Enhanced efficiency in detection of GW signals from supernovae

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Abstract

A new method has been developed to enhance the detection efficiency of gravitational waves (GW) signals from supernovae. Sixteen supernova waveforms from the Murphy et al. 2009 catalog have been used in presence of LIGO and Virgo science data. We have developed a new method of noise reduction based on Harmonic Regeneration Noise Reduction (HRNR) algorithm. A comparative analysis is presented to show detection statistics for a standard network analysis as commonly used in GW pipelines and the same by implementing the new method in conjunction with the network. The result shows improvement in detection statistics by at least 30% even for very weak signal to noise ratios (SNR). The improvement in the detection statistics grows steadily with increasing SNR.

Introduction

Supernovae in our universe are potential sources of GW [1-4] that could be detected in a network of GW detectors like LIGO, VIRGO, and GEO600. Core-collapse supernovae are very rare, but the associated gravitational radiation is likely to carry profuse information about the underlying process driving the supernovae. Calculations based on analytic models predict GW energies within the detection range of the Advanced LIGO detectors. The signals from these sources are weak and rare. Several methods have been proposed based on various likelihood-based regulators that work on data from a network of detectors to detect burst-like signals (as is the case for signals from supernovae) from potential GW sources. Thus, methods that can improve sensitivity of searches for GW signals from supernovae are desirable, especially in the advanced detector era. We have developed a new denoising method that works in conjunction with the standard network.

Analysis

Detection Statistic of the Network

The GW response of any one detector is a linear combination of the two unknown polarization waveforms $h_+(t)$ and $h_x(t)$ arriving at the detector from a certain direction θ_0, φ_0 on the sky. We assume the earth-centered, ecliptic reference frame here for defining the polar angle, θ, and azimuthal angle, φ. Maximum likelihood values are obtained as a function of θ and φ--this two-dimensional output, $S(\theta,\varphi)$, is called a *sky map*.

We can construct a detection statistic using the entire sky map. Two choices are presented in [6].

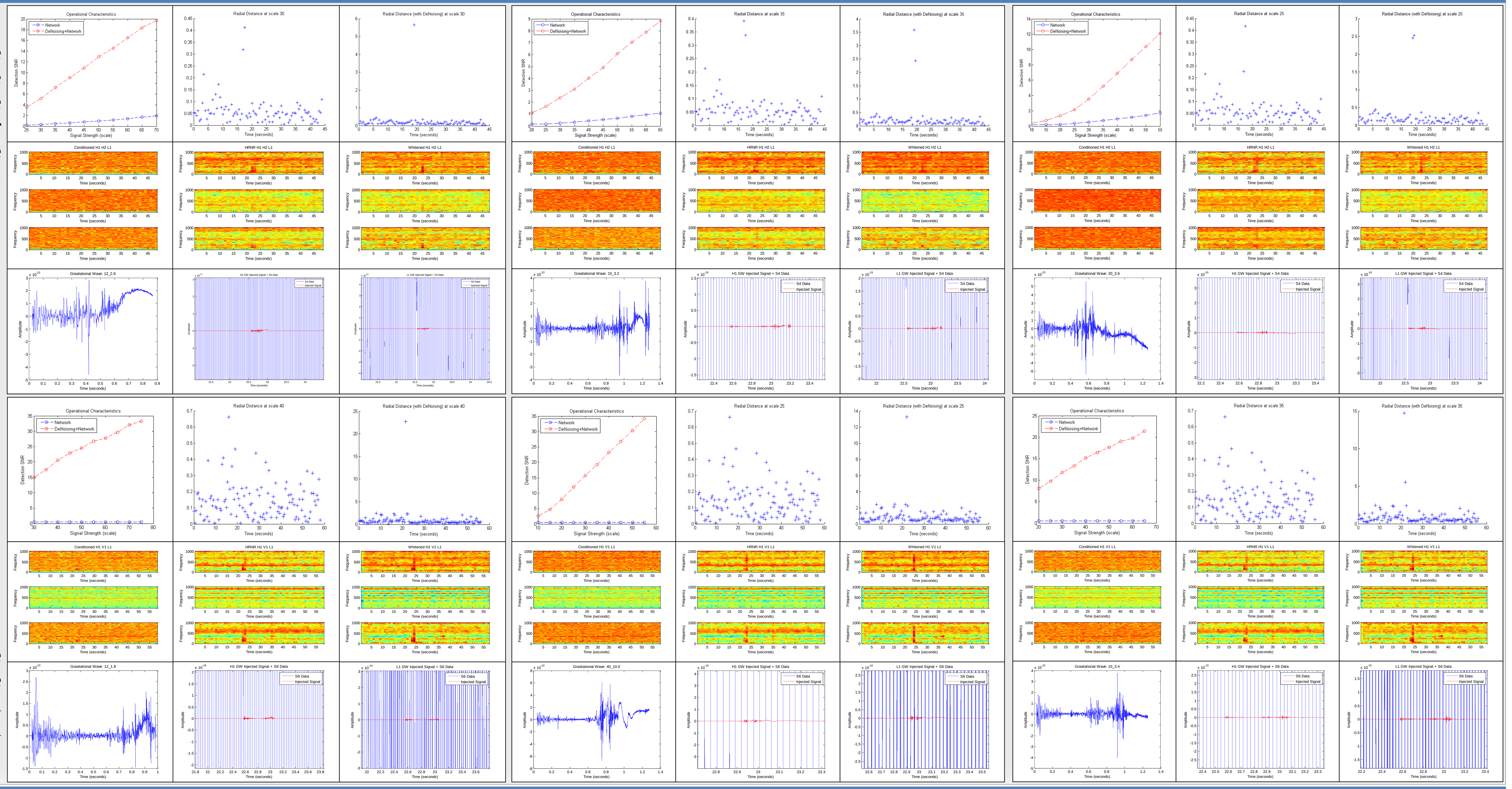
$$R_{mm} = \frac{max_{\theta,\varphi}\, S(\theta,\varphi)}{min_{\theta,\varphi}\, S(\theta,\varphi)}$$

where $(\max/\min)_{\theta\varphi} S(\theta,\varphi)$ represents a (maximum/minimum) value of $S(\theta,\varphi)$ on the $\theta - \varphi$ plane.

$$R_{rad} = \left[\left(\frac{max_{\theta,\varphi}\, S(\theta,\varphi)}{max_{\theta,\varphi}\, \overline{S}_0(\theta,\varphi)} - 1\right)^2 + \left(R_{mm}\, \frac{min_{\theta,\varphi}\, \overline{S}_0(\theta,\varphi)}{max_{\theta,\varphi}\, \overline{S}_0(\theta,\varphi)} - 1\right)^2 \right]^{1/2}$$

$$\overline{S}_0(\theta,\varphi) = E[S(\theta,\varphi)|\text{no signal in data}],$$

where $E[S(\theta,\varphi)|\text{no signal in data}]$ denotes an ensemble average over realizations of sky maps that do not have any GW signals. The second statistic, R_{rad}, is the radial distance of the observed values, in an appropriately scaled $(R_{mm}, max_{\theta,\varphi} S(\theta,\varphi))$ plane, from the mean location of the same quantities in the absence of a signal.



Method

How do we enhance the effective SNR?

Data is represented as $x(t) = s(t) + n(t)$ where $s(t)$ is the signal, $n(t)$ noise, and $x(t)$ noisy data. $S(p,k)$, $N(p,k)$ and $X(p,k)$ denote the k^{th} spectral component of a short time frame p of the signal $s(t)$, $n(t)$, $x(t)$. Our objective is to find an estimator $S(p, k)$ which minimizes the expected value of a given distortion measure conditionally to a set of spectral noisy features. $S(p, k)$ is obtained by applying a spectral gain $G(p,k)$ to $X(p,k)$ [5].

Decision Directed Approach

We compute a *posteriori* SNR

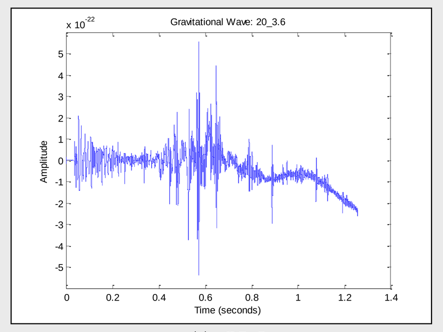
$$SNR_{post}(p,k) = |X(p,k)|^2 / \gamma_n(p,k)$$

Estimate the a *priori* SNR as

$$SNR_{prio}(p,k) = \beta\, |S(p-1,k)|^2/\gamma_n(p,k) + (1-\beta)P[SNR_{post}(p,k) - 1]$$

The chosen spectral gain is the Wiener filter.

$$G_{DD}(p,k) = SNR_{prio}(p,k)/[1 + SNR_{prio}(p,k)]$$



s(t) GW

Two-Step Noise Reduction (TSNR) Technique

As a second step, the gain is used to estimate the a *priori* SNR at frame (p+1)

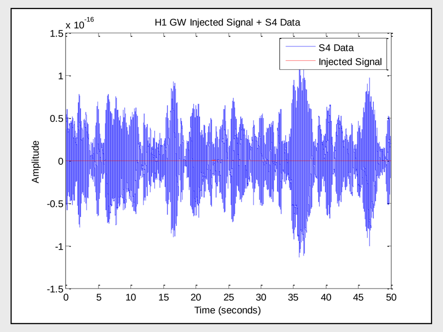
$$_{TSNR}SNR_{prio}(p,k) = |G_{DD}(p,k)X(p,k)|^2 / \gamma_n(p,k)$$

Spectral gain is computed as

$$G_{TSNR}(p,k) = {}_{TSNR}SNR_{prio}(p,k) / 1 + {}_{TSNR}SNR_{prio}(p,k)$$

Enhanced signal estimate is given by

$$S(p,k) = G_{TSNR}(p,k)X(p,k)$$



x(t) = Detector Data n(t) + Signal s(t)

Harmonic Regeneration Noise Reduction (HRNR) Technique

$S(p,k)$ obtained in the time domain may still suffer from distortion due to estimation errors introduced in the noise spectrum estimation. A correction needs to be applied to offset the errors. A non-linear function, NL, is first applied to

$$S(p,k) = S_{Har}(t) = NL\ S(p,k)$$

The a *priori* SNR is estimated as

$$_{HRNR}SNR_{prio}(p,k) = [\rho\, |S(p,k)|^2 + (1-\rho)|S_{Har}(p,k)|^2]/\gamma_n(p,k)$$

ρ is a parameter that controls the mixing of $S(p,k)$ and $S_{Har}(p,k)$

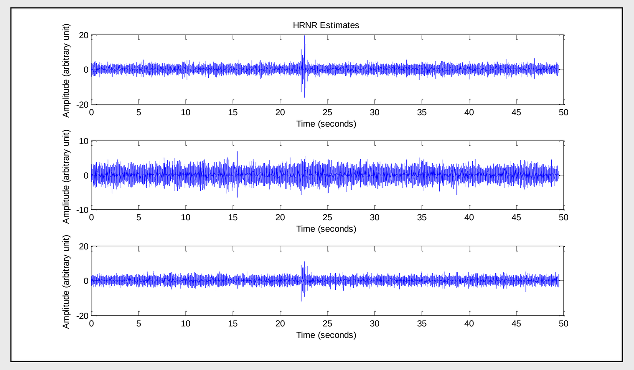
Input to the Network

The final spectral gain is computed as

$$G_{HRNR}(p,k) = {}_{HRNR}SNR_{prio}(p,k)/1 + {}_{HRNR}SNR_{prio}(p,k)$$

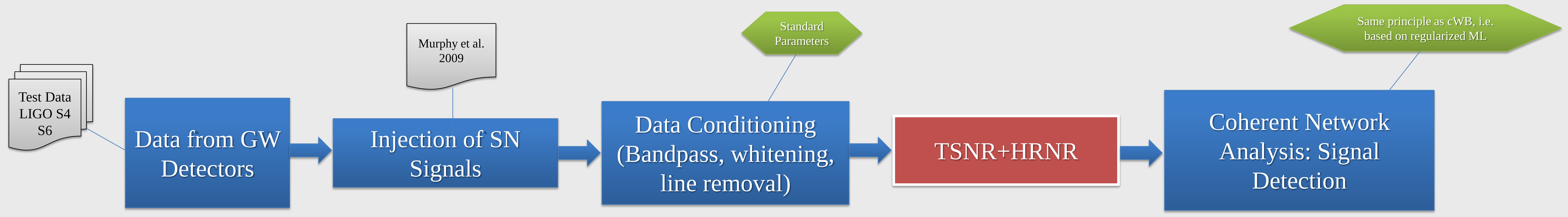
The final enhanced signal estimate is given by

$$S(p,k) = G_{HRNR}(p,k)X(p,k)$$



H1, H2, L1 Conditioned data after HRNR application

Pipeline



Conclusion & Future Work

- HRNR significantly improves the detection statistics of GW signals from supernovae even for very weak signals.
- HRNR works efficiently even with non-stationary, non-gaussian noise.
- HRNR is a stand-alone MATLAB code module that can be easily plugged in to existing search pipelines without having to make alterations.
- HRNR contains adjustable parameters that can in principle improve the results even more.
- More extensive testing with S6 data is underway.
- Will be applied to existing cWB-based supernova search pipeline.
- More supernova signals will be incorporated in the study.

References

[1] G. Pagliaroli, F. Vissani, E. Coccia, W. Fulgione, *Phys. Rev. Lett.* **103**, 031102 (2009).
[2] S. Scheidegger, S.C. Whitehouse, R. Kaeppeli, M. Liebendoerfer, *Class. Quantum Grav.* **27**, 114101 (2010).
[3] K. N. Yakunin, P. Marronetti, A. Mezzacappa, S. W. Bruenn, C. Lee, M. A. Chertkow, W. R. Hix, J. M. Blondin, E. J. Lentz, O. E. Bronson Messer, S. Yoshida, *Class. Quantum Grav.* **27**, 194005 (2010).
[4] astro1.phys.uniroma1.it/ericeschool/lectures/mueller1.pdf
[5] C. Plapous, C. Marro, P. Scalart, "Improved Signal-to-Noise Ratio Estimation for Speech Enhancement," *Audio, Speech, and Language Processing, IEEE Transactions on*, vol.14, no.6, pp.2098,2108, Nov. 2006 doi: 10.1109/TASL.2006.872621.
[6] K. Hayama, S.D. Mohanty, M. Rakhmanov, S. Desai, *Class. Quantum Grav.* **24**, S681 (2007).

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