**Gravitational Wave Detectors**

**Listening to the Universe**

Interferometer Detector

Interferometric detectors are designed to compare the time it takes light to travel in two orthogonal directions. The interferometer works by dividing a laser beam at the input splitter so that each beam travels along one arm. When the beams reunite at the output splitter, they are recombined onto the photodetector. If the two beams have taken equal time (or time differences that are multiples of the period of optical oscillation), there is destructive interference of the light (dark fringe) at the photodetector. A gravitational wave propagating through the detector causes the time difference to vary by stretching spacetime along one arm of the interferometer and compressing spacetime along the other, causing an amount of light proportional to the time difference to appear at the photodetector. This signal is proportional to the gravitational wave strain \(h\).

The optical components of the detector are suspended by pendula mounted on vibration isolation systems to reduce the disturbance from seismic noise. Within the interferometer, two classes of noise interfere with the measurements: photon counting noise limits the ability to determine the time difference (the ability to split the fringe), and radiation pressure noise moves the mirrors. The noise is reduced by regulating the amplitude, frequency, and beam jitter of the laser source. However, laser adjustments which reduce the photon noise will increase the pressure noise and vice versa. The standard quantum limit is the lowest noise level achievable by balancing these effects.

The next generation of interferometric detectors is expected to be limited by the standard quantum limit. Squeezing the state of light is a promising new technique which has been found to reduce noise caused by quantum effects. The squeezing of squeezed vacuum by a factor of 1/\(\sqrt{2}\) into the output port of the interferometer will reduce photon and pressure noise, improving sensitivity beyond quantum limits.

**LIGO - A Long Baseline Interferometer**

In recent decades, long baseline interferometers have been operating in the United States (LIGO), Italy (VIRO), Germany (EOO, part of the Virgo in Japan (KAGRA), and many International networks provide detector confidence and information to determine source position and wave polarization, and thereby a means to catch gravitational wave observations in electromagnetic and neutrino astronomy.

LIGO baselines gain sensitivity because gravitational wave displacements grow proportion to the arm length while more random noise is independent of the arm length. LIGO (Laser Interferometer Gravitational-wave Observatory) is a joint project of the California Institute of Technology and the Massachusetts Institute of Technology, sponsored by the National Science Foundation.

Between 2002 and 2010, LIGO operated three detectors that achieved sensitivities of \(h = 10^{-21}\) near 100 Hz. The 4-km Laser Interferometer Detector is located near Livingston, Louisiana, and the 4-km Hanford Detector is located near Richland, Washington. All three LIGO interferometers were upgraded in the Advanced LIGO program, and the upgraded LIGO interferometers are now currently installed. The upgrades for the second Hanford interferometer are in Washington, making them available for the new detector. The Hanford interferometer is the first in the Northern Hemisphere to be operable at both sites.

All three interferometers were run in coincidence to search for gravitational waves as well as to perform searches for a stochastic background of gravitational waves in high-rate gravitational wave sources. The detection of gravitational waves by LIGO would have required an observation at both sites, 5113 km (with Hanford) and 4113 km (with Livingston) in the 4-km LIGO interferometers and no detection in a host of environmental and apparatus monitors.

The initial interferometers did not detect any gravitational waves. However, they established upper limits on the flux of gravitational waves. The Advanced LIGO detector is designed to achieve more than a factor of 10 improvement in strain sensitivity over the initial interferometers, resulting in sensitivities which should make the detection of gravitational waves a routine occurrence.

**Advanced LIGO Sensitivity**

- **Early (2015 - 16):** 4 x 10^{-20}
- **Late (2017 - 18):** 4 x 10^{-21}
- **Late (2019 - 20):** 4 x 10^{-22}
- **Early (2020 - 21):** 4 x 10^{-23}

**Timeline**

- **1962:** A paper is published by Gertsmann and Puetzow proposing the use of interferometers for the detection of gravitational waves.
- **1971:** Weiss, Weiss, and Fordwork on the design of gravitational-wave ammeters.
- **1972:** Proposal is submitted for LIGO in the USA (3 x 4km, 1 x 2km), VIGO in Italy (3km), and GEO in Japan (10km).
- **1989:** Interferometer detectors become operational at Caltech (4km), MIT (10km), and in Tokyo (3km), Glasgow (10km), and Japan (10km).
- **1995:** Construction begins on the TAMA detector in Japan (300km).
- **2000:** LIGO achieves "first lock" of its three first-generation detectors.
- **2010:** The first-generation LIGO detectors cease operations. No gravitational wave detections are made with these interferometers; however, data from initial LIGO establish upper limits on the flux of gravitational waves.

**2015** The Advanced LIGO detectors begin operations.

LIGO’s advanced instruments should achieve a factor of ten improvement in sensitivity over their first-generation predecessors, eventually making gravitational wave detectors a routine occurrence.

This material is based on work supported by the National Science Foundation under Grant No. 0748038 and 1248382. Any opinions, findings, and conclusions expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.