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Accelerated Searches of Gravitational Waves Using Graphics Processing Units

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Abstract. The existence of gravitational waves was predicted by Albert Einstein. Black hole and neutron star binary systems will product strong gravitational waves through their inspiral and eventual merger. The analysis of the gravitational wave data is computationally intensive, requiring matched filtering of terabytes of data with a bank of at least 3000 numerical templates that represent predicted waveforms. We need to complete the analysis in real-time (within the duration of the signal) in order to enable follow-up observations with some conventional optical or radio telescopes. We report a novel application of a graphics processing units (GPUs) for the purpose of accelerating the search pipelines for gravitational waves from coalescing binary systems of compact objects. A speed-up of 16 fold in total has been achieved with an NVIDIA GeForce 8800 Ultra GPU card compared with a standard central processing unit (CPU). We show that further improvements are possible and discuss the reduction in CPU number required for the detection of inspiral sources afforded by the use of GPUs.

Keywords: General Relativity, Gravitational Waves, Graphics Processing Units, GPU
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INTRODUCTION

It is an exciting time for gravitational-wave astronomy. Several ground-based gravitational-wave (GW) detectors have reached initial design sensitivity in the US and in Europe. An integrated full year's worth of science data summing up to more than 10 terabytes has been accumulated from all three interferometers in coincidence. Enhanced LIGO started to operate in June 2009 and plans to continue until the end of 2011 with improved sensitivity [1]. Starting in 2011, an upgrade of Enhanced LIGO to Advanced LIGO (expected to operate in 2015) will enable a 10-fold improvement in sensitivity, allowing the detectors to monitor a volume of the universe 1000 times larger than current detectors. The detection rate of signals from coalescing binaries of compact objects for these advanced detectors is estimated to be tens to hundreds of events per year [1]. The detection of the first GW is possible with Enhanced LIGO and is virtually assured with Advanced LIGO.

Coalescing binary systems of neutron stars and black holes are among the most important GW sources targeted by current large scale GW detectors [2, 3] as these sources produce a very distinct pattern of gravitational wave. The optimal way to detect known waveforms in noisy data is to perform matched filtering. The matched filtering technique is performed by calculating the correlation between the gravitational wave

data and a set of known or predicted waveform templates [4, 5]. These templates are calculated by using the post-Newtonian expansion method to approximate the non-linear equations that describe the wave propagations [6]. For spinless, circular, binary systems each waveform is specified by a set of parameters including mass pair (m_1, m_2), orbital phase α at coalescence and effective distance D_{eff} from the detector. In our tests, second order post-Newtonian orbital phases and Newtonian amplitude were used.

The number of templates required depends on the parameter volume needed to be searched. The two masses of the compact binary objects were used as the main parameter. The low frequency cutoff was set to be 40 Hz while high frequency cutoff is the Nyquist frequency (half of the sampling frequency, 2 kHz in our case). In our experiments, the mass ranges were varied and the number of templates corresponding for each mass range were calculated. Thousands of templates are required [4] to analyze a data segment for mass ranges of 1.4–11 solar masses for each individual member of the binary. In the currently running search pipeline described in [2], each data segment is made up of 256 seconds of detector data down-sampled to 4096 Hz giving 2^{20} data points. This means that thousands of FFTs, each of 2^{20} data points, are required to filter one data segment through the template bank.

Graphics processing units (GPUs) were originally designed to render detailed real-time visual effects in computer games. The demands for GPUs in the gaming industry have enabled GPUs to become low-cost but very efficient computing devices. Therefore, we propose using GPUs as a cost-effective approach to reduce the computational cost in GW searches. In this paper, we report the first test of using a GPU in a modified existing data analysis pipeline described in [2] to search for GW signals from coalescing systems of compact objects (denoted the *inspiral search pipeline*). A previous report can be found in [7].

THE χ^2 CONSISTENCY TEST

In order to verify the signals and reject non-Gaussian transient noise, the χ^2 consistency test [8] is used as a time-frequency veto. The matched filter output is split into p frequency bands such that each contributes an equal amount to the SNR, and this yeilds p time series, $z_l(t)$, where l ranges from 1 to p. In stationary Gaussian noise with or without a gravitational wave signal, the statistic [2]

$$\chi^2(t) = \frac{p}{\sigma^2} \sum_{l=1}^{p} |z_l(t) - z(t)/p|^2. \tag{1}$$

is a χ^2-distributed random variable with $\nu = 2p - 2$ degrees of freedom. Transient departures from Gaussian noise that are poor matches for gravitational wave templates, or "glitches", are associated with large values of the χ^2 statistic, and this can be used to reject such noise events [2]. The χ^2 consistency test is literally the most time consuming part of the gravitational wave search pipeline. Therefore it would be beneficial to speed-up the χ^2 test using GPUs.

The implementation of the χ^2 test to a GPU implementation was done in two parts. Firstly, 16 sequential inverse FFTs were replaced with 16 parallel inverse FFTs. This

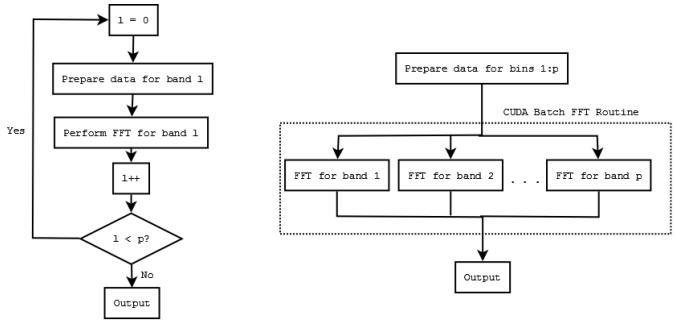

FIGURE 1. The comparison flow chart of the sequential FFTs and batched FFTs execution in the χ^2 calculation.

part was implemented by calling existing CUDA functions from the host code. The comparison of this implementation to the original one is shown in Figure 1. Secondly, we implement the GPU data parallelism on the addition operations of the χ^2 test. The additions sum up the χ^2 values from the different frequency bands in Eq. (1).

RESULTS

In the left hand side of Figure 2, the vertical axis shows the run time of the inspiral search pipeline while the horizontal axis shows the number of templates used for the search. It is shown that, at about 700 templates, the inspiral search using the original χ^2 implementation took about 6 hours to complete, while it required only about 20 minutes to complete with our GPU implementation. The speed-up factor of the GPU implementation compared to the CPU-only implementation is shown in the right hand side of Figure 2. The vertical axis shows the speed-up factor — the run time of the original CPU-only implementation divided by the run time of the GPU implementation. About 16 times speed-up was observed.

A normal computer with integrated graphics should consume about 220 W of power, or 3520 W for 16 single core computers, or 880 W for 4 quad core computers. In comparison, a single computer with GeForce 8800 Ultra consumes about 340 W of power. We could save some hardware costs and also reduce power consumption by an order magnitude.

CONCLUSION

We have shown that GPUs can significantly improve the speed of gravitational wave data analysis. We achieved a 16 fold speed-up in total by using a specially-written parallel GPU implementation of the χ^2 test, a waveform consistency test used within the gravitational wave search pipeline. We expect further speed-ups if we are allowed to change some of the search parameters and also if we replace more components in the

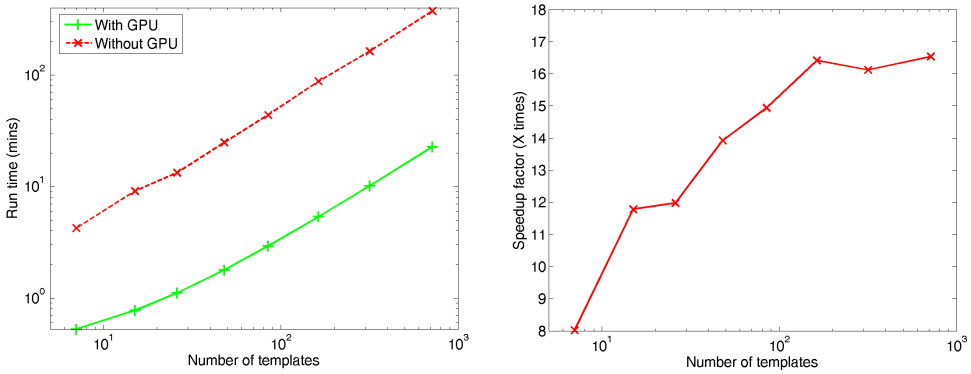

FIGURE 2. Graph on the left hand side shows the run time for executing the inspiral search with χ^2 veto enabled, both with and without GPU acceleration. Graph on the right hand side shows the speed-up factor of using the GPU in the χ^2 calculation. A plateau is shown in the speed-up factor at more than 200 templates.

pipeline with specially-written GPU implementations.

Our experiments were performed using a single GPU, while current new personal computers can be equipped with more than 3 GPUs. We would expect more than 48 fold speed-up using a 3 GPUs system when running a single-threaded search pipeline. Furthermore, if we can use the newest GPU on the market, which has about 1 TFLOPS of computing power, and assuming that the performance of these GPUs scales linearly, we would expect more than a 100 fold speed-up in a single core desktop computer.

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