LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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# Interferometer Diagnostics Tests and Tools

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Systems Engineering, Detector

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# 1 COMMENTS

stimulus in the case of ISC can be applied naturally to the digital control system

distinguish between on-line and off-line tests; stress that off-line is done in frames, and tools resemble (become!) data analysis tools

all stimulus to be readable by acq system

transient recorder mode very useful/important

# 2 ABSTRACT

Concepts for the tests of the detector and facilities are given to sufficient depth to permit a first cut estimate to be made for the hardware and software required. The emphasis is on system-wide global tests and facilities rather than tests devised to measure the performance of a particular subsystem. The tests and diagnostics being considered are carried out during all phases of the project including installation, commissioning and operations.

# 3 INTRODUCTION

This note describes desirable operation and diagnostic functions which may be implemented by LIGO CDS Data Acquisition, Diagnostics (previously called Remote Diagnostics) and Operator Interface hardware and software. In order to concentrate on functionality without preconceived configuration bias, no explicit distinction is drawn between Diagnostics and Data Acquisition subsystem roles.

Functional descriptions are loosely based on the typical operation and display capabilities found (or sorely missed) in the interferometer prototypes, such as the 40 meter, the PNI or any of the tabletop setups. This lends some concreteness, but it should be clear that inappropriate analogies will be inevitable. An “operator interface” comprising discrete hard-wired knobs, switches, oscilloscopes and test instruments has essentially unlimited signal bandwidth, but highly constrained display configuration and negligible automation. By contrast, the digital interface in LIGO will have arbitrary configuration flexibility and a great deal of automation, but may have restricted signal bandwidth (for a given channel or in aggregate). Operators and the controls themselves will have to adapt, and therefore a primary requirement (for both) is flexibility.

One important feature of the tests described here is that they require access to both on-line and stored data, as some tests require a baseline of days or months of data (seasonal variations in facility parameters, for instance). The software interface to the data, on-line and off-line, should support this need.

## 3.1. Relevant documents

The following documents are referred to for background about the CDS system structure:

- LIGO-T950054-01-C, CDS Control and Monitoring Design Requirements Document
- LIGO-T950120-00-C, CDS Control and Monitoring Conceptual Design
- T960009 LIGO Data Acquisition System Design Requirements Document
- T960010 LIGO Data Acquisition System Conceptual Design
- T960107 LIGO Interferometer Diagnostics System Design Requirements (CDS)

## 3.2. Issues yet to be addressed

- How best to use the 1/2 length interferometer in the diagnostics: correlate between points in the different interferometers, correlate the noise terms in each interferometer separately then correlate between interferometer outputs?
- Estimates for the total time of testing during operations. Does this cut into detector availability in a significant way?
- should all diagnostic tests, both top-level and those within a subsystem, be collected here to help determine the impact on CDS?

# 4 CLASSES OF TESTS

There are many types of tests and measurements that will be done in the LIGO to establish that the detector noise is minimized and the interactions of the facilities and the environment with the detector are understood. Typical types of tests are to:

(a) determine the operating points of the interferometer adjustable parameters
(b) determine the transfer functions of one output to another
(c) determine the transfer function of a perturbation to the interferometer output
(d) determine the cross-power spectrum of one output against another
(e) determine the sensitivity to a particular parameter by stimulation
(f) search for a minimum noise operating point for a particular parameter
(g) determine the stable region for a servo system
(h) measure the noise from a particular mechanism
(i) calibrate the sensitivity of the system
(j) measure the dynamic range of an output
(k) determine the linear range for a particular output
(l) determine the intermodulation products due to offsets, saturations and non linearities

The test signals come from points in the interferometer and its various sub-systems, the environmental monitoring system and the facility monitoring system. The diagnostic uses of the intercomparison of the full and half length interferometers at the Hanford site and the correlation of the information from the Livingston and Hanford site is not yet considered.

Some of the tests extend a time honored technique used in the development of all the gravitational wave detector prototypes to diagnose the sources of the limiting noise to the LIGO. The method has five elements:

1. The system is stimulated by either periodic or random excitation at a control point that simulates the effect of a particular noise source. The level of the excitation is chosen to be in the linear range of the system but sufficiently large to override the naturally occurring fluctuations at the gravitational wave output. Example: frequency modulation of the laser.
2. The transfer function is measured of the excitation to the point in the system most sensitive to the excitation and minimally sensitive to other sources of noise. Example: the light reflected from the interferometer.
3. A measurement is made of the transfer function of the excitation to the gravitational wave output of the system. Example: transfer function of frequency modulation to the GW output.
4. With the stimulation off, a measurement is made of the noise at the most sensitive point (e.g., reflected light) and the cross-correlation (cross power spectrum) to the gravitational wave output to determine the contribution of the specific noise source to the noise budget.

The method assumes a separation of the individual noise sources can actually be made. Often this is the case. Another method we will want to use is to sample several different points where noise enters the system at the same time and to use the outputs at various points in the system to solve simultaneously for a superposition of several noise sources at the gravitational wave output. It is then not necessary to make the approximation of a “diagonal” representation of the noise sources and it should be possible from the matrix of cross power spectra or cross correlation functions to solve for the contribution of each noise source and to develop the error and covariance matrices. A principal value decomposition of the multiple-input—multiple-output data will be useful.

Another class of tests are those used in optimizing the operating parameters of the interferometer. These tests search for stationary points in the range of an operating parameter. Often the stationary points are the places where the noise is minimized or the system sensitivity to drifts or gain changes is smallest. The stationary points are found by actively varying the parameter through periodic dithering coupled to a systematic variation in the parameter to find the extremum. The technique requires a detection system synchronous with the dither - a suppressed carrier modulation system. Many of these tests are focussed on one subsystem and can best be described in the context of the diagnostic tests of a given subsystem. Here we focus on inter-subsystem tests.

# 5 TEST PROPERTIES AND TOOLS

## 5.1. Recurrence

The tests recur:

- occasionally to set parameters after a change in configuration
- in a hunt for a problem
- periodically to maintain record of instrument and facility performance
- continuously as part of the operations data stream

## 5.2. Duration of tests

Two measures of the time scale of tests are relevant.

- the amount of time that the interferometer is unavailable for normal observation, due to excitation or unusual operating conditions. This can be minimized through the use of low-level pseudo-random excitation for some tests. At present, the sum of the test durations given the test frequencies outlined in Section 6 leads to an unavailability of 0.6%.
- the length of the data stream which must be analyzed to obtain the needed information. Many tests use on-line data and no (significant) storage will be needed. Other tests may use minutes of data (thus drawn from a disk farm) or months of data (drawn from tape archives).

## 5.3. Sequence and procedure interfaces

Many calibration, measurement and diagnostic functions will require multi-step sequences. These may involve hardware and software from several subsystems to work together properly. Automation can help accomplish these more efficiently, and will also insure consistent test conditions and parameters. Useful features will include:

- menu control of sequence parameters
- keystroke-capture macro programming, with post-editing of the file
- archiving tests and tests results with operator annotation
- conditional branching based on data from prior steps
- automatic test scheduling at fixed times or on software cue (e.g., “recalibrate 2 minutes after each lock acquisition”)

## 5.4. Use of state vector as data filter

The LIGO data stream (frames or database) will include a time tagged vector to register the state of each switch, flag for each test setup and a matrix with the adjustable parameters as elements. One of the uses for the operating vector and matrices is to enable search procedures in retrieving data associated with a particular apparatus configuration and test. Using the desired state as a filter, the whole data set would be scanned to create a data subset containing e.g., the complete datasets which qualify or to make a reduced data set consisting of e.g., just the barometric pressure and tiltmeter data for a period of time.

## 5.5. Data acquisition considerations

It is assumed that the Diagnostics system has effectively real-time access to the data and has real-time output and interferometer state-change capabilities. It must feel to an operator that when a software ‘knob’ is turned that the interferometer responds instantaneously. This probably leads to a ~1/10 second allowed pipeline delay for the process

data collected → screen update → knob-turn → signal sent to interferometer.

Active stimulus/ response testing of interferometer systems will be a part of periodic standard calibration sequences, start-up and alignment procedures, and most diagnostic investigations. For example, the primary calibration of the strain signal output will involve a swept sinusoidal test signal and/or a pseudorandom noise sequence applied to one TM suspension controller, a measurement of the response in the DAQ data stream, and signal processing to derive the complex transfer function (frequency response)[1]. In addition to DAQ system hardware, this type of test requires waveform generators near selected local units and analog multiplexers to direct their outputs to the correct stimulus points. For wideband responses, fast digitizers and associated input multiplexers will also be required. These additional degrees of freedom will be much easier to set up if graphical block diagram “test configuration” tools are available.

## 5.6. Operator and data interfaces for dedicated instruments

Inevitably some jobs will need to employ special-purpose, dedicated instruments. At a minimum, things like RF and optical beam form diagnostics will be done with direct laser beam or coax cable connections and special hardware that cannot practically be emulated by CDS. “Virtual” front panel operation and network transfer and storage of measurement data are required. While these functions are relatively routine nowadays, some LIGO-specific functions may have to be built, for example:

- recording the configuration of portable instrument I/O connections
- recording and associating interferometer state at time of a measurement with measurement data
- synchronizing instrument clocks and time-stamping transferred data (time of capture vs. time of transfer)
- determining authority for changes in portable test equipment I/O configuration

## 5.7. Remote wide band signal stimulus and capture

The ability to place the equivalent of an signal generator or oscilloscope at various points in the system under software control and to inject a wideband signal or capture a wideband signal record digitally for “slow” transmission through the network will be an important feature of a compre-

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[1] Calibration nominally belongs under the LSC’s work scope, but this generic test style is used virtually everywhere.

hensive diagnostic capability. This is could be realized via remote control of one or more oscilloscopes (see section 5.6.), or internal or VME-rack mounted A-D converters attached permanently or with cables to test-points on circuits. In order to establish correlations it is useful to capture (at least) two different time series simultaneously. The applications for such a system are numerous and include:

- measurement of peak excursions to uncover saturation
- measurement of oscillation instabilities in servo loops
- direct measurement of RF signals before demodulation
- direct measurement of all mixer outputs
- measurement of servo locking transients
- measurement of wideband servo transfer functions

Parameters for a wide band signal capture system: dual channel, 500 MHZ bandwidth, 50 dB (8 bit minimum) dynamic range, AC and DC coupling, level and slope triggering, two time base (delayed trigger capability). For a wideband signal generator: sine wave to 500 MHz, 50 ohm output, attenuator with 120 dB range

### 5.7.1. LOCATIONS FOR WIDEBAND ACCESS

For those connections used frequently (as determined from a survey of the diagnostics once documented), an automated access for wideband I/O may be worthwhile; otherwise, a coaxial connector available from the outside of the unit will be sufficient.

- common mode cavity output
- differential mode cavity output
- common mode Michelson output
- differential mode Michelson output
- common mode cavity wavefront sensor output
- differential mode cavity wavefront sensor output
- common mode Michelson wavefront sensor output
- differential mode Michelson wavefront sensor output
- all test mass position sensor outputs
- all RF signal inputs to mixers and mixer outputs

## 5.8. Processed data presentation

Data display and diagnostic processes will organize information and actively probe the interferometer's operation to permit efficient assessment of the machine's state, characterize its parameters and internal degrees of freedom, and troubleshoot problems. Some of these functions are expected to be computationally intensive, so a flexible system is required which can trade off between update rate, process complexity, and active channel count and bandwidth. We believe that a commercial graphical display software solution, perhaps also with significant calculational capability, will be the most effective solution to provide the presentation tools.

### 5.8.1. BASIC ANALYSIS TOOLS

Many of the desired functions are provided in dynamic signal analyzers like the HP3562/3 or SRS SR780. Emulating such dedicated signal analyzers may be a challenge, so it is probable that only a subset of capabilities can be provided. We may thus consider interfacing physical instruments so they can act as extensions of CDS. In any case, below is a summary of functional capabilities which will probably be used frequently. A commercial software package may fulfill these needs with minimal custom macros and called subroutines.

We will attempt to make the following list complete.

(a) plot data with adjustable axes (log and/or linear) and in different colors
(b) zoom and pan
(c) to screen-select data to fit to a linear, exponential or power law
(d) to make $\chi^2$ minimized fits to non-linear functions; plot: data, fit and residuals
(e) to take the Fourier transform of screen selected data
(f) to display the auto correlation function of screen selected data
(g) to take the cross correlation function of screen selected data pairs
(h) to determine the covariance of screen selected data pairs
(i) to calculate the cross amplitude spectrum of screen selected data pairs
(j) to calculate statistical parameters of screen selected data: mean, variance, p-p, coherence
(k) to display a histogram of the probability distribution of screen selected data
(l) to make a restricted class of wavelet transforms of screen selected data
(m) to extract the time-dependent power in a frequency band (narrowband AC voltmeter)
(n) indicate over-ranges, under-ranges, error conditions in general
(o) to archive tests and tests results with operator annotation

### 5.8.2. STANDARD DATASET PARAMETERS

File sizes of 4096 real numbers (2048 complex numbers), 16 bit real numbers will give sufficient resolution in time or frequency for most tests.

### 5.8.3. INTERFEROMETER AND SUBSYSTEM “STATE-SPACE” PRESENTATIONS

State readout and control of state transitions can be facilitated by a user interface having a graphical representation of operation modes and transition paths. Highlighting the current mode and “allowed” transitions (e.g. “cavity lock enabled” to “cavities locked” to “normal operation”) will promote efficient start-up and fault recovery. Explanatory depiction of interlock conditions *preventing* requested state transitions will also be helpful.

### 5.8.4. Power spectra

General features:

- ~ 1024-4096 points, DC-20, 200, 2kHz options

- “live” update, persistence, waterfall display options
- log mag vs. lin freq. (opt. log-log)
- “standard” axis range controls
- update procedure (incl. display update) completes in real time (i.e. t_proc < 1/2*f_max)
- cursors & markers
- trend plots of selected (marker) freq. bins or band averages to daughter display window
- zoom view to daughter window
- overlay “reference” spectrum trace (snapshot or recalled from library)
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Process recipe:

- •• digital LP filter time series, cutoff @ f_max
- •• decimate/resample to get 2048 pts. in 1/2f_max stretch
- •• vector multiply with Hamming window (raised cosine)
- •• FFT-->1024 complex frequency points-take magnitudes
- •• average each bin with last N FFT’s (N=0 to 100, say)
- •• vector multiply with last swept sine calibration (for Strain signal)
- •• do EU conversion (--> e.g. meters/root Hz for Strain signal)
- •• update display

### 5.8.5. Pulse height analyzer display

The prototypes have not yet achieved the kind of “on-line” time domain pulse analysis capability which we agree is needed to characterize, understand and eliminate nongaussian events, similar to the pulse search algorithm described in “Data Analysis Scenario and Data Flow Paradigm,” T960030.

General features:

- scans one or more channels for “significant” pulses (above selectable threshold)
- histograms number of pulses/energy bin vs. energy over previous N seconds for each chan.
- user selected prewhitening filter (from catalog)
- independently selected pulse template shape(s) (from catalog)
- simultaneous histograms for 1-5 template shapes
- configurable “dead-time” & multi-count reject features (linked w/filter selections)
- can trigger O’scope display of buffered time series data (raw or filtered version) for “big” events above user-set threshold
- snapshot, store/recall, overlay reference plot

Process recipe:

- •• hold unless data are qualified valid by IFO status bits (all $\overline{\text{LOCK}}$ low etc.)
- •• filter selected channel time series through prewhitening filter
- •• convolve filtered data stream with selected template(s)
- •• for each template, square convolution output and compare w/threshold
- •• if histogramming threshold exceeded, invoke deadtime/multi-count reject algorithm to

find "peak" value and time of event and report as single "pulse"
•• if "reporting" threshold(s) exceeded, flag oscilloscope process and pass corresponding waveform to it for display
•• update histogram(s) and refresh display

### 5.8.6. "Fast" Scope Displays:

General features:

Displays emulating a multichannel digital O'scope. Sensitivity, timebase, cursors, triggers, snapshot to daughter window/disk on trigger, freq. counter. Ability to hook into DAQ data stream channels or fast Diagnostics digitizers (and configure digitizer input routing as required).

Inline filters (e.g. to improve visibility of high-frequency signals in LF noise or to improve triggering on fast, small glitches) will also be useful.

### 5.8.7. Time Series ("Trend") Displays:

General features:

- display converted to EU
- "now" (most recent sample) digital values displayed in plot corner (with trace legends for multiple traces)
- optional LP filters (selectable passband)
- "roll" (strip chart) principal mode; most recent point on right, old data drop off left
- typ. 500 pt. display resolution (hi/lo envelope or avg. if data pts. > display pts. for selected timebase)
- timebase ~ 1 sec/cm to 500 sec/cm on screen
- displays and traces individually selectable
- vertical scale selectable
- cursors

### 5.8.8. XY scope displays

General features:

Like an analog XY oscilloscope to display pairs of (slow) signals as dots in a plane. Primary examples are ASC alignment error signals. Useful features include:

- multiple signal pairs per display (coded by "dot" shape and color, text legend)
- offset adjusts
- gain adjust for each channel (track X&Y, independent X&Y option)
- "persistence" mode to give track of selected dot over recent past (period selectable)
- LP filters (selectable pass frequency) to clean up fuzz
- optional EU conversions
- "freeze" to hold dot positions on logic trigger or command

### 5.8.9. Video beam displays

General features:

- images of optics, beams, images of beams on viewscreens as data source
- standard video rate (30 fps)
- moderate resolution adequate (e.g. 128 X 128)
- good bit depth/dynamic range (e.g. 16 bit/pixel)
- brightness, contrast, dark, gamma controls.
- pass TBD control signals back to video head (e.g. aperture, shutter, blanking, sync)
- metric/cursor capabilities, e.g.
  - cursor line slice to intensity vs. position graph in daughter window
  - centroid calculation & marker display
  - beam diameter calc
  - gaussian fit calc
  - intensity contour overlay or false color
  - mirror/flip

### 5.8.10. Audio output

The human ear/brain combination is highly developed at picking out weak signatures in noise and comparing weak tone frequencies. Listening to signals has proven to be a cheap and extremely powerful means of troubleshooting and debugging the prototypes. It should be fairly straightforward to send filtered versions of signals to workstation audio ports (for headphone monitoring or speaker broadcast).

General features:

- standard “built-in audio” characteristics (16 bit stereo @ 22 kS/sec/chan, say)
- selectable input source(s) (up to two for stereo comparison of signal pairs)
- selectable inline filter function (generally LP, HP, BP; simple “canned” shapes)
- optional AGC (adj. attack/decay) or selectable fixed volume
- optional blanking on trigger (e.g. cavity $\overline{\text{LOCK}}$)
- ability to “plug in” anywhere on the floor so you can listen while you smack things

## 5.9. Auxiliary file storage and manipulation

For several of the tests, in particular those where the stimulation amplitudes cannot be large or where one has to cross correlate a naturally occurring perturbation to the system for a long time to gain enough confidence in the correlation or to establish a narrow band correlation, it will be useful to calculate cross correlations and cross power spectra from long records of two signals. These are probably in the form of standard frames, with a subset of the data pulled out using a state filter or equivalent. It should be possible to store such files, which could of the order of 5 Mbytes, on readily accessible disk for off-line. The file storage is intended to be separate from the general facility archive for ease of manipulation and access and may consist of signals not normally recorded as part of a reduced archive dataset.

## 5.10. Auxiliary signal ports

To facilitate tests that require stimulation and sensing at points separated by large distances, it would be useful to include uncommitted data receiving and transmission channels which connect the central building experimental area with the 250 meter ports along the beam tube and the end and mid stations. Two lines per arm with a bandwidth of 5 kHz would suffice for most tests that have been thought of. Examples of tests that would use such a capability are: scattering measurements by baffles driven by stimulated mechanical motions, measurements of light scattered out of the interferometer beams along the tube, the transmission of unplanned triggers from one building to another for correlation studies. As in any new system it seems prudent to include some spare channels. Radio or IR links may provide workable means.

# 6 DESCRIPTION OF TESTS

In the following sections we detail many of the anticipated tests. The list is not yet complete, and in particular contains very few of the diagnostic tests internal to an individual subsystem. We hope that most techniques are illustrated by those tests which are detailed.

## 6.1. Frequently used techniques

In this introductory section, we describe in somewhat more detail some standard techniques used in many of the detailed test procedures.

### 6.1.1. Sinusoidal stimulus/power spectrum readout

Sine waves at selected frequencies and amplitudes are applied to one or more test points. The power spectra of output signals are monitored; by observing the relationship of the peak height to the noise background and knowing the size of the injected signals, one can immediately determine the SNR with respect to the injection point without separately measuring all the gain factors or interaction strengths (if the coupling mechanism is not well characterized or stable). Averaging of successive measurements is necessary to refine the power spectrum accuracy. Measurements of harmonics, two-tone intermodulation, and sideband amplitudes are also common.

### 6.1.2. Pseudorandom stimulus/power spectrum readout

This is functionally similar, but for nonlinear interactions[1] a sine wave test tends to underestimate the coupling. Using a noise-like test signal is often necessary to get the true interaction strength (i.e. that which applies for the “real” noise). A Gaussian random probability distribution is best

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[1] For example, coupling between mirror alignment and cavity length (quadratic) or amplifier saturation (limiting).

for most purposes. Ability to bandlimit the random noise sharply (e.g. a “box” bandpass) will help to get around a serious problem: to get a measurable interaction, broadband excitation may introduce so much additional signal power that the system goes *really* nonlinear. Analyzers often can synchronize the pseudorandom sequence to the sampling and frame rates; this can improve the measurement dynamic range and variance by allowing coherent (vector) averaging of successive FFT measurements.

Another advantage of the pseudorandom excitation is the possibility of it allowing low-level stimulus/response measurements without disturbing on-line operation significantly.

### 6.1.3. Pseudorandom stimulus/cross spectrum frequency response

This kind of test is principally meaningful for linear transfer functions. Stimulating a test point with a pseudorandom noise voltage, one collects two or more response waveforms and does a cross power spectrum for each pair. One of the response waveforms may be the stimulus itself, but frequency responses between any two affected points in the system may be needed. To insure that the cross power spectra measured are attributed to the same stimulus (and not naturally occurring noise on one input, for example) the quality of this kind of measurement needs to be monitored by averaging successive measurements and computing the “coherence function,” a measure of how much power at each displayed frequency actually came from your stimulus. The magnitude and phase of the transfer function are read out on a Bode plot or similar. One will combine (multiply/divide) such transfer functions with power spectra from various sources, including ones with different numbers of points or nonuniform point spacing. Math operations on transfer functions and power spectra are also commonly used (like “divide by frequency squared” to turn force into displacement).

### 6.1.4. Swept sine frequency response

This method for measuring linear transfer functions just applies sine waves at successive frequencies[1] and computes the relative magnitude and phase of the response waveform. At each frequency the measurement may be repeated to reduce the effect of noise; one may also compute the coherence function to determine the quality of the result at each point, as above. It is obviously more time-intensive than FFT methods, but because the stimulus amplitude can be varied at each frequency, it can achieve much higher dynamic range (you can measure a transfer function that varies by 120 dB over the selected frequency range if you like, virtually impossible with FFT-based methods). Also, since only a narrow band is excited at any given time, this measurement usually adds negligible signal power to the system under test so it is much less perturbative. In addition to the cross spectrum capabilities mentioned above, swept signal analyzers generally include handy features like:

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[1] Most useful if the amplitude for each frequency can be selected in advance to avoid overdriving resonances, for example; since the stimulus is also measured, this variation is divided out

- active interpolation of additional frequency points when adjacent measurements differ markedly, so narrow features and transitions get accurately represented
- auto source level adjustment, to keep the signal at a manageable amplitude in one of the channels
- active dwell time, to be sure the measurement uses a reasonable number of cycles (or enough averages to get an acceptable variance) at each frequency

### 6.1.5. Triggered pulse response

This kind of measurement simply injects pulses of a desired shape into selected test points and triggers an oscilloscope readout to capture one or more responses using multiple display traces (possibly including the stimulus itself). Pulse response waveforms give good indications of propagation delays and nonlinearities (especially rate limiting, which is hard to find otherwise). To an experienced operator it also gives a quick, intuitive summary of simple frequency responses and the performance of servo systems.

## 6.2. SENSING NOISE TESTS

### 6.2.1. LASER FREQUENCY NOISE IN THE GRAVITATIONAL WAVE BAND

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

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

### 6.2.2. LASER AMPLITUDE NOISE IN THE GRAVITATIONAL WAVE BAND

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

- technique: transfer function from laser power variation to LSC sensing ports, followed by cross power spectrum measurement of ambient power fluctuations and selected LSC port
- stimulus: sinusoidal variation of the laser power
  - $10^{-8} - 10^{-3}$ modulation depth
  - 1 Hz - 10 kHz
- response: each LSC sensing port
- analysis: standard transfer function tools
- visualization: log-log transfer function, log-log contribution to strain spectrum, coherence or other measure of confidence
- recurrence: once per week or per change in hardware
- duration:60 sec unavailability
- contingent tests:

### 6.2.3. AMPLITUDE NOISE AT THE SIDEBAND FREQUENCY

- technique: transfer function from modulation to LSC sensing ports, followed by cross power spectrum measurement of ambient modulation fluctuations and selected LSC port
- stimulus: sinusoidal variation of the modulation index for each modulation frequency
  - 1% of nominal modulation
  - 1 Hz - 10 kHz
- response: each LSC sensing port
- analysis: standard transfer function tools
- visualization: log-log transfer function, log-log contribution to strain spectrum, coherence or other measure of confidence
- recurrence: once per month or per change in hardware
- duration:60 sec unavailability
- contingent tests:

### 6.2.4. AMPLITUDE NOISE DUE TO UNINTENDED INTERFEROMETERS

- technique:
  - (1) determine effective amplitude of unintended ifos, via modulation of the laser fre-

quency either in a sweep or with sinusoidal modulation; study of interferometer spectrum for spectral ‘cliff’ (upconversion)

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

### 6.2.5. NOISE DUE TO INPUT BEAM POSITION AND ANGLE FLUCTUATIONS

- technique: transfer function from modulation from IO last mirror angle to LSC length sensing ports, followed by cross power spectrum measurement of ambient motion fluctuations (NEED SENSOR) and selected LSC port
- stimulus: single frequency sinusoidal drive to last IO mirror angle in tilt and twist
  - $10^{-12} - 10^{-7}$ rad rms
  - 1 Hz - 1 kHz
- response: each LSC sensing port
- analysis: study of strain spectrum; search for $1\omega$ and $2\omega$
- visualization: log-log transfer function, log-log contribution to strain spectrum, coherence or other measure of confidence
- recurrence: once per month or per change in hardware
- duration:60 sec unavailability
- contingent tests:

### 6.2.6. INTERMODULATION PRODUCTS DUE TO OFFSETS AND LARGE AMPLITUDE DEVIATIONS FROM NULL

- technique: Introduction of intentional offset from the dark fringe (or resonance condition for cavities; addition of signals; analysis of output to determine linearity of the system
- stimulus: offset from nominal operating point of optical system
  - static offset from 0.1x to 10x required operational offset, OR sinusoidal modulation, 0.1x to 10x required operational offset, 0.1 Hz - 100 Hz
  - modulation in laser frequency $10^{-7}$-0.01 Hz/$\sqrt{\text{Hz}}$, 1 Hz to 10 KHz

  - modulation in lengths (individual or CM/DM basis) $10^{-20} - 10^{-15}$ m rms, 1 Hz - 1 kHz
- response: all PSL/IO/LSC ports (strain, MI, RC, Frequency)
- analysis: study of sum and difference frequencies as function of variables; extraction of peak heights
- visualization: plot of distortion vs. parameters, fit to curve; projection of net effect on quiet strain spectrum
- recurrence: once per month or per change in hardware
- duration: 10 min
- contingent tests:

### 6.2.7. PHASE NOISE LIMITS DUE TO SCATTERING IN THE BEAM TUBE

- technique: transfer function from modulation from beam tube intentional excitation to LSC length sensing ports, followed by cross power spectrum measurement of ambient motion fluctuations and selected LSC port
- stimulus: PEM cart shaker attached to beam tube at point of interest
  - 1 Hz - 30 Hz for upconversion effects
  - 30 Hz - 1 kHz for direct effects
- response: PEM BT accelerometers, LSC length sensing ports
- analysis: differences of strain spectra with and without excitation for the 1-30 Hz band; signals at excitation frequency for 30 Hz - 1 kHz
- visualization: power in strain spectrum due to BT natural motion
- recurrence: once per month or per change in hardware
- duration:10 min of unavailability; 1 day setup for placement of PEM shaker etc.
- contingent tests:

## 6.3. OPTIMIZATION OF OPTICAL PHASE SENSITIVITY

### 6.3.1. SIGNAL TO NOISE OPTIMIZATION OF THE RF MODULATION INDEX

- technique: variation of the RF modulation depths to search for best performance in shot noise limited region of the spectrum
- stimulus:
  - fixed-frequency calibration peak (strain modulation), 10 Hz - 10 kHz, $S/N$ 10 - 100 in sample long enough to get 1% uncertainty in shot-noise region
  - variation (stepped in 1% to 10% increments with stationary points for strain measurement) of modulation depth, 0.1 nominal to 2x nominal (may be limited by interferometer servos to a smaller range). An intelligent search for a maximum cuts duration.
  - 1 Hz - 10 kHz
- response: measure of peak height of calibration in strain spectrum as a function of modulation depth; measure of shot-noise limited performance in regions without interfering features (peaks, etc.)

- analysis: fit to shot-noise limited level, fit to peak height, search for optimum
- visualization: strain spectrum for each step; plot of $S/N$ vs. modulation depth with peak indicated
- recurrence: once per week or per change in hardware
- duration:60 sec
- contingent tests:

### 6.3.2. MODE MATCHING INTO INTERFEROMETER

- technique: stepping of input mode parameters, measurement of circulating power in interferometer as measure of matching
- stimulus: stepping of the translation stage which varies the IO telescope mirrors, thus changing the matching. Magnitude of motion: TBD, according to initial state of matching. Each step will require reinjection of the beam, realignment, and interferometer tuning, and possibly a wait for thermal equilibrium
- response:
  - circulating power in the arm cavities (recycling cavity high-order modes are easily excited?), as monitored by photodiodes looking at ETM transmitted beam
  - $S/N$ in shot noise limited region
- alternative response: analysis of CCD camera looking at RM for first circularly symmetric mode; amplitude of mode as function of matching will allow faster convergence maybe
- analysis: fit to curve of power and $S/N$ as function of matching, identification of desired matching
- visualization: plot of power and $S/N$ as a function of matching with optimum point identified
- recurrence: once per month or per change in hardware
- duration:1 hour unavailability, TBD on translation and realignment realities for IO telescope
- contingent tests:

### 6.3.3. MIRROR ABSORPTION THROUGH CHANGE IN MODE MATCHING

- technique: Varying input power to the interferometer; looking at signals characteristic of mode matching to see the changes; use of a model to regress back to the change in mirror curvature and thus absorption
- stimulus: laser power stepped in factors of three, from 60 mW to 6 W net input power at RC
- response: light reflected from RC captured with a CCD and stored in frames for post-analysis
- analysis: calculation of the amount of $TEM_{01}$ as a function of input power; from this, calculation of an average of absorption in TMs.
- visualization: $TEM_{01}$ as a function of input power; absorption number
- recurrence: once per month or per change in hardware
- duration:10 minutes unavailability
- contingent tests:

### 6.3.4. HIGHER ORDER ARM CAVITY MODE SCAN

- technique: with other cavities misaligned, drive the ETM of the cavity of interest at uniform velocity through several $\lambda$. Measure the intensity vs. time on the ETM transmitted light.
- stimulus: 0.1 Hz ramp to the z input of the ETM suspension controller. Best if this is done with a closed loop control using the suspension sensors to reduce variations due to seismic input.
- response: photodiode measurement ETM transmitted light
- analysis: Plot of intensity vs. position, normalized to give free spectral range. Superposition of multiple traces to show variability; averaging to improve estimate. Identification of cavity modes by comparison with cavity model; analysis of the nature of the mismatch (simple misalignment suppressed) by comparison with the model
- visualization: Classic 'optical spectrum analyzer' (intensity vs. cavity length modulo $\lambda/2$)
- recurrence: once per month or per change in hardware
- duration:10 min unavailability
- contingent tests:

### 6.3.5. ARM CAVITY LOSS MEASUREMENT BY REFLECTION

- technique: with other cavities misaligned, the cavity of interest is locked and then unlocked. The difference in the reflected light allows an inference of the losses, once matching (test 6.3.4.) is known.
- stimulus: locking and unlocking of a single arm cavity. This might be performed using a mechanical dither of the ETM at ~100 Hz with a synchronous demodulation of the ETM transmitted light; or a subset of LSC RF locking electronics.
- response: photodiode measurement of the reflected light PO from the ITM
- analysis: application of the Fabry-Perot formula to infer losses based on known TM properties (transmissions) and light reflected.
- visualization: numbers on a screen
- recurrence: once per month or per change in hardware
- duration:10 min unavailability
- contingent tests:

### 6.3.6. ARM CAVITY LOSS MEASUREMENT BY RINGDOWN

- technique: With other optical cavities misaligned, the cavity under test is locked. Small step changes in the input light intensity are made, and the exponential drop-off in stored power is measured.
- stimulus: 1-10% step modulation of the laser intensity (<1 $\mu$sec rise/fall times), 1-30 Hz rep rate
- response: photodiode measurement of the ETM transmitted light
- analysis: fit to exponential decay/rise in the ETM transmitted light, with synchronous averag-

ing of the data. Inference of storage time, comparison with design storage time and previous measurements. Inference of additional loss.

- visualization: storage time and loss vs. time, vs. integrated light intensity; fits to models for decay as a function of time, products of time and intensity, etc.
- recurrence: once per week or per change in hardware
- duration:10 min non-availability
- contingent tests:

### 6.3.7. RECYCLING CAVITY LOSS MEASUREMENT

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

### 6.3.8. ETM SUSPENSION ACTUATOR AXIAL CALIBRATION

- technique: Form a Michelson interferometer using an auxiliary laser, with one arm using the ETM surface (as viewed through the optical relay system to bring out the ETM transmitted light) and the other arm a reference arm. All components except for the ETM COS components are outside of the vacuum. A slow sweep of the ETM is made to calibrate the fringe height. Then a small modulation of the mirror position is made and the rms motion inferred from the auxiliary interferometer output.
- stimulus:
  - For Aux Ifo Calibration: 0.1 Hz ramp to the z input of the ETM suspension controller. Best if this is done with a closed loop control using the suspension sensors to reduce variations due to seismic input.
  - For Susp Actuator Calibration: fixed-frequency and sweep sinusoidal excitation of the z input to the suspension actuator at levels corresponding to $\sim 10^{-10}$ to $10^{-15}$ m rms, 30 Hz - 1 kHz.
- response: Auxiliary Michelson antisymmetric photodiode output
- analysis:
  - measurement of the peak-peak output of the auxiliary interferometer while sweeping ETM. From this, the 'volts/$\lambda$' for the interferometer is measured. Fits made to peak and peak,

  multiple averages taken
  - measurement of the coil currents (at suspension controller test points) and the auxiliary interferometer photodiode output locked at the dark fringe or mid-fringe.
- visualization:
  - sweep of auxiliary interferometer vs. ETM position
  - motion of the ETM (as measured by the calibrated auxiliary interferometer) per ampere of suspension controller current, as a function of frequency (transfer function). Coherence.
- recurrence: once per month or per change in hardware
- duration:10 min unavailability
- contingent tests:

### 6.3.9. SUSPENSION ACTUATOR ANGULAR CALIBRATION

- technique: use of the optical levers to measure angular motion effected by the suspension actuators. Optical levers are calibrated by making known translations of the quadrant photodiodes and measuring their response in a preliminary measurement.
- stimulus: sinusoidal drive to each COC element suspension controller $\theta$ and $\phi$ input
  - $10^{-7} - 10^{4}$ rad
  - 1 Hz - 1 kHz
- response: calibrated optical lever output.
- analysis: form the transfer function from angle commanded to angle resulting as determined from the optical lever.
- visualization: the transfer function; coherence.
- recurrence: once per month or per change in hardware
- duration:60 sec
- contingent tests:

### 6.3.10. LENGTH CONTROL SYSTEM DIAGONALIZATION AND DIAGNOSTICS

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

- visualization: standard transfer function tools; matrix
- recurrence: once per month or per change in hardware
- duration:10 min unavailability
- contingent tests:

### 6.3.11. ANGLE CONTROL SYSTEM DIAGONALIZATION AND DIAGNOSTICS

- technique: Using calibrated suspension actuators, make equal in-phase or counter-phase angular motions of the two ETMs, or two ITMs, or RC. Observe the signals at the LSC and ASC sensors. The interferometer is in the operational state during the measurement.
- stimulus: sinusoids or pseudo-random excitation to the suspension controllers
  - 0.1 - 100x the ambient control force in the locked case.
  - 1 Hz - 10 kHz
- response: LSC and ASC outputs
- analysis:
  - standard transfer function tools; also, fixed-frequency transfer function vs. other interferometer parameters (like beam centering, suspension controller balance, offsets from nominal alignment, etc.)
  - formation of the complete matrix of motions to signals for the ASC
  - formation of the complete matrix of accidental coupling to the LSC
- visualization: standard transfer function tools; matrix
- recurrence: once per month or per change in hardware
- duration: 10 min unavailability
- contingent tests:

## 6.4. NOISE DUE TO RANDOM FORCES

### 6.4.1. SUSPENDED OPTICAL COMPONENT SEISMIC NOISE SENSITIVITY

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

### 6.4.2. SUSPENDED OPTICAL COMPONENT ACOUSTIC NOISE SENSITIVITY

- technique: measurement of the effect on the strain output for both monitored ambient acoustic excitation, and with applied excitation
- stimulus: PEM loudspeaker placed in the vicinity of VE containing COC element of interest; excitation waveform may be sinusoidal, swept sine, impulse, or pseudorandom
- response: PEM microphones, strain output
- analysis: transfer functions and ratios of power spectra of strain output over microphone output
- visualization: transfer functions
- recurrence: once per month or per change in hardware
- duration:60 sec per test, one test per mass
- contingent tests:

### 6.4.3. SUSPENDED OPTICAL COMPONENT MAGNETIC FIELD SENSITIVITY

- technique: measurement of the effect on the strain output for both monitored ambient magnetic field excitation, and with applied excitation
- stimulus: PEM magnetic field generator placed in vicinity of VE containing COC element of interest; excitation waveform may be sinusoidal, swept sine, impulse, or pseudorandom
- response: PEM magnetometer, strain output
- analysis: transfer functions and ratios of power spectra of strain output over magnetometer output
- visualization: transfer functions
- recurrence: once per month or per change in hardware
- duration:60 sec per test, one test per mass
- contingent tests:

### 6.4.4. SUSPENDED OPTICAL COMPONENT ELECTRIC FIELD SENSITIVITY

### 6.4.5. SUSPENDED OPTICAL COMPONENT TILT SENSITIVITY

### 6.4.6. PENDULUM LONGITUDINAL MODE Q

### 6.4.7. PENDULUM WIRE TRANSVERSE MODE Q

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

- response: strain output
- analysis: fits to exponential decays
- visualization: transfer functions; $Q$ vs. time (periodic tests over months to observe changes)
- recurrence: once per month or per change in hardware
- duration:10 min per resonance; ~2 resonances per wire; 2 wires per mass; 4 TMs
- contingent tests:

### 6.4.8. PENDULUM WIRE LONGITUDINAL MODE Q

- technique: excitation of the vertical motion of the SEI support beams at or around the resonant frequency of vertical motion (~11 Hz); measurement of the transfer function or of the ring-down time of the motion in the strain or control spectrum (coupling due to at least the earth's curvature) or the suspension sensors (nominally zero response, but certainly visible).
- stimulus: PEM shakers placed on the four support beam support points of the VE containing COC element of interest; excitation waveform may be sinusoidal at or swept sine around the (known) resonant frequency
- response: PEM accelerometer, strain output or other point in the LSC control system sensitive at ~11 Hz
- analysis: transfer functions and ratios of power spectra of strain output over accelerometer output; fits to exponential decays (if a ring-down test is made) or fits to linewidths in the transfer function (if a sweep around the resonance is used to determine its width and thus losses)
- visualization: transfer functions; $Q$ vs. time (periodic tests over months to observe changes)
- recurrence: once per month or per change in hardware
- duration:10 min
- contingent tests:

### 6.4.9. PENDULUM VERTICAL TO HORIZONTAL CROSS COUPLING

## 6.5. OPTIMIZATION TO MINIMIZE NOISE FROM RANDOM FORCES

### 6.5.1. SEARCH FOR ROTATION INSENSITIVE BEAM POSITION ON SUSPENDED COMPONENT

- technique: modulation in angle of the suspended optic; observation of the signal in the strain spectrum; motions of the beam and/or SEI actuators to observe size and sign of change of coupling; inference of point of no response, and placement of the beam/SEI at that point. Commands to the SEI coarse actuator are less desirable, as it will probably cause loss of lock in the interferometer. After locating the best point, SEI actuators may be used to re-center the optic.
- stimulus:

  - angular input to the SUS controller, in $\theta, \phi$; excitation waveform may be sinusoidal, swept sine, impulse, or pseudorandom
  - changes in the beam position on the mirror by commands to global ASC to change the optical axis affecting the beam on that mirror
- response: strain output
- analysis: transfer functions and ratios of power spectra of strain output over angular
- visualization: transfer functions
- recurrence: once per month or per change in hardware
- duration:60 sec per test, one test per mass
- contingent tests:

### 6.5.2. SEARCH FOR ASTATIC POINT IN SUSPENDED COMPONENT POSITION CONTROLLER

## 6.6. TESTS OF THE FACILITY/DETECTOR INTERFACE

### 6.6.1. CORRELATION OF RESIDUAL GAS PRESSURE FLUCTUATIONS WITH DETECTOR OUTPUT

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

### 6.6.2. CORRELATION OF TECHNICAL POWER FLUCTUATIONS WITH DETECTOR OUTPUT

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

- duration: non-invasive
- contingent tests:

### 6.6.3. CORRELATION OF FACILITY POWER FLUCTUATIONS WITH DETECTOR OUTPUT

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

### 6.6.4. CORRELATION OF FACILITY MONITORS WITH DETECTOR OUTPUT

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

# 7 DISPLAY ORGANIZATION

To help assess the functional capabilities discussed above, it is useful to note how an interferometer operator might use displayed information to understand and troubleshoot the machine. The displays could be grouped by subsystem, e.g., PSL, SUS, ASC, LSC, plus perhaps PEM seismic or acoustic monitors etc. In this view, separate displays showing data from each of these subsystems appear to have equal status and at first glance the operator would need to cycle through all the components to understand the system's state. However, the implicit logic of the interferometer's' operation (Figure 1) lets an operator concentrate on "higher level" functions and dig deeper only where needed.

Expressing the logic hierarchy in the organization of subsystem displays will thus improve operator efficiency. An example of a “top level” display organization with a useful, but not too detailed, function subset is shown in Figure 2. Here preference is given to “higher level” functions the operator will want to start with as his/her point of reference. A further prioritization of the information within the subsystem displays (e.g. in hideable “layers” as done on the PSL Controls), as well as separate consoles focussed on individual subsystems, will augment this top-level condensed information and support off-line test of isolated subsystems. This promotes efficient scanning and processing by a human operator without inhibiting deeper inquiry and diagnosis.

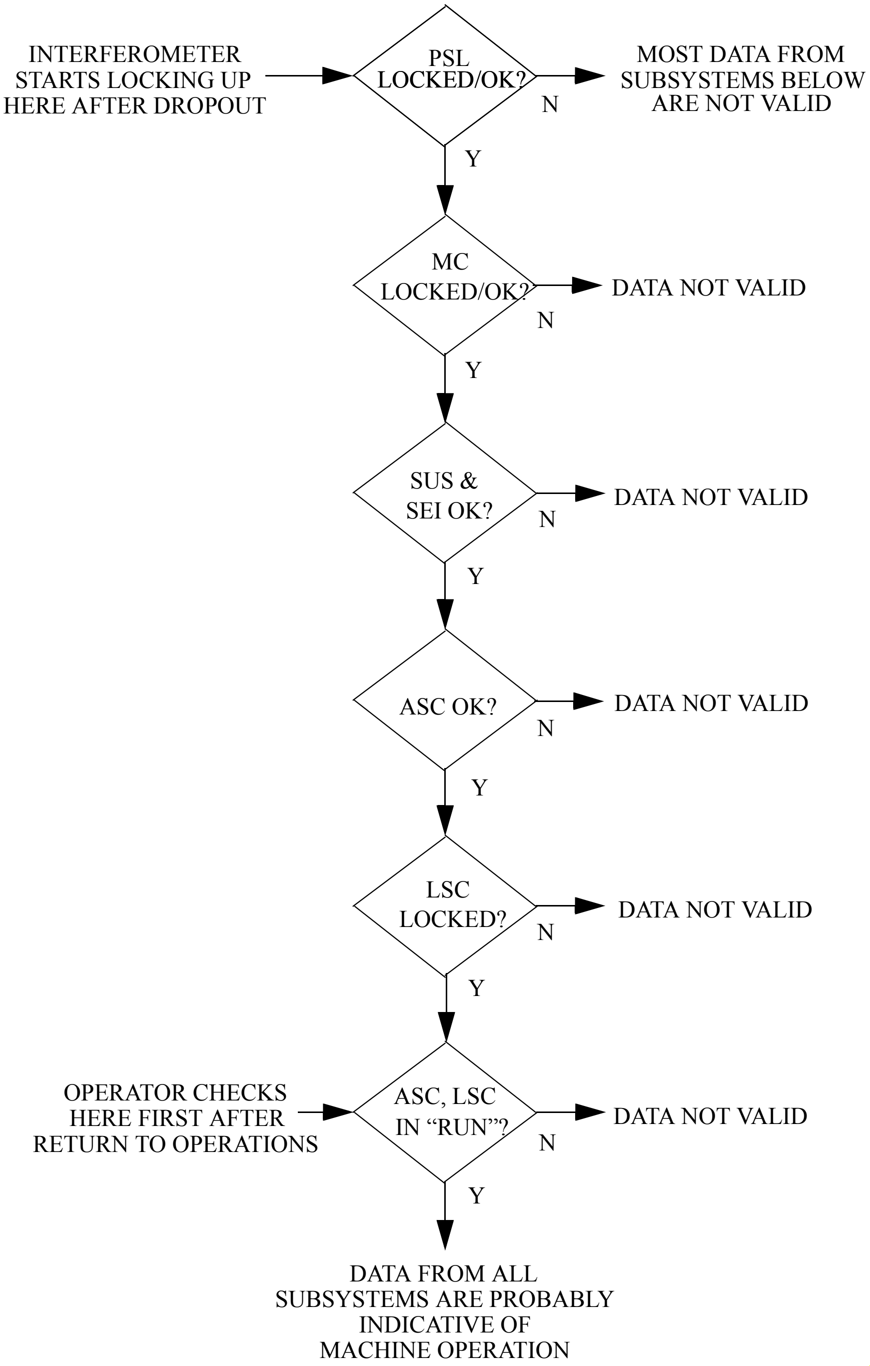

**Figure 1: Implicit "troubleshooting" logic used by operator to decide what screens are worth looking at and in which order.**

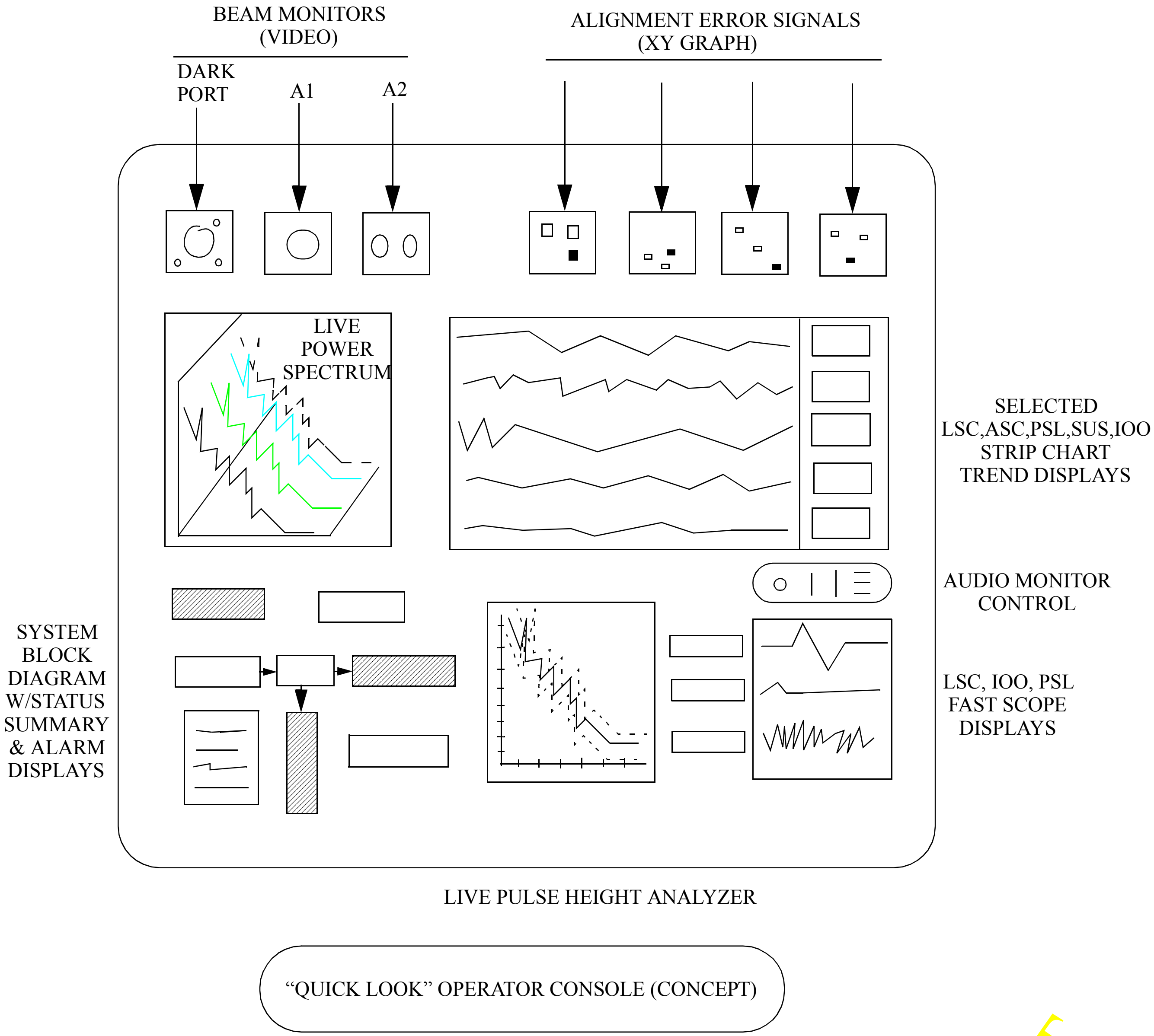

**Figure 2: Top level realtime data display example**

## THINGS TO THINK ABOUT

| *TEST* | *RECUR* | *LOCATION* | *BAND* | *RANGE* | *STIMULUS* |
|---|---|---|---|---|---|
| | | | *HZ* | *dB* | |
| 1.1 frequency noise | periodic | common mode cavity | DC - 10KHz | 60 | Pockels cell noise&swp sine |
| 1.2 amplitude noise | periodic | differential mode cavity | DC- 10KHZ | 60 | Amplitude regulator noise&swp sine |
| 3.1 seismic noise | periodic | differential mode cavity | DC- 1KHZ | 80 | PZT drivers active isol |
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