Time Delays in the LSC Digital Path

LIGO-T080039-00-D
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Time delays in the LSC-DARM path, from AS-Q to the OSEM coils, were measured at LHO. Time delays of approximately 2.5 samples at 16384Hz (152.5μs) were measured in the X and Y path of H1 and H2 (H2-Y was measured as 2.6 samples). This is expected from a single sample of processing delay in each the LSC and SUS computers, as well as a sample-hold delay. Similar results were found for the calibration injection path.

Ramp timing and DuoTone

Timing of digitally recorded data is carried out by sending timed signals to various ADCs for comparison with interferometer sensing channels. The PEM ADCs, located in the corner station and end stations (or mid stations for the 2km IFO), all receive a ~1ms long ramp whose leading corner is synchronous with the GPS second tick. This signal is not sent to the LSC ADC because this caused noise coupling into other channels. (A 1 pulse per second time series, a Dirac comb, has frequency components at every 1 Hz interval, also a Dirac comb.)

Instead, the LSC ADC is fed a pair of sine waves (960Hz and 961Hz) which have a once per second beat. This signal, called DuoTone, is also fed to the PEM ADC in the corner station. By comparing the relative time shift of the ramp and DuoTone signals as seen by the PEM ADC, it is possible to determine the timing of DuoTone relative to GPS time and finally to get timing information for signals fed to the LSC ADC. More on this system can be read in LIGO-T060304-00-D or by this address:
http://blue.ligo-wa.caltech.edu/gds/dmt/Monitors/DuoTone/DuoTone_Doc_v5.pdf

For the purpose of these timing measurements, the timing of the ramp signals was determined by exporting time series measurements in DTT and using a matlab script to find the leading corner relative to the digital time stamp. The ramp signal is a total of 16 samples long. This, along with some distortion due to filtering in the analog to digital conversion process, causes different ramp analyses to experience different systematic errors. Our measurement samples the center 8 samples of the ramp to perform a linear fit and find the intersection with the DC baseline. We perform the analysis on a number of ramps in a time series, then average the delays to get the quoted ramp delay. Our results vary somewhat from the TimeMon online DMT, results are compared in the Ramp Timing Biases Section.

The timing of the DuoTone signal was also measured by exporting from DTT and using the matlab 'cftool' curve fitting applet to fit a sum of sine functions to the data. A 2 second time series was used and the fit parameters were the amplitudes, frequencies and phase shifts of each sine. The resultant phase shift was used to find the timing relative to the digital time stamp. A DuoTone DMT also exists, and our analysis is in generally good agreement with this.

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Injecting Duotone into an AS channel

The end to end timing of the digital LSC path was measured by injecting the same DuoTone signal into the LSC ADC through an AS channel. A BNC T-junction from the DuoTone AWG excitation channel was fed into the LSC anti-aliasing board, bypassing the whitening filter. AS1I was used on the 4km IFO, AS1Q on the 2km. For the 4km, we adjusted the I/Q phase digitally to put the signal into the DARM path.

Reading the coil at the end (mid) station

The OSEM coil signals pass through anti-imaging boards which are equipped with LEMO style monitoring ports. Signals from these outputs were fed to the PEM ADC in order to use the GPS ramp as a reference.

For the 4km detector, there were free ports available. The X and Y coils were fed to `H1:GDS-TEST_7_0_10` and `H1:GDS-TEST_8_0_30` respectively. For the 2km, it was necessary to use channels nominally dedicated to the photon calibrator, `H2:LSC-ETMX_CAL` for X, and `H2:LSC-ETMY_CAL` for Y.

The PEM ADCU machines use an ICS-110B VME based ADC card. During the course of these time delay measurements, it was discovered that certain channels recorded on these units are time shifted relative to one another. Our choice of readback channels in the EX and EY stations happen to have this problem, and it is required that this time shift be measured and taken into account. The effect is measured by injecting white noise into the two channels being used in the ADC, and making a transfer function measurement in DTT. An iLog entry was made which outlines the measurement:
http://ilog.ligo-wa.caltech.edu/ilog/pub/ilog.cgi?group=detector&date_to_view=02/26/2008&anchor_to_scroll_to=2008:02:26:15:29:45-nicolas
The coil readback channel is advanced in time relative to the ramp signal in the EX and EY stations. The time shifts in the other stations were also measured but those were found to be negligible. This time shift can easily be removed. The corrections measured were:

EX: -61.0μs
EY: -61.1μs
(An advance relative to the ramp will be taken to be a negative number.)

Ramp Timing Biases

The timing ramps are derived from the GPS 1pps timing signal. There is expected to be some bias between the GPS tick and the leading corner of the ramp. If this bias varies among the various stations, this can create systematic errors in timing. The bias was measured by creating a timing signal with a portable function generator (AFG 3101) which was triggered on the 1pps signal.

The AFG 3101 arbitrary function generator by Tektronix is capable of producing an arbitrary time series specified by the user. A replica of the DuoTone was chosen and the AFG was externally triggered by a 1pps signal from the LIGO timing system. A rubidium clock also synchronized with the 1pps was used as the clock reference. A sample and hold delay of the triggered DuoTone must be accounted for. We chose a sampling rate of 131070 samples/s, this corresponds to a delay of 3.8μs.

The difference between the DuoTone beat (triggered on GPS) and the ramp corner was measured by exporting a time series from DTT and doing the analysis in matlab as outlined in the first section.

The bias was measured for three cases. In table 1, the row labeled *Bias* corresponds to the nominal configuration, where the ramp is injected into the channel labeled `GDS-GPS_RAMP_XX` and the triggered DuoTone is injected into either `GDS-TIME_MON` for the corner station, or the channel used for reading back the coil output for the outstations. *Swap* corresponds to a swap of the two channels, where the ramp is injected into the DuoTone channel, and vice-versa. The *TimeMon* row is similar to *Bias* although the timing of the ramp was simply taken from the TimeMon DMT page and not analyzed in matlab. In the case of the end stations, an inter-channel time shift of the ADC of ~61µs was accounted for, this was discussed in the previous section.

Table 1: Ramp Biases

(µs)	H1L1	H2L1	H2MX	H1EX	H1EY	H2MY
Bias	1.2	-3.2	-3.7	-4.5	-4.0	-3.8
Swap	5.6	-3.9	-3.8	-2.5	-4.0	-0.6
TimeMon	4.0	-0.3	-1.9	-3.8	-1.2	-1.6

A positive bias corresponds to the ramp coming before the GPS-triggered DuoTone beat.

Variations in the *Bias* measurements relative to the *Swap* measurements likely occur due to variations in the analog electronics of the channels of the ADC. *TimeMon* uses a different ramp analysis, and will have different systematics. The spread in data probably provides a rough estimate of the uncertainties of the measurements. For the time delay analysis, only the values in the row labeled *Bias* were used, because this was the configuration used during the measurement.

Measuring delays in the LSC path

The DuoTone signal, after passing through the AA board and entering the digital system, was directed through the LSC path. All digital filters were disabled so that any phase change measured as the signal progressed can be interpreted as a time delay. Using the transfer function measurement in DTT, the phase change between `LSC-TIME_MON` and various channels gives the time delay. Only phase changes where the signals have good coherence, at the dual sine frequencies of the DuoTone, are relevant.

This was done for the following channels:

```
H1/2:LSC-AS_Q
H1/2:LSC-ETM(X)_ULCOIL_IN1
H1:GDS-TEST_7_0_10
H1:GDS-TEST_8_0_30
H2:LSC-ETMX_CAL
H2:LSC-ETMY_CAL
```

Figure 1. shows a block diagram indicating the location of the various channels measured, the H1 X path is used as an example.

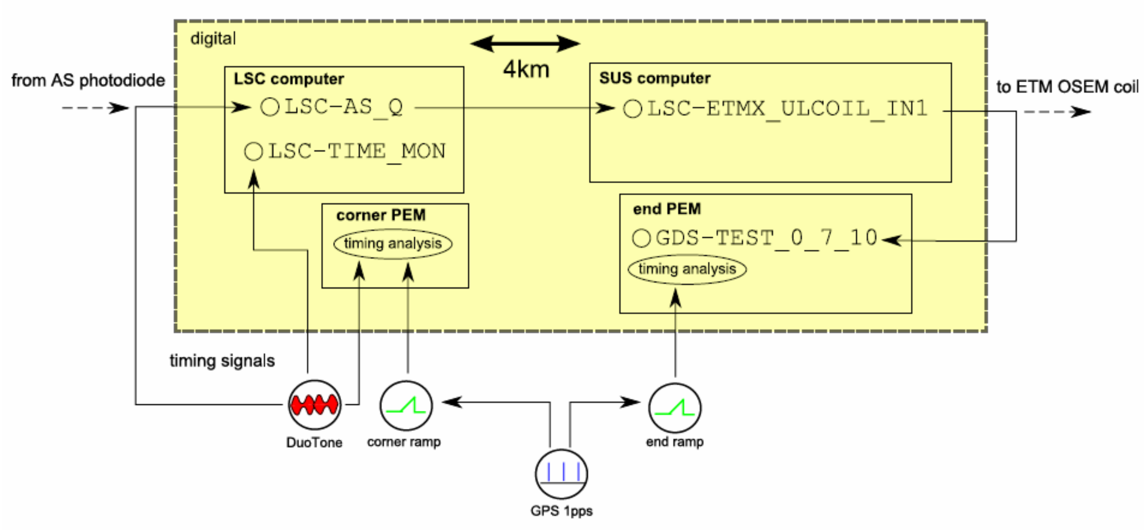


Fig. 1: Schematic block diagram of H1 X path

Other sources of phase delay

Analog filters will have a certain amount of phase delay which is a result of the filter shape and not time delay. These are not important to the measurement of delays in the digital system. Measurements of AA and AI filters are available online: http://www.ligo-wa.caltech.edu/~ehirose/Electronics/Post_S5/

These measurements can be used to remove the effects of the analog filters. To convert between phase and time, one can always use the formula:

$$\frac{\phi}{2\pi} = f\Delta t \,, \qquad (1)$$

where φ is measured in radians. In our measurements, f corresponds to 960Hz or 961Hz.

Analysis

To calculate the true time delay from injection into the AS channel to readout at the End or Mid station PEM ADC one must correctly account for the relative timing errors of the various ADCs. This is illustrated in Fig. 2.

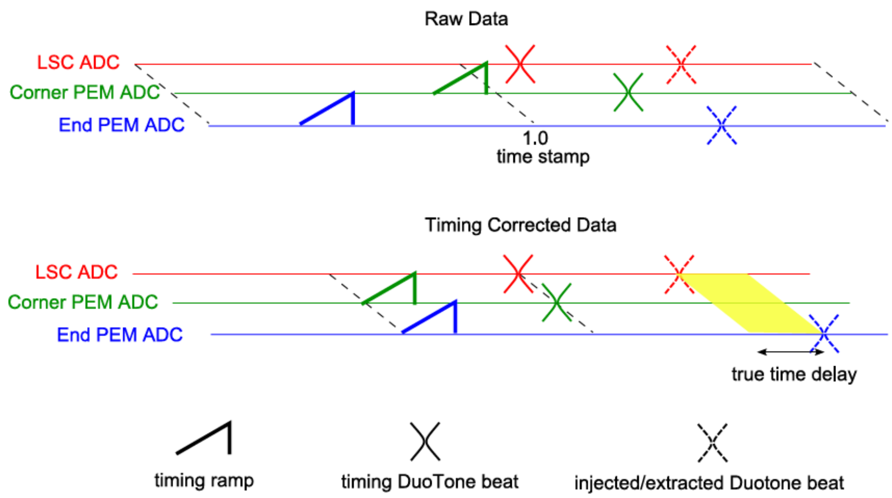


Fig. 2: Correcting for relative timing error in the ADCs

By aligning the events that are assumed to be coincident in 'real life,' one can correctly find time differences in other measured events. The Duotone signal sent to the LSC and corner PEM ADCs is time coincident, as well as the ramp signals at the corner and mid/end PEM ADCs.

Results

On February 6, 2008 (GPS 886301073) the following data were collected on the H1:
Note: the sign convention used is that a positive delay means that an event *lags* the digital time stamp by the amount given.

H1:

Ramp delays

H1:L1	43.7μs
H1:EX	48.6μs
H1:EY	12.1μs

Timing DuoTone

Corner PEM	49.7μs
LSC	3.3μs

Channel Delays, relative to LSC DuoTone

AS_Q	97.5μs
ETMX_UL_COIL	158.6μs
ETMY_UL_COIL	158.6μs
GDS-TEST_7_0_10 (X readback)	282.2μs
GDS-TEST_8_0_30 (Y readback)	244.8μs

Analog filter delays at 960Hz

AS1Q-AA	96.0μs
ETMX-AI	47.5μs
ETMY-AI	47.7μs

Note, we used channel AS1-I to inject the DuoTone into the LSC path, but we assume the AA filters are similar.

Data were also collected on Feb 8 (GPS 886556429) on the 2km detector.

H2:

Ramp delays

H2:L1	14.5µs
H2:MX	12.3µs
H2:MY	12.3µs

Timing DuoTone

Corner PEM	19.2µs
LSC	5.8µs

Channel Delays, relative to LSC DuoTone

AS_Q	97.8µs
ETMX_UL_COIL	158.8µs
ETMY_UL_COIL	158.8µs
LSC-ETMX_CAL (X readback)	307.0µs
LSC-ETMY_CAL (Y readback)	311.9µs

Analog filter delays at 960Hz

AS1Q-AA	96.2µs
ETMX-AI	47.2µs
ETMY-AI	47.4µs

In order to correct the timing of the end station readback channels, one must correct for the ramp timing as outlined in the Analysis section. Additionally, one must adjust for the ramp biases and remove inter-channel time shifts if they exist in the ADC. In practice the correction is as follows:

$$\begin{aligned}\Delta t_{\text{true}} &= \Delta t_{\text{raw}} - (t_{\text{mid/end ramp}} + \delta_{\text{mid/end ramp}}) \\ &\quad - t_{\text{GDS Duotone}} + (t_{\text{corner ramp}} + \delta_{\text{corner ramp}}) + t_{\text{LSC Duotone}} - \Delta_{\text{ADC}}\end{aligned} \quad . \qquad (2)$$

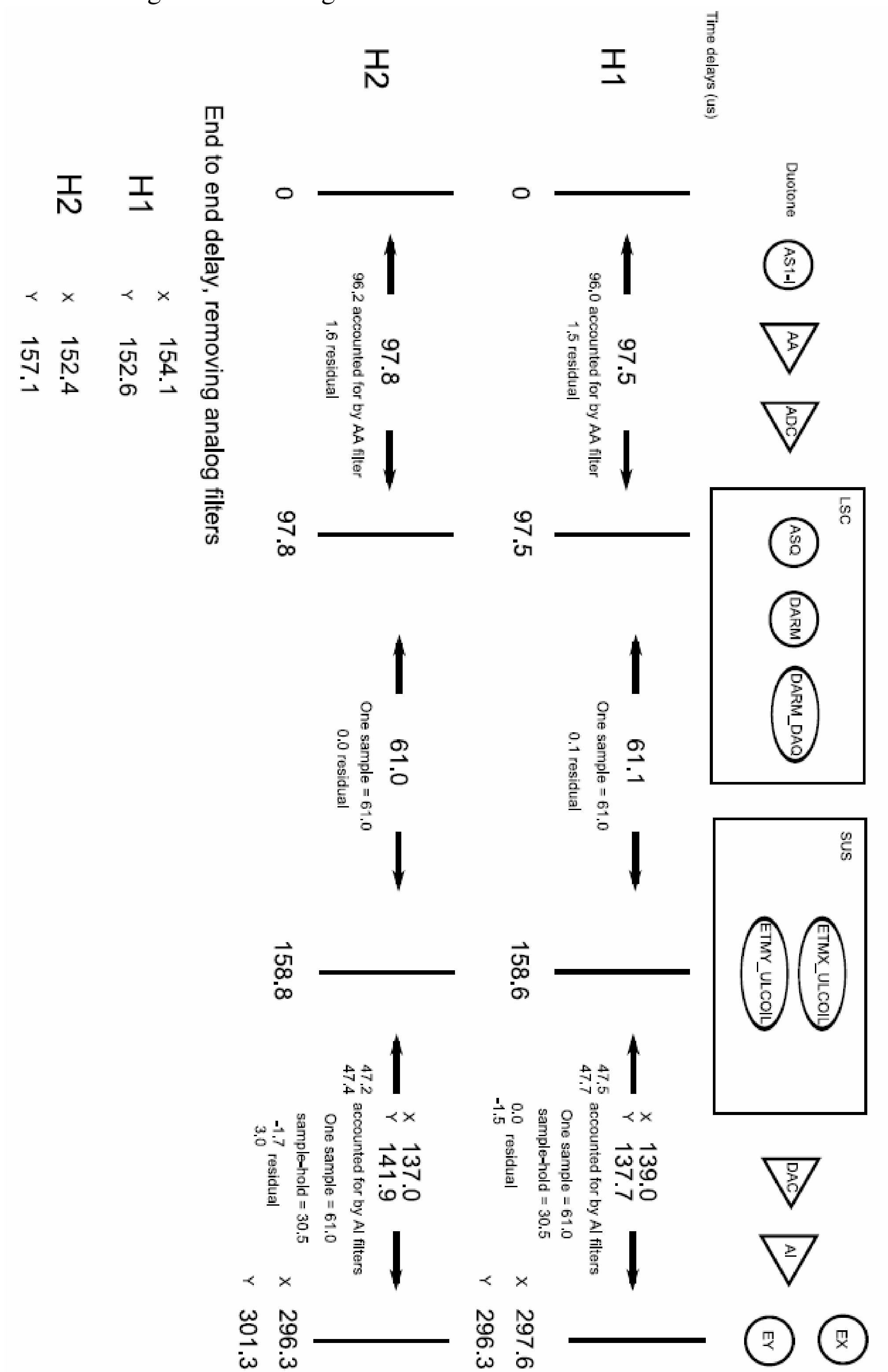
Here, Δt_{raw} is the time delay measured in the coil readback, $t_{\text{ramp}} + \delta_{\text{ramp}}$ is the ramp delay and bias for a given ADC, $t_{\text{GDS Duotone}}$ is the timing DuoTone beat delay measured in the corner PEM ADC, $t_{\text{LSC Duotone}}$ is the DuoTone beat delay measured in the LSC ADC, and Δ_{ADC} is the ADC time shift correction if it exists.

End to end delay

The total end to end delays of the various digital LSC paths (ignoring analog filters) are:
H1 X arm: **154.1µs, 2.5 samples**
H1 Y arm: **152.6µs, 2.5 samples**
H2 X arm: **152.9µs, 2.5 samples**
H2 Y arm: **157.7µs, 2.6 samples**

A sample cycle is 61.0µs for a 16384Hz sampling rate. It is expected to have a time delay which is approximately a half odd-integer number of samples. Processing delays in the system will make output signals lag input signals by some whole number of sample cycles. There appears to be a single sample delay each while the signal is processed in the LSC computer and the SUS computer. A further delay of one half samples arises from a sample-and-hold delay in the output DAC.

The data are arranged into the diagram below:



Excitation Delay

We also measured the time delay from the channel used for calibration line injection, LSC-DARM_CTRL_EXC, to the OSEM coil output of the AI filter. A DuoTone signal was created in AWG and used to excite the channel. This is similar to the above measurement, except the 'originating' signal begins in the digital domain. The ramp delay and bias will correct the error between the coil readback signal and the digital time stamp. Thus, the ramp delay, bias and ADC correction of the end/mid station only are required from equation (2).

On the 4km IFO, this was also done as a transfer function measurement at 960Hz between the excitation digital readback channel (CTRL_EXC) and the coil readback channels (GDS-TEST).

Measured delay on H1 from excitation to coil readback:

	Δt_{raw}	ramp correction	AI correction	Δt	samples
X	184.7µs	16.9µs	-47.5µs	**154.1µs**	**2.5**
Y	147.3µs	52.9µs	-47.7µs	**152.5µs**	**2.5**

The technique was slightly varied on the 2km, the difference being that instead of using AWG to create DuoTone, the existing calibration line at 1159.7Hz was used to measure the delay.

Measured delay on H2 from excitation to coil readback:

	Δt_{raw}	ramp correction	AI correction	Δt	samples
X	218.0µs	-8.7µs	-47.3µs	**162.0µs**	**2.7**
Y	209.4µs	-8.5µs	-47.5µs	**153.4µs**	**2.5**

Thanks

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