An Interferometric displacement sensor for test mass location.

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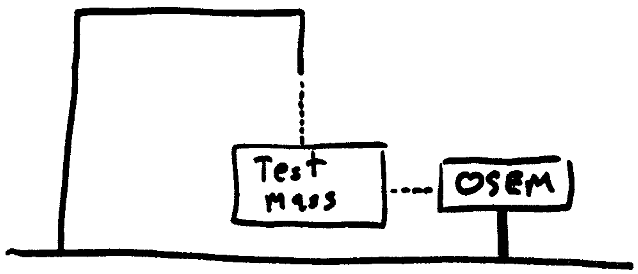
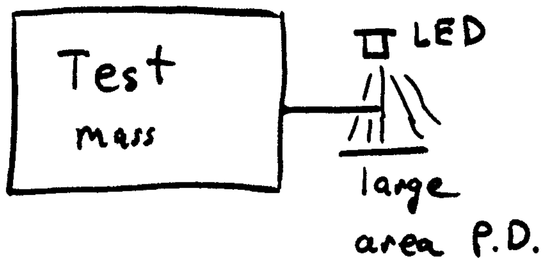
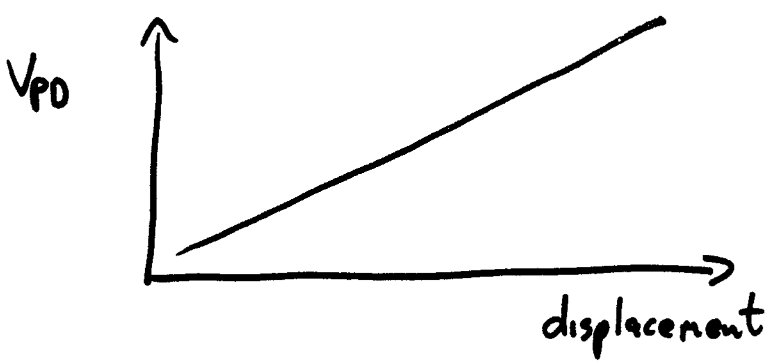
LIGO-G960130-00-D

Performance of existing shadow meter

(based on analysis by Alex Abramovici, 5-13-94)

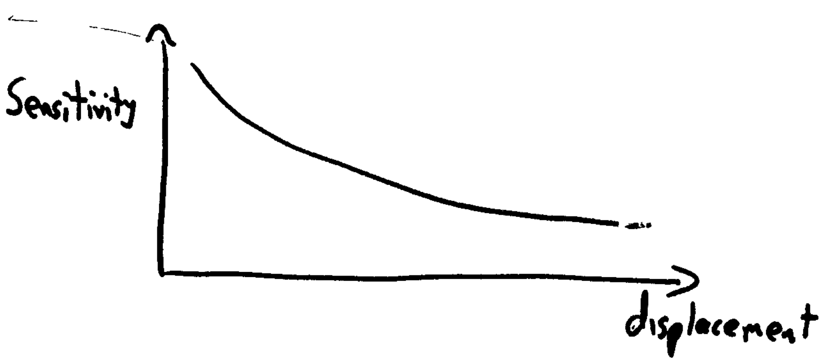




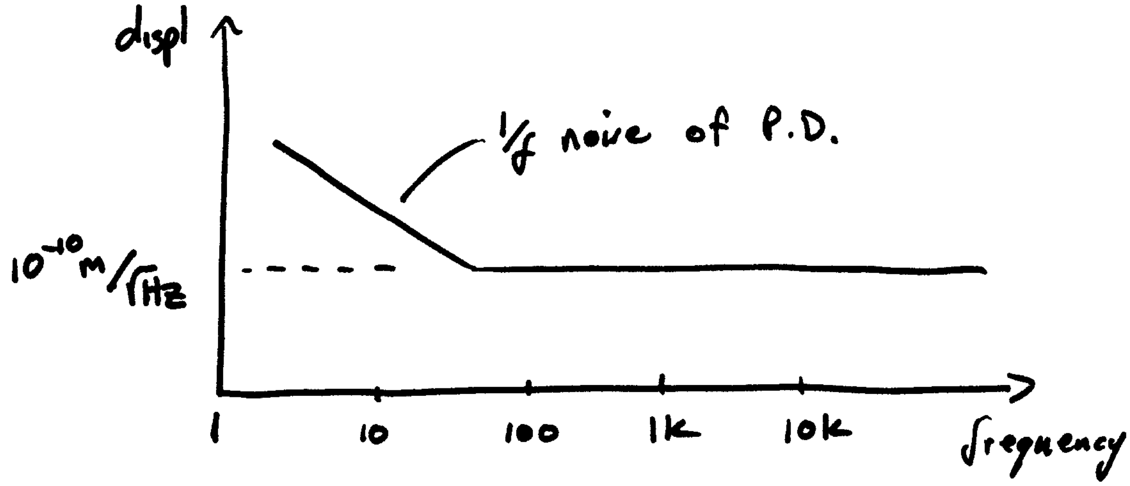


Shot noise $\sim \sqrt{V_{PD}}$

Sensitivity $\sim \frac{1}{\sqrt{V_{PD}}}$



Sensitivity vs frequency



\# when placed in feedback system, noise floor is attenuated by $\approx 1.3 \times 10^{-10}$

giving a contribution of
$\approx 1.3 \times 10^{-20}$ m/$\sqrt{Hz}$ at 100Hz (at actuator).

\# amplifier output noise contribution $\sim 1.1 \times 10^{-20}$ m/$\sqrt{Hz}$

and LIGO upper limit of 10^{-19} m/$\sqrt{Hz}$

\# sensor displacement noise is a significant noise source in the existing configuration however, it is well within the LIGO Limit.

\# dynamic range of shadow sensor

$$\approx \frac{10^{-4}}{10^{-10}} = 10^{6} \Rightarrow 120\,dB$$

Limits of sensitivity and dynamic range due to shot noise.

for an optical intensity measurement

$$\text{maximum dynamic range} = \sqrt{\frac{i_{PD}}{2e}}$$

where $i_{dc} = P_{opt} \cdot S$

assuming $S = 0.5$ A/W (at $\lambda = 0.8\mu m$) and $P_{opt} = 10mW$

maximum dynamic range $\simeq 1.2 \times 10^8$
$\simeq 160dB$

(or $\simeq 170dB$ for $P_{opt} = 100mW$)

implication for sensitivity:

if we require $\Delta L_{max} = 0.1mm$

⇒ shot noise floor $= 10^{-12} m/\sqrt{Hz}$ (10mW)

⇒ $10^{-11} m/\sqrt{Hz}$ for $\Delta L = 1mm$.

this limit is intrinsically optical

⇒ real devices are usually limited

by electronics dynamic range

Proposed specifications for the interferometric sensor.

\# assuming LIGO stage II requires a significantly smaller sensitivity limit than 10^{-19} m/$\sqrt{Hz}$.

\# dynamic range of 1mm (maximum excursion at ≃ 1Hz, due to pendulum resonances).

\# sensitivity of better than 10^{-12} m/$\sqrt{Hz}$ at 100 Hz.

\# sensitivity of better than 10^{-9} m/$\sqrt{Hz}$ bellow 100 Hz.

\# a non-contact measuring system

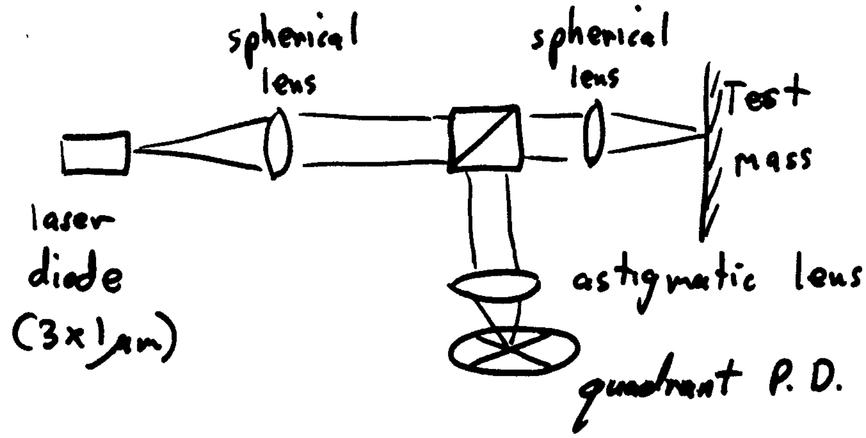
Three proposed methods of meeting these specs:

① astigmatic optical motion sensor

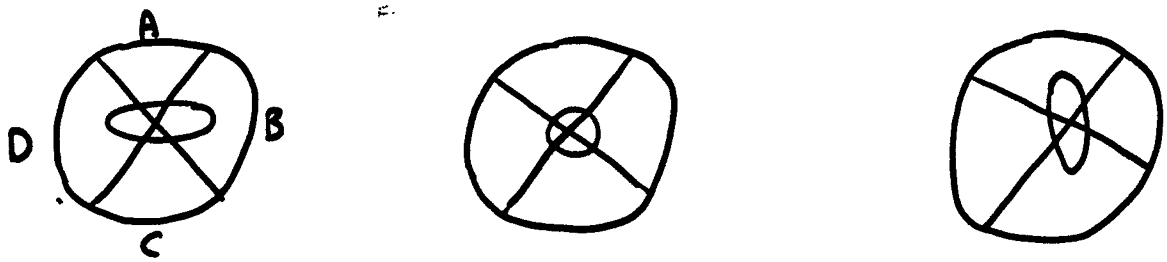
② fringe counting interferometer

③ tracking mirror interferometer

Astigmatic optical motion sensor



test mass near side of focus | test mass at focus | test mass far side of focus



signal out = (A+C) − (B+D)

Advantages

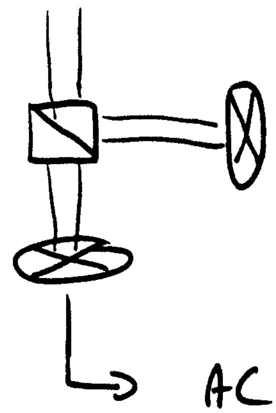
- simple (non-interferometric) optics
- gives vertical & horizontal motion as well (A−C = vert, B−D = hori)
- difference (balanced) detection ⇒ doesn't require a shot noise limited laser.

Disadvantages

- realistic lasers (single mode diode) limit power ≈ 100mW ⇒ dynamic range = 3×10^{8}
  ⇒ noise floor = 3×10^{-12} m/$\sqrt{\text{Hz}}$ for ΔL = 1mm

\# non-trivial electronic dynamic range issues

eg:



→ DC coupled for $\delta L \approx 1$mm, low frequency motion (DC ... 100Hz).

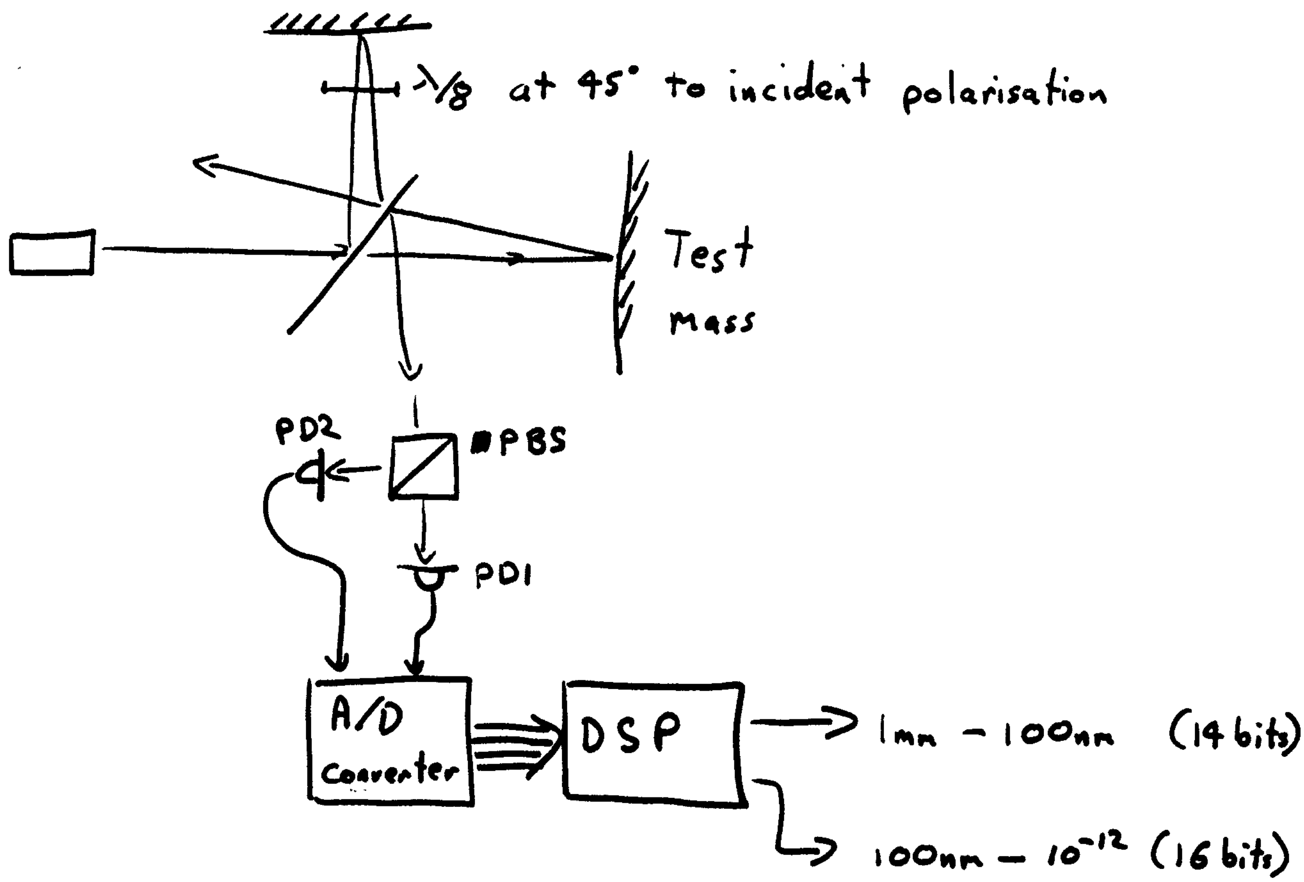
→ AC coupled for high sensitivity, high frequency response (100 ... 10kHz).

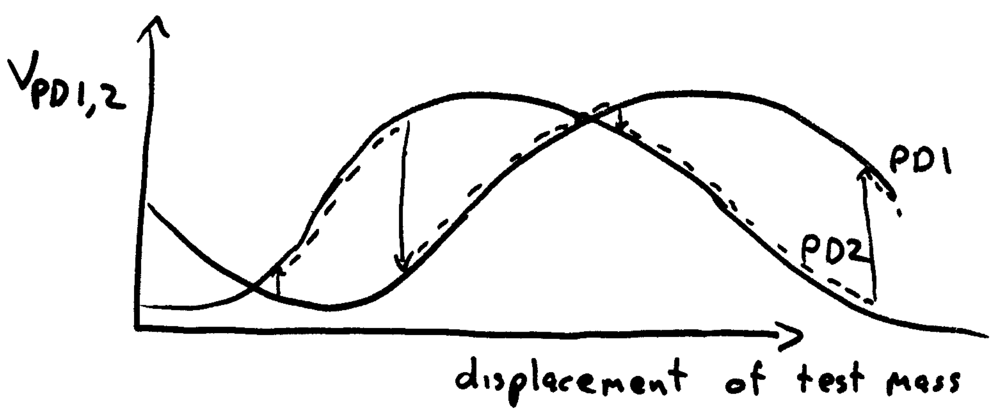
\# how to combine these 2 signals to give a useful feedback signal without reducing dynamic range?

⇒ cross-over network of some sort.

\# finalised optical design and all optics are in-house at ANU.

Fringe Counting Interferometer





PD1 & PD2 are 90° out of phase.

Advantages

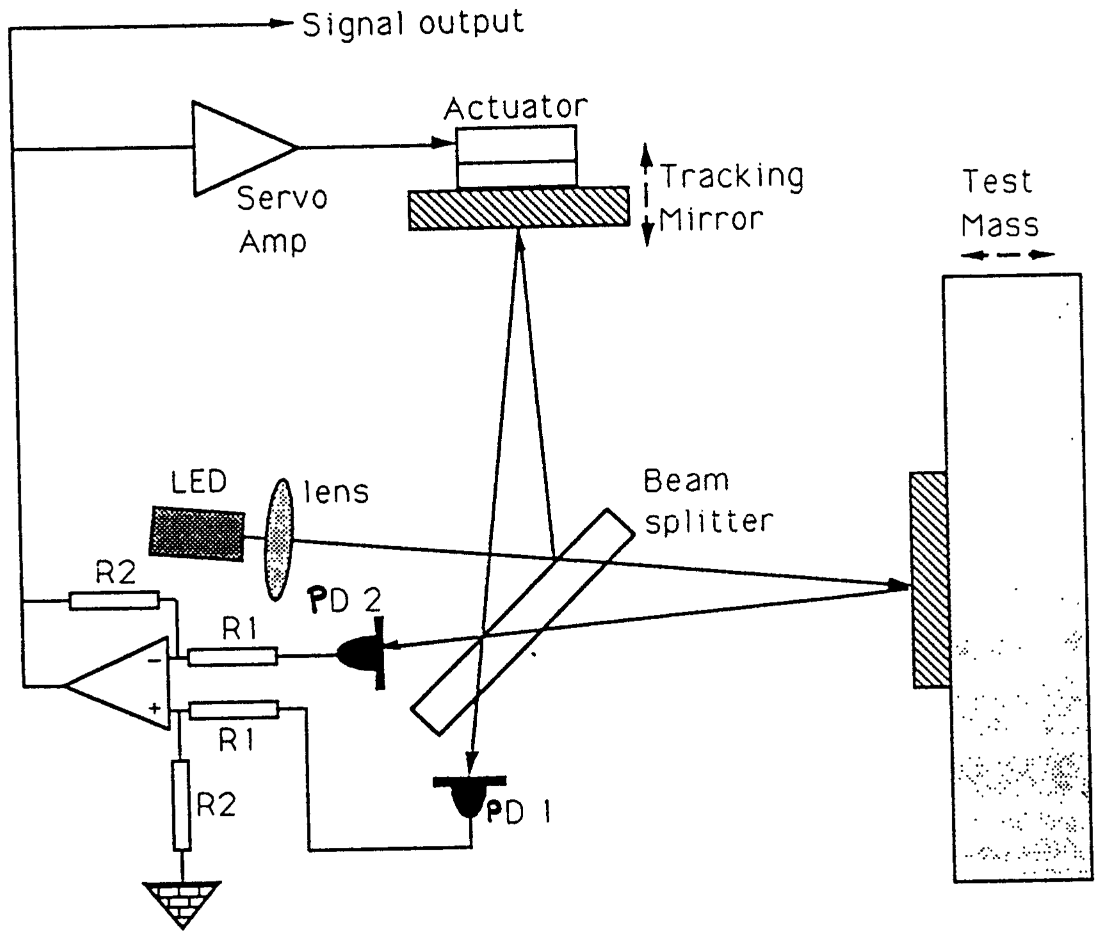
arbitary dynamic range
no internal feedback system

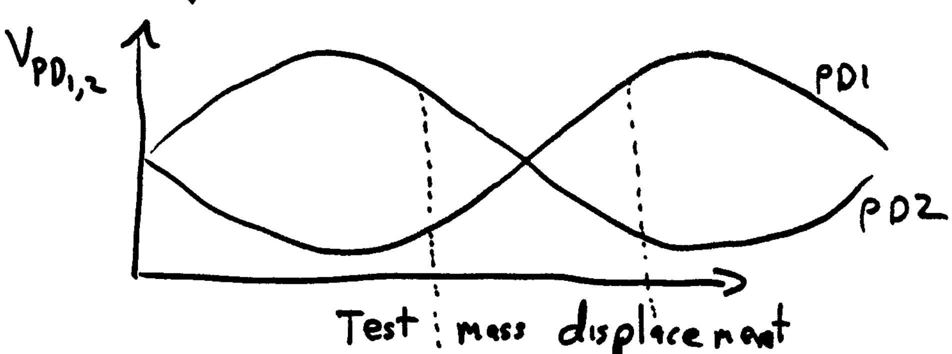
Disadvantages

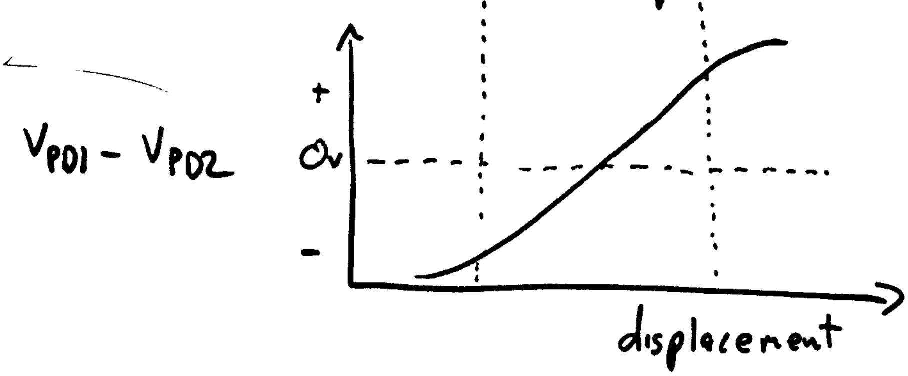
require a stable laser ($\Delta\nu \leq 100MHz$).

complex DSP task.   # relative motion only.

Tracking mirror interferometer







Actual Optical Design

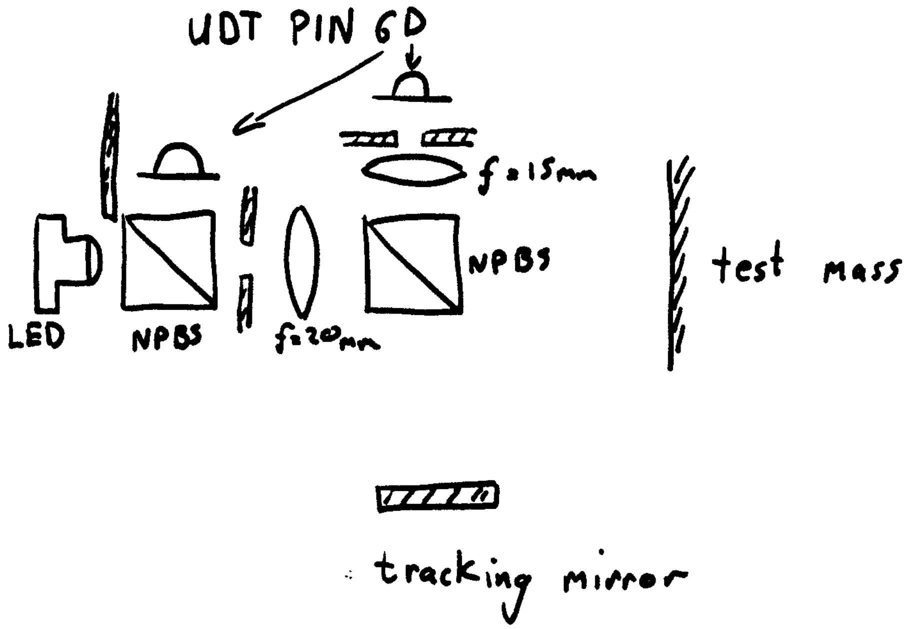


image active area of LED onto end mirrors, and LED can onto photo diodes.

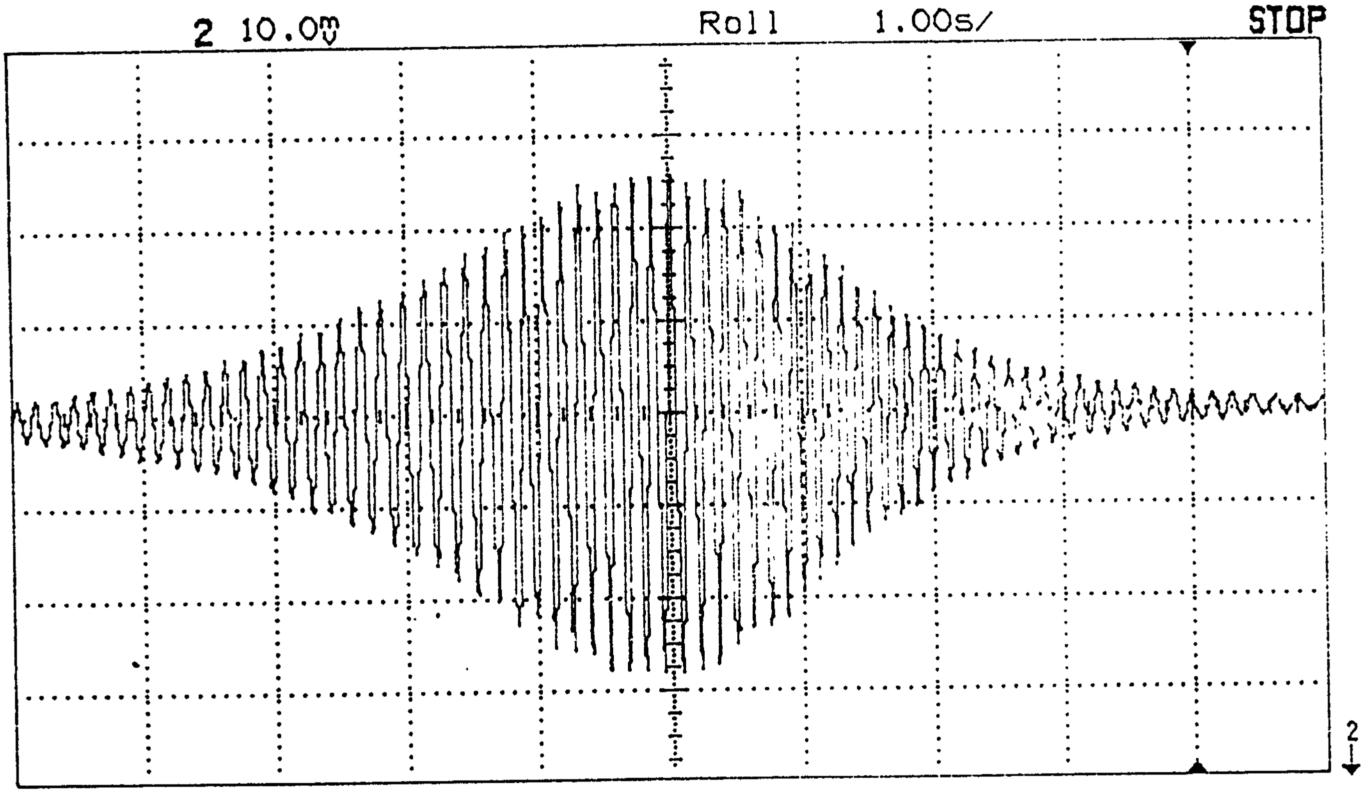
LED used is a Hitachi HE 8807 FL giving ≃ 10mW at 880nm (± 30nm) for $i = 100mA$

LED has a built in lens, output is ≃ colunated (large active area ⇒ family of output angles).

fringe visibility ≃ 0.7 at both detectors

apertures reduce effective power to ≃ 100μ watts. ⇒ 140 dB dynamic range possible
⇒ best sensitivity ≃ 2×10^{-14} m/$\sqrt{Hz}$

Autocorrelation of HE 8807FL

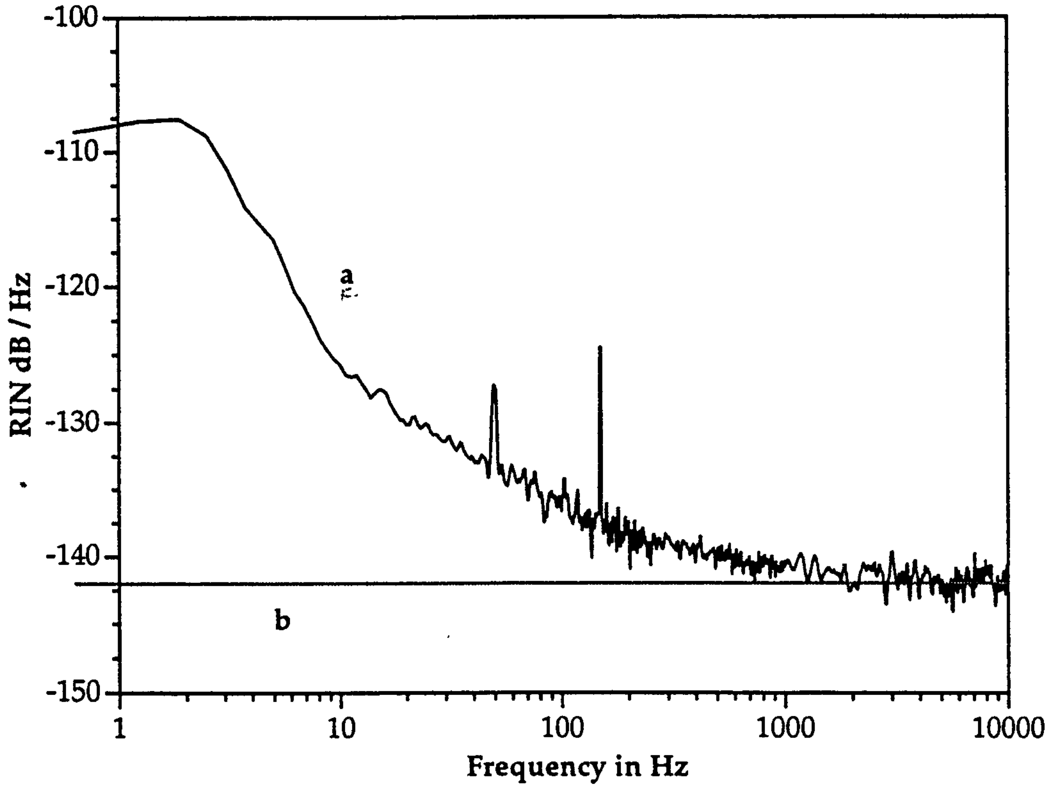


Fringe pattern of the HE8807FL: The pattern is obtained by monitoring the intensity at the antisymmetric port of the rigid Michelson interferometer while scanning the length of one arm through the fringe pattern. The vertical scale is in 10mV/div while the horizontal scale is 1sec/div and is proportional to the arm length difference in the Michelson interferometer.

free of structure and ~ Gaussian
⇒ 880 ± 30nm Gaussian spectrum

using a comparitor ⇒ absolute length reference.

RIN of LED HE8807fl

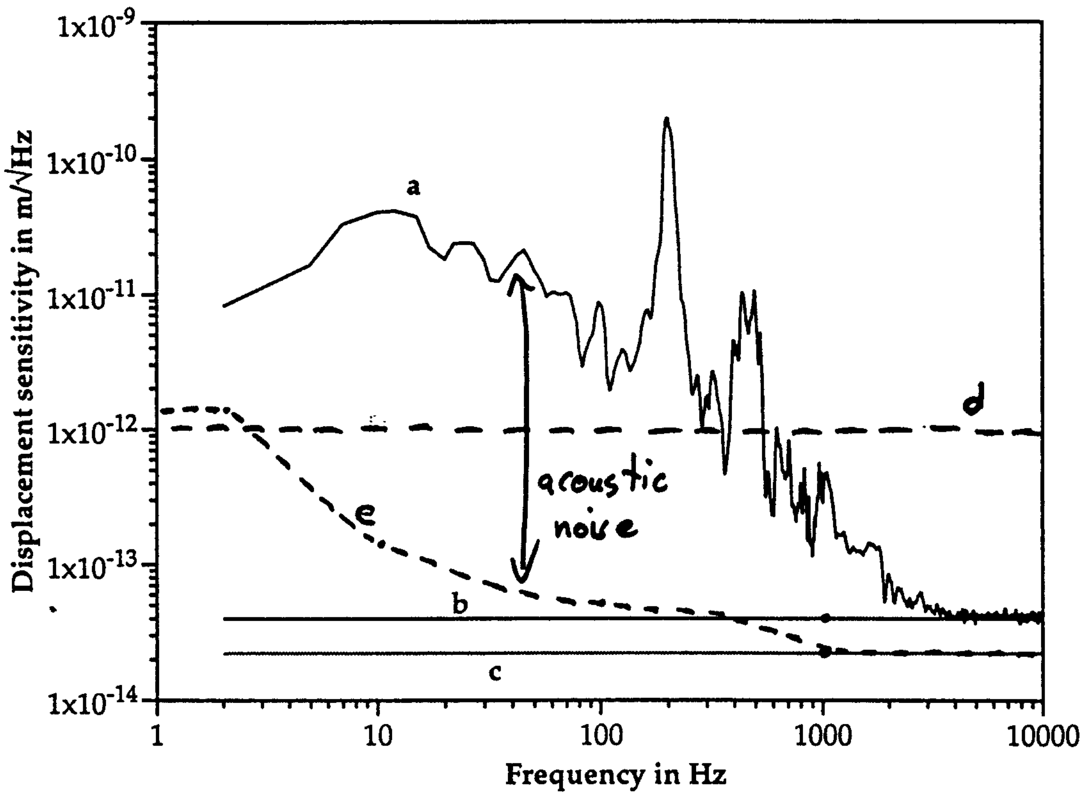


a: LED RIN experimental curve,

b: shot noise limit for the measurement in "**a**".

shot noise limited above ≃ 1 KHz

Free running sensitivity of LED sensor



a: free running noise floor of the LED sensor using a single detector,
b: predicted sensitivity based on optical power (shot noise) and electronic noise measurements,
c: predicted sensitivity based on optical power (shot noise) measurements alone,
d: initial sensitivity specification
e: sensitivity limit due to measured RIN

need to improve mechanical isolation of measurement.

Progress to date

1/ Build rigid interferometer, photodiode and LED circuits. Ensure free running system meets sensitivity specs.
(≃ 2 weeks to completion)

2/ Build tracking mirror / actuator system. Test for closed loop sensitivity.
(designed, several mock-ups made, yet to start construction).

3/ Packaging / vacuum compatibility
(yet to be addressed)

4/ Testing on LIGO suspension system
(mid '97)