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Basebanding vs. high-pass filtering for burst searches

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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. The principal information used to model the detector noise is its power spectral density. 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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1 Introduction

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.

The principal information used to model the detector noise is its power spectral density. 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. In this way the noise contribution to the detector output has, in a give detector, no correlations. Correspondingly, observed correlations become significant as indicators of gravitational wave event candidates. Leaving significant color in the data leaves trends in the data that can be mistaken for gravitational wave signals. This is overcome by setting thresholds high enough that the magnitude of the trends is typically below threshold, which weakens the sensitivity of the search.

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. Eliminating entirely the power below the low-frequency band-edge increases the signal-to-noise associated with any real signal in the detector band and increases the significance of identified events because, overall, the noise that remains is much better behaved (i.e., less “glitchy”, more stationary, more Gaussian). Correspondingly, all burst search seeks to reduce or eliminate the contributions from the low-frequency band before setting out to identify gravitational wave bursts.

Two methods have been proposed for the purpose of eliminating the low-frequency, out-of-band component of the detector noise. The first, which has been the method of practice, is to apply a high-pass filter to the “gravitational wave channel” (LSC-AS_Q) with band-edge at or near the low-frequency cut-off; the second is to shift the band of interest (i.e., the band above the low-frequency cut-off) so that its band-edge is at zero frequency, and to exclude power outside the band.

Applying a high-pass filter to the detector data for the purpose of eliminating the power in the out-of-band, low-frequency component of the detector signal is, however, incompatible with whitening the data. That is not the case if the data is basebanded to eliminate the out-of-band low-frequency power, in which case whitening can be performed either before or after the basebanding.

In this note we describe how basebanding can be implemented in the LDAS datacondAPI and show that the basebanding preserves the ability to localize a burst in time.

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);
- Apply a low-pass filter of bandwidth $\Delta f/2$ to z.

The complex quantity z will correspond to the signal in the band $(f_0, f_0 + \Delta f)$ shifted to the band $(-\Delta f/2, \Delta f/2)$.

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 mpiAPI 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 $\Delta f/2$;
- 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 = linfilt(b,a,r);
r = mix(phi,c,r);
r = real(r);
```

where

- `freq` is equal to $f_0 + \Delta f/2$;
- `b` and `a` are the coefficients of a (real) low-pass filter, with stop-band edge at frequency $\Delta f/2$;
- `c` is $\Delta f/2$.

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

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

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.

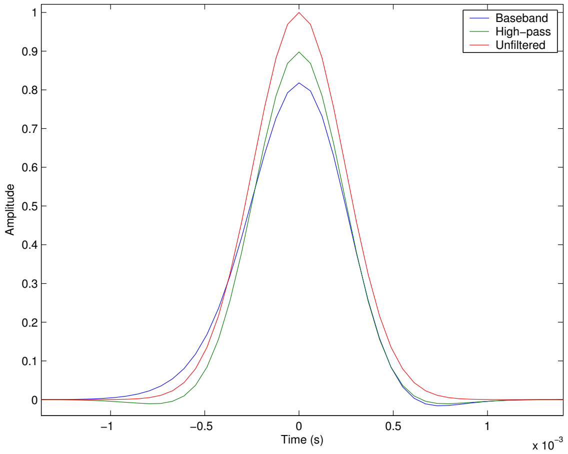

Figure 1: A 1ms width Gaussian pulse without filtering, basebanded to 100Hz with a 1938 (2048-100) Hz bandwidth, and high-pass filtered with a 100 Hz bandedge. The low-pass filter used in the basebanding is an order 25 Hamming window filter. The high-pass filter is an order 26 Hamming window filter. 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.

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.