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Gravitational Waves Lab

E. Long (UNH)

Abstract

This lab is based on analysis of publicly available gravitational wave data. For this lab, you will develop analysis skills to extract masses, velocities, and other parameters from massive compact object merger events.

Gravitational wave data from LIGO and VIRGO, analysis software tools, and tutorials on using each is available at `https://www.gw-openscience.org/`.

An easy way to get started with learning the python analysis code is to use colab.research.google.com – it connects to your Google account, but gives you immediate access to running python in Jupyter notebooks without requiring any installation. The 2020 Gravitational Wave Open Data Workshop has an introduction to setting this up that can be found as 'Option 1' at `https://github.com/gw-odw/odw-2020/blob/master/setup.md`. However, for actually doing your analysis it's recommended to instal conda on your local machine using Option 3 or Option 4 in the previous link. The main website for the Open Data Workshop is `https://www.gw-openscience.org/s/workshop3/`

For this lab, you will be analyzing at least two sets of gravitational data, and are welcome to explore more. The first event to analyze will be the same one analyzed in [1]: GW150914. The second event is your choice among those available in the Gravitational Wave Catalog available at `https://www.gw-openscience.org/eventapi/html/`.

Your goal is to:

- Choose cuts and filters that clean up the data as best you can
  - Be methodical and take your time with this, trying many different ways to clean your data. This will be the most important step to improve your uncertainties!
- Create a simple oscillating function and use it to fit the data. This can be done in multiple steps if you separate the major sections of the data in a clever manner, or all at once depending on the complexity of your function.
- Determine the chirp mass of the merger events, making sure to correctly determine the uncertainty of the chirp mass from the experimental data
  - Make sure to include the detector's strain noise as part of your error analysis, and how your cuts affect the signal-to-noise ratio
  - Determine the mass first by using the fit you made above, then by using the tools available in Bilby and compare the results from the two methods
  - Plot and fit a Gaussian to your chirp mass to help determine your uncertainty

- Utilize models ('approximants') to determine the masses of the merging objects, the mass of hte final object, and the luminosity distance of the merging objects as it changes with time
  - Use multiple models in order to determine the uncertainty on these numbers
  - Systematically play with the parameters in these models and discuss what you learn in how changing each parameter changes the resultant waveform
- When you have the total mass, find the objects' relative velocity as it changes with time
- As best you can, determine some physical quantities of the ring-down and create your own model to apply to this section of the data. The problems in Homework 1 included a simple example of this. Make sure to discuss what you learn from this in your paper.
- After you've determined your results (and only after – don't bias your results!), look up the discovery paper for your chosen event and compare your results with theirs
  - It's ok if your results don't perfectly agree with the published data! Their analysis will be much more in-depth, as they've had years to study this instead of weeks. In your discussion section, point out some things that the discovery paper included that you didn't that could be why these results differ, and the physical implications of them.
- As you do this work, if you think of other potentially interesting patterns to look for, I encourage you to explore it and include them in your report! Gravitational waves are a very new area of research, and there remains a lot of room for discovery utilizing this unique data.

To get started, go through the Day 1 and Day 2 tutorials on the Open Data Workshop, which can be found at `https://github.com/gw-odw/odw-2020`. There you can access analysis tool tutorials, as well as slides and videos of presentations by gravitational wave experts that will help you to begin downloading and looking at gravitational wave data.

When you get to the section on generating your own gravitational waveforms, you'll likely find the following website useful, particularly the list of different approximants: `http://pycbc.org/pycbc/latest/html/waveform.html`. A list of the various parameters can be found at `https://pycbc.org/pycbc/latest/html/pycbc.waveform.html?highlight=get_td_waveform#pycbc.waveform.waveform.get_td_waveform`. Some models work better for certain parameters ranges than others – if you get an error when attempting to run them, look up the range where the model is expected to be valid to ensure that you're within a usable range of the model. The 'Day 2' talks in the Open Data Workshop discuss some of the differences between these models and provide an overview of the most useful ones. However, keep in mind that the Day 2 talks can go quite in-depth – if you start to feel lost, that's ok, that's part of the learning process! Don't become too frustrated with them, and if you feel stuck go back to the tutorials to work with the parameters hands-on, or ask for help.

[1] B. Abbott *et al.* (LIGO Scientific, Virgo), Phys. Rev. Lett. **116**, 061102 (2016), arXiv:1602.03837 [gr-qc].