Problem Set 4 for Matched Filters/Bit of Radio. Due Wednesday November 2 at 11:59 PM

Key will be getting LIGO data from:

`https://www.gw-openscience.org/static/events/LOSC_Event_tutorial.zip`

While they include code to do much of this, please don't use it (although you may look at it for inspiration) and instead write your own. You can look at/use simple_read_ligo.py that I have posted for concise code to read the hdf5 files. Feel free to have your code loop over the events and print the answer to each part for that event. In order to make our life easy, in case we have to re-run your code (which we should not have to do), please also have a variable at the top of your code that sets the directory where you have unzipped the data. LIGO has two detectors (in Livingston, Louisiana, and Hanford, Washington) and GW events need to be seen by both detectors to be considered real. Note that my read_template functon returns the templates for both the plus and cross polarizations, but you can just pick one of them to work with.

Problem 1:

Find gravitational waves! Parts should include

a) Come up with a noise model for the Livingston and Hanford detectors separately. Describe in comments how you go about doing this. Please mention something about how you smooth the power spectrum and how you deal with lines (if at all). Please also explain how you window the data (you may want to use a window that has an extended flat period near the center to avoid tapering the data/template where the signal is not small).

b) Use that noise model to search the four sets of events using a matched filter. The mapping between data and templates can be found in the file BBH_events_v3.json, included in the zipfile.

c) Estimate a noise for each event, and from the output of the matched filter, give a signal-to-noise ratio for each event, both from the individual detectors, and from the combined Livingston + Hanford events.

d) Compare the signal-to-noise you get from the scatter in the matched filter to the analytic signal-to-noise you expect from your noise model. How close are they? If they disagree, can you explain why?

e) From the template and noise model, find the frequency from each event where half the weight comes from above that frequency and half below.

f) How well can you localize the time of arrival (the horizontal shift of your matched filter). The positions of gravitational wave events are inferred by comparing their arrival times at different detectors. What is the typical positional uncertainy you might expect given that the detectors area a few thousand km apart?

h) **If you have already taken 512** (and therefore already have a leg up on this assignment): plot the likelihood over the sky of the GW event happening at that location. To work with the full sky, you can use the healpix library, which has a python wrapper, healpy. You can get a list of lat/lon positions on the sky and plot full-sky maps via code like:

```
import healpy
nside=256
th,phi=healpy.pix2ang(nside,np.arange(healpy.nside2npix(nside)))
healpy.mollview(th)
```

To do this, you'll need to use the lat/lon of the LIGO sites, then for each sky pixel, compute the relative delay between Hanford and Livingston. Then go to your matched filter outputs (possibly needing to interpolate one of them) and find the likelihood of that delay. Please return a plot showing the allowed region(s).

Problem 2: Let's assume we have a circular dish that is illuminated by a feed with a Gaussian beam pattern. For simplicity, you may assume everything is plane-parallel, the Gaussian can go to infinity, *etc.* As a feed designer, you can pick the σ of the feed's beam relative to the dish radius. What value maximizes the signal at the feed? You'll have the usual A_{eff} gain but will need to scale that by the fraction of the feed beam that ends up on the primary. If the feed beam is too large, most of it ends up missing the primary, but if the feed beam is too small, most of the primary isn't getting used and A_{eff} is very small.

Plot the signal strength at the feed against σ (in units where the dish radius is 1). What is A_{eff}/A at the peak? What fraction of the feed beam ends up off of the primary? You might want to compare the contribution to T_{sys} from that part of the beam assuming it ends up on the ground ($T \sim 300K$) relative to the noise temperature of a good cryogenic receiver ($T_{feed} \sim 20-25$K).