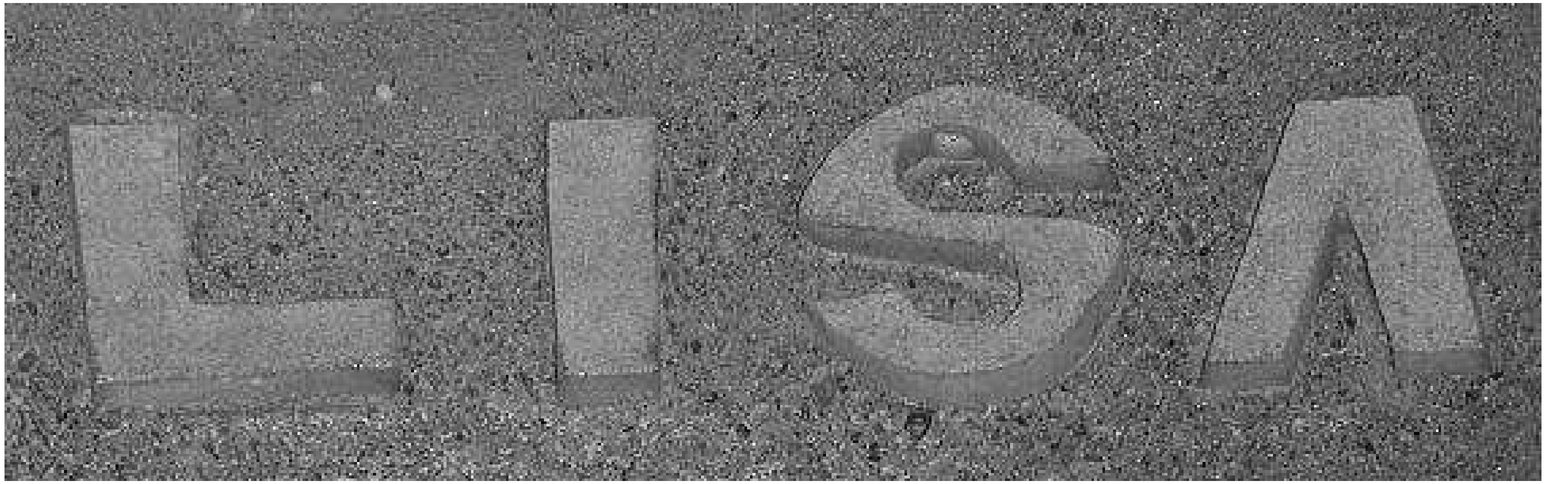


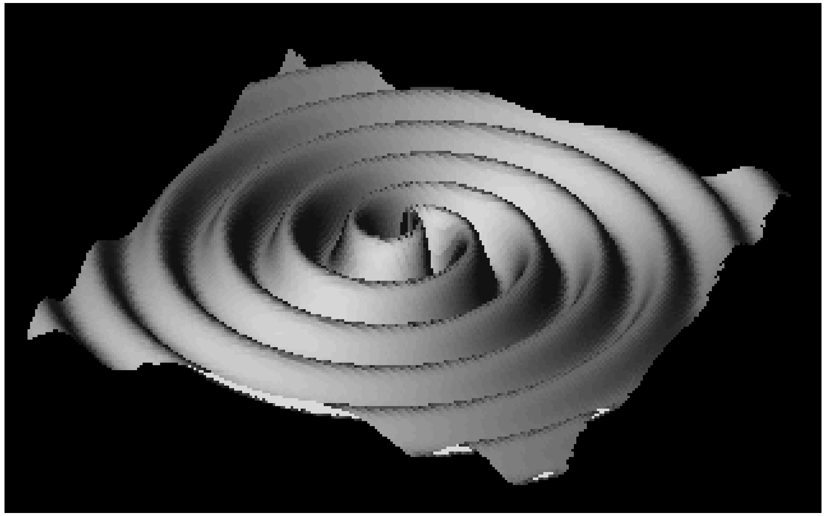
Building a feedback-controlled positioning system for the Eöt-Wash LISA small force measurement

or

My NSF summer: your tax dollars at work

Colin Connolly
advisor: Jens Gundlach
2003 UW Summer REU in Physics

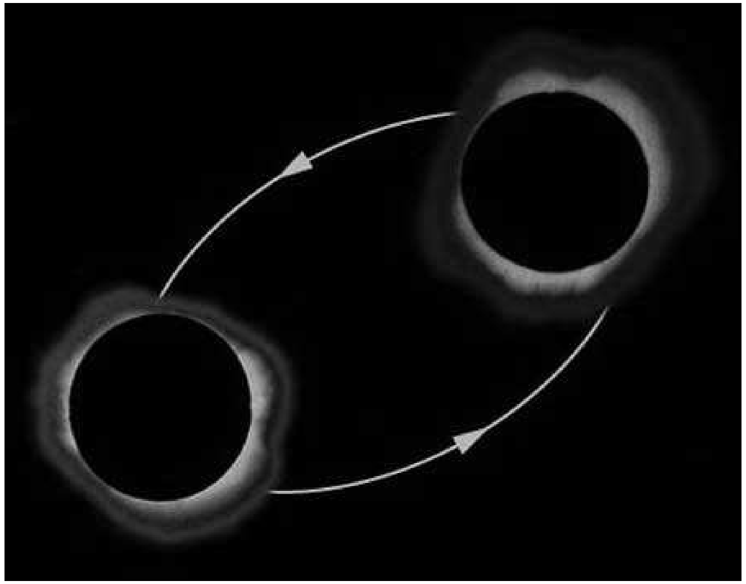
Gravitational Waves



- Predicted by Einstein's theory of general relativity
- Produced by a changing gravitational field
- Theorized to travel at the speed of light

Possible sources include:

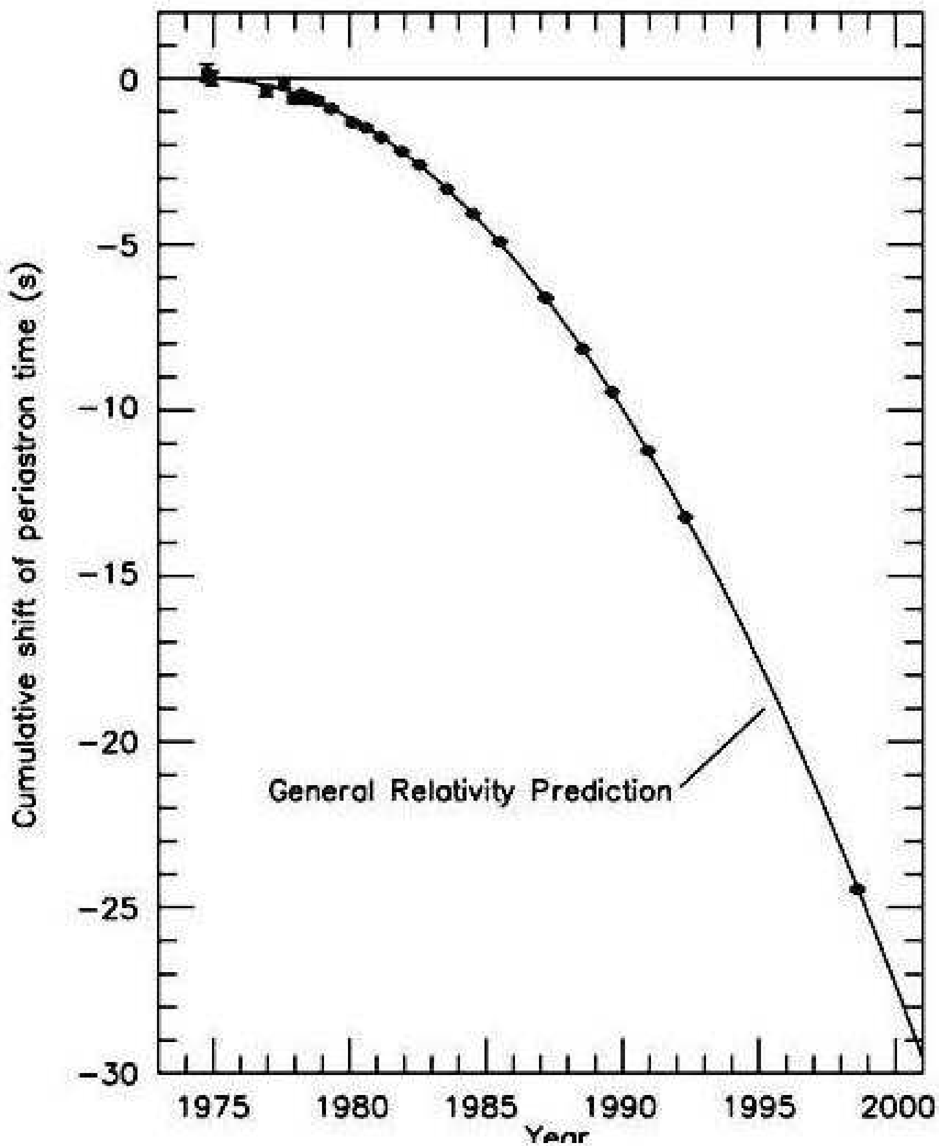
- Binary pulsars
- Stars falling into black holes
- Black hole mergers
- Residual background from the Big Bang



Indirect evidence for gravitational radiation

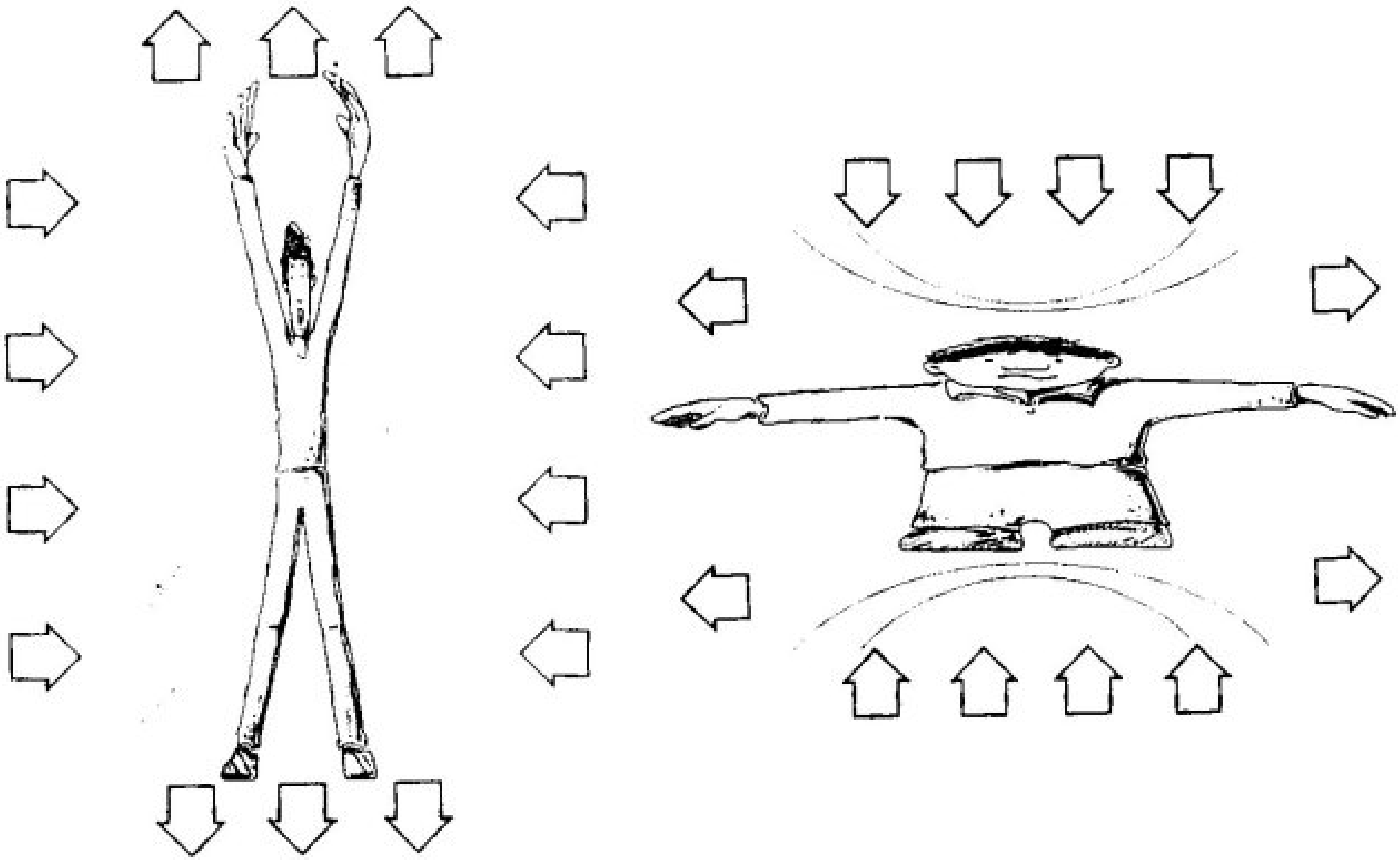
Observation of PSR 1913 + 16, the first discovered binary pulsar, by Joseph Taylor and Russell Hulse (1993 Nobel Prize) shows a shift in the rotational period over time, suggesting energy is being lost through gravitational waves.

The data agree with the general relativity prediction to within better than 0.5%.

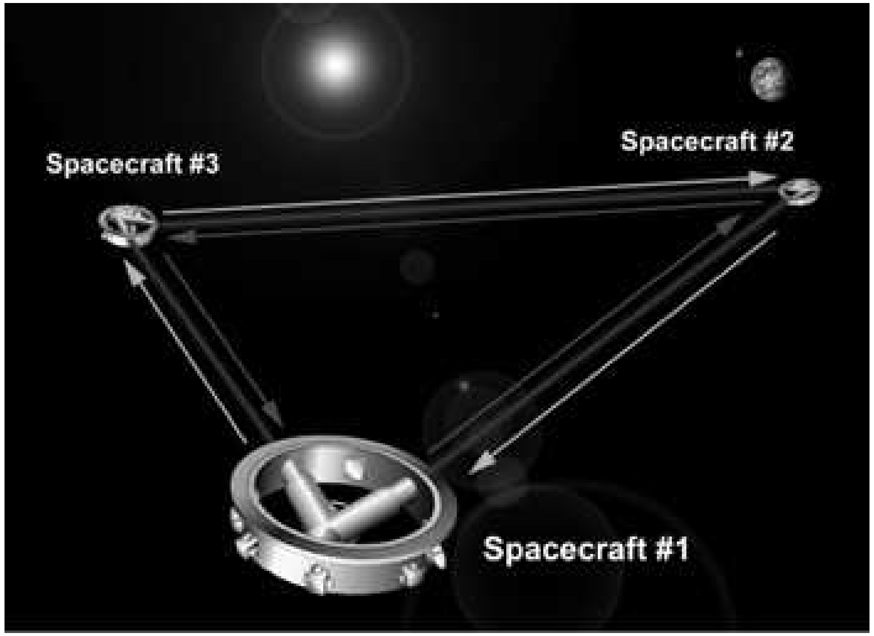


Gravitational waves stretch and shrink spacetime

(graphic not quite to scale)



Laser Interferometer Space Array (LISA)



- Joint collaboration between the European Space Agency and NASA.

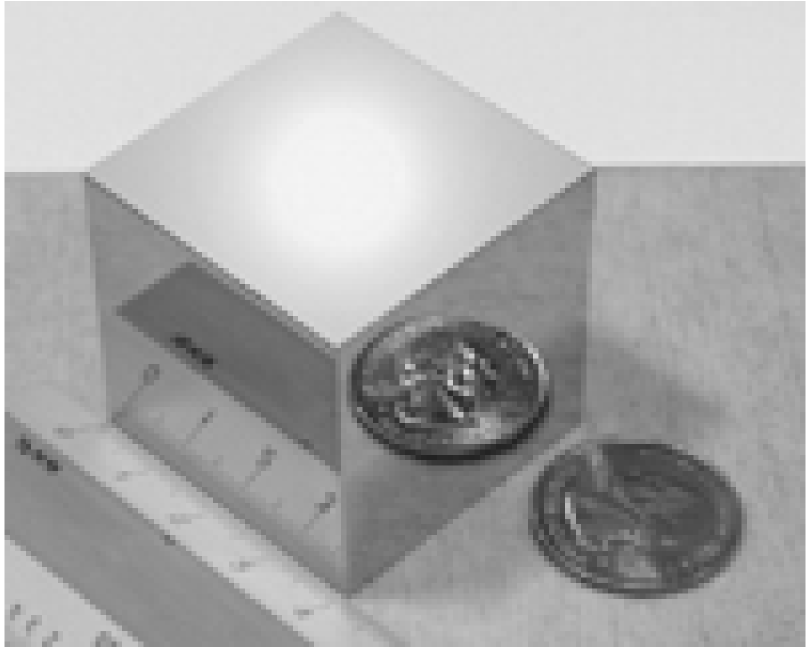
- Three very large Michelson-Morely interferometers
- Arm length of 5 million km
- Sensitive to 20-pm variations at frequencies down to 0.1 mHz
- Maximum acceleration noise ~ 1×10^{-16} *g* / $Hz^{1/2}$

What kinds of small forces?

Patch effect:

- A voltage can appear across two metals if the work functions of the two surfaces differ
- Arises from differences in the electrochemical potentials
- Can be caused by the metal surfaces being mosaics of patches exposing differing crystal planes or differences in alloy concentration
- Effect depends on the cleanliness and purity of the metals, alloy distribution, and surface structure

$$V_2 - V_1 = \frac{W_2 - W_1}{e}$$

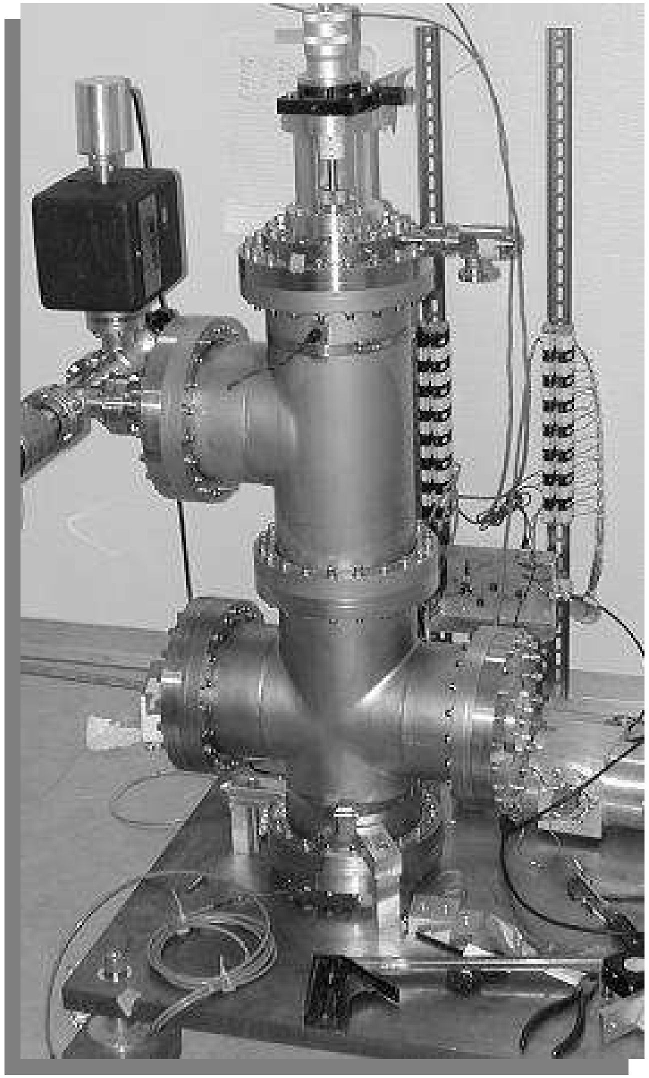


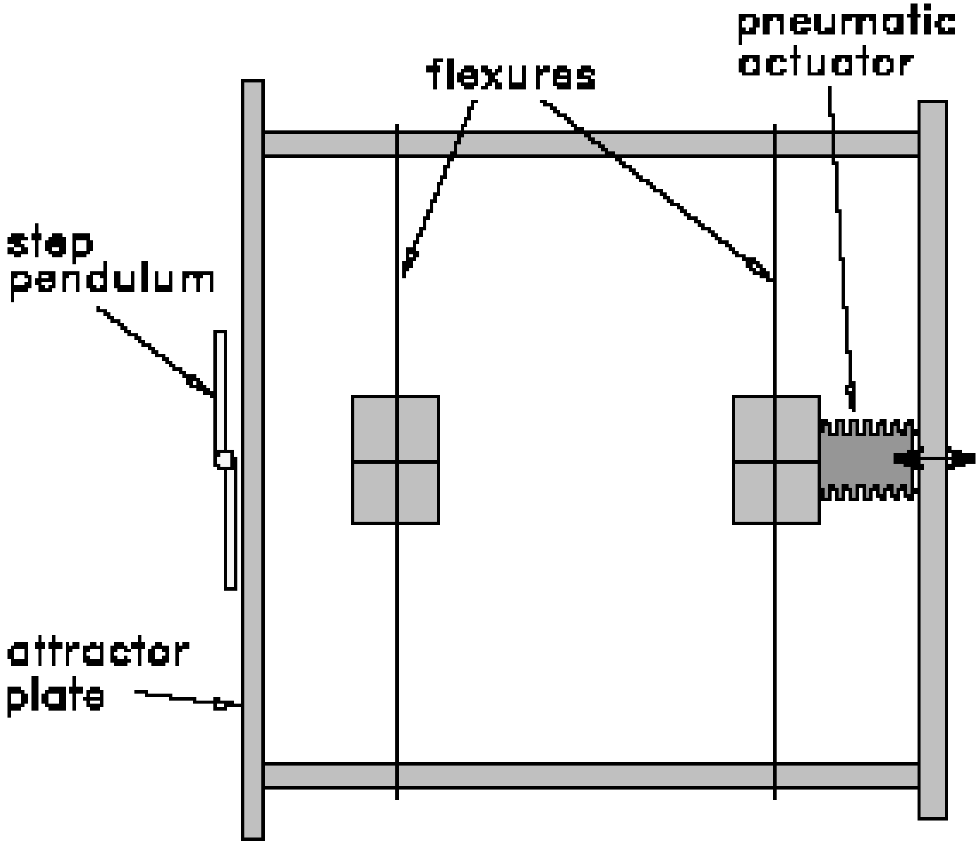
Others include:

- Outgassing, gravitational coupling, etc.

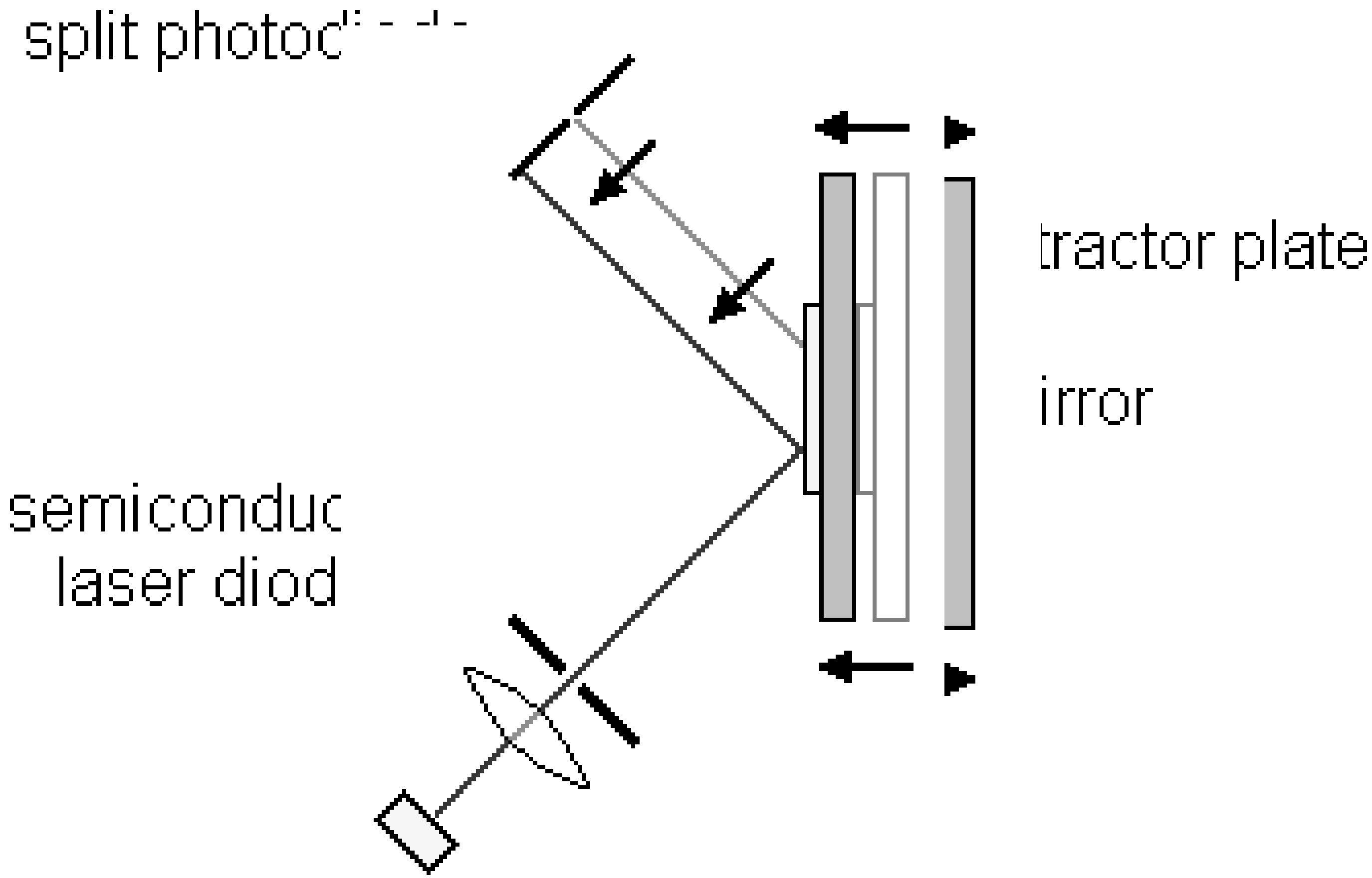
The Eöt-Wash group small force measurement for LISA

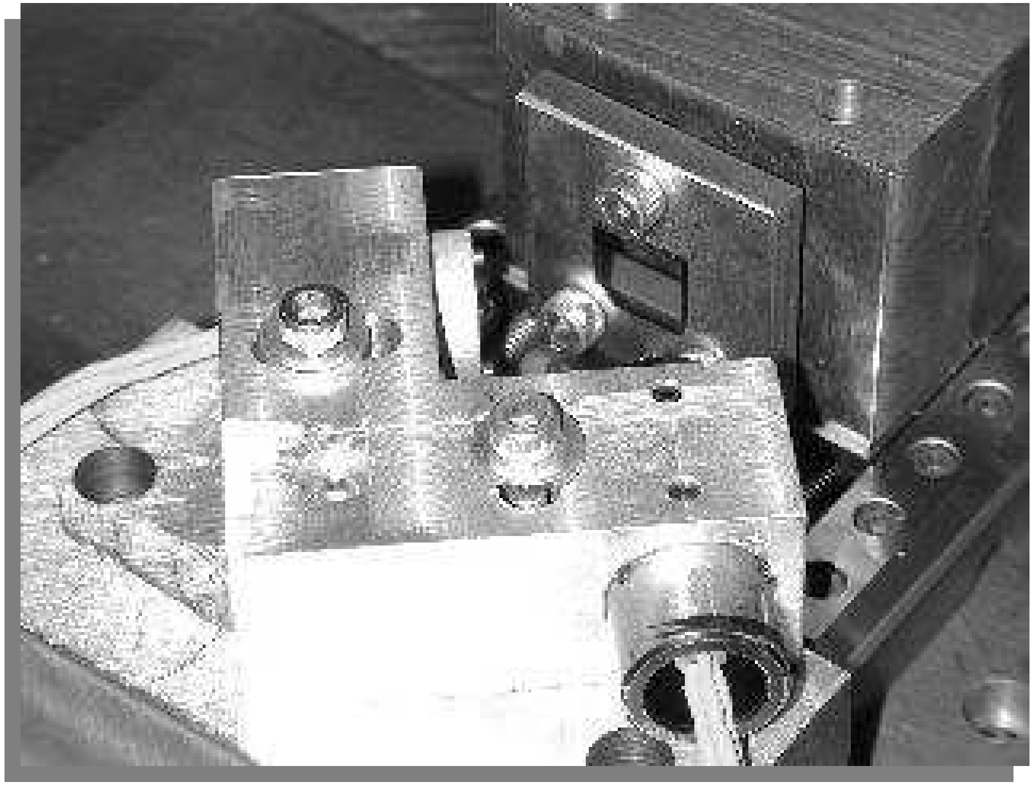
Experimental setup



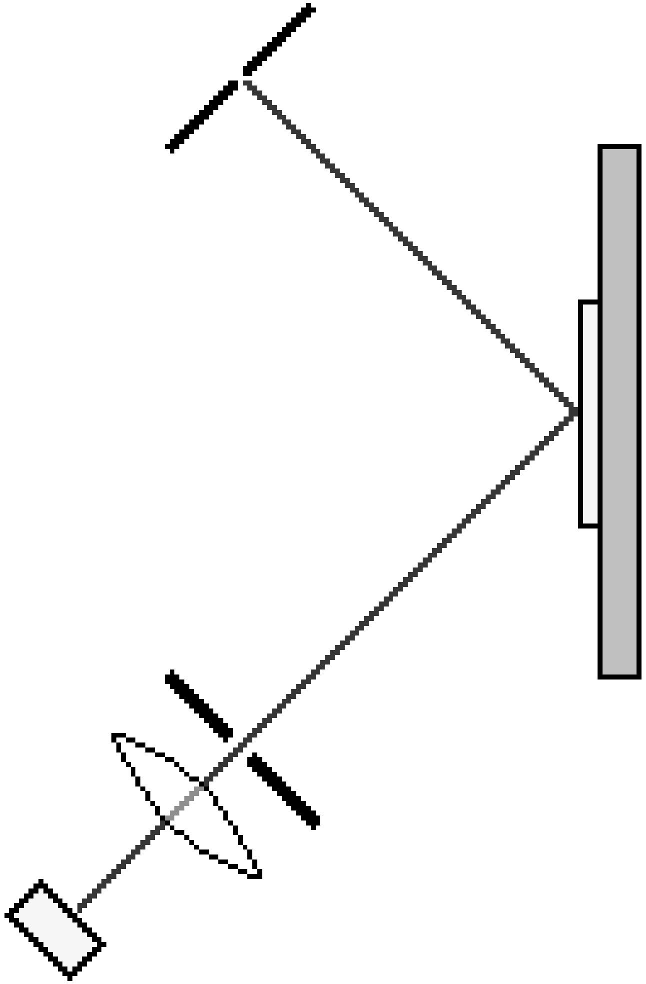


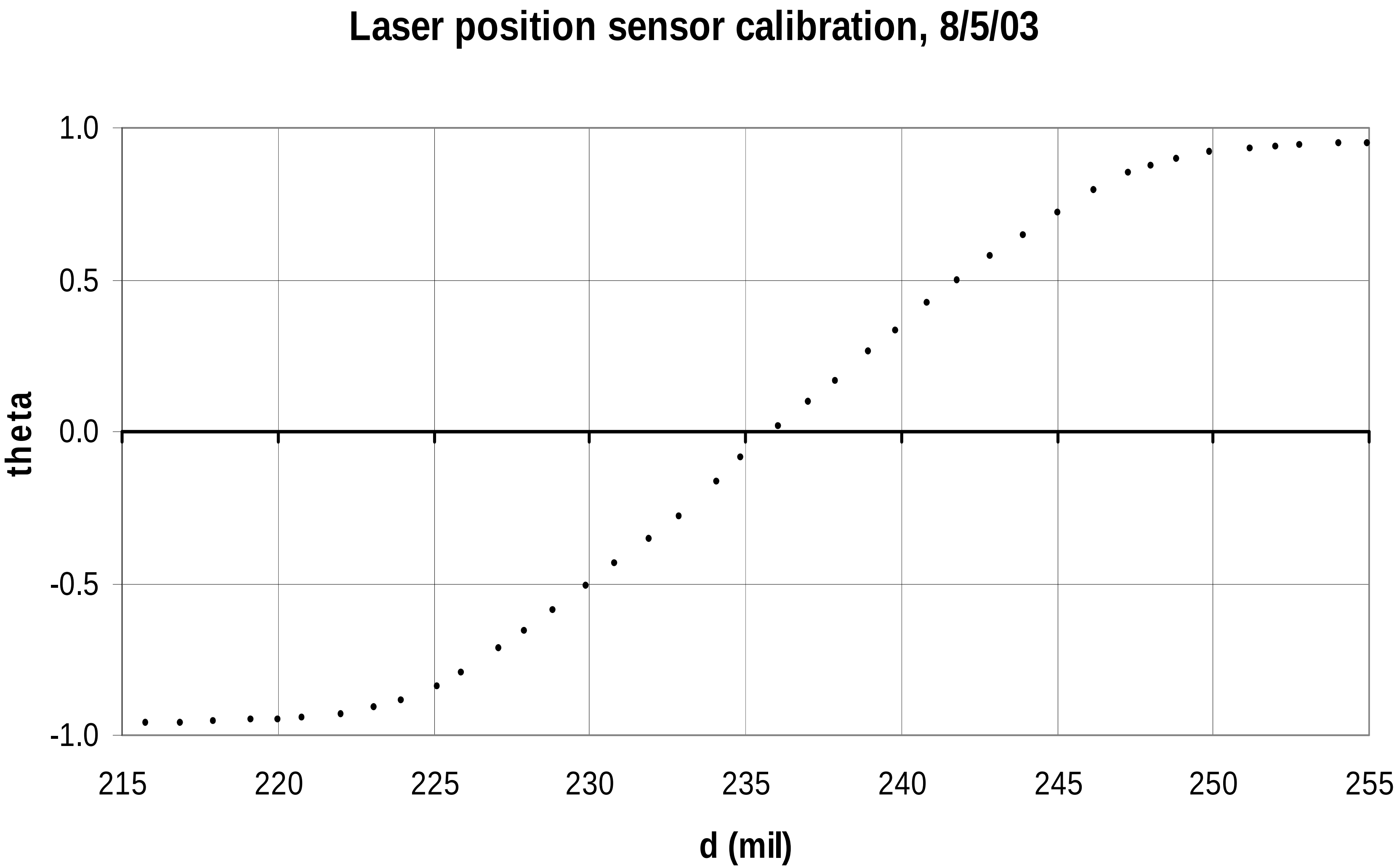
Infrared laser position sensor





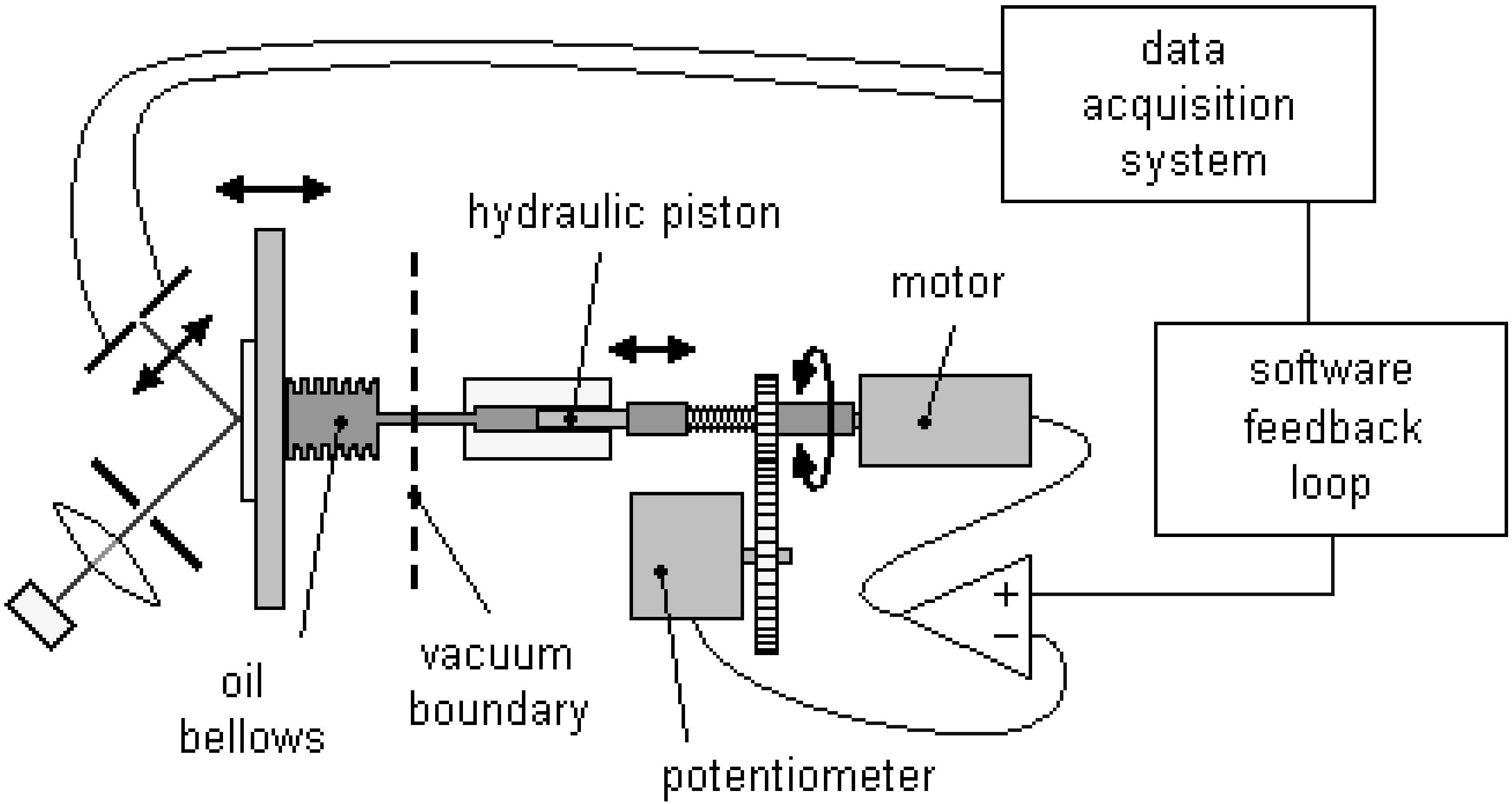
The real deal



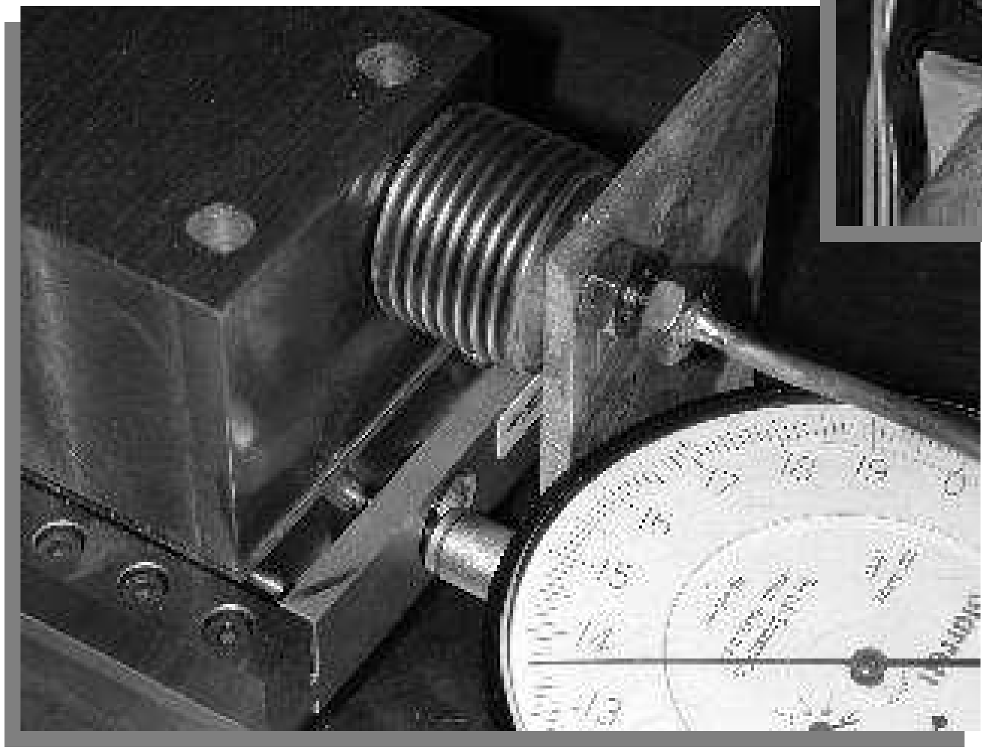

Laser position sensor calibration, 8/5/03
1.0
0.5
0.0
-0.5
-1.0
theta
215
220
225
230
235
240
245
250
255
d (mil)

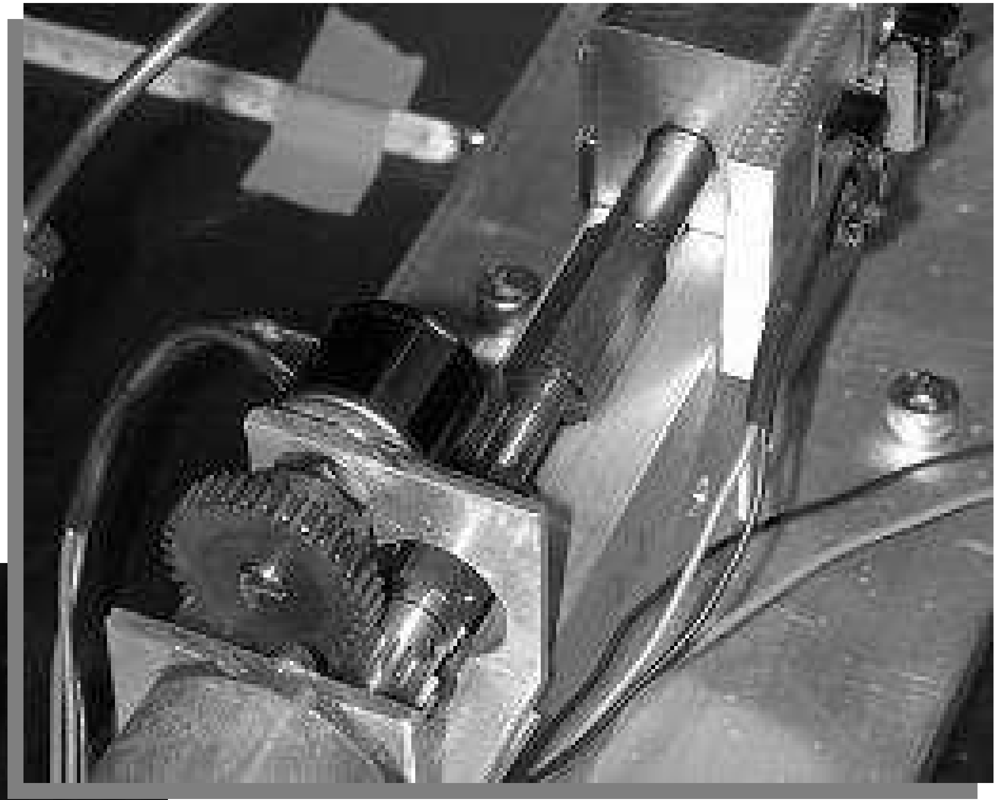
Attractor plate feedback-controlled positioning system

apparatus schematic



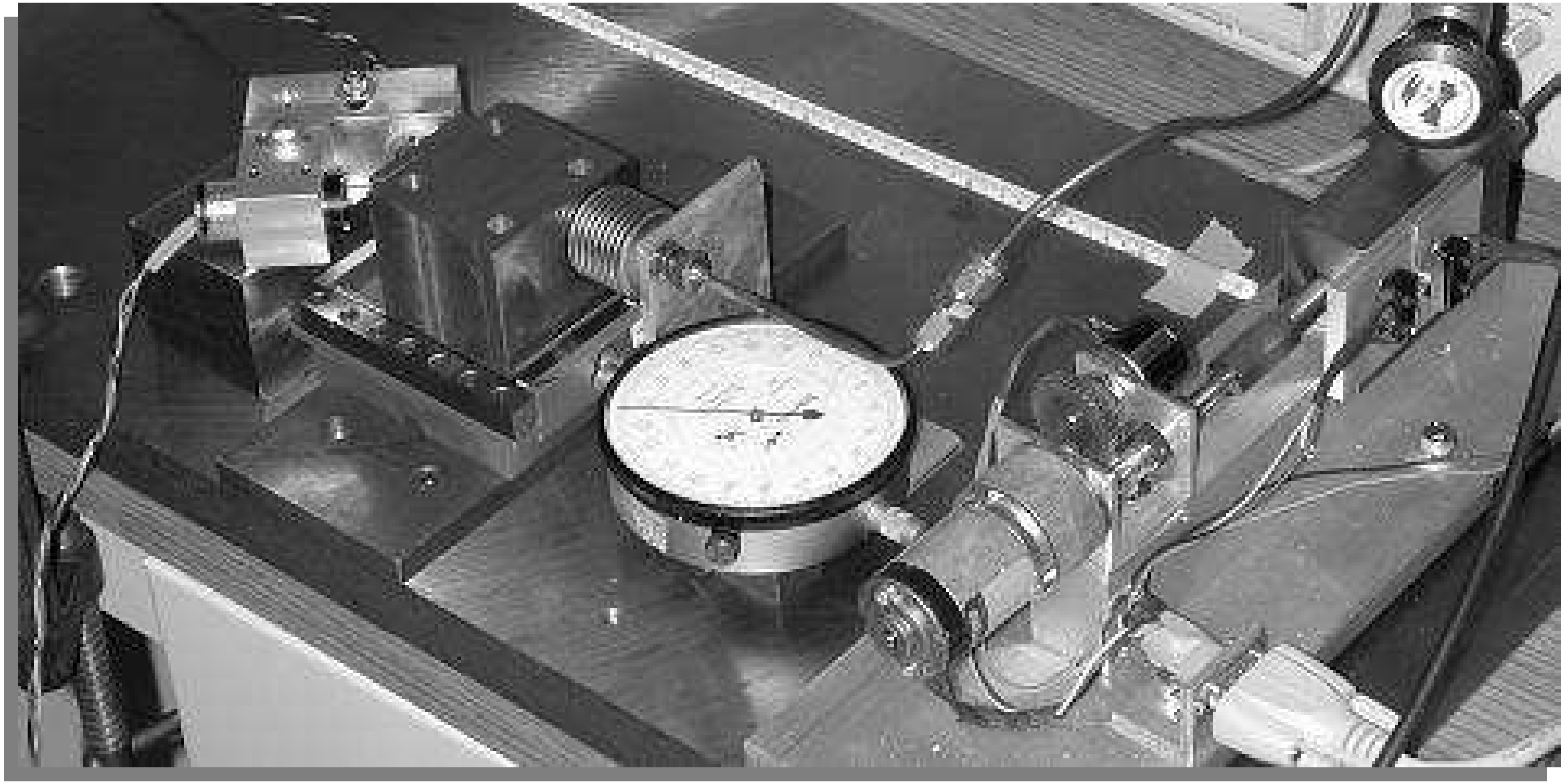
oil bellows





motor assembly

The whole 9×10^{-4} yards



The PID feedback loop

$$V_{output} = C_P e(t) + C_I \int e(t) + C_D \frac{d}{dt} e(t)$$

- P term is **proportional** to the error (difference between the current and target outputs)
  - Pushes the output to the target with exponentially decreasing power
- I term is the **integral** of the error over time
  - Builds up over time to force output to the target
- D term is the **derivative** of the error
  - Inhibits rapid change

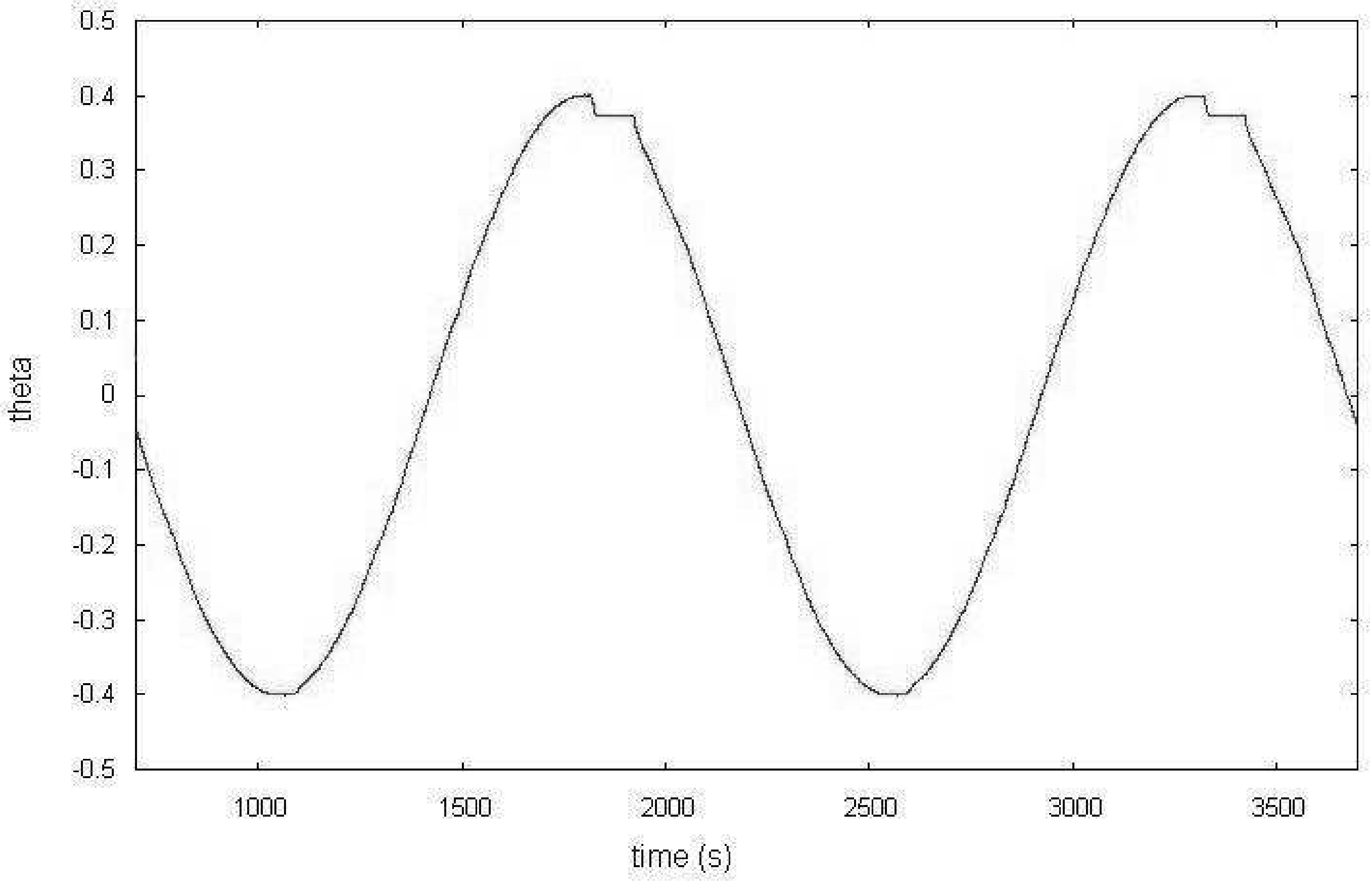
My **PI(D) feedback loop**

$$V_{output} = C_P\left(1 - g(e(t))\right)e(t) + C_I \int g(e(t))e(t)$$

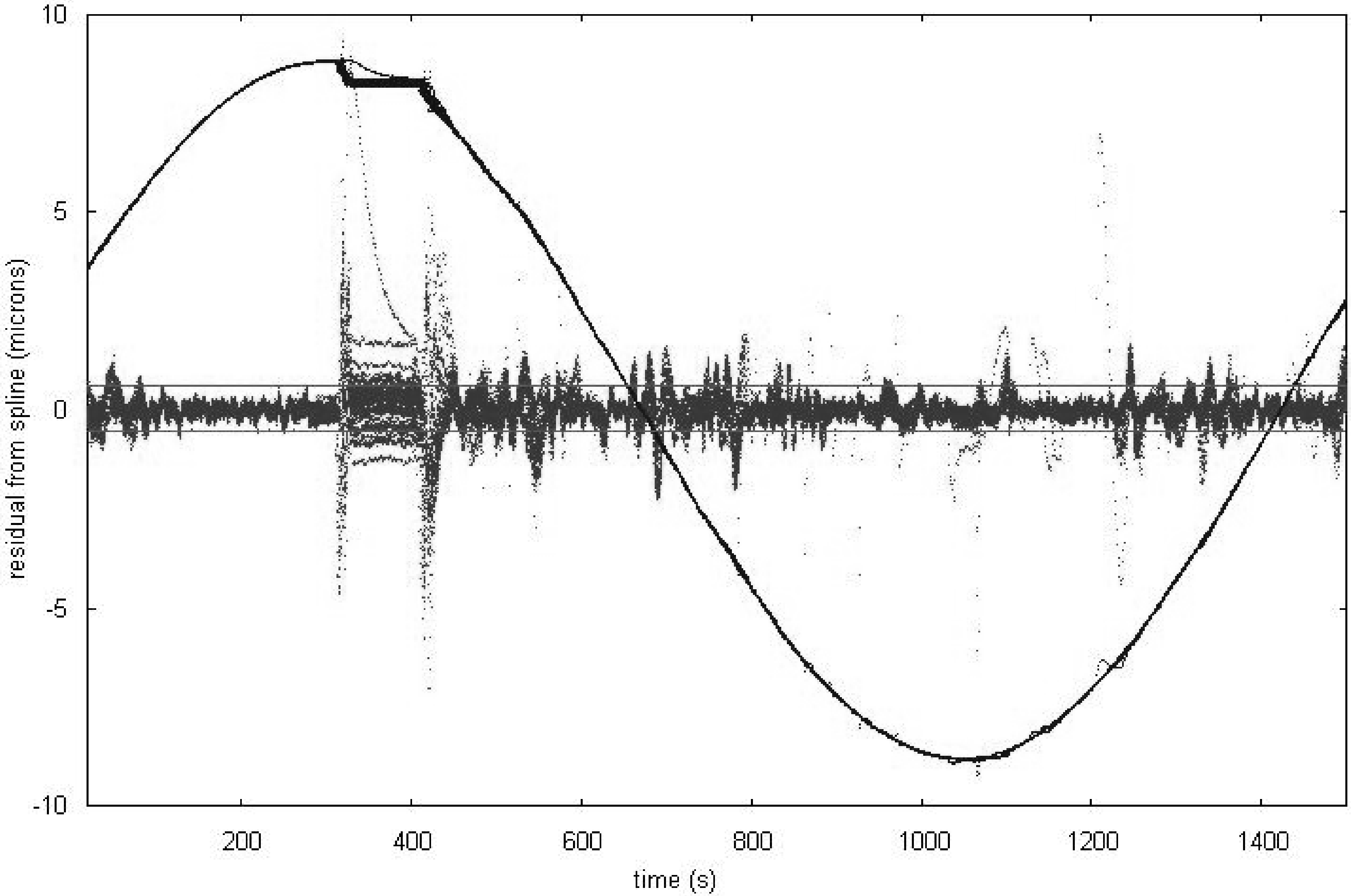
$$g(x) = e^{-ax^2}$$

- P term acts as a restoring force pushing against deviations from the target
- I term follows target closely for small errors
- D term doesn’t work due to phase delays
- Gaussian and notch functions limit range of P and I terms
- Additional software tricks attempt to limit noise and systematic errors
    - e.g. voltage bursts, acceleration limits

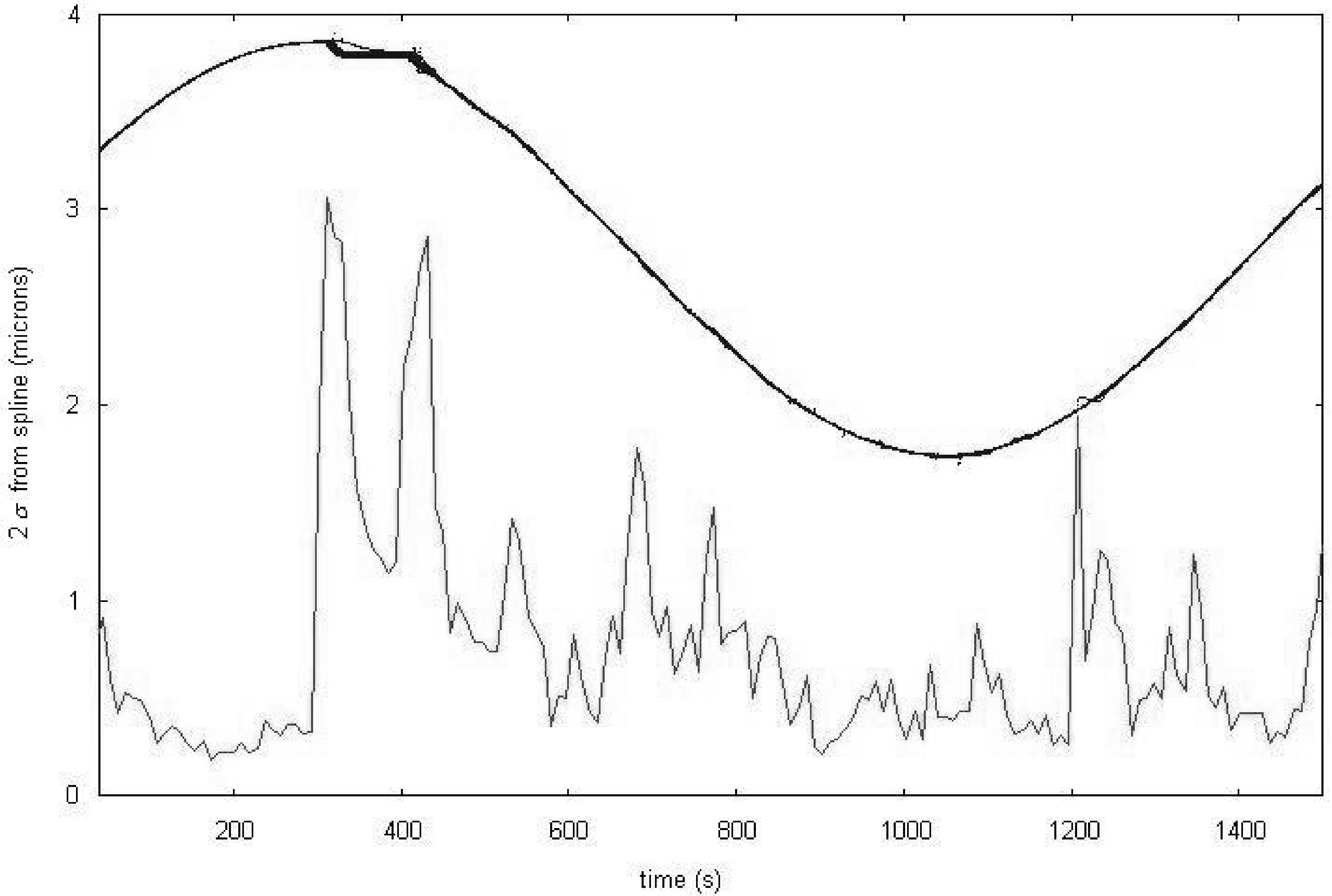
Feedback-controlled attractor plate motion, 8/18/03



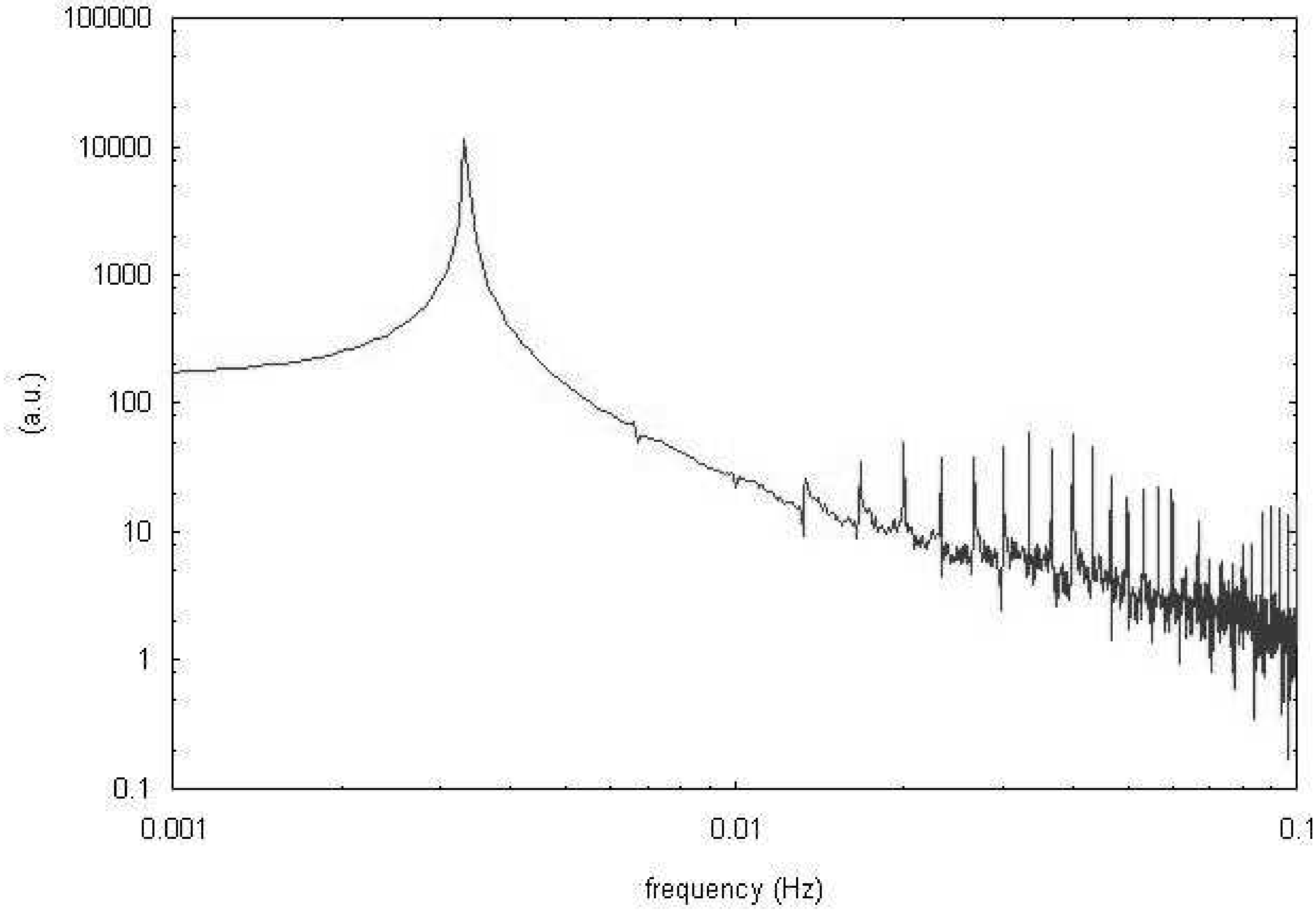
Residuals from cubic spline of one period



Two-σ bounds of averaged data
(motion is within these bounds 95% of the time)



Fourier transform of attractor plate motion



Summary

- Attractor plate follows oscillatory path with micron precision
- Position sensor is sensitive to at least 100 nm
  - Deviations in the plate’s motion can be measured and accounted for in analysis
- For the future:
  - Use a peristaltic pump to eliminate hysteresis and nonlinearities

Acknowledgements

- NSF
  - Money, housing, food, travel and the opportunity
- Jens Gundlach
  - Wisdom, expertise, guidance and patience
- Stephan Sclamminger and Eric Swanson
  - Additional wisdom, expertise, guidance and patience