Using Continuous GWs from Known Pulsars to Measure Gravitational Wave Speed

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1 Introduction

Gravitational waves (GWs) were predicted by Einstein in 1916 during his development of the Theory of General Relativity (GR) and finally detected directly in September 2015 by the Laser Interferometer Gravitational wave Observatory (LIGO)[1]. Now that direct measurements of the phenomena are possible, we can start to analyze their properties in more depth. Considering GR does not offer a complete description of gravitation (there does not exist a commonly accepted model for quantum gravity, which may be significant in case there are any surprises in this research), measuring their properties can be essential in testing GR to improve our understanding of this fundamental force.

We will look into the measurement and bounding of the speed of continuous gravitational waves by comparing variances observed in long-term signals using the motion of the detector relative to the source. We can use Doppler effects in the phasing of these waves to get an estimate for their speed, even in the absence of electromagnetic counterparts. However, in order to measure this speed, we will use a known EM signal and measure its continuous wave partner.

In this paper, we discuss the background behind the research (Section II), as well as how we will proceed (Section III). Finally, we propose a general timeline which will guide the objectives of the research over its 10 week course (Section IV).

2 Background

GWs are self-propagating fluctuations in space-time caused by massive bodies accelerating through space. While any massive body emits these, this radiation is absolutely negligible in most phenomena e.g. a small man-made satellite emits GWs at about 10^{-43} W and the Earth in its orbit of the Sun emits at about 10^{2} W (ignorable on solar scales, as the total electromagnetic output of the sun is about 10^{26} W)[2]. They were not observed in any form until 1974 with observations of the degradation of the orbit of the Hulse-Taylor Pulsar

(PSR B1913+16), which has been regularly monitored for the four decades since[3]. The measurements perfectly matched the theory and were the closest to direct observations of GW perturbations until last year, with GW150914. The announcement of the direct measurement by aLIGO made it clear that greater understanding of the phenomena is imminent.

There are two promising sources for the observation of GWs: compact binary coalescences (CBCs) (e.g. the black hole merger which caused GW150914) or orbiting bodies (e.g. PSR B1913+16). The latter gives signals with very long lifespans but smaller amplitudes, called continuous waves (CWs). The major focus of targeted CW searches are pulsars, which have known frequencies of rotation and locations in the sky (via radio astronomy measurements). These systems only create gravitational waves if the CW source (usually a pulsar) has an irregularity in its mass distribution: if the surface is not perfectly spherical, even a centimeter high bump from the surface would result in the emission of GWs.

In fact, continuous gravitational waves have not been directly observed yet. The tradeoffs for a continuous signal begin with the many unknowns of neutron star (NS) physics. These objects are somewhat understood, but unknown factors may impact their GW signals. Furthermore, their amplitudes are far smaller than those produced in CBCs, meaning that only analyzing long timescales worth of data can hope to reveal continuous wave signals[7]. The sensitivity of the measurements grows as the square root of the observing time via statistical data analysis.

CWs in general could have six polarizations: plus ($+$), cross ($\times$), vector x (xz), vector y (yz), breathing (b), and longitudinal (l). These represent the different basis tensors which could compose the signal. Different theories predict different polarizations: GR currently predicts only $+$ and $\times$ polarizations, but all could be present. This research will assume the two GR polarizations.

The angular frequency, ω, of the source dictates the frequency of a GW. From a non-moving point relative the source, a CW would give a sinusoid with angular frequency 2ω. However, Earth's rotation about both its spin axis and the Sun yields a different expected signal. When approaching the source, the signal has a positive frequency shift and while going away from the source, the signal has a negative frequency shift, in line with the Doppler effect. This shift is dependent on the ratio of the relative velocity of the detector to the source and the velocity of the wave, therefore by measuring this shift, one can measure the velocity. Research into the methods of doing such (including heterodyning data) have been well researched[4−6], but were generally unsuccessful in estimating the speed of GWs. However, since the first of those papers was published there have been major improvements to the sensitivity of the device.

3 Project Description

This project will analyze LIGO data from searches targeted on known pulsars, such as the Crab Pulsar (located in the Crab Nebula) and the Vela Pulsar (in the constellation Vela). We know their ω (30 rps and 11.195 rps respectively), so we have a concept of the signal we want. The primary goal of the research will be to modify the standard GR analysis code by adding an extra parameter which quantifies how different the speed is from c. The signal will fluctuate differently based on its speed, so we can measure its velocity by comparing the signal to those which would appear at various speeds of GWs[4].

The precision of these calculations is not fully known; whether the current LIGO run could detect small deviations (e.g. below 10^{-4}c) is unknown. While we will be able to measure these directly, current massive graviton models calculate GW speeds to lag no more than 4×10^{-26} m/s behind the speed of light,[4] so the bounds we derive will very likely contain c. However, checking these models is an obvious physical necessity, no matter the resolution.

By beginning with theoretical models, one can start to generate expectations for what any continuous wave would look like at any given velocity. Accounting for the different polarizations of GWs yields models which help to gain an even greater experimental understanding of the nature of GWs.

The analysis will be expanded, initially, to earlier data gathered during Science Runs 5/6 (LIGO; 4 Nov 2005 - 1 Oct 2007, 7 July 2009- 20 Oct 2010) and Observing Run 1 (aLIGO; Sept 2015 - Jan 2016). Results from S5 and S6 represent a longer runtime but a significantly louder noise compared to O1.

4 Proposed Timeline

- Weeks 1-2:
  - Understand targeted CW searches
  - Simulate a GR pulsar signal
  - Retrieve GR pulsar signal from my own matched filter (Gaussian and actual noise)
- Weeks 3-4:
  - Create modified waveform models with an extra parameter to account for GW speed other than c
  - Check overlap between GR templates and non-GR waveforms as a function of this extra parameter
- Weeks 5-6:
  - Learn about LALSuite pulsar estimation code and how to run it
  - Test implementation of variable GW speed
  - Perform sanity checks
- Weeks 7-8:
  - Bring it all together/ Start to analyze actual LIGO data

- Weeks 9-10:
  - Finalize Analysis
  - Write presentation
  - Write final report

5 References

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