LIGO's Thermal Noise Interferometer

Progress and Status

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LIGO-G020015-00-Z

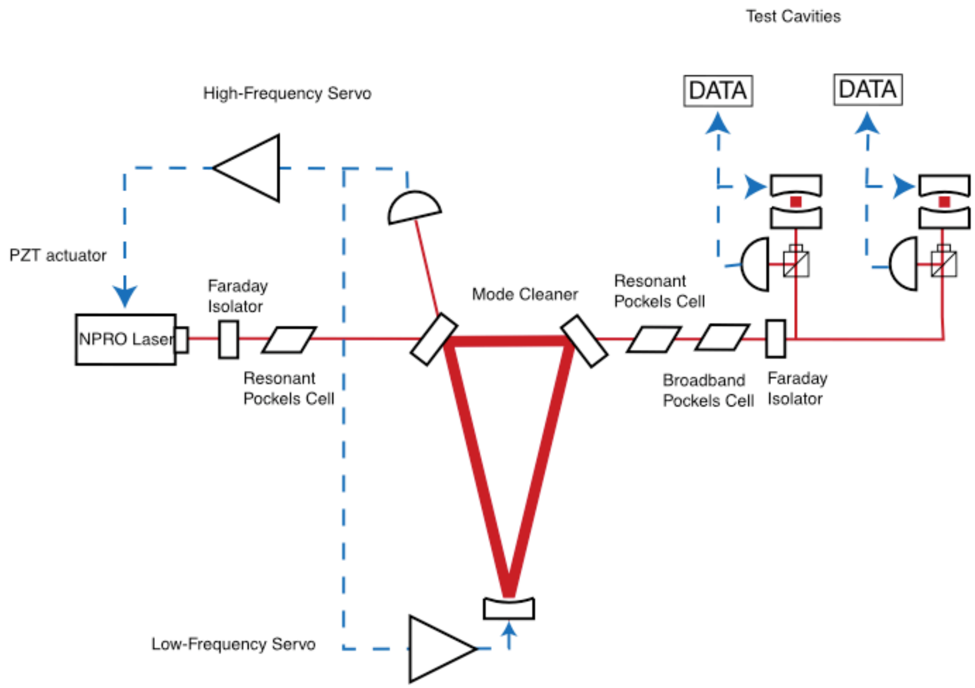
TNI Objectives

- Short Term
  - Characterize Sapphire for use in LIGO II: Noise Performance and Lead time.
  - Test Braginsky's model for Thermoelastic-Damping Noise (Intrinsic T fluctuations) in Sapphire.
- Long Term
  - Isolate and study different kinds of thermal noise relevant to LIGO, e.g. coating thermal noise.
  - Isolate and study non-Gaussian noise in suspensions and mirrors.
  - Reach (and Exceed) the Standard Quantum Limit.

Schedule: Major Milestones

- Summer 2001: First data (met).
- Fall 2001: Refine sensitivity to approach thermal noise levels (met).
- December 2001: Observe thermal noise in fused-silica mirrors (met?).
- January 2002: Install sapphire optics (not met!).
- Spring 2002: Additional noise reduction with sapphire mirrors, if necessary (may provide float).
- June 2002: Report on sapphire measurements to LIGO II material downselect committee.

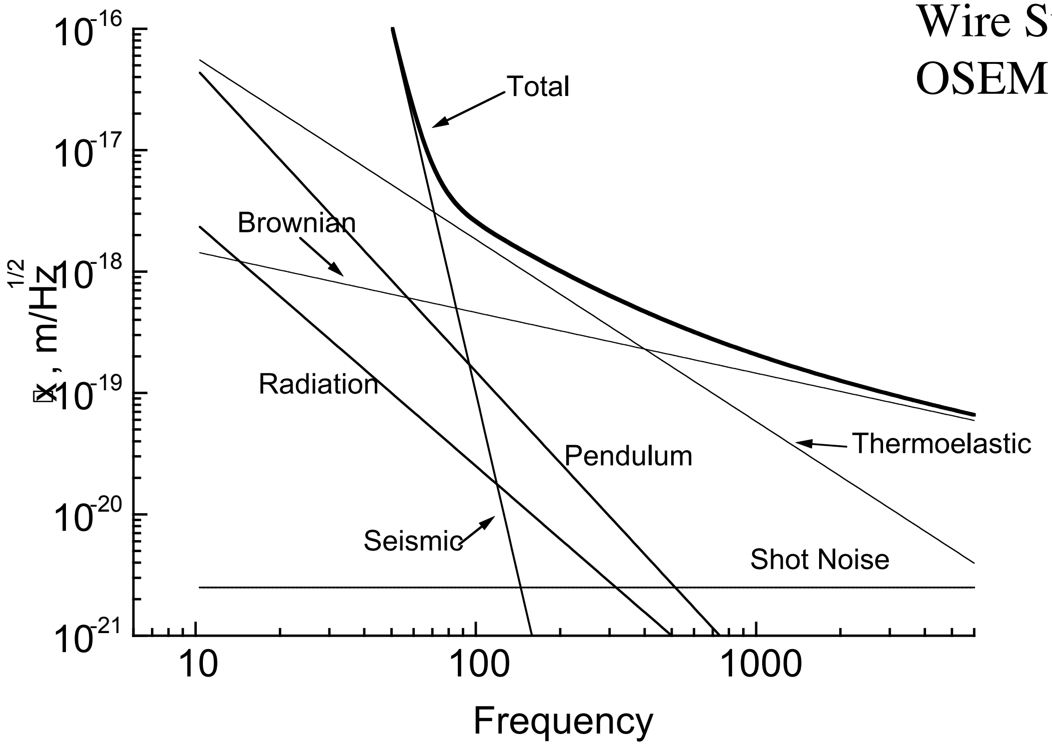
TNI Layout



Test Cavities
DATA
DATA
High-Frequency Servo
PZT actuator
Faraday
Isolator
Mode Cleaner
Resonant
Pockels Cell
NPRO Laser
Resonant
Pockels Cell
Broadband
Pockels Cell
Faraday
Isolator
Low-Frequency Servo

TNI Phase I Expected Spectrum

Fused-Silica Test Masses
Wire Suspensions
OSEM Actuation



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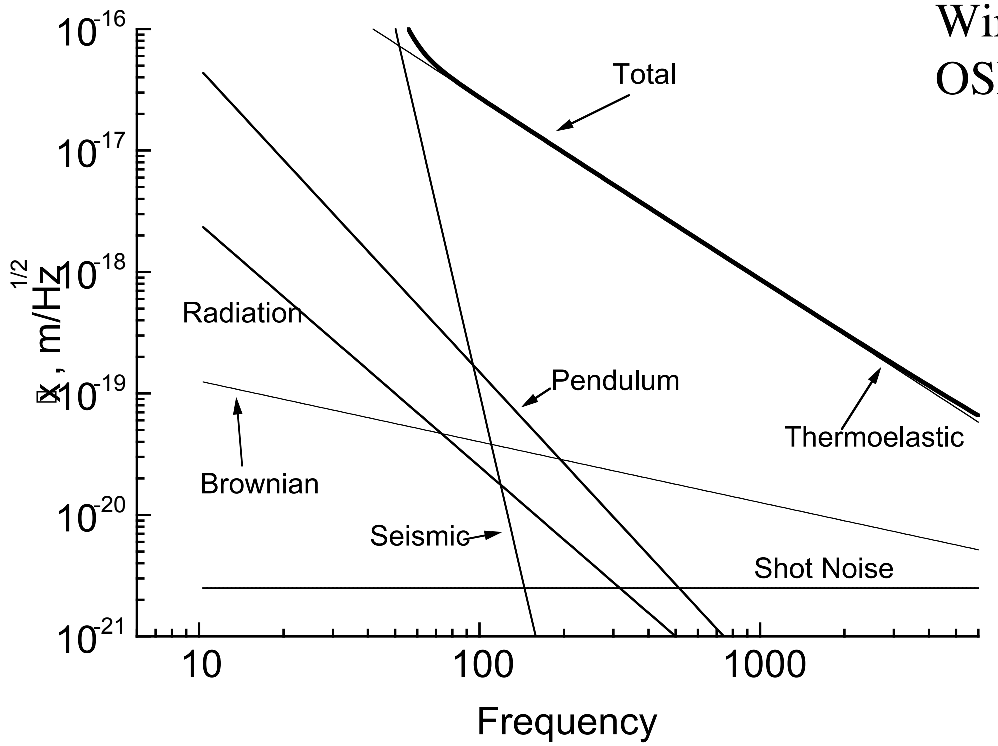
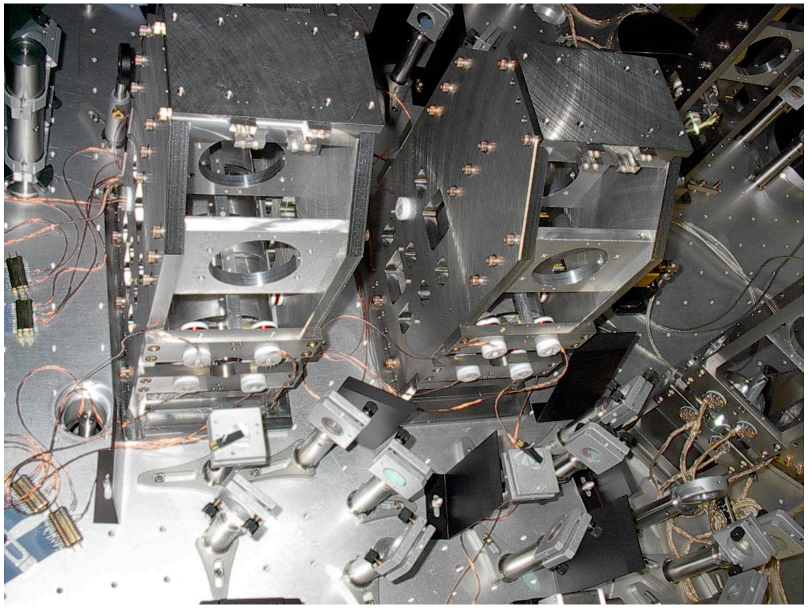
TNI Phase II Expected Spectrum



Sapphire Test Masses
Wire Suspensions
OSEM Actuation

Suspensions



- LIGO I - style suspensions.
- Wire cradles.
- Magnets on mirrors.
- OSEM damping and actuation.
- All on a single seismic isolation stack, inside one vacuum chamber.
- Fused silica mirrors in first stage.
- Sapphire mirrors in second stage.

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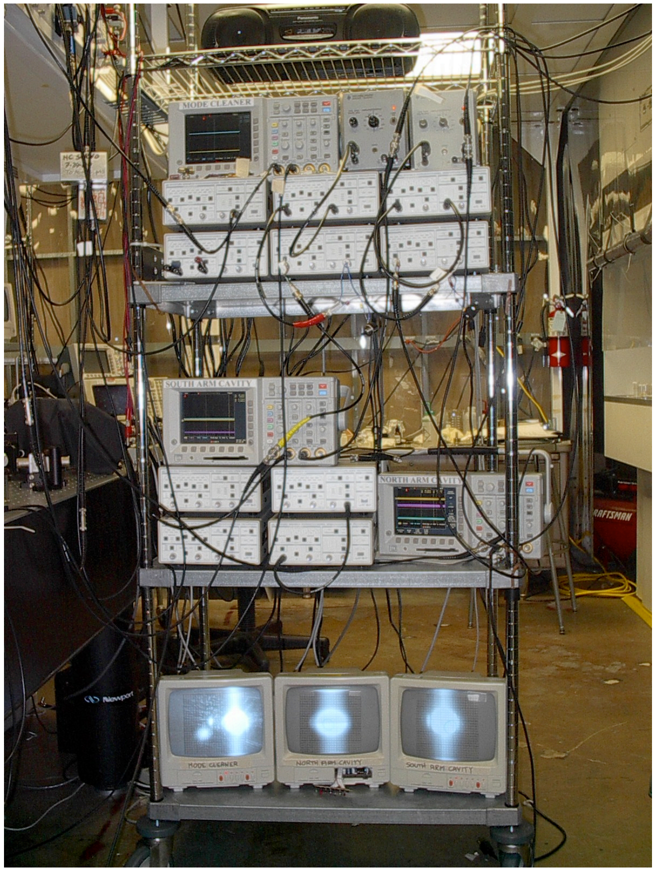
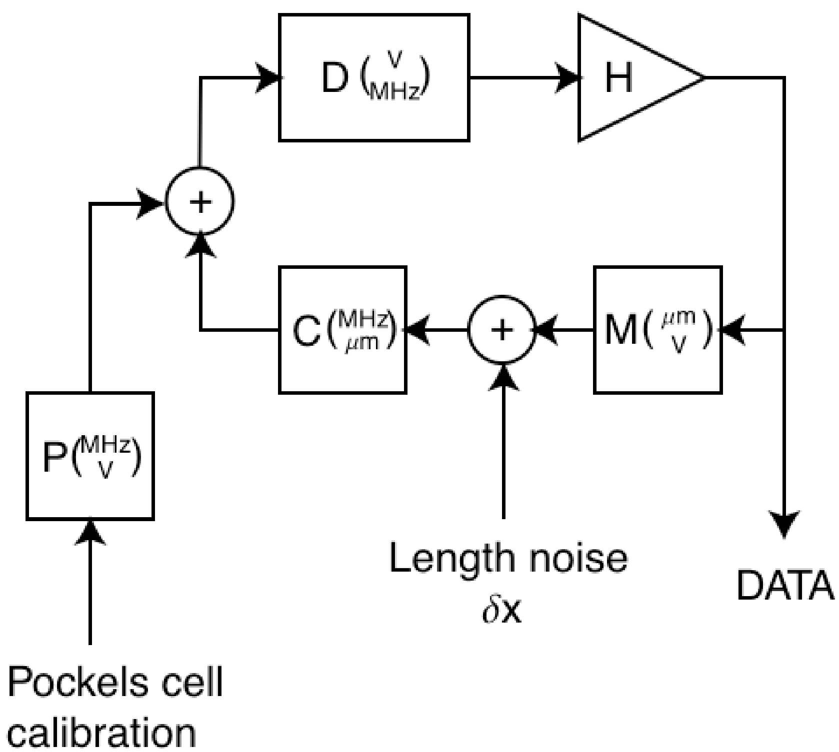
Electronics



- System designed for flexibility.
- Favor modularity with lots of measurement and injection points.
- Most filters are built out of SR560's and passive circuits.
- CDS supplies active notch filters, satellite boxes.
- Special thanks to Jay Heefner, Flavio Nocera, Janeen Romie, et al. for much support!

Arm cavity feedback servo and data extraction



$$\delta x = \left[\frac{1 + HDCM}{HDC}\right]\delta V_{DATA}$$

D = Discriminant
H = Feedback filter
M = Mirror response
C = Conversion factor
P = Pockels cell response

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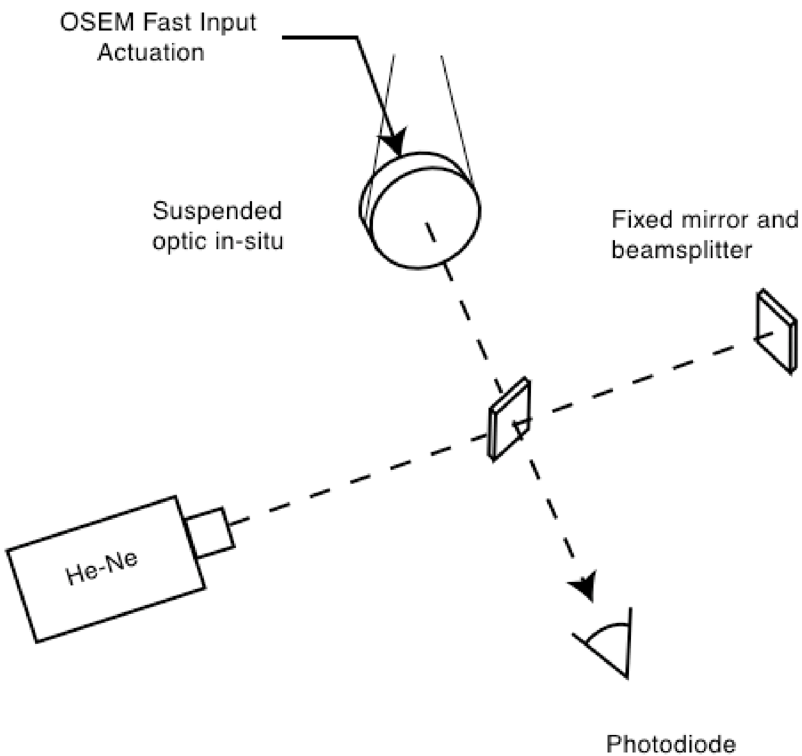
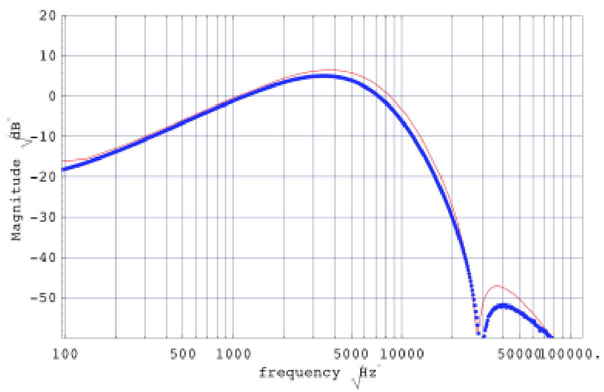
Mirror Response (M)

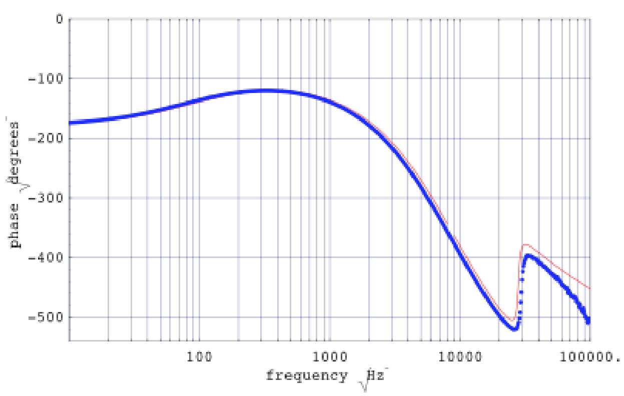


- Apply sinusoidal actuation
- Drive through several fringes
- Average
- Assume 2 poles at 1Hz

$$M(0) \square 1 \frac{\square m}{V}$$

Servo Filter (H)





- Simple electronic transfer function.
- Blue is data, red is model.
- This model is a prediction, not a fit.
- Passive lead: 100Hz - 10kHz
- 2 SR560's for a total of 4 poles at 10kHz
- Passive Notch Filter provides ~40dB at 27kHz

Conversion Factor (C)

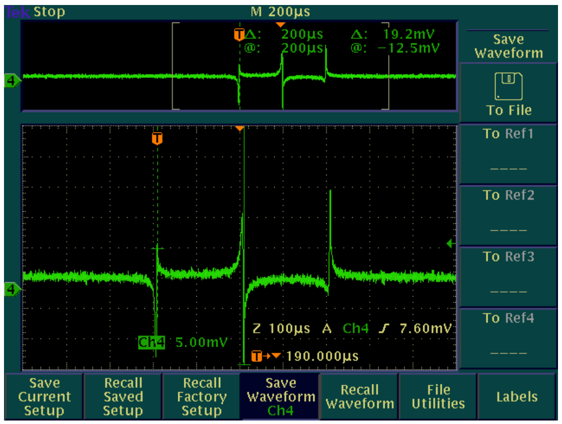
$$C = \frac{\nu}{L} = 3 \times 10^{4} \frac{MHz}{\mu m}$$

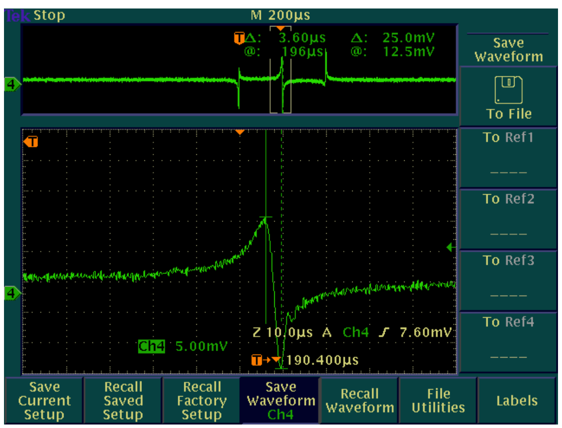
$$\nu = \frac{c}{\lambda} = 3 \times 10^{14} Hz$$

$$L = 1cm$$

- This is just math.
- Converts length change to frequency change.
- No poles or zeroes, just a number we can calculate.

Discriminant (D): Sweep Method



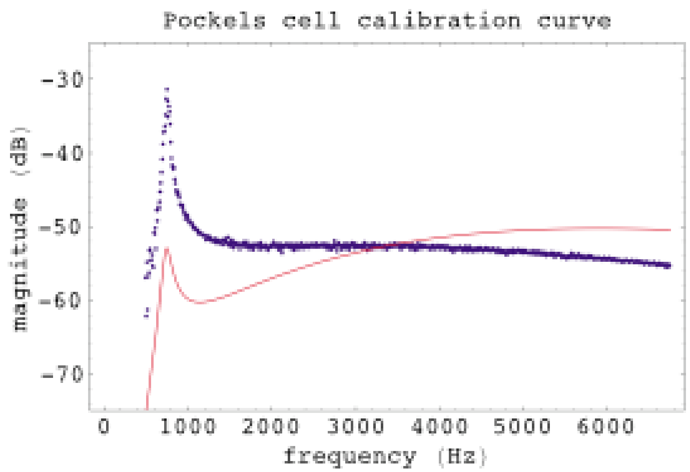


- Direct measurement of Pound-Drever-Hall error signal.
- Let mirror sweep through a fringe.
- Identify TEM-00 mode by visibility (not shown in this shot).

$$D = 2\frac{\Delta V}{\Delta t_c} \times \frac{\Delta t_{c-sb}}{14.75\,MHz}$$

- **This is only an estimate of D.**

Discriminant (D): Pockels Cell Method



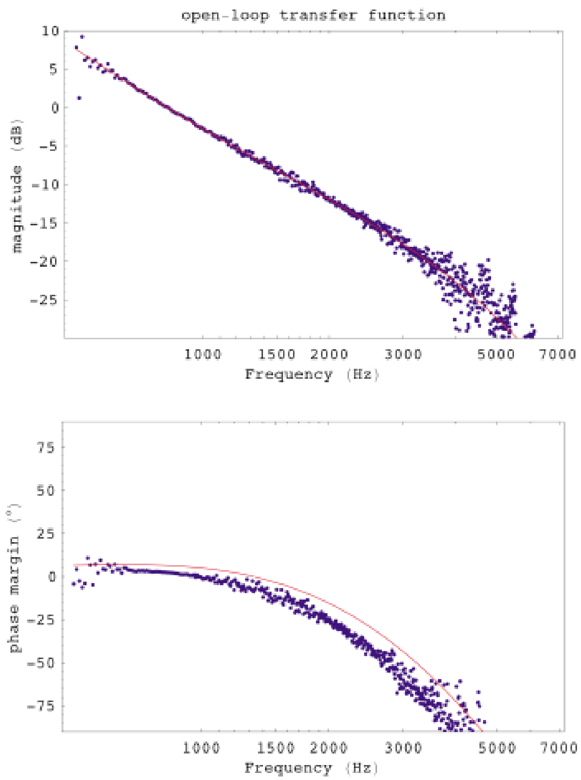
Expect: $T = \frac{DHP}{1 + DHMC}$

- Drive broadband Pockels cell and observe response at data port
- Blue is data, red is model.
- Assume manufacturer’s spec for Pockels cell response P:

$$P = 0.015\frac{Rad}{V} = 10^{-4}\frac{MHz}{V}\cdot\left(\frac{f}{1kHz}\right)$$

- Vary one parameter to fit: D
- D is consistent with value determined by scan, but…
- **No confidence in this method for accurate frequency scaling!**

Discriminant (D): UGF Method

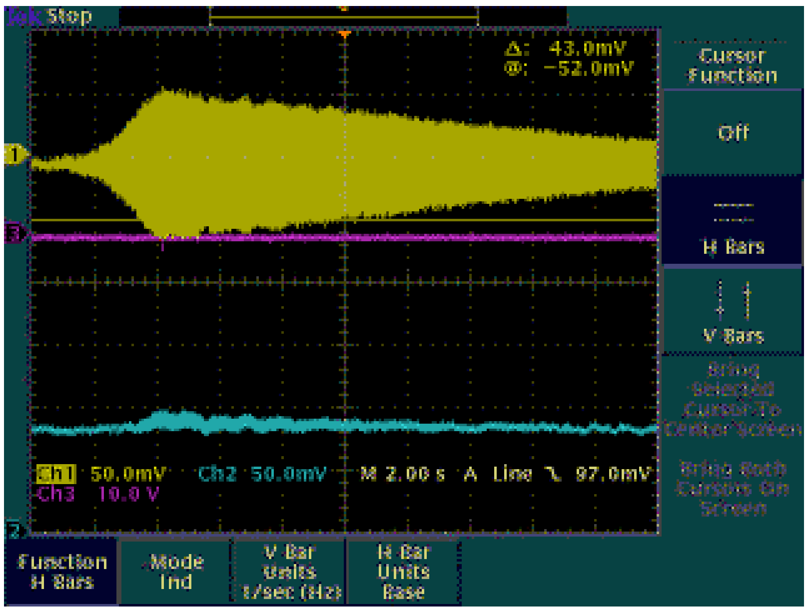


- Measure open-loop transfer function with system locked
- Fit theory to data
- New calibration for every lock
- Blue is data, red is model.
- One parameter varied for fit: D
- **This method appears to get frequency scaling right.**
- Values obtained are consistent with both other methods. Typical:

$$D = 9.0 \frac{V}{MHz}$$

Expect: $T = DHMC$

Thermal Noise Estimates: Mirror-Q Ringdown Measurements

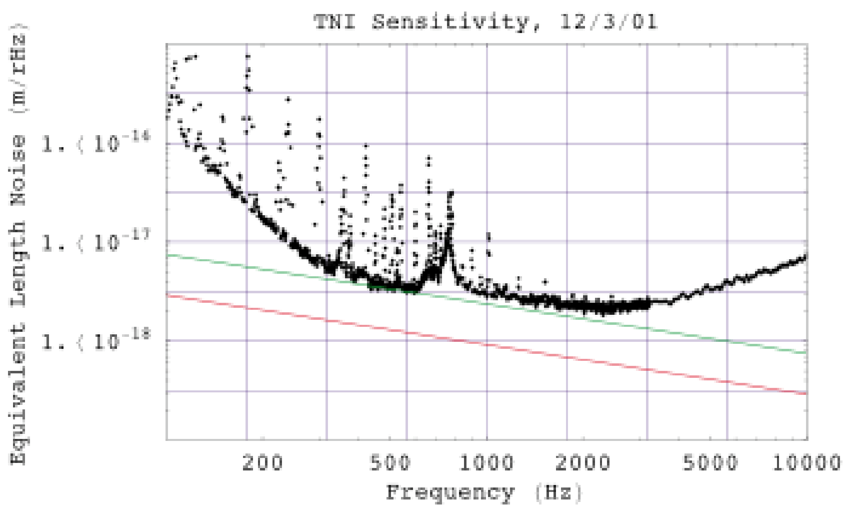


- With system locked, remove two poles from H to excite the lowest internal mode (27.5kHz).
- Re-engage poles and observe ringdown in error signal.
- Calculate mirror Q by

$$Q = \pi f_0 \tau$$

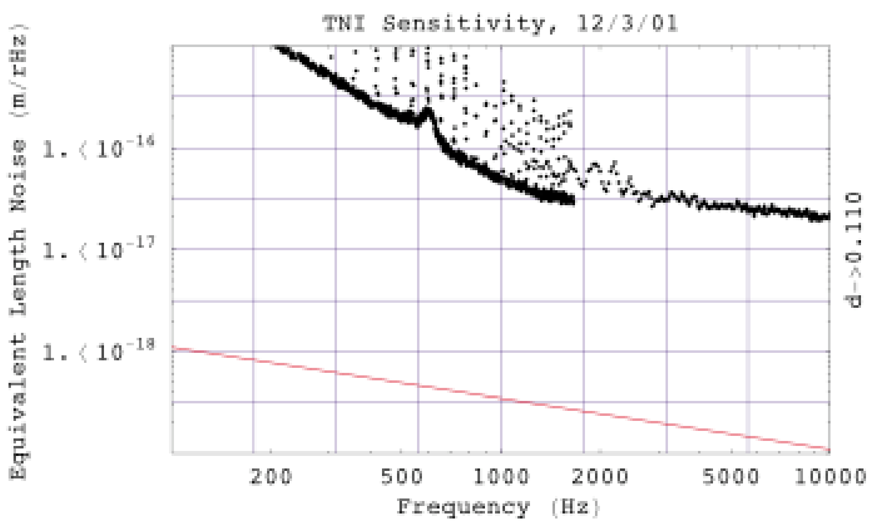
- Calculate mirror thermal noise by Levin's method: Direct application of Fluctuation-Dissipation Theorem.

TNI Sensitivity: South Arm Cavity



- **Black**: Data
- **Red**: Mirror Thermal Noise prediction for South Output mirror only. Estimated Q = 100,000 from ringdown measurement.
- **Green**: Mirror Thermal Noise prediction if Q = 15,000. Sets lower limit on mirror Q.
- **Amplitude and frequency dependence consistent with thermal noise.**

TNI Sensitivity: North Arm Cavity



- **Black**: Data
- **Red**: Mirror Thermal Noise prediction for North Output mirror only. Estimated Q = 700,000 from ringdown measurement.
- Noise curve is two orders of magnitude higher than thermal noise estimate for this cavity.
- No obvious 1/f^0.5 scaling.
- **Why is this cavity so noisy?**

Current Status and Results

- Level and frequency dependence of South Arm Cavity consistent with thermal noise.
- North Arm Cavity is noisier, does not appear to be thermal noise limited. (Why?)
- Other noise sources identified:
  - Laser frequency noise: above ~2kHz
  - Optical crosstalk between cavities: eliminated with Faraday Isolator just after last Pockels cell
- **Sensitivity of South Arm Cavity may now be good enough to see thermoelastic noise in sapphire.**

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Immediate Priorities

- Install sapphire optics. Further noise reduction should be done with sapphire mirrors!
- Identify source of excess noise in North Arm Cavity.
- Achieve North Cavity sensitivity comparable to South's.
- Identify and, if possible, reduce low-frequency noise.
- Model and quantify optical crosstalk noise. (Optional)
- Understand Pockels cell calibration curve. (Optional)

Conclusions

- **TNI sensitivity level in one arm is consistent with thermal noise in fused-silica mirrors. The noise floor is near the expected amplitude for thermal noise, and it displays the expected frequency dependence over approximately one decade, 300Hz-3kHz.**
- **More important, our sensitivity may be good enough to observe thermoelastic damping noise (Braginsky noise) in sapphire.**
- **Much work still needs to be done to reduce the noise in the North Cavity, and to reduce the noise in both cavities below 300Hz. This work can and should be done with sapphire mirrors in place.**

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