Monitoring Sco X-1 for the detection of gravitational waves with networks of gravitational wave detectors

Kazuhiro Hayama[1], Soumya Mohanty[1], Malik Rakhmanov[2], Shantanu Desai[3], Tiffany Summerscales[4]

[1]Center for Gravitational Wave Astronomy, University of Texas at Brownsville, 80 Fort Brown, Brownsville Texas 78520, US

[2]Southeastern Louisiana University, Hammond, LA 70402, US

[3]Center for Gravitational Wave Physics, Pennsylvania State University, University Park, PA 16802, US

[4]Department of Physics, Andrews University, Berrien Springs, MI 49104, US

E-mail: `kazuhiro.hayama@ligo.org`

Abstract. Searching for gravitational waves triggered by electromagnetic astronomical observations has several benefits: prior information about the source location enhances detection efficiency, and the use of time coincidence implies analysis of only a small stretch of data which allows sophisticated analysis with high computational costs. During postprocessing, knowledge about the source enables accurate reconstruction of the source parameters, leading to an astrophysical interpretation. In this paper, we present a triggered search pipeline called `RIDGE` and we demonstrate the search for gravitational waves from Sco X-1, in which X-ray bursts occur frequently, using simulated data. In the analysis, we consider the optimum network combination for Sco X-1.

1. Introduction

Currently, several interferometric gravitational wave (in short, GW) detectors around the world such as LIGO, VIRGO, GEO600, TAMA300 [1] have been taking data. Interferometric gravitational wave (GW) detectors are based on a Michelson interferometer. The quadrupole nature of a GW produces differential changes in the arm lengths of the detectors, being detected as changes in the interference fringe pattern. The data from GW detector preserve both amplitude and phase information. Therefore, it is possible to combine data streams from networks of detectors coherently. The coherent network approach enables us not only to enhance detection efficiency, but also to reconstruct parameters of a GW such as the waveform and the direction to the source [2]. Triggered searches involve looking for gravitational waves from sources such as gamma-ray bursts, magnetars, X-ray bursts, supernovae, blazars etc that also have an observable signature. Having an electromagnetic observation in coincidence with a potential GW signal allows for much higher confidence in the signal and has other important benefits as well: the time coincidence implies that only small data stretches need to be analyzed, which allows us to use algorithms with a high computational cost and to ignore long-term non-stationary behavior of detector noise. Knowing the source location enables accurate recovery of GW signal parameters, which are essential for astrophysical interpretation. Applying the triggered search, we consider the detection of GWs from Sco X-1 which is the low-mass X-ray binary with the
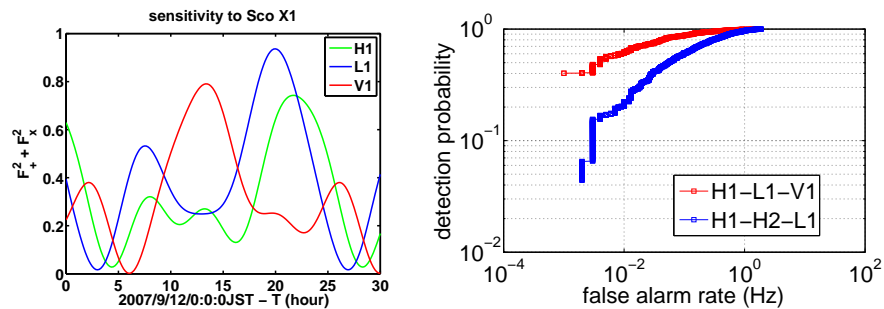
Figure 1. Left:The detector response as a function of time since September 12 (JST), 2007. H1 is the 4 km LIGO Hanford detector, L1 is the LIGO Livingston detector, and V1 is the VIRGO detector. Right: ROC curve at 13 hours. The blue line is for the LIGO only network and the red curve is for the LIGO-VIRGO network.

strongest X-ray emission [3]. In Sco X-1, strong X-ray bursts occur frequently [4], and GWs can be emitted along with the X-ray bursts. Besides searching for GWs associated with the X-ray bursts, we look for bursts even during the quiet phase of Sco X-1 by monitoring Sco X-1. When monitoring Sco X-1, the sensitivity of each GW detector to the direction of Sco X-1 varies in time because of the rotation of the earth. In this paper, we show results of Monte Carlo simulations with some networks of detectors for the detection of GWs from Sco X-1 using the coherent network analysis pipeline "RIDGE", which we have developed, and evaluate the effect of the network quantitatively. We also discuss which networks of detectors are effective for a long-term observation of Sco X-1 so as to provide maximum coverage with enhanced detection efficiency, by minimizing intervals where the network is"blind".

2. Overview of RIDGE pipeline

RIDGE is a fully coherent network analysis pipeline described in Ref. [5]. The pipeline consists of two main components, data conditioning, and generation of detection statistics. The aim of the data conditioning is to whiten the data, so as to remove frequency dependence and any instrumental artifacts in the data. In RIDGE, the data are whitened by estimating the noise floor using a running median [6], and narrow-band noise artifacts arising from sources such as power line interference, and mirror/suspension resonant modes are removed [7]. The resulting conditioned data is passed on to the next step consisting of the generation of a detection statistic. The generation of this statistic is based on maximum likelihood. The GW response of any one detector is a linear combination of the two unknown polarization waveforms $h_+(t)$ and $h_\times(t)$ arriving at the detector from a certain direction on the sky. It was shown that the problem of inverting a set of detector responses to obtain $h_+(t)$ and $h_\times(t)$ is an ill-posed one [8]. In RIDGE, the maximum likelihood is regularized by Tikhonov regularization to solve the problem [8]. The detection statistic is calculated using the regularized maximum likelihood at every sky location.

3. Monitoring Sco X-1

The detector response is a function of time and geographical location of the detector. Because of the rotation of the earth, the detector response is a periodic function with a 24 hour period.

The left plot in figure 1 shows the detector response of LIGO and VIRGO to the direction of Sco X-1 as a function of time since September 12 (JST), 2007. Here, the value of the detector response is defined by summing the squared antenna patterns for the two GW polarizations h_+, $h_\times$. From this figure, for the LIGO only network, the value of the squared antenna pattern exceeds 0.5 for about 33% of the time during a day. If VIRGO is added to this network, this

network coverage increases to 63% . To study the effect of the addition of VIRGO to the LIGO network quantitatively, we carried out Monte Carlo simulations. For the detector noise PSD, we used the design sensitivity curves for the LIGO and Virgo detectors as given in [1] and kept the locations and orientations the same as the real detectors. Gaussian, stationary noise was generated (2000 sec) at a sampling frequency of 16384 Hz. To simulate instrumental artifacts, we added sinusoids with large amplitudes at (54, 60, 120, 180, 344, 349, 407) Hz. The injected signals corresponded to a single source located at Sco X-1. We assumed that the $h_+(t)$ and $h_\times(t)$ waveforms were both sine-Gaussian signals defined by $A\sin(2\pi f_c t)\exp(-t^2/2\sigma^2)$ where the center frequency $f_c = 235$ Hz, $Q := 2\pi f_c \sigma = 9$ and A is a constant value. The $h_\times(t)$ waveform is a circularly polarized version of $h_+(t)$ which has been shifted in phase by $\pi/2$. The signal strength is specified in terms of the root-sum-square (hrss) value. We use hrss values of $7 \times 10^{-22} \mathrm{Hz}^{-1/2}$. The right plot in the Fig.1 is the Receiver Operating Characteristic (ROC) curve for the simulation at 13 hours after 2007/09/12 00:00 JST. It shows that the detection probability at the false alarm rate of 0.01 Hz is improved from 0.2 to 0.6 by adding VIRGO to the LIGO only network.

4. Discussion

We describe a coherent network analysis based approach to detect GWs associated with electromagnetic observations and study the sensitivity of current detector network of GWs from Sco X-1 with some network combinations. To monitor Sco X-1 with a sensitive detector response for a long period, it is essential to add VIRGO to the LIGO-only network. The LIGO–VIRGO network produces a detector response exceeding 0.5 for about 63% of a day. But even if the LIGO–VIRGO network is used, periods of "blindness" to Sco-X1 still exists. One approach to get rid of this blind periods is to add LCGT [9], which is a proposed cryogenic Japanese detector. We add LCGT-like detector whose sensitivity is 10 times worse than the design sensitivity (so that its sensitivity is similar to LIGO, VIRGO), and carried out Monte Carlo simulations. The simulation shows that the detector response of the LIGO–VIRGO–LCGT-like exceeds 0.5 for about 92% of the time. This shows that the current geographical location and orientation of LCGT is significantly benefitial to this search.

5. References

[1] Abbott, et al. 2004 *Nucl.Instrum.Meth.A* **517** 154, Acernese, et al. 2002 *Class. Quantum Grav.* **19** 1421, Willke, et al. *Class. Quantum Grav.* **21** S417, R. Takahashi, et al. *Class. Quantum Grav.* **S403**
[2] Y. Gürsel and M. Tinto 1989 *Phys. Rev.* **D 40** 3884
[3] Jeremy S. Heyl 2002 *Astrophysical Journal* **574** L74
[4] D. Psaltis et al. 1998 *Astrophysical Journal* **501** L95
[5] K. Hayama, S. Mohanty, M.Rakhmanov, S. Desai 2007 *Class. Quant. Grav.* **24** 681
[6] S. Mukherjee 2003 *Class. Quant. Grav.* **20** 925
[7] S. Mohanty 2002 *Class. Quant. Grav.* **19** 1513
[8] M. Rakhmanov 2006 *Class. Quant. Grav.* **23** S673
[9] K. Kuroda et al. 2006 *Progress of Theoretical Physics Supplement* **163** 54