SQL Related Experiments at the ANU

LIGO - G030180-00-D

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Experiments at the ANU

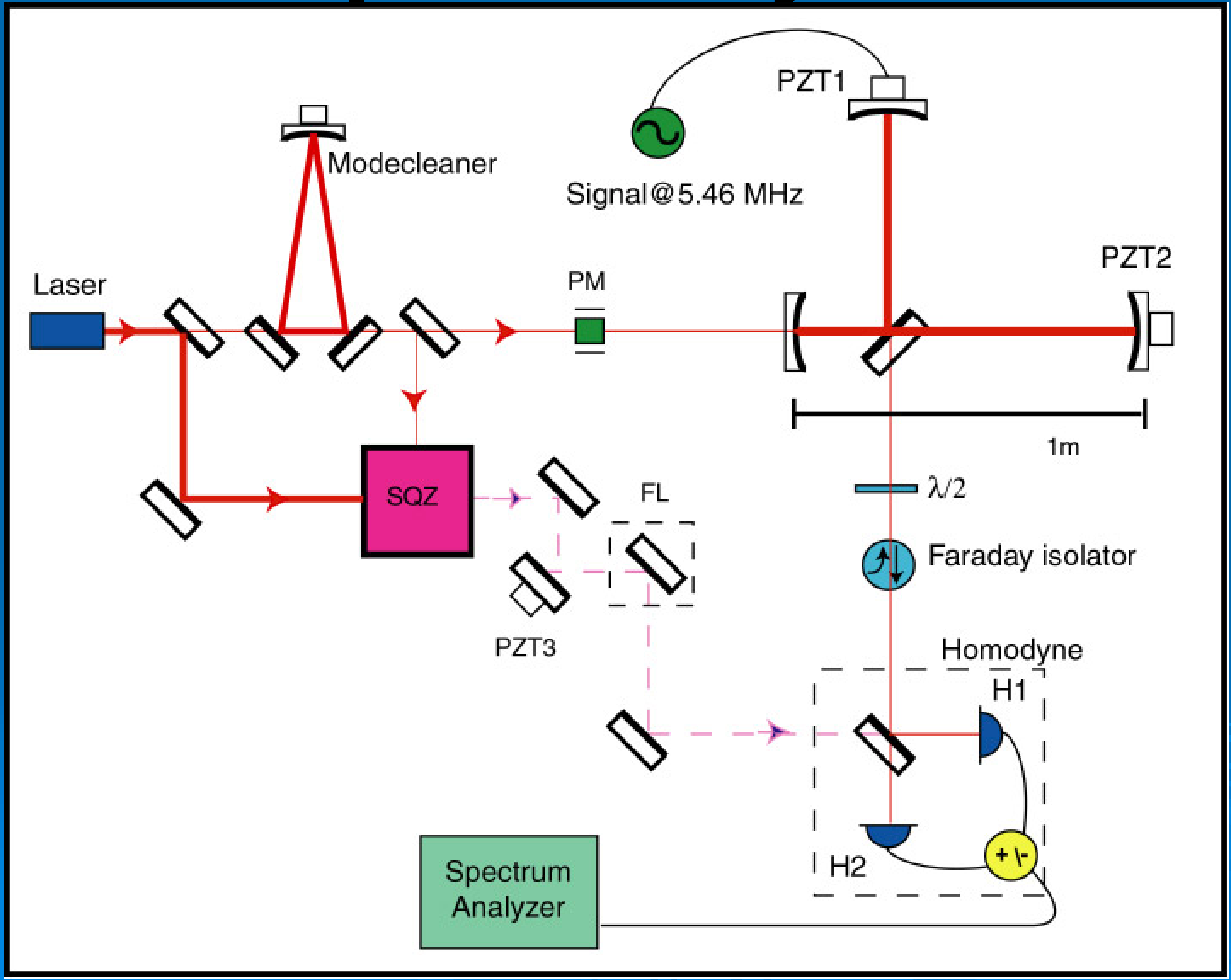
Squeezing enhanced power recycled Michelson
(K. McKenzie, D. A. Shaddock, B. C. Buchler, M. B. Gray, P. K. Lam, D. E. McClelland)

Speed meter control scheme and frequency response

(G. De Vine, Y. Chen, M. B. Gray, S. Whitcomb, D. E. McClelland)

Classical noise cancellation
(C. Mow-Lowry, B. S. Sheard, M. B. Gray, S. Whitcomb, D. E. McClelland)

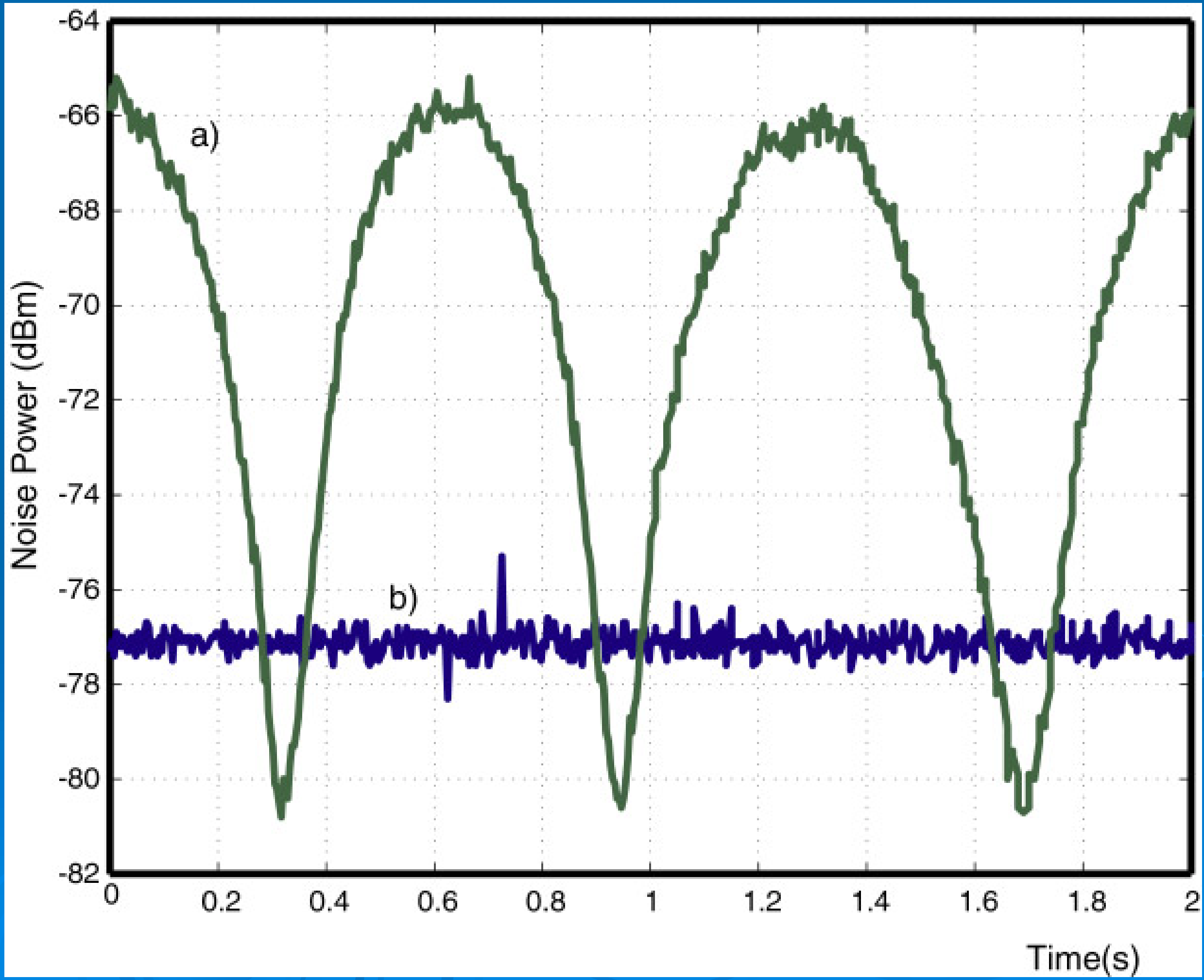
Squeezing Enhanced Michelson Optical Layout



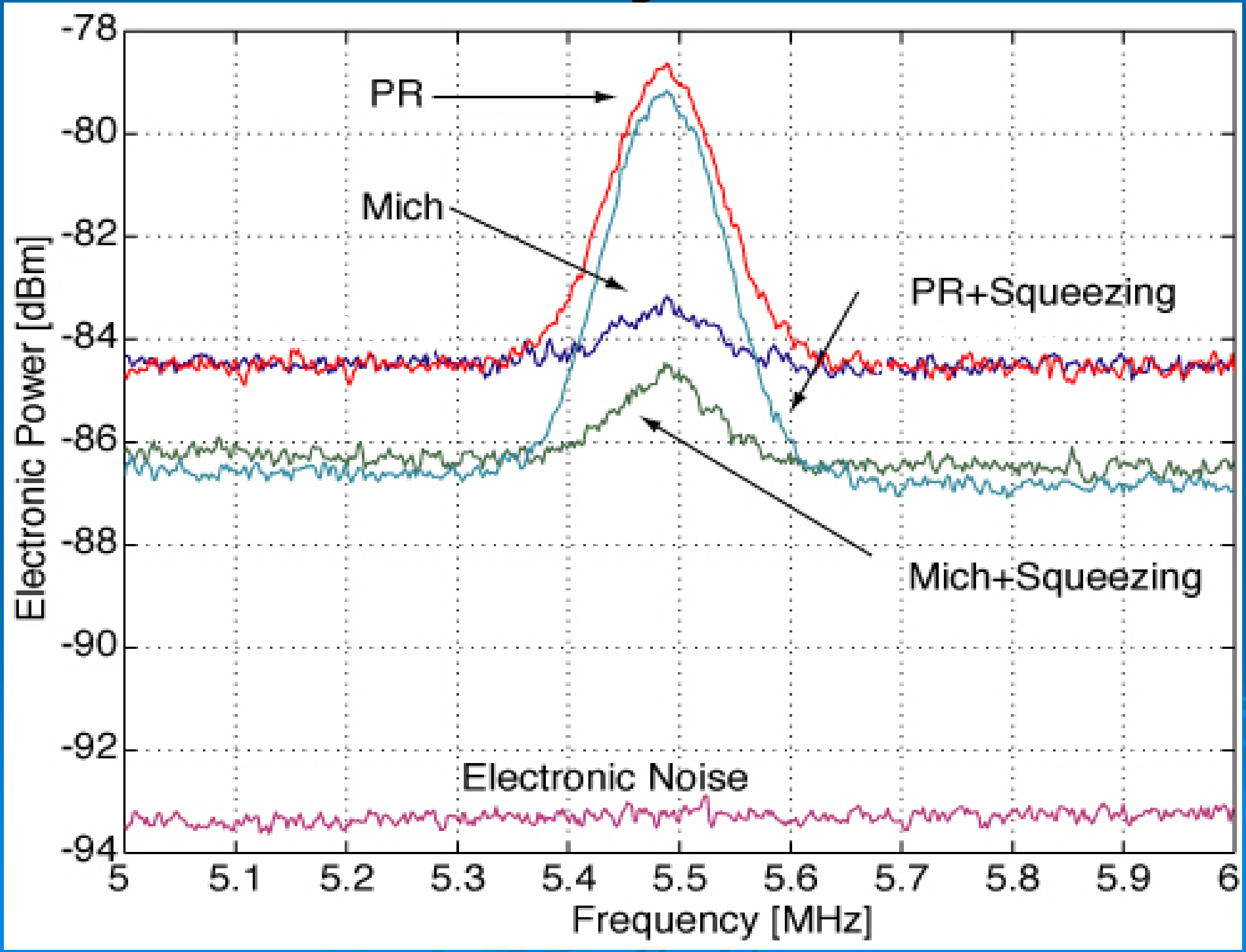
Squeezing Enhanced Michelson
Squeezed State Measurement

Squeezing at 5.5 MHz

3.5 dB below shot noise



Squeezing Enhanced Michelson Sensitivity Results



Squeezing Enhanced Michelson
Summary of Results

- First experimental demonstration of a gravitational wave detector configuration operating below the shot noise limit
- The control scheme, configuration, and injection optics for the squeezed state are compatible with full scale detectors

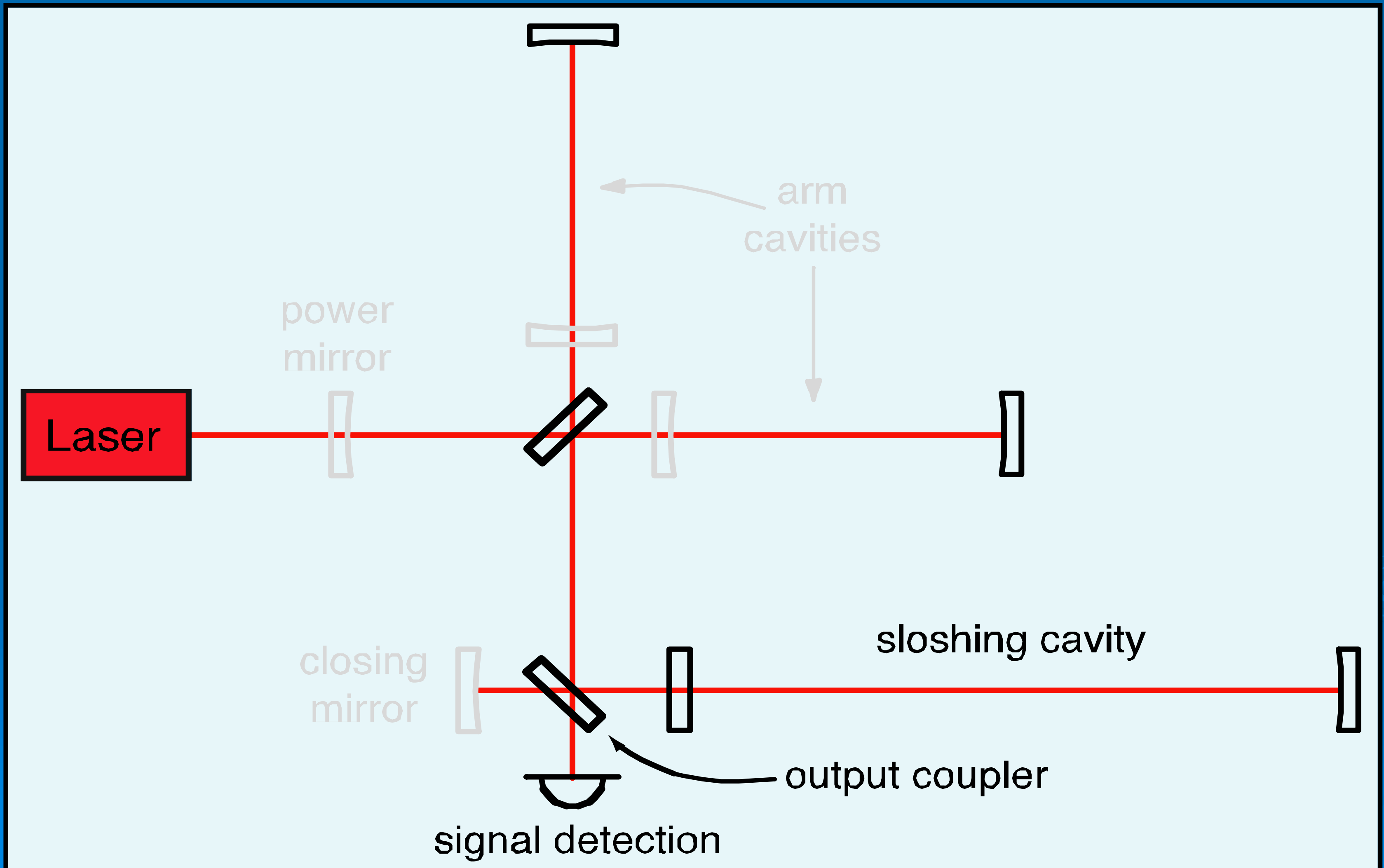
Speed Meter
Configuration Demonstration

- Measures relative velocity of end test masses
- Involves the addition of a “sloshing” cavity and a signal cavity output coupler for signal extraction
- Theory: e.g. Phys. Rev. D **66**, 022001 (2002)

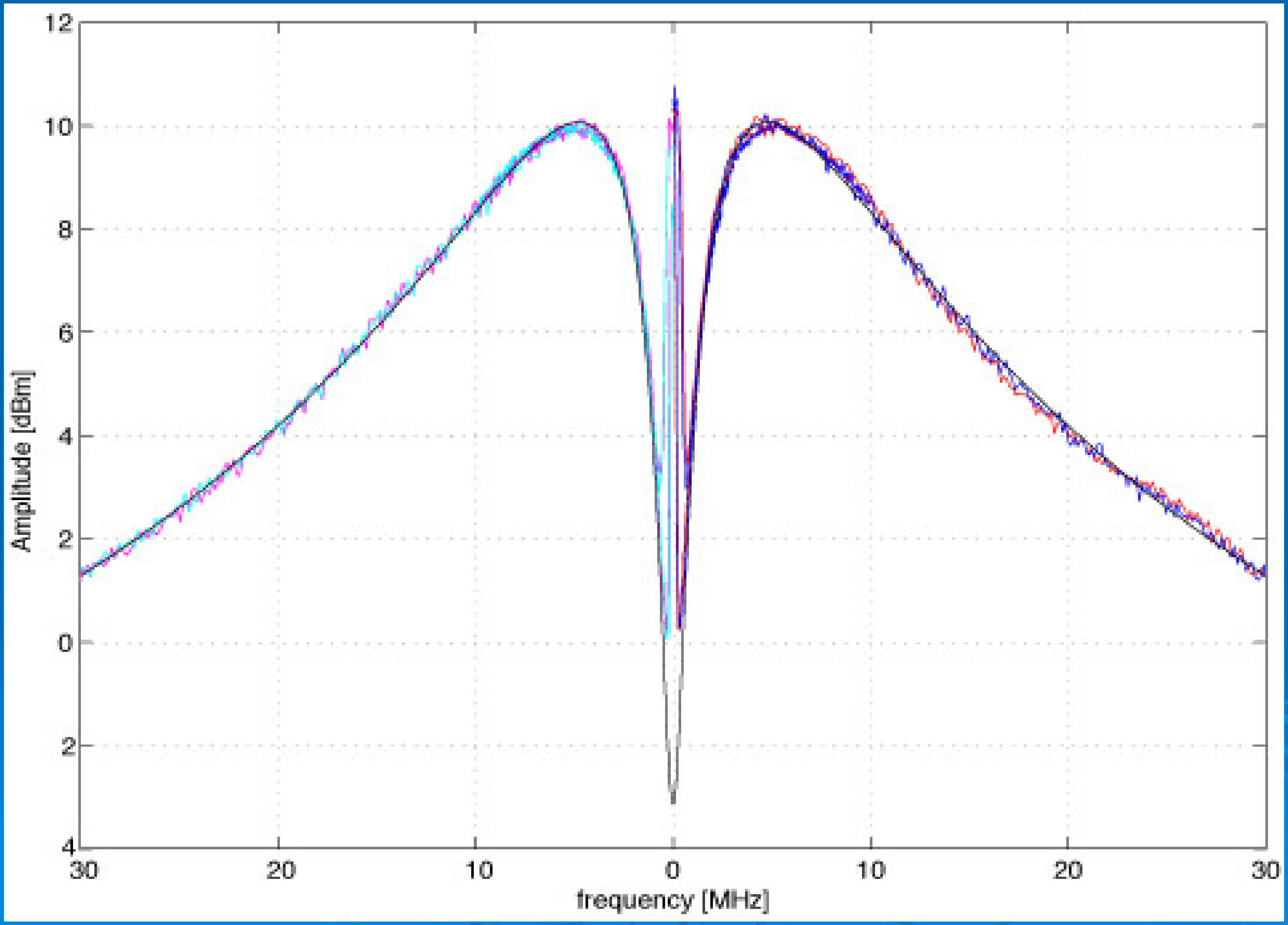
Speed Meter
How Does It Work?

- The sloshing cavity sends the GW signal back into the interferometer with a pi phase shift
- This then cancels the position signal (the interferometers response is like a differentiator up to the sloshing frequency)
- Thus the interferometer measures the relative velocity of the test masses
- Sloshing frequency determined by the storage time of the signal and sloshing cavities

Speed Meter
Optical Layout



Speed Meter
Frequency Response

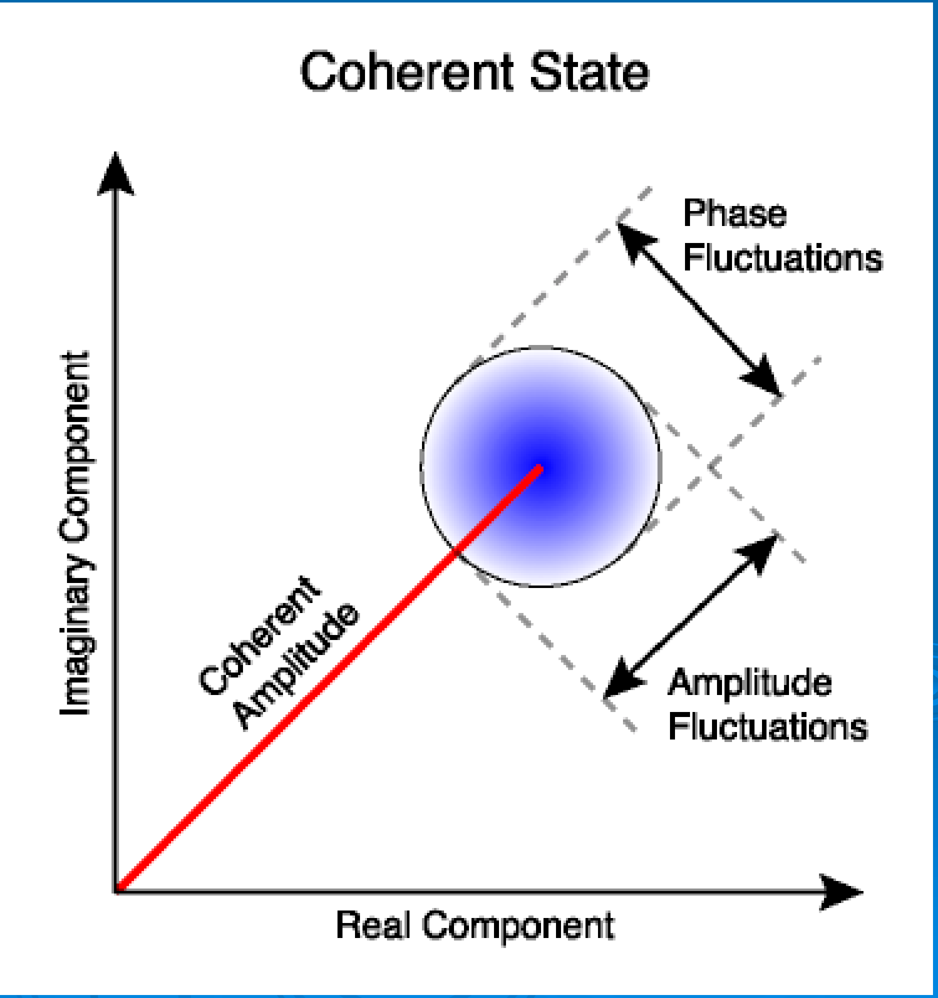


Speed Meter
Control and Readout

- An RF control scheme was devised using two resonant phase modulators
- Standard Schnupp and PDH techniques were used
- The frequency response was measured by injecting a ‘signal laser’ into the back mirror of an arm cavity
- The frequency response was in agreement with theoretical predictions

Noise Cancellation
The Standard Quantum Limit

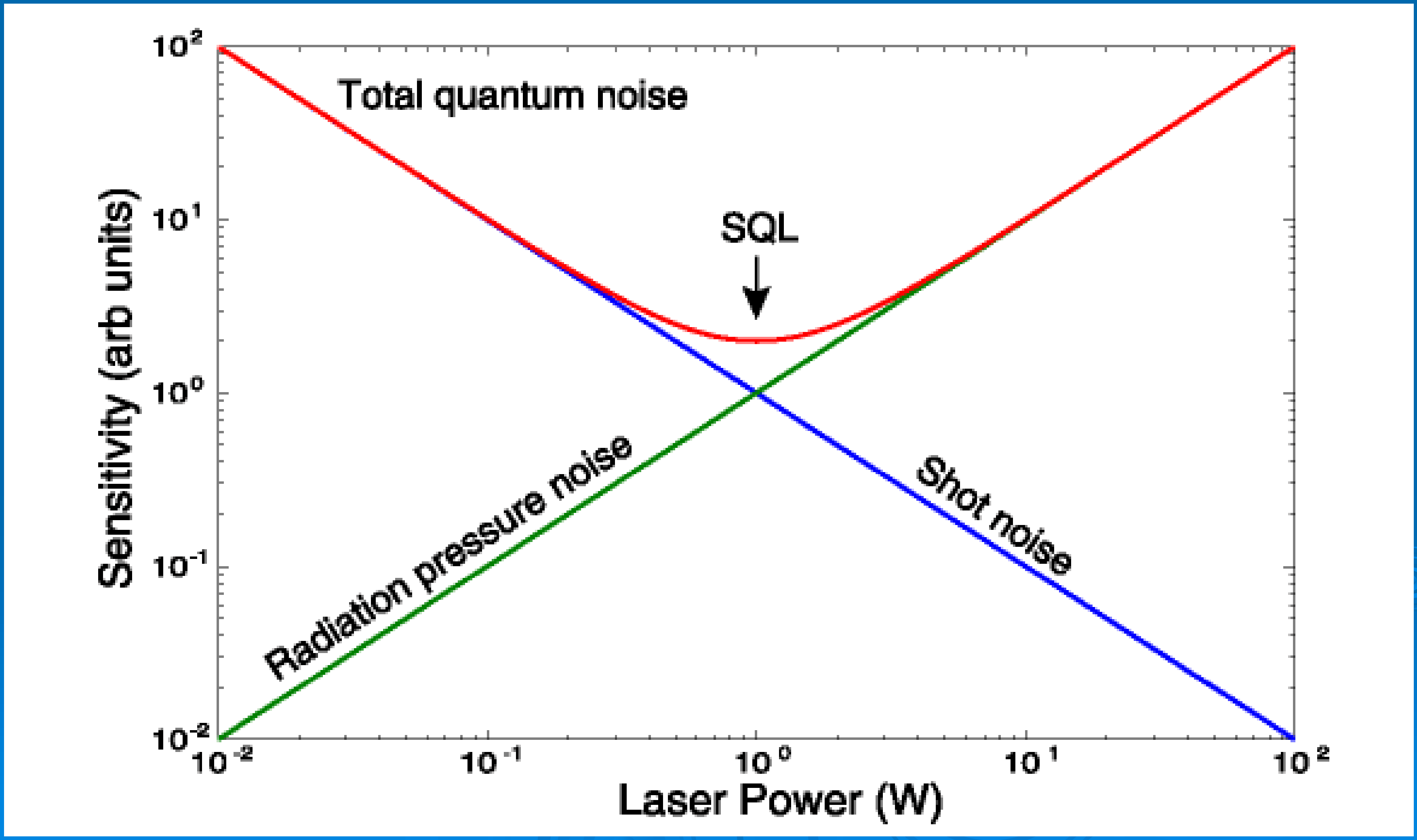
The Quantum noise of a coherent state, represented as a 'ball and stick'



Noise Cancellation
The Standard Quantum Limit

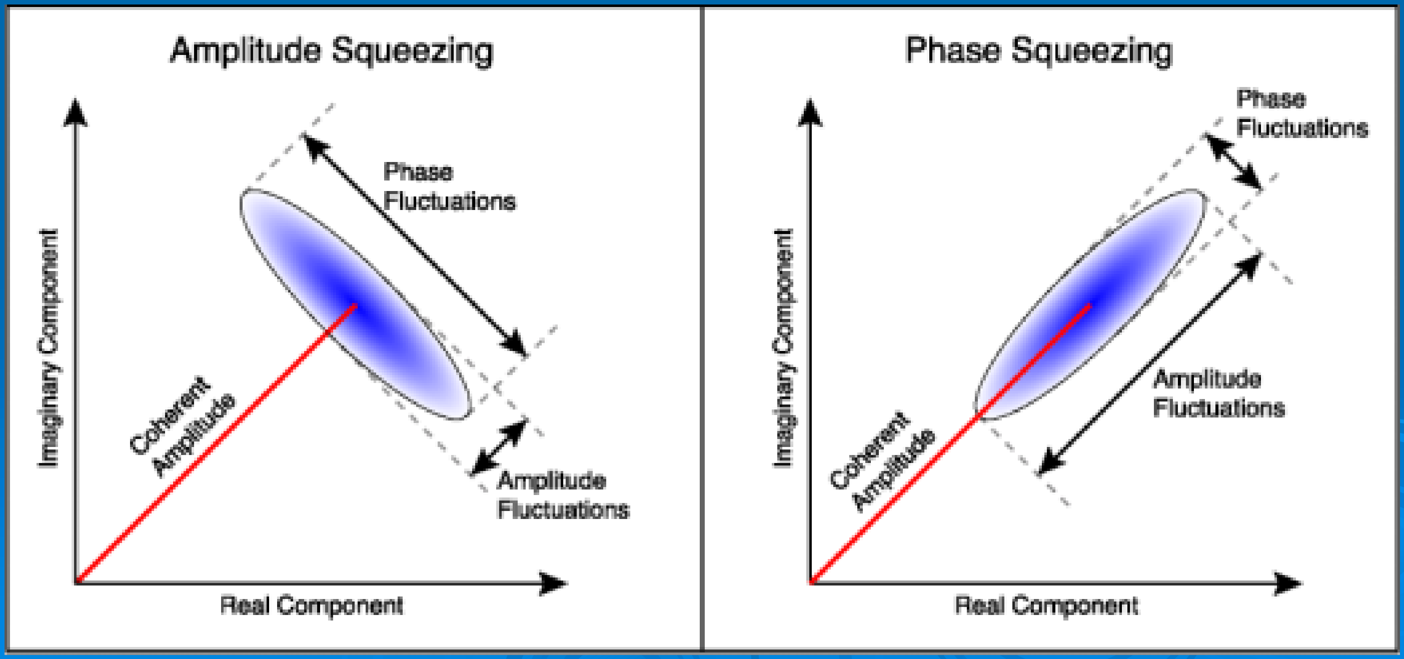
- Quantum phase fluctuations directly couple into GW measurements, and the limiting sensitivity is labeled – ***Shot Noise***
- Quantum amplitude fluctuations cause mirrors to move, via radiation pressure, resulting in – ***Radiation Pressure Noise***
- These two noise sources scale oppositely with power, producing a minimum at an ideal power

Noise Cancellation
The Standard Quantum Limit



Noise Cancellation
The Standard Quantum Limit

- Both Shot Noise and Radiation Pressure Noise limit sensitivity at the SQL
- How can we do better? Squeezing?

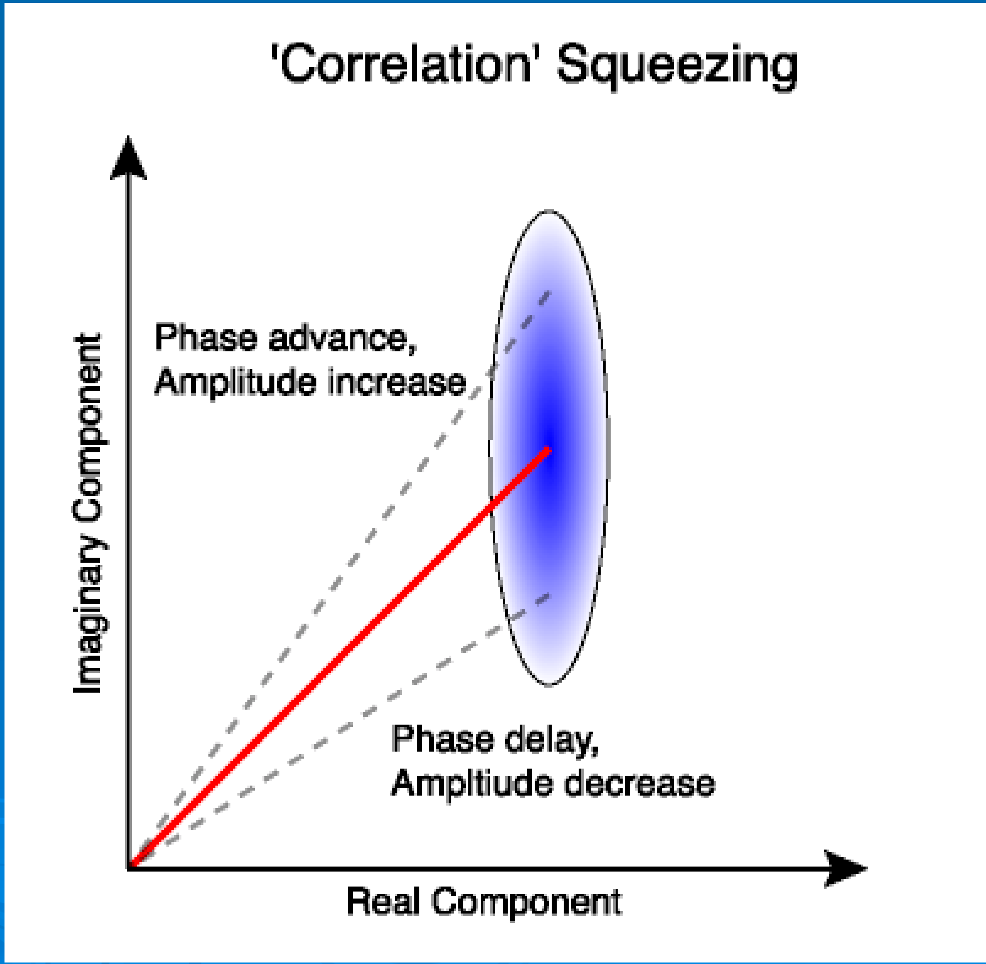


Noise Cancellation
The Principle

- At the SQL shot noise and radiation pressure noise are the same size
- If they are correlated with the appropriate phase, they will cancel
- Squeezing can be used to correlate the fluctuations
- Thus squeezing can be used to breach the SQL

Noise Cancellation
The Standard Quantum Limit

Squeezing at 45 degrees correlates fluctuations in the two quadratures



Noise Cancellation
The Classical Equivalent

- We performed a bench top experiment which is the classical analogue to breaching the Standard Quantum Limit
  - We used Amplitude modulation to replace radiation pressure noise, and
  - Frequency modulation to replace shot noise
- These artificially imposed noise sources can mimic quantum noise

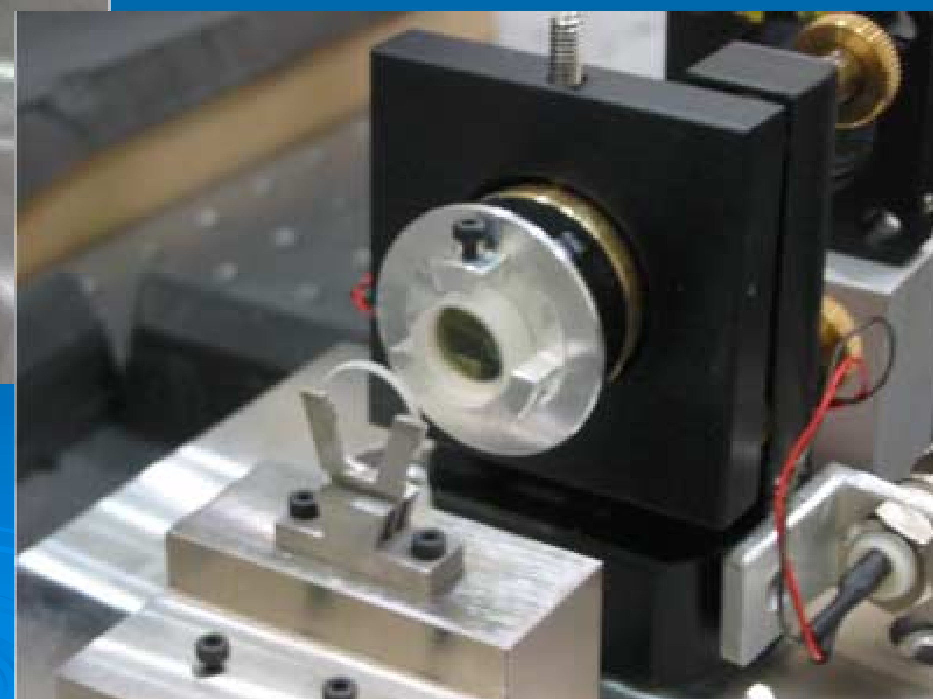
Noise Cancellation
The Classical Equivalent

- Performing this experiment in the classical regime greatly eases noise requirements, facilitating bench top work
- It provides proof of principle results
- Most importantly, it generates experience working with interferometers which are dominated by radiation pressure

Noise Cancellation
Experimental Design

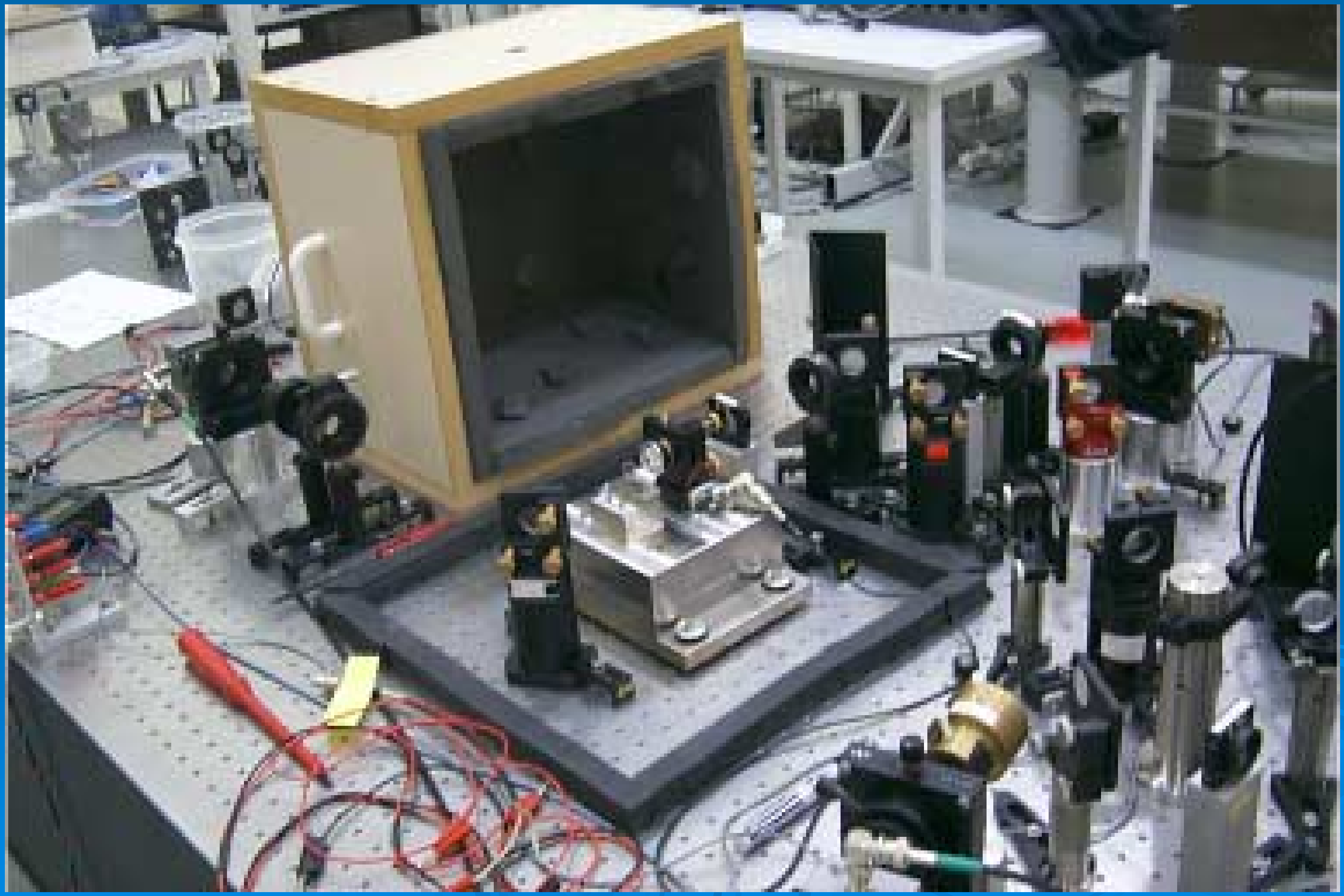
- There were several important features in the design:
  - Creating a bench top environment sufficiently quiet
  - The design of the lightweight mirror
  - The optical layout, and
  - Control and readout of the mirror position

Noise Cancellation
Experimental Design

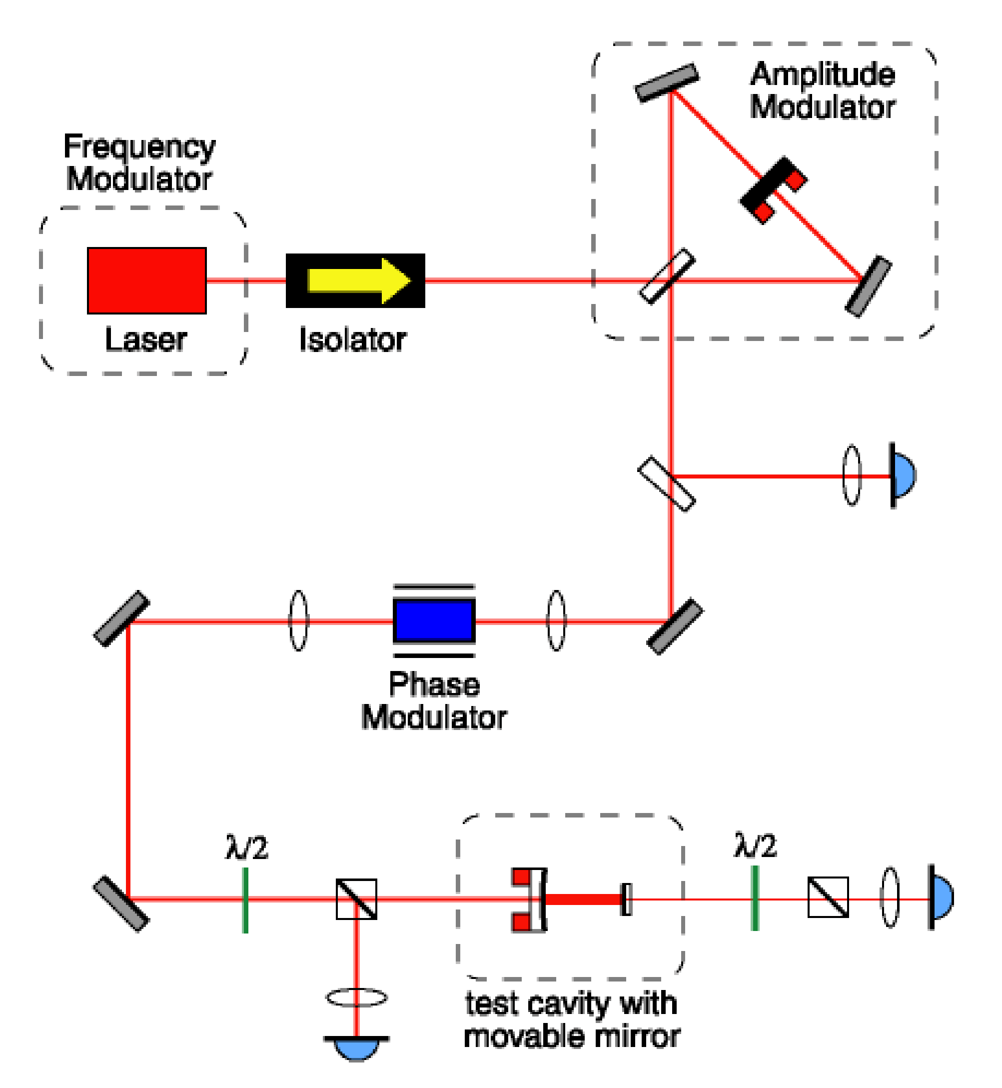


Noise Cancellation
Experimental Design

- The experiment uncovered



Noise Cancellation
Experimental Design

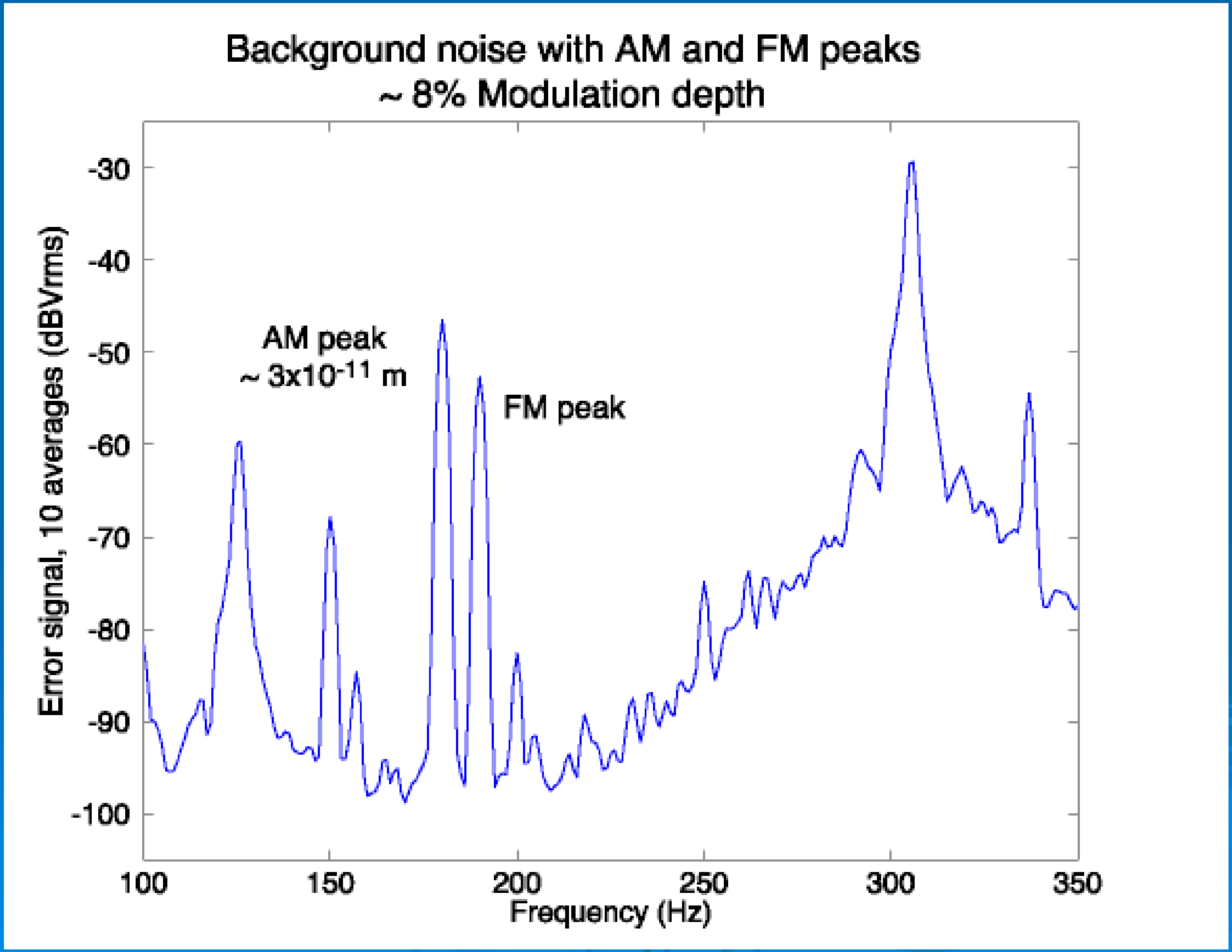


Noise Cancellation
Experimental Design

Some real numbers:

Standard input power	~ 200 mW
Circulating power	~ 40 W
Angular spring constant	~ 0.5 Nm/rad
Maximum optical force	~ 4 x 10^{-7} N
Maximum optical torque	~ 5 x 10^{-9} Nm
Predicted displacement	~ 10^{-11} m

Noise Cancellation Results

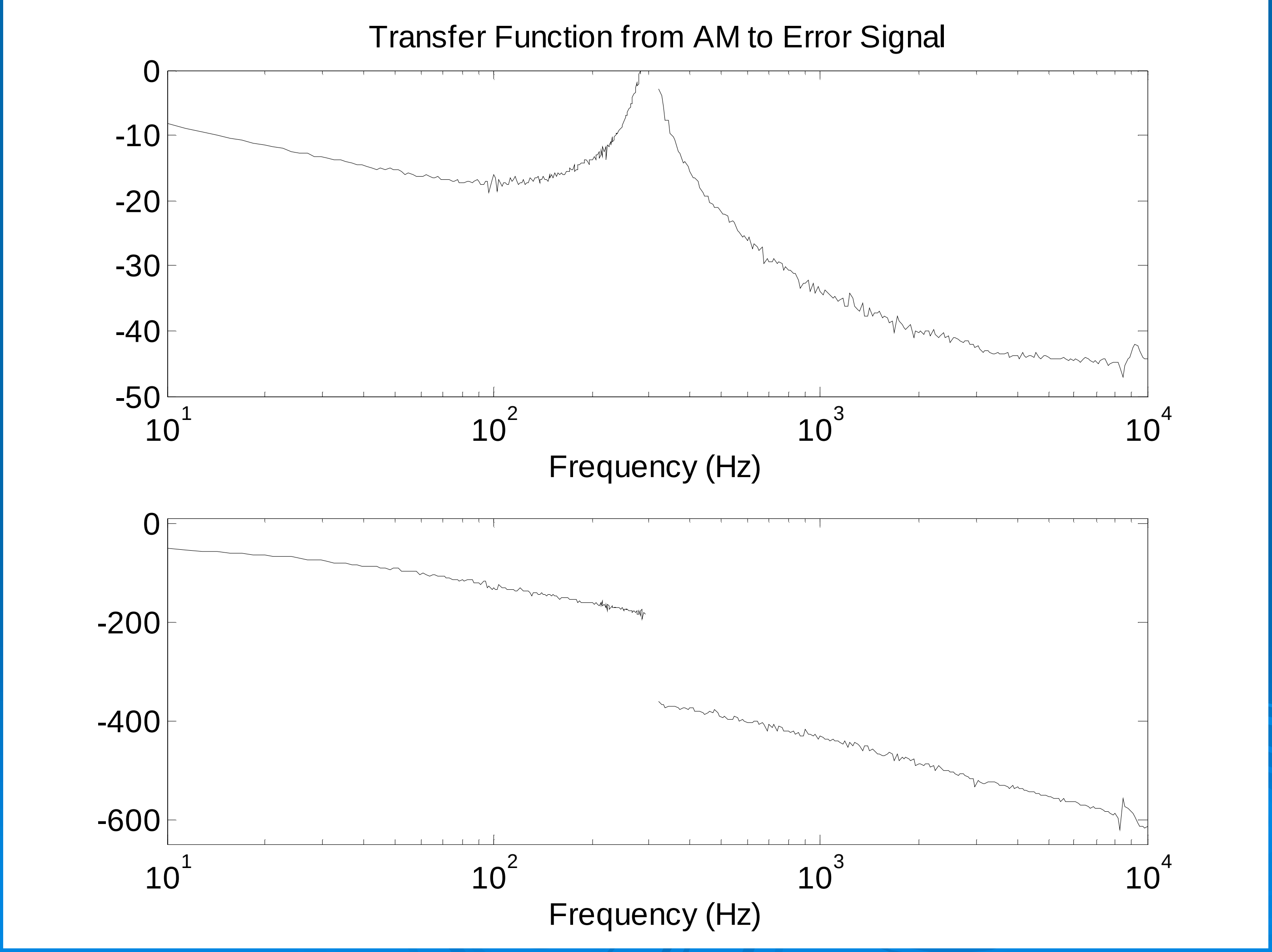


Noise Cancellation
Results

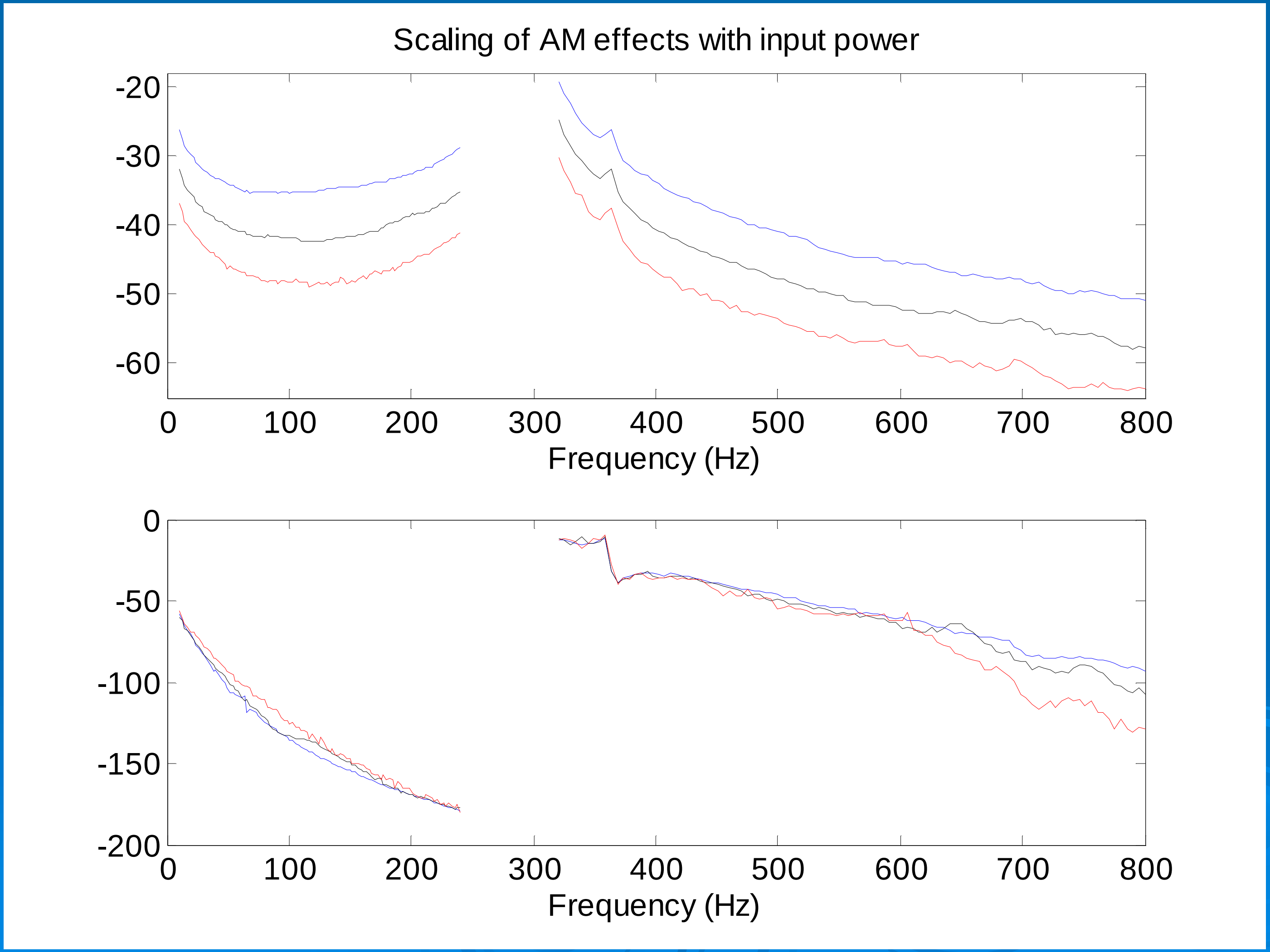
Verification that error signal disturbances from input AM were caused by radiation pressure was done in 3 ways:

- Measurement of the transfer function from amplitude modulation to error signal disturbance,
- Observation of the scaling of the error signal disturbance with input power, and
- A calibrated measurement of motion for a known driving radiation pressure force

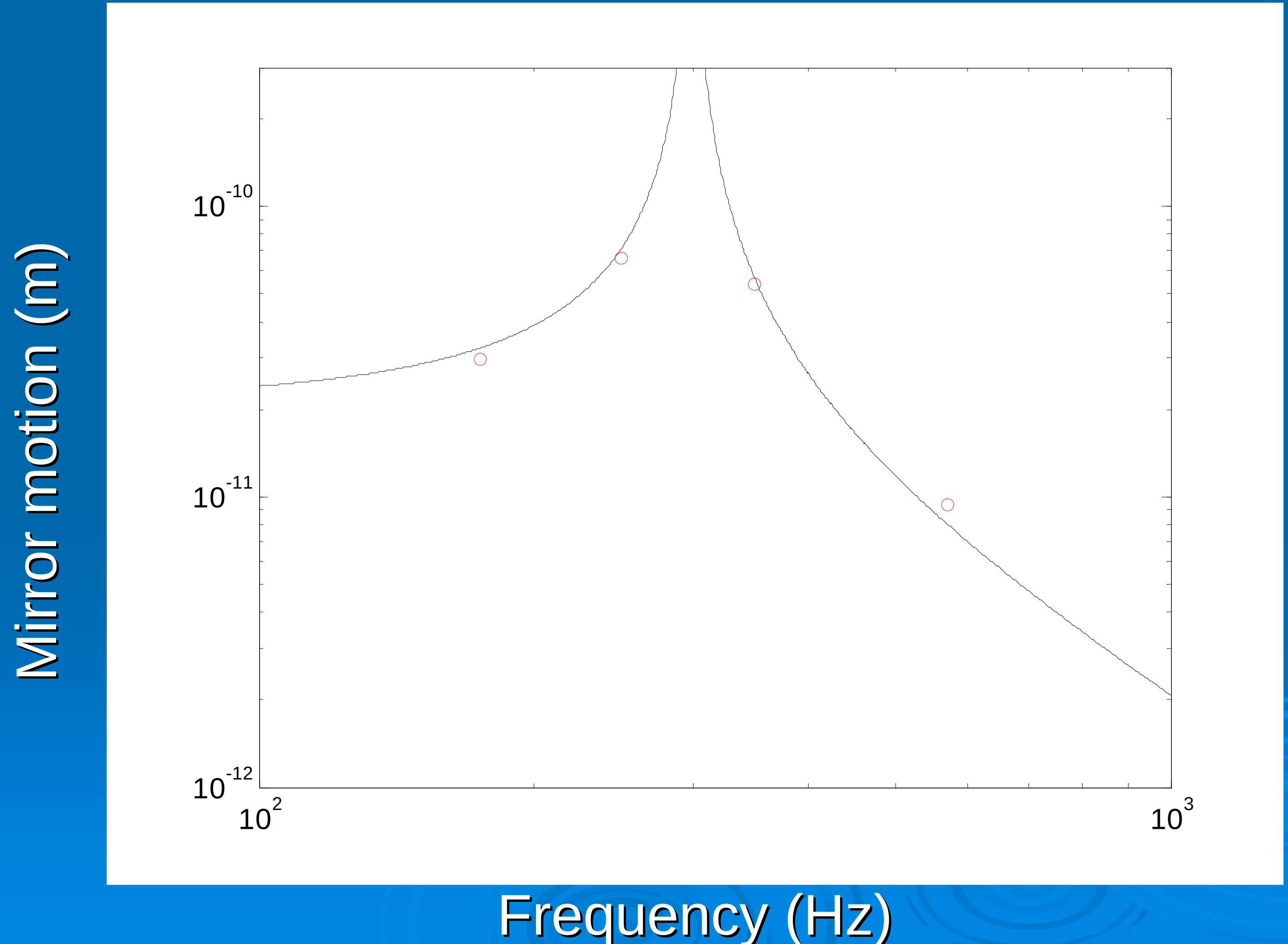
Noise Cancellation Results



Noise Cancellation
Results



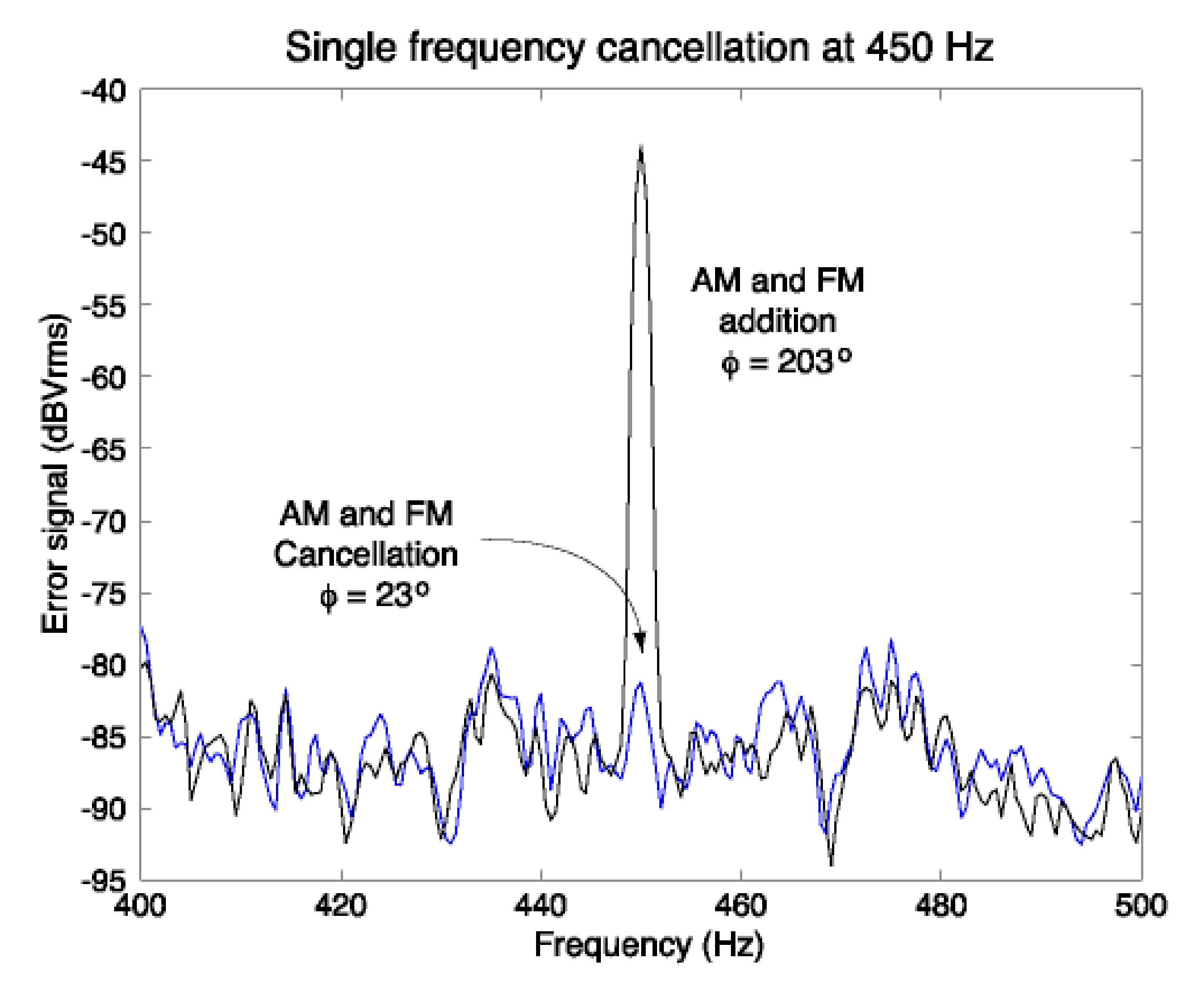
Noise Cancellation Results



Noise Cancellation
Results

- The first cancellation data was recorded at a single frequency by:
  - Introducing a sinusoidal AM signal
  - Adding an FM signal at a different frequency, and matching their error signal amplitudes
  - Phase locking the signals at the same frequency
  - Adjusting their relative phases and amplitudes until the peak reached a minimum

Noise Cancellation Results



Noise Cancellation
Results

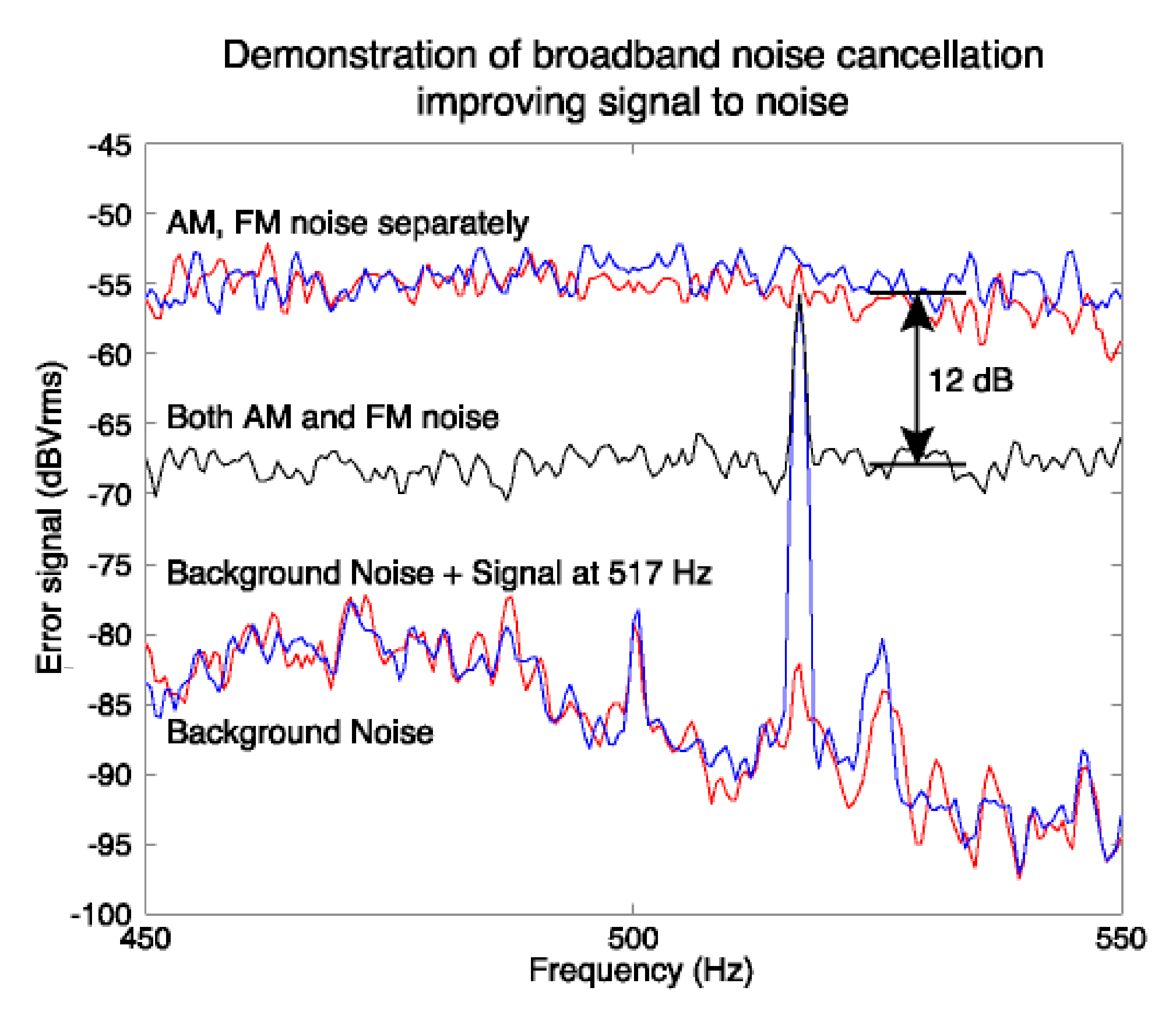
- To achieve broadband noise cancellation, bandwidth limited white noise was generated

- The signal was split, to supply inputs to both the amplitude and frequency modulators

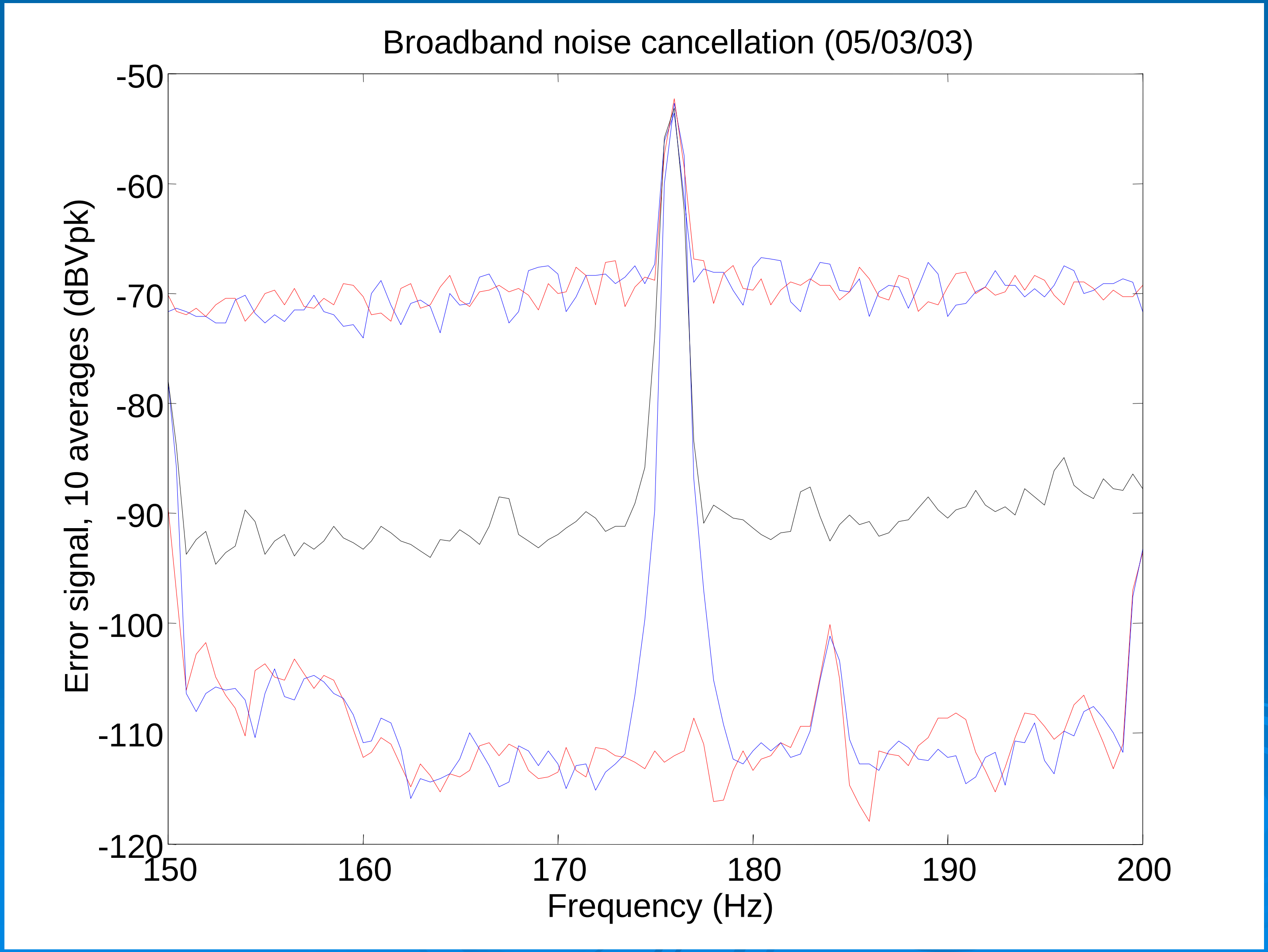
- To counter the effect of the mechanical transfer function, one path was shifted in amplitude and phase, then inverted

Noise Cancellation

Results



Noise Cancellation Results



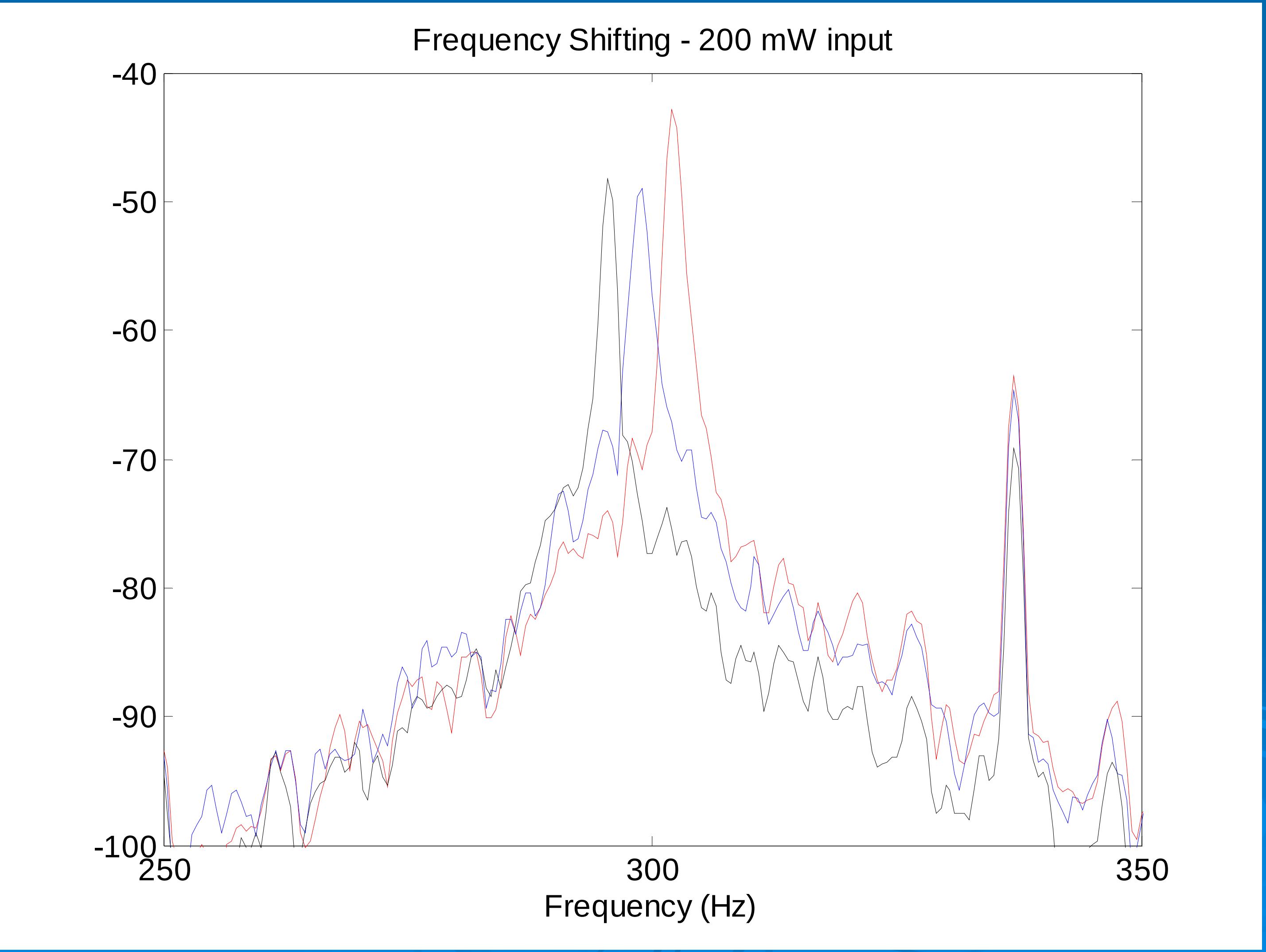
Noise Cancellation
Further Work

Several additions were made to the work shown here:

- An unmodulated, orthogonally polarized probe was used to readout cavity length
- Better optical power and cavity finesse measurements were made
- Measurements were made of frequency shifts from opto-mechanical coupling

Noise Cancellation

Further Work - Results



Conclusions

- A squeezing enhanced Michelson interferometer was shown to operate with sensitivity better than the shot noise limit
- A speed meter control scheme and frequency response was demonstrated
- Correlated noise in the same quadratures as shot noise and radiation pressure noise was shown to cancel in the presence of a movable mirror