

A novel method for detecting coalescing binaries in near realtime with Advanced LIGO and beyond

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Abstract. Conventional matched filter bank methods for the detection of gravitational waves from the inspiral of compact binaries are computationally expensive, have hundreds of seconds of unavoidable intrinsic latency, and require arrays of largely redundant matched filters. Novel detection methods that are more computationally efficient and have lower latency will be required to realize the full potential of advanced gravitational wave detectors that are currently under construction. In this paper, we describe a new detection method that exploits the properties of inspiral waveforms using multi-rate filtering, principal component analysis, and hierarchical detection. We provide receiver operating characteristics from a prototype search pipeline that is capable of low-latency or near-realtime detection with greatly reduced computational requirements in comparison with previously described methods.

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1. Introduction

In a series of detector upgrades that are now under way, LIGO and Virgo will become the first advanced gravitational wave detectors, gaining a tenfold improvement in amplitude sensitivity [CITATION NEEDED] and a corresponding thousandfold increase in observable volume in the local universe. It is anticipated that these detectors will be able to sense as many as 40 events per year [1].

As the gravitational wave detection horizon pushes outward, the ability to detect signals in near realtime will become valuable. Having an electromagnetic or neutrino counterpart to a gravitational-wave detection would not only increase the confidence in the detection but will also greatly improve the astrophysical information available from the event. Most models that predict simultaneous gravitational-wave and electromagnetic observations also predict that the peak amplitude of electromagnetic radiation will occur soon after gravitational-wave emission [2]. Thus in order to maximize the chance of a successful electromagnetic followup the latency of gravitational-wave signal analysis must be made minimal.

Work has already commenced to trigger gravitational-wave searches from electromagnetic observations [3]. LIGO observations ruled out the possibility of

*This is old news,
and doesn't seem
relevant to me:
EM-directed
gravitational wave
searches don't
benefit from
low-latency
detection pipelines.*

GRB070201 originating from the merger of a NSNS or NSBH system in the Andromeda galaxy [4].

In 2010, LIGO and Virgo completed a period of joint data taking during which several all-sky detection pipelines operated in a low-latency configuration [CITATION NEEDED]. Promising detection candidates were promptly sent for electromagnetic followup [CITATION NEEDED] to several telescopes including Swift, ROTSE, TAROT, and Zadko.

This question has been investigated and it seems at least possible that gravitational-wave detections could provide a region of the sky to prompt electromagnetic observation followups [2]. Much work is currently underway in providing the best possible source localization from gravitational-wave detector networks [5, 6, 7]. Collaborations are currently forming to provide infrastructure for the gravitational-wave Astronomers to provide targets of opportunity for electromagnetic astronomers [8]. Most models that predict coincident gravitational-wave and electromagnetic observations also predict that the peak electromagnetic fluence will occur soon after gravitational-wave emission [2]. Thus in order to maximize the chance of a successful electromagnetic followup the latency of gravitational-wave signal analysis must be made minimal.

*Cite an
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paper of Larry's?*

The parameter space of compact binary coalescence signals is large [9, 10]. It is a computationally burdensome task to analyze these signals with even moderate latency [11]. This work will describe how to exploit degeneracy in the signal parameter space to answer more quickly whether or not a gravitational-wave is present. Specifically we will explore using the singular value decomposition (SVD) to reduce the effective number of filters required to search the data. We note that others have applied the use of SVD to gravitational wave data analysis to analyze optimal gravitational-wave burst detection [12, 13] and coherent networks of detectors [14].

The paper is organized as follows. First we provide an overview of the standard method for detecting compact binary coalescence signals and describe how it can be modified to accomodate low latency analysis. We then describe the pipeline we have constructed to implement these changes. To validate the approach we present results of simulations and finish with some concluding remarks.

2. Method

2.1. The standard approach: matched filtering

Searches for gravitational waves from compact binary coalescences typically employ matched filter banks [15]. Potential inspiral signals are continuously parameterized by time, amplitude, phase, and a set of intrinsic source parameters θ , which in this paper we shall take to consist of the two component masses of a binary, $\theta = (m_1, m_2)$. Let $h_+(\theta)$ and $h_\times(\theta)$ be, respectively, the ‘+’ and ‘ \times ’ polarization gravitational wave signals that would arise from a fiducial face-on binary at some distance. Because, for inspiral signals, h_+ and h_\times are nearly in quadrature, they are generally combined into a single complex-valued template $h = h_+ + ih_\times$.

The detection procedure for just one set of intrinsic source parameters θ starts by *whitening* the measurement data stream x . This involves finding a linear filter that renders the detector’s noise IID and Gaussian. This filter is applied to the measurement, yielding the whitened data stream x^W . The same linear filter is applied to the template $h(\theta)$, yielding the whitened template $h^W(\theta)$. The matched filter is the

normalized cross-correlation of h^W and x^W ,

$$\rho(\theta) = \frac{h^W(\theta) \star x^W}{|h^W(\theta)|}.$$

This is called the signal to noise ratio, or SNR. The detection statistic is the modulus of this, $|\rho(\theta)|$, which has a χ^2 distribution with 2 degrees of freedom in the absence of signal.

To construct a filter bank, matched filters are realized for discrete signal parameters $\theta_1, \theta_2, \dots, \theta_N$, such that any possible signal will have a maximum cross-correlation of at least 0.97 with at least one template. Such a template bank is said to have a 97% *minimum match*. This technique is designed so that an inspiral signal can be detected without any prior knowledge of its intrinsic parameters: at most 3% of the SNR is lost by a signal's parameters not exactly coinciding with a template's. A trigger is reported for the template parameters θ_i and time t for which $|\rho|$ is a maximum over some moving interval in θ and t .

2.1.1. Latency and overhead The matched filter bank can be implemented with finite impulse response (FIR) filters. FIR filters are perfectly suited for realtime detection, because they do not introduce any latency at all. However, FIR filters are very expensive: for N templates of M samples each, a FIR matched filter bank costs $\mathcal{O}(MN)$ operations per sample.

Much more commonly, the matched filter bank is implemented using FFT convolutions, costing only $\mathcal{O}(M \lg N)$ per sample but having a latency of at least M samples. For example, for a bank of 1 ks templates sampled at 4096 Hz, the FFT implementation requires about 2.2×10^4 times fewer floating point operations per sample than the FIR implementation. However, the FFT implementation has a latency of at least 1 ks.

This presents a dilemma: it seems that low latency detection using the FIR implementation is prohibitively expensive, whereas computational cheap detection with the FFT method comes with minutes to hours of latency.

In the rest of the section, we will describe a detection strategy that makes use of some very general properties of inspiral template banks in order to evaluate a matched filter bank with far lower computational cost than the FIR method and far less latency than the FFT method.

2.2. Selectively reducing the sample rate of the data and template waveforms

Our first innovation is based upon the common knowledge that gravitational waveforms from the inspiral stage of compact binary coalescences are chirps: they are quasi-monochromatic and slowly evolving in frequency.

It is possible to strike a balance between the low latency of the FIR filter method and the low overhead of the FFT method by breaking the templates into disjoint time intervals, or *time slices*. The outputs of the filters for all of the time slices are delayed by the appropriate numbers of samples and then summed to produce the SNRs for original templates in the template bank. Each time slice may be implemented using either FIR filters or FFT convolution. If the i th time slice spans the times $[-t_{\text{end}}^i, -t_{\text{start}}^i]$ relative to the time of coalescence, then the latency is $\max(2(t_{\text{end}}^i - t_{\text{start}}^i) - t_{\text{start}}^i)$, where the maximum is taken over all time slices that are implemented using FFT convolution.

After introducing the \star notation for cross correlation, must we define it for continuous and discrete time?

Citation needed for template placement procedure?

\lg is \log_2 . Explain nomenclature? Switch to \log_2 ?

The time slice boundary notation is a little awkward and different identifiers are used in a few places in the source code. It would be nice to clean that up.

It may be worth pointing out that time-slicing buys you latency even without exploiting time-frequency structure. The downsampling really just buys you throughput. It may even be worth renaming the section.

We can exploit the time-frequency structure of the templates by processing each time slice at a reduced sample rate. In the quadrupole approximation [16], the frequency of gravitational radiation resulting from the inspiral of two compact objects evolves according to

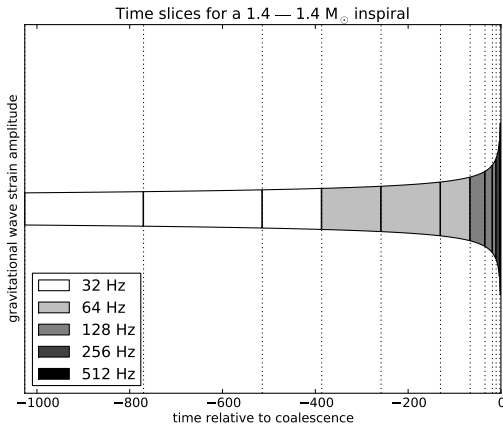
$$f = \frac{1}{\pi\mathcal{M}} \left[\frac{5}{256} \frac{\mathcal{M}}{-t} \right]^{3/8} \quad (1)$$

where \mathcal{M} is the chirp mass and t is the time relative to the coalescence of the binary [17, 18, 15, 19]. Typically the template is truncated at some time before coalescence, corresponding to a finite frequency which is often chosen to be the frequency at the innermost stable circular orbit, $f_{\text{final}} = f_{\text{ISCO}} = 4400 M_{\odot}/M$.

Applying the relationship $f/f_{\text{final}} = (t_{\text{final}}/t)^{3/8}$ it is possible to design time slices such that the templates are critically sampled at monotonically decreasing sample rates. The data stream is downsampled to many different sample rates, then filtered in each time slice, then upsampled to a high common sample rate, and summed. In order to work efficiently with radix-2 FFTs, sample rates and sample counts for time slices are both constrained to be powers of 2.

An example time slice design satisfying these constraints for a $1.4 - 1.4 M_{\odot}$ is shown in table 1 below. For this example, the latency for this time slice design is just 125.75 s even if all of the time slices are implemented with the FFT method. This set of time slices will require 619 operations per sample per template, compared with 372 for pure FFT cross-correlation without time slices, or 8.4×10^6 for the FIR filter method without time slices.

Table 1: Example of critically sampled, power-of-2 time slices for a $1.4 - 1.4 M_{\odot}$ template extending from $f_{\text{low}} = 10 \text{ Hz}$ to $f_{\text{ISCO}} = 1571 \text{ Hz}$ with a time frequency structure given by (1).



f_s (Hz)	$[t_{\text{end}}, t_{\text{start}})$	Samples
4096	$[-0.25, 0)$	1024
512	$[-2.25, -0.25)$	1024
256	$[-10.25, -2.25)$	2048
128	$[-18.25, -10.25)$	1024
...	$[-34.25, -18.25)$	2048
...	$[-66.25, -34.25)$	4096
64	$[-130.25, -66.25)$	4096
...	$[-258.25, -130.25)$	8192
...	$[-386.25, -258.25)$	8192
32	$[-514.25, -386.25)$	4096
...	$[-770.25, -514.25)$	8192
...	$[-1026.25, -770.25)$	8192

This idea has been demonstrated by the Virgo Collaboration's MBTA pipeline [20, 21], which operated in a low-latency mode during LIGO's sixth science run and Virgo's second science run in 2010.

A similar procedure can be applied for any signal family that is piecewise band-limited, as long as the time-frequency evolution is understood, either symbolically as in equation (1), or numerically.

Way too many citations here.

I didn't mention the upsampling and downsampling overhead, but I included it in my calculation. Should I describe this here, in an appendix, or in a publicly available tech note in the DCC?

MBTA should be cited in the introduction.

2.3. Reducing the number of filters with the singular value decomposition

Our second innovation exploits the fact that the templates in inspiral template banks are, by design, highly correlated. It is possible to greatly reduce the number of matched filters required to achieve a particular minimum match by designing an appropriate set of orthonormal *basis templates*. A purely numerical technique based on the singular value decomposition (SVD) is demonstrated by the authors in [22].

One may regard a bank of N discretely sampled templates of length M samples, $h^W(\theta_i; t_j) = [\mathbf{H}]_{ij} = H_{ij}$, as a matrix. The singular value decomposition is an exact factorization that exists for any matrix such that

$$H_{ij} = [\mathbf{V}\mathbf{\Sigma}\mathbf{U}]_{ij} = \sum_{k=1}^N v_{ik}\sigma_k u_{kj}, \quad (2)$$

where \mathbf{V} and \mathbf{U} are both unitary matrices and $\mathbf{\Sigma}$ is a diagonal matrix. For our purposes, we associate the rows of \mathbf{U} with a minimal set of basis templates, which become the kernels of basis filters. These filters give rise to the orthogonal SNRs, $[\rho^\perp]_k = \rho_k^\perp = \mathbf{U}_k \star x^W$. The rows of $\mathbf{V}\mathbf{\Sigma}$ become reconstruction coefficients that map linear combinations of the orthogonal SNRs from the basis filters back onto SNRs for the original templates of interest: $\rho_i = \sum_k [\mathbf{V}\mathbf{\Sigma}]_{ik} \rho_k^\perp$.

In many applications of the SVD, including ours, the matrix can be well approximated by truncating the summation in equation (2) at $L \ll N$:

$$H'_{ij} = \sum_{k=1}^L v_{ik}\sigma_k u_{kj} \quad (3)$$

The cumulative sum of squares of the *singular values*, σ_k , measures the Frobenius norm of the approximation, such that

$$\frac{\|\mathbf{H}'\|}{\|\mathbf{H}\|} = \left(\sum_{k=1}^L |\sigma_k|^2 \right)^{1/2} \left(\sum_{k=1}^N |\sigma_k|^2 \right)^{-1/2}. \quad (4)$$

This is also called the SVD tolerance. In our application, it relates to how much SNR is lost by discarding $N - L$ of the basis filters with the lowest singular values.

This result differs from other work that models gravitational-wave chirp signals in approximate ways [23, 24, 25] by starting with an exact representation of the desired template family and producing a rigorous approximation with a tunable accuracy.

2.4. Composite detection statistic and hierarchical detection

Although the SVD allows us to reduce the number of matched filters, this comes at the price of having to perform a matrix multiplication by the reconstruction matrix $\mathbf{V}\mathbf{\Sigma}$ at every sample. In some circumstances, this matrix multiplication may be more expensive than applying the orthogonal matched filters.

Further speedup may be gained in a hierarchical detection scheme. In general, the orthogonal SNRs alone provide some indication of whether any template in the original template bank is likely to have a large SNR. Consider some composite detection statistic that is a scalar function of the orthogonal SNRs, $\Gamma(\rho_1^\perp, \rho_2^\perp, \dots, \rho_L^\perp)$. Suppose that we can infer the distribution of Γ for a data stream with the signal present or with the signal absent. Then we may use a threshold crossing of Γ to trigger the conditional application of the expensive reconstruction matrix only during the times when a signal is likely to be present.

I'm sweeping the complex nature of the templates under the rug here. Is it OK to regard our packing of the real and imaginary parts of the SVD as an implementation detail? It makes the math a little more concise.

This sounds confrontational to me, but these are good citations. Can we tone it down?

We should cite [26] here.

The composite detection statistic that we employ is a weighted sum of squares, $\Gamma = \sum_{k=1}^L w_k (\rho_k^\perp)^2$, with the particular weights

$$w_k = \frac{\sigma_k^2}{\sigma_k^2 + N/A^2}. \quad (5)$$

Here, A is a desired SNR scale that is set by the analyst. As the authors show in [27], this choice of weights has a better receiver operating characteristic for a signal of SNR = A than some other obvious choices, $w_k = \sigma_k^2$ or $w_k = 1$.

3. Implementation and Analysis

The detection method described above is much more efficient in terms of floating point operations than the traditional matched filter bank method. However, time slices and conditional reconstruction greatly complicate queueing, synchronizing, and bookkeeping of intermediate signals. A low latency implementation capable of recruiting more than one CPU core would be difficult to achieve within the familiar serial programming framework because of the nontrivial time-delay relationships between samples. Due to these complications, we chose to prototype the search using an open source signal processing environment called **GStreamer**. Primarily used for playing, authoring, or streaming media on Linux systems, **GStreamer** is an integral component of the popular **Gnome** desktop.

Table 2: Operation counts per sample for six different detection methods. The operation counts for LLOID assume a reconstruction duty cycle of 5%. Note that the FIR method with LLOID is almost 10 times faster than the conventional FFT method, despite having substantially lower latency.

operations/sample	method
3 714 580 480	conventional FIR method
49 937	conventional FFT method
1 587 712	FIR method with time slices
173 926	FFT method with time slices
51 285	FIR method with LLOID
5 110	FFT method with LLOID
2 146	same, with cascade topology
1 612	same, with cascade topology 2

4. Results

5. Conclusions

Acknowledgments

LIGO was constructed by the California Institute of Technology and Massachusetts Institute of Technology with funding from the National Science Foundation and

We now have a pretty good description of time slices, the SVD, and conditional reconstruction. We still need to tie it all together. Should I mention GStreamer at all?

Citation for GStreamer?

It would be good to illustrate the layout of this particular template bank: masses spanned, time slice layout ...

Do we need separate "analysis" and "results" sections for this paper?

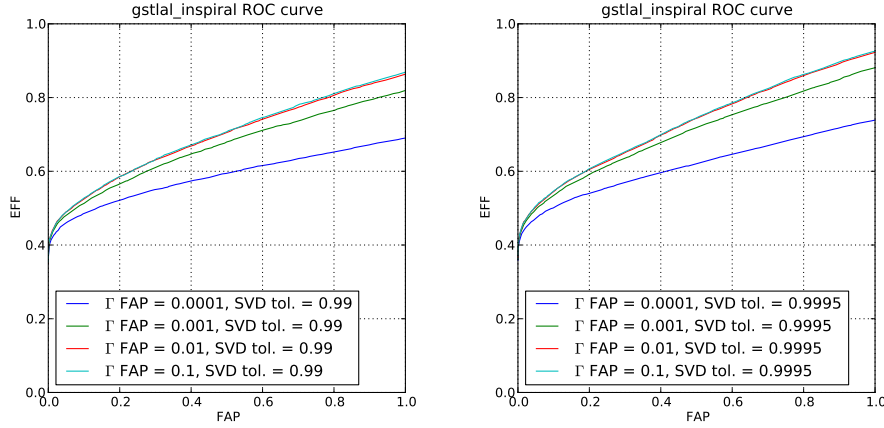


Figure 1: Receiver operating characteristic (ROC) curve of detection efficiency (EFF) versus false alarm probability (FAP).

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Appendix A. Floating point operation counts

The filter bank can be implemented using finite impulse response (FIR) filters, which are just sliding window dot products. If there are M templates of length n , and the data stream contains N samples, then applying the filter bank requires $2MNn$ operations.

More commonly, the matched filters are implemented using the FFT convolution. This entails applying FFTs to blocks of D samples, with $2n \leq D$, each block overlapping the previous one by n samples. There are $N/(D-n)$ such blocks. Modern implementations of the Cooley-Tukey FFT, such as the ubiquitous `fftw`, require about $4N \lg N$ operations to evaluate a DFT of size N [28]. A D sample cross-correlation consists of a forward FFT, an D sample dot product, and an inverse FFT, totaling $8D \lg N + 2D$ operations per block. Per sample, this is $(8 \lg D + 2)/(1 - n/D)$ operations.

The FIR filter implementation has the advantage that it has no intrinsic latency, whereas the FFT convolution has at least the latency of the FFT block size $D \geq 2n$. For example, for a $1.4 - 1.4 M_\odot$ template with duration ~ 1 ks, the FFT convolution has a latency ≥ 2 ks. However, the FIR filter implementation has the disadvantage of much greater overhead per sample than the FFT convolution. For a 1 ks template sampled at 4096 Hz, the FIR implementation requires about $n/8 \lg 2n = 2.2 \times 10^4$ times more operations per sample than the FFT implementation.

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I just yanked this from the methods section. It needs to be made more concise, maybe turned into a table of CPU budgets for various components of LLOID. This is more commonly known as "overlap-save". We should find someone else's operation count and cite it.

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