LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Timing System: Final Design

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1 Motivation

Timing is a mission critical part of the LIGO detector for the following reasons: *(i)* the coincident and coherent observation using a network of GW detectors is only possible, if the relative timing of the data streams agree within a high degree of accuracy, *(ii)* a network of interferometric gravitational wave detectors can only recover the polarization angles and the sky direction, when the relative timing of the data-streams is well known and verified, *(iii)* in the case of a coincident detection of gravitational waves with an astrophysical event, such as a GRB or a supernova, the absolute timing has to be known to compare the two events, and *(iv)* the timing jitter of the digitization of the gravitational wave signal can directly contribute to the noise level, i.e., the astrophysical reach of the LIGO interferometers.

The timing system of initial LIGO was based on a network of independent clocks controlled by the Global Positioning System (GPS). The system was providing the timing signals used in the controls and data acquisitions systems. The interferometer length sensing and control software also incorporated several internal consistency and synchronization checks. Additionally, a second independent timing system, based on a Cesium clock, to complement the GPS-based system was commissioned to provide the required redundancy, diagnostic and monitoring capabilities and to ensure the reliable operation of the detectors.

2 Scope

This is the design of the advanced LIGO timing system that is based on the timing system in initial LIGO. It consists of two independent systems: one based on a GPS clock and one based on an atomic (Cs) clock; as well as additional diagnostics hardware and software. The system based on the atomic clock will be reused in advanced LIGO without any major changes. The units currently installed at the LHO mid stations will no longer be needed and they shall serve as spares. The tubes of the cesium clocks have a limited lifetime and will be replaced when they stop working.

The GPS based timing distribution system will use a modern GPS clock as its primary reference. The timing signal is distributed through fibers to all (L)VEAs and all equipment which requires synchronization to GPS. This is the primary timing synchronization system, whereas the fully independent atomic clock system is used for verification and diagnostic only.

One very important consideration in the current design is to strengthen the diagnostics capability and the ability to be able to track all synchronization errors. The current synchronization of the converter boards relies on counting clock cycles and being accurate for days, weeks and months. For this design all timing signals have to be continuously monitored to detect immediately and to prevent the propagation and persistence of timing errors.

2.1 Clock signals for converters, power supplies and RF oscillators

A converter board would typically need three timing signals for proper synchronization. The first timing signal will typically be the sampling clock itself or a multiple of the sampling clock. The second (1PPS/64 bit GPS Time) and third (DuoTone) timing signals are used to synchronize to the GPS epoch in seconds with sub-sample accuracy. Synchronous switching power supplies will also need a clock which is aligned to GPS—typically in the range of 2^{16} Hz to 2^{19} Hz.

2.1.1 2**N clock

The basic sampling rates for advanced LIGO are 16384 Hz and 2048 Hz. Some systems may run even slower at 256 Hz. In all cases the clock frequency will be of the form 2^N. A typical timing slave module will internally run at a much higher clock frequency such as 2^{26} Hz from which all other timing signals will be derived.

2.1.2 1 PPS signal

The 1 pulse-per-second (PPS) signal is a positive edge signal which is used to align the converter boards with a GPS second. RF oscillators will be synchronized to GPS using the 1 PPS signal by using a phase-locked loop (PLL). The 1 PPS signal is also used for timing comparisons between the atomic clock system time, the main GPS derived time and various derived 1PPS signals.

2.1.3 Converter start-up and monitoring

Advanced LIGO's commercial ADC and DAC boards typically have only one timing input for the sampling clock. A special start-up procedure has to be applied to start the conversion process aligned to the 1 PPS mark with sub-sample precision. This start-up procedure has to be implemented external to the converter boards. The synchronization then relies on counting clock cycles for as long as the system is up. To monitor the synchronization periodically one channel of each ADC board has to be used to acquire an additional timing signal (see DuoTone section) which is then analyzed to check the timing accuracy. For a DAC one channel has to be used to output a timing signal which is then read back through and another ADC channel and compared against the external DuoTone signal.

2.1.4 RF source synchronization

Relevant RF frequency generators will either be locked to a 1 PPS signal or to another RF source. The later is implemented when accurate phase coherence is required at RF frequencies. It is possible to phase-lock RF frequency generators located in two separate buildings. This will require a fiber noise eater to stabilize the fiber delay. However, no need for such a system has been identified at this time.

2.2 GPS time

The distribution system for the GPS clock is based on a 2^{23} Hz clock signal. Its positive edges define a low jitter clocking signal which can be used to lock the VCXO in the slave module. The negative edges can be set at 25%, 50% and 75%. This in turn is used to broadcast a 1 PPS marker, the GPS second information as well as additional status and diagnostics data. This signal is distributed through fibers and each link is bidirectional. The return link is used to mirror the internal timing signal of the slave module, to return error codes and to transmit diagnostic information. This way the fan-out and master modules are able to monitor the slave timing and make sure any synchronization errors are detected and reported back to the computer stations.

2.2.1 Time stamps on data streams

Since a timing slave module regenerates a full GPS clock, it can provide an accurate time stamp to the converters. This time stamp can then be added to the data stream before it is processed by the computer back-end. This will remove any ambiguity on the data received and processed by the computer back-ends. Conversely, a data stream which arrives with a full time stamp at the DAC board can be unambiguously aligned to the output clock.

2.2.2 DuoTone

DuoTone is a way to initialize, calibrate and to provide recorded end-to-end diagnostics of the timing of an ADC or DAC channel. For an ADC channel two sine wave frequencies which are 1 Hz apart are generated by a hardware device which is locked to the 1 PPS signal. This DuoTone signal is then injected into an ADC channel and analyzed in software. The absolute and relative phases of the two sine waves then allows us to regenerate the timing of the 1 PPS signal and thus calibrate the timing of the ADC channels. For a DAC channel the DuoTone signal will be generated by the computer back-end of the DAC board and it will be aligned to its 1 PPS signal. This DuoTone signal is then read back through an additional ADC channel.

2.2.3 IRIG-B code

The IRIG-B signal is a timing code providing second-of-the-year information modulated on a 1 kHz carrier signal. This is an industry standard and timing translators for IRIG-B signals are readily available from commercial vendors. Two ADC channels per interferometer are used to record IRIG-B signals from the atomic clock and the GPS based timing systems, respectively. This will add an independent time stamp to the data stream and can be used to regenerate the GPS epoch in case any ambiguity arises. The IRIG-B signal is monitored real time and it is not propagated beyond the mass storage room. The low data rate diagnostic information is recorded in the frames.

2.3 Redundancy and diagnostics

The GPS based primary system is the sole timing standard to clock the converter boards or any other system. The GPS based system has no long hold-over capability and it is required that the primary GPS receiver is locked to satellites at all times. The independent diagnostic system, based on the atomic clock and independent GPS receivers, has long holdover capability and sufficient redundancy; however, it is used purely for diagnostics.

2.3.1 Atomic clock

The optically distributed (free running and precisely calibrated) atomic clock time serves as the reference time for timing comparisons. The atomic clock itself runs in a stable environment powered through a dedicated UPS system to make sure power failures shorter than 48 hours will have no effect on it. A transportable military grade rubidium based clock is also provided to allow for independent checks of the fiber distribution at different stations.

2.3.2 GPS receiver ensemble

The GPS based timing system will use a single high-reliability GPS receiver as its primary reference. However, 2 or 3 additional GPS receivers from different manufacturers shall be installed for redundancy. They serve as an independent check on the primary GPS receiver and protect us against design/manufacturing bugs.

2.3.3 Time-interval counters

Time interval counters are used to record the difference in timing between the different timing standards and redundant time sources. The 1 PPS signal of the atomic clock based system will typically serve as the reference tick and all other signals will be compared to it. The other ticks come from the individual GPS receivers as well as the outputs of the timing distribution systems in the different stations.

2.4 Network time stamp

Computer stations in the control room will need to be synchronized with UTC to within a few milli seconds. A stand-alone NTP server will serve as the primary network timing server. It will be backed up by time servers on the internet.

2.5 Online monitoring and recording

An important design criterion is the ability to self-monitor the health of the timing system. The GPS based fiber distribution system implements local clocks in all its slave modules. These local clocks are locked to the master unit through the 2^{23} Hz signal distributed over the fiber. If there is a transmission error, the local clock will recognize this and report an error on its return link. Furthermore, each slave module sends back an identical timing signal derived from its own local clock through its return fiber. This enables the master/fan-out units to recognize any slave errors. Error conditions are then propagated backwards to the master unit where they will be sent to a computer. This information will also be sent to the frame writer and archived as part of the data stream.

2.5.1 Alarms

Some timing errors such as the loss of satellite lock of the primary GPS receiver are fatal. Any indication that the primary timing system is no longer operating safely within specification has to be alarmed. Similarly, the loss of the atomic clock for an extended period of time can be regarded as nearly fatal and has to be corrected in a timely manner. Timing glitches such as a converter which is out of synchronization for a couple of seconds are not fatal. These glitches will have to be recorded but may not require an alarm.

2.5.2 DMT

The data monitoring tool (DMT) will be used to analyze recorded IRIG-B and DuoTone signals. Their results will be recorded and made available for control room monitoring using standard DMT infrastructure.

3 Requirements

3.1 Arrival time reconstruction

The ability to reconstruct the arrival time of a gravitational wave signal with '*infinite*' signal-to-noise ratio shall be within 10 μs of UTC.

3.1.1 Timing error budget

The following timing error budget is used for the design.

Error budget	Accuracy	Units
Primary GPS receiver	500	ns
Master timing unit	1	μs
Fan-out with long fiber (>100m)	1	μs
Fan-out with short fiber (<100m)	200	ns
Slave module	200	ns
Converter board	1	μs

This leaves about 5 μs for other calibration uncertainties. These other uncertainties include the uncertainty in reconstructing an *h(t)* signal at the relevant frequencies as well as the uncertainties associated with the determination of an exact arrival time relative to the converter clocks.

3.2 Clock signal jitter

Jitter on the converter clock signals cannot dominate the converter noise budget. A specific requirement has to be developed for each converter board. However, it is unlikely that our XO based 2^N primary oscillator will not be sufficient. [Specs TBD]

3.3 1 PPS accuracy

An external 1 PPS signal is required to represent the GPS mark of its timing unit to within 10 ns.

3.4 Oscillator frequencies

There shall be no free-running oscillator frequencies at critical places. All such oscillators have to be locked to GPS to prevent corresponding beat node frequencies to drift in and out of the gravitational wave band.

3.5 Redundancy and hold-over

There is no requirement on hold-over and redundancy in the primary timing system. However, adequate spare units have to be stocked and ready to be swapped in at the sites to allow for immediate repairs and troubleshooting.

3.6 Reported status and error conditions[1]

The synchronization of each converter board has to be checked at least once in every minute. All synchronization errors of converter boards have to be reported and archived.

The phase error of an RF oscillator which is locked to a 1 PPS signal has to be recorded at least once a minute and archived as part of the data stream.

The synchronization of each slave and fan-out module has to be monitored at all times. All synchronization errors of slave and fan-out modules have to be reported and archived.

The status of the timing system in each station relative to the atomic clock has to be monitored on a second-by-second basis and reported at all times.

The relative timing of the ensemble of GPS clocks relative to the atomic clock has to be monitored on a second-by-second basis and reported at all times.

The IRIG-B signals are recorded in the data stream, monitored and results are archived at all times.

The DuoTone signal of the converter board that records the strain signal has to be recorded to the data streams and archived at all times. The same requirement holds for the converter board of the final actuator controlling the differential arm cavity length.

DuoTone signals of less critical systems have to be analyzed at least once every minute and results have to be reported and archived.

[1] Elaborated in test document.

4 Design Concepts

The advanced LIGO timing system is based on the same concepts as the final state of the initial LIGO timing system. The basic design is to have a primary system and a diagnostic (secondary) system which are independent from each other. The primary system is used for generating the time stamps and the clocking signals. The secondary system is used for diagnostics only.

4.1 Primary timing system

The primary system is based on local clocks which are synchronized through fiber optics. The local clocks are crystal based and are locked to an upstream clock through a timing signal distributed by the fibers. Fan-out modules are used to lock multiple downstream clocks to a single upstream clock. This then leads to a tree-topology for the timing synchronization with a single master clock at its root. The master clock is an oven-stabilized crystal oscillator that in turn is locked to a GPS receiver. The local clocks at the end of each branch are used to synchronize the converter boards, the RF synthesizers and all other devices which require timing synchronization. The current system installed in initial LIGO, is based on this concept. It will be adopted and enhanced for advanced LIGO, but will provide essentially the same functionality.

4.1.1 Master clock

All commercial time standards output a 1 PPS (one pulse-per-second) signal that can be used to synchronize the LIGO timing system. The fundamental clock frequencies for the LIGO ADCs and DACs are derived from a 2^N Hz clock. We shall use a master oscillators based on oven-stabilized low noise crystals (OCXO) that runs at Hz (33.554432 Hz) and are locked to a 1 PPS signal using a phase-locked loop (PLL). This master oscillator is locked to a commercial GPS clock.

4.1.2 2^N fiber distribution system

To implement a reliable link for timing distribution we shall use a fiber coupled timing signal that runs at 8.388608 MHz. The timing signal is a square wave signal with 50% duty cycle using the positive edges for synchronization. To mark the location of the 1 PPS signal the two closest negative edges to the positive edge aligned with the 1 second mark are moved inwards making the pulse starting at the 1 second mark half as long as the others and the one before 50% longer than the others (see timing diagram). Basically, the clock signal is determined by the positive edges whereas the interval length between the negative edges determines the location of the 1 PPS signal. This type of timing signal has 50% duty cycle overall and is well suited to be distributed through an AC-coupled fiber link. Since the 1 PPS signal is modulated onto the main clock signal only a single fiber link is required.

The above scheme can easily be extended to broadcast a GPS time stamp and to communicate status conditions. In the extended scheme more of the negative edges are used to encode data bits. An example of such an extended scheme is described in LIGO-T070218.

We propose to use a return link for diagnostics purposes. This return signal is the same type of clocking signal but is derived from the slave clock, therefore, indicating the exact state of the slave clock. The diagnostics return link is used to *(a)* determine that the slave is locked to the master and to *(b)* measure the timing delay in the fiber link. We propose to implement a time adjust on the master side that allows the clock to be shifted ahead. This will compensate for the time delay in the fiber and guarantee accurate timing of the slave. Since the returned diagnostics signal has passed through the fiber delay twice, it is straightforward to determine the delay and further diagnostics can be implemented to check that the time adjustment is half the total round-trip delay.

4.1.3 Fan-out modules

Since each timing slave needs its own clock signal feed with time adjustment and diagnostics we propose to use a separate timing distribution board that sits between the master oscillator and the slave clocks. This fan-out module would basically look like a slave clock. It would further provide multiple outputs to synchronize slave modules in the LVEA or any of the out-buildings. Both single-mode fiber and multi-mode fiber are supported for long range (> 1 km) and short range (< 1 km), respectively.

4.1.4 Slave modules

A slave module implements a crystal oscillator (VCXO) running at 2^{26} Hz that is locked to the positive edges of the timing distribution signal using a PLL. It regenerates the timing distribution signal from its internal clock and compares the location of the 1 PPS mark to the one in the received timing signal. If the 1 PPS marks differ for a couple of consecutive seconds the internal counters are zeroed with the external 1 PPS and an error flag is set. It is envisioned that slave modules come in different variety depending on the ADC and DAC modules they are driving. A slave module will generate all the necessary clock signals for an ADC or DAC from its internal oscillator which should be immune to noise on the timing distribution system.

4.2 The timing diagnostic system

The timing diagnostic system is based on an atomic clock. The timing is distributed through proven commercial fiber based communication links. Local timing signals are available in each building. The purpose of this secondary timing system is to serve as an independent reference with long hold over capability for timing comparison with the primary system. The timing diagnostic system is a mostly commercial system. Significant part of it is currently deployed in initial LIGO, proven very reliable and will be carried over essentially unchanged. In each outbuilding a single GPS clock will be installed as an additional diagnostics. Timing comparator modules based were developed and will be installed in all outbuildings.

4.3 DuoTone hardware

An important aspect of the timing system is to verify and monitor the timing of the data acquisition system. This has proven to be a challenging, albeit solvable task in initial LIGO. The main problem is that most converter boards expect a clock signal but do not provide a synchronization input. This then requires the system to start on a 1 PPS marker (with subsample precision) and to rely on the counting of clock cycles for extended periods of time. For advanced LIGO it would be reassuring to ensure that every converter board has a built in monitor system and able to guarantee synchronization in hardware. For commercial converter boards these are most likely impossible and software assurances will be needed. The hardware based GPS synchronized DuoTone generator diagnostics must to be implemented as a monitor.

The DuoTone hardware generates two sine waves which are spaced 1 Hz apart. The frequencies for initial LIGO are 960 Hz and 961 Hz, partially coinciding with a 60 Hz power line harmonic to save spectral range. The dual sine wave approach was chosen to minimize harmonics and to avoid ambiguities within 1 second. Any timing signal sampled by a converter board will leak into the main signals through crosstalk and therefore has to have minimal frequency content. For advanced LIGO a special timing slave board will be developed to generate the DuoTone signals.

The baseline design calls for each ADC board to dedicate one channel for a DuoTone signal. The same is true for a DAC board: one channel has to be dedicated for a DuoTone signal which is generated by the computer back-end. Alternatively, a DuoTone signal acquired through an ADC channel can be looped back. This DAC generated DuoTone signals have to be read back by an ADC board to make them available for analysis. The number of ADC channels dedicated for DuoTone signals in a given data acquisition subsystem is the sum of the number of ADC boards and the number of DAC boards. This means that any subsystem which contains one or more DAC boards has to contain at least one ADC board.

DuoTone signals are analyzed at least by the DMT in real time.

5 Implementation

An overview of the advanced LIGO timing system is shown in Figure 1.

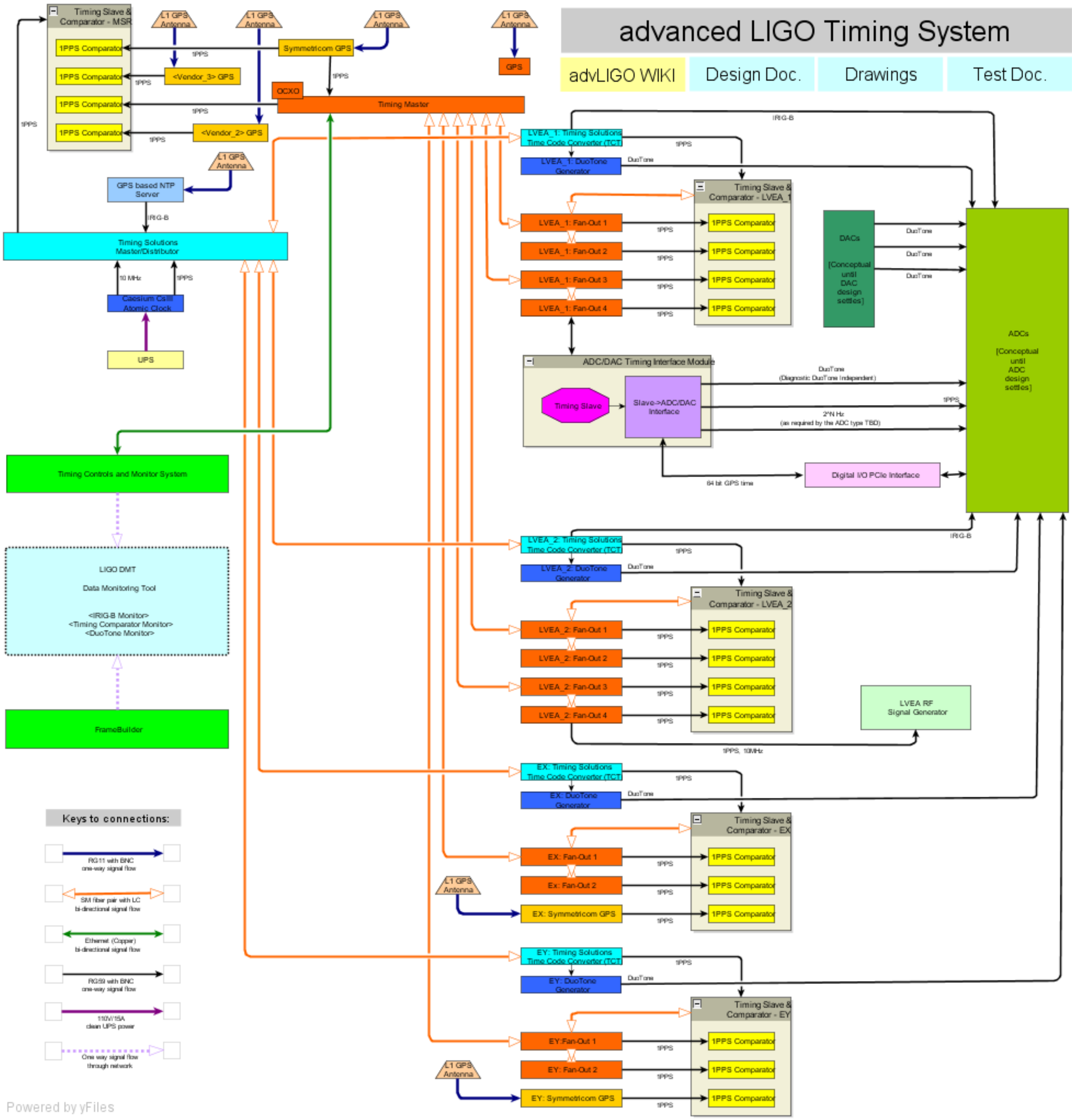

Figure 1 Overview of the advanced LIGO timing system

5.1 2^N fiber distribution system

The 2^N fiber distribution system consists of the main GPS clock, a master module, a series of fan-out modules as well as some specialized slave modules to synchronize RF frequencies and to clock converter boards.

5.1.1 Distribution modules

A list of modules which constitute the main fiber-based timing distribution system is provided below:

Module	Brand	Description	Location
Master GPS	Symmetricom 58503B	Main GPS clock	MSR
Master/fan-out	D070011-B	Master fiber distribution unit	MSR
Fan-out EX1	D070011-B	Fiber Fan-out module EX for H1/L1	EX
Fan-out EX2	D070011-B	Fiber Fan-out module EX for H2	EX
Fan-out EY1	D070011-B	Fiber Fan-out module EY for H1/L1	EY
Fan-out EY2	D070011-B	Fiber Fan-out module EY for H2	EY
Fan-out LVEA1	D070011-B	Fiber Fan-out module LVEA1 for H1/L1	LVEA
Fan-out LVEA2	D070011-B	Fiber Fan-out module LVEA2 for H1/L1	LVEA
Fan-out LVEA3	D070011-B	Fiber Fan-out module LVEA3 for H1/L1	LVEA
Fan-out LVEA4	D070011-B	Fiber Fan-out module LVEA4 for H1/L1	LVEA
Fan-out LVEA5	D070011-B	Fiber Fan-out module LVEA5 for H2	LVEA
Fan-out LVEA6	D070011-B	Fiber Fan-out module LVEA6 for H2	LVEA
Fan-out LVEA7	D070011-B	Fiber Fan-out module LVEA7 for H2	LVEA
Fan-out LVEA8	D070011-B	Fiber Fan-out module LVEA8 for H2	LVEA

Shaded rows are only implemented for H2.

The timing fan-out and master modules are based on the same circuit boards. The master module is equipped with the following options:

- An oven-stabilized oscillator at 2^{26} Hz which is locked to the 1 PPS signal from the main GPS clock,
- A GPS timing receiver (M12M timing oncore receiver from iLotus) which is used to generate a timestamp based on the GPS seconds passed since January 6, 1990, 00:00 UTC,
- An Ethernet uplink to a computer to report status and timing errors.

A fan-out module can be connected to an output of the master module or the output of another fan-out module. A slave module can be connected to an output of a master or fan-out module. The timing distribution network is fully bidirectional and forms a star topology.

5.1.2 DAQ slave modules

For the commercial system a separate timing slave was developed which includes clocking signals, a possibility to enable the converter at the 1 PPS mark as well as a DuoTone generator. Each commercial PCI Express expansion chassis containing ADCs and DACs will require one of these DAQ slave modules. Each ADC board is required to set one channel aside for recording a DuoTone signal. Each DAC board is required to set one channel aside to output a DuoTone signal. Each DAC DuoTone signal has to be read back by an ADC channel. The DAQ slave module for the commercial system is D070TBD.

5.1.3 RF generator slave modules

Relevant RF frequencies will be synchronized with a 1 PPS signal using a phase-locked loop (PLL). Each locked RF frequency requires a module D050309-B (OnePPS Locking) as well as a 1PPS fan-out module D070TBD (1PPS FO). The following frequencies need to be synchronized.

Purpose	Description	Frequency H1/L1	Frequency H2
IFO	Main RF sideband; the low and high frequency sidebands are phase-locked together by different means	TBD	TBD
MC	Mode cleaner RF sidebands	TBD	TBD
PMC	PMC RF sidebands	TBD	TBD
REFCAV	Reference cavity RF sidebands	TBD	TBD
PSL	Injection locking to power amplifier	TBD	TBD

At the present time RF frequencies are provided to the LVEA only. If phase-locked interferometer RF frequencies are required in the end stations, a special RF fiber distribution system with fiber length compensation has to be developed. This is currently not in scope.

5.2 Atomic clock and timing comparison system

The atomic clock and timing comparison system consists of a cesium atomic clock, an independent fiber based distribution system from a commercial vendor, a series of timing comparators and a set of DuoTone generators.

Module	Brand	Description	Location
Atomic clock	Symmetricom CsIII	Cesium clock	MSR
UTCG	Symmetricon	Time code generator and fiber distribution	MSR

	UTCG	hub	
FEC	Symmetricom FEC	Fiber expansion chassis for H2	MSR
TCT EX	Symmetricom TCT	Time code translator to receive timing signals in EX	EX
TCT EY	Symmetricom TCT	Time code translator to receive timing signals in EY	EY
TCT LVEA1	Symmetricom TCT	Time code translator to receive timing signals for H1/L1	LVEA
TCT LVEA2	Symmetricom TCT	Time code translator to receive timing signals for H2	LVEA
TComp MSR	D070TBD	Timing comparator for 1PPS signals	MSR
TComp EX	D070TBD	Timing comparator for 1PPS signals	EX
TComp EY	D070TBD	Timing comparator for 1PPS signals	EY
TComp LVEA1	D070TBD	Timing comparator for 1PPS signals H1/L1	LVEA
TComp LVEA2	D070TBD	Timing comparator for 1PPS signals H2	LVEA
DTG EX	D070TBD	DuoTone Generator	EX
DTG EY	D070TBD	DuoTone Generator	EY
DTG LVEA1	D070TBD	DuoTone Generator for H1/L1	LVEA
DTG LVEA2	D070TBD	DuoTone Generator for H2	LVEA

The cesium clock and its associated timing distribution system will be carried over from initial LIGO. However, the cesium tubes have a finite lifetime and possibly have to be replaced in the advanced LIGO time frame.

5.3 GPS receiver ensemble

The GPS receiver ensemble consists of additional GPS receivers which are used for independent verification. Two additional independent GPS clocks (preferably from different manufacturers) are located in the MSR and compared with the main GPS clock. GPS clocks in the end stations are used to verify the fiber distribution systems. A network time server is used to synchronize computer clocks.

Module	**Brand**	**Description**	**Location**
GPS EX	Symmetricom 58503B	GPS clock in EX	EX
GPS EY	Symmetricom 58503B	GPS clock in EY	EY

GPS 2	TBD	Second GPS clock in MSR	MSR
GPS 3	TBD	Third GPS clock in MSR	MSR
NTP	Symmetricom SyncServer S250	NTP server	MSR

5.4 Floor plan

TBD. [Needs full documentation and input from CDS main.]

5.5 Connections

The advanced LIGO timing system requires the following long haul fiber runs:

Fiber	**Begin**	**End**	**Fibers H1/L1**	**Fibers H2**
Single mode	MSR	EX	4 (2 pairs)	—
Single mode	MSR	EY	4 (2 pairs)	—
Multi mode	MSR	LVEA	6 (3 pairs)	6 (3 pairs)

A list of fiber patch cords is given below:

Fiber	**Begin**	**End**	**Connector**
Master/Fan-out modules:			
SM	MSR master out1	MSR patch panel EX	LC/FC
SM	MSR master out2	MSR patch panel EY	LC/FC
MM	MSR master out3	MSR patch panel LVEA	LC/FC
MM	MSR master out4	MSR patch panel LVEA	LC/FC
MM	MSR master out5	MSR patch panel LVEA	LC/FC
MM	MSR master out6	MSR patch panel LVEA	LC/FC
SM	EX patch panel	EX Fan-out 1 input	FC/LC
SM	EY patch panel	EY Fan-out 1 input	FC/LC
MM	LVEA patch panel	LVEA Fan-out 1 input	FC/LC
MM	LVEA patch panel	LVEA Fan-out 3 input	FC/LC
MM	LVEA patch panel	LVEA Fan-out 5 input	FC/LC
MM	LVEA patch panel	LVEA Fan-out 7 input	FC/LC

MM	EX Fan-out 1 out1	EX Fan-out 2 input	LC/LC
MM	EY Fan-out 1 out1	EY Fan-out 2 input	LC/LC
MM	LVEA Fan-out 1 out1	LVEA Fan-out 2 input	LC/LC
MM	LVEA Fan-out 3 out1	LVEA Fan-out 4 input	LC/LC
MM	LVEA Fan-out 5 out1	LVEA Fan-out 6 input	LC/LC
MM	LVEA Fan-out 7 out1	LVEA Fan-out 8 input	LC/LC
Atomic clock timing distribution:			
SM	UTCG/FEC out1	MSR patch panel EX	LC/FC
SM	UTCG/FEC out2	MSR patch panel EY	LC/FC
SM	UTCG/FEC out3	MSR patch panel LVEA	LC/FC
SM	UTCG/FEC out4	MSR patch panel LVEA	LC/FC
SM	EX patch panel	EX TCT input	FC/LC
SM	EY patch panel	EY TCT input	FC/LC
SM	LVEA patch panel	LVEA TCT 1 input	FC/LC
SM	LVEA patch panel	LVEA TCT 2 input	FC/LC
Slave modules:			
MM	MSR master out3	MSR TComp input	LC/LC
MM	EX fan-out 1 out2	EX TComp input	LC/LC
MM	EY fan-out 1 out2	EY TComp input	LC/LC
MM	LVEA fan-out 1 out2	LVEA TComp 1 input	LC/LC
MM	LVEA fan-out 5 out2	LVEA TComp 2 input	LC/LC
MM	LVEA fan-out 1 out3	LVEA 1PPS FO input	LC/LC
MM	LVEA fan-out 5 out3	LVEA 1PPS FO input	LC/LC
Converters:			
MM	TBD	TBD	LC/LC

A list of 1 PPS signal connections:

Cable	**Begin**	**End**	**Connector**
coax	Main GPS PPS out	Master module PPS in	BNC
coax	Main GPS PPS out	MSR TComp in2	BNC

coax	GPS 2 PPS out	MSR TComp in3	BNC
coax	GPS 3 PPS out	MSR TComp in4	BNC
coax	Master module PPS out	MSR TComp in5	BNC
coax	Cesium clock	UTCG PPS input	BNC
coax	UTCG PPS output	MSR TComp in1	BNC
coax	EX fan-out 1 PPS out	EX TComp in3	BNC
coax	EX fan-out 2 PPS out	EX TComp in4	BNC
coax	EX TCT PPS out	EX TComp in1	BNC
coax	EX GPS PPS out	EX TComp in2	BNC
coax	EY fan-out 1 PPS out	EY TComp in3	BNC
coax	EY fan-out 2 PPS out	EY TComp in4	BNC
coax	EY TCT PPS out	EY TComp in1	BNC
coax	EX GPS PPS out	EY TComp in2	BNC
coax	LVEA fan-out 1 PPS out	LVEA TComp 1 in2	BNC
coax	LVEA fan-out 2 PPS out	LVEA TComp 1 in3	BNC
coax	LVEA fan-out 3 PPS out	LVEA TComp 1 in4	BNC
coax	LVEA fan-out 4 PPS out	LVEA TComp 1 in5	BNC
coax	LVEA TCT 1 PPS out	LVEA TComp 1 in1	BNC
coax	LVEA fan-out 5 PPS out	LVEA TComp 2 in2	BNC
coax	LVEA fan-out 6 PPS out	LVEA TComp 2 in3	BNC
coax	LVEA fan-out 7 PPS out	LVEA TComp 2 in4	BNC
coax	LVEA fan-out 8 PPS out	LVEA TComp 2 in5	BNC
coax	LVEA TCT 2 PPS out	LVEA TComp 1 in1	BNC
coax	EX TCT 1 PPS	EX DTG 1 PPS in	BNC
coax	EY TCT 1 PPS	EY DTG 1 PPS in	BNC
coax	LVEA TCT 1 1 PPS	LVEA DTG 1 1 PPS in	BNC
coax	LVEA TCT 2 1 PPS	LVEA DTG 2 1 PPS in	BNC

A list of IRIG-B signal connections:

Cable	**Begin**	**End**	**Connector**

coax	Cesium clock IRIG-B out	UTCG IRIG-B input	BNC
coax	LVEA TCT 1 IRIG-B out	PEM ADC chn TBD	BNC
coax	LVEA TCT 2 IRIG-B out	PEM ADC chn TBD	BNC

A list of recorded DuoTone signal connections:

Cable	**Begin**	**End**	**Connector**
coax	LVEA DTG 1 out1	H1/L1 AS port ADC	BNC
coax	LVEA DTG 1 out2	H1/L1 REFL port ADC	BNC
coax	LVEA DTG 2 out1	H2 AS port ADC	BNC
coax	LVEA DTG 2 out2	H2 REFL port ADC	BNC
coax	EX DTG out 1	H1/L1 ETMX drive ADC	BNC
coax	EX DTG out 2	H1/L1 photon cal. ADC	BNC
coax	EX DTG out 3	H2 ETMX drive ADC	BNC
coax	EX DTG out 4	H2 photon cal. ADC	BNC
coax	EY DTG out 1	H1/L1 ETMY drive ADC	BNC
coax	EY DTG out 2	H1/L1 photon cal. ADC	BNC
coax	EY DTG out 3	H2 ETMY drive ADC	BNC
coax	EY DTG out 4	H2 photon cal. ADC	BNC

See section *DAQ slave module* for additional DuoTone connections.

A list of miscellaneous signal connections:

Cable	**Begin**	**End**	**Connector**
RG11	LVEA GPS antenna 1	Main GPS	BNC
RG11	LVEA GPS antenna 2	GPS 2	BNC
RG11	LVEA GPS antenna 3	Main GPS	BNC
RG11	LVEA GPS antenna 4	Master module	BNC
RG11	LVEA GPS antenna 5	NTP server	BNC
RG11	EX GPS antenna 2	EX GPS	BNC
RG11	EY GPS antenna 1	EY GPS	BNC
coax	Cesium clock 10 MHz	UTCG 10 MHz in	BNC

coax	EX TCT 10 MHz	EX DTG 10 MHz in	BNC
coax	EY TCT 10 MHz	EY DTG 10 MHz in	BNC
coax	LVEA TCT 1 10 MHz	LVEA DTG 1 10 MHz in	BNC
coax	LVEA TCT 2 10 MHz	LVEA DTG 2 10 MHz in	BNC
CAT 5E	Master module	control computer	RJ45

5.6 Software

The DMT will be used to monitor the IRIG-B signal as well as the DuoTone signals. There are six DuoTone signals per interferometer which are permanently archived.

Channel	Description	Location
AS port	Monitors the ADC which samples the AS port signal	LVEA
REFL port	Monitors the ADC which samples the REFL port signal	LVEA
ETMX drive	Monitors the drive read-back of ETMX	EX
ETMY drive	Monitors the drive read-back of ETMY	EY
ETMX cal	Monitors the photon calibrator light power in EX	EX
ETMY cal	Monitors the photon calibrator light power in EY	EY

Each ADC and DAC board will generate an additional DuoTone signal. These signals will be analyzed by a DMT monitor but are not necessarily recorded for prosperity in case of subcritical subsystems. All DuoTone signals will generate an alarm when the timing is out of specification.

Additionally, the front-end for the commercial ADC and DAC boards may implement its own verification and initialization software, but this is not required as long as the alarms from the DMT DuoTone monitor are made available to the front-end. A front-end which is out-of-synchronization has to resynchronize automatically.

5.6.1 Timing controls and monitor system

The master module of the main timing distribution system is hooked up to a computer using an Ethernet connection. This computers runs software to read the status and error messages transmitted by the master module and translates them into the slow EPICS control system. It also sends channel information to the frame builder.

For control channels the computer will translate slow EPICS commands and sends them to the master module.

[Reference to software doc]

5.6.2 IRIG-B monitor

The IRIG-B monitor developed for initial LIGO will be used.

5.6.3 DuoTone monitoring

Except for the LSC system[2], timing diagnostics of initial LIGO data streams rely on *'ramp'* signals2 (GPS synchronized, 1Hz rate). The LSC timing diagnostics was based on a different principle, where only a small set of frequencies can be contaminated by crosstalk. The gravitational wave data stream's timing must be tracked with a resolution of ~O(1μs) and timing problems bigger than 0.5 s are diagnosed through different tools (i.e., IRIG-B). These constraints allow us to use only two (GPS and phase synchronized) sinusoids with frequencies 1Hz from each other. Initial LIGO used 960Hz and 961Hz signals; 960 is a harmonic of 60Hz to further preserve GW signal frequency space.

The phase of these sinusoids can be determined in the digital domain. The resolution achieved in practice in the past for minute trends was in ~O(50ns). The only coincident zero crossing (per second) clearly and unambiguously marks the GPS 1PPS second tic in the digital data, therefore allows us to determine the relative time shift between the time stamps of the data and the absolute GPS time.

The phase of the dual sinusoids shall be synchronized to the GPS tic at the waveform generation. Therefore the advanced LIGO DuoTone monitor will be a simplified version of the one originally developed for initial LIGO where synchronization was achieved in software. [ref].

The DuoTone monitors shall also be able to achive ~O(1μs) resolution when monitoring end-to-end timing/phase through the Photon Calibrators. [Ref]

6 Costs and schedule

TBD. [Needs full documentation and input from CDS main.]

6.1 Costs

TBD. [Needs full documentation and input from CDS main.]

6.1.1 Equipment

Qty.	**Req.**	**Unit**	**Price**	**Ext.**
6+2	4	Symmetricom 58503B		
2	2*	Symmetricom CsIII		
2	2	Symmetricom SyncServer S250		

[2] The ramp signals are ~O(1ms) long and start/terminate sharply. Therefore they are good approximations for a 'Dirac comb'. The Fourier transform of a Dirac comb is also a Dirac comb. This means that if there is a cross talk between channels, a Dirac comb (1Hz spacing) will contaminate the neighboring channels' frequency spectrum. By S5 we have reached the sensitivity that this contamination was unacceptable for the gravitational wave channel in the LSC.

2	0	Symmetricon UTCG (use existing)		
1	0	Symmetricom FEC (use existing)		
7+4	0	Symmetricom TCT		
20+6	26	D070011-B (master/fan-out)		
9+3	12	D070TBD (TComp)		
7+3	10	D070TBD (DTG)		
3+2	5	D070TBD (1PPS FO)		
15+5	20	D050309-B (OnePPSLocking)		
TBD		D070TBD (DAQ slave module)		
2	2	TBD GPS		
2	2	TBD GPS		

(*) The existing cesium clocks will need replacement when their tube expires at an unknown date.

6.2 Schedule

TBD. [Needs full documentation and input from CDS main.]