Sensing and vetoing loud transient noises for the gravitational-wave detection

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The multi-messenger astronomy starts with the recent observations of gravitational-wave and its electromagnetic counter parts, GW170817, since the first detection of gravitational-wave, GW150914. To understand how the gravitational-waves are detected in the laser interferometer, in this review article, we briefly review the gravitational-wave and the sources generating it. It is then followed by the basic principle of the laser interferometer as a gravitational-wave detector and its noise sources. The search algorithms currently used in the gravitational-wave observatories are summarized and the sensing/vetoing algorithms in the detector characterization are described to see how the high power noises are suppressed and the data quality is monitored.

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I. INTRODUCTION

The detection of gravitational-wave opens a new window for understanding the mysterious secrets of the Universe [1]. Just two years after the first detection, we became to know the origin of the heavy elements spread in the Universe by observing gravitational-wave and electromagnetic signals coming from the neutron star merger, together with the collaboration between gravitational-wave and electromagnetic counterparts communities [2–5]. This obviously presents the fact that the detection of gravitational-wave became a new tool of understanding the Universe. The ground-based laser interferometer detectors such as LIGO [6], Virgo [7], GEO 600 [8], and KAGRA [9] will be soon operating cooperatively and the tool will be even more exquisite.

Since the gravitational interaction is incomparably weaker than other interactions as is well-known, the detection of gravitational-waves is very hard and it is only expected to be observed from disastrously energetic events in the Universe. Apart from the signal coming from the Universe, there are a number of noise sources affect the gravitational-wave detector that should be suppressed in various ways, such as seismic isolation, high power laser, and high finesse mirrors, etc. The successful detection can be made only if we isolate those noise sources from the real gravitational-wave signals. Even though the best technologies are adopted, there remain noises comparable to the gravitational-waves.

The matched filter used in gravitational-wave search is the most powerful technique to distinguish the gravitational-wave signals from the noises, since we know the analytic waveforms of the gravitational-waves from the motion of binary compact stars. However, its efficiency is not good enough because there are many harmful noises originated from instrumental anomalies of the detector and environmental disturbances nearby detector. In addition, there exist gravitational-wave sources with unmodeled waveforms such as core-collapsing supernovae. This is why the detector characterization and the data quality check are necessary. In brief, the investigation of noises that have nothing to do with the real signals can improve the data quality and detection efficiency.

In this review article, we present the key ingredients in the detection of gravitational-waves, e.g. the detector, target sources, and data analysis algorithms for the search and the data quality. We briefly review the sources generating gravitational-waves in Sec. II. The basic principles and the noise sources in the laser interferometer detector are summarized in Sec. III. The search algorithms in data analysis are classified into two types according to target sources in Sec. IV. One is the modeled search based on the matched filter, and the other is unmodeled search using wavelets. The detector characterization and the data quality analysis are covered in Sec. V. Finally, some remarks are summarized in Sec. VI.

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II. GRAVITATIONAL WAVES

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In the general theory of relativity, the gravitation is described by the geometrical structure curved by matter distribution [10]. The governing equation is a simple field equation built upon the general covariance, which is the well-known Einstein field equation [11–15]

\[ G_{\mu\nu} = 8\pi G_N T_{\mu\nu}, \]

where \( G_N \) is a Newton’s constant. Hereafter we set \( G_N = 1 \). The gravitational-waves can be calculated by fluctuations on the Minkowski background in the linearized gravity

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad |h_{\mu\nu}| \ll 1. \]

Plugging the linearized metric (2) into the Einstein equation (1), we obtain a wave equation in the Lorentz gauge

\[ \Box h_{\mu\nu} = -16\pi T_{\mu\nu}, \]

which describes the gravitational-waves [16].

Omitting the energy-momentum tensor in Eq. (3), the vacuum wave equation is simply written as

\[ \Box h_{\mu\nu} = 0, \]

which describes the propagation of the gravitational-waves. The solution to the vacuum wave equation (4) is a monochromatic plane wave

\[ h_{\mu\nu} = A_{\mu\nu} \exp(ik^\alpha x_\alpha), \]

where \( A_{\mu\nu} \) is the amplitude tensor of the gravitational-wave and \( k_\alpha = (\omega, k_1, k_2, k_3) \) is the wave vector. The null vector condition of \( k^\alpha k_\alpha = 0 \) implies that the gravitational-waves are propagating at the speed of light, and the orthogonality between the amplitude tensor and the wave vector \( A_{\mu\nu} k^\nu = 0 \) shows that they are transverse waves.

The residual symmetry can be fixed by the transverse-traceless gauge, and the gravitational-waves are written as

\[ h^{TT}_{\mu\nu} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & 0 & 0 \\ 0 & 0 & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \]

where \( h_+ \) and \( h_\times \) represent plus polarization and cross polarization, respectively. The two polarizations are depicted in Fig. 1.

1. Generation of the Gravitational-Waves

As the electromagnetic wave is generated by the acceleration of a charged object, the acceleration of a massive objects can also generates the gravitational-wave. The wave equation (3) is solved as

\[ h_{\mu\nu}(x) = -16\pi \int d^4x' G(x - x') T_{\mu\nu}(x'), \]

where \( G(x - x') \) is the Green’s function and \( T_{\mu\nu} \) is the stress-energy of a source. Since this equation depends on boundary conditions, the retarded Green’s function can be chosen,

\[ G(x - x') = -\frac{1}{4\pi|x - x'|} \delta(x_{ret}^0 - x'^0), \]

where \( x'^0 = ct' \), \( x_{ret}^0 = ct_{ret} \), and \( t_{ret} = t - |\vec{x} - \vec{x}'| \) is the retarded time. Then, the gravitational-wave generated by the source is given by

\[ h_{\mu\nu}(x) = 4 \int d^3x' \frac{1}{|\vec{x} - \vec{x}'|} T_{\mu\nu}(t - |\vec{x} - \vec{x}'|, \vec{x}). \]

Assuming that the gravitational-wave source is far enough and relatively slow to move, we can reformulate the solution with the quadrupole moment \( Q_{ij} \) [17]

\[ h_{ij}(t, \vec{x}) = \frac{2}{r} Q_{ij}(t - r), \]

where the dot represents the derivative with respect to \( t \).

Note that the amplitude of the gravitational-wave is proportional to the energy-momentum tensor and that it generates a stronger intensity for a high variation in time. However, since the magnitude of the gravitational-wave is quite small, the gravitational-waves with observable amplitude are limited to violent astronomical and cosmological events such as the collisions of the compact binaries, the supernova explosions, and the inflation, etc. These gravitational-wave sources will be covered in the next section.

| \( k^\alpha x_\alpha \) | Plus | Cross |
|-----------------|-----|-------|
| 2\pi            | ![Plus](plus.png) | ![Cross](cross.png) |
| \((2n+\frac{1}{2})\pi \) | ![Plus](plus.png) | ![Cross](cross.png) |
| \((2n+1)\pi \)   | ![Plus](plus.png) | ![Cross](cross.png) |
| \((2n+\frac{3}{2})\pi \) | ![Plus](plus.png) | ![Cross](cross.png) |
Table 1. Some types of the gravitational-wave sources are listed with their frequency domains.

| Type                        | Source                             | Frequency          |
|-----------------------------|------------------------------------|--------------------|
| Transient                   | merging of binary systems          | 10 Hz - few kHz    |
|                             | supernova explosion                | few kHz            |
| Persistent                   | inspiral of binary systems         | few mHz            |
|                             | rotating neutron stars             | few mHz            |
|                             | primitive background radiation     | $10^{-18} - 10^{-15}$ Hz |

2. The Sources of the Gravitational-Waves

The gravitational-waves can be classified into two types: transient waves and persistent waves (see Table 1).

A. Transient wave sources

Typical transient gravitational-wave sources are the merging process of binary systems, the supernova explosions, and the collapse of massive stars.

The compact binary system emits the gravitational-waves in the process losing the orbital energy of the two celestial bodies, and then radiate short and strong signal during the merging process [18–20]. The waveform of this kind of gravitational-wave signal is called the chirp signal, since the amplitude and the frequency of the waveform grow exponentially from inspiral phase to merging phase. The event rate of the coalescence of the binary neutron stars (BNS) is expected to be hundreds to thousands Gpc$^{-3}$yr$^{-1}$ [2], and that of the binary black holes (BBH) is several to hundreds Gpc$^{-3}$yr$^{-1}$ [21]. The frequency at the peak amplitude is hundreds to thousands Hz for BNS and tens to hundreds Hz for BBH.

The supernova explosion occurs when a white dwarf in a binary system reaches sufficiently high temperature to ignite nuclear fusion by the companion object or when a massive star’s core collapses. These events are estimated to occur several times a year within the range of 20Mpc, and the frequency of the gravitational-waves radiation is below a few kHz [22,23].

B. Persistent wave sources

Persistent sources are a type of the gravitational-wave that is radiated continuously by the early inspiral phase of the binary system, the rapidly rotating neutron stars, primordial sources, or the cosmological inflation, and so on. The astrophysical origin of binary inspiral sources consists mainly of the white dwarfs, neutron stars, and black holes. Since these stars emit low-frequency gravitational-waves around a few mHz, direct detection is difficult before the merge. However, since the orbital energy is slowly lost over a long period, indirect detection of the gravitational-waves is possible by observing the change rate of the binary orbit [24].

Rotating neutron stars, called pulsars, emit the gravitational waves around 200 Hz frequency by the effects of heavenly pulses which induced by strong magnetic fields and internal instabilities, seismic activity or acceleration [25–28].

The gravitational-waves emitted by stochastic sources are a type of primordial gravitational-wave presumed to have originated in the primitive universe and the background noise that does not interact with the matter after the Planck era. The frequency of this background radiation is about $10^{-18} - 10^{-15}$ Hz [29–33].

III. GRAVITATIONAL-WAVE DETECTOR

The direct detection of gravitational-wave has been tried by J. Weber since 1960s using his resonant bar detector [34, 35]. Despite of his unsuccessful scandal of false detection in his experiments, his pioneering work has lead to long-lasting efforts all over the world to detect the gravitational-wave from the Universe.

This section introduces the basic idea of laser interferometer as a gravitational-wave detector and various noise sources from instrumental and/or environmental origins that may be harmful against the successful detection of gravitational-wave [36,37].

1. Laser Interferometric Detector

The basic idea of laser interferometric gravitational-wave detector is as follows: First, the incident laser light is split into two arms on the beam splitter. The light reflected from the mirrors located at the end of both arms with the exactly same arm length returns to the beam splitter, and the combined light enters the photon detector. Ideally, if the two test masses at both ends are not affected by the gravitational-waves at all, then the light combined in the beam splitter will has complete destructive interference and will not be measured in the receiver since they travel along the same distance. On the other hand, if the length of both arms changes by the effect of the gravitational-wave polarization, the interference patterns between destructive and constructive interferences will be observed repeatedly [38]. (Fig. 2)

Interferometers have constraints to detect the gravitational-waves related to the length of the arms. If the wavelength $\lambda = 2\pi/\omega$ of the incident gravitational-waves are shorter than $L_z$, it will be able to sense signals. Otherwise, the detection is difficult to expect [14, 15]. This relationship is evident in

$$L \approx 750km \left(\frac{100Hz}{f}\right).$$ (12)
To detect the gravitational-waves nearby 100 Hz, the construction of an interferometer with an arm length of about 750 km should be considered. However, building such huge facilities on the ground is challenging because of the structural and financial problems, so it is necessary to devise a capable method detecting the gravitational-waves with relatively shorter arm length. The Fabry-Perot cavities are designed to meet this needs [39, 40].

The Fabry-Perot cavities are as simple as folding the arms of an interferometer. The key is to make the effect of using light multi-pass in the arms to create the impact of increasing the effective arm length of the interferometer. So, it has the same result as extending to 1,000 km near 300Hz, which is almost equivalent to the targeted wavelength of the gravitational-wave. In addition to the extending the effective arm length, Fabry-Perot cavity amplifies the laser power inside the cavity, which contains a great amount of photons enhancing the detector sensitivity remarkably.

The basic idea of observing gravitational-waves using a Michelson interferometer is quite simple, but it is necessary to meet very complex requirements with the high sensitivity required for observations. The laser beam must be focused on the mirror very precisely and must also have the correct wavelength and constant intensity. Multiple reflected beams in the Fabry-Perot cavities must be correctly incident in the beam splitter, and each mirror at ends must be completely stationary in position without vibrating. In addition, mirrors are required with extremely high level of coating and polishing to prohibit unwanted thermal instabilities caused by scattered beam lights in the cavities [39, 41, 42].

2. Noise Sources for Laser Interferometer

To achieve the designed sensitivity, many noise sources should be analyzed in order to reduce them and eliminate the reasons of such noises. Their origins are very diverse but mainly from instrumental and environmental origins: photon shot noise, mechanical thermal noise, radiation pressure noise, seismic noise, and Newtonian noise, etc. (Fig. 3) This part will cover fundamental noise sources applied to ground-based gravitational-wave detectors.

Detectors based on optical equipment must be accompanied by reading noise in the process of read-out photons such as photon shot noise and radiation pressure noise as typical noise sources.

Photon shot noise can be generated when reading the number of photons integrated into the photon detector due to the errors of the counted number of photons following the Poisson distribution. Since this noise depends on the photoelectric effect, it has a close correlation with the power of the laser with a relationship as

$$n_{\text{shot}} = \frac{1}{l} \sqrt{\frac{\hbar c \lambda_{\text{laser}}}{4\pi \eta P_{\text{laser}}}},$$

(13)

where $\eta$ is the quantum effect of the photodiode, $\hbar$ is the reduced Planck constant and $l$ is the length of the interferometer arm. $\lambda_{\text{laser}}$ and $P_{\text{laser}}$ are the laser wavelength and power, respectively. Equation (13) implies that it is useful to use a high power laser to lower the photon shot noise [43, 44].

Radiation pressure noise is caused by the influence of the laser on the mirror of the interferometer arm end. This effect on the sensitivity of the interferometer is affected by

$$n_{\text{radiation}} = \frac{1}{M \pi^2 l^4} \sqrt{\frac{\hbar P_{\text{laser}}}{\pi^3 c \lambda_{\text{laser}}}},$$

(14)

where $M$ is the mass of the mirror. Equation (14) indicates that it is proportional to the laser power as opposed to the photon shot noise like uncertainty principle in quantum mechanics. And the larger the mass of the mirror, the less the radiation pressure noise [45, 46].

The noise caused by ground motions is one of any noise sources that cannot be excluded from detectors constructed on the ground [47, 48]. Therefore, highly vibrating motions in the low-frequency range may adversely affect the vibration of mirrors in the interferometer. Then this obviously prohibits the detection of the
gravitational-wave signal. The limitations of the ground vibration on the sensitivity give as

\[ n_{\text{seismic}} \sim 10^{-17} \left( \frac{f}{\pi} \right)^2. \]  
(15)

In order to isolate the mirror from the impact of such vibration, it requires installing seismic isolation devices, typically using the pendulums and/or springs. So, the isolation rate of vibration for a single pendulum is given by

\[ R_{\text{pen}} = \frac{1 + \frac{1}{Q_{\text{pen}}} f/f_{\text{pen}}}{1 + \frac{1}{Q_{\text{pen}}} f/f_{\text{pen}} - \left( \frac{f}{f_{\text{pen}}} \right)^2}, \]  
(16)

where \( f_{\text{pen}} \) and \( Q \) are the resonant frequency and quality factor (Q-factor) of the pendulum, respectively. As seen from equation (16), the isolation rate of the vibration depends on \( (f_{\text{pen}}/f)^2 \) if it is much larger than its resonant frequency and its ratio is negligibly small compared to the Q-factor. The Vibration Isolation System (VIS) used in the interferometer achieves a higher attenuation rate utilizing a multi-pendulum and produces an isolation rate of about \( 10^{-8} \sim 10^{-9} \) at about 100 Hz.

The thermal noise in the interferometer is caused by the internal motion of the mirror and the vibration of the wire in the VIS [49–52]. As discussed previously, the pendulum has a resonance frequency lower than the observation frequency range, but the wires are restricted by thermal noises as

\[ n_{\text{thermal}} = \sqrt{\frac{4k_B T f_{\text{pen}}}{M Q f^5}}, \]  
(17)

where \( k_B \) and \( T \) are the Boltzmann constant and the temperature of the system, respectively. This vibration is transferred from the harmonic oscillation of the wire which is approximately described as follows for the mass of the wire \( m_{\text{wire}} \) and has a dominant influence at around 1 Hz [50]

\[ f_n \simeq n \pi f_{\text{pen}} \frac{M}{m_{\text{wire}}}. \]  
(18)

On the other hand, the resonant frequency caused by the internal motion of the mirror from thermal disturbances is higher than the detection frequency region, which is a dominant effect at around 1 kHz [53–55]. The sensitivity variation for thermal noise is given by

\[ \delta h_{\text{thermal}} \simeq \sqrt{\frac{4k_B T}{m_{\text{eff}} Q f_{\text{int}} f}}, \]  
(19)

where \( m_{\text{eff}} \) is the effective mass of the internal mode and \( f_{\text{int}} \) is the resonant frequency in the mirror. Therefore, cooling the temperature of the VIS and test masses can achieve the low thermal noise, and it is possible to enhance the frequency range that can observe the gravitational-waves.

Other noise sources dominating the interferometer sensitivity can be briefly summarized as follows [13–15].

- **Amplitude noise**: it is related to the statistical distribution of the laser photon emission by the optical oscillation appearing at the output of the laser.
- **Laser phase noise**: it is related to vibration due to the instability of laser frequency.
- **Mechanical thermal noise**: it is the vibration associated with the material of the mirror and the vibration caused by the Brownian motion in the mirror.
- **Cosmic-ray noise**: it is the noise caused by the cosmic-ray reaching the antenna. It turned out that this noise source cannot be a major disturbance for detection of gravitational-wave [56].
- **Gravitational gradient noise (Newtonian noise)**: it is the noise caused by changes in gravitational field due to atmospheric pressure, low-frequency seismic vibrations of earth movements, and so on.
- **Electric field and magnetic field noise**: it is the noise generated by the small influence of the electric field and the magnetic field on the device.

### IV. DATA ANALYSIS

We have seen the various types of gravitational-wave sources. The detection of each type of gravitational-wave requires the corresponding search method. Since the main frequency band of the ground-based laser interferometer detectors is from around 10 Hz to a few kHz, so that the main targets are the compact binary coalescence (CBC)s and the bursts [57–60]. A glimpse of data analysis pipeline for transient searches is depicted in Fig. 4.

#### 1. Search for Compact Binary Coalescences

Since the waveform of the CBCs can be calculated by the post-Newtonian approximation and/or the numerical relativity, the search for the CBC is based on the matched filter with the waveform bank. The LIGO Scientific and Virgo Collaborations (LVC) have developed PyCBC [61–63] and GstLAL [64–66] for the CBC search. To infer the physical parameters of the gravitational-wave candidates, Bayesian inference is used with two independent sampling algorithms - Markov Chain Monte Carlo (MCMC) and nested sampling techniques in the
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The coherence is defined as follows

$$c(\tau) = \frac{\int_{f_1}^{f_2} \tilde{h}(\omega) \cdot \tilde{s}(\omega) \exp(-i\omega\tau) d\omega}{\sqrt{\int_{f_1}^{f_2} |\tilde{h}(\omega)|^2 S(\omega) d\omega \int_{f_1}^{f_2} |\tilde{s}(\omega)|^2 S(\omega) d\omega}}. \quad (24)$$

Since the relative magnitude of the phase and polarization component of gravitational-wave is implied from a given template, the confidence for each coherence is defined as the sum of the squares for the respective polarization components by

$$\rho^2(\tau) = c_{1}\rho^2 + c_{0}^2(\tau), \quad (25)$$

where the signal-to-noise ratio is defined as

$$SNR = \frac{\rho(\tau)}{\sqrt{2}}. \quad (26)$$

If the given template is exactly matched to the gravitational-wave signal, the $\rho^2(\tau)$ is maximum, and if the SNR exceeds the given threshold, this signal designates as the gravitational-wave event candidate. The process of finding the most correlated known waveform template from the observed data containing the gravitational-wave is called the matched filtering technique.

PyCBC is a specific pipeline based on the matched filter analysis in frequency domain. To reduce non-Gaussian noises which may have large matched-filter SNR, PyCBC additionally calculates chi-squared tests [61]. The chi-squared statistic computes how different the matched-filter trigger from the waveform and correct the SNR of each trigger. If triggers from multiple detectors match the same template and appear within a time window of the propagation time plus the uncertainty (5 ms), this coincident trigger is set as an event candidate. When an event candidate is found, its significance is measured by the false alarm rate (FAR), that is, how frequently a background noise trigger occurs with the corrected SNR equal to or higher than the candidate event.

However, we cannot obtain the pure noise data that is free of the gravitational-wave. To obtain the detection statistic of background noises, the PyCBC introduces the time-slide trick. The triggers from one detector is arbitrarily shifted in time domain with amount larger than the propagation time of the gravitational-wave to another detector. Then, the new coincident triggers are now free of the gravitational-wave. Since we assume two detectors are sufficiently apart from each other to have no correlated noise, the detection statistic of the background noise is independent of the time-shift.

Another pipeline searching CBC signal, GstLAL performs the matched filter analysis in time domain. Similar to the chi-squared statistic, the GstLAL computes the goodness-of-fit between the measured and expected SNR time series to suppress the large-SNR noises [64]. Both the matched-filter SNR and the goodness-of-fit are
used as the trigger parameters in the GstLAL. A coincident event is ranked by calculating a likelihood ratio using trigger parameters. To obtain the significance of an event candidate, the GstLAL calculates the likelihood ratio of the background noise using the distribution of triggers that are not coincident in time.

2. Search for Bursts

The waveform of the gravitational-wave bursts can be calculated only in some specific cases so that we cannot use the matched filter. For this reason, various unmodeled search algorithms have been developed by LVC – the coherent waveburst (cWB) [72], the omicron-LALInference-Burst (oLIB) [60], and the BayesWave [73, 74] algorithms. These methods identify event trigger signals that occur in multiple detectors and reconstruct the waveform of the signal through the maximum likelihood method [75]. We briefly introduce these algorithms in this section (for details, see [76]).

The cWB pipeline is one of the unmodeled search pipelines for the gravitational-wave transients in broad band [72]. In the time-frequency map of the Wilson-Daubechies-Meyer wavelet transform [77], the combined data of two LIGO detectors is used to identify a transient event as a cluster with various frequency resolutions. For each trigger, the data are coherently analyzed to reconstruct the waveforms in the grid of sky locations [78]. The best waveforms and sky location are selected with a likelihood statistic.

The oLIB [60] is an unmodeled search pipeline using an event trigger generator called Omicron [80] which is based on the Q-transform [81]. In the time-frequency map of the Q-transform, the triggers (excess power) are clustered based on time, central frequency, and quality factor. Then, the coincident triggers are analyzed coherently with a sine-Gaussian wavelet and the Bayesian inference algorithm. Using the time-slide trick, the background triggers are obtained to measure the FAR.

The BayesWave algorithm describes a trigger identified by cWB as a linear combination of sine-Gaussian wavelets [73]. The wavelets are selected by MCMC for signal and glitch models which are characterized by the BayesLine [74]. The sum of sine-Gaussian wavelets reconstructs the waveform for the signal model. Once the posterior distributions are obtained for each model, the Bayesian inference marginalizes the posteriors to rank the hypotheses.

V. DETECTOR CHARACTERIZATION

The strain data detected by a ground-based laser interferometer is typically non-stationary and non-gaussian due to instrument behaviors and environmental issues around the detector. In addition, there exist transient noise signals with various durations due to the causes of instrumental artifacts and environmental influences. These non-stationarity and non-gaussianity of the data limit the search sensitivity, and the limited search sensitivity lowers the significance of a gravitational-wave event potentially originated from an astrophysical origin. The significance of a gravitational-wave event which is detected by the analysis techniques described in the previous section is basically measured by the probability of a false detection due to coincident noises in a search background. Studying the characteristic of the search background and the correlations between $h(t)$ and the instrumental and the environmental noises is most important. If we detect a gravitational-wave event with high significance, the software and hardware configuration is fixed and data is collected for applying the time-shift technique in order to calculate the false alarm rate of the event [62]. During the time collecting the data to be used for search background, the stability of the search background is guaranteed, and a high significant excess noise which is comparable to the significance of the event must be removed from the analysis. The stability of the search background depends on the variability of the detector performance and the variability can be checked by the variation of the maximum sensitive distance [56]. During the time including GW150914 [1], the mean value of the maximum sensitive distance of LIGO Hanford detector is 1906 Mpc, and the 90% range of the sensitive distance is $\sim$1800-2000 Mpc. The mean value of the maximum sensitive distance of LIGO Livingston detector is 1697 Mpc, and the 90% range of the sensitive distance is $\sim$1500-1900 Mpc. These were determined to be sufficiently stable throughout the period of the data used for the calculation of the significance of the event [56].

The time when its corresponding data is noisy and contains non-gaussian transient noises is not suitable to be analyzed for searching a signal originated from an astrophysical origin. In order to mitigate noise sources and improve the search sensitivity, we need to identify the cause of the problems and sense the abnormal artifacts that occur during the whole operation of the detectors. If we identify a noise and fully understand the mechanism of the noise source, we apply an appropriate technique to software and hardware configuration or directly to data [56,79]. However, there still exist noise sources not fully understood and the coupling mechanisms between $h(t)$ and the witness channels of the noises are still vague. The time segments corresponding those noises cannot be removed by a simple way and are marked as data quality (DQ) vetoes. DQ vetoes are applied depending on a specific search analysis described in previous section, and the corresponding time is rejected before the search analysis. DQ vetoes are basically generated by the identification of the noises and the study of their sources and the coupling mechanism between $h(t)$ and the wit-
The time series data corresponding to each segment is projected onto the 3-dimensional parameter space tiles in a finite region of parameter space, \([t^\text{min}_c, t^\text{max}_c] \times [f^\text{min}_c, f^\text{max}_c] \times [Q^\text{min}, Q^\text{max}]\) with a constant quality factor \(Q\). The density of the tiles should be maximized to obtain the fastest analysis speed. However, the number of tiles must be determined with a minimum density to ensure the highest detection efficiency. Since the trade-off between these two conflicting concepts is required, the parameter space tiles are determined so that the fractional energy loss due to mismatch among tiles can be smaller than the threshold, \(\mu^\text{max}\). The mismatch metric of the tiles used in Omicron is given by

\[
\delta s^2 = \frac{4\pi^2 f_c^2}{Q^2} \delta t_c^2 + \frac{2 + Q^2}{4 f_c^2} \delta f_c^2 + \frac{1}{2Q^2} \delta Q^2. \tag{30}
\]

Note that the non-diagonal \(\delta \delta Q\) term in the metric has been neglected in here.

The minimum number of tiles, \(N_{t_c} \times N_{f_c} \times N_Q\), which satisfies the threshold, \(\mu^\text{max}\) is obtained from the integration of the mismatch metric, equation (30), over the three dimensions as follows

\[
\begin{align*}
N_{t_c} & \geq \frac{s_{t_c}}{2\sqrt{\mu^\text{max}/3}}, & s_{t_c} & = \frac{2\pi f_c}{Q} (\mu^\text{max} - \mu^\text{min}), \\
N_{f_c} & \geq \frac{s_{f_c}}{2\sqrt{\mu^\text{max}/3}}, & s_{f_c} & = \frac{\sqrt{2 + Q^2}}{2} \ln \left(\frac{f^\text{max}_{c}}{f^\text{min}_{c}}\right), \\
N_Q & \geq \frac{s_Q}{2\sqrt{\mu^\text{max}/3}}, & s_Q & = \frac{1}{\sqrt{2}} \ln \left(\frac{Q^\text{max}}{Q^\text{min}}\right),
\end{align*}
\]

where \(N_Q, N_{f_c}(Q^p),\) and \(N_{t_c}(Q^p, f^q_c)\) are the numbers of logarithmically-spaced \(Q\) planes, logarithmically-spaced frequency rows in each \(Q\) plane, and linearly-spaced time bins, respectively. Using the above relations, the resolution of the optimized tile can be determined as follows

\[
Q^g = Q^\text{min} \left[ \frac{Q^\text{min}}{Q^\text{max}} \right]^{(0.5+q)/N_q} \quad (0 \leq g < N_Q),
\]

\[
f^q_c = f_{c \text{ min}} \left[ \frac{f_{c \text{ max}}}{f^q_{c \text{ min}}} \right]^{(0.5+l)/N_{f_c}(Q^p)} \quad (0 \leq l < N_{f_c}(Q^p)),
\]

\[
t^{q \text{ min}}_c = t^\text{ min}_c + \frac{(m + 0.5)(t^\text{ max}_c - t^\text{ min}_c)}{N_{t_c}(Q^q, f^q_c)} \quad (0 \leq m < N_{t_c}(Q^q, f^q_c)).
\]

Q-transform is a modified short-time Fourier transform re-defined on the parameter space tiles of a constant quality factor \(Q\) with optimized resolutions [80, 92]. According to the definition of Q-transform [80], the transform coefficient \(X\) for a time series \(h(t)\) can be obtained by

\[
X(t_c, f_c, Q) = \int_{-\infty}^{+\infty} dt h(t) e^{-2i\pi f_c t} e^{-2i\pi f_c t} = \int_{-\infty}^{+\infty} df \hat{h}(f + f_c) \hat{\omega}^*(f + f_c, Q) e^{2i\pi f t}. \tag{33}
\]
The window function, $\tilde{\omega}(f, f_c, Q)$ in frequency domain is Gaussian and real, then

$$\tilde{\omega}(f, f_c, Q) = \tilde{\omega}^*(f, f_c, Q) = W_g \exp \left( -\frac{f^2}{2 f_c^2} \right). \quad (34)$$

By using normalization condition such as

$$\int_{-\infty}^{+\infty} |\tilde{\omega}(f, f_c, Q)|^2 df = 2, \quad (35)$$

then, the normalization factor $W_g$ is given by

$$W_g = \sqrt{\frac{2 Q}{\pi f_c}}. \quad (36)$$

The list of tiles generated by the Omicron is a set of $(q, l, m)$ tiles with signal-to-noise ratio (SNR), $\rho_{qlm}$ which is defined by

$$\rho_{qlm}^2 = \frac{|X_n(t_{qlm}, f_{ql}, Q)|^2}{\langle |X_n(t_{qlm}, f_{ql}, Q)|^2 \rangle / 2}, \quad (37)$$

where $X_n$ is the $Q$-transform coefficient of $h(t)$ which is a waveform we want to detect and $X_n$ is the coefficient of $n(t)$ which is noise of a detector. In general, the time series data $x(t)$ is described as $x(t) = h(t) + n(t)$. $\langle \cdot \rangle$ in the denominator of Eq.(37) means the expectation value of $Q$ transform energy for noise obtained from multiple measurement. For a stationary stochastic noise, the expectation value can be regarded as the noise power spectral density integrated over the frequency window of tile $(q, l, m)$. When the SNR of a tile is higher than a given threshold, $\rho_{\text{min}}$, which means the tile’s energy is higher than the background noise spectrum on given localized parameter sets, we call it a trigger (See Fig. 5). The SNR is the standard of the trigger selection in gravitational wave data analysis, and the standard varies with specific data analysis pipelines.

The Omicron triggers produce an effect similar to signals which get matched filtering with sine-Gaussian bank waveforms for each event that have a specific shape in a time-frequency plane, in a short period.

2. Vetoing: Transient Characterization

In general, if the origin of the many noises acquired at the beginning of the observation is recognized or entirely understood, these noises can be precisely excluded from the analysis. However, it is difficult to comprehend the specific origin even if the triggers are recognized through the sensing process. There are currently two main types of methods utilized to satisfy the requirement, hierarchical veto method (h-veto) [94] and used percentage veto (UPV) method [81]. These methods are effective for the study of the background noise reduction in gravitational-wave signals and helps improve detector performance and data quality. This part will review these two methods.

A. Hierarchical-veto method

The h-veto method has one of the most characteristic features that potential correlations or mechanisms which are revealed by the hierarchical process applying the statistical interpretation between two channels. It is easy to recognize what the characteristics are by following each algorithm consists of three main steps. pre-process, process and post-process. (Fig. 6)

The pre-process is the process of confirming basic condition and necessary information for analysis such as the time interval, frequency range, SNR threshold of triggers, time window, and significance threshold. It is possible to prevent the gravitational-wave signal from being mistaken for noise by additionally setting the unsafe channel list. The safe channel is an auxiliary channel which is basically independent of the main channel. If an auxiliary channel is highly correlated, the channel is classified as unsafety channel and excluded from the actual analysis. While the unsafe channels are excluded from the analysis, h-veto enter the process stage with the conditions given at the initialization.

The process step is the central process of h-veto. This process is performed step by step over a round, as its name suggests. First, it creates a possible veto condition for all auxiliary channels according to the given time windows and SNR threshold. Based on the generated conditions, the significances of the channels are calculated.

The significance is defined by a statistical indicator that represents the probability of observing as many or more coincident triggers between the auxiliary channels and the main channel with the Poisson distribution. (Fig. 5)

$$S = -\log_{10} \left[ \sum_{k=n}^{\infty} P(\mu, k) \right], \quad (38)$$

where $n$ represents the number of matches in the trigger on the main channel and triggers in the auxiliary channel for a given time $T_{\text{tot}}$. $P(\mu, k)$ is the Poisson probability
Fig. 6. Flowchart of the h-veto algorithm [94].

\[
P(\mu, k) = \frac{\mu^k e^{-\mu}}{k!},
\]

(39)

where \(\mu\) represents the expectation value that any trigger of both channels coincide with each other, and it is defined as follows,

\[
\mu = \frac{N_h N_{aux} T_{win}}{T_{tot}},
\]

(40)

where \(N_h\) and \(N_{aux}\) are the number of triggers for the main channel and auxiliary channel, respectively.

Next, compare the values of all channels and declare the channel with the highest significance as round winner in the given window and SNR range. If the significance value of this round winner is higher than the significance threshold, it proceeds to the next round.

In the second round, it calculates again the significance from the analysis time except the time segments corresponding to the coincident triggers of the first round winner channel. This is the core of the h-veto algorithm which analyzes the change of significance and the change of characteristics of noise mechanism by excluding first round winner. If this significance value is lower than the significance threshold, h-veto is interrupted, otherwise, progress to the third round. As the result, the channel with the highest significance value declares the second round winner. After several rounds, if the significance is lower than the criterion, the Process step ends and record the statistical information and veto segments.

The final output of the statistical information by h-veto is divided into three types. One is the significance drop plot which is the most specific information of this method, the other is the SNR plot of the vetoed triggers through each round, and the last one is the Deadtime-Efficiency plot to examine the validity of the h-veto results.

A significance drop plot provided at each round shows how the significances of the remaining channels change since the triggers in \(h(t)\) corresponding to the coincident triggers of the round winner channel are reject. If some channels exit that changes with the significance of the vetoed channel, these channels are called families. If these families channels founded, it implies that the signals in the acquired data at the analysis time are influencing each other on these channels or are highly correlated with each other (Fig. 7). A time-trigger SNR plot can be used to see how much of the triggers are correlated with each other and vetoed in each round.

The Deadtime-Efficiency plot is important information to determine the validity of the veto results delivered by h-veto. Deadtime is the percentage of vetoed time for the whole time, and it is calculated by \(\text{DeadTime} = \frac{(100 \times T_{vetoed})}{T_{tot}}\). Efficiency is the percentage of the vetoed trigger for the full trigger in the main channel, and \(\text{Efficiency} = \frac{(100 \times N_{GWvetoed})}{N_{GWtot}}\). If the ratio of two values is greater than 1, then this veto is useful, and if it is close to 1, it no different from vetoing the trigger arbitrarily as follows,

![Fig. 7. Significance drop plots of the h-veto algorithm result [94].](image-url)
if \( \frac{\text{Efficiency}}{\text{DeadTime}} \gg 1 \), veto is useful,

if \( \frac{\text{Efficiency}}{\text{DeadTime}} \sim 1 \), same time removed at random.

### B. Used Percentage Veto method

The UPV is a method of presenting and analyzing how closely the triggers coincide between the main channel and the auxiliary channels. This determines the time-coincidence trigger that satisfies the ±1 coincidence window that increases the trigger SNR threshold from 50 to 5000 sequentially. The final outputs of the results are Used Percentage, Efficiency-Deadtime ratio and Random Used Percentage indices.

Used Percentage is an indicator of the rate at which triggers match between the main channel and the auxiliary channels defined as follows.

\[
\text{Used Percentage}(\rho) \equiv 100 \times \frac{N_{\text{aux}}^{\text{coin}}(\rho)}{N_{\text{tot}}^{\text{aux}}(\rho)}, \quad (41)
\]

where \( N_{\text{aux}}^{\text{coin}}(\rho) \) is the number of triggers in the auxiliary channel and main channel at the trigger SNR threshold \( \rho \), and \( N_{\text{tot}}^{\text{aux}}(\rho) \) is the total number of triggers in the auxiliary channel. This value reveals how the two channels are correlated.

Deadtime-Efficiency ratio is the value used to determine the effectiveness of the veto with the threshold as already noticed in the previous subsection for h-veto process. UPV also uses this indicator. Random Used Percentage is a value related to determining how adequately the Used Percentage calculated above is manifesting the correlation between the two channels. This describes the Used Percentage value when the triggers of the auxiliary channel randomly distributed.

\[
\text{Random Used Percentage}(\rho) \equiv \text{Deadtime}(\rho) \times \frac{N_{\text{GW}}^{\text{aux}}}{N_{\text{tot}}^{\text{aux}}(\rho)}, \quad (42)
\]

Once these three indicators are calculated for each threshold, the UPV creates a veto segment for each channel based on the criterion. This describes the time window around the trigger peak time using a trigger SNR threshold with Used Percentage greater than 50% for each the auxiliary channel and is rounded to the integer time according to the convention.

#### 3. Channel Safety Study

Unsafe Channels are auxiliary channels that are strongly correlated with the main channel. If the gravitational-wave passes through the arms of the interferometer, the photon detector of the Michelson interferometer observes the variation of the position of the mirror at the end of the arm directly. At this time, if the auxiliary channel that detects the location of the test mass is classified as a safe channel for the veto process, the gravitational-wave signal acquired from the main channel is considered to be noise and is likely to be vetoed. Therefore, it is important to evaluate the safety of channels to prevent this mischance.

A hardware injection technique is used to analyze the correlation between channels by injecting an artificial signal with high SNR directly into the mirrors to achieve this demand, and it is used to check whether a device is operating normally or to calibrate it by inputting a specific frequency signal. In the channel safety study, signals such as Sine-Gaussian signal or CBC are injected for confirmation of channel safety and commissioning of the equipment [67], and then the vetoing analysis is conducted on the hardware injected time segments.

In h-veto method cases, if the significance is greater than 3, it is considered to have a statistically meaningful high correlation which increases the possibility to be an unsafe channel. The coherence analysis is used to determine the unsafety channel with the statistics presented by the significance drop plot, the Deadtime-Efficiency plot, and the time-triggered SNR plot. The estimated channel is finalized through the data quality evaluation process.

In UPV method cases, it is performed through Safety Probability that is the veto probability of the same auxiliary channel during N hardware injections investigated by examining the safety using the Poisson cumulative density function.

\[
\text{Safety Probability} \equiv 1 - F\left( N_{\text{vetoed}}^{\text{inj}} - 1 \Big| N_{\text{exp}}^{\text{inj}} \right), \quad (43)
\]

where \( F(x|y) \) is the Poisson cumulative density function and, \( N_{\text{vetoed}}^{\text{inj}} \) and \( N_{\text{exp}}^{\text{inj}} \) are numbers of vetoed injections and the expected number of injections vetoed from the deadtime when the triggers are randomly distributed respectively.

The unsafe channels presented mainly through these two methods are finally determined in the detector characterization group and the glitch group.

### VI. SUMMARY

So far we have dealt with the technical procedures based on interferometer detector that will enable this. The transient signals recorded from photon detectors reproduce the waveforms through a maximum likelihood method in multiple detectors, or identify the gravitational-waves through a matched filter analysis, for burst and CBC signals, respectively. And we review the detector characterization process needed to ensure
high reliability and accuracy of the signal analysis that are noise characteristics of interferometric gravitational-waves detectors and channel safety diagnosis. It is expected to continue to develop new analytical techniques and more efficient data analysis using machine learning and useful systems. Now the dawn of gravitational-wave astronomy is coming in the near future.

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**REFERENCES**

[1] B.P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. 116, 061102 (2016).
[2] B.P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. 119, 161101 (2017).
[3] B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations], Astrophys. J. 850, no. 2, L39 (2017) doi:10.3847/2041-8213/aa9478 [arXiv:1710.05836 [astro-ph.HE]].
[4] B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration, Fermi Gamma-ray Burst Monitor, and INTEGRAL), Astrophys. J. Lett. 848, L12 (2017).
[5] B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration, Fermi Gamma-ray Burst Monitor, and INTEGRAL), Astrophys. J. Lett. 848, L13 (2017).
[6] J. Aasi et al. (LIGO Scientific Collaboration and Virgo Collaboration), Class. Quantum Grav. 32, 074001 (2015).
[7] F. Acernese et al. (Virgo Collaboration), Class. Quantum Grav. 32, 024001 (2015).
[8] H Grote (for the LIGO Scientific Collaboration), Class. Quantum Grav. 27, 084003, (2010).
[9] K. Kuroda, Class. Quantum Grav. 27, 084004 (2010).
[10] A. Einstein, The foundation of the General Relativity, Annalen der Physik, 1916.
[11] C. W. Misner and K. S. Thorne, Gravitation, Princeton University Press (October 24, 2017).
[12] S. Carroll, Spacetime And Geometry: An Introduction To General Relativity, Pearson India; 1st edition (2003).
[13] J. D. E. Freighton and W. G. Anderson, Gravitational-Wave Physics and Astronomy: An Introduction to Thory, Experiment and Data Analysis, Weinheim, Germany: Willey-VCH (2011).
[14] K. Riles, Prog. Part. Nucl. Phys. 68, 1 (2013).
[15] M. Maggiore, Gravitational Waves: Volume 1: Theory and Experiments, Oxford University Press; 1 edition (2007).
[16] A. Einstein, On gravitational waves, Preussische Akademie der Wissenschaften (1918).
[17] I. Chakrabarty, Gravitational Waves: an introduction arxiv:physics/9908041 (1999).
[18] K. A. Postnov and L. R. Yungelson, Living Rev. Rel. 9, 6 (2006).
[19] J. A. Faber and F. A. Rasio, Living Rev. Rel. 15, 8 (2012).
[20] J. Aasi et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. D 89, 102006 (2014).
[21] B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations], Astrophys. J. 833, no. 1, L1 (2016) [arXiv:1602.03842 [astro-ph.HE]].
[22] T. W. Baumgarte and S. L. Shapiro. Numerical Relativity: Solving Einsteins Equations on the Computer, Cambridge University Press, (2010).
[23] A.C. Phillips. The Physics of Stars, chapter 6.2 Collapse of a stellar core, John Wiley and Sons Ltd (1999).
[24] B. Sathyaparakash and B. F. Schutz. Living Rev. Rel. 12.2 (2009).
[25] E. Thrane et al., Phys. Rev. D 83, 083004 (2011).
[26] K. Riles, Prog. Part. Nucl. Phys. 68, 1 (2013).
[27] B. Abbott et al., Astrophys. J. Lett. 683(1), L45 (2008).
[28] P. Goldreich and W. H. Julian. Pulsar Electrodynamics, The Astrophysical Journal, 157 (1969).
[29] P. A. R. Ade et al., Phys. Rev. Lett. 112, 241101 (2014).
[30] K.A. Olive et al. (Particle Data Group), Chin. Phys. C 38 090001 (2014).
[31] P. A. R. Ade et al. (Planck Collaboration), Astron. Astrophys. 571, A16 (2014).
[32] L. P. Grishchuk, Class. Quantum Grav. 10, 2449 (1993).
[33] X. Siemens, V. Mandic, and J. D. Creighton, Phys. Rev. Lett. 98, 111101 (2007).
[34] R. A. Hulse and J. H. Taylor, Astrophys. J. 195, L51 (1975).
[35] J. M. Weisberg, D. J. Nice, and J. H. Taylor, Astrophys. J. 722, 1030 (2010).
[36] A. Abramovici et al., Science 256 325 (1992).
[37] R. Vogt, F. Raab, R. Drever, K. Thorne, R. Weiss, LIGO-M930006-00-M Proposal to the NSF for the initial LIGO (Includes Technical Supplement dated May 1993)
[38] F. J. Raab, Proceedings of the SPIE, "Overview of LIGO instrumentation", Vol. 5500, pp. 11-24 (2004).
[39] R. Adhikari. Gravitational radiation detection with laser interferometry, Technical Report LIGO-P1200121-v1 (2012).
[40] J. Mizuno, PhD thesis, Comparison of optical configurations for laser-interferometric gravitational-wave detectors, Hannover University (1995).
[41] J. Aasi et al. (The LIGO Scientific Collaboration), Class. Quantum Grav. 32, 074001 (2015).
[42] K. Kuroda, Class. Quantum Grav. 27, 084004 (2010).
[43] C. M. Caves, Phys. Rev. D 23 1693 (1981).
[44] P. R. Saulson, Fundamentals of interferometric gravitational wave detectors, World Scientific (1994).
[45] B. J. Meers, Phys. Rev. D 38, 2317 (1988).
[46] B. P. Abbott et al. (LIGO Scientific Collaboration), Nature Phys. 7, 962 (2011).
[47] M. A. Barton and K. Kuroda, Review of Scientific Instruments 65, 3775 (1994).
[48] M. A. Barton, N. Kanda, and K. Kuroda, Rev. Scientific Inst. 67, 3994 (1996).
[49] D. Shoemaker et al., Phys. Rev. D 38, 423 (1988).
[50] P. R. Saulson, Phys. Rev. D 42, 2437 (1990).
[51] B. P. Abbott et al. (LIGO Scientific Collaboration), Rep. Prog. Phys. 72, 076901 (2009).
[52] G. Gonzalez., Class. Quantum Grav. 17, 4409 (2000).
[53] A. Gillespie, and F. Raab, Phys. Rev. A 178, 213 (1994).
[54] G. M. Harry et al., Class. Quantum Grav. 19, 897 (2002).
[55] B. P. Abbott et al. (LIGO Scientific and Virgo Collaborations), Class. Quant. Grav. 33, 134001 (2016).
[56] J. Abadie et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. D 85, 082002 (2012).
[57] B. P. Abbott et al. (LIGO Scientific Collaboration), Phys. Rev. D 80, 102001 (2009).
[58] B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. D 94, 069903 (2016).
[59] R. Lynch, S. Vitale, R. Essick, E. Katsavounidis, and F. Robinet, Phys. Rev. D 95, 104046.
[60] T. Dal Canton et al., Phys. Rev. D 90, no. 8, 082004 (2014) doi:10.1103/PhysRevD.90.082004 [arXiv:1405.6731 [gr-qc]].
[61] S. A. Usman et al., Class. Quant. Grav. 33, no. 21, 215004 (2016) doi:10.1088/0264-9381/33/21/215004 [arXiv:1508.02357 [gr-qc]].
[62] A. H. Nitz, T. Dal Canton, D. Davis and S. Reyes, arXiv:1805.11174 [gr-qc].
[63] K. Cannon et al., Astrophys. J. 748, 136 (2012) doi:10.1088/0004-637X/748/2/136 [arXiv:1107.2665 [astro-ph.IM]].
[64] S. Privitera et al., Phys. Rev. D 89, no. 2, 024003 (2014) doi:10.1103/PhysRevD.89.024003 [arXiv:1310.5633 [gr-qc]].
[65] C. Messick et al., Phys. Rev. D 95, no. 4, 042001 (2017) doi:10.1103/PhysRevD.95.042001 [arXiv:1604.04324 [astro-ph.IM]].
[66] J. Aasi et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. D 88, 062001 (2013).
[67] S. Mohapatra et al., Phys. Rev. D 90, 022001 (2014).
[68] M. van der Sluys, V. Raymond, I. Mandel, N. Christensen, V. Kalogera, R. Meyer, and A. Vecchio, Classical Quantum Gravity 25, 184011 (2008).
[69] M. V. vanv, C. Rover, A. Stroeer, V. Raymond, I. Mandel, N. Christensen, V. Kalogera, R. Meyer, and A. Vecchio, Astrophys. J. 688, L61 (2008).
[70] J. Veitch and A. Vecchio, Phys. Rev. D 81, 062003 (2010).
[71] S. Klimenko et al., Class. Quantum Grav. 25, 114029 (2008).
[72] J. Cornish and B. Littenberg, Class. Quantum Grav. 32, 135012 (2015).
[73] B. Littenberg and J. N. Cornish., Phys. Rev. D 91, 084034 (2015).
[74] S. Klimenko, S. Mohanty, M. Rakhmanov, and G. Mitselmakher, Phys. Rev. D 72, 122002 (2005).
[75] B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. D 93, 122004 (2016).
[76] V. Necula, S. Klimenko and G. Mitselmakher, J. Phys. Conf. Ser. 363, 012032 (2012). doi:10.1088/1742-6596/363/1/012032.
[77] S. Klimenko et al., Phys. Rev. D 93, 042004 (2016).
[78] B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Class. Quantum Grav. 35, 065010 (2018).
[79] F. Robinet, Omicron: An Algorithm to Detect and Characterize Transient Noise in Gravitational-Wave Detectors, https://tds.ego-gw.it/ql/?c=10651.
[80] S. Chatterji et al., Class. Quantum Grav. 21, S1809 (2004).
[81] A. Ajith, M. Hewitson, J. R. Smith, H. Grote, S. Hild, and K. A. Strain, Phys. Rev. D 76, 042004 (2007).
[82] J. Aasi et al. (LIGO Scientific Collaboration and VIRGO Collaboration), Class. Quantum Grav. 29, 155002 (2012).
[83] N. Christensen for the LIGO Scientific Collaboration and the Virgo Collaboration, Class. Quantum Grav. 27, 194010 (2010).
[84] T. Accadia et al., Class. Quantum Grav. 27, 194011 (2010).
[85] A. Di Credico for the LIGO Scientific Collaboration, Class. Quantum Grav. 22, S1051 (2005).
[86] R. Essick et al., Class. Quantum Grav. 30, 155010 (2013).
[87] H. A. G. Gabbard, F. Robinet, Characterization of the Omicron Trigger Generator and Transient Analysis of aLIGO Data, IREU Final Report.
[88] L. Blackburn et al., LIGO-G100158-00-Z (2005).
[89] J. Slutsky et al., Class. Quantum Grav. 27, 165023 (2010).
[90] L. Blackburn et al., Class. Quantum Grav. 25, 184004 (2008).
[91] J. C. Brown, J. Acoust. Soc. Am. 89, 425 (1991).
[92] T. Isogai (for the LIGO Scientific Collaboration and the Virgo Collaboration), Conf. Ser. 243 012005 (2010).
[93] J. R. Smith et al., Class. Quantum Grav. 28, 235005 (2011).