Search for gravitational waves on short duration in TAMA300 data: stellar core collapse and black hole

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Abstract. We present the results of TAMA300 data analysis for short duration gravitational waves. The excess power filter, alternative linear filter (ALF) and TF(time-frequency) clustering methods have been employed for burst gravitational waves from stellar-core collapse, and matched filtering method used for the ringdown gravitational waves from black hole quasi-normal oscillations. The observational range of TAMA for the burst gravitational waves is roughly \(\sim 1\) kpc, and the range for black hole ringdown covers most of our galaxy. We have developed a new method ‘time-frequency (TF) clustering’ to find the burst waves. This is a TF clustering method on spectrogram (sonogram). Using this method, we can efficiently identify some predicted gravitational wave forms[2] and can exclude typical unstable spike-like noises.

1. Introduction
TAMA300 is a 300 m baseline laser interferometric gravitational wave detector in Mitaka, Tokyo, Japan[1]. The interferometer is of Fabry-Perot-Michelson type with a power recycling technique. The sensitivity of the detector is \(3 \times 10^{-21} [/\sqrt{Hz}] \) around 1kHz, and the integral observation time is more than 3000 hours. These observation data of TAMA300 detector is served to search for gravitational waves which has a short time duration. Time duration as Possible sources of such gravitational waves are stellar-core collapse of supernovae, and quasi-normal mode oscillation of black holes, since the typical time scale 10\(\sim\)100 msec which corresponds to the good sensitive observation band 100Hz\(\sim\)1kHz of ground-based gravitational wave detectors as TAMA300.

2. Searches for short gravitational waves in TAMA300
In TAMA data analysis, the excess power filter, alternative linear filter (ALF) and TF(time-frequency) clustering method are employed for burst gravitational waves from stellar-core collapses, and matched filtering method is employed for the ringdown gravitational waves from back hole quasi-normal mode oscillations. TAMA’s search threshold amplitude for the burst gravitational waves is \(h_{rss} \sim 10^{-17} \sim 10^{-18}\), which is of the order of magnitude in the case of a

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stellar core collapse at a distance of $\sim 1$ kpc. We obtain the upper limit the galactic event rate as $5 \times 10^3$ events/day using the excess power filter[3], and 0.55 events/day for $h_{rss} > 10^{-17}$ using the ALF trigger[4]. We also have also carried out data analysis to search for ringdown gravitational waves using efficient matched filter templates[5]. The trigger rate of black hole ringdown waves obtained $< 3.4 \times 10^{-2}$ events/hour for SNR $> 20$ [6].

3. A new approach : Time-frequency clustering method
We have developed a new method by examining 'clustering' of signal powers in time-frequency domain. Comparing with past TF-cluter studies[8] to find efficient power filter window, our study is in order to extract characteristics of gravitational wave signals with a multi-parameter representation[7]. We used predicted burst gravitational waves by Dimmelmeier et al.[2] (DFM waveforms). TAMA real data and DFM waveform software injected on TAMA data are used for following studies.

3.1. Spectrogram : Time-frequency domain representation of data
The sampling interval of TAMA’s is 50µsec (=20kHz sampling). We split time series data to 3.2 msec chunks. Time shift of next chunk is 0.8 msec, thus the neighbor chunks overlap 2.4 msec. For each of the chunks, signal powers are calculated by using FFT (short-time Fourier transform, STFT) with a Hanning window. The frequency resolution in the STFTs is 312.5Hz. From the signal powers of the chunks at given times, we can construct a ‘spectrogram’ in time-frequency domain. The figure 1 and 2 are examples of spectrogram of TAMA data around spike like noise, and typical DFM waveform embedded in the TAMA300 data. Each ‘pixel’ represents the signal power at a given time and a frequency. SFTP spectrum at each frequency band is normalized using average noise.

![Figure 1. TAMA spike like noise](image1.png)

![Figure 2. burst GW injected TAMA noise](image2.png)

Spectrogram example: The color illuminated pixels connect as ‘cluster’ of signal.

3.2. Cluster identification and parameters
To identify and define a cluster are as follows: 1) We find all pixel which magnitude exceed signal-to-noise ratio (SNR) = 3. 2) We assume that a local maximum pixel is a ‘peak’ of the cluster. The peak specified with its time $t_0$ and frequency $f_0$. 3) If one of a 8 pixels around the peak of the cluster exceed the cluster threshold, this pixel is ‘connected’ pixel. The cluster threshold is settled as square root of SNR of the peak pixel. 4) We check the neighbor of connected pixels, again. 5) If no more connected pixel cannot be found, we define the peak and these connected pixels as one ‘TF-cluster’ 6) We exclude pixels which belongs to previous cluster, and iterate 2)-5) for other local peak.

The identified TF-cluster can be characterized with these parameters; area $S$ : the number of pixels in the cluster, volume $V$ : the sum of a magnitude of pixels in the cluster, $tNs$ : a
N-th moment of distribution the numbers of pixels along the time axes, \( tNv \): a N-th moment of magnitude distribution along the time axes, \( fNs \): same as a \( tNs \) along the frequency axes, \( fNv \): same as a \( tNv \) along the frequency axes.

3.3. Selection criteria, efficiency and noise reduction

Some combinations of the parameters makes possible to separate GW signal from many noises. The figure 3 and 4 show the example of two combination which efficiently separate the gaussian noise from the DFM wave forms. The figure 3 and 4 show the separation using two combinations, \(-2.0 \leq f1s \leq 2.0 \) and \( f2s \leq 5.0 \) and \( \sqrt{t1s^2 + f1s^2/S} \leq 0.15 \). One can see that the DFM waveforms can be efficiently separated from spike noises in the figure 3, and from gaussian noises in the figure 4.

The parameters selection for clusters which peak SNR > 3 achieved 50% average efficiency for injected DFM waveforms at 350 pc (\( h_{rss} \sim 2 \times 10^{-19} \)) for type I burst[2], and at 170 pc for average. The reduction for noise event clusters by spike signals are more than one order improvement beyond the SNR > 100, and factor several for SNR < 80. It means that TF-cluster method is efficient for larger signal case.

4. Summary

TAMA have been developed searched for short duration gravitational waves, for physics target of stelar-core collapse and black hole oscillation. Also we recently practice the newer search algorithm as TF-cluster using many cluster shape parameters. The method is efficient to select gravitational event and reject noise fake as larger SNR case.

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