LIGO's Thermal Noise Interferometer: Progress and Status

Eric Black

LSC Meeting Review

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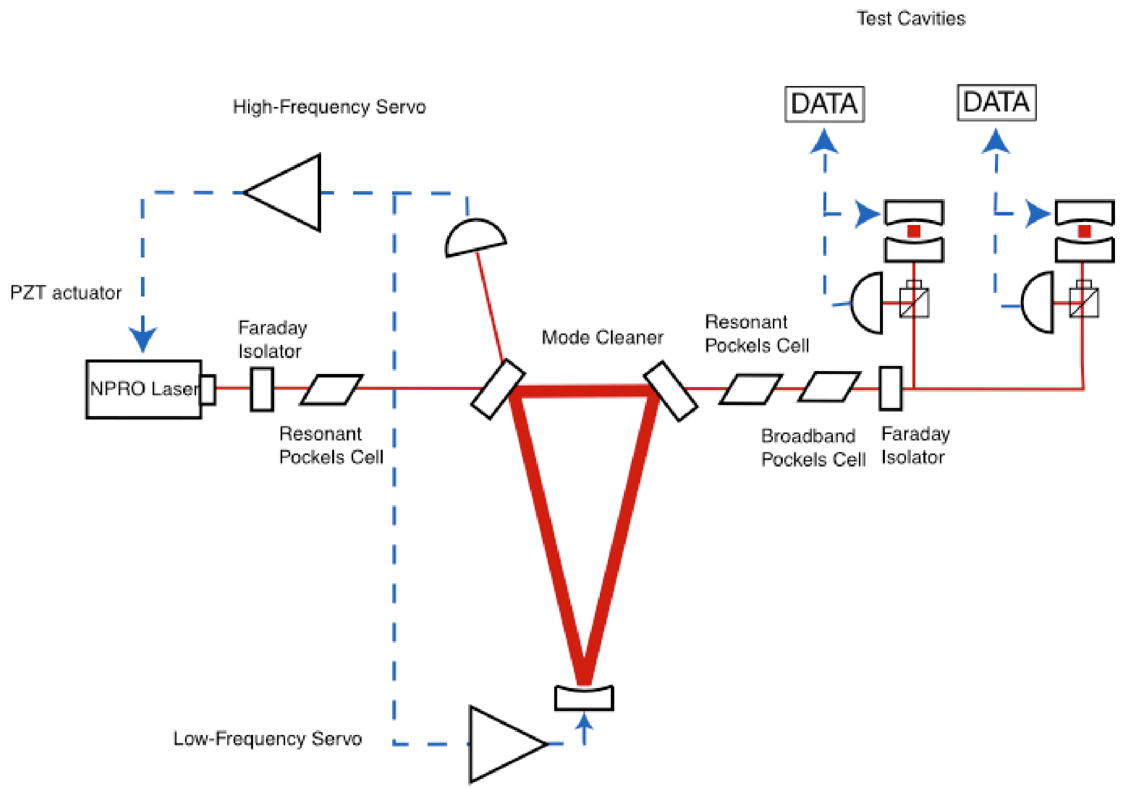
Ken Libbrecht, Shanti Rao (Caltech)
Seiji Kawamura (TAMA)

G030100-00-R

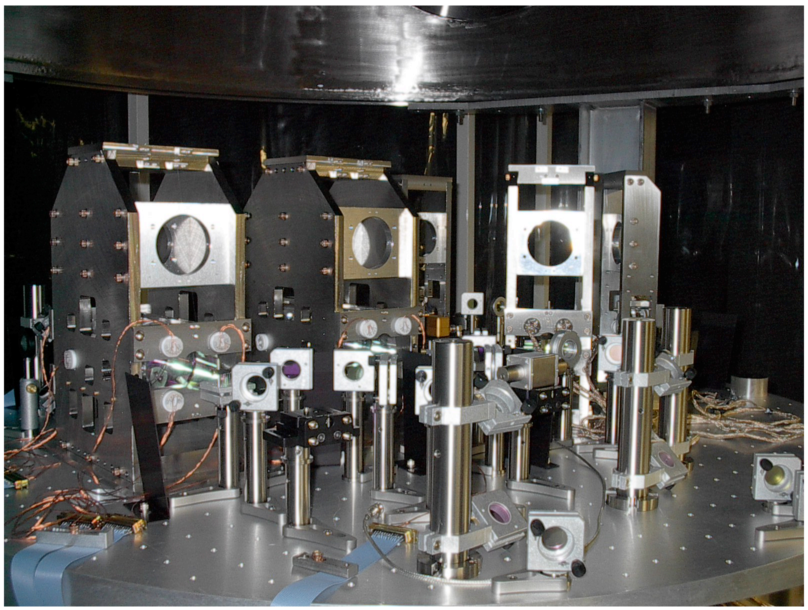
TNI Purpose and Goals

- Short Term
  - Isolate and study different kinds of thermal noise relevant to LIGO, e.g. coating thermal noise.
  - Characterize Sapphire for use in LIGO II: Noise Performance, lead time, etc.
- Long Term
  - Isolate and study non-Gaussian noise in suspensions and mirrors.
  - Reach (and Exceed) the Standard Quantum Limit.
- Along the way
  - Identify *and quantify* any unexpected noise sources at sensitivity levels relevant to gravitational-wave detection.

TNI Layout

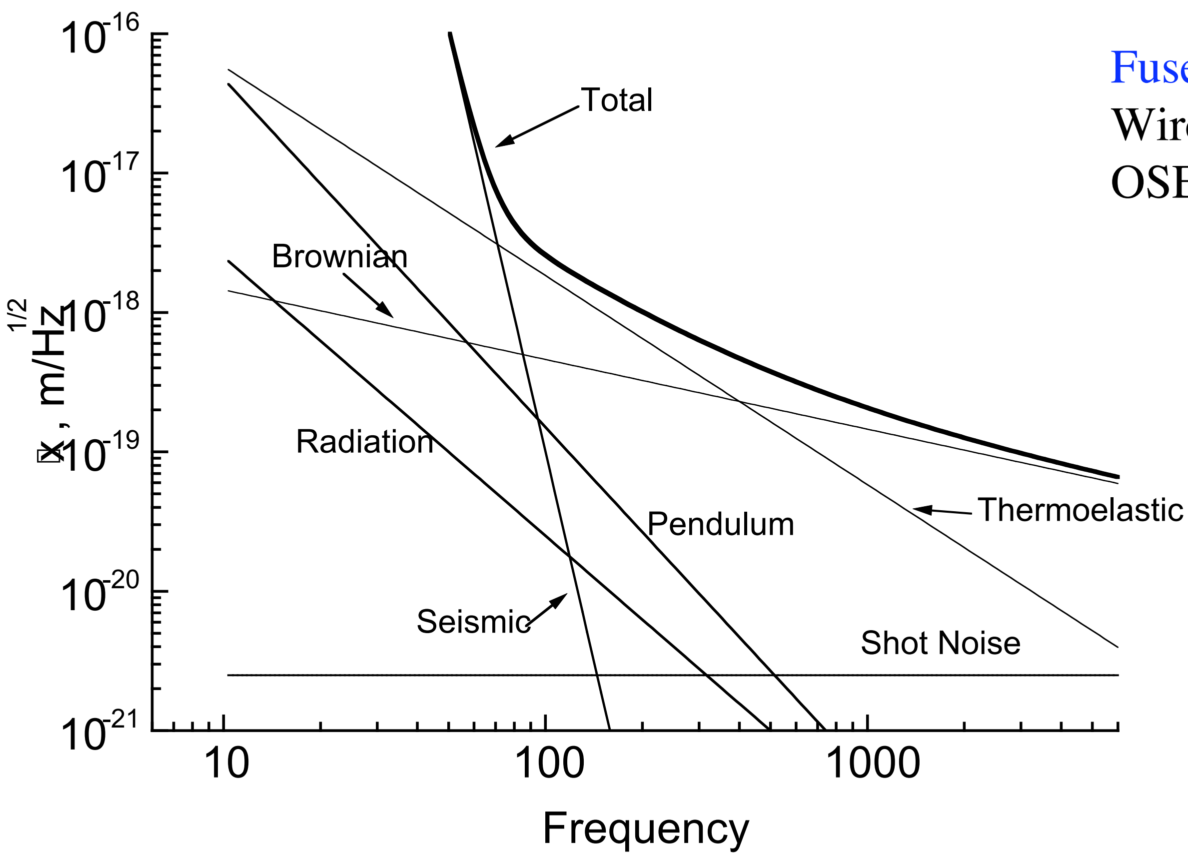

Test Cavities
DATA
DATA
High-Frequency Servo
PZT actuator
Faraday
Isolator
NPRO Laser
Resonant
Pockels Cell
Mode Cleaner
Resonant
Pockels Cell
Broadband
Pockels Cell
Faraday
Isolator
Low-Frequency Servo

TNI Hardware



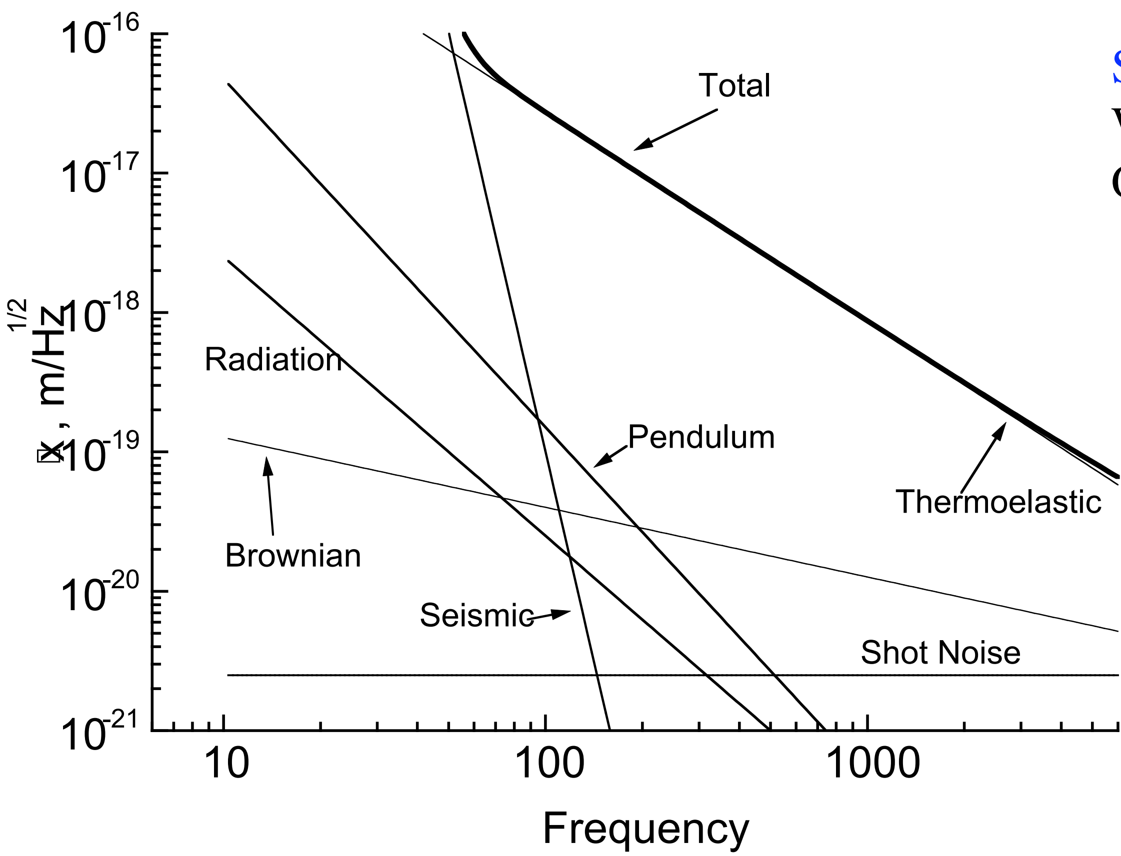
- Mode cleaner, arm cavities all contained in one chamber, mounted on a single stack.
- Wire suspensions similar to LIGO-I Small Optics Suspensions.
- OSEM actuation, all analog.
- Laser: 750mW NPRO (Lightwave).
- All hardware constructed (purchased) and installed.

TNI Phase I Expected Spectrum



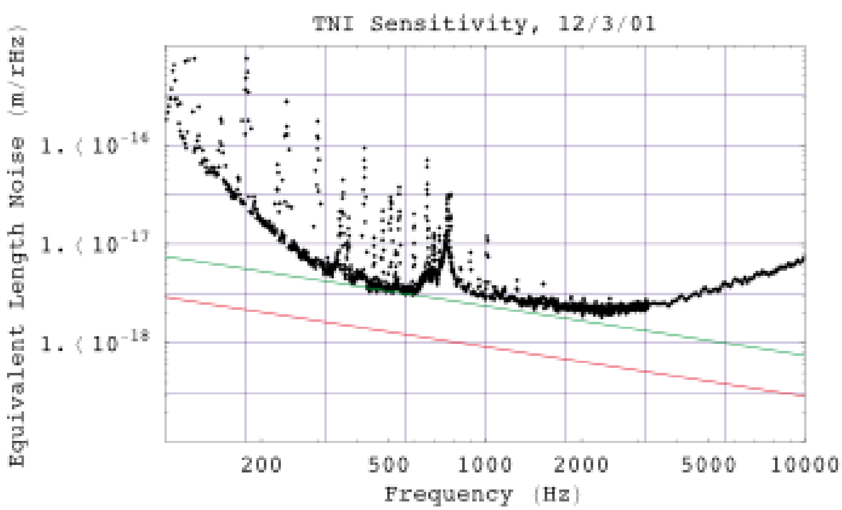
Fused-Silica Test Masses
Wire Suspensions
OSEM Actuation

TNI Phase II Expected Spectrum



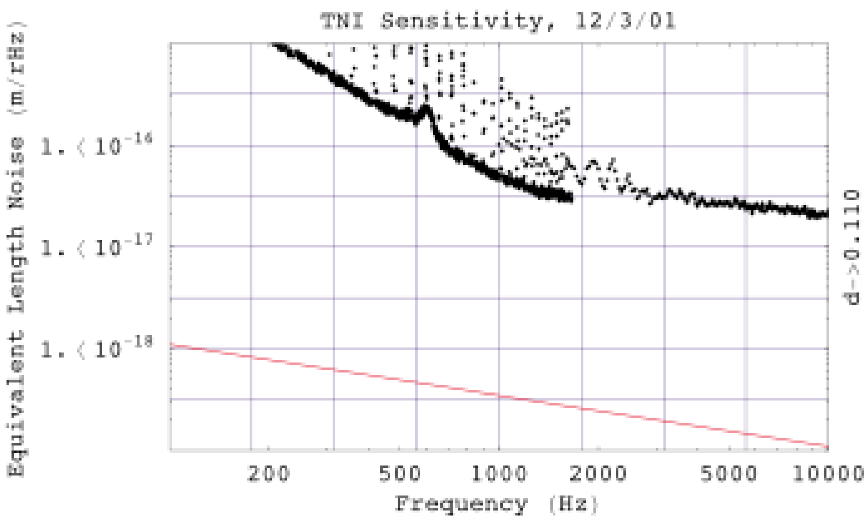
Sapphire Test Masses
Wire Suspensions
OSEM Actuation

Early Results: South Arm Cavity Sensitivity (12/01):



- **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 appeared to be approximately consistent with thermal noise.**

Early Results: North Arm Cavity Sensitivity (12/01):



- **Black**: Data
- **Red**: Mirror Thermal Noise prediction for North Output mirror only. Estimated Q = 700,000 from ringdown measurement.
- Noise curve was two orders of magnitude higher than thermal noise estimate for this cavity.
- No obvious 1/f^0.5 scaling.
- **North Arm Cavity (NAC) was significantly noisier than the South Arm Cavity (SAC).**

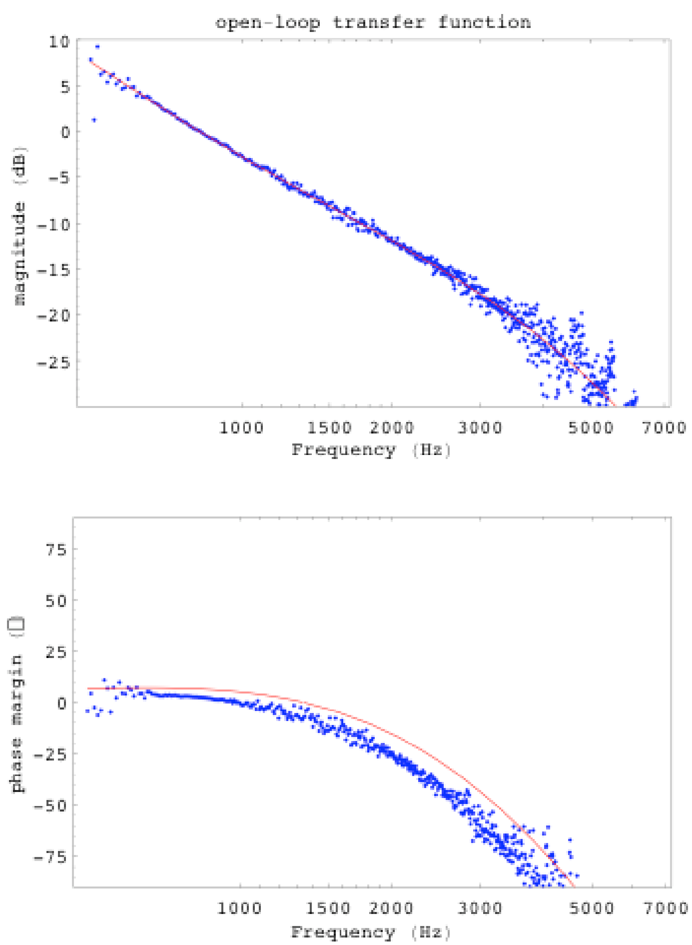
Early results summary: 12/01-2/02

- SAC sensitivity appeared to be quite good, with a best value of 1.5e-18m/√Hz.
- NAC noise floor was not as good, above 1e-17m/√Hz at all frequencies.
- NAC's optical gain lower than SAC's by two orders of magnitude.
- Lock acquisition was *very* difficult. Acquisition time was approx. 2hrs, phase margin was only 1.6°, bandwidth less than ~750Hz.
- Ringdown Q measurements were made in both SAC and NAC output masses, allowing us to predict the thermal noise in both cavities.
- SAC noise floor was within a factor of 3 of the expected thermal noise level.
- SAC noise floor exhibited an $f^{-1/2}$ frequency dependence, as expected of thermal noise.
- NAC noise floor exhibited no $f^{-1/2}$ frequency dependence, level was two orders of magnitude above expected thermal noise floor.
- Was SAC's noise floor limited by thermal noise?
- Why was NAC's noise floor so high, optical gain so low?
- Can the lock be improved?

Schedule: Major Milestones

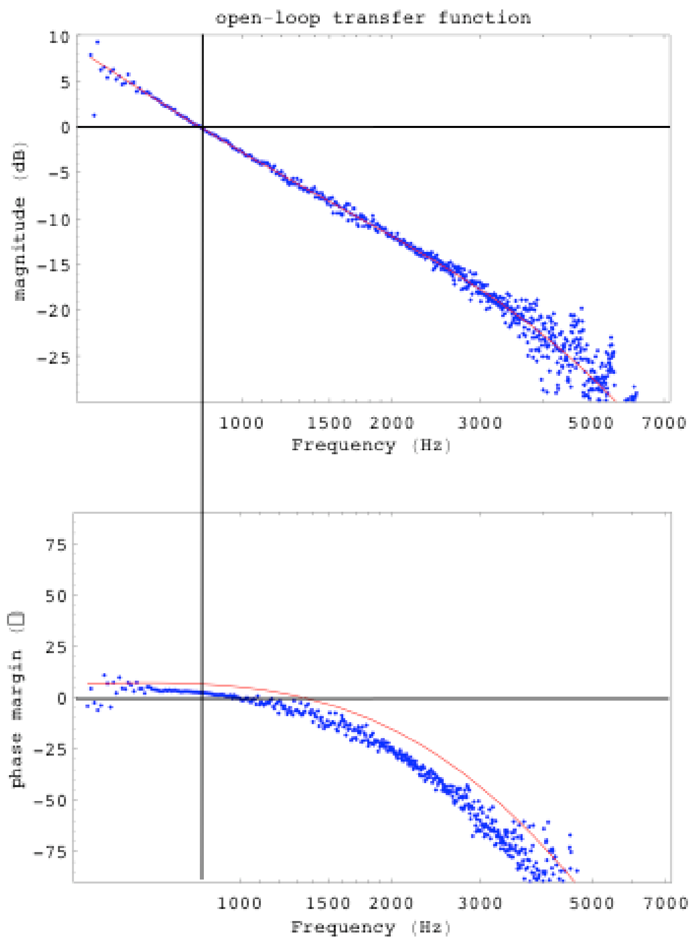
- Summer 2001: First data (met).
- Fall 2001: Refine sensitivity to approach thermal noise levels (met).
- December 2001: Observe thermal noise in fused-silica mirrors (met?).
- February 2002: Review held. Committee recommends delaying Sapphire installation in favor of further Fused Silica research, instrument improvement. Specifically,
  - Improve lock acquisition, stability.
  - Indentify individual noise source contributions.
  - Get NAC's noise as good as SAC's.
- 2002: Improvements,
  - Improve lock acquisition, stability (met).
  - Identify individual noise source contributions (met).
  - Get NAC's noise as good as SAC's (initially, noise got *worse*, progress made since).

Bandwidth and Phase Margin (12/01)



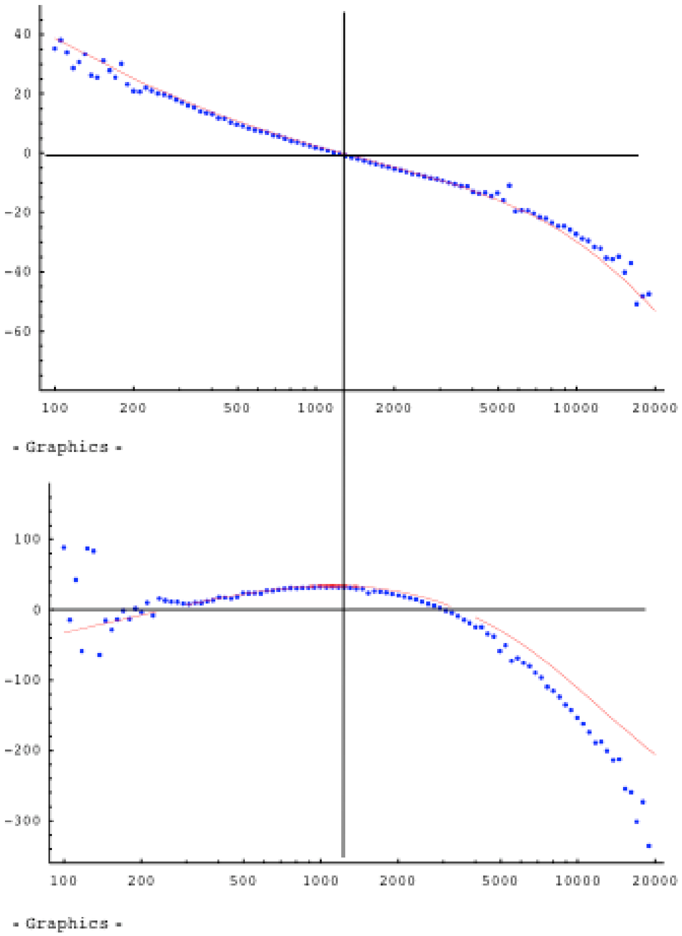
- Lock acquisition very difficult in the beginning.
- System took ~2hrs to lock, night only!

Bandwidth and Phase Margin (12/01)



- Lock acquisition very difficult in the beginning.
- System took ~2hrs to lock, night only!
- Bandwidth ~750Hz.
- Phase margin more problematic, ~2°.
- Little or no gain margin.
- Must improve before serious science attampted!

TNI Progress Since 2/02: Lock Acquisition Improvement

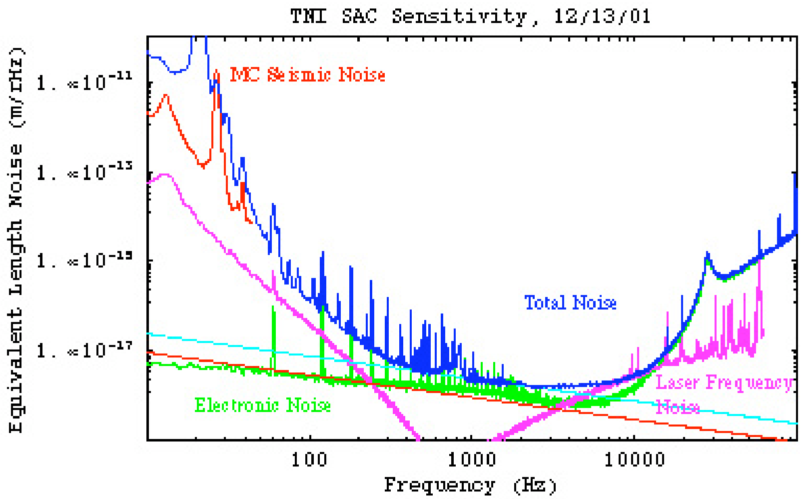


- Active Notch filter array replaces single, passive notch (many thanks to Flavio Nocera).
- Phase margin now positive up to ~2.5kHz.
- Unity-gain frequency (UGF) of ~1.5kHz sufficient for rapid and robust lock.
- Phase margin now ~25°.
- Both NAC and SAC acquire TEM00 modes within minutes (sometimes seconds), even during the day.
- Both arm cavities hold lock for hours at a time.
- Lock acquisition problems resolved.

TNI Progress Since 2/02 II: North Arm Cavity Improvement

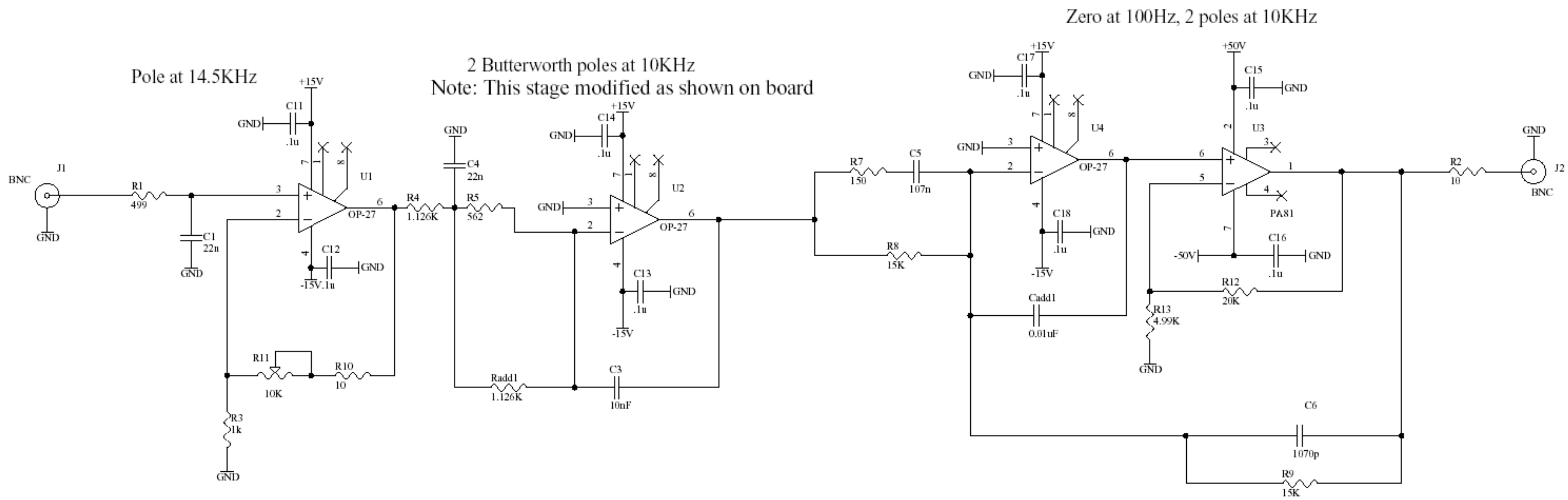
- Why was NAC's optical gain lower than SAC's by two orders of magnitude?
  - Power incident on NAC was 1/2 of the power incident on SAC: Beamsplitter (50UNP) meant for unpolarized light, gave 70/30 for p-polarization.
  - NAC's RF photodiode had lower response than SAC's: NAC's RF photodiode tuned to 29.4MHz; should have been 14.75MHz.
- Beamsplitter replaced to provide 50% for p-polarization.
- NAC's RF photodiode replaced by 14.75MHz model (or so we thought).
- Total power incident on both cavities increased by x2 by optimizing polarization, which was 45° to horizontal.
- Power differences resolved between NAC and SAC, error signal roughly matched (within a factor of two).

TNI Progress Since 2/02 III: Noise Breakdown (SAC)



- Noise Sources identified:
  - Electronic noise.
  - Laser Frequency noise.
  - Seismic noise in Mode Cleaner (imposed on laser frequency noise)
- Electronic noise very close to total noise floor!
- Further noise breakdown deferred until after servo improvements.

Electronics: New Servo Filter Design

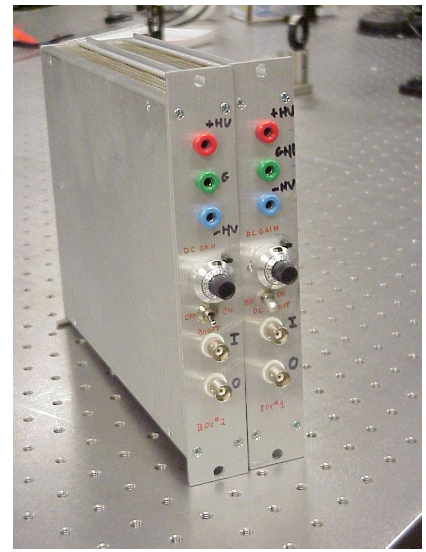


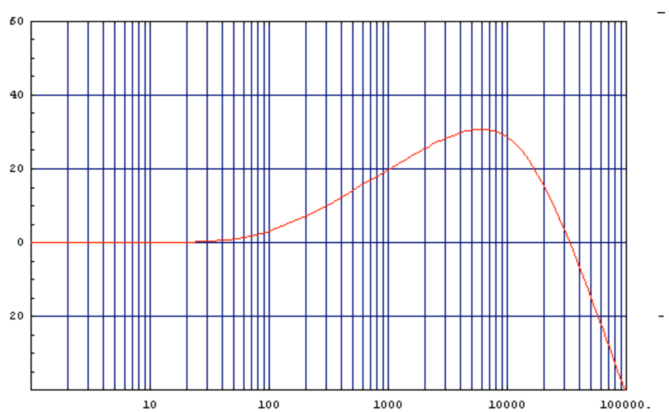
- Old servo used passive lead (attenuates at dc) + SR560's. Lead to good acquisition, but poor noise performance.
- New servo built by Kyle Barbary, SURF student, uses active lead.
- Low noise op-amps and small resistor values used.
- High-Voltage op-amp in feedback loop of low-noise op amp.

Special thanks to Jay Heefner (CDS)

NEW Servo Filter Design

- Housed in NIM module for low line noise, good shielding.
- Gain adjustable from 1 to 10.
- Low frequency boost switch added for additional stability once lock is achieved.





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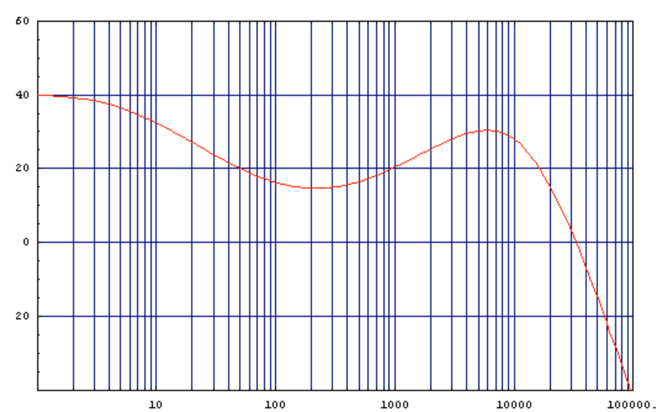

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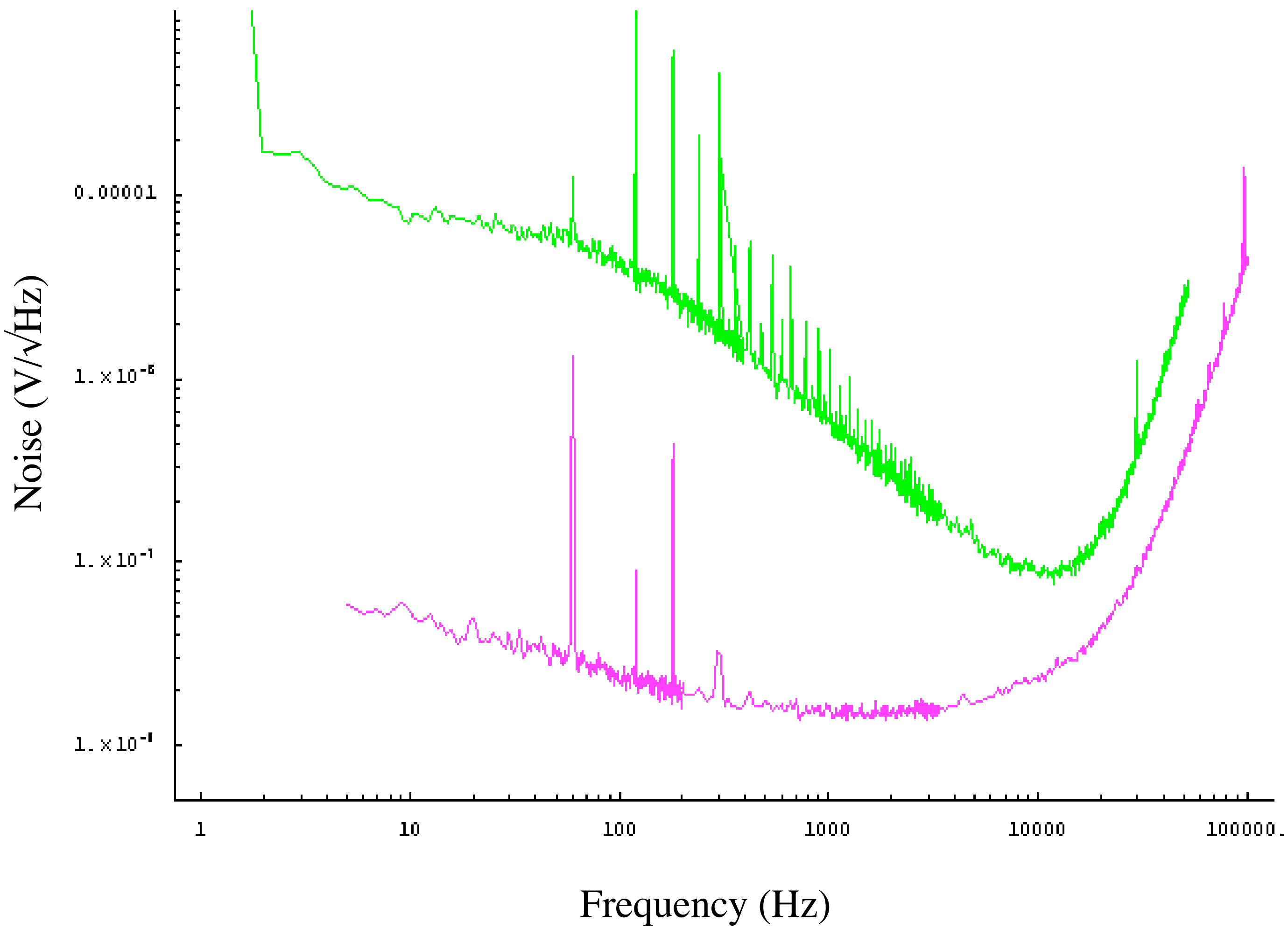
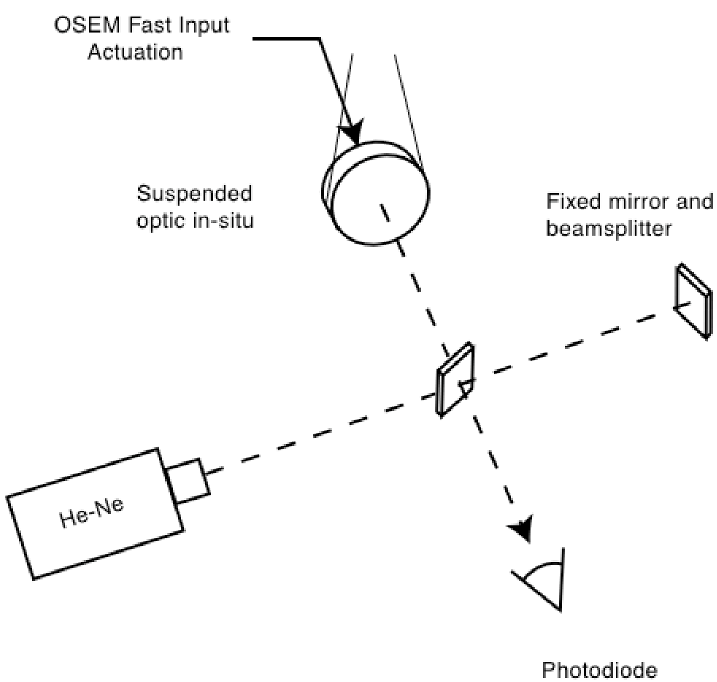
Noise Performance



- Green is old circuit *input referred* noise
- Purple is new circuit *input referred* noise

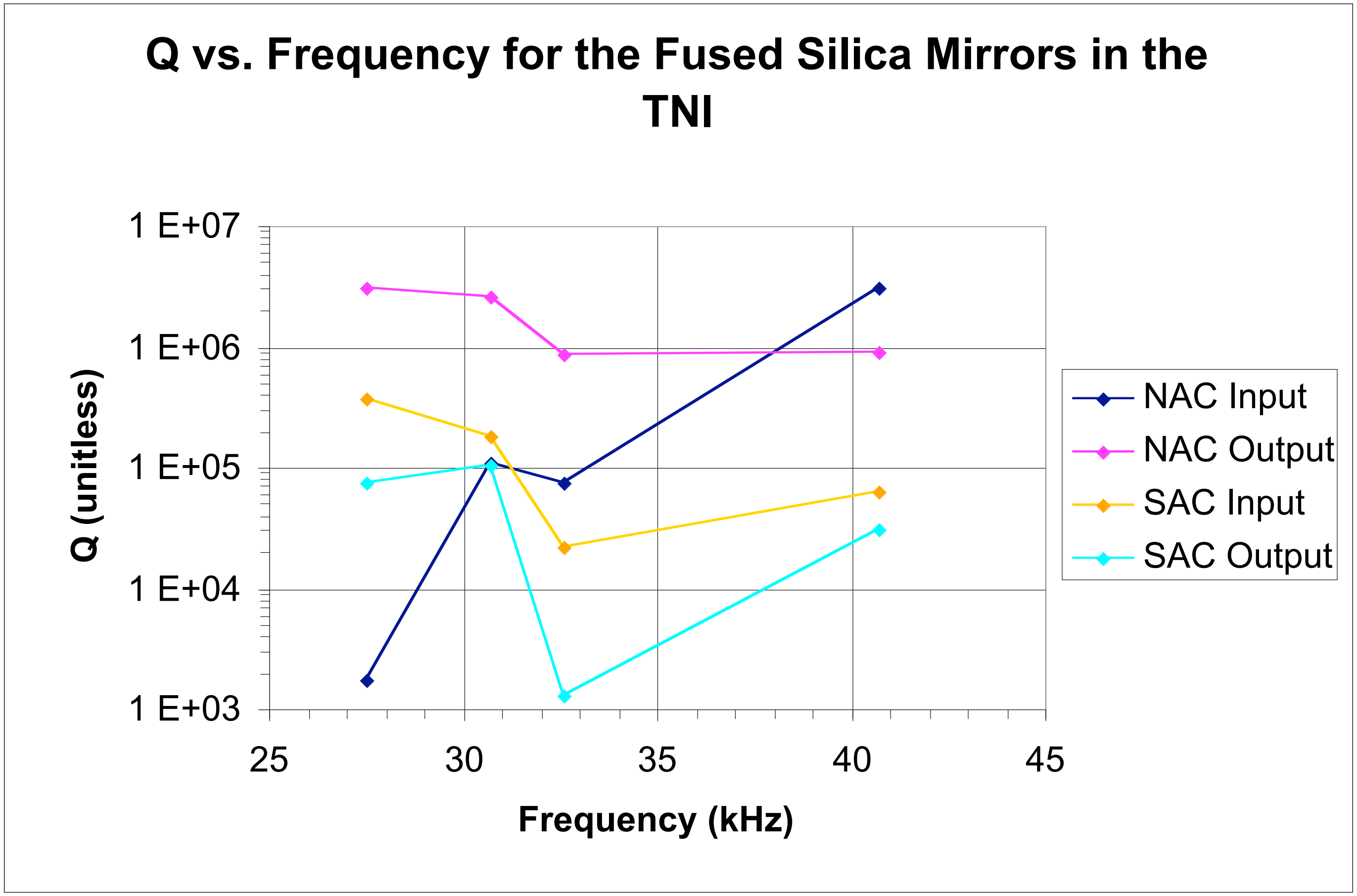
Mirror Response (M) Recalibration



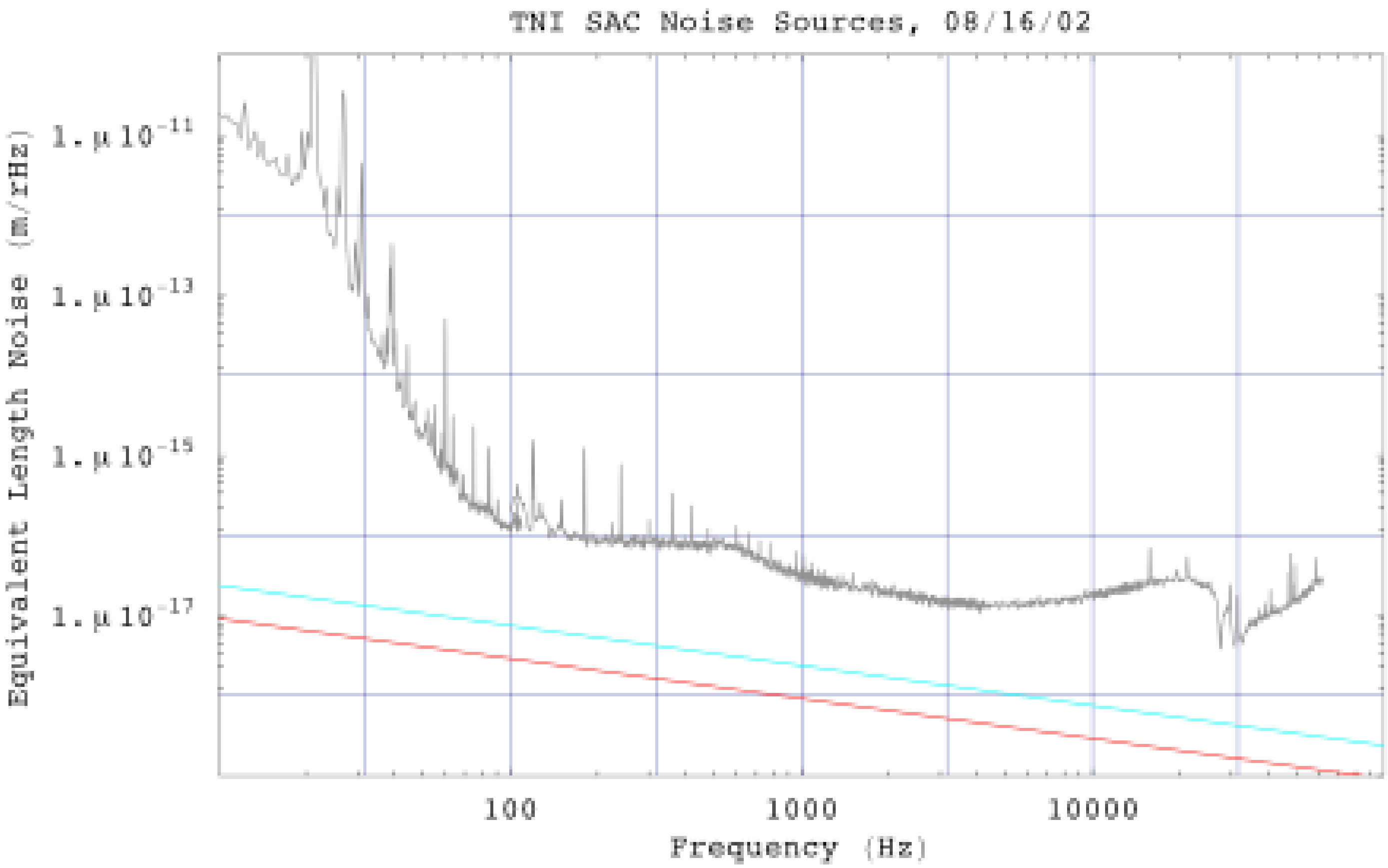
- Original mirror response calibration used auxilliary Michelson interferometer.
- First, rough estimate gave 1.0μm/V at dc.
- Recalibration using laser PZT response (well known) yields 0.63μm/V at dc.
- All previous noise curves were actually lower by 40% than originally estimated.
- Best noise estimate (December) 1.5e-18m/√Hz -> 9.4e-19m/√Hz.

Q Measurements in Fused Silica Test Masses

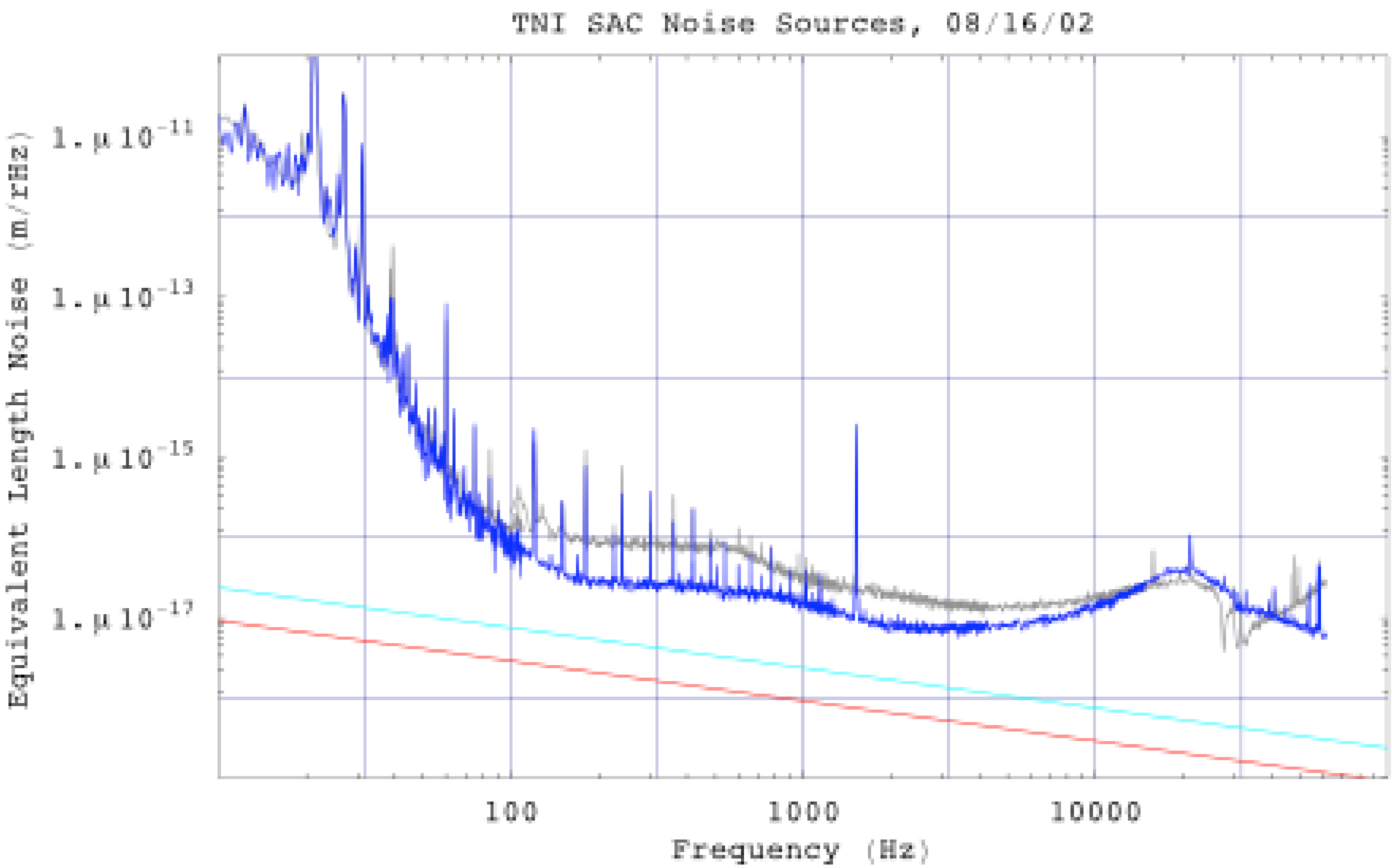
- Q measurements were found to vary from 1700 to over 3 million.



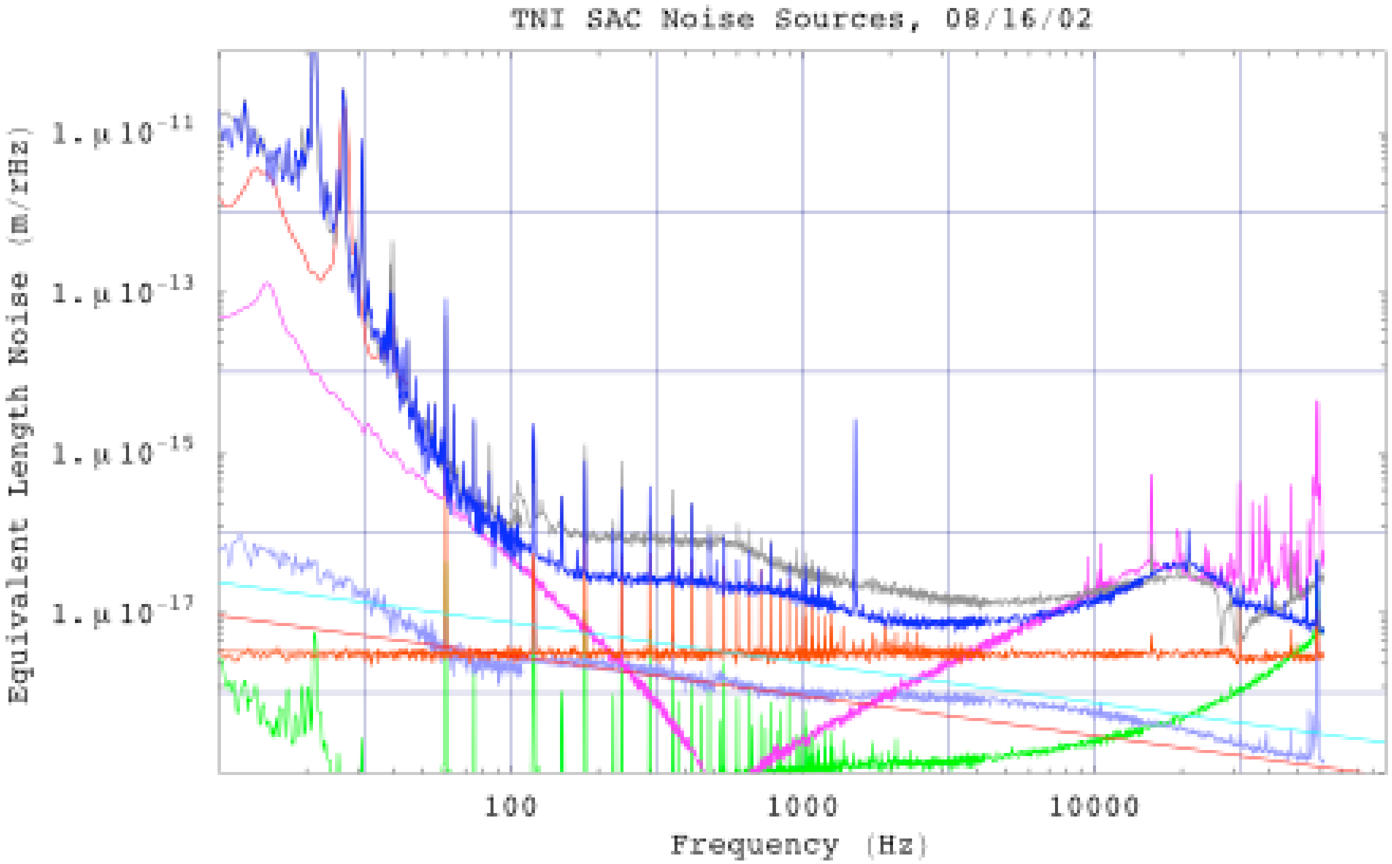
TNI SAC Noise After First Round of Improvements



TNI SAC Noise After First Round of Improvements



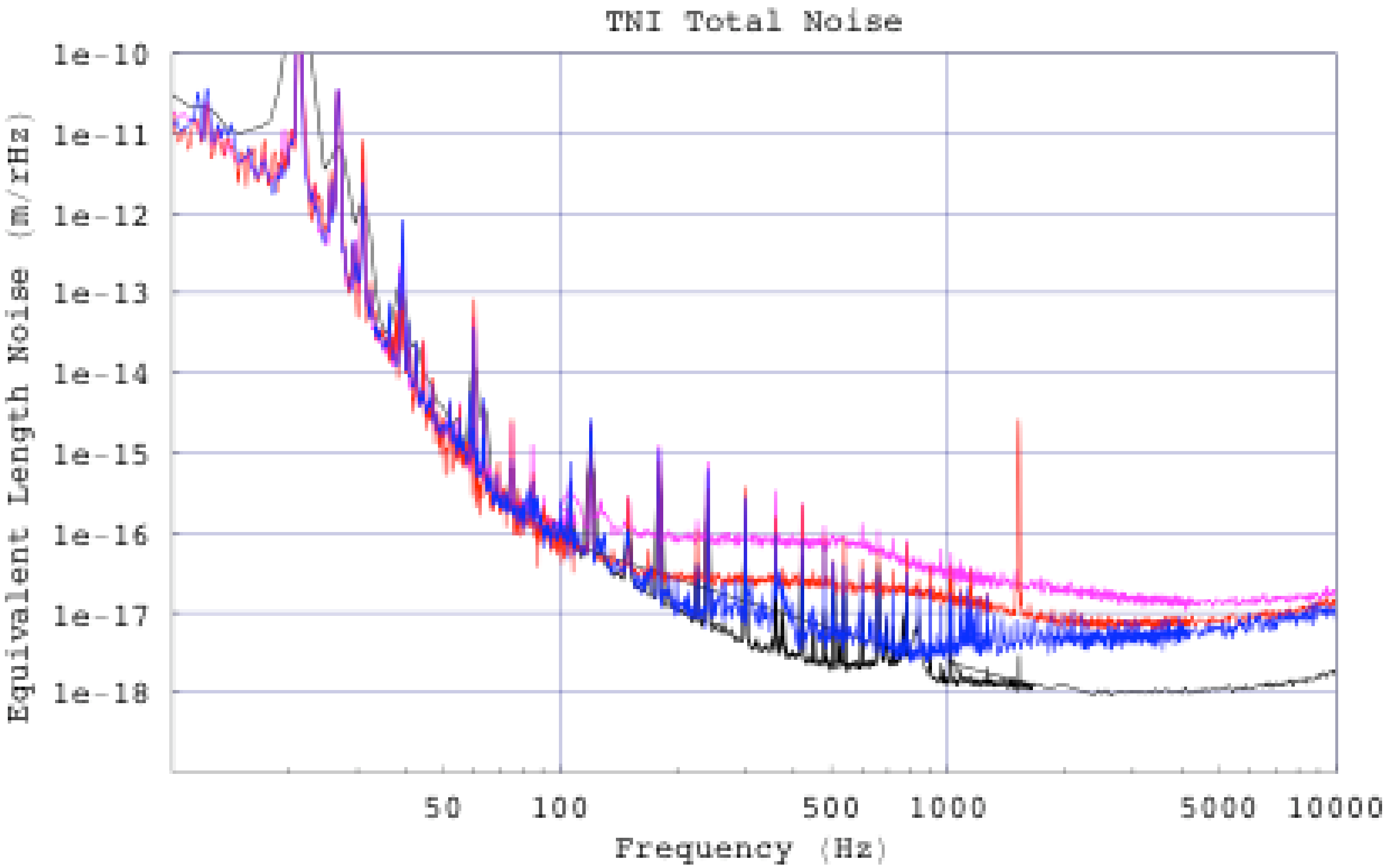
TNI SAC Noise After First Round of Improvements



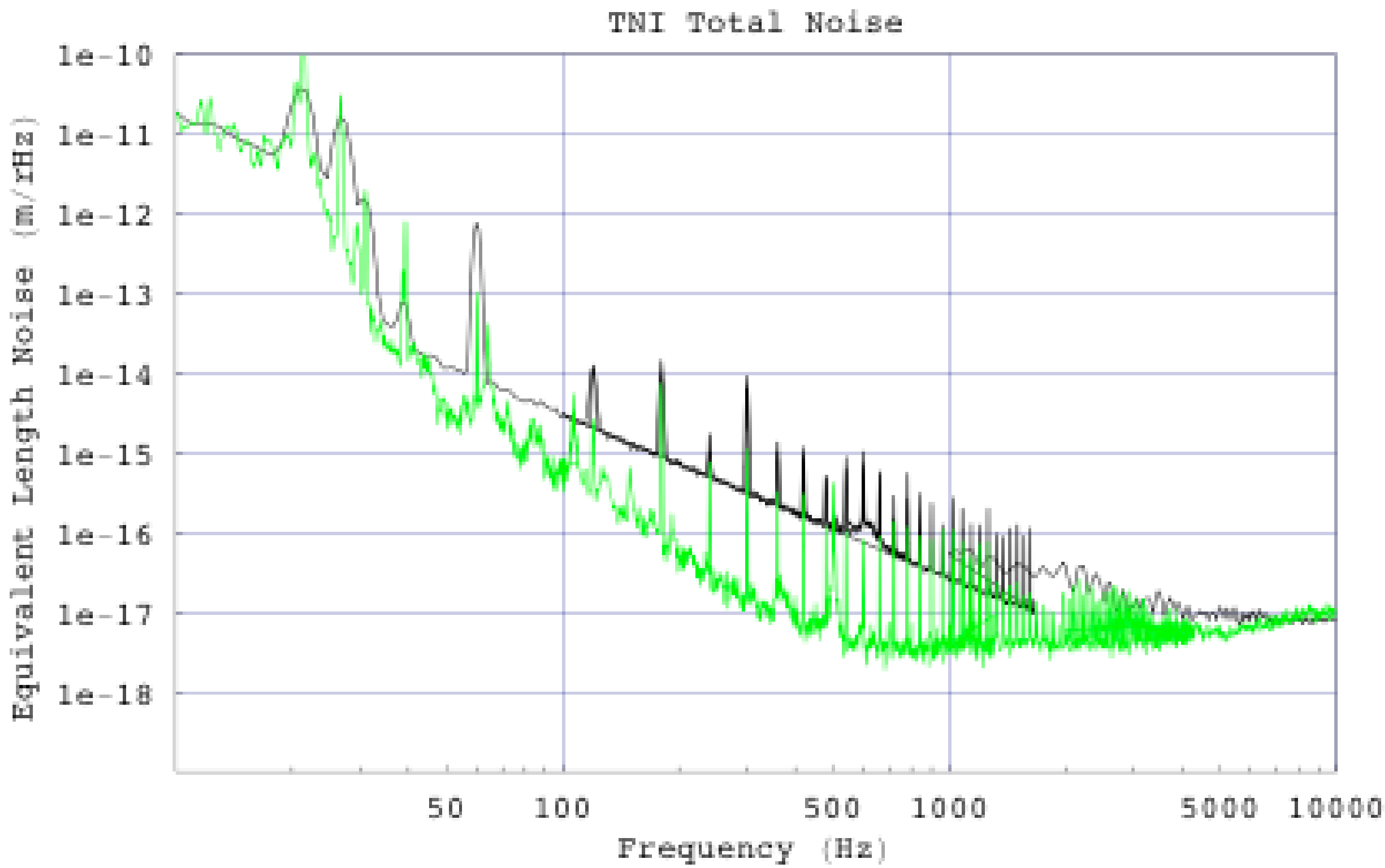
Second Round of Improvements

- Complete realignment for improved visibility
  - Visibility and discriminant increased substantially in all three cavities (NAC, SAC, and MC), expect corresponding decrease in shot noise.
  - Transient locks caused temporary problems, solved *ad hoc*.
  - Mode cleaner now oscillates at moderate gains, limiting our ability to suppress laser frequency noise above ~3kHz.
- Checked all photodiodes
  - None were tuned to the correct frequency.
  - Rich Abbot & Dave (re)tuned. We will monitor for drift.
- Improved bandwidth for NAC
  - Excite additional mirror modes, violin-mode fundamental!
  - Constructed and installed additional notch filters to remove.
- Other noise sources identified.
  - Scattered Light: identified major source, suppressed but did not eliminate.
  - Acoustic coupling: identified but not addressed (dominant?).
  - Air-current noise: identified but not addressed (dominant?).
  - Origin of most peaks identified: 60Hz, violin modes, bounce & roll modes, etc.

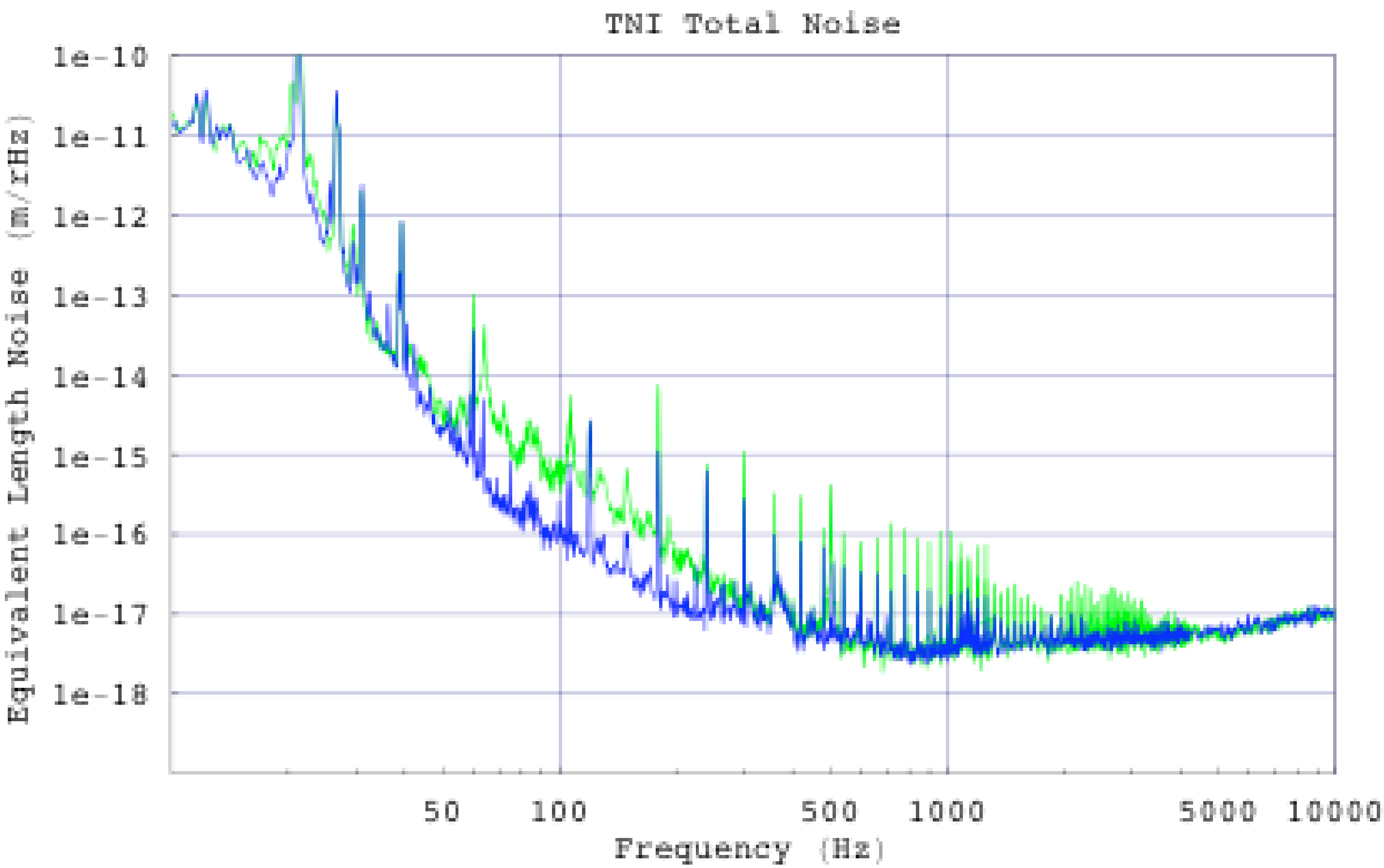
Sensitivity after Second Round of Improvements: SAC



Sensitivity after Second Round of Improvements: NAC



Sensitivity after Second Round of Improvements: NAC and SAC



Conclusions I: The Instrument

- Second round of improvements focus on
  - Improving alignment, visibility
  - Quality Control of RF photodiodes
  - Additional notch filters for NAC
  - Resolving transient locks, again *ad hoc*.
  - Identifying and suppressing sources of scattered light noise.
- Results
  - SAC noise now nearly down to "best ever" spectrum.
  - NAC noise substantially better than before, currently "best ever" for this arm.
  - NAC and SAC noise floors now identical over most frequency ranges.
- Still to do:
  - Resolve mode cleaner oscillations, increase gain.
  - Recalculate noise breakdown with latest improvements.
  - Suppress remaining scattered light noise.
  - Address acoustic coupling, air-current noise?

Science: Substrate Thermal Noise and Observed Q's

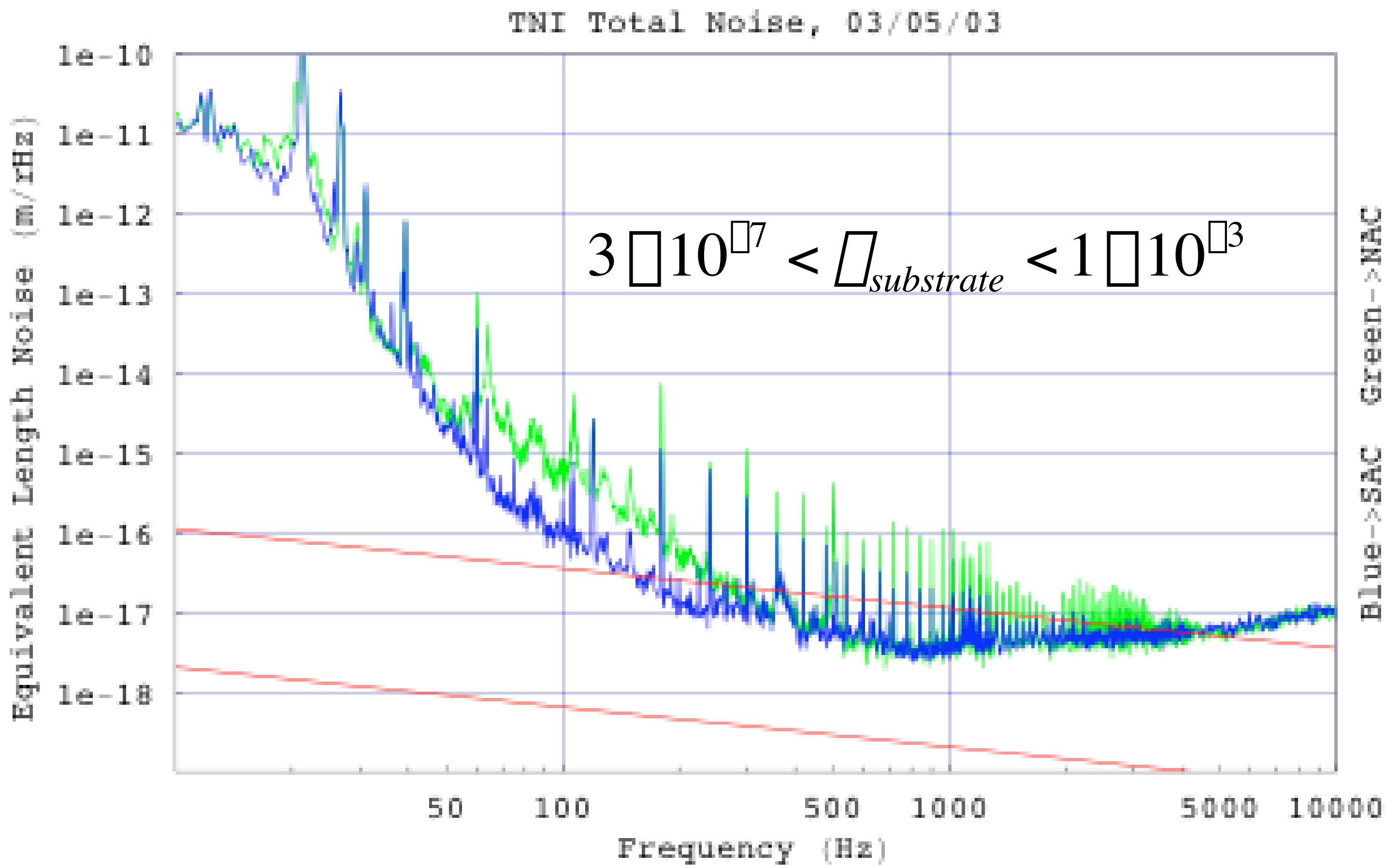
- Mirror Q's may be determined by localized losses, e.g.
  - Barrel polish (visibly poor)
  - Magnets glued on backs and sides
  - Contact with suspension wires
- Expect bulk thermal noise to be lower than estimates based on Q measurements
  - Yamamoto, *et al.*, Phys. Lett. A 305, pp. 18-25 (2002)
  - Measured mirror Q's in the TNI range from 1e3 to 3e6.

$$\phi_{substrate} = \frac{1}{Q}$$

$$\Rightarrow \quad 3 \times 10^{-7} < \phi_{substrate} < 1 \times 10^{-3}$$

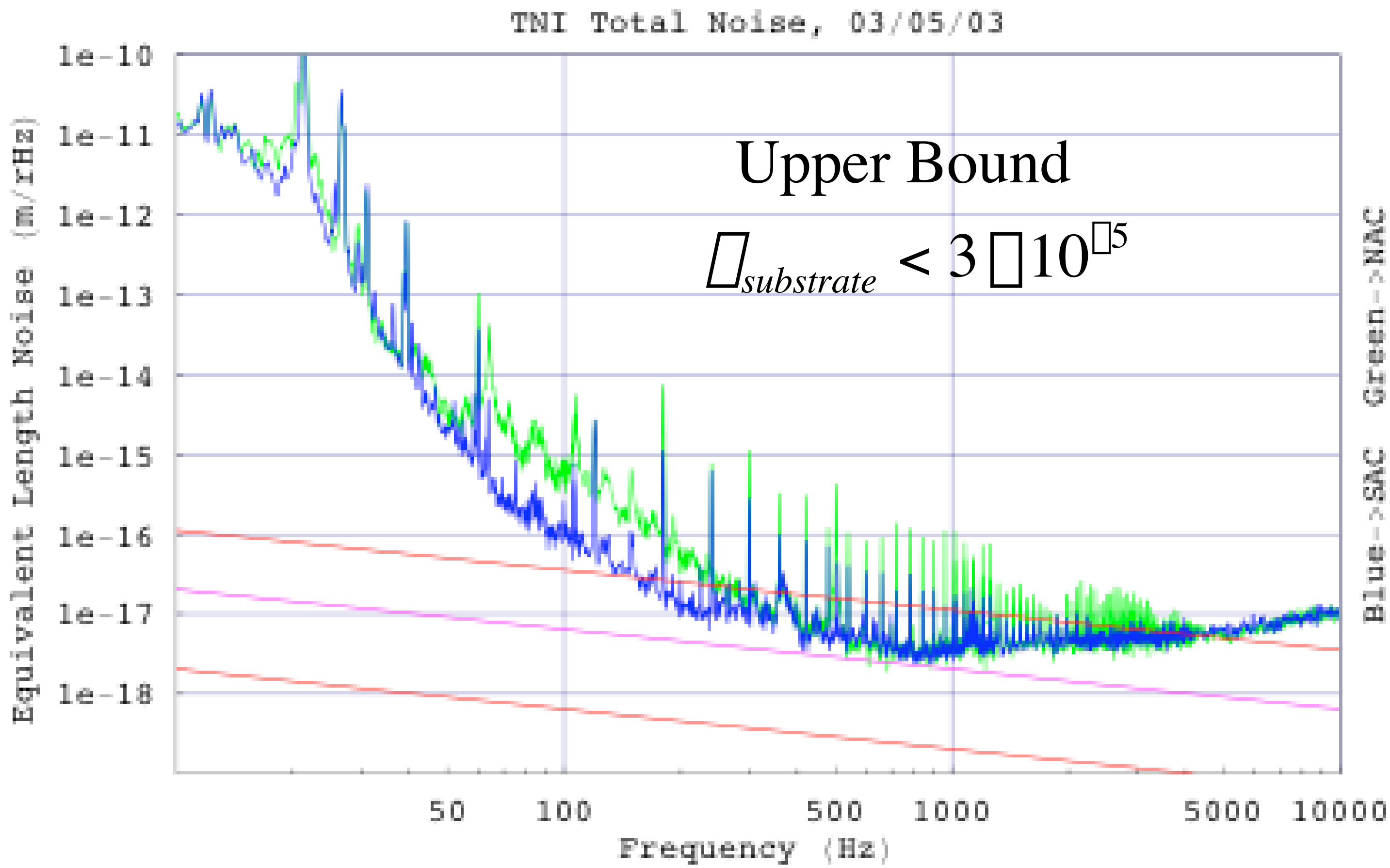
$$S_x(f) \approx \frac{2k_B T}{\pi^{3/2} f} \frac{1}{wY} \phi_{substrate}$$

Substrate Thermal Noise Estimates: Based on Q Measurements



$$3 \times 10^{-7} < \phi_{substrate} < 1 \times 10^{-3}$$

Substrate Thermal Noise Estimates: Based on Minimum Noise Curve



Upper Bound

$\phi_{substrate} < 3 \times 10^{-5}$

Science: Coating Thermal Noise

- Coating thermal noise, best estimate…
  - Crooks, *et al.*, Class. Quantum Grav. 19 (5) pp. 883-896 (2002)
  - Harry *et al.*, Class. Quantum Grav. 19 (5) pp. 897-917 (2002)

$$S_x(f) \approx \frac{2k_BT}{\pi^{3/2} f}\frac{1}{wY}\left(\phi_{substrate} + \frac{1}{\sqrt{\pi}}\frac{d}{w}\left(\frac{Y'}{Y}\phi_{\parallel} + \frac{Y}{Y'}\phi_{\perp}\right)\right)$$

$$\sim \frac{k_BT}{wYf}\left(\phi_{substrate} + \frac{d}{w}\phi_{coating}\right)$$

•Ringdown coating-Q measurements give $\phi_{\parallel}$, but only direct measurement can give $\phi_{\perp}$?

•Condition required to distinguish coating thermal noise from substrate thermal noise:

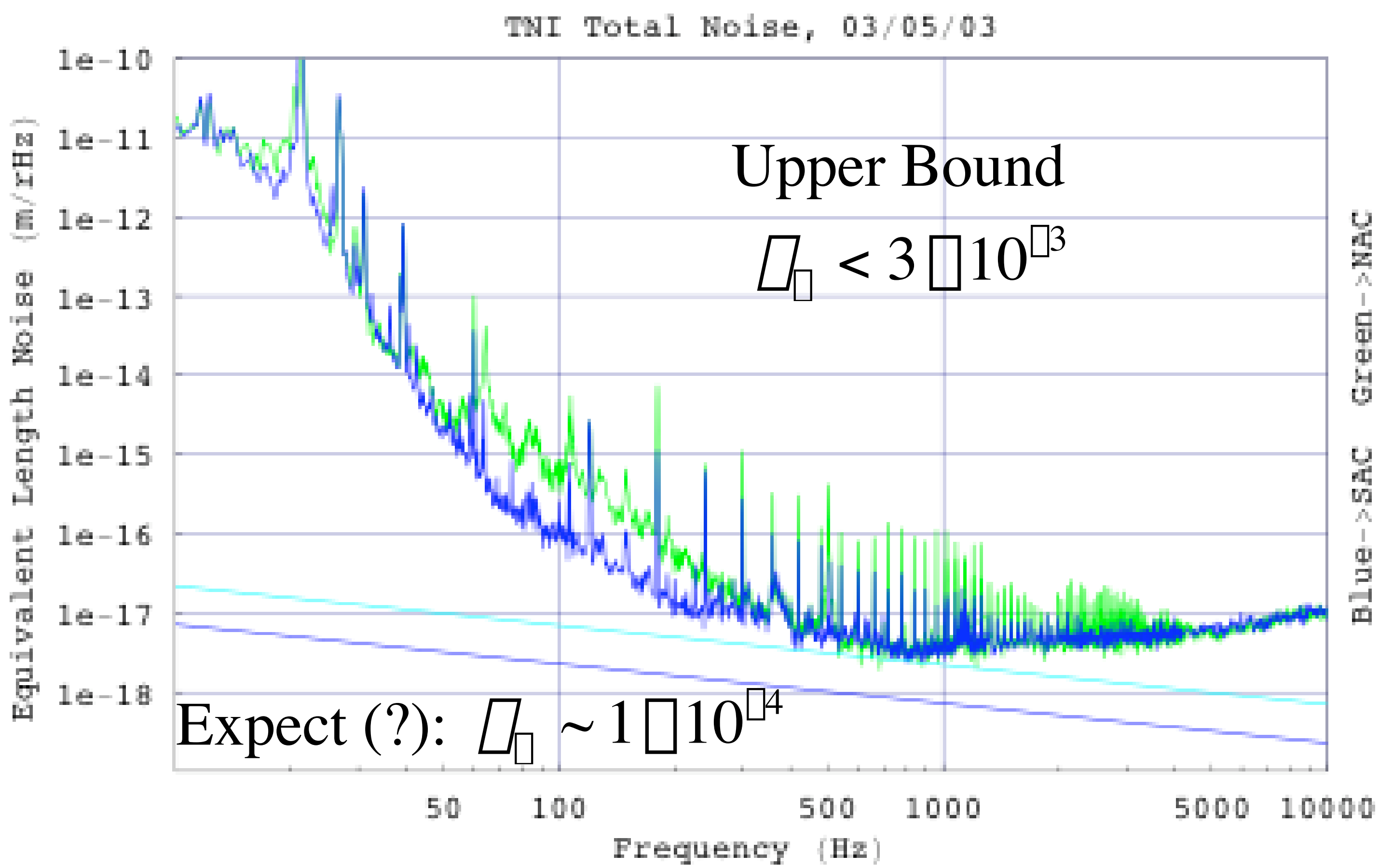
$$\phi_{coating} >> \frac{w}{d}\phi_{substrate}$$

For the TNI, $\frac{w}{d} \approx \frac{160\mu m}{5\mu m} = 32$

Expect: $\phi_{coating} \sim 1\times10^{-4}$ $\phi_{substrate} \approx 3\times10^{-7}$

Condition met by factor of ten in TNI?

Coating Thermal Noise Bound



Upper Bound

$\phi_\perp < 3 \times 10^{-3}$

Expect (?): $\phi_\perp \sim 1 \times 10^{-4}$

Assuming: $\phi_\parallel = 1 \times 10^{-4}$