Mitigating the effects of instrumental artifacts on source localizations

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Instrumental artifacts which materialize as glitches in strain data can overlap with gravitational wave detections and significantly impair the accuracy of sky localizations of compact binary coalescence (CBC) signals. To understand how this effect works, we developed a sky localization algorithm of our own. It returned accurate sky maps with the exception of those using gravitational wave signals with glitches present. When gating the noise to remove these glitches, we learned that there were other factors in our code that contributed to the inaccurate sky localization. In addition to these results, we discuss the future work to create an executable that can correctly reconstruct the signal-to-noise ratio of gravitational wave signals interrupted by glitches.

I. INTRODUCTION

Detection of gravitational waves requires extreme sensitivity to changes in length on the order of 10^{-18} m [1]. The level of strain sensitivity renders LIGO detectors susceptible to noise transients (also called glitches), which are bursts of excess power in the strain data. Often, what causes these glitches is difficult to determine. They can be the result of either external environmental or internal instrumental interactions that alter the actual strain. Glitches are more likely to overlap with gravitational wave (GW) events that occur for a longer period, such as binary neutron star (BNS) events. As detection of GW events from BNS mergers become increasingly frequent [2], we expect to see more instances of noise transients overlapping with GW signals as seen in the case of BNS merger GW170817 [3]. This is problematic for many reasons, especially because noise transients diminish the accuracy of rapid sky localization and parameter estimates of the source. In order to gain useful and accurate astrophysical information from a GW event, it is important these glitches be mitigated in a way that minimizes bias in localization measurements.

There are multiple approaches one can use to try and address this. For GW170817, the effects of the noise transient were mitigated by applying a window function to remove it. Additionally, the glitch waveform was reconstructed with a model that could be subtracted from the data [3], as shown in Figure 1. This method was ad hoc in nature, different approaches are necessary to find a generalized solution for all GW events.

An alternative to window functions is inpainting [4], where the affected data are zeroed out and some data around the hole is replaced by values obtained from analytical calculations. Effectively, it minimizes the amount of data that is zeroed and preserves more of the signal.

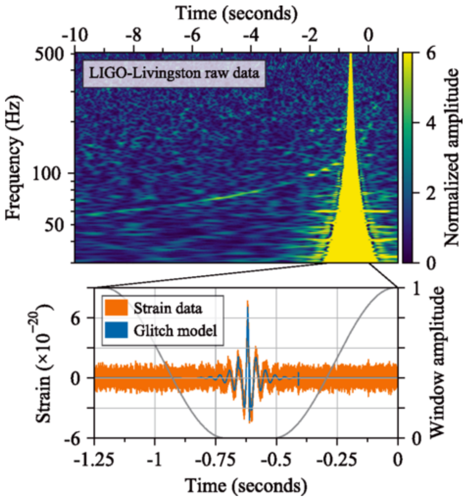
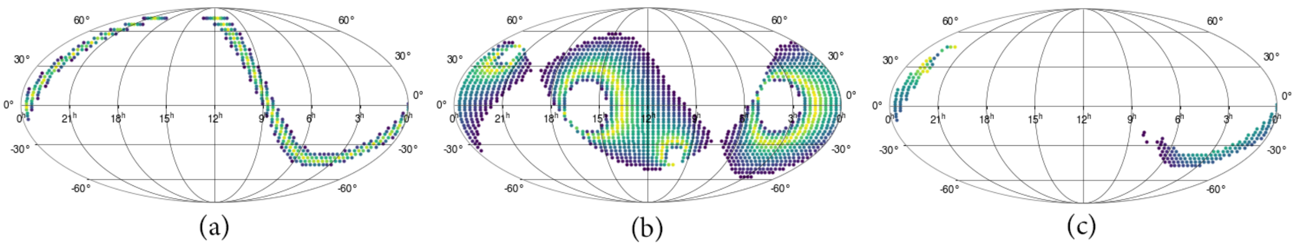


FIG. 1. *Top panel*: Time-frequency plot of LIGO Livingston data for GW170817 with the glitch present. *Bottom panel*: Strain data of the glitch, with a grey window function used to zero it out. The reproduced model of the glitch is shown with the blue curve. Replicated from [3]

Our ultimate project goal is to write a tool that is able inpaint a hole around a noise transient and reproduce the correct signal-to-noise ratio (SNR) timeseries without the glitch. When a glitch appears in the strain data, the SNR increases as a result. If we can correct the SNR by the right amount, we can translate this result to an accurate skymap in BAYESTAR [5], the sky localization algorithm used by *LIGO-Virgo*.

In this report, we will summarize our progress on this project and discuss the next steps to fulfill our goals.



(a) (b) (c)

FIG. 2. Molleweide projection of a skymap grid, with axes representing degrees of longitude and latitude. The colorbar corresponds to how each grid point matches the given parameters of the event, yellow indicating the grid points with the best match. (a) Time delay skymap of the Hanford (H1) and Livingstion (L1) LIGO detectors for event GW190814 [6]. (b) Amplitude ratio skymap of H1 and L1 for GW190814. (c) Combined time delay and amplitude ratio of H1 and L1 for GW190814.

II. PROGRESS

A. Skymap tool development

To begin the project, we made a custom tool using *PyCBC* [7] which creates maps showing a probable region where a GW source can be located on the sky.

The first step to creating these skymaps is to matched filter the LIGO data (obtained from [8]) to find a GW signal. We do this by using given physical parameters for an event such as mass components and spin to model a waveform template. We layer this template over our data and integrate to confirm where we have a potential signal.

After matched filtering the data, we can use our template waveform to calculate the SNR timeseries of the event. From the SNR timeseries we can determine the time and amplitude of the signal in each detector. Combining these quantities, we calculate the time delay and amplitude ratios of the signal for the two detectors and use them to plot our skymaps. To make a complete skymap, we average the error and offset of both the time delay and amplitude ratios. In Figure 2, we show a plot demonstrating how time delay and amplitude ratio skymaps are combined to constrain the location of event GW190814.

Finally, we applied this tool to all events in the GWTC-1 release [9] and compared them to skymaps generated with BAYESTAR [5]. Figure 3 shows an example of the correct skymaps overlaying the ones we made with our algorithm for comparison.

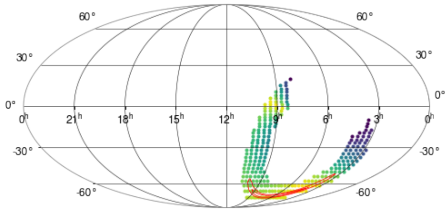


FIG. 3. Molleweide projection of a skymap grid, with axes representing degrees of longitude and latitude. The colorbar corresponds to how each grid point matches the given parameters of the event, yellow indicating the grid points with the best match. The skymap shows time delay and amplitude ratio skymap for GW event GW150914. The contours in red indicate the official skymap for this event created with BAYESTAR. The we can see that the skymap made with our custom tool agrees with the official one.

B. GW170817

When creating our skymap for BNS merger GW170817, we could see that the sky localization shown in Figure 4 is incorrect. The cause of this is clearly shown in figure 1 as an instrumental artifact in the raw data. It can also be found by looking into the SNR timeseries for this event that the glitch increases the calculated SNR, severely impacting the matched filtering process and therefore sky localization.

To fix this, we used an inverse Planck window function [10] to mitigate the glitch in the SNR timeseries. The resulting skymap does overlap with the BAYESTAR map, but the coloring is off where we would expect the highest likelihood to be.

To verify what went wrong, we used the data which removed the effect of the glitch with the technique we outlined in the introduction. The resulting skymap had the same issue, so we narrowed the cause down to two options. The priors we assumed could be insufficient to localize the event, and our error estimation from the detector sensitivity was too simplified. We assumed that the Hanford and Livingston detectors are equally sensitive, which is not true in reality. This factor appears to be the most likely contributor to the colormap offset in Figure 5.

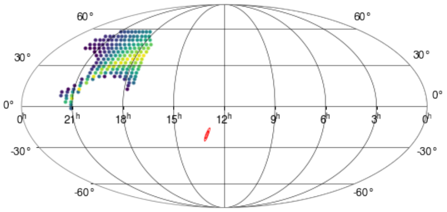


FIG. 4. Molleweide projection of a skymap grid, with axes representing degrees of longitude and latitude. The colorbar corresponds to how each grid point matches the given parameters of the event, yellow indicating the grid points with the best match. The skymap shows time delay and amplitude ratio skymap for BNS merger GW170817. The contours in red indicate the official skymap for this event created with BAYESTAR. Due to the presence of an instrumental artifact in the raw data, our calculation is different than the correct one.

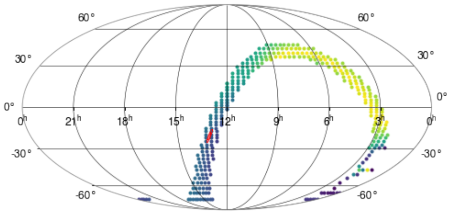


FIG. 5. Molleweide projection of a skymap grid, with axes representing degrees of longitude and latitude. The colorbar corresponds to how each grid point matches the given parameters of the event, yellow indicating the grid points with the best match. Time delay and amplitude ratio skymap for BNS merger GW170817. The contours in red indicate the official skymap for this event created with BAYESTAR. The shape of the custom skymap overlaps with the official, but the colormap is still off due to our priors and error estimation.

III. FUTURE TASKS

Going forward, we will go through the steps of inpainting and signal processing using detailed *PyCBC* tutorials.

Using the tools provided in the tutorials, we will go on to create an executable that can automatically matched filter, inpaint, and correct the SNR timeseries for GW strain data.

After this executable is completed, it will then be tested rigorously to ensure that it is accurate to real and simulated GW events. The most important knowledge to gain from testing is whether or not this way of correcting for noise transients introduces a bias when localizing sources.

If time permits, we will also develop a tool that can detect glitches in the data automatically to determine where the corrected SNR method needs to be applied.

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