LIGO’s Thermal Noise Interferometer

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LIGO Science Seminar

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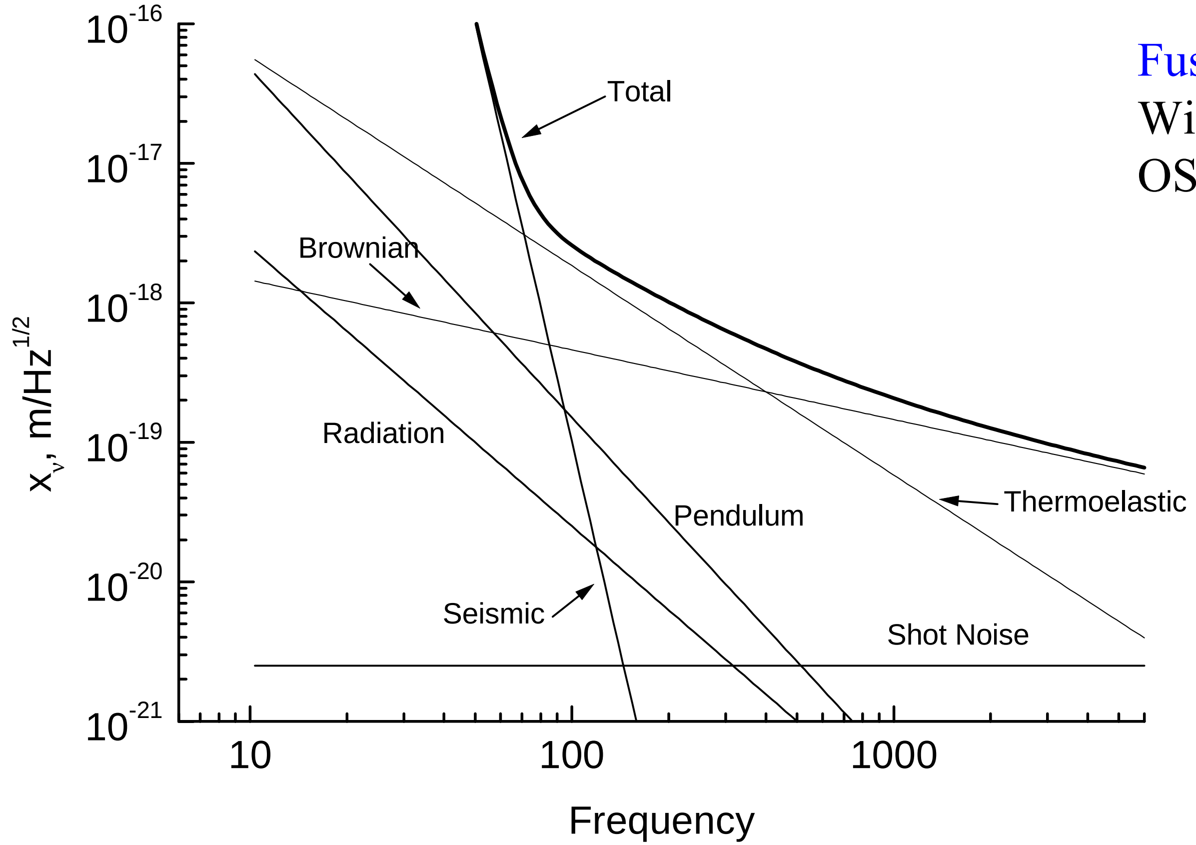
G020459-00-R

TNI Purpose and Goals

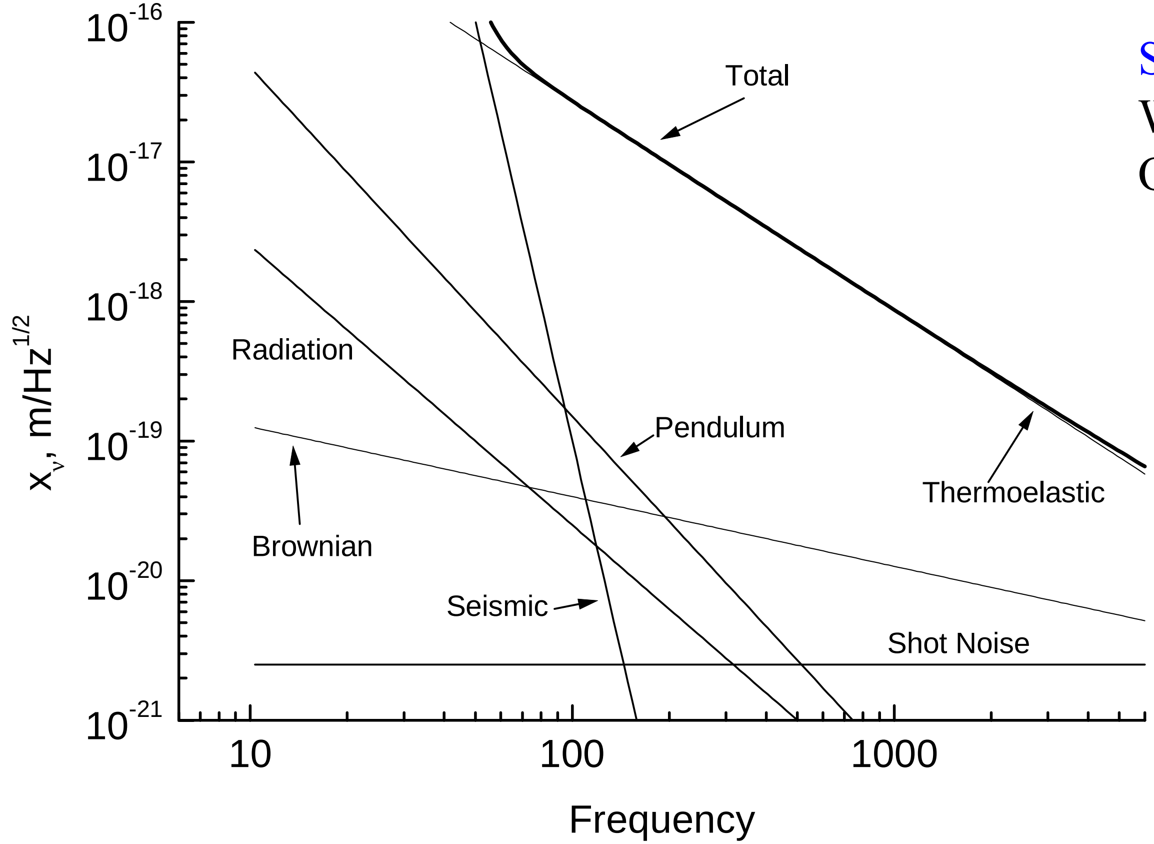
- Short Term
  - Isolate and study different kinds of thermal noise relevant to LIGO, e.g. coating thermal noise.
  - Characterize Sapphire for use in LIGO II: Noise Performance and Lead time.
  - Test Braginsky's model for Thermoelastic-Damping Noise (Intrinsic T fluctuations) in Sapphire.
- Long Term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

TNI Phase I Expected Spectrum



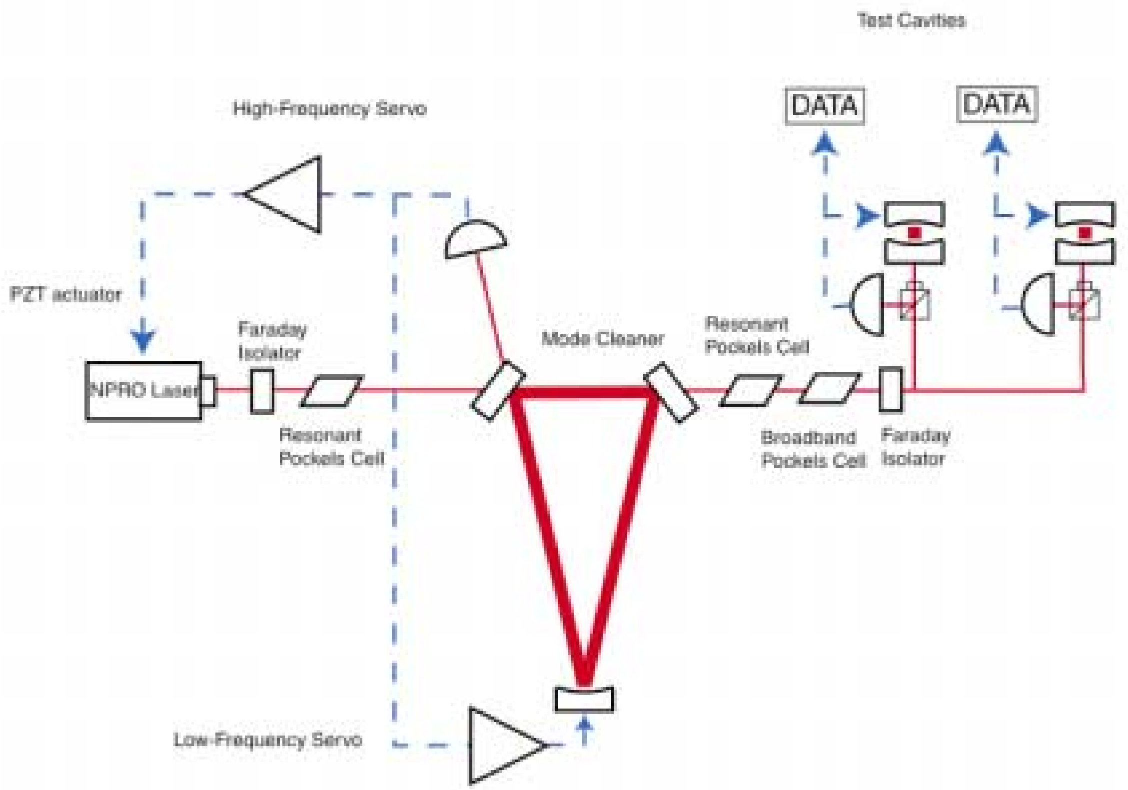
Fused-Silica Test Masses
Wire Suspensions
OSEM Actuation

TNI Phase II Expected Spectrum



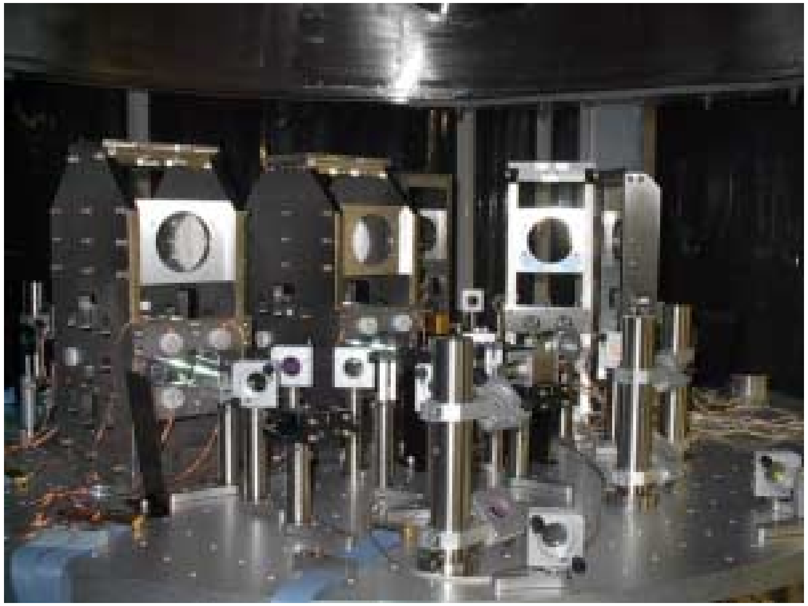
Sapphire Test Masses
Wire Suspensions
OSEM Actuation

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

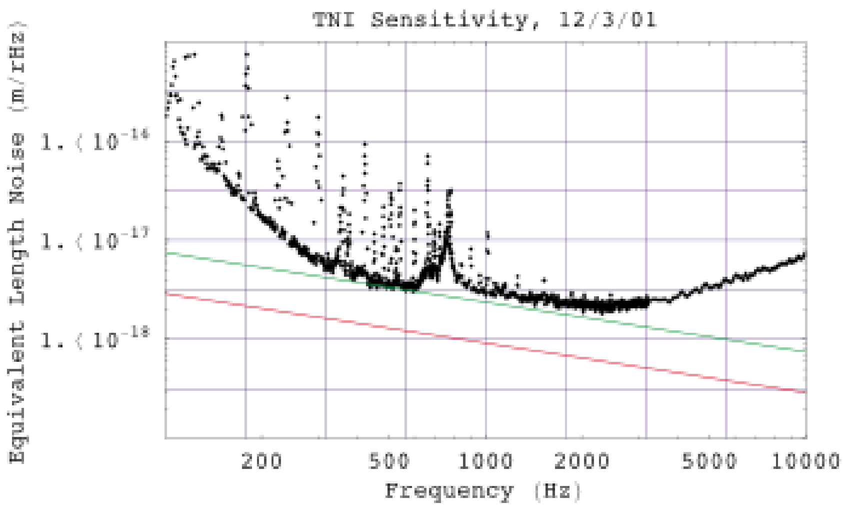


- Mode cleaner, arm cavities all contained in one chamber, mounted on a single stack.
- Wire suspensions similar to LIGO-I Small Optics Suspensions.
- OSEM actuation, all analog.
- Laser: 750mW NPRO (Lightwave).
- All hardware purchased, installed, and commissioned.

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 2001: Review prompts schedule change: Delay Sapphire installation in favor of further Fused Silica research.
- Spring-Summer 2002: Improve noise in NAC, identify individual contributions to noise curve (partially met).
- August 2002: Change in AdvLIGO mirror-material downselect date gives us more opportunities for Fused Silica research.

TNI Sensitivity (12/01): 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 appear to be consistent with thermal noise.**

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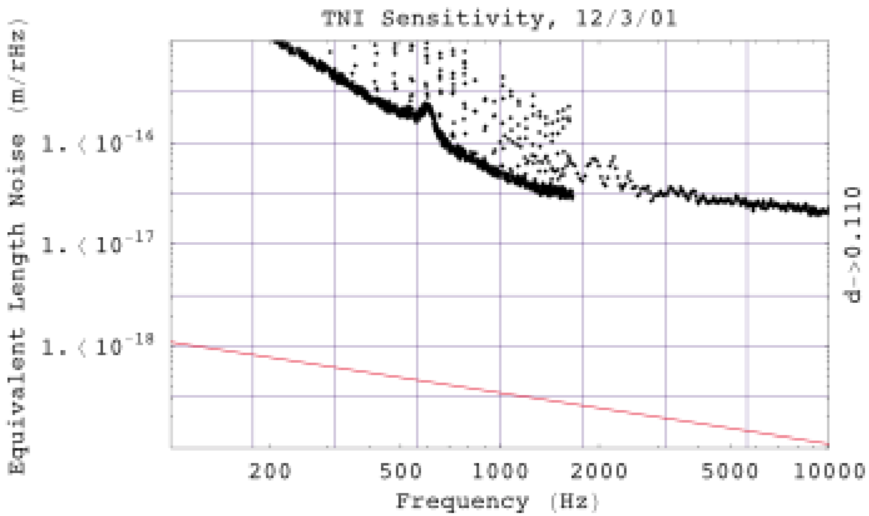
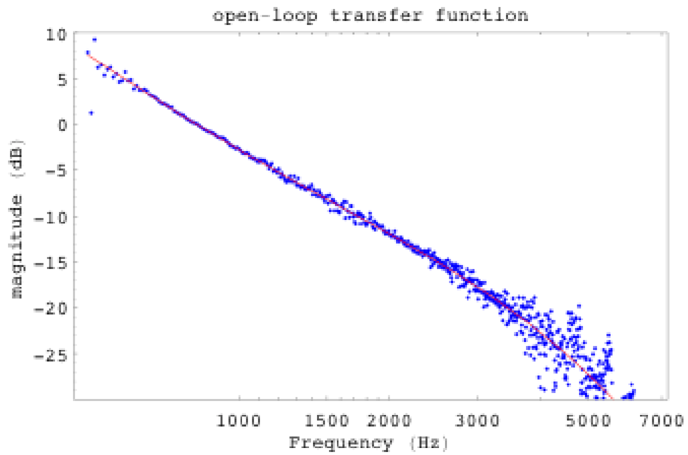
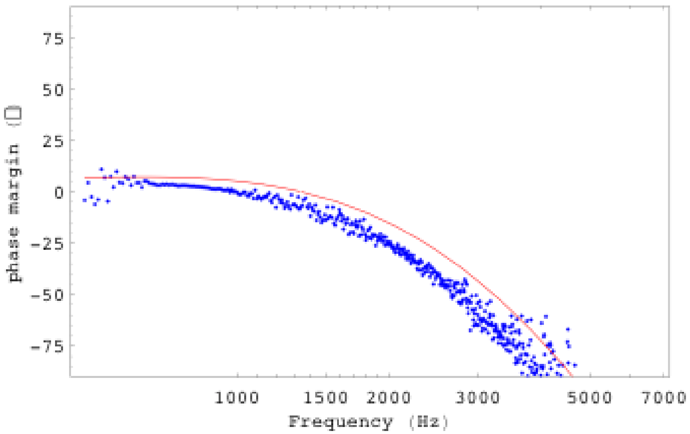
TNI Sensitivity (12/01): North Arm Cavity



- **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?**

Bandwidth and Phase Margin (12/01)





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

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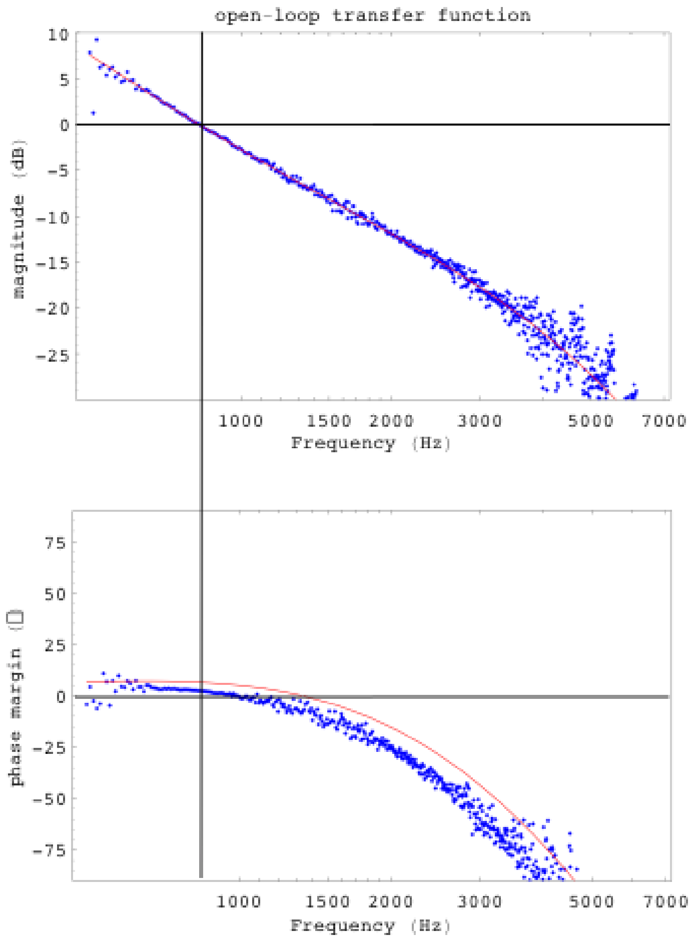
Bandwidth and Phase Margin (12/01)



- 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!

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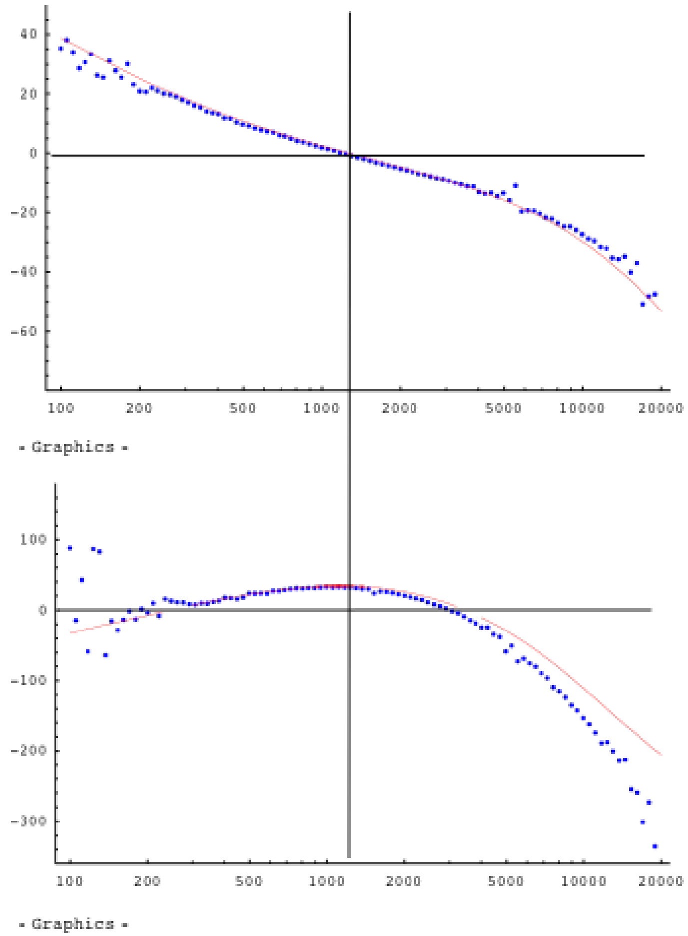
First interesting results: 12/01-2/02

- 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 ~750 Hz.
- 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?

TNI Progress Since 2/02: Lock Acquisition Improvement

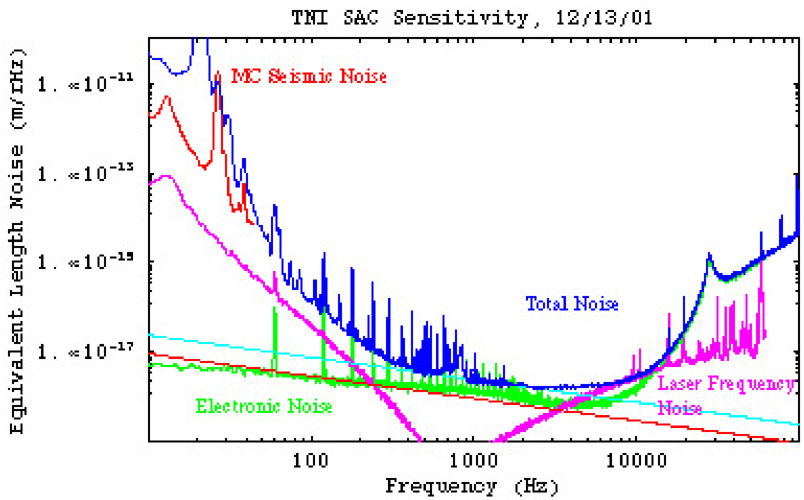


- Active Notch filter array replaces single, passive notch (many thanks to Flavio Nocera).
- Phase margin now positive up to ~2.5kHz.
- Unity-gain frequency (UGF) of ~1.5kHz sufficient for rapid and robust lock.
- Phase margin now ~25°.
- Both NAC and SAC acquire TEM00 modes within ~15s, even during 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

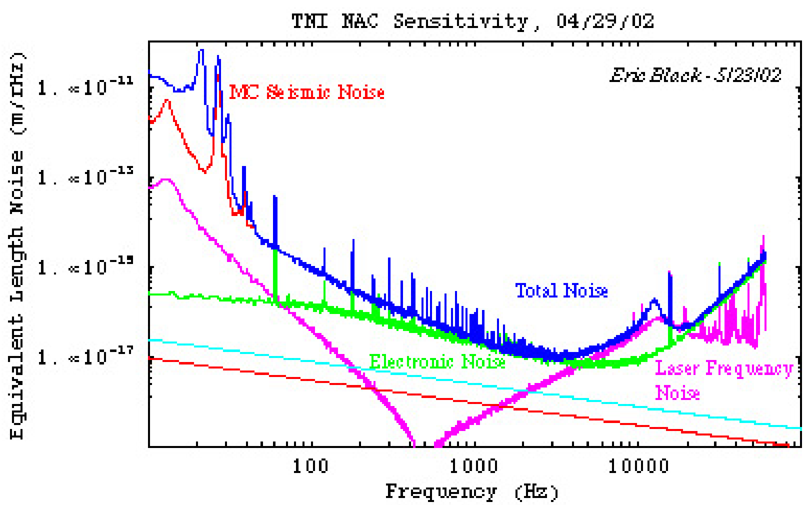
- Why was NAC's optical gain lower than SAC's by two orders of magnitude?
  - Power incident on NAC was 1/2 of the power incident on SAC: Beamsplitter (50UNP) meant for unpolarized light, gave 70/30 for p-polarization.
  - NAC's RF photodiode had lower response than SAC's: NAC's RF photodiode tuned to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

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



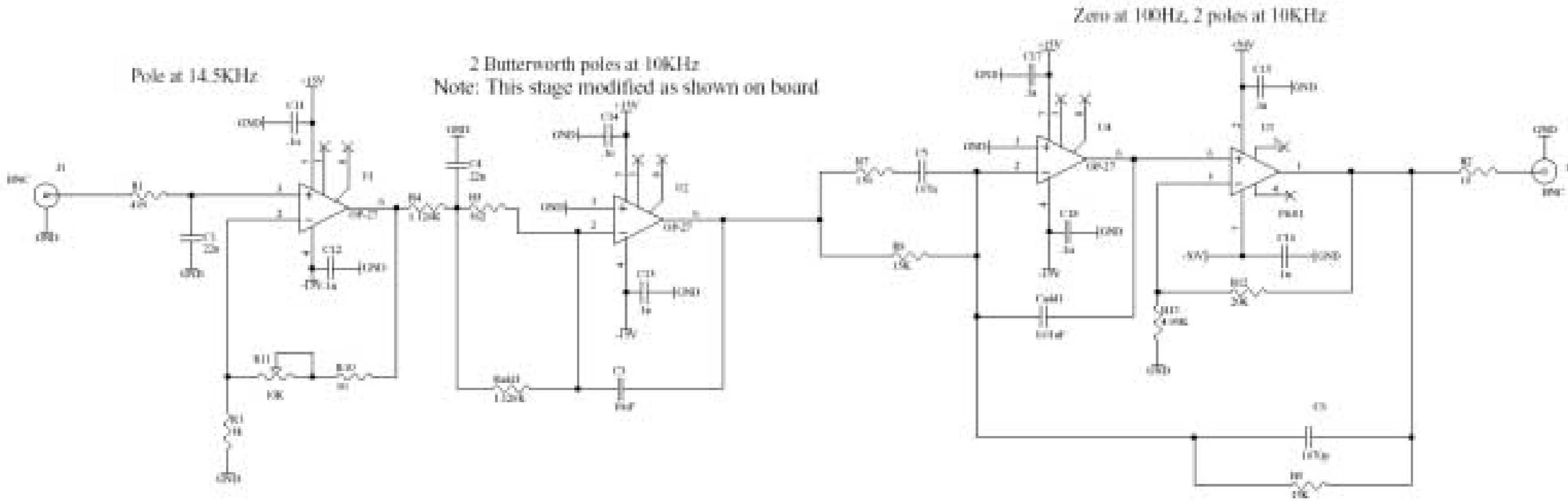
- Noise Sources identified:
  - Electronic noise.
  - Laser Frequency noise.
  - Seismic noise in Mode Cleaner (imposed on laser frequency noise)
- Electronic noise very close to total noise floor!
- Further noise breakdown deferred until after servo improvements.

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



- After servo improvements.
- After NAC RF photodiode replaced.
- Before polarization, beamsplitter corrected.
- Electronic noise clearly dominates.

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)

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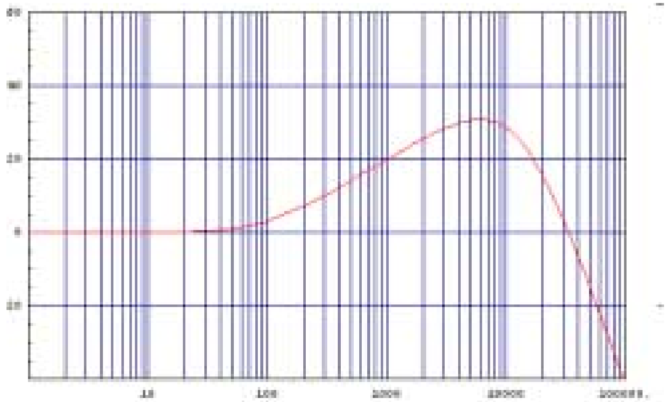
NEW Servo Filter Design

- 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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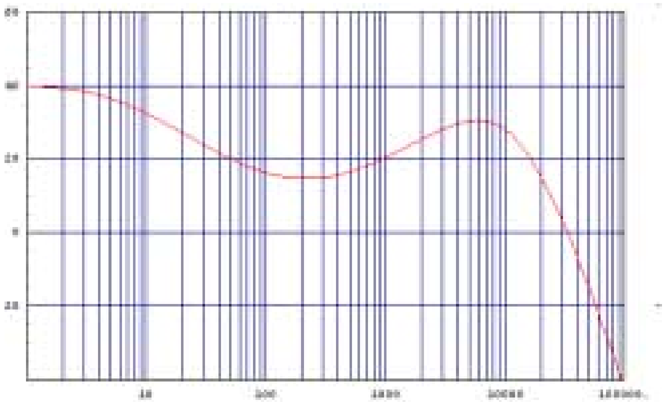

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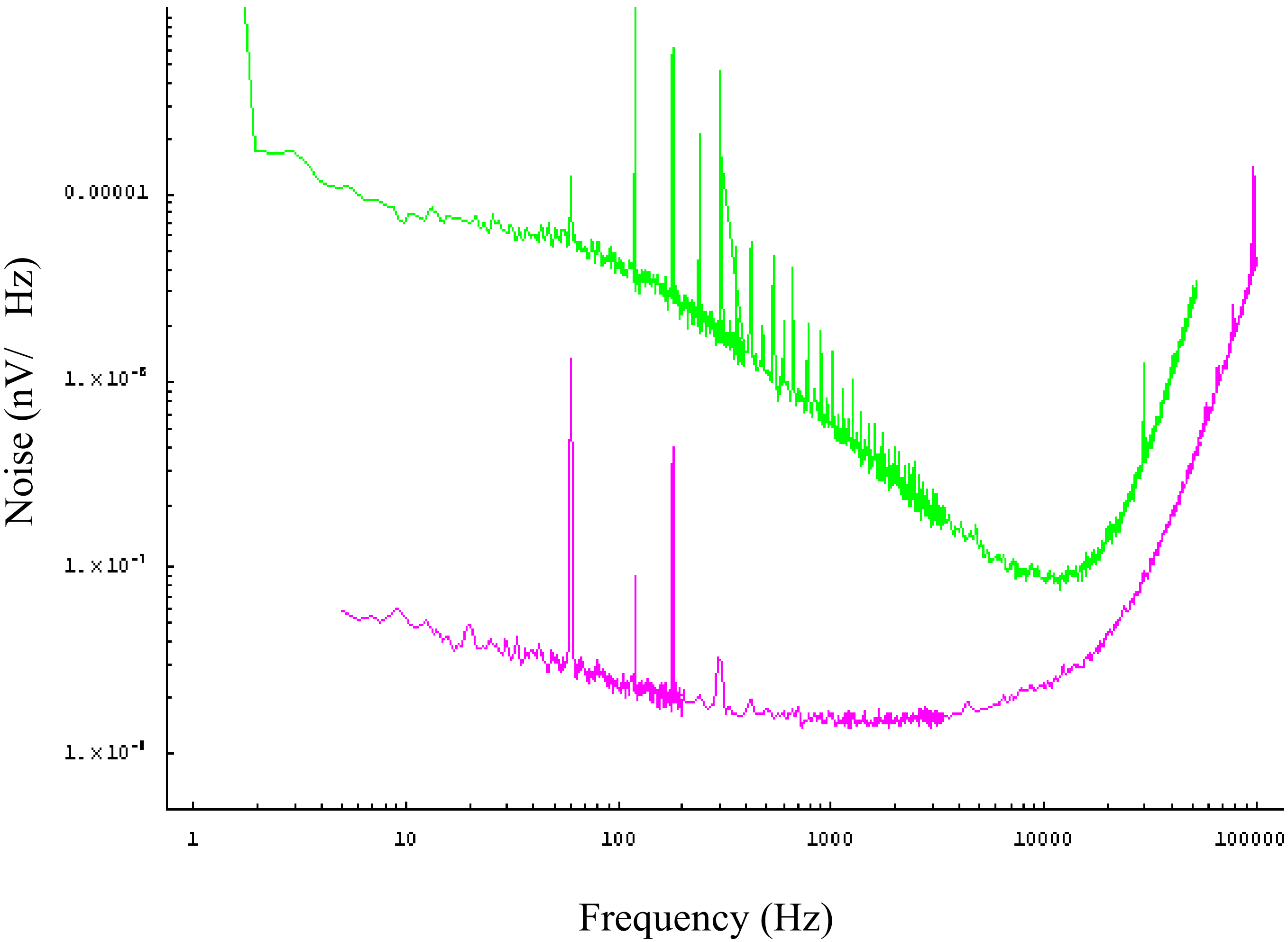
Noise Performance



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

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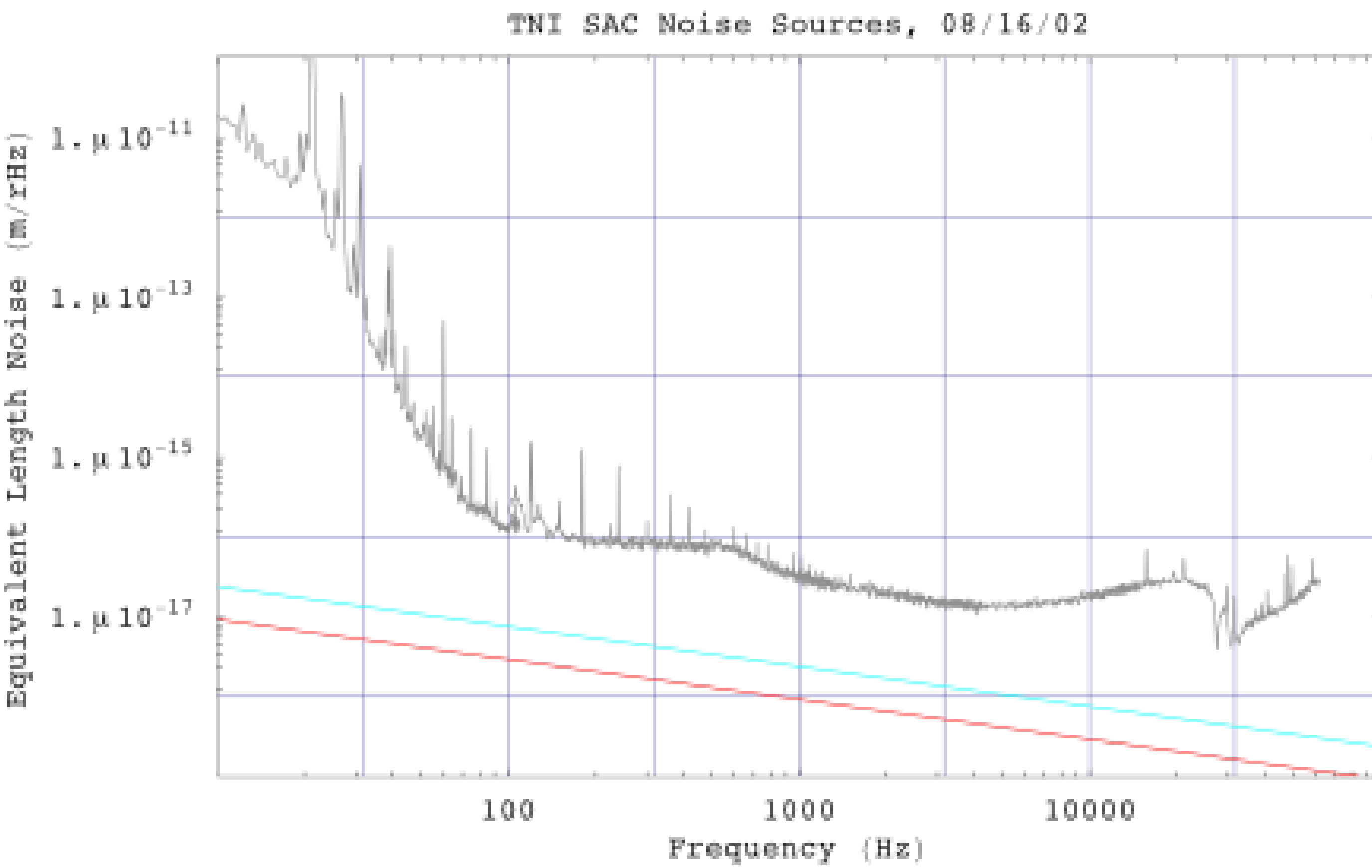
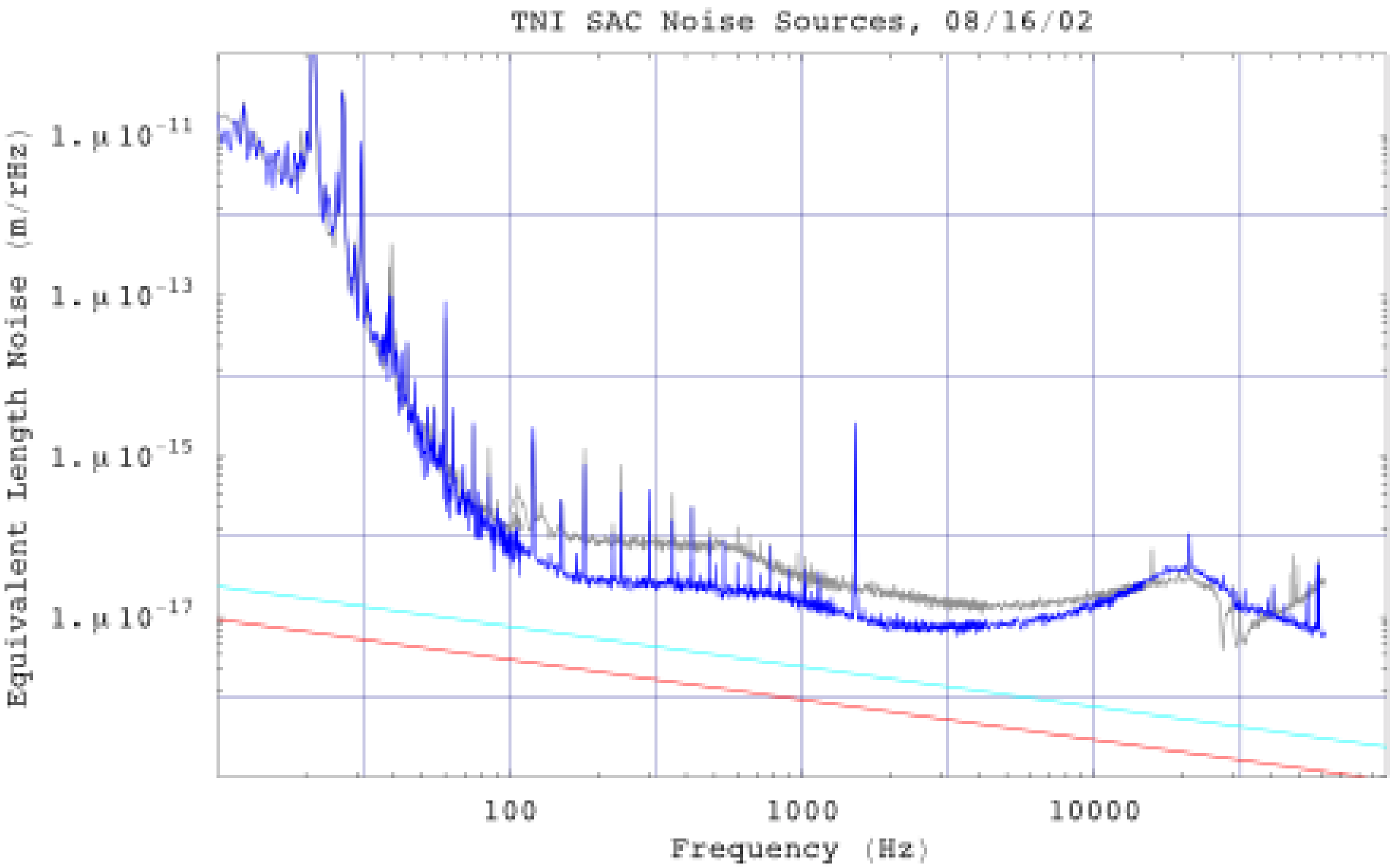
Power equalized between NAC, SAC

- Total power incident on both cavities increased by x2 by optimizing polarization, 45° to horizontal.
- Faraday Isolator rotated by 90°, half-waveplate inserted to restore horizontal (p) polarization.
- Beamsplitter replaced to provide 50% for p-polarization.
- Reflected power, error signal differences resolved between NAC and SAC.

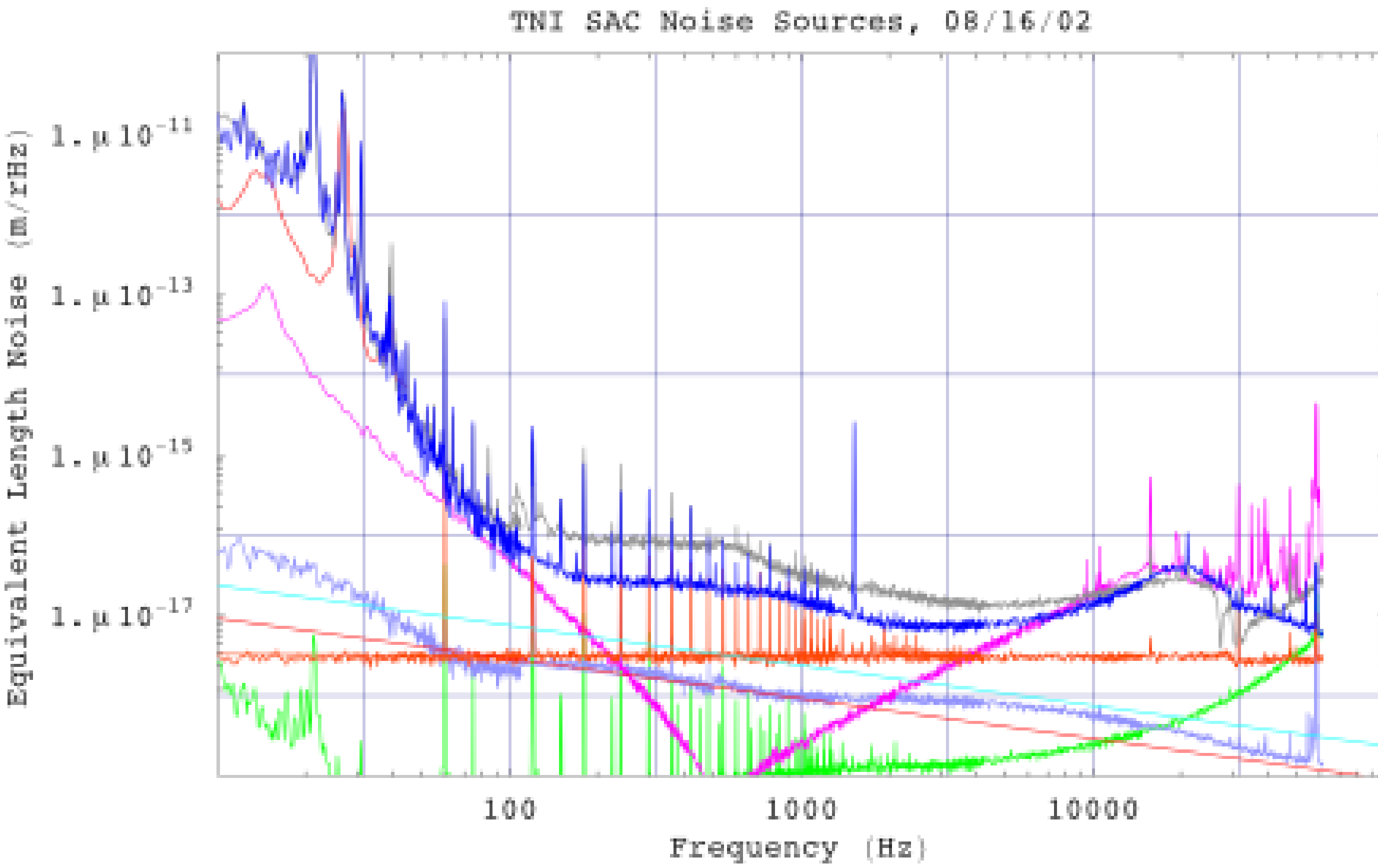
TNI SAC Noise After Improvements



TNI SAC Noise After Improvements

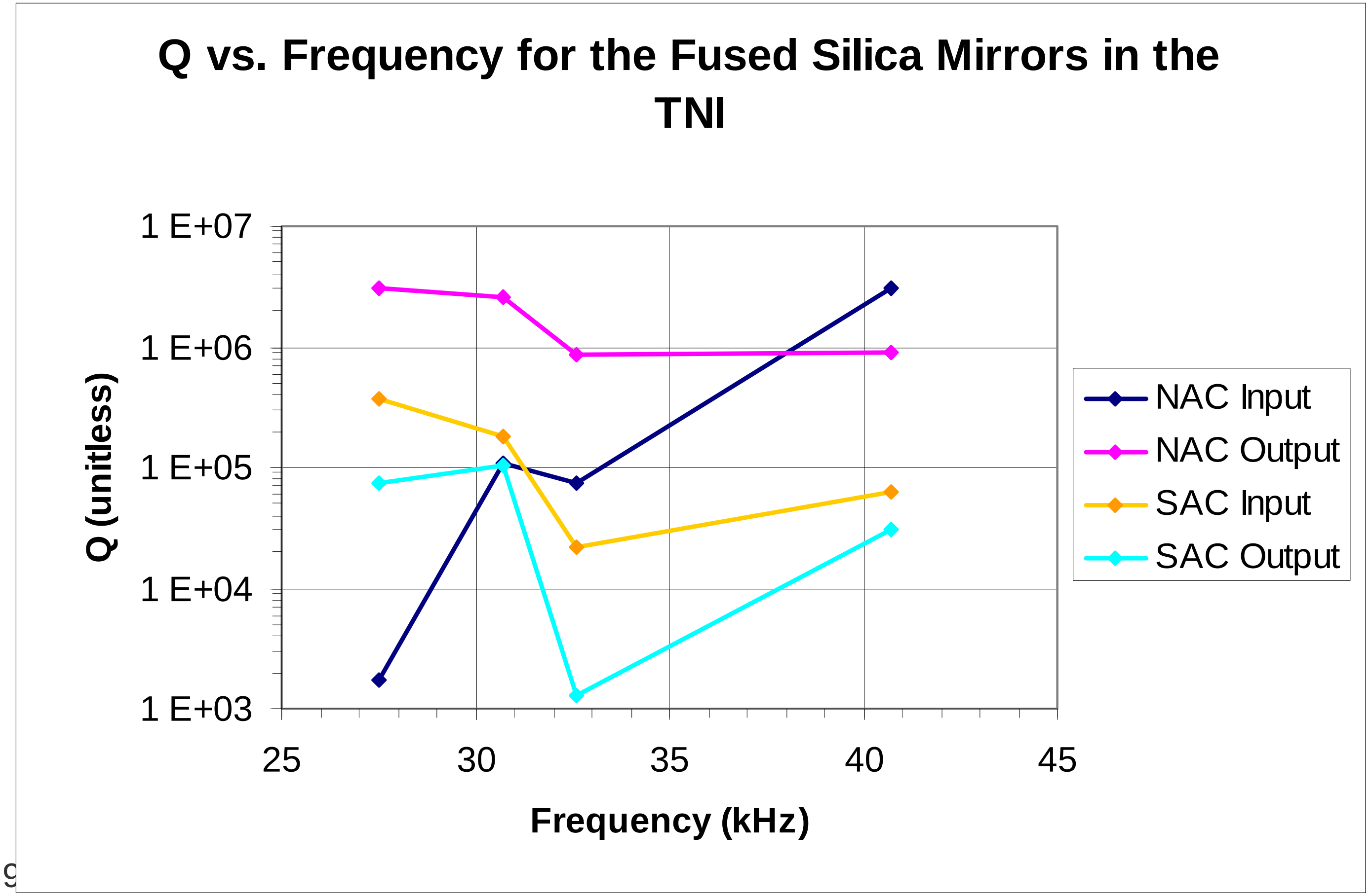


TNI SAC Noise After Improvements

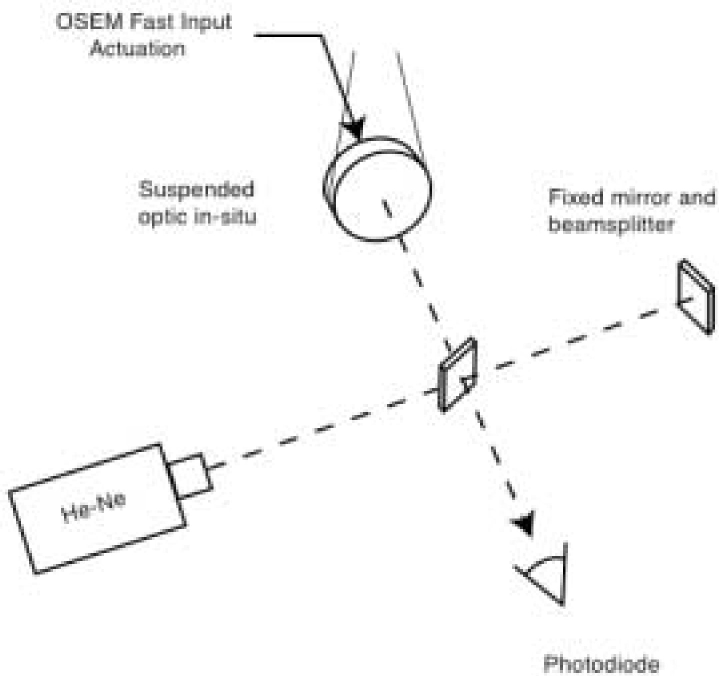


Q Measurements in Fused Silica Test Masses

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



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 0.6µm/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.

Conclusions

- TNI is up and running, has been taking data since 12/01.
- Changes in downselect date will allow us to pursue fused silica measurements, measure coating thermal noise.
- Recent effort has focussed on improving lock acquisition, balancing North and South Arm Cavities.
- TNI servo problems resolved.
- Differences between NAC and SAC error signals resolved.
- Five contributing noise sources identified and measured. More must follow.
- Recalibration of mirror transfer function M confirms initial, rough estimate, reduces all previous noise curves by x0.6. Best noise curve now 9e-19m/√Hz.
- SAC noise up after changes implemented, but coming down.
- Reasonable to expect surprises when Sapphire installed.
- Sapphire optics can be installed at any time, but we hope to get useful data out of fused silica first.