Localization of gravitational wave sources with network of advanced GW detectors [1]

Abstract: The localization of gravitational wave (GW) sources is extremely valuable for the future GW astronomy. It will enable joint observations between the GW detectors and other astronomical instruments. We present studies on the source localization capabilities with the future network of advanced GW detectors and describe their fundamental properties. We estimate the accuracy of the source localization by injecting all two signals into simulated detector noise, and study its dependence on the strength and waveform morphology of the injected signals. We consider different network configurations including the advanced LIGO and Virgo detectors, the LCGT detector and a possible detector in Australia (LIGO-Australia).

Introduction and Motivations

The identification of GW source counterparts by joint observations with GW detectors, electromagnetic (EM) telescopes or neutrino detectors can allow a multi-messenger investigation of the astrophysical source and may improve the confidence of the GW discovery. In addition to detection of GWs, LSC and Virgo performed searches of GWs under EM triggers on a regular basis, and only last year jointly announcing capabilities of the GW network achieved the basic performances to perform an experiment search on wide field telescopes under GW candidate triggers. In this work we investigate the direction resolution of GW detectors networks, considering simulated data of 2nd generation interferometers, which should be online in the next years and could provide a robust detection of GWs, namely Advanced LIGO, Advanced Virgo, Large Cryogenic Gravitational Telescope and, possibly, LIGO-Australia.

The major challenges for this work are:
• point to the GW candidate source, with an uncertainty within the EM instrument field of view (typically < few square degrees)
• perform the sky localization in real time with low latency to allow the observations of EM transients

We apply the Coherent Waveburst algorithm (6):

- Time-frequency analysis
- Use of wavelet transform
- Coherent analysis
- Synthesis of detectors as single instrument
- Likelihood approach
- Maximum or likelihood of signal/noise ratio vs null hypothesis
- Estimate source direction
- Maximum of the Sky statistics
- Reconstruct waveform shape
- Applying inverse wavelet transform
- Choice of constraints on waveform polarization
- as-modelled (no-constraint), elliptical, circular, linear

We investigate the performances for source localization and reconstruction of GW using networks of advanced GW interferometers. The considered algorithm shows quite uniform performances over a wide range of ad hoc signal classes. We show quantitatively the improvements achievable by increasing the number of detector sites. In particular, additional detectors as LCGT and/or LIGO-Australia will significantly improve the accuracy for source localization and increase the fraction of the sky in which the network is capable to estimate both GW polarization components. E.g., the error function improves to less than one square degree for signals to noise ratio of 10 at the detectors, a figure which sufficiently matches the field of view of available EM telescopes. A robust detection of GWs is anticipated in the next five years as advanced detectors come online; the astrophysical detection potential of burst searches will directly depend on their source localization capabilities.

Test signals

- White-noise waveforms (WNB): Burst of white Gaussian noise in a frequency band [f1 - f2] with duration t. Random polarization

- Gaussian waveforms (GWB):

We define the Signal-to-Noise Ratio $SNR = \frac{\int S(t) \cdot h(t) \cdot dt}{\sqrt{\int S(t)^2 \cdot dt}}$ with $S(t)$ being the signal waveform and $h(t)$ being the detector response.

Signal waveform estimates can be reconstructed from the solution of the likelihood function $L(p|\mathbf{d})$.

We consider the following detectors:

- Advanced LIGO [2] – Livingston, LA, 4 km arms (L)
- Advanced Virgo [3] - Cascina, Italy, 3 km arms (V)
- Large LIGO, Advanced Virgo, Large Cryogenic Gravitational Telescope

Considered networks:

- LIGO-Australia (L-V-A) Australia
- Advanced LIGO [2] – Livingston, LA, 4 km arms (L)
- Advanced Virgo [3] – Cascina, Italy, 3 km arms (V)

We apply the WNB to the L-V-A network and 100 different realizations of the GW signal. Observations of all sky with the L-V-A network, the number of injections is approximately 3500 for each waveform.

Directional Resolution

The Direction Resolution $DR$ is defined as the area of $90\%$ confidence region for a single source injection.

Reconstruction Accuracy

The Reconstruction Accuracy $RA$ is defined as the area of correlated portion of the reconstructed signal and the true signal.

Conclusions

We investigated the performances for source localization and reconstruction of GW using networks of advanced GW interferometers. The considered algorithm shows quite uniform performances over a wide range of ad hoc signal classes. We show quantitatively the improvements achievable by increasing the number of detector sites. In particular, additional detectors as LCGT and/or LIGO-Australia will significantly improve the accuracy for source localization and increase the fraction of the sky in which the network is capable to estimate both GW polarization components. E.g., the error function improves to less than one square degree for signals to noise ratio of 10 at the detectors, a figure which sufficiently matches the field of view of available EM telescopes. A robust detection of GWs is anticipated in the next five years as advanced detectors come online; the astrophysical detection potential of burst searches will directly depend on their source localization capabilities.

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