

Research on the analytical development and progress of gravitational wave detection technology

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Abstract. This article demonstrates the basic principle and the recent progress of gravitational wave detection based on information retrieval and literature review. The article describes and illustrates the gravitational wave, including the description of the adopted field equation and its properties. There is also a demonstration of the principle behind the first direct gravitational wave detection. Some other potential ground-based detectors, e.g., KAGRA and space-borne detectors, are also listed and contrasted. Since gravitational waves tend to retain themselves from interacting with matter, which travels from a much earlier time than Electromagnetic waves and should be a vital component to Cosmology studies, the space-borne detectors Taiji and LISA will also interlace with each other to explore deeper space in the 2030s, which would be significant progress in gravitational wave Astronomy. This article employs literature analysis that examines papers that discuss the nature of gravitational waves and their detection. These analyses will shed light on gravitational wave detection development.

Keywords: Gravitational wave detection, Space-borne detectors, Cosmology.

1. Introduction

Gravitational wave (GW) is a controversial topic since its birth. Even Einstein, the predictor of GW, had a struggle before announcing his discoveries. General Relativity defined gravity as the geometrical curvature in space-time. It is not a typical force that common folks are familiar with, and the geometrical explanation is essential in understanding space-time. The planets are not attracted by stars but in free fall and perform an inertial motion, indicating it does not receive force, including gravity defined not to be a force. The elliptical orbit is due to the motion projection of Minkowski space on three-dimensional space. As stated above, Einstein had doubts in determining whether if the gravitational wave exists. In fact, he submitted his paper which argues that gravitational wave does not exist since the field equation has solutions with singularity. However, the singularities were resulted from the coordinate singularities in the cylindrical coordinates. It is the adjustment to the formula that led Einstein to be convinced of the existence of the gravitational wave [1].

A gravitational wave is extremely different from an Electromagnetic wave since it does not interact with matter severely as an EM wave does. On this basis, it does not need to concern about the issues of being scattered or impeded from matters in the clusters. Since generating GW only have a requirement for accelerating huge masses, the observation of dark matter and black holes could be conducted even if they do not emit any EM wave. This is crucial in the present study of cosmology [2].



There are several ways of gravitational wave detection. An instrument called Weber bar was designed to detect a gravitational wave, which is the earliest design for a GW detector but was judged to be discredited. The indirect detection uses the property of gravitational waves. The pulsar would radiate energy in the form of a gravitational wave, and by observing this orbital energy loss, the deduction could be performed [3]. The recent detection of the gravitational wave is a direct detection, which uses the idea of the interferometer. There is also a future design from China and ESA for space-borne detectors, and they will be discussed later.

The rest of the paper is organized as follows: Section 2 will illustrate the concept of the gravitational wave, along with the field equation and its solutions. Section 3 will cover the detailed demonstration of the principle behind the first detection of the gravitational wave. Section 4, 5, and 6 will discuss other detectors besides LIGO (shown in Fig. 1) and their technical merits.



Figure 1. The first detection of the gravitational wave is based on the report of the LIGO and Virgo collaboration.

The LIGO (Laser Interferometer Gravitational-Wave Observatory) has two observatories in different states to prevent seismic wave from interfering the two observatories simultaneously. The arms of the observatories have a length of around 4 km [4].

2. Basic descriptions of gravitational wave

A gravitational wave is a transparent disturbance propagating in space-time that travels at the speed of light. Any object with a physical volume will unavoidably suffer tidal force, i.e., the object that interacts with them will suffer distortion. Gravitational waves advent when the distortion effect is sufficient to travel to a distant place, where the effect is still observable.

Types of galactic events to create observable gravitational waves:

Burst from a supernova

Two extreme massive stars in orbit with another

Black holes merger

The famous Einstein field equation follows:

$$R_{ab} - \frac{1}{2}Rg_{ab} + \Lambda g_{ab} = \kappa T_{ab} \quad (1)$$

where κ is for Einstein gravitational constant and Λ is for cosmological constant [5]; T_{ab} is for the stress-energy tensor, which describes the energy and momentum in space-time; R is for scalar curvature; R_{ab} is for Ricci curvature tensor and g_{ab} is for metric tensor.

In general, we have the left-hand side describing the curvature of space-time and the right-hand side describing how motion behaves in particular space-time [3]. This equation has overwhelming complexity, and it is only possible to simplify them and obtain solutions when certain conditions are met. Based on the definition, we have

$$G_{ab} = 8\pi T_{ab} \quad (2)$$

When the Einstein tensor vanishes, implying the stress-energy tensor disappears, it would have a vacuum solution. This could also be used to define the vacuum region as where the Einstein tensor disappears. This vacuum solution would then be an instance of the exact solutions of Einstein's function.

3. Detection of gravitational waves

Likewise, like electromagnetic waves, gravitational waves also receive instrumental and environmental noise. Thus the detectors are placed distant from each other.

An improved version of the Michelson interferometer is used to determine the strain effect of the gravitational wave as the variation in length for orthogonal arms. Two mirrors with a distance of 4 km are treated as test masses inside each arm. The difference could be used to determine the strain amplitude of the gravitational wave by the equation:

$$\Delta L(t) = \delta L_x - \delta L_y = h(t)L \quad (3)$$

where h is the projection of the strain amplitude upon the detector [6].

The variation in the length will prevent the light wave in the interferometer from arriving in phase, which could create a light signal proportional to the strain of the gravitational wave on the detector.

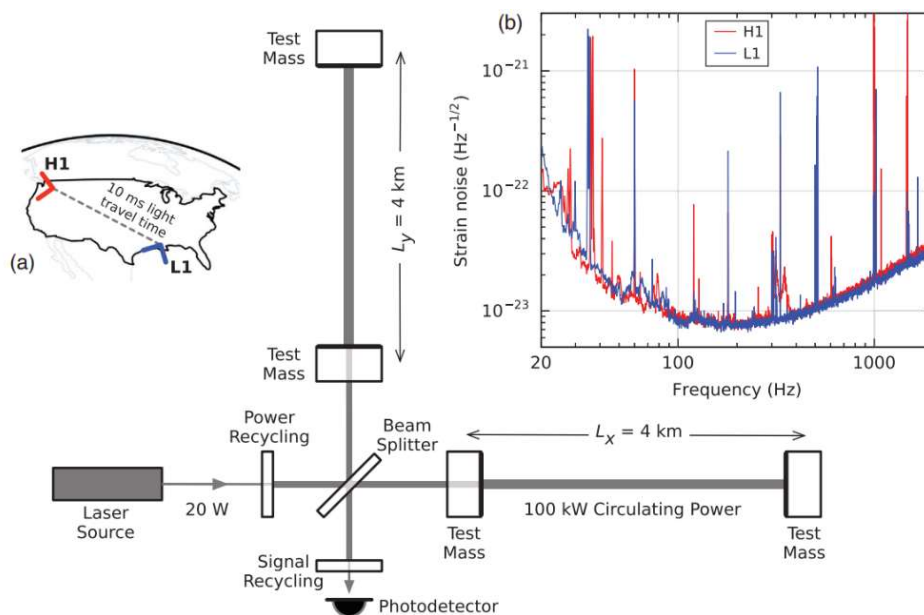


Figure 2. The illustration of the detectors of the gravitational wave

The gravitational wave that travels orthogonally to the detector and polarized to the optical cavities will generate the squeezing or stretching effect on the two arms that the photodetector reads. (a) The site and orientation of detector H1 and L1, (b) The noise brought by the apparatus in the vicinity [6].

As shown in Fig. 2., the optical cavity of the detector reinforces the strain influence of the gravitational wave to 300 times. Additionally, the Power recycling mirror strengthens the laser power input. The input power varies from 20 W to 700 W when the laser arrives at the beam splitter and increases to 100 kW for the circulation inside the cavity. Furthermore, the signal recycling mirror optimizes the withdrawal process of the gravitational wave signal by the expansion of the bandwidth of the cavity. The detected graph of wave front matches one of Einstein's general relativity predictions, which confirms the validity of Einstein's theories.

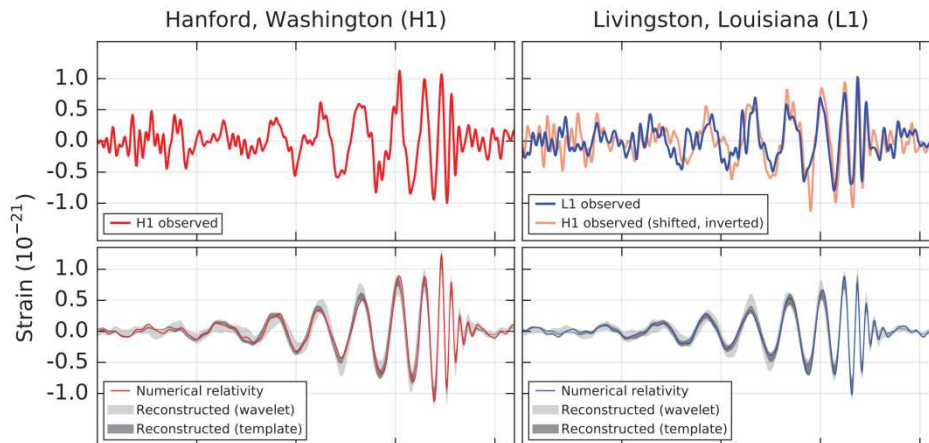


Figure 3. The comparison of the observed strain of the gravitational wave on the top right

L1 has a time delay, and H1’s graph is shifted and inverted (due to the detectors’ relativity orientation) for visual distinguish. A graph of the consistency between the projection of strain on the detectors using Numerical relativity with two reconstructed graphs. The blackhole coalesces model has a consistency of 99.9%, and the wavelet combination model has a consistency of 90% [6].

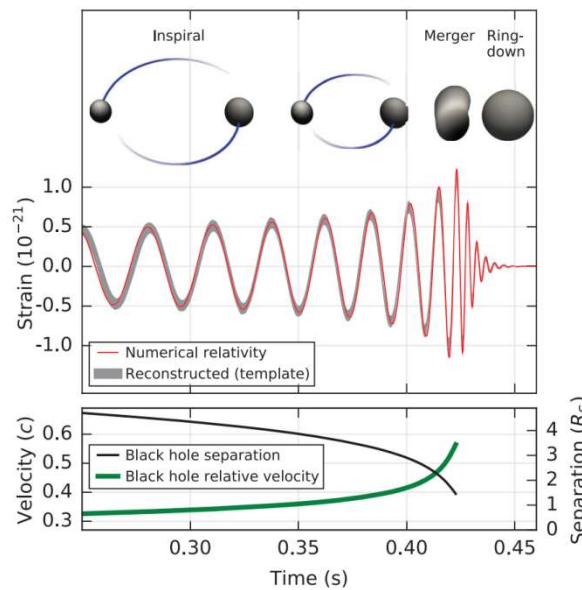


Figure 4. The gravitational wave strain amplitude comparison with the template waveform

The difference with FIG.3. is that it abandoned the use of bandwidth filter. The bottom one is a separation and relative velocity graph with time [6].

4. An enhanced design of gravitational wave detection in Japan.

The uniqueness of this detector KARGRA is set out from 2 enhancements:

- covered. It is built underground to avert the influence of noise from the vicinity
- It uses cryogenic mirrors to avoid the effect of thermal noise.

These ensured it to have an identical sensitivity of LIGO and Virgo, which verifies it to be a competitive candidate in the gravitational detector. The sketch is depicted in Fig. 5, collected from Ref. [7].

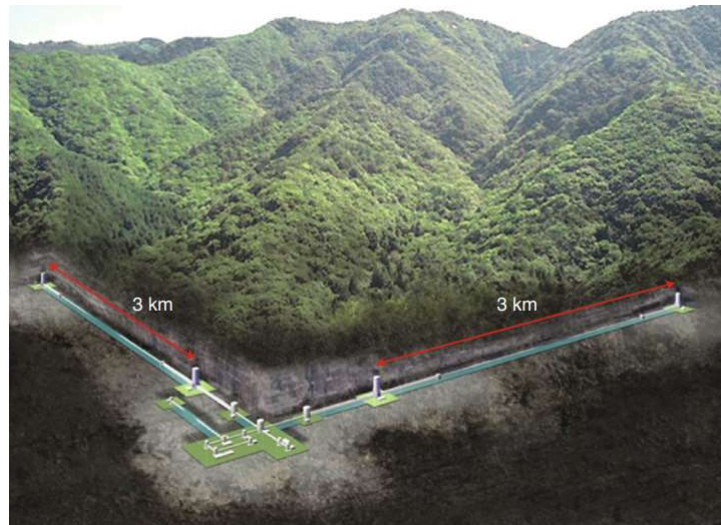


Figure 5. The concept image of the cryogenic detector underground [7]

5. Detector design for Chinese GW program

The program named Taiji has space-borne antennas that detect gravitational waves, which is used to enhance the precision of fractional uncertainty of the Hubble constant. In other words, the satellite itself carries a gravitational wave detector. The detector also has a better precision on gravitational waves location. Yet, more utility on precision will be achieved when the network of Taiji and LISA, which ESA operates, will be attained in the 2030s. A pilot satellite, Taiji-1, is launched in 2019, and Taiji-2 consists of two pathfinder satellites, will demonstrate Taiji technologies.

Another space-borne gravitational wave detector also launched by China is named TianQin that uses a similar idea of laser interferometer, which is composed of three spacecraft and a DRS (Disturbance reduction system) to reduce noise [8]. In contrast, Taiji has a GRS (gravitational reference sensor), which reads the noise from the thrusters by measuring the distributing acceleration of Taiji-1 [9].

When three satellites are all launched, Taiji would be able to have a detector based on a similar Michelson-type interferometer design. In contrast, they have a separation of 3 million kilometers since Taiji is a space-borne detector. The master satellite sends a beam identical to the laser in ground-based ones, while the other spacecraft send back a high-power phase replica. The master spacecraft hit the local laser with the beam being sent back and generate a beat note. When a gravitational wave passes by, measurements on the distance from local test mass to the local interferometer, local interferometer to remote interferometer, remote interferometer to remote test mass will be recorded. The phase of the beat note will be converted to GW signal and analyzed.

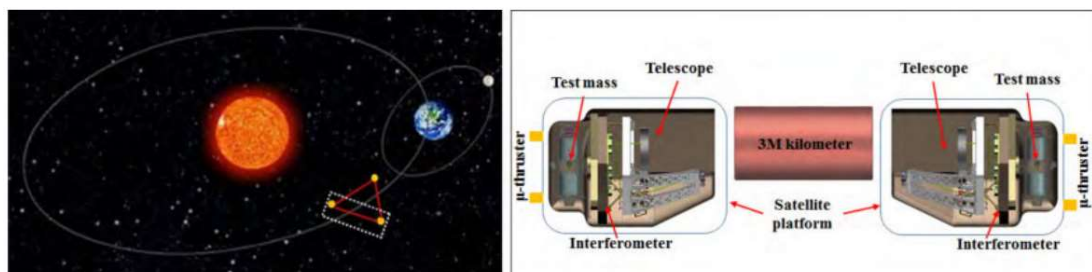


Figure 6. The interferometry using laser between satellites [10] (left panel) and a diagram demonstrating the structure of the laser linkage between satellites (right panel)

The telescope is responsible for transferring or transmitting beams to other spacecraft.

Taiji will be launched in approximately 2033, and the roadmap of the Taiji mission is given in Ref. [10], which also covers the schedule of the pathfinder. The pathfinder will cover most Taiji technologies except for TDI (time delay interferometer), while several tests on the technology will still need to be done before launching the program. Taiji-1 has already succeeded during its operation in 2019, proving that the roadmap is feasible [10].

6. LISA being another preponderant candidate by using TDI

LISA is a space-borne GW detector planned to be launched in 2034 by ESA and NASA. It is one of the low-frequency detectors sensitive to mHz gravitational waves, including Taiji and TianQin projects.

Since the arm length, which is the separation of the satellites, of the detectors differs due to the gravity, the laser noise could not be avoided since the fluctuation of the laser will be delayed inside this differed length of the arm. The relative motion of the satellites causes a first-order Doppler beat-note. In fact, the TDI can cancel such noise both from the instrument and GW, and it is already implemented in LISA [11]. More details will be available to access in the original article from the reference.

7. Conclusion

In summary, this article discussed the basic information about gravitational waves and the recent progress in the corresponding detection accordingly. Specifically, the nature of the gravitational wave and the Einstein field equation are introduced primarily. Subsequently, a basic outline is demonstrated for LIGO, and Virgo designed a GW detector to craft one of the most outstanding uncovering in Physics. Afterward, the Japanese detector's modifications for better precision and the grand space-borne detector scheme launched by China and ESA, which could be a crucial point to further progress in cosmology, are introduced thoroughly. The future of gravitational wave study is still a puzzle until programs like Taiji have proceeded. It might be essential for studies on unpuzzling the universe since it can transfer information that Electromagnetic waves could not carry. These descriptions and comparisons between state-of-art GW detectors offer a guideline for preliminary elements in the gravitational wave detector principle, which pave the way for scholars who prefer to understand this fascinating phenomenon.

References

- [1] Cervantes-Cota, Jorge L., Salvador Galindo-Uribarri, and George F. Smoot. "A brief history of gravitational waves." *Universe* 2.3 (2016): 22.
- [2] Dekel, Avishai, and Jeremiah P. Ostriker, eds. *Formation of Structure in the Universe*. Cambridge University Press, 1999.
- [3] Taylor, Joseph H., and Joel M. Weisberg. "A new test of general relativity-Gravitational radiation and the binary pulsar PSR 1913+ 16." *The Astrophysical Journal* 253 (1982): 908-920.
- [4] LIGO Lab | Caltech. 2021. LIGO's Dual Detectors. Available at: <https://www.ligo.caltech.edu/page/ligo-detectors>.
- [5] Kramer, D., et al. "Exact solutions of Einstein's field equations." Berlin (1980).
- [6] Abbott, Benjamin P., et al. "Observation of gravitational waves from a binary black hole merger." *Physical review letters* 116.6 (2016): 061102.
- [7] Akutsu, T., et al. "KAGRA: 2.5 generation interferometric gravitational wave detector." arXiv preprint arXiv:1811.08079 (2018).
- [8] Luo, J., L. S. Chen, and H. Z. Duan. "TianQin: A space-borne gravitational wave detector, submitted to." *Class. Quantum Grav* (2015).
- [9] Yue-Liang, Wu, et al. "China's first step towards probing the expanding universe and the nature of gravity using a space borne gravitational wave antenna." *Communications Physics* 4.1 (2021).
- [10] Luo, Ziren, et al. "The Taiji program: A concise overview." *Progress of Theoretical and Experimental Physics* 2021.5 (2021): 05A108.
- [11] Tinto, Massimo, and Sanjeev V. Dhurandhar. "Time-delay interferometry." *Living Reviews in Relativity* 24.1 (2021): 1-73.