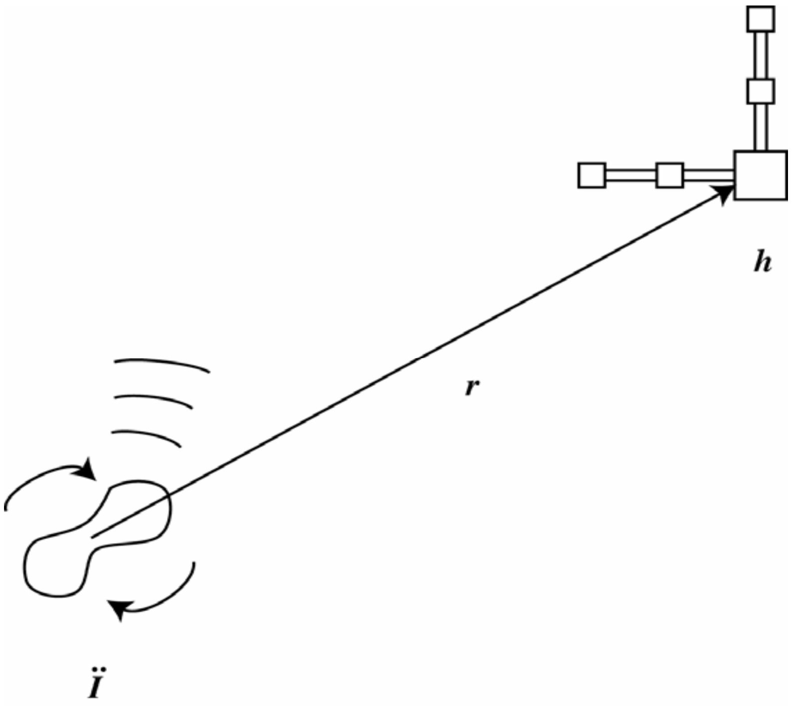
Thermal noise issues

Chinyere Ifeoma Nwabugwu
Louisiana State University
August 05, 2005

Eric Black, Akira Villar,
Kenneth G. Libbrecht, Kate Dooley, Royal Reinecke, Richard Kirian

LIGO-G050355-00-R

Range of Gravitational Radiation



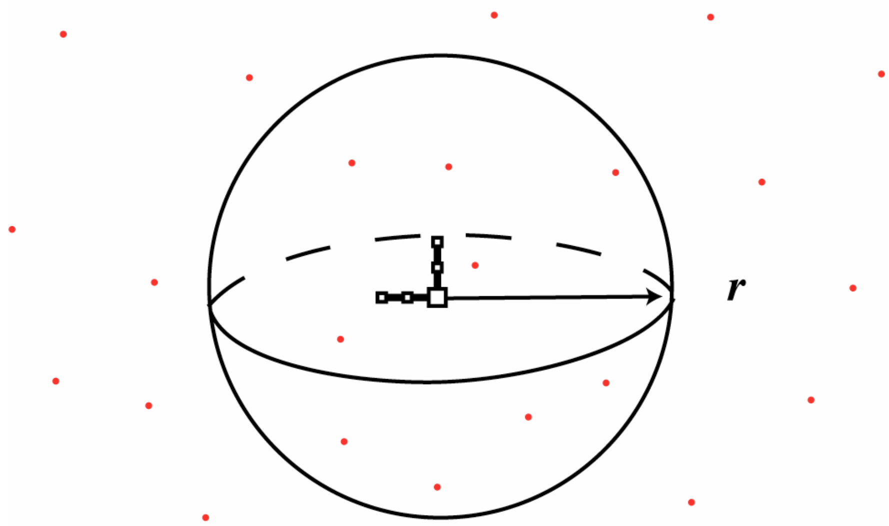
- Energy density must fall off as $1/r^2$.
- Energy density is the square of the strain amplitude *h*.
- Amplitude falls off as 1/r.

$$h_{\mu\nu} = \frac{2G}{c^2} \frac{\ddot{I}_{\mu\nu}}{r}$$

- Therefore, the *range* of a detector that is sensitive to a given strain *h* scales as 1/*h*

$$r \sim \frac{1}{h}$$

Event Rate vs. Range



- For isotropic distribution with density ρ, the number of sources included in radius r is given by

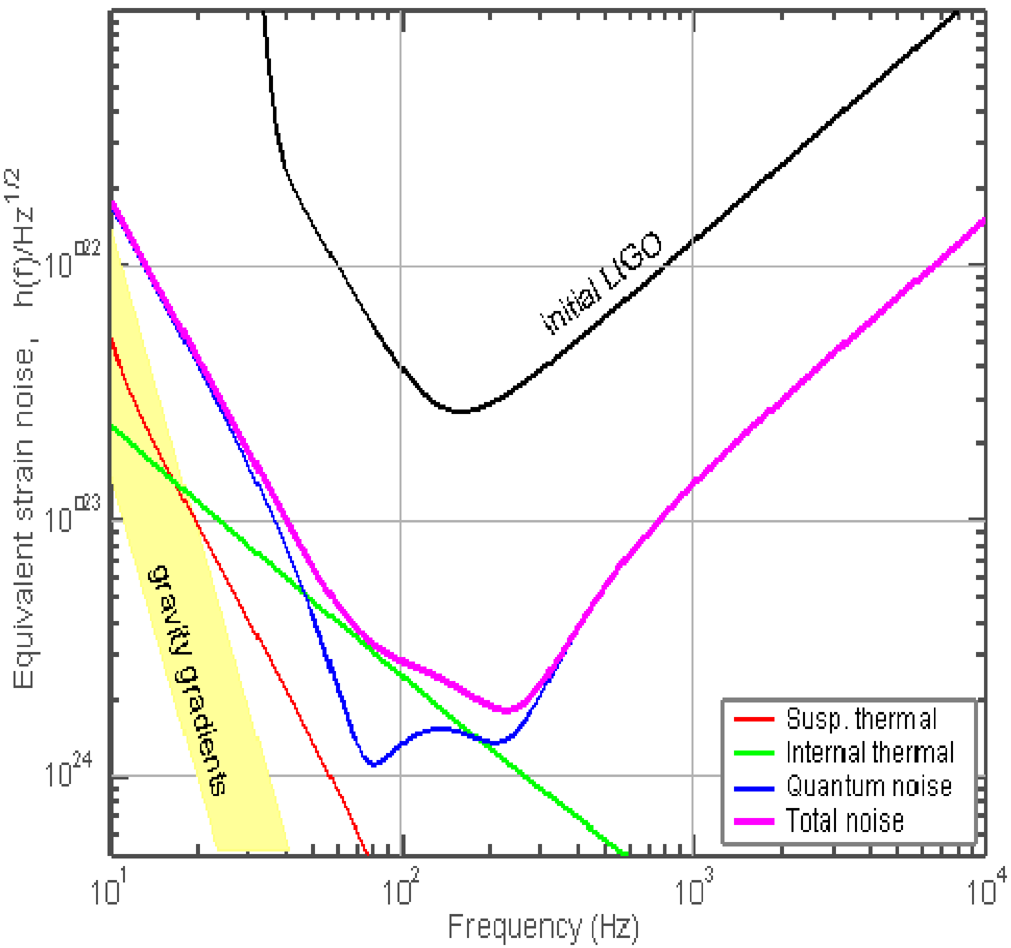
$$N = \rho\left(\frac{4}{3}\pi r^3\right)$$

- Event rate proportional to number of sources included in range, or

$$N \sim \left(\frac{1}{h}\right)^3$$

- Small reductions in detector noise floor h result in big increases in number of sources N within detector's range!

What will AdLIGO's range be?



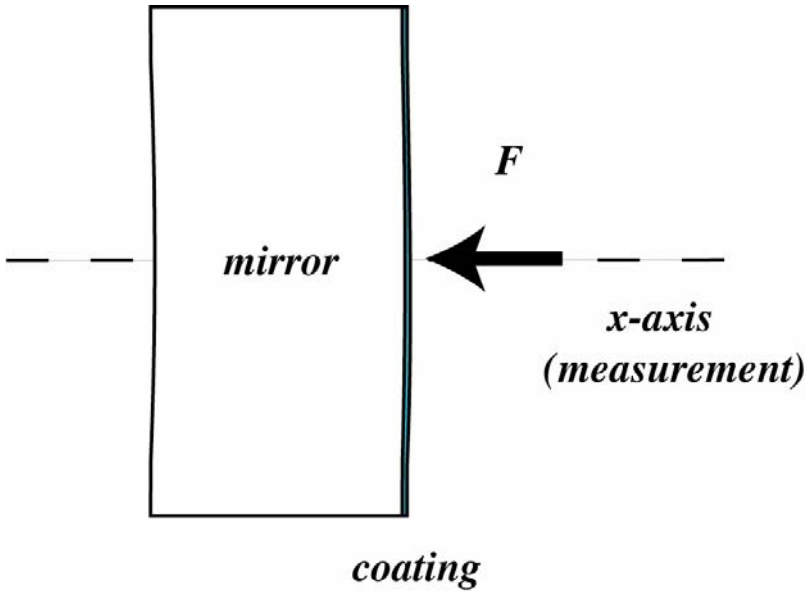
Need to know fundamental limits to *h*.

- Seismic
- Thermal
- Shot (Quantum)

Thermal noise limits *h* at the lowest levels, determines ultimate reach of detector.

Mirror thermal noise is expected to dominate at the lowest noise levels, and to set the ultimate range of an advanced interferometric gravitational wave detector.

Mirror thermal noise

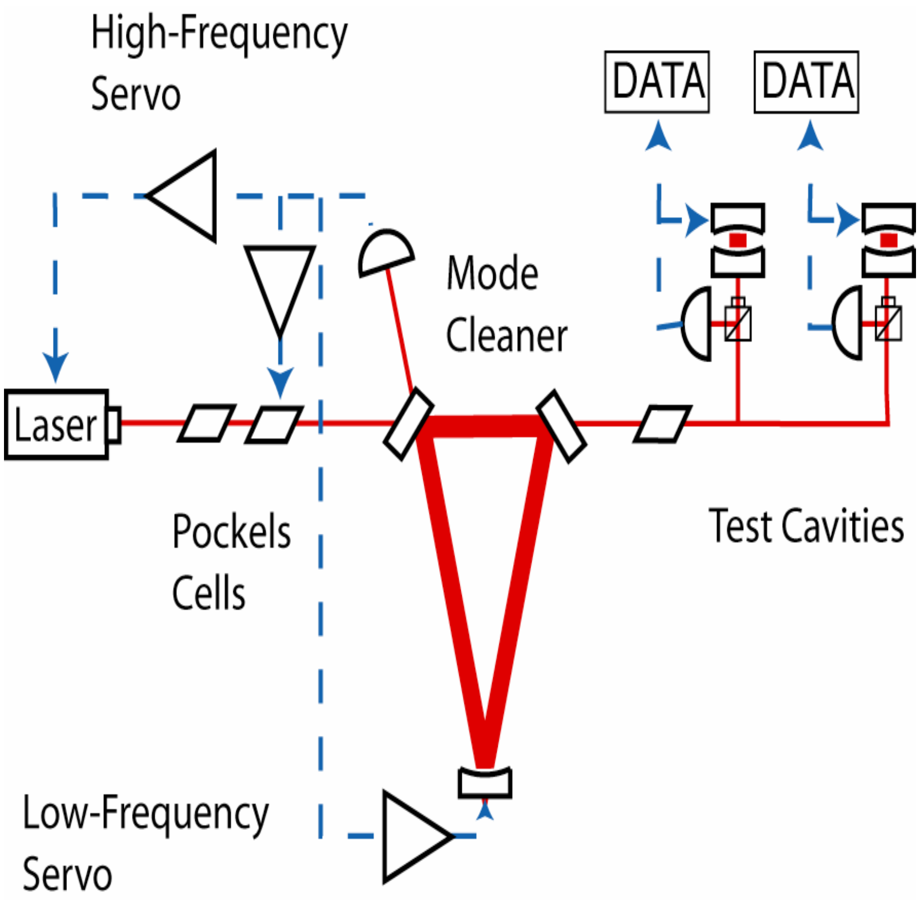


- Fluctuation-dissipation theorem relates noise spectrum to losses.

$$S_x(f) = \frac{k_B T}{\pi^2 f^2} \mathrm{Re}\left\{ \frac{\dot{x}(f)}{F e^{i 2\pi f t}} \right\}$$

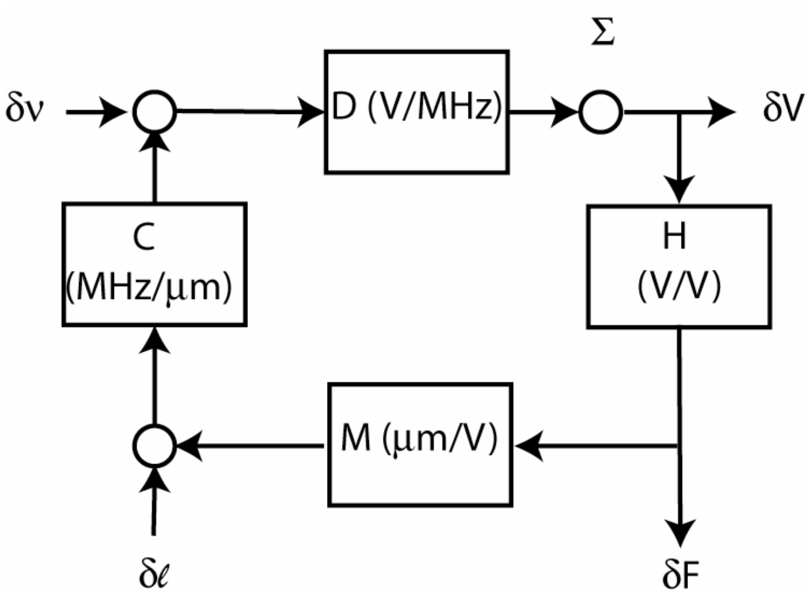
- Structural damping loss
  - Substrate thermal noise
  - Coating thermal noise
- Thermoelastic damping loss (Braginsky noise)
  - Substrate thermoelastic noise
  - Coating thermoelastic noise

Thermal Noise Interferometer (TNI): Direct Measurement of Mirror Thermal Noise



- Short arm cavities, long mode cleaner (frequency reference) reduce laser frequency noise, relative to test cavity length noise.
- Measurement made as relevant to LIGO, AdLIGO as possible.
- Want to measure thermal noise at as low a level as possible in a small interferometer.
  - Low-mechanical-loss substrates: Fused Silica, Sapphire
  - Silica-Tantala coatings
  - Largest practical spot size

TNI Calibration



- Extract length noise from error signal

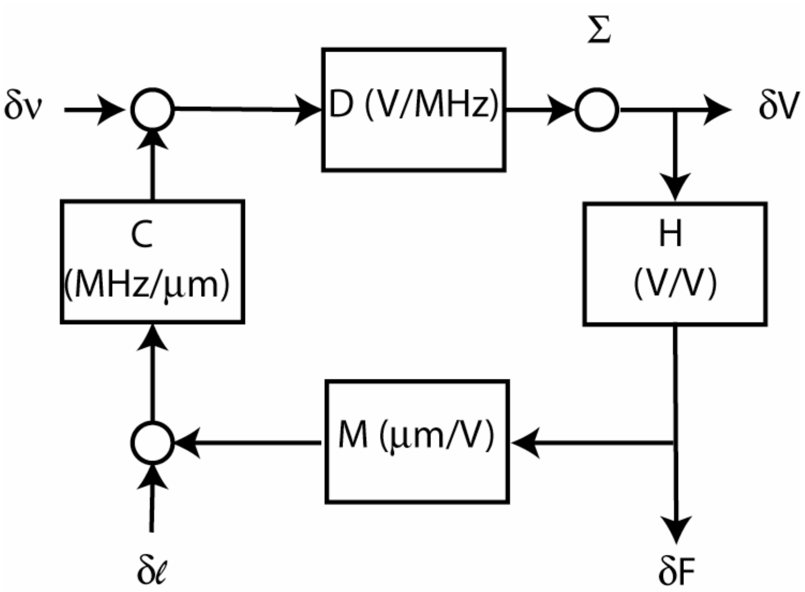
$$\delta \bullet = \frac{1 + DHMC}{DC}\,\delta V$$

- Must know each transfer function accurately!
- Electronic transfer function *H* specified by design, verified by direct measurement.
- Conversion factor *C*

$$C = \frac{\nu}{L}$$

- Mirror response *M* was measured prior to my arrival
- One of my duties this summer was to find D

Calibration: Finding a value for D



- δl is the thermal noise

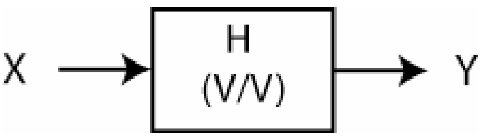
$$\varepsilon = \delta l \times \frac{DC}{1+DHMC}$$

- We need to know DC, DHMC

M, C, H

- We know M, C
  - C = $3\times10^{16}\, Hz/m$
  - M = $\dfrac{0.36\,\mu m/v}{(1+i\, f/_{1Hz})^2}$
- We think we have H but we need to verify

Measure H



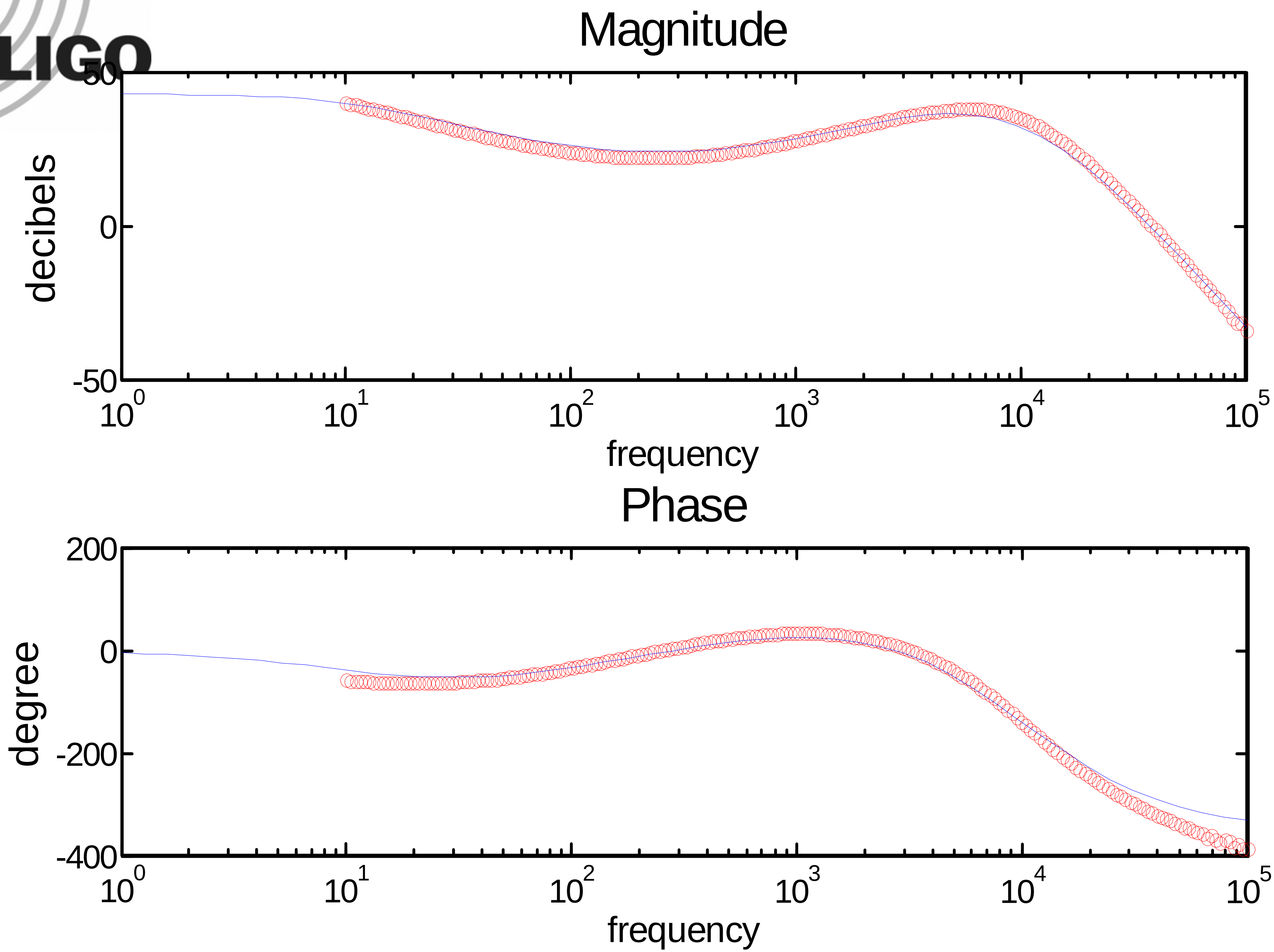
$$H=\frac{Y}{X}$$

- H has 6 poles, 2 zeroes and dc value of 6
- Looks like this

$$\left[\frac{0.1}{(1+i\,{}^{f}\!/_{10000})^2}\right]\bullet\left[\frac{0.01(1+i\,{}^{f}\!/_{100})}{(1+i\,{}^{f}\!/_{10000})}\right]\bullet\left[\frac{100}{(1+i\,{}^{f}\!/_{10000})^2}\right]\bullet\left[\frac{60(1+i\,{}^{f}\!/_{600})}{1+i\,{}^{f}\!/_{10}}\right]$$

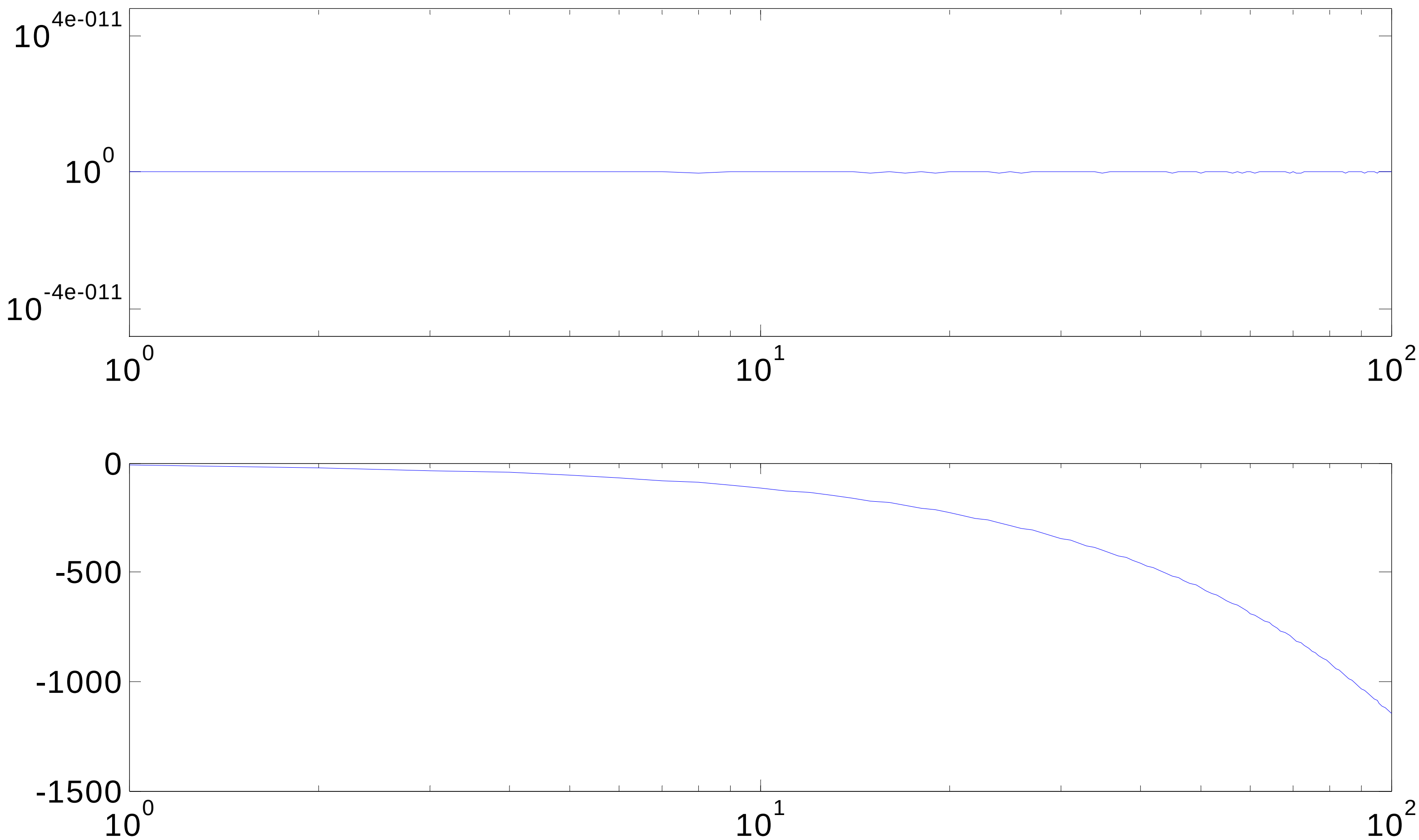
Spectrum Analyzer

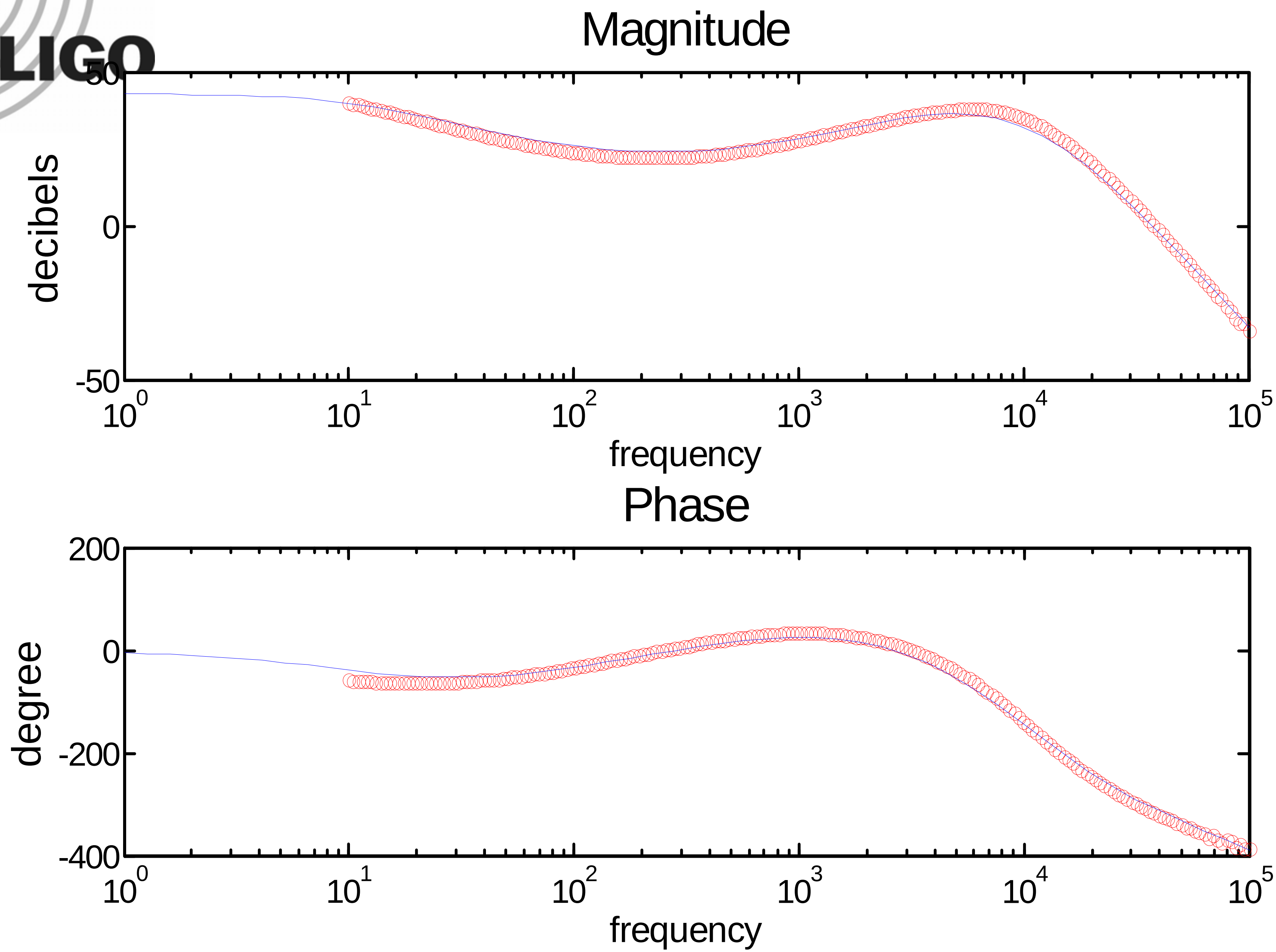
- Very powerful tool
- Aids in measurement of the electronic transfer function, H



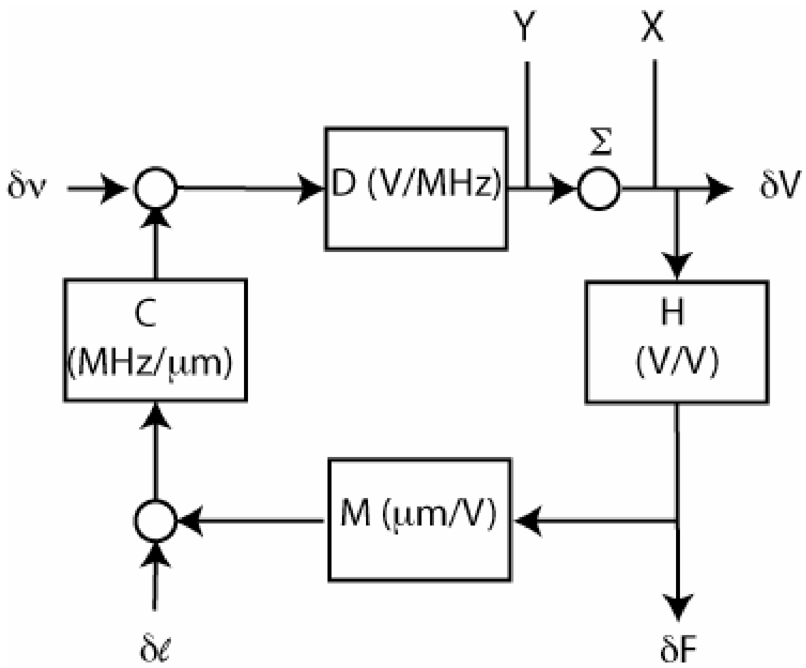
Magnitude
50
0
-50
decibels
10^0
10^1
10^2
10^3
10^4
10^5
frequency
Phase
200
0
-200
-400
degree
10^0
10^1
10^2
10^3
10^4
10^5
frequency

Introduction of Exp. function to account for time lag



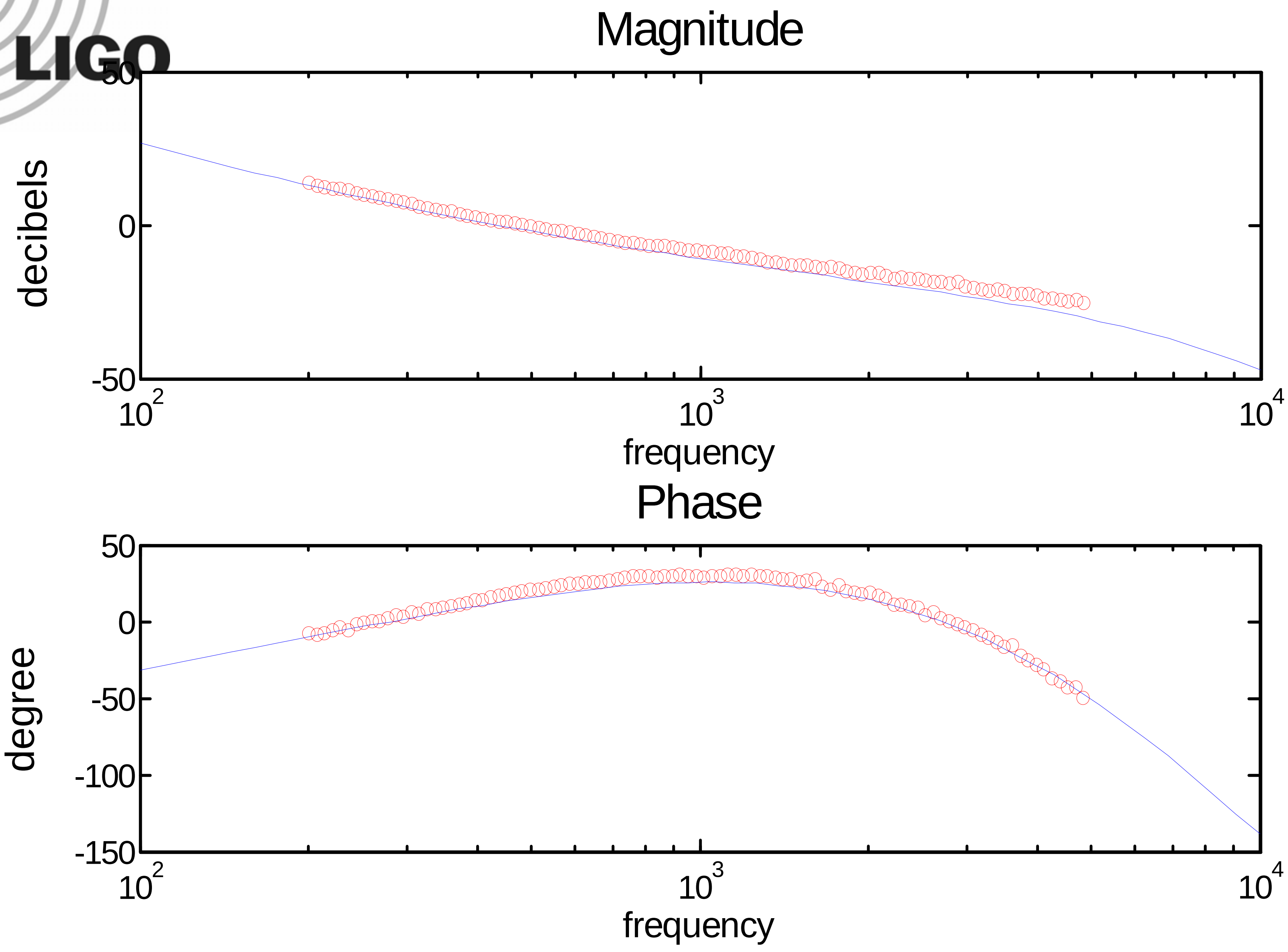

Magnitude
50
0
-50
decibels
10^0
10^1
10^2
10^3
10^4
10^5
frequency
Phase
200
0
-200
-400
degree
10^0
10^1
10^2
10^3
10^4
10^5
frequency

How to measure D



- Measurement of D can only be done when the instrument is in lock
- Y = XHMCD

$$\frac{Y}{X} = HMCD$$

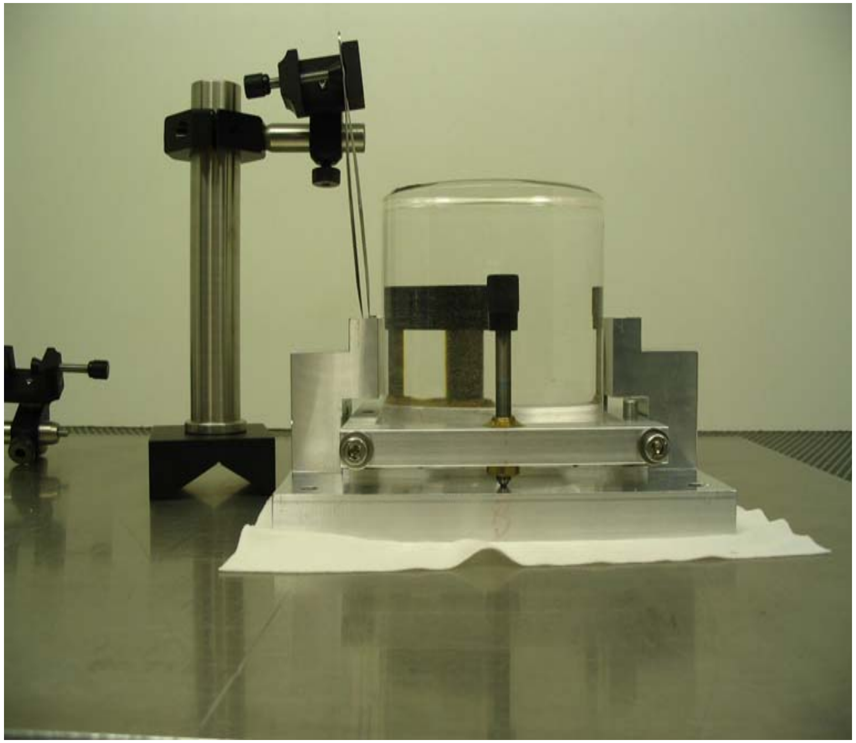


Chinyere Ifeoma Nwabugwu SURF
2005

LIGO

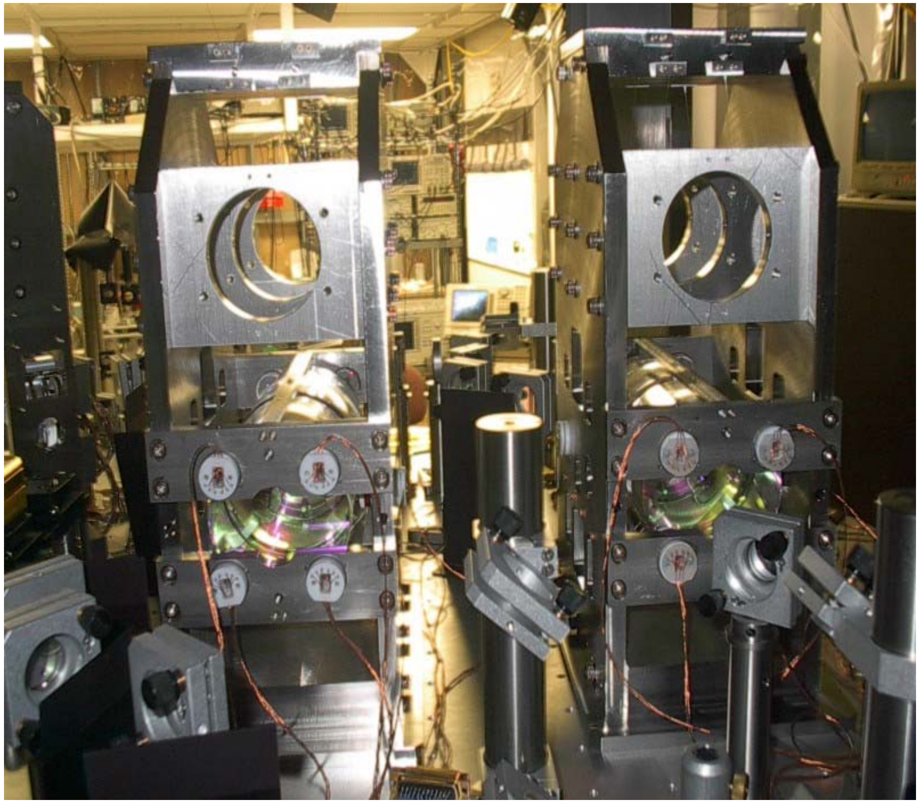
Mirrors are late ☹

Gluing magnets to mirrors



- Mirror has a curved surface with coating and flat surface with no coating
- One magnet on the side and 4 on flat side of the mirror
- Guiding wires on each side of mirror to guide stand-offs
- Glue used: Epoxy (vacuum compatible)
- Very delicate procedure indeed!!

Suspension of mirrors in cavity

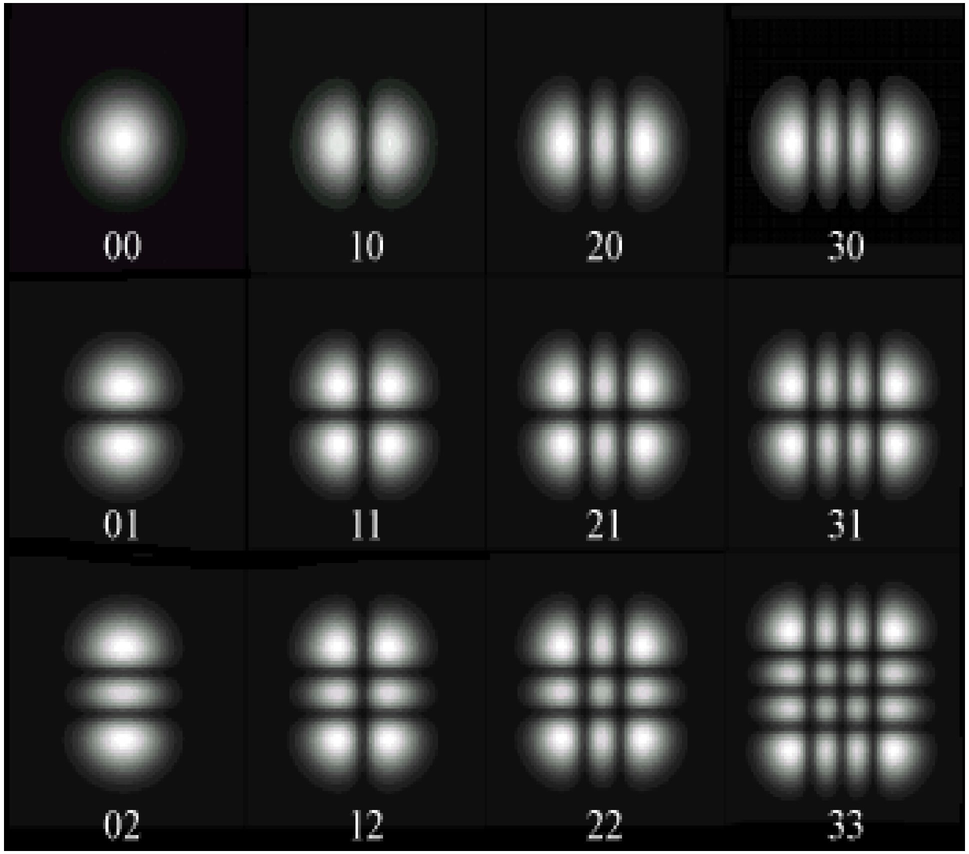


- Balance mirrors on 0.006 inch steel wires
- Use the earthquake stoppers and wire stand-offs to aid us
- Fix the OSEM's (Optical sensor electro-mechanical actuator) in place

Alignment

- For mode cleaner, we adjust the periscope right before the chamber
- Adjust beam splitter and mirrors into NAC and SAC

Locking the instrument



- In a fabry-perot cavity when the length of the cavity is equal to an integral number of wavelengths, there is total transmission i.e. reflected power is 0.
- There are different modes resulting from Transverse Electromagnetic Field TEM_{xy} but we always lock to the 00 mode, TEM_{00}
- Before locking, we work hard to increase the visibility of the TEM_{00}. We see this on the oscilloscope as a dip and it is the percentage of transmitted light relative to the reflected light

Future work

- Close the chamber
- Pump out to restore vacuum state
- Take data and analyze it
- Determine whether or not the advanced coating are better than the old ones

Acknowledgements

- My mentor: Eric Black
- Kenneth Libbrecht
- Akira Villar
- Kate Dooley
- Royal Reinecke
- Richard Kirian
- Helena Armandula
- Jean-Marie Mackowski
- Jay Heefner
- Chris Mach

Questions???

Chinyere Ifeoma Nwabugwu SURF
2005