# The Laser Interferometer Gravitational-wave Observatory Scientific Data Archive

Lee Samuel Finn

Department of Physics and Center for Gravitational Physics and Geometry, The Pennsylvania State University, University Park PA 16802, USA

#### Abstract

LIGO — The Laser Interferometer Gravitational-Wave Observatory — is one of several large projects being undertaken in the United States, Europe and Japan to detect gravitational radiation. The novelty and precision of these instruments is such that large volumes of data will be generated in an attempt to find a small number of weak signals, which can be identified only as subtle changes in the instrument output over time. In this paper, I discuss the how the nature of the LIGO experiment determines the size of the data archive that will be produced, how the nature of the analyses that must be used to search the LIGO data for signals determines the anticipated access patterns on the archive, and how the LIGO data analysis system is designed to cope with the problems of LIGO data analysis.

#### 1 Introduction

Despite an 83 year history, our best theory explaining the workings of gravity — Einstein's theory of general relativity — is relatively untested compared to other physical theories. This owes principally to the fundamental weakness of the gravitational force: the precision measurements required to test the theory were not possible when Einstein first described it, or for many years thereafter.

It is only in the last 35 years that general relativity has been put to significant test. Today, the first effects of static relativistic gravity beyond those described by Newton have been well-studied using precision measurements of the motion of the planets, their satellites and the principal asteroids. Dynamical gravity

 $<sup>^1~</sup>$  Supported by the National Science Foundation award PHY 98-00111 to The Pennsylvania State University

has also been tested through the (incredibly detailed and comprehensive) observations of the slow, secular decay of a pair of the Hulse-Taylor binary pulsar system [1]. What has not heretofore been possible is the direct detection of dynamical gravity — gravitational radiation.

That is about to change. Now under construction in the United States and Europe are large detectors whose design sensitivity is so great that they will be capable of measuring the minute influence of gravitational waves from strong, but distant, sources. The United States project, the Laser Interferometer Gravitational-wave Observatory (LIGO), is funded by the National Science Foundation under contract to the California Institute of Technology and the Massachusetts Institute of Technology.

Both LIGO and its European counterpart VIRGO will generate enormous amounts of data, which must be sifted for the rare and weak gravitational-wave signals they are designed to detect. To understand the LIGO data problem, one must first understand something of the LIGO detector ( $\S$ 2) and the signals it hopes to observe ( $\S$ 3), since these determine the size of the data archive and place challenging constraints on its organization. In the following sections I describe the magnitude and character of the data generated by LIGO ( $\S$ 4), how the data will be collected and staged to its final archive ( $\S$ 5), the kinds of operations on the data that must be supported by the archive and associated data analysis system ( $\S$ 6), anticipated data access patterns ( $\S$ 7), some of the criteria involved in the design of the LIGO Data Analysis System (LDAS) ( $\S$ 8), and a proposed strategy for the staged use of the several components of the LIGO Data Analysis System ( $\S$ 9).

#### 2 The LIGO Detector

The LIGO Project [2] consists of three large interferometric gravitational wave detectors. Two of these detectors are located in Hanford, Washington; the remaining detector is located in Livingston, Louisiana.

At each LIGO site is a large vacuum system, consisting of two 4 Km long, 1 m diameter vacuum pipes that form two adjacent sides of a square, or arms. Laser light of very stable frequency is brought to the corner, where a partially reflecting mirror, or beamsplitter, allows half the light to travel down one arm and half the light to travel down the other arm. At the end of each arm a mirror reflects the light back toward the corner, where it recombines optically at the beamsplitter.<sup>2</sup> This basic configuration of lasers and mirrors, illustrated

 $<sup>^{2}</sup>$  In fact, LIGO utilize several additional mirrors that permit the light to traverse the detector arms many times before recombining at the beamsplitter. This detail,

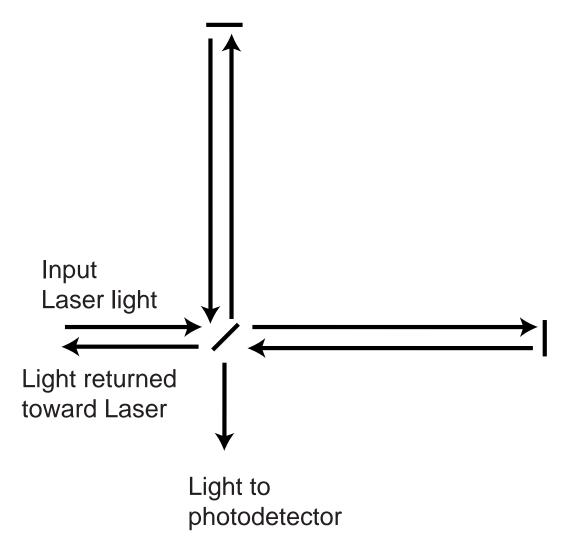


Fig. 1. A schematic diagram of a simple interferometer, showing the light paths. schematically in in figure 1, is called an interferometer.

The nature of light is such that, when it recombines in this way at the beamsplitter, some of the light will travel back toward the laser and some of the light will travel in an orthogonal direction. The amount of light traveling in each direction depends on the ratio of the difference in the arm lengths to the wavelength of the light, modulo unity. The laser light wavelength used in LIGO is approximately 1000 nm; consequently, by monitoring the amplitude of the light emerging from the beamsplitter and away from the laser, each LIGO interferometer is sensitive to changes in the arm length difference to much better than one part in  $10^{10}$ .<sup>3</sup>

while important for increasing the sensitivity of the detector, is not important for understanding the basic operation of the instrument.

<sup>&</sup>lt;sup>3</sup> How much better depends on the laser power incident on the beamsplitter and the number of arm transversals before recombination at the beamsplitter (see previous footnote). The initial LIGO instrumentation will be capable of measuring changes

The signature of a gravitational-wave incident in a single LIGO interferometer is a time-varying change in its arm length difference. Since the arm length difference is a single number at each moment of time the "gravitational-wave" data channel is a single number as a function of time: a time-series.

The two Hanford interferometers are of different lengths: one has arms of length 4 Km, while the other has arms of length 2 Km. The Livingston interferometer has 4 Km arms. Together the three interferometers can be used to increase confidence that signals seen are actually due to gravitational waves: the geographic separation of the two sites reduces the likelihood that coincident signals in the two detectors are due to something other than gravitationalwaves; additionally, a real gravitational wave will have a signal in the 2 Km Hanford interferometer of exactly half the amplitude as the corresponding signal in the 4 Km Hanford interferometer. Finally, while each interferometer is relatively insensitive to the incident direction of a gravitational wave signal, the geographic separation of the two 4 Km detectors, together with data from the French/Italian VIRGO detector, may permit the sky location of an observed source to be determined from the relative arrival time of the signal in the several detectors. Joint analyses of of the output of several interferometers is critical to the scientific success of the gravitational wave detection enterprise.

## 3 LIGO Signals

The nature of the signals expected to be present in the LIGO data stream determines the character of the data analysis. That, in turn, determines how the data will be accessed, the archive structure and the data life-cycle. In this section we consider the types of signals that may be expected in the LIGO data stream [3] and how these determine the amount of data that must be archived and made accessible.

Despite its unprecedented sensitivity, the LIGO detectors will be able to observe only the strongest gravitational radiation sources the Universe has to offer. These are all astronomical in origin. It is in this sense that LIGO is an observatory, as opposed to an experiment: while in an experiment both the source and the receiver can be controlled, astronomical sources can only be studied *in situ*.

The most intense radiation LIGO may observe are thought to be short bursts of radiation, such as arise shortly before or during the collision of orbiting neutron stars or black holes. These bursts of radiation are expected to last

in the arm length difference to better than one part in  $10^{21}$  of the arm length.

from seconds to minutes. The character of the anticipated *burst sources* is such that, for many, the only anticipated signature of the source is the imprint it leaves in a gravitational wave detector. Consequently, LIGO cannot rely on some other instrument, such as an optical or gamma-ray telescope, to signal when to look, or not look, for most burst sources.

Since burst sources of gravitational radiation are expected, for the most part, to leave no significant signature in instruments other than gravitational wave detectors, we have very little real knowledge of the expected rate of burst sources. Present estimates of burst rates are based on limited astronomical observations of nearby burst source progenitors, coupled with theoretical estimates of their formation rate and evolution. These estimate suggest that the rate of burst, from anticipated sources, observable directly in the initial LIGO instrumentation from anticipated sources is unlikely to exceed one per year in the most optimistic scenarios (planned enhancements and upgrades will increase the expected rate by several orders of magnitude).

These estimates are, in reality, quite weak. The rate estimate for bursts from inspiraling binary neutron star systems, which is the firmest of all event rates, is uncertain by several orders of magnitude. Several anticipated burst sources are unobservable except by gravitational wave detectors. Finally, all source rate estimates apply only to *anticipated* burst sources, and the nature of our knowledge of the cosmos gives good reason to believe that there may be unanticipated sources that these new detectors can observe. The proper conclusion, then, is that the initial observations will inform us more than we can anticipate them.

In addition to burst sources, LIGO may also be able to detect radiation from sources that are long-lived and nearly monochromatic. The instantaneous power in these *periodic sources* will be much less than in the burst sources; however, through coherent observation over several month or longer time scales a measurable signal may emerge. Unlike burst sources, periodic signals are always "on"; like burst sources, continuous observations over month to year periods are necessary if LIGO is to have a reasonable prospect of observing any that are present.

Finally, LIGO may be sensitive to a *stochastic signal*, arising from processes in the early Universe or from the confusion limit of, *e.g.*, a large number of sources each too weak to be detected individually. Like a periodic source, a stochastic signal is always on; also like a periodic source, LIGO will require continuous observation over a period of several months if it is to detect a stochastic signal of even the most optimistic strength. Lastly, unlike either a burst source or a periodic source, a stochastic signal appears in a single interferometer to be no different than intrinsic detector noise: it is only in the correlation of the output of two or more geographically separated detectors that a stochastic signal can be distinguished from intrinsic instrumental or terrestrial noise sources.

Detection of any of the anticipated LIGO sources thus requires continuous and high duty-cycle observations over periods of months to years. Additionally, the signature of gravitational wave sources in LIGO is apparent in the behavior of the detector over a period of time, which may be quite long. As a consequence, LIGO data cannot immediately be organized into "events" that are cataloged, stored and analyzed independently: the temporal relationships in the detector output is of fundamental importance and must be preserved over the entire duration of the experiment if the data is to be analyzed successfully. Finally, analysis of the LIGO data for at least one potential source — a stochastic signal — *requires* the cross-correlation of the data from several, geographically separated interferometers, which places an additional requirement on the simultaneous accessibility of data from multiple interferometers at the same epoch.

## 4 LIGO data types

The LIGO data archive will include the data collected at the instrument, information about the data and the instrument, and information derived from the data about the data and the instrument. Different classes of data will have different lifetimes; similarly, the kind of access required of different data classes are different. In recognition of this, several different high-level data types will be supported by LIGO, and different data classes will be stored in different cross-reference databases, catalogs or repositories.

In this section I describe the four different data types and three different catalogs that will be created and maintained for LIGO data. The first two data types — frame data (§4.1) and meta-data (§4.2) — are long-lived objects associated with their own catalogs. The third data type — "events" (cf. §4.3) — is also associated with its own catalog, but is more transient. The fourth data type — "light-weight" data — is intended to support import and export of LIGO data to and from the LIGO Data Analysis System (LDAS), so that investigations can take advantage of the wide range of general purpose tools developed for studying data sets.

#### 4.1 LIGO frame data and frame data catalog

LIGO data will be recorded digitally. Since LIGO is sensitive only to radiation at audio frequencies, the gravitational-wave channel is recorded with a bandwidth typical of audio frequencies: 8.192 KHz, corresponding to a Nyquist sampling frequency of 16.384 KHz.<sup>4</sup> The signal itself will be recorded with 2 byte integer dynamic range; consequently, the gravitational-wave channel generates data at a rate of 32 KBytes/s/IFO (where IFO denotes a single interferometer).

By itself this is a relatively modest data rate: 2 days of a single LIGO interferometer's gravitational-wave channel could fit on a single uncompressed exabyte tape. In order for each LIGO interferometer to achieve the requisite sensitivity, however, numerous control systems must operate to continuously adjust the laser, mirrors and other detector sub-systems. Additionally, physical environment monitors will record information on the seismic, acoustic, electromagnetic, cosmic ray, power-grid, residual vacuum gas, vacuum contamination, and local weather conditions that could affect the detector operation [4]. There will be 1,262 data channels of this kind recorded at the Hanford, Washington Observatory, and 515 data channels recorded at the Livingston, Louisiana Observatory at a variety of rates and dynamic ranges, corresponding to a total data rate of 9,479 KBytes/s at Hanford and 4,676 KBytes/s at Livingston [5,4]. In the course of a year, LIGO will have acquired over 416 TBytes, and the first LIGO science observation is expected to last for 2 yrs, from 2002 to 2004.

#### 4.2 LIGO meta-data and meta-data catalog

In addition to LIGO data arising from the instrument control systems and environmental monitors, a separate data catalog will be accumulated consisting initially of at least the operator logbook, instrument state or configuration information, and other summary information about each detector and its physical environment that may be deemed relevant to the later understanding of the data stream. The resulting *meta-data* is neither continuous nor periodic. On the other hand, entries are keyed to the main data, either precisely or by epoch. The rate of meta-data is expected to be, on average, 10 KBytes/s [6].

Meta-data entries will include text narratives, tables, figures, and camera images. Entries may also include snippets of data derived or summarized from one or more channels of the main LIGO data stream, from other experiments or from observations made at other facilities. Finally, the meta-data is, unlike the main data stream, meant to be extensible: as the LIGO data stream is analyzed, annotations and results will be summarized as meta-data. The meta-data is thus the record of everything that is known or learned about the frame data at any give time or during any give epoch.

<sup>&</sup>lt;sup>4</sup> We adopt the usual, if confusing, convention that a KHz is  $10^3$  Hz, while a KByte is  $2^{10}$  bytes.

#### 4.3 LIGO event data and event data catalog

As analysis proceeds, certain features of the LIGO data will be identified as "events". These will be recorded in an *event data catalog*, which is distinct from the meta-data catalog. An event, in this context, is not necessarily of short or limited duration and may not even have a definite start or end time: for example, evidence of an unanticipated coherent, periodic signal in some data channel would be considered an event.

Some data features classified as events may eventually be recognized as gravitational wave sources; however, the vast majority of events will be instrument artifacts or have some other, terrestrial or non-gravitational wave origin. As events are investigated and come to be understood, they will move from the event catalog to the meta-data catalog.

### 4.4 LIGO "light-weight" data

The LIGO Data Analysis System (LDAS) will provide specialized tools for the efficient manipulation of LIGO frame data, meta-data and event data. To permit LIGO data analysis to take advantage of the much wider range of general purpose tools developed for investigating data sets, a mechanism for exporting relatively small amounts of LIGO data to these applications, and importing the annotated results of investigations made outside the LDAS framework, will be provided. This mechanism will be provided in the form of a "light-weight" data format, which is sufficiently flexible that it can be be read and written by other applications (*e.g.*, Matlab [7]) with a minimum amount of overhead.

Light-weight data will not have the permanence of event data, meta-data or raw data: the results of investigations undertaken outside the LDAS framework will eventually be integrated into the LDAS framework as event data or metadata.

#### 5 The LIGO data life-cycle

During normal operations, the LIGO Livingston Observatory will generate data at a rate of 4,676 KBytes/s; the LIGO Hanford Observatory, with its two interferometers, will generate data at a rate of 9,479 KBytes/s (cf. §4.1). Meta-data (cf. §4.2) is expected to be generated at a mean cumulative rate of approximately 10 KBytes/s.

Data generated at the sites is packaged by the data acquisition system into *frames*. A frame [8] is a flexible, self-documenting, formatted data structure, with a header consisting of instrument state and calibration information followed by one or more channels of LIGO data over a common epoch. A frame may also contain meta-data fields. While the period of time, number and identity of the channels covered by a frame is flexible, the data acquisition will write a series of uniform frames of approximately 1 s duration.

The frame data object used to hold LIGO data from acquisition onward was developed cooperatively with the VIRGO project, with the explicit goal of reducing the logistical problems that would arise in future, collaborative data analysis exercises.

Immediately after it is closed, each acquired frame is passed to the "on-line" LIGO Data Analysis System (LDAS) at the corresponding site (Hanford or Livingston). The on-site or on-line LDAS maintains the past 16 hours of frame data on local disk (corresponding to just over 520 GBytes at Hanford and just over 256 GBytes at Livingston). Each hour the least recently acquired data is transferred to more permanent storage (*e.g.*, tapes) and purged from the system.

As data is transferred to more permanent storage, several redundant and identical copies will be made. One copy from each site will be shipped via commercial carrier to a central, long-term archival center, associated with the "off-line" LIGO Data Analysis System and located on the Caltech campus. This data will be in transit for at least one and up to several days. After it arrives at the central data archive, the data from the two LIGO sites will be ingested into the archive.

It is at the central data archive that LIGO data from the two observatories will first be accessible either widely simultaneously; prior to that data acquired at Hanford will only be available at Hanford and data acquired at Livingston will only be available at Livingston.

As data is ingested into the archive a combination of compression and selection of the data will occur, reducing the volume by approximately 90%.<sup>5</sup> The compression and selection will not be uniform in time: certain epochs chosen at random or deemed particularly interesting, either because of instrument testing or diagnoses, or because of suggestive behavior of the gravitationalwave channel, may be recorded at full bandwidth. Once the data has been successfully ingested and verified, redundant data at the interferometer sites will be purged and the central data archive will become the single repository and authoritative source for LIGO data.

 $<sup>^{5}</sup>$  A determination of which data channels may be compressed using lossy algorithms, or discarded entirely, has not yet been made.

The central LIGO data archive will hold up to 5 yrs of accumulated data from three interferometers. Beyond that period the data volume will be reduced further by a combination of compression and selection of the data, except that the gravitational-wave channel will be preserved with full fidelity indefinitely.

## 6 LIGO Data Analysis

LIGO data are time series. The principal component of the gravitational wave channel is noise; all anticipated signals have amplitudes small compared to the noise. All detectable signals have some characteristic that gives them a coherence that is not expected of noise. For example, weak burst sources are detectable if their time dependence or energy power spectrum is well known; periodic signals are detectable when their frequency is Doppler-modulated by Earth's rotation and motion about the sun; a stochastic signal is manifest as a cross-correlation of the noise in the gravitational-wave channel of two detectors with a frequency dependence characteristic of the separation between the detectors.

The principal tool for time series data analysis is linear filtering; correspondingly, the important computational operation are linear algebra operations, eigenvalue/vector analyses, discrete Fourier transforms, and convolutions. The eigenvalue/vector analyses do not involve high dimensional systems; however, the discrete Fourier transforms and convolutions can involve very long vectors: for periodic signal searches over a large bandwidth, the vector dimensions correspond to weeks to months of the gravitational-wave channel at full bandwidth.

To meet the estimated computational needs of LIGO data analysis, three Beowulf clusters of commodity personal computers will be constructed. Two of these, each sized to provide approximately 10 Gflops of sustained computing on a prototypical analysis problem (detection of a radiation burst arising from the inspiral of a compact neutron star or black hole binary system), will be located at the observatory sites in Hanford and Livingston; one, sized to provide approximately 30 Gflops of sustained computing on this same problem, will be co-located with the LIGO data archive (cf. §5). These Beowulf clusters form the computational muscle of the LIGO Data Analysis System, which is described further in §8.

### 7 Data access patterns

Access to data collected during LIGO operations places constraints on data organization, the mechanisms by which data are retrieved from the archive, and the mechanisms by which data are annotated. The challenges of manipulating a data archive as large as LIGO's requires that the archive organization archive organization and mechanisms for ingestion, access and annotation reflect the anticipated data access patterns. Many of these decisions regarding the data archive have not yet been made; consequently, in this section I can describe only the nature of the anticipated data access patterns that are considerations in these decisions.

"Users" of LIGO data comprise scientists searching for radiation sources and scientists monitoring and diagnosing instrument performance. (Scientists involved in the real-time operation of the detectors real-time instrument operations will require access to data as it is generated and before it is migrated to the central data archive. This does not directly affect the central data archive, but does affect the organization and accessibility of the data at each site.) Some of these user types sub-divide further: for example, searching for gravitational wave bursts requires a different kind of access than searching for periodic or stochastic gravitational wave signals. Each user type requires a different kind of visibility into the data archive. These patterns of access can be distinguished by focusing on

- data quantity per request,
- predictability of data requests,
- number of data channels per request,
- type of data channels requested.

The data access patterns for gravitational wave signal identification are expected to be quite complex. The character of burst, periodic and stochastic signals in the detector lead to access patterns that differ markedly in data quantity, number of channels, and type of data channels per request. Additionally, the analysis for signals of all three types will have an automated component, which makes regular and predictable requests of the archive for data, and a more "interactive" component, which makes irregular and less predictable requests of the archive.

Data analysis for burst signals generally involves correlation operations, wherein a signal template, describing the expected character of the signal, is correlated with the observed data. The correlations will generally be performed using fast transform techniques; consequently, the *minimum* period of time that a data request will involve is the length of a template. Since burst signals are expected to be of relatively short duration and the detector bandwidth is relatively large, the templates are themselves short. Consequently, the data requests are expected to be for segments of data of relatively short duration.

Periodic signal sources are manifest in the data as a frequency modulated but otherwise nearly monochromatic signal. The frequency modulation is determined entirely by the source's sky position. For these sources, the signal power is expected to be of the same magnitude of the noise power only when the instrument bandwidth can be narrower than at most 1/month. Thus, data requests associated with periodic signal searches will involve segments much longer than for burst sources.

Stochastic signals appear in the data stream of a single detector no different than other instrumental noise sources. They become apparent only when the data streams of two or more detectors are cross-correlated. For a schematic picture of how a stochastic signal is identified, let  $x(\tau)$  be the cross correlation of the gravitational wave channels  $h_1(t)$  and  $h_2(t)$  of two detectors; then

$$x(\tau) = \frac{1}{T} \int_{0}^{T} dt_1 h_1(t_1) h_2(t_2 + \tau)$$
(1)

for T large compared to the correlation time of the detector noise. The stochastic signal is apparent in  $x(\tau)$  as excess power at "frequencies" (inverse  $\tau$ ) less than the light travel time between the two detectors. For the two geographically distinct LIGO detectors, this corresponds to frequencies less than approximately 100 Hz. To detect a stochastic signal is to detect this excess power.

Estimates of the strength of possible stochastic signals suggest that detection might require years of data. Nevertheless, because the signal signature is the (incoherent) excess power the volume of data per request need not be great at all: data segments of duration seconds will be sufficient. What is unique about stochastic signal analysis, however, is that the analysis *requires* data from both the Hanford and Livingston interferometers simultaneously.

The automated component of the gravitational wave data analysis will make the greatest demands, by data volume, on the LIGO data archive: the full length of the gravitational wave channel, as well as a subset of the instrument and physical environment monitor channels will be processed by the system. These requests will be predictable by the archive; consequently, pre-reading and caching can be used to eliminate any latency associated with data retrieval for these requests.

As discussed in §9, data analysis will almost certainly be hierarchical, with an automated first pass selecting interesting events that will be analyzed with increasing levels of interactivity. At each stage of the hierarchy, the number of events analyzed will decrease and the volume interferometer data requested of the archive (in channels, not time) will increase. Shortly after operations begin we can expect that the analyses performed at each level of the hierarchy, except the upper-most, will be systematized, meaning that the requests, while less frequent, are still predictable. Thus, an event identified at one level can lead to the caching of all data that will be needed at the next level of the hierarchy, again eliminating the latency involved in the data requests.

Scientists who are diagnosing or monitoring the instrument can be expected to have similar access patterns to scientists searching directly for gravitational wave events. The principal difference is that the data volumes are expected to be smaller (the study is of noise, not signals of low level embedded in the noise) and the range of channels involved in the analysis larger (many of the diagnostic channels recorded will not directly influence the gravitational wave channel even if they are important for understanding and tuning the operation of the detector.)

Finally, an important class of users, especially as the observatories are coming on-line, will be more interactive users who are "experimenting" with new analysis techniques, or studying the characteristics of the instrument. (Interactive, in this usage, includes small or short batch jobs that are not part of an on-going, continuous analysis process.) These users, which include scientists searching for data, diagnosing or monitoring the operations of the detectors, will be requesting relatively small volumes of data, both by segment duration and by channel count.

## 8 Accessing and manipulating LIGO Data

User access to, and manipulation of, the LIGO data archive will be handled through the LIGO Data Analysis System (LDAS). While the general architecture of the LDAS has been determined, most of its design and implementation details have yet to be determined; consequently, in this section, I will describe LDAS only in the broadest of terms.

At the highest level, LDAS consists of three components: two "on-line" systems, one each at the Hanford and Livingston sites, and one "off-line" system located with the central data archive on the Caltech campus. The on-line systems are responsible for manipulating and providing access to data that has not yet been transferred to the central data archive, while the off-line system provides the equivalent functionality for data stored in the central data archive.

The bulk of LIGO data analysis will take place entirely within LDAS: users

will, generally, see only calculation results or highly abstracted or reduced summaries of the data. This capability is critical given both the sheer volume of the LIGO data as well as the geographically distributed LIGO Science Collaboration membership, which includes researchers based throughout the North America, Europe, Japan and Australia. Except for operations that involve exporting LIGO data to applications outside of LDAS (where issues of network bandwidth arise), LDAS is required to support users not physically co-located with the data archive in parity with local users. To meet this requirement the LDAS is being designed to be more than a data archive, library or repository: it is a remotely programmable data analysis environment, tailored to the kinds of analysis that is required of the full bandwidth LIGO data.

In the LDAS model, data analysis involves an action taken on a data object. The user specifies the data, the action, and the disposition of the results. At the user level there are several different ways of specifying the same data: *e.g.*, by epoch ("thirty seconds of all three gravitational-wave channel beginning Julian Day 2453317.2349"), by logical name ("Hanford magnetometer channel 13 of event CBI1345"), or by some selection criteria ("gravitational wave channels from Hanford-2 from Julian Day 2453238 where beamsplitter seismometer rms is less than 13.23"). There will be a variety of analysis actions available to the user, which may be built-up from a set of "atomic" actions like discrete Fourier transform, linear filtering, and BLAS-type operations. These operations are denoted "filters." Finally, the results of these filter actions on the data can be stored for further action, displayed in some fashion (*e.g.*, as a figure or table), or exported from the LDAS as light-weight data.

Figure 2 is a block diagram schematic of the LDAS system. The user interaction with LDAS will be through either an X11 or web-based interface. These two interfaces generate instructions to the LDAS in its native control language, which will be Tcl with extensions. Instructions to the LDAS are handled by the Distributed Data Analysis Manager. This software component is responsible for allocating and scheduling the computational resources available to LDAS. In particular,

- it determines what data is required by the user-specified operation and requests it from the appropriate data archives, which are shown below the Data Analysis Manager on the block diagram;
- it allocates and instructs the analysis engines (the Beowulf cluster) on the operations that are to be performed on the data, including pre-conditioning of the data stream (in the Data Conditioning Unit), generalized filtering operations (in the filter units), and event identification and management operations on the output of the filtering operations (in the Event Manager); and
- it disposes of the results of the analysis, either back into the data archive,

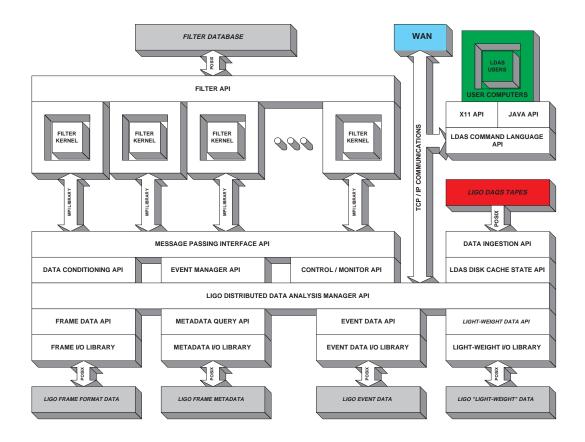


Fig. 2. Block diagram of the LDAS software components. With permission from LIGO-T970160-06.

onto a disk cache, or back to the user in the form of, e.g., a figure.

The Distributed Data Analysis Manager never itself actually manipulates the data; rather, it issues instructions to the other units that include where to expect data from and where to send results to. The other units (the data archives, the data conditioning unit, the filters and the event manager) then negotiate their own connections and perform the analysis as instructed.

#### 9 On-line and off-line data analysis

The LDAS sub-system installed at each LIGO observatory and at the central data archive will be functionally equivalent, although their relative scales will vary: the sub-system installed at the central archive will have access to data from all three interferometers and computing resources adequate to carry out more sophisticated and memory intensive analyses than the sub-systems installed at the separate observatories, which will only have access to data collected locally over the past several hours.

When operating as a scientific instrument, LIGO will acquire data automatically. Correspondingly, a significant component of the data analysis resources are devoted to an automatic analysis of the data carried out in lock-step with data acquisition. The details of that automatic analysis have not been decided on, nor has the disposition of the automatic part of the data analysis among the LDAS components at the observatories and the centralized data archive. Nevertheless, certain fundamental requirements that any data analysis system must fulfill suggest how the analysis workload at the observatories might differ from that undertaken at the central data archive and how the total data analysis workload might best be distributed.

A principal requirement of the data analysis system is that it maintain pace with the data generated by the instrument: unanalyzed data is no better than data never taken. Sophisticated data analysis can maximize the probability of detecting weak signals when present and minimize the probability of mistakenly identifying noise as a signal; however, the most sophisticated analyses cannot be carried out uniformly on all the data while still maintaining pace with data acquisition rates.

Another important consideration is that the computational resources placed at each site have access only to locally acquired data no more than several hours old. Computational resources located with the central data archive, on the other hand, are available to work with data from all three sites over nearly the entire past history of the detector: only data acquired during the immediate past several days, before it reaches the archive, will not be available for analysis.

This last caveat is an important one: while many potential gravitational wave sources are not expected to have an observable signature in more conventional astronomical instruments (*e.g.*, optical or  $\gamma$ -ray telescopes), some anticipated sources may very well have such a signature that follows a gravitational wave burst by moments to hours. In this case, prompt identification of a gravitational wave burst could be used to alert other observatories, allowing astronomers to catch some of these sources at early times in their optically visible life. Exploiting gravitational wave observations in this way requires onsite analysis, since data will not reach the central archive for several days after it has been acquired.

All these considerations suggest a two-pass strategy for data analysis. The first pass takes place at the observatory sites: in it, all data acquired during normal operations is subjected to quick, but relatively unsophisticated, analyses whose goal is to rapidly identify stretches of data that *might* contain a burst signal. No consideration is given, in the on-line system, to searching

for stochastic or periodic gravitational wave signals. In accepting the goal of identifying candidate burst signals in the on-site system, one willingly accepts a relatively high level of false alarms in order to achieve a relatively high detection efficiency.

The on-site systems can also monitor the detector behavior, identifying and flagging in the meta-data periods where detector mis-behavior disqualifies data from further analysis.

Periodically, then, analysis at the site will identify intervals that include candidate gravitational wave bursts. If an identified candidate is believed to be among the type that can be associated with observations at another astronomical observatory, a more sophisticated analysis can be triggered to determine the likelihood of an actual detection in this limited data interval. If the identified candidate is not of this kind, or if the more sophisticated analysis suggests that the event is not conclusively a gravitational wave, then the data segment can be flagged in the meta-data by the on-site system for later consideration.

Thus, the first pass of the data does three things:

- (1) it keeps up with the flow of data;
- (2) it flags data segments that bear at least some of the characteristics that we associate with gravitational waves;
- (3) it flags data segments as disqualified from further analysis for gravitational waves; and
- (4) it handles time-critical analyses.

The second-pass of the data takes place in the LDAS component co-located with the central data archive. Here we capitalize on the work performed at the sites by focusing attention on the "suspicious" data segments identified at the sites. The time available for this more critical and in depth analysis is expanded in proportion to the fraction of the entire data stream occupied by the suspicious data segments; additionally, the computational resources are used more effectively, because data from the two sites is available simultaneously to the analysis system.

Finally, analysis aimed at periodic and stochastic gravitational wave signals is performed exclusively in the off-site system. This choice is made both because the analysis is not time critical and the duration of the data that must be analyzed in order to observe evidence of a signal is long compared to the time it takes to move the data from the sites to the central data archive.

Thus, the second pass of the data

- (1) keeps up with the flow of *interesting* data;
- (2) introduces more critical judgment into the analysis process; and

(3) handles analysis tasks that are *not* time critical.

The apparently conflicting requirements of keeping up with the data flow while still maintaining a high degree of confidence in the final results are thus satisfied by splitting the analysis into two components. The first component identifies "interesting" data segments that are subjected to a more critical and time consuming — examination in the second component. The second component of the analysis takes place only at the data archive, where access to the entire LIGO data stream from both detectors is available, while the first component takes place at the individual sites where, only limited access to recent data from a single instrument is available.

### 10 Conclusions

LIGO is an ambitious project to detect directly gravitational waves from astrophysical sources. The signature that these sources produce in the detector output are not discrete event that occur at predictable times, but manifest themselves in weak but coherent excitations, lasting anywhere from seconds to years, that occur randomly in one or more "detectors". Correspondingly, the data acquired at LIGO are time series and the analysis depends on correlating the observed detector output with a model of the anticipated signal, or crosscorrelating the output of several detectors in search of coherent excitations of extra-terrestrial origin.

The duration of the signals, their bandwidth, and the randomness of their occurrence together require that LIGO be prepared to handle on order 400 TBytes of data, involving three detectors, per year of operation. The nature of the time-series analysis that will be undertaken with this data and the geographical distribution of the scientists participating in the LIGO Science Collaboration pose requirements on the data archive and on the analysis software and hardware.

Data collected from LIGO are divided into two kinds: frame data and metadata. Frame data is the raw interferometer output and includes instrument control and monitoring information as well as physical environment monitors. Meta-data includes operator logbooks, commentary, and diagnostic data about the data and the instrument: *i.e.*, it is data about data. (If the frame data is the Torah, then the meta-data is the Talmud.) As LIGO data is analyzed, a third category of data is created — "event" data, which includes results of intermediate analyses that explore the detector behavior, highlight a possible gravitational wave source, or set limits on source characteristics. As event data matures, it becomes meta-data: further commentary on the data. LIGO data analysis will be carried out by collaborating scientists at institutions around the globe. The character of the analysis and the volume of the data precludes any significant analysis being carried out on computing hardware local to a given collaborator. To support LIGO data analysis, a centralized LIGO Data Analysis System (LDAS) is being built, which is designed to support remote manipulation and analysis of LIGO data through web and X11 interfaces. In this system, significant amounts of data rarely leave LDAS: only highly abstracted summaries of the data are communicated to local or distant researchers.

Finally, there is an inherent conflict involved in the twin requirements of keeping pace with the flow of the data and maintaining high confidence in the conclusions reached by the analysis. This conflict is exacerbated by the geographical separation of the LIGO detectors: the bandwidth of the data generated at each site makes it infeasible to bring all the LIGO data together for analysis until several days after it has been acquired. By taking advantage of local computing at each site and the approximately one day that the data from each site is locally available, this conflict can be mitigated: data local to a site can be analyzed using tests of low sophistication, to identify subintervals of the LIGO time series that have "suspicious" character. After the data from the two sites is brought together at the central archive, more time consuming — but sophisticated — analyses can focus on those suspicious intervals.

It is a pleasure to acknowledge Kent Blackburn, Albert Lazzarini, and Roy Williams for many helpful and informative discussions on the technical details of the LIGO data analysis and archive system design. The ideas discussed here on the use of the on-line and off-line data analysis system have been informed by discussions with Rainer Weiss. This work was supported by National Science Foundation award PHY 98-00111 to The Pennsylvania State University.

#### References

- [1] J. H. Taylor, R. N. Manchester, A. G. Lyne, and F. Camilo. Catalog of 706 pulsars, May 1995. Available at (http://www.pulsar.princeton.edu).
- [2] Alex Abramovici, William E. Althouse, Ronald W. P. Drever, Yekta Gürsel, Seiji Kawamura, Fredrick J. Raab, David Shoemaker, Lisa Sievers, Robert E. Spero, Kip S. Thorne, Rochus E. Vogt, Rainer Weiss, Stanley E. Whitcomb, and Michael E. Zucker. LIGO: The laser interferometer gravitational-wave observatory. *Science*, 256:325–333, April 1992.
- [3] Kip S. Thorne. Gravitational radiation. In Stephen Hawking and Werner Israel, editors, 300 Years of Gravitation, pages 330–458. Cambridge University Press, Cambridge, 1987.

- [4] R. Bork and J. Heefner. Pem data acquisiton preliminary design. Technical Report LIGO-T970165-00-C, Laser Interferometer Gravitational Wave Observatory, LIGO Document Control Center, California Institute of Technology, October 1997. Internal working note.
- [5] Daniel Sigg and Peter Fritschel. LIGO channel count. Technical Report LIGO-T980004-00-D, Laser Interferometer Gravitational Wave Observatory, LIGO Document Control Center, California Institute of Technology, March 1998. Internal working note.
- [6] LIGO Data Analysis Group. LIGO metadata, event and reduced data requirements. Technical Report LIGO-T980070-02-E, Laser Interferometer Gravitational Wave Observatory, LIGO Document Control Center, California Institute of Technology, July 1998. Internal working note.
- [7] Matlab, a technical computing environment for high-performance numeric computations in linear algebra, is a product of The MathWorks, Inc.
- [8] LIGO Data Group and VIRGO Data Acquisiton Group. Specification of a common data frame format for interferometric gravitational wave detectors. Technical Report LIGO-T970130-B-E & VIRGO-SPE-LAP-5400-102, Laser Interferometer Gravitational Wave Observatory and The VIRGO Experiment, LIGO Document Control Center, California Institute of Technology, October 1997.