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LIGO-T960027-01-I

From mike@tristan.mit.edu Fri Apr 19 08:53 PDT 1996
To: betty@tristan.mit.edu
Cc: dhs@tristan.mit.edu
Subject: oops: more copies

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Sorry, I guess you need more copies after all; looks like

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        Rolf Bork
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        Stan Whitcomb

are supposed to get their own paper copies too.  Let me know
if there are problems.

Thanks again,

Mike


----- Begin Included Message -----

Betty-

Since David is in transit, he asked me to ask you to distribute a
document to the LSC design review panel.  This panel consists of

Jay Heefner
Seiji Kawamura
Albert Lazzerini
Jennifer Logan

at Caltech, plus

Peter Fritschel
David Shoemaker
Rai Weiss

at MIT.  I have already given the document out to Rai, David and
Peter.  If you could please print out the file

~mike/T960027/lsc_cdd.fm5.ps  (a printer-ready PostScript file)

and distribute it to the Caltech people, I would be most appreciative.
They have been forewarned and are expecting it today.

Thanks,

Mike

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LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Length Sensing and Control Subsystem Conceptual Design Description

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Distribution of this draft:

LSC DRR Committee

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of the LIGO Project.

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CONTENTS

ABSTRACT

We present a conceptual design and supporting analysis for the LIGO Detector Length Sensing and Control subsystem. Principal modes of operation, functions for each mode, and underlying assumptions and dependencies are discussed. A sample control system design for the low-noise Detection mode is presented; its performance is analyzed and compared with established requirements. Focus areas for the preliminary design phase are also highlighted.

Keywords: length sensing, modulation, asymmetry, readout, calibration, acquisition, photodiode, photodetector, topology, shot noise.

1. LSC SUBSYSTEM DESCRIPTION

1.1. Interferometer System Context

The initial LIGO detector system (Figure 1) employs three power-recycled Michelson interferometers with Fabry-Perot cavity arms, each of length 2 km (at Hanford) or 4 km (at Hanford and Livingston). The main Core Optics (CO) components comprising each of these interferometers' optical systems are suspended as pendulums, mounted on seismic isolation stacks (SEI) within the vacuum envelope. They are illuminated by prestabilized laser light (PSL), which is modulated, filtered and modematched to the interferometer by a mode cleaner and other input optics (IOO). Alignment of the core optics to a common optical axis is achieved and maintained by optical lever and wavefront sensors (ASC) acting through suspension actuators (SUS). Light reflected from the core optics is shaped and directed by output optics telescopes and relay mirrors (IOO) to fall on photodetection units, which form the principal input signal interface of the Length Sensing and Control (LSC) system. The LSC provides control loop correction output signals to adjust the distances between core optics (through SUS and SEI) and to tune the laser frequency (through IOO and PSL), and provides the calibrated strain readout to the data acquisition system (CDS DAQ).

1.2. LSC Subsystem Roles

The LSC subsystem is responsible for maintaining optical resonance in the interferometer such that a linear signal, proportional to metric strain, is available at the readout. To accomplish this, LSC must determine and control the four independent length degrees of freedom shown in Figure 2. Each of these lengths must be held to an integral number of half-wavelengths of the laser light ($\lambda = 1.06\ \mu m$) with high accuracy, ranging from 2 nm to less than 1 pm, to achieve the required precision in the strain readout. The readout is derived from the correction signal required to counteract $\mathbf{L}_-$, the difference in the Fabry-Perot arm cavity lengths.

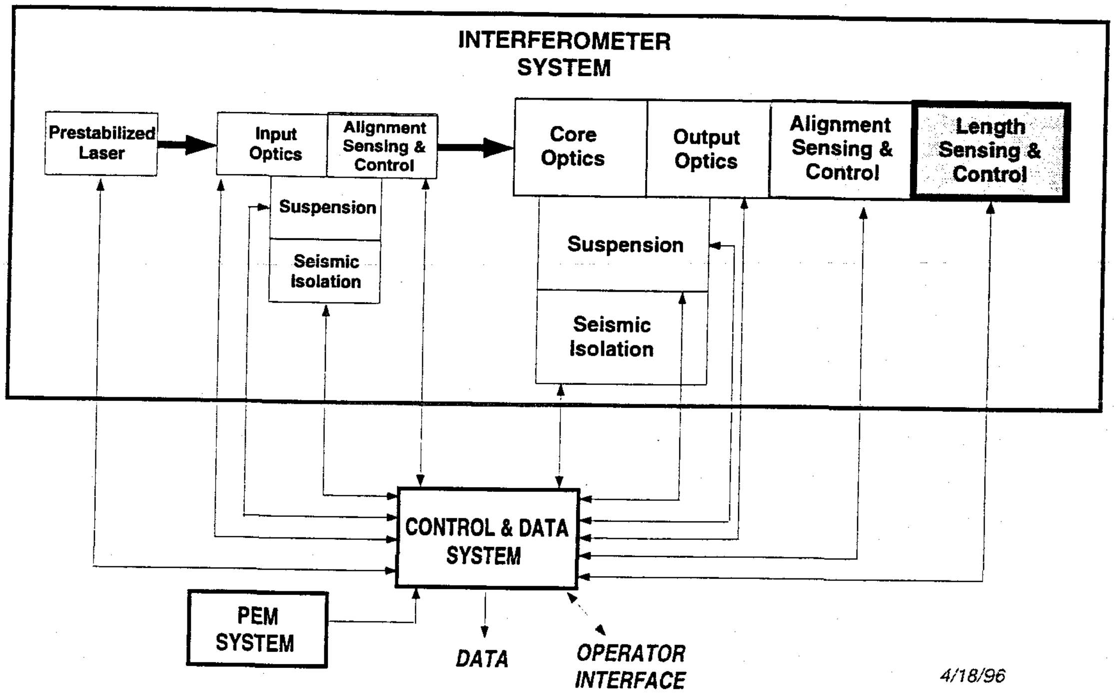

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Figure 1: LIGO Detector subsystems (LSC highlighted).

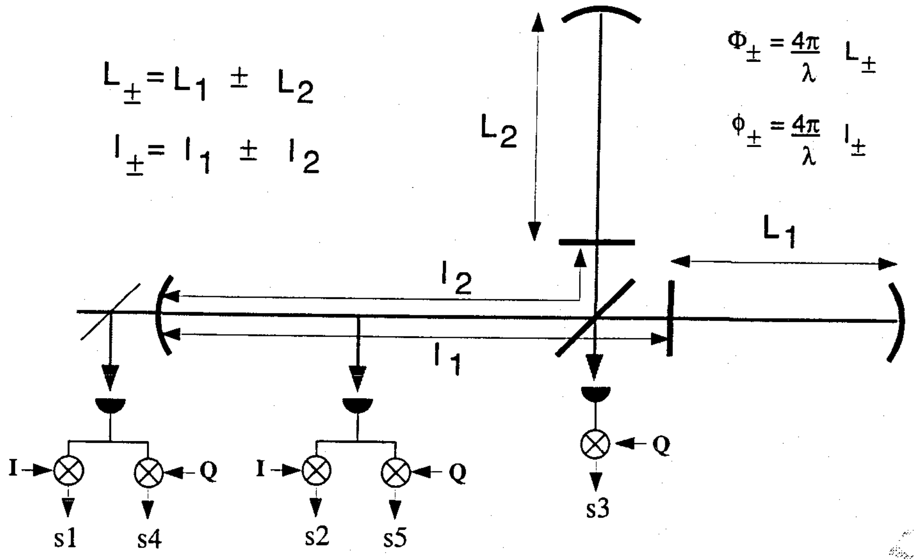

Figure 2: Power recycled interferometer with asymmetry readout: lengths and readout signals.

Functional requirements on the LSC subsystem are detailed in LIGO-T960058-00-I, “LSC Design Requirements.” While requirements on accuracy and noise are most stringent for *detection* of gravitational signals, initially or after an interruption the lengths and velocities will be random and incommensurate with the laser wavelength; thus linear signals are not available. LSC must provide a means for *acquisition* of the linear operating state, wherein dynamic reserve and "intelligent" use of the limited sensor information available to bootstrap toward normal operation are more important than low noise. In addition, LSC must provide *diagnostic and calibration* functions, both for its own operation and commissioning and to support diagnosis of other subsystems. These functions will include operation of reduced optical systems and invasive tests. The requirements for each of these missions are different and (in some cases) conflicting, so it is necessary to define subsets of LSC functionality in terms of distinct modes of operation.

1.3. Modes of LSC Operation

1.3.1. Acquisition

At startup or after an interruption the six[1] core optics will be under local SUS control, with random motions averaging several microns in amplitude. After the Alignment Sensing and Control (ASC) subsystem achieves adequate alignment to enable optical resonance, the LSC will be engaged in Acquisition mode. In this mode LSC will interpret the superposition of complex, nonlinear transients generated as each pair of mirrors passes briefly through resonance, slow the mirrors if needed, and sequence a series of robust control loops to achieve simultaneous resonance in all cavities. This control mode is characterized by the need for high dynamic range, precise sequence triggering and timing, and possibly nonlinear predictive signal processing; signal-to-noise ratio is a secondary issue.

1.3.2. Transition

After acquisition, a settling period is required. Control loops capable of maintaining the tight control and low noise level appropriate for signal detection will have compromised dynamic reserve and narrow operating margins, making them vulnerable to overload from residual transient excita- tions or alignment variations. Wire and mirror resonances are permitted to settle down (or are actively damped), filters allowed to equilibrate, and self-tests are completed to verify that residual excitations do not exceed Detection mode limits. After cavities are in resonance and the circulating fields equilibrated, the ASC subsystem is permitted to advance to its Detection mode (wherein alignment signals are derived from the wavefront sensors). Alignment adjustments are then permitted to converge and settle.

1.3.3. Detection

The Detection mode is essentially the normal operating state of the interferometer, in which the strain readout is provided at the design noise level. This performance target, and the minimum fraction of time the interferometer may be in this mode, descend directly from the Science Requirements Document LIGO-E950018-00-E.

Control loop gains for each degree of freedom affect the readout noise through a number of effects. The design must strike a balance between competing noise effects and implementation constraints, such as dynamic range limits, mechanical resonances, and propagation delays (see Section 3.).

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[1] eight, for the Washington 2 km interferometer

The strain signal readout (and possibly other monitored signals, TBD) must have a traceable and accurate absolute calibration throughout the measurement frequency band (40 Hz to 10 kHz) available at all times in Detection mode. Aside from initial calibration errors, there will be fluctuations in the effective transfer function from strain to readout voltage due to changes in modulation source output, tuning, photodiode quantum efficiency, laser output, optical alignment, etc. These may necessitate continuous end-to-end calibration, as well as periodic frequency response calibration measurements (see Section 6. below).

In addition to calibrating the readout signal, it will be necessary to filter it to suit the dynamic range of the digital recording system. Significant spectral whitening is required to represent the strain signal digitally within CDS DAQ word length and sample rate constraints. This function is provided by the LSC readout. Although this filtering will not be trivial, the causal delay constraints which limit realtime servo filter transfer functions do not apply to the readout.

1.3.4. Diagnostic and Calibration

This operating “mode” actually includes an expandable set of modes, loosely defined by the common properties that:

- special degrees of freedom or parameters are enhanced to enable separability and characterization
- the interferometer is not required to provide astrophysical data at the design sensitivity.

Diagnostic mode categories currently under consideration are described below, in order of increasing degree of invasiveness (and, inversely, by their expected frequency of application).

1.3.4.1 Stimulus-response diagnostics

Stimulus-response diagnostic testing must be available for all control states (i.e. transition to this diagnostic mode must be directly accessible from Acquisition, Transition and Detection operating modes, as well as from other Diagnostic modes). In this mode a test signal (generated by CDS Remote Diagnostics equipment/software) is directed to an injection test point or points, and system outputs are monitored (by a combination of CDS Remote Diagnostics and Data Acquisition equipment/software) to determine the transfer function and other characteristics. The amount of test signal power required for accurate measurements, and the presence of the additional waveform source and readout connections, will generally limit the usefulness of strain data recorded during these tests.

One example, expected to arise frequently, is a swept sine calibration to determine the overall frequency response between gravitational wave strain and LSC readout voltage (see Section 6.). Sinusoidal test signals at successive frequencies are applied to a summing node in the L_- loop to apply forces to the test masses, simulating the effect of gravitational waves; the response magnitude and phase are recorded, and normalized by the known electromechanical coefficients of the electronics and actuators. Other tests in this category involve simultaneously adding an offset or out-of-band signal to another test point, to determine parametric sensitivities (e.g. to laser intensity noise).

Most other interferometer subsystems and the interferometer as a whole will also be subjected to stimulus-response tests. LSC-supported readout of test signals injected throughout the interferometer will be a principal means to gauge other subsystems' performance and interactions. Tests in this category are discussed further in LIGO-T960031-00-E, "CDS Online Diagnostic and Readout Functions."

1.3.4.2 Variations in control topology

To isolate control path interactions and noise sources it will be necessary to disable or disturb one or more feedback paths while leaving other paths operational. For example, the common-mode $\mathbf{L}_+$ loop could be operated with feedback to the SEI/SUS actuators disabled or attenuated, or with feedback to the PSL disabled or attenuated. Each of these conditions would temporarily compromise sensitivity, but would enable effective separation of laser frequency, seismic and electronic noise effects, as well as permit effective characterization of the "disabled" feedback path's transfer function. However, reallocation of loop gain or dynamic range may be necessary to accomplish this. Such diagnostic control variants will be considered throughout the controls design process; where feasible, Acquisition and Detection mode control solutions which provide these capabilities naturally will be favored. Other examples of diagnostics involving control topology variation may include:

- removal of DM (or CM) length control signals from ITM (or ETM) drive paths
- disabling SEI drift/tidal motion feedback for one or more optics
- radical alteration of $\mathbf{L}_-$ loop gain (to probe relationship between auxiliary sensor shot noise, residual fringe error, and intensity noise, for example; see 3.1.).

1.3.4.3 Variations in optical topology

To successfully commission the LIGO detector, verify operation of its component subsystems, and determine its parameters for subsequent optimization, it is necessary to operate subsets of its optical system. LSC controls will support the following "reduced" interferometer optical configurations:

- recycled singlebounce Michelson interferometer (ETM's blocked or grossly misaligned).
- simple Michelson interferometer (RM removed, ETM's blocked or grossly misaligned)
- coupled cavity (BS removed, or high reflector substituted)
- unrecycled FP michelson (RM removed)
- single, uncoupled Fabry-Perot cavity (RM removed, one cavity blocked or misaligned)

With the possible exception of the first (recycled Michelson), each of these involves radical alteration of the in-vacuum optics, so use of these modes after commissioning is expected to be infrequent. The design optimization will favor solutions which provide these capabilities automatically as subsets of the normal control modes, to minimize the additional investment of dedicated hardware and software in these applications. This depends on early delineation of the commissioning sequence.

1.4. Conceptual Design Overview

Where possible, we have tried to indicate how the design presented below is responsive to the requirements set forth in LIGO-T960058-00-I, “LSC Design Requirements Document.” In many cases there are significant design variations and options available and under active consideration; some are discussed briefly in Appendix D and referenced documents. Design analysis is in its early stages, and prototype testing has not yet begun, so significant revisions are possible; this document will be updated or superseded to reflect such changes, as necessary.

Figure 3 shows the conceptual design broken into its functional subunits; these are defined and described later in this document. The principal signal and control interfaces with other detector subsystems are also shown here. Some of these interfaces have special characteristics, which we highlight next.

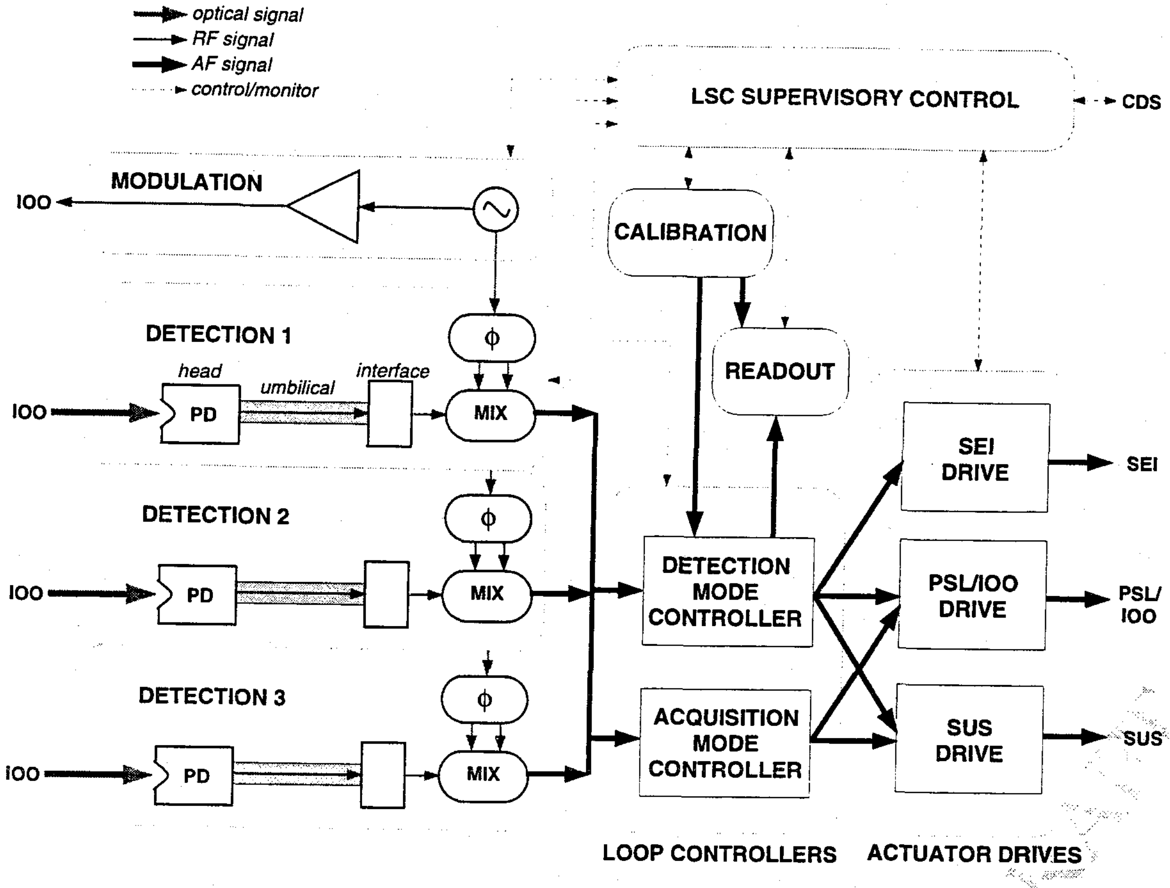

Figure 3: LSC subsystem functional block diagram, showing principal signal interfaces.

1.4.1. Closely related interferometer subsystems

The length sensing and control functions depend on successful operation of all other detector subsystems. LSC’s special role in system-level detector diagnostics is a direct consequence of this hierarchical dependence. In addition, certain direct functional interdependencies with other subsystems strongly impact LSC design strategy and implementation.

1.4.1.1 Input/Output Optics and Prestabilized Laser

The prestabilized laser/input optics mode cleaner combination is expected to deliver light with a fractional frequency stability no better than 4×10^{-18} $Hz^{-1/2}$ at 100 Hz. A possible 1% mismatch in the storage time or loss of the arm cavities would translate this into an apparent strain noise of 4×10^{-20} $Hz^{-1/2}$, exceeding the SRD noise goal by a factor of 2000. As a result, high-gain wideband feedback is required from the common-mode L+ loop to reduce the residual laser fractional frequency fluctuation to the level of $3\ 10^{-22}$ $Hz^{-1/2}$ near 100 Hz. To effect this correction, LSC will pass a filtered, wideband signal derived from demodulator output **s1** (Figure 2) back to the IOO and PSL.

The close coupling between LSC and IOO/PSL control loops requires a large degree of design coordination. LSC loop characteristics will depend critically on the transfer function provided by IOO/PSL, which in turn depends on the IOO/PSL stabilization loop gains, operating conditions (e.g., power on internal photodetectors, modulation index, and cavity visibilities), and reference cavity and mode cleaner storage time. Also, although the transmission of the IOO mode cleaner will be normalized by PSL intensity stabilization, variation in the mode cleaner storage time will alter the transfer function from LSC correction signal to laser phase. The LSC loop's tolerance to variations in each of these parameters is small; the demand for high frequency noise suppression conspires with cavity bandwidth limits to sharply constrain LSC gain and phase margins (see Section 3.).

Dynamic range of the IOO/PSL servo will also be critical, especially during LSC acquisition. Prototype experience suggests that laser loop designs which appear robust in normal "standalone" operation do not necessarily survive this test. An adequate signal-to-noise ratio commensurate with the final frequency noise budget must also be preserved through the IOO/PSL loop extension. Finally, the LSC-generated RF modulation voltage must interface with an IOO electrooptic cell to provide pure phase modulation of the requisite index, with a minimum of residual amplitude and polarization modulation and tolerable thermal distortion.

1.4.1.2 Seismic Isolation and Suspension

LSC will also feed signals to the core optics suspensions and seismic isolation stacks to actuate length control. The transfer function, noise, dynamic range, filtering and other characteristics of these signal paths factor into the design of the LSC loop controllers. Initial accuracy and stability of the transfer function over temperature and time will also figure in the LSC calibration budget. Dynamic range of both SUS and SEI actuators will largely affect the availability of the interferometer and times required for lock acquisition and transition.

Sequencing and state transitions in the SUS and SEI subsystems will be governed by LSC signals. During Acquisition local test mass damping will be active, but for noise reasons the local damping must be disabled before transition to Detection mode. Conversely, after loss of lock, local damping is reinstated immediately to reduce transient motion. On loss of lock SEI actuators may be signaled by LSC to hold their last settings, execute a scan, or return to midrange.

1.4.1.3 Control and Data System

LSC is peculiar among detector subsystems in that its WBS description contains no actual hardware (or software, for that matter). All LSC implementation is provided by Control and Data System (CDS) personnel and materials. This is a reflection of the subsystem's nature; LSC functions are all electronic. One symptom is an unusual coupling with CDS, such that an LSC/CDS "interface" appears to defy definition. As a result we suppress the formal boundary between "IFO LSC" and "CDS LSC" throughout this document, and consider the design as an integrated effort.

1.4.1.4 Alignment Sensing and Control

Length sensing acquisition depends on alignment being within ~ a few 10^{-7} radians of ideal for all optics; readout at the design noise level requires 10^{-8} radians or less (see LIGO-T952007-00-I, "ASC Design Requirements Document"). However, ASC achievement of this higher resolution (the ASC "Detection" mode) requires wavefront sensing to be active, and this in turn requires resonance in all cavities. This chicken-egg problem leads to the alternation of state transitions depicted in Figure 4. The inter-subsystem signaling is best handled at the supervisory control level, although availability and transition time requirements may force a lower-level "hardware" sequence logic to be adopted for speed.

ASC uses samples of the same interferometer output beams used for LSC, and the space near the chamber beam I/O ports will be shared between LSC detector heads and ASC wavefront sensor heads. Since the ASC reserved space requirements are expected to be larger (even though most of the beam power goes to LSC detector heads) the detector support platforms are carried under the ASC scope of work.

ASC also requires LSC to provide modulation sidebands suitable for wavefront sensing operation. In the current design concept for both subsystems, this has no serious impact; modulation frequency and depth adequate for LSC needs is also considered adequate for ASC functions. The dependence is nonetheless noted in case designs evolve otherwise.

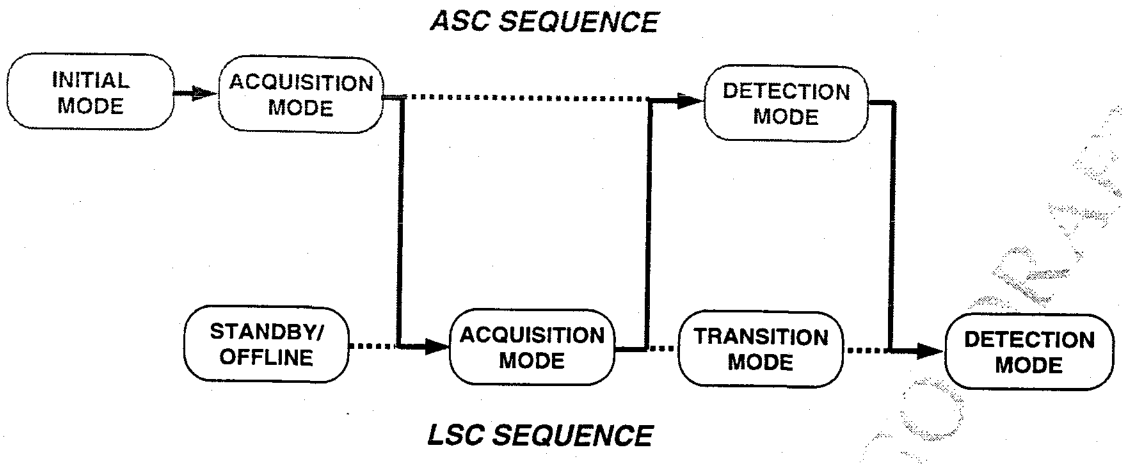

Figure 4: LSC and ASC state transitions during lock acquisition

1.4.2. Equipment Locations and Inter-Station Signal Transmission

IOO relay optics will provide optical beams to LSC photodetectors mounted near the vacuum envelope (_outside_ the vacuum envelope) in the corner station LVEA. The beam providing signals **s2** and **s5** is derived from the wedge reflection off the ITM. Approximate locations of this and the other outputs are shown in Figure 5; Table 1 shows which signals originate in each location.

Each photodetector is supplied with power and control instructions and transmits its signals via an umbilical back to the nearest CDS equipment rack in the LVEA. Most of the LSC control loop functions are implemented here. Actuation and state signals generated for CDS, IOO, SUS and SEI actuators, and data readouts for CDS DAQ and control functions are passed to the corresponding controllers by coaxial cable or network data link within the corner station.

LSC signals passed to end station SEI and SUS actuators may need to be treated differently because coaxial cables are not available between station buildings in the LIGO facilities. Practical limitations on the bandwidth and dynamic reserve of CDS data links provided between LIGO stations will probably demand special hardware and/or software to encode the precision length control signals without adding unacceptable noise artifacts. Implementation of these links is a significant area of concern, and will be a high priority of the preliminary design.

This picture is under construction.

Figure 5: LSC equipment locations in corner station LVEA (Livingston site shown).

Signals	*LA*	*WA 4k*	*WA 2k*
s1, s4	LHAM-2	WHAM-2	WHAM-8
s2, s5	LHAM-5	WHAM-5	WHAM-11
s3	LHAM-6	WHAM-6	WHAM-12

Table 1: LSC photodetector locations by Vacuum Equipment chamber designation (preliminary; see PSI V049-5-001 or equivalent for chamber designation key.)