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Optimizing the Global Placement of Gravitational Wave Detectors Using Programming Simulation Methods

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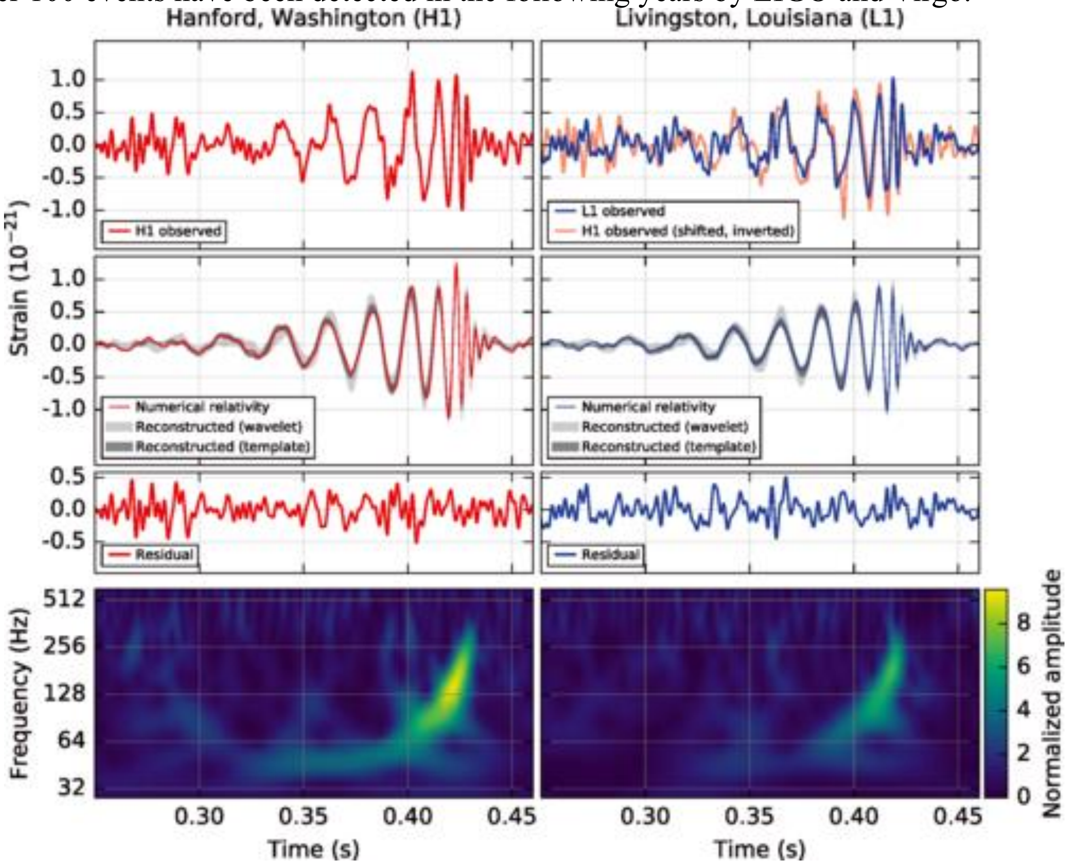
Abstract: This research paper focuses on optimizing the global placement of gravitational wave (GW) detectors to enhance the sky localization accuracy for GW events. Proposed by Einstein's General Theory of Relativity, gravitational waves carry valuable information about cosmic events such as black hole mergers. The study uses Python and the BILBY framework to simulate various global locations for new GW detectors and specifically evaluates locations in Antarctica, South Africa, and Alaska. By simulating a binary black hole merger event at a set sky location, the study compares the difference in sky localization accuracy between different detector networks to find the optimal one. Results show that adding detectors in Antarctica and South Africa will significantly improve sky localization accuracy. Nevertheless, whether the environment in the areas is suitable for future constructions of detectors remains to be answered.

1. Introduction

The idea of detecting gravitational waves originated after Einstein's theory of general relativity was published in 1915[1]. There had been various attempts to detect gravitational waves, including by Joseph Weber in the 1960s using his "antennas" – a large metal cylinder of about 2 meters in length and 1 meter in diameter[2], which was later discredited. There were additional detectors placed in several locations around the globe in the 1970s[3], which found no significant results. Despite some unsuccessful efforts towards the detection of gravitational waves, another study in the late 1970s found some indirect evidence of the existence of gravitational waves by observing the orbital decay resulting from the gravitational wave radiation in a binary pulsar[4]. According to Cervantes-Cota et al.[1] (2016), this indirect finding again triggered more attempts to detect gravitational waves, this time using interferometers.

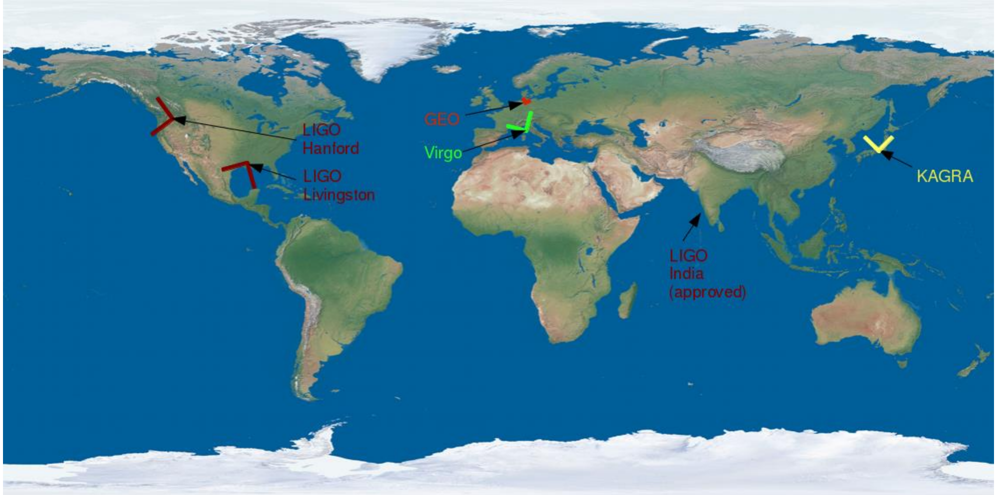
The design of the modern-day gravitational-wave interferometers was perfected during the late twentieth century and the early twenty-first century with the construction and implementation of Laser Interferometer Gravitational-wave Observatory (LIGO) and other similar interferometers around the globe, according to Pitkin et al.[5] (2011).

On September 14, 2015, an email from LIGO to Marco Drago, a physicist of the Max Planck Institute for Gravitational Physics in Hanover, Germany, revealed the first discovery of the detection of the gravitational event GW150914, evident in both the Hanford and Livingston site detectors[6], as shown in Figure 1. Two years after LIGO's first detection, on August 14, 2017, GW170814 was detected by the first combined effort of the Advanced LIGO and Advanced Virgo detectors[7]. Since then, over 100 events have been detected in the following years by LIGO and Virgo.



Note. From “Observation of Gravitational Waves from a Binary Black Hole Merger”, by B. P. Abbott et al., 2016, *Physics Review Letters*.

Figure 1: The Gravitational-wave Event GW150914



Note. This graph includes ground-based gravitational wave detectors that are either being constructed or working. From *A Worldwide Network*, by the Virgo Collaboration[11].

Figure 2: Current Worldwide Location of Interferometers

Although space-based interferometers are also being implemented, which are considered beneficial to the overall detection rate of gravitational events[8], there are significant differences in the detection range between space-based and ground-based interferometers[9]. In recent years, new ground-based interferometers around the globe are continuously joining the existing network, including KAGRA located in Japan and LIGO-India located in India (see Figure 2). According to Cai et al.[10] (2023), the addition of the new interferometers will significantly increase the localization accuracy of gravitational wave events. This paper will simulate the sky localization accuracy of gravitational wave events using new ground-based interferometers to optimize global detector placement and maximize detection accuracy.

2. Background

2.1 Gravitational Waves

The idea that gravitational waves exist was predicted by Einstein's General Theory of relativity. Gravitational waves are disturbances of spacetime that propagate at the speed of light [12]. Gravitational waves form from various sources, including interaction of black holes, coalescence of binary star systems—pairs of stars in orbit around their common centre of gravity, stellar collapses, and pulsars (Pitkin et al., 2011). A major motivation for searching for gravitational waves, and the most straightforward one, is to test the theory of general relativity [12]. Gravitational waves also reveal some properties of the universe that are undetectable using other signals[13]. Unlike electromagnetic waves which lose energy while propagating through the universe, gravitational waves interact very weakly with matter[12], so gravitational waves preserve the original information about their origin, which allows for deeper research.

2.2 Gravitational Wave Interferometers

Current gravitational wave detectors are interferometers. The design of interferometers has evolved since the origination of gravitational wave detectors. Unlike optical telescopes that point at a certain direction in the sky for signals, interferometers used for gravitational waves rely mostly on their size and length and are not specified for a particular area in the sky. The interferometers used nowadays are several kilometers in scale, such shown in Figure 3, and they detect gravitational wave events from interference patterns caused by subtle distortion in spacetime[14]. According to Figure 4, the interferometer has two perpendicular arms, and each of the arms are several kilometers long – the specific length is dependent on the available land. Inside the arms, a single laser source emits a laser at the beam-splitting mirror, where the laser light is split into two portions. Each portion continues to travel along an arm and is reflected by the mirrors fixed at the end of each arm. The reflected laser joins again at the beam-splitting mirror, and the recombined laser is transmitted to the light detector. In its normal state, the two arms are aligned so that the two portions of laser cancel each other, and no signal will appear in the light detector. On the other hand, when there is a gravitational wave event occurring, the arms will vary in length, resulting in a light signal in the light detector.

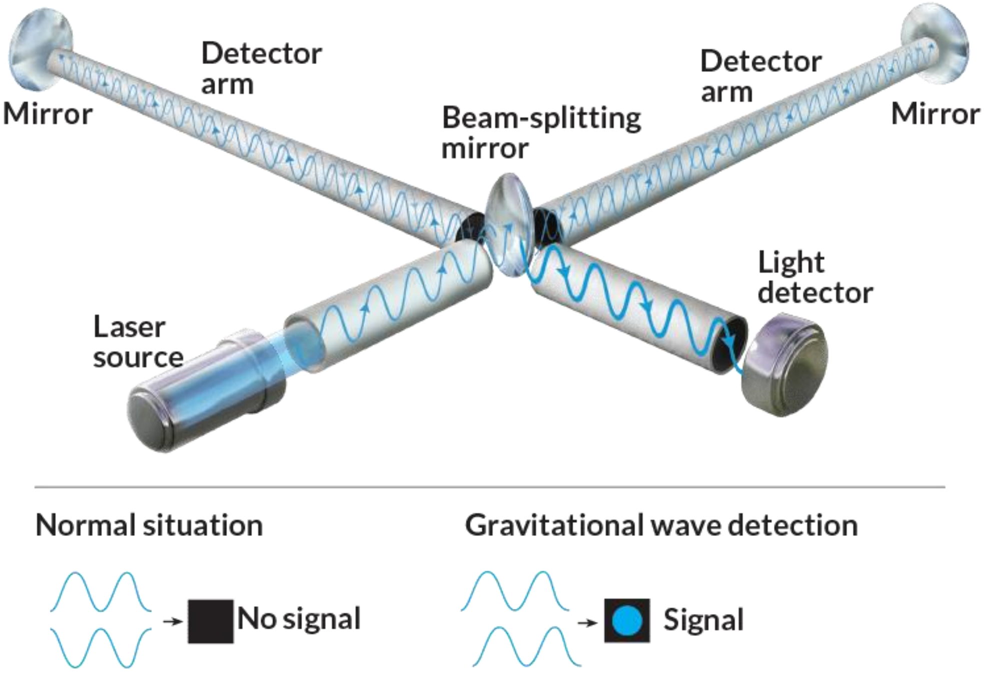
The change in length of the detecting arms is given by

$$\Delta L = h\, L, \tag{1}$$

where h is the gravitational wave strain amplitude, and L is the original length of the arms. Therefore, for a given gravitational wave event, a longer original arm length means more detectable changes in length, which will allow for the detection of weaker gravitational wave events. For this reason, interferometers constructed nowadays tend to be as extensive as possible in order to improve detection rates.

Note. Virgo is a laser interferometer with two 3km arms perpendicular to each other. It is located at the European Gravitational Observatory in the countryside near Pisa, Italy. From *Detector[15]*, by N. Baldocchi. Copyright 2021 by Virgo.

Figure 3: Top View of Virgo



Note. From *Trio wins physics Nobel Prize for gravitational wave detection[16]*, by N. R. Fuller.

Figure 4: A Simplified Diagram of Modern Interferometers

2.3 Sky Localization

When observing gravitational wave events, one important purpose is to get the sky localization of the wave source[17]. The process of sky localization is done by combining data from multiple detectors to triangulate the source of the gravitational wave event. The difference in the relative timing of detection is used to determine the sky location of the gravitational wave source. Therefore, adding more detectors at different locations will provide more precise timing information, and thus it helps scientists improve the sky localization accuracy.

By accurately determining the sky location of a gravitational wave event, scientists can then search for the specific source of the event by detecting the electromagnetic signals coming from that location. Determining the sky location of gravitational wave events will help scientists gain insights into environments of the host galaxies. Since gravitational waves are independent of redshift, the signals can serve as standard indications of the distance from the gravitational wave source. By combining the sky localization and the observed signal source, the expansion rate of the universe can be measured. Interferometers detect signals from various binary mergers, including black holes and their masses and spins, so the sky localization of binary black holes can also provide valuable information about the black holes' distributions in the universe as well as their properties.

3. Methods

3.1 Bayesian Inference and BILBY

Bayesian inference is a widely used framework in modern astronomy, especially in the research of gravitational waves[18]. It helps analyze detected gravitational wave signals by estimating parameters like masses and spins of the binary merger, and it also helps construct sky maps using the parameters[19].

The study of gravitational waves is rapidly growing in recent years, and more data sources – such as the datasets of LIGO and Virgo – have been open for public use[20]. Therefore, to allow both scholars and the public to use gravitational wave data for studies, a user-friendly code is necessary[19], and BILBY is one of this kind.

According to Ashton et al.[19] (2019), BILBY is a Python-based expert-level parameter estimation framework. It allows users to perform estimation on both open-access data of LIGO or Virgo and self-conducted simulation data.

3.2 Simulation

The simulation process of this research is Python-based. In this study, a gravitational wave event of binary black holes at a set sky location was simulated. Interferometers at set sensitivity were simulated for their detection of the gravitational wave event. Then, BILBY was used to recover the sky localization of the simulated event with the detector networks, and the results were compared to get a maximum localization accuracy.

The parameters of the gravitational wave event as well as the sensitivity of each detector was kept the same for every interferometer, and the only variables being changed were the longitude and latitude of the new interferometer in the network. The other two existing interferometers of LIGO were kept unchanged in all trials, and they were combined with the new detector to form a new triple-detector network. Three sets of triple-detector networks were tested for the optimization, and a double-detector network with only the two existing interferometers of LIGO was tested for comparison.

To simulate the binary merger as the source for the gravitational wave event, a pair of right ascension (RA) and declination (DEC) was selected randomly and kept the same in all four trials. In this research, the RA was set at 1.375 radians, and the DEC was set at -1.2108, where the negative sign indicates a location south of the celestial equator. Parameters of the gravitational wave source were also kept constant. The duration of the event was set at 4.0 seconds, the sampling frequency was set at 2048.0 Hertz, and the minimum frequency was set at 20 Hertz. The two masses of the binary black holes were 29.0 and 36.0 times the mass of the sun. The spin magnitudes were 0.4 and 0.3, where ranging from 0 to 1, 0 indicating no spin and 1 indicating maximum spin. The tilts were 0.5

and 1.0 in radians. The luminosity distance of the gravitational wave event was set at 2000.0 megaparsecs. The waveform model used in this study is IMRPhenomPv2. The parameters were injected into the waveform generator to produce the simulated gravitational-wave signal for each interferometer.

To set up the new interferometers in the networks, the Hanford detector of LIGO was chosen as the template interferometer, which means all the new interferometers created were the same with the Hanford detector in sensitivity, arm lengths, noise sources, etc. By choosing specific latitudes and longitudes for each new detectors and setting up the interferometers of Hanford and Livingston, the network was set up and allowed to run. At the end of each trial, corner plots with parameters of masses, mass ratio, RA, and DEC were generated, and the results were used for BILBY to generate skymaps.

3.3 Skymaps

Skymaps are visual tools used to show the results of sky localization. Several parameters on the skymaps are crucial for interpreting the results.

The color-shaded regions on the skymaps show the credible regions in the sky where the gravitational wave event was found, and the size of each credible region is given in square degrees. There are usually a 50% and a 90% credible region shaded with different colors for distinction. The area of 50% means there is a 50% chance that the wave source lies within that area, and the area of 90% means the wave source has a 90% chance to lie within that area. The smaller the probability region is, the more precise the gravitational wave source is localized.

Skymaps also use celestial coordinates (right ascension and declination) to indicate the position of the gravitational wave event in the sky. Right ascension (RA) is “the east–west coordinate by which the position of a celestial body is measured”[21], and it is measured in radians, degrees, or hours (where 1 radian is equal to 57.2958 degrees, and 1 hour is equal to 15 degrees); declination (DEC) is “the angular distance of a body north or south of the celestial equator”[22], and it is measured in radians or degrees. A combination of RA and DEC values expresses the specific location of the source.

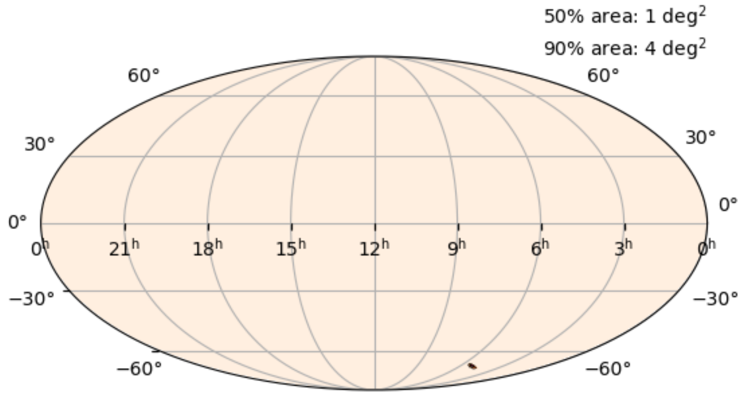
4. Results

After properly setting up the interferometers for simulation, BILBY generates skymaps to show the results. By comparing the results of triple- and double-detector networks, there is clear evidence that adding a new detector elsewhere around the globe will significantly improve the sky localization accuracy of the current detector network.

4.1 Dome Argus, Antarctica

Stable and dry air conditions in Antarctica results in minimal atmospheric turbulence, and the vast ice sheets experience low seismic activities[23]. So few noise sources will create a suitable environment for constructing gravitational wave interferometers.

By adding a detector in Antarctica to the network, the skymap result shows high accuracy in sky localization (see Figure 5), with the 50% probability area being 1 deg^2, and the 90% probability area being 4 deg^2. This result is the most precise set among the three new sets of triple-detector networks, and it shows significant improvement from the existing double-detector network, which is enough to maximize the localization accuracy for the wave source.



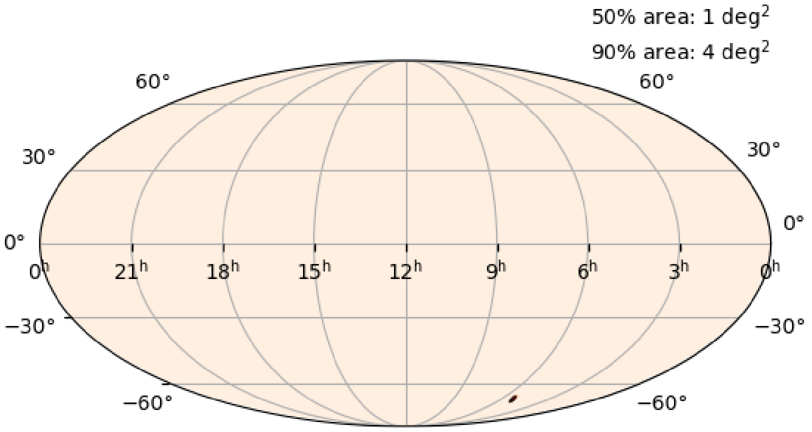
Note. This graph is the sky localization result by the triple-detector network in which the new interferometer is located in Dome Argus, Antarctica, with the longitude and latitude being 80.37°S, 77.35°E.

Figure 5: Skymap with New Detector at Dome Argus, Antarctica

4.2 Karoo, South Africa

The extensive open plains of Karoo provides suitable land for constructing large-scale interferometers[24], and the arid air provides a low-noise-source environment for detectors.

When a new detector in the network is located in Karoo, the simulation result also shows high accuracy in sky localization (see Figure 6), in which the 50% probability area is 1 deg^2 and the 90% probability area is 4 deg^2. This result is identical to that of the Antarctica case, which means these two locations are both worthy of choosing for building the new ground-based interferometer.



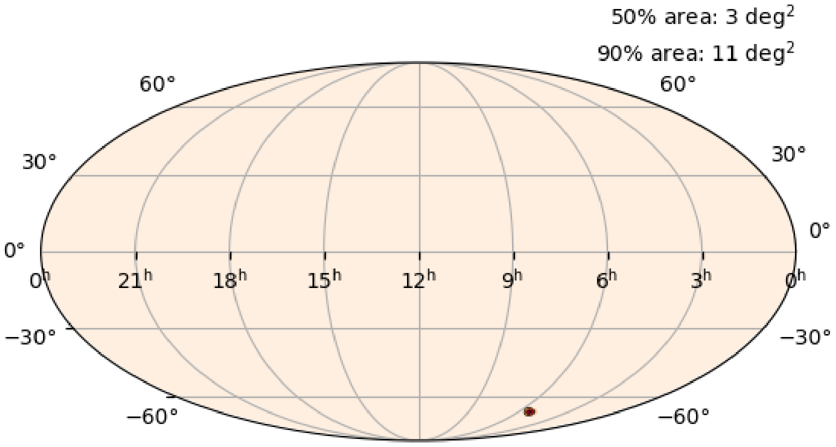
Note. This graph is the sky localization result by the triple-detector network in which the new interferometer is located in Karoo, South Africa, with the longitude and latitude being 32.35°S, 22.57°E.

Figure 6: Skymap with New Detector at Karoo, South Africa

4.3 Tanana Valley, Alaska

Tanana Valley is at a high latitude of the north hemisphere. Since there is currently no gravitational wave interferometers at high latitudes, an addition of a detector in Alaska may potentially increase the detection rates and accuracy of gravitational wave events.

When the new detector is set at Tanana Valley, Alaska, the skymap result shows generally small probability areas (see Figure 7), where the 50% area is 3 deg^2 and the 90% area is 11 deg^2. This result is not as precise as that of the previous two cases, which means adding a new detector in Alaska may not be as beneficial.



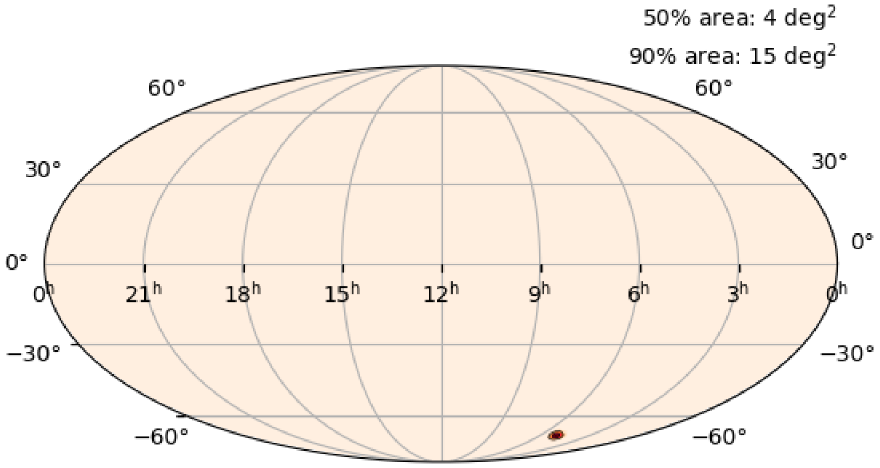
Note. This graph is the sky localization result by the triple-detector network in which the new interferometer is located in Tanana Valley, Alaska, with the longitude and latitude being 64.40°N, 147.00°W.

Figure 7: Skymap with New Detector at Tanana Valley, Alaska

4.4 Without New Detectors

A controlled trial is added to compare the triple-detector results with the current situation. In this set, the two detector used for simulation is the two detectors of LIGO, which are both located in the northern and western hemisphere.

In this double-detector network, the result (see Figure 8) is 4 deg^2 for the estimation of 50% area and 15 deg^2 for the 90% area. While the result in this case is reasonably precise, the results of the previous three trials show significant improvements from it.



Note. This is the sky localization result without the addition of a new detector. The longitudes and latitudes are 46.58°N, 119.39°W for Hanford Detector and 30.50°N, 90.74°W for Livingston Detector.

Figure 8: Skymap by Two Detectors of LIGO

Based on the summary of results in Table 1, it can be concluded that for the given simulated gravitational wave event and other similar events, a new detector added in Antarctica or South Africa will maximize the detection accuracy of the global gravitational wave interferometers network.

Table 1: Sky Localization Results of Four Networks

	50% Area (deg^2)	90% Area (deg^2)
New in Antarctica	1	4
New in South Africa	1	4
New in Alaska	3	11
Without New	4	15

5. Conclusion

Gravitational waves are precise indicators and message carriers of the universe, and there is profound significance in studying them. The study of gravitational waves requires the construction of interferometers, methods like sky localization, and programming tools like BILBY and skymaps. This research chooses three new locations (Antarctica, South Africa, and Alaska) for the new interferometer, and the results in the former two locations show great improvements in the sky localization accuracy.

The results of Antarctica and South Africa show that they are both strong candidates for the location of a new detector, and both locations have relatively stable and low noise environments. But the site selection process should also take other factors into consideration. For instance, the natural environment in Antarctica is harsh and uninhabitable, and Antarctica is harder for human to approach, which can make the long-term construction activity difficult to be continued, whereas the natural environment of South Africa is more suitable for the long process of building an interferometer. Therefore, for the future construction of a new ground-based interferometer, South Africa is considered a better location due to its relatively mild environment.

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