International Journal of Modern Physics D
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# REAL-TIME GRAVITATIONAL-WAVE BURST SEARCH FOR MULTI-MESSENGER ASTRONOMY

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Received 28 Feb 2010
Revised 27 Jun 2010
Communicated by David Blair

Existing observations of the universe mostly come from electromagnetic (EM) waves, representing so-called multi-wavelength astronomy. In order to enable multi-messenger astronomy, direct detection of gravitational waves (GWs) has to be processed in nearly real time. In this work, we discuss algorithm and infrastructure challenges for GW burst (GWB) search to enable multi-messenger astronomy involving GWs. A real-time computing infrastructure for LIGO (Laser Interferometer Gravitational-wave Observatory) GWB data analysis is presented, using advanced computing technologies.

*Keywords*: Gravitational waves; real-time burst search; multi-messenger astronomy.

## 1. Introduction

The so-called multi-wavelength astronomy with electromagnetic (EM) waves has been the major source of progress on astrophysical research for many years. In recent years, since many large-scale facilities are operating or under construction, e.g. for direct detection of gravitational waves (GWs), we are entering a new era of multi-messenger astronomy[1].

LIGO (Laser Interferometer Gravitational-wave Observatory)[2] is the most sensitive facility currently in operation to detect GWs by measuring the interference of two laser beams, since the armlength of the interferometer is changed when the gravitational wave passes by. Other similar efforts include Virgo[3], GEO600[4], TAMA300[5], AIGO[6] and LCGT[7], which together form a network of GW detectors.

New challenges have to be addressed to enable multi-messenger astronomy involving GWs. For example, in order to enable rapid EM follow-up of GW candidates or prompt follow-up of external EM and particle triggers with GW detectors, GW data analysis has to be processed in nearly real time (e.g. generating GW burst candidates within minutes). In this work, a brief introduction to the status of LIGO burst data analysis is given. Detailed algorithm and infrastructure are presented using advanced computing technologies to enable real-time GW burst (GWB) search.

## 2. LIGO GWB Data Analysis

In general, GWB data analysis includes the following steps: burst trigger generation, veto analysis, coincidence and coherent analysis. In this section, a brief introduction is given below.

### 2.1. *Trigger generation*

GWBs are short duration (much shorter than 1 second) gravitational-wave signals with little assumption on signal morphology. Existing pipelines involving LIGO burst trigger generation include the Omega pipeline[8], KleineWelle[9] and the coherent WaveBurst (cWB) pipeline[10]. A trigger is described with properties, e.g. GPS start time, duration, central frequency, and so on.

### 2.2. *Veto analysis*

Veto analysis is used to identify periods when the interferometers produce data of questionable quality. It involves making use of information from auxiliary channels to safely and effectively veto triggers in deleterious times due to instrumental glitches and environmental disturbances. Veto is essential to improve data analysis efficiency, especially in real-time scenarios. If a trigger is vetoed, corresponding follow-ups are not required.

### 2.3. *Coincidence and coherent analysis*

In general, a GWB signal has to appear from multiple GW channels of multiple GW detectors. A coincidence method finds excess energy triggers in each detector and select time (-frequency) coincidence triggers, usually within a window of [-.25s, +.25s] by experience. In this way, the number of GW candidates is reduced further. Coherent follow-up of remaining triggers after veto and coincidence analysis can perform further cuts, e.g. the amplitude consistency cut or correlation consistency cut.

## 3. Real-Time GWB Search

Real-time requirements add more constraints to GWB search pipelines, which have to be processed within minutes instead of hours or days without manual intervention. New algorithm and computing infrastructure are required, especially in the case of Advanced LIGO[11] with larger computation requirements.

### 3.1. *Motivation*

Astrophysical processes which produce GW signals strong enough to be detected must release a lot of energy, so it is very likely that some of that energy is emitted in the form of EM radiation, which is generally much easier to detect, if looking in the right direction[12]. So rapid EM follow-up of GW candidates motivates real-time GWB search. In the case of external triggers and their follow up with GW detectors, real-time GW burst searches may provide information about an astrophysical event (even if no GW signal is detected).

### 3.2. *Online vs. offline*

Traditional LIGO data analysis are performed at either online or offline mode. Online data monitoring with data streams as input is usually processed at observation sites. At the offline mode, data analysis is performed off-site using data production instead of original data streams. These are illustrated in Fig. 1.

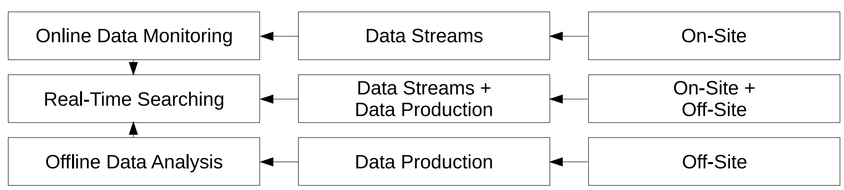


Fig. 1. LIGO data analysis styles.

New real-time search is performed somehow in between. It tries to achieve reasonable offline data analysis sensitivity and accuracy within a much shorter time, by utilization of online monitoring results or new computing methods.

### 3.3. *Real-time computing infrastructure*

Fig. 2 presents a real-time GWB search pipeline. An OmegaMon[13] is developed using DMT (Data Monitor Tool)[14] for statistical tracking of burst triggers generated from the Omega pipeline. SVM (Support Vector Machines)[15] techniques allow us to

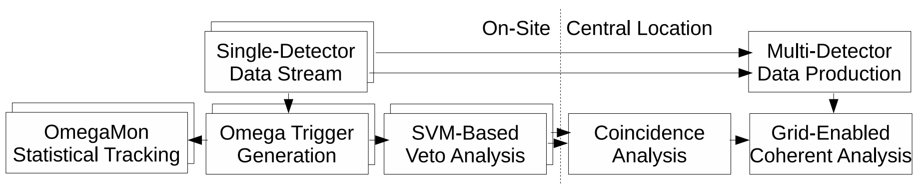


Fig. 2. Real-time GWB search pipeline.

use information from all available auxiliary non-GW channels together to reject GW noise transients due to instrumental artifacts. SVM-based veto can be processed fast enough to meet real-time requirements with reasonable efficiency.

At the central location, veto-passed triggers from each detector are collected together for coincidence analysis. And coincidence-passed triggers are followed up with coherent analysis accelerated by using LDG (LIGO Data Grid)[16] computing and data storage resources. The whole pipeline has to be finished in minutes for rapid EM follow-ups. It can also be triggered by external EM events as prompt GW follow-ups.

## 4. Conclusions

In this work a real-time infrastructure for LIGO GWB search is presented using various algorithms and computing technologies. This is essential to address challenges brought by multi- messenger astronomy involving GWs.

Ongoing work include implementation of the OmegaMon, SVM veto algorithms and grid-enabled environment and building a real-time infrastructure at Tsinghua University for the LIGO sixth science run and Advanced LIGO.

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