Characterization of Hardware Injections in LIGO Data

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Objectives

- Data from S6 run contains simulated signals from compact binary coalescences (CBCs) that were injected into the H1 and L1 detectors.
- Signals were produced by physically moving test masses.
- We’re seeking to retrieve these signals through matched filtering.
- The injection times and merger times of the injections are recorded, so the signal to noise ratios (SNRs) should be easily retrieved.
Compact Binary Coalescences

- Three stages: inspiral, merger, ringdown

- Three types: neutron star-neutron star (NSNS), neutron star-black hole (NSBH), black hole-black hole (BHBH)

Image from ligo.org
Chirp Waveform

- Signals appear in data as chirp waveforms.
- Chirp waveforms are determined by the masses of the binaries.
- NSNS have the longest waveforms, because they reach the merger phase at high frequencies.
- BHBH have the shortest waveforms, because they reach the merger phase at low frequencies.
Distribution of Masses

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Chirp Waveform (cont.)

![Chirp Waveform Graphs](image-url)
Matched Filter

\[ z(t) = 4 \int_0^\infty \frac{\tilde{s}(f)\tilde{h}^\ast_{\text{template}}(f)}{S_n(f)} e^{2\pi if t} \, df \]

\[ \sigma_m^2 = 4 \int_0^\infty \frac{|\tilde{h}_{1Mpc,m}(f)|}{S_n(f)} e^{2\pi if t} \, df \]

\[ \rho_m(t) = \frac{|z_m(t)|}{\sigma_m} \]
Power Spectral Density

- Took average power spectrum

- Took the mean of the power spectrum of eight segments

- Segment defined as the length of the data that is later multiplied by the template
Hardware Injections

- EOBNRpseudoFourPN: makes up the bulk of the injections.
- GeneratePPNtwoPN: can be reasonably approximated using FindCHIRP template.
- SpinTaylorT4threePointFivePN: has spin.
Final Approach

- Used lalapp coinv to make the templates used to produce the injections.
- Took 100 seconds of data because the templates are 100 seconds long.
- Wrote script to identify the template using the injection time.
Lessons Learned

- Neglected windowing – take care so that the merger is centered in the data.

- Offset in recovered time = injection time + 100 – merger time

- Templates already normalized to effective distance.

- Edit xml files so that coinj works.
Recovered SNRs for L1

![Graph showing the relationship between recovered SNRs and expected SNRs for different classes: NSNS, NSBH, and BHBH. The graph displays a positive correlation, with points clustering around a line that represents the expected SNR values.]
Recovered SNRs for L1

Recovered vs Expected SNR for Successful Injections in the L1 Interferometer

- Red dots: NSNS
- Blue dots: NSBH
- Green dots: BHBH
Unsuccessful Injections in L1

Recovered vs Expected SNR for Unsuccessful Injections in the L1 Interferometer

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Recovered SNRs for H1
Recovered SNRs for H1
Unsuccessful Injections in H1

Truncated Recovered vs Expected SNR for Unsuccessful Injections in the H1 Interferometer
Discrepancies

- Unexpected: possible signals when status is recorded as “Not in science mode,” “GRB alert,” and “Injection compromised.”
- Anomalies: when the ratio of the recovered to the expected SNR is lower than 0.5 or higher than 2, and expected SNR is higher than 6.
- Deceptive: injection marked as “Successful” but the recovered time differs greatly from the merger time.
- Shorties: injections that don’t have 100 seconds of data.
Discrepancies

- 85 injections that produced questionable results
- Could plot Fourier-transformed data against frequency template and average power spectrum as sanity check
- Could run omega scan on both merger and recovered times as sanity check
Accounting for Shorties

- Still grabbed 100 seconds of data using getsegs from readligo.py.

- If data missing from end of segment, zero-padded end.

- If data missing from beginning of segment, zero-padded beginning.
Discrete Fourier Transform

\[ \hat{x}[k] = \Delta t \sum_{j=0}^{N-1} x[j] e^{-2\pi i j k / N} \]

\[ \hat{x}[k] \approx \hat{x}(k\Delta f) \text{ for } 0 \leq k \leq \lfloor N/2 \rfloor \]

- The discrete Fourier transform approximates the continuous Fourier transform at frequency \( k\Delta f \).
- The nature of the transform is that the length of the template affects the outcome of the transform.
Successful Injection
Successful Injection
Unsuccessful Injection
Unsuccessful Injection
Omega Scan - Glitch

H1:LDAS-STRAIN at 931443438.000 with Q of 11.3

Normalized tile energy
Omega Scan – Glitch

H1:LDAS-STRAIN at 931443438.000 with Q of 11.3
Omega Scan – Injection Present
Future Work

- Currently we’re working with the lists H1biinjlist.txt and L1biinjlist.txt.
- We need to ascertain that those two lists contain all of the hardware injections.
- There are six injections in the H1biinjlist.txt that cannot be matched to any injection in the parameter files.
- The burst injections also need to be retrieved.
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Backup Slides
Chirp Waveform (cont.)

\[ h_+(t) = -\frac{1 + \cos^2 \iota}{2} \left( \frac{GM}{c^2 D} \right) \left( \frac{t_c - t}{5GM/c^3} \right)^{-1/4} \]
\[ \times \cos[2\phi_c + 2\phi(t - t_c; M, \mu)], \quad (3.1a) \]
\[ h_\times(t) = -\cos \iota \left( \frac{GM}{c^2 D} \right) \left( \frac{t_c - t}{5GM/c^3} \right)^{-1/4} \]
\[ \times \sin[2\phi_c + 2\phi(t - t_c; M, \mu)] \quad (3.1b) \]

- Plus and cross represent the two polarizations.
- D is distance from source.
- M is total mass; \( \mu \) is reduced mass; \( \eta \) is reduced mass over total mass; slanted M \( M \) is chirp mass, or \( \eta^{3/5}M \).
FindCHIRP Approach

\[ \tilde{h}(f) = -\left(\frac{5\pi}{24}\right)^{1/2} \left(\frac{GM}{c^3}\right) \left(\frac{GM}{c^2D_{\text{eff}}}\right) \left(\frac{GM}{c^3}\pi f\right)^{-7/6} e^{-i\Psi(f;M,\mu)} = \left(\frac{1\text{ Mpc}}{D_{\text{eff}}}\right) A_{1\text{ Mpc}}(M, \mu) f^{-7/6} e^{-i\Psi(f;M,\mu)} \]

\[ A_{1\text{ Mpc}}(M, \mu) = -\left(\frac{5}{24\pi}\right)^{1/2} \left(\frac{GM_\odot/c^2}{1\text{ Mpc}}\right) \left(\frac{\pi GM_\odot}{c^3}\right)^{-1/6} \left(\frac{M}{M_\odot}\right)^{-5/6} \]

\[ \Psi(f; M, \mu) = 2\pi f t_0 - 2\phi_0 - \pi/4 \]

\[ + \frac{3}{128\eta} \left[ v^{-5} + \left(\frac{3715}{756} + \frac{55}{9}\right) v^{-3} - 16\pi v^{-2} + \left(\frac{15293365}{508032} + \frac{27145}{504}\eta + \frac{3085}{72}\eta^2\right) v^{-1} \right] \]

\[ v = \left(\frac{GM}{c^3\pi f}\right)^{1/3} \]
Problems Encountered

![Graph showing scatter plot of recovered SNR vs expected SNR]
Initial Attempts

- Tried running FINDChirp matched filter on S5 hardware injections.
- Results were successful, which confirmed that the templates were correct.
- Switched to third order Post-Newtonian approximation for frequency template.
- Switched window from 4 seconds to 16 seconds and then 32 seconds
Initial Attempts (cont.)

- Chirp times are the durations of signals that start at the lowest frequencies and end at the frequencies at which the systems coalesce.

\[
\tau_0 = \frac{5}{256 \pi \nu f_L} (\pi M f_L)^{-5/3},
\]

\[
\tau_3 = \frac{1}{8 \nu f_L} (\pi M f_L)^{-2/3}.
\]
LALSuite Approach

- First tried IMRPhenomC from XLALSimInspiralChooseFDWaveform.

- Employed EOBNRv2 from waveforms.py in LALSuite.

- Could not find original EOBNR function.
Problems Encountered

- NSNS binaries had worst recovered vs expected SNR ratio.

- EOBNRv2 produces EOBNRv2pseudoFourPN templates.
Signals Recovered

![Graph showing recovered SNR vs. expected SNR for different types of signals: NSNS, NSBH, and BHBH.](image)

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LIGO-G09xxxxx-v1

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Form F0900041-v1
Omega Scan – No Glitch

H1:LDAS-STRAIN at 941731219.000 with Q of 45.3
Omega Scan – No Injection

![Graph of H1:LSC-ETMX_EXC_DAQ at 939830415.000](image)