Finding Electromagnetic Counterparts of Gravitational Wave Signals in the Transient Universe

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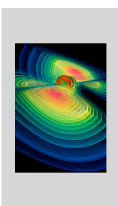
Introduction

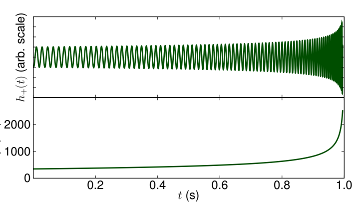
Gravitational waves have an important role to play in the era of multi-messenger astronomy. This role depends crucially on the ability of ground-based detectors to quickly and accurately identify the sky location that a gravitational wave signal originated from.

Inspiral Sources

The focus of the current study is inspiral sources. In particular, the results are based on a set of 1657 signals injected into stationary Gaussian noise colored with the initial LIGO and Virgo design power spectral densities. We only consider injections recovered simultaneously in both 4km LIGO detctors and Virgo. The injections were made randomly from a family of 2PN waveforms with the following properties:

- Uniformly distributed from 1-15 solar masses
- Maximum total mass of 20 solar masses
- Logarithmically distributed in distance





Sky Localization

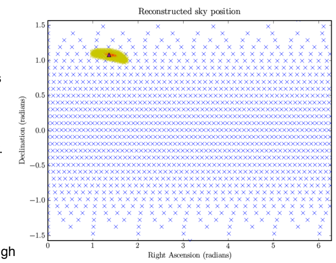
Triangulation

The most basic method of sky localization is triangulation based on timing information obtained in the measurement process.

Time of arrival

The most readily available timing information is the arrival time of the signal in the detector, which is measured in the matched filtering process. Errors arise from the the fact that discrete template banks are used and the 'best' template is chosen by maximizing the the signal-to-noise-ratio (SNR). The essential problem is that

- SNR does not accumulate uniformly across the frequency band of the detector.
- Phase difference does accumulate uniformly across the frequency band.

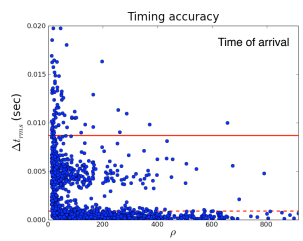


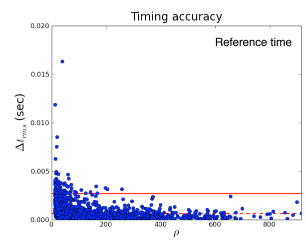
Reference time

A simple solution to the problems inherent in using the arrival time is to instead measure the time the gravitational wave signal crosses some frequency in the high SNR region of the frequency band [1]. This frequency must be the chosen to be the same in each detector. For the intitial LIGO and Virgo detectors the optimal reference frequency is near 150Hz.

Comparison

The following are plots of the rms timing error for the injection set as computed with using the time of arrival and the time the signal crosses a reference frequency of 140Hz. In each plot, 90% of the signals fall below the solid red line and 60% fall below the dashed red line.





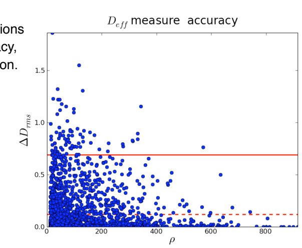
Further enhancement

Sky localization from timing information alone can at best identify two possible locations in the sky (symmetric about the plane the detectors lie in). To help lift this degeneracy, we use the effective distance measured at each detector along with timing information. More specifically, for detectors A and B, we compute:

$$\Delta(D^2_{\rm eff}) = \frac{D^2_{\rm A} - D^2_{\rm B}}{D^2_{\rm A} + D^2_{\rm B}} - \frac{\tilde{D}^2_{\rm A}(\theta,\phi) - \tilde{D}^2_{\rm B}(\theta,\phi)}{\tilde{D}^2_{\rm A}(\theta,\phi) + \tilde{D}^2_{\rm B}(\theta,\phi)}$$

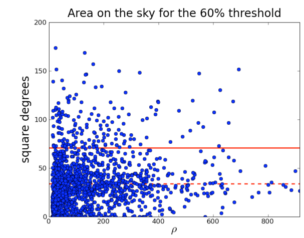
where

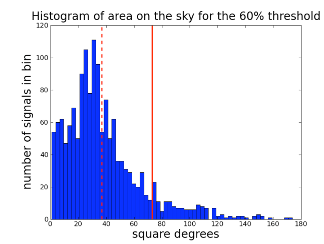
$$\tilde{D}^2(\theta,\phi) \propto \frac{1}{F^2_+(\theta,\phi,\psi=0) + F^2_\times(\theta,\phi,\psi=0)}$$



Results

Using the combined (reference) timing information and effective distance measure, with a threshold set to guarantee that 60% of the time the injections are located within the region identified, we find that typical sources can be localized to within tens of square degrees.





Astrophysical Priors

Accuracy in sky location can be improved by using a galaxy catalog [2] to identify plausible host galaxies. Additionally, rapid identification with triggers from other ongoing transient searches (neutrino, cosmic ray, etc.) can further narrow the region of interest.

References

[1] Acernese et al 2007 Class. Quantum Grav. 24 S617

[2] Kopparapu, Hanna, Kalogera, O'Shaughnessy, González, Brady Fairhurst 2008 ApJ 675 1459

LIGO-G0900571-v2