Chapter

Interferometric Gravitational Wave Detectors

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Abstract

The existence of gravitational waves is an important proof of Einstein's theory of general relativity and took 100 years to be achieved using optical interferometry. This work describes how such a detector works and how it can change the way of seeing the Universe. Kilometers size laser interferometers are being built around the world in the way to make gravitational astronomy; detectors already built in the United States, Italy, and Japan will join efforts with detectors built in Japan and India and provide humanity with the means to see gravitational interactions of black holes and neutron star. Interactions, without these detectors, will be forever out of our sight.

Keywords: interferometric, gravitational waves, gravitational wave detectors, interferometric gravitational wave detectors, gravity

1. Introduction

Gravitational waves are ripples in the curvature of spacetime that propagate like waves, traveling outward from the source; they travel at the speed of light (299,792,458 m/s) and squeeze and stretch anything in their path as they pass. Do not confuse it with gravity waves that are waves generated when the force of gravity in a fluid medium or, when it is the case, at the interface between two different media, tries to restore equilibrium, as an example of these waves there are the wind waves on the interface between the atmosphere and the ocean.

Predicted in 1916 [1, 2] by Albert Einstein based on his theory of general relativity, [3] and detected in 2015, gravitational waves transport energy in the form of gravitational radiation, oscillation of spacetime itself. This theory predicts that the presence of mass causes spacetime to warp. When massive objects move around themselves, this curvature is altered, sending ripples of gravitation out of the universe carrying unbelievable amounts of energy. As these sources are very distant by the time, these disturbances catch up with us; they are almost imperceptible because they are weaker and gravitational waves interact very weakly with matter. Because of that, it was only a century after Einstein's prediction that scientists developed a sensitive enough detector—a Laser Interferometer Gravitational-Wave Detector, some kilometers long interferometer and were able to confirm the existence of gravitational waves [4].

The existence of gravitational waves is also a consequence of the Lorentz covariance of general relativity since it brings the concept of a finite speed of propagation of gravity.

Gravitational waves did not exist in the Newtonian theory of gravitation, which postulates that physical interactions propagate at infinite speed.

There was already indirect evidence of gravitational waves before its first direct detection. Measurements of the Hulse-Taylor binary system suggested that gravitational waves were more than a hypothetical concept. This system is one of the potential sources of detectable gravitational waves. These potential sources include binary compact star systems composed of white dwarfs, neutron stars, and black holes.

0ne way of thinking about gravitational radiation is as the messenger that carries information about changes in gravitational fields that attract one thing to another [5].

Several gravitational wave observatories (detectors) are under construction or in operation around the world [6]. In 2017, the Nobel Prize in Physics was awarded to Rainer Weiss, Kip Thorne, and Barry Barish for their role in detecting gravitational waves [7]. In these gravitational wave detectors and previous ones, the use of interferometry was essential for the operation of such a detector.

2. Some history

The possibility of gravitational waves was discussed in 1893 by Oliver Heaviside using the analogy between the inverse square law of distance in gravitation and electricity [7]. In 1905, Henri Poincaré proposed for the first time the existence of gravitational waves, which emanated from accelerated bodies and propagated at the same speed of light, this is dictated by the transformations of Lorentz [8] and implies an analogy that, accelerating electric charges produce electromagnetic waves, accelerating masses must emanate gravitational waves. When publishing his theory of gravitation (the general theory of relativity) in 1915, Einstein did not agree with Poincaré's proposal, as in his theory there are not gravitational dipoles, essential for the emission in the electromagnetism theory. However, based on a weak field approximation, he concluded that there should be three kinds of gravitational waves (named by Hermann Weyl as longitudinally-longitudinally, transversely-longitudinally, and transversely-transverse).

These approximations made by Einstein were criticized by several researchers and even Einstein had doubts. In 1922, Arthur Eddington wrote a paper entitled: "The propagation of gravitational waves" [8], in which he showed that two of the three types of waves proposed by Einstein were only mathematical artifacts produced by the system of coordinates and they were not really waves. This also cast doubt on the physicality of the third type (transversely transverse); however, Eddington proved that these would travel at the speed of light in all coordinate systems, so he did not rule out their existence.

In 1956, Felix Pirani corrected the confusion caused by the use of several coordinate systems by reformulating gravitational waves as the manifestation of the Riemann tensor observables. The Pirani work was ignored at that time mainly because the scientific community was concerned with another issue of whether gravitational waves could transport energy. This question was solved by Richard Feynman using a thought experiment presented at the first conference for General Relativity in 1957 known as the Chapel Hill Conference. His argument, known as the sticky bead argument, presents that: if a gravitational wave passes orthogonally to the beaded rod (a rod if some bead), the effect of it is to deform the bead and the rod, but as the rod is longer, the bead moves beads over the rod; this movement causes friction and then heat, which meant the passing gravitational wave would have energy. Afterward, Hermann Bondi (who was skeptical of the existence of gravitational waves) published a more complete version of this argument.

After this conference, the scientific community took the existence of gravitational waves more seriously. Joseph Weber began to design and build a gravitational wave detector. It was the start of many gravitational wave detectors that are called Weber bars. Weber claimed to have detected gravitational waves in 1969 and 1970, the signals coming from the Galactic Center [9]. However, the high detection frequency quickly cast doubt on the validity of his observations, as the Milky Way's implied rate of energy loss would drain our galaxy's energy on a much shorter timescale than the galaxy's inferred age. It got worse when in the middle of the 1970 decade, the build of other Weber bar experiments by other groups around the world failed to detect such signs. By the end of the 1970 decade, the consensus was that Weber's detections were some kinds of noise.

The first indirect evidence of gravitational waves was discovered in 1974 by Russell Alan Hulse and Joseph Hooton Taylor Jr., using their discovery of the first binary pulsar. Results were published in 1979, showing the measure of the orbital period decay of the, so-called, Hulse-Taylor pulsar, which precisely describes the angular momentum and energy loss due to gravitational radiation emission predicted by general relativity. A discovery that gave them the 1993 Physics Nobel Prize.

This indirect detection of gravitational waves motivated further searches, despite Weber's discredited result. Some groups continued to improve on Weber's original concept. Using very low temperatures (cryogenic) for the bars, in high-vacuum systems and under vibrational isolation. There were many of these projects around the World. One of these groups built a Niobium bar resonant-mass gravitational wave detector [10]. In this detector, the vibrations caused by the passage of gravitational waves in the niobium bar are measured by a microwave parametric transducer. In this system, microwaves are pumped into a microwave cavity and the vibrations of the microwave cavity are connected to the niobium bar causing microwave signals in the microwaves to leave the cavity. This signal now must be amplified, but it mixes with the original microwave signal, which is too strong for the low-noise microwave amplifier; then the microwave carrier signal is removed by the use of an interferometer that cancels only the microwave carrier. A similar system can be seen in **Figure 1**. This is another use for interferometers in gravitational wave detectors; unfortunately, this kind of detector never made a detection, maybe because of a poor choice in the frequency range [11].

Other experimental groups pursued gravitational wave detection using laser interferometers. This idea of using appears to have been around for a long time by several independent groups, for example in 1962 ME Gertsenshtein and VI Pustovoit [12] and in 1966 by the group of Vladimir B. Braginskiĭ. The first prototype appeared in the 1970 decade built by Robert L. Forward and Rainer Weiss. In the following decades, increasingly sensitive detectors were constructed, culminating in LIGO and Virgo detectors.

After years and years of null results, the first detection of gravitational waves was made by LIGO on September 14, 2015, as the signal, named GW150914, probably came from the merger of two black holes [13, 14]. A year earlier, LIGO could have been brought down when scientists from the BICEP2 (Background Imaging of Cosmic Extragalactic Polarization 2) experiment claimed to have detected a weak signal in the CMB (Cosmic Microwave Background) that appeared like evidence of gravitational waves originating in the beginning universe. This evidence, according to researchers, could have been a smoking gun proof of the theory of cosmic inflation, which

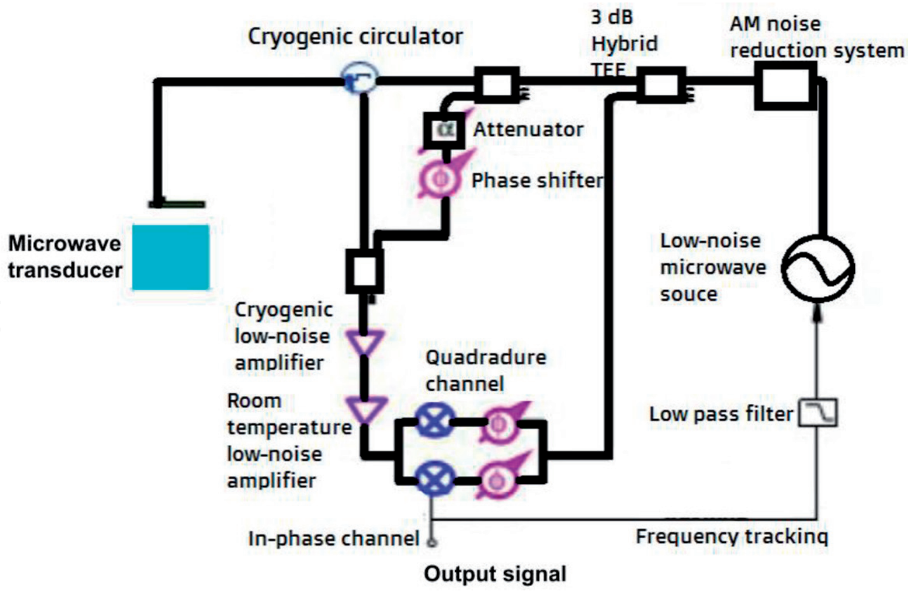

Figure 1.
Schematics of a similar electronics of Niobè gravitational wave detector showing a microwave interferometer (between the cryogenic circulator and the cryogenic low-noise amplifier) used to cancel the microwave carrier signal that will degrade the performance of the cryogenic low-noise amplifier.

postulates that very shortly after the Big Bang (10^{-32} seconds after), the expanding universe experienced a period of very rapid expansion (a factor of 10^{26} times). This fast expansion would have created ripples over the CMB, the fossil cosmic radiation that fills the universe being the first detectable electromagnetic radiation in Universe history. However, the BICEP2 signal detected could be explained also by Milky Way dust, making the scientists withdraw the claim that gravitational waves had been detected.

3. Detection

The interferometry system essentially works by measuring the variations that occur in light beams, which are arranged along two different arms. This analysis occurs when we observe the variations and interferences in the return of the light beams, which overlap, since according to the Theory of Relativity light always travels the same distance using the same time, this is our ideal ruler, eliminating the error of a form of measurement that also suffers from the geometric variations caused by ripples. All this technology must be sensitive enough to be able to detect variations of less than a thousandth of a proton.

A powerful laser beam passes through the beam splitter allowing the two generated beams to have the same phase and to be separated perpendicularly by the arms of 4 km each; at the end, they are reflected by the mirrors [13]. Everything was designed so that normally the phases of the waves of the originally emitted light beam and the reflected one generate a destructive effect, so nothing is detected by the photodetector. For the occasion of a gravitational wave passing by the Earth, causing spacetime expand and contract infinitesimally in one direction, thus generating interference arising from the physical property of the wave behavior of light when the phases produce a more constructive effect, thus a signal is detected. **Figure 2** shows the schematics of such a detector.

This is not so straightforward, as the gravitational wave passes through the detector, the gravitational wave also changes the spacetime between the two mirrors, if this

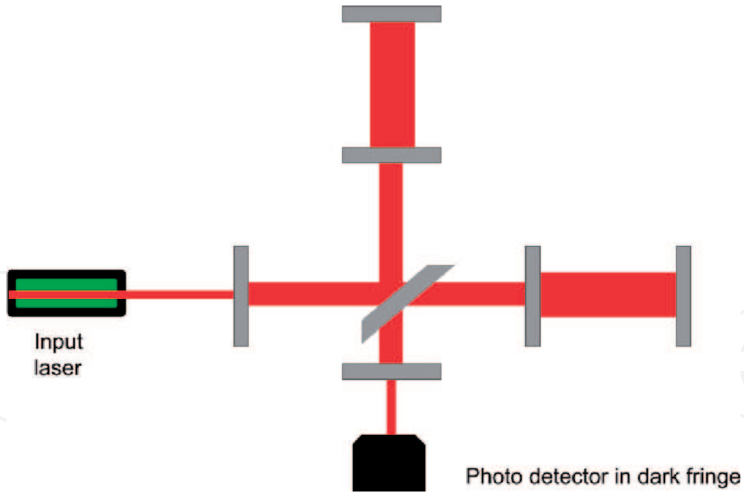

Figure 2.
Schematics of a laser-interferometric GW detector.

space was made of some material, the length of this material will also change by the gravitational wave, but the passage of gravitational wave does not change the speed of light, then the laser will travel in a shorter time in one arm and a larger time in the other arm then changing the interference pattern in the photodetector.

The fact that there are two observatories is a way of circumventing the possibility of confusing the detection of small earthquakes or some other local source of noise since when detecting a signal, this signal will be compared with that detected by the other observatory. It is only confirmed that this jolt was generated by gravitational waves if the generated signal has the same characteristics, for example, exactly the same profile in frequencies, since the observatories are exactly the same. Importantly, this all takes place in a vacuum, thus ensuring that the light will not have an unstable medium that could alter it in some way. Among the improvements to the observatories, the laser was updated to generate a higher frequency, there was an implementation of fused silica in the mirrors to reduce random mirror movements, and also their suspension was improved to reduce thermal noise and seismic isolation, making the observatories more sensitive for detection [14].

3.1 Indirect

In 1974, the most plausible indirect detection of gravitational waves was made by Joseph Taylor, Jr. and Russell Alan Hulse, when observing pulsars surrounding a neutron star (neutron stars are less dense cousins of black holes). That is the Hulse-Taylor binary, a pair of stars, which is a pulsar [15]. The characteristics of its orbit can be deduced from the Doppler shift of radio signals emitted by the pulsar. Each of the stars is about 1.4 M (M being the mass of the Sun) and the radius of their orbits is around 0.013 of the distance between Earth and Sun, smaller than the diameter of the Sun. The combination of smaller separation and bigger masses means that the energy emitted by the Hulse and Taylor binary will be much larger than the energy emitted by the Earth and Sun system by a factor of approximately 10^{22} times.

Information about the orbit can be used to estimate the amount of energy and angular momentum that would be emitted in the form of gravitational radiation. As the energy is emitted, the pulsars must get closer to each other. Measurements in the Hulse-Taylor system were performed over 30 years ago. The change in the orbital period corresponds to the prediction of gravitational radiation, assumed by general relativity to be within 1 part in 500. Russell Hulse and Joe Taylor, in 1993, were awarded the Physics Nobel Prize for this remarkable work, which was the first indirect evidence of gravitational radiation. This binary system, from the present until the time of the merger, is estimated to have a lifespan of a few hundred million years [16].

3.2 Direct

After that scientists were motivated to prove its existence. In the mid-1990s they were simulating the Black Hole merger, until the arrival of the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Italian Gravitational Wave Interferometer Detector (Virgo) at the end of the 20th century made slow progress needing much improvement. The challenge was not the physics itself or the equipment only, but the math behind it. Einstein's equations are called constraint equations, in which the solutions must always satisfy specific conditions, which is difficult since there are 10 equations with thousands of terms [17]. These simulations were necessary as the detectors needed a set of templates for the detected signal in order to establish the source of the signal, but using numerical relativity the set of these templates is still being built. Just to remember that Bayesian statistics is used in the detection.

In late 2015, researchers from the LIGO (Laser Interferometer Gravitational-Wave Observatory) project observed "distortions in spacetime" caused by a pair of black holes, about 30 solar masses each, in the process of merging [14, 17]. The signal was detected in the two LIGO sites on September 14, 2015 at 6:50:45 a.m. PDT, the event was named GW150914. The signal oscillated from 35 Hz to 250 Hz, with a time difference of 7×10^{-3} s between the detection of each observatory, and a maximum amplitude of 1.0×10^{-21}. Thus, coinciding with the shape predicted by Einstein almost exactly 100 years ago for an encounter of massive bodies, in the case of black holes that surround each other until they meet and merge, thus resulting in a significant warping in spacetime. To the relief of many, the merger took place at a distance of ~1.3 billion light-years from Earth. The masses of the initial black holes were 29 M and 36 M, (solar mass, M, approximately 1.99×10^{30} kg); the mass of the resulting black hole was 62M, and approximately 3.0 Mc^2 of energy was converted into gravitational waves to the rest of the Cosmos [14]. The signal of this measurement can be seen in Ref. [14]: the detected signal measured in the two observatories (located in Hanford, WA e Livingston, LA) are shown. First row shows the signal detected in the interferometers; it is shown a difference in time signal over the signal at the Louisiana observatory due to difference in the signal arrival time. Second row shows the expected signal of signal for the optimal source template previously calculated. Third row shows the residuals from rows 1 and 2. Row 4 shows the signal in the frequency domain against time.

In June 2016, the second burst of gravitational waves from merging black holes was announced, suggesting that such detections will soon become routine and part of a new kind of astronomy [18].

On June 1, 2017, for the third time, scientists announced that they had detected the infinitesimal reverberations of spacetime [19].

4. The real detectors

The interferometric gravitational wave detectors are very complex machines, besides being very big vacuum systems, need to have very powerful lasers, and so on.

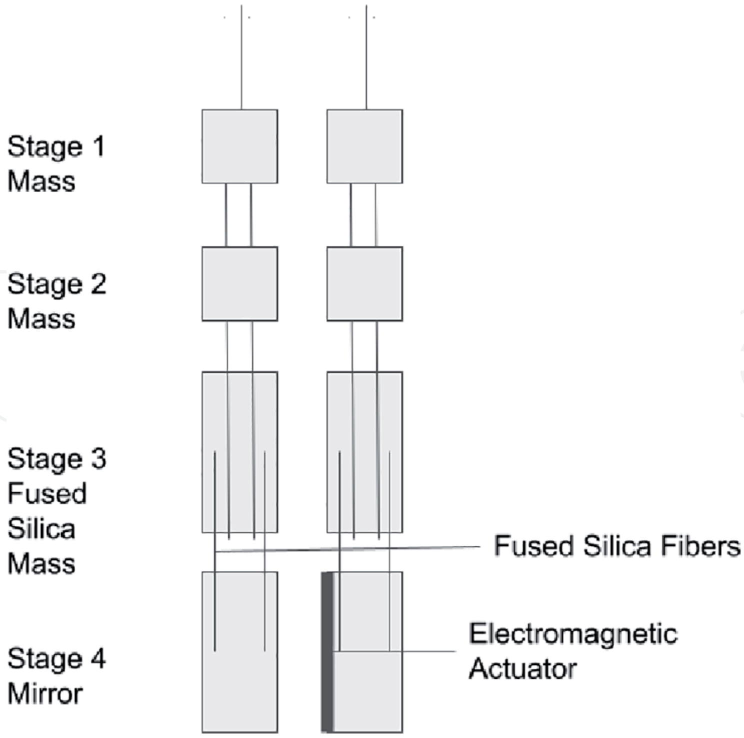

Figure 3.
Schematics side view of the mirror suspension system of the LIGO detector showing the electrostatic actuator which is used to keep the detector locked in.

The interferometer must be set in a dark fringe condition, but the mirrors are connected to the ground by the suspension, so they vibrate what could change the dark fringe condition. Then a very good suspension that attenuates the vibrations is used, **Figure 3** shows an example of such suspension (this example is about the LIGO detector). The Italian detector Virgo has a more sophisticated suspension which makes this detector more sensitive at lower frequencies.

The Virgo suspension is more complex, it is composed of an inverted pendulum and 6 masses suspended by its center, plus a collection of 18 LVDTs (Linear Variable Displacement Transducers), 5 accelerometers, 23 coils, three piezoelectric devices and 21 motor drivers. All these devices together are called the super attenuator. With a super attenuator for every suspended mirror.

These details show that it is very difficult to keep the interferometer locked in, it also depends on active systems.

But how sensitive the interferometer must be to make such measurements. The first measurement of gravitational waves was of displacement 10^{-18}, as the arms are 4 km long, and the variation in length was 4×10^{-15}. As the power inside the arms is 100 kW with an input power of 20 W, has a recycling factor of 5000 which makes the real sensitivity of the interferometer close to 10^{-12} m.

5. Conclusion

The Gravitational wave interferometric detector successfully detected gravitational waves with unprecedented sensibilities, for the position of the mirror the measurement precision was done in an order of 10^{-18} meters over square root of Hz. For such achievement, the mirror position should be stable for a factor of 10^{-13} m r.m.s.

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Conflict of interest

The authors declare no conflict of interest.

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