Matched Filter Recovery of S5 Hardware Injections

M. Sung and W. Jonhson
Louisiana State University

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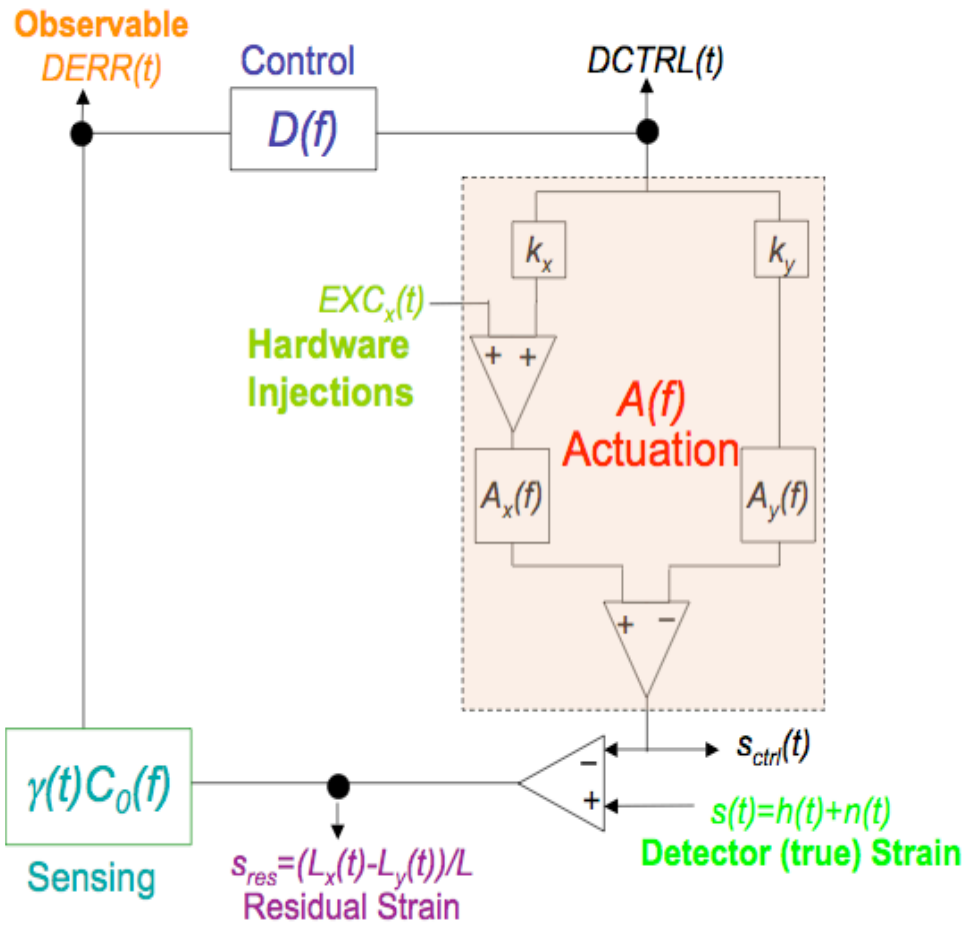
Hardware Injection Analysis

- Direct test for measuring the absolute size of signal and detector time response.
- Successive application of linear filters:
  - Whitening filters, single and double.
  - Matched filter using the injected waveforms
- On both *DERR(t)* and strain, *h(t),* data.
- Improved algorithm and fixed many bugs.

Servo Diagram of IFO



• Infer strain *s(f)* from observable *DERR(f)*:

$$s(f) = R(f)DERR(f)$$

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

$$R(t,f) = \frac{1+\gamma(t)G_0(f)}{\gamma(t)C_0(f)}$$

where open loop gain $G_0(f)$:

$$G_0(f) = D(f)A(f)C_0(f)$$

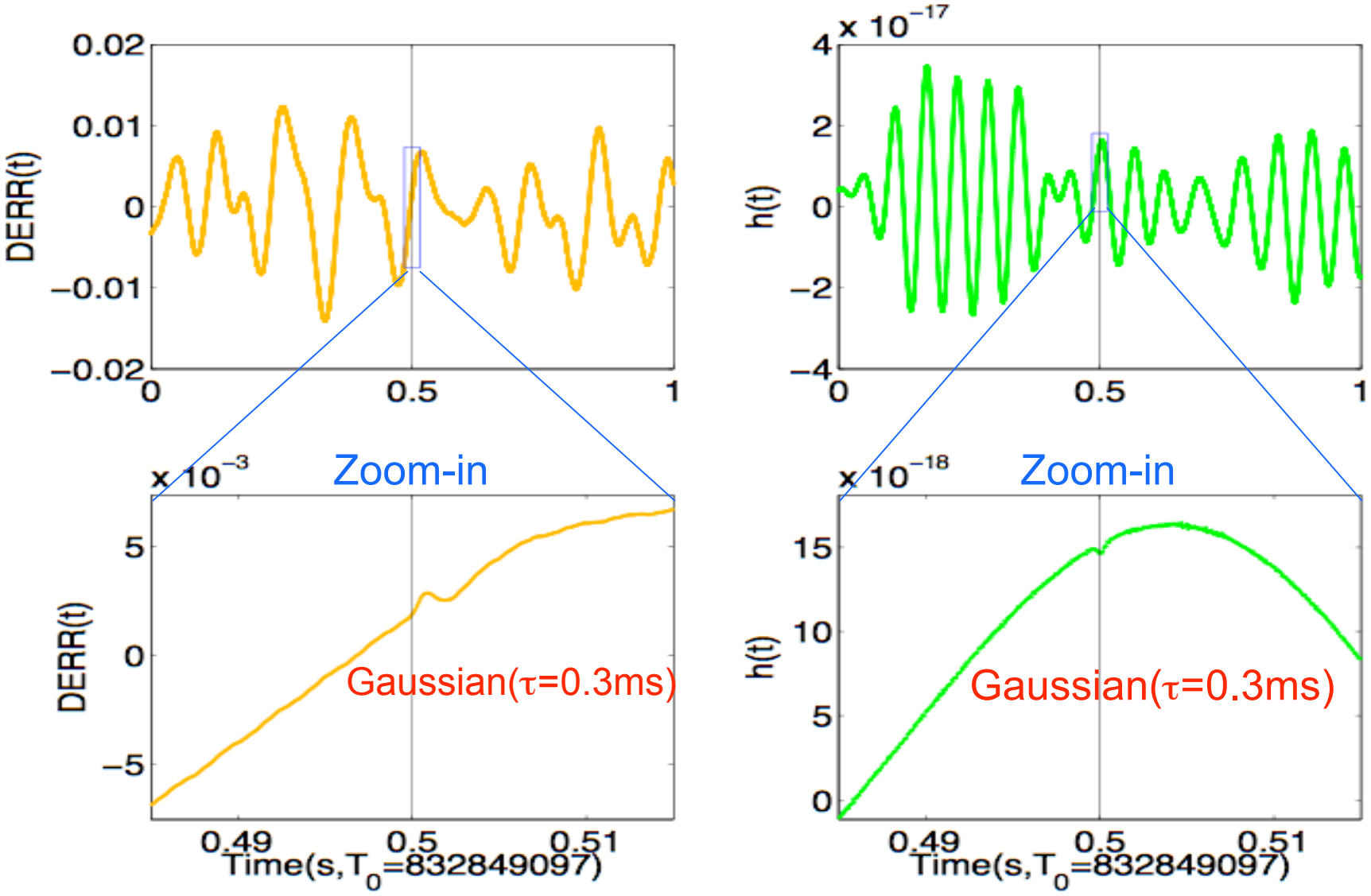
• $EXC_x(t)$ for hardware injections:

$$EXC_x(f) = -h_{inj}(f)/A_x(f)$$

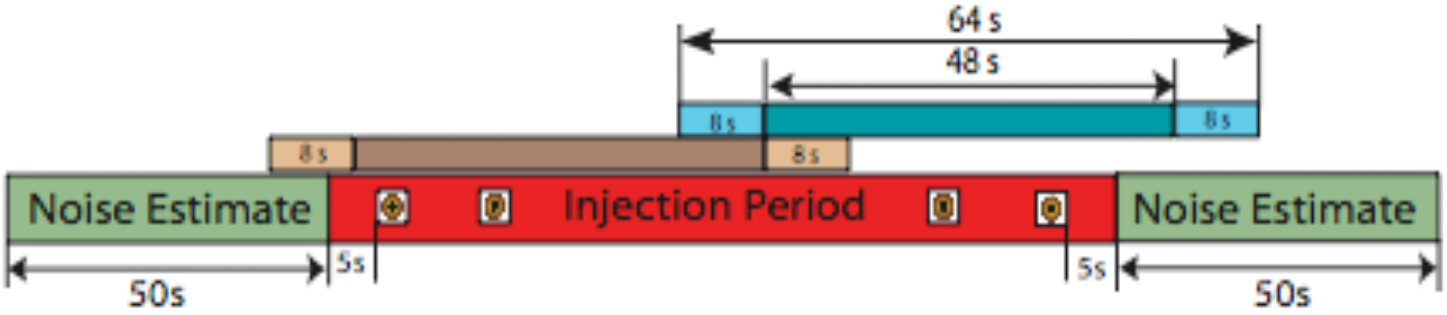
S5 Burst Injections

- Twenty different burst waveforms in strain, *h(t)*
  - Four Gaussians: σ = 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_{cutoff} = 220Hz)
  - Band-limited white noise burst: f = 250Hz, δf = 100Hz and σ = 30ms
  - Ringdown: f = 2600Hz δt = 30ms
- 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.

Short Gaussian injection - Impulse Response: *DERR(t)* and *h(t)*



Analyzing Injection Data

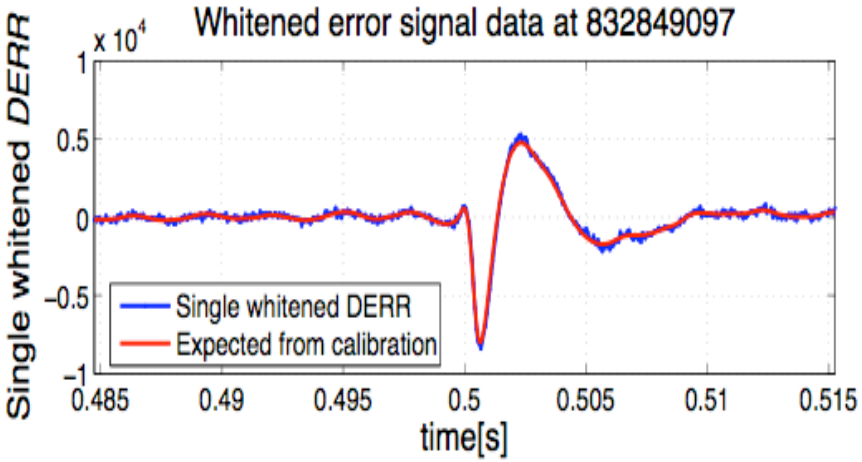


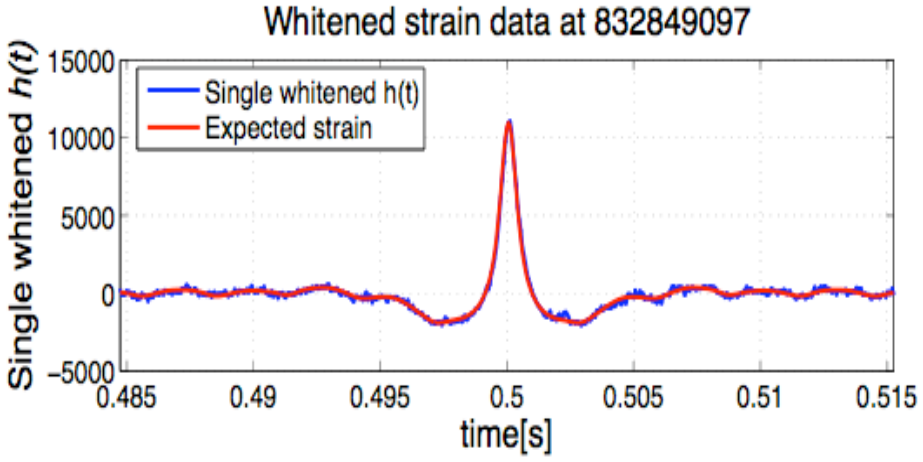
- Time windows of 64s, Tukey windowing to use the middle 48s
- Whitening filters
  - Single whitening: $sw(t) = \int_0^\infty df e^{-i2\pi ft} \frac{1}{\sqrt{S(f)}} d(f)$
  - Double whitening: $dw(t) = \int_0^\infty df e^{-i2\pi ft} \frac{1}{S(f)} d(f)$

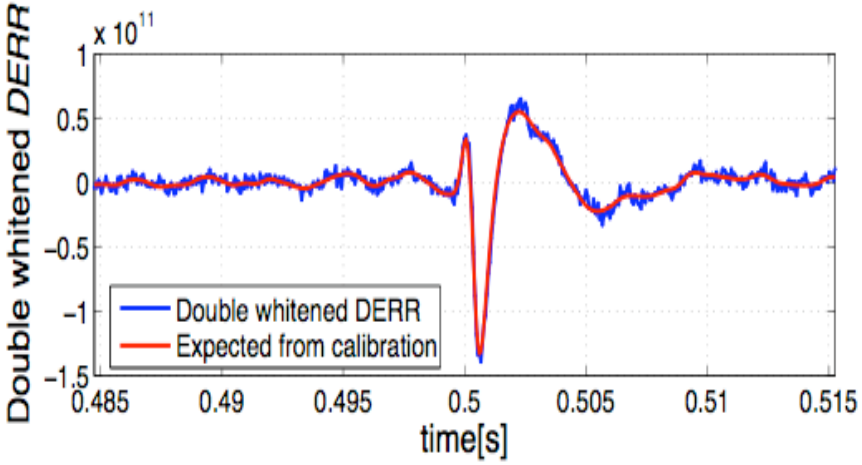
- Data, *d(f)* - either *DERR(f)* or strain, *h(f),* in frequency domain
- *S(f)* - Power spectral density of noise from
  - Either *DERR(t)* or strain, *h(t): $S_e(f)$* or *$S_s(f)$.*
  - Two 50s long data before and after injection period.

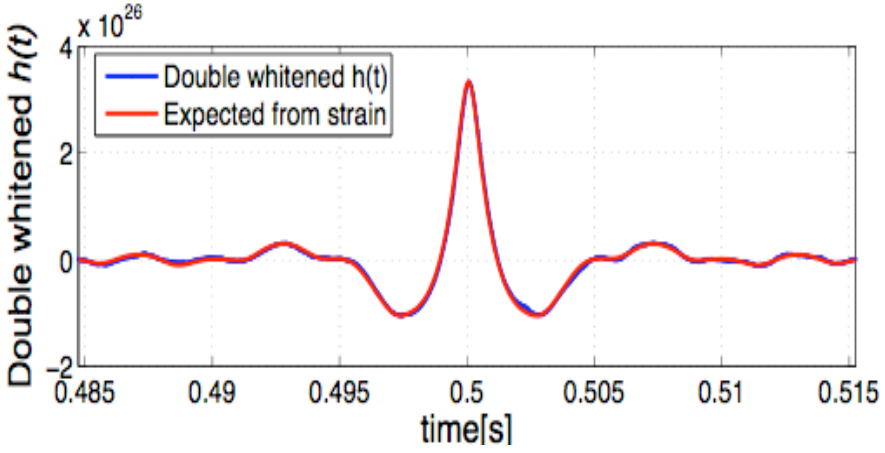
Whitened Data

or whitened impulse response









Using *DERR(t)*

Using *h(t)*

Optimal Linear Filter

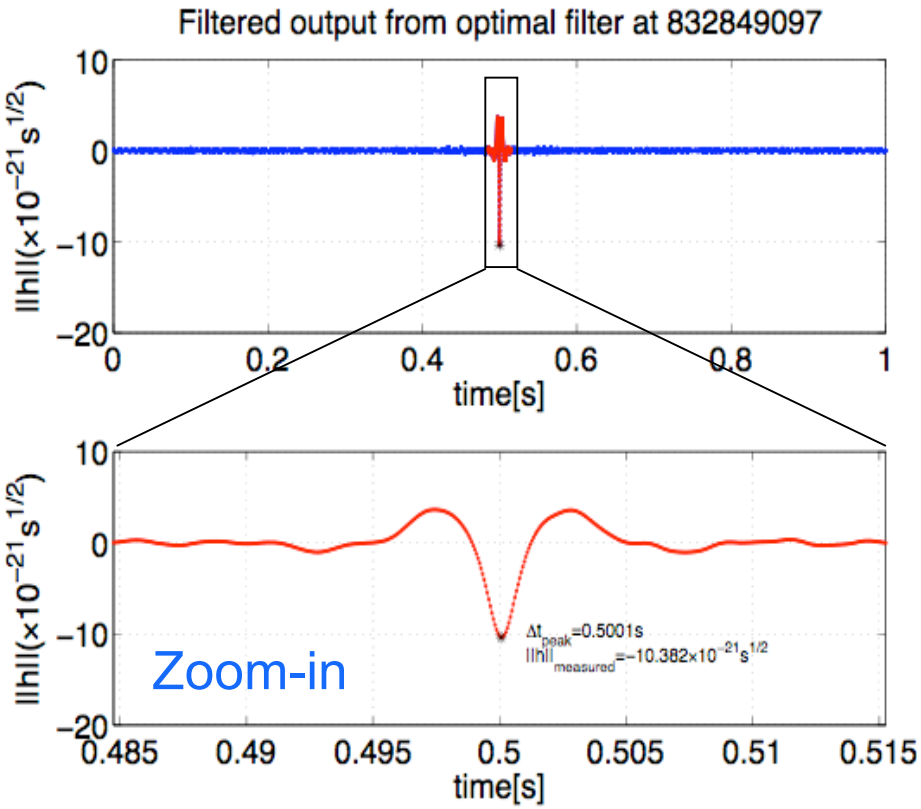
$$||h_\alpha(t)|| = N_\alpha \int_0^\infty df e^{-i2\pi f t} k_\alpha^*(f) \frac{1}{S(f)} d(f)$$

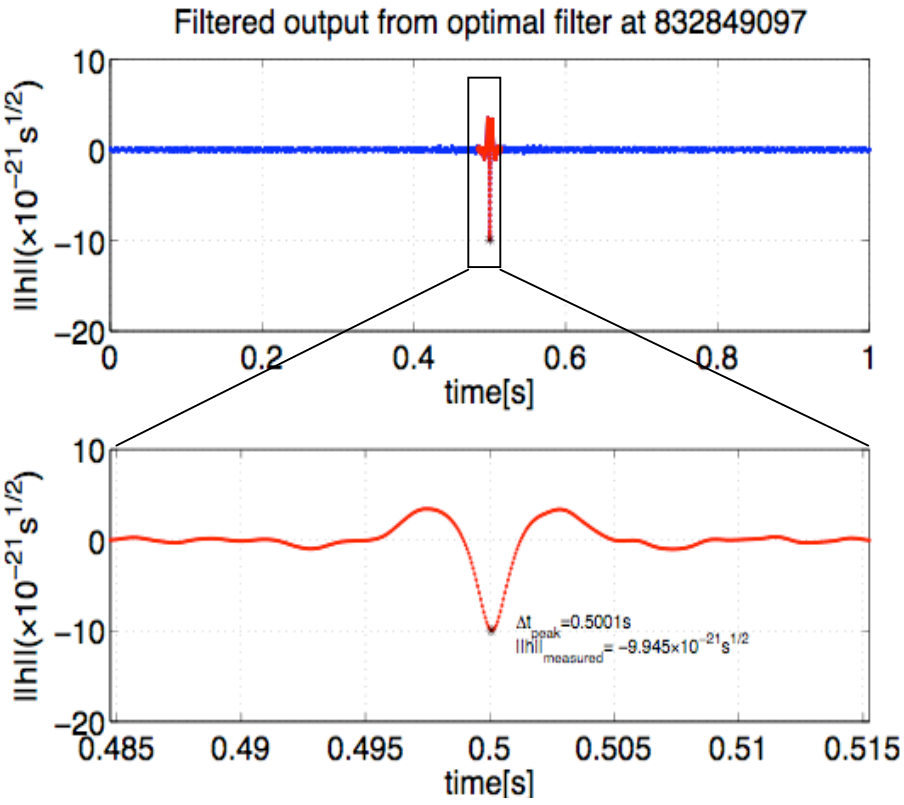
- A standard method from classical signal processing.
- Templates for matched filter:

  $k_\alpha(f) = h_{inj}(f)/ R(f)$ for *DERR(t)*

  $k_\alpha(f) = h_{inj}(f)$ for *h(t)*
- Optimized for the measured stationary noise of detector - Double whitening.
- It is also a *linear* measure of the strength;
  - Choose normalization so $||h_\alpha||$ is unbiased estimate of true h_{rss} of this waveform, k_α.
  - Response functions cancel , i.e., the equivalent expressions for either observable *DERR(t)* or strain *h(t).*

Filtered output from loud Gaussian





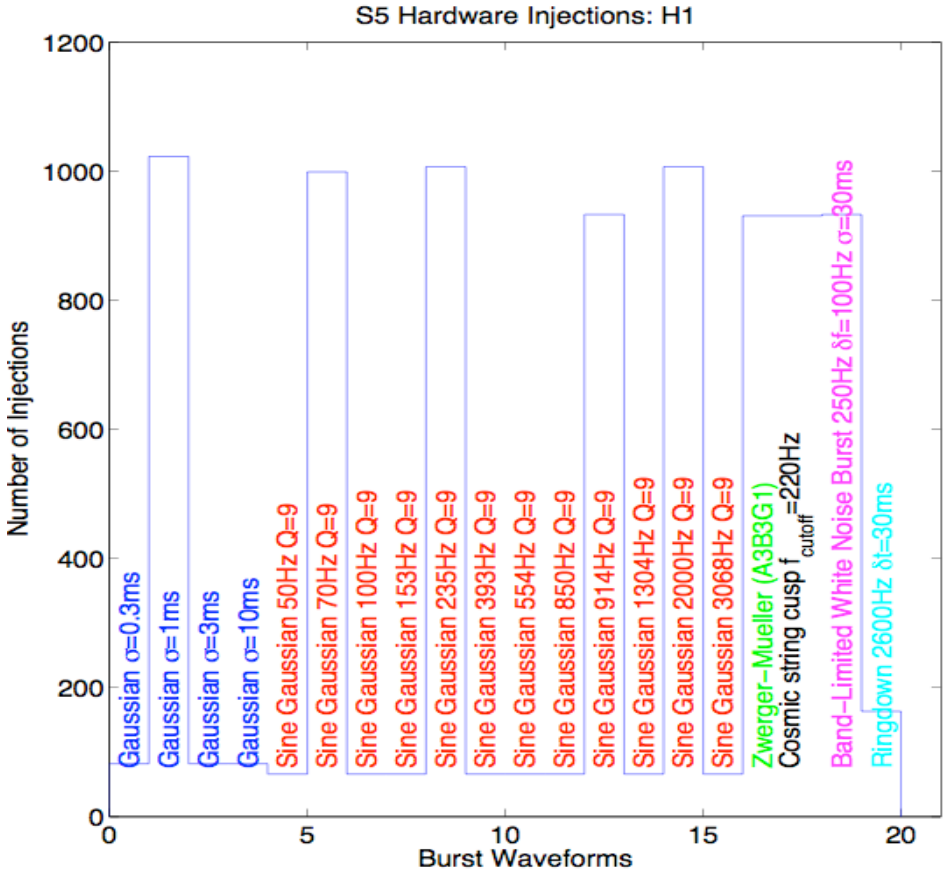
- Injected Strength: $10 \times 10^{-21} s^{1/2}$
- Injected time offset: 0.5 s

- From *DERR(t)*:
  - Measured strength: $10.382 \times 10^{-21} s^{1/2}$
  - rms(noise): $0.0383 \times 10^{-21} s^{1/2}$
  - Measured time offset: 0.5001s

- From *h(t)*:
  - Measured Strength: $9.945 \times 10^{-21} s^{1/2}$
  - rms(noise): $0.0365 \times 10^{-21} s^{1/2}$
  - Measured time offset: 0.5001s

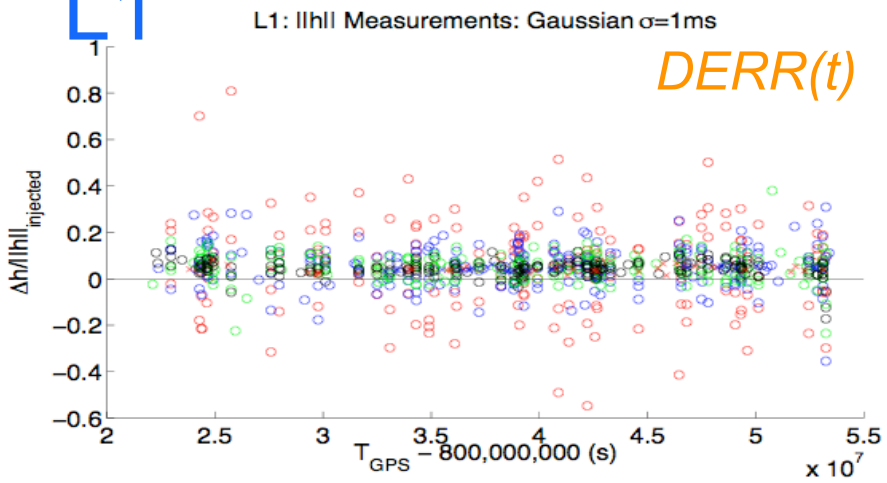
Statistical study on burst injections

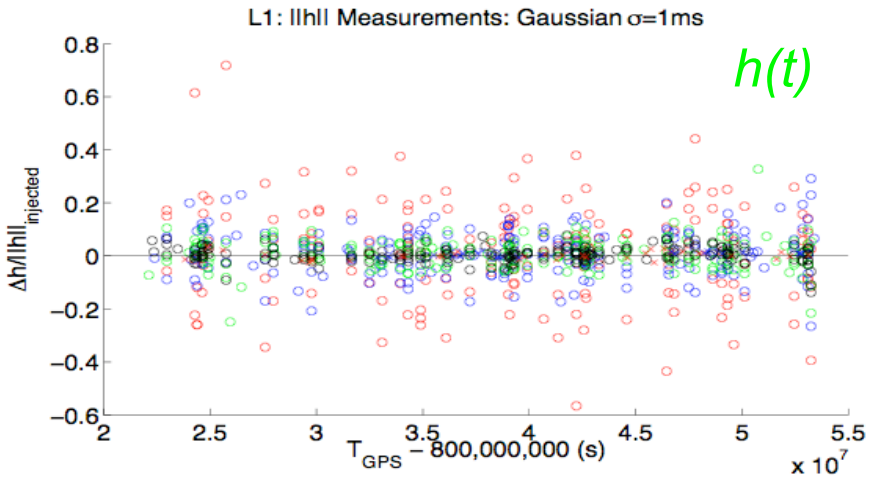
- Duration of used injections: Jan 20 2006 - Jan 21 2007
- Total Burst injections:
  - L1: 7656
  - H1: 8701
  - H2: 9670
- Calibration:
  - Injections - used actuation function from V1
  - *DERR(t)* - V3, 60s factors (H2: V2)
  - *h(t)* - C02: V2, 1s factors

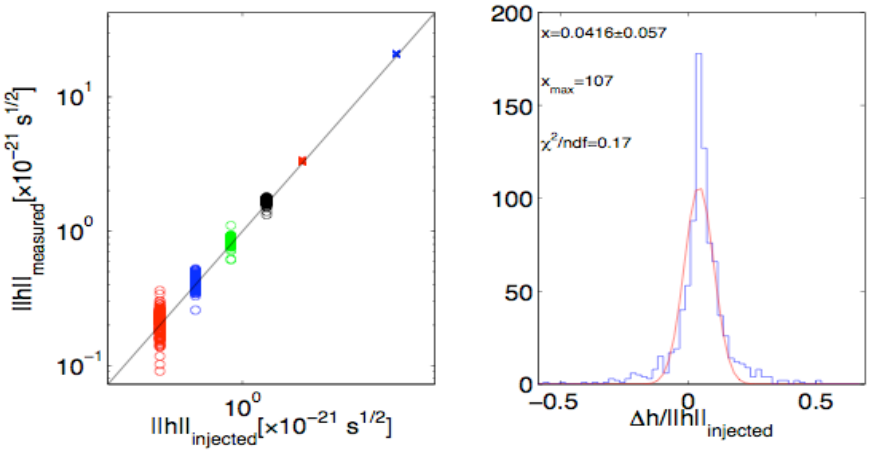


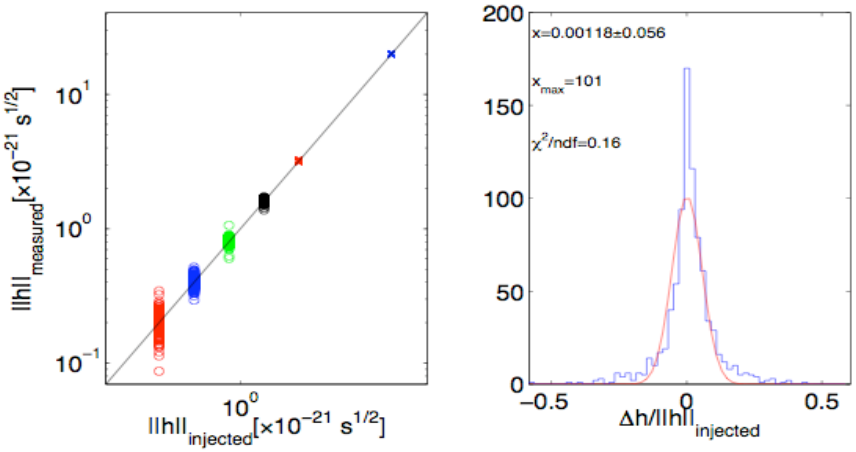
Gaussian σ=1ms: Strength Measurement

L1







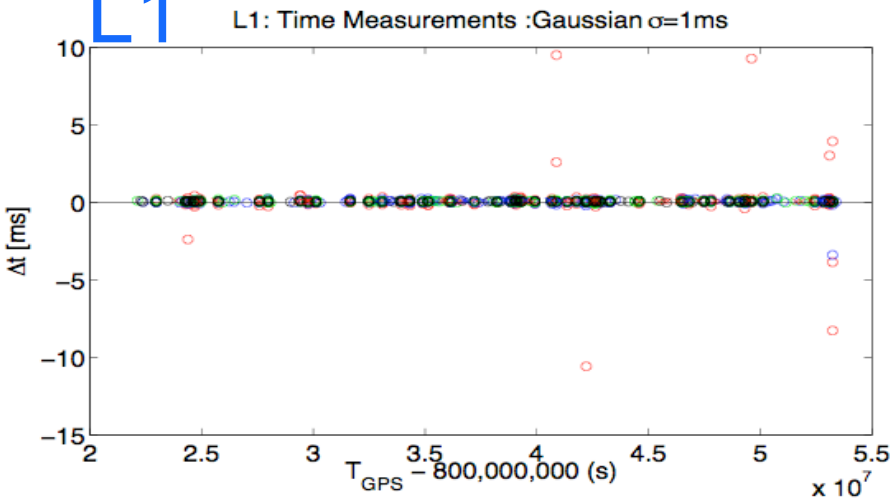


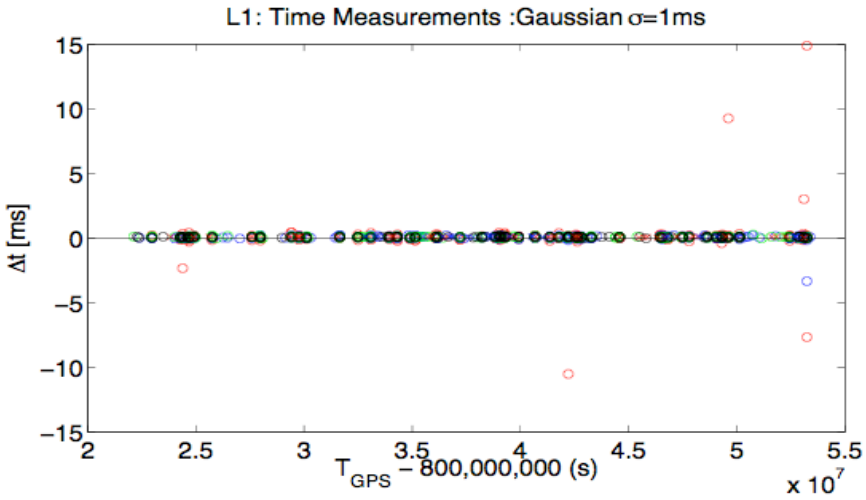
$\Delta h/\|h\|_{injected}$=4.2±5.7%

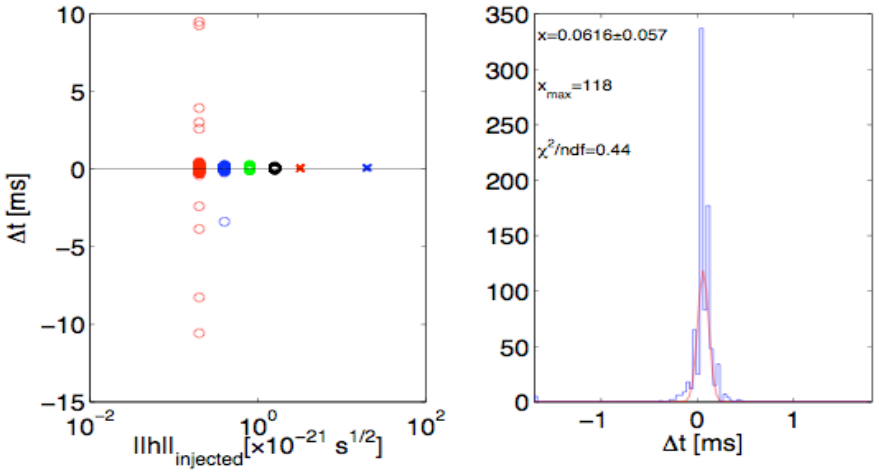
$\Delta h/\|h\|_{injected}$=0.1±5.6%

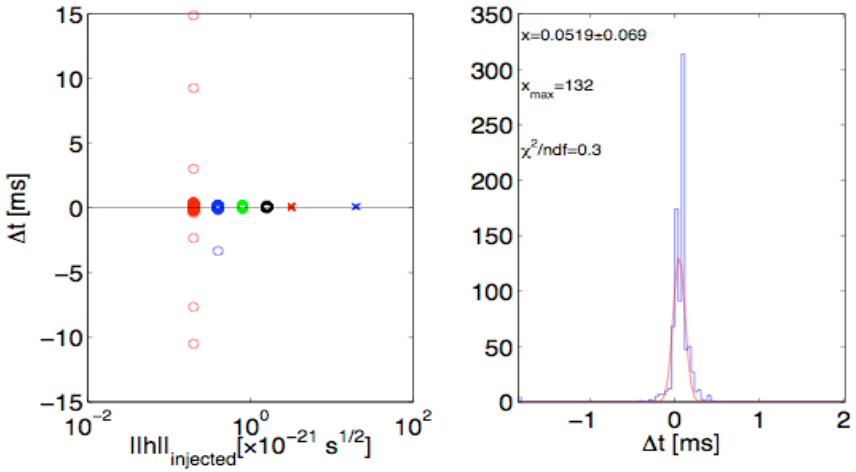
Gaussian σ=1ms: Time Measurement

L1





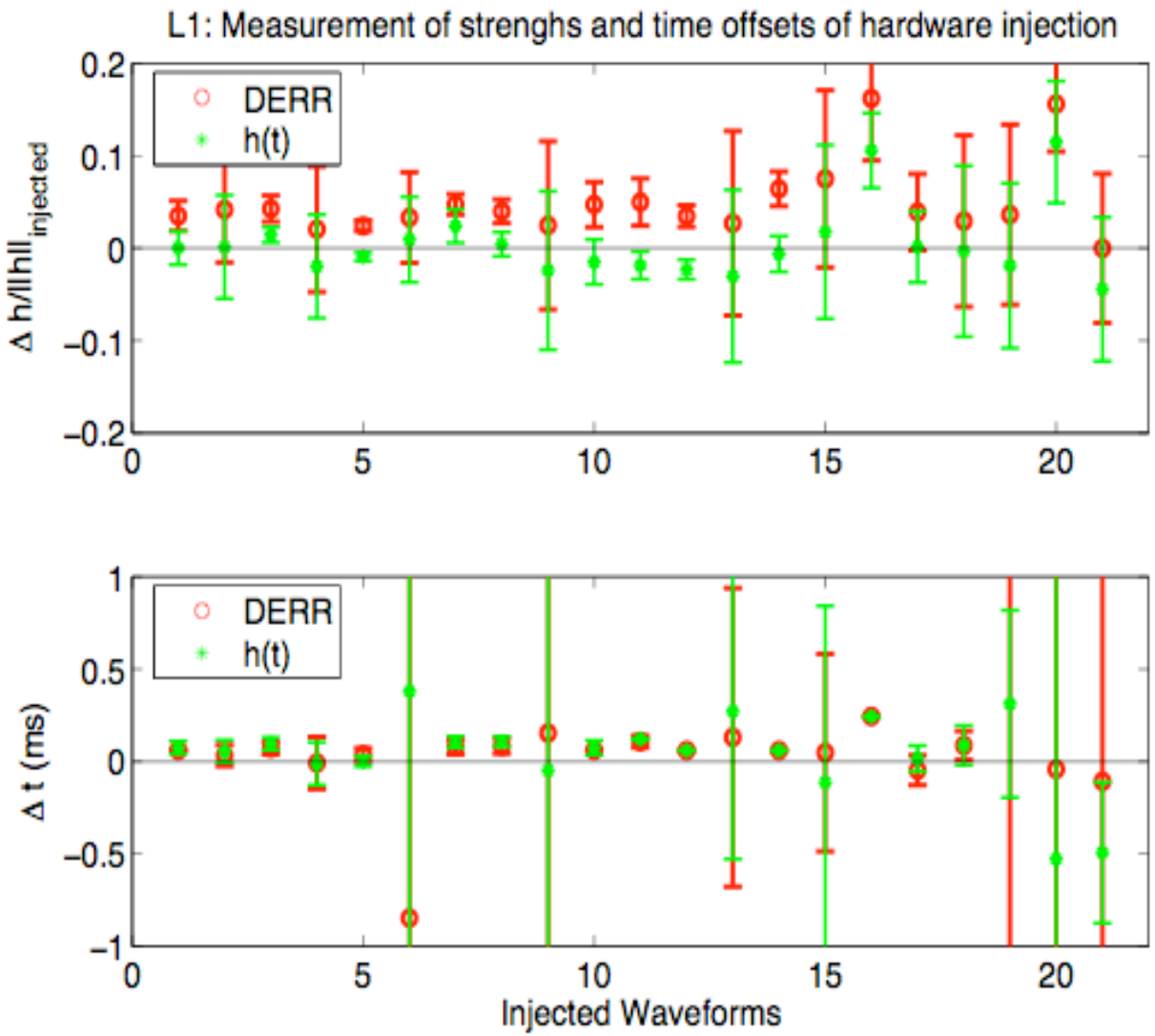




Δt = 0.06±0.06 ms

Δt = 0.05±0.07 ms

Measuring Burst Injections: L1

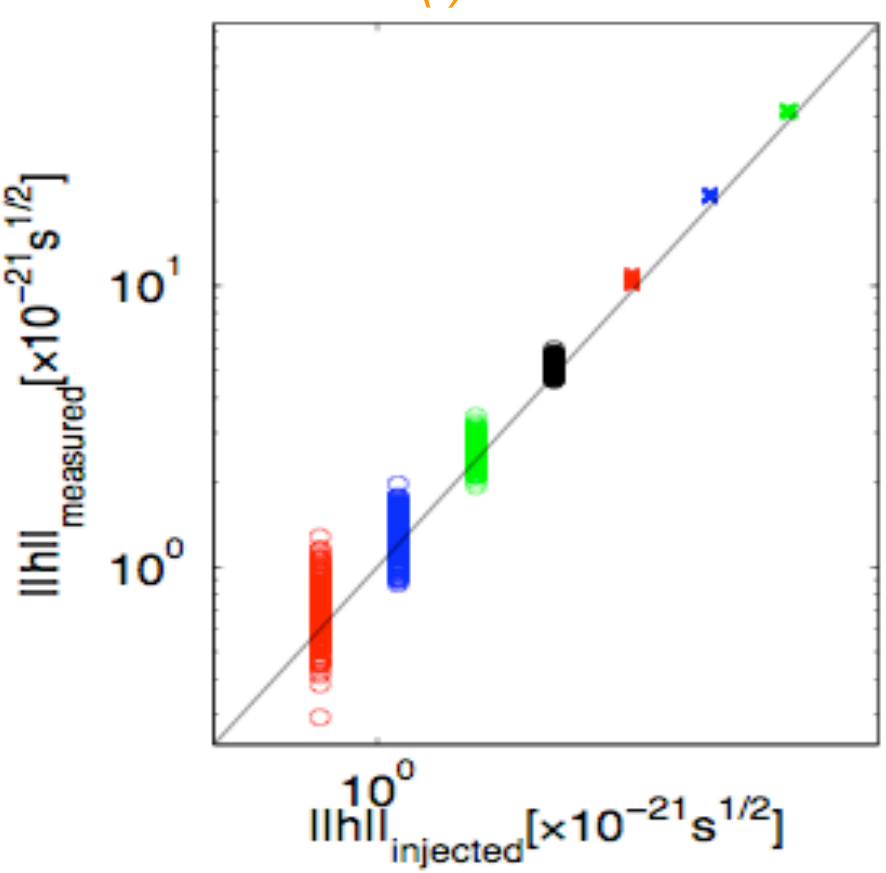


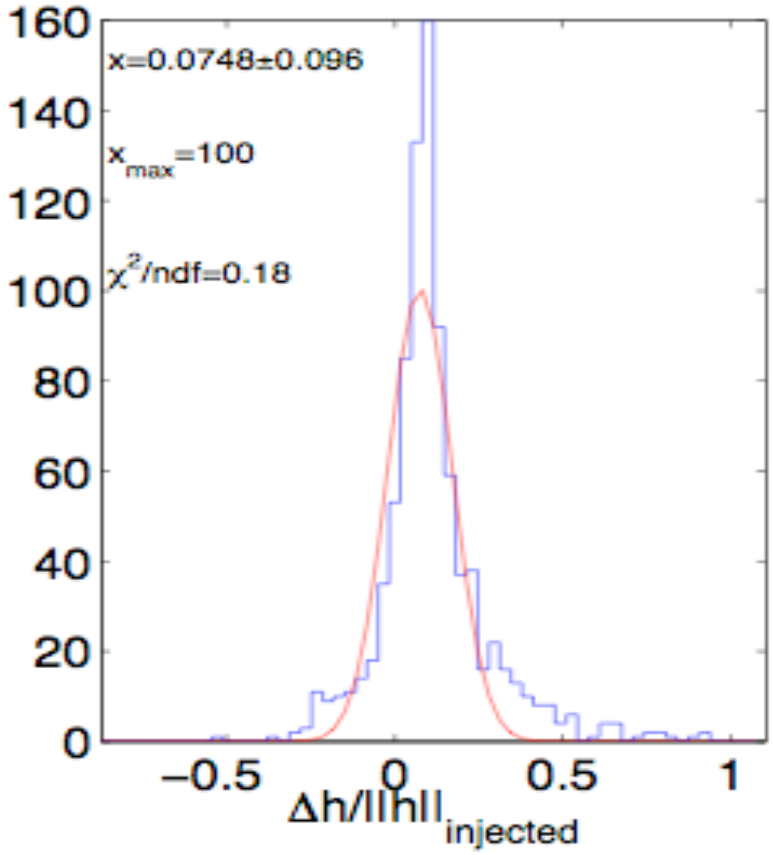
20 Waveforms injected:

- 4 Gaussians
  - 0.3 ms (1)
  - **1.0 ms (2)**
  - 3.0 ms (3)
  - 10ms(4)
- 12 sine-Gaussians
  - 50 Hz (5)
  - **70 Hz (6)**
  - 100 Hz (7)
  - 153 Hz (8)
  - **235 Hz (9)**
  - 393 Hz (10)
  - 554 Hz (11)
  - 850 Hz (12)
  - **914 Hz (13)**
  - 1304 Hz (14)
  - **2000 Hz (15)**
  - 3068 Hz (16)
- **Zwerger-Mueller (17)**
- **Cosmic string (18)**
- **Band-limit white noise (19)**
- Ringdown (20)

L1: llhll Measurements on SG2000

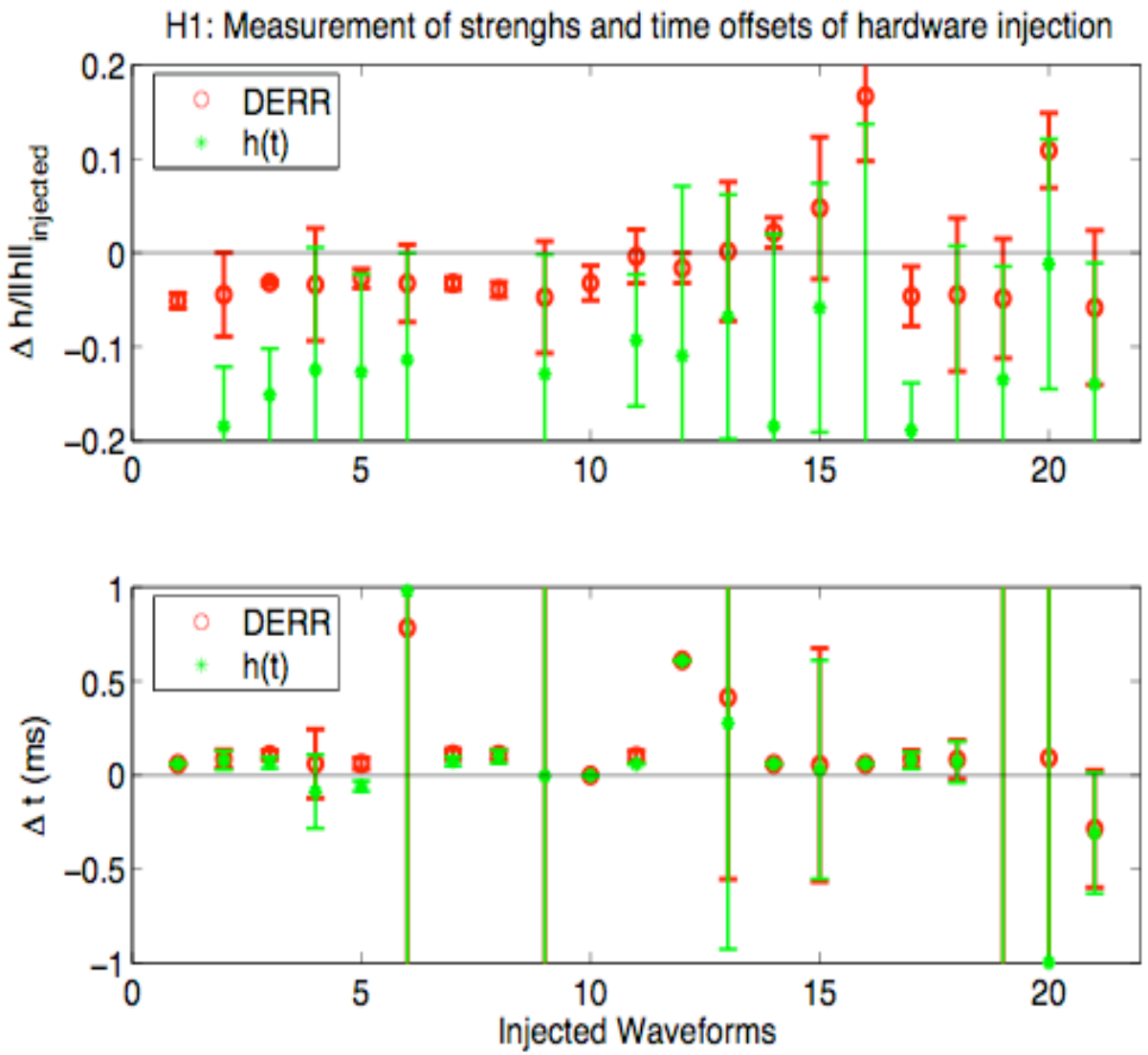
DERR(t)





- Big error bar is due to low intensity injections.

Measuring Burst Injections: H1



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  - 393 Hz (10)
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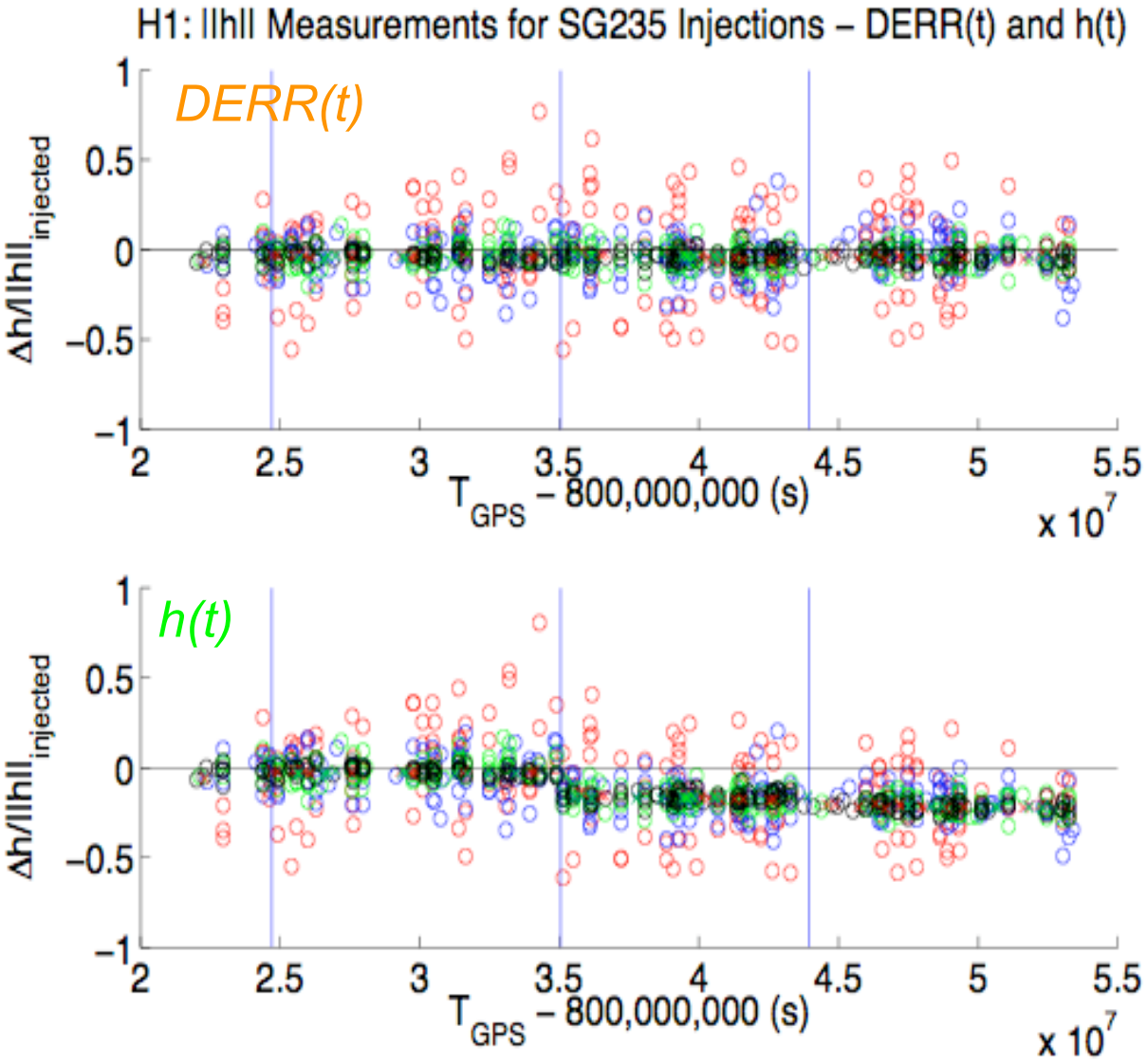
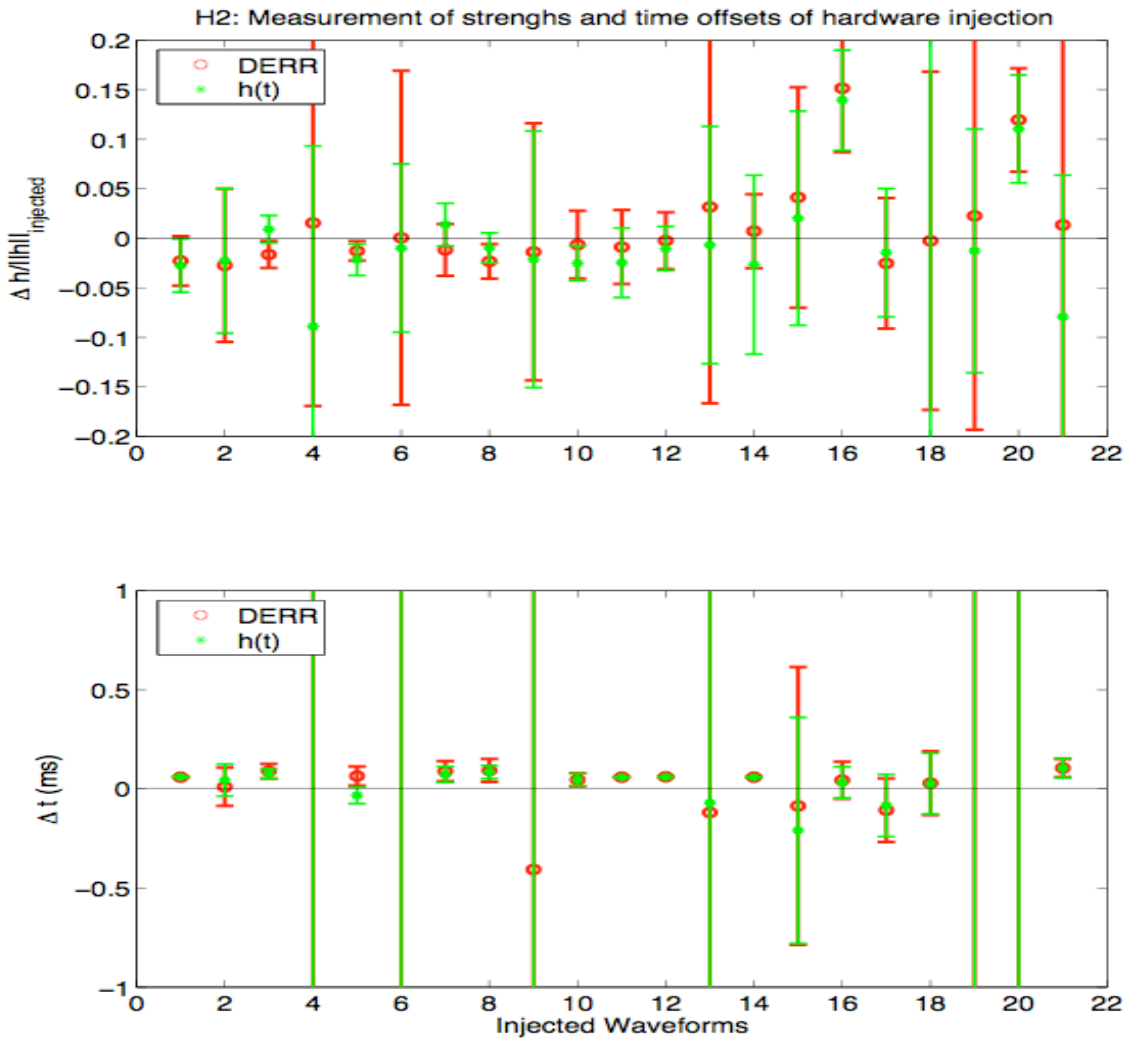
  - 850 Hz (12)
  - **914 Hz (13)**
  - 1304 Hz (14)
  - **2000 Hz (15)**
  - 3068 Hz (16)
- **Zwerger-Mueller (17)**
- **Cosmic string (18)**
- **Band-limit white noise (19)**
- Ringdown (20)

H1: Measurements on SG235



- Different calibration model was used in *DERR(t)* and *h(t)* - V3 and V2.
- Strain data shows different epochs, defined in V3 model.

Measuring Burst Injections: H2



Same calibration V2

20 Waveforms injected:

- 4 Gaussians
  - 0.3 ms (1)
  - **1.0 ms (2)**
  - 3.0 ms (3)
  - 10ms(4)
- 12 sine-Gaussians
  - 50 Hz (5)
  - **70 Hz (6)**
  - 100 Hz (7)
  - 153 Hz (8)
  - **235 Hz (9)**
  - 393 Hz (10)
  - 554 Hz (11)
  - 850 Hz (12)
  - **914 Hz (13)**
  - 1304 Hz (14)
  - **2000 Hz (15)**
  - 3068 Hz (16)
- **Zwerger-Mueller (17)**
- **Cosmic string (18)**
- **Band-limit white noise (19)**
- Ringdown (20)

Summary

- Burst hardware injections of one year are recovered by using linear filters - whitening and match.
- Most injections are recovered well from both *DERR(t)* and *h(t).*
- Comparison between *DERR(t)* and *h(t):*
  - L1 - Overall good agreement with different biases.
  - H1- Noticeable disagreement, probably due to different versions of calibrations (V2 and V3).
  - H2 - Good agreement from using the same calibration (V2)
- On waveforms injected:
  - Sine-Gaussian with 3068Hz and ringdown - Bigger bias in ||h|| measurement.
  - Big error bars are due to injections with smaller strengths.

What's next?

- New code to be installed in the online analysis.
- Add inspiral templates.
- Noise spectra comparison before and after filtering
- SNR/Detection probability