# Implementation of de-noising methods in the cWB pipeline for the analysis of LIGO/Virgo gravitational data

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A total variation method is proposed to de-noise the gravitational wave data taken by the International Gravitational Wave Network. We use a regularized version of the Rudin-Osher-Fatemi method to de-noise and extract gravitational wave signals from the data. This method has previously proven to deliver satisfatory results when de-noising numerically generated gravitational waves injected in simulated noise. The method needs a parametrization which will determine the efficiency of the de-noising, ranging from a small reduction of the noise present in the data to the removal of a huge portion of the data, including the detected signal. Currently, its implementation in the cWB data analysis pipeline is under developement. We will shortly provide results of its effectiveness with real data taken by the LIGO/Virgo interferomenters during O3.

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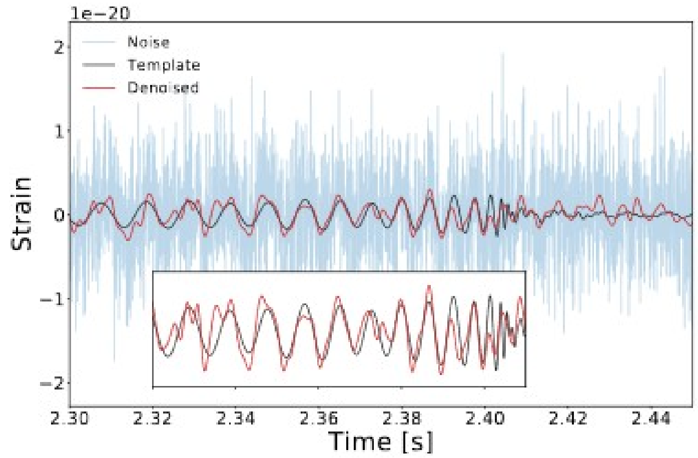
# Introduction and proposal

Interferometric detectors are collecting an important amount of gravitational wave (GW) signals. Gravitational interferometer's data is dominated by noise, mainly composed of non-stationary residuals and spurious transitory structures knows as glitches

Great effort is spent on the data analysis of these signals to eliminate or reduce sources of noise. In addition, the search of GW signals depends of the use of pre-calculated templates and matched filtering techniques, based on bayesian inference and posteriors calculations.

We propose the use of  total variation (TV) methods to  process the data. By reducing the TV present in the data it may be possible to remove unwanted information while preserving the signal containing the GW.

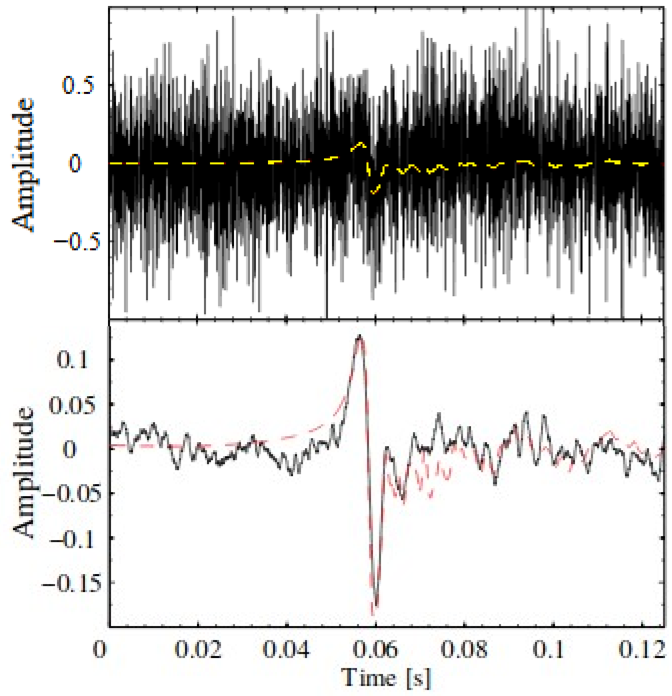



Denoising of signal BBH0001 of the Mroué catalog. Black line: original template, red line: denoised signal. Inset: time zoom on only original template and de-noised signal.

Valencia's Virgo group has tested the TV regularization ROF (rROF) model using simulated data with Gaussian white noise and injections of templates in small samples of experimental LIGO noise.

The ROF method reduces the amount of noise by reducing the signal gradients, while allowing discontinuities and avoiding the Gibbs effect. ROF can be considered a general purpose tool that doesn't use any prior information about the signal under de-noising.

We extend the investigation of this kind of methods, and pursue its integration in experimental data analysis pipelines.




Top panel: injection of GW signal (thin yellow line) in simulated Gaussian white noise

Botton panel: result after de-noising the data in top panel (solid line), compared to signal (dash line)

# rROF method in cWB pipeline

The rROF method for minimizing the total variance of a given signal depends on a number of parameters. Their optimal values will lead to the best possible result.

$$u = \underset{u}{\mathrm{argmin}} \left\{ \int \sqrt{\left( |\nabla u|^2 + \beta \right)} + \frac{\lambda}{2} \| u - f \|_{L2}^2 \right\}$$

Different choices of the parameter values will lead to different results, ranging from an insufficient subtraction of noise to the removal of an important part of the signal of interest. Performing a scan of the possible parameter values we can find the optimal set.

An study on the influence of these parameters values in the de-noising results is under study, for different types of GWs and different kinds of noise, i.e., for the different interferometers. An software package has been build to automatize such procedure. The evaluation of the quality of a de-noising is measured by using as an estimator the first Wasserstein Distance.

Once the parameter adjustment is complete, the use of templates for the identification and analysis of GW signals should become unnecessary. Particularly useful for pipelines and analysis systems unable to use templates, in most cases due to the impossibility to calculate them.

One of such pipelines is the Coherent Wave Burst (cWB) pipeline, used by the LIGO/Virgo Collaboration (LVC). It searches for coherent transient signals among the three interferometers investigating any possible structural similarity, without assuming any prior knowledge. To find one of this coherent signals could lead to identify a new GW. This pipelines has already been able to identify a few new detections during O3.

The implementation of the rROF de-noising method in the software infrastructure of the cWB pipeline is the final goal of this study, providing then an efficiency improvement.

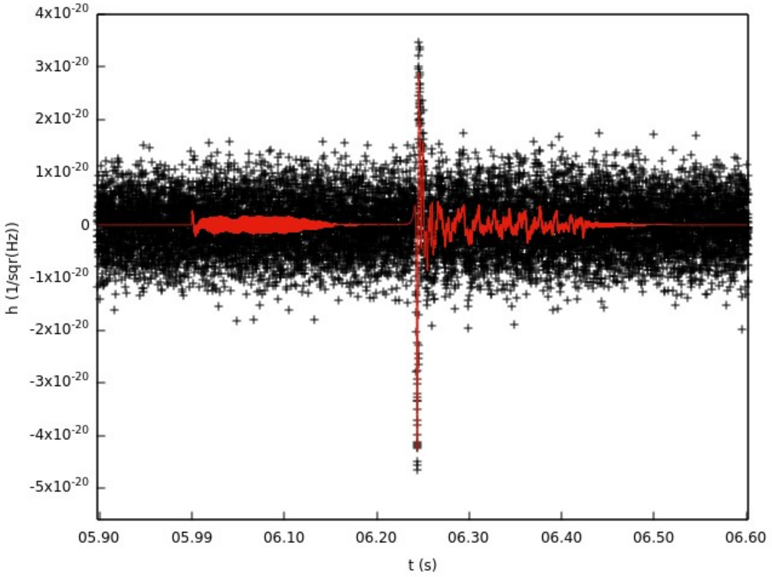
# Results

Different sets of the five parameters needed by the method will lead to different results of the de-noising. A scale based on the first Wasserstein Distance (WD) has been defined to measure the quality of the de-noising. One of the most important and sensible parameters is the regularization parameter, which regulates the fidelity of the de-noising data with respect to the signal.

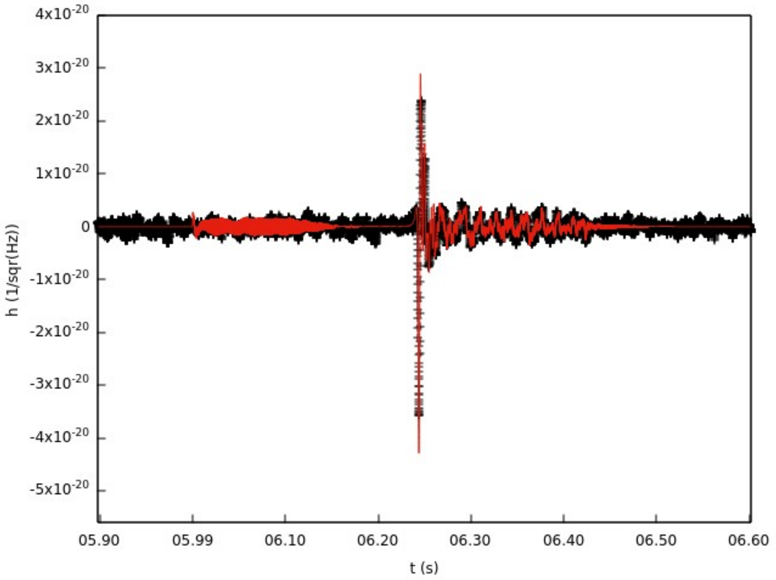
The WD scale ranges from 100 for the original data sample to 0 for the GW signal itself, or the GW template in the case of an injection. This procedure has been applied to injections of numerically simulated Core Collapse SuperNova (CCSN) waveforms in real LIGO O2 and O1 data.

Implementing the rROF de-noise method in the cWB pipeline will leads us to perform similar studies with BBH or BNS injections, among others, using the latest data of the O3 period.

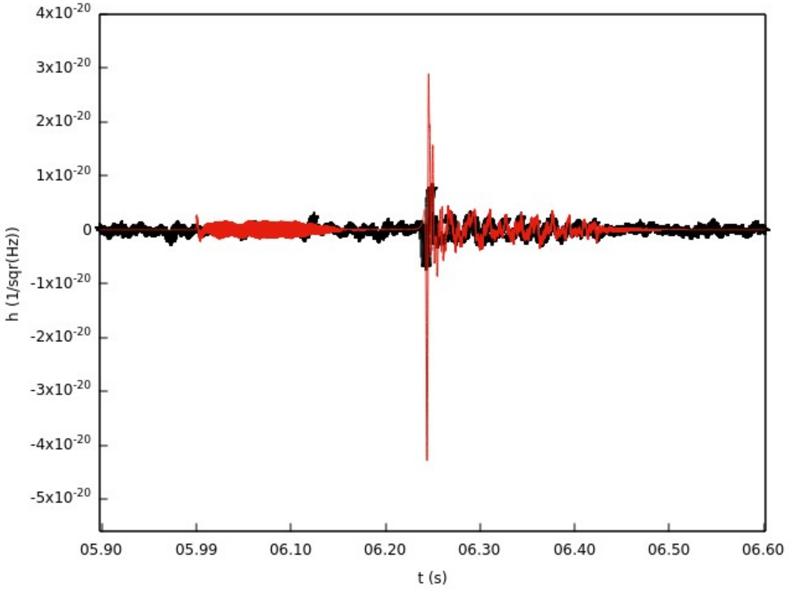
Original data, WD = 100




De-noised data, WD = 6




Wrong de-noising, WD > 100



# Outlook

At present, the implementation of the rROF method in the cWB pipeline has been completed and it is under its testing phase. One of this tests consist of the analysis of known GW data segments, such as the GW150914 event, in order to determine the correctness of the new code.

The analysis of  data from several detected events will help study the effect of introducing the rROF de-noise in the cWB pipeline. In addition, we plan to analyse the possibility of a better identification and/or parameter estimation of the GW signal present in the data after introducing the de-noising technique.

Matched filtering is our only possibility for modelled sources by means of templates calculated from general relativity. In the case of a successful outcome of our investigation, the introduction of rROF de-noising in the cWB pipeline offers the possibility to improve the cWB performance.

To analyse GW data with alternative methods other than matched filtering, as cWB does, will help with unmodelled sources such as CCSN bursts, cosmic strings or any other unknown astrophysical event.