LIGO's Possible Application in Seismology

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Abstract

LIGO is a collaboration project that intends to detect tiny disturbances in space called gravitational waves. The project is operated by MIT and Caltech jointly. The purpose of this article is to brief on LIGO, especially on its finctionality, how it is constructed, and the way it detects gravitational waves. Then, the possible application of LIGO in the field of Seismology is analyzed with examples showing the effects of earthquakes on data collected by LIGO. Then, further application of LIGO in Seismology other than detecting seismic waves produced by major earthquake events is discussed. Further research on the same topic with more data in the future is suggested at the end of the article.

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Brief Introduction of LIGO

LIGO stands for Laser Interferometer Gravitational-Wave Observatory, and is intended to detect one of the last unconfirmed phenomenon of Einstein's Relativity Theory: gravitational wave. The LIGO Project was initiated in 1995 and was funded by the NSF (National Science Foundation), and consists of two observatories: one in Livingston, LA, and the other in Hanford, WA.$_{(FIG.1)}$ The LIGO observatories underwent two major upgrades, enhanced LIGO (eLIGO) and advanced LIGO (advLIGO). The total cost of the whole project is approximately 620 million dollars, making the LIGO Project one of the most ambitious projects ever funded by the NSF. The improvements of LIGO aimed at increasing the apparatus's power, sensitivity, data processing ability, and ability to filter out background noise signals. These improvements enabled LIGO to detect events occurring farther away, from the initial 10 mega parsec to the (expected) 200 mega parsec now. The LIGO observatories have undergone several runs, including six scientific runs and two observation runs, with O3 (observation run 3) already started. LIGO has thus far detected 30 clear events emitting gravitational waves, most of which are caused by black holes and supermassive neutron star pairs.[1][2]

Theoretical Basis of LIGO

As stated above, gravitational wave is a phenomenon predicted by general relativity. General relativity treats space and time not as distinctive coordinates

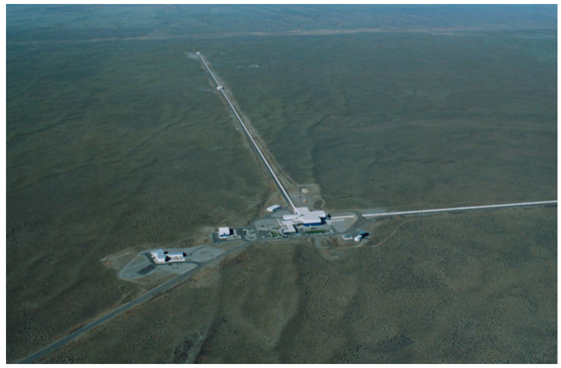


Figure 1: LIGO facility at Hanford, WA. This facility comprises of two arms stretching out 4 kms and perpendicular with each other; the arms are channels for laser beams to pass through [1]

used to describe events, but as an entirety called space-time. Objects with tremendous mass, or equally a huge amount of energy, can distort the geometry of space-time, as described by the famous Einstein field equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}.$$

Once distorted, space-time can yield strange consequences, such as the dilation (or the slowing) of time at a place where space-time is curved by a massive star, for instance. According to more modern theories, gravity is carried by a massless boson with spin -2 that is called graviton, and since every type of particle corresponds to a distinctive particle field, space-time itself is such a field for the case of graviton. Tensor, then, is a measurement of the curvature of the gravitational field. Such curvature can be caused by a stationary object of large mass, and in our solar system, the sun is the most influential object that creates the curvature in space-time. However, the curvature created by stationary objects is also stationary: after propagating through space, a formed curvature will not change till the object that causes such curvature changes, and the curvature's effect on other celestial objects is called gravity. Here is a point that often causes confusion and misconception: gravity is not a force, as many conceive and plotted by the Newtonian mechanics equation

$$F_g = G\frac{m_1 \cdot m_2}{r^2}.$$

The actual situation is that gravity is only an effect caused by the space-time curvatures when objects are undergoing "free-fall motion", while such objects are simply following straight lines in their local space-time. When for the next time thinking about how planets revolve around their host stars, imagine not that a force named gravity pulling the planets, acting as the centripetal force and pulling the planets in a circular orbit. Instead, think of the effects of the massive stars as causing the "coordinates" of space-time, rather than exerting a direct force on the planets. Then what events cause gravitational waves? Quadrupole distortions can. These distortions are most commonly caused when two massive objects are revolving about each other, but there are also other forms of gravitational waves, such as the stochastic gravitational waves (caused some 14 billion years ago, by the Big Bang or other cosmological events), gravitational wave bursts (caused by the formation of supernovae or black holes), and continuous gravitational waves (caused by a spinning or oscillating neutron stars; for the reason that gravitational waves formed by such stars are often continuous and the wave shape resembles the electromagnetic waves' shape induced by pulsars, such sources of gravitational waves are called as "gravitational pulsars"). Distortions caused by revolving objects are most easily discerned, and consist of most part of discernible signals received by LIGO. These distortions are most easily found since the gravitational waves caused by them are unique: the waves exhibit increasing amplitude and frequency, a signal called by many scientists as "CHIRP".$_{(FIG.2)}$ The one very basis for the formation of gravitational waves is there must be asymmetric in the distribution of mass for stars, or other celestial objects, if they were to incite such waves. Gravitational waves propagate through space at the speed of light, and are transverse waves, causing differences in the "density" of space. Gravitational waves also have two types of polarization: "x" type and "+" type, signifying the orientation of the gravitational waves. The most readily measureable effects of gravitational waves are the prolongation or contraction in space itself, and measuring such changes is the way LIGO managed to detect gravitational waves.

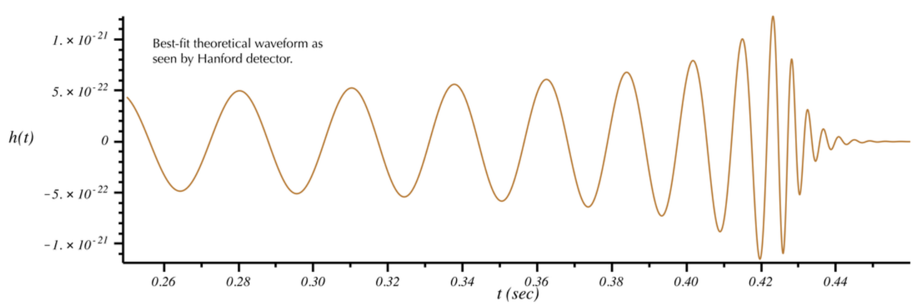


Figure 2: gravitation "CHIRP" caused by rotating pair of massive objects; note the increasing amplitude and frequency as a function of time [3]

Ways to Detect Gravitational Waves

There were other attempts to detect gravitational waves before the LIGO Project. The idea was not new; gravitational wave is but another phenomenon originating in the solutions of Einstein's field equations. The principle of the apparatus designed to detect gravitational waves is also simple enough: build two massive objects, use some sort of spring to connect them, and measure the changes in the length of the spring caused by passing gravitational waves. Reality is much more difficult than theories, though: such machines are extremely susceptible to other background noises and vibrations. Even worse is the required sensitivity of such machines: as the contraction or prolongation in space, or in other words the strength of the gravitational waves, is given by the equation measuring strain:

$$h = \frac{\Delta L}{L}$$

(a ratio of the change in length of space to the original length of space). Simple calculations would show that the typical h(strain) caused by gravitational waves is extremely small, ranging from roughly 10-20 to 10-23. Due to such limitations in sensitivity, background vibrations, and other technical difficulties, pioneers in the field of studying gravitational waves never did find any signal of a gravitational wave. Joseph Weber, Professor of University of Maryland, built the prototype of the apparatus used to detect gravitational waves and claimed to have detected such waves, yet ended in vain due to the claim's inability to hold up to further scrutiny. Despite Weber's failure, LIGO referred to the professor's name when publishing the first detection of gravitational waves in honor of the advancements in the field by Weber. More modern techniques include

Michelson interferometer, a way to exclude some of the background noises and allow researchers to measure the change in length of the space as apparatus constructed according to such technique can be extraordinarily large, making detections easier (not hard to see, as the sample length increases, the change in the length also increases). The Michelson interferometer comprises of two heavy mirrors and another half-plated mirror to split the laser into two beams and into two directions, and a detector to measure any difference in the length travelled by the two beams of laser in the form of detected phsae difference between the two beams.$_{(FIG.3, FIG.4)}$ Such differences in the distance travelled by the laser may cause a phase shift, that is, the electromagnetic waves may have their peaks and troughs occurring non-simultaneously. The waves that become out of phase will interact with each other, making the overall intensity of light decrease and thus enable de tection of microscopic changes in the length of space. The Michelson interferometer was pioneered by four figures, Michelson, Morley, Rainer Weiss and Ron Drever.[4]

Development of LIGO and Detection of Gravitational Waves

LIGO was funded by NSF and is held and operated jointly by MIT and Caltech. It has two facilities, designed to correct potential errors made by one of the facility. Right after the second upgrade of the advLIGO, scientists were excited to find out an actual gravitational wave event detected: event GW150914. It occurred on September 14th, 2015 at 9:50:45 UTC, and was recorded by both LIGO facilities. This was surprising outcome, as advLIGO was just installed

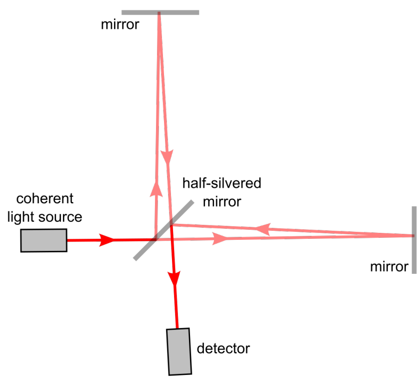


Figure 3: the basic structure of Michelson Interferometer [5]

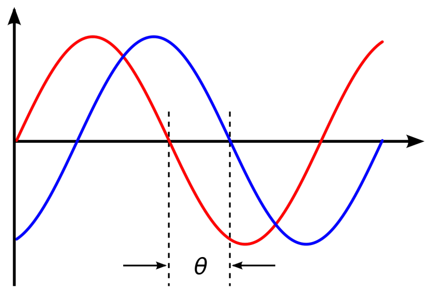


Figure 4: A phase difference in electromagnetic waves cause a decrease in intensity, as it is in the case of double-silt experiment; also helps LIGO function properly [5]

to increase LIGO's sensitivity at all frequencies.$_{FIG.5}$ The updates aimed at increasing the sensitivity bound caused by light's quantum nature, vibrations of atoms, vibration background noises, and optical component sensitivity, etc. of LIGO at all frequencies, which is then finally bound by gravity gradient and residual gas, which are close to impossible to improve under current technical conditions. There is another upgrade on the schedule of LIGO, aLIGO+, costing some 35 million dollars to employ squeezed laser beams and update detectors to further increase LIGO's sensitivity and pushing the detection limit further into space. As LIGO itself announced, "the upgrade can let scientists detect an event every single day, on average."

Mathematical Approach to Filter out Signal

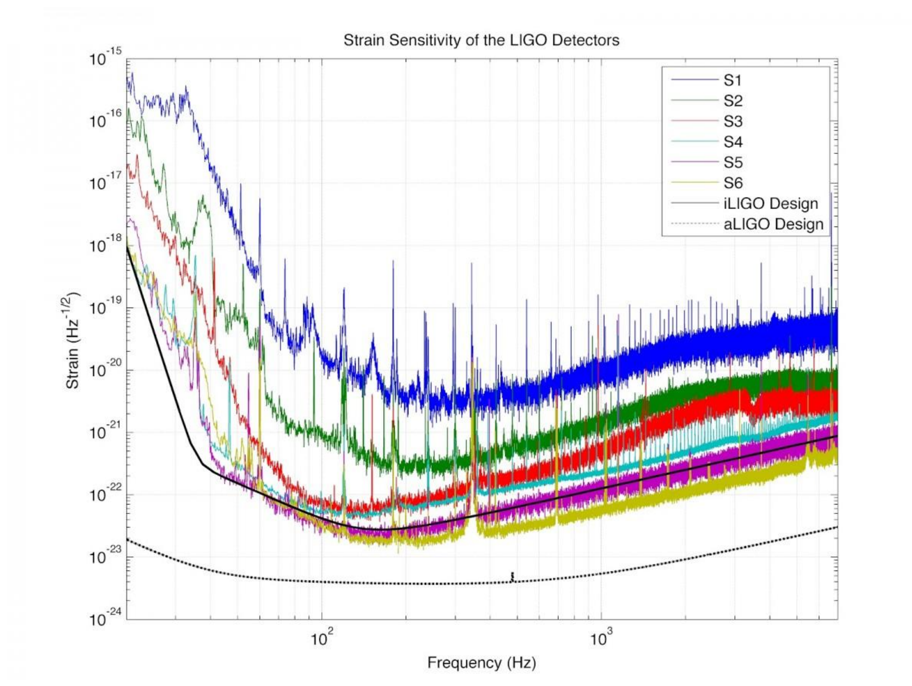


Figure 5: The improvements in LIGO's sensitivity over the several scientific runs and how they approach the initial target sensitivity of LIGO

In the experiments performed by LIGO, the detected gravitational disturbs are stored in hdf5 files, and in a form of a time series of data. If there were a gravitational disturbance happening at a constant frequency, how to find out such signal is straightforward: take the Fourier transformation of the strain data and at some constant frequency, a spike of data amplitude would show up. (Fourier transformation is a mathematical technique to break down a function as a sum of many discrete sine functions with different frequencies)The reality, however, is more complicated than this assumed situation and requires more careful analysis. Take the example of two revolving black holes: as the two black holes orbit, they give off their gravitational potential energy in the form of gravitational waves and come closer to each other. And as they come closer, their angular velocity would increase, giving the created gravitational waves higher and higher frequency and amplitude. Moreover, the rotation of earth around the sun and earth's self-rotation would also create shifts in the collected data in the long run, not to mention those "noises" created by both natural and human activities. To solve this problem, a technique called "matched filtering" is invoked: manual templates created by models of potential gravitational-wave-causing events are used to match possible events recorded in data. Assume that data is a function of t, x(t), and template is h(t), then taking an integral

$$F \approx \int_0^T \frac{h(t)x(t)}{S_h(t)} dt$$

would denote the degree to which the data fits the template. The idea is that noises and disturbances caused by other factors would cancel out in the integral, and the actual event would become more evident. Another technique employed in the analysis of the data is band pass filtering, where the data can be manually smeared off constituent frequencies outside the band pass range. This technique is especially useful for the analysis in this article as all seismometers are set to a data recording range of 288Hz and thus the earthquake-triggered signals we desire to filter out are all within the frequency range of $0 \sim 144$Hz.

One Source of Noise in LIGO: Earthquakes

LIGO relies on the difference in the distance travelled by two laser beams to sense gravitational waves. This is convenient as it is precise, though there are still many sources of noise. As the whole LIGO apparatus is placed on ground, events that could trigger vibrations in ground could shift the position of apparatus, like beam splitter, mirror, and photodetector. Such shifts in the positions of apparatus would cause shifts in data, too, and such is the so-called "noise" in the strain data collected by LIGO. Sources for noises can be as big as earthquakes and tsunami, and can be as small as the trucks passing by and logging. Since LIGO is extremely sensitive as it has to detect small vibrations in space, the effect of big earthquakes on LIGO is evident: their seismic waves can be present in strain data collected by LIGO, and an earthquake large enough can knock LIGO offline: one part could be that such vibrations caused by earthquakes are so large that they make the laser beam deviate from the route and the photodetector picks up no signal, and the other possibility is that upon receiving seismic waves on other seismometers, LIGO shuts down temporarily as virtually no useful data could be collected during the impact interval of such large-scaled earthquakes. Shown in figure 6 is the strain versus time plot made starting from UTC 2015, 16th of September, 22:30:07. Roughly 2260 seconds into the data a huge spike shows up, which dwarfs all other signals, making the general plot resemble a straight line. It is reasonable to say this spike in data is caused by the Chile earthquake happening at UTC 22:54:33 that has a magnitude of 8.3, as there are no other potential sources of noise, and virtually no gravitational wave event could reach up to such a magnitude of exponent -

16(most of gravitational wave events have a distribution of around $10^{-23\sim-26}$.[6] The actual Chile earthquake did last much longer than the spike shown in the plot, and the data file plotted has 4096 seconds' worth of data. But when the plot was generated through python, nothing shows up after 2300 seconds. The only plausible explanation is that the seismic wave is so large or the effect of the earthquake so significant that LIGO was shut down temporarily by either manual manipulation or spontaneous reaction of the apparatus. The data plotted in the figure was obtained from officical data site of LIGO. (gw-openscience.org) The plot is made by a python script modified from the tutorials provided by the Gravitational Wave Open Science Senter.[7]

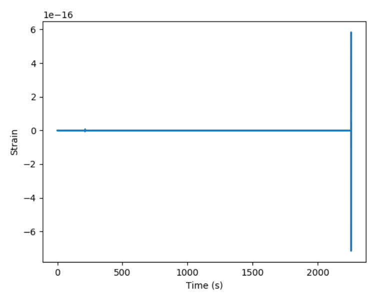


Figure 6: figure of LIGO strain data during Chile Earthquake

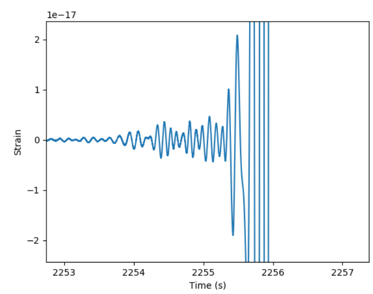
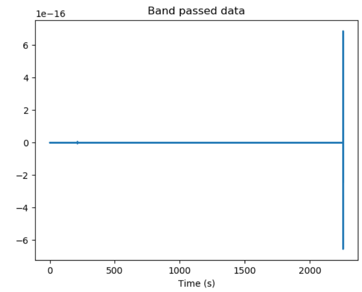


Figure 7: the zoomed in figure of the spike in the previous figure

Deeper Analysis of Data Collected During the Chile Earthquake

The data plotted in figure 6 is collected from LIGO Hanford, as Livingston Observatory was not running in the time interval. The plotted data lasts from GPS time 1126477824 to 1126522880. The seismic wave produced in Chile Earthquake arrived about 2260 seconds into the data file, at GPS time 1126480084 or UTC time 23:07:47, taking some 680 seconds to travel from South America to Hanford. The precise epicenter of the 2015 Chile earthquake was at 46kms offshore from Illapel, Chile, and that location is at some 5653 miles (around 9100km) away from Hanford, California. Considering that primary waves (longitudinal waves), or P waves (transverse waves), can travel through both solid and liquid, the actual distance travelled by primary waves from Illapel to Hanford is shorter than 9100km, and considering a typical speed of 5.5-7.0 km/s, the spike in the LIGO's strain data 680 seconds could either be one of the precursor waves of the earthquake or the primary wave itself. It is highly possible that the spike plotted is only the weaker part of the seismic waves, as the stronger secondary waves cannot travel through large parts of earth's mantle. The strain data in the spike gradually increases in strength, and the overall frequency of the strain remains the same during the spike. Also, after applying a band pass filter of cap frequency of 144 Hz, the frequency that is higher than those of earthquakes, the overall strain strength of the data does not change much and the spike remains largely unmoved. The frequency of the strain data at the spike is also <144Hz, within the expected frequency range for a typical earthquake.$_{(FIG.8)}$

Earthquakes' Effect on LIGO's Ability to Collect Data



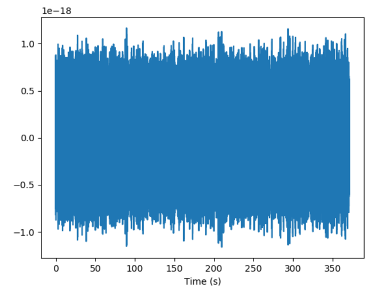


Figure 8: band pass filtered data from figure 6

Figure 9: plotted strain data during the Ferndale Earthquake

The effect of earthquakes on LIGO's collected strain data varies according to the distance between the LIGO observatories and the epicenter as well as the magnutude of the earthquake event. As already examined, the effect of large earthquakes such as Chile Earthquake on LIGO is significant and outstanding. However, the effect of Ferndale Earthquake that happened at 2016-12-08 14:49:45 UTC on the collected strain data by LIGO is much more limited, as exemplified by the band pass filtered data in figure 9, where no notable fluctuation appears.

Conclusion

In the preceding paragraphs, the background information of LIGO and how it functions is presented. Then the mathematical techniques on which the analysis of the data is based are analyzed as well as those employed in this article.

The specific example of Chile Earthquake with magnitude of 8.3 is examined, where the huge spike on the plotted strain data is most possibly the detected seismic wave produced in the Chile Earthquake incident. The effects of these huge earthquakes within a decent range from LIGO observatories are evident: they simply knock LIGO out of service due to their large seismic waves produced. However, the effects of smaller but yet closer earthquakes on LIGO are still to be determined. Due to a relative short amount of time LIGO is in service and limited accessible data of LIGO, such analysis is inconvenient and may become more feasible when LIGO releases more of its data collected during observation run 3 and scientific run other than 5 and 6.

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