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Basebanding vs. high-pass filtering for burst searches

Lee Samuel Finn

Distribution of this draft:

LIGO I Collaboration

California Institute of Technology
LIGO Project - MS 51-33
Pasadena CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

WWW: http://www.ligo.caltech.edu/

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Abstract

Searches for unmodeled gravitational wave sources proceed by looking for correlations in the detector output that are inconsistent with detector noise. All the unmodeled burst searches seek to whiten the detector data — i.e., remove the color associated with the detector noise — before searching for differences between the detector output and the expected behavior owing to detector noise. Another important feature of the LIGO detector data is that the detector band begins at a positive frequency. Below that frequency the strain- equivalent noise amplitude grows so rapidly and the noise character (e.g., “glitchiness”, non-stationarity, non-Gaussianity) is so poor that contributions from the low-frequency band hinder the search for burst gravitational wave sources. The practice to date for eliminating the low-frequency detector noise has been to apply a high-pass filter to the detector data. This practice is, however, incompatible with whitening the data. In this note we describe how the low-frequency noise can be eliminated in a way compatible with whitening through a five line addition to the instructions given to the LDAS datacondAPI as part of all burst searches.

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Contents

1 Introduction

Present LIGO searches for unmodeled gravitational wave sources proceed by looking for correlations in the detector output that are inconsistent with detector noise. This takes place on two levels: first, in individual interferometers where candidate events are identified; second, in requiring coincidence between the output of two or more detectors. The search for an inconsistency between the character of the actual detector output and that expected from the detector noise is the guiding principle behind all of the unmodeled burst searches implemented to date.

Three related issues arise as we try to condition the data in anticipation of a search for burst gravitational waves: increasing the quality of the data, maximizing the ratio of signal power to noise power, and correlations in the noise at different times.

- The quality of the noise — by which we mean the rate of glitches, or high-amplitude, non-Gaussian events — is poor in the LIGO low-frequency band. Correspondingly, we need to strongly suppress the power in this band.

- LIGO rms noise amplitude increases rapidly at low frequencies. We don’t expect this to be the case for gravitational wave signals that we are most sensitive to. Correspondingly we increase the overall ratio of signal energy to noise energy if we strongly suppress the power in the low frequency band relative to the power in bands where the differential signal to noise is largest.

- All our burst searches look for unexpected correlations in the data as evidence for a gravitational wave burst. This search takes one of two forms. In the time-domain searches like SLOPE the correlation is an unexpected trend in time toward higher signal amplitudes (i.e., increased slope). In time-domain searches like BlockNormal the trigger is an unexpected change in the noise statistics. In either case, making the data white — i.e., filtering the data so that its autocorrelation vanishes except at zero-lag — removes trends in the noise that would increase the false rate of these event trigger generators.

  Similarly, in the time-frequency searches TFCLUSTERS or POWER the correlation is an excess signal energy in one or more tiles (or clusters of tiles) in the time-frequency plane. Correspondingly, we seek to make the noise contribution to the data white — i.e., remove the color associated with the detector noise — so that the noise contribution to the energy in every frequency bin is constant and there are no correlations in the noise at different times. A significantly higher power in one band compared to another, or a correlation in the detector output at different times, thus becomes significant as an indicator of a gravitational wave burst.

If steps are not taken to reduce the contribution from bands where the noise energy is much greater than the signal energy or the noise is poorly behaved, or if correlations are left in the data, then higher thresholds are required in order to maintain confidence that identified events are of gravitational wave origin. These higher thresholds weaken the sensitivity of the search.

Suppressing the noise power in the low-frequency band relative to the higher frequency bands, as is required to reduce the significance of glitches there and increase the overall ratio of signal energy to noise energy, is inconsistent with making the noise contribution white and removing correlations in the noise at different times. In this note we describe *basebanding:* the construction of a new gravitational wave data stream from the original data stream such that a particular frequency band of interest in the original data is shifted so that the low-frequency band-edge is at zero frequency, the high-frequency band-edge is at the Nyquist frequency and the originally out-of-band noise contribution vanishes.

2 Basebanding in the datacondAPI

Let the band in which the detector is sensitive be defined by a low-frequency band-edge f_0 and a bandwidth Δf: i.e., the band in which we search for gravitational wave signals is $f_0 < f < f_0 + \Delta f$.

The simplest approach to basebanding would be to apply a (software) lock-in amplifier to the gravitational wave signal, with bandwidth Δf and band-center f_0:

- Mix the detector data with a local oscillator tuned to the frequency $f_0 + \Delta f/2$, reporting the in-phase and quadrature phase components as a single complex number z equal to (in-phase)$+i$(quadrature-phase);
- Decimate (with anti-aliasing) to a bandwidth Δf (i.e., to a frequency range $[-\Delta f/2, \Delta f/2]$);

The complex quantity z will correspond to the signal in the band $(f_0, f_0 + \Delta f)$ shifted to the band $(-\Delta f/2, \Delta f/2)$ and there is no power in the signal outside of this band.

This simplest approach to basebanding makes the gravitational wave signal complex. While not a problem in principle for any of the methodologies, as implemented they all assume a real signal. Additionally, while there are no technical impediments to working with the complex output of a lock-in amplifier in LDAS or LAL, the software coordinator has ruled that passing the complex output of a lock-in between the datacondAPI and the wrapperAPI is forbidden. Nevertheless, we can meet our goals within policy by letting z modulate a complex carrier at a frequency $-\Delta f/2$. After this operation the signal band $(f_0, f_0 + \Delta f)$ is mapped to $(0, f_0 + \Delta f)$ and there is no power outside of this band in the modulated carrier. The real (or imaginary) part of the modulated carrier corresponds to an overlap of the signal in the positive and negative frequency part of the carrier; however, since there is no power in the negative frequency part of the band the result is entirely equivalent to the original signal. We can perform our gravitational wave data analysis on the real part of the modulated carrier, which we refer to as r.

(It is straightforward to verify that the original in-band signal can be reconstructed from the real (imaginary) part of the modulated carrier through the following steps:

- Mix the signal with a local oscillator at frequency $\Delta f/2$;
- Decimate (with anti-aliasing) the signal to a bandwidth Δf;
- Low-pass filter to a bandwidth $\Delta f/2$;
- Mix the signal with a local oscillator at frequency $-(f_0 + \Delta f/2)$;
- Take the real part and multiply by a factor of 4.

The result will be the original signal in the original band.)

In the LDAS datacondAPI four instructions are required to produce r from the raw detector output g (i.e., LSC-AS_Q):

```
phi = 0;
r = mix(phi, freq, g);
r = resample(r,p,q);
r = linfilt(r,b,a);
r = mix(phi,c,r);
r = real(r);
```

where

- `freq` is equal to $f_0 + \Delta f/2$;
- `p, q` are integers with p/q equal to $\Delta f/f_s$, where f_s is the original signal sample rate;
- `b` and `a` are the coefficients of a (real) half-band low-pass filter;
- `c` is $\Delta f/2$.

If an FIR linear filter is used then the form of the linfilt command can be simplified to

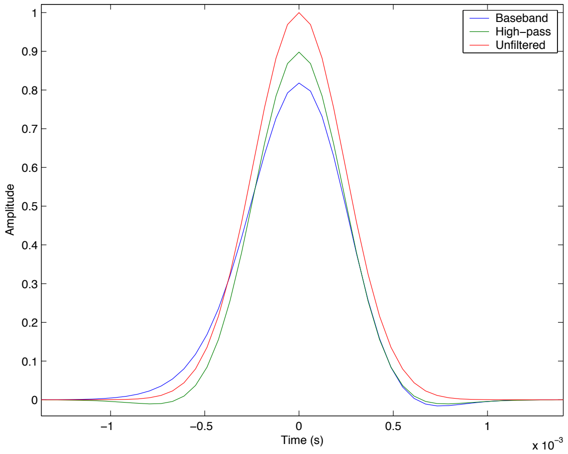

Figure 1: A 1ms width Gaussian pulse without filtering, basebanded to 100Hz with a 1938 (2048-100) Hz bandwidth, and high-pass filtered with a 100 Hz bandedge. The low-pass filter used in the basebanding is an order 25 Hamming window filter. The high-pass filter is an order 26 Hamming window filter. The basebanded signal has been multiplied by two in order to match the scales. (Noise is attenuated to the same degree that signal is in all three cases.) All three pulses are of the same width; correspondingly, the precision with which we can localize a burst in time is not, in principle, affected by the choice of high-pass filter or baseband approach. The ability to carry forward the analysis with whitened data, however, is possible only with the baseband approach.

```
r = linfilt(r,b);
```

Finally, if g is white then r will be white; if g is not white, then r can be whitened before sending it forward to any of the burst search methods.

3 Timing resolution

Figure 1 compares a 1 ms width Gaussian pulse, sampled at 16 KHz, the same pulse filtered through an order 26 Hamming window designed high-pass filter, and the same pulse basebanded as described above using an order 25 Hamming window designed low-pass filter. In both cases the band-edge is 100 Hz and the detector is presumed sensitive to gravitational waves up-to the Nyquist frequency.

4 Conclusion

The LIGO detector band does not extend to zero frequency and the noise in the low-frequency, out-of-band regime is of high amplitude and very poorly behaved. Eliminating the power in the out-of-band regime increases the signal to noise for in-band gravitational wave signals and improves the overall noise character, allowing for more efficient detection at lower false alarm probability.

At the same time, all current searches for burst gravitational wave sources operate best when they operate on detector data whose noise is white. The combination of keeping the analysed data white in noise while having no contribution to the power from the out-of-band noise is not possible through high-pass filtering of the detector data stream. It is, however, simply accomplished by the basebanding procedure described here, which can be carried out in the LDAS datacondAPI.

POWER and TFCLUSTERS operate in the frequency domain and carry-out whitening in the search filter itself. Since they operate in the frequency domain they offer the possibility of excluding triggers arising from out-of-band signal power. Nevertheless, the thresholds they set for a given false rate depend also on the "glitchiness" of the noise. Passing poorly behaved, out-of-band noise to these filters unattenuated requires the use of higher thresholds since the power in these glitches can bleed into the band of interest, leading to undesired triggers at lower thresholds that are possible if the out-of-band power is not present at all.

The basebanding approach offers other advantages, as well: in particular, changing the stop-band edge of the low-pass filter allows one to set the signal band width to any desired value. In the "high-pass" filter approach either a second low-pass filter must be used or the high-pass filter must be replaced by a band-pass filter. In either case the process requires more filters, or filters of higher-order, in order to single-out the band of interest.