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# Precision Engineering in the Laser Interferometer Gravitational-wave Observatory (LIGO)

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### Introduction

The excitement surrounding gravitational wave astrophysical observation stems from the significant differences between electromagnetic waves and gravitational waves, the need for experimental confirmation of the existence of gravitational waves and the desire to explore gravitational wave sources. A gravitational wave is a propagating distortion of spacetime which alternately produces out of phase elongations and contractions of space along two axes perpendicular to the propagation direction. The strength of the wave is characterized by its strain, the fractional changes in the lengths along the two axes. Even the strongest gravitational waves that LIGO might detect are predicted to have strains of  $10^{-20}$  or less.

The observations to be carried out by the Laser Gravitational-wave Observatory (LIGO)<sup>1</sup> are expected to provide fundamental and new information including direct measurement of strong field gravity, detailed information of the relativistic equations of motion through the observation of compact stellar systems (such as black hole/neutron star binaries) and direct measurement of the polarization states and speed of gravitational waves (in conjunction with other interferometric gravitational wave detectors). Possible sources include coalescing binary compact systems (neutron stars and black holes), supernovae, rotating pulsars and the stochastic background (as a result of the big bang and the gravitational analog to the cosmic microwave background). The astrophysical information derived from LIGO observations has a high probability of uncovering phenomena of cosmological significance which cannot be observed by electromagnetic astronomy.

The LIGO detector senses the changes in space by comparing the lengths of two perpendicular arms using a Michelson interferometer. In order to detect these cataclysmic, astrophysical events, the initial LIGO detector is designed to sense a gravitationally induced strain of ~  $10^{-20}$  rms over a detection band of 40 Hz to 5 kHz and  $10^{-21}$  rms in a few hundred Hz band near 100 Hz. This strain corresponds to a displacement, over a 4km baseline, of only  $10^{-18}$  m rms, or 1/1000 the diameter of the nucleus of an atom.

## **Project Scope**

The LIGO project<sup>2</sup> is a National Science Foundation sponsored project being managed jointly by the California Institute of Technology and the Massachusetts Institute of Technology. The project entails the design and construction of two large interferometer observatories (Figure 1), one in eastern Washington on the U.S. Department of Energy's Hanford Site and the other in Livingston, Louisiana near

Louisiana State University. Two widely separated sites are required so that environmental perturbations to the interferometers can be expected to be independent and hence uncorrelated. The gravitational waves signals will be correlated and this property is used in making the observation.

The layout of each observatory is a an "L" with each leg 4km long. At the vertex of the "L" is a large corner station building complex, which includes a building to house the lasers and vertex interferometer optics and an operations and support building to house the control rooms, supporting labs and offices. Each site also has two end station buildings which house the optics and vacuum equipment associated with the end masses of the two 4km long arms, as well as supporting labs and preparation areas. At the Hanford site, there are mid-station buildings on each arm to house a 2 km long interferometer. The operation of a half length and a full length interferometer at the Hanford observatory serves several functions: it improves the rejection of accidental coincidences by imposing a triple coincidence for a valid burst event, is a diagnostic for gravitational waves by demanding that a true signal be in the ratio of the interferometer lengths and finally enables a broad-band search for a stochastic gravitational wave background limited by the environmental correlations at a single site. At both sites an environment monitoring system is used to measure the environmental perturbation to the interferometers to reduce the singles rate in a burst search, to measure the background perturbations that could influence a periodic and stochastic gravitational wave measurement, and as a diagnostic for interferometer development.



Figure 1. LIGO Observatories: Hanford, Washington and Livingston, Louisiana

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The 4km long, 1.22 m diameter vacuum enclosure between the buildings is internally baffled to reduce scattered light, has very low allowable air leakage rate (< 10-9 atm cc/s, He) and very low outgassing rates (H2 < 10-13 torr-liters/cm2/s, H2O < 10-15 torr-liters/cm2/s and even lower for higher mass hydrocarbons). The LIGO vacuum system is the world's largest ultra-high (<  $10^{-9}$  torr) vacuum system with a pumped volume of roughly 20,000 m<sup>3</sup>. The large chambers (Figure 2) which house the detector are unique to LIGO and have been designed with maximum port access for external viewing and alignment systems and ease of detector installation.

The facilities have been built for a 30 year plus life with consideration for the addition of future interferometers which share the same aperture (beam The project tube). was started, after a lengthy period of enabling research, Currently in 1990. all facilities have been built (buildings and vacuum systems) and the detector systems are being concurrently built and installed. All three interferometers are expected



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Figure 2. Vacuum chambers which house the detector

to be commissioned and at design sensitivity by the end of 2001.

## **Principles of Operation**

A Michelson interferometer is chosen as the basic topology since the sensitivity of its differential length measurement to the laser frequency stability can be made small. Phase instability of the laser results in displacement noise in an interferometer with unequal path lengths. The difference in light travel time can be made small in the Michelson, so that excessive demands are not made on the stability of the laser. Two methods are employed to increase the light power used to sense the motion of the test mass mirrors (and thereby decrease the effect of shot noise). The first method is to incorporate resonant (Fabry-Perot) cavities in the Michelson arms<sup>3</sup>. The arms of the interferometer, and the finesse ("bounce" factor) of the Fabry-Perot cavities can be made as large as is consistent with the condition that the storage time of the light is less than one-half the period of the gravitational wave that is to be detected. The second method is to "recycle" the light from the bright fringe output port of the Michelson (i.e. light going back from the interferometer toward the laser) by reflecting it back into the interferometer<sup>4</sup>. This arrangement (Figure 3), called a power recycling interferometer, can result in an additional gain of about 30 in power.

The measurement goal of  $10^{-18}$  m rms requires a phase shift measurement of  $10^{-9}$  rad rms. Since the phase measurement shot noise limit varies inversely with the square root of the number of photons incident on the beamsplitter during the measurement "period"

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(0.01 sec for a 100 Hz lower measurement band frequency)  $10^{18}$  photons are required in 0.01 sec. This corresponds to about 100 W of power (at 1.064 microns).incident on the beamsplitter.

In the basic optical topology of Figure 3, four resonant conditions are required for operation corresponding to four degrees of freedom:

- differential motion of the cavities (the gravitational wave signal, or L<sub>1</sub>-L<sub>2</sub>)
- common mode motion of the cavities (L<sub>1</sub>+L<sub>2</sub>)
- differential motion of the Michelson arms formed by reflection off of the near sides of the input test mass mirrors (l<sub>1</sub>-l<sub>2</sub>)
- common mode motion of the Michelson arms (l<sub>1</sub>+l<sub>2</sub>)



#### Figure 3. Power Recycled Michelson Interferometer

The interferometer is held on a fixed

fringe by a servo system which maintains optical resonance in both arms; the output signal of the servo system is proportional to the differential strain in the two arms induced by the gravitational wave. In order to mitigate the effects of laser amplitude fluctuations (above shot noise), a modulation scheme is employed to shift the measurement to a higher frequency<sup>5</sup> (about 10 MHz). Several methods for phase detection using modulated light and several control topologies<sup>6,7</sup> have been explored for use on the full-scale LIGO system. The servo system signals are derived from the photodetector by synchronous detection at the modulation frequency.

In addition to controlling these lengths, it is necessary to control the laser frequency and the alignment<sup>8</sup> of the optics (pitch and yaw to the  $10^{-8}$  rad level). By locking the laser system to the very stable, long Fabry-Perot cavities a frequency stability of  $10^{-7}$  Hz/ $\sqrt{\text{Hz}}$  can be achieved. Angular alignment is achieved via a specialized wavefront sensing technique.

All the optical components in the phase sensitive part of the interferometer are suspended as pendula to reduce the coupling to seismic and thermal noise and to provide a means to control the optical path lengths in the interferometer. The suspensions are mounted to optics platforms which are seismically isolated with constrained-layer damped springs and masses. The amplitude of vibrational motion of the atoms in the mirrors exceeds the gravitational wave signal but occurs at a frequency of ~10<sup>13</sup> Hz, far above LIGO's gravitational wave band (~5 kHz). However, thermal excitation does excite the normal modes of the mirrors at frequencies of ~ 20 kHz with amplitudes on the order of  $10^{-16}$  m. The interferometer averages this effect over many periods and is sensitive only to the changes of amplitude, which are made small by ensuring that the mechanical resonances of the mirrors have high Qs.

The design parameters for the initial LIGO detectors are summarized in Table 1. Also presented in the table are sample parameters for contemplated enhanced interferometers.

Characteristics	Nominal Initial	Sample Enhanced	
	Interferometer	Interferometer	
Arm Length (m)	4000	4000	
Laser & Wavelength (µm)	Nd:YAG, 1.064	Nd:YAG, 1.064	
Input Power (W)	6	100	
Contrast Defect	$3 \times 10^{-4}$	$3 \times 10^{-4}$	
Mirror Loss	$1 \ge 10^{-4}$	1.3 x 10 <sup>-5</sup>	
Power Recycling Gain	30	380	
Arm Cavity Storage Time (s)	8.8 x 10 <sup>-4</sup>	$1.3 \times 10^{-3}$	
Total System Optical Loss	0.04	0.003	
Mirror Mass (kg)	11	40	
Mirror Diameter (m)	0.25	0.40	
Mirror Internal Q	$1 \ge 10^6$ (fused silica)	$3 \times 10^7$ (sapphire)	
Pendulum Q	$1 \ge 10^7$	$1 \ge 10^8$	
Pendulum Period (s)	0.74 s (single pendulum)	1 s (double pendulum)	
Seismic Transmission	T(100  Hz) = -100  dB	T(10  Hz) = -100  dB	

#### **Table 1 LIGO Interferometer Parameters**

### **Sensitivity Limits**

The LIGO detectors will have their greatest sensitivity over the frequency range 40 Hz to 5 kHz. The sensitivity spectrum of the detector is the root sum square of a number of displacement or phase noise sources (Figure 4). The sensitivity is limited by seismically induced motion at low frequencies, by shot noise at high frequencies and bv thermal noise for frequencies in between.

Experiments at Caltech and MIT have demonstrated the



#### **Figure 4. Noise Sources**

requisite displacement  $(10^{-18} \text{ m/\sqrt{Hz}})$  and phase noise sensitivity  $(10^{-10} \text{ rad/\sqrt{Hz}})$  on 40m and 5m scale research interferometers. If the performance of these research interferometers can be achieved, reliably, on the longer (4km) baseline of the LIGO system, LIGO's performance goals will be achieved. An example sensitivity spectrum from Caltech's 40m research interferometer is shown in Figure 5. These research interferometers have also been used to test control and locking sequence algorithms, digital control techniques, wavefront sensing techniques and suspension designs.





The features marked "S" and "W" are seismic and suspension wire resonances respectively. By design the seismic resonances are below the sensitive detection band. The high Qs of the suspension wire resonances ensure that very little of measurement spectrum is masked. The inset is an expanded view of one set of wire resonances and a comparison to predicted response.

## Subsystem and Component Requirements & Design

The LIGO system level requirements flow down to some demanding subsystem and component level performance requirements, such as:

- Test mass optics with < 2 ppm surface absorption and < 5 ppm/cm bulk absorption, surface figure error <  $\lambda/1200$ , and surface microroughness of 0.2 nm rms
- Suspensions with low mechanical loss pendulums (10<sup>-4</sup>) and internal test mass/mirror modes (10<sup>-6</sup>), low eddy current damping (10<sup>-6</sup>) and low electro-static forces. This is accomplished through careful design of suspension clamps and wire standoff and



Figure 6. Installation of a suspended mirror

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magnet attachments and use of high grade, highly polished fused silica test masses.

- Suspension control electronics, actuators and sensors capable of 500  $\mu$ rad and 20  $\mu$ m dynamic range and output referred noise < 5 x 10<sup>-20</sup> m/ $\sqrt{Hz}$  above 40 Hz. A low noise, high voltage operational amplifier circuit, with local feedback control, and high order analog filter achieves requirements.
- Seismic isolation of large optics tables in the vacuum chambers with ground motion attenuation of -200 dB at 100 Hz is accomplished with a four stage, passive, cascaded mechanical filter employing constrained-layer damped springs.



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Figure 7. Seismic isolation system

• Pre-stabilized laser system with frequency stability of 0.01 Hz/ $\sqrt{\text{Hz}}$  and relative intensity stabilization of 10<sup>-7</sup> 1/ $\sqrt{\text{Hz}}$ .

# Collaborations

To maximize scientific return, LIGO will be operated as an element of an international network of gravitational wave detectors involving other long baseline interferometric detectors (Table 1) and acoustic bar detectors. A global network of detectors will is required to determine polarization and the source position on the sky. Simultaneous observations also improves the confidence of a detection.

Project	Country	Number	Length (km)	Status
LIGO	United States	2	4.0	
		1	2.0	under
VIRGO	Italy & France	1	3.0	construction
GEO600	Germany & Britain	1	0.6	
TAMA	Japan	1	3.0	
AIGO	Australia	1	1.0	proposed

 Table 2 International Gravitational Wave Interferometer Projects

In additional to observational cooperation, there are a number of scientific and engineering collaborations within the LIGO Scientific Collaboration which consists of 18 institutions, principally involved in astrophysical data analysis and advanced research and development for next generation upgrades to the LIGO-I detector.

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<sup>&</sup>lt;sup>2</sup>http://www.ligo.caltech.edu/