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Timing Witness Signals Indicate Trustworthy Timing for G184098, a BBH Event Candidate

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Synopsis

Advanced LIGO data is taken by a DAQ that is directly driven in hardware by the Advanced LIGO Timing Distribution System that ensures end-to-end hardware-based timing signal integrity between the received GPS signal and the ADC boards. The Advanced LIGO Timing Diagnostic System is a separate additional hardware that provides additional layers of timing information and crosschecks to enable us to have versatile diagnostic information.

As an extra precaution, we examined the timing witness signals to ensure that the aLIGO datastream's timing was perfect around Event Candidate G184098, later named GW150914, observed at 1126259461 = Mon Sep 14 09:50:44 UTC 2015. We found that the DuoTone witness indicated excellent timing performance on the sub-microsecond level and the IRIG-B signals indicated precise second decoding.

1. Introduction

The advanced LIGO timing system is implemented in hardware. Each and every board in the chain was tested multiple times in different environments, including end-to-end test using long fibers - it performs for tens of ns and the GPS is rated for few hundred ns. This is the primary performance measure of the well-working timing system that is below 1µs.

Additionally, independent hardware generated GPS synchronized timing witness channels are recorded along with the aLIGO datastream: the DuoTone and the IRIG-B datastreams at each end-stations. The phase of the DuoTone signals allows sub-microsecond accuracy determination of the datastream's shift from the perfect agreement with the GPS time. Since the DuoTone signal is repeated in every second, it is prudent to also look at the IRIG-B signal that has a phase allowing time verification on the ms level and a full timecode allowing the determination of absolute YEAR:MONTH:DAY-HOUR:MINUTE:SECOND. Therefore the DuoTone and IRIG-B signals together cover all possible timeshifts, and the most feared small shifts redundantly.
In this document we provide visual proof that the phase of the witness signals did not move from the nominal value even for a second during the hour surrounding the GW150914 event.

2. DuoTone Signal Measurements

Each aLIGO ADC chassis contain a timing Slave board with a DuoTone daughterboard installed. The Slave-DuoTone assembly pairs provide the precise pulses that allow the ADC to record the aLIGO data at 65536Hz rate; the phase of this low phase noise ADC clock is synchronized to the GPS 1PPS rising edge. Besides this mission critical functionality, each DuoTone board provide a so called DuoTone diagnostic signal(***Y***):

Y1 = ***A*** * sin(2 * pi * 960 * (T + ***ΔT***));
Y2 = ***A*** * sin(2 * pi * 961 * (T + ***ΔT***));
Y = Y1 + Y2 + ***ΔA;***

960Hz is chosen as it is a harmonic of 60Hz, to further preserve GW signal frequency space. The identical individual amplitude $\boldsymbol{A}$ is nominally 2.5V centered around $\boldsymbol{\Delta A}$ =0V and $\boldsymbol{\Delta T}$ describes the position of the GPS 1PPS rising edge compared to the 0° common phase of the generated DuoTone, which we call the 'coincident zero crossing' (the time where the phase of both sinusoidal components becomes zero). The coincident zero crossing clearly and unambiguously repeats once in every second. The sinusoids produced by the slave-duotone timing stack (see e.g. LIGO-E0900019) are thus hardware synchronized to the GPS time in every second with a well-characterized delay of $\boldsymbol{\Delta T}$ for the zero crossing (see LIGO-T1500513), and therefore even order of ~>microsecond deviations in timing performance would result in alteration of duotone signal shape and change in zero crossing time.

We checked for deviations in duotone signal shape by '*stacking'* 1 second long consecutive segments of duotone signals (i.e. plotting each 1 second long segments on top of each other). The data covered two half-an-hour long time intervals closest to the event candidate time. On figures 1-4, each consecutive second of the measured DuoTone signal was plotted and *stacked* on top of each other for a 30 minutes long data window. The x axis represents one second duration of DuoTone segments. Since the DuoTone repeats its waveform every second, ideally all DuoTone curves on the plot are identical to each other, and they should look like a single curve on the plot even though the plot has 30x60=1800 curves plotted on top of each other. If there are seconds where the timing of the DuoTone signals are shifted from the nominal value, or where the signal suffered some sort of degradation, noise, or glitching, the *stacked* signal's curve would no longer resemble a single waveform, lose fidelity and the deviation from normal would be clearly visible to the human eye. In the next 4 pages (figures 1-4) we show the *stacked* curves for the X-end-stations of the LLO and LHO aLIGO observatories. There are no visible deviations from the normal—as intended, the signal is periodic to a high degree of accuracy, giving the *stacked* plots the appearance of a single second of DuoTone signal.

Figure 1

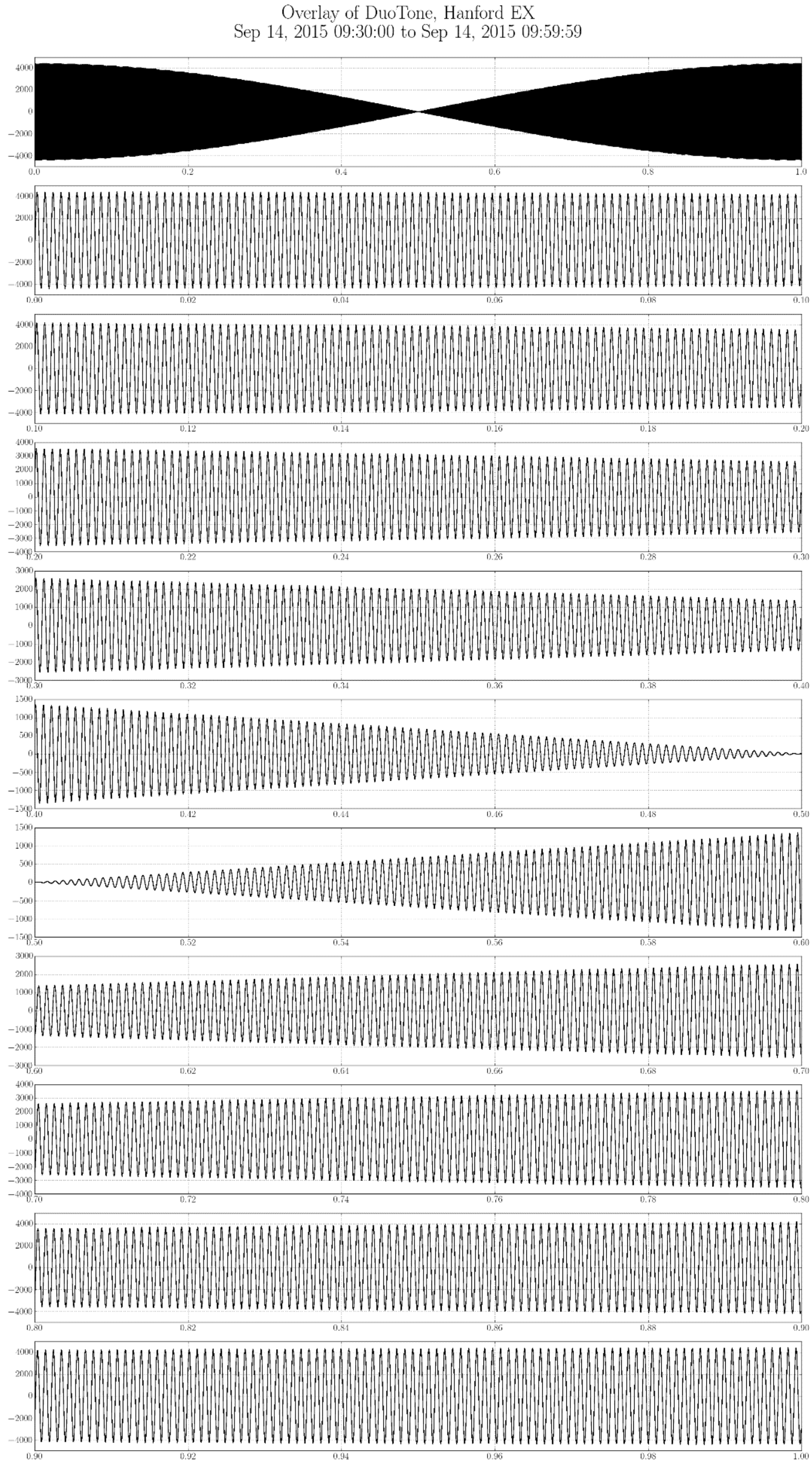

Overlay of DuoTone, Hanford EX
Sep 14, 2015 09:30:00 to Sep 14, 2015 09:59:59

Figure 2

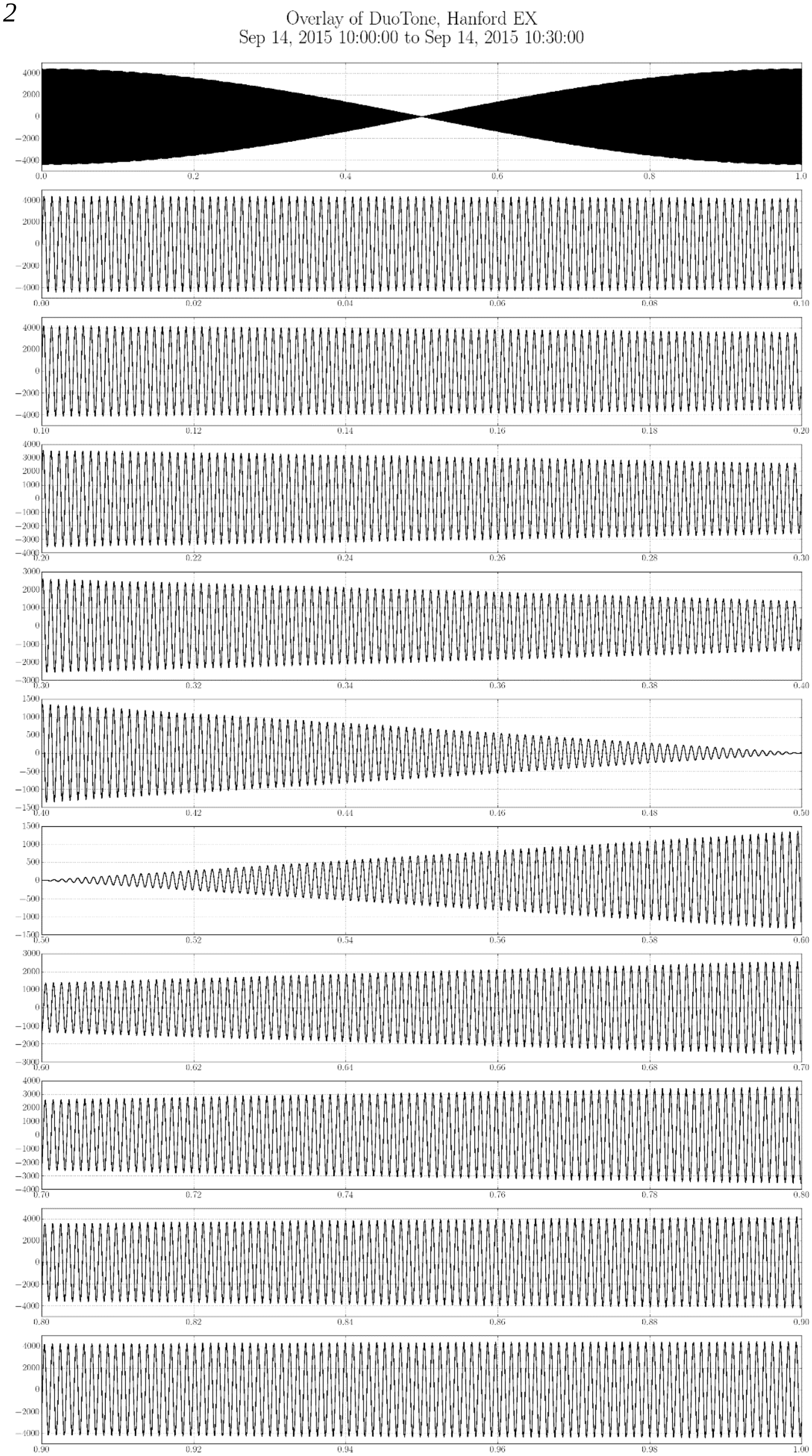

Overlay of DuoTone, Hanford EX
Sep 14, 2015 10:00:00 to Sep 14, 2015 10:30:00

Figure 3

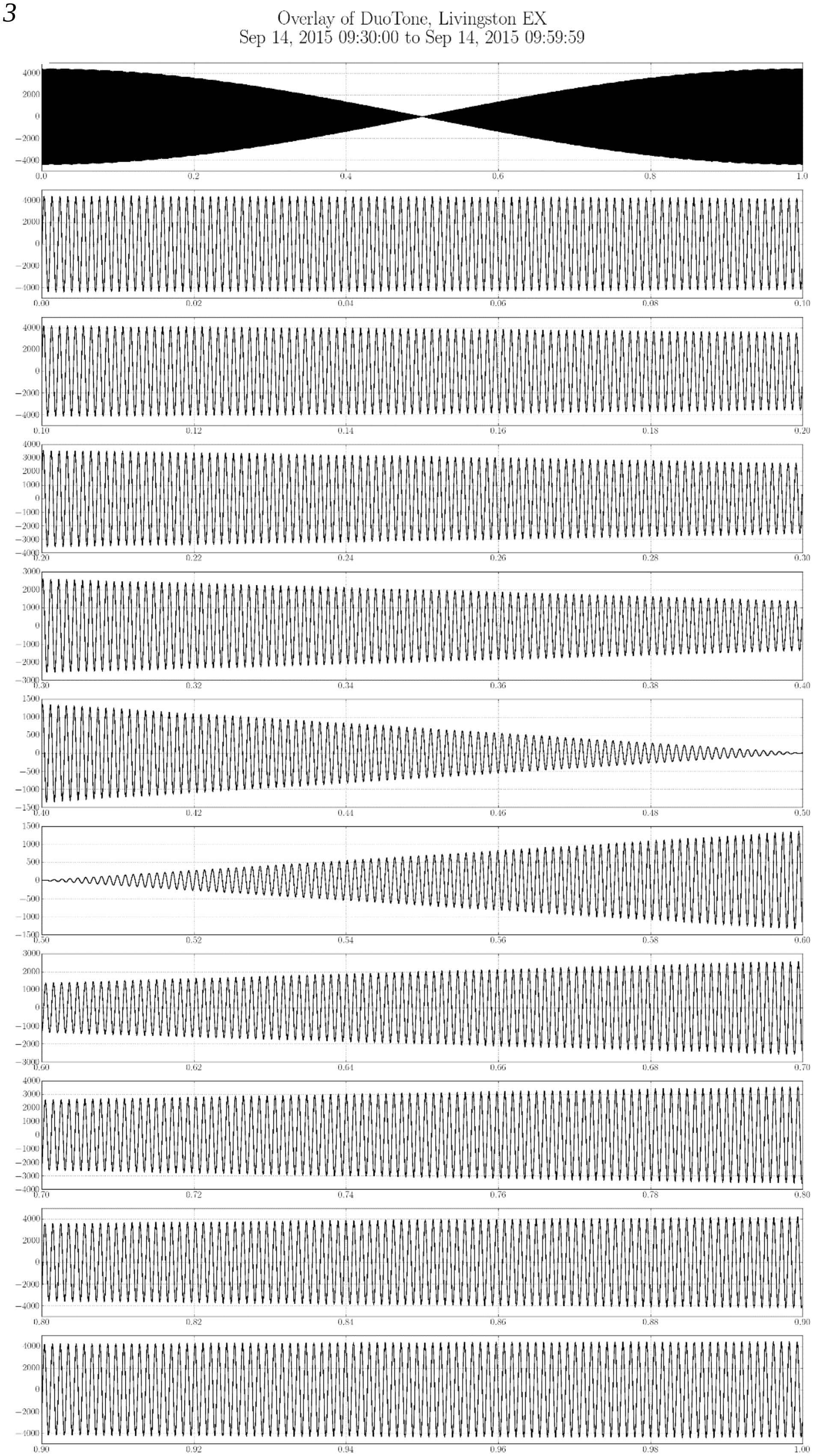
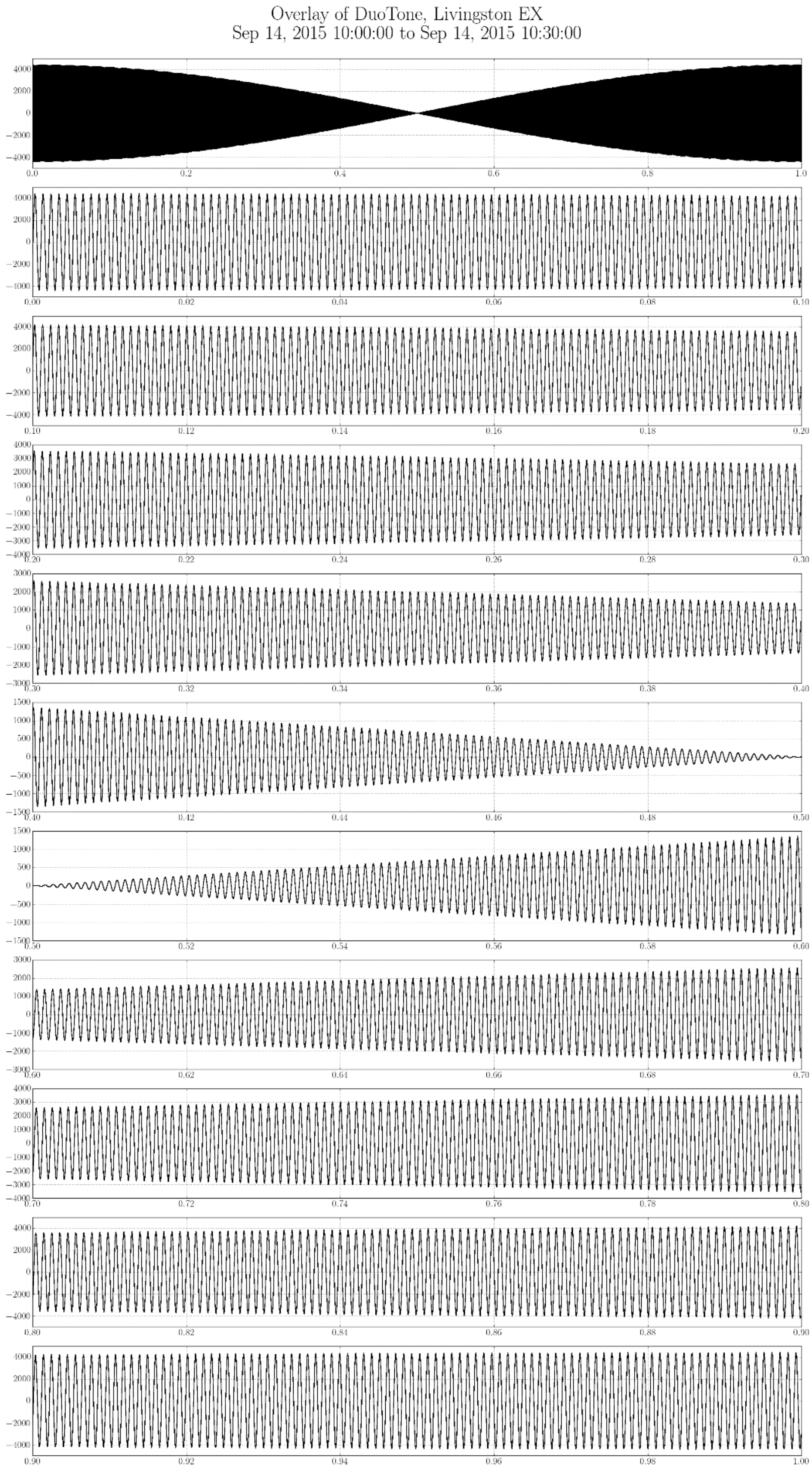

Overlay of DuoTone, Livingston EX
Sep 14, 2015 09:30:00 to Sep 14, 2015 09:59:59

Figure 4


Overlay of DuoTone, Livingston EX
Sep 14, 2015 10:00:00 to Sep 14, 2015 10:30:00

3. IRIG-B Signal Measurements

Each second of the IRIG-B signals were downloaded and *stacked* on top of each other (i.e. each 1 second long segment was plotted on top of each other). If there are seconds where the IRIG-B signals are shifted from the nominal value, or where glitches or excessive noise were present, then (as with the stacked DuoTone signals) the *stacked* signal's curve would lose fidelity and the deviation from normal would be obvious to the human eye. One notable difference between the DuoTone and IRIG-B signals is that the IRIG-B signal changes slightly each second, since the width of each pulse encodes information about the timestamp. So the *stacked* IRIG-B signal is not expected to exactly resemble a single second worth of IRIG-B data, though the rising edges should nonetheless occur in phase. In the next 4 page, in figures 5-8, we show the overlays recorded at the X-end-stations of the LLO and LHO aLIGO observatories. There are no visible deviations from the expected appearance.

Figure 5

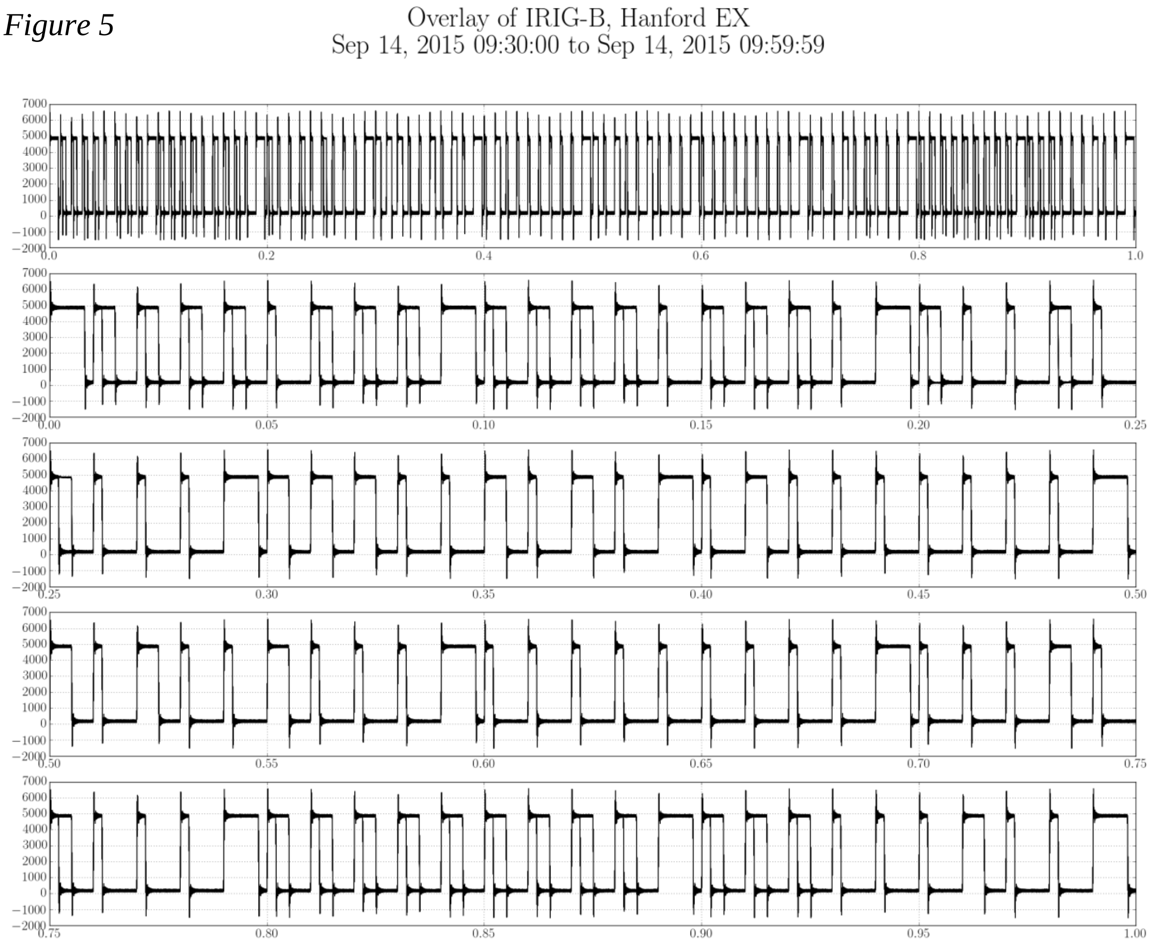

Overlay of IRIG-B, Hanford EX
Sep 14, 2015 09:30:00 to Sep 14, 2015 09:59:59

Figure 6

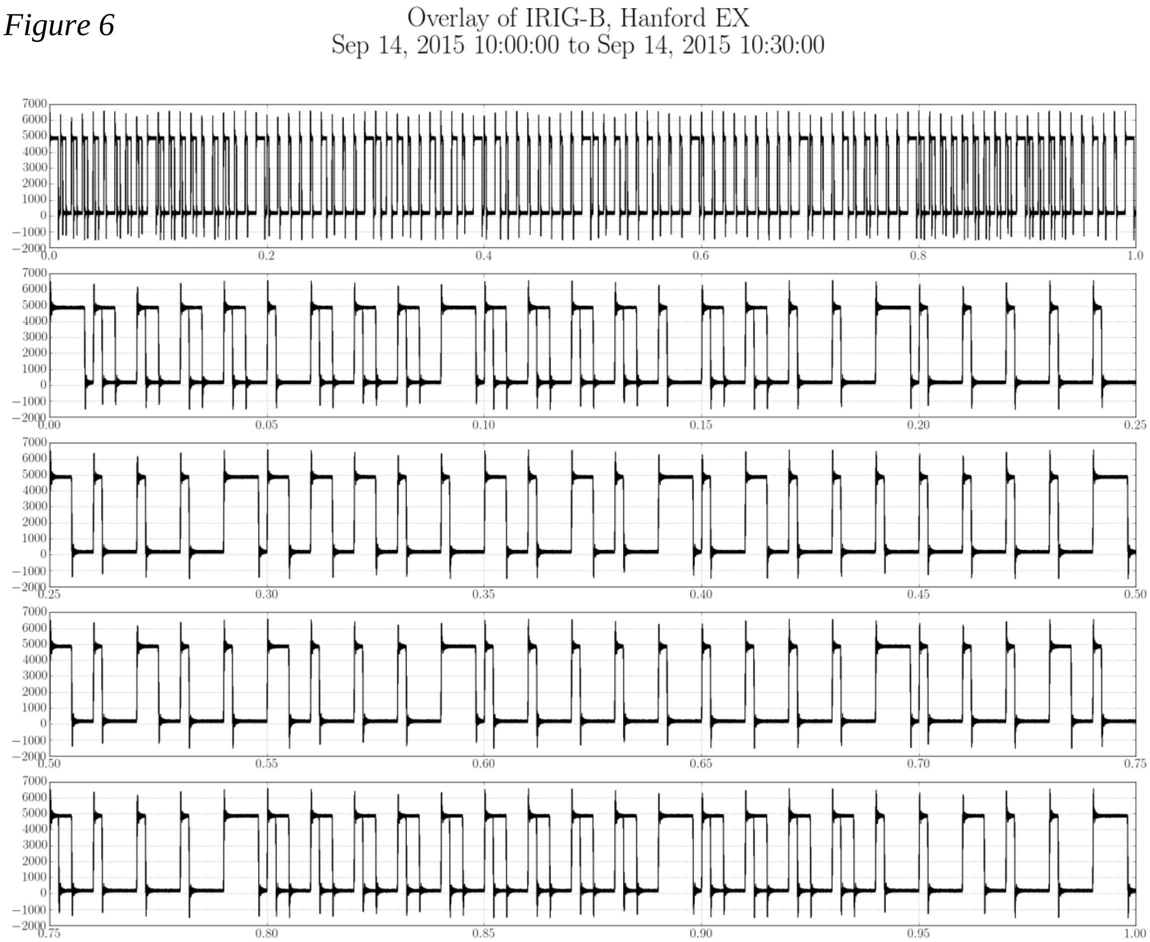

Overlay of IRIG-B, Hanford EX
Sep 14, 2015 10:00:00 to Sep 14, 2015 10:30:00

Figure 7

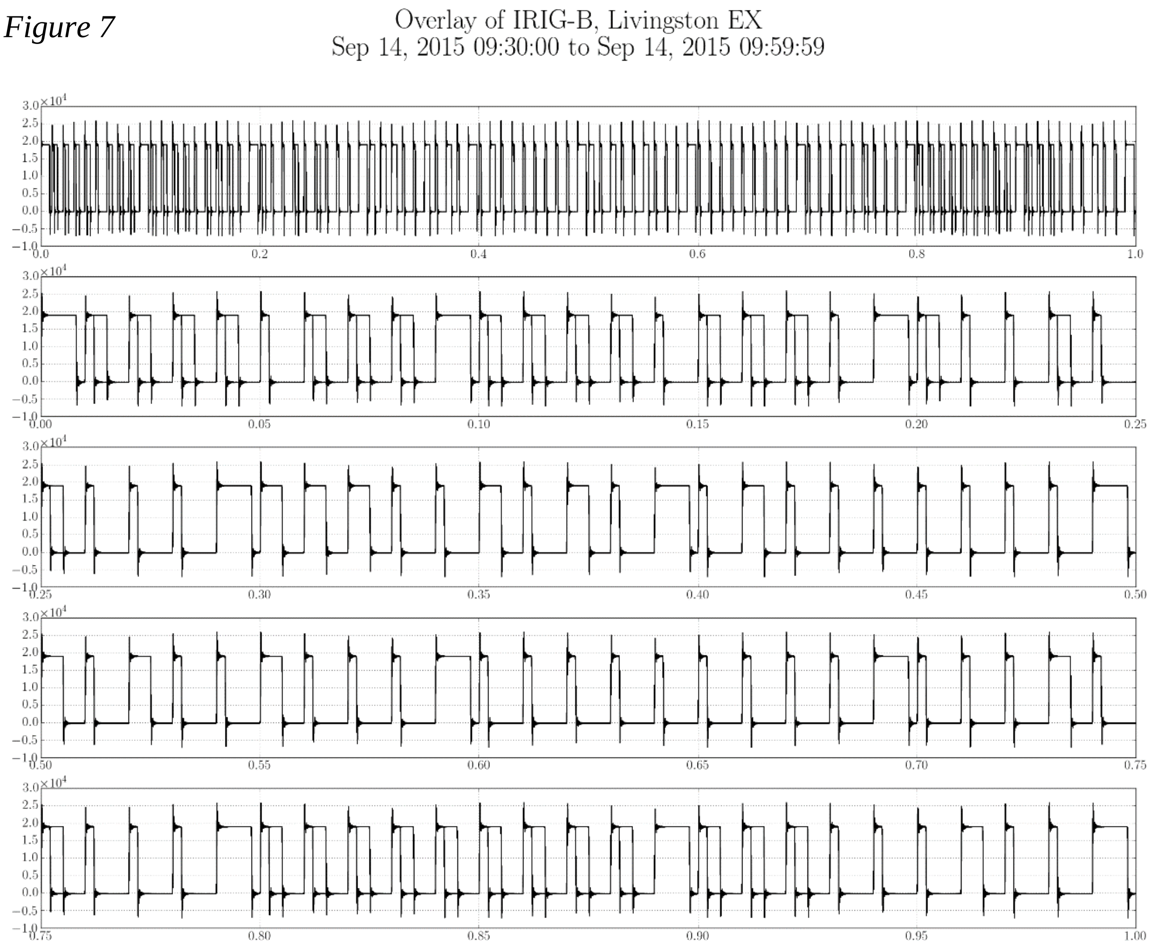
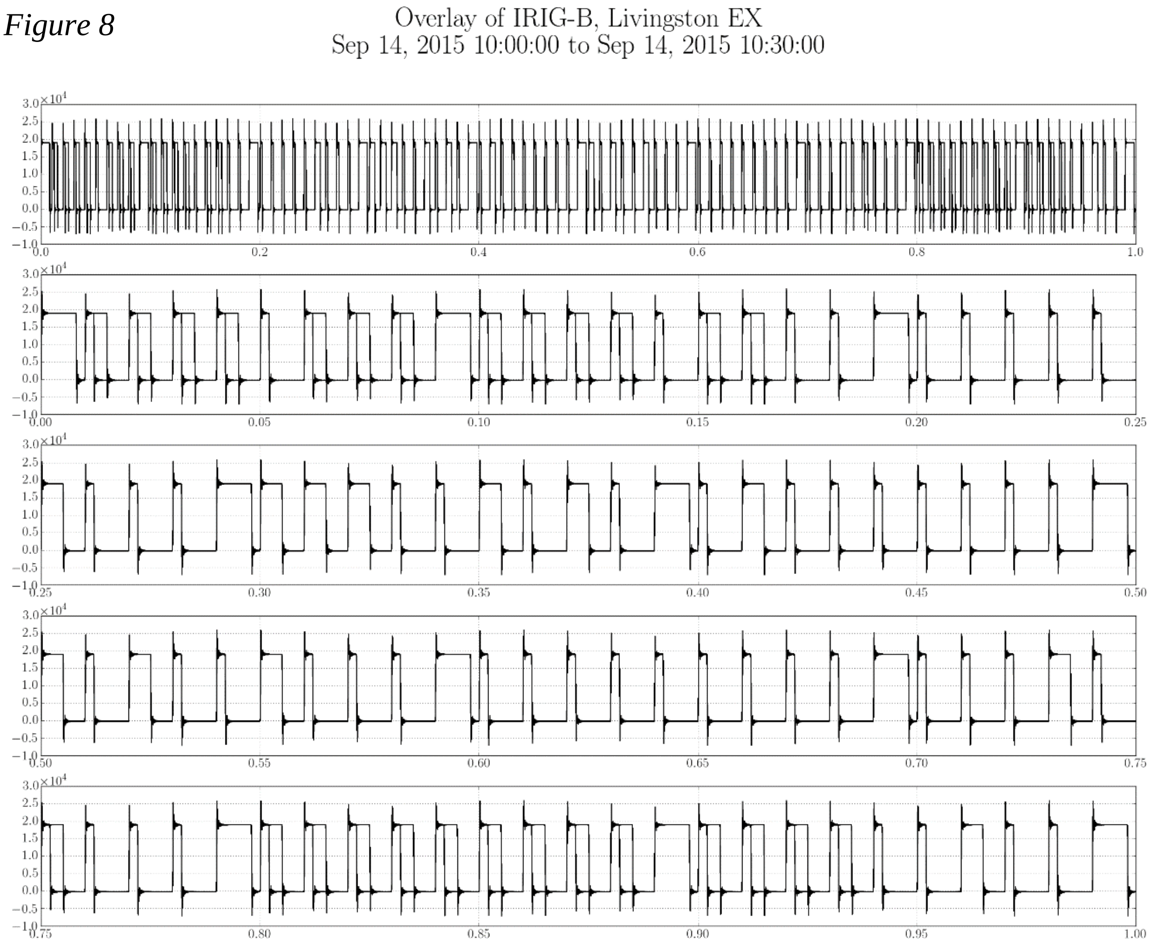

Overlay of IRIG-B, Livingston EX
Sep 14, 2015 09:30:00 to Sep 14, 2015 09:59:59

Figure 8


Overlay of IRIG-B, Livingston EX
Sep 14, 2015 10:00:00 to Sep 14, 2015 10:30:00

4. DuoTone Signal Phase

Beyond *stacking* 1 second long segments of duotone signals on top of each other (see section 2), we also averaged the one second long waveforms and plotted the averaged DuoTone signal to verify the agreement and errors to higher accuracy.

The following 6 pages (figures 9-14) show the zero crossing region of the second-to-second average of the DuoTone witness signals around the second edge, zoomed-in at different magnifications in the x-axis. When the DuoTone signals are symmetric around the 0V level, the zero crossing should be delayed compared to the second tic of the datastream by ~63μs (6.7μs of this is due to and inherent delay on the timing Slave-DuoTone stack (see LIGO-T1500513), and the rest is due to 65536Hz to 16384Hz decimation filter (see Section 6 below).

On the figures the open circles reflect the average signal, the green error bars indicate the standard deviation, and the ends of the fine black error bars show the maximum/minimum for each data point. The line through the data points guide the eye to help visualize the zero crossing, which is most visible at the medium timescale plotted, and is at a bit above 63μs. The plots indicate precise agreement with the expected place of the zero crossing and confirm the independent verification measurement by LHO and LLO rapid response team discussed in Section 6 of this document.

The purpose of this study was not the measurement of the already known DuoTone delay, but to verify the stable microsecond-level performance of the timing system at around the time of the candidate event. The DuoTone witness signals indeed indicate *very small errors*: The highest magnification of a representative data point (the last plot of three for each detector) shows in green the standard deviation of measurements for the point closest to the zero crossing for the hour surrounding the GW150914 event candidate and the error bars indicate the observed maximum and minimum.

Figure 9 Zero crossing region of the second-to-second average of the DuoTone witness signals around the second edge at Hanford EX for the hour surrounding the GW150914 event candidate. The line through the data points guide the eye to help visualize the zero crossing. Please note that the errors on each point are so small that they are covered by the circular symbol.

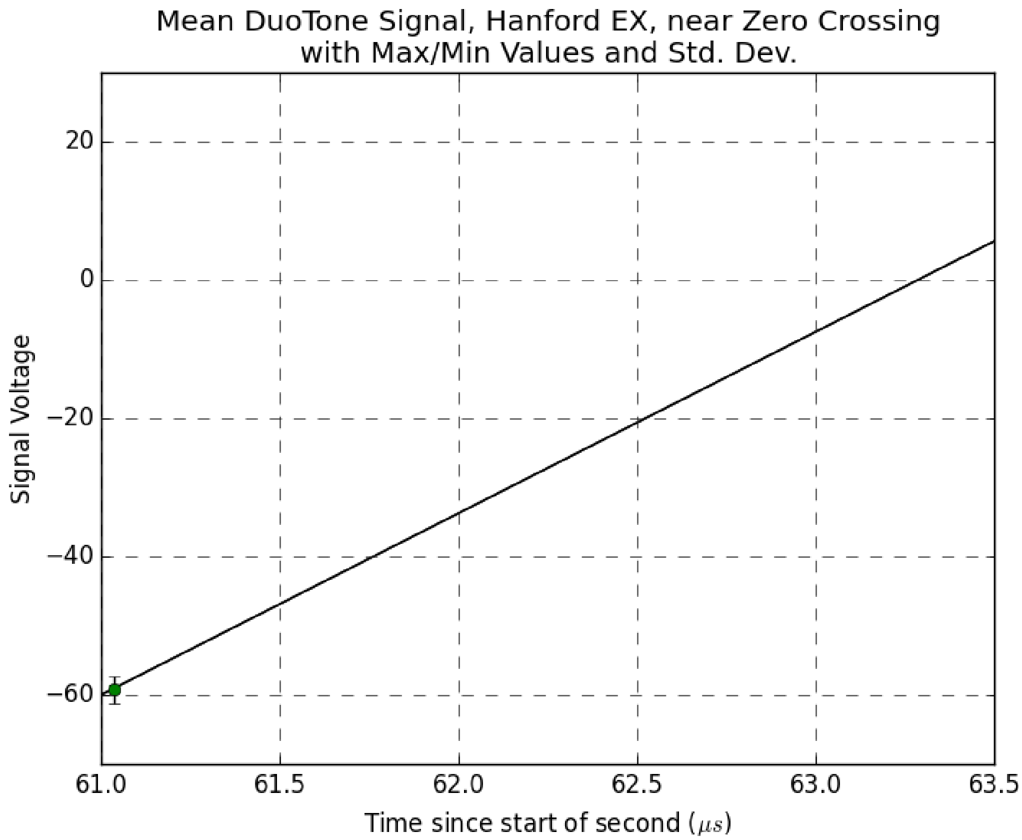


Figure 10 Zero crossing region of the second-to-second average of the DuoTone witness signals around the second edge at Hanford EX for the hour surrounding the GW150914 event candidate. Open circle reflect the average signal, the green error bars indicate the standard deviation, and the ends of the fine black error bars show the maximum/minimum for each data point. Please note that the green error bar is so small that it is still covered by the circular symbol. The line through the data points guide the eye to help visualize the zero crossing which is best visible on this magnification setting and is at ~ 63.3μs, out of which 62.6μs =6.7μs (DuoTone generation delay) + 55.9 μs (decimation filter delay) is accounted for.

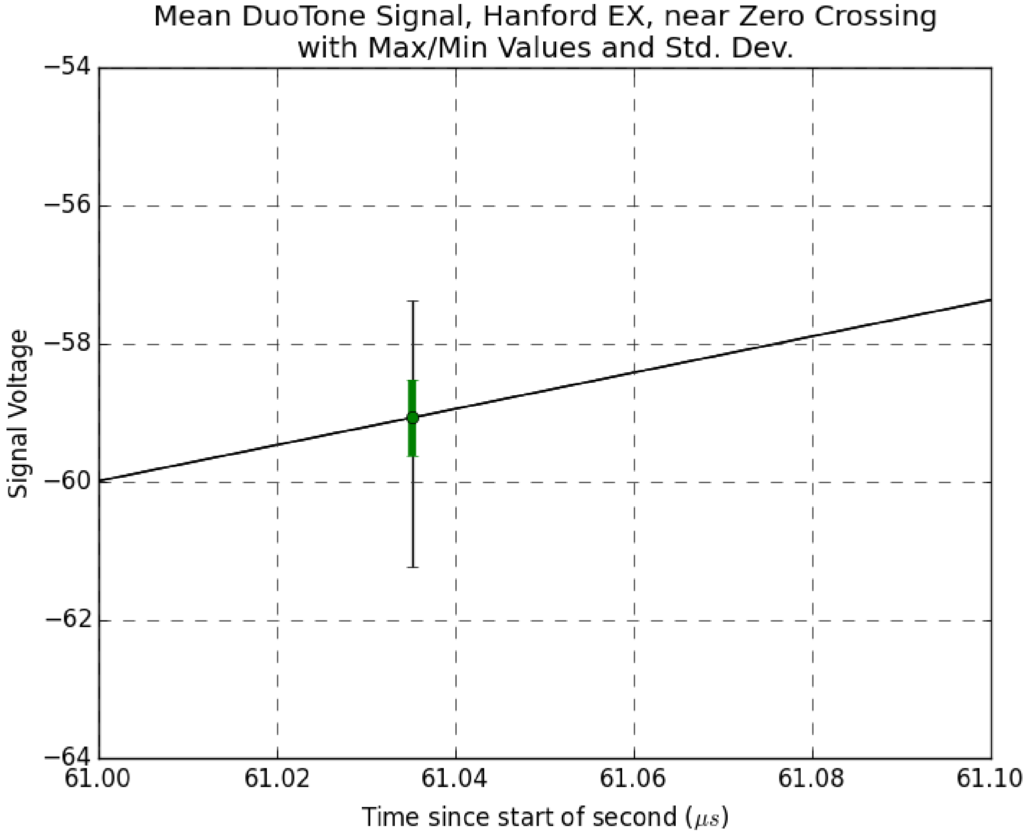


Figure 11 Zero crossing region of the second-to-second average of the DuoTone witness signals around the second edge at Hanford EX for the hour surrounding the GW150914 event candidate. The open circle reflect the average signal, the green error bar indicates the standard deviation, and the ends of the fine black error bar shows the maximum/minimum for the data point. The size of the green error bar indicates very small error on the zero crossing.

Figure 12 Zero crossing region of the second-to-second average of the DuoTone witness signals around the second edge at Livingston EX for the hour surrounding the GW150914 event candidate. The line through the data points guide the eye to help visualize the zero crossing. Please note that the errors on each point are so small that they are covered by the circular symbol.

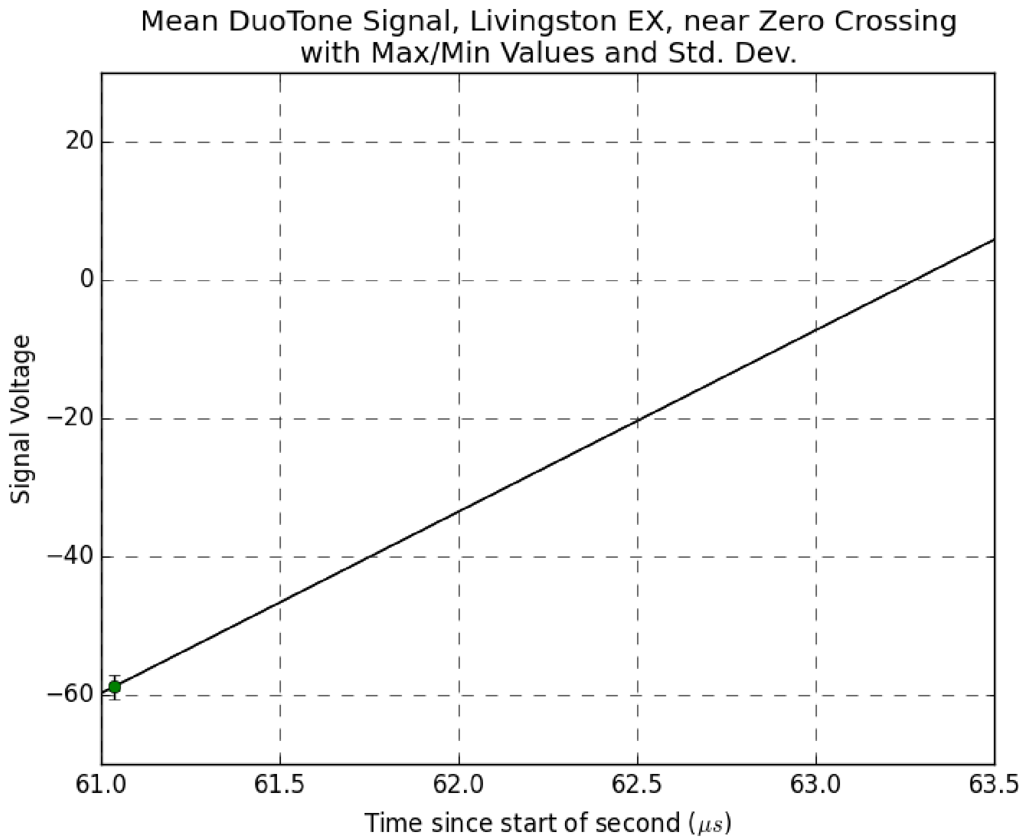


Figure 13 Zero crossing region of the second-to-second average of the DuoTone witness signals around the second edge at Livingston EX for the hour surrounding the GW150914 event candidate. Open circle reflect the average signal, the green error bars indicate the standard deviation, and the ends of the fine black error bars show the maximum/minimum for each data point. Please note that the green error bar is so small that it is still covered by the circular symbol. The line through the data points guide the eye to help visualize the zero crossing which is best visible on this magnification setting and is at ~63.3µs, out of which 62.6µs =6.7µs (DuoTone generation delay) + 55.9 µs (decimation filter delay) is accounted for.

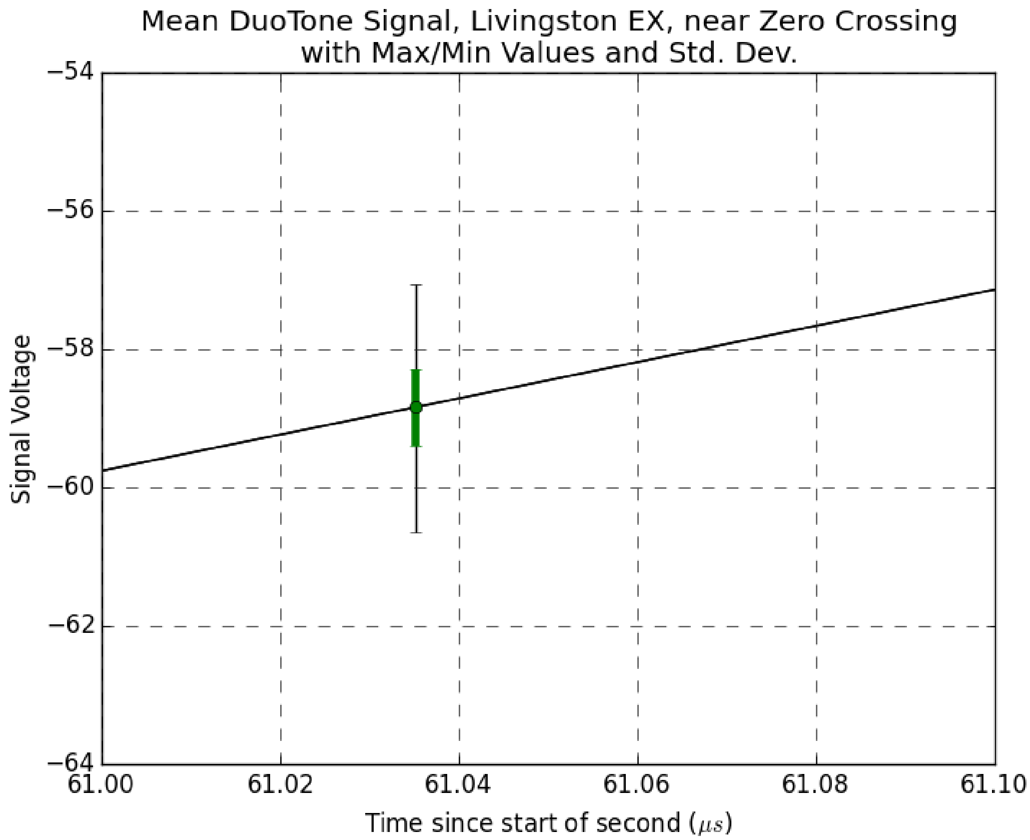
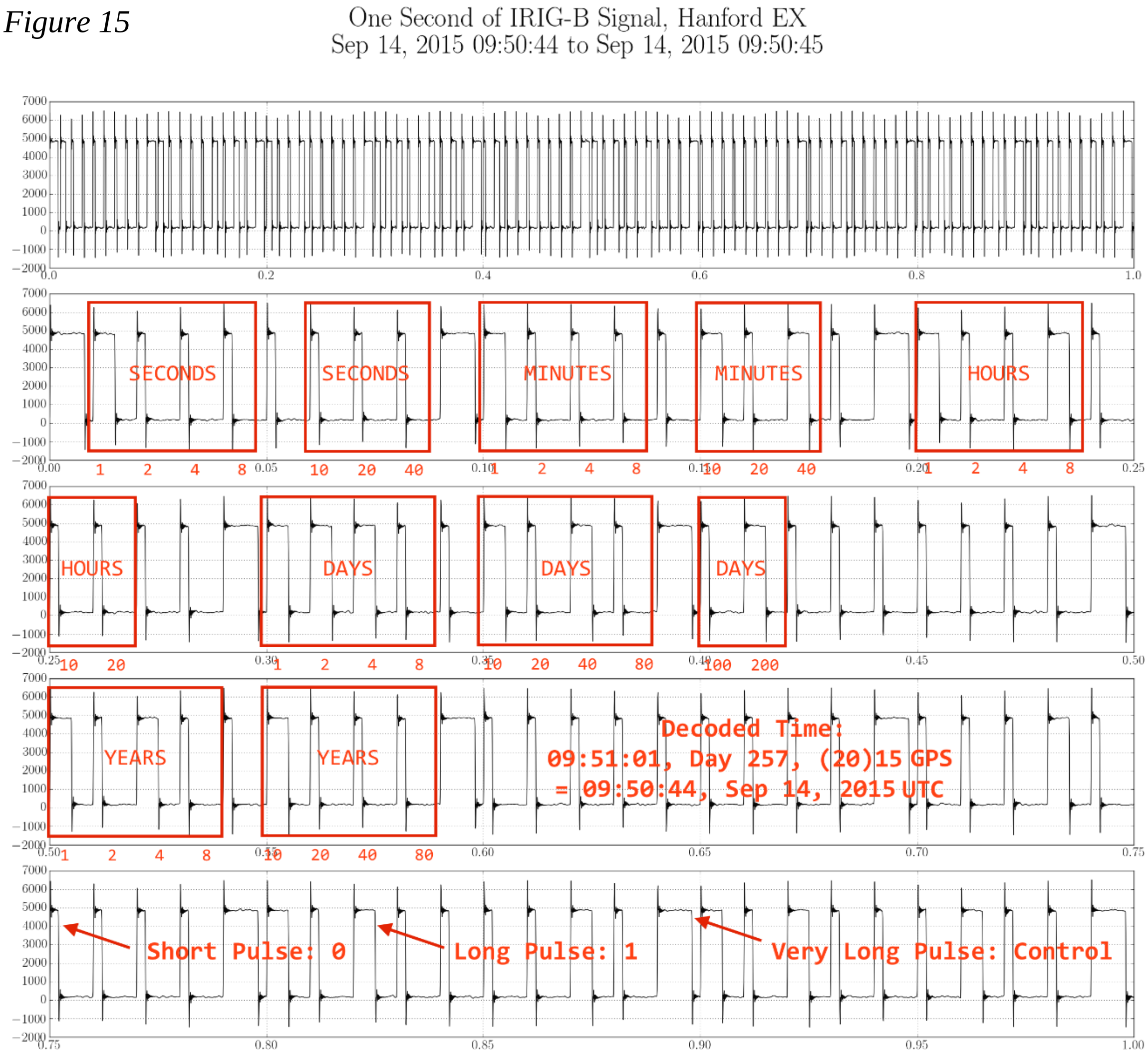


Figure 14 Zero crossing region of the second-to-second average of the DuoTone witness signals around the second edge at Livinston EX for the hour surrounding the GW150914 event candidate. The open circle reflect the average signal, the green error bar indicates the standard deviation, and the ends of the fine black error bar shows the maximum/minimum for the data point. The size of the green error bar indicates very small error on the zero crossing.

5. IRIG-B Signal Decoding

The IRIG-B signal was decoded by hand at the time of the candidate event GW150914, observed at 1126259461 = Mon Sep 14 09:50:44 UTC 2015. The time code was found to be in agreement with the timestamp of the datastream. Figure 15 below explains the decoding of IRIG-B data. This agrees with the independent verification by the rapid response team at EVNT log 11263.

Figure 15



6. DuoTone measurements by the sites' rapid response team (Keita Kawabe and Keith Thorne)

The rapid response team at the sites independently performed a shorter timescale cross check of the timing at the sites soon after the event. The studies are in agreement with that of the timing group's, and show that the timing system performed according to specifications. These independent measurements are summarized below by Keita Kawabe.

Right after the LIGO sites were notified about GW150914, local staffs started analyzing the timing of a subset of aLIGO real-time system that is most relevant to the timing of the calibrated strain of aLIGO instruments for 10 minutes window including the event time, and no sign of malfunction was found. These efforts are documented in the following three EVNT log entries, 11263, 11230 and 11217.

EVNT log 11263 was about IRIG-B, which was already fully described in previous sections. In this section, DuoTone analysis shown in EVNT log 11230 and 11217 are discussed.

aLIGO DAQ and control system comprises multiple Input/Output Processors (IOPs) and multiple user models. User models are responsible for the real time control of the IFOs while IOPs allow the user models to access the outside world by providing ADC and DAC, among other things.

aLIGO timing system provides so-called duotone signal as one of its timing diagnostic tools for all IOPs. Each IOP works at 65536Hz clock cycle and measures DuoTone with one ADC channel, bypassing anti-alias filter.

Three user models, namely the end station calibration models for photon calibrators (PCal, not related to the timing system) and the corner station OMC model, receive DuoTone signal from their corresponding IOPs after decimation to 16384Hz and then send the data to be written on the frame files. This allows us to perform finer timing analysis of the ADCs used by these models, as the timing of aLIGO calibrated strain is directly dependent on the timing of the waveforms recorded by these ADCs. These data were available at both sites at the time of GW150914.

In addition, the end station calibration model sends the DuTone data back to IOP to be output from DAC that PCal uses. The signal is then measured by another ADC channel after passing through analog anti-imaging and anti-aliasing filter. This allows us to measure the round-trip time (user – IOP – DAC – anti imaging – anti aliasing – ADC – IOP – user), which is useful for health check of the calibration user model and DAC timing when and only when some anomaly is found in the PCal wave form recorded by ADC. Otherwise this is not essential in that the timing of aLIGO calibrated strain data is not directly dependent on the DAC timing. This was available at LHO but not at LLO at the time of GW150914. See Figure 16 for a simplified DuoTone routing diagram of the end station calibration model.

The analysis codes used for the above-mentioned EVNT logs are in aLIGO calibration SVN:
https://svn.ligo.caltech.edu/svn/aligocalibration/trunk/Common/MatlabTools/timing/
The script used to generate the plots on the EVNT logs is
https://svn.ligo.caltech.edu/svn/aligocalibration/trunk/Common/MatlabTools/timing/commissioningFrameDuotoneStat.m/.
The plots in EVNT logs are reproduced here on Figure 17 and Figure 18.

For ADC, the analysis simply measures the start point of DuoTone relative to the second marker of the data by calculating the time where the phase of both of the two sine components in DuoTone becomes zero, and compares the result with the expected timing. DuoTone repeats itself every second, so each second produces one number representing the difference between the expected and the measured. Results for 10 minutes window (600 data points) were plotted as a histogram. Red lines in the histogram shows the measured timing offset for one second starting GPS time 1126259462. For DAC, the analysis measures the round-trip time of duotone signal and compares the result with expected. Table 1 lists various delays accounted for by the analysis code.

It's worth noting that "DAC timing offset" plots for L1 shows a seemingly very large timing offset with equally large spread, but this is due to the fact that the channels were measuring noise at the time of the event. To paraphrase the log attached to EVNT log 11230:

There is no reason to get worried about somewhat-smaller-than-millisec offset in "DAC timing offset" in the LLO plots on Figure 18 because:

1. *At LLO, DAC timing monitor channels were measuring noise at the time of the event and the results don't mean anything.*[1]
2. *Timing calibration of aLIGO strain data depends on PCAL ADC timing. All ADC timing signals were available at the time of the event and were found good.*
3. *PCAL DAC timing monitor channels are useful only for diagnostic purpose when some PCAL anomaly is found, but there's no report of any anomaly in PCAL.*

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[1] EVNT log 11230 entry states *"DAC timing monitor channels were not available at LLO at the time of GW150914 in that the channels were there but the timing signals were not routed to the ADC. These channels were "turned on" later at LLO on Oct. 06 2015."* Though this is true in that the DAC timing monitor channels were later "turned on", it was Nov. 03, not Oct. 06 2015 that these channels became available for both end stations at LLO (https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=22339).

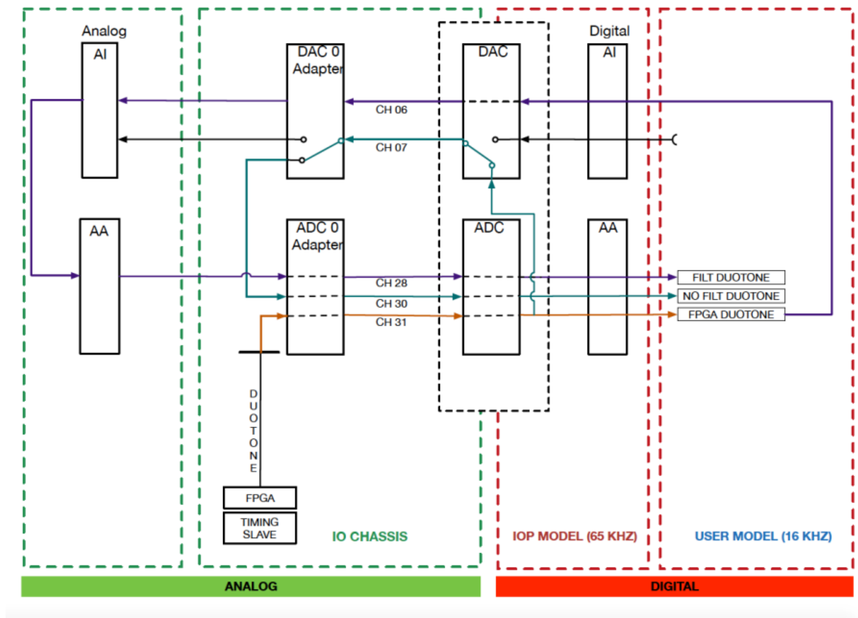

Figure 16: Schematic of the duotone routing for the end station calibration user model and its associated IOP. "FPGA DUOTONE" was used to monitor the ADC timing, and "FILT DUOTINE" for DAC timing. For OMC, only "FPGA DUOTONE" is available.

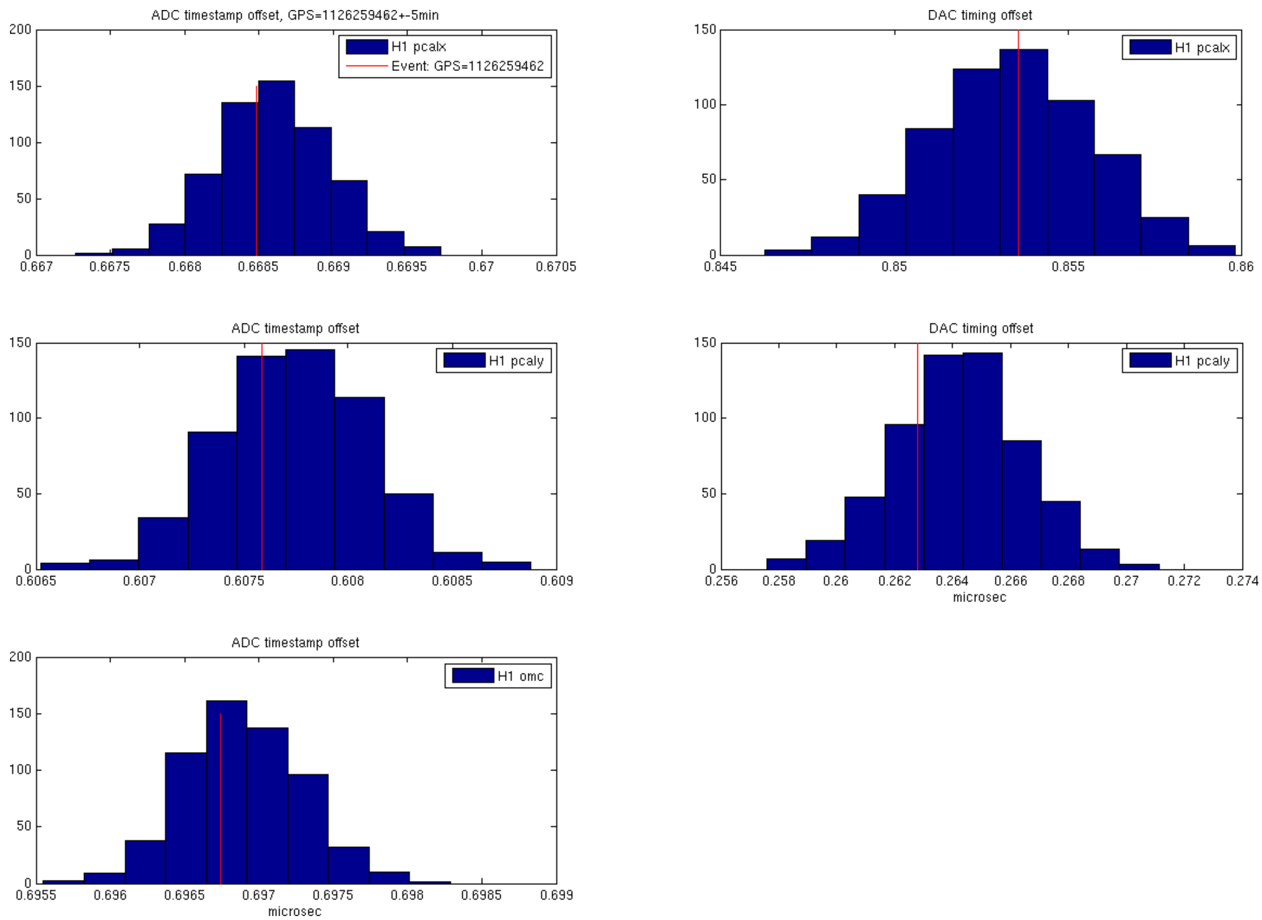

Figure 17: Rapid response team: Histogram of duotone timing offset from the expected number for [-5, +5] minutes window covering the event for H1. Red line shows the timing offset for one second starting the event GPS time of 1126259462. This plot appeared in EVNT log 11217.

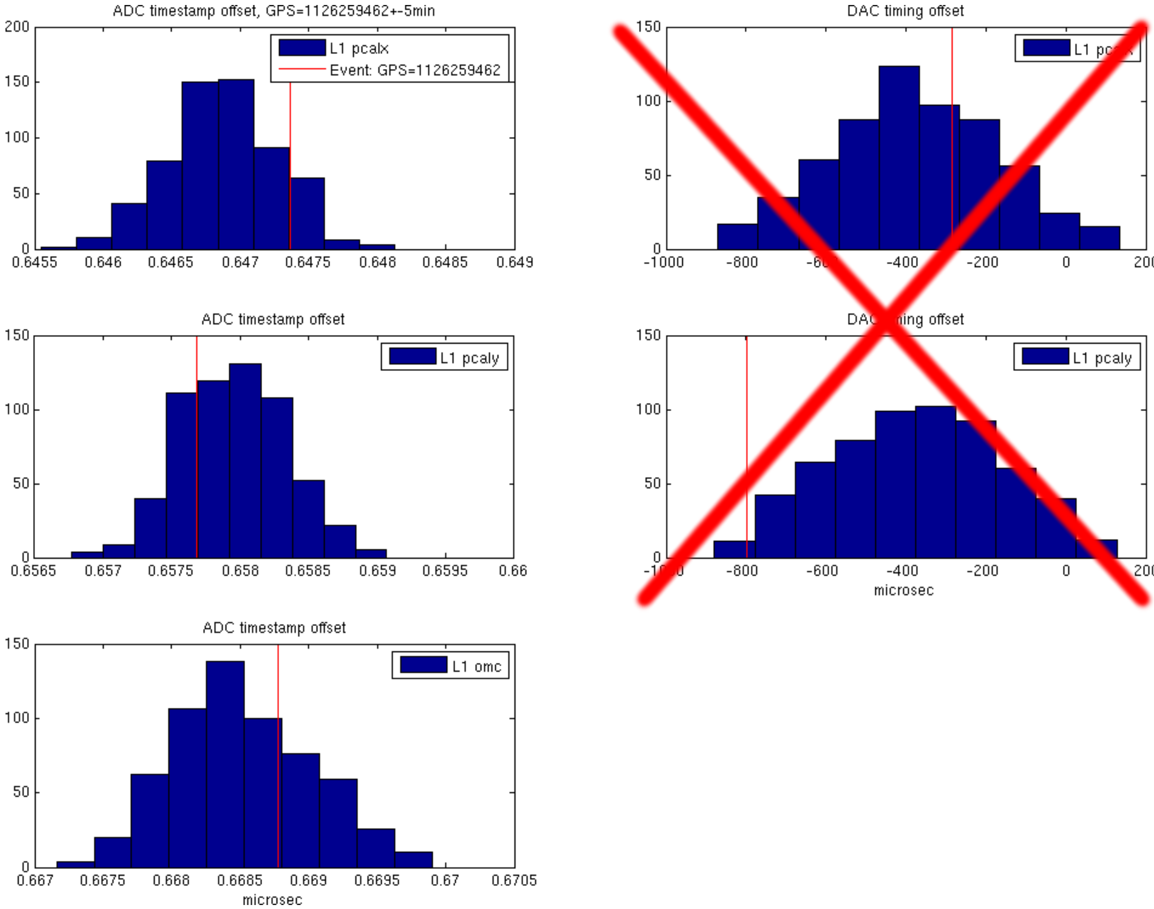

Figure 18: Rapid response team: Histogram of duotone timing offset from the expected number for L1. This plot appeared in EVNT log 11230. The channels necessary to produce "DAC timing offset" plots were measuring just noise at LLO at the time of the event, therefore the "DAC timing offset" plots don't represent anything. This doesn't mean in any way that the timing was suspect at LLO.

Table 1: Delays accounted for by the analysis for EVNT log 11217 and 11230.

Delays accounted for	ADC measurement (sec)	DAC measurement (sec)
Duotone delay relative to the timing slave	6.699E-6	None
64kHz to 16kH decimation filter	55.93E-6	
One user model cycle to pass the data to IOP	None	1/16384
16kHz to 64kHz up-sampling filter	None	55.93E-6
One IOP cycle to send the data to FIFO	None	1/65536
2 FIFO buffers in front of 64kHz DAC output	None	2/65536
Nominal DAC clock edge offset relative to ADC	None	1/2/65536
Zero-order hold	None	1/2/65536
Anti-imaging after DAC	None	39.83e-6
Anti-aliasing before ADC	None	39.83e-6
Total	62.629e-6	313.57e-06

7. Conclusion

All the sanity checks shown in this document indicate that the timing performance of the aLIGO detectors around the candidate event GW150914, observed at 1126259461 = Mon Sep 14 09:50:44 UTC 2015 is according to specifications.

8. Acknowledgments

Many thanks to Daniel Sigg and Szabolcs Márka for assisting with the work and commenting. ZM and SC are grateful for Keita Kawabe for his comments and for writing the appendix, and for the rapid response team at the sites (Keita Kawabe at LHO and Keith Thorne at LLO) for doing the initial timing checks. Many thanks for Bruce Allen for reviewing this document as part of the detection committee.