New Folder Name LIGO CDS

LIGO PROJECT

CALIFORNIA INSTITUTE OF TECHNOLOGY

Internal Technical Note	LIGO-T930001-01-C **CDS_N_001**	**v1.1a**	December 15, 1993
	number	*version*	*date*

Some preliminary notes on the LIGO Control and Data System (CDS)

subject

Volker Schmidt

author(s)

A. Abramovici, J. Camp, D. Durance, S. Kawamura, A. Kuhnert, F. Raab, R. Savage,
L. Sievers, R. Spero, K. Thorne, R. Vogt, S. Whitcomb, M. Zucker,
W. Althouse, V. Schmidt, G. Stapfer,
F. Asiri, J.. Chapsky, G. Hiscot, L. Jones,
P. Fritschel, Y. Hefetz, D. Shoemaker, R. Weiss

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1 Purpose

This note is intended as a trigger for further discussions. It lists, in a rather unstructured way some of the ideas which come to my mind when trying to organize my work. Please do not take it as specification or anything definite. It is a basis for discussions and I would appreciate receiving your comments and other reactions. Please check whether the emphasis is on the arguments you think it should be. Check it especially for things which are completely missing.

2 Structure of LIGO

LIGO, as seen from the Control and Data System (CDS), is structured in sites, systems, subsystems, local units, etc. The essential feature of this subdivision is to organize it in such a way as to minimize the cross connections between the various units. Cross connections can be:

- functional connections
- physical connections (e.g. optical path)
- signal (cabling) connections

The functional subdivision will normally not reflect the physical structure of LIGO.

3 Functional description of LIGO

In order to be able, to specify the LIGO CDS, the LIGO plant has to be described in a functional way giving all necessary information for interfacing it with CDS. This functional description, while geared towards the interfacing with CDS, will certainly be useful for other purposes as well.

The functional description will be organized according to the functional structure mentioned above. It will be a top-down description of all units which may require connections to CDS. For convenience it is advisable to extend the same type of functional description also to those units of LIGO which will not be connected to CDS. The description has to take into account not only the connections necessary for normal operation of LIGO, but also the needs during commissioning and troubleshooting of the plant.

The functional description will be organized by plant items, not according to the types of equipment. This will potentially increase the size of the description, but this can be limited by using cross references to the description of similar units.

Each unit has to be described in terms of

- name of the unit
- who is responsible for the unit
- short description of component units
- location of the equipment
- list of units to which to be connected functionally
- commissioning procedure
- normal operation procedure
- detailed description of the remote/local operation
- Maintenance requirements (relevant to CDS)
- detailed signal list for all external connections
- functional code (see page 7)

3.1 Unit Name It is important to establish unique and clear unit names. Similar objects in different parts of the system should be named with similar terms.

3.2 Unit responsibility Each unit should have clearly assigned responsible person(s) who are familiar with the unit to a sufficient detail, to be contacted for any query concerning the unit.

3.3 Unit component description This is normally a short description of the physical components, their spacial arrangement. It often consists of lists of items giving make and type of equipment.

3.4 Location of the equipment This is a description of the physical lay-out of the unit, indicating the relative and absolute positions of all components.

For the definition of locations it is very useful to agree on a universal coordinate system for the entire LIGO.

3.5 Functional description The functional description is normally arranged into three sections:

- functional connections
- normal operation
- commissioning
- maintenance and troubleshooting

The functional connections regard connections between parts of the same unit and connections with other units.

The description of normal operation should include all possible aspects of routine operation, including possible automatic start-up procedures, alignment procedures, etc.

The commissioning aspects regard both the initial commissioning of the plant as well as the re-commissioning after a plant shutdown (either planned or unexpected)

An important aspect is to consider from the beginning the unit's operational aspects for planned maintenance and for troubleshooting. In the present context it is important to define early in which of these operations CDS can or should be involved and which of them are to be executed exclusively in local mode (see page page 14).

3.6 Signal lists The most important tool for interfacing CDS with the LIGO plant are comprehensive signal lists. These signal lists should be established very early in the definition procedure. In the initial phases of the project they should be considered as working tools not as reference documents.

The signal lists should include for every single signal at least the following information;

- unique signal name
- unique signal code (see page 7)
- signal description
- source unit
- destination unit
- type of signal (analogue, digital with number of bits, ...)
- input or output (with respect to CDS)
- for analogue signals:
  - signal type (voltage, current)
  - signal range
  - frequency of signal
  - sampling frequency or frequencies
  - for analogue plant monitoring signals in addition:
    - lower alarm threshold
    - lower notification threshold
    - upper notification threshold

    - upper alarm threshold
- signal storage requirements (for fast signals)
- trend recording requirements (for slow signals)

In order to be able to handle the enormous amount of information (my estimate is that there will be certainly several thousand signals) the use of a flexible, user-friendly and powerful database is required from the very beginning. This signal database will initially contain only a restricted number of fields for each entry. It will grow in both "directions": the number of signals will increase as more components of the plant are added; it will increase possibly even more "horizontally" in step with the increased level of detailed information available for each signal.

The signal database will eventually have to be linked to the other databases described below (see pagepage 7). The signals will have to "connected" to the (copper or fibre optic) cables on which they travel. These cable in turn will be "connected" to physical units.

4 Plant structure

It has to be decided whether to aim at a plant functional structure with a fixed number of layers or an open number of layers. This influences on the naming conventions (see page page 7).

I could envisage a fixed three layer structure for the functional description of LIGO, and consequently of CDS:

- site:
  (Hanford. Livingston, Caltech, MIT)
- subsystem
  (Vacuum, General Services, Auxiliary Physics, Interferometer #n, ...)
- local unit
  (Prestabilized Laser, Mode Cleaner, Conditioning Optics, Optical Interferometer, Auto-Alignment, ...)

A rough estimate indicates that there would be about 22 subsystems. I do not know how many local units there will be per subsystem. A desirable number would be around 20.

Figure 1 shows a tentative functional block diagram of LIGO. This illustrates the concept of site and subsystem subdivision. In this figure I have subdivided each of the remote sites in the following way.

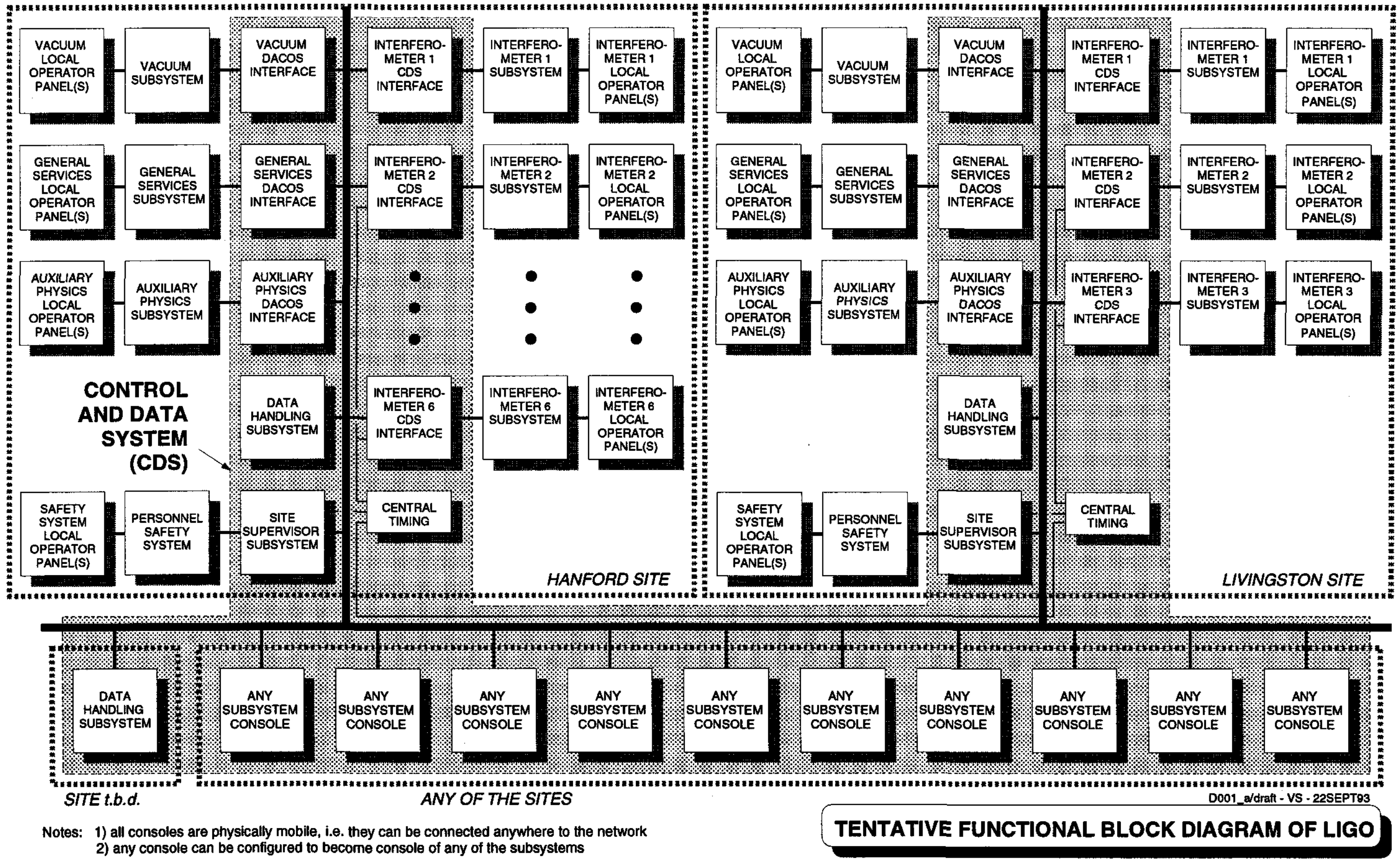

VACUUM LOCAL OPERATOR PANEL(S)
VACUUM SUBSYSTEM
VACUUM DACOS INTERFACE
INTERFERO-METER 1 CDS INTERFACE
INTERFERO-METER 1 SUBSYSTEM
INTERFERO-METER 1 LOCAL OPERATOR PANEL(S)
GENERAL SERVICES LOCAL OPERATOR PANEL(S)
GENERAL SERVICES SUBSYSTEM
GENERAL SERVICES DACOS INTERFACE
INTERFERO-METER 2 CDS INTERFACE
INTERFERO-METER 2 SUBSYSTEM
INTERFERO-METER 2 LOCAL OPERATOR PANEL(S)
AUXILIARY PHYSICS LOCAL OPERATOR PANEL(S)
AUXILIARY PHYSICS SUBSYSTEM
AUXILIARY PHYSICS DACOS INTERFACE
INTERFERO-METER 3 CDS INTERFACE
INTERFERO-METER 3 SUBSYSTEM
INTERFERO-METER 3 LOCAL OPERATOR PANEL(S)
CONTROL AND DATA SYSTEM (CDS)
DATA HANDLING SUBSYSTEM
INTERFERO-METER 6 CDS INTERFACE
INTERFERO-METER 6 SUBSYSTEM
INTERFERO-METER 6 LOCAL OPERATOR PANEL(S)
SAFETY SYSTEM LOCAL OPERATOR PANEL(S)
PERSONNEL SAFETY SYSTEM
SITE SUPERVISOR SUBSYSTEM
CENTRAL TIMING
HANFORD SITE
LIVINGSTON SITE
ANY SUBSYSTEM CONSOLE
SITE t.b.d.
ANY OF THE SITES
D001_a/draft - VS - 22SEPT93
Notes: 1) all consoles are physically mobile, i.e. they can be connected anywhere to the network
2) any console can be configured to become console of any of the subsystems
TENTATIVE FUNCTIONAL BLOCK DIAGRAM OF LIGO

Figure 1

4.1 Vacuum subsystem The vacuum subsystem includes the entire vacuum plant with all its auxiliaries independently of their location on site.

At present I do not know whether there will be just one CDS interface with "the" vacuum system or there will be a number of CDS components interfaced to various units in the vacuum system. The main difference between the two options is that in the first case the vacuum system is a single system capable of complete operation without the presence of CDS. In the second case centralized operation of the system requires the availability of CDS.

4.2 General Services subsystem This system could contain the following units:

- monitoring of the electrical mains
- temperature monitoring in various places
- general information on the operational status of equipment
- interface with building monitoring system (see page page 15)
- interface with closed circuit TV (see page page 18)

4.3 Auxiliary Physics subsystem

This subsystem could re-group a number of auxiliary measurements required for the interpretation of the interferometer data. It will contain the following measurement units:

- seismic measurements
- ambient noise measurements
- cosmic ray measurements

4.4 Personnel Safety Subsystems The Personnel safety systems (see page page 15) are completely independent subsystems whose status information is made available to CDS. No commands can be issued by CDS to the personnel safety systems.

4.5 Interferometer subsystems At present I would imagine that each Interferometer, including its auxiliaries constitutes one subsystem. Each Interferometer is composed of the following local units:

- prestabilized laser
- mode cleaner
- conditioning optics

- optical interferometer
- auto-alignment
- suspension
- seismic isolation

4.6 CDS "subsystem" CDS is to be formally considered another subsystem of LIGO. Internally it is structured according to the LIGO plant to which it is connected (see page page 12)

5 Coding Conventions

We should establish very soon coding conventions for the entire LIGO. This applies to everything from entire subsystems down to signal names. The purpose is mainly to create a unique identifier for every single object we may be talking about.

When establishing a coding convention, one has to select basically between mnemonic and non-mnemonic (numbering) schemes. There is an infinity of possibilities. My personal preference is for mnemonic systems. They are generally better accepted by users and are less error prone. On the other hand they have two disadvantages:

- they are less economic in length which costs computer power and memory (but both are cheap today)
- only the first codes which you assign are obvious, and you quickly come to situations with naming conflicts

Another important aspect is the careful distinction between type description and type naming convention as opposed to item description and naming. For example the Draft ICD Handbook is a type description of one interferometer subsystem. In LIGO there will eventually be nine of these units; therefor there will be only one type description, but nine item based descriptions.

6 Database

In order to handle the information compiled in the functional descriptions, we need a suitable database which will initially contain things like:

- signal descriptions
- unit names

This database will quickly grow and contain information on various aspects of the plant, like

- cables,
- equipment types
- equipment items,
- location of equipment

7 Tasks of CDS

The tasks of CDS are to provide the following functions to the LIGO plant:

- acquisition of physics data
- handling of physics data
- acquisition of plant status data
- handling of plant status data
- handling of plant alarms
- remote[1] plant start and stop
- remote plant diagnostics
- remote plant operation
- data transfer to remote sites (other organizations)

CDS does not provide the following functions:

- feedback control
- personnel safety functions

7.1 Physics data acquisition This is the prime task of CDS: the acquisition of data from

- the interferometers
- auxiliary physics measurement (seepage 6)

7.2 Physics data handling The physics data handling system receives acquired data from all subsystems which produce physics relevant data. The data are continuously monitored for suspect events.

Some data channels are continuously stored. Other data channels are only completely stored if they were collected during time windows around suspect events. If they were not acquired during such a window, they are stored in a drastically reduced form.

[1] for definition see page 14

All acquired physics data require

- short term storage
- continuous analysis

All data to be fully stored require

- packaging
- "shipment" to long term storage

All data to be stored in reduced form require

- data reduction
- packaging
- "shipment" to long term storage

7.3 Plant data acquisition CDS monitors the status of the entire plant on a continuous base. This includes data from all relevant plant components. CDS maintains a complete plant status image (PSI). PSI is the base for all plant related activities of CDS (commands and monitoring).

7.4 Plant data handling Plant data handling provides the functions:

- continuous monitoring of analogue signals
- continuous monitoring of digital signals
- alarm generation

Typically the continuously monitored signals are checked on whether they are within allowed limits. If warning or alarm thresholds are exceeded alarm messages are generated and sent to the operator consoles.

7.5 Remote plant operation CDS provides the tools for remotely operating the entire plant. This includes

- issuing of single commands to single units under human operator control and responsibility (remote manual mode)
- the generation of automatic or semi-automatic sequences of plant commands (remote automatic mode)

In both cases plant interlocks are implemented within CDS. Please note that these interlocks have to be backed up in the local units (see page 15). A typical problem in this area is to decide which interlocks to build in and how to allow for bypassing them.[2]

7.6 Operator Interface

Consoles provide the only operator interface to LIGO in remote operation. Consoles are interacting with the plant via the corresponding CDS subsystems. Consoles are not involved in any other plant related activities. All plant related automatic processes run on the subsystem components of CDS. Consoles are the only user interfaces to these processes. The basic concept is that the failure of a console or console-subsystem connection does not alter the plant status nor does it interrupt plant operation.

Consoles can be expected to be subsystem-dedicated, i.e. one console can issue commands to all components of exactly one subsystem. No console is allowed to issue commands to more than one subsystem. This is necessary to avoid conflicts in plant commands. Consoles may read data from any subsystem at any time (provided that such reading does not change the subsystem status).

Re-assigning a physical console to another subsystem is possible but is not considered part of normal operation.

Consoles that interact with physics data acquisition components may functionally be different from those which interact only with the plant components. It could well be that there will be two types of consoles (identical hardware, but running different software):

- plant operation consoles
- physics data consoles.

7.6.1 Plant operation consoles Plant operation consoles provide the following functions:

- access to plant status information by means of
    - mimic diagrams
    - signal lists

[2] My experience is that people put a lot of interlocks in which they need to take out afterwards or which they bypass afterwards, especially in non-operating situations (commissioning and troubleshooting)

- issuing of commands to the plant
- alarm handling
- trend recording for slowly changing signals (e.g. temperatures, pressures)

7.6.2 Physics data consoles Physics data consoles provide all functions of the plant operation consoles, plus the following functions to handle "fast" data:

- data display
- access to all data handling programs

8 Requirements for CDS

There are a number of general requirements for CDS most of which stem from the fact that LIGO is a large installation, and not a laboratory experiment; at the same time it is a physics experiment which will change over time.

One basic problem of CDS is the fact that its expected lifetime (one computer generation is about five years) is much shorter than the expected lifetime of the plant to which it is interfaced (20 years). There is no recipe to overcome this (unless you decide to burn down LIGO once its computer system is outdated).

The following is a general list of requirements which apply to both hardware and software components of the system.

8.1 Modularity The system should not be monolithic; it should be build in a modular way from well defined building blocks. This allows for an easy increase of the power of the system and for the gradual modernization by replacing components.

8.2 Flexibility The system has to be extremely flexible in order to be able to cope with future requirements of the experiment. LIGO is as big as an industrial plant, but it is a physics experiment.

8.3 Expansibility LIGO will grow with time. The signal numbers per unit will grow with time. Requirements are initially nearly always underestimated[3].

[3] I lived a beautiful example of this: In 1978 when I joined the JET fusion experiment, physicists there estimated the amount of data per shot to be around 200 kBytes; JET today acquires routinely around 20 MBytes per shot

8.4 Reliability LIGO and its CDS have to be reliable for two important reasons: LIGO is required to operate on a 24-hour / 365-day basis in order to be useful especially when in coincidence mode. LIGO is large and access to plant components is tedious and time consuming.

8.5 Internal standardization The limitation of the number of different types components (internal standardization) helps meeting all four of the before mentioned requirements.

8.6 Industry standards

The use of industry standards wherever possible, often reduces the development cost and risk, and again normally improves reliability. In addition it renders the system, if well chosen, more resistent against changes in the market place.

8.7 Compatibility with other experiments Compatibility with other institutions (mainly VIRGO) is another requirement which has both technical and commercial reasons.

8.8 Standardization of local interfaces The standardization of the interfaces (signals) between CDS and the local equipment is an important aspect of the local unit design.

8.9 Self-diagnostics In order to make the system reliable, CDS has to be equipped from its very beginning with extensive self-diagnostics.

9 Structure of CDS

CDS has to reflect the structure of the plant to which it is connected.

As LIGO, it will internally be organized in systems, subsystems , local units, etc. Many of these will correspond one-to-one to components of the LIGO plant. In addition, there will also be units which do not correspond to plant components. (examples: internal diagnostics unit for CDS, all hardware components of CDS)

As mentioned before, CDS is to be formally considered another subsystem of LIGO. At present I can see the following functional structure (see Figure 1):

- site supervisor systems
    - subsystem interfaces
        - local unit interfaces

In addition to the CDS components which structurally correspond to plant units there are some components which do not have such counterparts:

- supervisor systems
- timing system(s)
- data handling subsystems (see page 8)
- operator consoles (see page 10)

9.1 Supervisor systems At both remote sites the local CDS equipment will work functionally under a supervisor system. Tasks of the supervisor systems include:

- status monitoring of all CDS equipment at the site
- interface to the local personnel safety system
- handling of the site timing system

9.2 Timing System The Timing System provides precise time reference for all data acquisition channels independent of their location. It consists of two separate timing systems at both observatory sites. The two systems are synchronized.

The system precision is xxx μs.

Timing system information at the sites is locally transmitted via fibre optic cables.

Timing system synchronization between sites uses the GPS satellite based system.

9.3

10 Local unit requirements

All local units should be as self-contained as possible. This means they should have as few external links (both functional and physical) as possible. They should be equipped with extensive self-diagnostics.

It has to be carefully checked whether some subsystems should also be required to be capable of local operation without the availability of CDS. I could imagine that such a requirement has to be put to the vacuum system.

11 Modes of Operation

Local units or subsystems may work in different modes of operation:

- local mode: in this case the equipment is operated by an operator near to the equipment using manual controls typically arranged on a local control panel
- remote mode: in this case the operator uses (a part of) CDS; he operates the equipment from a CDS console.

The term remote refers to the fact that the equipment is operated not directly by the operator, but through (parts of) CDS.

Remote mode operation can be carried out in different ways: Remote operation can refer to the plant in normal operation as well as under commissioning or troubleshooting.

Remote operation can be executed from consoles placed in different locations ("mobile consoles"): the console can be

- near the equipment
- in the site control room
- at a remote site (Caltech, MIT, anywhere on Internet)

It can be envisaged that normal operation will take place from consoles in the site control room in Hanford and Livingston.

It is obvious that the mobile console concept requires that at any time only one console may be active for a given subsystem. Care has to be taken to avoid multiple consoles.

The fact that a unit can be operated either remotely or locally requires that all units be equipped with a local/remote switch. There are two problems related to this:

Care has to be taken in assigning which entities can be placed independently from each other in either remote or local mode; basically the choice is between a single switch for an entire subsystem (unlikely!) or at the local unit level or even below that (if more levels were to be defined). My experience is, that you can commit big errors here!

The second aspect is the secure handing of the handing over control from local to remote and vice versa. Imagine a simple key operated local/remote switch on a local panel somewhere on the site. You have to guarantee that you cannot put the unit into remote without being sure, that the corresponding part of CDS is operational. Vice versa you should not be able to put the unit into local mode without the consent of the CDS or its operator. There are local/remote interlock schemes for handling these cases, but they have to be built-in from the beginning, a retrofit is prohibitively complicated (and will never be done).

12 Plant protection

CDS will provide all necessary plant monitoring facilities to provide the remote operator with the necessary information. It will provide all possible interlocks for the operation of the plant.

But CDS cannot guarantee the protection of the plant in case of plant faults or external intervention nor can it guarantee to be itself absolutely fault-free. All local units have to be designed with a maximum of built-in self-protection. No local unit may depend on CDS for its own integrity. This includes necessary protection also against failure (erroneous action) of CDS.

It has to investigated, whether an independent, centralized second layer of plant protection is required for LIGO. Such a system should be very robust and possibly crude. Its tasks are to intervene and prevent any major damage to the plant (not to people — see below).

13 Personnel Safety

CDS cannot provide functions which are required to protect people from possible dangers. Personnel safety has to be provided by independent measures. This does not exclude that CDS may provide an additional layer of interlocks intended also for personnel safety.

14 Building Monitoring

It has to be decided whether or not to incorporate the tasks of general building monitoring (of those parts of the buildings which are not LIGO-operation related) into the CDS. Such building monitoring tasks can regard:

- fire detection system
- indoors climate in various locations
- outdoors meteorological conditions
- doors
- status of electrical supply

As the LIGO sites will eventually be operated on a 24-hour / 365-day basis, it is well conceivable that such building monitoring should be incorporated into CDS especially as the same type of monitoring is to be done for the LIGO-operation related buildings in any case.

Another solution could consist in buying a turn-key building monitoring and alarm system and interfacing it (partially) to CDS (A minimum of interfacing is required in any case, e.g. monitoring of plant mains supply).

A specific problem with turn-key systems will be cabling, as LIGO presents longer distances than most of these systems are made for (no fibre optic transmission).

15 Physical Lay-out

The physical arrangement of CDS equipment is in principle independent of the functional arrangement. However there will be many cases where the functional requirements are difficult to fullfil in their ideal form. The main aspects which will play a role are:

- space limitations
- accessibility of equipment
- signal transmission speed limitations
- signal transmission quality considerations
- "cross talk" between critical LIGO components and components of CDS
- cost

15.1 Field equipment In placing the CDS field equipment a number of factors are important:

- fast electrical signals require short connections
- it is easy (and cheap) to transport digital signals over long distances on fibre optic cables; this applies generally also to computer networks
- the use of fibre optic transmission for analogue signals is normally much less attractive; the cost of these links is high and often technically unsatisfactory (drift problems)
- accessibility could well become a key issue; if CDS equipment is placed near to LIGO interferometer components, any access to this equipment may disturb the operation of LIGO

15.2 Control room(s) While all CDS consoles are, in principle, mobile, they will normally be placed in control rooms. I envisage three control rooms for LIGO:

- Caltech Remote Control Room

- Hanford Site Control Room
- Livingston Site Control Room

The consoles could be arranged as follows:

- Caltech Remote Control Room
    - central data handling console
- Hanford Site Control Room
    - Hanford Supervisor console
    - Hanford Vacuum console
    - Hanford General Services console
    - Hanford Auxiliary Physics console
    - Hanford Interferometer 1 console
    - Hanford Interferometer 2 console
    - Hanford Data Handling console
- Livingston Site Control Room
    - Livingston Supervisor console
    - Livingston Vacuum console
    - Livingston General Services console
    - Livingston Auxiliary Physics console
    - Livingston Interferometer 1 console
    - Livingston Interferometer 2 console
    - Livingston Data Handling console

15.3 Data handling computers The data handling tasks may require considerable on-line computing power. This may lead to the necessity of having the computers placed in proper "old-fashioned" computer rooms with strict air conditioning requirements and space for storage of tape archives.

15.4 Cabling Cabling is a humble but important aspect of CDS.

Cables and connectors should be standardized a much as possible. This is especially true for fibre optic cables. An efficient policy in this field saves a lot of money and effort[4].

4 this applies obviously also to non-CDS activities

Another aspect is that one should not forget cabling requirements in the early phase of space assignment. It is highly recommended to provide a freeway-like system of cable trays from the beginning. This is especially true for LIGO which has a very unusual lay-out. Separation of the cable trays according to either cable type or signal type is useful.

16 Closed circuit TV

LIGO will have one or more closed circuit TV systems. It is important to find a clear understanding on whether any of the systems may ever be required to be connected to CDS.

Index

BATCH START

STAPLE
OR
DIVIDER

Comparison of 2 Fixed Mass Interferometer Testbeds and the Resulting Recommendation for the Initial LIGO Interferometer Design

David Shoemaker, Joe Giaime,
Fred Raab, Martin Regehr, Lisa Sievers

September 23, 1993

LIGO-T930001-00-D

Objective and Overview

To arrive at a recommendation for an initial LIGO interferometer design, experimental and analytic/numerical work has been performed on two trial schemes. A summary of the results to date of that research is presented here, with the objective of moving toward a selection of a single scheme for further refinement (through experiment and modeling) and ultimately a design of the initial LIGO optical topology and modulation system.

The basic optical layout of a power recycled Michelson with Fabry-Perot cavities is shown in Figure 1. **The differences in the schemes discussed in this write up, lie in the means for sensing the distances between the optical components.** The most important is the differential cavity motion ($L_1 - L_2$ in Figure 1), which is the **readout system for the gravitational waves (GW).** In addition, '**auxiliary lengths**' consisting of the near mirror Michelson path length difference ($l_1 - l_2$), the cavity common mode motion ($\frac{L_1+L_2}{2}$), and the recycling cavity length ($\frac{l_1+l_2}{2}$) must all be controlled.

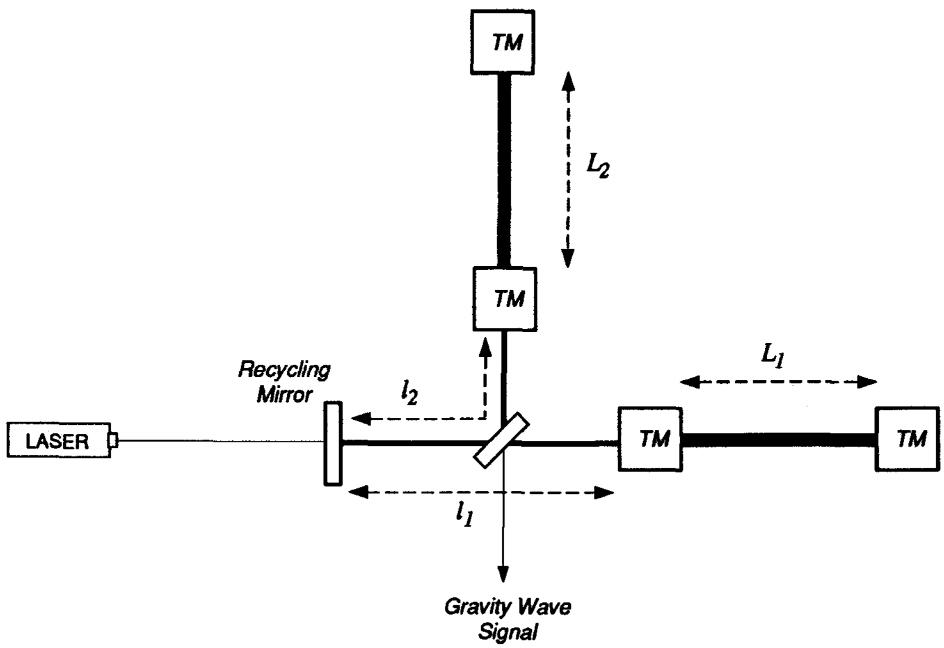


Figure 1 Optical layout of a power recycled Michelson with Fabry-Perot cavities.

Experiments have been performed on two Fixed Mass Interferometers (interferometer setups on optical tables) which have tested two complete schemes for the LIGO interferometer, the Asymmetry and the MZ/Subcarrier schemes. These are described on pages 3–6.

Tables describing the experiments and calculations performed to evaluate and compare the two schemes, and significant issues that have not yet been satisfactorily addressed, follow on pages 7 and 8.

Because each of the two complete schemes which were tested experimentally contain separable elements which can be independently employed in the LIGO interferometer, the Synopsis and Discussion on pages 9–11 compares the GW readout methods, and auxiliary length sensing systems for lock acquisition and operation, separately.

The Recommendation of the team working on this task (pages 12–14) selects a GW readout system, and a lock acquisition auxiliary readout system. It leaves open two options for the choice of auxiliary readout system for the operational mode.

An outline of the additional work which is necessary to arrive at a LIGO interferometer design is shown on page 15.

An index of the working documents and contact people for more detailed technical information is in preparation as an appendix.

Description of the Asymmetry and MZ/Subcarrier Schemes

Asymmetry Scheme

1. Signal Extraction (see Figure 2)

   1. Gravity Wave Signal $(L_1 - L_2)$:

      - Sidebands at the antisymmetric output are produced by a common mode phase modulation before the interferometer and an asymmetry in the near mirror interferometer ($l_1 - l_2 \approx 60$cm). This asymmetry is chosen so that the loss in the modulation sidebands due to the asymmetry approximately equals the carrier loss on reflection from the cavities.
      - GW signal is extracted by demodulating antisymmetric port photocurrent

   2. Auxiliary Length Signals

      - extracted by demodulating photocurrent at two additional optical outputs:

        1. A signal from light reflected back towards laser
        2. Two signals are obtained from the pick-off inside recycling cavity (signal is demodulated both 'in phase' and also in 'quadrature phase').

           The pick-off quadrature phase output responds to $l_1 - l_2$, since changes in this degree of freedom enlarge one sideband and diminish the other.

           In phase output responds both to $L_1 + L_2$ (since carrier phase changes with this degree of freedom) and to $l_1 + l_2$ (since carrier and sideband phases change, but at different rates, with this degree of freedom).

      - 'Recycling cavity length', $l_1 + l_2$, signal (and, if demodulation phase not precisely set, 'Michelson near mirror difference' signal, $l_1 - l_2$) only available in linear combination with 'average arm cavity length' signal, $L_1 + L_2$.

2. Servo Systems:

- Signals are fed back to the laser frequency controller and the two arm cavity end mirrors, the beamsplitter, and the recycling mirror as shown in Figure 2.

3. Locking Techniques

- Fixed Mass Interferometer: beam splitter servo loop broken, beam splitter moved back and forth through at least one order until resonant condition established. At this point, beam splitter servo loop re-connected. Works very reliably in tabletop experiment (typical time to reacquire is less than one second). Mechanism not understood.
- LIGO Hanging Interferometer: it is not known whether this same procedure will work in LIGO.

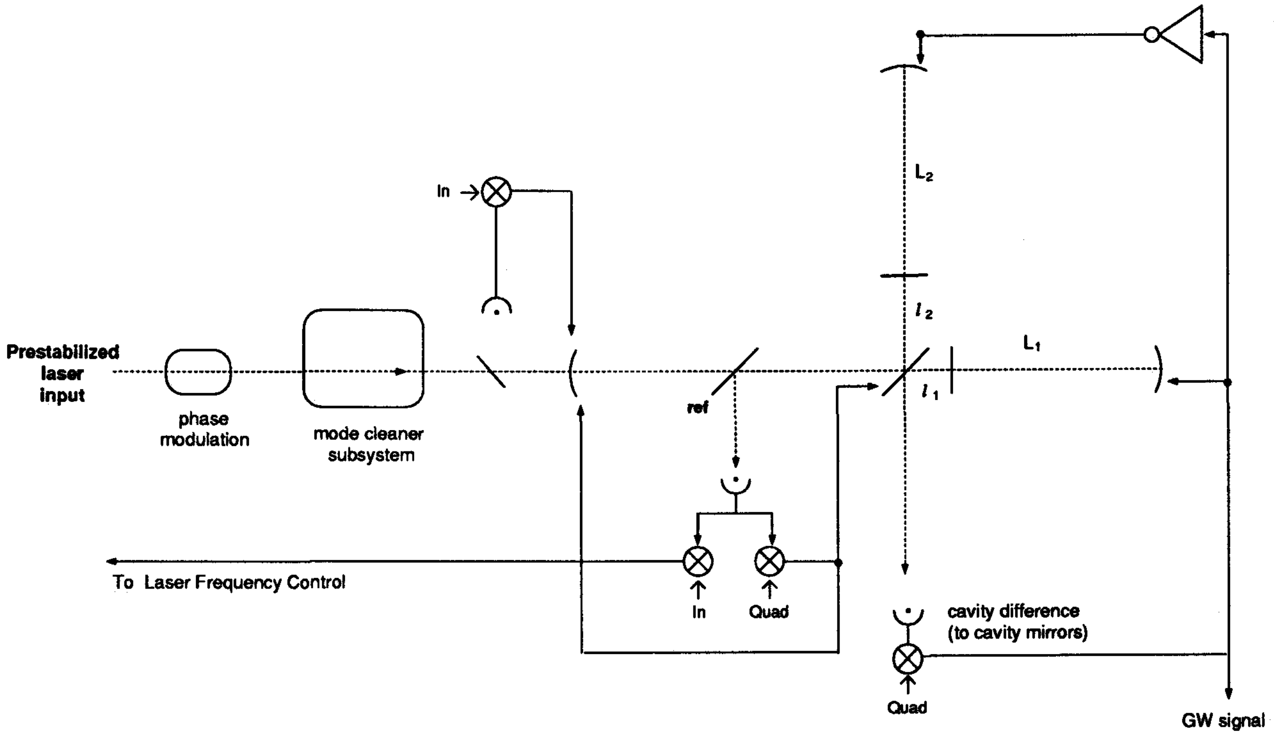


Figure 2 Schematic of a LIGO Asymmetry Scheme Showing Optical Layout, Modulation, and Control Signal Paths.

MZ/Subcarrier Scheme: Mach-Zehnder Gravity Wave Readout and Subcarrier Auxiliary Readout

1. Signal Extraction (see Figure 3)

1. Gravity Wave Signal

   - The GW signal is detected by comparing the antisymmetric port phase with an RF phase modulated reference beam (at f_3) in a Mach-Zehnder interferometer.

2. Auxiliary Length Signals: There are four auxiliary lengths to be detected, two which use the carrier light, and two which use a frequency-shifted subcarrier (FSS). The FSS is at a frequency which is not resonant in the arm cavities and so only senses motion of the near mirrors.

   - The common-mode cavity error, $L_1 + L_2$, appears as the phase of the cavity light emerging from the symmetric port of the main BS, and circulating in the RC. This phase is detected by comparison with phase-modulation sidebands at f_1, on PD5.
   - The error signal used to hold the MZ at mid-fringe is derived from the carrier f_1 sideband light emerging from both ports of the main BS. A $2f_1 + f_3$ term on the PD2 and PD3 contains the signal.
   - The length of the RC is obtained with a phase modulation at f_4 which is imposed on the FSS; f_4 is chosen so these sidebands reflect from the RC. This is sensed at PD1.
   - To measure $l_1 - l_2$, a modulation of the FSS at f_2 and a small asymmetry ($l_1 - l_2 \approx 1\text{cm}$) is used (as for the GW signal recovery in the asymmetry scheme). This is sensed at PD4.

2. Servo Systems: Signals are sent to the two arm cavity end mirrors, the Michelson beamsplitter, the recycling mirror, the Mach-Zehnder beamsplitter, and the laser frequency controller as shown in Figure 3. (Although the laser frequency feedback loop is not needed for the operation of this servo design it is required for meeting the specs on stability of the light at the input of the interferometer).

3. Locking Techniques:

- Fixed Mass Interferometer:

  The Michelson interferometer is brought near the dark fringe. The recycling cavity loop is brought to within $\lambda/2$ of resonance and the loop is closed. The arm cavities are adjusted to be out of resonance for the FSS (the natural mirror motions are such that in the FMI they remain so for ≈ 1 minute; in LIGO ≈ 10 seconds). The Michelson and MZ loops are closed. The arm cavities are brought within a linewidth of resonance and the arm common-mode loop closed. The arm differential-mode loop is closed.

- LIGO Hanging Interferometer: it is not known whether this same procedure will work in LIGO.

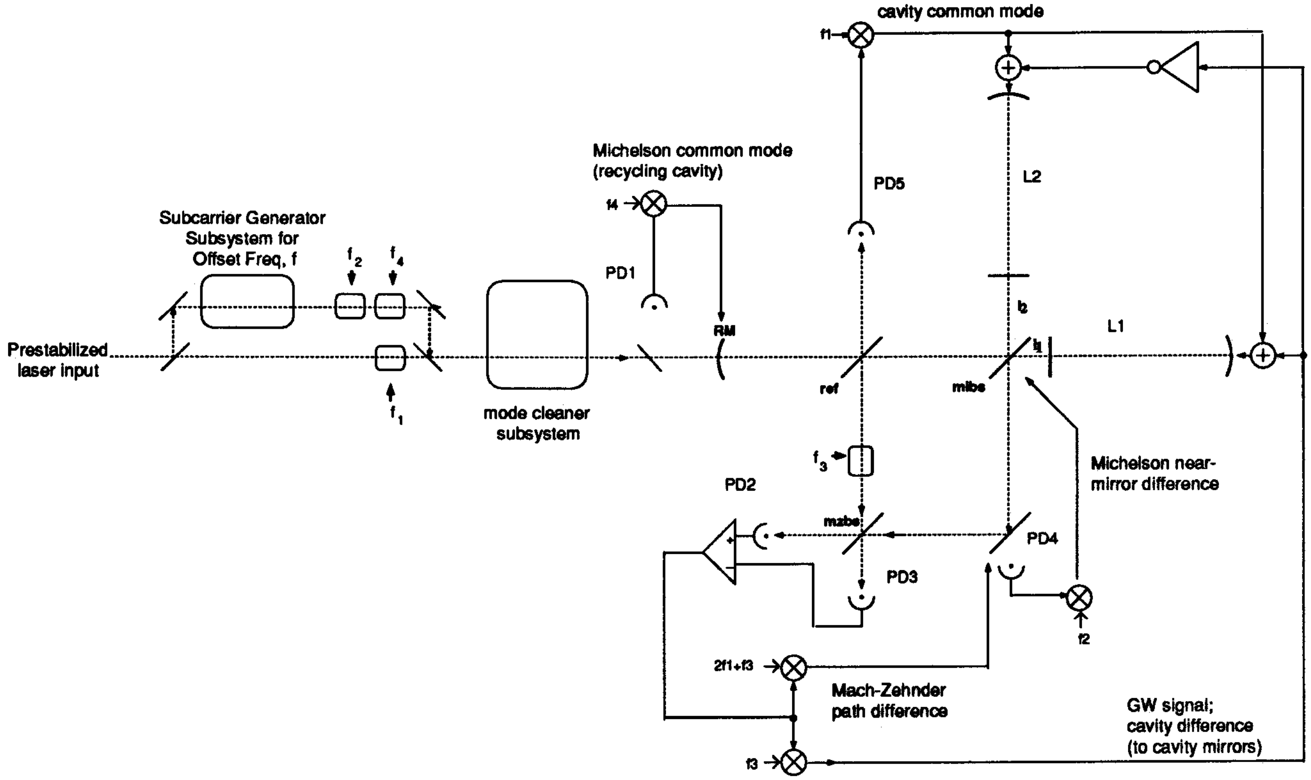


Figure 3 Schematic of a LIGO MZ/Subcarrier Scheme Showing Optical Layout, Modulation, and Control Signal Paths.

Experimental Tests and Calculations/Modeling Done for Verifying Feasibility of the Two Schemes

TESTS		ASYMMETRY SCHEME	MZ/SUBCARRIER SCHEME
Shot Noise Sensitivity	**Calc.**	The two schemes were identical over a set of parameters corresponding to probable scenarios for LIGO.	
Low Frequency Optical Response	**Exper.**	Agreement between model and experiment within a factor of ≈ 2 (likely experimental error) of optical response between end cavity mirror and GW signal. Other signals not yet verified.	Most (i.e. 23 of 25) matrix elements relating motions and signals measured. The diagonal elements (including GW signal) agree to factor of ≈ 3 to 4 (likely experimental error). Unexpected sensitivity of subcarrier (FSS) signals to near cavity mirror motion.
	Calc.	Calculations for both schemes have been completed and models showed no surprises	
High Frequency Optical Response	**Exper.**	It is very difficult to conduct experiments on short cavities to verify high frequency response. No experiments have been succesfully done to test model.	
	Calc.	Numerical model complete; no surprises. Analytical derivation supports numerical model qualitatively (not yet compared in detail)	GW frequency response expected to be the same as for Asymmetry Scheme.
Mechanisms for Noise Coupling Due to Asymmetry	**Calc.**	Analyzed in some detail: frequency noise coupling, mode matching loss, intensity noise coupling, beam wiggle. No problems found.	NA
Table Top Locking Capability	**Exper.**	Both lock onto the TM00 mode consistently and remain locked for stretches of minutes	
Sensitivity to Misalignment	**Exper.**	No systematic studies performed	
Sensitivity to RF Phases, Gains, DC Offsets	**Exper.**	No unexpected sensitivities in the fixed mass interferometer tests	

Issues Not Addressed By or Not Resolved in Experiments or Calculations

ISSUES NOT ADDRESSED	POSSIBLE CONSEQUENCES	EFFORT/APPROACH TO RESOLVE	RISK
Servo Loop Design for Common Mode Degrees of Freedom (Asymmetry Scheme only)	Each common mode feedback loop could be complicated (e.g. Bandwidth requirements might necessitate several notch filters in servo loop so test mass modes aren't excited)	Detailed servo modeling and analysis required. Preliminary results suggest this is not a problem.	low
Signal to noise issues in servo loop design for beamsplitter controller (both schemes)	Requirements for greater low frequency seismic isolation of beam splitter and/or better frequency or intensity control	Detailed servo modeling and analysis required. Preliminary results expected in a few weeks	unknown but modeling can predict
Experimentally Observed Sensitivity of Subcarrier Signal to Arm Cavity Lengths (MZ/Subcarrier Scheme only)	Mixing of cavity and near mirror readout and/or reduced acquisition range.	Change in experimental measurement technique to avoid possible PZT tilting effects; numerical analysis underway	moderate to low
Mirror Figure Imperfections Leading to Excitation of Recycling Cavity Higher Order Spatial Modes by Carrier Sidebands (Asymmetry GW Readout only; will not affect choice of auxiliary sensing scheme)	In Gravity Wave signal, excess shot noise, excess sensitivity to beam motion, photodiode non-uniformity, and/or mirror misalignments	Numerical analysis underway. Preliminary results due in next few weeks.	unknown but modeling can predict
Mirror Figure Imperfections Leading to Excitation of 4 Km cavities by subcarrier and (carrier and/or subcarrier) sidebands. (both schemes)	Unexpected coupling of auxiliary signals to arm cavity lengths; dependence of auxiliary signals on alignment and beam position.	Numerical analysis underway. Preliminary results due in next few weeks.	unknown but modeling can predict
Effects of Higher Harmonics of Modulation Frequencies (MZ/Subcarrier Scheme only)	May put constraints on mode cleaner design (i.e. lower finesse of mode cleaner cavity)	Calculation needs to be done with all of the frequencies present to check for interference in a LIGO design	low
Acquisition of Locked State of LIGO Interferometer (both schemes)	Need for additional sensing scheme (such as dithering of test masses) or for mechanisms reducing the background seismic motion	Small modeling effort underway. Hanging interferometer test will probably provide helpful insight	low

Synopsis and Discussion of Differences of the Two Schemes

The experimental and theoretical work have convinced us that the schemes outlined above are workable. Both 'lock', both should deliver an acceptable LIGO GW sensitivity, and both can control all of the needed motions. It would be possible to test most aspects of either scheme in either the 5M or 40M suspended interferometer prototypes (however vacuum modifications/ additions would be necessary to test the MZ scheme in the 40M, and the size of the asymmetry available in the 5M is limited but probably sufficient). Thus, to choose a single scheme, some more detailed considerations are needed. We highlight the advantages and disadvantages of the schemes below.

The fixed mass interferometers described on the preceding pages use a mixture of techniques for the GW readout and the auxiliary length control for both 'lock acquisition' and 'operation mode' ('operation mode' is the time while the interferometer is locked and data is being taken). These can be independently chosen for LIGO, so we discuss them separately. We believe a synthesis of the two schemes may be the best choice for the initial LIGO.

1. **Gravity Wave Readout**: Asymmetry or MZ (MZ/Subcarrier Scheme) readout.

   - Calculations and limited experimental results indicate that the shot-noise limited sensitivity of the two means of GW readout is effectively the same for the quality of optical components we expect to have in the initial LIGO. Thus, this very important measure is not a way to differentiate between the schemes.
   - The clearest **advantage of the Asymmetry Scheme** is its optical simplicity. By contrast, the MZ system requires roughly 6 more suspended masses (one additional telescope, two Pockels cells, a folding mirror, and the second beamsplitter). With these extra components comes another length control and alignment control system, although with relatively relaxed performance requirements.
   - The most important potential **disadvantage of the Asymmetry system** is the asymmetry itself: it might introduce sensitivity to various defects in the input laser beam. Straightforward calculations have not shown any significant problem due to the length asymmetry (asymmetries due to optical imperfections are typically more important). Numerical modeling to study this is now underway.

2. **Auxiliary Length Readout for *Lock Acquisition*:** Asymmetry or Subcarrier readout of the near mirror positions.

- Both schemes have been used successfully to lock a recycled table top interferometer. However, lock acquisition has not been modeled for either scheme and conditions affecting lock acquisition will be very different in suspended mass interferometers than in fixed mass prototypes.
- The principal **advantage of the subcarrier approach** is the independence of the recycling cavity resonance condition from the arm cavity resonance condition. This allows a step-wise locking procedure to be followed, where the recycling cavity and near-mirror Michelson are locked sequentially, and then the 4 km arm cavities are locked afterwards. Moreover, it does not require feedback to the laser frequency during lock acquisition. Both schemes will use a feedback path to the laser during interferometer operation, but in the Asymmetry Scheme this path is necessary for acquisition. Because we have not modeled the acquisition for a LIGO interferometer (where significantly different time constants may qualitatively change the acquisition problem) this added flexibility is welcome; the step-wise locking procedure may prove to be a significant aid in experimentally troubleshooting any observed lock acquisition problems.
- A **disadvantage of the subcarrier approach (MZ/Subcarrier scheme)** is that there are more optical components at the input to the interferometer (before the mode cleaner).
- The main **advantage of the asymmetry approach** is that the optics and hardware are simpler, and that there are fewer optical frequencies for which we must understand the behavior of the optical system (including the mode cleaner).

3. **Auxiliary Length Readout for *'Operation Mode'*:** Asymmetry or Subcarrier readout of the near mirror positions.

- The principal **advantage of the Subcarrier approach** is that the GW readout and each of the auxiliary readouts are, to a high degree, orthogonal to each other; the independence of the signals would make the servo control easier to design and analyze. An unexpected sensitivity of the subcarrier to the cavity lengths has been observed in the fixed mass interferometer. Experiments are underway to understand this observation. The possibility of coupling to higher order spatial modes in the arm cavities via mirror imperfections is being addressed with numerical modeling, and may provide an explanation for the observed coupling.

- A potential **disadvantage of the Subcarrier approach** is that all of the modulation frequencies must fit through the mode cleaner while being sufficiently spaced apart (modulo the mode cleaner free spectral range) to prevent interference between the various signals. This problem is being analysed; at present it appears that an 8 kHz mode cleaner bandwidth would be wide enough.
- The main **advantage of the asymmetry approach** is that the optics and hardware are simpler, and that there are fewer optical frequencies for which we must understand the behavior of the optical system.
- A potential **disadvantage of the asymmetry approach** is that the coupled 'average recycling cavity' length signals may make servo design for these degrees of freedom more difficult. Modeling is underway to test this but preliminary results suggest that this will not be a problem.

Recommendation for Scheme to be Used in LIGO

1. Recommendation for the **GW readout**: Asymmetry GW readout

   - Asymmetry scheme has important advantages in its simplicity and the Mach-Zehnder scheme has no established compensatory advantage over the asymmetry scheme.
   - The only remaining uncertainty for the Asymmetry readout is the influence of higher order spatial modes of the modulation sidebands brought about by mirror and substrate imperfections, and we expect an answer soon from numerical modeling.

2. Recommendation for ***Lock Acquisition*** **Auxiliary Length Readout**: Subcarrier length readout is included in the lock acquisition design, independent of which scheme is chosen for 'operational mode'

   - If the Subcarrier scheme is chosen for 'operation mode', the subcarrier scheme will also be used as the means for lock acquisition.
   - If the Asymmetry scheme is chosen for 'operation mode', ideally the Asymmetry locking scheme would be used for locking the interferometer under normal conditions. The reason for including the Subcarrier capability is for handling situations where difficulties exist in acquiring lock, such as during initial installation or when changes are made to the interferometer. The added flexibility of being able to lock 2 degrees of freedom at a time should provide valuable troubleshooting capabilities.

3. Recommendation for ***Operation Mode*** **Auxiliary Length Readout**: The above choices permit two options for Operation Mode. The advantages of each option are listed below.

   - Because of the independence of the GW and auxiliary signals, the Subcarrier auxiliary sensing system has advantages over the Asymmetry; the independence of the signals makes the servo control easier to design and analyze, and may aid in troubleshooting the interferometer. While there is some increased technical complexity in this approach, the needed elements will be in place for the acquisition scheme recommended above.
   - The Asymmetry method of auxiliary sensing has an advantage over the Subcarrier auxiliary sensing since it has the smallest number of frequencies and therefore the fewest active optical components. Potential difficulties associated with overlapping (or

nearly overlapping) modulation sidebands will be avoided with this scheme. The subcarrier used for acquisition could be designed to noise specifications adequate for lock acquisition only since the subcarrier would be shut off after acquisition.

A summary of the recommendation is as follows:

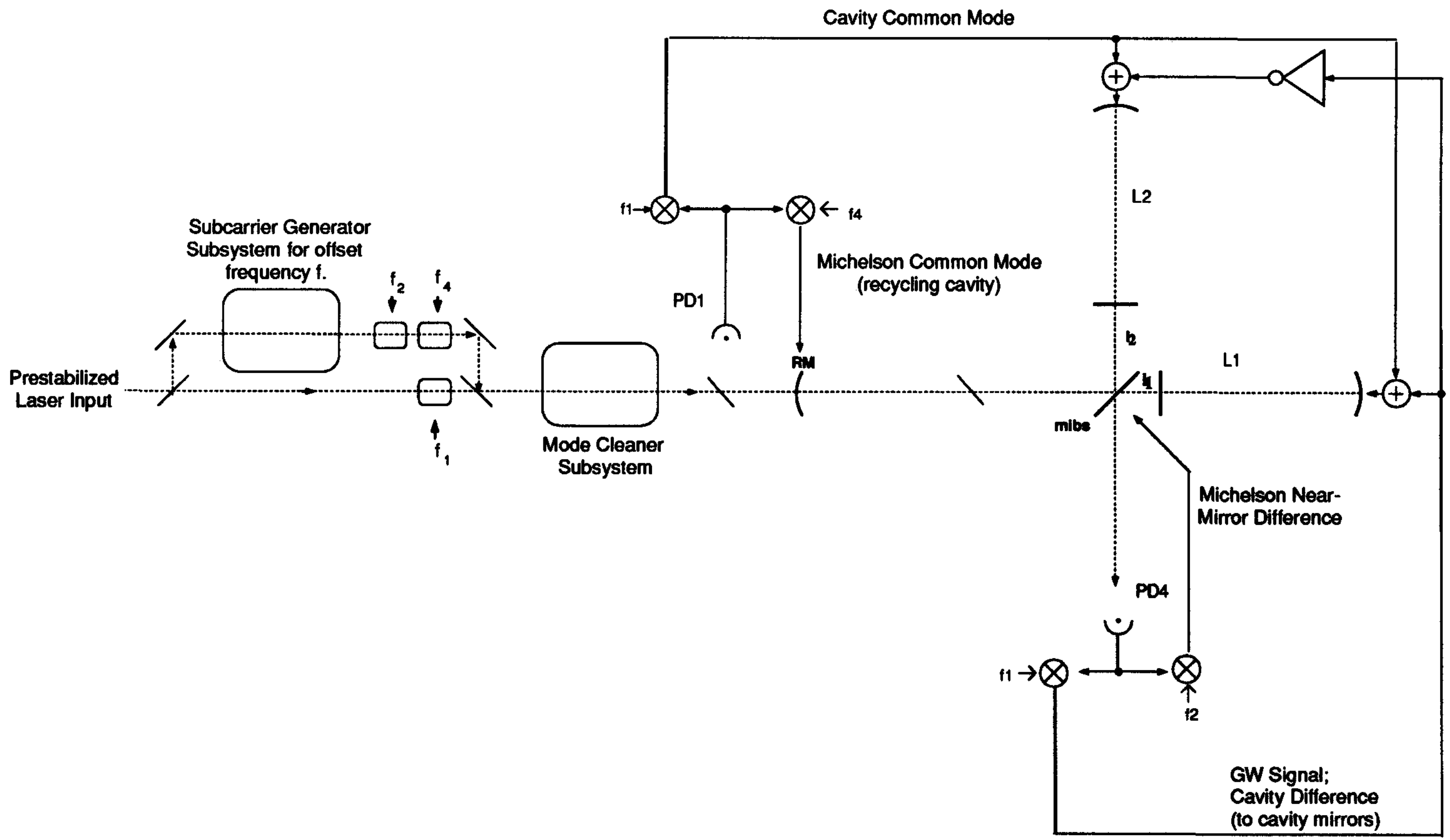
GW Readout: Asymmetry GW readout

Auxiliary Length Readout for Lock Acquisition:
Subcarrier readout included as means for Lock Acquisition

Auxiliary Length Readout for Operation Mode:
2 options have been discussed, we have not been able to find a convincing argument for choosing one over the other

1. Subcarrier readout (layout shown in Figure 4)
2. Asymmetry readout (layout for normal operations shown in Figure 2, layout for diagnosing lock acquisition problems shown in Figure 4)

Figure 4 Layout for Scheme1 (hybrid scheme where gravity wave signal detection is done using Asymmetry scheme, and servo control and lock acquisition are done using the Subcarrier method). This figure also depicts the lock acquisition layout used for toubleshooting acquisition problems in Scheme 2. The method for subcarrier generation has not been decided for the two different schemes.



Next Step in R&D Program for LIGO

1. Further fixed mass interferometer experiments and breadboarding
   - finish low frequency measurements, comparison with models
   - finish (if feasible) frequency-response measurements on MIT FMI
   - if a hybrid is chosen, we may need an FMI of that hybrid
   - if chosen, more complete tests of a frequency shifting prototype
   - if suggested by modeling, tests of lock acquisition
   - if suggested by modeling, consequences of high-order spatial modes
2. Modeling
   - finish low and high frequency response model of signal paths
   - incorporation of shot and seismic noise into models
   - incorporation of controller mechanical dynamics into models
   - acquisition modeling
3. Suspended interferometer tests
   - test of shot noise sensitivity on 5m instrument (simple recycled MI)
   - test of system on 40m instrument (complete topology)