Accurate measurement of the time delay in the response of the LIGO gravitational wave detectors

Yoichi Aso[1,2,6], Evan Goetz[3], Peter Kalmus[1], Luca Matone[1], Szabolcs Márka[1]
Joshua Myers[5], Brian O'Reilly[4], Rick Savage[5], Paul Schwinberg[5]
Xavier Siemens[7], Daniel Sigg[5] and Nicolas Smith[8]

[1]Columbia University, [2]California Institute of Technology, [3]University of Michigan,
[4]LIGO Livingston Observatory, [5]LIGO Hanford Observatory, [6]University of Tokyo
[7]University of Wisconsin at Milwaukee, [8]Massachusetts Institute of Technology,

1. Introduction

In order to find weak gravitational wave (GW) signals hidden in a noisy background, good timing accuracy of the measured detector signals is required. For coincident/coherent searches using multiple detectors, timing errors can result in false rejections of real signals or reduction of SNR. For continuous wave searches, inaccurate time stamps will de-phase the integrated signals and reduce the resultant SNR.

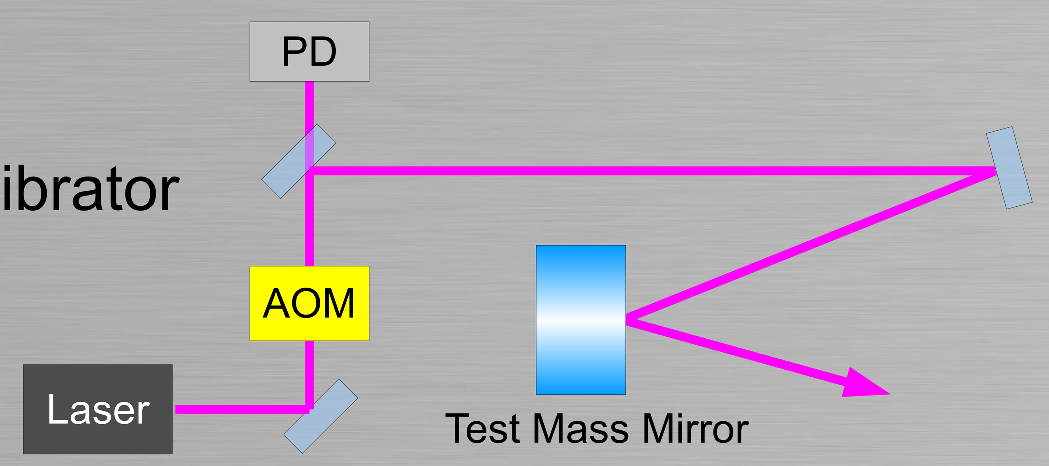
In this work, we present a method to accurately measure the time delay in an interferometer. Our scheme uses an auxiliary laser to impose photon radiation-pressure force on a test mass (photon calibrator). The induced force is measured by the interferometer. By comparing the calibrated output of the interferometer and the power modulation pattern of the photon calibrator, we can deduce the time delay in the measurement chain.

A test measurement performed at the LIGO Hanford site showed that our method can achieve 1μsec relative accuracy. The agreement with the standard calibration for LIGO was about 10μsec.

2. Photon Calibrator (PCal)

- Photon calibrator is a device to apply a force on a test mass.
- An auxiliary laser (Nd:YLF) is intensity modulated by an AOM
- The variation of the radiation pressure imposed on the mirror acts as an actuator
- The intensity variation of the laser is monitored by a witness PD

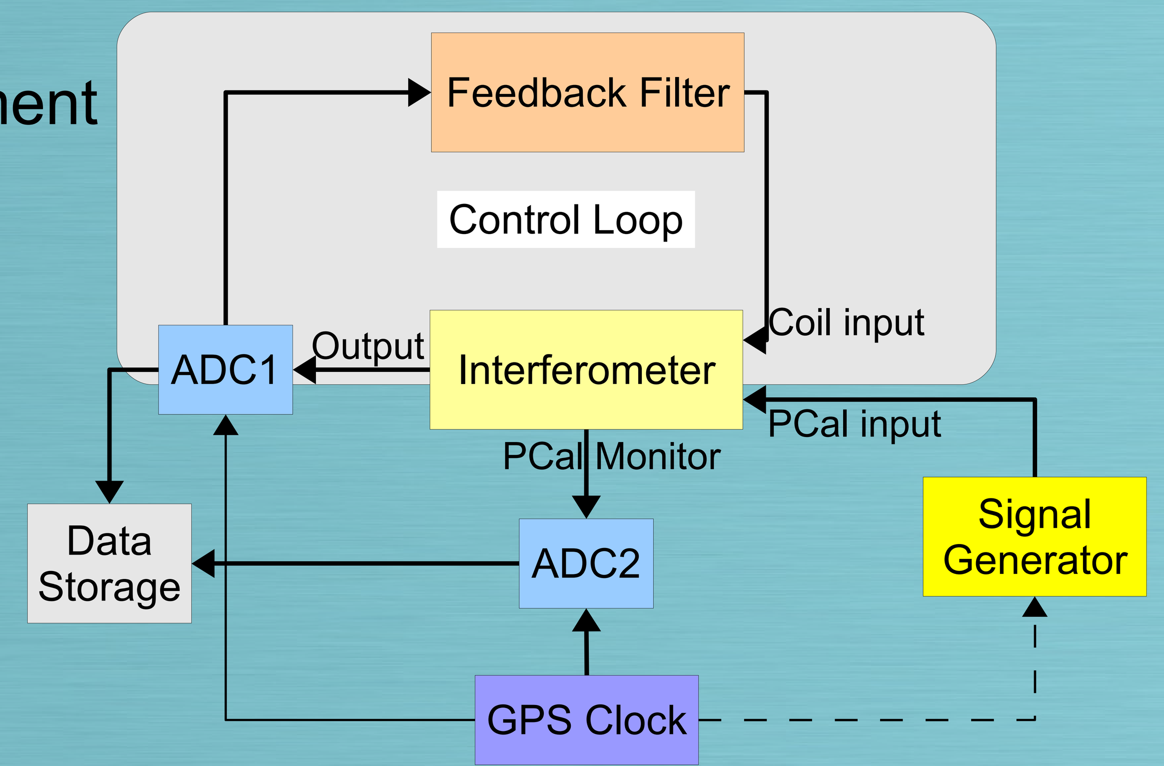
Fig. 1
Photon Calibrator



3. Measurement

- We injected two super-imposed sinusoids (110Hz and 111Hz) into the IFO through the PCal.
- The laser power modulation of the PCal is monitored by a PD and the signal is recorded by an Analog to Digital Converter (ADC). This monitor signal is called p(t) in the following.
- The differential arm length signal (DARM error) of the interferometer is also recorded by an ADC.
- DARM error is converted to the strain signal, h(t), by the LIGO's standard calibration process.
- h(t) and p(t) are compared to get the time delay.

Fig.2
Measurement Overview



4. Analysis

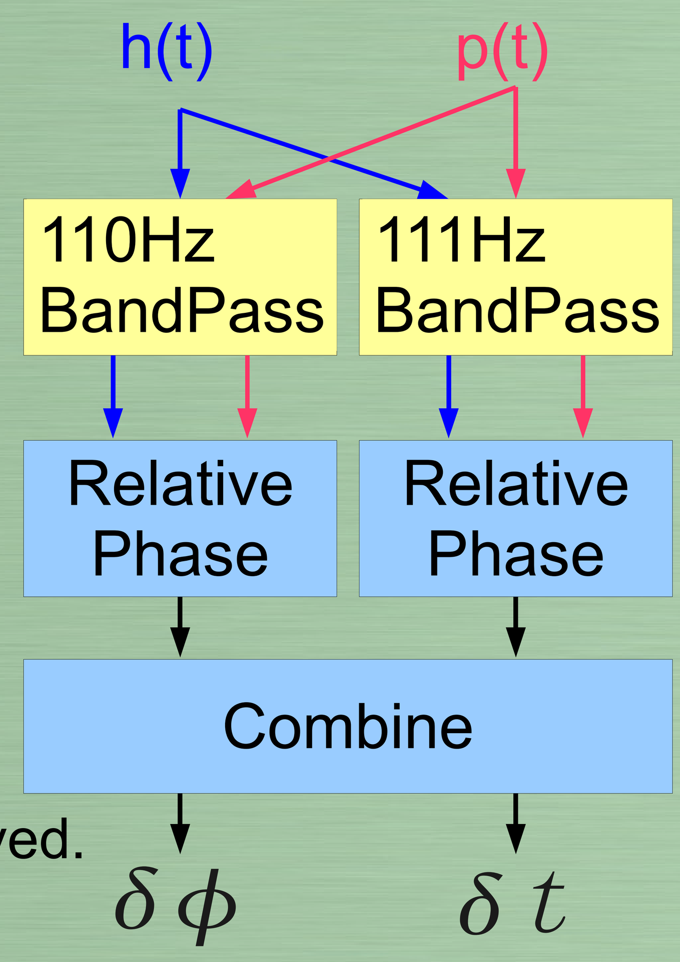
- A sinusoidal signal going through a linear system gains a phase
- The earned phase can be decomposed into two components:
  δt : time delay like part (linearly proportional to the frequency)
  $\delta\phi$: residual phase delay (not linear in frequency)

$$p(t)=\sin(\omega t) \longrightarrow h(t)=\sin[\omega(t+\delta t)+\delta\phi]$$

Our goal is to measure δt and $\delta\phi$ independently

⟶ Necessary to use two frequencies

- h(t) and p(t) are passed through band pass filters to extract single frequency components.
- Relative phase of h(t) and p(t) at each frequency is measured.
- By combining the obtained phases we can deduce δt and $\delta\phi$. (see [1] for mathematical details)
- By using closely spaced two sinusoids, a wide measurement range can be achieved.



5. Results

- Measurement: LIGO H1 during the post S5 period (for 10h)
- h(t) was generated with a preliminary calibration
- 10 hour data was divided into 100sec long segments
- δt and $\delta\phi$ were measured for each segment
- 30-segment averages were also calculated

Fig.3 Time delay (δt)

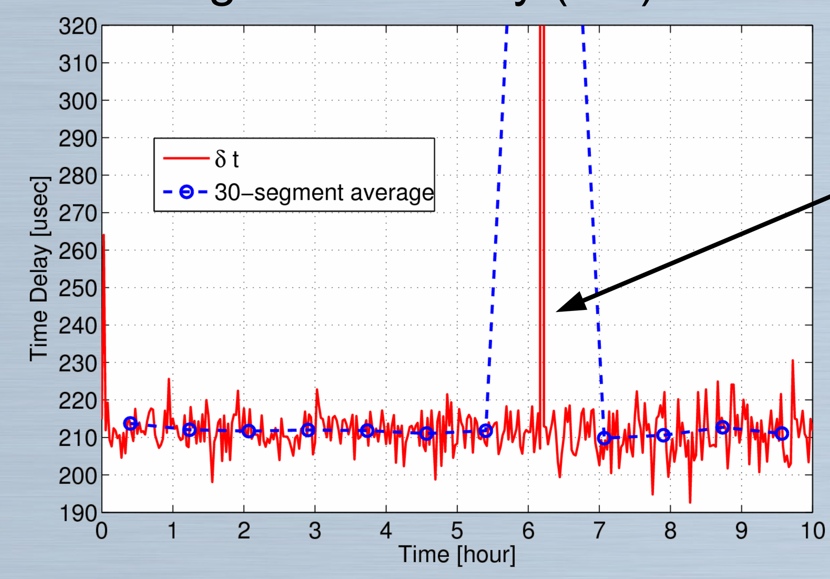
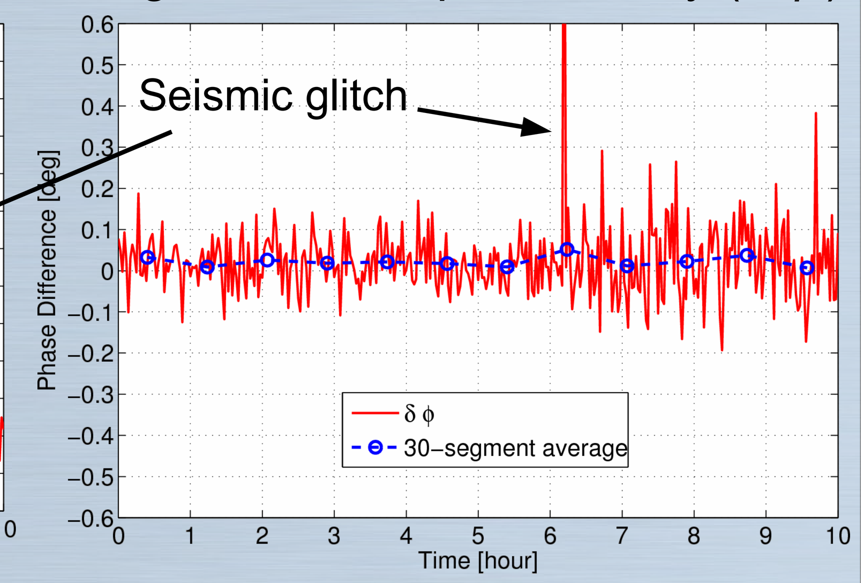


Fig.4 Residual phase delay ($\delta\phi$)



Mean δt	Error of δt	Mean $\delta\phi$	Error of $\delta\phi$
٢١١.٤ μs	$\pm 0.26\,\mu$s	0.019°	$\pm 0.0039^{\circ}$

Table 1: Measurement result

- There was a large seismic excitation at about 6 hours
- The numbers in Table 1 were calculated excluding the glitch

6. Interpretation of the measured time delay

- If the calibration is perfect, the measured time delay should be zero
- Although a non-zero time delay was measured, it can be mostly explained by the known corrections to the preliminary calibration
- The residual uncertainty (10 μs) reached the required level of the LIGO's timing accuracy (10 μs)

Effect	Value	Uncertainty
Measured delay	$+211.4\,\mu$s	$1\,\mu$s
ADC2 delay	$-25.5\,\mu$s	$1\,\mu$s
Monitor photodetector delay	$-4\,\mu$s	$2\,\mu$s
Systematic error in the calibration model	$-173.7\,\mu$s	$10\,\mu$s
Remaining total	$+8.2\,\mu$s	$10\,\mu$s

Conclusion

- A method to measure the time delay from the exerted force on a test mass to the interferometer output using the PCal was proposed.
- The test performed at the LIGO Hanford site proved the effectiveness of the method.
- Our understanding of the timing uncertainty in the detector output reached the required level of LIGO.
- This method can provide an independent verification of the standard Calibration.

Details of this work are reported in the following paper.

[1] *Class. Quantum Grav.* **26** (2009) 055010

LIGO-G0900519