Vibration Control Feedback R&D
at
University of British Columbia

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UBC

NANOBEAM 2002

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on Nanometre-Size Colliding Beams
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Outline

Introduction

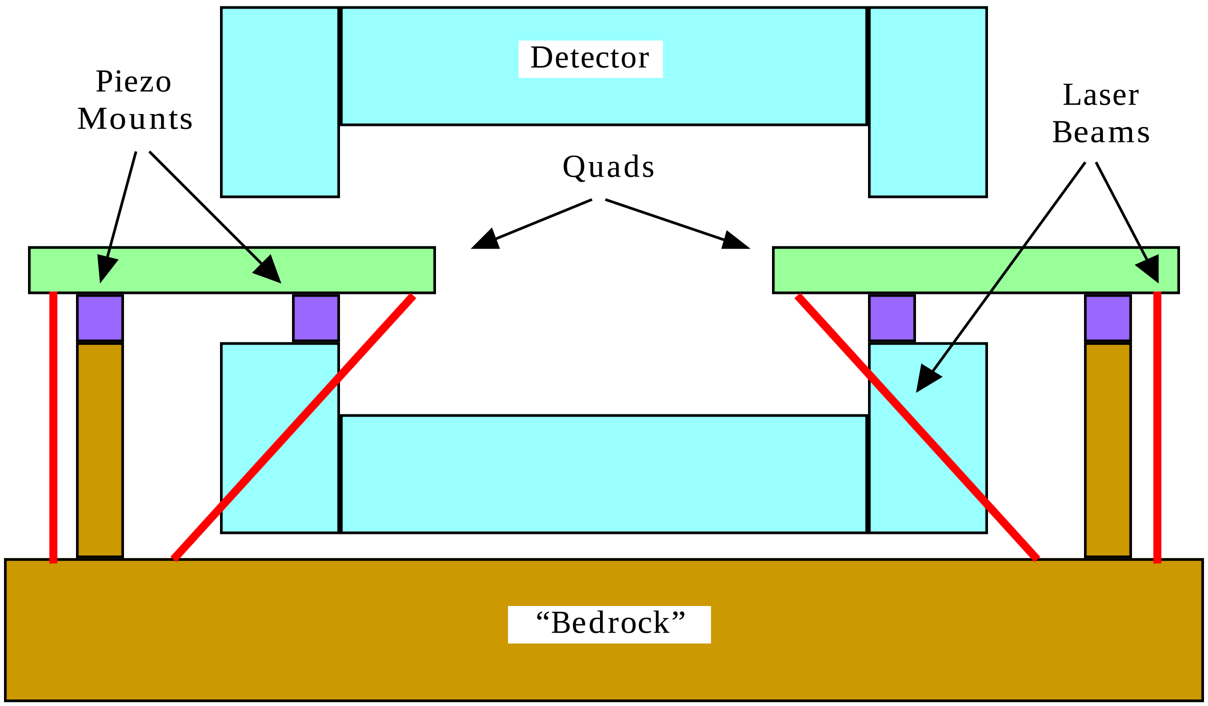
Feedback Test Platform Results

Interferometer Resolution and Feedback Results

Conclusion

Optical Anchor Concept

Measure quad positions with interferometer(s) referenced outside detector
Correct quad positions with piezoelectric(s)



Feedback artificially stiffens supports to simulate a true rigid connection to bedrock

Needs light paths through the detector to "bedrock" or other external references (and other external interferometer arms not shown here).

Alternative Concepts

Intra-Train Beam-Beam Feedback

- Use first bunch(es) deflection to re-steer later bunches
- “Easy” with TESLA bunch train, “hard” with NLC bunch train

Inertial Stabilization

- Put geophones or accelerometers on magnet, and feed back to keep signal zero
- Advantage: No holes in detector
- Advantage: No excitation of internal modes of quad package
- Disadvantage: No DC control because signal fall off below sensor resonance
- Workaround: Use beam-beam deflection for DC control signal
- Challenge: detector-compatible sensor with low noise, low enough resonant freq to match with beam-beam feedback’s limited sampling rate

Inertial stabilization is “anti-control:” trying to keep forces away from quad

- May be done passively at high frequency: mount to anything with a soft spring
- Active control needs to deal with low frequencies, and touch-up high frequencies

Optical anchor is “true-control” of quad position relative to a reference

- May be done passively at low frequencies: mount to reference with a hard spring
- Active control needs to to do real work at high frequencies
- Active control needs to deal with any difference between support position and the reference position
- Reference for optical anchor could itself be a floating object

Alternative Paradigm

Quad supports

- Hard
  - good passive control of position & resistance to on-girder forces
  - transmits external noise into quad package w/o active control
- Soft
  - good passive control of high-frequency vibrations from supports
  - poor passive control of on-girder forces
  - requires soft actuator with long range (electric or magnetic)
- Touch detector or only touch ground? Coupling from test of machine?

Quad position information

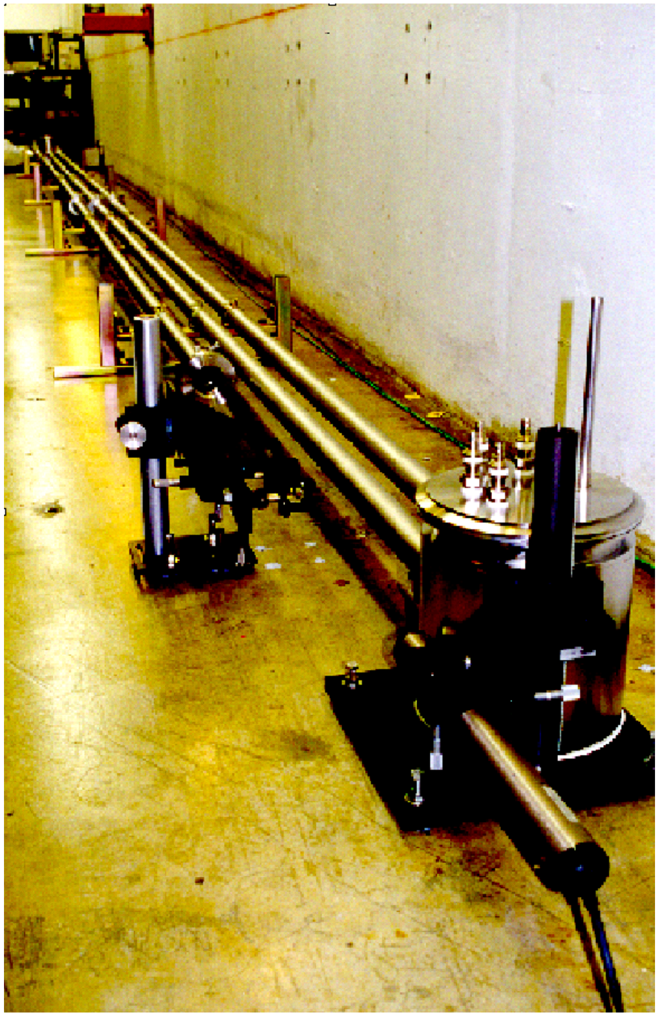
- Beam-Beam Deflection
- Interferometric (possibly capacitive too)
  - relative to ground, or relative to some other object (floating?)
- Geophone (velocity) or accelerometer
  - signal goes to zero below sensor resonance

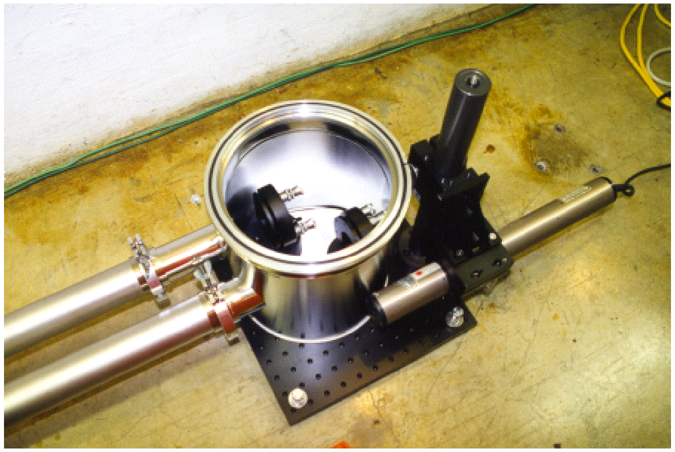
What to do with the quad position information

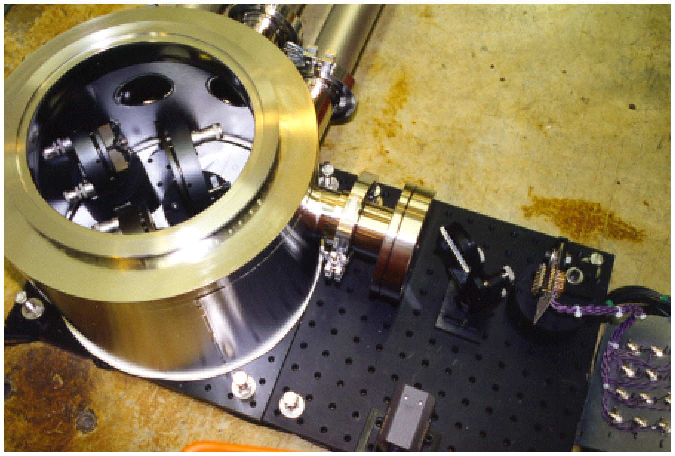
- Re-steer the beams
- Re-position the quad
  - piezoelectric (hard)
  - electric, magnetic (soft)
- Keep quad fixed relative to ground (which point?) (or at least try)
- Keep quad fixed relative to inertial reference (which one?) (or at least try)

Optical Anchor R&D at SLAC

Idea originated at SLAC, and was developed by Mike Woods,
who built a 10 meter folded interferometer in the very quiet and stable Sector 10 adit
and demonstrated 0.2 nanometer resolution and 20 nm / hour drifts
operating in air, but in a metal system designed to be pumped down to vacuum







Optical Anchor R&D at UBC

Our goal at UBC is to demonstrate feedback control of a 100 kg test mass to sub-nanometer precision over a 10 meter baseline.

This required development on several fronts

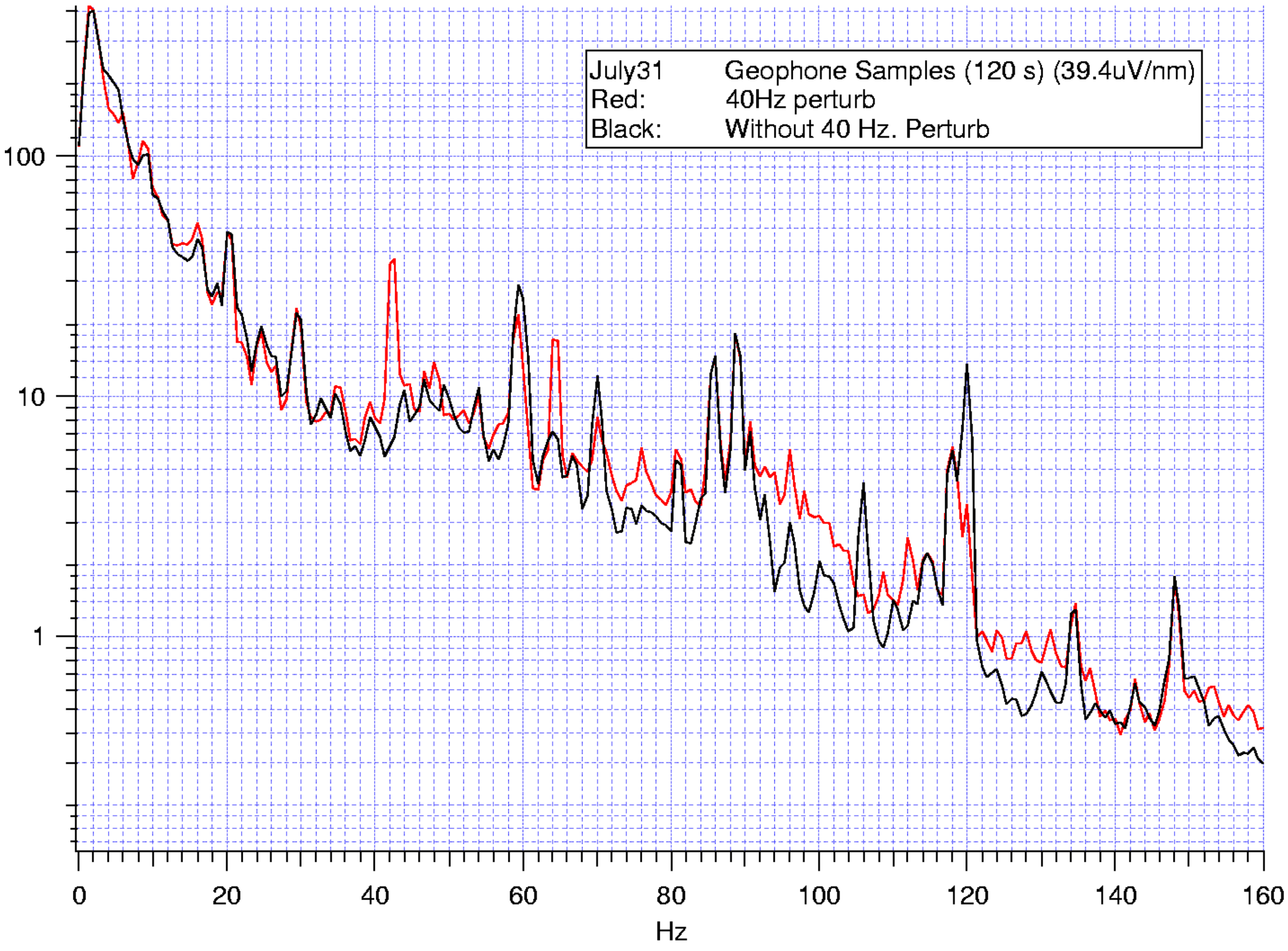
- Multi-kilohertz interferometer data acquisition (vs 256 Hz)
- Real-time reconstruction of interferometer data (vs offline)
- Piezoelectric control of a large test mass (Mike Woods started this, too)
- Integrating the test-mass into the interferometer
- Real-time feedback algorithm development

The interferometer equipment was moved from SLAC and set up in my lab in the basement of the Physics Building.

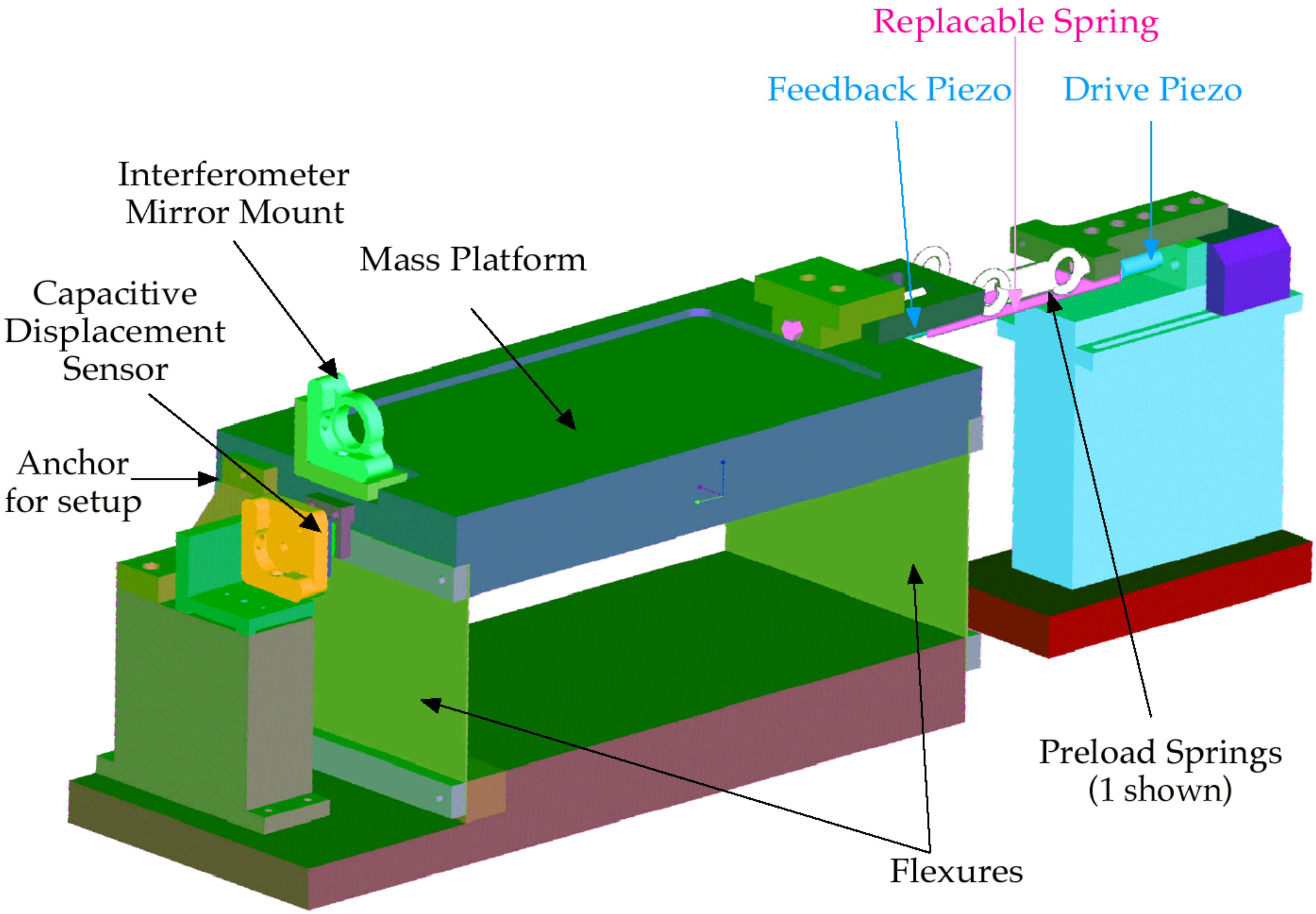
We built a test-mass platform, and integrated it into the interferometer.
We bought and built electronics and wrote software for reconstruction and feedback.

Ground Motion in Physics Basement

Spectrum from 1-Hz Mark L-4 vertical geophone, in nanometers



UBC Nanometer Feedback Test Platform



Replacable Spring

Feedback Piezo

Drive Piezo

Interferometer
Mirror Mount

Mass Platform

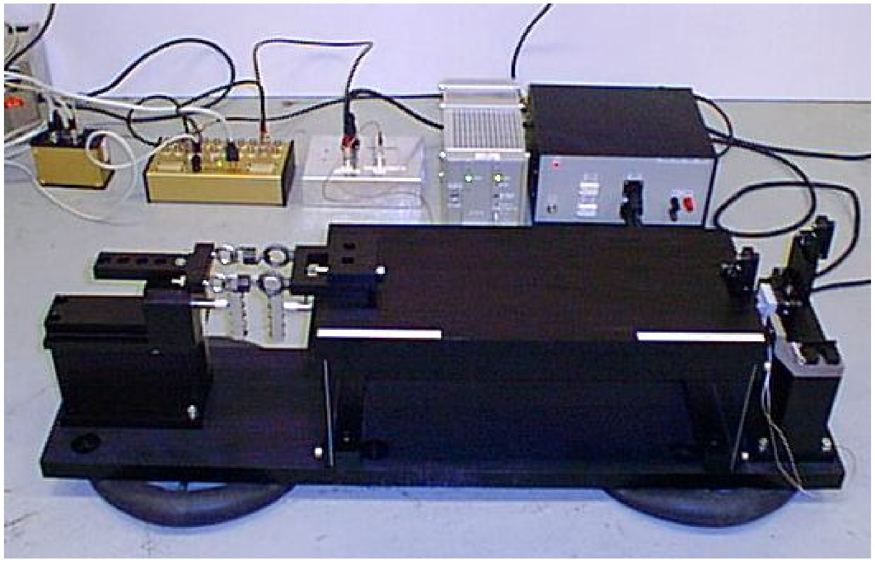
Capacitive
Displacement
Sensor

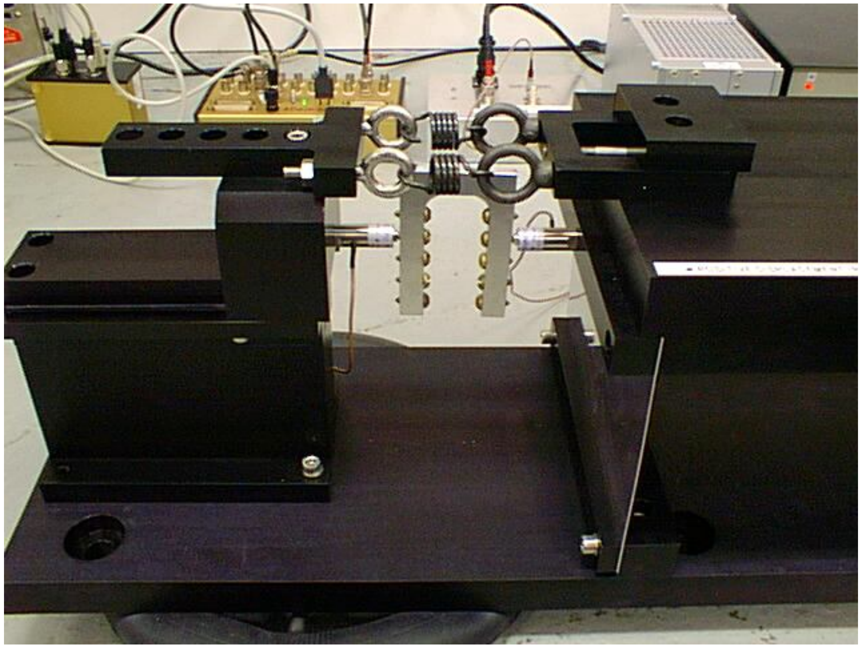
Anchor
for setup

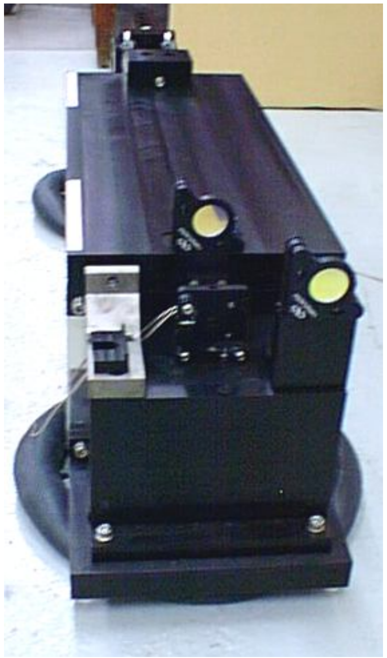
Preload Springs
(1 shown)

Flexures

Feedback Test Platform Today







Feedback Test Platform History

First tried using a rigid rod between the piezo and end post, using interferometer data, but this always oscillated. Measured response to piezo step was very complex....

Tried soft spring (and softer flexures) to lower resonant frequency. Also switched to feeding back on capacitive position sensor (interferometer problems later fixed).

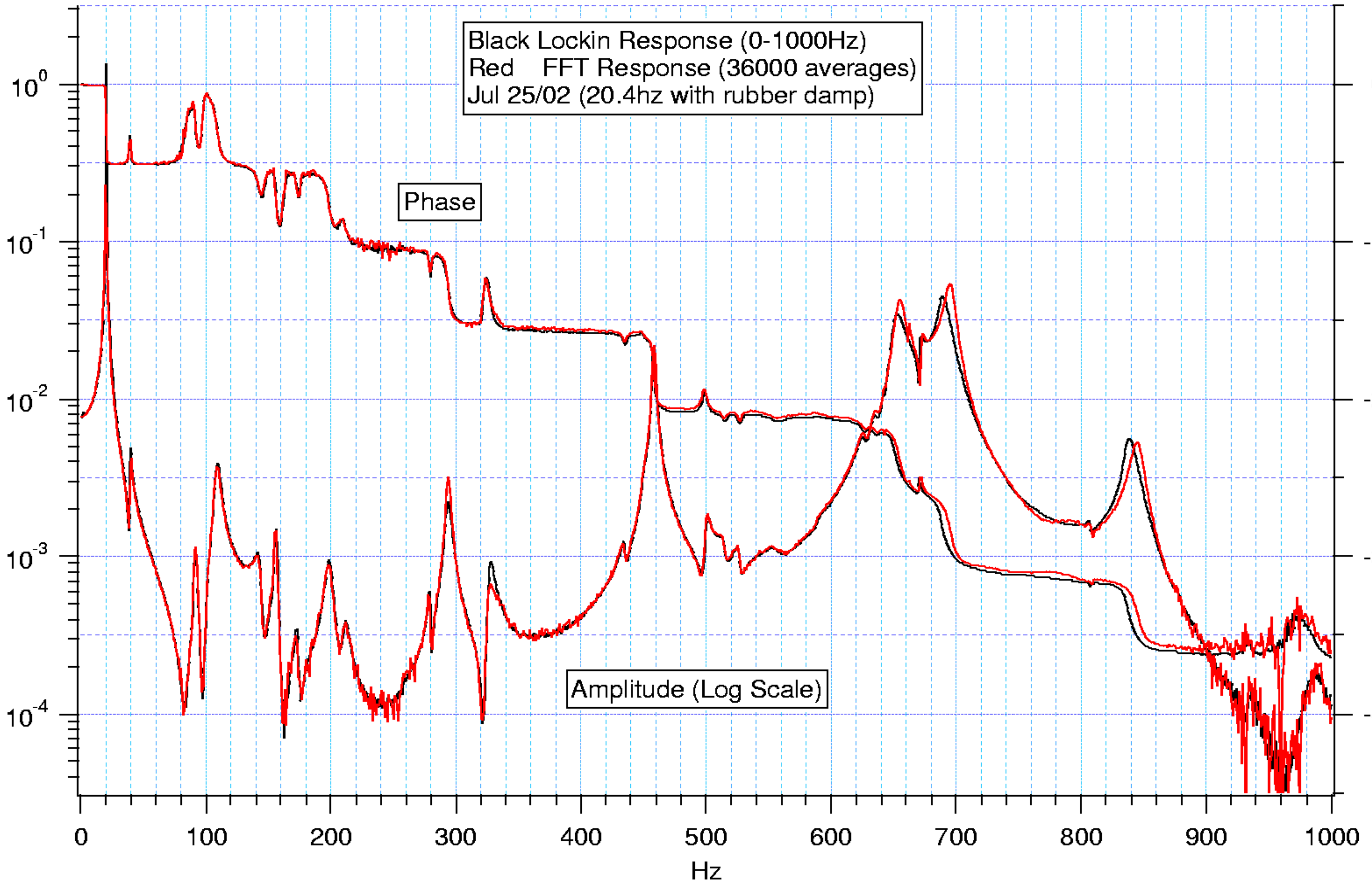
Feedback derivative-term could damp large motions of resonance, but increasing proportional or even derivative gain caused high frequency oscillations, of spring!

Did simulations to try to understand source of oscillations.
Built high-current piezo driver to remove one source of loop delay
Built better springs with fewer internal modes, and variable stiffness.

Continued improvement, but still not able to do much more than damp resonance (and track the ground better at low frequency than passively done by the spring).

Did detailed studies of dynamics of the platform by measuring amplitude and phase response to piezo excitation vs frequency, and also response to square-wave excitation by the piezo.

Platform Isn’t Just a Simple Mass on a Spring



Control Algorithms

Classical proportional-integral-derivative (PID) control with low-pass filtering of position and velocity couldn't do much more than damp the fundamental without oscillating at high frequencies.

Added "resonators:" software narrow-band filters with adjustable frequency and width, and option to either notch-out of signal for PID feedback, or also actively control with separate gain and phase controls for each.

Tuning algorithm:

- Creep up PID gains until it sings (literally...)
- Look at on-line FFT to find frequency
- Set a resonator frequency, and control that oscillation by width, gain, phase
- Repeat until no further progress can be made

Narrow-band feedback on coherent ground motions

- Tune a resonator to a line in the ground-motion spectrum
- Set gain and phase according to lock-in response at that frequency
- Actively control from that resonator
- Toggle bit so resonator updates from raw signal not residual
- Resonator response amplitude and phase seek to cancel out the line
- Even works at frequencies beyond our broad-band control limits

Cap nm PSD ☑ Autoscale ☐ Freeze Skip Factor 20 RMS 1.92123

Resid_R PSD ☑ Autoscale ☐ Freeze Skip Factor 20 RMS 1.36032

View Control Panel

Static 🟩 Sync ■

			Autoscale	Freeze	Skip Factor
Chan 1	Cap nm	Launch Scope	☑	☐	20
Chan 2	Resid_R	Launch Scope	☑	☐	20
Chan 3	Cos Res 1	Launch Scope	☑	☐	15

ADWIN Debug Panel

ADWIN Status

ADWIN Online 🟩

ADWIN Load 69%

Free DRAM 16958152

Free Chip Prog Mem 119888

Free Chip Data Mem 41352

Int L

igor_id
igor_co
adwin_v
pc_wat
spm_id
spm_ve
slow_he
fast_hea
par_9
fast_del
worst_fa
worst_fl
PC_PAF
fast_cha
fast_cha
sel_cap
sel_opt
buffer_c
lockin_c
num_res
par_21
par_22

Ltd.

Ltd.

Z Control Panel

Resonator Control

Cap Sensor 6326.4 nm

Setpoint 0.0 nm Cap 🟩

Opt Sensor 0.0 nm

Setpoint 0.0 nm Opt ■

Error

19.3 nm Position

19.3 nm Error

1000

Prop. Gain 0.000000 0.005

Int. Gain 0.000000 1.0

Diff Gain 0.000000 0

Diff Time Constant mS 2.500000

Setpt Av Track ■

Allow Abs Setpt 🟩

Manual Setting 35.8% Manual 🟥

35.8% Piezo Pos Auto ■

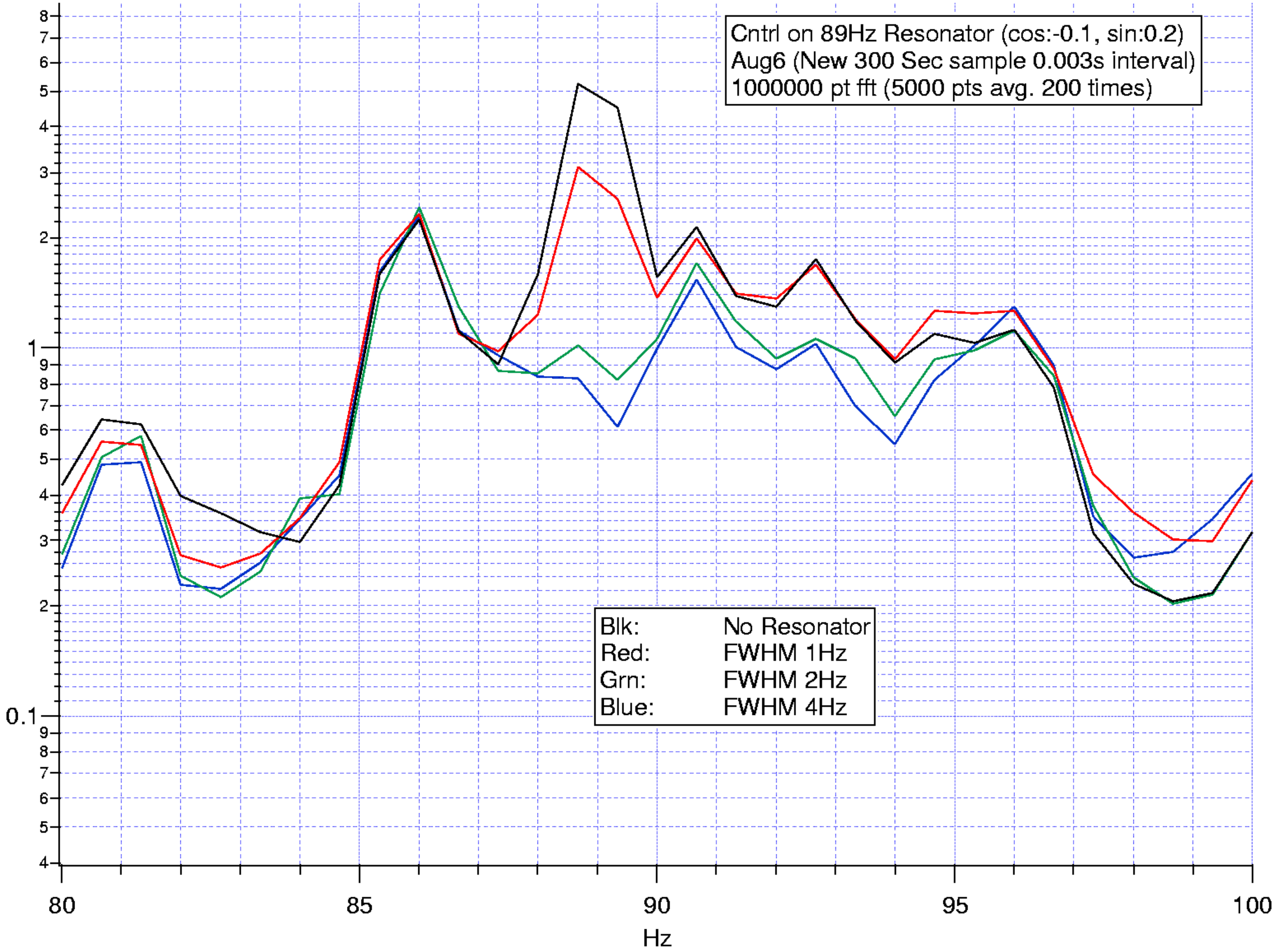
Resonator Control Panel

Resonator Control

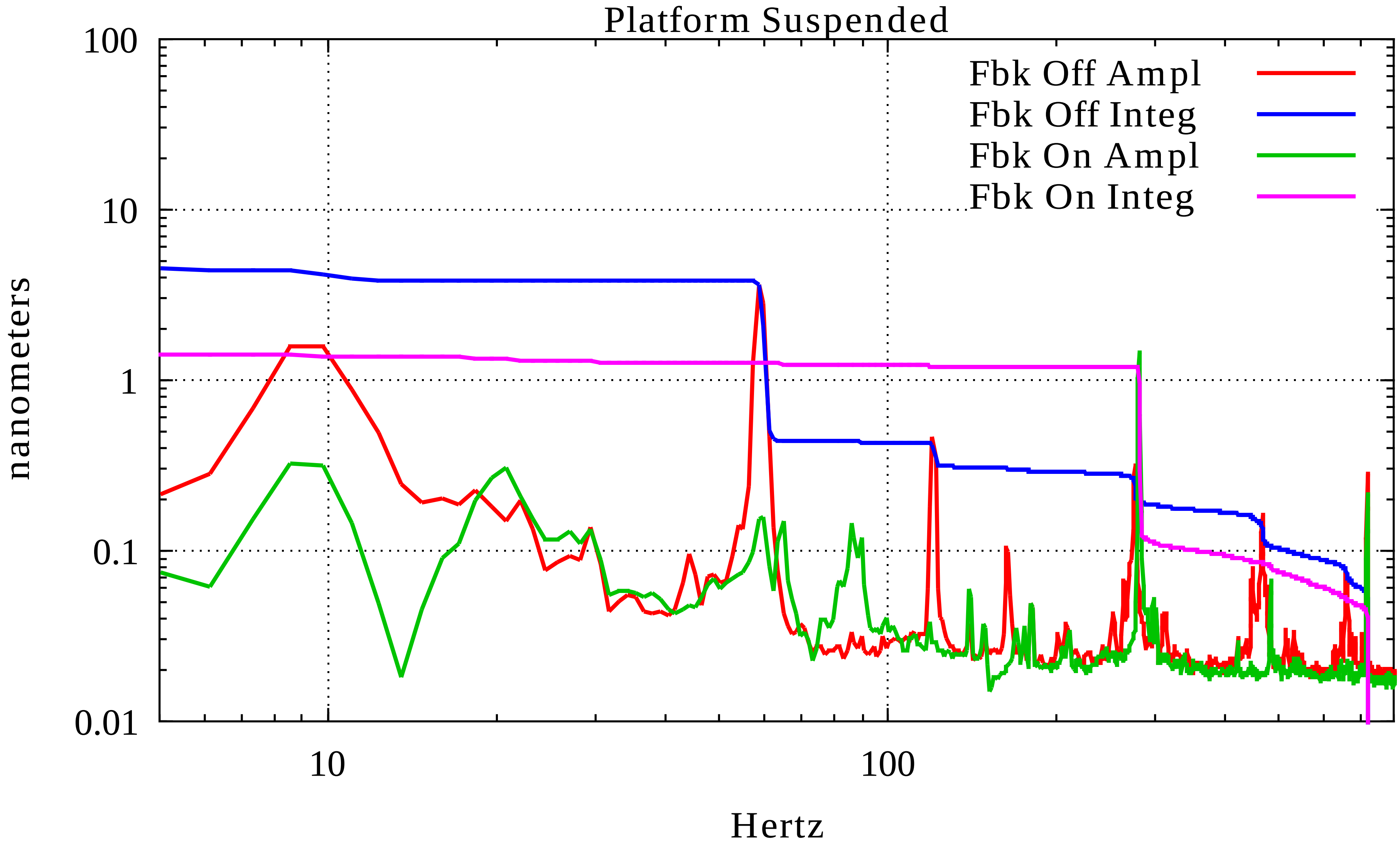
Source Cap nm Smooth TC 2

Chan	ON	Freq (Hz)	Half Width (Hz)	Amplitude	Ampl (Smoothed)	Probe Only (No Notch in ctrl_resid)	Ctrl On	Ground (No Notch in resid)	Gain	Phase (deg)
0	☑	0	0.01	6307.81	6307.02	☐	☐	☐	0	0
1	☑	57	15	3.90166	4.70865	☐	☑	☐	0.01	90
2	☑	10	3	5.80951	5.28568	☐	☑	☐	0.007	0
3	☐	1	1	0	2.8026e-44	☐	☐	☐	0.1	0
4	☐	40	10	0	5.60519e-45	☐	☐	☐	0	0
5	☐	58	10	0	2.8026e-44	☐	☑	☐	0.01	100
6	☐	89	2	0	5.60519e-45	☐	☐	☐	0.15	90
7	☐	120	10	0	2.8026e-44	☐	☐	☐	0	0
8	☐	275	10	0	2.8026e-44	☐	☐	☐	0.03	-50
9	☐	74	5	0	2.8026e-44	☐	☑	☐	0.01	90
10	☐	85	20	0	2.8026e-44	☐	☑	☐	0.01	80
11	☐	0	0	0	0	☐	☐	☐	0	0
12	☐	0	0	0	0	☐	☐	☐	0	0
13	☐	0	0	0	0	☐	☐	☐	0	0
14	☐	0	0	0	0	☐	☐	☐	0	0
15	☐	0	0	0	0	☐	☐	☐	0	0
16	☐	0	0	0	0	☐	☐	☐	0	0

Example of Narrow-Band Ground Motion Control

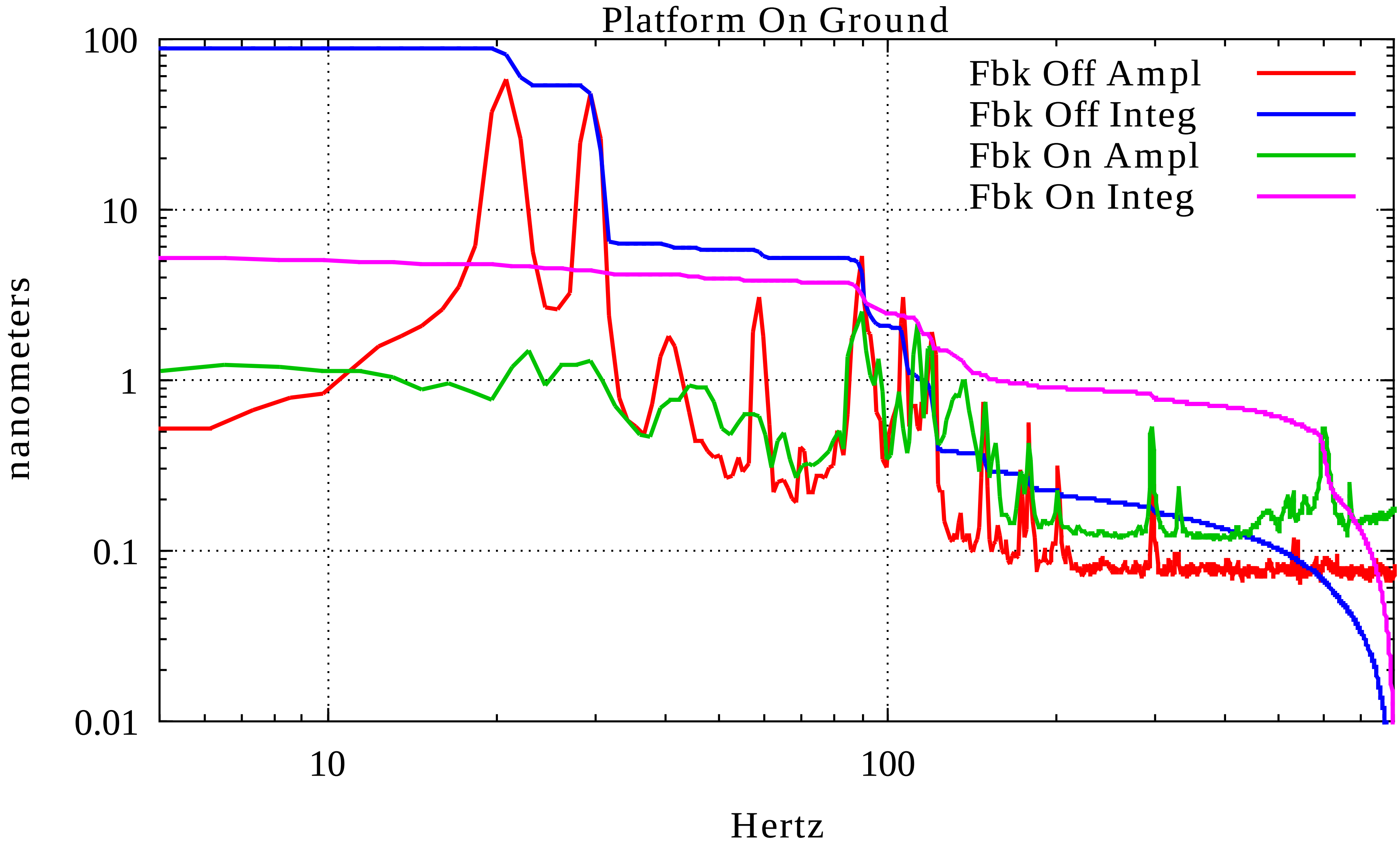


Best Results Resting on Isolators



Down to 1.5 nanometer RMS at 5 Hz (although was only 4.5 to begin with)

Best Results Resting on Ground



From 90 nm down to 5 nm at 5 Hz

Why Can’t We Do Better?

In principle, if the platform behaves like a simple mass on a spring,
we should be able to re-position the platform in two “ticks” (but 3 piezo moves)

- Move piezo far enough beyond goal that platform gets halfway there in one tick
- Move piezo an equal distance in the opposite direction on the next tick.
  this kills the velocity built up in the first tick, exactly when we reach the goal
- Move piezo to target position to hold the already-stopped platform in place

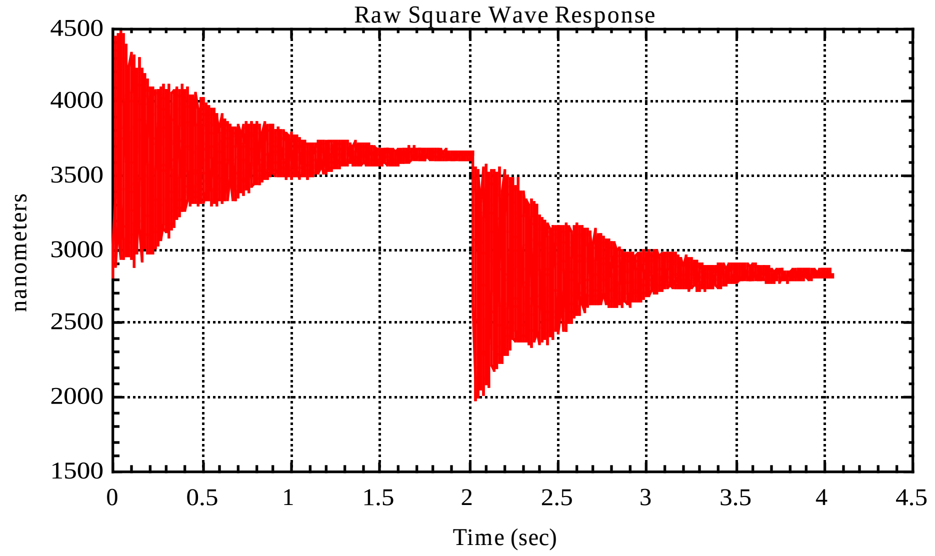
Note that time required has nothing to do with the natural frequency,
only on the sampling rate (although the gain required does depend on the frequency)

For 5 kHz sampling, we should be able to reposition the platform in 0.4 milliseconds

The problem is, we excite all the modes with the first piezo move. The second piezo move can be constructed to kill the motion of the fundamental, but it isn’t the right phase to kill the motion in all the other modes. We can kill the excitation of the other modes too, but it takes additional ticks.

We used the measured square-wave response of the platform to find a command sequence that produces the fastest response (minimum RMS deviation from unity during sequence), no residual ringing (minimum RMS deviation from unity after the end of the sequence with high weight), and reasonable control power (minimum RMS command deviation from linear ramp with low weight).

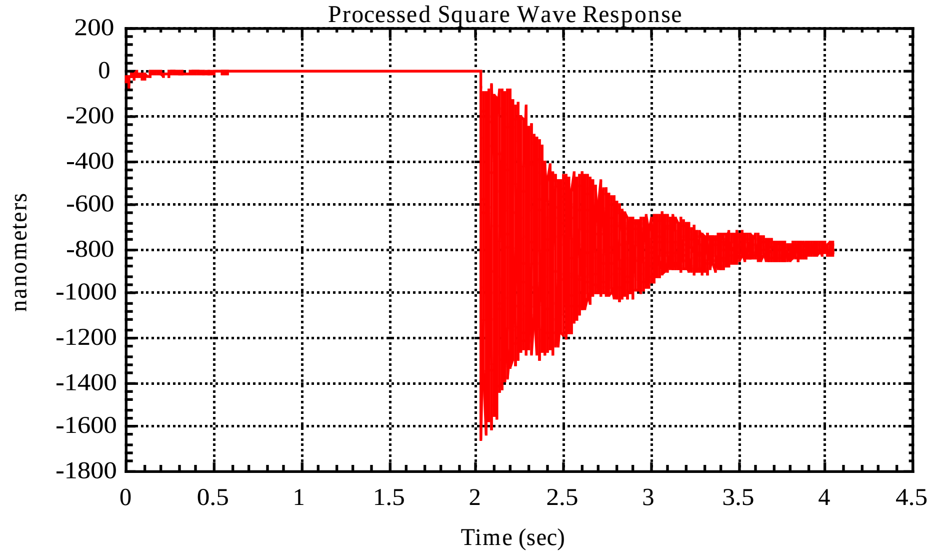
Square Wave Response

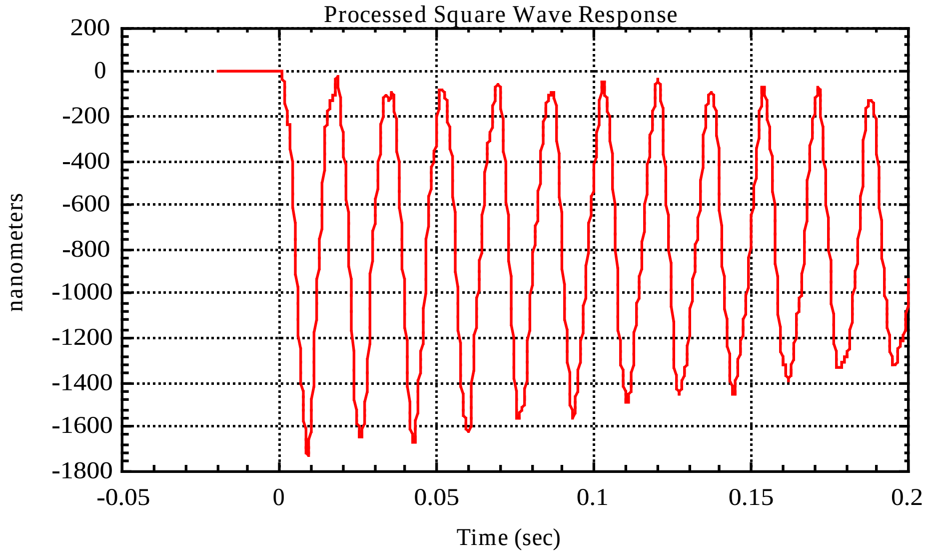


Fit first half to decaying sinusoid, subtract.

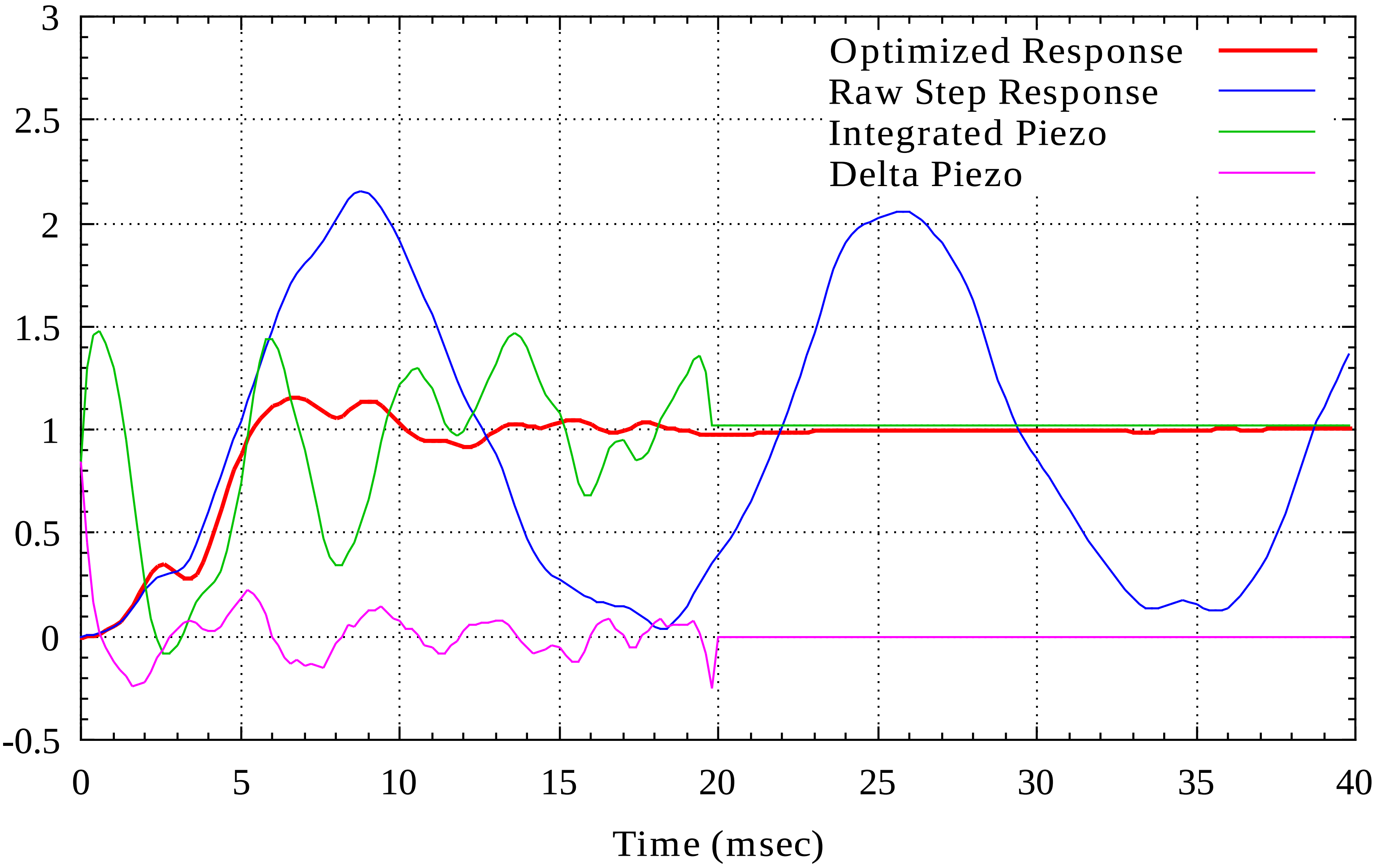
Repeat for first few resonances

Early part of second half shown below





Calculated Optimal Commands and Response



Should be able to position platform in ≈ 5 milliseconds, about 1/4 cycle of fundamental, but much worse than naive 0.5 msec if there were no other resonances!

Test Platform Summary and Plans

Intended to build a simple mass-on-a-spring, but reality was much more complicated (a better model of what reality will probably be like than we had intended....)

Control to lightly damp fundamental and lower frequencies is pretty easy

“Resonators” help control oscillations due to resonances, but aren’t a panacea

Resonators do let us apply narrow-band control for coherent ground motions that are above our broad-band control limits

We can make the platform track the “ground” to 1.5 nm when it is isolated, and reduce 90 nm relative motions down to 5 nm when on the ground

Resonances prevent us from using high broad-band gain to significantly stiffen system

We plan to test whether the calculated optimized-command-sequence really works, and try to turn it into a feedback algorithm.

We also plan to make a stiffer base-plate and grout it down to the floor to get rid of some of the resonances.

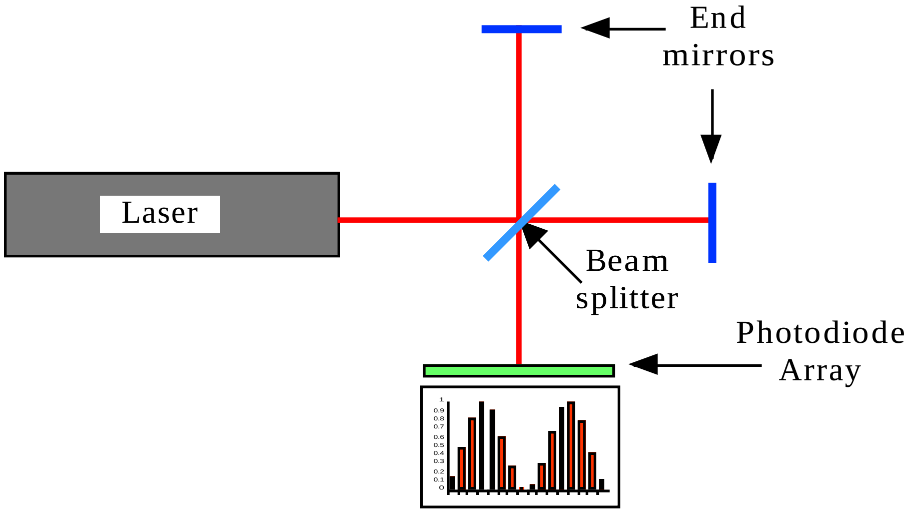
We also plan to speed up the step-response by using a stiffer piezo acting directly on a large reaction mass, which will be tied to a post by a spring.

Interferometer Introduction

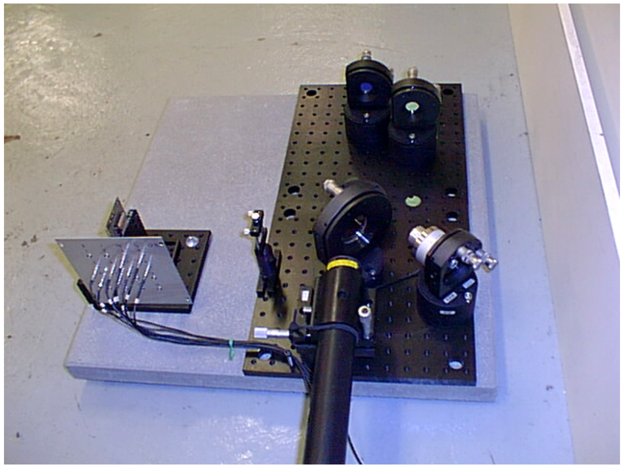
Michelson interferometer, with beams at slight angle at photodiode array to make fringes on photodiode array.

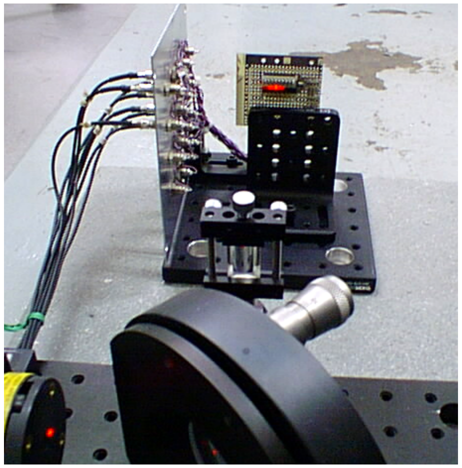
Moving end mirror moves fringe pattern, fit pattern to measure motion to a tiny fraction of a wavelength.

632 nm HeNe is ≈100 nm / radian.



We fold one arm of the interferometer parallel to the other with a 45° mirror, so we can easily vary the length (and cancel some things between arms). The 45° mirror is on a piezo for calibration and feedback studies





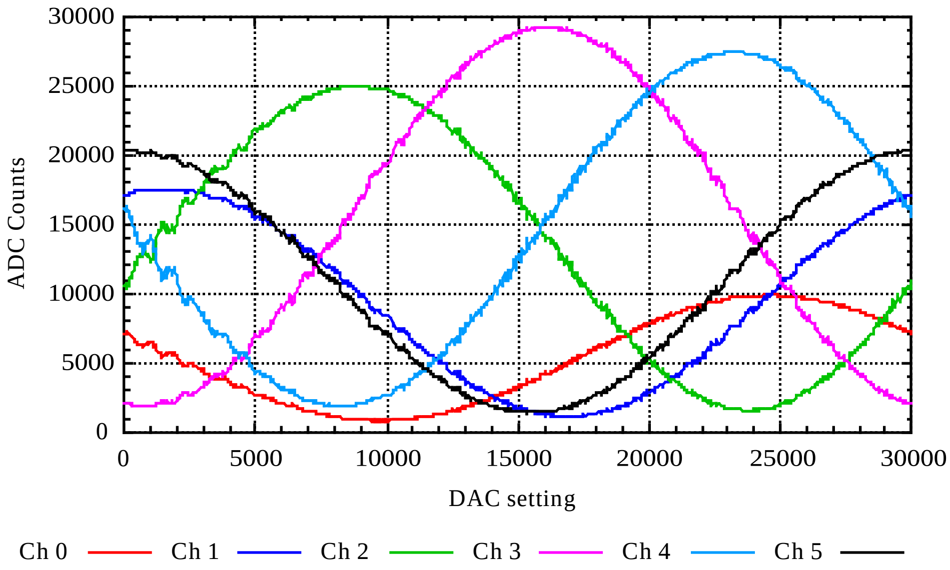
Interferometer Calibration

Move piezo through about a wavelength.

Digitize each diode each step

Fit each diode to offset sinusoid.

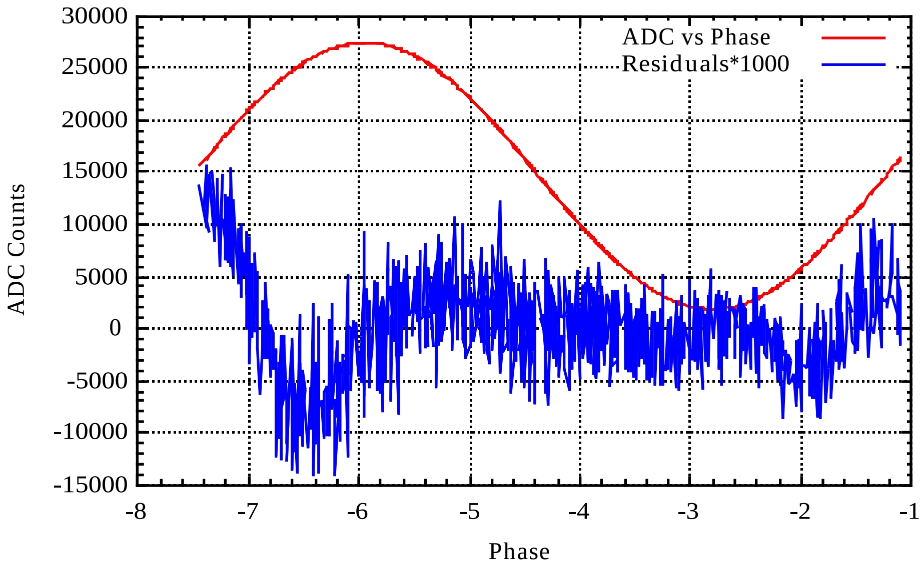
Note that ground vibrations are superimposed.



Use parameters to calculate phase deviation from vibration for each piezo setting.

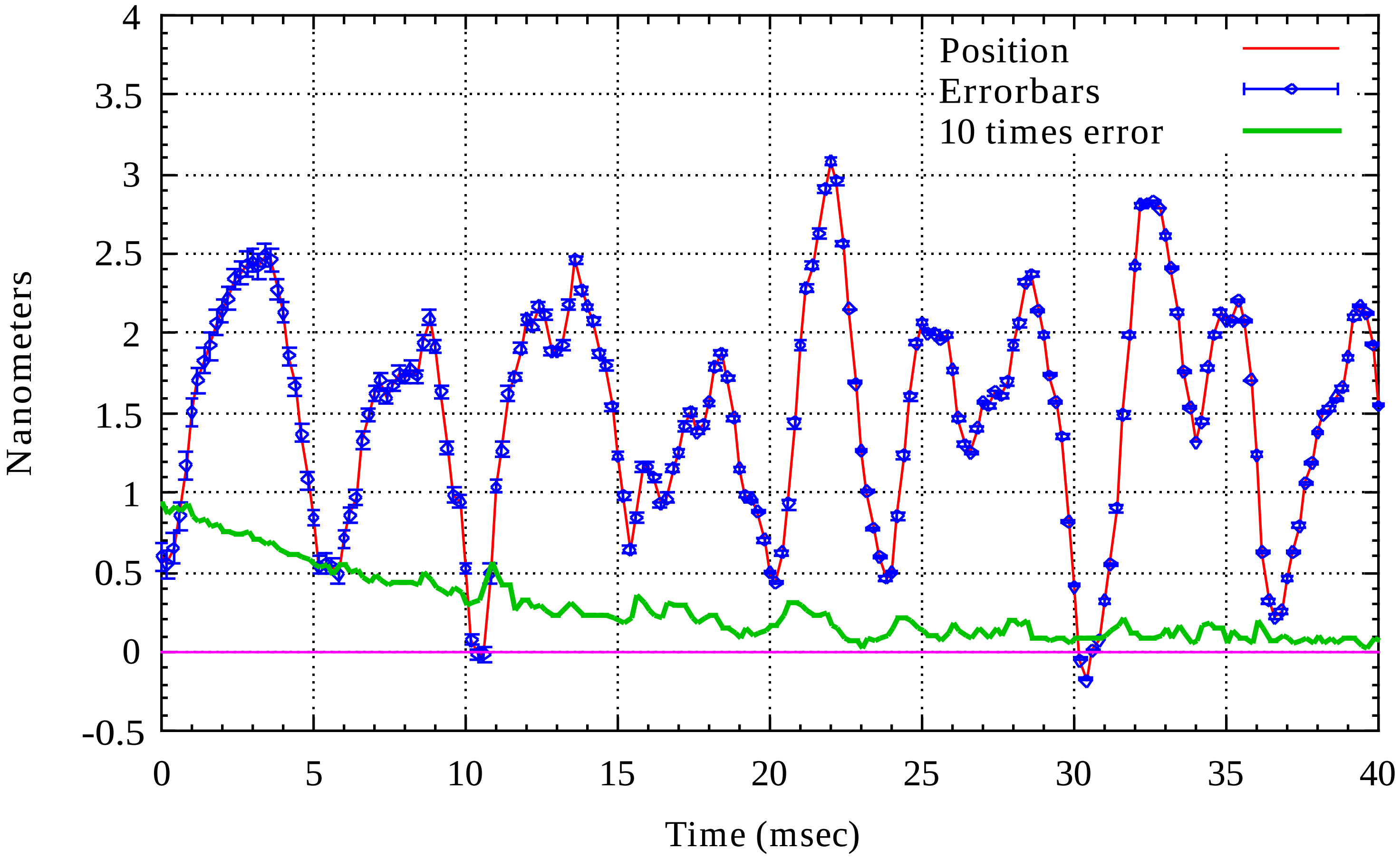
Fit offset sinusoids to diodes vs phase.

Residuals are now very tiny.



Position Reconstruction

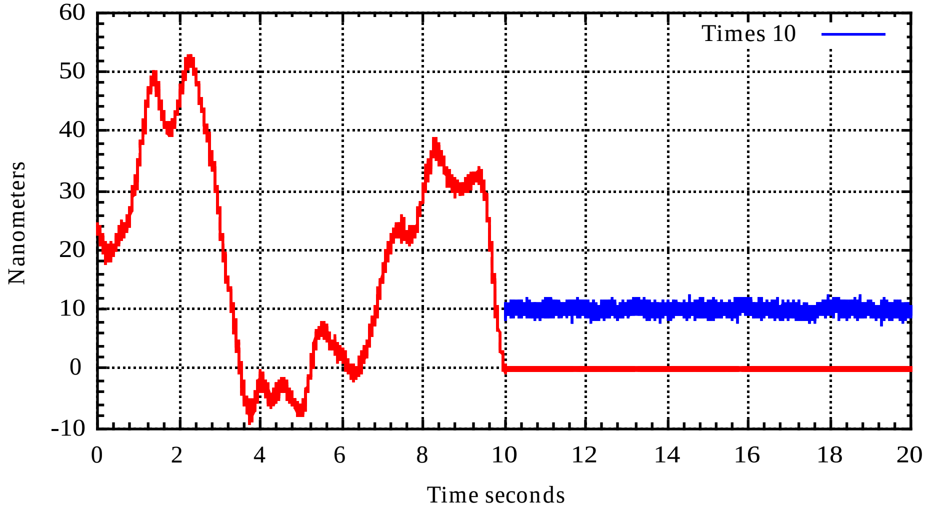
Read 6 photodiodes at 100 kHz, DMA to memory, interrupt handler does nonlinear fit for phase (=position), intensity, with errorbars. Calibration parameters are tweaked by a small fraction of the residuals divided by derivatives. Repeat at 5 kHz.

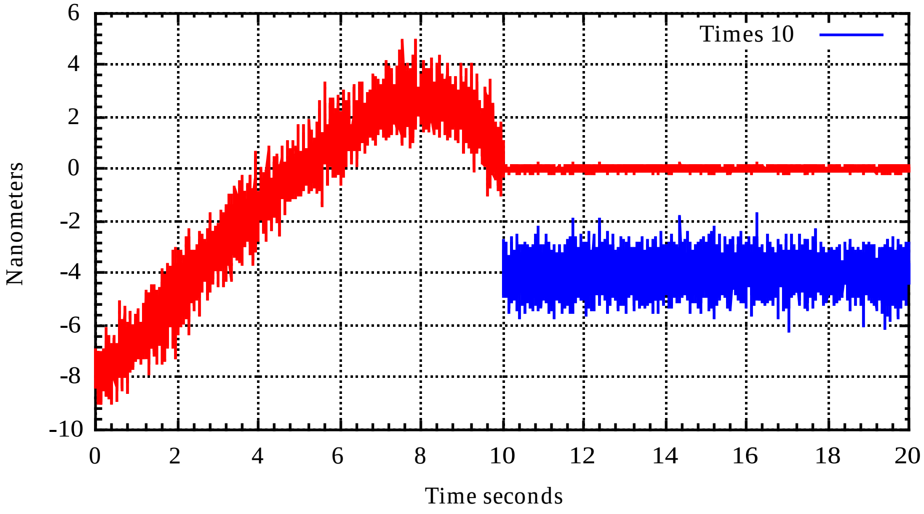


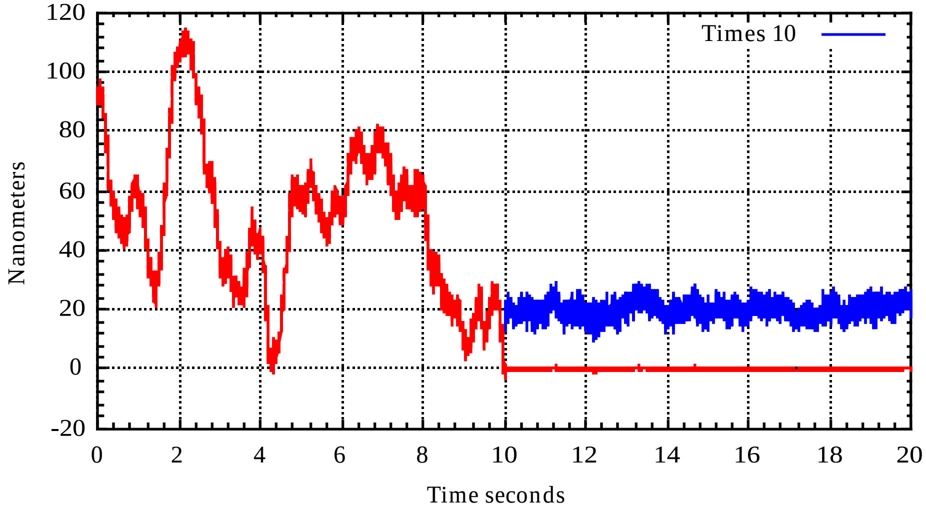
Position error starts at < 1 nm, reduces to ≈ 0.01 nm after parameters settle.

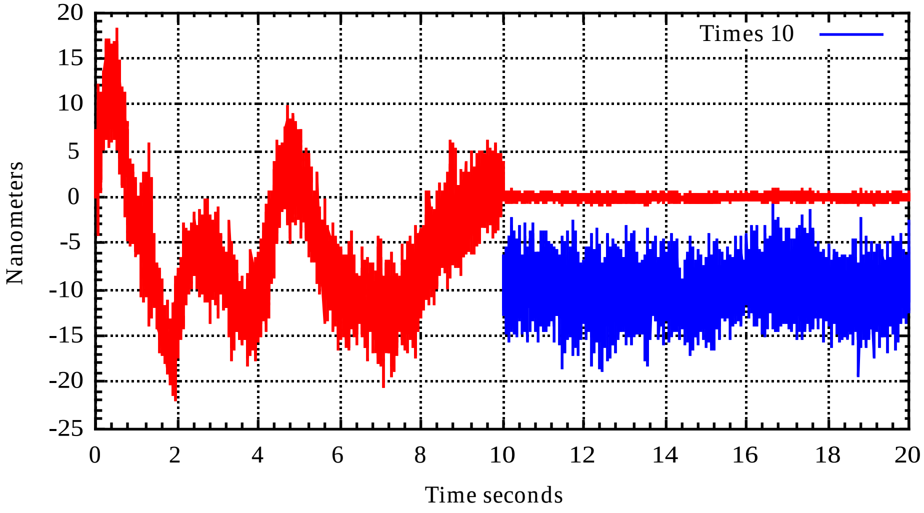
Feedback on Piezo Mirror

Simple PID feedback on the piezo mirror gives control as good as 0.06 nm!


On Isolator, No Box: RMS = 17.5 before, 0.07 after

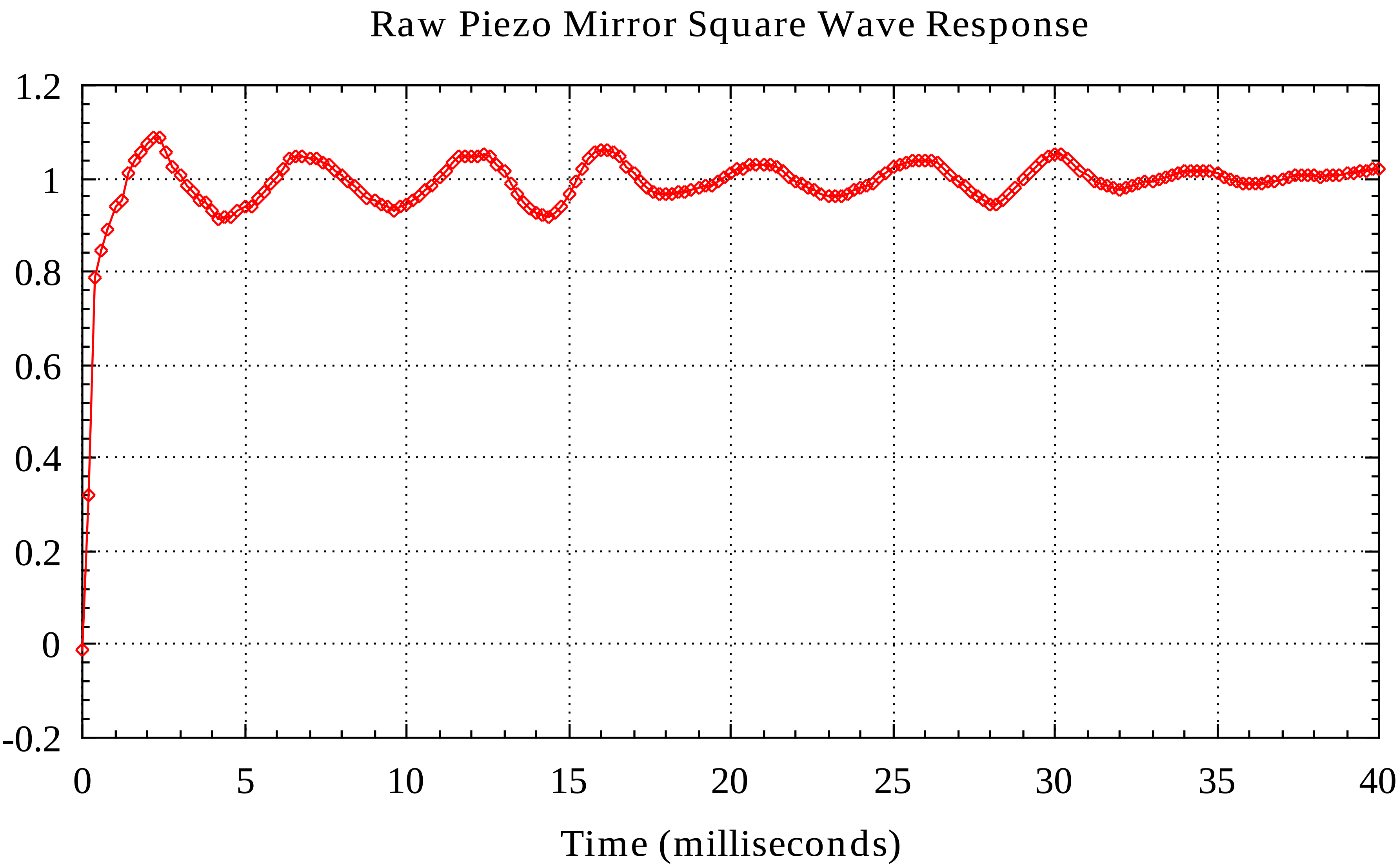

On Isolator, With Box: RMS = 3.4 nm before, 0.06 nm after


10 Meters in Air: RMS = 25.4 nm before, 0.27 nm after


10 Meters in Tubes: RMS = 6.9 nm before, 0.24 nm after

What Does “In Box” and “In Tubes” Mean?

Why Piezo-Mirror Feedback Works Better


Raw Piezo Mirror Square Wave Response

We get a large fraction of the way there in just 2 ticks!

Conclusions

We can make the test platform track the “ground” to 1.5 nm when it is isolated,
and reduce 90 nm relative motions down to 5 nm when on the ground

Test platform experience shows real control requires clean system
high natural frequency, few resonances

Plan to explore stiff piezos, reaction mass, grouting stiffer baseplate to floor

Interferometer capable down to 0.01 nanometers!

Air currents can give drifts of dozens of nanometers, but they are slow
slow beam-beam feedback probably could easily deal with them

Piezo-mirror feedback easily gets to sub-nanometer scale, as low as 0.06 nm!

The work has been done by me and a succession of students, mostly undergrads

- Ken Yau, engineering-physics (computer) co-op student
- Jason Thompson, eng-phys (mechanical) co-op student
- Parry Fung, engineering-physics (computer) summer and ApSci thesis student
- Travis Downs, eng-phys (computer) NSERC summer student
- Russ Greenall, physics graduate student