LIGO SURF - Interim Report 1

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Motivation:

The Hubble-Lemaitre Constant H_0 is an important quantity in cosmology because it characterizes the rate at which the Universe is expanding, and it can be measured from a cosmological distance-redshift relation. However, two classical methods of measuring H_0 have led to seemingly inconsistent results, known as the "Hubble tension". One method uses type Ia supernovae (whose redshifts are provided by their spectra) as "standard candles" to infer the (luminosity) distance, while the other method relies on the acoustic features in the Cosmic Microwave Background (whose redshift corresponds to the surface of last scattering and is well-calculated) as a "standard ruler" to measure the (angular-diameter) distance. The tension has triggered people's interests in searching for alternative methods of constraining H_0, and it turns out that gravitational-wave (GW) observations is a promising candidate.

It has been well realized that a GW signal can serve as a "standard siren", as one can easily obtain the source's luminosity distance from the signal's amplitude. If one can also somehow infer the source's redshift, it will then allow for a measurement H_0. One way to achieve so is to identify the host galaxy with an EM counterpart, and this method has been successfully demonstrated by the GW170817 event [1]. However, it may not be guaranteed that an EM counterpart can always be found (e.g., the line of sight to the source may lie in the Galactic plane). Thus a way of inferring the redshift using the GW signal alone would be of great significance. One such possibility is to use the internal modes of a neutron star.

Under certain conditions the neutron stars cause tidal effects on each other which excite modes within the neutron stars. The following technique was used by [4], except they only considered the effects of the specific f and g modes, our analysis will focus primarily on the r-modes within the neutron stars. We will choose to focus primarily on the r-mode because it is now thought to have a considerably strong supplemental effect on the merger for the possible detectable frequency range of future generation detectors. For a given binary neutron star inspiraling gravitational wave data we are able to measure the r-mode resonance which allows us to find the redshifted spin frequency of the binary. This spin frequency can be mapped to the spin parameter referred to as $\chi = S/M^2$, where $S \sim f_{spin} MR^2$ is referring to the spin angular momentum. The mass is redshifted by a factor of $(1 + z)$. This measured value of χ is really shifted by a factor of $1/(1 + z)^2$. With this redshifted spin parameter we can compare it to the Point Particle Orbit which also gives us a measurement of χ, this measurement of the spin parameter experiences no redshift. By comparing the two measurements of χ we are able to deduce what the redshift value z would be for a given binary.

We will finally use the Fisher Matrix technique to determine how well we can measure the cosmological redshift z.

Progress:

As of the date this report is due, I am currently working on incorporating the f-mode analysis discussed in [4]. More specifically I am trying to recreate a similar plot to their figure 1. To do this I first had to recreate the work done in [2] to lay the framework for the code we are using in the project. This involved initially only looking at the Point-Particle phase contribution $\Psi_{pp}(f)$ instead of trying to include the tidal effects $\Psi_{tidal}(f)$ on the total phase $\Psi(f)$. Currently I have been able to extract errors on a list of parameters such as $(\ln D_L, M_1, M_2, \phi_c, t_c, \beta)$ and I will need to alter this list of parameters as this project goes on to compensate for new physics. Implementing the parameter known as β was a large step because that introduced the effects of spin into the calculation of the waveform which was not initially accounted for in the first attempt at recreating [2]. This parameter β is closely related to the spin parameter χ discussed in the motivation section which will be crucial for extracting information about the redshift of the binary.

In doing this I learned how to use the Fisher Metric Technique to get the expected errors on each input parameter for a given waveform in the frequency domain $\tilde{h}(f)$. The Fisher Metric is a matrix constructed in such a way that $\Gamma_{ij} = \left(\frac{\partial h}{\partial \theta_i} | \frac{\partial h}{\partial \theta_j}\right)$ where θ is the input parameters going into the waveform function. To extract the errors one needs to invert Γ, the square root of the diagonals corresponds to the errors on each parameter. This technique will allow me to extract the errors on the cosmological redshifts needed to recreate figure 1 of [4]. Once this is accomplished I will need to begin working on incorporating the effects of the r-mode on the tidal phase contribution. This is where we look to [3] for the new physics to be added.

Obstacles:

This summer has had quite a few unforeseen problems and obstacles for such a short time frame. Unfortunately, I have had a couple family emergencies that have altered the lives of everyone involved. This did cause a bit of a halt in my research progress but I have made sure that it hasn't impacted my research severely and my project is still making progress in a timely fashion. Obstacles directly related to the project have just been unforeseen bugs in my code that I have had to spend a good deal of time fixing. I struggled a lot initially understanding how to get the initial framework for the project in code and felt slightly overwhelmed, but luckily my mentor was very patient and helped me overcome that large initial hurdle. The hardest thing for me to understand was how to handle constructing the matrix with all the partial derivatives because in my previous python courses, we had only dealt with numerically differentiating and integrating single variable functions. I expect to see lots of bugs in the future moving forward, which should be expected with any project involving code. I would also expect there to be a bit of a challenge going forward in needing to know the linear algebra necessary to do calculations, while I did take a linear algebra course at my home institution and got a good grade, it was an awful experience and the class did not teach linear algebra as well as it should have. I expect to just have to refer to an old textbook to re-learn any necessary material for what I need to do and it shouldn't be a big deal.

References

[1] B. P. Abbott and et al. "A gravitational-wave standard siren measurement of the Hubble constant". In: *Nature* 551.7678 (Nov. 2017), pp. 85–88. DOI: `10.1038/nature24471`. arXiv: `1710.05835 [astro-ph.CO]`.

[2] Curt Cutler and Eanna E Flanagan. "Gravitational waves from merging compact binaries: How accurately can one extract the binary's parameters from the inspiral waveform?" In: *Physical Review D* 49.6 (1994), p. 2658.

[3] Eanna E Flanagan and Etienne Racine. "Gravitomagnetic resonant excitation of Rossby modes in coalescing neutron star binaries". In: *Physical Review D* 75.4 (2007), p. 044001.

[4] Chris Messenger and Jocelyn Read. "Measuring a cosmological distance-redshift relationship using only gravitational wave observations of binary neutron star coalescences". In: *Physical review letters* 108.9 (2012), p. 091101.