Displacement calibration techniques for the LIGO detectors

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for the
LIGO Scientific Collaboration

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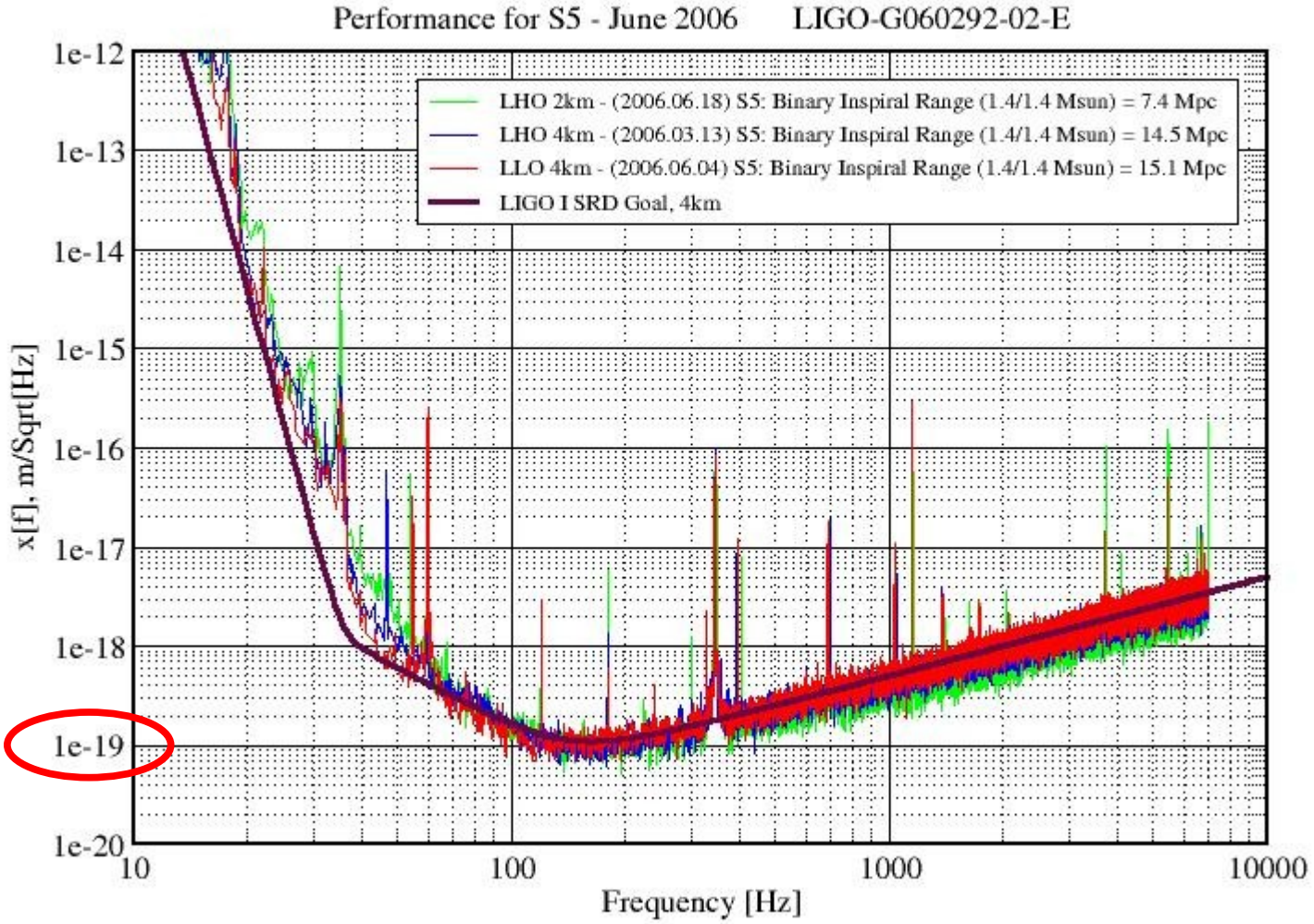
LIGO

LSC

Displacement Sensitivity for the LIGO Interferometers

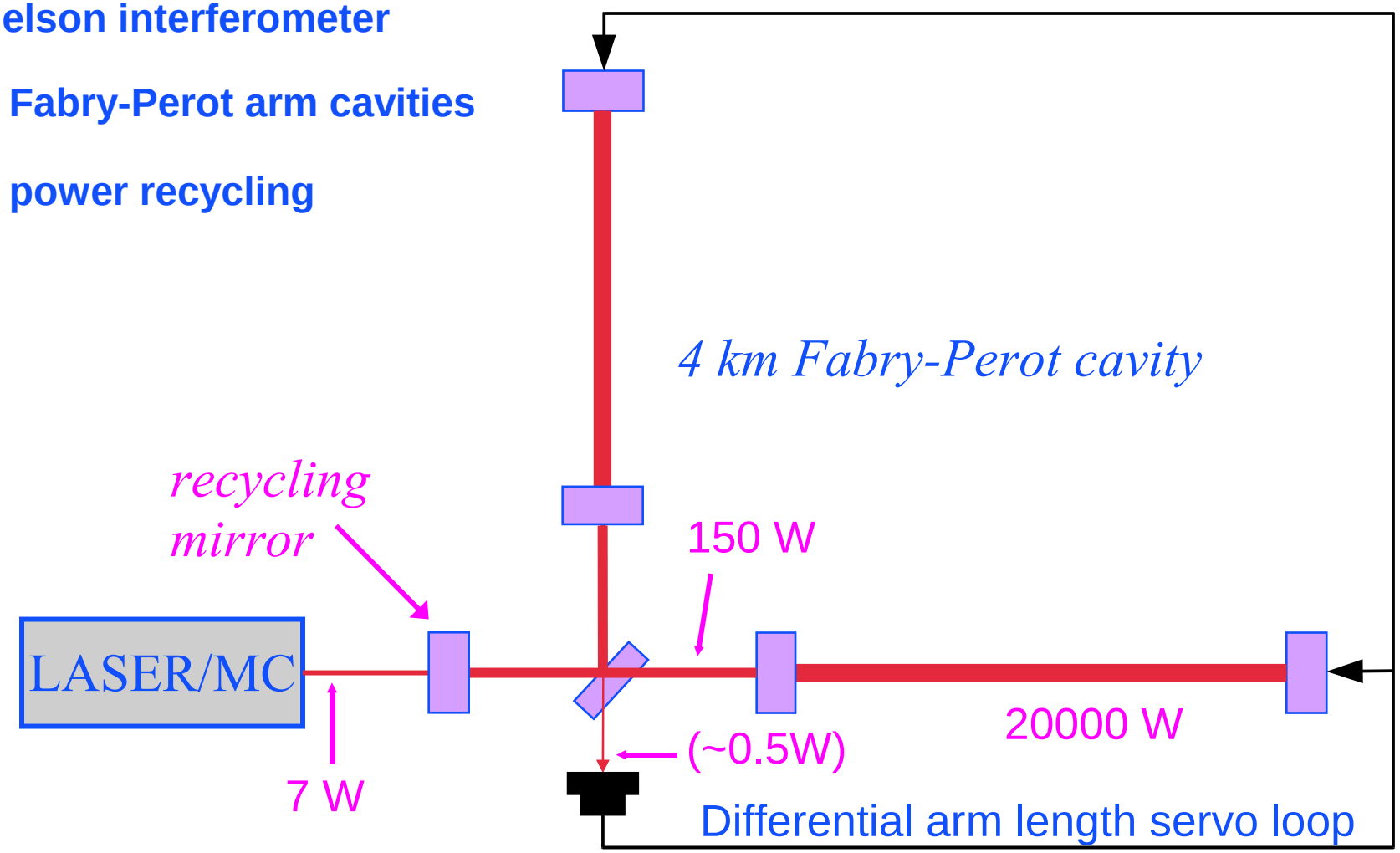


The LIGO Interferometers

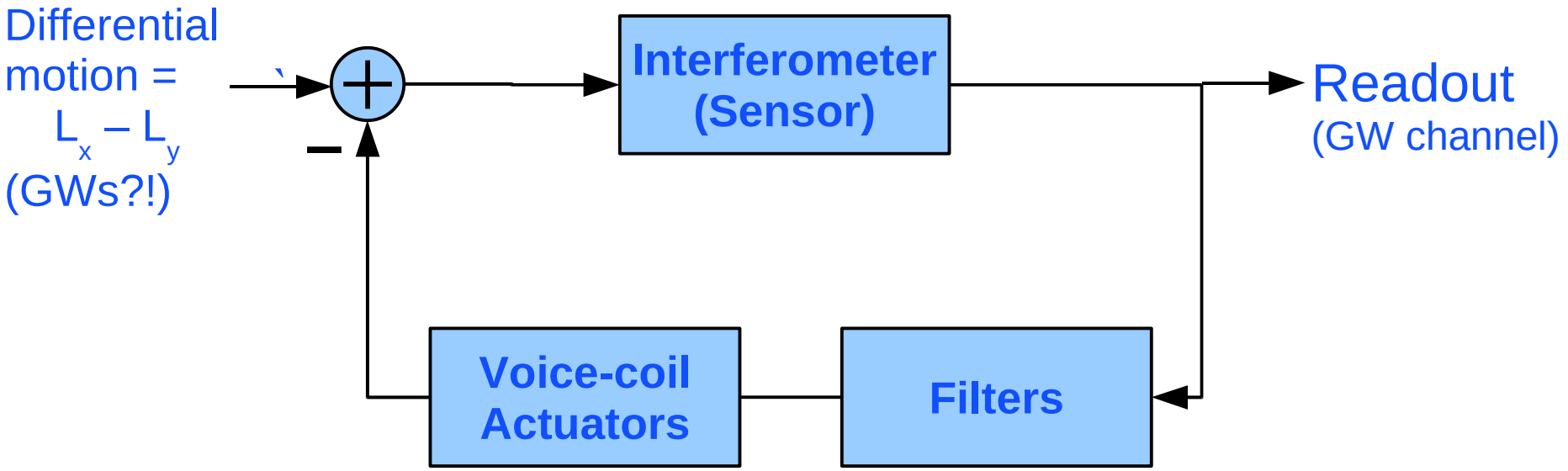
Michelson interferometer

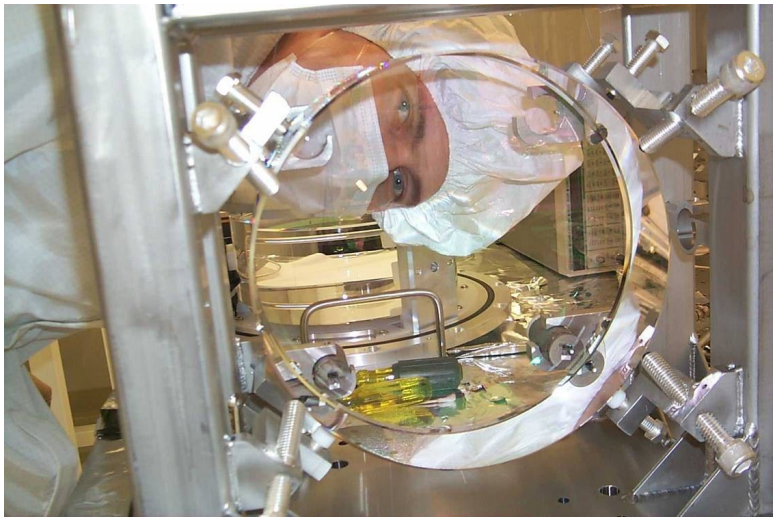
With Fabry-Perot arm cavities

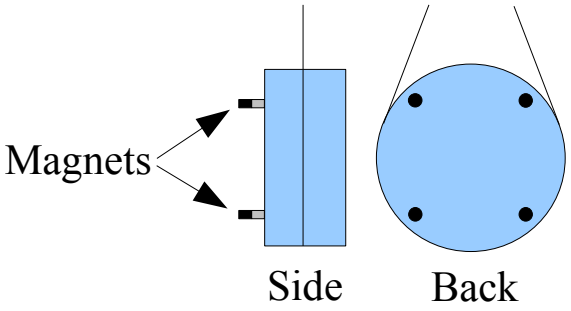
With power recycling



Differential arm length servo loop schematic

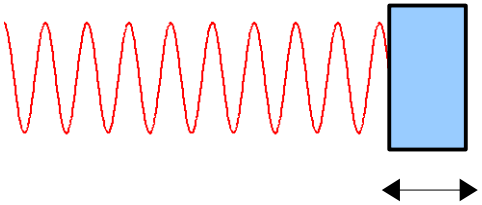




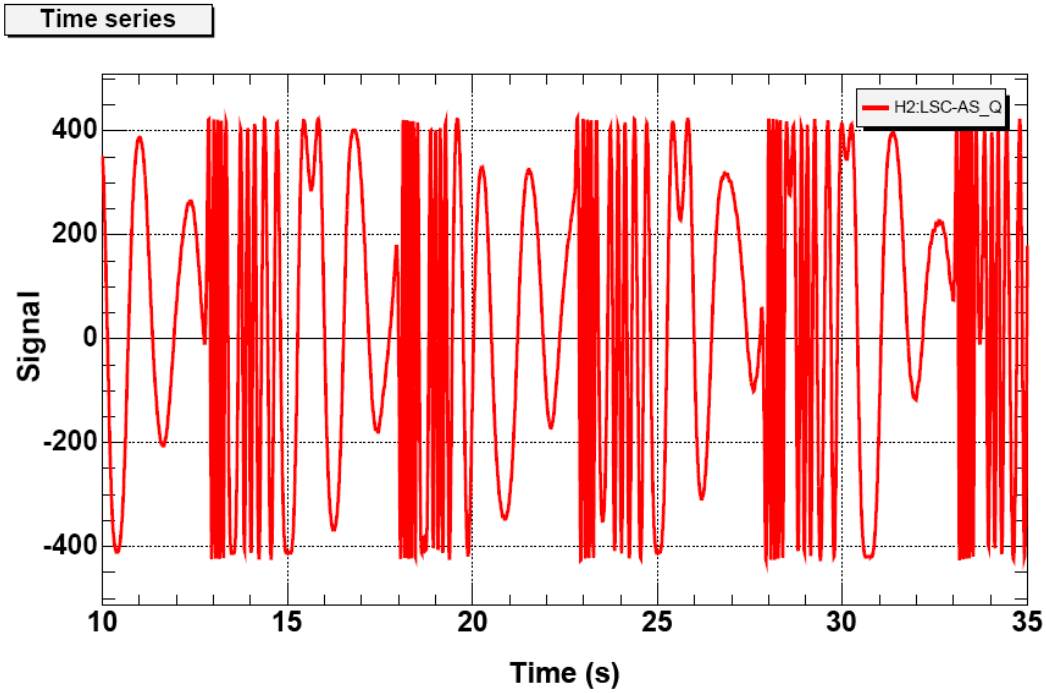


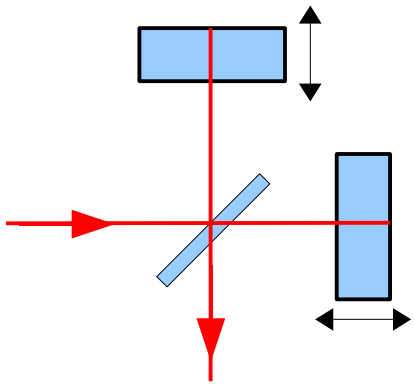
Simple-Michelson technique

- Leverage calibration from the laser wavelength (10^{-6} m)



- Set interferometer into simple configurations to determine actuation

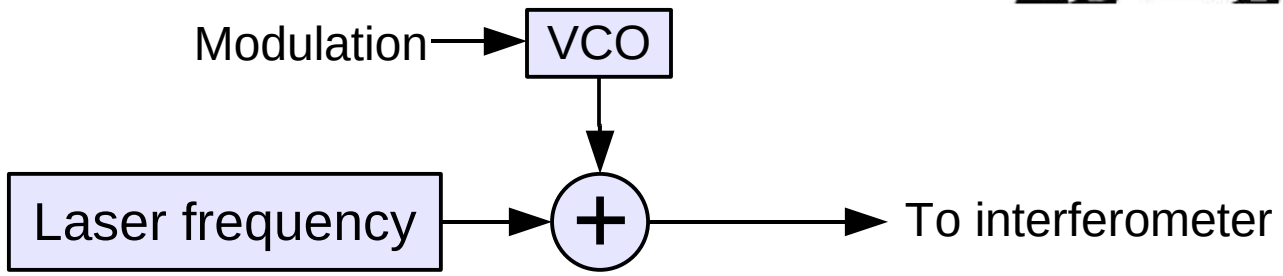




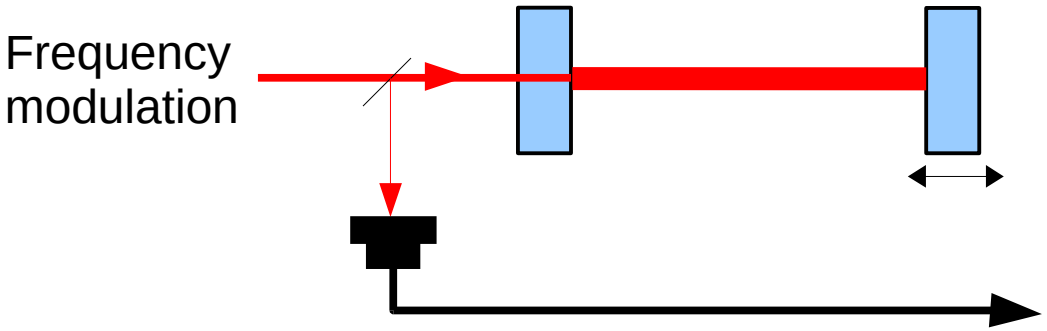
Frequency modulation technique

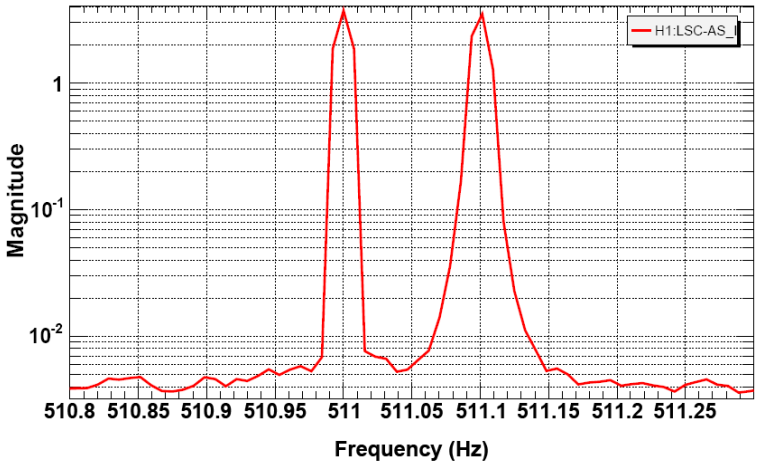
- Vary the laser frequency

$$\Delta L = L\frac{\Delta f}{f}$$



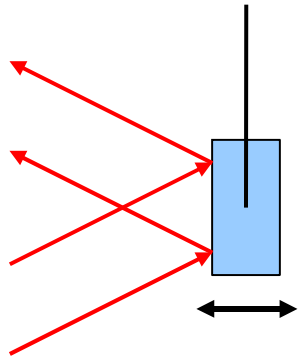
- Compare peaks in error signal from frequency with the length modulation for a single arm cavity





Radiation pressure technique – Photon calibrator

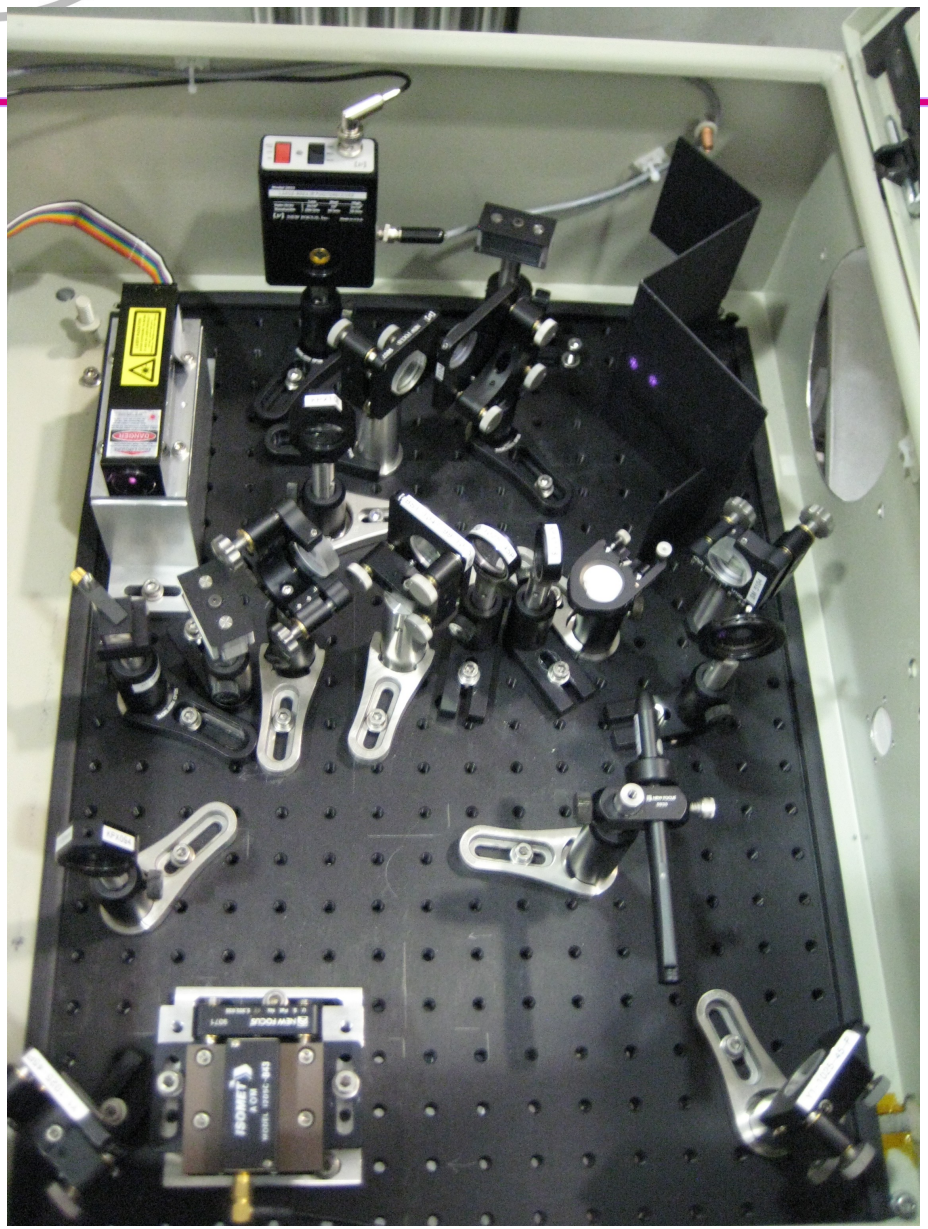
- External force on the end mirror using two beams (to avoid sensing mirror deformation) from an auxiliary, power-modulated laser

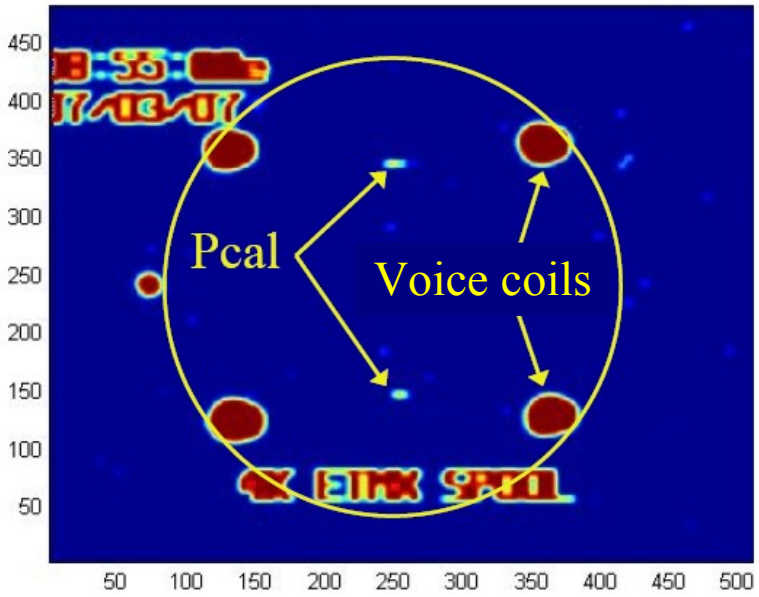


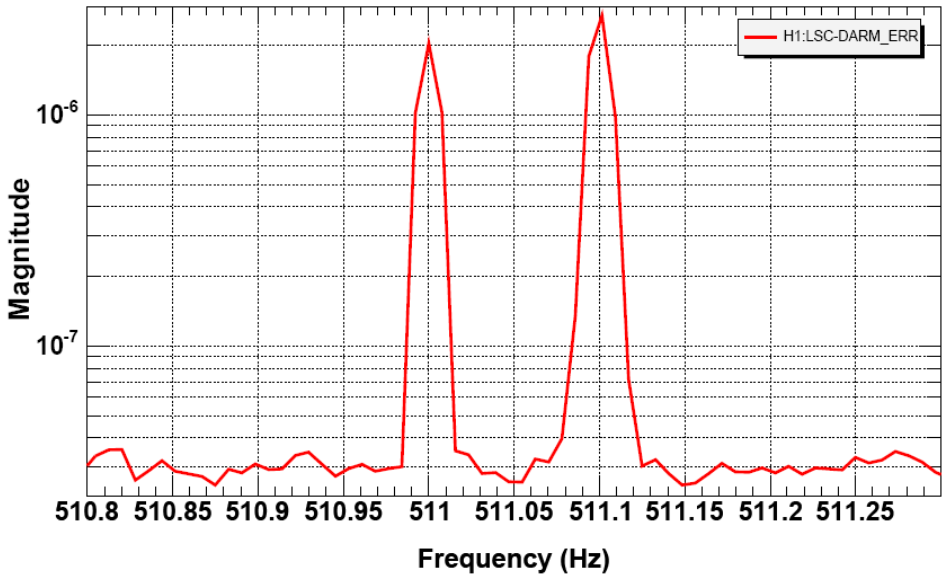
$$\Delta L(\omega \gg \omega_0) \approx \frac{2P_0 \cos\theta}{Mc\omega^2}$$

- Compare peaks in error signal of photon calibrator with the voice-coil actuator signal for the full interferometer

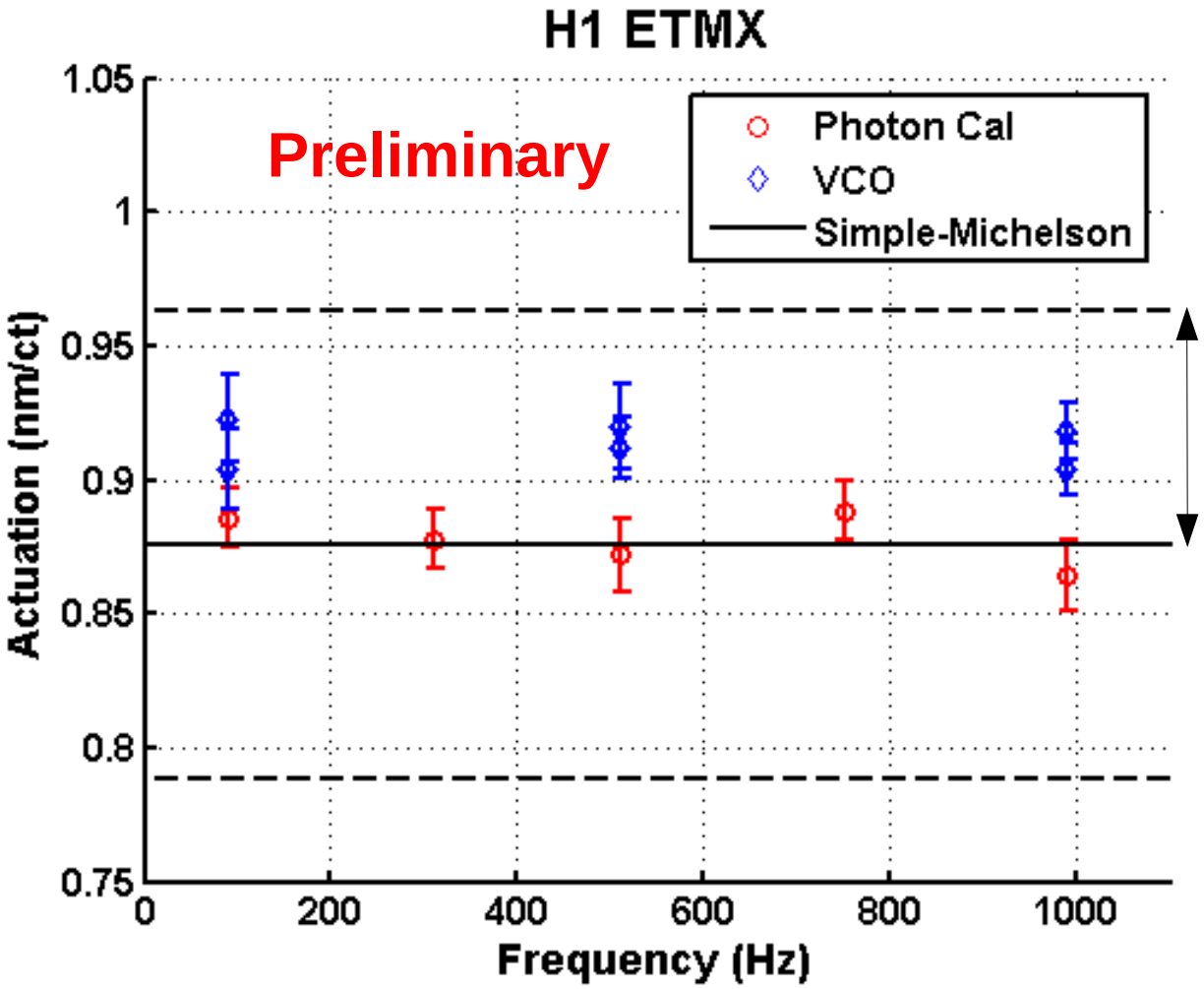
LIGO




Pcal
Voice coils
450
400
350
300
250
200
150
100
50
50
100
150
200
250
300
350
400
450
500


H1:LSC-DARM_ERR
10^{-6}
10^{-7}
Magnitude
510.8
510.85
510.9
510.95
511
511.05
511.1
511.15
511.2
511.25
Frequency (Hz)

Example comparison of techniques:
Measured actuation strengths (nm/ct)



2σ error bar for simple-Michelson technique

2σ error bars for Photon cal and VCO

Summary

- Three different techniques for measuring the voice-coil actuation coefficient of the LIGO end test masses agree at the 5 percent level
  - » Simple-Michelson: Based on laser wavelength, various configurations
  - » VCO: Based on frequency modulation, single-arms locks
  - » Photon calibrator: Based on radiation pressure, full interferometer configuration
- We use the actuation results to determine sensitivity and set astrophysical upper limits
- Future science runs of LIGO will use a combination of these techniques to reduce systematic errors

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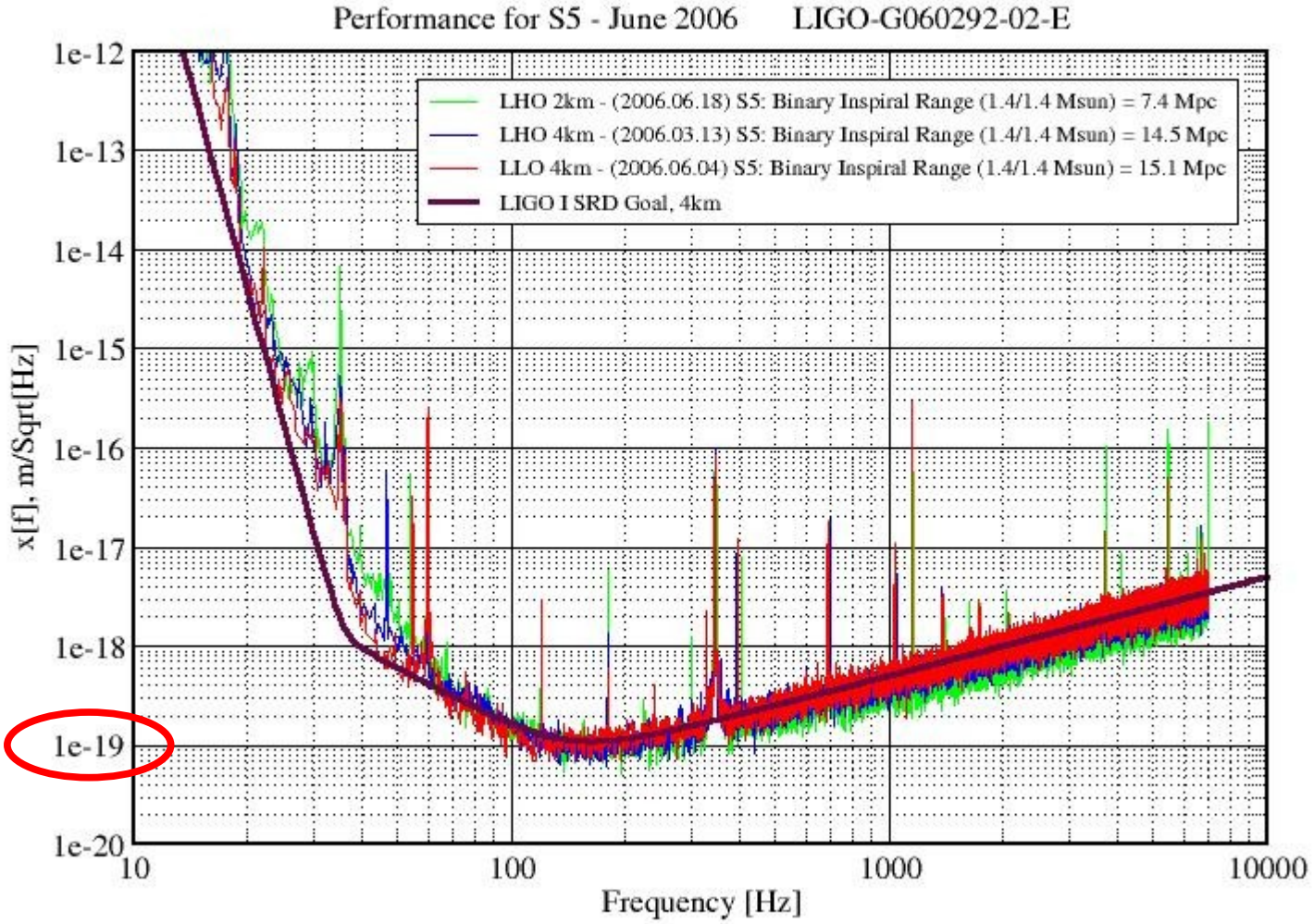
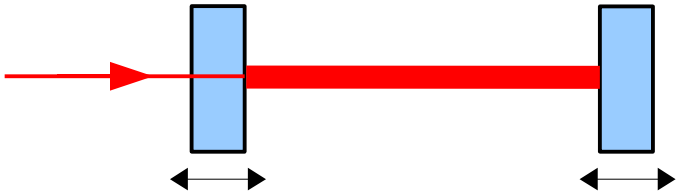
Displacement Sensitivity for the LIGO Interferometers



Simple-Michelson Technique

- Allow simple-Michelson to swing freely through fringes
  - » Derive the slope of the error signal at the zero crossing from the max-min value
  - » Calibrates the error signal when the simple-Michelson is locked
- Measure the open loop gain of the simple-Michelson loop when it is locked
- For one of the Michelson mirrors, measure the transfer function of the excitation signal to the error signal
  - » Closed loop measurement
- Obtain the voice-coil calibration for the mirror
  - » Using closed loop transfer function measurement, open loop gain measurement, the error signal calibration and the transfer function for a suspended mass (pendulum)
- Use different configurations
  - » Symmetric or asymmetric simple-Michelson
  - » Single arm, Fabry-Perot cavity

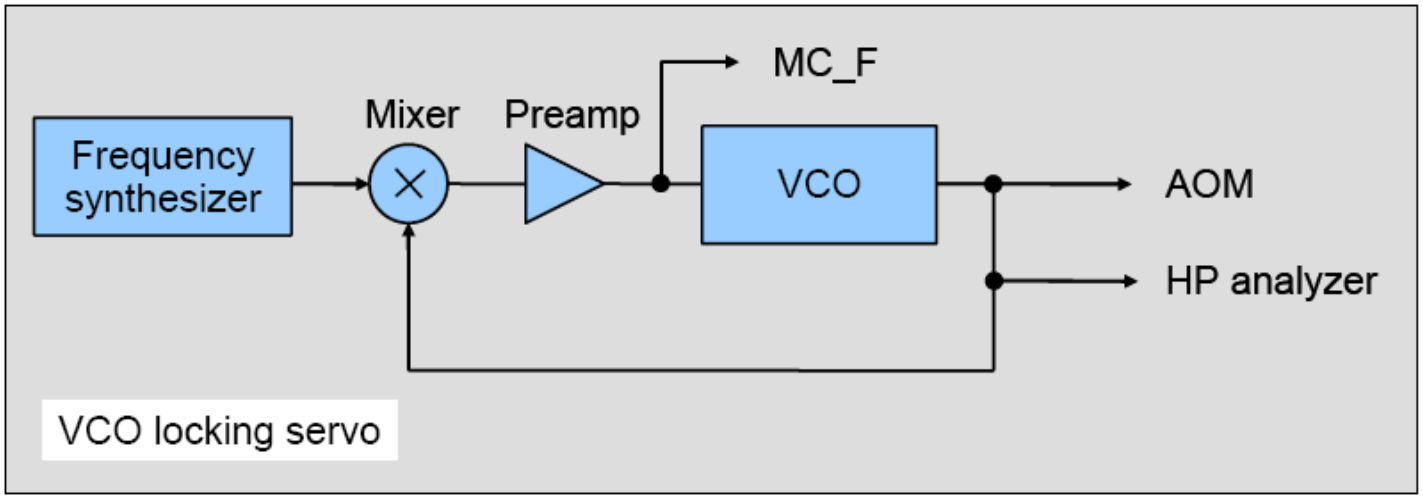


Outline of frequency modulation technique

- Calibrate the frequency modulation coefficient of the VCO for the laser frequency stabilization servo
  - » Lock the 80 MHz VCO modulation frequency to a frequency synthesizer
  - » Inject frequency modulation and measure the modulation sideband to 80 MHz carrier ratio using an RF spectrum analyzer

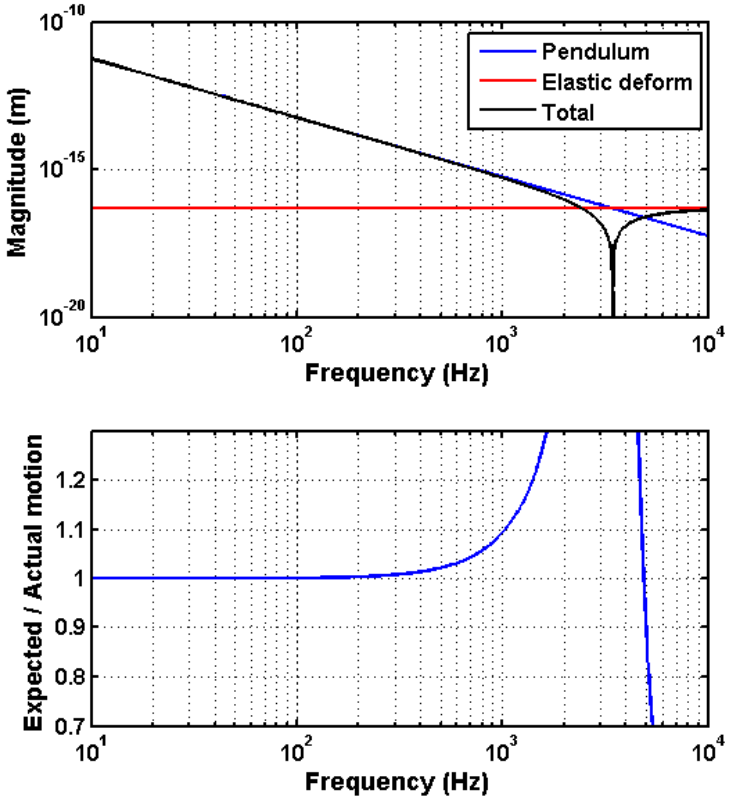
$$\frac{P_{SB}}{P_{carrier}} = \frac{J_1(\Gamma)^2}{J_0(\Gamma)^2} \qquad \frac{J_1(\Gamma)}{J_0(\Gamma)} \cong \frac{\Gamma}{2} = \frac{\Delta f}{2 f_{\mathrm{mod}}}$$

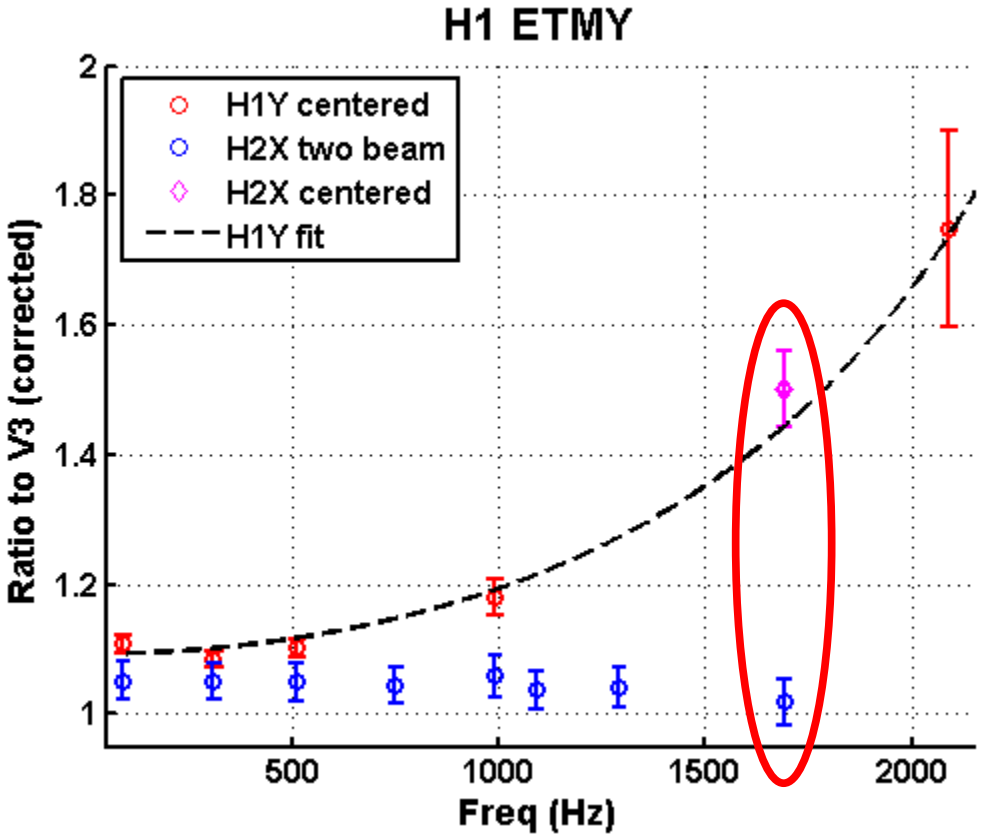
VCO calibration in Hz/count



Elastic deformation

- Photon calibrator beam elastically deforms the mass where it reflects from the ETM (S. Hild, et. al. 2007 Class. Quantum Grav. 24 5681-5688)





Comparison of the techniques