Systematic survey for monitor signals to reduce fake burst events in a gravitational-wave detector

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Abstract. We present methods and results to reduce fake burst events induced by nonstationary noises. To reduce these events, we systematically surveyed monitor signals recorded with a main (or gravitational-wave) signal of a gravitational-wave detector so as to watch the detector. Our survey was to check whether or not there was a coincidence between the main and monitor signals when we found a burst event from the main signal. If there was a coincidence, we rejected this event as a fake event induced by nonstationary noises, regarding the main signal as being dominated by nonstationary noises. As a result, we succeeded to reject about 90% of the burst events of which the SNR values were larger than 10 as fake events, with an accidental probability of about 5% to reject burst-gravitational-wave candidates.

1. Introduction
Recently, several interferometric gravitational-wave detectors started observation runs [1, 2, 3, 4]. The data collected from these observation runs were analyzed to look for gravitational wave signals. As a result of the data analysis, upper limits on the event rate of Burst-Gravitational-Waves (BGWs) were set [5, 6, 7]. However, they were too large to have astronomical significance. For example, the upper limit on the event rate of supernova explosions, which emit BGWs, was about 2000 1/s in the Milky Way in the latest data analysis of TAMA300 [6]. On the other hand, it was typically 0.03/yr based on astronomical observation. It is natural to think that the large upper limit is caused by fake events induced by nonstationary noises. Thus, it is important and necessary to reduce these fake events. In order to do this, we systematically survey monitor signals that are recorded with a main (or gravitational-wave) signal so as to watch the detector, since we expect a high reduction efficiency by using multiple monitor signals.

In our previous study [8], we investigated only one monitor signal, which was a laser intensity signal in a power-recycling cavity of the interferometer, to reduce fake events. This was because the strongest correlation existed in between the main signal and the intensity signal. However, the reduction efficiency of the previous study was not enough. We needed to study other monitor signals, since they might have a strong correlation. In this article, we present a systematic survey method for multiple monitor signals to reduce fake events, and a result obtained by applying it to TAMA300 data. We aimed so that we could apply our systematic method to new monitor signals without studying noise sources and properties.
2. Data from TAMA300
We used about 200 hours of observation data collected by TAMA300 in the ninth data-taking run (DT9), which spanned 6 weeks from November 2003 to January 2004 [2]. TAMA300 is an interferometric gravitational-wave detector located at the Mitaka campus of the National Astronomical Observatory of Japan in Tokyo. The data used in this study included the main signal and 4 monitor signals: a common motion signal in the arm cavity, the laser intensity signal in a power-recycling cavity, a differential motion signal from the beam splitter to the front mirrors\(^1\), and a dark-port power signal. These signals were recorded with a 20kHz, 16bit data-acquisition system [9].

3. Method of data analysis
3.1. Overview of our method
In this section, we present an overview of our method to reduce fake events by a systematic survey of the monitor signals.
At first, we whiten the main and monitor signals by the average power spectrum, estimated from 10 minutes of data before them, since the noise levels of these signals usually change over time. At the same time, we remove line peaks in the Fourier domain. Next, we extract burst events from the main signal by using a burst event trigger described in Section 3.2. We then survey monitor signals to check whether or not there is a coincidence between the main and monitor signals when we find a burst event. We show a method of the survey in Section 3.3. If there is a coincidence, we reject this burst event as a fake event induced by nonstationary noises, since the monitor signals as well as the main signal include nonstationary noises that induce fake events. If this is not the case, we record this burst event as a BGW event candidate. Before these processings, we optimize our analysis parameters: time windows, frequency windows, and thresholds for the monitor signals. We describe a method to optimize the analysis parameters in Section 3.4.

3.2. Burst event trigger
We extract nonstationary components from the main signal as burst events, since we only know that BGWs appear as nonstationary components in the main signal. In this work, we apply a power filter as the burst event trigger to the main signal, since a power filter has high sensitivity to nonstationary components. A power filter calculates the square of the averaged signal power in a given time-frequency-window of the time-frequency space by using the Fast Fourier Transform (FFT), which is repeated with half of the time-window-shift. Power filter outputs mean the signal-to-noise-ratio (SNR) when signals are whitened properly. In the present work, we used 12.8 ms and 801-2000Hz as time-frequency-windows. This time window corresponds a typical duration time of BGWs from supernova explosions [10]. This frequency window corresponds around the floor level in TAMA300 DT9 [2]. If the SNR is larger than 3, which is the priori given threshold, we record the output as a burst event. When burst events are overlapped or continued, we treat these events as one burst event. This trigger is basically same one in the previous work [6].

3.3. Survey for the monitor signals
We survey monitor signals to reduce fake events according to the following steps. We apply a power filter to the main and monitor signals around the data stream at which we find a burst

\(^1\) This signal can be interpreted as a main (or gravitational-wave) signal of a small detector with a single-bounce Michelson interferometer of which base lines are about 5m. On the other hand, base lines and finesse of the arm cavity are 300m and 520, respectively. Then, a sensitivity of this detector is 4 order worse than that of the arm cavity. Realistically, we can neglect the influence of the gravitational wave of this signal,
event. If the SNR of the main signal is larger than 3, and at least a SNR of the monitor signals is simultaneously larger than the threshold, we recognize there is a coincidence. Then we reject this burst event as a fake event induced by nonstationary noises, regarding the main signal (and the monitor signals) as being dominated by nonstationary noises. If we do not recognize a coincidence, we record this burst event as a BGW event candidate. In this situation, we use 801-2000Hz as the frequency window of the main signal. The time windows for the main and monitor signals, the frequency windows and the thresholds for the monitor signals are our analysis parameters, optimized in Section 3.4.

3.4. Optimization of analysis parameters
We optimize our analysis parameters by analyzing of a subset of data called playground data so that the rate of coincidences becomes high and the rate of accidental coincidences becomes low. The length of playground data is about 3% of all data. The rate of the coincidences is the probability that there is a coincidence when there is a burst event. For the time windows and the frequency windows which are used to apply power filter, we select optimal value(s) from multiple candidates. On the other hand, the thresholds is set based on the rate of accidental coincidences.

Here, we present details of the optimization of our analysis parameters for one monitor signal. We prepare 12 frequency-window-candidates and 6 time-window-candidates: 12.8 ms, 25.6 ms, 51.2 ms, 102.4 ms, 204.8 ms, and 409.6 ms. At first, we apply a power filter to the main and the monitor signals by each time-frequency-window. If the SNR of the main signal is larger than 3, and at least a SNR of the monitor signals is simultaneously larger than the threshold, we recognize there is a coincidence. Then we reject this burst event as a fake event induced by nonstationary noises, regarding the main signal (and the monitor signals) as being dominated by nonstationary noises. If we do not recognize a coincidence, we record this burst event as a BGW event candidate. In this situation, we use 801-2000Hz as the frequency window of the main signal. The time windows for the main and monitor signals, the frequency windows and the thresholds for the monitor signals are our analysis parameters, optimized in Section 3.4.

Figure 1. Flow chart of our reduction analysis of fake events.
Table 1. Results of the optimization for analysis parameters.

| signal name          | frequency window       | time window                |
|----------------------|------------------------|----------------------------|
| intensity signal     | 101-600Hz              | 102.4 ms, 204.8 ms, 409.6 ms |
| common motion signal | 101-600Hz              | 51.2 ms, 204.8 ms, 409.6 ms |
| differential motion  | 501-1100Hz             | 51.2 ms, 102.4 ms, 409.6 ms |
| dark-port power signal | 101-800Hz            | 102.4 ms, 204.8 ms, 409.6 ms |

than 3 and the SNR of the monitor signal is simultaneously larger than a given threshold in the following steps, we recognize there is a coincidence between the main and monitor signals. For each time-frequency-window, we set the threshold so that the rate of accidental coincidences, which is calculated by using the time-shifted monitor signal, is 0.5%. By using the obtained thresholds, we estimate the rate of the coincidences for each time-frequency-window. After that, we select the frequency window which have the highest rate of the coincidences as optimal vale. Finally, we select 3 time windows so that the overlapped rate of the coincidences is largest as optimal vales. The overlapped rate of the coincidences is the probability that there is at least one coincidence by using multiple time-window-candidates when there is a burst event.

In addition to our optimization, we select the monitor signals, since it is inefficient for our survey to use a monitor signal that has a low rate of coincidences. Thus, we set the rule that the rate of the coincidences should be larger than 1%. If a monitor signal dose not fulfill this rule, we do not use this signal for the analysis of all data.

4. Analysis result

We show our results in Figs 2 and 3. Figure 2 shows the event rates of BGW candidates and burst events. Figure 3 shows the survival rate of burst events based on our analysis. It is clear from Figs 2 and 3 that we have succeeded to reduce many burst events as fake events. For example, we rejected about 90% of burst events of which the SNR values were larger than 10 as fake events. We obtain a reduction rate of burst events with subtracting the survival rate from unity. The reduction rate calculated form the time shifted monitor signals is an accidental probability to reject burst events. Here, this probability is basically the same as the probability to accidentally reject BGW candidates. We show the reduction rate and the accidental probability at some SNR vales in Table 2. From Table 2 the accidental probability is about 2-5%. On the other hand, the probability is about 1-1.5% from an analysis of the playground data. This difference of the probability is made by a difference in the data quality of the playground data from that of all data. In addition, we found a trend of increasing the accidental probability with increasing the SNR threshold from table 2. I am investigating a cause of the trend now. Here, I show one possibility for the trend to be made. The trend might be made by insufficiency of time-shift to calculate the accidental probability.

In addition to these results, we obtained some knowledge from analyzing the playground data. The first one is that the typical duration time of nonstationary noises is larger than 50 ms. We used time windows of 51.2 ms, 102.4 ms, 204.8 ms and 409.6 ms (Table 1). They correspond the duration time of nonstationary noises. The second one is that the rate of coincidences between the main and the dark-port power signals is smaller than 1%, which is described in Section 3.4. Thus, we did not use this signal for the analysis of all data.

We should note another point. We tried a correlation analysis, such that when at least one coefficients of correlation between the main signal and the monitor signals was larger than a
Table 2. Reduction rate for burst events and accidental probability for BGW candidates (or burst events) of which the SNR threshold are larger than 3, 5, 10 and 15.

| SNR threshold | Reduction rate | Accidental probability |
|---------------|----------------|------------------------|
| 3             | 48%            | 1.9%                   |
| 5             | 68%            | 2.9%                   |
| 10            | 90%            | 4.8%                   |
| 15            | 97%            | 4.6%                   |

Figure 2. Event rates as a function of the SNR threshold. The solid line shows BGW candidates and the dash line shows burst events. The vertical axis is the event rate and the horizontal axis is the SNR threshold.

threshold, which was optimized from analysis of playground data, we regarded these signals as being dominated by nonstationary noises. We rejected burst events induced in the main signal of this time. As a result, this analysis did not increase reduction efficiency with increasing calculation time. However, we found that there was a high correlation between the monitor signals, such as between the dark-port power signal and the differential motion signal from the beam splitter to the front mirrors. We have a new possibility to diagnose the detector by a combination analysis of these signals.

5. Conclusion
We systematically analysed about 200 hours of data collected in TAMA300 DT9. As a result, we succeeded to reject about 90% of the burst events, of which the SNR values were larger than 10 as fake events, with an accidental probability of about 5% to reject BGW candidates, without studying noise sources and properties. The larger accidental probability will be decreased by
Figure 3. Survival rate of burst events as a function of the SNR threshold. The solid line is our results. The dash line is our results in the case of using the time shifted monitor signals. The vertical axis is the survival rate and the horizontal axis is the SNR threshold. The survival rate becomes lower for higher SNR bursts.

using a more careful choice of the playground data than in this study.

Finally, we describe challenges in the future. First, we must experiment on hardware injection test to confirm that the nonstationary noises are not caused by huge gravitational-waves. The hardware injection test is to move the mirrors in a way that affects the interferometer as huge gravitational-waves. Second, we will improve our method to optimize the analysis parameters so that the method will become simple and easy. Third, we will increase the reduction efficiency of fake events by applying our method to other monitor signals recorded at different sampling rates from the main signal.

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