LIGO Scientific Collaboration

Determine upper limits on event rates for inspiralling compact binaries with LIGO engineering data

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DRAFT

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1 Scientific problem addressed

Coalescing compact binaries are among the best understood sources of gravitational waves in the frequency band of LIGO and other earth based detectors. We propose to analyse engineering data, acquired using the 2km interferometer at Hanford and the 4km interferometer at Livingston, to determine upper limits on the event rates of inspiralling compact binary systems.

Our target population will include typical neutron star binaries in which the elements are each $1.4\,M_\odot$. Specifically, the data stream will be searched for signals which match the post-Newtonian gravitational waveform for non-spinning bodies having total masses in some range centred on the NS binary mass. The mass range will be chosen based on available computational resources and estimates of waveform accuracy within the pass-band of the interferometers.

Having carried the analysis through to conclusion for the chosen population, it will be straightforward to place upper limits on other binary populations.

We anticipate learning a great deal about the data and the instruments over the course of this project. While this is secondary to developing and testing a pipeline for analysis of this kind, it might be considered scientifically more interesting since the astrophysical limits will likely be several orders of magnitude higher than expected rates.

2 Computational and analysis methods

The search for inspiral events will begin with (i) time series from the two interferometers, (ii) calibration information for each interferometer and (iii) channel(s) to characterize the quality of the gravitational-wave data.

In addition, the search will use servo loop signals, PEM channels, etc, to discriminate good/bad data and veto events observed in the gravitational wave channels. Over 1000 different channels are recorded for each interferometer. As our work plan develops and experience is gained, we will establish the most important channels for this search type.

2.1 Data flow pipeline

1. **On-site, real-time analysis**: The data from each intereferometer will be searched for inspiral signals at each site in real time. This stage of the search will be executed on the LDAS Beowulf clusters at the two sites. The search codes will be built to run within LDAS as dynamically loaded shared object libraries; the structure of the search codes will follow the specification provided in the wrapperAPI baseline requirements. Events generated by the search codes will be inserted into the database for later analysis. This will be considered the first cut through the data. Some use will be made of vetoes based both on the nature of the inspiral signal itself, and on the auxilliary channels.

   In addition, we expect the DMT to provide triggers which will be inserted into the database. A subset of PEM channels may also be analyzed in real-time to detect noise bursts and these events injected into the data base

2. **Off-line analysis**: The first cut will produce an excess of events for further follow up analysis.

This stage of the search need not occur in real-time.

(a) *Correlation of inspiral and PEM events*: Auxilliary channels, identified to provide vetoes, will be searched for burst events. When such a noise burst is coincident with an event identified by the inspiral search code, that inspiral event will be vetoed if it could be caused by the noise registered in the PEM channel.

(b) *Coincidence between interferometers*: After vetoes have been applied to the inspiral event lists from each intereferometer, events coincident within the XXms time window and by signal parameters will be retained for combined analysis. All other events will be discarded. The different response of the two interferometers may provide an additional veto.

(c) *Combined analysis using both data streams*: The segments of data which produces the list of events retained at this stage will be reanalysed using coherent multidetector methods. This will provide the final cut in the analysis pipeline. Events below a suitable threshold will be discarded.

3. **Simulation to determine efficiency**: Independent of the statistical method used to place an upper limit on the rate of inspirals, it will be important to determine the efficiency of the pipeline to detect the target population of sources. This will be achieved by re-analyzing the data with simulated signals injected through the same pipeline discussed above. The fraction of the population detectable by the pipeline is paramount to determining an upper limit.

4. **Statistical analysis**: Several statistical techniques exist to determine the upper limit on inspiral events. All require the same type of output, but each makes more or less use of the resulting output. A method will be chosen to determine the best upper limit withouth precluding detection of a signal.

2.2 Computational and analysis tools

Cataloging: Simulated and astrophysically plausible events will be injected into the LIGO relational database tables. These cataloged events will be the outputs of astrophysical event filters (e.g. output of inspiral chirp filters that satisfy certain threshold criteria). The outputs will be generated using codes under development by the LSC. Two independent inspiral codes should be available: (i) traditional templated code and (ii) an FCT based code. Both codes will be tested in advance of the data run, but it is likely that only one of them will be used during the real-time portion of the analysis.

Instrumental triggers will also be injected into the LIGO relational database tables. These cataloged events will be outputs of detector characterization methods (e.g. identifying transients in some of the PEM channels). Some amount of experimentation will be needed to determine an adequate set of channels to examine. We anticipate that the E2 data will be very useful for this purpose.

Searching The LIGO relational database will be queried (using the LDAS software) to determine astrophysical and instrumental correlations. During this stage of the search, different queries will be carried out to determine a list of events consistent with binary inspiral. For example, these events should be seen in the GW channel *only*, satisfy some form of χ^2 veto test, be observed with same physical parameters (masses, etc) in each interferometer, etc. The tools for database mining already exist, however this phase of the analysis will benefit greatly from quicklook software which can easily link to the database. Such tools will be developed (under MATLAB for example).

It may be possible to use the LIGO E2 data to construct queries that reduce the false alarm rate without reducing the correct detection rate too much. This can be determined by Monte-Carlo injection of simulated signals into the data stream.

Finally, some subset of these candidate events should be followed up using a coherent two interferometer search technique. That is, data from both interferometers should be combined in the filtering process. This should enhance the detection efficiency. No code is yet under development for this stage of the search. One deliverable from this project should be LAL compliant code for this purpose.

Simulation: The injection of simulated signals into the GW channels will play an important role in the statistical interpretation of the results from the database queries. This is an off-site analysis task which should be undertaken using the same analysis pipeline, but using data containing the simulated signals. Much of the software needed for injecting signals is already under development within LAL; the rest will be developed and tested as part of this project. This analysis will be carried out off-site, probably at Caltech or other suitable LSC facilities.

Statistical Analysis: The statistical methods to be used in this analysis are reasonably well understood. To accurately deteremine the statistical significance of the search output, however, an accurate log must be kept of all analysis performed on the data over the course of the project. A format for this log and a mechanism to maintain and make use of it will be developed as part of this project.

3 Required resources

Software: This project requires software to carry out searches for binary inspiral waveforms in LIGO data. It is assumed that templated and FCT based search codes will be implemented in LAL and available under LDAS. It is also assumed that the LDAS software pipeline will be available for on-site analysis of the data in the manner proposed for the full-scale science runs in the future.

Hardware: Availablility of a Beowulf cluster at each site is required for the first cut analysis. Follow-up analysis will be carried out on LIGO facilities at CACR and UWM.

Data: Data from the LIGO E2 run will be used during the testing and development phase. This will be essential to develop a search strategy in advance of the data taking. Data from LIGO E?? will be used to determine the upper limit; it is assumed that coincident data from two interferometers will be available.

Personnel: Jordan Camp, Tom Prince, Peter Shawhan will participate in the analysis effort. WE NEED TO FLESH THIS OUT A LOT. HOW MUCH TIME WILL THEY COMMIT? DO WE NEED OTHER MEMBERS OF THE LDAS TEAM TO AID IN DEVELOPMENT AND IMPLEMENTATION? ETC?

4 Work plan

THIS CAN BE ASSEMBLED AFTER THE NEXT TELECON WHEN THE TASK-PEOPLE LIST HAS BEEN COMPILED AND AGREED TO.