Coincident event search using TAMA300 and LISM data

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Abstract

We discuss a method of coincidence analysis to search for gravitational waves from inspiraling compact binaries using the data of two laser interferometer gravitational wave detectors. For the purpose to test above methods, we performed a coincidence analysis by applying these methods to the real data of TAMA300 and LISM detectors taken during 2001.

1. Introduction

Several laser interferometric gravitational wave detectors, such like TAMA300, LIGO, GEO600, and VIRGO, have already been constructed or expected to be finished its construction soon.

TAMA300 is an interferometric gravitational wave detector with 300m baseline length located at Mitaka campus of the National Astronomical Observatory of Japan in Tokyo ($35.68°N, 139.54°E$). LISM is an interferometric gravitational wave detector with 20m baseline length located at Kamioka mine, Gifu ($36.25°N, 137.18°E$). The TAMA300 and LISM observed during August 1st and September 20th,2001(JST). This observation is called Data Taking 6 (DT6) among the TAMA collaboration and the LISM collaboration. The best sensitivity of the TAMA300 was about $5 \times 10^{-21}/\sqrt{\mathrm{Hz}}$ around 800Hz. The best sensitivity of the LISM was about $6.5 \times 10^{-20}/\sqrt{\mathrm{Hz}}$ around 800Hz.

Although, the sensitivities of TAMA300 and LISM are different for one order of magnitude, it is a very good opportunity to perform coincidence analysis since long data are available, and both detector have shown good stability which allow us to perform such analysis.

2. Matched filtering

We assume that the time sequential data of the detector output $s(t)$ consists of a signal plus noise $n(t)$. To characterize the detector's noise, we denote the one-sided power spectrum density of noise by $S_n(f)$. We also assume that the

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wave forms of the signals are predicted theoretically with sufficiently good accuracy. We call these waveforms as *templates*. We adopt templates calculated by using the post-Newtonian approximation of general relativity [3]. We denote the parameters distinguishing different templates by θ^μ. They consist of the coalescence time t_c, the chirp mass $\mathcal{M}(\equiv M\eta^{3/5})$ $(M = m_1 + m_2)$, and non-dimensional reduced mass $\eta(\equiv m_1 m_2/M^2)$. In this analysis, we did not take into account of the effects of spin angular momentum. The templates corresponding to a given set of θ^μ are represented in Fourier space by two independent templates $\tilde{h}_c$ and $\tilde{h}_s$ as $\tilde{h}(f) = \tilde{h}_c(f)\cos\phi_c + \tilde{h}_s(f)\sin\phi_c$, where ϕ_c is the phase of wave [7].

We define a filtered output by $\rho(t_c, m_1, m_2, \phi_c) \equiv 2\int_{-\infty}^{\infty} \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_h(f)} df = (s|h)$. We can analytically take the maximization over ϕ_c which gives $\rho(t_c, m_1, m_2) = \sqrt{(s|h_c)^2 + (s|h_s)^2}$. We can see that ρ has an expectation value $\sqrt{2}$ in the presence of only Gaussian noise. Thus, the signal-to-noise ratio is given by $SNR = \rho/\sqrt{2}$

Analyzing the real data, we have found that the noise contained a large amount of non-stationary and non-Gaussian noise [5]. In order to remove the influence of such noise, we introduce a χ^2 test [2]. In this paper, we do not explain a χ^2 test in detail which was explained by the Tanaka and Tagoshi [7].

We searched for the mass parameters, $1.0M_\odot \le m_1, m_2 \le 2.0M_\odot$, which is a typical mass region of neutron stars. In the mass parameter space, we prepared a mesh. The mesh points define templates used for search. The mesh separation is determined so that the maximum loss of SNR becomes less than 3%. The typical value of the number of template is about 700 for TAMA300, and 400 for LISM.

We perform matched filtering search using TAMA300 and LISM data independently. We obtain ρ and χ^2 as functions of masses and the coalescing time t_c. In each small interval of coalescing time Δt_c, we looked for an event which had the maximum ρ. In the search we report in the following sections, we choose $\Delta t_c = 25$msec.

3. A coincidence analysis

Each event in the event list, obtained by the matched filtering search independently performed for two detectors, depends on t_c, M, and η. If they are real events, they should have the same parameters in both event lists. However, we may observe real events with different parameters by the effects of detectors' noise and other effects. Therefore we have to determine the allowed difference of parameters by taking into account of these effects, in order not to lose real events by coincidence analysis.

Time selection: First we discuss the coalescence time t_c. The distance between TAMA300 and LISM is 219.92km. Therefore, the maximum delay of the signal arrival time is $\Delta t_{\rm dis} = 0.73$msec. The effect of detectors' noise to the estimated value of t_c can be evaluated by the Fisher information matrix [4]. We denote the 1σ value of error for each detector as $\Delta t_{c\mathrm{TAMA,LISM}}$. We can determine allowed error of t_c due to noise by $\Delta t_{\mathrm{noise}} = \sigma \times \Delta t_c$ where $\Delta t_c \equiv \sqrt{\Delta t_{c\mathrm{TAMA}}^2 + \Delta t_{c\mathrm{LISM}}^2}$. Finally, we define the allowed difference of t_c as follows. If the parameters t_c^{TAMA}, t_c^{LISM} of the each pair of events satisfy $|t_c^{\mathrm{TAMA}} - t_c^{\mathrm{LISM}}| < \Delta t_{\mathrm{dis}} + \Delta t_{\mathrm{noise}}$, the event is recorded as a candidate event. Note that ,we do not explain in detail here, we find that if we adopt $\sigma > 3$, we will be able to obtain very high detection probability even in the case of real data. Thus, in the analysis discussed in the next section, we adopt $\sigma = 3.29$ which precise value is adopted because it corresponds to 0.1% probability to lose real events in Gaussian noise case.

Mass selection: Next we discuss the mass parameters. The error of estimated parameter of the chirp mass and reduced mass due to noise can also be evaluated by the Fisher matrix. We denote it by $\Delta\mathcal{M}_{\mathrm{noise}}$ and $\Delta\eta_{\mathrm{noise}}$, which are evaluated from each detector as $\Delta\mathcal{M}_{\mathrm{noise}} = \sigma\sqrt{\Delta\mathcal{M}_{\mathrm{TAMA}}^2 + \Delta\mathcal{M}_{\mathrm{LISM}}^2}$, $\Delta\eta_{\mathrm{noise}} = \sigma\sqrt{\Delta\eta_{\mathrm{TAMA}}^2 + \Delta\eta_{\mathrm{LISM}}^2}$, where $\Delta\mathcal{M}_i$ and $\Delta\eta_i$ are 1σ value of error induced by each detector's noise. Along with the error due to noise, we also have to take into account of the effect of the finite mesh size. When the amplitude of the signal is very large, the errors evaluated by the Fisher matrix becomes smaller than the value of finite mesh size, since the error of the parameter due to noise is inversely proportional to the value of ρ. We denote the error due to the finite mesh size as $\Delta\mathcal{M}_{mesh}$, $\Delta\eta_{mesh}$. We determine the allowed difference of the chirp mass and the reduced mass so that if the parameters $\mathcal{M}^{\mathrm{TAMA}}$, $\mathcal{M}^{\mathrm{LISM}}$, η^{TAMA} and η^{LISM} of each pair of events satisfy $|\mathcal{M}^{\mathrm{TAMA}} - \mathcal{M}^{\mathrm{LISM}}| < \max(\Delta\mathcal{M}_{\mathrm{noise}}, \Delta\mathcal{M}_{\mathrm{mesh}})$, $|\eta^{\mathrm{TAMA}} - \eta^{\mathrm{LISM}}| < \max(\Delta\eta_{\mathrm{noise}}, \Delta\eta_{\mathrm{mesh}})$, the pair of event is adopted as a candidate event.

Amplitude selection: Next we discuss the amplitude. When the sensitivity of the detectors is different, the signal-to-noise ratio observed by each detector will be different. Further, since the direction of the arm of each interferometer will be different in general, the signal-to-noise ratio will be different in each detector even if the sensitivity is the same. Even in such cases, we can still require consistency condition to the events and reduce the number of fake events. In our case, the sensitivity of TAMA300 is typically 15 times better than that of LISM. We can simply express this effect by δ_{sens}. The arm direction of LISM is rotated from that of TAMA300 for 60 degrees. Real events will be detected with different SNR by each detector depending on its incident direction and polarization. A simple and straightforward way to evaluate the allowed difference of amplitude is to perform simulations. To evaluate only the effect of different arm direction, we assume two detectors have identical noise power spectrum. We them perform simulations by generating the Galactic events and by evaluating the difference of ρ which are detected by each detector. We them determine the value of δ_{simu} such that for more than 99.9 % of events, we have $-\delta_{\mathrm{simu}} \le \log\left(\frac{\rho_{\mathrm{TAMA}}}{\rho_{\mathrm{LISM}}}\right) \le \delta_{\mathrm{simu}}$. There is also an error due to noise in the estimated value of ρ which can also be estimated by the Fisher matrix in the same way as t_c, $\mathcal{M}$ and η. We denote it as $\delta_{\rm noise}$. By combining the above two effects, we determine the allowed difference of ρ_{TAMA} and ρ_{LISM} by $\delta_{\rm sens} - \delta_{\rm simu} - \delta_{\rm noise} \le \log\left(\frac{\rho_{\rm TAMA}}{\rho_{\rm LISM}}\right) \le \delta_{\rm sens} + \delta_{\rm simu} + \delta_{\rm noise}$.

4. Application to TAMA300 and LISM data

We performed a matched filtering search using TAMA300 and LISM data respectively. For the purpose of test analysis, we analysed 26.0 hours of data for which both detector were locked. As results of matched filtering search, there were 159,935 events for TAMA300 and 109,609 events for LISM. For these candidate events, we performed a coincidence analysis by requiring consistency among the parameters. The consistency conditions are imposed in the order of the coalescence time selection, the mass selection and the amplitude selection. In Table 1., we show the results of the coincident event search. Significant number of fake events are removed by taking coincidence.

Table 1. Results of the coincidence analysis. $n_{\rm obs}$ is the number of coincident events. $\bar{n}_{acc}$, $\bar{\sigma}_{acc}$ are the estimated number of accidental coincidence and its standard deviation.

	n_{obs}	$\bar{n}_{acc} \pm \bar{\sigma}_{acc}$
after time selection	486	581.06 ± 228.15
after time and mass selection	74	86.73 ± 34.25
after time, mass and amplitude selection	63	68.35 ± 33.14

Next, we estimate the number of accidental coincident events by a usual procedure of shifting one of two sets of data by a time [1]. The number of accidental coincidence and its standard deviation is shown in Table.1. We can see that the number of coincident events obtained after each selection is completely agree with the number of accidental coincidence. Thus, we conclude that we find no signature of gravitational wave events in the data used here.

Complete results of the analysis, including an upper limit to the event rate using TAMA300 and LISM data will be reported elsewhere [6].

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