SURF 2003: First Progress Report
LIGO Interferometer Data Analysis of Transients

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1 Introduction

Gravitational waves are a phenomenon predicted by the Theory of General Relativity. However, almost 90 years on from the formulation of General Relativity, gravitational waves have yet to be detected, owing to the tiny effect they are predicted to have on the world around us. Because of this, it is unknown what types of gravitational waves may exist, although several propositions have been made as the the kinds of gravitational waves that my be generated by specific mechanisms.

The Laser Interferometer Gravitational-Wave Observatory (LIGO) project began construction in 1994, with the aim of detect gravitational waves. It consists of two facilities based at Hanford, Washington, and Livingston, Louisiana. Both facilities work by using laser interferometry to measure minute relative movements in two test masses at the ends of 4km long vacuum tubes, arranged at right angles. From these measurements, and considerable data processing and statistical analysis, it is hoped observations of gravitational waves can be made.

The first scientific operation of LIGO (referred to as science run 1, or S1) took place in August 2002. After collecting and analyzing the data produced, various corrections and improvements were suggested, including the basis for my SURF project. A second science run (S2) was undertaken during the spring, the results of which are currently being discussed, and a third science run (S3) is scheduled for the Autumn.

Whilst running, signals from the laser interferometers, as well as other measurements of interest, are first digitized and then recorded electronically. The observatories generate between 3 and 6 megabytes of data per second, which is far too much for a human to process. To get round this, several simple statistical procedures are applied to the data to automatically make a note of things that might be of interest; these notes are called triggers. One of the properties that are being looked for are transients, which are short, sharp changes in the data that do not fit with what would have been expected. At present, triggers for transients are being generated many times a second, which precludes human examination of each event. My SURF project is concerned with the further analysis of these transients, and their detailed classification.

2 The Project

My SURF project is to further analyze and classify the LIGO data transients in the regions indicated by triggers, in an effort to differentiate between false alarms and candidates for real gravitational wave signals, and to provide data to assist the classification of the potential signals. This will hopefully reduce the transients of interest to a sufficiently small number that a human can analyze each one to look for gravitational waves, possibly helped by the characteristics that have been used to classify the transients.

I intend to approach this by developing and applying various statistical procedures and tests. Such procedures could well include Bayesian, Classical, or Bootstrap statistical analysis, and other techniques such as frequency analysis.

Bayesian analysis involves thinking about a problem and quantifying what you would expect to happen, and then updating that expectation using the data. Bayesian analysis is used frequently in computer learning applications, and is probably the closest kind of statistical analysis to the human thinking process. It may however yield biased results, depending on what your prior beliefs were.

Classical analysis, in contrast, involves working with the data from the start. Typically, a hypothesis is suggested, and then the data is analyzed to see if it provides overwhelming evidence against the hypothesis, in order to rule it out. Such analysis is obviously very conservative in its outcome, but its accuracy is guaranteed.

Bootstrap analysis is an attempt to analyze the data, whilst making the fewest assumptions about what might or might not be present. Bootstrap analysis is the most open minded of the three, although it is the least good at noticing subtle differences.

All these techniques may be applied straight to the data, or to specific frequencies that may or may not be present in the data. Other statistical procedures and methods for their application may well become apparent during the project.

Once I have investigated the different options open to me, I intend to produce various computer programs that implement some of these procedures. Once tested on artificially generated data to check their behavior, I will apply them to sections of the S2 data, to ascertain if they give useful classifications of transients. Utilizing the successful programs developed, I finally plan to look for other characteristics that may be of use to help classify transients.

3 Current Progress

After all the necessary paperwork and setting up, I spent the remainder of my first week looking at a small sample of the LIGO S2 data. From this, it became apparent that some form of frequency analysis was going to be needed, since the signal is dominated by a 30Hz component.

In the second week, I brainstormed various different types of statistical analysis that could be used, and began implementing a few of them in computer programs, to test their efficiency. As a starting point, I worked on a natural extension to the process used to generate transients triggers (which bases its testing on outliers on a normal distribution) by using bootstrap analysis to look for outliers. Unfortunately, this proved not to be as useful as I had expected, although I have a few ideas of how it might be made more useful.

Following this, I investigated a new method named “BlockNormal” analysis that was presented in a talk I attended during the first week by Patrick Sutton. The procedure assumes normally distributed data, and looks for change points, where the data changes from being best described by one sort of normal distribution, to best being described by another. As described in the talk it involved Bayesian methods, and one extension that I investigated was converting the procedure to use Classical analysis. The resultant “Classical BlockNormal” procedure yields very good results in artificially generated normal data, but has difficulty coping with slowly varying changes, and of course can only deal with data that is distributed normally.

During the end of the second week and the beginning of the third week, I implemented a piece of software that provides a testbed for the various procedures I will be working on. It allows analysis to be performed on actual S2 data or on artificially generated data, and in the future will be extended to provided preprocessing of the data to put it into a form that the tests find most easy to deal with.

Most recently, I have been working on a natural extension to the BlockNormal method, which is to introduce Bootstrap analysis to get round the normal limitation. At the suggestion of my mentor, I implemented a test based on the Kolmogorov-Smirnov two-distribution two-tailed test, which is effectively a Bootstrap method in disguise. This test works very well, but is unfortunately much slower than the Classical BlockNormal procedure.

4 What's Next

The following obvious goals would directly help progress the project:

- Integrate the current statistical procedures into the existing DMT software framework, and apply the procedures to filtered, whitened S2 data in the neighborhood of transients triggers. This would show the performance of these procedures in real-life situations.
- Implement Fourier conversion in the testbed, so that testing can be based in frequency space, or in frequency banded time space.

In addition, there are several lines of investigation currently open to me to further investigate and develop useful statistical procedures:

- Work on the initial Bootstrap Outlier method to make it more useful.
- Investigate using the Classical BlockNormal or Kolmogorov-Smirnov procedures to test for two changes in distribution, with a common distribution either side, instead of just looking for one change. This would better help detect transients, and attempt to quantify their duration, but would need quite a lot more computation.
- Modify the Classical BlockNormal or Kolmogorov-Smirnov test to use a sliding time window, to get around anomalies caused by very small numbers of samples at the extremities of the testing region.
- Implement a frequency space conversion in the testing platform, to enable the statistical tests to work with specific frequency components.
- Look into current statistical research into better forms of Kolmogorov-Smirnov tests that are more powerful and/or easier to compute.