Results of the Hardware Injections performed on the LIGO Interferometers

Myungkee Sung
for the LIGO Science Collaboration

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LIGO Hardware Injections

- Hardware injections are the only direct test of detector time response.
  - Detector deforms gravitational waveform in a predictable (?) way.
  - Detector response function quantifies this deformation.
- Injections are also a good test for measuring the absolute size of signal.
- Hardware injections on the S5 run of LIGO
  - Burst/Inspiral injections, pulsar injections, stochastic injections, special injections.
  - Very little dead time - <0.5% of livetime due to burst/inspiral injections
- Analysis consists of successive application of linear filters on raw data (error signal):
  - Whitening filters, applied once and twice.
  - Transformed template (from strain to error signal)
- Diagnostic tool with prompt analysis after each injection.
- KleineWelle analysis of veto safety of auxiliary data channels
• Infer strain \( s(f) \) from observable \( DERR(f) \):

\[
s(f) = R(f)DERR(f)
\]

• Calibration team measures this detector response function \( R(t,f) \):

\[
R(t,f) = \frac{1 + \gamma(t)G_0(f)}{\gamma(t)\gamma_0(f)}
\]

where open loop gain \( G_0(f) \):

\[
G_0(f) = D(f)A(f)C_0(f)
\]

• \( EXC_x(t) \) for hardware injections:

\[
EXC_x(f) = -h_{inj}(f)/A_x(f)
\]
Burst Injections

• Twenty different burst waveforms in strain, \( h(t) \)
  
  - Four Gaussians: \( \sigma = 0.3, 1.0, 3.0, 10 \) ms.
  - Sine-Gaussians (Q=9) with 12 frequencies from 50Hz to 3068Hz
  - Supernova waveform: Zwerger-Mueller (A3B3G1)
  - Cosmic string - cusp (\( f_{\text{cutoff}} = 220\)Hz)
  - Band-limited white noise burst: \( f = 250\)Hz, \( \delta f = 100\)Hz and \( \sigma = 30\)ms
  - Ringdown: \( f = 2600\)Hz \( \delta t = 30\)ms

• Various settings of strengths and time for each injections
  
  - Same waveform injected to three IFOs with time shifts (if in science mode).
  - Two regular injections daily on average, each with three waveforms.
  - Loud injections of Gaussians and sine-Gaussian at least once per week for studying coupling to auxiliary channels and impulse response of detector.
Gaussian ($\sigma = 0.3\text{ms}$) injection

- Use actuation function, $A_x(f)$, to calculate the excitation function:
  \[ EXC_x(f) = -\frac{h_{\text{inj}}(f)}{A_x(f)} \]

- Note: this injection is approximately an impulse in strain.
Result of injection
or impulse response

DERR data w/ Gaussian (σ=0.3ms) injection at 833364049

Zoom-in
Analyzing Injection Data

- Matlab scripts (python scripts for controlling jobs)
- Use $DERR(t)$ data
- Time windows of 64s, Tukey windowing to use the middle 48s
- Whitening filters
  - Single whitening filter:
    $$sw(t) = \int_0^\infty \frac{derr(f)}{\sqrt{S(f)}} e^{-2\pi ift} df$$
  - Double whitening filter:
    $$dw(t) = \int_0^\infty \frac{derr(f)}{S(f)} e^{-2\pi ift} df$$
  - Noise estimate, $S(f)$, from two 50s long data before and after injection period.
Whitened DERR
or whitened impulse response
Optimal Linear Filter

\[ \|h(t)\| = N_\alpha \int_0^\infty \frac{d_\alpha^*(f)derr(f)}{S(f)} e^{-2\pi ift} \, df \]

- A standard method from classical signal processing.
- Matched filter study: template from injected waveforms with the detector response function (Calibration):
  \[ d_\alpha(f) = h_{\text{inj}}(f)/R(f) \]
- Optimized for the measured stationary noise of detector - Double whitening.
- It is also a linear measure of the strength;
  - Choose normalization so \(\|h\|\) is unbiased estimate of true \(h_{\text{rss}}\) of this waveform.
  - Response functions cancel, i.e., the equivalent expressions for either observable \(DERR(t)\) or strain \(s(t)\).
Filtered output from loud Gaussian

- **Strength Measurement**
  - Injected: $20 \times 10^{-21} s^{1/2}$
  - Measured: $19.984 \times 10^{-21} s^{1/2}$
  - $\text{rms(noise)}$: $0.0357 \times 10^{-21} s^{1/2}$

- **Time measurement**
  - Injected time offset: 0.5 s
  - Measured time offset: 0.5001 s
Supernova waveform: Zwerger-Mueller (A3B3G1)

- **Strength Measurement**
  - Injected: $0.6 \times 10^{-21}s^{1/2}$
  - Measured: $0.661 \times 10^{-21}s^{1/2}$
  - rms(noise): $0.04168 \times 10^{-21}s^{1/2}$

- **Time Measurement**
  - Injected offset: 0.3555s
  - Measured offset: 0.3558s
# Hardware injection monitoring

- snapshot of online display for scimons -

<table>
<thead>
<tr>
<th>Intended Injection Parameters</th>
<th>Resulting Waveforms</th>
<th>Results</th>
<th>Direct Response (DARM_ERR whitened)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{Inj}}=832561960$</td>
<td><img src="image1" alt="Waveform" /></td>
<td>$\epsilon_h = (\text{hrss} \text{expected})^{-3/2} \text{hrss}<em>\text{peak}/\sigma</em>{\text{noise}}$ $\sigma_{\text{noise}}$ $\text{rms(noise)}$</td>
<td>$\chi^2=0.874915$ (sw), 0.859358 (dw)</td>
</tr>
<tr>
<td>Sine-Gaussian</td>
<td><img src="image2" alt="Waveform" /></td>
<td>$\text{hrss}_\text{peak} = -8.292 \times 10^{-21} \text{s}^{1/2}$</td>
<td>$\epsilon_h = -5.243$, $\sigma = 5.560 \times 10^{-23} \text{s}^{1/2}$</td>
</tr>
<tr>
<td>$f=70 \text{Hz}$ $Q=9$</td>
<td><img src="image3" alt="Waveform" /></td>
<td>$\Delta t_{\text{peak}} = 0.7980 \text{s}$</td>
<td>$\delta(\Delta t) = 0.0000 \text{s}$</td>
</tr>
<tr>
<td>$t_{\text{offset}}=0.798 \text{s}$</td>
<td><img src="image4" alt="Waveform" /></td>
<td>$\text{hrss}_\text{peak} = 4.8 \times 10^{-21} \text{s}^{1/2}$</td>
<td>$\epsilon_h = -0.106$, $\sigma = 8.468 \times 10^{-23} \text{s}^{1/2}$</td>
</tr>
<tr>
<td>$\text{hrss}=8 \times 10^{-21} \text{s}^{1/2}$</td>
<td><img src="image5" alt="Waveform" /></td>
<td>$\Delta t_{\text{peak}} = 0.7980 \text{s}$</td>
<td>$\delta(\Delta t) = 0.0000 \text{s}$</td>
</tr>
<tr>
<td>$T_{\text{Inj}}=832561970$</td>
<td><img src="image6" alt="Waveform" /></td>
<td>$\text{hrss}_\text{peak} = 4.8 \times 10^{-21} \text{s}^{1/2}$</td>
<td>$\epsilon_h = 0.874915$ (sw), 0.859358 (dw)</td>
</tr>
<tr>
<td>Sine-Gaussian</td>
<td><img src="image7" alt="Waveform" /></td>
<td>$\Delta t_{\text{peak}} = 0.7980 \text{s}$</td>
<td>$\delta(\Delta t) = 0.0000 \text{s}$</td>
</tr>
<tr>
<td>$f=914 \text{Hz}$ $Q=9$</td>
<td><img src="image8" alt="Waveform" /></td>
<td>$\text{hrss}_\text{peak} = 8 \times 10^{-21} \text{s}^{1/2}$</td>
<td>$\epsilon_h = -1.474 \times 10^{-21} \text{s}^{1/2}$</td>
</tr>
<tr>
<td>$t_{\text{offset}}=0.798 \text{s}$</td>
<td><img src="image9" alt="Waveform" /></td>
<td>$\Delta t_{\text{peak}} = 0.7980 \text{s}$</td>
<td>$\delta(\Delta t) = 0.0000 \text{s}$</td>
</tr>
<tr>
<td>$\text{hrss}=1.4762 \times 10^{-21} \text{s}^{1/2}$</td>
<td><img src="image10" alt="Waveform" /></td>
<td>$\epsilon_h = 0.092$, $\sigma = 2.803 \times 10^{-23} \text{s}^{1/2}$</td>
<td>$\chi^2=1.060200$ (sw), 0.962461 (dw)</td>
</tr>
</tbody>
</table>

- Mismatched Filter Study

- $\chi^2$ values indicate goodness of fit.
Gaussian $\sigma=1\text{ms}$: Strength Measurement

$L1$: 452 Injections

$\Delta||h|| = ||h||_{\text{measured}} - ||h||_{\text{injected}} = -0.31\pm1.1 \text{ rms(noise)}$
Gaussian $\sigma=1\text{ms}$: Time Measurement

\[ \Delta t = t_{\text{measured}} - t_{\text{injected}} = -0.15\pm0.14\text{ ms} \]
Measuring Burst Injections

• Jan. 19 - Aug. 23, 2006
• Number of injections:
  • H1 - 5018
  • H2 - 5958
  • L1 - 4098
Veto Safety Study using Hardware Injection

- Transients identified by KleineWelle algorithm on auxiliary data channels at the time of injections
- Injections from 272 days of S5 run
- From DERR:

![Graphs showing significance vs. injected ||h|| and ΔTime (s)]
Veto Safety Study using Hardware Injection

- **RMP (Recycling Mirror Pitch)** - Safe

- **ASI (Antisymmetric port In-Phase)** - Unsafe

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**Injected $||h||$**

**Significance**

**Injected $||h||$**

**Significance**

**DeltaTime (s)**

**DeltaTime (s)**
Summary

• Hardware injection provides very useful tools to understand the performance of interferometers.
• Injections during S5 are analyzed by using
  - Whitening filters
  - Optimal linear filters
  - KleineWelle algorithm
• Prompt result from hardware injections is available and used as a diagnosis tool.
• From statistical study, detector response to injected waveforms is analyzed.
• Veto safety study on auxiliary data channels with transients from KleineWelle algorithm.