RECOVERING HARDWARE INJECTIONS IN LIGO S5 DATA

Ashley Disbrow
Carnegie Mellon University

Roy Williams, Michele Vallisneri, Jonah Kanner
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Outline

• LOSC Open Science Data Release
• Hardware Injections of compact binary coalescence signals
  • What are these?
  • What do we expect to find in the data?
• How to generate a
• Template matching and signal recovery
• Recovery of Hanford 2 hardware injections
  • Was the match successful?
  • Do we see what we expect?
• Summary of Final Results for All Detectors
LIGO Open Data Release

• LIGO archival data will be released to public as open source data
  • S5 science run 2005-2007
  • H1 and H2 at LHO, L1 at LLO
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- LOSC – LIGO Open Science Center
  - Provides access to data
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  • Provides access to data
• In preparation for the release:
  • Software, cookbooks, wikis, tutorials, and teaching materials
  • Bring 8 year old book-keeping up to date
  • Recover and document hardware injection signals
Hardware Injections

- Inject Compact Binary Coalescence signal into data
  - Move ETMs (mirrors) using magnetic actuators
  - Important for instrument calibration and evaluating the efficiency of searches for signals
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  1. Successful
  2. Not in Science Mode
  3. Injection Process Off
  4. GRB Alert
  5. Operator Override
  6. Injection Compromised
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\[ \text{Unsuccessful} \]
10 – 10 Solar Mass Hardware Injection

H1:LSC-STRAIN at 832948455.000 with Q of 11.3

Notice the chirp!
1.4 – 1.4 Solar Mass Hardware Injection

Notice the chirp!

H1:LSC-STRAIN at 817645695.000 with Q of 45.3
Generate Template

- Create Compact Binary Coalescence templates
  - 1.4 – 1.4 Solar mass binary
  - 3 – 3 Solar mass binary
  - 10 – 10 Solar mass binary
  - 1.4 – 10 Solar mass binary

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

- \( \tilde{h}(f) \) – Strain/Hz
- \( A \) – Mass dependent amplitude
- \( f \) – frequency
- \( \Psi(f; M, \mu) \) – Phase of source
Determining the Amplitude of the Template

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

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

\[ M \] – Chirp mass, units of solar mass
Determining the Amplitude of the Template

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\[ \mathcal{M} \quad \text{– Chirp mass, units of solar mass} \]

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

- Cross-correlate template against the data
  - Perform correlation with template starting at different times
- Look for the time shift when the cross-correlation between the template and data is high
H2 Successful Injections

- 1.4 – 1.4 solar mass binary
- 3 – 3 solar mass binary
- 10 – 10 solar mass binary
- 1.4 – 10 solar mass binary
H2 Successful Injections

1.4 – 1.4 solar mass binary
3 – 3 solar mass binary
10 – 10 solar mass binary
1.4 – 10 solar mass binary
H2 Successful Injections

- 1.4 – 1.4 solar mass binary
- 3 – 3 solar mass binary
- 10 – 10 solar mass binary
- 1.4 – 10 solar mass binary
H2 Unsuccessful Injections

- 1.4 – 1.4 solar mass binary
- 3 – 3 solar mass binary
- 10 – 10 solar mass binary
- 1.4 – 10 solar mass binary

Graph showing the relationship between recovered SNR and predicted SNR for H2 unsuccessful hardware injections.
H2 Unsuccessful Injections

1.4 – 1.4 solar mass binary
3 – 3 solar mass binary
10 – 10 solar mass binary
1.4 – 10 solar mass binary
H2 Unsuccessful Injections

- 1.4 – 1.4 solar mass binary
- 3 – 3 solar mass binary
- 10 – 10 solar mass binary
- 1.4 – 10 solar mass binary
H2 Unsuccessful Injections

This looks like a detection!
Where Did This Match Come From?

- 10 – 10 solar mass binary located 10 Mpc from Earth
- Marked Injection Compromised
Where Did This Match Come From?

- 10 – 10 solar mass binary located 10 Mpc from Earth
- Marked Injection Compromised
Spectrogram of The Injection

H2:LSC-STRAIN at 824214406.000 with Q of 22.6
## Summary Table of Final Results

<table>
<thead>
<tr>
<th>Detector</th>
<th>H1</th>
<th>H2</th>
<th>L1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total # Injections</td>
<td>1200</td>
<td>1282</td>
<td>1271</td>
</tr>
<tr>
<td>Successful Injections</td>
<td>870</td>
<td>929</td>
<td>770</td>
</tr>
<tr>
<td>Successful Injections, Predicted SNR &gt; 8</td>
<td>614</td>
<td>333</td>
<td>545</td>
</tr>
<tr>
<td>For Injections with Predicted SNR &gt; 8, Injections with Recovered SNR &gt; 6</td>
<td>608</td>
<td>322</td>
<td>538</td>
</tr>
<tr>
<td>Successful Injections, Data Unavailable</td>
<td>21</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>Unsuccessful Injections</td>
<td>46</td>
<td>45</td>
<td>51</td>
</tr>
<tr>
<td>Unsuccessful Injections with Recovered SNR &gt; 6</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Unsuccessful Injections, Data Unavailable</td>
<td>263</td>
<td>289</td>
<td>436</td>
</tr>
</tbody>
</table>
Conclusions

- LOSC will release S5 data to the public
- We search the data for hardware injections
- Our search is successfully identifies whether an injection is successful or unsuccessful
- We find some injections where we do not expect to, referencing past documentation
  - i.e. the detection we discussed
- We will continue to explain these unexpected points and summarize them in the final paper
Acknowledgements

• Mentors: Jonah Kanner, Roy Williams, and Michele Vallisneri
• Collaborators: Alan Weinstein and LOSC
• LIGO and National Science Foundation
• Caltech
H1 Successful Injections
L1 Successful Injections

![Graph showing correlation between recovered and predicted SNR for successful hardware injections](image)
Template Matching: Signal-to-Noise

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

- \( \rho_m(t) \) – Amplitude signal to noise ratio of matched filter output
- \( z(t) \) – Matched filter output
- \( \sigma_m \) – A measure of the sensitivity of the instrument

\[ \rho_{\text{Predicted}} = \frac{\sigma_m}{D_{\text{eff}}} \]

- \( \rho_{\text{Predicted}} \) – Predicted signal-to-noise ratio
- \( D_{\text{eff}} \) – Effective distance from source to Earth
Template Matching: Matched Filter Math

\[ z(t) = 4 \int_{0}^{\infty} \frac{\tilde{s}(f) \tilde{h}_{\text{template}}^{*}(f)}{S_n(f)} e^{2\pi i ft} df. \]

- \( z(t) \) – Matched filter output
- \( \tilde{s}(f) \) - Data in frequency domain
- \( \tilde{h}_{\text{template}}^{*}(f) \) - Complex conjugate of template
- \( S_n(f) \) - Power Spectral Density of noise