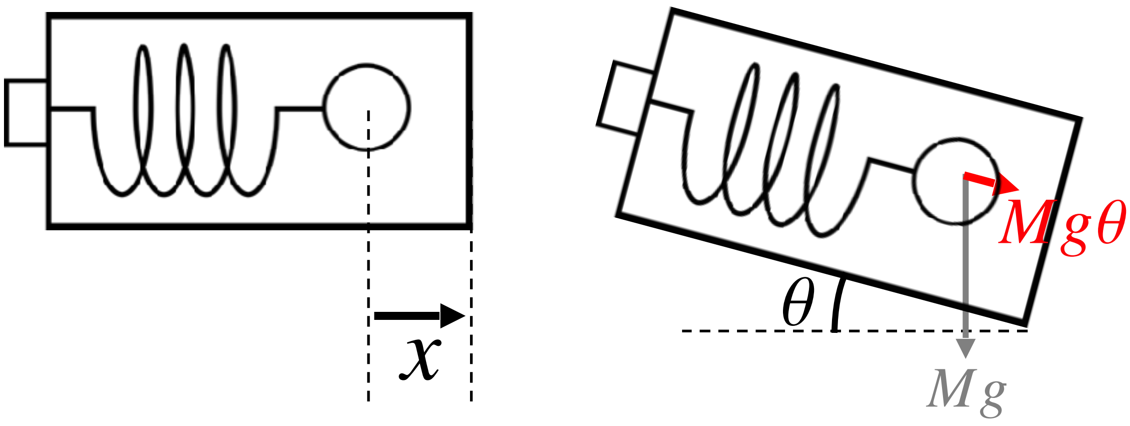
◉ Direct

- Mechanical
- Liquid
- Gyroscope
- etc…

◉ Indirect

- Subtraction of signals of vertical motions

Tilt-to-Translation Coupling



$$M\ddot{x} = Mg\theta$$

$$\tilde{x} = -\frac{g}{\omega^2}\tilde{\theta}$$

- Coupling ∝ f^{-2} → for low frequency this effect is terrible
- In principle, all inertial sensors suffers from this coupling under earth gravity!
- How to reduce (or avoid) this coupling?
  - Measure tilt motion to subtract this effect

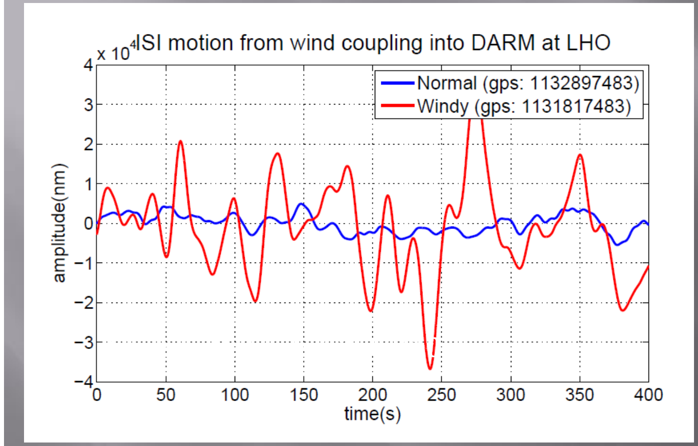
Lock Loss by Seismic Tilt Noise

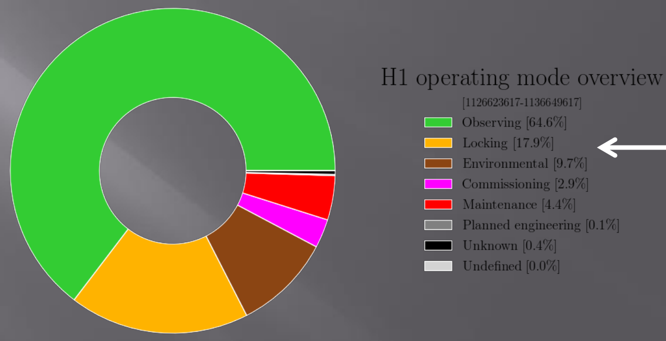
Lock Loss during O1

Venkateswara, [LIGO-G1701922]

Wind-tilt limits duty cycle, adds noise

- Earthquakes, High Wind and High Microseism caused significant down-time in the first Observation run of aLIGO.
- All are primarily related to the problem of tilt-horizontal coupling producing too much ISI motion.



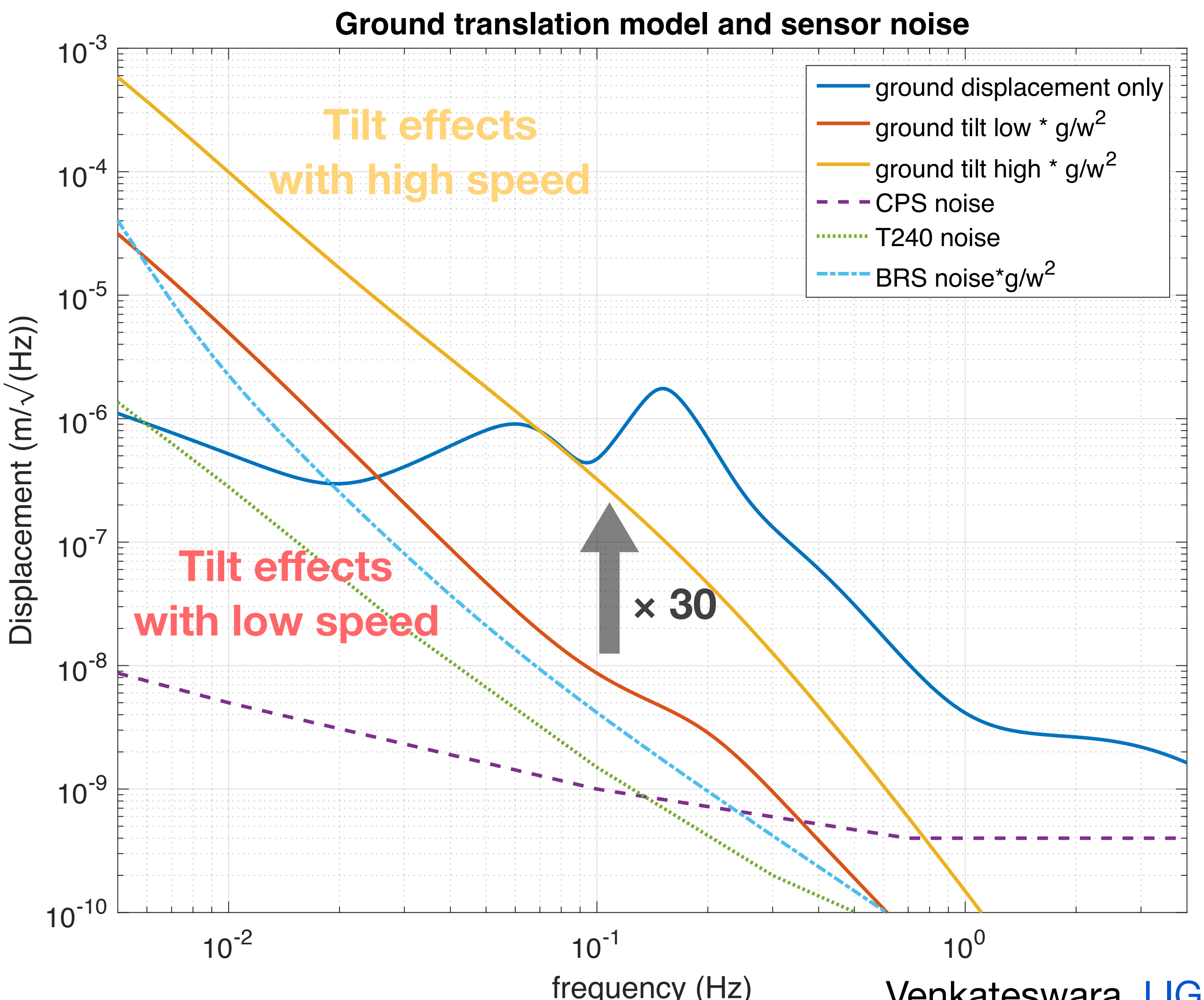


LHO Operator Time accounting in O1
Source: DetChar Summary Pages

Solution: Inertial rotation-sensors, Tilt-free seismometers or ring-laser gyroscopes…

24

Tilt Contribution wrt Wind Speed



Venkateswara, LIGO-P1800038

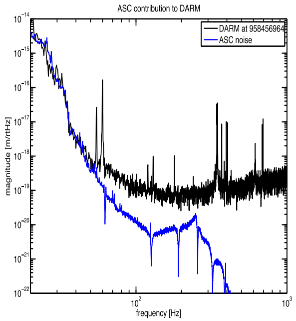
Motion Control at Low Frequency

Widen observation band of detectors lower (e.g. below 5Hz)

- At low frequency many noises are coupled (linearly or non-linearly) to mirrors' motion

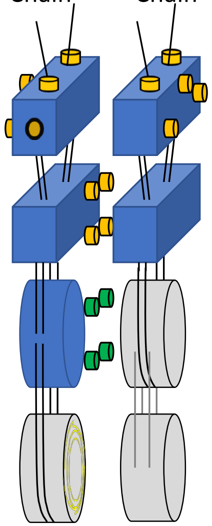
The problem

1. Angular control is a limiting noise source

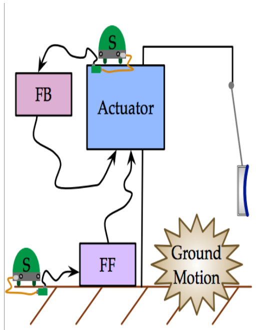


Dooley, P1100125

2. Coupling mechanisms, including suspension coupling from length drive to angle, and back to DARM

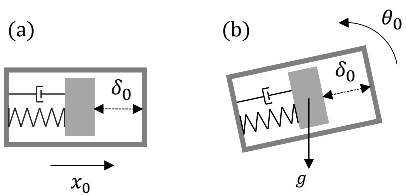


3. The length drive is necessary because the isolation tables aren't perfectly quiet…



Driggers, G1500001

4. … due in part to tilt-to-translation coupling in seismometers



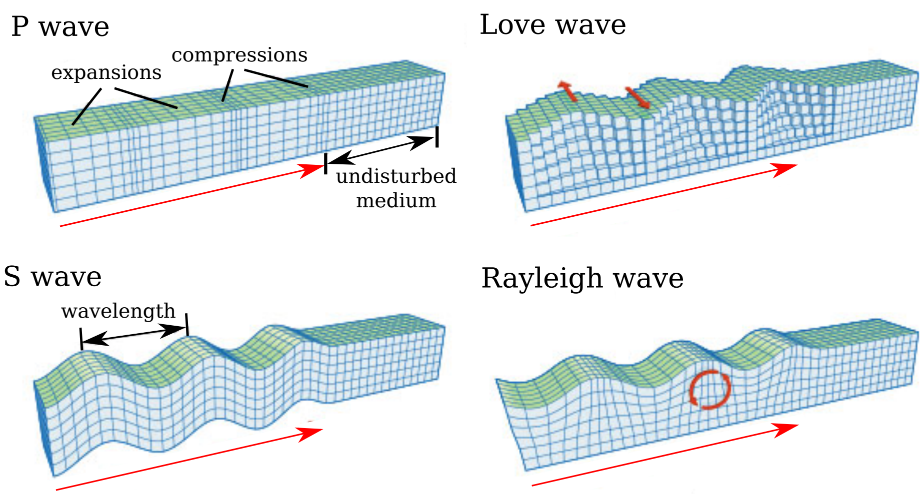
F. Matichard et al, P1400061

5. **To reduce tilt-to translation coupling we have to measure tilt with high sensitivity**

Mow-Lowry, LIGO-G1801755

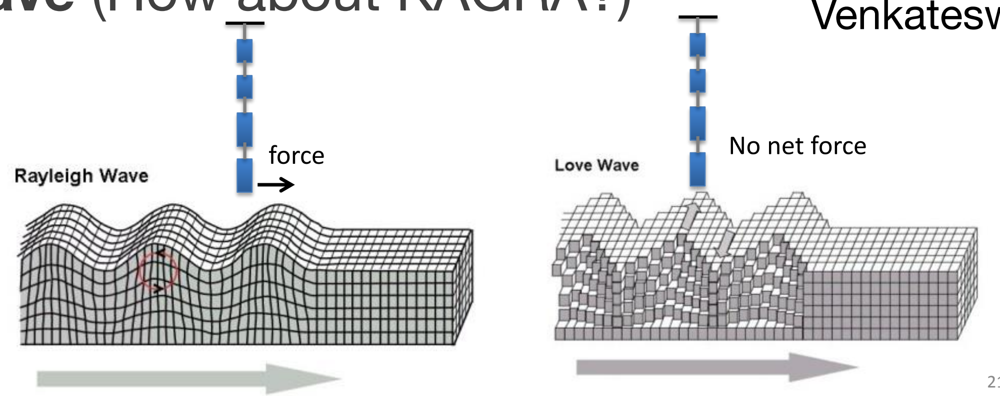
Seismic Newtonian Noise

- Seismic Newtonian noise is caused mainly by seismic waves
  - ◉ Surface waves
    - ▶ Rayleigh wave
    - ▶ Love wave
  - ◉ Body waves
    - ▶ P-wave
    - ▶ S-wave



McManus, Ph.D thesis

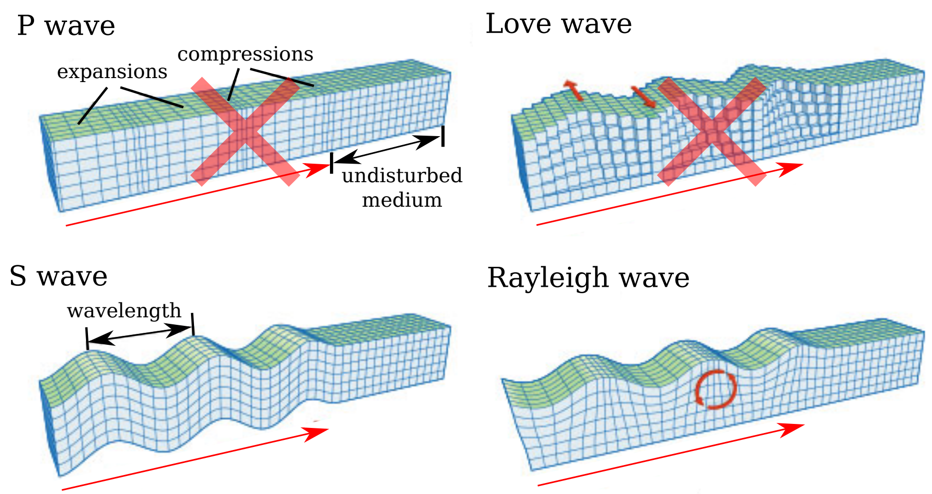
- For surface detectors like aLIGO and adVirgo, dominant source is **Rayleigh wave** (How about KAGRA?)



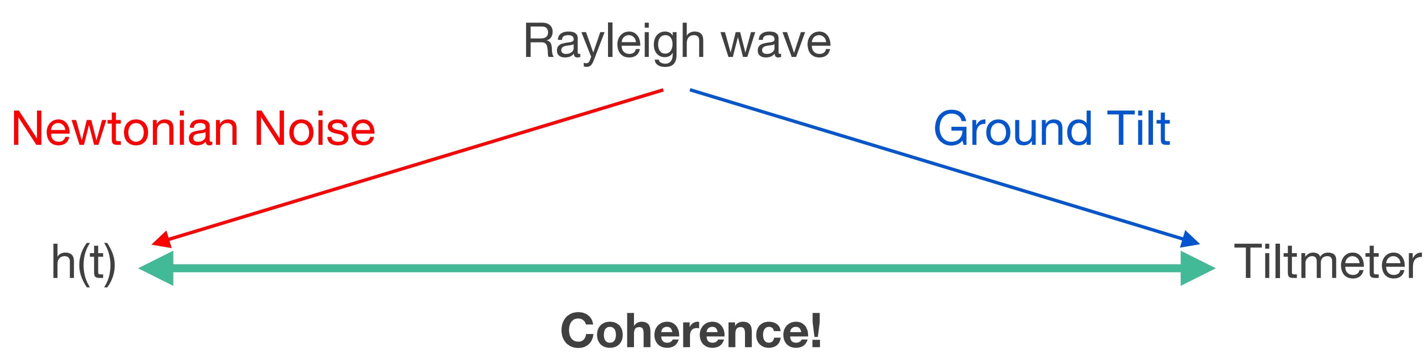
Venkateswara, LIGO-G1600451

NN Estimation with Tiltmeter

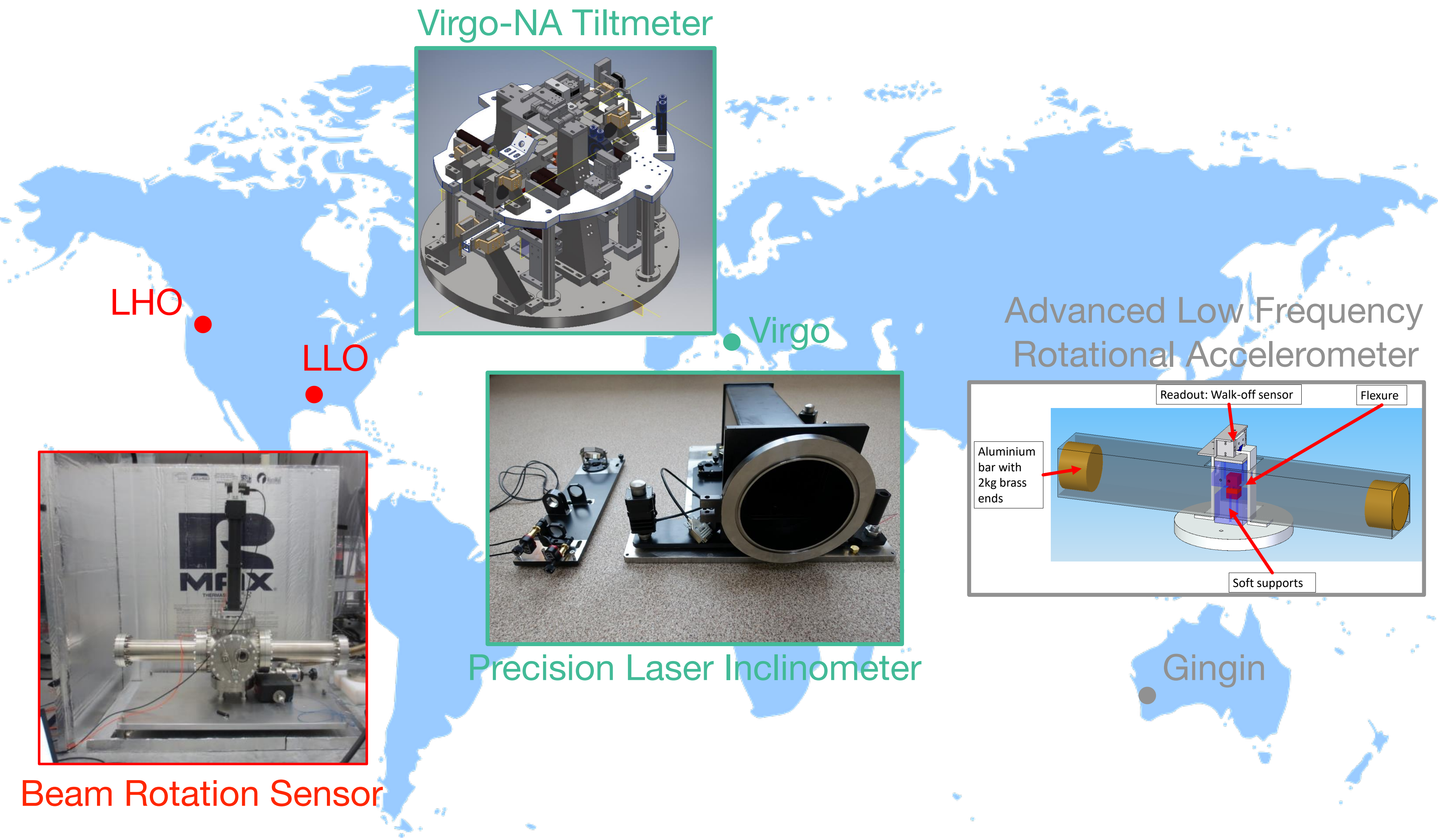
- Tiltmeter can see those waves which tilt the ground (**Rayleigh**, **S**)



- If measured wave is Rayleigh wave-dominant…



Tiltmeter in the World

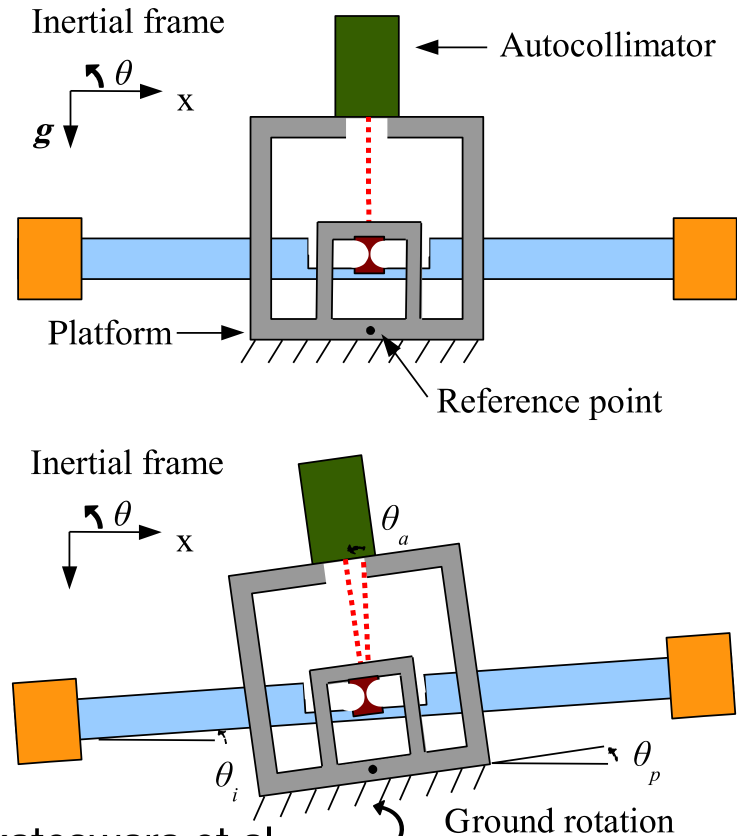


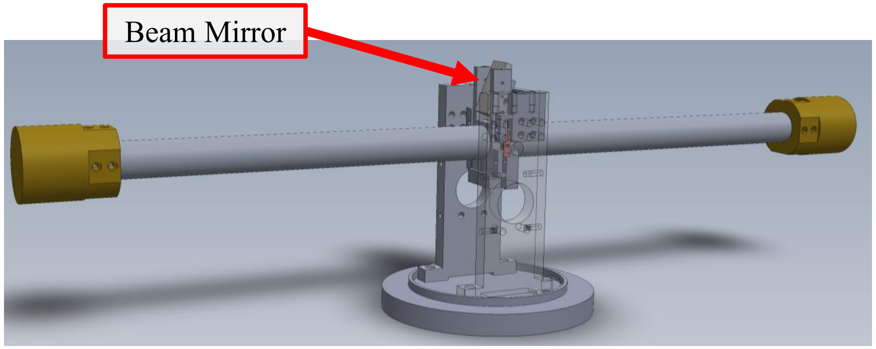
Beam Rotation Sensor (BRS)

- Developed by Eöt-Wash group in University of Washington
- 6 BRSs was installed in aLIGO
  - LLO: End X, End Y
  - LHO: Input X, Input Y, End X, End Y

Measure ground tilt by measuring differential angle btw the floor and low frequency beam balance

- Resonant frequency: 3-8 mHz
- Tilt Measurement: Autocollimator

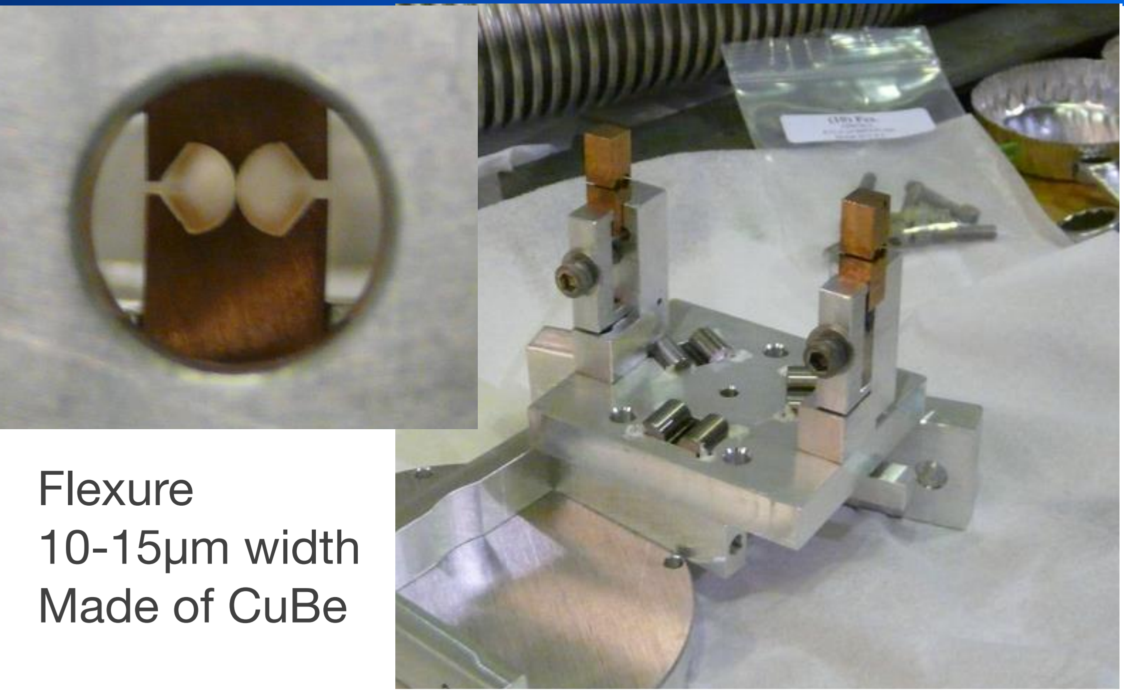




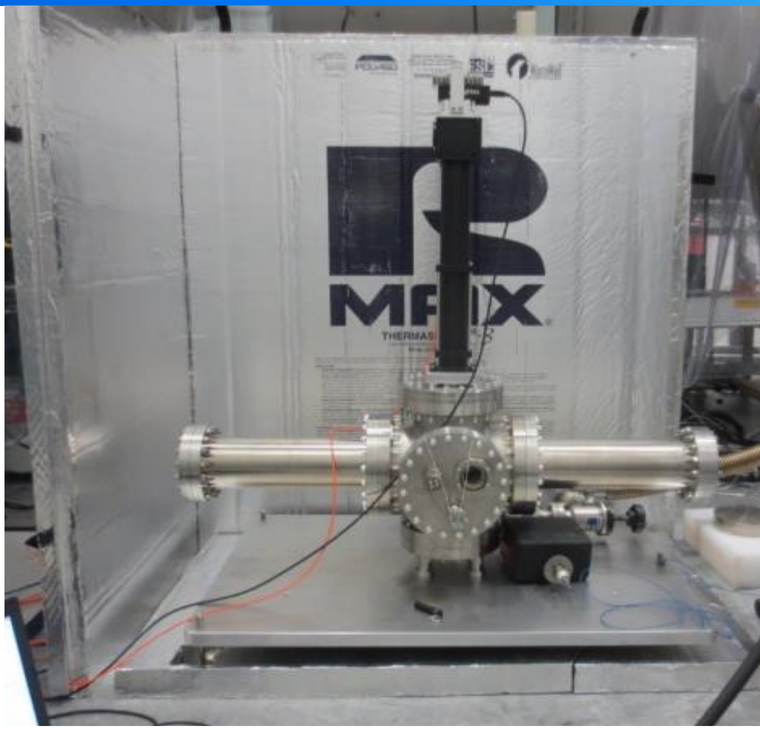
LIGO-G1801085

Venkateswara et al., Bull. Seismol. Soc. Am., **107**, no. 2, 709–717

Beam Rotation Sensor (BRS)

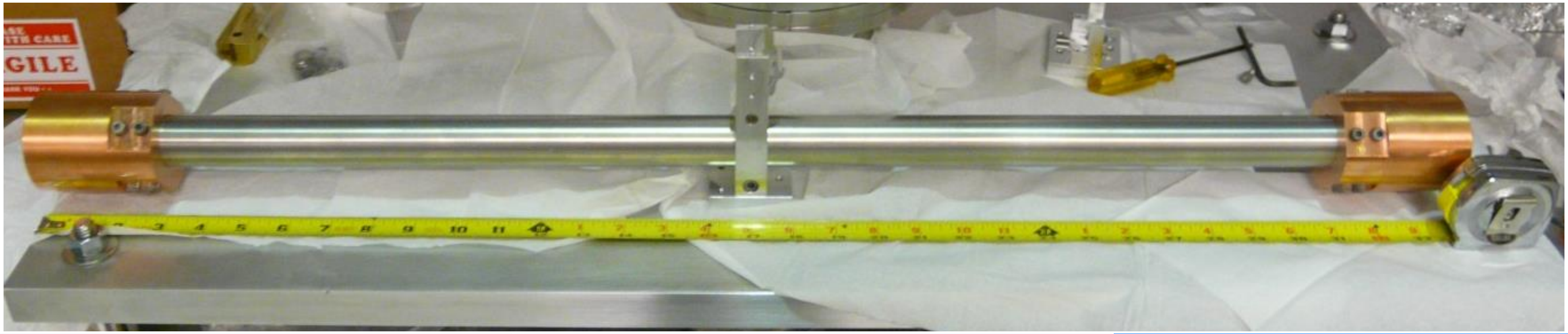


Flexure
10-15μm width
Made of CuBe



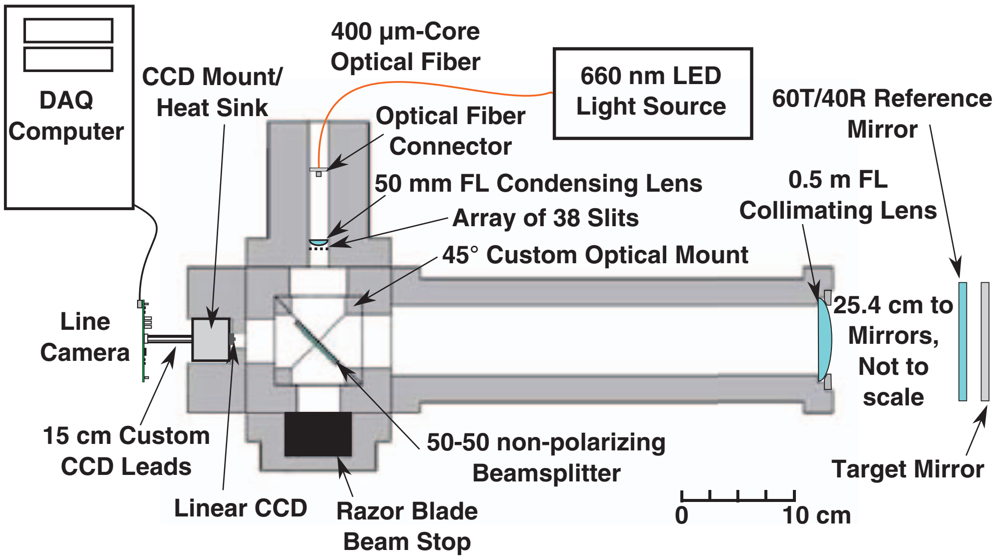
BRS at End X of LHO

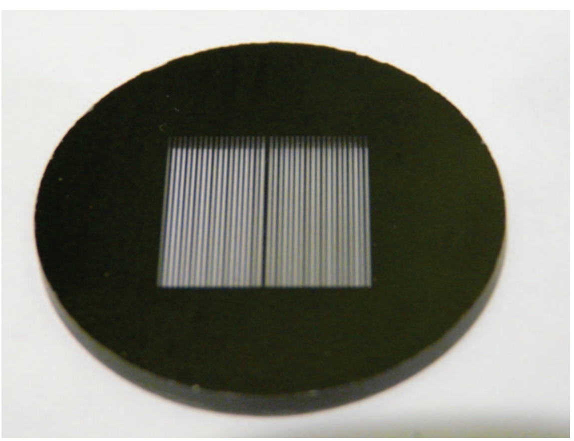
Beam
1m, 4.5 kg



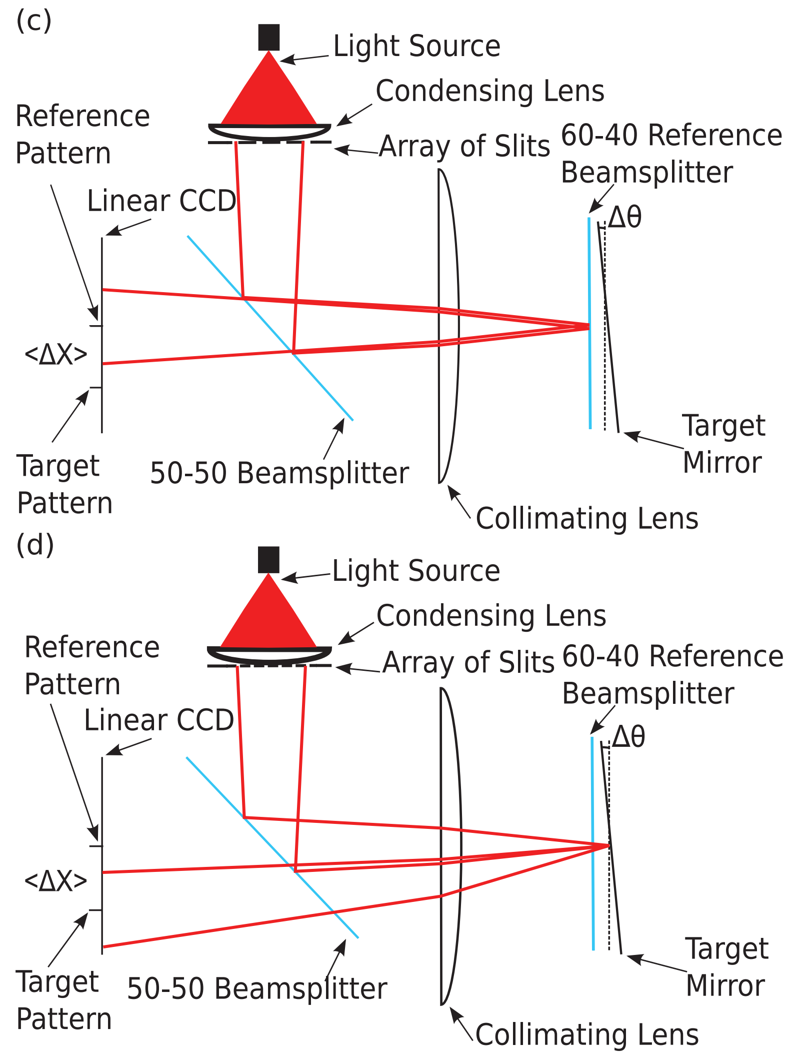
Autocollimator

Arp et al., [Rev. Sci. Instrum. **84**, 095007 (2013)]





Slit array

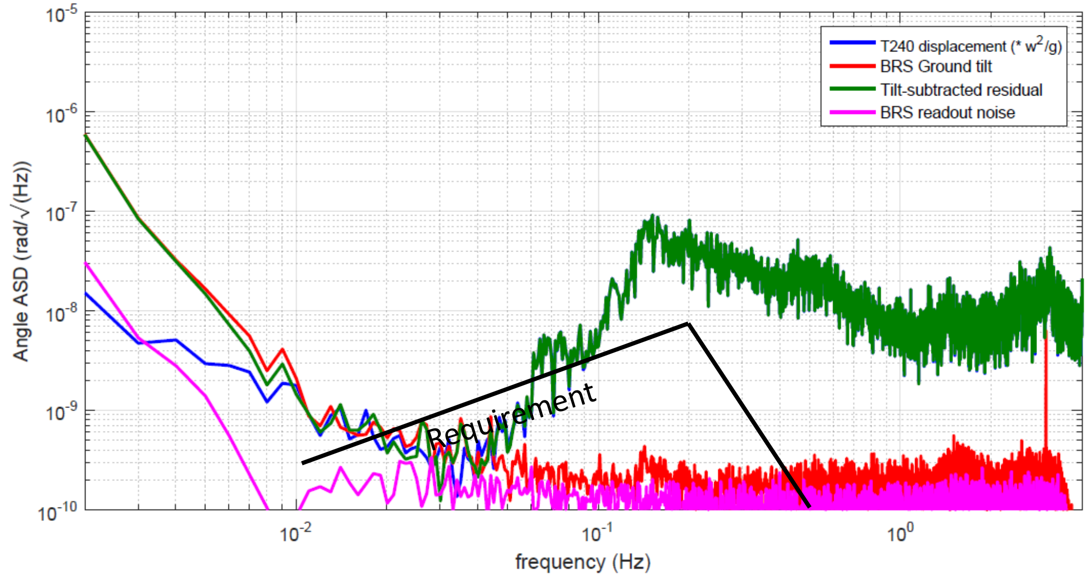


Sensitivity in LHO

Venkateswara, [LIGO-G1600451]

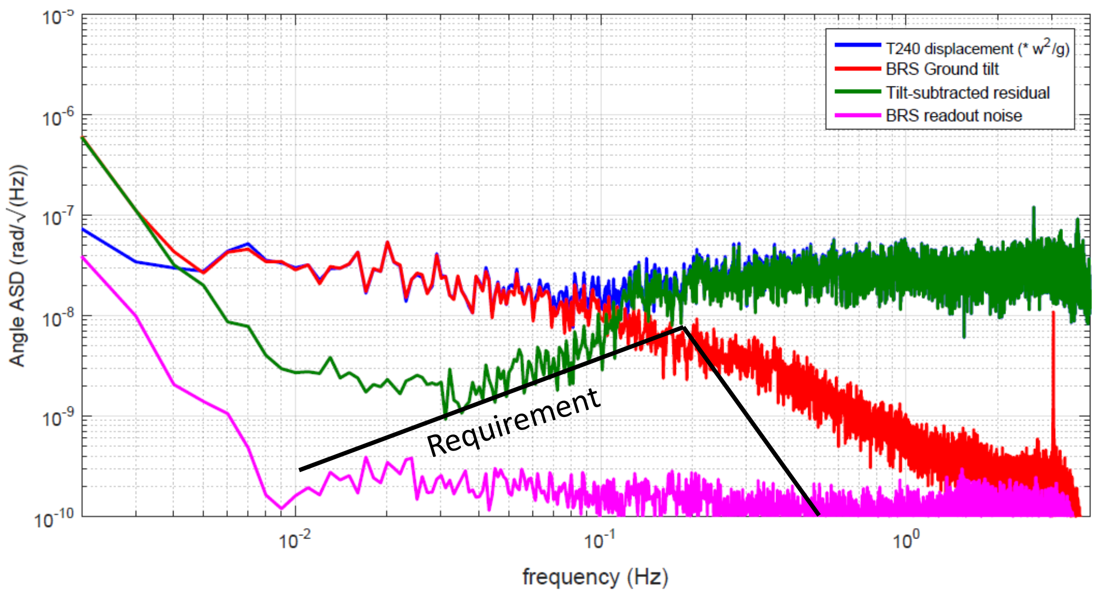
Quiet day

- Above 30 mHz BRS spectrum is limited by sensor noise



Windy day

- BRS spectrum seems to measure ground tilt up to 2Hz



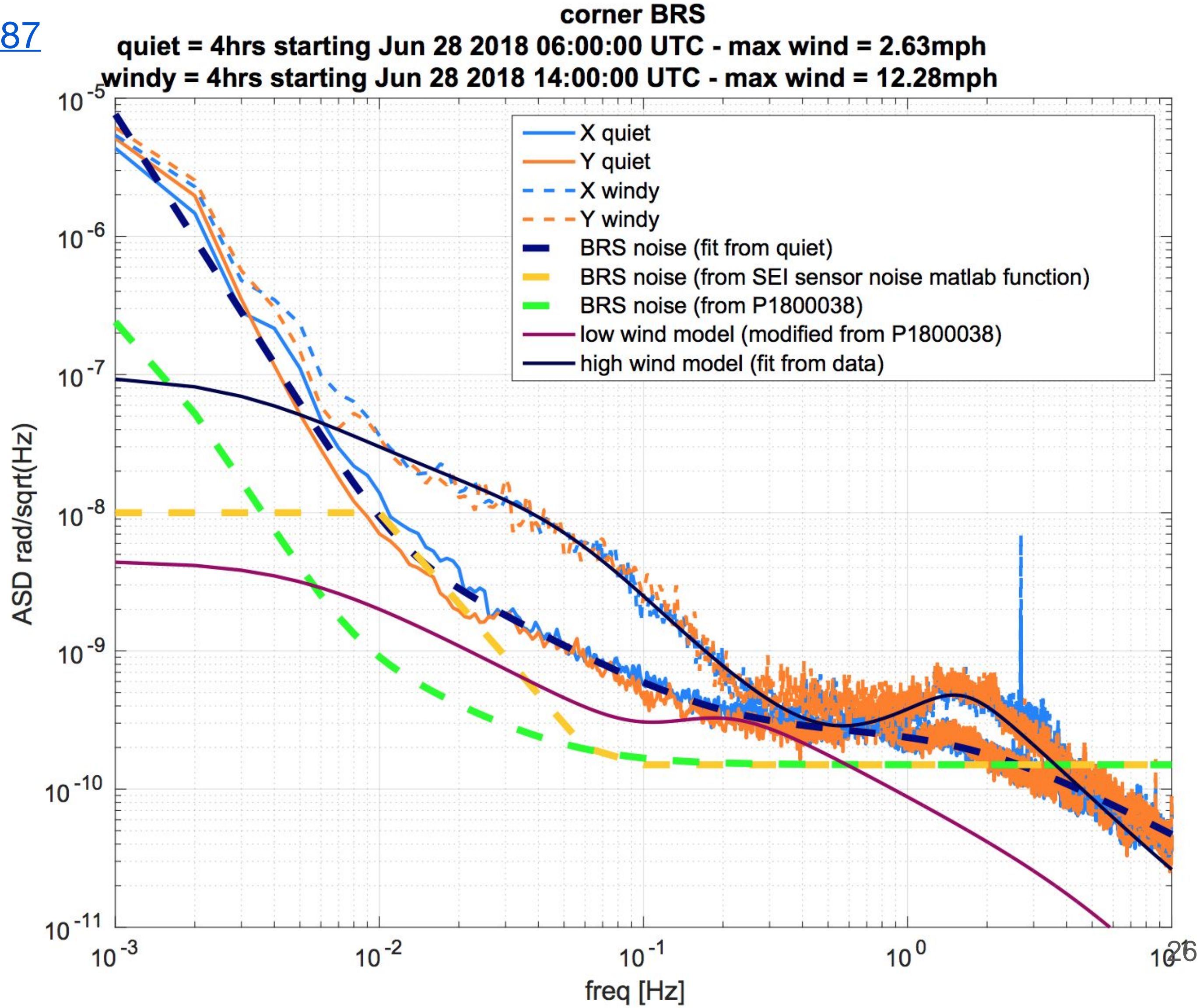
Either quiet or windy day, subtraction to tilt coupling seems to work well

Sensitivity in LLO

Pele&Ross, [LIGO-G1801687]

BRSs in LLO at Input X/Y

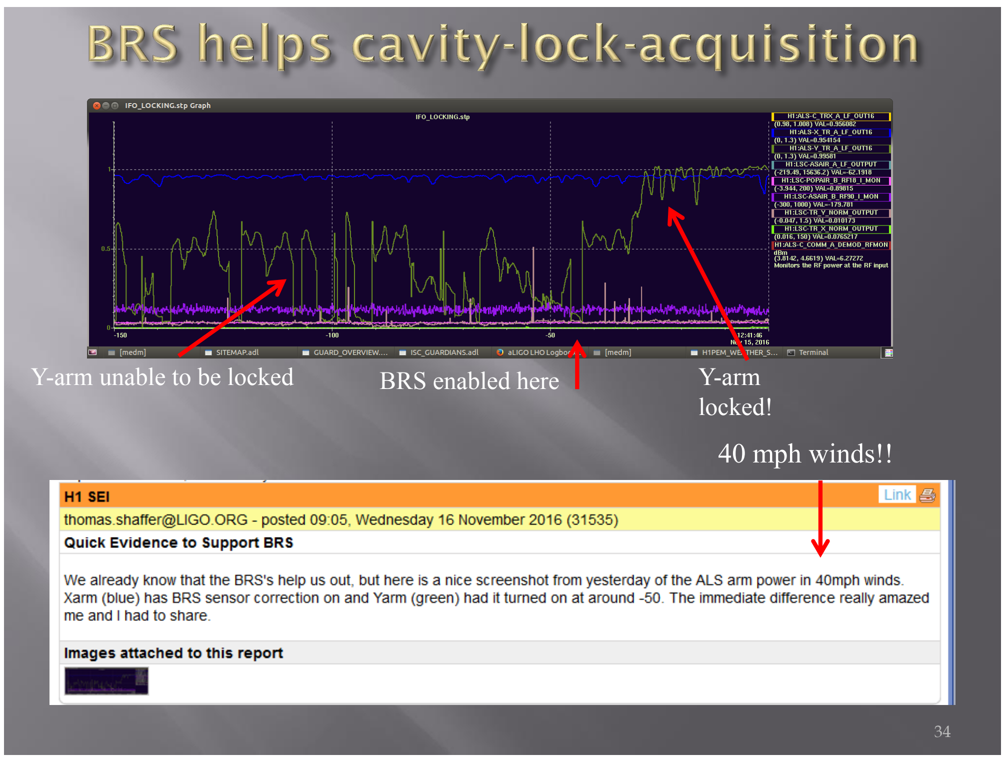
- With high speed they could see ground tilt
- With low speed the spectra are limited by sensor noise

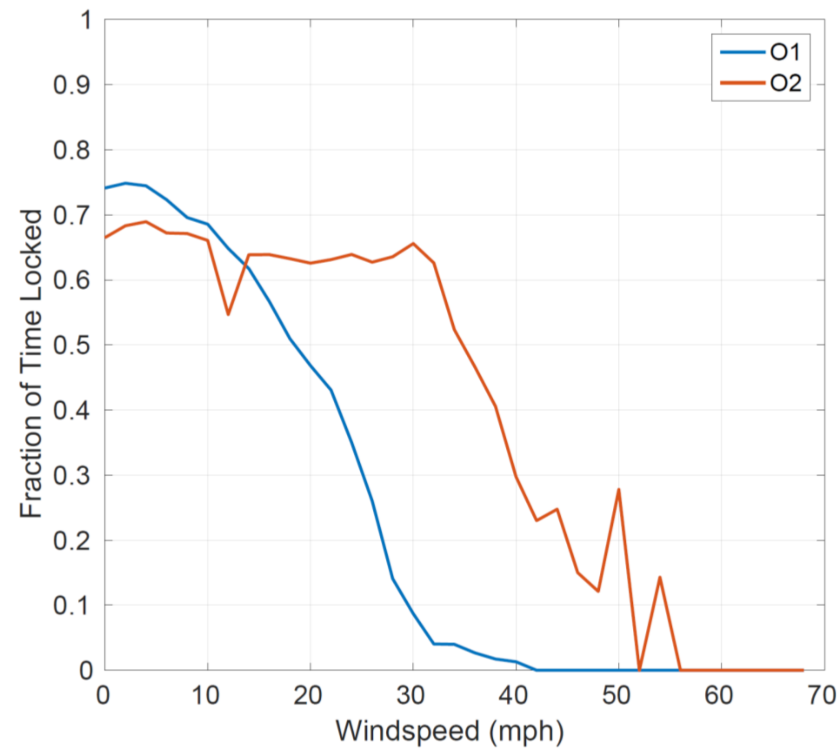


Contribution to Duty Cycle

- Improvement in duty cycle in O2
  - Possible to lock even in high wind speed
  - ~8% increase in overall duty cycle
  - GW160104 was detected with 20 mph (9m/s) wind speed

Venkateswara, [LIGO-G1701922]

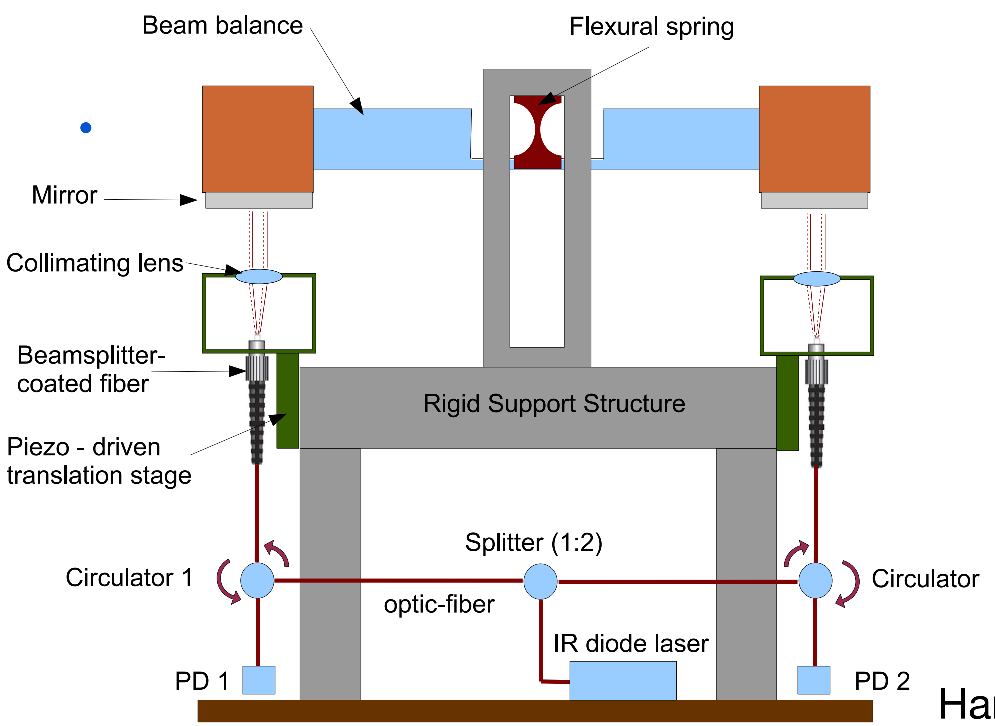


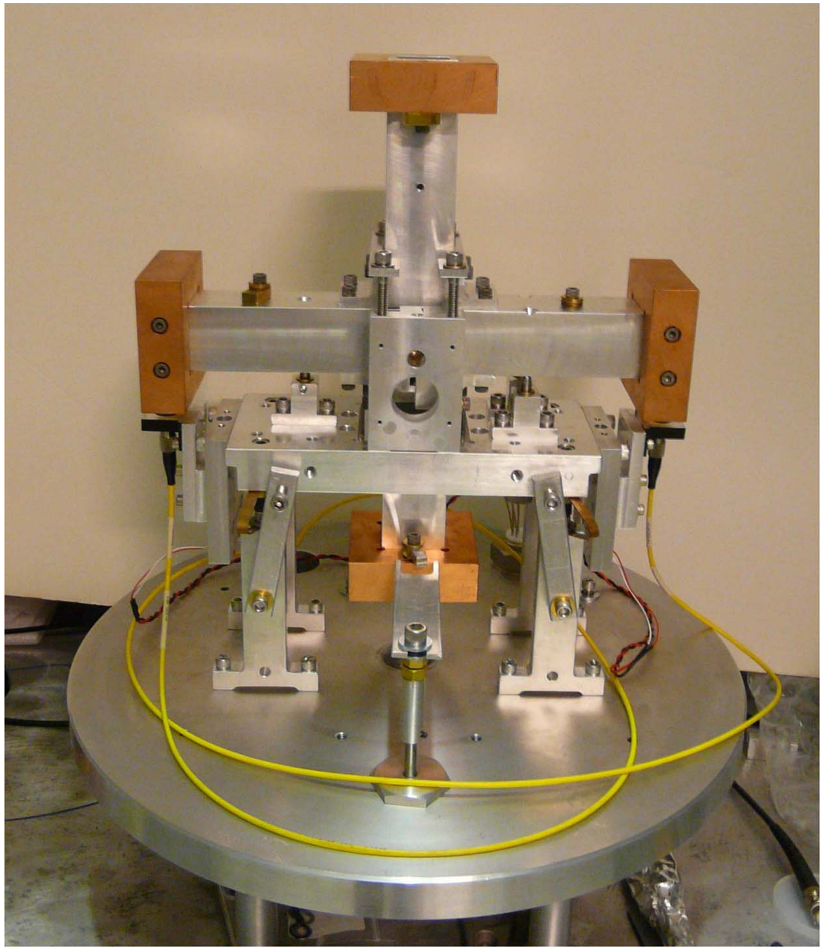


Next Plan: Compact BRS

Compact BRS (cBRS)

- Compact design (~30cm)
- Interferometric readout
- Vacuum compatible
- Lower coupling to gravity gradients
-





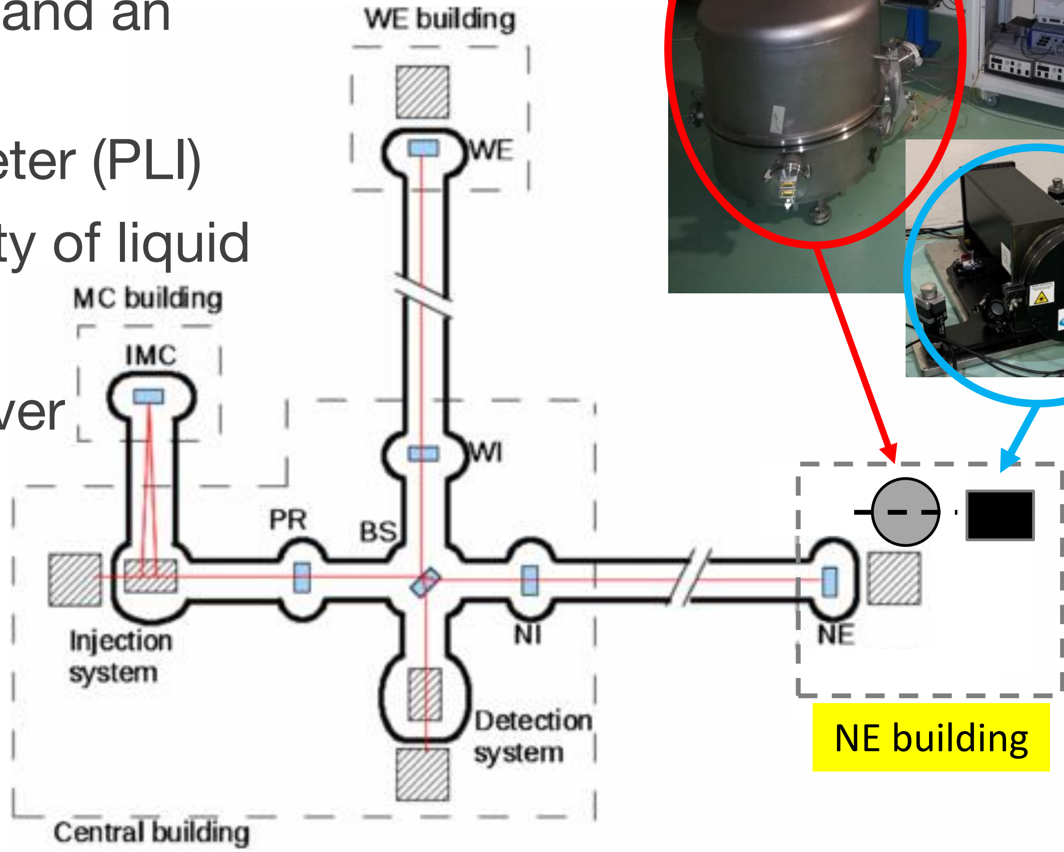
Harms & Venkateswara, [CQG, **33** 234001 (2016)]

Tiltmeters in advVirgo

Errico, [LIGO-G1901629]

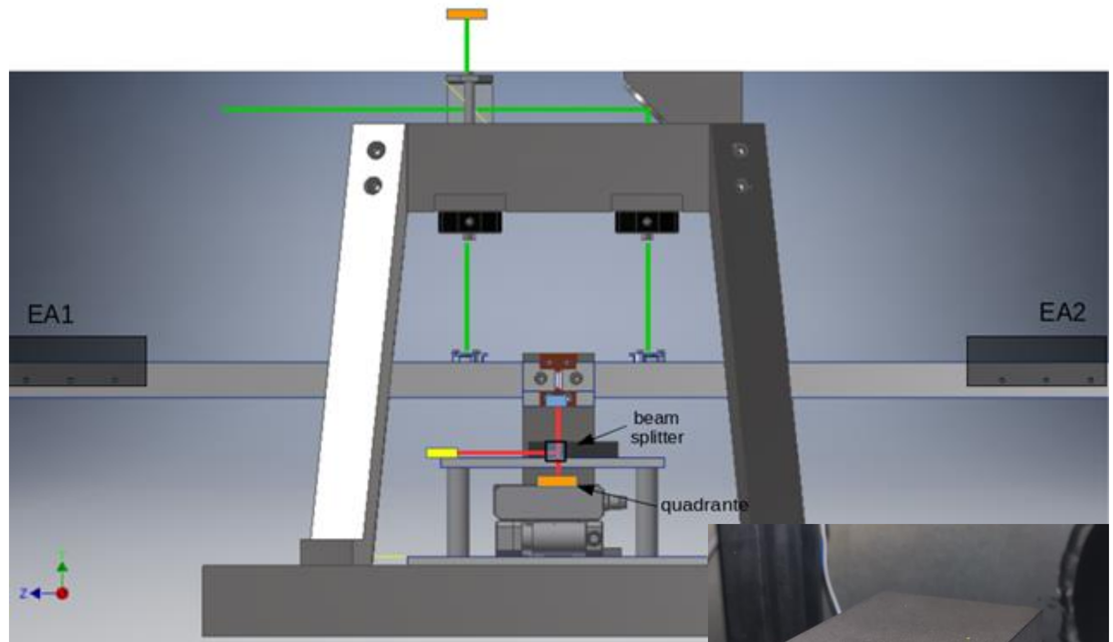
Two types of tiltmeters are installed at NE:

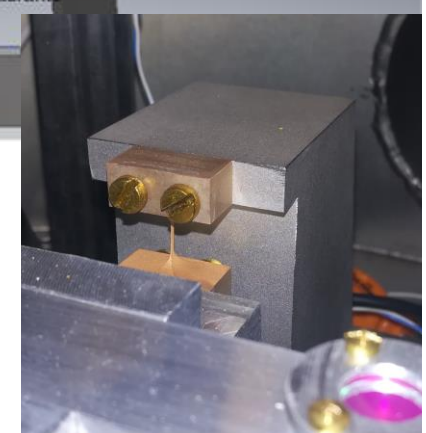
- Tiltmeter (I don't know its actual name)
  - BRS-like tiltmeter
  - Read by an optical lever and an interferometer
- Precision Laser Inclinometer (PLI)
  - Make use of horizontality of liquid
  - Measure tilt of liquid surface by an optical lever



Virgo-NA Tiltmeter

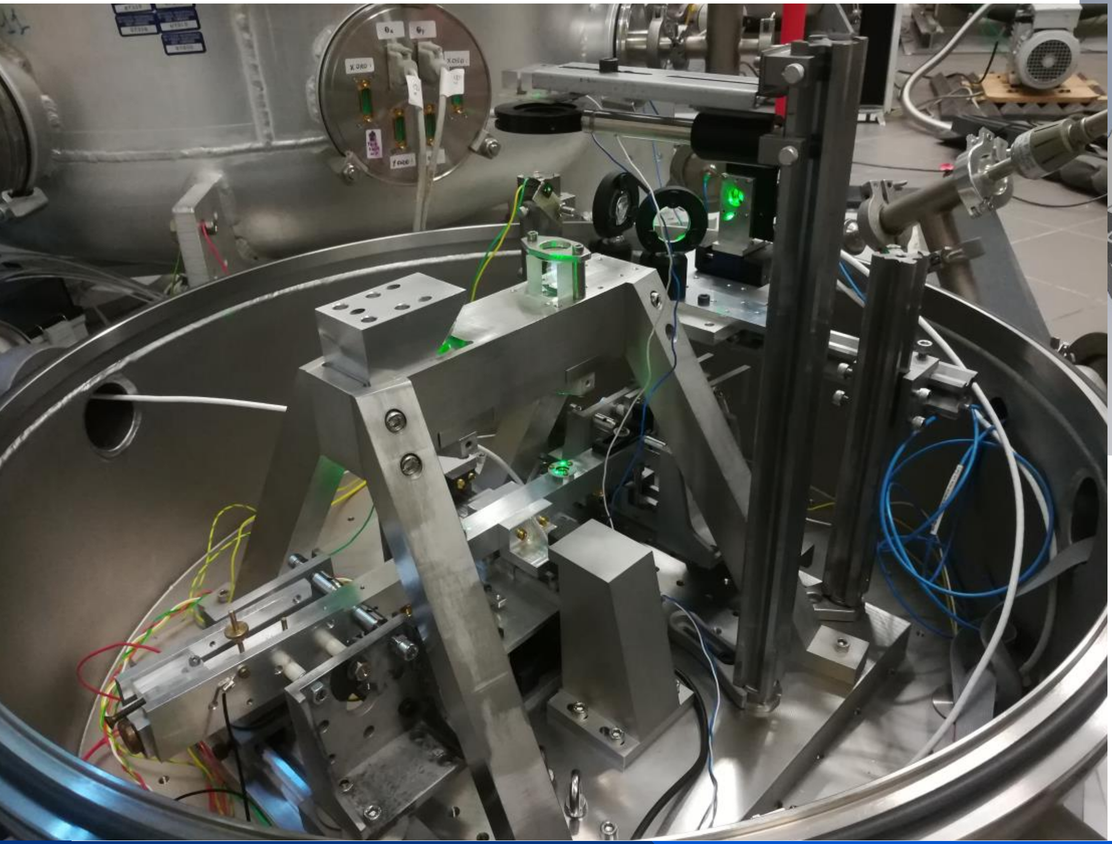
- Developed by Virgo-Napoli group
- Basically, the configuration is almost the same as BRS in LIGO
- Difference
  - ◉ Readout scheme
    - ▶ Optical lever
    - ▶ Interferometer
  - ◉ Feedback
    - ▶ UGF: 200 mHz

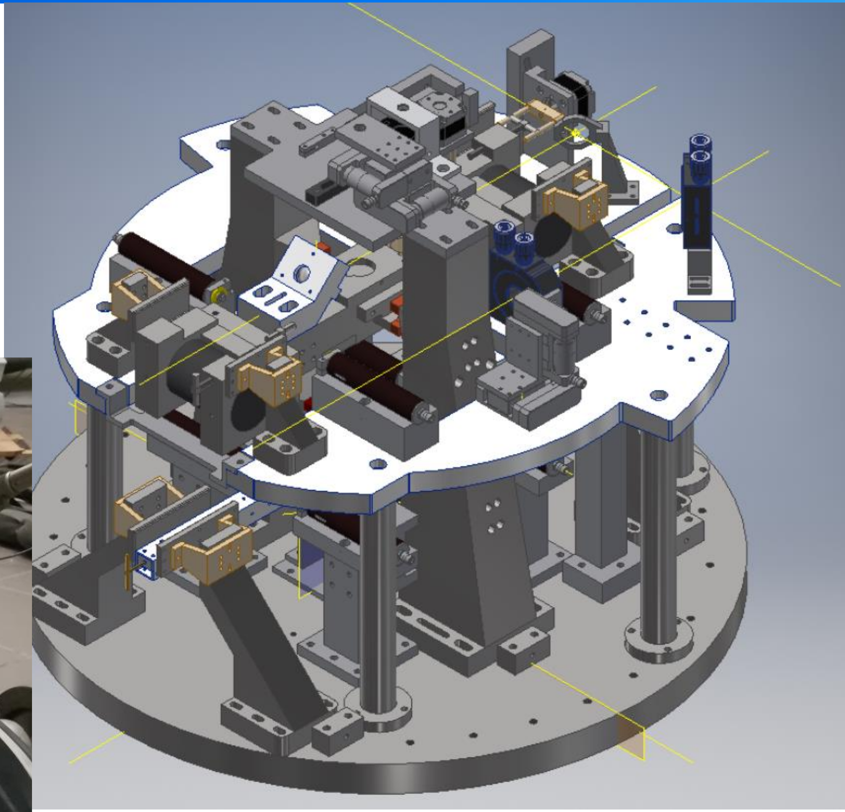




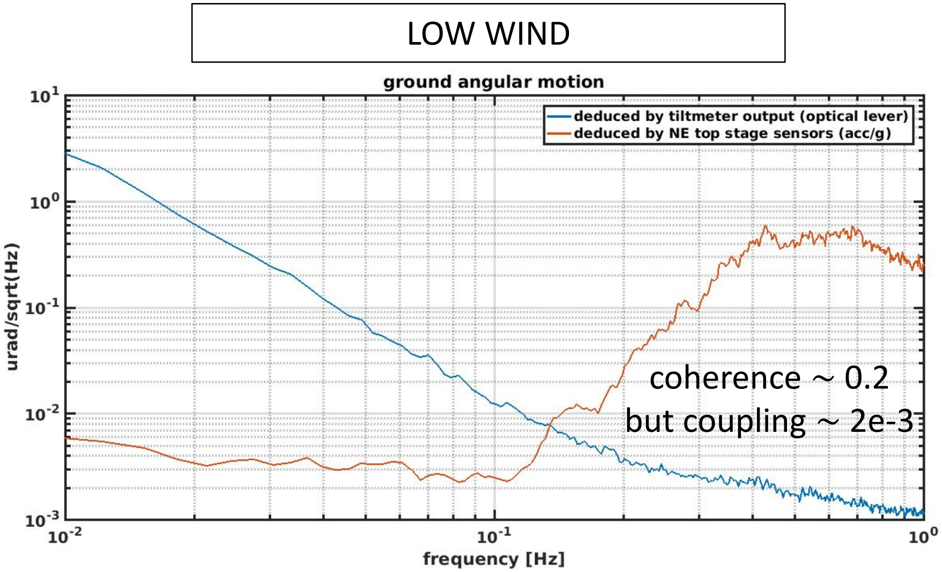
Virgo-NA tiltmeter & joints

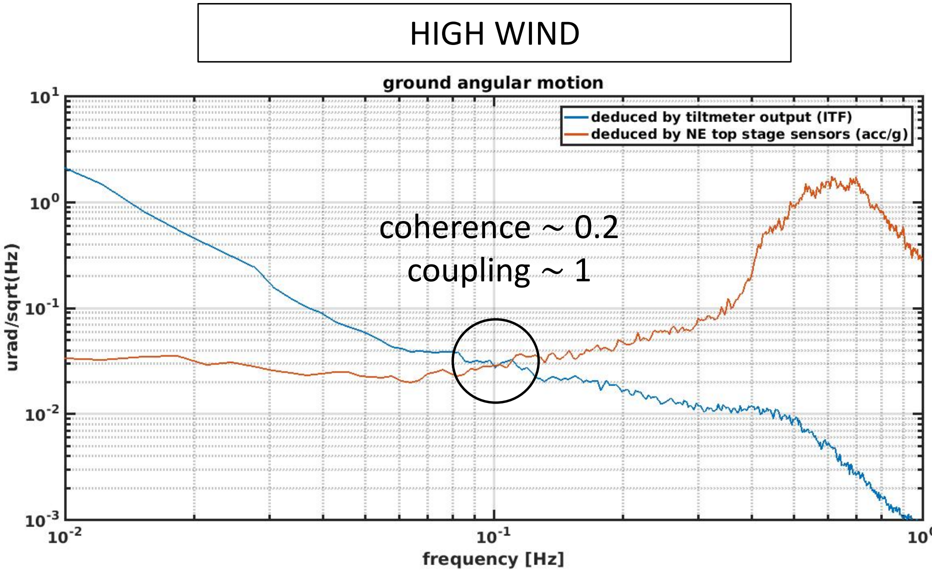
Virgo-NA Tiltmeter





Sensitivity at Low Frequency



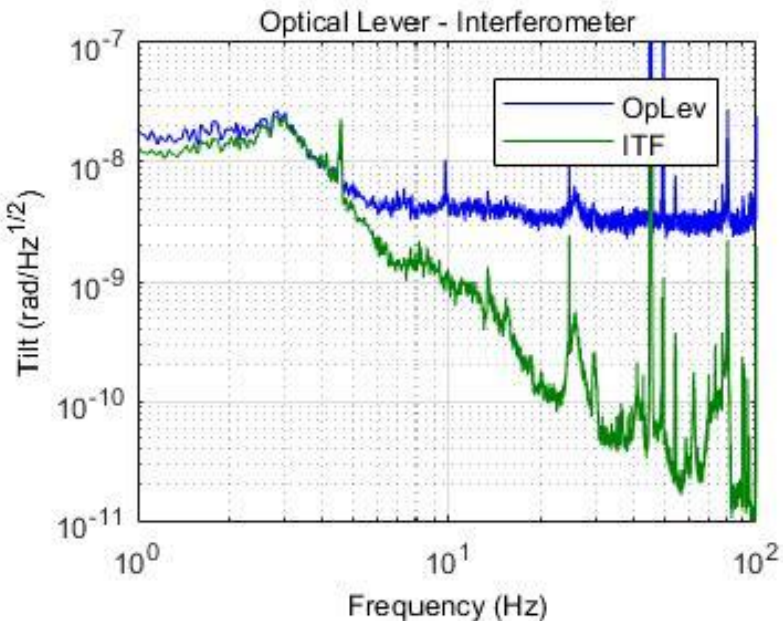


- Below 100 mHz tiltmeter sensitivity is always limited by other noise sources;
- **Above 100 mHz transversal accelerations ('fake tilts') are highly rejected**;
- At 100 mHz tiltmeter sensitivity is sufficient to detect tilts only in high-wind conditions (acc/g @ 100 mHz is a real tilt).

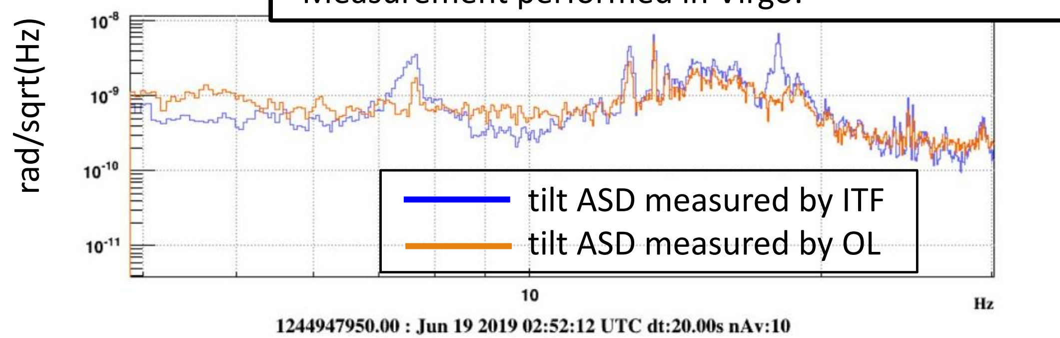
- For now the sensitivity is not enough to measure ground tilt motion below 100 mHz even windy condition
- Limited by actuator noise?

Sensitivity above 1 Hz

An upper limit to ITF sensitivity:



Measurement performed in Virgo:



@ 30 Hz and above: $\sim 5 \cdot 10^{-11} \frac{rad}{\sqrt{Hz}}$

Close to the sensitivity required for NN studies. Some structures in this region are due to **mechanical vibrations of the vacuum chamber**.

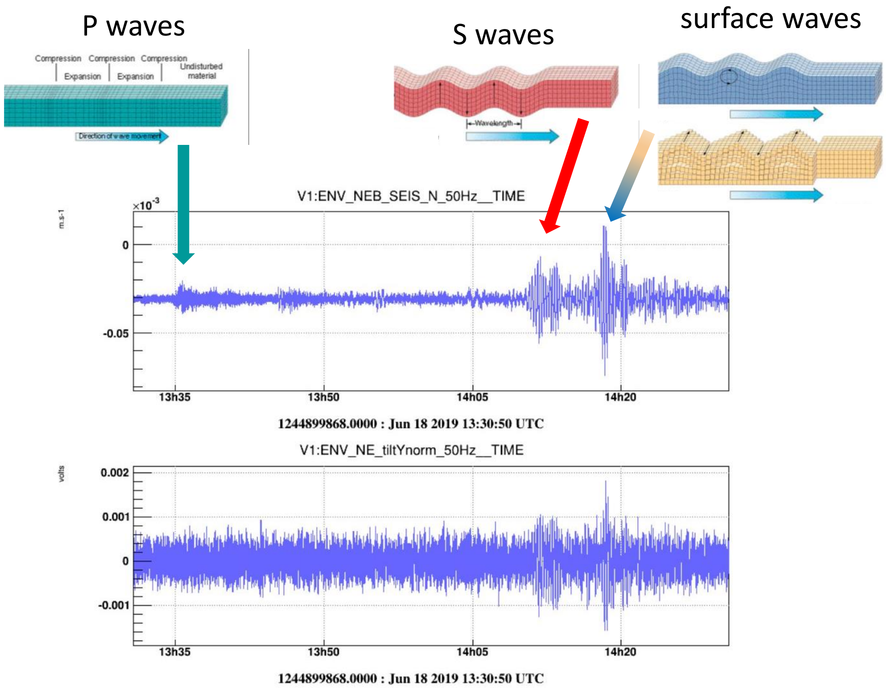
Response to Seismic Waves

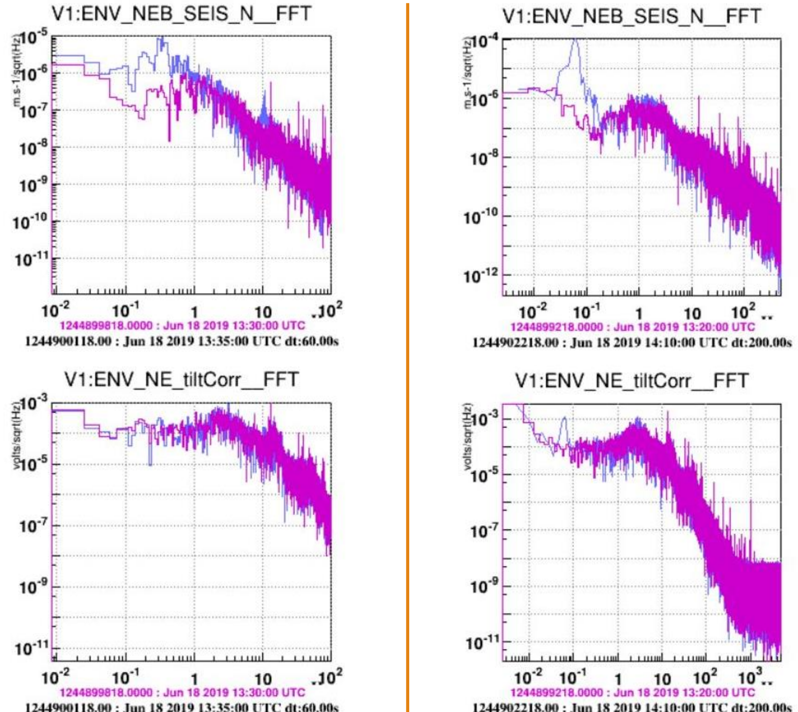
Response of accelerometers and our tiltmeter during an earthquake (Japan, 2019/06/18)

Different wave types should be seen in different ways in accelerometers/tiltmeter.

Our tiltmeter responded mainly to those waves that tilted the ground

(as a tiltmeter should do).





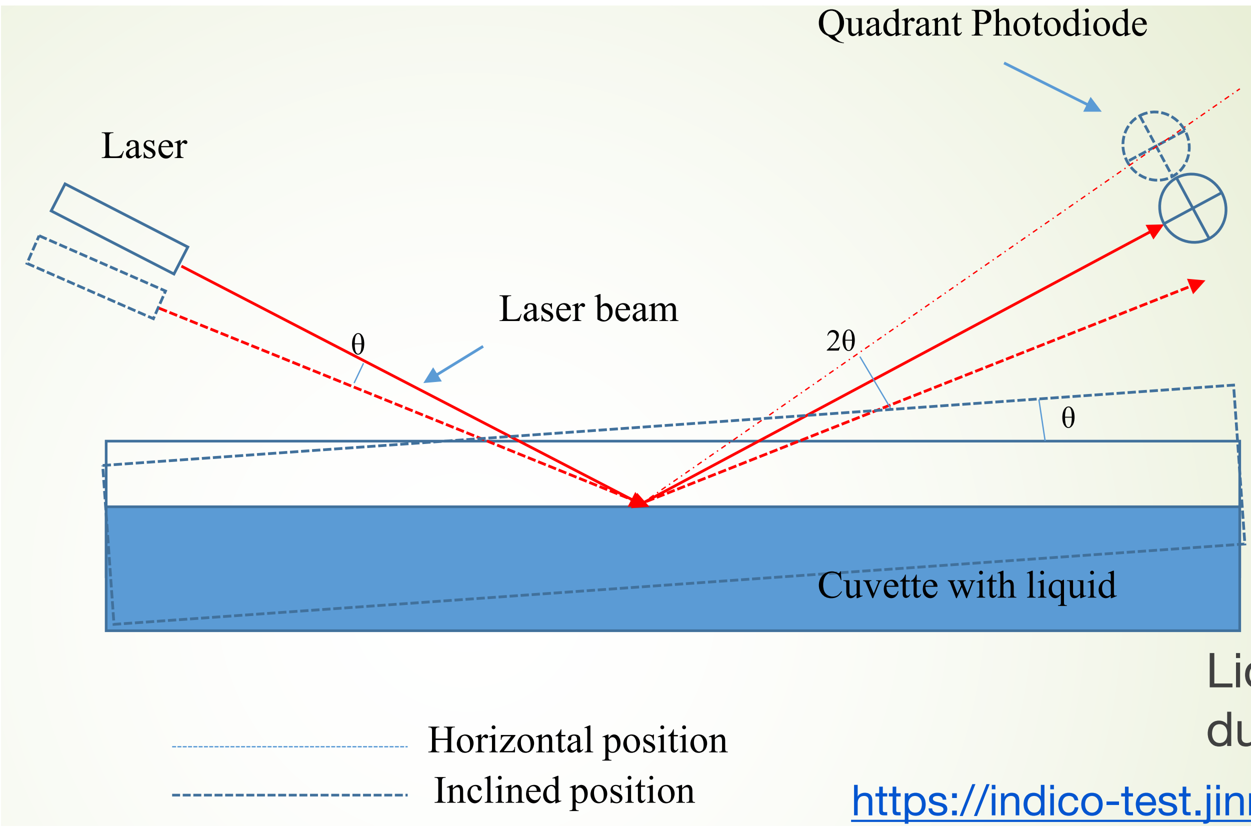
pre-/during P waves

pre-/during S waves

- Have potential to see NN due to Rayleigh wave

Precision Laser Inclinometer

- Developed by a group in CERN and JINR (Russia)
- Measure beam tilt reflected from liquid surface by an optical lever
  - No translational coupling
  - Possible to measure 2 DoF of tilt motion

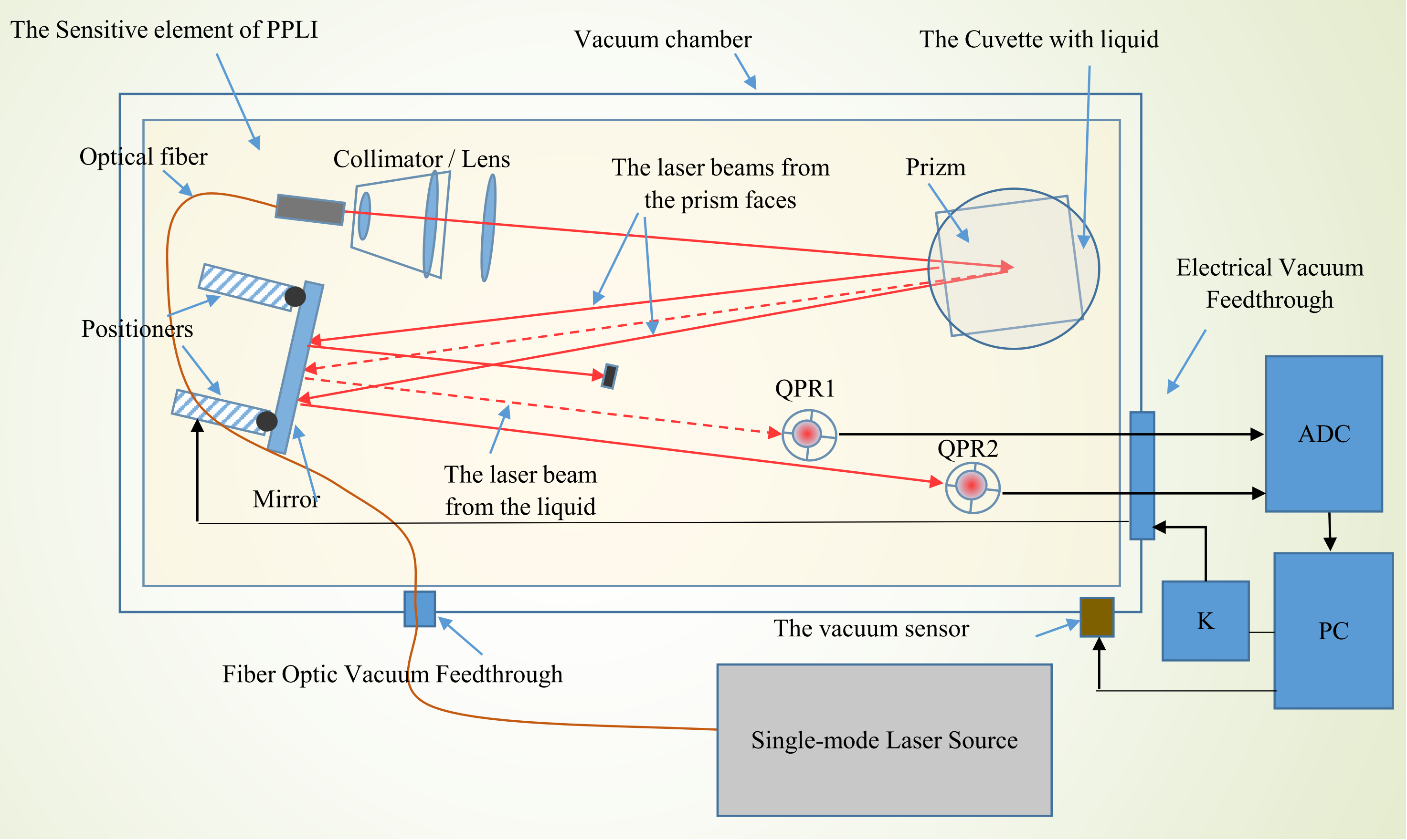


Measure laser inclination by a optical lever

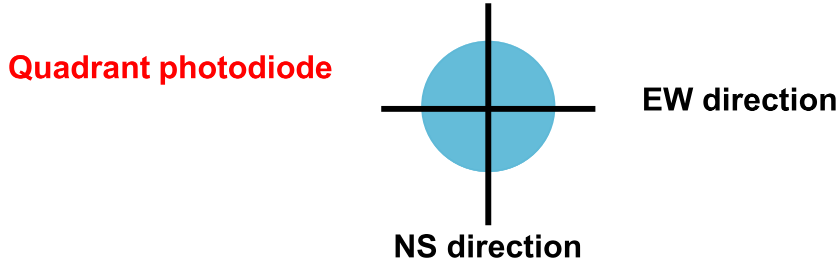
Liquid surface keeps horizontal due to earth's gravity

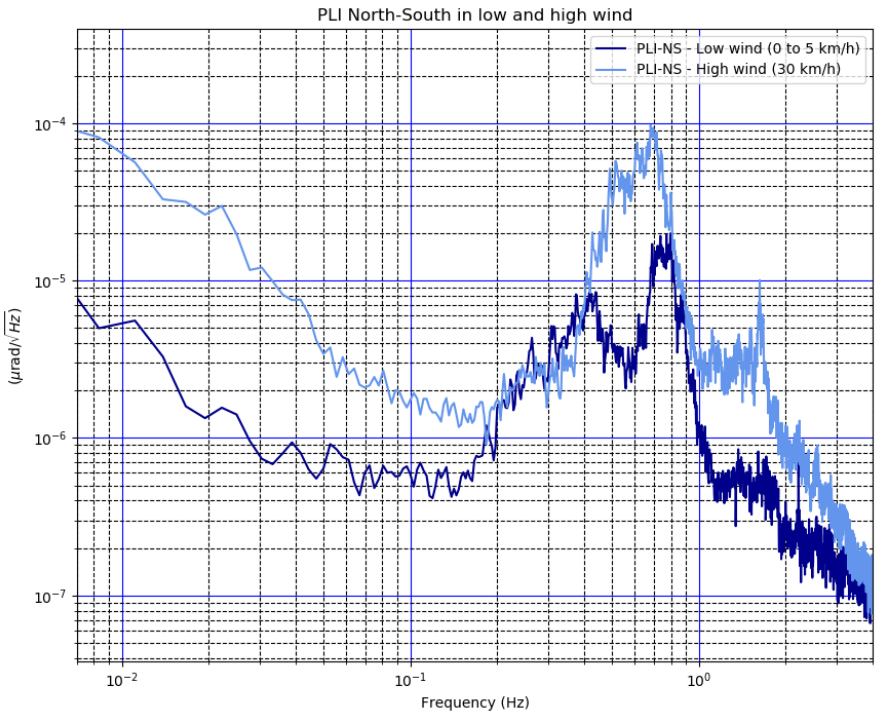
https://indico-test.jinr.ru/event/410/contributions/3014/

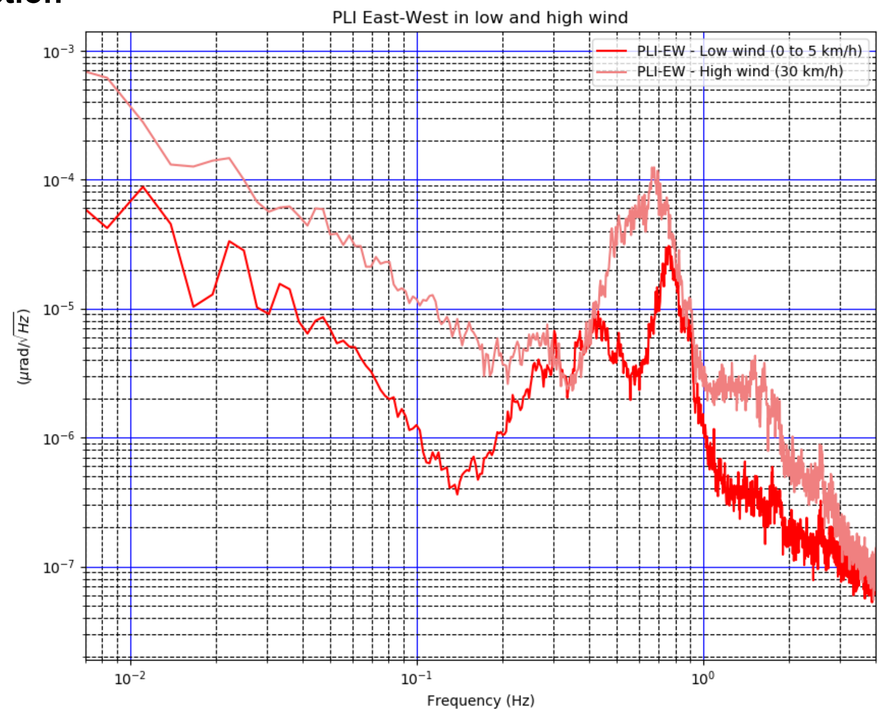
Precision Laser Inclinometer



Sensitivity of PLI



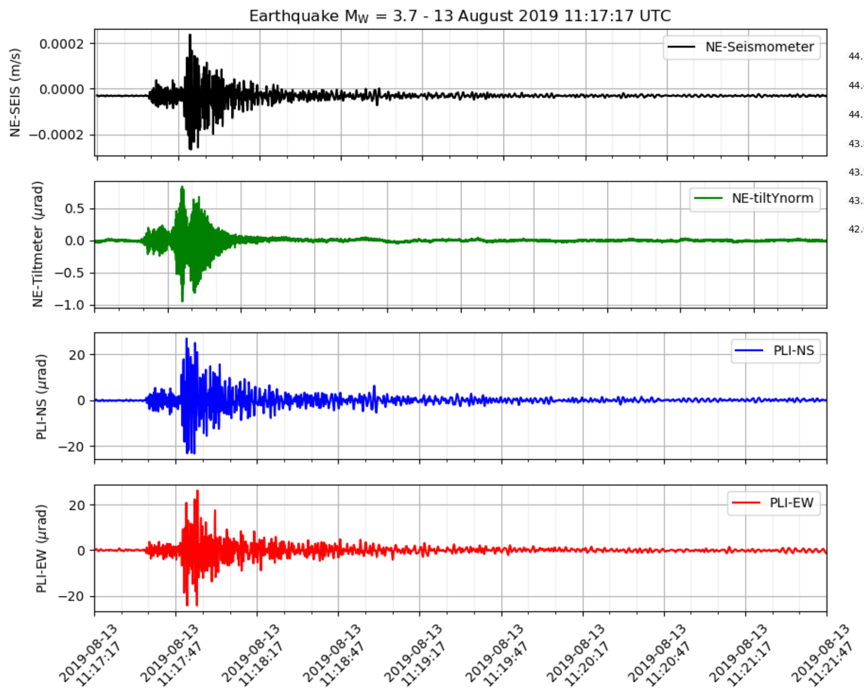




- Much more sensitive than tiltmeter
- Discrepancy btw results from BRS (too small?)

Response to Earth Quake

Several tiny earthquakes: examples

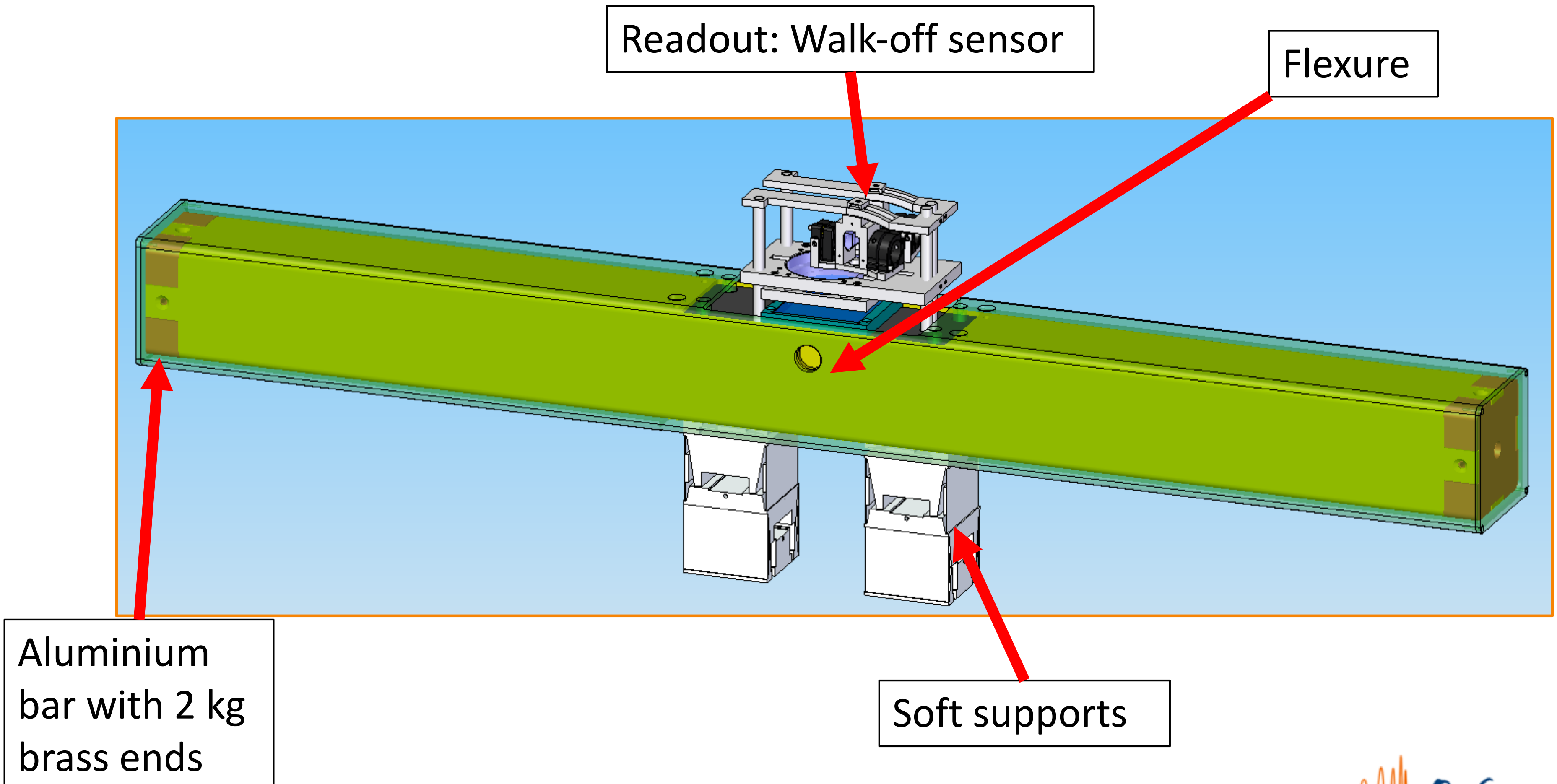


105 km from Virgo
M_W = 3.7
Clear arrival of P waves after ~ 20 s
Comparison with Napoli's tiltmeter and seismometer in NEB

17

Advanced Low Frequency Rotational Accelerometer

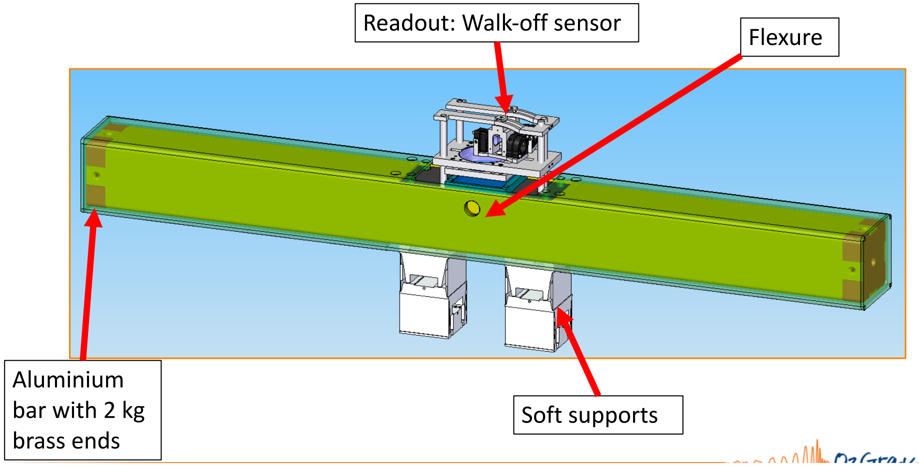
- Developed by a group in UWA
- Plan to be installed in Gingin facility, Australia



Advanced Low Frequency Rotational Accelerometer

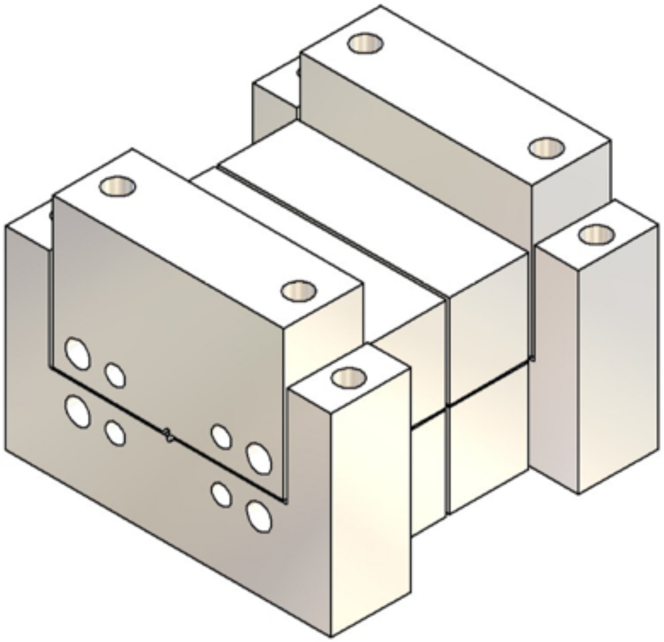
- Developed by a group in UWA
- Plan to be installed in Gingin facility, Australia

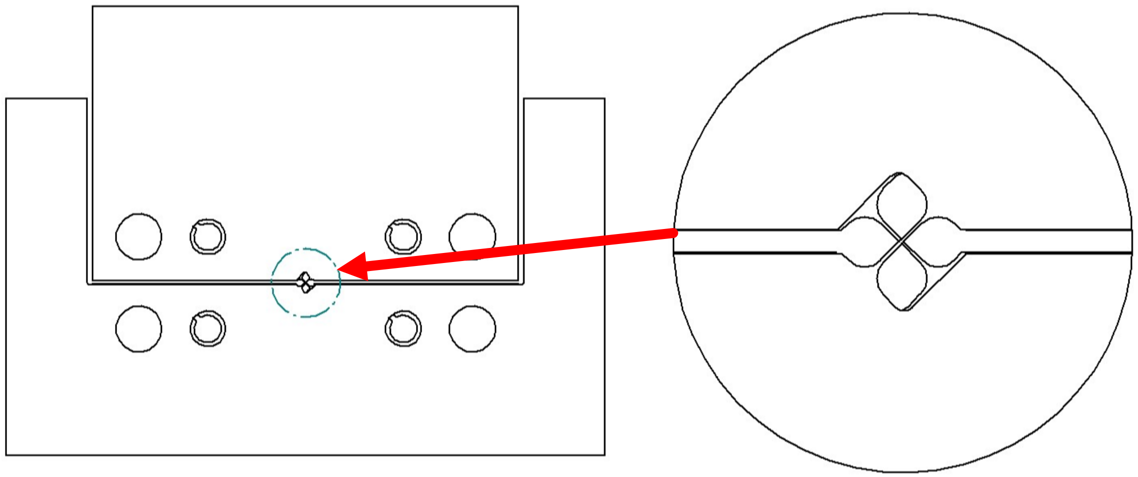
- The design looks similar to BRS, but many differences
  - Mechanical
    - Flexure: different shape (cross flexure)
    - Soft supports: reduction of higher frequency seismic motion
  - Readout
    - Walk-off sensor: amplification of angular response
  - DoF
    - Operation in horizontal and vertical direction



Cross Flexure Design

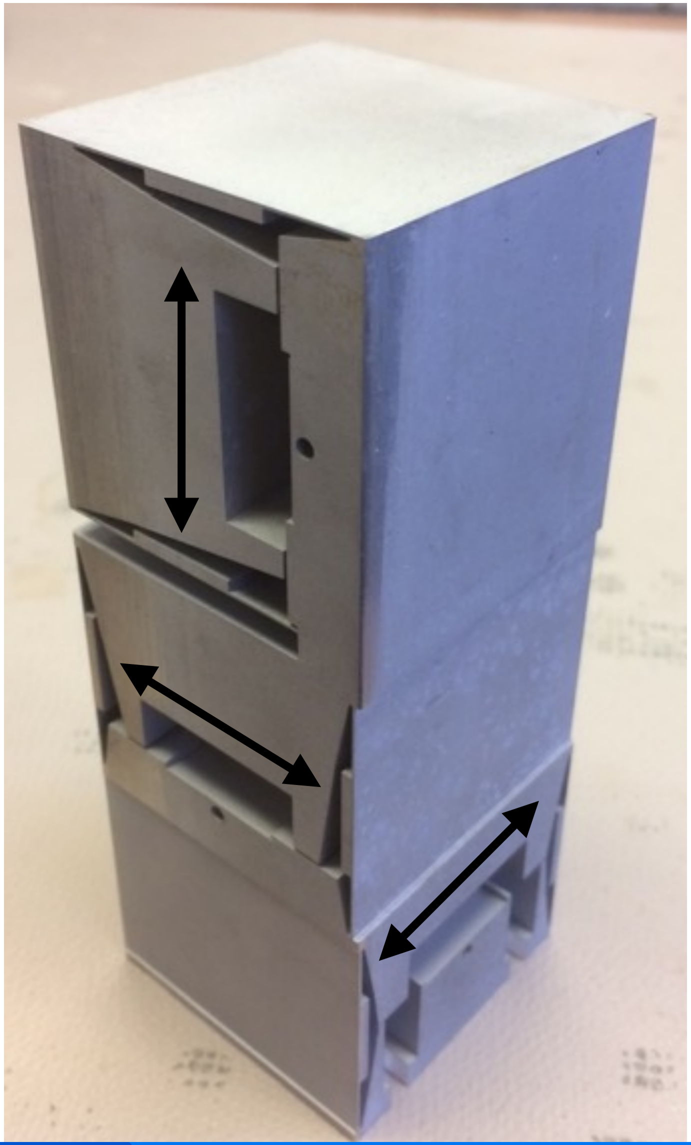
- 4 identical 5 degree flexures
  - 10 μm thick, 200 μm long
  - Resonant frequency: 10 mHz
- It allows to operate in both horizontal and Vertical mounting





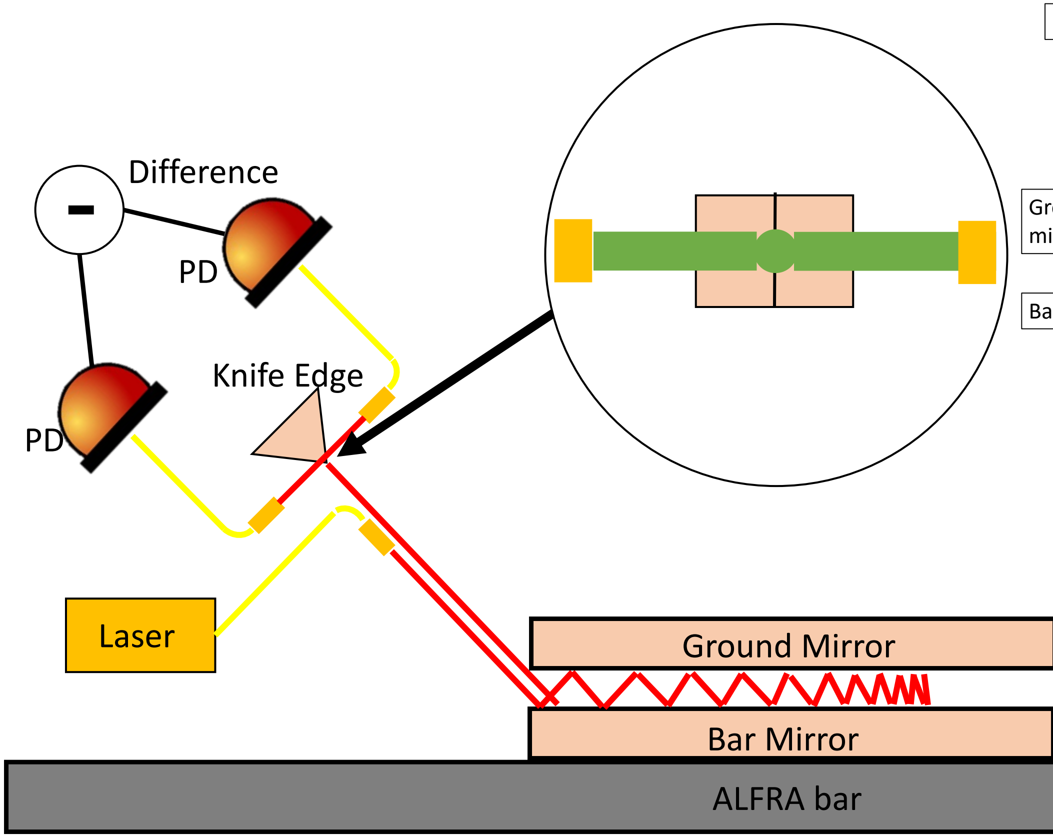
Soft Supports

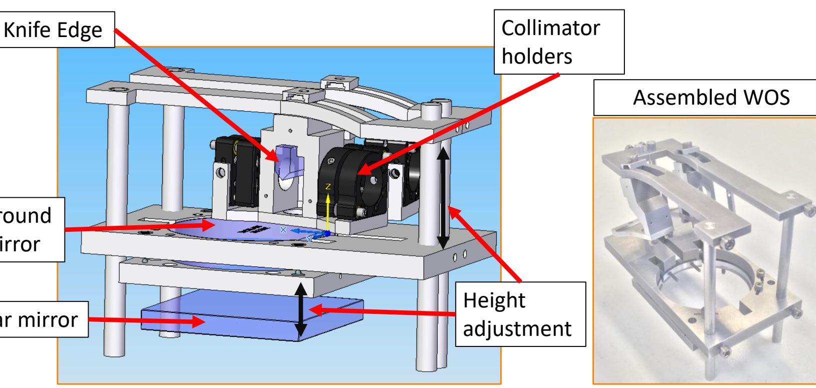
- Reduce higher frequency seismic motion in x, y, and z direction
- Eddy current damping for each DoF

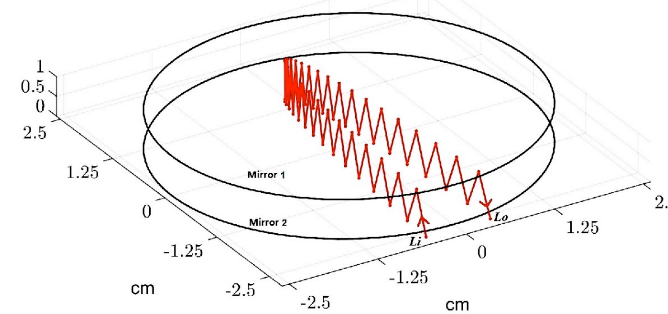


Walk-off Sensor

- Laser bounces btw two mirrors → angular response is multiplied
- Knife edge: beam reflects away from the prism, then we can take Ids far away from ALFRA to reduce thermal dissipation

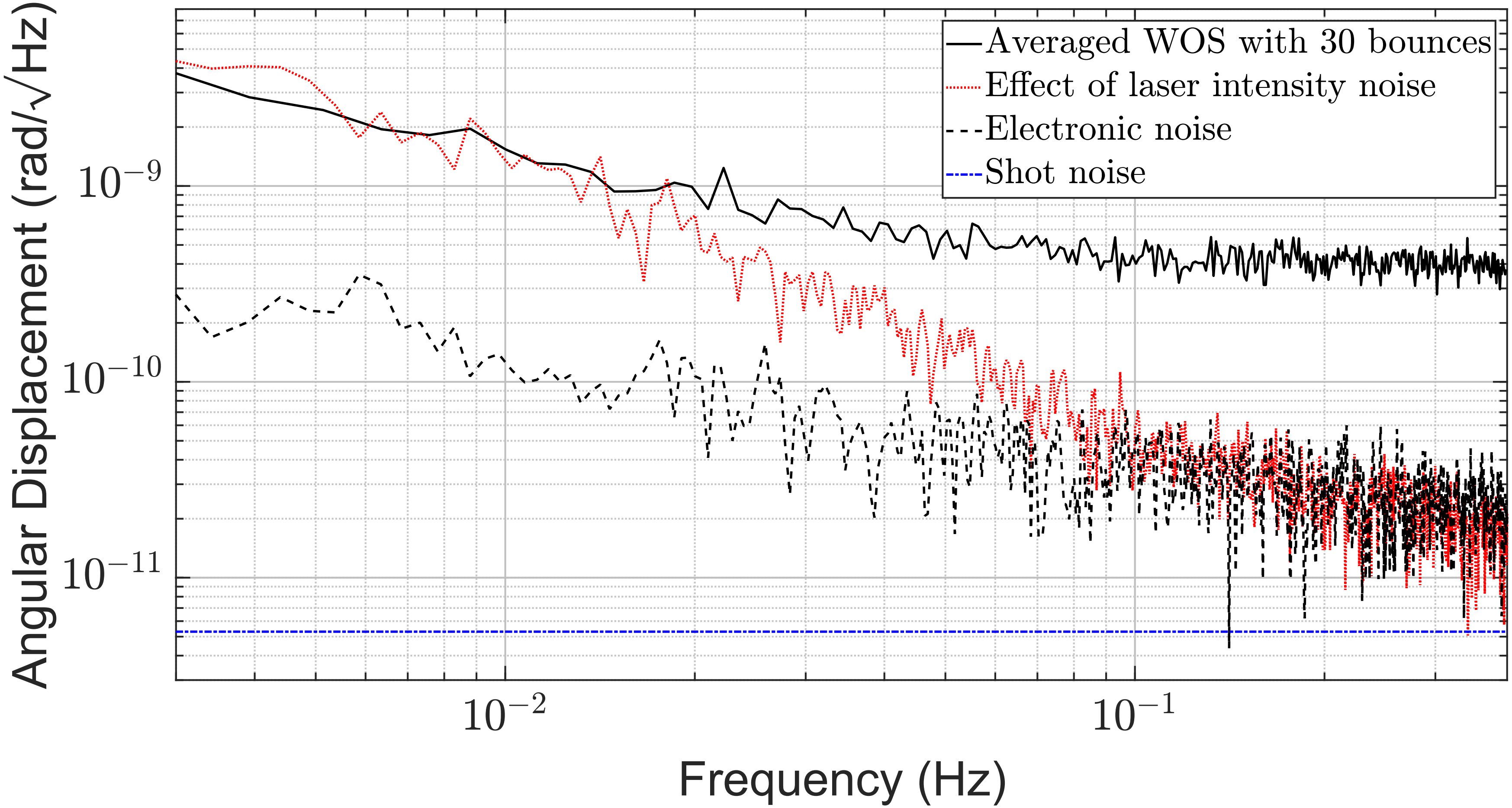






Sensitivity of Walk-off Sensor

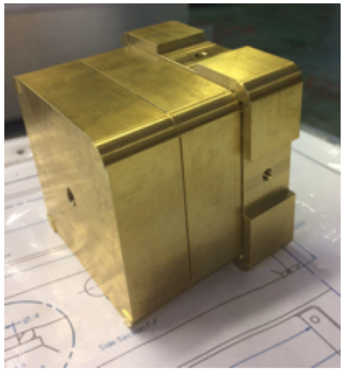
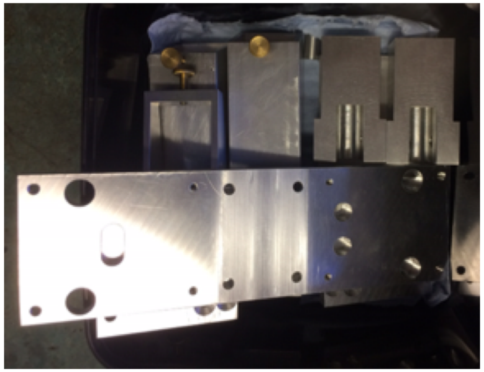
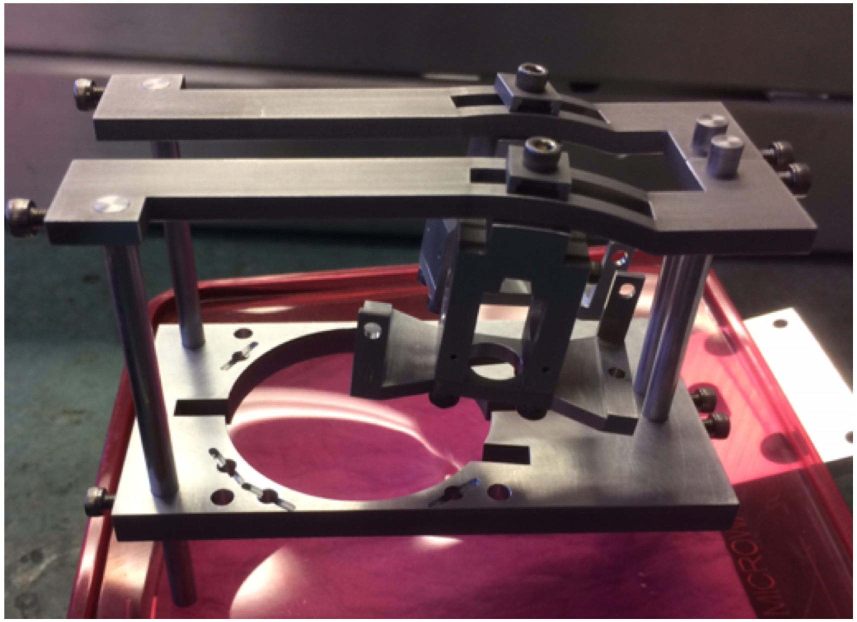
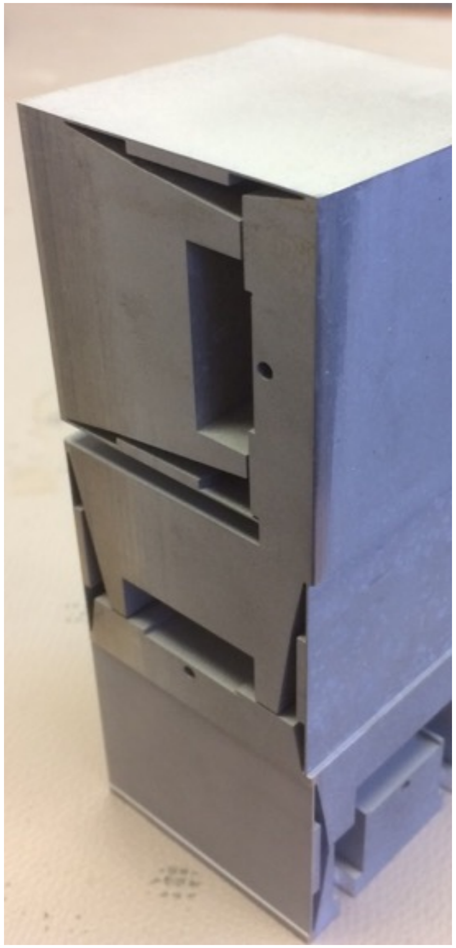
McCann et al., Rev. Sci. **90**, 045005 (2019)



- Even in air the sensitivity reaches to 10^{-9} rad/√Hz
- Below 10 mHz intensity fluctuation is dominant

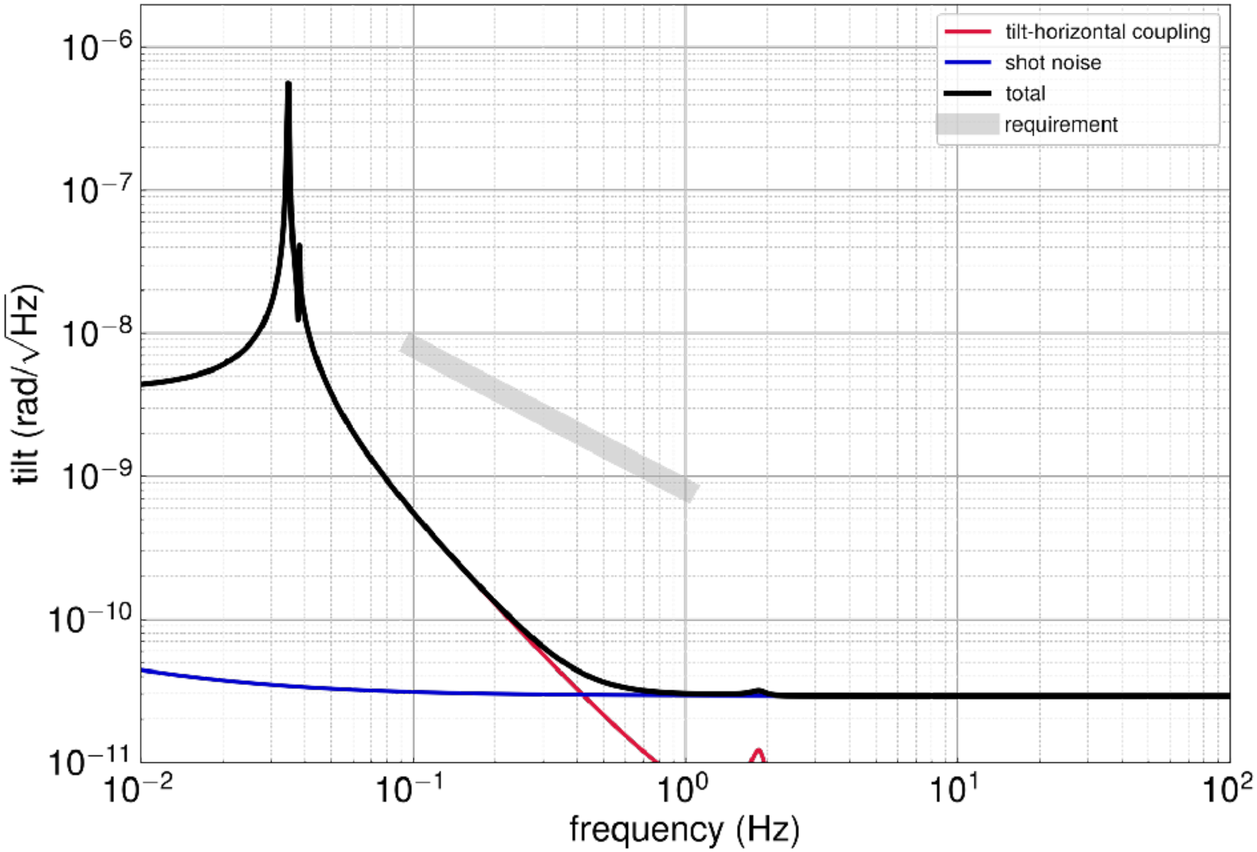
Future Plan

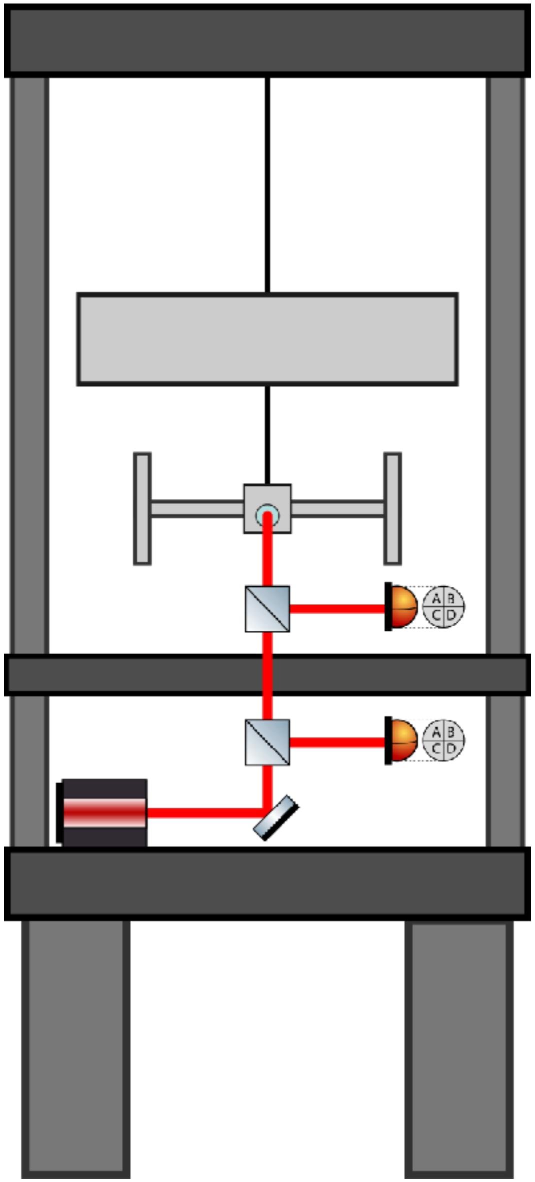
- Components are gathering
- Assembly has began

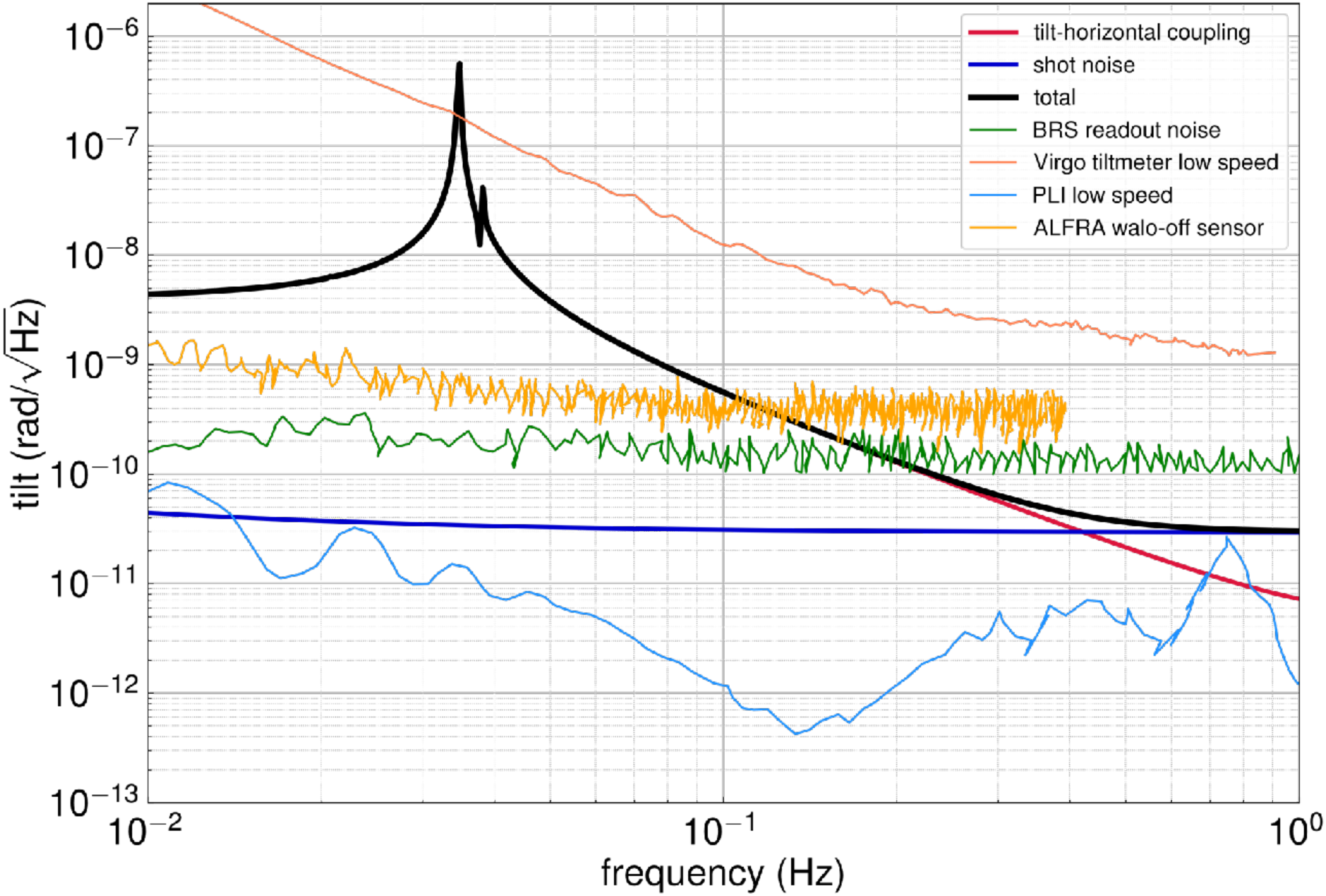
Tiltmeter for AVIT

- Pendulum type
- Readout by optical levers
- We can measure 3 DoFs (Pitch, Roll, Yaw)





Comparison of Tiltmeters



Application to KAGRA

- Are tiltmeter necessary for KAGRA?
  - Reduction of tilt-to-translational coupling
    - If we use strain meter to reduce RMS in low frequency, tilt meters is not necessary for this purpose
      - In fact, strain meter exists only X arm
      - For Y arm tiltmeter is effective?
    - KAGRA is underground. Does seismic tilt motion get noisy due to high speed wind?
      - Depends on the coupling path
  - Newtonian noise reduction
    - Repeatedly, KAGRA is underground. Situation is different from aLIGO & advVirgo. I'm not sure what kind of seismic wave is dominant in KAGRA…
      - If S wave is dominant, tiltmeter couldn't measure it so sensitively as P or Rayleigh wave.

Summary

- Tiltmeter is hot
- There are two kinds of motivation for tiltmeter
  - Low frequency RMS
  - Newtonian noise
- For 3G detectors, tiltmeters will be necessary to increase sensitivity at low frequency. But for even 2G detectors, tiltmeters are useful for making detectors more robust.
- Fortunately there seems to exsist room to compete with others
- How about joining the race?