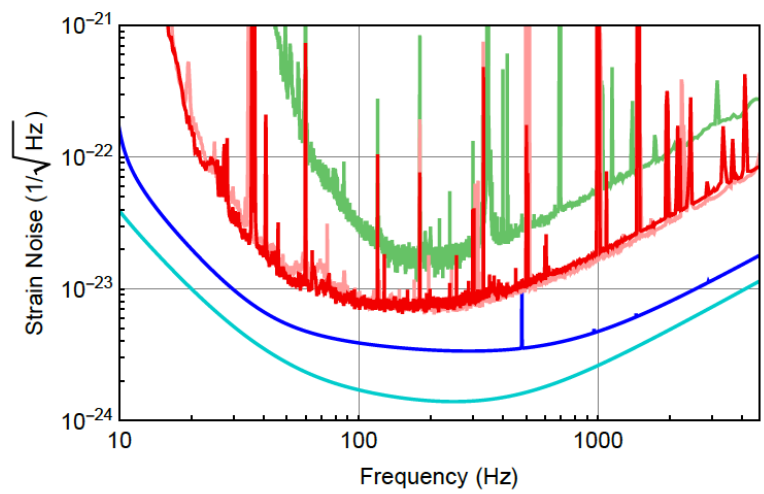
GW150914: THE ADVANCED LIGO DETECTORS IN THE ERA OF FIRST DISCOVERIES

On September 14, 2015, the two detectors of the Advanced Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO) observed the passing gravitational waves generated by a coalescing pair of black holes. This event has been given the title GW150914. This paper describes the status and sensitivity of the detector during the first observation run.

The L-shaped Advanced LIGO detectors consist of two perpendicular arms, each two and one-half miles (4 kilometers) long. A optical mirror is hanging at each end, well isolated from any seismic disturbance. During the first half of each cycle, the gravitational waves from GW150914 slightly stretched one of the two arms, while shortening the other, followed by the opposite effect during the next half-cycle. The resulting length difference between the two arms was tiny - a mere 4e-18 meters, or about 1/200th the diameter of a proton. This length difference was read out by interfering the laser beams returning from the two arms, and recording the resulting light on a photo detector. A number of additional optical cavities (in the arms, at the input and at the output of the interferometer) are needed to enhance the sensitivity of the light to arm length differences.

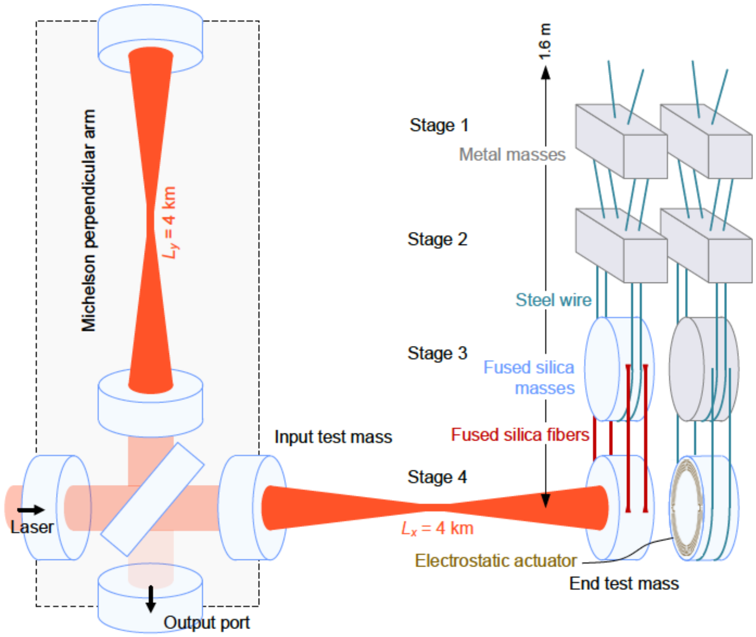
FIGURES FROM THE PUBLICATION

For more information on the meaning of these figures, see the preprint at arXiv.org, available here.



The current gravitational wave strain sensitivity (which is expressed as the fractional change in length of the interferometer arm caused by the passing gravitational wave) of the two Advanced LIGO detectors is shown as a function of frequency (the two red traces). Also shown are the best sensitivity of initial LIGO (the green trace), the Advanced LIGO design sensitivity (the blue trace), as well as the anticipated sensitivity after possible future upgrades to Advanced LIGO (the cyan trace). Note that the sensitivity, or limiting detector noise, is measured in strain per square root Hz, meaning that the size of the noise fluctuations in any frequency interval can be calculated by squaring the shown trace, integrating it over the frequency interval, and again taking the square root.

During the first observation run the Advanced LIGO detectors were not yet operating at their design sensitivity. The light source was an infrared laser operated at 20 Watt, resulting in a circulating power in the arm of 100 kWatt. This still is a factor of 7.5 below the design value. Once at design sensitivity, and depending on the position in the sky, an event like GW150914 can be measured with a signal-to-noise ration of up to 100, meaning that the gravitatinal wave form can be measured with about 1% precision.



Simplified diagram of an Advanced LIGO interferometer. Four highly reflective test masses form two optical arm cavities. At lower left, a mirror is placed between the laser and the beamsplitter, and increases the power stored in the arms to 100 kW. Another mirror is placed between the beamsplitter and the GW readout photodetector, which alters the frequency response of the interferometer to differential arm length changes. The main mirrors are suspended by a four-stage pendulum system to isolate them from seismic disturbances.

What limits the sensitivity of Advanced LIGO?

At frequencies above 100Hz Advanced LIGO is limited by the fact that the photo detectors can measure laser power only in increments of individual quanta, that is individual photons. The random arrival time of individual photons (or "shots") creates a measurement noise, the so-called shot noise. Below 20Hz the interferometers are currently limited by noise form the various servo control loops needed to operate the interferometers.

Between 20Hz and 100Hz there is still some unexplained noise.

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Freely readable preprint of the paper describing the details of the full analysis and results is available here.

GLOSSARY

Black hole: A black hole is the relic of a massive star that has reached the end of its life. When a massive star has exhausted its nuclear fuel, it dies in a catastrophic way--a supernova--that can result in the formation of a black hole: an object so massive and dense that nothing can escape from inside it, not even light. Black holes are usually only observed by their gravitational effects on nearby objects, such as gas or nearby stars.

Servo control loop: A servo control loop is a system that manages and controls the behavior of a device. A common illustration of a servo control loop is the cruise control device in many automobiles. Once set, the loop maintains the speed of the car without needing input from the driver.

Optical cavity: An optical cavity is formed by two mirrors, forcing the laser to bounce back and forth multiple times. If the separation between the mirrors is an exact multiple of the laser wavelength, the laser power will build up in the cavity, reaching a value that is higher than the input power. For this to work, the cavity length and alignment have to be precisely controlled. In Advanced LIGO this is achieved with a number of servo control loops.

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