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ANALYSIS OF BURST SIGNALS IN LIGO DATA
Optimizing burst search algorithms in the time-frequency domain

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Abstract

There are gravitational wave sources (such as supernovae and binary black hole mergers), which emit waveforms for which no good model exists. The filtering of such burst signals should be as general as possible with minimal a priori assumptions on the waveforms. Those filters are very sensitive to non-stationary noise (producing fake signals) as well as to gravitational wave bursts. Such fake signals can be dramatically reduced when working in coincidence with other detectors. This work focuses on optimizing burst search algorithms by characterizing certain classes of modeled bursts in the time-frequency plane.

1. Introduction

LIGO (Laser Interferometer Gravitational-Wave Observatory) is a facility dedicated to the detection of cosmic gravitational waves. Gravitational waves were predicted long time ago, but because detection techniques were not sufficiently advanced, could not have been detected because their effect on objects on Earth are exceedingly small.

Strength of gravitational force

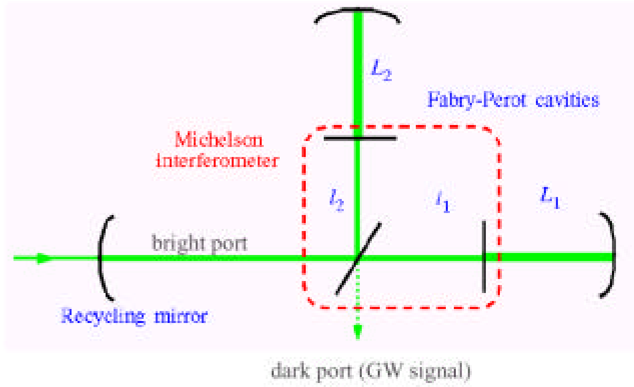
Interaction	Strength	Acts on	Charge	Carried by	theory
Strong nuclear	10	Quarks	Color	Gluons (*g*) (massless)	QCD
Electromagnetic	10^{-2}	Charged particles	Electric charge	Photon (γ) (massless)	QED
Weak nuclear	10^{-13}	Quarks, leptons	"flavor" charge	W^+, W^-, Z^0 (massive)	QFD
Gravitational	10^{-40}	All particles	Mass	Graviton(*G*) (massless)	GR…?

As we can see in the given table, gravitational force is very weak, but at large scales (planets, stars,…) it dominates.

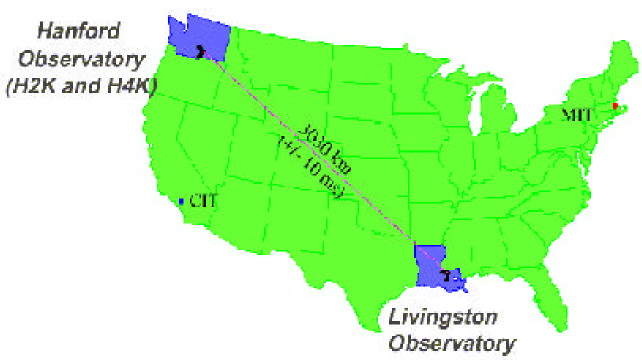
The method used for detecting such small oscillations is the laser interferometer. The device that is used is a Michelson interferometer. It can detect displacements much less than the diameter of a nucleus (amplitudes of displacements caused by gravitational wave emission are about 10^{-20}m). It consists of a laser that emits electromagnetic waves of very precise frequency in order not to affect the measurements.

This electromagnetic wave goes through a semi-transparent mirror, which splits it into 2 components. Each one of them enters a Fabry-Perot resonant cavity in each of the two arms of the Michelson interferometer in which the very small displacement caused by a possible gravitational wave is amplified many times (the number of bounces of the light in the Fabry-Perot resonant cavity). Differential motion of the two Fabry-Perot cavities is detected in the Michelson dark port and is the signature of gravitational waves.

In order to detect such small displacements the device must be isolated from all environmental noise.



In order to reduce the effort of an accidental source of vibrations located on Earth there are two observatories and three interferometer detectors: Hanford, WA (4km and 2km interferometers) and Livingston, LA (4km interferometer). There is a 40m LIGO interferometer prototype in Caltech.



LIGO at Hanford, Washington

The distance between two interferometers at Hanford and Livingston is 3030km which means that they should detect a same event within +/- 10ms.

The sources of gravitational waves are very massive objects. Those massive objects emit gravitational waves when they are accelerated to speeds close to the speed of light. Typical gravitational wave sources are black holes or neutron stars that orbit one another, and supernova explosions.

There are different kinds of gravitational wave signals. Some of them are well modeled while for some signals accurate mathematical models don't exist. There are well modeled signals for binary black hole or neutron star inspirals. Anticipated sources for which the physics is too complex to allow computation of detailed gravitational waveforms include core-collapse of massive stars in supernovae, and the accretion induced collapse of white dwarfs. It is also very difficult to obtain gravitational waveforms from black hole mergers because the gravitational radiation from them results from highly non-linear self-interaction of the gravitational field. Zwerger Muller [8] catalog is a first attempt at predicting the complex behavior of SN explosions and resulting gravitational radiation, serving only as a preliminary guide to the kinds of waveforms we might be looking for. There are 78 waveforms computed

There are different filter techniques for modeled and unmodeled gravitational wave signals. The most highly developed technique for detecting gravitational waves (for waveforms which are known in advance) is matched template filtering.

In searching for unmodeled burst sources filter techniques should be as general as possible and with minimal a priori assumptions on the waveforms. One such filter technique is the excess power statistic [6]. The excess power statistic is a method that compares power of the data in the estimated frequency band and for the estimated duration to the known statistical distribution of the noise power. The signal is detectable if the excess power is much greater than the fluctuations in the noise power.

Other filter techniques that have been explored in the literature [7] include:

- Filters based on autocorrelation such as Norm filter (NF, which computes the maximum of the autocorrelation of the data, and NA filter, which looks at the norm of the autocorrelation function).
- The bin counting method BC - computes the number of bins (in a time frequency spectrograms) in a window size N those value exceeds some threshold which is chosen by maximizing the signal to noise ratio.
- Linearfit filter LF - fits the data to a straight line in a window of size N. There are two cases: if only noise is in the data, the slope and the offset of the fitted line are zero on average which is not case if there is noise + signal.
- Advanced Linearfit filter ALF - we obtain this filter if we take uncorrelated combinations of the slope and offset (which are two correlated random variables).
- The peak correlator filter is based on correlating the data with peak (or pulse) templates.

2. Methods and algorithms

In many burst search algorithms (such as excess power, bin counting, etc), the data are binned in the time-frequency plane. Preliminary models (such as "ZM" supernova collapse waveforms generated by Zwerger and Muller [8]) suggest that the GW bursts occupy a limited duration and bandwidth in the time-frequency plane, and it is of interest (for designing and tuning search algorithms) to explore the regions in that plane where the models predict the largest signal strength

to appear. The goal of this work is to determine the time frequency binning which maximizes the strength of the signal in the presence of random noise. White noise is used for now, but colored noise should be used for future studies.
We used two algorithms.

I Algorithm

- Calculate mean noise power for each frequency and all time bins
- Calculate S/N for fixed time and each frequency bin. If it is above chosen threshold add up power of all frequency bins in each time bin
- Calculate total (s+n power)/expected noise power and plot it vs number of fft points (nfft)
- Repeat algorithm for 78 ZM waveforms

II Algorithm

- Use all possible bin size combinations for $10Hz<\Delta f<1000Hz$ and $0.01s<\Delta t<1s$
- Calculate (s+n)power/expected noise power for each bin and different bin size
- Make 3D plot with Δt vs Δf vs bin power only for bins which S/N exceed threshold
- Repeat algorithm for 78 ZMwaveform

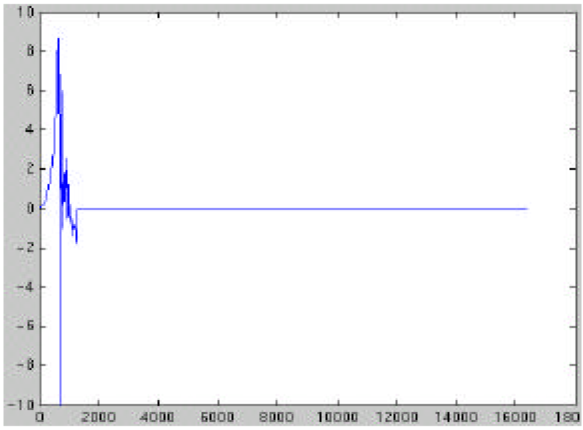
The analysis in the time frequency domain is done by making spectrograms of the signals.
I generated one second of white noise sampled by 4096 Hz. All ZM waveforms which are used are resampled to 4096 frequency and normalized. There are next relations between parameters which we use to make spectrogram and Δt and Δf:

P - sampling frequency, 16384, but can be downsampled (eg, to 2048) to reduce computation time with little loss of sensitivity
window size = $P/\Delta f$
number of overlap = P-1-(window size / Δt)
nfft = window size
number of overlap < window size

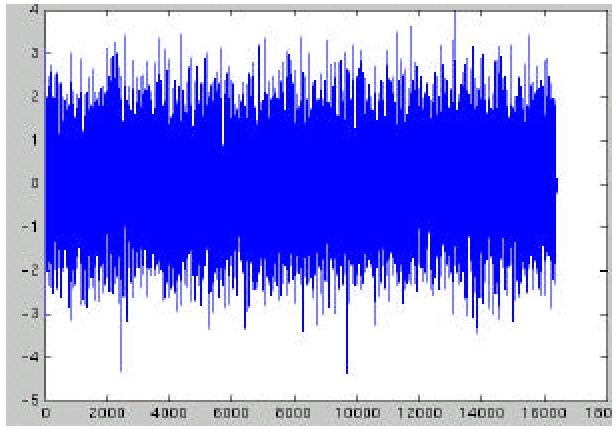
The Matlab function *specgram* computes the windowed discrete-time Fourier transform of a signal using a sliding window. The spectrogram is the magnitude of this function. Different values for the parameters give us different bin size.
The function which was used has the form:

specgram(X, nfft, sampling frequency, window size, number of overlap).

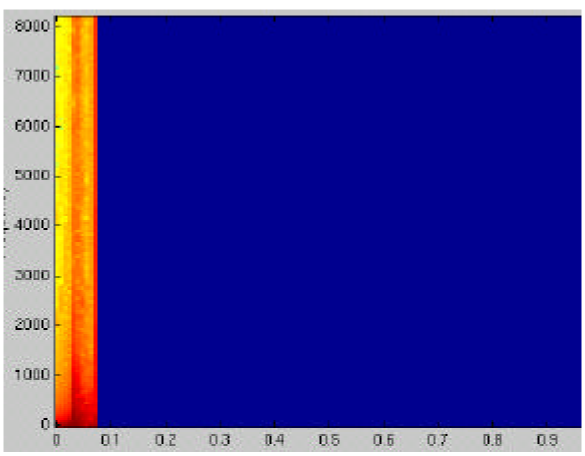
The next pictures show one waveform from the ZM catalog and its spectrogram, and spectrogram of the white noise.



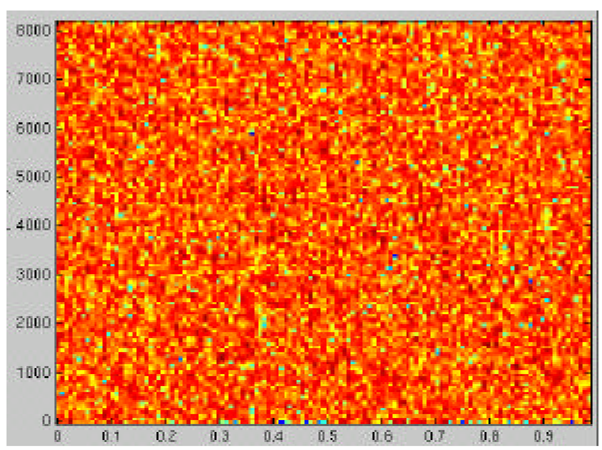
ZM waveform



White noise



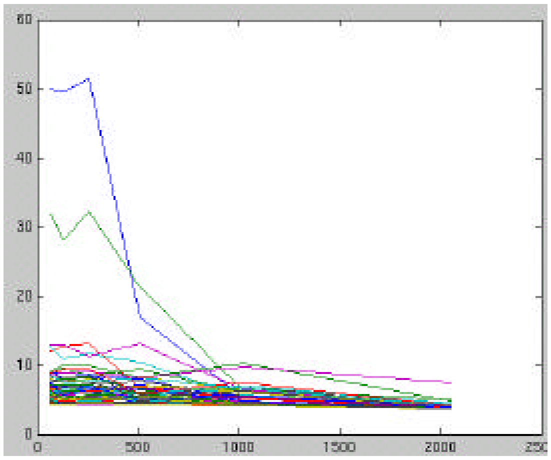
spectrogram of the ZM waveform

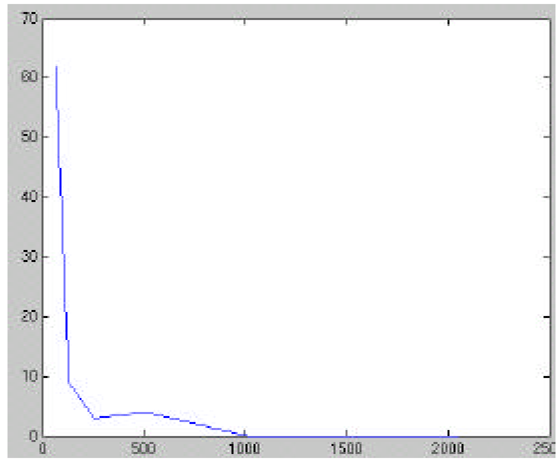


spectrogram of the white noise

I Algorithm results

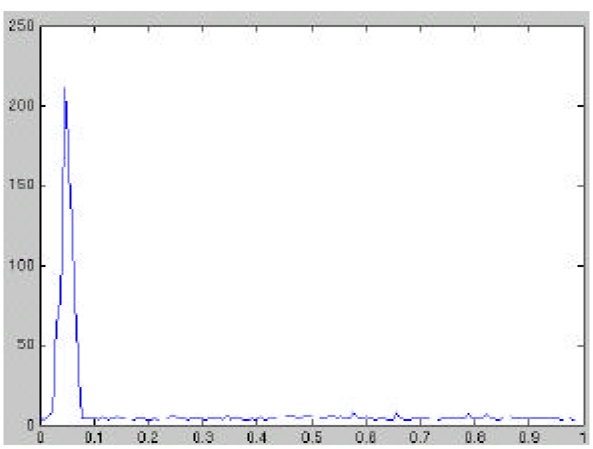
Results of the first algorithm are shown in the next two graphs. Number of fft points (nfft) is from 64 to 2048. The first graph represents signal to noise ratio vs nfft. There are plotted values for all 78 ZM waveforms. Next graph shows number of maximum signal to noise ratios for each signal, and we can concluded that almost all s/n maximums for all signals are for nfft = 64. This reflects the fact that the ZM bursts are of short duration; most of their amplitude occurs over less than 5ms (82 samples).

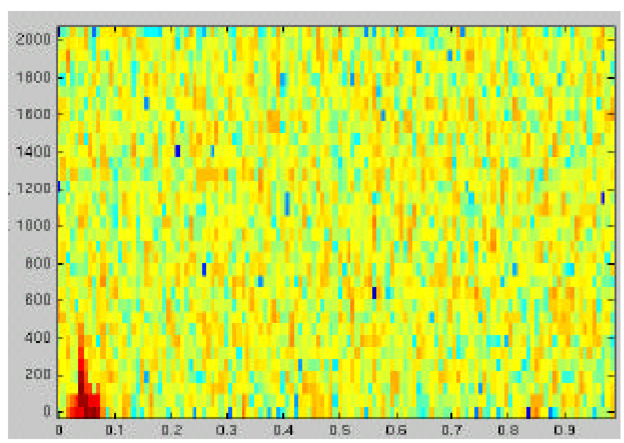




S/N for all 78 ZM waveforms vs nfft

The next two graphs show total power of the ZM signal (calculated only for bins which S/N ratio exceeds a threshold of 3) and spectrogram of the same signal. For number of fft points = 64 the bin size is $\Delta t=0.0078$s and $\Delta f=64$Hz.



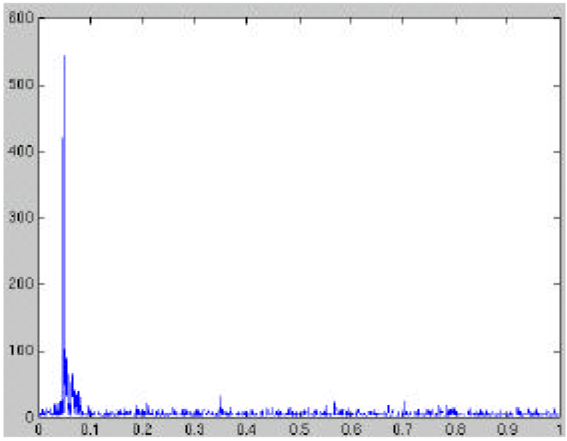


Total power of the signal for nfft=64

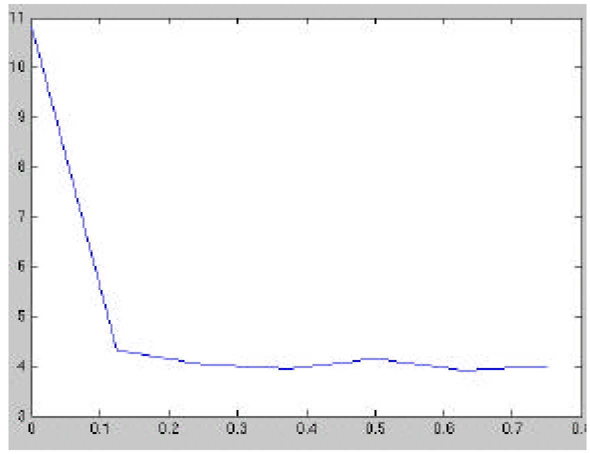
NFFT=64; Dt=0.0078s; Df=64Hz;

The next four graphs represent the total signal power for nfft=16 and 1024 and their spectrograms. If we compare total signal power (calculated only for bins which S/N exceed given threshold) for nfft=16

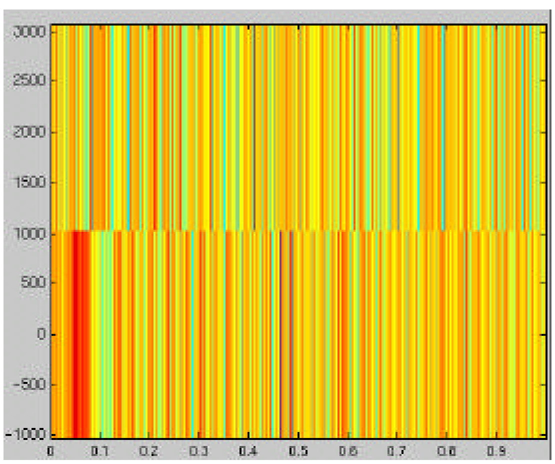
(Δt=0.002s, Δf=256 Hz) and nfft=1024 (Δt=0.125s, Δf=4Hz) we can see that the total signal power in the first case is ~ two orders of magnitude bigger then the total signal power in the second case.



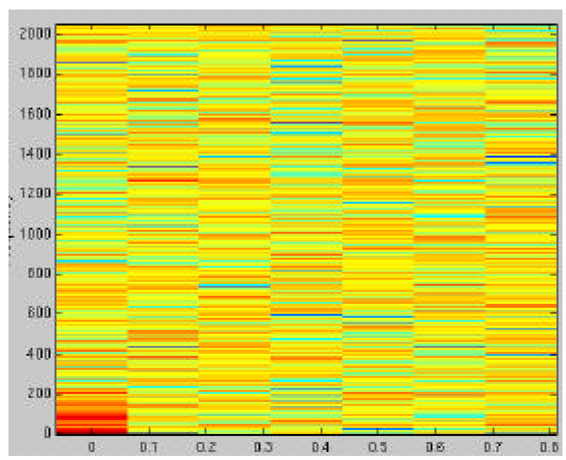
Total signal power for nfft=16



Total signal power for nfft=1024



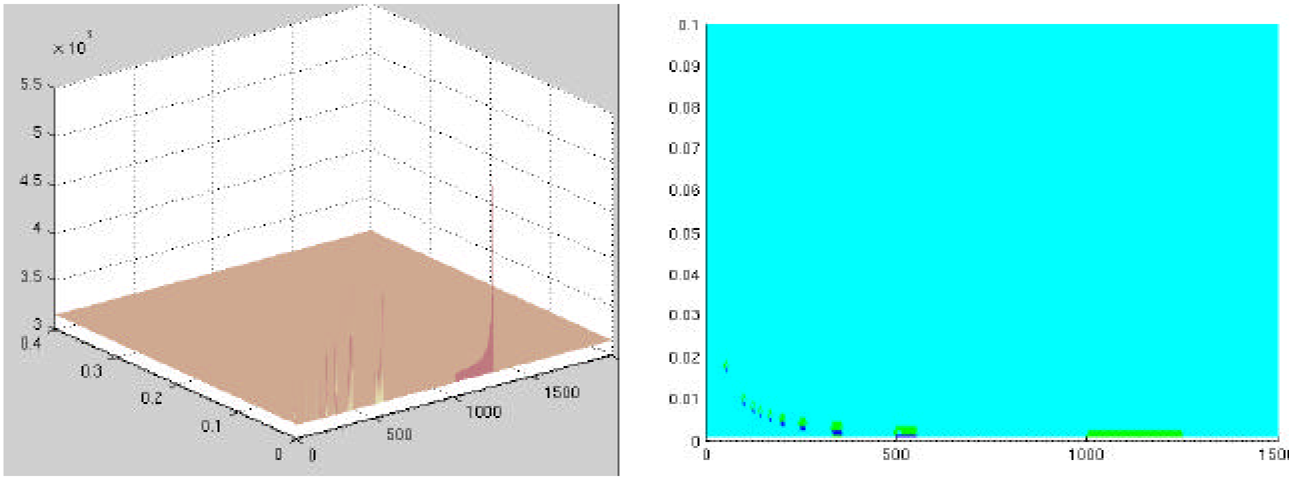
NFFT=16; Dt=0.002s; Df=256Hz;



NFFT=1024; Dt=0.125s; Df=4Hz;

II Algorithm results

II Algorithm results are shown in the next two graphs. In the first graph are plotted S/N values calculated for each bin and plotted only for bins which the S/N exceeds a threshold of 3. The second graph is the same as the first one but with zoomed area.



S/N for each bin that exceed threshold vs Dt vs Dt

We can see here that maximum S/N ratio is for bins which duration is Δt ~ 2ms and Δf ~ 1000 kHz

3. Conclusion

Both algorithms give the same results. It is better to use larger Δf and smaler Δt. The size of Δt is limited by our sampling frequency. If sampling frequency is P=4096, Δt is >=0.000244s.

White noise was used in this work. Real detector noise will contain significant colored components. This means that this analysis should be repeated using colored noise. Generally speaking, the excess power method is a useful tool for characterizing and investigeting the non-Gaussian components of the noise. It can provide a simple and automated procedure for garnering statistical information about noise bursts.

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