LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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Technical Note LIGO-T0900050 07/29/08

Test Result Description Document for the Advanced LIGO Optical Timing Distribution System

Imre Bartos, Maxim Factourovich, Szabolcs Márka,
Zoltán Raics, Paul Schwinberg and Daniel Sigg

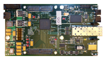
This is an internal working note
of the LIGO Project.

California Institute of Technology
LIGO Project – MS 51-33
Pasadena CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, MIT NW22-295,
185 Albany St.,Cambridge, MA 02139 USA
Phone (617) 253 4824
Fax (617) 253 7014
E-mail: info@ligo.mit.edu

Columbia University
Columbia Astrophysics Laboratory
Pupin Hall - MS 5247
New York NY 10027
Phone (212) 854-8209
Fax (212) 854-8121
E-mail: geco.cu@gmail.com

WWW: http://www.ligo.caltech.edu



Test Result Description Document
for the
Advanced LIGO Optical Timing Distribution System

We present some test results that provide information on the proper operation of the Advanced LIGO Optical Timing Distribution System.

Tests

In the following, we present test results that provide information on the proper operation of the OTD. The test setup geometry is illustrated, including the test equipment used is shown on Figure 1.

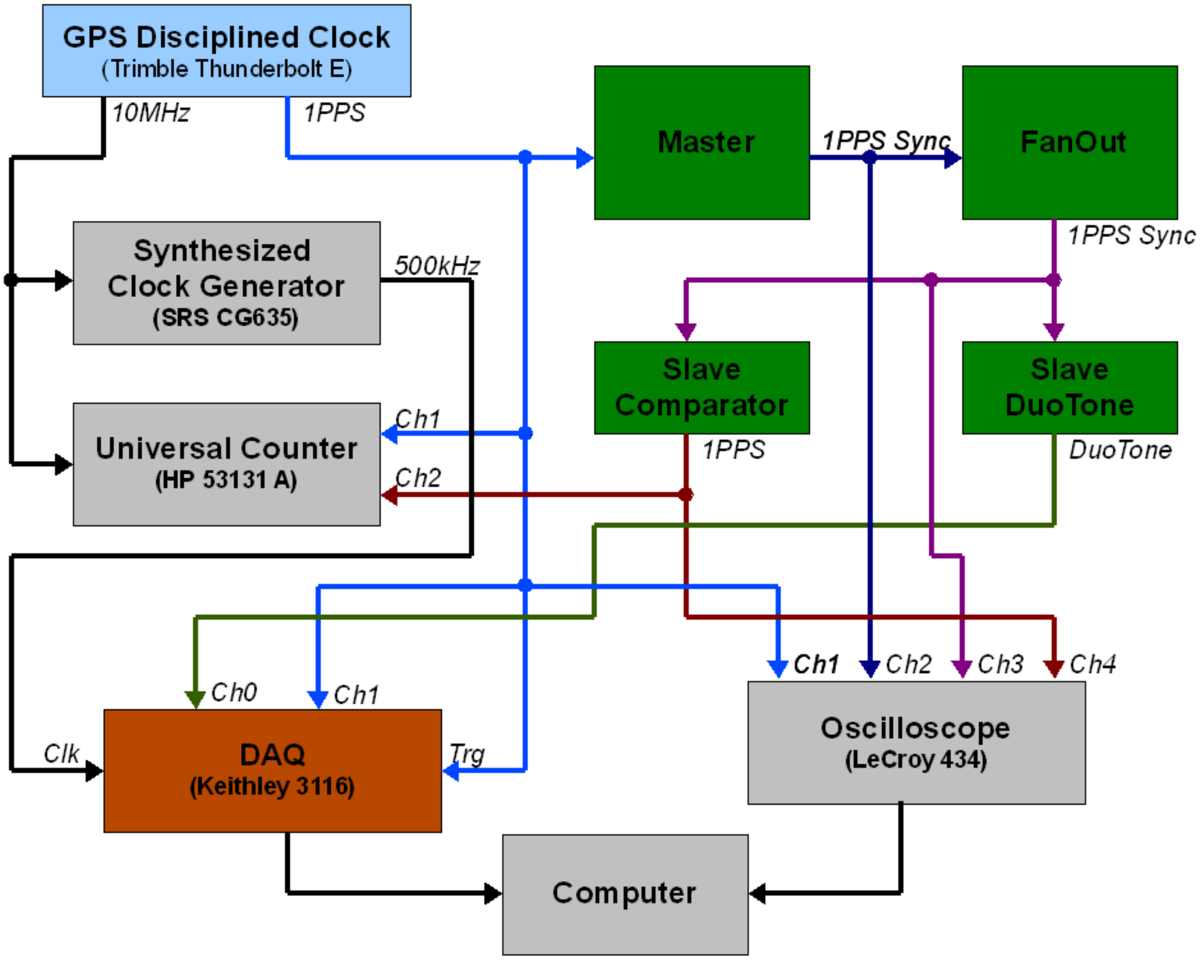


Figure 1 Generic test setup geometry of the timing distribution system.

GPS timing variation among manufacturers for exposed devices

The OTD relies on a GPS clock to which it synchronizes its own internal clock. Different GPS receiver implementations are available commercially, albeit one has to be careful, as some seemingly different manufacturers rely on identical GPS receiver cores (e.g., OnCore). In this test, we compare two different GPS receivers; one is the workhorse of the CellPhone industry (Trimble) and the other is the standard in laboratory applications (HP).
We compared their 1PPS signal using a precision Universal Counter (HP53131-A-225MHz). The two GPS devices were (i) Trimble Thunderbolt E GPS disciplined clock. It relies on an internal OCXO to optimize phase noise and other performance measures that are crucial in CellPhoneTowers, and (ii) HP58503-A-GPS Time and Frequency Reference Receiver. We have used HP L1 GPS antenna for the HP unit and Trimble L1 GPS antenna for the Trimble unit. The antenna were installed at prime high location at the roof with ~2π sky coverage and connected through continuous LMR-400 low loss cables to the receivers. Results for an extended comparison are shown in Figure 2 and Figure 3. Different statistical parameters of the relative deviation are:

Median	= 54 ns
99% confidence interval	= 826 ns
Max	= 273.3 ns
Min	= -455.2 ns

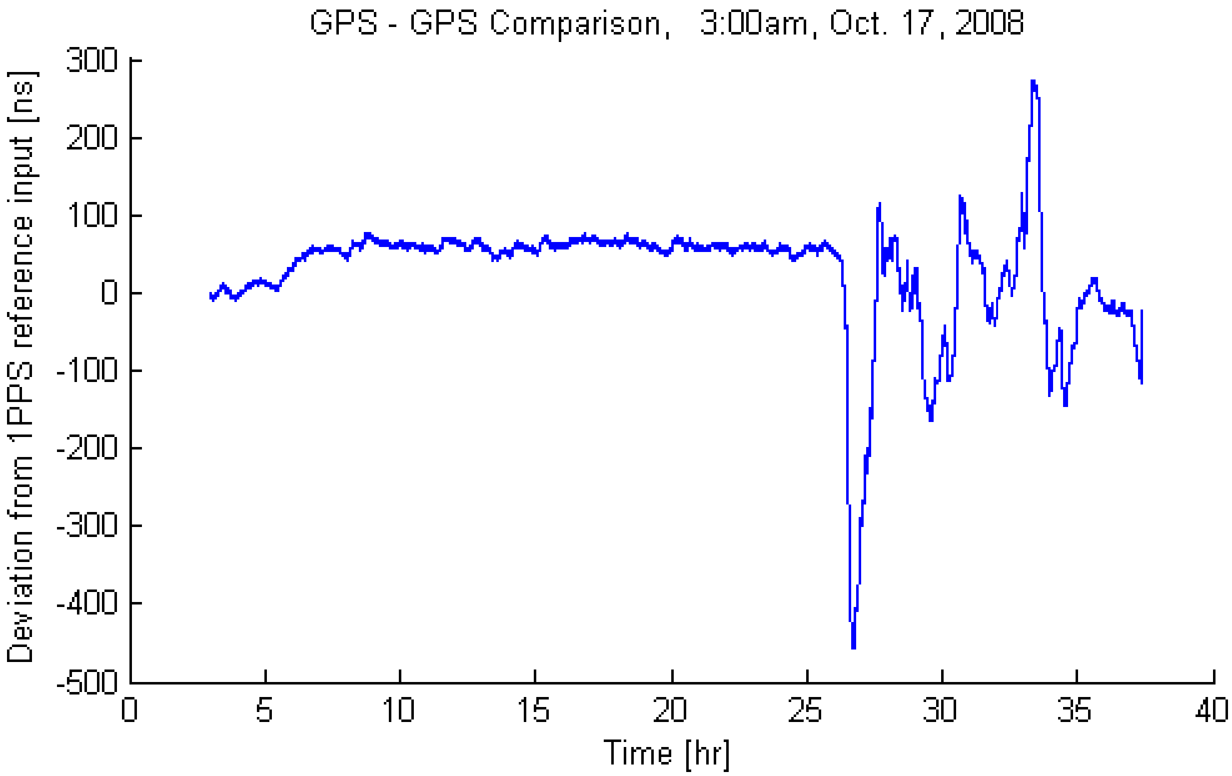


Figure 2 TrimbleGPS - HPGPS 1PPS relative precision comparison test. The time axis zero corresponds to 3:00am, Oct. 17, 2008. The different behavior patterns correspond to varying level of activity around the devices.

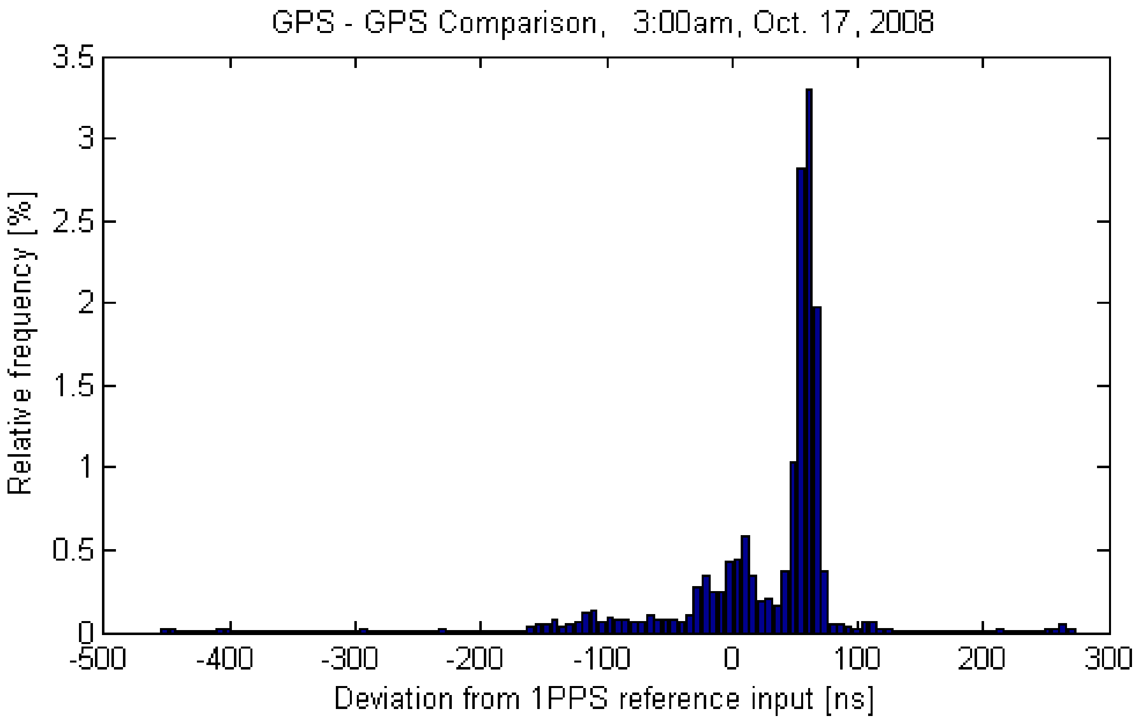


Figure 3 TrimbleGPS - HPGPS 1PPS relative precision comparison test histogram.

We conclude that the deviation of the two GPS receivers always stays well below the 1 microsecond level, even in extreme environments, not expected at the LIGO sites. We budget in ±400ns as a conservative error estimate. We note that careful environmental control can result in substantial improvement if it is required in the future.

GPS 1PPS to Master-FanOut-Slave 1PPS Comparison

The main purpose of the OTD is to provide synchronized clock signals throughout the detector. This means that the main feature of the system is the level of synchronization between the clock outputs at different parts of the system. This feature can be tested by determining the level of synchronization between the 1PPS signals of different components. Namely, the system works properly if the internal clock of each Slave module is properly synchronized to the global GPS clock. In the following we present measurement results quantifying the deviation of the 1PPS signals of the global GPS clock, as measured using the HP-58503-A-GPS receiver, and a Slave module that is connected to the Master through a FanOut module. This test therefore measures whether the output of the full Master-FanOut-Slave system is properly synchronized to the external 1PPS at all times.
To also test the proper compensation for time delay due to transmission through long fibers, we connected the Master and FanOut modules with a 4km long (patched) fiber. This will be the case when connecting the central Master and a FanOut located at one of the end stations of the LIGO observatories. Results are shown below on *Figure 4* and *Figure 5*.

The statistical parameters of the result are the following:

Median = 14.3 ns
99% confidence interval = 6.2 ns
Max = 24.0 ns
Min = 10.5 ns

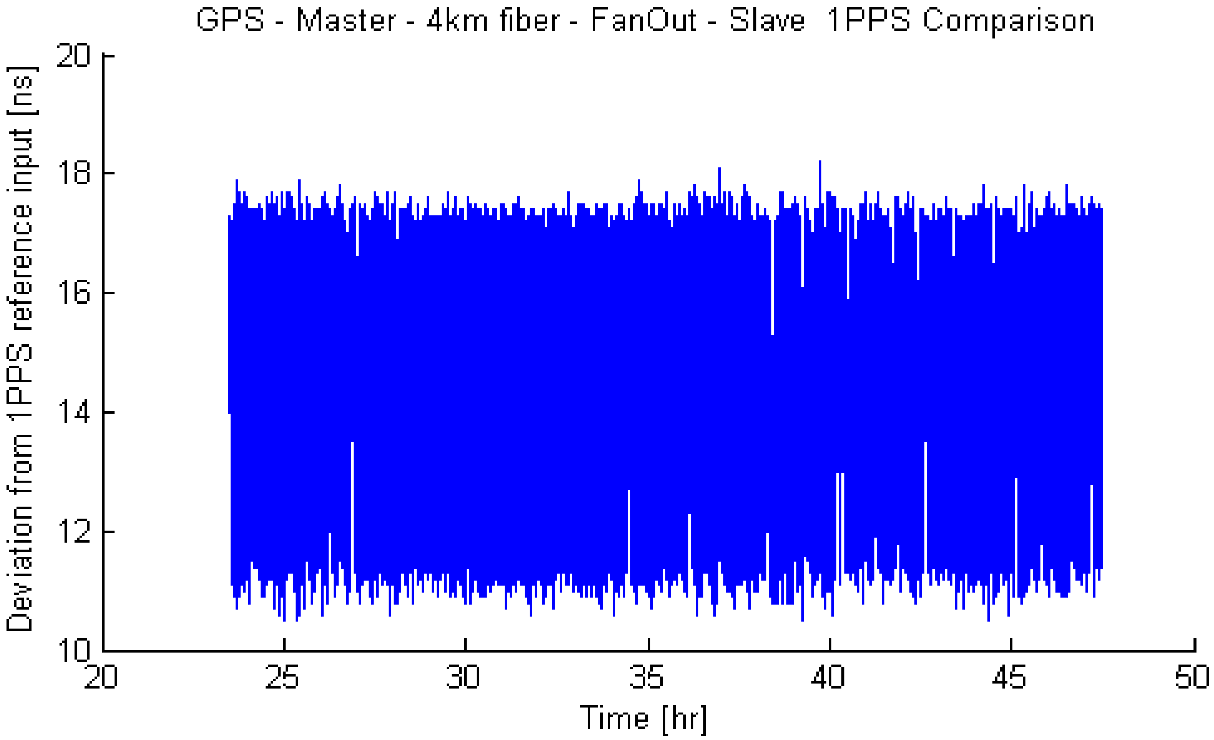
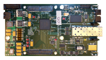


Figure 4 Comparison of 1PPS signals from the GPS receiver (HP 58503 A) and a Slave module at the end of a Master-FanOut-Slave system. The Master and FanOut modules are connected through a 4km long (patched) optical fiber. The figure shows the deviation as a function of time.



We conclude that the deviation between the 1PPS from the GPS receiver and the Master-FanOut-Slave system is safely below the ~385ns safety margin for the end-to-end system. The result also shows that the Master-FanOut-Slave system synchronizes properly to the external 1PPS signal, and that it properly compensates the time delays due to transmissions between different modules. The test was executed with open chassis in a busy laboratory environment and there were no attempts made to shield devices and components from environmental disturbances. Therefore it is expected that in a closed chassis and undisturbed rack, the field deployed system's performance will be at least comparable to the test results.

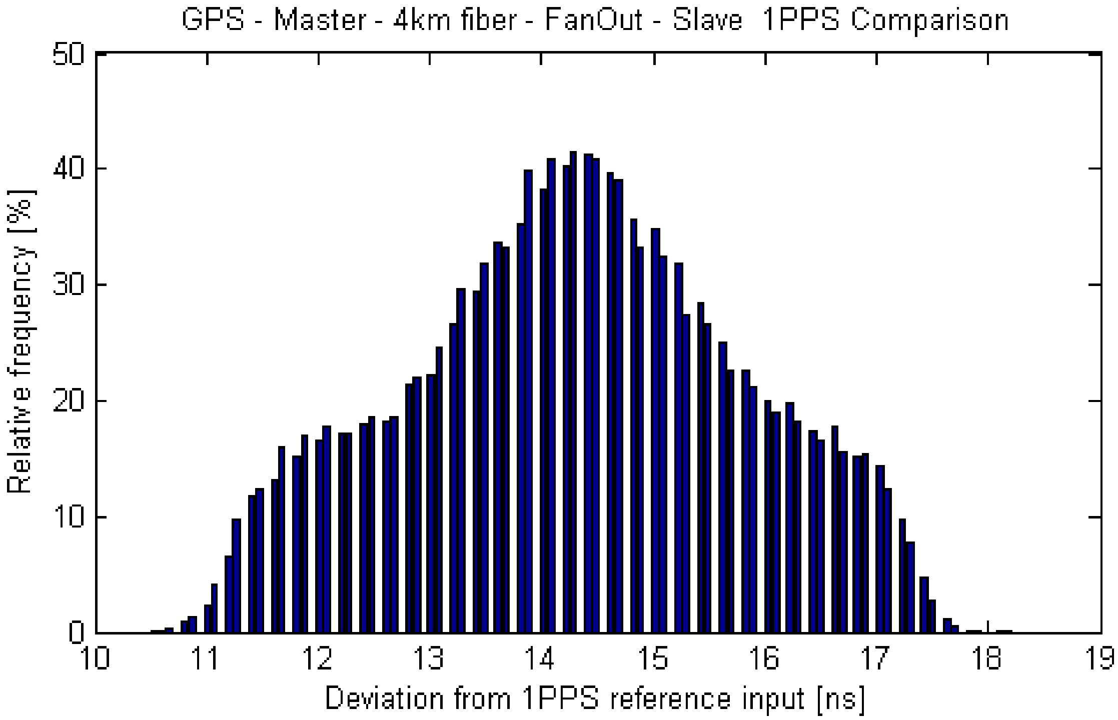


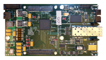
Figure 5 Comparison of 1PPS signals from the GPS receiver (HP 58503 A) and a Slave module at the end of a Master-FanOut-Slave system. The Master and FanOut modules are connected through a 4km long (patched) optical fiber. The figure shows the histogram of the deviations.

Duotone Signal Test

In order to archive timing diagnostic information along with the gravitational wave channel, we provide a GPS synchronized sinusoidal signal, called '*DuoTone*'. It consists of the sum of two sinusoids with 1Hz difference in frequency. The frequency difference allows us to recover the timestamp from the digitally recorded data any time in the future up to ±0.5 second delay. The recovery can be done with sub µs precision for high SNR DuoTone signals and with ~10µs precision for very low SNR DuoTone signals (see e.g., LIGO-P080072). Traditionally, the frequencies were 960Hz and 961Hz, purposely coincident with a 60Hz power line harmonic.

The purpose of this test was to determine the synchronization precision of the DuoTone signal's zero phase and the GPS 1PPS rising edge. By definition, they should be synchronized to very high degree. Consequently, we compared the 1PPS signal of the GPS receiver to the timing recovered from the DuoTone signal emitted at the end of the Master-FanOut-Slave-DuoTone chain. Both the GPS 1PPS and the DuoTone signal were acquired and stored on a computer using a synchronized Keithley DAQ device - Model KUSB-3116 High Performance Multifunction Data Acquisition Module. (See Figure 1 for the test setup geometry.) The DuoTone signal and the GPS 1PPS was connected to channel 0 and 1 of the DAQ, respectively. Measurements were started using the GPS 1PPS that was connected to the AD External Trigger input of the DAQ. To provide a high precision external clock to the DAQ device, a synchronized Synthesized Clock Generator (SRS CG635) was connected to the AD Clock input of the DAQ device. The Synthesized Clock Generator was set to provide a 500 kHz signal, the maximum allowed sampling frequency of the DAQ device. We used the 10 MHz output of the GPS Receiver (Trimble Thunderbolt E) to lock the internal clock of the Synthesized Clock Generator. We used the system to record 7 seconds long intervals of the duotone signal as well as the GPS 1PPS, with 250 kHz frequency each. The recording process was started by the GPS 1PPS.

The 7 s long DuoTone intervals were filtered with an 8th order zero phase bandpass filter (designed in Matlab), centered at 960 Hz with approximate cutoff frequencies at 860 Hz and 1060 Hz. After filtering, the first and last seconds of the intervals were removed to eliminate the filter transients at both ends. This left 5 s long intervals to analyze. The phase of the two sinusoid components of the duotone signal was then determined using the IEEE STD 1057 algorithm, for a fast three parameter least square fit to sine wave using matrix operations. It was applied separately for 960 and 961 Hz. The analysis code was validated through simulations.



The statistical parameters of the results are the following (see Figure 6 and Figure 7):

Mean = - 4960.4 ns
STD = 85.6 ns
Max = - 4571.4 ns
Min = - 5325.6 ns

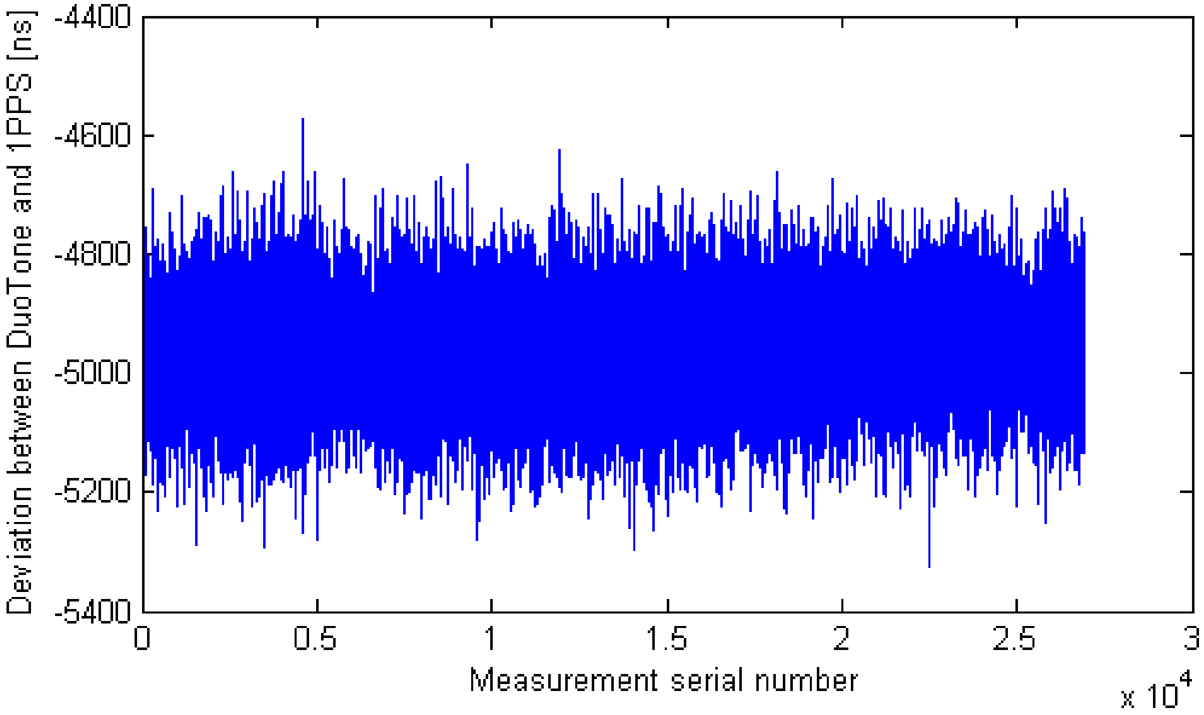


Figure 6 Results from the DuoTone phase– 1PPS comparison measurement. The figure shows the deviation as a function of measurement serial number. The scatter around the arbitrary DC level describes the accuracy of the measurement.

We conclude that the duotone signal is precisely locked to the GPS 1PPS signal and can be used for the archived timing purpose. We note that the channel to channel and other DC delays in the final DAQ system must be characterized and corrected for in future analyses.

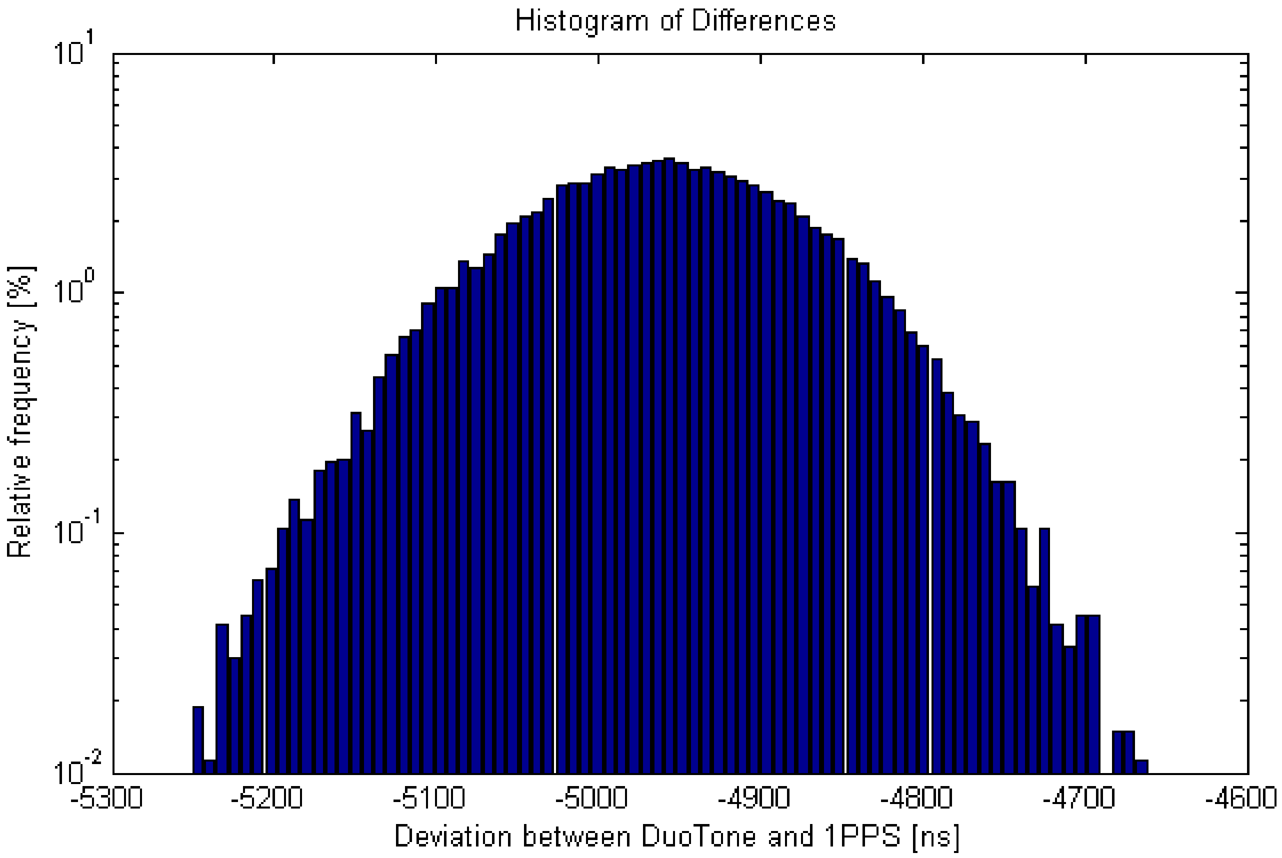


Figure 7 Results from the DuoTone phase– 1PPS comparison measurement. The figure shows the deviation as a histogram. The scatter around the arbitrary DC level describes the accuracy of the measurement.

The ADC/DAC Clock Test

The Slave+DuoTone Module is also used to provide synchronized 2^N clock signals to external devices. We tested the precision of this clock signal using an output of square waves with ~262 kHz (2^{18} Hz) frequency. The rising edge of the GPS 1PPS was compared to the rising edge of the square wave closest to the GPS 1PPS coming from the DuoTone board. We used the Universal Counter (HP 53131 A 225 MHz) to measure the deviation.

The statistical parameters of the results are the following (see Figure 8 and Figure 9)

Median = 28.8 ns
99% confidence interval = 6.0 ns
Max = 32.3 ns
Min = 25.3 ns

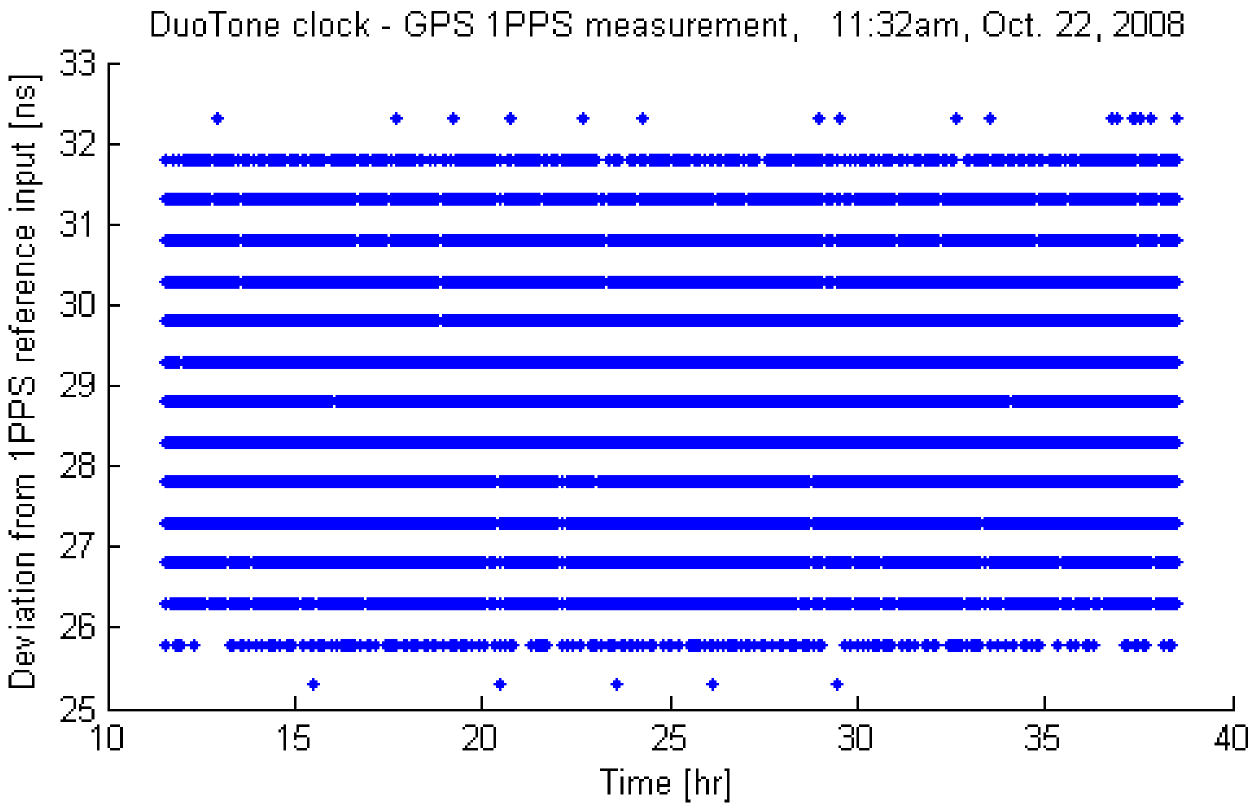


Figure 8 Deviation between the rising edge of the GPS 1PPS and the closest rising edge of the 2^{18}Hz square wave Clock. The figure shows the deviation as a function of time. The apparent line features correspond to the resolution of the Universal Counter.

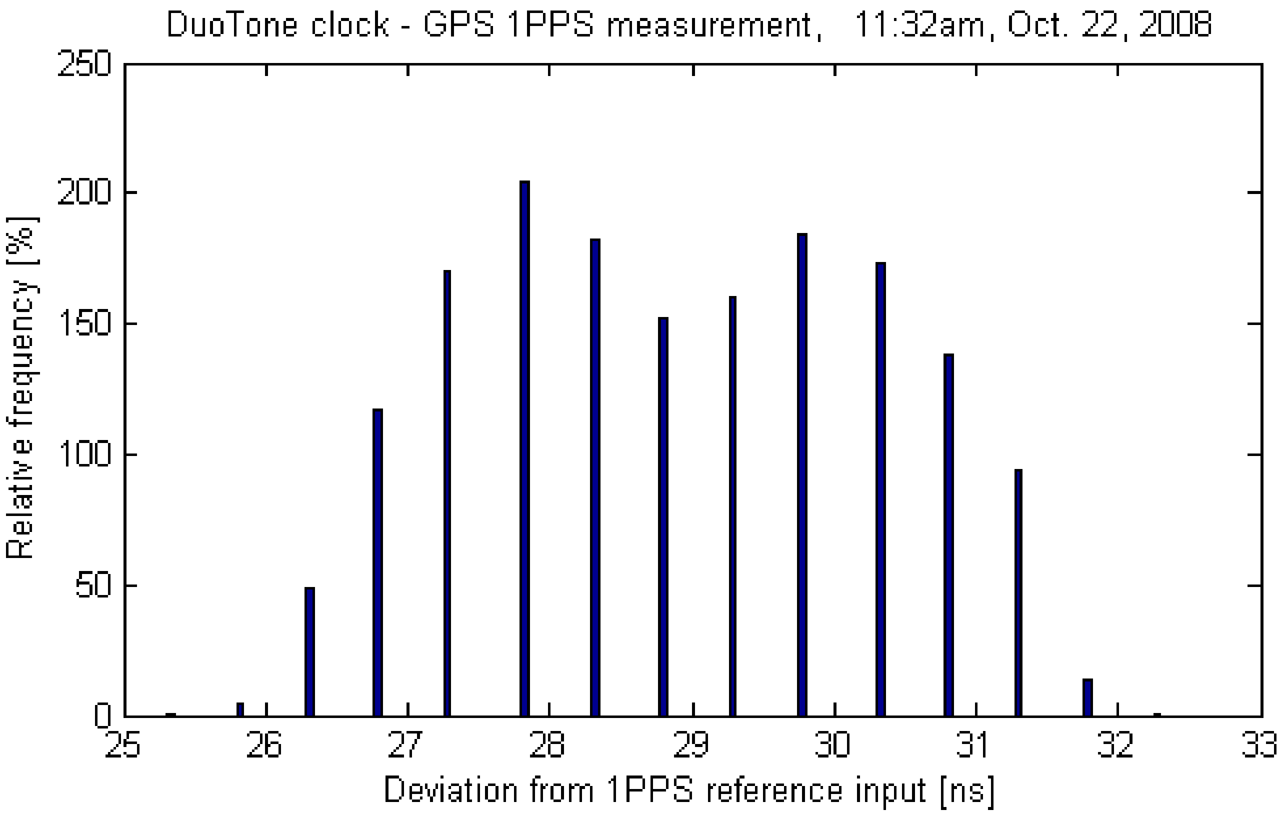


Figure 9 Deviation between the rising edge of the GPS 1PPS and the closest rising edge of the 2^{18}Hz square wave Clock. The figure shows the deviation as a histogram.

To further test the precision of the Clock signals, we set up two Slave+DuoTone Modules, both connected to the same FanOut, which is connected to the Master. We measured the deviation of these clocks using a Universal Counter (HP 53131A). The Universal Counter measured the deviation between the two clock signals 10 times per second.

The statistical parameters of the results are the following.

Median	= -2.2 ns
99% confidence interval	= 2.0 ns
Max	= -0.0 ns
Min	= -3.7 ns

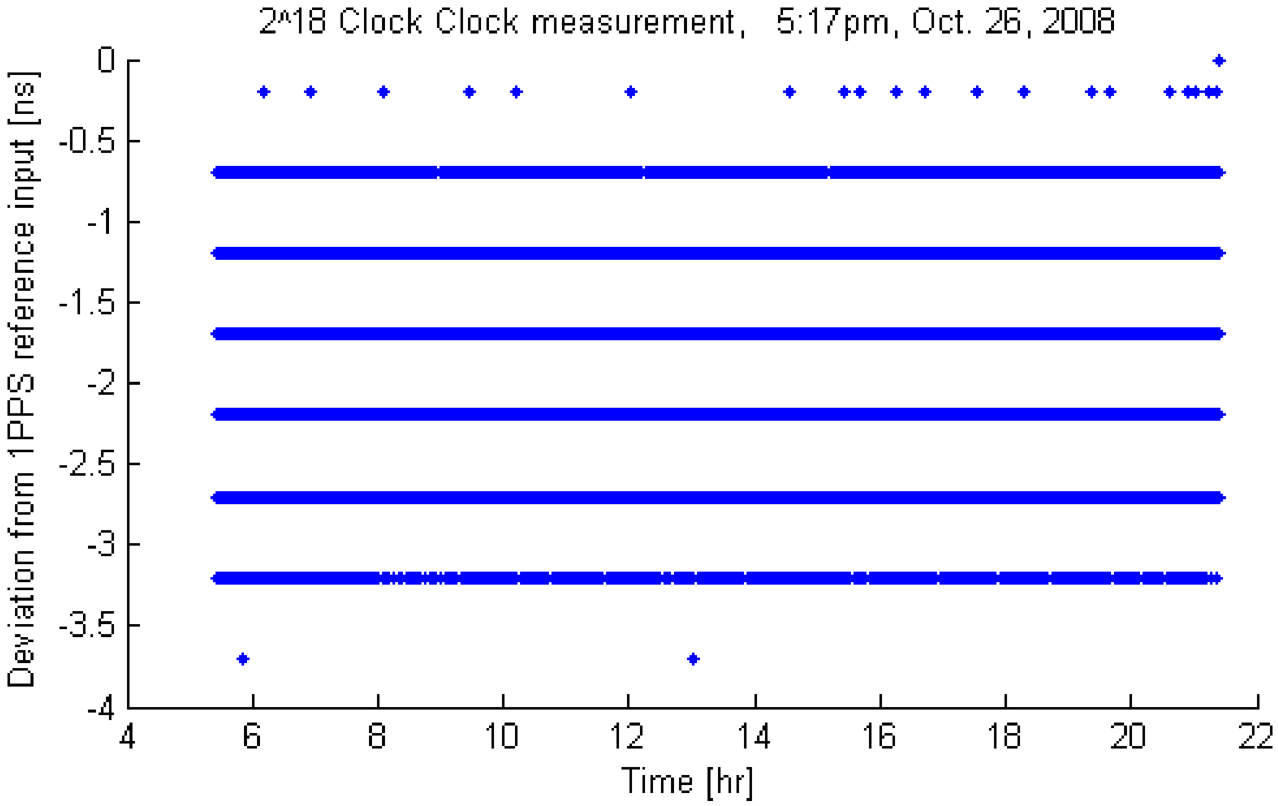


Figure 10 Results of the comparison of two 2^{18}Hz clocks from two Slave+DuoTone boards. Both boards were connected to the same FanOut board. The figure shows the deviation between the two clock signals as a function of time.

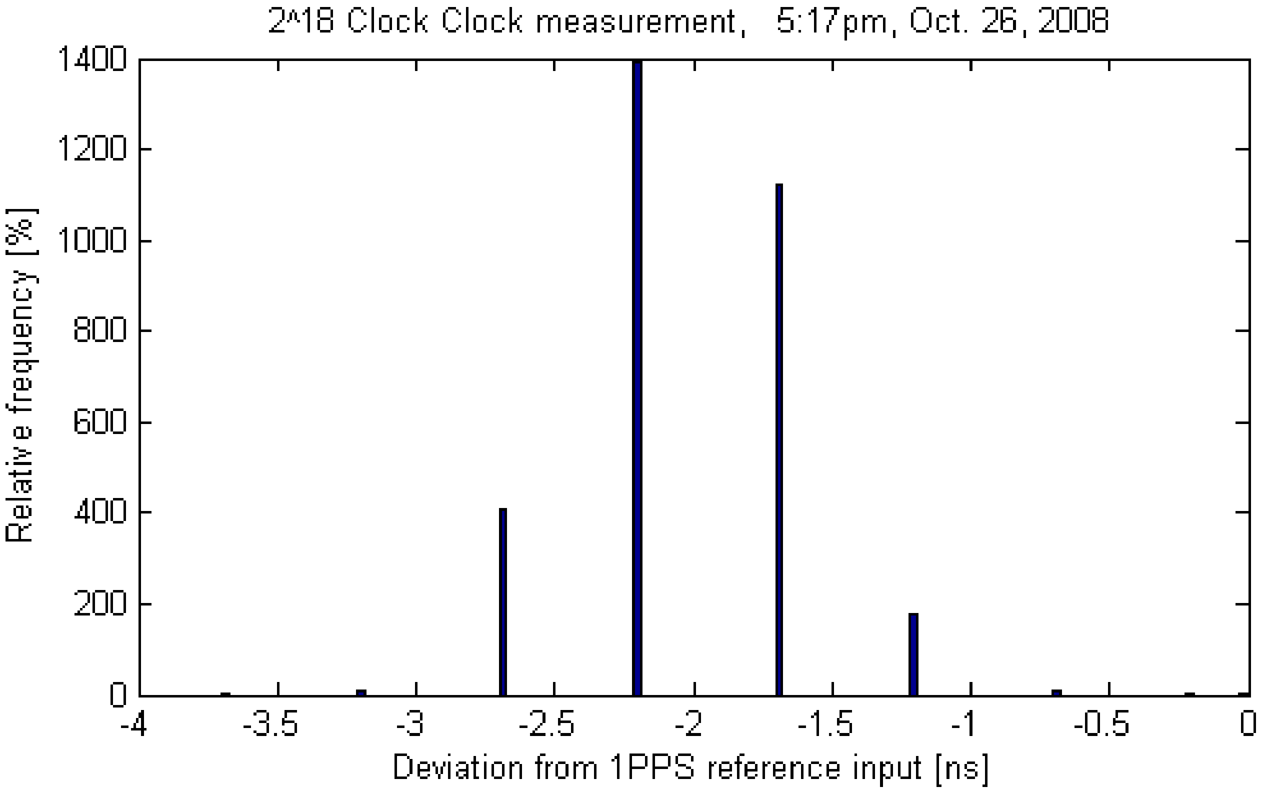


Figure 11 Results of the comparison of two 2^{18}Hz clocks from two Slave+DuoTone boards. Both boards were connected to the same FanOut board. The figure shows the deviation between the two clock signals as a histogram.

We conclude that the deviation between the Clock signals from the two Slave+DuoTone Modules and to the GPS 1PPS is safely below the ~385ns safety margin for the end-to-end system. The result also shows that the Master-FanOut-Slave system synchronizes properly to the external 1PPS signal, and that it properly compensates the time delays due to transmissions between different modules. The test was executed with open chassis in a busy laboratory environment and there were no attempts made to shield devices and components from environmental disturbances. Therefore it is expected that in a closed chassis and undisturbed rack, the field deployed system's performance will be at least comparable to the test results.

Shutdown/SwitchOn Test

The OTD is required to be resistant against possible power outages, affecting any of its components. It has to be able to restore itself and resynchronize automatically after it has been turned off and on. To demonstrate this property of the system, we performed a Shutdown/SwitchOn test.

We measured the deviation between the external GPS 1PPS, coming from the GPS Receiver (Trimble Thunderbolt E), and a Timing Comparator board connected to a Master-FanOut-Slave chain. The 1PPS' were compared using a Universal Counter (HP 53131A). (This setup is functionally equivalent to the Slave+DuoTone Module from the viewpoint of this test.)

After starting the measurement, we first turned off the whole Master-FanOut-Slave system, and kept it turned off for 1 min, after which we turned on the whole system back again. After several minutes, when the system has recovered itself and resynchronized, we turned off the Master-FanOut system and kept it off for 1 min, while keeping the Slave board on. We then turned the Master-FanOut system back on, and waited several minutes for it to resynchronize. After several minutes, we turned off only the Slave board, while keeping the Master-FanOut system on. We kept the Slave off for 1 min, after which we turned it on. For the whole period of the three off/on switches, the Universal Counter was turned on and was measuring.

The results of the measurements are shown in Figure 12. We marked the times of turn-ons with a vertical red line. Note that, for the turned-off periods, the Universal Counter does not record the measurement since there is no signal.

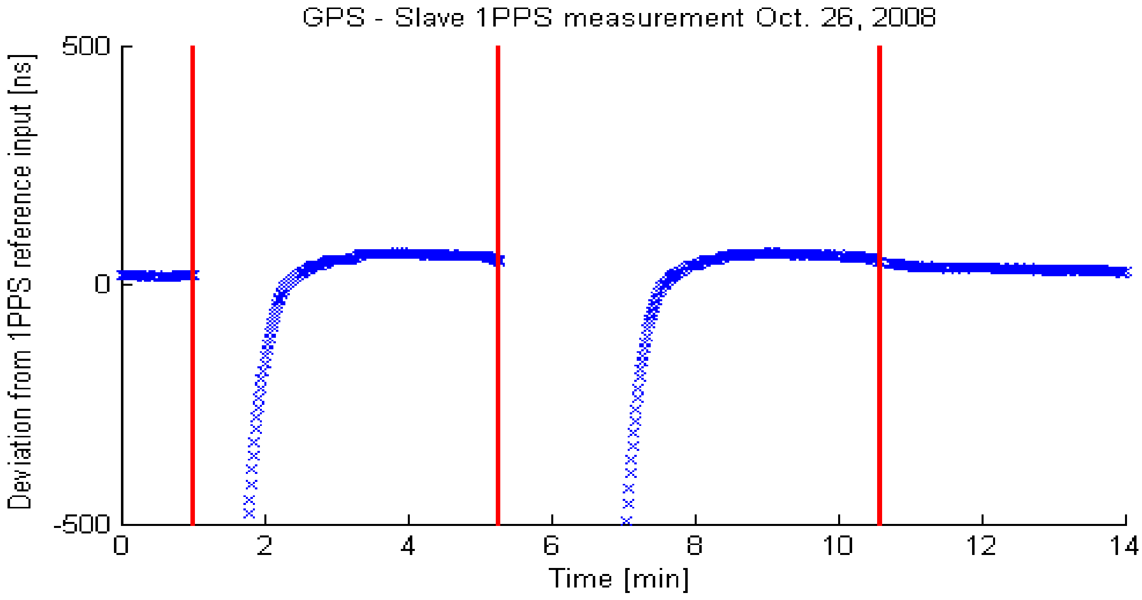
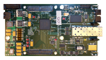


Figure 12 Deviation between the external GPS 1PPS and the 1PPS from the Slave+Comparator Module, as part of a Master-FanOut-Slave system. The red lines show the times when some of the boards were turned off and on. The modules that were turned off and on for the three cases are: (i) Master, FanOut, Slave, (ii) Master, FanOut, and (iii) Slave, respectively. The durations of turned off states were 1 min. Note that the Universal Counter does not record the deviation when any of the boards is turned off.

One can see that, after the Master-FanOut system was turned off and on, independently of whether the Slave was also turned off and on, the system has recovered and resynchronized its 1PPS signal in a few minutes. When the Master and FanOut modules remained on and the Slave was turned off and on, the system has recovered and resynchronized in a few seconds. We therefore conclude that the OTD is resistant to power outages and it recovers automatically after some or all of its components are temporarily turned off.



External 1PPS Unplug Test

Another realistic situation for external perturbation is when the external 1PPS, to which the Master module synchronizes itself, fails to send a few pulses. Normally in this situation, the Master module simply switches to its failover GPS input. It could happen, however, that the failover GPS 1PPS input is not placed properly or it is missing for some other reason. In such situation our expectation from the OTD is that it should quickly recover from and resynchronize itself to the external 1PPS.

To test this feature, we used a test setup where the Master module was initially locked to an external 1PPS coming from a Trimble Thunderbolt E GPS disciplined clock. Then the GPS 1PPS input has been disconnected for a few seconds. During the test, we were comparing the 1PPS coming from the Trimble Thunderbolt E GPS disciplined clock to the 1PPS from the 1PPS output port of the Master. We used a Universal Counter (HP 53131A) for the comparison and recorded the data on a computer. Results are shown in Figure 13. At the start of the test, the Master module was locked to the external 1PPS, as shown by the time deviation, and also signaled by the LEDs on the Master module (the ON, 1PPS and OCXO LEDs exhibited ½ Hz blink synchronously, and the GPS LED exhibits 2 Hz

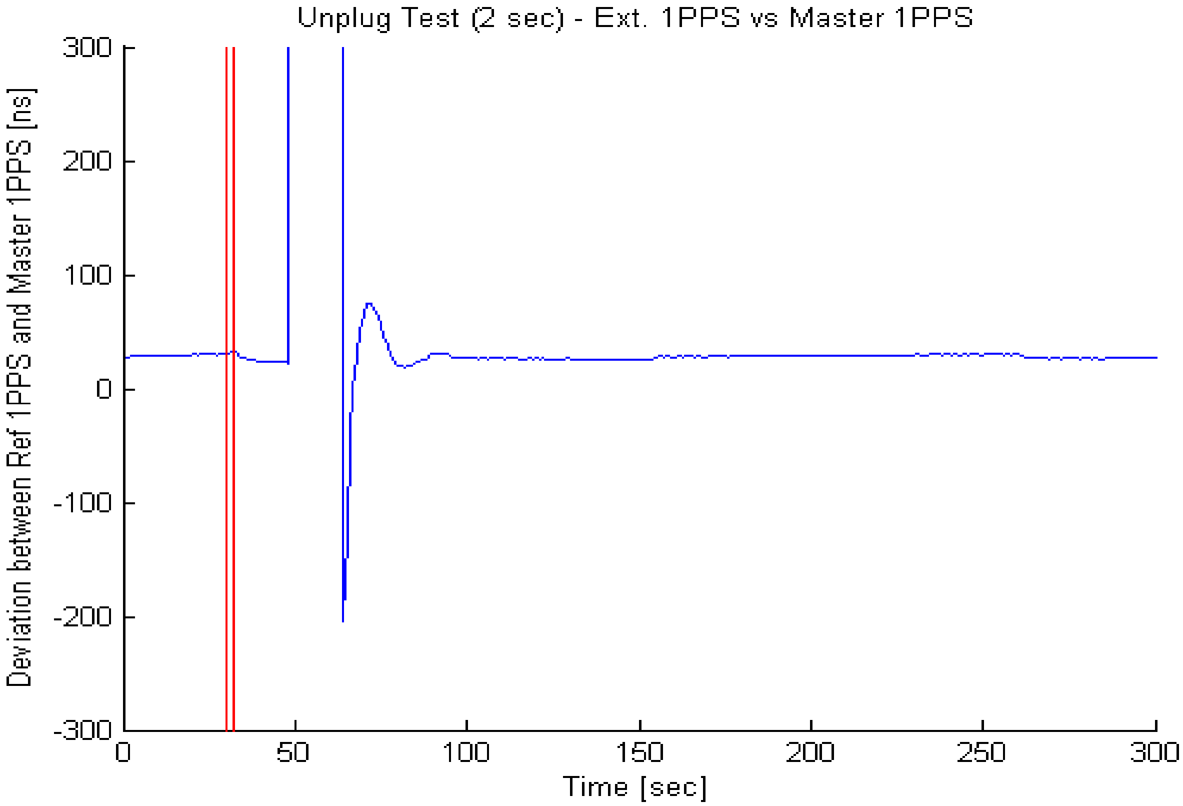
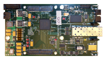


Figure 13 Deviation between a reference 1PPS signal obtained from a Trimble Thunderbolt E GPS disciplined clock and the 1PPS from the 1PPS Output of the Master module. The Master module was initially locked to the reference 1PPS. The two red lines show the time of unplugging and replugging the reference 1PPS to the 1PPS Input port on the Master module

blink). After 30 seconds, the external 1PPS was unplugged from the Master 1PPS Input connector, and it was reconnected 2 seconds later. The disconnection and reconnection are marked with red vertical lines on Figure 8. The deviation between the reference 1PPS and the Master 1PPS are shown in Figure 13. One can see that the system recovered from the loss of reference signal within a minute.

When the external 1PPS was unplugged (at time = 30 s), the OCXO LED on the front panel of the Master module instantly signaled that the OCXO is not locked (2 Hz blink), and the 1PPS LED turned off, signaling that is no external 1PPS is being received. After the external 1PPS was reconnected at time = 32 s, the 1PPS LED started to signal that the module is receiving external 1PPS at 49 second. The OCXO LED started to signal that OCXO is locked (½ Hz blink) at time=62s.

We conclude that the OTD can quickly recover from the loss of External reference 1PPS signals. We also conclude that the OTD successfully detects the lack of signal and its synchronization status. We emphasize that there should be practically no deviation if the failover GPS antenna is connected and locked, since the Master module would automatically switch and use the GPS 1PPS as reference.



Fiber Unplug Test

To test the system's response to unplugging the optical fiber, we tested two different setups. In the first setup, we measured the deviation between the external 1PPS provided by a Trimble Thunderbolt E GPS disciplined clock and the 1PPS from a Slave+Comparator module connected to the Master through a FanOut module. In the second setup, we compared the same external 1PPS to the FanOut module that is connected to the Master module. In both cases, the Master was synchronized to the external 1PPS.

To test the system's reaction to the disconnection of the fibers, we disconnected the fiber between the Slave+Comparator and the FanOut for the first setup, and between the FanOut and the Master for the second setup. In both cases we reconnected the modules with the fiber after 2 seconds. The reaction of the deviation between the two compared 1PPS values to the disconnection was very similar in the two cases. At the moment of disconnection, the deviation started growing with about 100 microseconds every second as long as the fiber was disconnected. After the fiber was reconnected, the deviation did not change any more until the 9th second after the original *disconnection*, when the deviation got back to the original synchronized value as if nothing has happened. Upon disconnection, the output LED on the downlink module providing the synchronization 1PPS turned off, and turned on, initially showing that the uplink module is not synchronized (2 Hz blink). It showed again that the uplink module is synchronized at the 17th second.

We conclude that disconnecting the fibers between two OTD modules interferes with synchronization only for a very short amount of time: the modules perfectly synchronize again in ≤ 8 seconds after reconnecting the modules. We also conclude that the OTD successfully detects the lack of signal and its synchronization status.