Constraining Astrophysical Parameter Bias due to Glitches in Third-Generation Gravitational-Wave Detectors

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Transient detector noise or "glitches" which coincide in time and frequency with gravitational wave signals have been demonstrated to significantly bias inference of astrophysical parameters. Glitch-mitigation methods, including joint compact binary coalescence (CBC)-glitch inference, can reduce this bias; however, low-SNR glitches can still bias parameter estimates even below the threshold of detectability. This challenge will become increasingly important for third-generation detectors such as Cosmic Explorer (CE), which are expected to detect gravitational-wave events at an unprecedented rate. The effect of glitches on these detectors is unknown: improved sensitivity may reduce the relative impact of some glitches, while undetected glitches could still bias parameter estimates, particularly for black hole spin measurements. This project will simulate fixed-amplitude and fixed-SNR glitch scenarios to investigate how increased detector sensitivity affects glitch-induced BBH parameter bias, and to assess whether existing mitigation strategies remain effective for third-generation detectors.

I. INTRODUCTION

Gravitational waves (GWs) are traveling-wave perturbations of spacetime generated by an accelerating mass-energy quadrupole moment. Extreme astrophysical events such as binary black hole (BBH) mergers or binary neutron star (BNS) mergers produce GWs with amplitudes strong enough to be detected on Earth. The Laser Interferometer Gravitational-Wave Observatory (LIGO) has detected over 200 gravitational-wave events to date, with many more observations still to come from the most recent observing run [1].

Using GW waveform models and Bayesian inference, the parameters of the astrophysical event can be estimated from the GW signal. For BBH mergers, these parameters include the masses of the black holes, their spins, the sky position, and the distance to the source, among other parameters. Accurate parameter estimation is crucial to identifying the source of the GWs and localizing the signal's sky position, which has enabled important scientific advances in gravitational-wave physics, tests of general relativity, and broader astrophysical studies [2]. The spins of the black holes are of particular interest, as they give insight into the origin and evolution of the binary system, which could help address open questions regarding binary stellar evolution and the existence of BBH subpopulations [3–5].

The broad characteristics of the BH spins are encoded in two parameters, $\chi_{\rm eff}$ and $\chi_{\rm p}$, which describe the BH spin aligned with the orbital angular momentum and the BH spin parallel to the orbital plane, respectively. Previous observations (GW191109_010717 and GW200129_065458) have exhibited spins not aligned with the angular momentum of the orbital system, or spins in the plane of the binary [6, 7]. This suggests that the systems could have been formed through dynamical interactions rather than through isolated binary evolution, where the progenitor stars are born and evolve together as a binary system [5].

However, these conclusions may be biased by transient noise, known as "glitches." Typically, the process of parameter estimation assumes as a baseline a transient signal and stationary Gaussian noise [8]. If a glitch is suspected, one method is to model it as a separate component of the data and subtract the best fitting estimate before proceeding with analysis [9]. A more robust approach is joint compact binary coalescence (CBC)-glitch inference, in which the properties of the compact-binary signal and the glitch are inferred simultaneously. This allows the analysis to marginalize over multiple possible glitch realizations rather than relying on a single best-fit subtraction [10]. Despite these mitigation strategies, Udall *et al.* [11] showed that glitches can still significantly bias spin parameter estimates, even for glitches with signal-to-noise ratio (SNR) below the threshold of detectability. Figure 1 illustrates this bias in the case of a simulated waveform, demonstrating that even using various subtraction and joint CBC-glitch inference methods, the effective spin parameters remain substantially biased.

This project focuses on how the issue of glitch mitigation and parameter bias will evolve with third-generation detectors. The upcoming detectors Cosmic Explorer (CE) and Einstein Telescope (ET) [12, 13] will be able to detect an unprecedented number of GW signals. CE in particular is expected to observe 10^5 BBH mergers (one every 5 minutes) and 3×10^5 BNS mergers (one every 100 seconds) per year of observation [14]. Currently, parameter estimation for a single source can take days, or longer if a glitch overlaps with the signal (which occurs in about 10% of cases). Moreover, the process of joint BBH-glitch inference is not fully automated and must be manually assessed at each step. With the increased detection rates

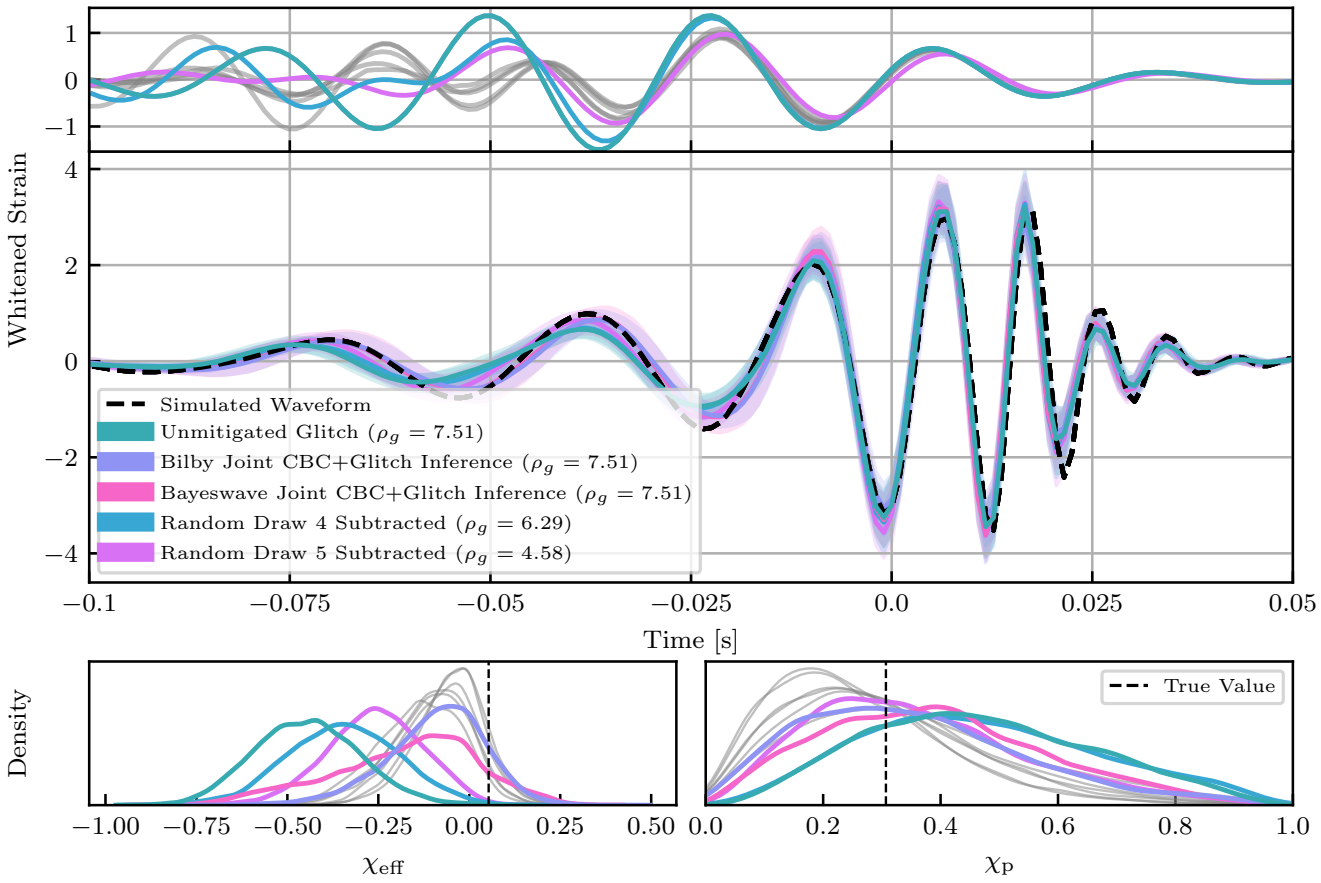


FIG. 1. Reproduced from Figure 7 of [11]. Results of the inference-subtraction procedure for a simulated glitch overlapping with a CBC signal, comparing the performance of various glitch mitigation strategies on spin parameter recovery. Glitch parameters were inferred only in the presence of Gaussian noise (before CBC injection) for the point estimate cases, and inferred jointly with the CBC in the other cases. Notable cases are highlighted in color. The top panel shows the glitch residuals after subtraction in the point estimate cases, as well as the full glitch in the unmitigated case. The middle panel displays the posterior CBC reconstructions for each of the cases, with the true waveform illustrated in black dashes. The bottom panels show the posteriors of both $\chi_{\rm eff}$ and $\chi_{\rm p}$ resulting from each of the methods, with the true value indicated by a black dashed line. The parameters are significantly biased when the glitch is unmitigated or subtracted, whereas this bias is improved with joint inference methods.

of third-generation detectors, it will no longer be practical to treat every glitch-contaminated event with the same level of manual intervention. It is therefore crucial to understand how glitches scale with detector sensitivity in order to identify when full joint BBH-glitch inference will be necessary, and to develop scalable glitch mitigation pipelines to ensure accurate parameter estimates across a high volume of events.

II. OBJECTIVES

We aim to simulate the increased sensitivity of CE in order to extend past studies of glitch-induced parameter bias such as [11]. In doing so, we hope to clarify whether glitches are expected to continue to pose a significant problem in producing accurate parameter estimates with third-generation detectors.

The GW strain amplitude is fixed by the physics of the source, but with increased CE detector sensitivity, we expect the noise to decrease, thus increasing the signal SNR. However, it is unclear how the glitches will be impacted. In this project, we will consider two limiting cases: 1) the glitch amplitude remains constant and 2) the glitch SNR remains constant. Based on simple scaling arguments outlined in Udall *et al.* [11], we expect these cases to affect parameter estimation differently. Our simulations aim to test whether these expectations hold.

For the first case, the absolute BBH parameter bias is expected to remain approximately comparable to the bias at current detector sensitivity, while the posterior widths are expected to decrease as detector sensitivity improves, resulting in a greater statistical deviation between the true and measured value. For the second case, we expect the absolute bias to decrease with respect to the bias at current detector sensitivities, but predict that

the standard deviation from the true value will remain similar.

We therefore intend to simulate both scenarios to test these predictions, assess how different assumptions about glitch scaling affect parameter estimation, and to determine whether existing mitigation strategies are effective for third-generation detectors. This will allow us to determine whether glitch-induced biases will remain astrophysically significant with future detectors.

III. APPROACH

We will use simulated data based on real past events with known parameters, but simulate the instrument response and power-spectral density (PSD) to model CE detector conditions. In order to investigate how glitches with varying amplitude and SNR affect the accuracy of parameter estimates, we will reproduce several key figures from past LIGO glitch studies (such as Figure 2, reproduced from [11]), but this time in the case of the CE noise spectrum, to determine possible conclusions regarding third-generation detectors.

For this analysis, we will use Bilby to perform astrophysical parameter estimation with simulated data. Bilby is a Python library designed to perform GW data analysis using Bayesian inference [15]. We will also make use of the model BayesWave [16] to perform joint CBC-glitch inference, assessing the resulting parameters' degree of accuracy compared to the known true values.

To summarize, the preliminary deliverables of this project are:

1. Reproduce Figure 1 using the LIGO PSD as a validation test for the simulation and parameter-estimation pipeline.

2. Produce a CE analogue of Figure 1 for glitches with fixed SNR, comparing the resulting spin-parameter bias to the LIGO case. If time permits, repeat this analysis using the LIGO A$^\sharp$ PSD.

3. Produce a corresponding fixed-amplitude version of Figure 1, allowing comparison between the case of fixed amplitude and fixed SNR.

4. Reproduce the relevant portion of Figure 2 using the LIGO design PSD, again as a baseline validation step.

5. Extend Figure 2 to CE/LIGO A$^\sharp$ to examine how the relationship between glitch SNR and parameter bias changes under future detector noise curves.

Due to the open-ended nature of the problem of glitch mitigation, we allow several weeks to explore additional mitigation possibilities based on initial results.

IV. TIMELINE

Weeks 1-2: Become comfortable with parameter estimation methods and running the analysis software. Work through the GW open data workshop and Bilby and BayesWave tutorials. Attend lectures on GWs.

Week 3: Reproduce results from previous papers to ensure that analysis is being performed properly. Write first interim report.

Weeks 4-6: Investigate CE sensitivity and begin simulations of glitch mitigation in a CE environment. Reproduce figures from [11] to assess how detector sensitivity impacts glitch mitigation. Write second interim report.

Weeks 7-9: Based on the results of the simulations, investigate how glitch mitigation techniques can be developed or modified to reduce parameter bias. Assess how these techniques can be optimized to accommodate increased data volume and event frequency expected in third-generation detector operations. Begin writing final report.

Week 10: Write final report and deliver final presentation.

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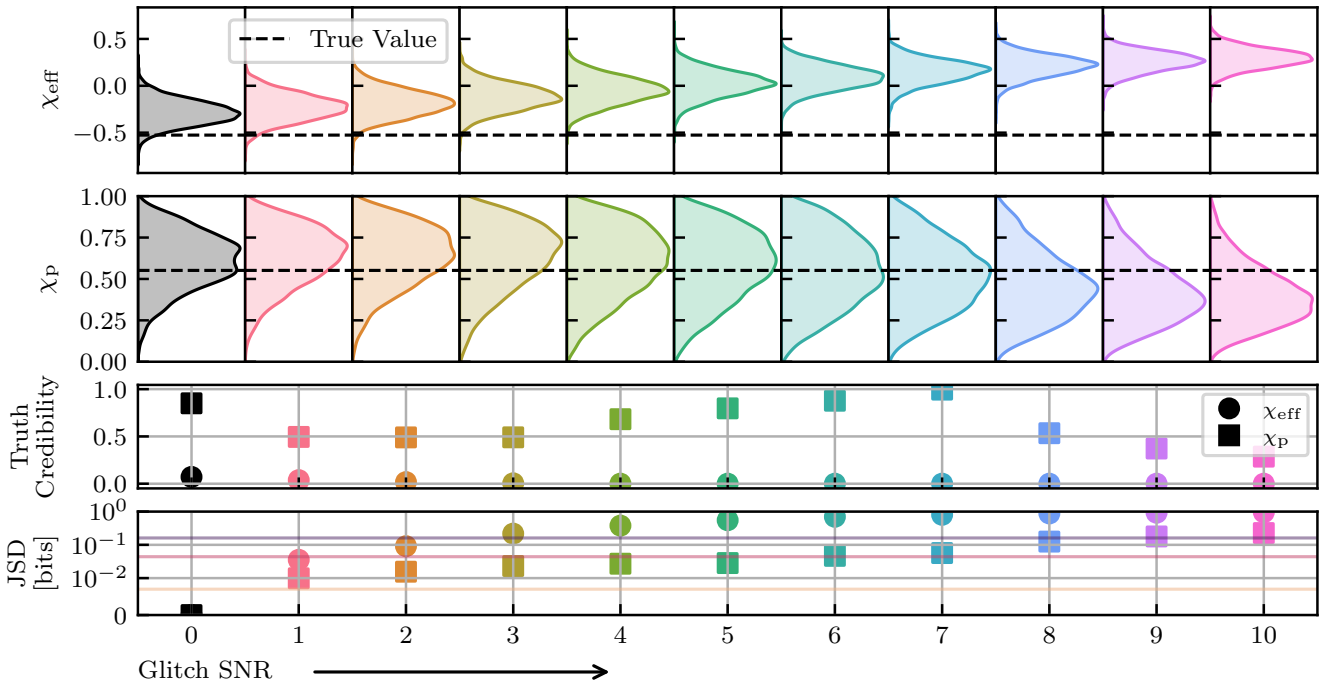


FIG. 2. Adapted from Figure 4 of [11], showing spin parameter estimations for varying glitch SNRs compared to the true values. The top two panels illustrate the posteriors for $\chi_{\rm eff}$ and $\chi_{\rm p}$ in comparison to their true value which is dashed in black. The bottom panels show the credibility of the true value and the JS divergence of the given posterior against the CBC-only posterior. The glitch SNR increases from left to right.

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