Research on the Innovation and Development of Gravitational Wave Detection Technology

Fengxi Li

Abstract.

According to Einstein's general theory of relativity, gravity is described as the curvature of space-time caused by gravitational sources, and to prove the existence of gravitational waves, many scientific research institutes around the world have begun to build equipment to try to detect gravitational waves in the vast background signals of the universe. At present, gravitational waves have been detected by many scientific research institutions and scientists. Now, the detection of gravitational waves has shifted to the direction of high precision and accuracy. This paper starts with the laser interferometer, the most basic instrument for gravitational wave detection. It expounds on the latest development progress and key technologies of gravitational wave detection in the current physical world, including noise suppression and gravitational wave detection spacecraft projects. In terms of laser interferometers, this paper describes their principle and key technologies and puts forward the difficult problems that still need to be tackled and studied. In terms of noise suppression, this paper describes the noise and interference that may be generated and how to suppress the noise to avoid interfering with the accuracy of the experiment. It also points out the shortcomings of current noise suppression techniques. For gravitational wave detection spacecraft projects, this paper first focuses on several key projects in the world, then describes the technologies and shortcomings of spacecraft, and puts forward the direction of improvement and in-depth research on these technologies. This paper aims to summarize the key technologies of gravitational wave detection in the world today and point out the direction of its future development.

Keywords: Gravitational wave detection; laser interferometer; space gravitational wave detection spacecraft; laser interferometer noise suppression.

1. Introduction

Gravitational waves are a major prediction of general relativity. To prove this prediction, many scientists and scientific research institutions have tried to measure gravitational waves directly to prove their existence. Gravitational waves are generated due to the merger between massive celestial bodies, causing great disturbance in the surrounding space, and the energy travels outward in the form of gravitational waves.[1] .In 2016, LIGO and the Virgo Scientific Collaboration announced their first observation of gravitational waves, the first direct observation of gravitational waves in human history. Gravitational wave detection will provide a more accurate test of Ireland's general theory of relativity and open up new windows for physics and astronomical exploration [2]. At present, the laser interferometer used to measure gravitational waves has been relatively mature, with laser interferometry as the basic principle, the wavelength of the light wave to achieve distance traceability and the use of a variety of methods to control the error to achieve ultra-high precision space distance measurement [2]. The accuracy of the measurement and the accuracy of the data are the challenges that need to be overcome today. Due to the force majeure in the measurement process, a variety of noise will be produced to interfere with the measuring instrument, so noise suppression is also an important research direction of gravitational wave detection, low temperature, circulation system, suspension system, low noise photoelectric detection technology and so on are often used to suppress noise mode, but in the material cost and technology popularization still need to be improved[3-4]. At present, several space gravitational wave detection spacecraft projects have been carried out in the world, including LISA, eLISA, "Taiji," "Tianqin," etc., and the formation, operation, and measurement instruments carried by spacecraft are all important technologies among which the important key technologies will be elaborated in this paper.[5-6].In this paper, we will start with the simplest laser interferometer, explain its principles and the technologies used, shift the focus to noise suppression technology and spacecraft technology, and gradually describe the development of gravitational wave detection in recent years and propose the next research directions.

2. The Technology of the Laser Interferometer

2.1 Principle of Laser Interferometry

Lasers have many advantages, including high intensity, directivity, spatial homogeneity, narrow bandwidth, and monochromaticity. Laser interferometers are mainly used in applications where high-precision length measurement is required and can also be used as a calibration instrument for precision machine tools or measuring instruments. The main body of the laser interferometer is the Michelson interferometer and frequency-stabilized hydrogen helium laser, which cooperates with various mirrors and refractors to carry out measurement work. Laser interferometers are available in both single-frequency and dual-frequency classifications.

2.1.1 Single-frequency Laser Interferometer

A laser beam is emitted from a stabilized hydrogen-helium laser, then passes through a beamsplitter and splits into two ways, one reflected by a fixed mirror and the other by a movable mirror, which then merges again on the beamsplitter to produce interference fringes. The principle is shown in Figure 1.

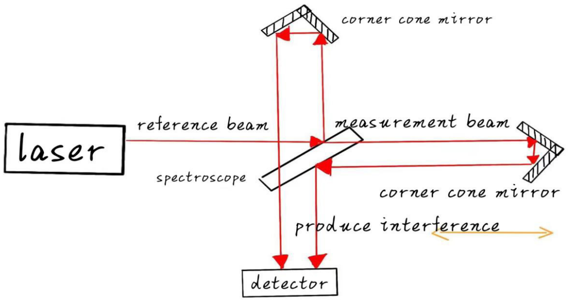

Figure. 1 Schematic diagram of single-frequency laser interferometer

With the movement of the movable mirror, the intensity change of the interference fringe is converted into an electrical pulse signal by the photoelectric conversion element and circuit in the receiver, which is shaped and amplified by the electronic computer to calculate the displacement of the movable mirror.

2.1.2 Dual-frequency Laser Interferometer

The measurement principle of a dual-frequency laser interferometer, also known as a laser heterodyne interferometer, is shown in Figure 2 [1].

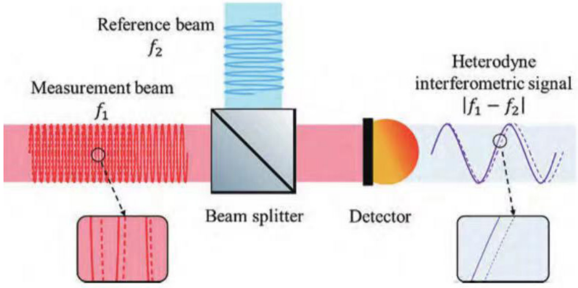

Figure. 2 Schematic diagram of dual-frequency laser interferometer

The dual-frequency laser interferometer adds an axial magnetic field to the original stabilized-frequency hydrogen-helium laser, and due to the frequency traction effect and Zeeman splitting effect, the laser produces two different frequencies of left-handed and right-handed circularly polarized light. After passing through the 1/4 waveplate, two linearly polarized lights perpendicular to each other are divided into two ways by the beamsplitter: one passes through the polarizer to become the reference beam, and the other passes through the polarizer and then splits into two channels. As the movable mirror moves, the beam is reflected through the mirror, and the measurement beam is synthesized into a measurement beam, which is shaped, amplified, and calculated with the reference beam to obtain the displacement of the movable mirror. The superposition of two sine waves with a high frequency but a small difference in frequency produces a low-frequency beat signal, which is the difference between the frequencies of the two sine waves. Taking the classical Michelson interference structure as an example, a periodic change in the phase of the heterodyne interference signal corresponds to a half-wavelength change in displacement, have:

$$\mathrm{L} = \frac{\lambda}{2} \times \frac{\phi}{2\Pi} \tag{1}$$

Where λ is the laser output wavelength, L is the equivalent displacement of the test mass, and φ is the phase of the heterodyne interference signal[1].

2.2 The Key Technology of Laser Interferometer

The high-precision measurement of laser interferometers has always been a challenging field, and the key technologies include differential wavefront sensing, high-precision phase measurement technology, and low-light phase locking technology.

2.2.1 Differential Wavefront Sensing

Differential wavefront sensing compares the laser wavefront phase, and the measurement principle is shown in Figure 3 [1].

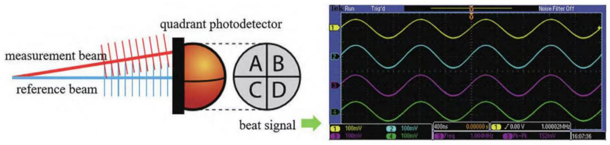

Figure. 3 Differential wavefront sensing and four-channel beat frequency signals

As with a normal photodetector, the measurement beam meets the reference beam and is incident on the surface of the four-quadrant detector, and the two beams of light produce a beat frequency phenomenon. A four-quadrant detector detects this phenomenon and converts it into a four-way AC signal called a heterodyne interferometric signal. When the target motion is measured, the four-way AC signal fluctuates separately, and the translation or rotation information of the target can be inverted. This technology greatly improves laser-ranging accuracy and can be important in future research experiments.

2.2.2 High-precision phase measurement technology

In the laser heterodyne measurement process, the optical path difference of the reference mirror relative to the measuring mirror is measured by the phase change of the beat frequency signal. The relationship between the phase difference φ of the optical signal of the measuring arm and the measured distance is as follows:

$$\Phi = \frac{4\Pi L}{\lambda} \tag{2}$$

Where L is the measured distance, and λ is the resultant wavelength. The phase difference φ measured by the phase meter [2]. It follows that the accuracy of the measured distance depends largely on the accuracy of the phase meter. At the same time, due to the relative change in the position of the measuring mirror, the reflected laser light will undergo a Doppler shift, and the measurement signal will also change accordingly. When measuring with a phase meter, the new frequency must exist within the measurement bandwidth of the phase meter; if the measuring mirror speed is too fast, it may cause the frequency to exceed the phase meter bandwidth and the ranging system to fail. Therefore, all dual-frequency laser interferometers have a maximum measurement speed limit. However, it is very difficult to achieve high-precision measurement in a wide range of bandwidths, and none of the commercial phase meters on the market have this capability, so the technology of phase meters still needs to be tackled. It solves the accuracy problem of the long bandwidth of the phase meter itself to work better for high-precision phase measurement.

2.2.3 High-precision, low-light phase-locking technology

Direct reflection interferometers use the far-end satellite as a mirror and receive the propagating laser light. This is suitable for occasions where the distance is not far away and has no intrinsic effect on the laser energy when propagating. However, when ultra-long-range ranging is performed, the laser is significantly weakened as it propagates and cannot be detected by the detector, which requires high-precision, low-light lock-in technology. This technology can lock the weak incident laser carrying the target signal with the local laser and use the high-frequency local laser instead of the incident laser to complete the propagation and range. In ultra-long-distance space gravitational wave detection, high-precision low-light phase-locking technology will be widely used because of the adaptation of long-distance and high-precision ranging technology.

3. Noise Suppression Technique

3.1 Possible Noise Produced by Laser Interferometer

The noise of a laser interferometer can be divided into two categories: detection noise and displacement noise. Detection noise refers to the error caused by the detection instrument during the detection process, and displacement noise refers to the interference caused by the movement of the mirror surface to the experimental data.

3.1.1 Detect Noise

The detection noise mainly includes quantum noise, laser frequency stability, dark current, and laser power stability. Quantum noise is the noise generated by the quantum properties of light, including shot noise and radiated pressure noise. In the frequency band above 100 Hz, the main noise source for laser interferometers is shot noise [3]. Radiation granulation noise is noise caused by the radiation pressure of a laser when the mirror is subjected.

3.1.2 Displacement Noise

Displacement noise includes seismic, thermal, and controller noise, among others[3]. Seismic noise is a major source of low-frequency displacement noise generated by surface movements caused by various factors, such as wind, waves, and small earthquakes. Thermal noise originates from the irregular movement of molecules, which affects all frequency bands[4].

3.2 Improvements to Suppress Noise

3.2.1 Suspension System and Cryogenic Mirror Technology

It is the world's mainstream behavior to isolate seismic and thermal noise by combining the interferometer with a seismic isolation platform and a suspension device. The suspension system filters out horizontal disturbances above the resonant frequency, while using materials with a high-quality factor in the suspension system partially mitigates thermal noise. Japan's KAGRA has implemented cryogenic mirrors made of sapphire to reduce the effect of thermal noise on experimental results further. However, due to the cost of materials and other issues, there are still quite a few low-temperature mirrors that can be applied to practical experiments, and this part of the technology still needs to be tackled.

3.2.2 Double Circulation

Dual cycling includes power recycling and signal recycling. Power recycling is used to suppress shot noise, in which the laser power in the interferometer increases, but the laser power and loss bandwidth do not. On the other hand, signal recycling has only recently been applied to interferometers, which can increase the time that gravitational wave-modulated sideband signals are stored in the interferometer to achieve enhancement of specific bands. Information recirculation is a relatively new technology; only some of the newly produced laser interferometers are equipped with this technology; because this technology can suppress noise to a large extent and the use cost is not high, it can be widely used in space gravitational wave detection experiments.

3.2.3 Low-noise photodetectors

The noise of the laser source directly impacts the sensitivity of ultra-high-precision inter-satellite laser interferometry. The photoelectric negative feedback method is an effective technical means to suppress the noise of low-frequency laser intensity [4]. Photodiodes are key devices in photoelectric detection, so their noise performance can affect the performance of the entire photoelectric detection. To meet the laser intensity noise requirements of the space gravitational wave detection program, the dark current of the photodiode needs to be small enough, much smaller than the photocurrent converted by the laser. Figure 4 illustrates the framework of a low-noise detector for space gravitational waves[5].

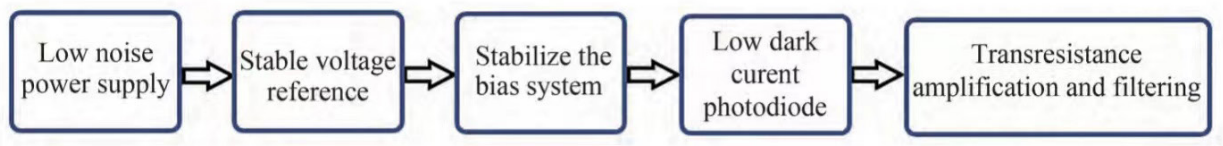

Figure. 4 System architecture of low noise space gravitational wave detector

As shown in the figure, the space gravitational wave low-noise detector starts from a low-noise power supply, and through a stable voltage reference and a stable bias structure, the key technology is a low-dark photodiode, and the purpose of cross-resistance amplification and filtering is realized. The low-noise photoelectric detection technology is still immature, and the update and iteration of photodiodes still need to be broken through experiments and research.

4. Application of gravitational wave detection in space

4.1 Space gravitational wave detection project

4.1.1 LISA Detection Spacecraft System

The LISA detection system consists of three spacecraft in a stable near-regular triangle in orbit around the Sun, flying in Earth orbit at a position about 20° behind the Earth. The schematic diagram of the formation configuration is shown in Figure 5 [6].

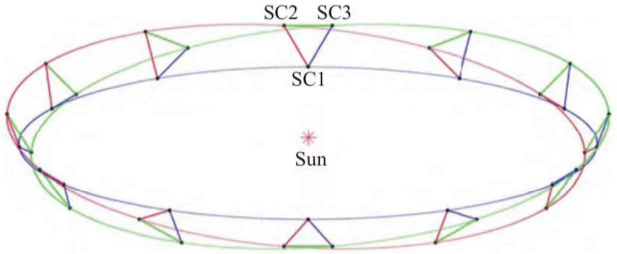

Figure. 5 Schematic diagram of LISA space gravitational wave detector configuration

4.1.2 eLISA/NGO detection spacecraft systems

The system follows some of the configurations and structural designs of LISA and can be regarded as a simplified version of LISA. However, for various reasons, it is somewhat different from LISA, and there are three main differences: 1) the topology of the three spacecraft is different; 2) the laser measurement of the formations is different; 3) The arm length is different.

4.1.3 Spacecraft systems of the "Tianqin" and "Taiji" programs

The Tianqin program is China's first gravitational wave detection program, which uses the regular triangular formation mechanism of the common orbital constellation and operates in the geocentric orbit. The "Tai Chi" program is the first space gravitational wave detection program proposed and implemented in China, adopting the same orbiting and formation scheme as LISA. Its test satellite, "Taiji-1," was successfully launched on August

31, 2019[7].

4.2 Method and key technologies of space gravitational wave detection

4.2.1 No drag control technology

The drag-and-drop control problem involves the control method and the control strategy. The current research includes two types of research objects: 1) attitude stabilization and control of satellite multi-body systems and 2) Orbit control of the satellite without a towing control system[6]. Drag-free control technology is widely used in space gravitational wave detection projects and is a key technology to ensure high-precision gravitational wave detection. Its importance is self-evident, so it must still be iterated and developed for higher-precision space gravitational wave detection.

4.2.2 orbit and formation design and control

The tow-free spacecraft needs to maintain a stable long-term orbit configuration during operation, so the design and control of orbit and formation are the most important links in whether the gravitational wave signal can be detected. The control problems can be divided into 1) the dynamic evolution mechanism and perturbation influence mechanism of very long baseline formations; 2) the design technology of high-stability formation configuration considering multiple perturbations and complex multi-constraints; 3) High-precision formation control of spacecraft without towing [6]. Orbit and formation control determine the relative position of the space gravitational wave detection spacecraft, which affects the measurement data and results. Toravitational waves more easily, the spacecraft's orbit and formation need to be carefully considered[8].

4.2.3 Space inertial sensors

Space inertial sensors are one of the key payloads of space gravitational waves, composed of quality inspection, electrode cages, front-end electronics systems, and auxiliary systems [9]. The main functions of inertial sensors include: 1) measuring the non-conservative force experienced by the spacecraft and feeding it back to the no-drag system, canceling the interference of the non-conservative force in the final calculation; 2) Providing an inertial reference for laser interference. Space inertial sensors are important technologies to avoid interference with the data received by the spacecraft. To a certain extent, the sensor's sensitivity determines the accuracy of the experimental data, so research on the sensor should be developed to improve its accuracy[10].

5. Conclusion

The key technologies in gravitational wave detection technology, including dual-frequency laser interferometer, basic noise suppression technology, and space spacecraft technology, can meet the basic ranging needs of gravitational wave detection. Dual-frequency laser interferometers use principles such as light reflection to measure gravitational wave fluctuations in a very small range. Noise suppression technology significantly correlates with the accuracy of measurement results, and most laser interferometers currently use suspension systems, double circulation systems, and other technologies to minimize noise interference with measurement results. The detection of gravitational waves in space spacecraft is a popular project worldwide, and many countries are researching this field. However, the urgent need for gravitational wave detection is to pursue ranging accuracy. Laser interferometers, especially the widely used dual-frequency laser interferometers, high-precision phase meters, four-quadrant detectors, etc., are the main directions.

Regarding noise suppression, the selection and cost of raw materials for cryogenic mirror technology and the operation of suspension and circulation systems still need to be considered and studied. In space gravitational wave detection spacecraft projects, the instruments on board spacecraft led by LISA and the formation and orbit design are still problems that need to be considered. Gravitational wave detection is a promising field, and it is hoped that more scientists and scientific research institutions will join the research in the field of gravitational wave detection.

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