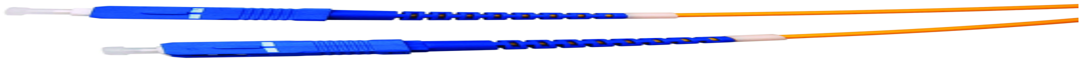

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
-LIGO-

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aLIGO Timing System Checks During O3B

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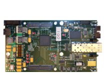


Abstract

Advanced LIGO (aLIGO) data is recorded by a data acquisition system (DAQ) that is driven entirely by the GPS-backed aLIGO Timing Distribution System. Several independent clocks' 1PPS signals are used in timing diagnostics studies as witness signals. At each site, a Microsemi 4310b Cs-III Cesium-standard atomic clock checks for transient or short-term timing problems (see LIGO-T1700298 for details), and two CNS Clock II GPS clocks and a GPS-backed NTP server check for long-term/absolute timing problems.

We measured the time delay between aLIGO Timing Distribution System 1PPS and the aforementioned Timing Diagnostic System's CNS Clock II GPS clock's and and a GPS-backed NTP server's 1PPS signals for the second half aLIGO's third observation run (O3B). We also checked the atomic clock's calibration during O3B. We also performed checks of the DuoTone time delays and IRIG-B timing outputs for the GW event candidates of O3B which can be found in LIGO-T190671.

1. Introduction

The aLIGO Timing **Distribution** System is a custom timing solution that provides end-to-end timing signal integrity at the hardware level, ensuring absolute synchronization across all aLIGO sites to the GPS time standard (and UTC) below the required tolerance.

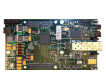
Auxiliary to the timing distribution system, there are **diagnostic** features which rely on a heterogeneous set of independent clocks to continuously measure the ***Timing Distribution System***'s accuracy and performance on different time scales. These diagnostic features and independent clocks are functionally distinct from the Timing Distribution System, and collectively are called the aLIGO ***Timing Diagnostic System***. The Timing Diagnostic System checks, among other things, guarantees that the Timing Distribution System is synchronized to GPS time. One of the main functions of the Timing Distribution System is to mark the start of each second with a voltage pulse ("One Pulse Per Second" or "1PPS"), which can be compared to independent Timing Diagnostic System reference clock 1PPS signals to verify that the Timing Distribution System's 1PPS is consistent within specifications.

One of the reference signal types used at each site are CNS Clock II GPS clocks that provide long-term consistency measurements. These measurements can pinpoint local problems related to the GPS receiver or distribution system, however the GPS space segment is not tested by them.

2. Timing System Performance prior to O3

During LIGO's third observation run (O3), the **Timing Distribution System** performance – regarding CNS Clock II GPS clock, a GPS-backed NTP server Time Difference, the recorded DuoTone delays, and the atomic clock drift - was well within specification during all observing time segments.

a. NTP servers and CNS II clocks



The GPS-backed NTP server in the Mass Storage Room (MSR) at the Corner Station at Hanford showed variations from mean of less than ±125ns vs. the **Timing Distribution System** 1PPS signal at all times, which all but one lock segment showing variations from the mean of less than ±80ns. (Figure 1: Timing Difference between the NTP Server and the Timing System's internal 1PPS signal at LHO during O3B).

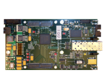
The CNS II clock located at end stations X showed variations of less than ±125ns from the mean time difference at all times, and for all but one lock segment showed variations from the mean of less than ±80ns. (Figure 2: Timing Difference between X End CNS II GPS Clock and the Timing System's internal 1PPS signal at LHO prior to O3) There was one time segment during which the difference between the LHO CNS II Y end station GPS time and 1PPS time exceeded 1µs, which occurred the on February 26, 2020 22:01 UTC and is related to a DAQ restart (*see aLOG*). Aside from this time segment, variations at the Y end station remained within ±250ns of the mean at all times with the majority of times showing variations of less than ±80ns. (Figure 3: Timing Difference between Y End CNS II GPS Clock and the Timing System's internal 1PPS signal at LHO during O3B).

The data not taken marker at 117 days of O3B on the NTP server and X end plots were due to the same DAQ restart on February 26, 2020 22:01 UTC (*see aLOG*). The data not taken marker 38 days into O3B on the Y end station plot was caused by a failure in the fiber link between the slow controls Beckhoff chassis at the Y end station on December 9, 2020 10:31 UTC (*see aLOG*).

Note: Data is only plotted during segments when the detectors were in observing mode (DQ Flag: H1:DMT-ANALYSIS_READY:1), and the segments with no points plotted in Figures 1, 2, 3 correspond to times when LHO was not in observing mode.

The NTP server at the Corner Station at Livingston showed variations from mean of less than ±120ns vs. the **Timing Distribution System** 1PPS signal at all times (Figure 4: Timing Difference between the NTP Server and the Timing System's internal 1PPS signal at LLO prior to O3), with most values within ±90ns. The CNS II clocks in the X station showed variations of less than ±1µs from the mean time difference for the majority of O3B with most variations less than ±150ns (Figure 5: Timing Difference between X End CNS II GPS Clock and the Timing System's internal 1PPS signal at LLO during O3B). There were, however, 7 segments during which the variation from the mean exceeded ±1µs and there were various other times when there was a large scatter of time differences within the ±1µs threshold. These outliers and the scatter of time differences towards the end of the run are associated with an issue with the GPS antenna at the X-end of LLO as they all corresponds to times when the GPS antenna was tracking 0 to 2 GPS satellites. In the case of the outliers, the GPS antenna at the X station was tracking between 0 and 1 satellite.

The CNS II clocks in the Y station at Livingston showed variations of less than ±100ns for the majority of times during O3B (Figure 6: Timing Difference between Y End CNS II GPS Clock and the Timing System's internal 1PPS signal at LLO during O3B); however, outliers appeared in every lock segment, lasting no more than a second where the time difference jumped from on the order of 100ns to approximately -0.4 s, -0.49 s, or +0.49 s. These occurred during 2967 separate seconds during O3B.



The data not taken lines in the LLO plots were caused by 1) a DAQ process restart on December 5, 2019 (*see* aLOG), 2) a Beckhoff connection issue which caused lock loss on December 21, 2019 (*see* aLOG), 3) a DAQ restart on January 17, 2020 (*see* aLOG), 4) lock loss due to a Beckhoff connection issue on February 3, 2020 (*see* aLOG), 5) a data concentrator failure and restart on February 23, 2020 (*see* aLOG), 6) a DAQ screen meltdown and reset on March 6, 2020 (*see* aLOG), 7) a DAQ screen meltdown and reset on March 11, 2020 (*see* aLOG), 8) a DAQ restart on March 15, 2020 (*see* aLOG), 9) a DAQ restart on March 17, 2020 (*see* aLOG), 10) a DAQ error on March 17, 2020 (*see* aLOG) and 11) a DAQ restart on March 24, 2020 (*see* aLOG).

Note: Due to the anomalous times throughout O3B for the Y End CNS II GPS Clock at LLO, we only show the mean time difference during minutes of O3B where the errors of -0.4 s, -0.49 s, or +0.49 s were not present in Figure 6 (relevant channel name: L1:SYS-TIMING_Y_FO_A_PORT_9_SLAVE_CFC_TIMEDIFF_2; DQ Flag: L1:DMT-ANALYSIS_READY:1).

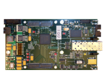
b. Atomic Clock Drift

The Cs-III 1PPS signal has very low jitter, with a base Allan deviation of 5.0e-14 (source: Microsemi Cs-III fact sheet). This means that short timescale variations from the mean in the time difference between the TDS and Cs-III 1PPS signals can be interpreted as jitter in the TDS 1PPS signal. Over time, though, the Cs-III 1PPS will tend to drift linearly away from the TDS 1PPS. This happens because the Cs-III 1PPS signal is not synchronized to Global Positioning System (GPS) time via satellite connection, whereas the TDS 1PPS is. Consequently, any difference between the Cs-III period and 1 second (as measured by GPS) will be compounded over time. **It must be noted that this long-term linear drift is expected behavior, and that it does not hinder in any way the use of the time-difference timeseries in measuring jitter in the TDS 1PPS signal.**

Nonetheless, maintaining a small average time difference makes it easier to plot and measure jitter, and it is therefore important to recalibrate the Cs-III clock every few months to minimize the drift rate. This is accomplished by first finding the drift coefficient by taking a line-of-best-fit over multiple months of time difference data (starting at the most recent calibration). The residual of this line is the TDS 1PPS jitter, while the slope of the line is the drift coefficient.

For both LHO and LLO we calculate the piecewise- linear drift during each week of O3B. At LHO and LLO, the observed drift behavior was gradual and piecewise-linear (as expected) and would not interfere with the short-timescale phase noise measurements that the Cs-III is used for (Figure 7: Atomic clock drift at LHO, Figure 8: Atomic clock drift at LLO). The calibration is sufficiently good that the shorter timescale (likely environmentally caused) piecewise-linear drift of the Cs-III clock is larger than the long-term drift. Further calibration was thus not performed, as it would likely amount to over-fitting and would not produce a qualitative improvement in long-term drift.

3. Conclusion



The time differences measured by the **Timing Diagnostic System**’s CNS II GPS clocks and the DuoTone delays leading up to O3 indicate that the **Timing Distribution System** performance did not suffer from problems. Additionally, the time differences measured by the Cs-III cesium clocks indicate that the **Timing Distribution System** performance did not suffer from short-term or transient problems.

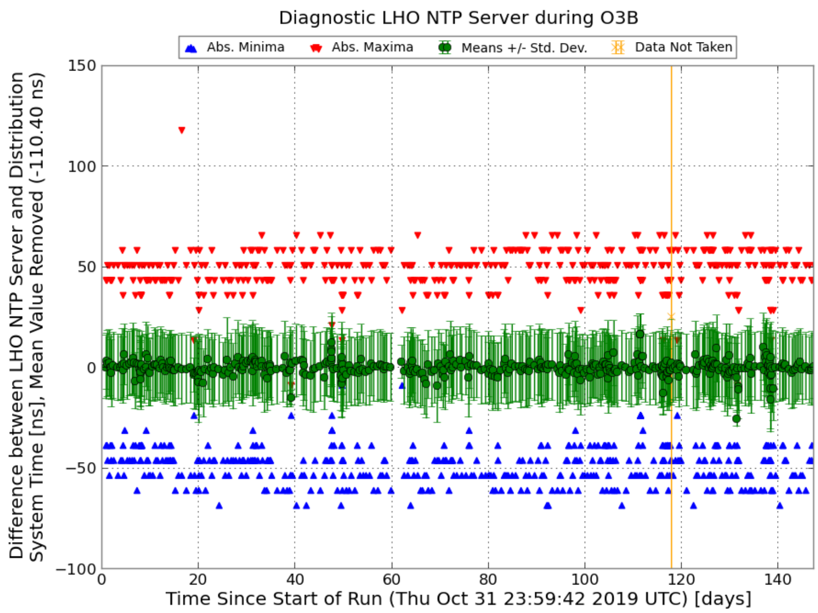


Figure 1: Timing Difference between the NTP Server and the Timing System's internal 1PPS signal at LHO during O3B. (EPICS channel name: H1:SYS-TIMING_C_MA_A_PORT_2_SLAVE_CFC_TIMEDIFF_3; *DQ Flag: H1:DMT-ANALYSIS_READY:1*)

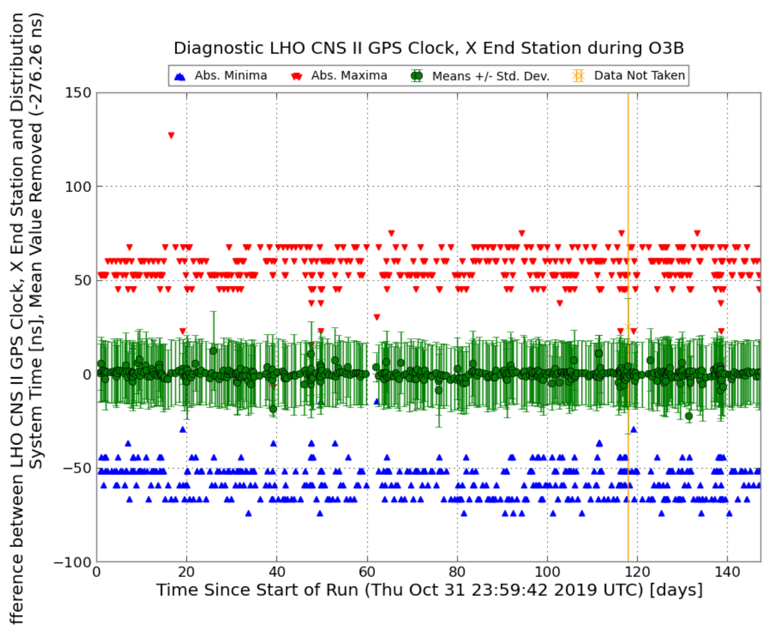
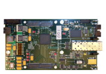


Figure 2: Timing Difference between X End CNS II GPS Clock and the Timing System's internal 1PPS signal at LHO during O3B. (EPICS channel name: H1:SYS-TIMING_X_FO_A_PORT_9_SLAVE_CFC_TIMEDIFF_3; *DQ Flag: H1:DMT-ANALYSIS_READY:1*)



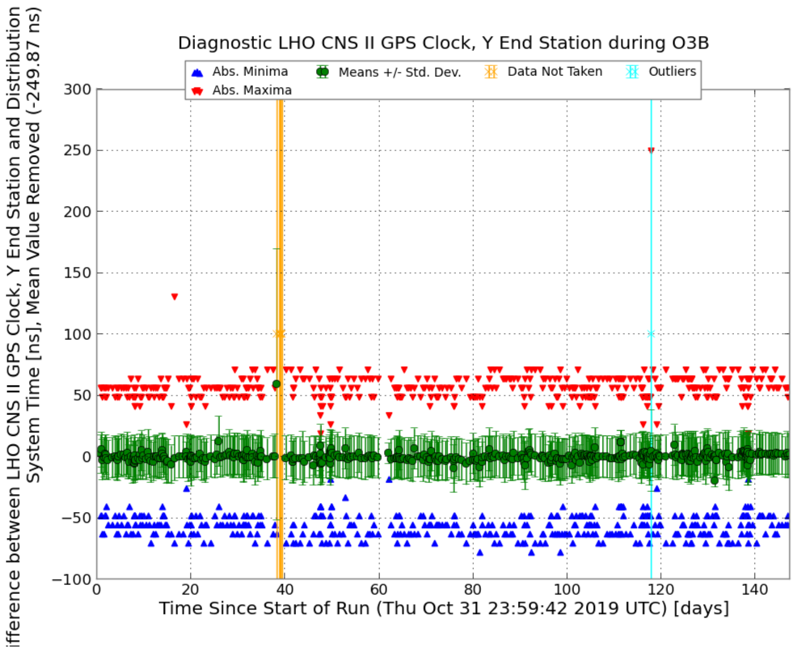


Figure 3: Timing Difference between Y End CNS II GPS Clock and the Timing System's internal 1PPS signal at LHO during O3B. (EPICS channel name: H1:SYS-TIMING_Y_FO_A_PORT_9_SLAVE_CFC_TIMEDIFF_3; *DQ Flag: H1:DMT-ANALYSIS_READY:1*)

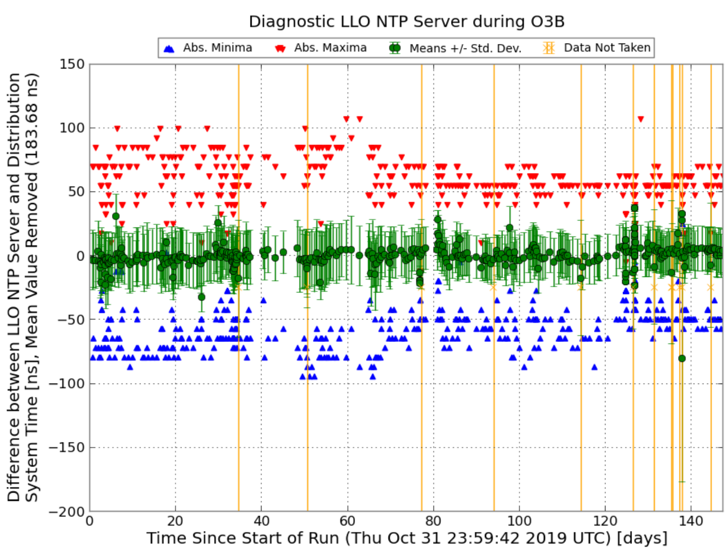


Figure 4: Timing Difference between the NTP Server and the Timing System's internal 1PPS signal at LLO during O3B. (EPICS channel name: L1:SYS-TIMING_C_MA_A_PORT_2_SLAVE_CFC_TIMEDIFF_2; *DQ Flag: L1:DMT-ANALYSIS_READY:1*)

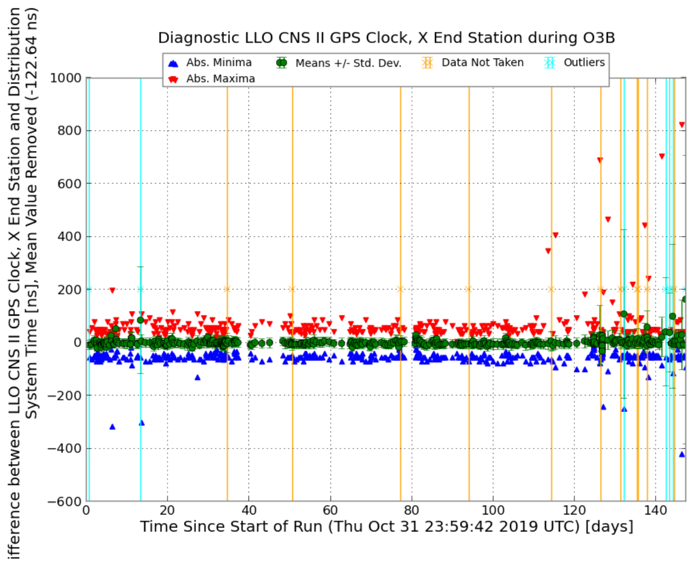


Figure 5: Timing Difference between X End CNS II GPS Clock and the Timing System's internal 1PPS signal at LLO during O3B. (EPICS channel name: L1:SYS-TIMING_X_FO_A_PORT_9_SLAVE_CFC_TIMEDIFF_2; *DQ Flag: L1:DMT-ANALYSIS_READY:1*)

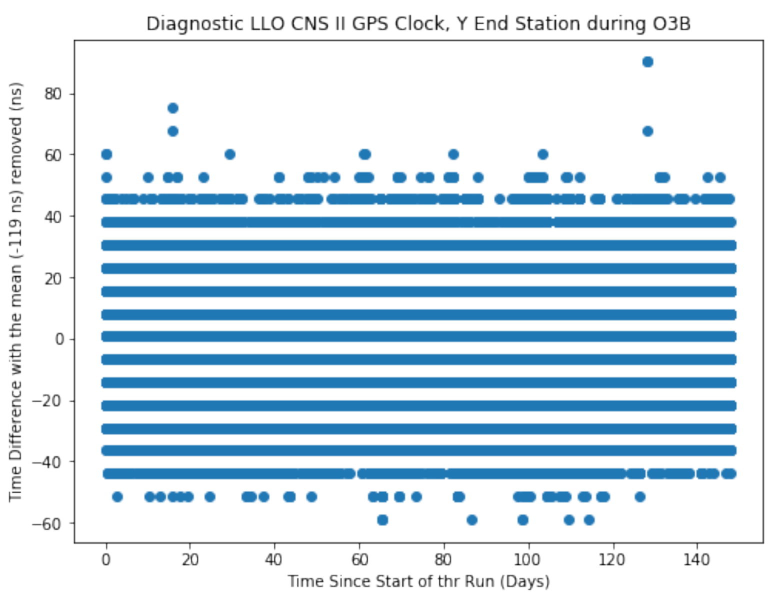
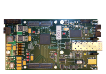


Figure 6: Timing Difference between Y End CNS II GPS Clock and the Timing System's internal 1PPS signal at LLO during O3B. (EPICS channel name: L1:SYS-TIMING_Y_FO_A_PORT_9_SLAVE_CFC_TIMEDIFF_2; *DQ Flag: L1:DMT-ANALYSIS_READY:1*)



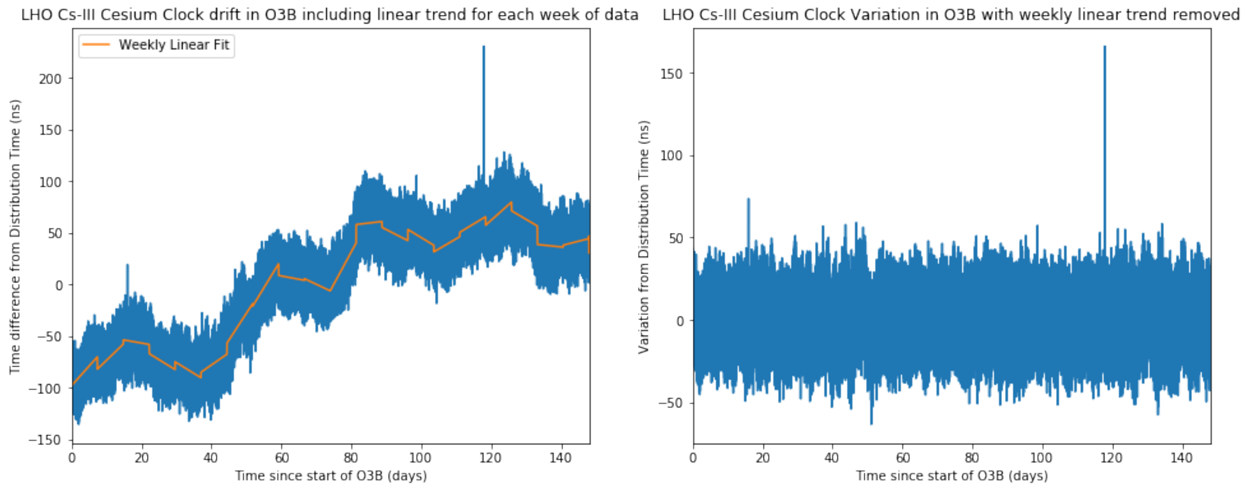


Figure 7: Atomic clock drift at LHO (EPICS channel name: H1:SYS-TIMING_C_MA_A_PORT_2_SLAVE_CFC_TIMEDIFF_1)

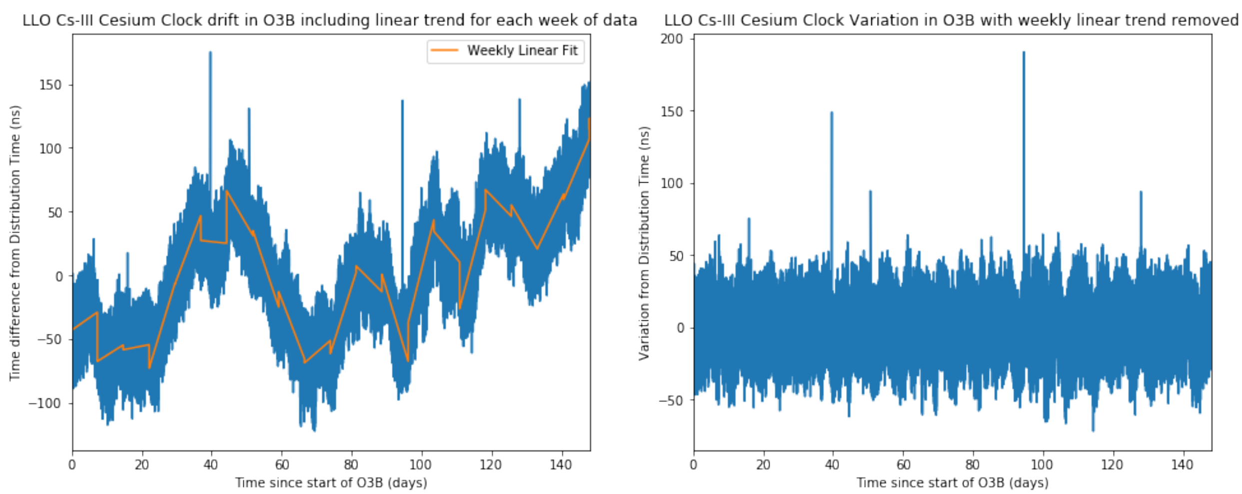


Figure 8: Atomic clock drift at LLO (EPICS channel name: L1:SYS-TIMING_C_MA_A_PORT_2_SLAVE_CFC_TIMEDIFF_1)