LIGO SURF - Interim Report 2

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Progress:

Over the past month I have been able to overcome the steep learning curve that is the reproduction of results from several research papers that our project is heavily based on. Early on in the project the first line of business was to recreate results from Cutler and Flanagan [1]. Initially we used their most basic analysis method of using a waveform that incorporates a 0th order Post Newtonian expansion for the point particle phase contribution with no tidal effects or spin being accounted for. We used this simple model with only 4 free parameters for me to learn how to apply the Fisher Matrix technique numerically to our model gravitational waveform and extract the best possible measurement errors. The parameters being $(\ln D_L, \phi_c, t_c, \ln \mathcal{M})$ After this was successfully accomplished I needed to raise the order of the Post Newtonian expansion from 0th order to 1.5th order as well as including spin. This research paper had already included this later in their analysis, so I continued to recreate their more advanced results. This added in a new parameter known as (β) which which encodes all the necessary information about the spin effects of the binary.

After this basis was set I needed to learn how to incorporate at least one mode into the tidal effect phase contribution so that we can incorporate the desired cosmology. My introduction to incorporating the neutron star modes was through the f-mode. My goal was to recreate the analysis done in Messenger and Read [3] by recreating their figure 1. In doing this we had gone back and forth in deciding what would be the most efficient parameters to use. We ended up adding the reduced mass (μ) and the cosmological redshift (z) to the existing list of parameters which ended up as $(\ln D_L, \phi_c, t_c, \ln \mathcal{M}, \mu, \beta, z)$. This ended up having several hiccups that I had to keep fixing in order to actually recreate the desired plot. One of those problems that we had was realizing that between the two papers there was actually a different detector sensitivity profile used and we had to account for this in my code.

In order to reassure ourselves that my code was working properly I plotted the phase contributions separately as a function of frequency (point-particle and tidal) to see if my phase functions were in line with what they should be. This also offered as a sanity check for my unit conversions since my experience in working with geometric units is so fresh. I also plotted the relative errors with respect to each parameter as a function of step size as a method to see where the Fisher Matrix procedure is most numerically stable with respect to step size of each parameter that we are working with. This allows us to know with confidence that our results are not dependent on numerical instabilities with respect to step size in our numerical partial differentiation.

Once this was accomplished I had successfully incorporated the point particle phase contribution at 1.5 PN order with spin, as well as f-modes which allowed us to be able to use the cosmology methodology discussed in Messenger and Read [3]. This was a big milestone for our research because the rest of the project is focused on incorporating a slightly more complicated tidal mode known as r-modes in combination with the effects of f-modes. I have started working on putting the r-modes in by starting fresh with the simplest point particle phase contribution (0 PN order without spin or cosmology) and slowly adding the physics back into the waveform analysis. As of writing this I am almost done incorporating the basic r-modes and will be adding in new physics in the coming week.

Remaining Goals:

Our primary goal for the remainder of the project is to successfully incorporate a waveform including 1.5 PN order, spin, f-modes, and r-modes. To do this we will be going back to a simple point particle phase function and slowly add the physics back in on top of the r-modes and a 0PN point particle phase function. We will be making use of the r-modes discussed in Flanagan and Racine [2] and add them in combination with f-modes in a similar way to Yu and Weinberg [4]. Once this is accomplished we will spend some time looking into whether or not we can relax assumptions made about the equation of state of a neutron star and investigate other inertial modes that might be contributing to merger waveform. Due to unexpected awful events occurring within my family, I had to slow down progress this summer to help in anyway I can to alleviate the pain of my siblings and relatives but I still kept this project as my top priority and intend to keep it that way, but that is why we are a little behind schedule.

References

[1] 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.

[2] 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.

[3] 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.

[4] Hang Yu and Nevin N Weinberg. “Dynamical tides in coalescing superfluid neutron star binaries with hyperon cores and their detectability with third-generation gravitational-wave detectors”. In: *Monthly Notices of the Royal Astronomical Society* 470.1 (2017), pp. 350–360.