LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Global Diagnostics System Final Design

Rolf Bork, David Shoemaker, Daniel Sigg, John Zweizig

Distribution of this draft:

GDS

This is an internal working note
of the LIGO Project.

LIGO Hanford Observatory
P.O. Box 1970 S9-02
Richland, WA 99352
Phone (509) 372-8106
FAX (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (504) 686-3100
FAX (504) 686-7189
E-mail: info@ligo.caltech.edu

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 - MS NW17-161
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

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

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1 INTRODUCTION

1.1 PURPOSE

This document describes the final design of the Global Diagnostics System (GDS). The information in this document supersedes that presented in the preliminary design (T970172-A), the design requirement document (T960107-00), the conceptual design (T960108-00) and the interferometer diagnostics document (T970078-00).

The diagnostics system provides means to diagnose the interferometer system and to support the operations; access to the GDS is provided from the control room or any other display station located on the site[1]. The GDS will deliver real-time status information of the detector performance and support initial installation and commissioning of the detector. It includes tools to view and record data on-line, to monitor the behavior of the instrument and to do invasive diagnostics tests using an excitation system (see Fig. 1). The GDS does not include a data acquisition system, but rather relies on the CDS DAQ system for collecting data at audio frequencies (T980026-00, T980017-00, T980030-00 and T980036-00). One can use the remote-controlled cameras (owned by ASC) and digitizing oscilloscopes (owned by their subsystems) for visual inspections and to look at wide bandwidth signals, respectively. The GDS implements an excitation system for performing stimulus-response tests and a compute engine for monitoring the health of the detector. It uses workstations in the control room (T970171-00) to analyze and display the results of a stimulus-response test, and it uses the database server of the LDAS system to record the results of the data monitors (T990001-06).

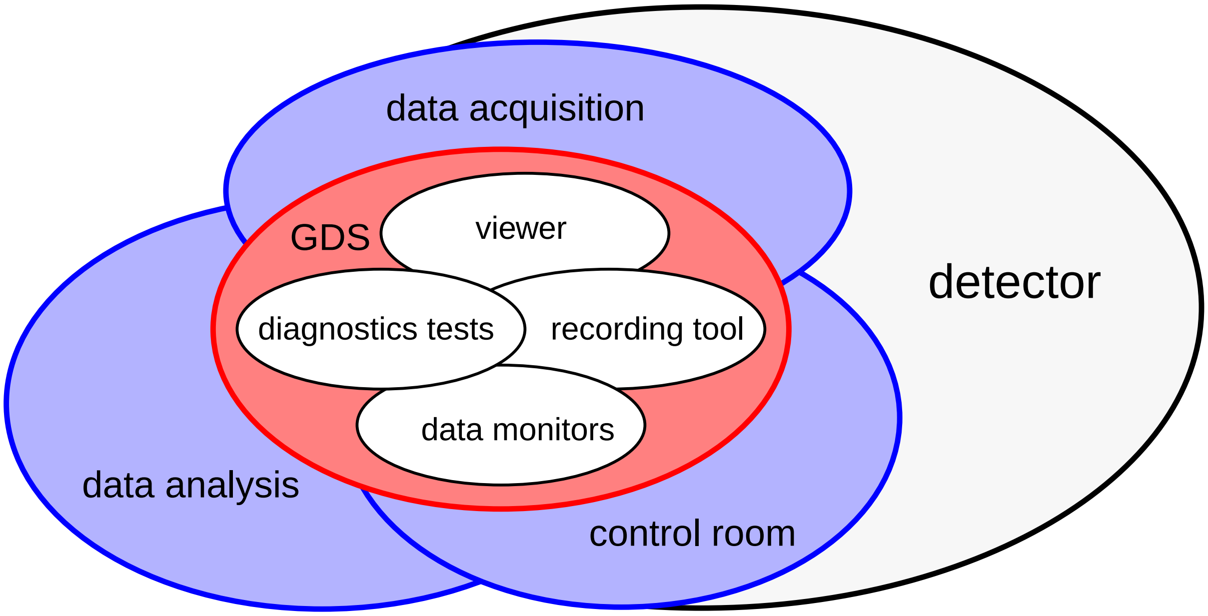

Figure 1: System overview.

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[1] Technically, there is no problem in proving access rights to remote sites, but current CDS policy is not to allow anybody access to control room machines from outside the control and monitoring network.

1.2 GOALS

The goals of the GDS can be summarized as follows:

- Assist the operators in the control room and in the experimental areas to successfully run the experiment. The operators must be able to view data in real-time, to make diagnostics tests involving an artificial excitation, to verify and monitor the performance of the instrument while running and to have access to a diagnostics summary of the detector over the past few months.
- Provide immediate answers (minutes rather than days or months) to important questions such as: what is the quality of the gravitational-wave data written to disk? And, are all of the subsystems working properly?
- Assist the operator in establishing and in automating diagnostics procedures which are used to diagnose and find problems with the instrument.
- Assist the user in learning about the behavior of the instrument, in classifying abnormal environmental events, in identifying the exact machine state, in correlating the signals of different sensors and, ultimately, in reducing the large amount of measured data to a set of relevant and comprehensible statistical quantities.
- Assist in improving the instrument performance incrementally in nominally steady-state regime, i.e. providing the first step towards system identification.

The presented system is using the following hardware and software tools to implement the above requirements:

- The functions of a ‘digital oscilloscope’ are provided by the CDS data viewer.
- The equivalent of a simple ‘tape recorder’ is provided by the CDS JD client.
- Statistical summaries and trends are provided through trend frames which are written by CDS frame builder.
- The capabilities of an arbitrary waveform generator are provided by the GDS excitation engine.
- The functions of a network/spectrum analyzer are provided by the GDS diagnostics test system.
- Performance measures, triggers on environmental events and flag channels are calculated by the GDS data monitoring tool.

1.3 CHANGES TO PRELIMINARY DESIGN

This document reflects several changes since the publication of the preliminary design document. A few of the key changes are:

- The data monitoring tool (formerly known as search tool) has been moved from a real-time CPU to a (SUN) workstation which receives the data from a network data server.
- The compute engine at the front-end has been eliminated. Instead, the data monitor tool makes use of a symmetric multi-processor machine to do the number crunching.
- The real-time data distribution unit has been eliminated in favor of transferring the data to the diagnostics test tool through the network data server.
- The conceptual design of the software has been advanced significantly; most of the software for the excitation engine and the diagnostics kernel have been written.

- The video system, the fast oscilloscopes and the permanent diagnostics screens are no longer mentioned in this document. The interested reader is referred to the PDR (T970172-A).

1.4 DEFINITIONS AND ACRONYMS

The following acronyms are used in this document:

AF	Audio Frequency	GW	Gravitational Wave
AM	Amplitude Modulation	IFO	(LIGO) Interferometer
API	Application Program Interface	I/O	Input / Output
ASC	Alignment Sensing and Control	IOO	Input Optics
CDS	Control and Data Systems	ISC	Interferometer Sensing and Control
COC	Core Optics Components	LHO	LIGO Hanford Observatory
COS	Core Optics Support	LLO	LIGO Livingston Observatory
DAQ	Data Acquisition	LSC	Length Sensing and Control
DCU	Data Collection Unit	NDS	Network Data Server
DMT	Data Monitor Tool	PEM	Physical Environment Monitor
EM	Electro-Magnetic	PSL	Prestabilized Laser
EPICS	Experimental Physics Industrial Control System[1]	RF	Radio Frequency
FPI	Fabry-Perot Interferometer	SEI	Seismic Isolation
FFT	Fast Fourier Transform	SUS	Suspension System
FM	Frequency Modulation	SYS	Detector System Engineering
GDS	Global Diagnostics System	TBD	To Be Determined

[1] originally developed by LANL and now maintained by a consortium of DOE.

When referring to the front and back-end of the diagnostics system, we distinguish between real-time hardware implemented on VME systems and the workstations used to display, store and analyze the data after they are collected, respectively.

1.5 OVERVIEW

A schematic view of the data flow at the observatories is shown in Fig. 2. The signals of the detector and the physical environment monitor are collected by data collection units (DCUs) which come in three flavors: analog data collection units (ADCUs) which control analog-to-digital converters to sample analog signals, digital data collection units (DDCUs) which interface the digital servo systems and the network data collection unit (NDCU) which collects the data stored in the EPICS database using the ATM/ethernet network. Analog and digital signals can be injected into the detector, into the excitation system of the physical environment monitor and into the digital servo systems through the GDS excitation engines.

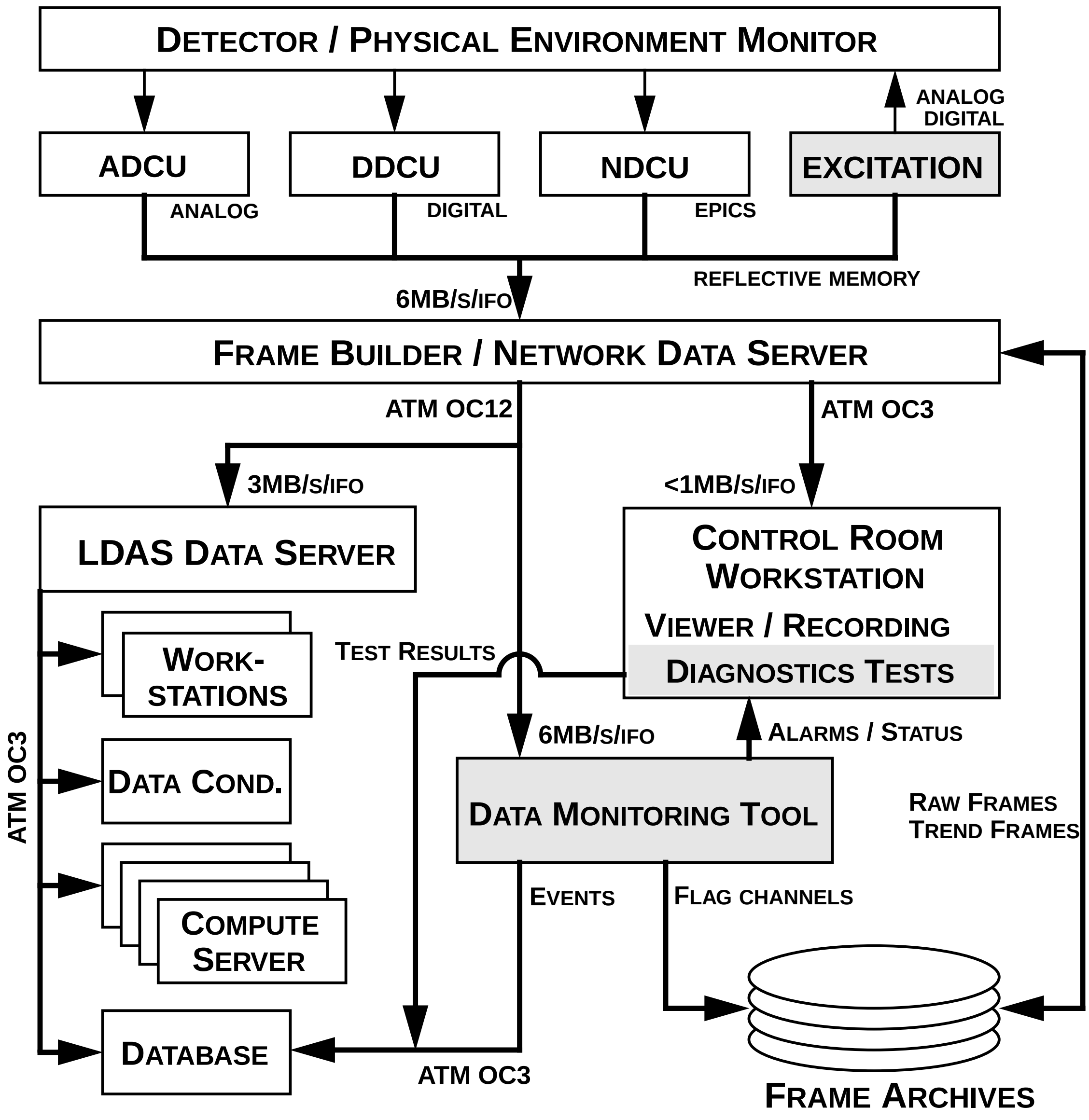

Figure 2: Schematic view of the diagnostics system (gray), the data acquisition system and data analysis system (LDAS).

Data collection units, excitation engines and the network data server are interconnected by a high speed reflective memory network. Part of the network data server is a frame builder which stores the full data stream to disk and tape. The network data server also makes the data available upon request to work stations in the control room, to the GDS data monitoring tool and to the LIGO data analysis system.

1.5.1 Data Viewer

When working in the control room or in one of the station buildings operators can invoke a data viewer which implements the equivalent functionality of a digital oscilloscope[1]. Its key features are:

- ➢ Display a selection of channels in real-time.
- ➢ Play back old data from disk.
- ➢ Trigger on signal channels crossing preset levels.
- ➢ Estimate the power spectral density of signals.

1.5.2 Recording

Managing the LIGO data archive, i.e. making old data on tape accessible to the user and distributing the data stream to on-site users, is a responsibility of the LDAS. For recording a few channels in a commonly accessible data format the CDS group provides JDclient. Its key features are:

- ➢ Users can request a subset of channels at reasonable data rates to be stored in a private file.
- ➢ The network data server is used to obtain the most current data.
- ➢ Supported file formats are ASCII, straight binary and frame.

1.5.3 Excitations

Excitation signals which are used to probe the detector are managed by the GDS excitation engine. The excitation engine is a real-time VME system using the same CPUs, reflective memory boards and timing circuits as the data acquisition system. Its main features are:

- ➢ Generates arbitrary waveforms including: sine, square, triangle, ramp, white noise, colored noise and arbitrary.
- ➢ Sweeps over frequency or amplitude.
- ➢ Supports multiple waveforms per channel.
- ➢ Synchronized to a GPS clock.
- ➢ Provides analog or digital output signals of 8 kHz bandwidth.
- ➢ Controls remote stand-alone signal generators with bandwidths up to 15 MHz.

1.5.4 Stimulus-Response Tests

Stimulus-response tests can be performed from any workstation in the control room or in the experimental areas. The main features are:

- ➢ Time series measurements involving trigger signals.
- ➢ Sine response tests: multiple input/output, two-tone intermodulation**,** harmonic distortion.
- ➢ Swept sine response test for measuring transfer functions.
- ➢ Fourier tools for estimating power spectral densities and cross-correlations.
- ➢ Pseudo-random stimulus / power spectrum readout tests.
- ➢ Parameter scanning and optimization.
- ➢ Simple command line and graphical user interfaces.

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[1] Help pages at: http://www.ligo.caltech.edu/~hding/Viewer/Help

1.5.5 Data Monitors

Continuous monitoring of the performance of the apparatus during operation is provided by the GDS Data Monitoring Tool (DMT). The DMT will run on a symmetric multi-processor computer such as a SUN E-450 which receives the full data stream from the data acquisition system. The data monitor tool has the ability to perform analysis tasks on all channels shortly after they are acquired. This analysis capability provides an important tool for the intelligent reduction of the data to be in the main archives. For certain channels it might be sufficient to store statistical summaries only—rather than the full data stream. The main features of the data monitor tool are:

- On-line access to current data.
- Geared to provide immediate feedback on the how well the instrument is working.
- Implements triggers on environmental and auxiliary channels.
- Calculates performance monitors and statistical summaries; generates flag channels.
- Triggers can be used to rise an alarm in the control room.
- Monitor outputs are stored in the LDAS database.

2 VIEWING AND RECORDING TOOL

The viewing tool was developed as part of the DAQ system and is described in there. The DAQ system also provides a recording tool to write reduced sets of data in simple file formats.

3 DIAGNOSTICS TEST TOOL

The diagnostics test tool is described in a separate manual: T990013-A. This tool also has a web page "www.ligo-wa.caltech.edu/gds" which gives a detailed description of the state of the diagnostics test software.

4 DATA MONITORING TOOL

4.1 OVERVIEW

4.1.1 Scope

The Data Monitor Tool provides a hardware and software environment for development and operation of on-line Data Monitors for LIGO. Data Monitors have the following operational and functional properties:

- The monitors will perform on-line screening of the data requiring significant computational power. The monitors are foreseen to provide a much more detailed picture than can be provided by the tests running parasitically on the data acquisition front-ends. All available raw data channels (including those that aren't archived to tape) will be made available to the monitors.
- The monitors are geared to provide immediate feedback on the how well the instrument is working. The response time of the data monitor displays will be fast enough to inform operators immediately if a fault is detected and to be useful as feedback in any optimization procedures. For this, the monitors require on-line access to *current* data.
- The monitors will generate event and status summary output including triggers describing faults or operational transients and summaries of factors affecting the sensitivity of the interferometer.
- The standard Frame format was chosen as the data input format to facilitate the development and testing of monitors off-line.

Data monitors will be used to perform a wide variety of tasks that will be useful for operational and calibration purposes as well as to flag transients in the data for use during later analysis. A full list of planned monitor functions is given in Appendix D. These tasks fit generally into the following categories:

- Detect and tag known terrestrial signals or disturbances to the interferometer, *e.g.*, seismic activity or sudden strain relief in suspension wires.
- Search for pathological conditions, *e.g.*, servo gain peaking.
- Gauge current state or performance of the instrument, *e.g.*, measure in-spiral observation volume or excitation state of a suspension wire.
- Check data integrity, *e.g.*, look for bit errors, discontinuities, repeated data, etc.
- Test and diagnose the instrument interactively.

Several related functions will not be supported by the Data Monitor Tool because these functions are already better addressed by other GDS and LIGO components. Functionality that is not covered by the Data Monitor Tool includes (the components that perform these functions are noted in parentheses):

- View time series on-line (CDS viewing tool).
- Summarize the data stream on-line, *e.g.*, compare to limits, average signals (DAQ system).
- Dedicated hardware characterization and diagnosis (GDS diagnostic test tool and stand-alone tests).
- Off-line analysis of non-real-time data (LDAS).

4.1.2 Usage Model

The Data Monitor Tool is foreseen to be used by operators, observatory personnel and visiting scientists (collectively “users”) in the following capacities.

1. **Innovation Tool Box:** LIGO users will need a toolbox to identify faults or sources of noise, currently seen in the data. To discover the source of these problems will require that on-line data be available and that the data be easily manipulated. These innovative sessions will be supported by the Data Monitor Tool with an on-line interactive scientific work station environment. A similar environment can be used off-line or on-line for prototyping monitor programs.
2. **Display Manager:** Interactive monitor applications can also be used to display detailed information about running conditions such as the current sensitivity of the interferometers or the amplitudes of external noise sources.
3. **Development Environment:** The DMT will provide an interpretive environment for the testing and debugging of data monitor algorithms. To simplify the translation to or from the production monitor or analysis context the development environment will exploit the same function library and use a command language can be compiled and run in the background.
4. **Production Monitors:** The Data Monitor Tool will provide an environment for running on-line monitoring applications continuously in the background without need for operator intervention. This includes the mechanisms needed to supervise the process execution, to provide access to data and to report unusual events (triggers) or other results.

All user processes are completely independent of one another allowing the DMT hardware and software to be shared by many different applications using the DMT in any combination of the usage modes.

4.2 HARDWARE ENVIRONMENT

The data monitor applications and all the DMT-specific support processes will run on a “Computation Server” consisting of a Symmetric Multi-Processor (SMP) system, connected to a Network Data Server over a high-speed link. Each interferometer will have a separate Computation Server. In addition to the high-speed data link, the Computation Server will be connected to the CDS and LDAS private networks to provide access to EPICS and to the LDAS data-base.

In prototype systems, the DMT data demands will be moderate and the standard CDS Frame Builder should be able to serve the data to the DMT compute server without difficulty. In the final configuration, the DMT will require more data than the standard frame builder can easily supply. We are thus proposing to build a dedicated DMT frame builder which would get data directly from the reflective memory network and serve it to the DMT compute server(s). The software for the dedicated servers can be identical to that used for the CDS Frame Builder.

A detailed discussion of the requirements and implementation options for the DMT hardware is given in Sections 4.2.1 and 4.2.2. Fig. 3 below shows a block diagram of the base-line hardware configuration with the components that are unique to the Data Monitor Tool.

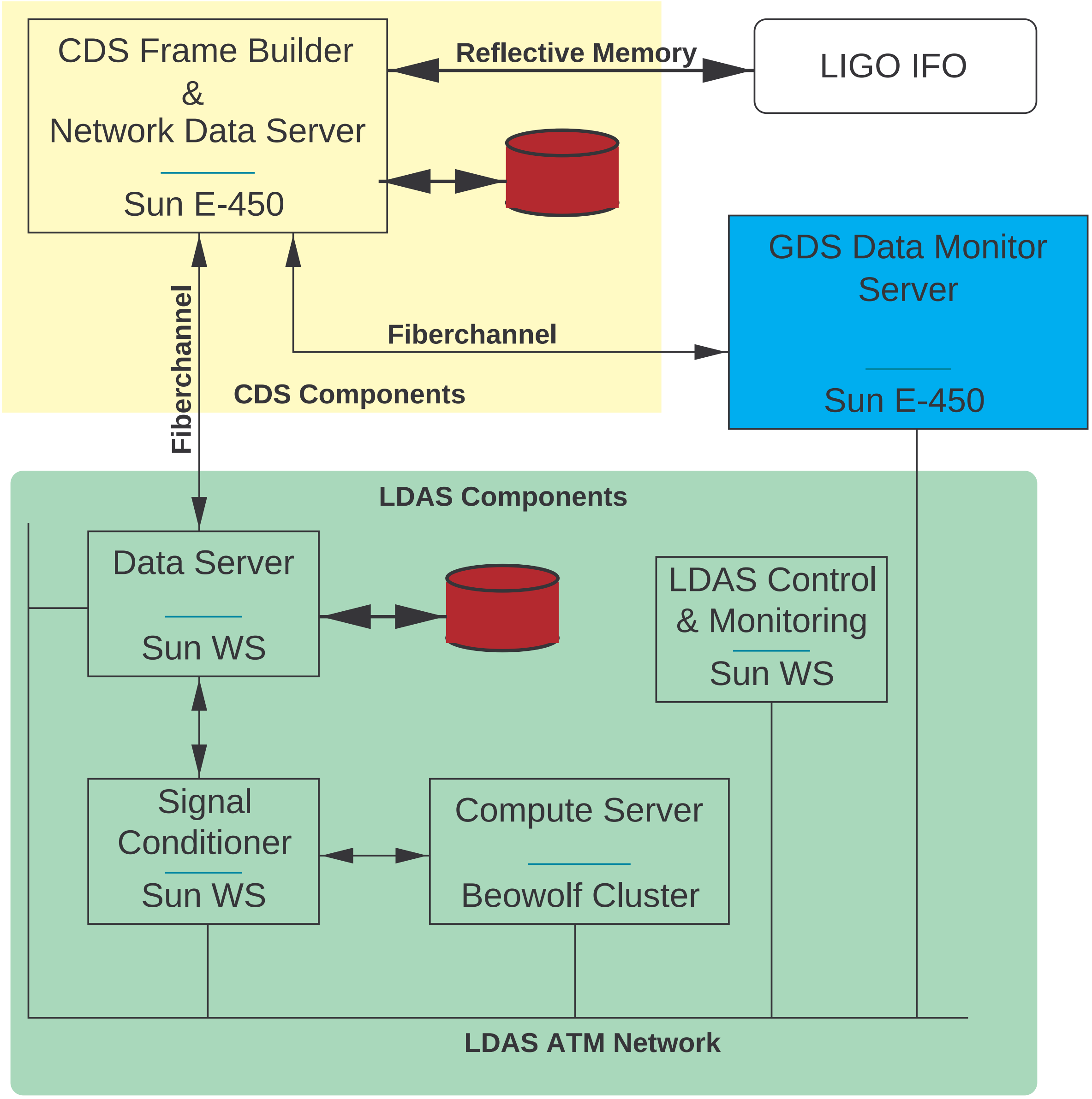

Figure 3: Block diagram of on-line hardware components.

4.2.1 Monitor Computation Server Requirements

The hardware platform on which the DMT software will run must meet the following requirements:

1. It must support a Unix-like symmetric multi-processing operating system (*e.g.* Solaris, AIX or Linux).
2. It must integrate easily and logically with existing computer hardware and with current operational procedures and expertise.

3. All processors in a multi-CPU configuration must have direct access to a shared memory pool.
4. The combined floating point computational capability must be sufficient to perform a double-precision DFFT on all data in each frame in the 1-second frame real-time interval.
5. In addition to the computational load in (4) the processor must be able to handle the simultaneous unpacking of 20 MB of frame data and to perform of various management functions such as receiving and buffering data from the network and routing triggers.
6. Processor data caching must allow a Fourier transform to be performed on a 64 thousand point[1] double precision complex data array at full speed. This requires of order 512 kB to 1 MB of Level-2 data cache.
7. Memory capacity must be adequate to buffer ~128 MB of data (e.g. sixteen 8-MB frames) to be accessible by all the processors and to run up to 32 parallel processes (about twice the number of major subsystem components) without recourse to swapping. About 60% of the applications will run in the foreground, within an elaborate on-line environment. The memory requirement is expected to be of order 1 GB.
8. Disk capacity must be sufficient to store executables and data files needed by the application programs and the environment under which they run. Anticipated disk needs are moderate and do not exceed ~10 GB.
9. The Data Monitor processor must be connected to the two isolated observatory networks belonging to CDS and LDAS. It must also have a high speed connection with the Network Data Server for requesting and receiving the raw on-line data. The NDS connection is now assumed to be over an ATM OC-12 line, although fiber-channel and gigabit-ethernet have also been suggested.

4.2.1.1 Notes on computation server speed requirements:

Because the exact load on the DMT computation server is unknown, we attempted to deduce the server speed requirements (requirements 4-5) based on scaling arguments. The stated requirements correspond to an expected load. A reasonable additional margin (a factor of 1.5-2.0) should be left for scope creep and demand usage. Thus, although it is unlikely that a Fourier transform will be performed on all of the interferometer channels, we assumed that the computation represented by a transform of all channels is indicative of the complexity of the job at hand.

To put this requirement in terms of real computers, the number of floating point operations needed by Matlab to perform an FFT is tabulated in Table 1 for various data lengths: a 167 MHz Sun Ultra-1 workstation can do about 20.6 MatLab MFLOP/s.

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[1] For example: 8 kHz bandwidth (DAQ Nyquist frequency) and 0.1 Hz resolution (micro-seismic).

Table 1: Matlab benchmarks for processing load.

Rate	# Channels	kFLOPS/ Ch	MFLOPs
16,384	67	680.1	45.6
2,048	252	69.8	17.6
256	43	6.9	0.3
64	60	1.4	0.1
16	88	0.3	0.0
All	**510**		**63.6**

Likewise, the frame unpacking requirement is based on the assumption that the frame will be unpacked 2.5 times. It is clear that the unpacking the entire data frame for each of the monitor processes that may be run would provide an enormous load on the monitor server. We have thus assumed that where possible, production monitors will be grouped together according to the channels that they treat. The same Ultra-1 can unpack a 1MB Frame in 20 ms. Given these considerations, we calculate that the necessary compute power will be 5-7 Ultra-1 equivalents *e.g.* a 4-processor Sun system with >233 MHz CPUs.

4.2.2 Hardware Options

Two configurations have been identified that are thought to satisfy all the above requirements. These are *(i)* a Sun enterprise server running Solaris and *(ii)* an Intel-based PC enterprise server running Linux. The options are discussed in the following sections.

4.2.2.1 Sun/Solaris Solution

LIGO CDS is presently using a Sun E-450 server as a Frame Builder and Network Data Server. This makes the E-450 or a similar machine from Sun the primary option for a DMT computation server. The E-450 can have up to four 400 MHz Ultra-Sparc II processors, providing enough computational capacity for all the currently foreseen applications. The greatest attraction of the Sun/Solaris solution is the uniformity it would give to the overall system. No additional system management expertise would be needed and the fast interconnect to the NDS could be purchased off the shelf without fears of incompatibilities or limits on future upgrades (for a cost estimate see Appendix A.3).

4.2.2.2 Intel/Linux Alternative

The Intel/Linux alternative benefits from the mass production of PCs for home use, but compatibility with Linux will demand that extra care be taken in choosing a configuration. Because of the voluntary nature of the Linux development model, drivers and other system support are not always available for high-end and newly produced peripheral interfaces. Also, the SMP Kernel is not yet supported directly by the usual Linux distributors (Red Hat, Suse, etc.) and so it must be compiled from the published sources. This is not seen to be a problem, and reports indicate that the SMP version runs stably.

Keeping these concerns in mind, a configuration including:

- Four 400 MHz Pentium II Xeon processors with 1MB Cache
- 1 GByte EDO RAM
- 27 GByte RAID-5 disk array with 16MB cache
- A 100baseT Ethernet adaptor
- Floppy disk, CDROM, Rack-mounting bracket, etc.

is commercially available (probably from more than one manufacturer) at a very competitive price. An ATM OC-12 adaptor would have to be added to this configuration to furnish the necessary network bandwidth.

4.3 SOFTWARE COMPONENTS

A block diagram of the major Data Monitor software components and their interrelationships is shown in Fig. 4.

4.3.1 Application Environment

The application environment provides access to the data, interfaces to services such as generation of triggers and access to data bases, and a data analysis function library. For practical purposes, the Data monitor applications can be divided into two groups: foreground and background. The foreground processes will run under a scientific work-station environment that provides an

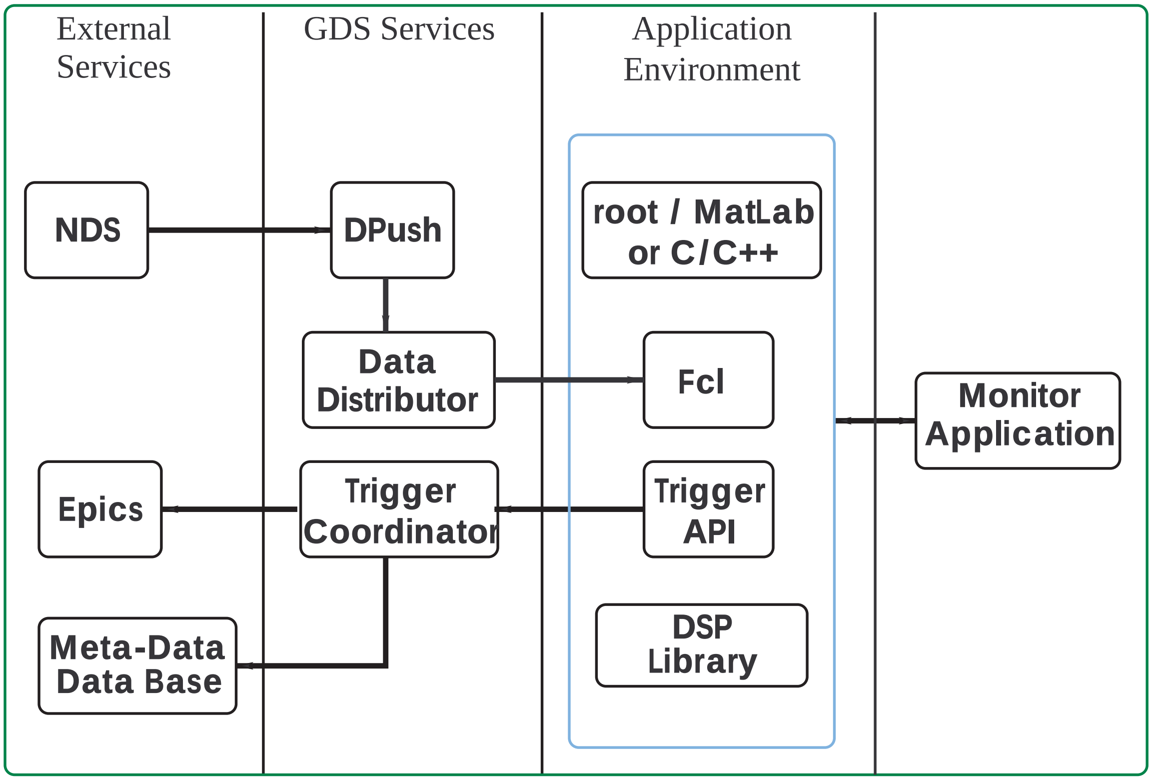

Figure 4: DMT software components.

interpretive programming language, interactive use, a graphical display package and a comprehensive tool-set for application development and testing.

The background processes will not receive or provide data interactively to operators, but they will have the same on-line data access and trigger generation capabilities as the foreground processes. Some additional support for communication with the background processes, such as parameter setting and report generation, will be included in the application library.

Both foreground and background applications will share a extensive function library that will provide the basic interfaces with other LIGO components and many analysis resources. These are summarized in Section 4.3.1.3.

4.3.1.1 Foreground Environment

The initial foreground environment implementation will be based on ROOT, a C++ interpreter and graphics and data manipulation toolbox developed at CERN and tailored to the needs of high energy physics. ROOT will be compiled with basic LIGO frame and trigger I/O functions, specialized data types and analysis functions. Higher level functions such as GUI windows, specialized function (*e.g.* Bode plots) and prototype monitors will be implemented with ROOT macros (interpreted C++ functions). Should experience show that a higher performance interactive capability is necessary, certain applications could be compiled with the ROOT libraries.

ROOT provides a nearly ideal base environment in that it was developed for physics data manipulation, it has an extensive scientific graphics package and GUI primitives and its interpretive language (C++) can be compiled directly and used in production monitors. Its only shortcoming is that no comprehensive signal processing library has been written for use with root. This shortcoming will be remedied by adding linking the LIGO algorithm library to ROOT as the library functions are defined and written.

Foreground applications will receive on-line data from the Data Distribution sub-system Consumer API and the LDAS FrameCPP library. Triggers (notification of unusual or pathological data sequences) are generated by the application code with the Trigger API. The Digital Signal Processing (DSP) Library will contain a suite of signal processing methods that may be used to analyze the data. These (will) include filtering, FFT, wavelets and series manipulation packages[1].

4.3.1.2 Background Environment

Mature monitor algorithms will if necessary be translated to C or C++ and run in the Background environment. The basic background process structure treats each monitor algorithm as a C++ object. This structure has the flexibility to allow monitor functions to be combined, run as threads or incorporated into other structures as the number of monitors and their configuration evolves.

Within this structure, each monitor type to be implemented is described as a class based on a generic data monitor class. To implement a monitor, the user defines whatever private data objects are needed and defines initialization, termination and frame processing methods. Other member data and methods may be defined in the base class as a need for them is established.

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[1] The algorithm library is a joint development effort between LDAS, LSC and GDS.

A parallel C-language environment is being maintained in order enlist a maximum number of LSC contributors to the data monitor development effort. The C environment is conceptually a wrapper function for the C-language monitor functions. In practice, because the C frame library (FrameL) uses a different internal representation than the C++ library (framecpp), parts of the base functions must be repeated.

4.3.1.3 Application Environment Library

An application environment library will be shared by all versions of the monitor environment. Implemented in the library will be interfaces to the various DMT services such as:

- Data distribution system interfaces
- Trigger manager interfaces

and utility functions to address such as:

- Parameter access and recording functions
- Report generation
- Frame data manipulation

and suitably wrapped versions of the analysis algorithm library which will include general signal processing and more specific LIGO analysis functions.

4.3.2 GDS Services

DMT-specific services provide the monitor applications with access to on-line data, a means to generate and record triggers, and access to other external resources. A Process Management subsystem will make sure that any necessary monitors are running in the background and provide the background processes with the appropriate parameters. the major services are described in the following sections.

4.3.3 Data Distribution Sub-System

The Data Distribution sub-system receives real-time interferometer data from a CDS Network Data Server (NDS) and distributes it by way of shared memory buffers to all active DMT applications. By using shared memory buffers, the data distributor makes all data available to the monitors with a minimum of overhead. The Data distributor is composed of four pieces. A Distributed Buffer Manager allocates empty shared memory buffers to producers and filled buffers to consumer processes. A consumer API provides an interface to the buffer manager for the processes that read and process the interferometer data. The Data Pusher (DPush) requests current data from the Network Data Server and copies the data to an available shared memory buffer. Utility programs for monitoring and maintaining the shared memory control structures. These components are discussed in more detail in the following sections.

4.3.3.1 Shared Memory Buffer Manager

The Shared Memory Buffer Manager is distributed among the data producer and consumer processes. All control and status information (buffer queues, semaphores, etc.) needed to manage the buffers are stored with the data in the same shared-memory segment. Appropriate functions have bee written to interface each of the frame access packages (FrameL, FcL and framecpp) to the shared memory buffer manager.

4.3.3.1.1 Shared memory manager interface (LSMP)

The share memory manager base class manipulates the shared memory partition. It allocates and releases resources (memory, semaphores and access rights) used to synchronize the memory access. Each partition is given a name by which it is referenced.

4.3.3.1.2 Data consumer interface (LSMP_CON)

The consumer interface provides read access to the shared memory buffers. Each memory partition has a fixed number (this is a compilation parameter, usually 16) of consumer slots. If a process wants to access to the data it allocates a consumer slot from the partition. At the time it registers, the consumer may specify a number of buffers that are to be reserved for it. When a buffer is filled, it is reserved for all consumers that haven’t met their quota. When a consumer requests a buffer, it is given a pointer to the oldest buffer reserved for it. The consumer may optionally wait for the next buffer if none are available. The reservation is canceled when the consumer returns the buffer. No buffer will be reused until all reservations have been canceled.

4.3.3.1.3 Data producer interface (LSMP_PROD)

The producer interface provides write access to the shared memory buffers. A producer process is given a pointer to a free buffer on request. The producer interface will optionally block if no free buffers are available. A buffer is considered to be free if it is not reserved for any consumers and at least one consumer has seen the data. The oldest unreserved full buffer may optionally be scavenged if this mode of operation is specified at the time the partition is created.

4.3.3.1.4 Timing

Timing tests of a prototype Buffer Manager were run on a 167 MHz Sun Ultra-1 Workstation with 128 MB of 83 MHz memory. These showed a minimal per-record overhead and no obvious bottleneck in accessing the shared memory, even when several processes were competing for the same data. Sustained data access rates approached 100MB/s and the per-record overhead was <100µs/frame.

4.3.3.2 Data transfer program (DpushF)

DpushF copies frames from the Network Data Server to the shared memory buffers. A version of DpushF exists and is running stably with the current version of the NDS. A test

4.3.3.3 Shared Memory Maintenance Utilities

The following utilities are currently written and working.

- **smcreate:** Creates a shared memory partition with a specified name, buffer length and number of buffers.
- **smdump:** Dumps the current status of a named partition.
- **smraw:** Registers as a consumer and write a hex-dump of the beginning of each buffer read to the standard output.
- **smrepair:** Removes expired consumer entries (those for which the pid is invalid) and frees buffers reserved by the expired consumers.

4.3.4 Triggers & Trigger Control

The trigger coordinator routes triggers as appropriate for logging as meta-data or for enunciation on the operator’s console. Preselection of triggers will be implemented to avoid saturating either the operator log, the meta-database or the operators patience.

4.3.4.1 Overview and Requirements

Triggers describe unusual events detected by the monitor application programs. The event may result from many sources including: hardware or electronic failures, instrumental glitches, natural or factitious external stimuli and pathological conditions.

The *Trigger Manager* is a DMT sub-system that encodes the triggers and routes them to all appropriate trigger handling components, *e.g.* the meta-Database, an operator alarm screen or an operations expert system. The requirements on the Trigger manager are the following:

- Provide a means to identify triggers exactly.
- Maintain a routing table that describes the destinations and conditions for routing each type of trigger.
- Maintain connected interfaces to the meta-database, to the EPICs alarm subsystem and to any other appropriate system (*e.g.* an expert system) that may be adopted in the future.
- Evaluate conditions for routing.

4.3.4.2 Trigger Generation

The trigger generation process must be understood formally in order to determine which data are necessary to describe a trigger. Fig. 5 gives a schematic description of the trigger generation process. Within this framework, trigger generation is broken up into five stages. Stages denoted as rectangles are data stages. The only processing associated with them is accessing or building descriptors of the data. The stages denoted as circles are correspond to computational stages that transform the data and/or make decisions. The five stages are:

1. Collect or access the raw input data. The raw input data are typically a single channel from a single frame, although in some cases several channels may be needed or frames may be merged.

2. Transform the data into a representation that will be used by the trigger. The transformation may use data from channels other than the principal channel listed in (1) and may result from the composition of several elementary transformations. Examples of transformations are:
   - Fourier transform
   - Decimation
   - Linear superposition of several channels
   - Histogram
   - FIR/IIR digital filter
   - Trivial (*i.e.*, use the raw data)
3. The transformed data constitute a series defined by a few standard parameters and a data vector. A time series, a frequency series or a histogram can be represented in this manner.
4. The transformed data series is scanned by a detector function. The detector function might compare the transformed series elements, its integral, variance or other property to a threshold.
5. If the property under test surpasses the threshold, a trigger is generated. The trigger is identified by a unique trigger ID and by trigger result data such as:
   - The time offset into the epoch (if known) or frequency band.
   - Value of property that exceeded the threshold
   - Intermediate results (*e.g.* fit parameters) produced in evaluating the property.

The boxes below each stage in the figure contain a list of the data needed to describe the process or the data that forms the stage. Note that the descriptors for the calculational stages are static, *i.e.*, they are independent of the input data and describe only the processing function and its static parameters.

This model is not meant as an implementation specification. Not all monitor processes are expected to first transform data and then run a function to generate the trigger. Nevertheless, the

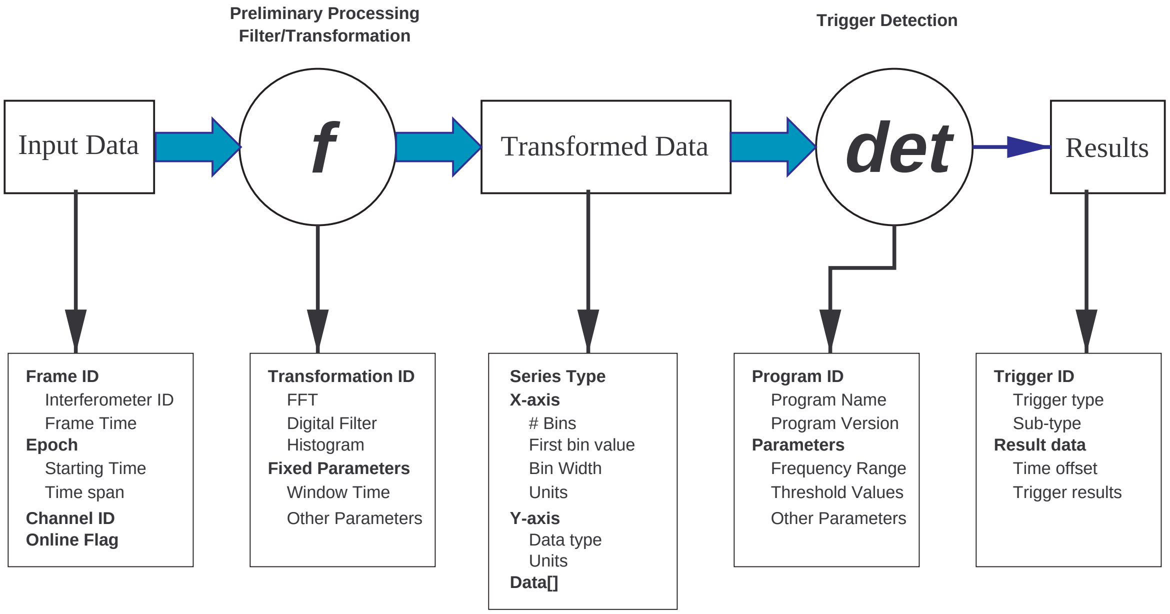

Figure 5: Trigger generation.

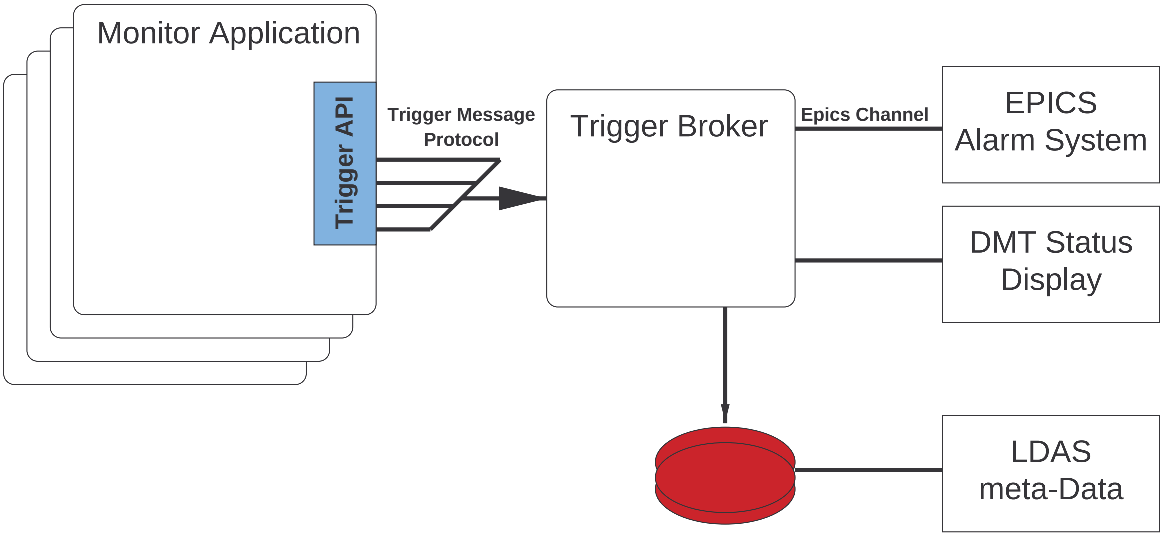

Figure 6: Trigger broker.

model is sufficiently general that an arbitrary monitor can be described within the framework. The transformation is separated from the detection phase because the transformed data will be important for interpreting the trigger in many cases. The output of the transformation thus defines the data that will be stored with the trigger report and can be used for further characterization or analysis of the trigger.

4.3.4.3 Trigger Manager Architecture

A software architecture that meets the requirements enumerated in Section 4.3.4.1 is shown in Fig. 6. The architecture consists of the following components:

- **Trigger Generation API**: Encodes triggers identified by the data monitors and sends them to the Trigger Broker.
- **Trigger Broker**: routes trigger objects to one of more final destinations based on the trigger properties and on current conditions.
- **Trigger Loggin**g: Stores trigger objects in the meta-database.
- **Operator Notification**: Announce important events to the operators.
- **Trigger Manager Control**: A user-friendly means to specify the routing conditions for various trigger types and to display trigger summaries.

4.3.4.4 Trigger Generation API

The Trigger Generation API encodes a description of each stage of the trigger generation process described in the model above. A description of each stage is optionally created as an object. The objects are then collected together into a trigger object and sent to the Trigger Broker. The communication channel to be used between the monitor process and the Trigger Broker is not yet defined, but will likely be either socket or IPC (Unix interprocess communication package) message based.

4.3.4.5 Trigger Broker

The Trigger Broker is an independent process which will run on the DMT compute server. It has three major responsibilities:

- Route triggers to the appropriate destination servers.
- Prevent flooding of message and database channels.
- Look for certain combinations of coincident triggers to be routed to an expert system for immediate analysis.

The Trigger Broker receives all triggers from the Data Monitor Applications and routes them to one or more destinations based on the trigger type and a routing table managed by the trigger broker. In the future, certain combinations of (nearly) coincident triggers will be selected for sending to one or more expert system for immediate analysis.

4.3.4.6 Trigger Logging

Triggers will be logged to the meta-Database under the control of LDAS. Present plans are for the triggers to be written by the Trigger Broker to a communication area (disk files in a mutually accessible directory). LDAS will then convert the trigger records to XML and record them in the meta-database. The intermediate format and the synchronization protocol between the Trigger Broker and LDAS have not yet been defined.

4.3.4.7 Trigger Control Interface

The Trigger Control Interface will allow operators to modify the Trigger Broker parameters (routing tables, etc.) dynamically. It will also maintain a monitor status display in cooperation with the Trigger Broker.

4.3.4.8 Operator Notification

Operators will be notified by way of either the CDS (EPICS) Alarm Manager or a special monitor status display. The Epics alarms have the advantages that the annunciation software exists, the alarms are announced on the primary display terminal and a positive response is required from the operator. To their detriment, the EPICS alarms are inflexible in that alarms must be defined at start-up time and rapid re-triggering of alarms is limited. This effectively limits the use of EPICS alarms to drawing attention to DMT status display or to use by a few mature monitors with well-established function and usefulness.

The Monitor Status display will be maintained by the Trigger Broker and the Trigger Control Interface and will show *e.g.,* a list of running monitors, the global status and a summary of recent triggers.

APPENDIX A IMPLEMENTATION AND COST ESTIMATE

A.1 IMPLEMENTATION

A.1.1 EXCITATION ENGINE

The excitation engine will be installed into rack 1X5 for the 4K interferometers and into 2X5 for the 2K interferometer, respectively. The rack drawings for the 2X5 rack in Hanford can be found at D990016-00-C.

A.1.2 DATA MONITORING TOOL

The computers for the data monitoring tool will be installed into rack MSR5 and MSR6 in the mass storage room (next to the data acquisition hardware).

A.2 SCHEDULE

The GDS schedule for the 2K interferometer at Hanford is as follows:

Task	**LHO 2K**	
	start	**stop**
excitation engine		
software development	1/1/98	6/30/99
hardware installation	5/1/99	7/31/99
test point manager		
software development	9/1/98	4/28/99
integration test with DAQS and ISC	5/1/99	6/30/99
diagnostics kernel		
test software	8/1/98	7/31/99
command line interface	1/1/99	5/1/99
GUI	4/1/99	12/31/99
data monitoring tool		
data distribution	1/1/99	5/31/99
trigger manager	6/1/99	10/1/99
signal processing library[1]	3/1/99	12/31/99
application environment	3/1/99	10/1/99
prototype at LHO	5/1/99	6/1/99
final hardware	8/1/99	12/31/99

[1] Coordinated effort with LDAS and LSC.

A.3 COST ESTIMATE

Table 2: Hardware at both sites, all interferometers.

Pos	Qty.	Item	Unit	Ext.
excitation engine (LVEA, 1 / ifo)				
1	1	VME crate	3200	3200
2	2	Baja4700E-200-64, CPU	8500	19000
3	1	VMIC 5588, reflective memory	7400	7400
4	1	VMIC 5591, optical bypass switch	1200	1200
5	1	Brandywine syncclock32, GPS slave	1200	1200
6	1	CDS timing board	1000	1000
7	1	ICS 115, 32 channel DAC	9595	9595
8	1	CDS AA filters, 32 chn	6000	6000
				48595
excitation engine (mid/end, 1 / ifo)				
9	2	ICS 115, 4 chn	3595	7190
10	2	CDS timing board	1000	2000
11	2	CDS AA filters, 4 chn	1000	2000
				11190
data monitoring tool (MSR, 1 / ifo)				
12	1	SUN450, 4x400MHz, 4MB cache, 1GB RAM, 3x9GB disk, 17” monitor	50000	50000
13	1	ATM OC12, ForeRunnner HE622 & NM-1/622MMSCLC	6000	6000
				56000
network data server for DMT (MSR, 1 / site)				
14	1	SUN Ultra10, 330MHz, 512MB RAM, 9GB disk	4000	4000
15	1	VMIC 5588, reflective memory, PCI	9000	9000
16	1	VMIC 5591, optical bypass switch	1200	1200
17	1	ATM OC12, ForeRunnner HE622 & NM-1/622MMSCLC	6000	6000
				20200
hardware total (3 ifos)				
				387755
software support				
18	1	CDS 1 FTE, 6 month	50000	50000
total				
		allocated		**180000**
		estimate		**437755**
		difference (CCB)		**–257755**

APPENDIX B CHANNEL LIST

The channel list is described in two separate documents: T990032-00 and T980004-00. The convention for naming DAQ channels can be found at T990033-00.

APPENDIX C LIST OF DIAGNOSTICS TESTS

This list is intended to be a ‘living document’ which will require significant refinement and amplification to establish sufficient information to code tests. Its initial use is to establish the test templates, magnitude of the task, and required hardware. The initial source of the information is LIGO-T970078-00, *“Interferometer Diagnostics Tests and Tools”*.

C.1 SENSING NOISE TESTS

C.1.1 Laser Frequency Noise in the Gravitational Wave Band

Test Description: The sensitivity to laser frequency fluctuations of the gravitational wave output at the antisymmetric port of the beamsplitter is measured by impressing a swept sine and/or a wide band random noise at the controller or summing junction of the laser frequency control loop. The transfer function of the demodulated interferometer output at the antisymmetric port to frequency fluctuation stimulus as measured at the demodulated recycling mirror reflection port is determined. The noise budget attributable to frequency noise is determined by measuring the cross power spectrum (covariance) of the interferometer output at the antisymmetric port with that at the reflection port of the recycling mirror with the stimulus off.

- technique: transfer function from laser power variation to LSC sensing ports, followed by cross power spectrum measurement of ambient power fluctuations and selected LSC port
- stimulus: sinusoidal variation of the laser power, 10^{-7}-0.01 Hz/$\sqrt{\mathrm{Hz}}$, 1 Hz to 10 KHz
- response: each LSC sensing port
- analysis: standard transfer function tools
- visualization: log-log transfer function, log-log contribution to strain spectrum, coherence or other measure of confidence
- recurrence: once per week or per change in hardware
- duration: 60 sec unavailability
- contingent tests: input beam angular deviations, input beam amplitude fluctuations

C.1.2 Laser Amplitude Noise in the Gravitational Wave Band

Test Description: The sensitivity of the gravitational wave output at the antisymmetric port of the beamsplitter to amplitude fluctuations of the input light is measured by impressing a swept sine and/or a wide band random noise at the summing junction of the amplitude control loop. The transfer function of the demodulated interferometer output at the antisymmetric port to the signal at the common mode Michelson port is measured. The noise budget attributable to amplitude fluctuations is determined by measuring the cross power spectrum (covariance) of the interferometer output at the antisymmetric port with that at the Michelson common mode port with the stimulus off.

- technique: transfer function from laser power variation to LSC sensing ports, followed by cross power spectrum measurement of ambient power fluctuations and selected LSC port
- stimulus: sinusoidal variation of the laser power
  - $10^{-8} - 10^{-3}$ modulation depth
  - 1 Hz - 10 kHz

- response: each LSC sensing port
- analysis: standard transfer function tools
- visualization: log-log transfer function, log-log contribution to strain spectrum, coherence or other measure of confidence
- recurrence: once per week or per change in hardware
- duration: 60 sec unavailability
- contingent tests: none

C.1.3 Amplitude Noise at the Sideband Frequency

- technique: transfer function from modulation to LSC sensing ports, followed by cross power spectrum measurement of ambient modulation fluctuations and selected LSC port
- stimulus: sinusoidal variation of the modulation index for each modulation frequency
  - 1% of nominal modulation
  - 1 Hz - 10 kHz
- response: each LSC sensing port
- analysis: standard transfer function tools
- visualization: log-log transfer function, log-log contribution to strain spectrum, coherence or other measure of confidence
- recurrence: once per month or per change in hardware
- duration: 60 sec unavailability
- contingent tests: none

C.1.4 Amplitude Noise due to Unintended Interferometers

- technique:
  - (1) determine effective amplitude of unintended interferometers, via modulation of the laser frequency either in a sweep or with sinusoidal modulation; study of interferometer spectrum for spectral ‘cliff’ (up-conversion)
  - (2) determine ambient variations in critical paths (identified above) through addition of sinusoidal modulation of the position of one of the optics in question with a ‘shaker’ and synchronous demodulation to find baseband motion?
- stimulus (1): sinusoidal variation of the modulation index for each modulation frequency
  - 1% of nominal modulation
  - 1 Hz - 10 kHz
- stimulus (2): PEM shaker driven by CDS
- response: each LSC LSC sensing port
- analysis: Inference of straylight amplitude; inference of physical motion of scatterers
- visualization: log-log transfer function, log-log contribution to strain spectrum, coherence or other measure of confidence
- recurrence: once per month or per change in hardware
- duration: 10 min
- contingent tests:

C.1.5 Noise due to Input Beam Position and Angle Fluctuations

- technique: transfer function from modulation from IO last mirror angle to LSC length sensing ports, followed by cross power spectrum measurement of ambient motion fluctuations (NEED SENSOR) and selected LSC port
- stimulus: single frequency sinusoidal drive to last IO mirror angle in tilt and twist
    - $10^{-12} - 10^{-7}$ rad r.m.s.
    - 1 Hz - 1 kHz
- response: each LSC sensing port
- analysis: study of strain spectrum; search for 1ω and 2ω
- visualization: log-log transfer function, log-log contribution to strain spectrum, coherence or other measure of confidence
- recurrence: once per month or per change in hardware
- duration: 60 sec unavailability
- contingent tests: none

C.1.6 Intermodulation Products due to Offsets and Large Amplitude Deviations

- technique: Introduction of intentional offset from the dark fringe (or resonance condition for cavities; addition of signals; analysis of output to determine linearity of the system
- stimulus: offset from nominal operating point of optical system
    - static offset from 0.1x to 10x required operational offset, OR sinusoidal modulation, 0.1x to 10x required operational offset, 0.1 Hz - 100 Hz
    - modulation in laser frequency 10^{-7}-0.01 Hz/$\sqrt{\mathrm{Hz}}$, 1 Hz to 10 KHz
    - modulation in lengths (individual or CM/DM basis) $10^{-20} - 10^{-15}$ m r.m.s., 1 Hz - 1 kHz
- response: all PSL/IO/LSC ports (strain, MI, RC, Frequency)
- analysis: study of sum and difference frequencies as function of variables; extraction of peak heights
- visualization: plot of distortion vs. parameters, fit to curve; projection of net effect on quiet strain spectrum
- recurrence: once per month or per change in hardware
- duration: 10 min
- contingent tests: none

C.1.7 Phase Noise Limits due to Scattering in the Beam Tube

- technique: transfer function from modulation from beam tube intentional excitation to LSC length sensing ports, followed by cross power spectrum measurement of ambient motion fluctuations and selected LSC port
- stimulus: PEM cart shaker attached to beam tube at point of interest
    - 1 Hz - 30 Hz for up-conversion effects
    - 30 Hz - 1 kHz for direct effects
- response: PEM BT accelerometers, LSC length sensing ports
- analysis: differences of strain spectra with and without excitation for the 1-30 Hz band; signals at excitation frequency for 30 Hz - 1 kHz

- visualization: power in strain spectrum due to BT natural motion
- recurrence: once per month or per change in hardware
- duration: 10 min of unavailability; 1 day setup for placement of PEM shaker etc.
- contingent tests: none

C.2 OPTIMIZATION OF OPTICAL PHASE SENSITIVITY

C.2.1 Signal-to-Noise Optimization of the RF Modulation Index

- technique: variation of the RF modulation depths to search for best performance in shot noise limited region of the spectrum
- stimulus:
    - fixed-frequency calibration peak (strain modulation), 10 Hz - 10 kHz, S/N 10 - 100 in sample long enough to get 1% uncertainty in shot-noise region
    - variation (stepped in 1% to 10% increments with stationary points for strain measurement) of modulation depth, 0.1 nominal to 2x nominal (may be limited by interferometer servos to a smaller range). An intelligent search for a maximum cuts duration.
    - 1 Hz - 10 kHz
- response: measure of peak height of calibration in strain spectrum as a function of modulation depth; measure of shot-noise limited performance in regions without interfering features (peaks, etc.)
- analysis: fit to shot-noise limited level, fit to peak height, search for optimum
- visualization: strain spectrum for each step; plot of S/N vs. modulation depth with peak indicated
- recurrence: once per week or per change in hardware
- duration:60 sec
- contingent tests: none

C.2.2 Mode Matching into Interferometer

- technique: stepping of input mode parameters, measurement of circulating power in interferometer as measure of matching
- stimulus: stepping of the translation stage which varies the IO telescope mirrors, thus changing the matching. Magnitude of motion: TBD, according to initial state of matching. Each step will require reinjection of the beam, realignment, and interferometer tuning, and possibly a wait for thermal equilibrium
- response:
    - circulating power in the arm cavities (recycling cavity high-order modes are easily excited?), as monitored by photodiodes looking at ETM transmitted beam
    - S/N in shot noise limited region
- alternative response: analysis of CCD camera looking at RM for first circularly symmetric mode; amplitude of mode as function of matching will allow faster convergence maybe
- analysis: fit to curve of power and S/N as function of matching, identification of desired matching
- visualization: plot of power and S/N as a function of matching with optimum point identified
- recurrence: once per month or per change in hardware

- duration: 1 hour unavailability, TBD on translation and realignment realities for IO telescope
- contingent tests: none

C.2.3 Mirror Absorption through Change in Mode Matching

- technique: Varying input power to the interferometer; looking at signals characteristic of mode matching to see the changes; use of a model to regress back to the change in mirror curvature and thus absorption
- stimulus: laser power stepped in factors of three, from 60 mW to 6 W net input power at RC
- response: light reflected from RC captured with a CCD and stored in frames for post-analysis
- analysis: calculation of the amount of TEM_{01} as a function of input power; from this, calculation of an average of absorption in TMs.
- visualization: TEM_{01} as a function of input power; absorption number
- recurrence: once per month or per change in hardware
- duration: 10 minutes unavailability
- contingent tests: none

C.2.4 Higher Order Arm Cavity Mode Scan

- technique: with other cavities misaligned, drive the ETM of the cavity of interest at uniform velocity through several λ. Measure the intensity vs. time on the ETM transmitted light.
- stimulus: 0.1 Hz ramp to the z input of the ETM suspension controller. Best if this is done with a closed loop control using the suspension sensors to reduce variations due to seismic input.
- response: photodiode measurement ETM transmitted light
- analysis: Plot of intensity vs. position, normalized to give free spectral range. Superposition of multiple traces to show variability; averaging to improve estimate. Identification of cavity modes by comparison with cavity model; analysis of the nature of the mismatch (simple misalignment suppressed) by comparison with the model
- visualization: Classic ‘optical spectrum analyzer’ (intensity vs. cavity length modulo $\lambda/2$)
- recurrence: once per month or per change in hardware
- duration: 10 min unavailability
- contingent tests: none

C.2.5 Arm Cavity Loss Measurement by Reflection

- technique: with other cavities misaligned, the cavity of interest is locked and then unlocked. The difference in the reflected light allows an inference of the losses, once matching (test C.2.4) is known.
- stimulus: locking and unlocking of a single arm cavity. This might be performed using a mechanical dither of the ETM at ~100 Hz with a synchronous demodulation of the ETM transmitted light; or a subset of LSC RF locking electronics.
- response: photodiode measurement of the reflected light PO from the ITM
- analysis: application of the Fabry-Perot formula to infer losses based on known TM properties (transmissions) and light reflected.
- visualization: numbers on a screen
- recurrence: once per month or per change in hardware

- duration: 10 min unavailability
- contingent tests: none

C.2.6 Arm Cavity Loss Measurement by Ring-down

- technique: With other optical cavities misaligned, the cavity under test is locked. Small step changes in the input light intensity are made, and the exponential drop-off in stored power is measured.
- stimulus: 1-10% step modulation of the laser intensity (<1 μsec rise/fall times), 1-30 Hz rep rate
- response: photodiode measurement of the ETM transmitted light
- analysis: fit to exponential decay/rise in the ETM transmitted light, with synchronous averaging of the data. Inference of storage time, comparison with design storage time and previous measurements. Inference of additional loss.
- visualization: storage time and loss vs. time, vs. integrated light intensity; fits to models for decay as a function of time, products of time and intensity, etc.
- recurrence: once per week or per change in hardware
- duration:10 min non-availability
- contingent tests: none

C.2.7 Recycling Cavity Loss Measurement

- technique: ETMs misaligned, Michelson locked, recycling cavity locked. Small step changes in the input light intensity are made, and the exponential drop-off in stored power is measured.
- stimulus: 1-10% step modulation of the laser intensity (<1 μsec rise/fall times), 1-30 Hz rep rate
- response: photodiode measurement of the BS PO light intensity
- analysis: fit to exponential decay/rise in the PO intensity, with synchronous averaging of the data. Inference of storage time, comparison with design storage time and previous measurements. Inference of additional loss.
- visualization: storage time and loss vs. time, vs. integrated light intensity; fits to models for decay as a function of time, products of time and intensity, etc.
- recurrence: once per month or per change in hardware
- duration:10 min non-availability

C.2.8 ETM Suspension Actuator Axial Calibration

- technique: Form a Michelson interferometer using an auxiliary laser, with one arm using the ETM surface (as viewed through the optical relay system to bring out the ETM transmitted light) and the other arm a reference arm. All components except for the ETM COS components are outside of the vacuum. A slow sweep of the ETM is made to calibrate the fringe height. Then a small modulation of the mirror position is made and the r.m.s. motion inferred from the auxiliary interferometer output.
- stimulus:
  - For auxiliary interferometer calibration: 0.1 Hz ramp to the z input of the ETM suspension controller. Best if this is done with a closed loop control using the suspension sensors to reduce variations due to seismic input.

  - For suspension actuator calibration: fixed-frequency and sweep sinusoidal excitation of the z input to the suspension actuator at levels corresponding to $\sim 10^{-10}$ to 10^{-15} m r.m.s., 30 Hz - 1 kHz.
- response: Auxiliary Michelson antisymmetric photodiode output
- analysis:
  - measurement of the peak-peak output of the auxiliary interferometer while sweeping ETM. From this, the ‘volts/λ’ for the interferometer is measured. Fits made to peak and peak, multiple averages taken
  - measurement of the coil currents (at suspension controller test points) and the auxiliary interferometer photodiode output locked at the dark fringe or mid-fringe.
- visualization:
  - sweep of auxiliary interferometer vs. ETM position
  - motion of the ETM (as measured by the calibrated auxiliary interferometer) per ampere of suspension controller current, as a function of frequency (transfer function). Coherence.
- recurrence: once per month or per change in hardware
- duration: 10 min unavailability
- contingent tests: none

C.2.9 Suspension Actuator Angular Calibration

- technique: use of the optical levers to measure angular motion effected by the suspension actuators. Optical levers are calibrated by making known translations of the quadrant photodiodes and measuring their response in a preliminary measurement.
- stimulus: sinusoidal drive to each COC element suspension controller θ and ϕ input
  - $10^{-7} – 10^{4}$ rad
  - 1 Hz - 1 kHz
- response: calibrated optical lever output.
- analysis: form the transfer function from angle commanded to angle resulting as determined from the optical lever.
- visualization: the transfer function; coherence.
- recurrence: once per month or per change in hardware
- duration:60 sec
- contingent tests: none

C.2.10Length Control System Diagonalization and Diagnostics

- technique: Using calibrated suspension actuators, make equal in-phase or counter-phase axial motions of the two ETMs, or two ITMs, or RC. Observe the signals at the LSC and ASC sensors. The interferometer is in the operational state during the measurement.
- stimulus: sinusoidal or pseudo-random excitation to the suspension controllers
  - 0.1 - 100x the ambient control force in the locked case.
  - 1 Hz - 10 kHz
- response: LSC and ASC outputs
- analysis:
  - standard transfer function tools; also, fixed-frequency transfer function vs. other interferometer parameters (like beam centering, suspension controller balance, offsets

    from nominal alignment, etc.)
  - formation of the complete matrix of motions to signals for the LSC
  - formation of the complete matrix of accidental coupling to the ASC
- visualization: standard transfer function tools; matrix
- recurrence: once per month or per change in hardware
- duration: 10 min unavailability
- contingent tests: none

C.2.11Angle Control System Diagonalization and Diagnostics

- technique: Using calibrated suspension actuators, make equal in-phase or counter-phase angular motions of the two ETMs, or two ITMs, or RC. Observe the signals at the LSC and ASC sensors. The interferometer is in the operational state during the measurement.
- stimulus: sinusoidal or pseudo-random excitation to the suspension controllers
  - 0.1 - 100x the ambient control force in the locked case.
  - 1 Hz - 10 kHz
- response: LSC and ASC outputs
- analysis:
  - standard transfer function tools; also, fixed-frequency transfer function vs. other interferometer parameters (like beam centering, suspension controller balance, offsets from nominal alignment, etc.)
  - formation of the complete matrix of motions to signals for the ASC
  - formation of the complete matrix of accidental coupling to the LSC
- visualization: standard transfer function tools; matrix
- recurrence: once per month or per change in hardware
- duration: 10 min unavailability
- contingent tests: none

C.3 NOISE DUE TO RANDOM FORCES

C.3.1 Suspended Optical Component Seismic Noise Sensitivity

- technique: measurement of the effect on the strain output for both monitored ambient seismic excitation, and with applied excitation
- stimulus: PEM shaker applied to the seismic isolation support beams, in x, y, z; excitation waveform may be sinusoidal, swept sine, impulse, or pseudorandom
- response: PEM accelerometers, strain output
- analysis: transfer functions and ratios of power spectra of strain output over accelerometer output
- visualization: transfer functions
- recurrence: once per month or per change in hardware
- duration:10 min (attaching shaker, shaking, removal of shaker) per mass
- contingent tests:

C.3.2 Suspended Optical Component Acoustic Noise Sensitivity

- technique: measurement of the effect on the strain output for both monitored ambient acoustic excitation, and with applied excitation
- stimulus: PEM loudspeaker placed in the vicinity of VE containing COC element of interest; excitation waveform may be sinusoidal, swept sine, impulse, or pseudorandom
- response: PEM microphones, strain output
- analysis: transfer functions and ratios of power spectra of strain output over microphone output
- visualization: transfer functions
- recurrence: once per month or per change in hardware
- duration:60 sec per test, one test per mass
- contingent tests: none

C.3.3 Suspended Optical Component Magnetic Field Sensitivity

- technique: measurement of the effect on the strain output for both monitored ambient magnetic field excitation, and with applied excitation
- stimulus: PEM magnetic field generator placed in vicinity of VE containing COC element of interest; excitation waveform may be sinusoidal, swept sine, impulse, or pseudorandom
- response: PEM magnetometer, strain output
- analysis: transfer functions and ratios of power spectra of strain output over magnetometer output
- visualization: transfer functions
- recurrence: once per month or per change in hardware
- duration:60 sec per test, one test per mass
- contingent tests: none

C.3.4 Suspended Optical Component Electric Field Sensitivity

TBD.

C.3.5 Suspended Optical Component Tilt Sensitivity

TBD.

C.3.6 Pendulum Longitudinal Mode Q

TBD.

C.3.7 Pendulum Wire Transverse Mode Q

- technique: excitation of the wire ‘violin string’ resonances using the suspension actuators; measurement of the peak in the strain spectrum, ring-down time.
- stimulus: suspension actuators axial input. Sine excitation at the fundamental and harmonics of the suspension wires; cutoff of excitation once at 10-100x the ambient motion to observe ring-down.
- response: strain output

- analysis: fits to exponential decays
- visualization: transfer functions; Q vs. time (periodic tests over months to observe changes)
- recurrence: once per month or per change in hardware
- duration:10 min per resonance; ~2 resonances per wire; 2 wires per mass; 4 TMs
- contingent tests: none

C.3.8 Pendulum Wire Longitudinal Mode Q

- technique: excitation of the vertical motion of the SEI support beams at or around the resonant frequency of vertical motion (~11 Hz); measurement of the transfer function or of the ring-down time of the motion in the strain or control spectrum (coupling due to at least the earth's curvature) or the suspension sensors (nominally zero response, but certainly visible).
- stimulus: PEM shakers placed on the four support beam support points of the VE containing COC element of interest; excitation waveform may be sinusoidal at or swept sine around the (known) resonant frequency
- response: PEM accelerometer, strain output or other point in the LSC control system sensitive at ~11 Hz
- analysis: transfer functions and ratios of power spectra of strain output over accelerometer output; fits to exponential decays (if a ring-down test is made) or fits to line widths in the transfer function (if a sweep around the resonance is used to determine its width and thus losses)
- visualization: transfer functions; Q vs. time (periodic tests over months to observe changes)
- recurrence: once per month or per change in hardware
- duration:10 min
- contingent tests: none

C.3.9 Pendulum Vertical to Horizontal Cross Coupling

TBD.

C.4 OPTIMIZATION TO MINIMIZE NOISE FROM RANDOM FORCES

C.4.1 Search for Rotation Insensitive Beam Position on Suspended Component

- technique: modulation in angle of the suspended optic; observation of the signal in the strain spectrum; motions of the beam and/or SEI actuators to observe size and sign of change of coupling; inference of point of no response, and placement of the beam/SEI at that point. Commands to the SEI coarse actuator are less desirable, as it will probably cause loss of lock in the interferometer. After locating the best point, SEI actuators may be used to re-center the optic.
- stimulus:
  - angular input to the SUS controller, in θ, ϕ; excitation waveform may be sinusoidal, swept sine, impulse, or pseudorandom
  - changes in the beam position on the mirror by commands to global ASC to change the optical axis affecting the beam on that mirror

- response: strain output
- analysis: transfer functions and ratios of power spectra of strain output over angular
- visualization: transfer functions
- recurrence: once per month or per change in hardware
- duration:60 sec per test, one test per mass
- contingent tests: none

C.4.2 Search for Astatic Point in Suspended Component Position Controller

TBD.

C.5 TESTS OF THE FACILITY-DETECTOR INTERFACE

C.5.1 Correlation of Residual Gas Pressure Fluctuations with Detector Output

- technique: RGA real-time measurements are correlated with some LSC signals to determine if pressure fluctuations are influencing the detector performance
- stimulus: none, or possible use of remote-control-valved leak in BT or VE
- response: PEM RGAs in BT and VE, LSC sensing signals
- analysis: correlation; averaging of time series; statistics of gas pulses; comparison with calculated waveforms
- visualization: correlation function; time series of pressure and time series from detector; histograms
- recurrence: once per month or per change in hardware
- duration: if using gas pulse, 10 min; otherwise, non-invasive
- contingent tests: none

C.5.2 Correlation of Technical Power Fluctuations with Detector Output

- technique: Power monitor real-time output is correlated with LSC signals
- stimulus: none
- response: PEM power monitor, LSC sensing signals
- analysis: correlations; statistics of power fluctuations
- visualization: correlations; histograms
- recurrence: once per month or per change in hardware
- duration: non-invasive
- contingent tests: none

C.5.3 Correlation of Facility Power Fluctuations with Detector Output

- technique: Power monitor real-time output is correlated with LSC signals
- stimulus: none

- response: PEM power monitor, LSC sensing signals
- analysis: correlations; statistics of power fluctuations
- visualization: correlations; histograms
- recurrence: once per month or per change in hardware
- duration: non-invasive
- contingent tests: none

C.5.4 Correlation of Facility Monitors with Detector Output

- technique: Each facility monitor with real-time output is correlated with the LSC and ASC signals to find the influence on the interferometer performance
- stimulus: none; or Facility equipment can be power cycled, change in operating parameters (speed, temperature, etc.)
- response: Facility status flags and sensors, LSC/ASC sensors
- analysis: correlations; statistics; comparison of waveshapes, harmonic structure
- visualization: correlation, histograms, time series
- recurrence: once per month or per change in hardware
- duration: non-invasive
- contingent tests: none

APPENDIX D LIST OF MONITORS

D.1 PERFORMANCE MONITORS

Performance monitors are used to monitor the performance of the detector during detection mode. If none of the performance monitors indicates a problem, the operator can be fairly confident that the instrument is working fine and that good data are taken. Performance monitors can be divided into the following categories:

Monitor	Description
GW noise	Looks for excessive noise in the gravitational-wave band of the antisymmetric readout; calculates the observable volume for a ‘standard’ inspiral.
Calibration	Checks the validity of the current calibration of the antisymmetric port readout.
Beam intensity	Checks the power levels in the interferometer, the mode cleaner and at the laser output.
Laser source	Looks for higher than usual FM and AM noise on the laser light and spurious signals in the reference cavity and pre-mode cleaner control signals.
Modulation	Checks modulation depth and modulation frequencies.
Servo r.m.s.	Looks for larger than usual r.m.s. fluctuations in the control and error signals of the interferometer length, mode cleaner length and alignment servo loops.
Oscillations	Looks for oscillations and gain peaking in the length and alignment servos.
Narrow band features	Looks for suspension violin string resonances and test mass resonances at the antisymmetric port.
Actuator saturation	Looks for saturation in the control signals.
Photodiode	Monitors the health of the RF photodiodes, watches temperature, bias voltage and increased dark current.
Excitation	Monitors the excitation and calibration system to make sure that it is really off when it should be turned off (as during detection mode).
SUS Coil driver	Looks for spurious signals above 50 Hz in the SUS coil driver read-backs
SUS local sensor	Looks for spurious signals measured by the local SUS sensors
Optical lever	Looks for spurious alignment fluctuations measured by the optical levers
Seismic	Looks for increased seismic activity measured by the seismometers, the tiltmeters and the accelerometers
Vibration	Looks for excessive vibrations of the beam tube and the vacuum tanks measured by the accelerometers
EM fields	Looks for spurious signals in the magnetic field detectors and increased activity in the EMI sensors
Acoustic noise	Looks for acoustic activity above the usual background noise
Weather storm	Looks for extreme weather conditions

The following tests can be used for monitoring the performance:

Test	**Description**	**Category**
Power	Calculates the power in a frequency band using the FFTs of the data channels; uses a higher limit for the trigger	GW noise Laser source SUS coil driver Vibration Acoustic noise Servo oscillations
Burst	Searches for (unknown) peaks in the FFTs of the data channels	GW noise Laser source SUS coil driver Servo oscillations
Peak	Differentiates the time trace and checks the resulting trace against a higher limit	GW noise Laser source SUS coil driver SUS local sensor Optical lever Earthquake Vibration
R.M.S.	Calculates the r.m.s. of the time trace; uses a higher limit for the trigger — lower limit for dead channel test	Servo r.m.s. SUS local sensors Optical lever Earthquake EM Storm
Limit	Checks the time trace against lower and higher limits	Beam intensity Modulation Photodiode Excitation Weather storm

D.2 BROKEN CHANNEL INDICATORS

The purpose of a broken channel indicator is to monitor the activity on channels related to sensor readings and raise an alarm when the channel stops working or when the channel data looks faulty (e.g., sticky bit).

D.3 STATIONARY BEHAVIOR

D.3.1 IFO CHANNELS

The IFO channels include the dark port, other longitudinal degrees of freedom and orientational degrees of freedom.

- 60 Hz and harmonics contamination of IFO channels (amplitude and phase)
- Violin mode amplitudes
- Stack vibration level
- Internal mirror resonance amplitudes
- Total non-Gaussian noise level (frequency of outliers, contribution to rms)
- Distortion from “normal” ambient power spectrum
- Correlation coefficients among longitudinal and orientational degrees of freedom (from continuous principal value decomposition, as opposed to transfer function measurements)
- General operational state (good lock, marginal lock, unlocked)
- Strain sensitivity in various frequency bands.
- Maximum viewing distance for inspiral standard candle(s)

D.3.2 ENVIRONMENTAL CHANNELS

The environmental channels include *e.g.*, seismometers, tilt-meters, accelerometers, microphones, Strain sensitivity in various frequency bands.

- Distortion from “normal” ambient power spectrum
- Correlation coefficient with dark port (and other key IFO channels) inferred from principal value decomposition)

D.4 TRANSIENT BEHAVIOR

D.4.1 IFO CHANNELS

- Search for impulses of known shape (wire relaxation, dropped hammer, railed mechanical actuator, etc) using matched filters.
- Flickering optical modes, i.e. oscillations in the down-converted interefrometer signals.
- Violin mode ringdown / ringup
- Servo instability
- Generic band-limited rms growth
- Out-of-band resonance excitation
- Large-amplitude excursion
- Onset of electronic analog or digital saturation
- ADC / DAQ malfunction (lost/duplicated data, sticky bit)
- Dust particle falling through beam (may be tough!)
- Non-stationary time-frequency behavior (waterfall/carpet plots, wavelet analysis)

D.4.2 ENVIRONMENTAL CHANNELS

- External Stimula, *e.g.* Tremors/quakes, gunshots, big trucks, lightning, wind gusts.