LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Generic Requirements & Standards for Detector Subsystems

Dennis Coyne (ed.) for LIGO Systems

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This is an internal working note of the LIGO Project.

* *N.B.: This document was erroneously referred to as E010123-00 in the past.*

California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW17-161
175 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

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

Change Record

Revision	Date	Changes
00	1 Jul 2001	Initial release, coincident with the Systems Design Requirements Review
01	5 Jun 2005	1) Completed the section on earthquakes 2) Added a section on acoustic noise emission requirements 3) Completed the section on EMI/EMC requirements

Table of Contents

List of Figures

List of Tables

1 Introduction

The intent of this document is to provide a common set of guidelines, standards and requirements for the LIGO Detector (science instrument). Since this document has been written after the Initial LIGO construction phase, it applies to new designs (Advanced LIGO (AL) and Initial LIGO (IL) upgrades) but is not retroactive in scope. The scope of this document is principally on the engineering and implementation requirements and not the performance requirements.

Each AL Detector subsystem, or major IL upgrade project, should write a set of requirements which call out the provisions in this document which apply, or state how and why a deviation from these requirements is needed.

1.1 Purpose

This document defines the generic requirements and standards for all subsystem designs for the Advanced LIGO (AL) detector. The AL detector is currently defined as a single major upgrade to the Initial LIGO (IL) Detector. These requirements apply even for more modest upgrades to the IL Detector.

1.2 Scope

This document defines, or refers to, the requirements and standards that transcend any particular subsystem and are thus generic. More detailed requirements or standards are referenced where applicable. The scope includes all aspects (mechanical, electrical, optical, etc.) and all phases (design, analysis, test, fabrication, assembly, installation) of the Detector.

1.3 Definitions

TBD

1.4 Acronyms & Naming Convention

A standard naming convention for all subsystem components shall be developed, documented and uniformly applied in all subsystem documentation, in order to avoid confusion and conflicts with names from other LIGO subsystems. The SUS naming conventions will be an input to a revision to the current LIGO Naming Convention, E950111-A.

40m Lab	R&D/Test Facility at LIGO/Caltech
AC	Alternating Current
ADC	Analog to Digital Converter
ADCU	Analog Data Collection Unit
AL	Advanced LIGO
AM	Amplitude Modulation
AOS	Auxiliary Optics System (subsystem in AL)
API	Application Programmer's Interface
ASC	Alignment Sensing / Control (detector subsystem)
ATM	Asynchronous Transfer Module
BS	Beamsplitter (optical component)

BSC	BeamSplitter Chamber (large vacuum chamber)
BPCU	Beam Pointing Control Unit
BT	Beam Tube
BTE	Beam Tube Enclosure
CA	Channel Access (EPICS Control & Monitoring system network protocol)
CC	Civil Construction
CDS	Control and Data System (detector subsystem)
CIT	California Institute of Technology
CMS	Control and Monitoring System (a part of CDS)
COC	Core Optics Components (detector subsystem)
COS	Core Optics Support (detector subsystem)
CP	Chiller Pad (part of FAC)
CP	Compensation Plate (optical element part of TCS)
DAQS	Data Acquisition System
DC	Direct Current (steady state - low frequency)
DCC	Document Control Center
DCU	Data Collection Unit
DET	Detector system
DIA	Data Information Area (of reflected memory)
DMA	Direct Memory Access
DRD	Design Requirements Document
EDCU	EPICS Data Collection Unit
EDSU	EPICS Data Server Unit
EMC	Electro-Magnetic Compatibility
EMI	Electro-Magnetic Interference
EOM	Electro-Optic Modulator (optical hardware)
EPICS	Experimental Physics and Industrial Control System
ETM	End Test Mass (optical component)
FAC	Facilities (part of CC)
FCMS	Facility Control and Monitoring System
FCR	Facility Control Room
FFT	Fast Fourier Transform
FI	Faraday Isolator (optical component)
FIFO	First In First Out
FM	Frequency Modulation
FM	Fold Mirror
FR	Faraday Rotator (optical component)
GDS	Global Diagnostic System
GPS	Global Positioning System
GUI	Graphical User Interface
GW	Gravitational Wave
HAM	Horizontal Access Module
HVAC	Heating Ventilation and Air Conditioning
HWCI	Hardware Configuration Item
HWP	Half-Wave Plate (optical hardware)
Hz	Hertz

ICD	Interface Control Document
IFO	Interferometer
IL	Initial LIGO
INS	Installation
I/O	Input/Output
IOO	Input Optics (detector subsystem, formerly named Input / Output Optics)
IP	Internet Protocol
ISR	Interrupt Service Routine
ITM	Input Test Mass (optical component)
IXS	Information eXchange Services
LA	Louisiana
LASTI	LIGO Advanced Systems Test Interferometer (test facility at LIGO/MIT)
LDAS	LIGO Data Analysis System
LHAM	Horizontal Access Module at Louisiana Site
LHO	LIGO Hanford Observatory
LIGO	Laser Interferometer Gravitational-Wave Observatory
LLO	LIGO Livingston Observatory
LSC	Length Sensing / Control (detector subsystem)
LOS	Large Optic Suspension
LVEA	Laser and Vacuum Equipment Area (of the LIGO observatories)
MAP	Memory Allocation Pointer (reflected memory)
MC	Mode Cleaner
MCM	Mode Cleaner Mirror
MIT	Massachusetts Institute of Technology
MMT	IFO Mode Matching Telescope
MSR	Mass Storage Room
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
MZ	Mach-Zender Interferometer
NDS	Network Data Server
Nd:YAG	Neodynium doped Yttrium Aluminum Garnet (laser gain medium)
OSB	Operations Support Building
PDD	Preliminary Design Document
PDH	Pound-Drever-Hall (reflection locking technique)
PEM	Physics Environment Monitoring
PM	Phase Modulation
POSIX	Portable Operating System Interface (IEEE Standard 1003.1)
PSL	Pre-Stabilized Laser (detector subsystem)
PZT	Piezo-electric Transducer (mechanical hardware)
RAID	Removable Array of Independent Drives
RAM	Random Access Memory
RC	Radius of Curvature of a Reflective Mirror
RF	Radio Frequency
RM	Recycling Mirror
SAH	Sensor Actuator Heads
SCSI	Small Computer Standard Interface

SEI	Seismic Isolation
SOS	Small Optic Suspension
SRD	Science Requirements Document
SRS	Software Requirement Specification
SUP	Support Equipment
SUS	Suspension Subsystem (sometimes also Suspension assembly)
SYS	Detector Systems Engineering
TBD	To Be Determined (or To Be Done)
TCP	Transport Control Protocol
TCS	Thermal Compensation System
TGG	Terbium-Gallium-Garnet (optical material used in Faraday Isolators)
TFP	Thin Film Polarizer (optical hardware)
TNI	Thermal Noise Interferometer (R&D/Test interferometer at LIGO/Caltech)
UDP	User Datagram Protocol
UF	University of Florida
VE	Vacuum Equipment
VEA	Vacuum Equipment Area
VME	Versa Module Eurocard
WA	Washington
WFS	Wave Front Sensors

1.5 Applicable Documents

1.5.1 Management Plans

Document #	Title
M950090-A	Guidelines for Detector Construction Activities
T950065-01	Guidelines for Design Requirement Documents
M950001-C	LIGO Project Management Plan (Initial LIGO)
	E030647, Advanced LIGO Detector Subsystem Interface Control Document
M040004-00	Record of Decision/Agreement (RODA)
NA	RODA Status Web Page

1.5.2 Configuration Control & Documentation

Document #	Title
L960237-00	LIGO Document Change Notice
L960641-05	Electronic Submissions to the Document Control Center
G960249-00	Electronic Submissions to the Document Control Center
Form DCN-04	Document Change Notice (DCN) Form

(06/2004)	
L950003-B	LIGO Document Numbering System
	Inspection Form
	Traveler Form
T960051-02	Integrated Layout Drawings: Usage & Maintenance
M950005-00	LIGO Configuration Management Plan
E030350-A	LIGO Drawing Requirements

1.5.3 Mechanical & General Technical

Document #	Title
T980044-A	Determination of Global and Local Axes for the LIGO Sites
E950111-A	LIGO Naming Conventions
D980226-00	HAM Chamber Port Designations
D980227-00	BSC Chamber Port Designations
D980229-00	BSC Chamber Door Port Designations
D980228-00	Adaptor Port Designations
E950084-01 [DCC only has –00 and not electronic]	LIGO System Specification (for Initial LIGO, but facility limits all apply)
C961574-00 need scanned DCC copy	Civil Construction, Facilities: Design Configuration Control Document, Final Issue
E970063-01	Seismic Isolation System: Fabrication Process Specification, E970063
DOT/FAA/AR-MMPDS-01	"Metallic Materials Properties Development and Standardization (MMPDS)", Jan 2003 [NON-BINDING] (Note: This is the replacement for MIL-HDBK-5.)
MSFC-00000254	Astronautics Structures Manual (lots of useful tables on fastener strengths, etc.)
NASA-STD-5001	Structural Design and Test Factors of Safety for Space Flight Hardware
	T050047-00, Preliminary Results from the Measurement of Creep in Maraging Blades
	MIL-C-104B, Crates, Wood; Lumber and Plywood Sheathed, Nailed and Bolted

1.5.4 Electrical

Document #	Title
E960036-A	LIGO EMI Control Plan and Procedures
E960177-00	LIGO Cable Numbering and Marking Standard
E020986-01	LIGO Interferometer Electronics EMC Requirements

1.5.5 Software

Document #	Title
T970130-F	Specification of a Common Data Frame Format for Interferometric Gravitational Wave Detectors (IGWD)
T960004-A	CDS Software Development Plan & Guidelines (SDP)

1.5.6 Vacuum & Contamination

Document #	Title
E960022-B	LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures
	E960050, LIGO Vacuum Compatible Materials List
	M990034, LIGO Hanford Observatory Contamination Control Plan
T040111-00	Galling Tendencies and Particles Produced by Ultra Clean Screw Threads
SLAC-TN-86-6	SLAC Technical Specification for Vacuum Systems [NON-BINDING]
C981212-00 need electronic copy in DCC	Cleaning Process Control Procedures: S/S Support Tubes and Alum HAM & BSC Weldments
D972202-E	SEI "weld configuration & weld procedure" drawing

1.5.7 Acoustics

Document #	Title
T030075-00	Notes on the Acoustic Emission of VME Crates at LIGO
	S4 Environmental Disturbances, LIGO-G050217-00

1.5.8 Earthquake & Seismic

Document #	Title
P040015-00	Long Term Study of the Seismic Environment at LIGO
	Earthquake Risk & Recovery: Lessons from the 28 Feb 2001 Olympia, WA Quake, G010208-00

1.5.9 Quality Assurance, Reliability, Transportability

Document #	Title
M960076-A make external link	LIGO Project Quality Assurance Plan

1.5.10 Safety

Document #	Title
	M950046, System Safety Management Plan
	M960001, LIGO Laser Safety Program
	M980140, LIGO Hanford Observatory Emergency Action Plan
	M990148, LIGO Livingston Observatory Laser Safety Plan
	M990184, LIGO Livingston Observatory Emergency Action Plan
	M000009, LIGO Livingston Observatory Security Procedures
	M020131, LIGO Hanford Observatory Laser Safety Plan with Added Engineering Controls and Interlock Hardware
	M040112, LIGO Livingston Laser Safety Plan

2 Review Requirements

2.1 Design and Test Reviews

The required design reviews are defined in the Guidelines for Detector Construction Activities as follows:

- Design Requirements Review (DRR)
- Preliminary Design Review (PDR)
- Final Design Review (FDR)
- Prototype Test Review (if applicable)
- First Article Test Review (if applicable)
- Pre-shipment Review

This document defines the nature and requirements of each review, as well as the manner in which they are conducted. These reviews are applicable to each subsystem and to the overall Detector system.

In addition to these standard reviews, the Detector management may require special design reviews if they deem it appropriate, or "incremental" design reviews. For example, timely resolution of technical issues, or schedule lead times for specific elements of a subsystem development, may compel the project to split a comprehensive review into several, "incremental" reviews.

2.2 Approval & Release Process

While most technical documentation is uncontrolled and unreleased (which does not mean it is not valuable), the documentation associated with contracting and fabrication is controlled so that the effect of changes (on cost, schedule, interfaces, etc.) can be ascertained. This documentation applies to all engineering specifications, drawings, procedures, development plans, test plans, interface control documents, etc. Generally in the LIGO document numbering scheme, it is the E and D documents which are approved for release and are controlled through the Document Change Notice (DCN) process (though all documents can be handled with a DCN). Once a document is formally released, all changes must be recorded with new revisions through additional DCNs.

3 Configuration Control

3.1 Design Configuration Control

3.2 Interfaces Definition & Control

3.3 Physical Configuration Control

4 Documentation Requirements

4.1 Documentation Numbering & Electronic Filing

All documents shall be numbered and identified in accordance with the LIGO documentation control numbering system LIGO document TBD

All documents shall be filed electronically in the LIGO Document Control Center (DCC) database in Adobe AcroBat (*.pdf) form

All documents shall be filed in Adobe AcroBat version 3.0 format.

4.2 Source Files

All source files for all released engineering documentation (drawings, specifications, procedures, etc.) shall be archived in the DCC. If there is a one-to-one correspondence between a source file and a drawing, then both can be submitted at the same time with the approved DCN for release.

For drawing source files associated with more than one released LIGO drawing, the procedure for submittal, and the guidelines for naming, are pending. In the interim, CDROM collections, with a descriptive title, can be submitted and given a LIGO document number by the DCC.

4.3 Design, Analysis & Test

4.3.1 Design Requirements Document (DRD)

4.3.2 Conceptual Design Document (CDD)

4.3.3 Preliminary Design Document (PDD)

4.3.4 Final Design Document (FDD)

4.3.5 Technical Design Memorandum

4.3.6 Test Plans and Procedures

4.3.7 Prototype Test Plans & Results

4.4 Fabrication and Process Specifications

4.5 Engineering Drawings and Associated Lists

A complete set of drawings suitable for fabrication must be provided along with Bill of Material (BOM) and drawing tree lists. The drawings must comply with LIGO standard formats and must be provided in electronic format. All documents shall use the LIGO drawing numbering system, be drawn using LIGO Drawing Preparation Standards, etc.

4.6 Technical Manuals and Procedures

4.6.1 Procedures

Procedures shall be provided for, at minimum,

- Initial assembly and check-out of equipment
- Initial installation and setup of equipment
- Normal operation of equipment
- Normal and/or preventative maintenance
- Test of new equipment
- Troubleshooting guide for any anticipated potential malfunctions

4.6.2 Manuals

Any manuals to be provided, such as an operator's manual, shall be provided with delivery of the detector subsystem equipment.

5 Testing Requirements

5.1 Fit Check

Every item shall be fit checked in assembly tests before delivery to the installation effort.

5.2 Assembly

Assembly tooling and procedures shall be developed for each subsystem and tested prior to delivery of first article and production hardware.

5.3 Function

Every

5.4 Performance

5.5 Self-Test

5.6 Installation

6 Mechanical Characteristics & Standards

6.1 Naming Conventions

6.2 Part Numbers

All fabricated LIGO parts shall have a part number designation. The part number is identical to the drawing number, including the revision letter.

6.3 Serial Numbers

Parts for which data is to be collected for individual items (inspection data, performance data, characteristics, etc.) need to have individual serial numbers.

6.4 Coordinate Systems

The coordinate system definition shall be in accordance with LIGO-T980044

6.5 Structural Safety Factor

All Factors of Safety (FS) are to be used with minimum ("S basis" or equivalent) yield and ultimate values for the material[1].

The factors of safety given in the sections below are not meant to cover large uncertainties in the environment and loads, nor are they meant to accommodate unevaluated stress concentration factors. In general for the LIGO Detector components, the service environment and loads are well known (controlled). The material properties, composition and history are likewise (generally) well known and controlled. Engineering judgment should be used if situations arise for which an increased factor of safety might be warranted due to uncertainties in the material, environment or loading conditions.

For safety critical structures (personnel or machine safety), detailed finite element analysis of stress is required.

Discussion/background (not a requirements statement): The factors of safety in the following sections, as well as the proof test magnitude for brittle or bonded structures, is based upon NASA-STD-5001, "Structural Design and Test Factors of Safety for Space Flight Hardware". However, this is not called out as a binding document here – only a reference.

which prescribes a FS = 1.25 for yield and 1.4 for ultimate for metallic, safety critical structures (same as JA-418). As I recall this should be used with "A-basis" yield and ultimate values for the material (which refers to a high statistical certainty that the material has a higher yield or ultimate

[1] S-Basis material values are defined as the value for which 99% of a normal distribution have a higher value with a 95% confidence. S-basis material properties are provided in "Metallic Materials Properties Development and Standardization (MMPDS)", Jan 2003, DOT/FAA/AR-MMPDS-01 (Note: This is the replacement for MIL-HDBK-5.)

value). I don't think the fracture mechanics criteria (e.g. stress intensity factors) are applicable since the elongation at failure is >5% (i.e. solution annealed maraging steel is ductile).

6.5.1 Metal (other than maraging steel)

For metallic structures other than maraging steel, the FS should be a minimum of 1.25 for yield and 1.4 for ultimate.

6.5.2 Maraging Steel

For maraging steel components which form flexural elements of a LIGO passive isolation system, use a FS or 1.8 for yield. [TBR] See also section 6.7.2 on maraging heat/load treatment to accelerate creep.

Background/discussion (not a statement of requirement): LIGO uses maraging steel for cantilevered blade spring flexures, in plate form, and for suspended pendulum links/flexures, in rod or wire form. Generally these are safety critical structures (non-redundant and supporting a heavy load and/or an expensive asset, such as a core optic.). In addition, these maraging steel elements form passive vibration isolation elements in proximity to the sensitive, low noise, optical elements. Noise due to creep or relaxation must be minimized in part by keeping stresses low. Discussions on maraging steel in these applications can be found in the following references:

G050099-00, Maraging Steel: SUS perspective

G050211-00, Maraging Steel: SEI Perspective

6.5.3 Bonds

For the bonds of composite structures (metallic or non-metallic), the FS shall be a minimum of 2.0 for ultimate.

6.5.4 Glass & Ceramics

For non-metallic, brittle structures, the FS should be a minimum of 3.0 for ultimate stress.

6.5.4.1.1 Proof Testing

For all components or assemblies that are to be placed into the LIGO vacuum system, proof testing on the actual end article must be performed for all bonds (to metallic or non-metallic components) and all non-metallic, brittle structures. Proof testing is to be done to a factor of 1.2 over the maximum service load and shall be done in an inert environment to minimize flaw growth.

6.5.4.1.2 Inert Environment for Fused Silica Fibers or Ribbons

To minimize flaw growth, the fused silica fibers or ribbons are to be kept in an inert environment (free of moisture) as much as possible. In particular the fibers are to be stored in a moisture free environment. Ribbons or fibers are to be proof tested before welding into a suspension assembly.

6.6 Materials

6.7 Processes

6.7.1 Cleaning

All materials used inside the vacuum chambers will be cleaned in accordance with E960022-B, LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures. Final cleaning & vacuum preparation of parts should be performed after all processing has been completed, if at all possible. Cleaning shall be performed at intermediate steps to insure cleanliness when subsequent fabrication or assembly steps limit the effectiveness of final cleaning; For example the OSEM coil former and coil wire will be cleaned and vacuum baked prior to winding. Care will be taken to insure proper handling in processing steps following intermediate cleaning steps.

The various suspensions will use 2 or 3 different types of Optical Sensor and Electro-Magnetic actuator (OSEM) assemblies. The assembly procedure for the "Hybrid OSEM" (used on the Recycling Mirrors Suspension and Mode Cleaner Suspension), including cleaning steps in given in E030084-02, "Hybrid OSEM Assembly Specification". A similar procedure will be developed for all OSEM variants used in the suspension assemblies.

Parts or assemblies shall be capable of disassembly for cleaning, or joined in such a way as to facilitate cleaning and vacuum preparation procedures; i.e., internal volumes shall be provided with adequate openings to allow for wetting, agitation and draining of cleaning fluids and for subsequent drying.

All SUS parts will be detergent and solvent cleaned in ultrasonic baths and then vacuum baked, and qualified for LIGO vacuum service with an RGA measurement, with the exception of the lower structure of all BSC suspensions (and potentially the upper structure of the combined FM/ITM suspension). These large components will be detergent cleaned and air baked, with qualification for LIGO vacuum service via an FTIR test. In all cases the procedures will comply with E960022.

6.7.2 Creep Acceleration

Maraging steel flexural elements used for passive isolation in the suspension systems (close to the final isolated test mass/optic) shall be treated to bake out creep in advance of installation. In the final clamp assembly, under its nominal loading, the maraging steel shall be baked at 100C to 200C for 7 days. The load must then remain applied to the maraging steel. [TBR]

Background/discussion (not a statement of requirement): LIGO uses maraging steel for cantilevered blade spring flexures, in plate form, and for suspended pendulum links/flexures, in rod or wire form. These maraging steel elements form passive vibration isolation elements in proximity to the sensitive, low noise, optical elements. Noise due to creep or relaxation must be minimized in part by keeping stresses low. The creep rate should also be reduced by appropriate heat and load treatment to accelerate creep. A discussions on maraging steel creep can be found in the following reference:

T050047-00, Preliminary Results from the Measurement of Creep in Maraging Blades

6.8 Welding and Brazing

6.8.1 Welding Metal

None of the SUS component welds form a pressure vessel. In general the SUS components are stiffness critical structure, not strength critical, so that weld strength is not an issue. The principal concern for SUS welds is vacuum cleanliness.

Before welding, the surfaces should be cleaned (but baking is not necessary at this stage) according to the UHV cleaning procedure(s). All welding exposed to vacuum shall be done by the tungsten-arc-inert-gas (TIG) process. Welding techniques for components operated in vacuum shall be in accordance with the best ultra high vacuum practice, such as the SLAC "Technical Specification for Vacuum Systems", SLAC-TN-86-6 (section VI. Welding and Brazing and Appendix I.D)

In particular all vacuum welds shall be full penetration wherever possible to eliminate trapped volumes or difficult to clean crevices, i.e. virtual leaks. All weld procedures for components operated in vacuum shall include steps to avoid contamination of the heat affected zone with air, hydrogen or water, by use of an inert purge gas that floods all sides of heated portions.

The welds should not be subsequently ground (in order to avoid embedding particles from the grinding wheel).

The SUS group intends to use the Initial LIGO Seismic Isolation System: Fabrication Process Specification, E970063, as a guide for welding requirements and process sequence, as well as the associated detailed processing procedures developed by Allied Engineering to implement E970063 (e.g. "Cleaning Process Control Procedures: S/S Support Tubes and Alum HAM & BSC Weldments", C981212-00).

Weld preparation details shall be called out on the drawings developed by SUS. Each of these welds will be worked out with a welder experimentally to insure full penetration and minimal heat distortion of the parts (e.g. as part of the prototype development efforts). The specific examples in the SEI "weld configuration & weld procedure" drawing, D972202 will serve as initial guidance for the SUS welding details. These weld preparation details are all for full penetration welds suitable for in-vacuum service. They are typically for joining aluminum plate from 0.25 to 0.75 inches thick.

6.8.2 Welding Fused Silica

Requirements for welding fused silica fibers or ribbons to fused silica ears (which are bonded to a suspended mass) are pending completion of the enabling R&D.

6.8.3 Dip Brazing

Due to the high porosity and inability to guarantee removal of all salts and fluxes, dip brazing is not acceptable for parts intended for LIGO vacuum service.

6.9 Finishes

Surface-to-surface contact between dissimilar metals shall be controlled in accordance with the best available practices for corrosion prevention and control. Extra-vacuum surfaces requiring protection shall be painted LIGO blue or otherwise protected in a manner to be approved. Metal components intended for vacuum service shall have quality finishes on all surfaces, suitable for vacuum. All sharp edges and corners shall be rounded. All materials shall have non-shedding surfaces. Aluminum components used in the vacuum shall not have anodized surfaces.

Tight fit/tolerance sliding contacts should be avoided if possible in the LIGO vacuum. If necessary then low outgassing, vacuum compatible, solid, non-organic lubricants should be used, in accordance with E960050, LIGO Vacuum Compatible Materials List.

6.10 Bolted Joints & Threaded Fasteners

All in-vacuum fasteners shall use oversize tapped threads to prevent galling, in accordance with E030350, Drawing Requirements.

Unless other overriding design considerations dictate an alternate set of materials, or thread treatment, all in-vacuum fasteners shall comply with the following requirements to prevent galling. If an alternate design choice is recommended, then this choice must be shown by test[2] not to gall after LIGO cleaning procedures and service in vacuum:

> Aluminum: LIGO aluminum in-vacuum parts that are expected to be disassembled (such as clamps for securing optical table components into the aluminum optics table) must use stainless steel screws in Nitronic-60 (N60) thread inserts for the tapped holes, to reduce the amount of generated particles and to reduce the risk of galling. For parts that are disassembled rarely, stainless steel screws shall be used in 0.005” oversize tapped aluminum parts.
>
> Stainless Steel: Silver-plated, stainless steel screws shall be used in 0.005” oversize tapped stainless parts.

6.11 Drawing Standards

see E030350

6.12 CAD Standards

see E030350

[2] Testing similar to that reported in T040111, Galling Tendencies and Particles Produced by Ultra Clean Screw Threads

6.13 Interchangeability

6.14 Workmanship

6.15 Human Engineering

6.16 Preparation for Delivery

Packaging and marking of equipment for delivery shall be in accordance with the Packaging and Marking procedures specified herein.

6.16.1 Preparation

- Vacuum preparation procedures as outlined in LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022-00-D) shall be followed for all components intended for use in vacuum. After wrapping vacuum parts as specified in this document, an additional, protective outer wrapping and provisions for lifting shall be provided.
- Electronic components shall be wrapped according to standard procedures for such parts, including electrostatic protection, as appropriate.

6.16.2 Packaging

Procedures for packaging shall ensure cleaning, drying, and preservation methods adequate to prevent deterioration, appropriate protective wrapping, adequate package cushioning, and proper containers. Proper protection shall be provided for shipping loads and environmental stress during transportation, hauling and storage. The shipping crates used for large items should use for *guidance* military specification MIL-C-104B, Crates, Wood; Lumber and Plywood Sheathed, Nailed and Bolted. Passive shock witness gauges should accompany the crates during all transits.

For all components which are intended for exposure in the vacuum system, the shipping preparation shall include double bagging with Ameristat 1.5TM plastic film (heat sealed seams as practical, with the exception of the inner bag, or tied off, or taped with care taken to insure that the tape does not touch the cleaned part). Purge the bag with dry nitrogen before sealing if the components absorb water.

6.16.3 Marking

see E030350

Appropriate identification of the product, both on packages and shipping containers; all markings necessary for delivery and for storage, if applicable; all markings required by regulations, statutes, and common carriers; and all markings necessary for safety and safe delivery shall be provided.

Identification of the material shall be maintained through all manufacturing processes. Each component shall be uniquely identified. The identification shall enable the complete history of each component to be maintained (in association with Documentation “travelers”). A record for each component shall indicate all weld repairs and fabrication abnormalities.

For components and parts which are exposed to the vacuum environment, marking the finished materials with marking fluids, die stamps and/or electro-etching is not permitted. A vibratory tool with a minimum tip radius of 0.005" is acceptable for marking on surfaces which are not hidden from view. Engraving and stamping are also permitted.

All component parts shall be marked with their part number and, if appropriate, serial number.

6.17 Assembly

6.18 Installation

7 Electrical Characteristics & Standards

7.1 Naming Conventions

7.2 Grounding & Shielding

7.3 EMI/EMC

All LIGO Detector electrical/electronics equipment shall meet the Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) requirements of the following two documents:

- LIGO EMI Control Plan and Procedures, E960036-A
- M. Zucker, "LIGO Interferometer Electronics EMC Requirements", E020986-01

In particular, as stated in E960036-A:

- LIGO digital electronics shall conform to FCC Part 15, Subpart J regulations for radiated nd conducted emissions form Class B computing devices
- LIGO digital and analog electronics shall conform to the selected portions of MIL-STD-461E called out in LIGO-E960036-A, for both electromagnetic emission and susceptibility to ambient environment
- LIGO-E960036-A also calls out requirements on DC Power Supplies, Circuit Shielding and Grounding (digital, baseband analog and RF) as well as cabling standards.

Relevant examples of the implementation of LIGO acceptable EMI/EMC practice is included in the following documents:

- M. Zucker, J. Heefner, "EMC, “Shielding and Grounding Retrofit Plan”, E020350-08
- B. Abbott, "Installation of RFI Mitigated HEPI System at LLO", E040288-00, 18 Jun 04

7.4 Cabling

see E960177-00

7.5 Connectors

7.6 Bus Architecture

7.6.1 EPICS control interface

7.6.2 Workmanship

7.6.3 Software Characteristics & Standards

7.7 TBD

7.8 GUI Human Engineering

8 Vacuum Compatibility Requirements

see E960022

see E960050

8.1 Tribology

8.2 Materials

8.3 Qualification

8.4 Fabrication

8.5 Cleaning

9 Acoustic Requirements

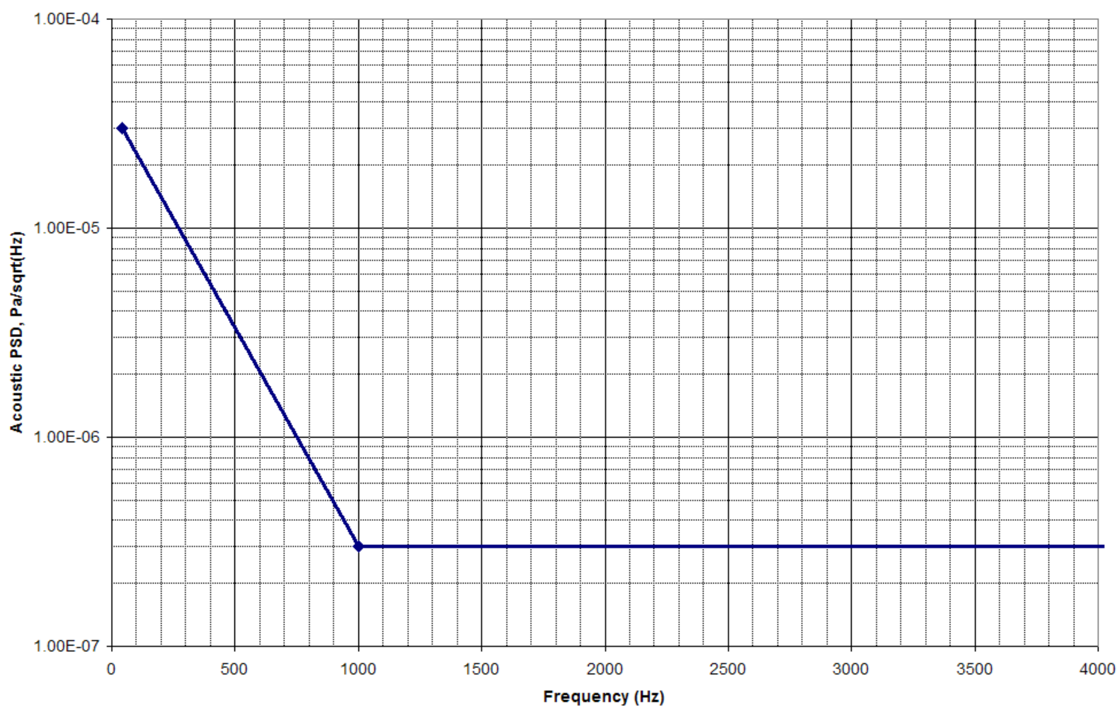
9.1 Emission in the LVEA and VEA Areas

Requirement:

Equipment shall be designed to produce the lowest levels of acoustic noise as possible and practical. Electronic cooling fans are not permitted in the LVEA or VEA areas. The acoustic noise level from any one subsystem is limited to the power spectral density shown in the Figure below, i.e.

3×10^{-5} Pa/√Hz at 10 Hz , 3×10^{-7} Pa/√Hz at 1 kHz and above

Figure 1: Acoustic Broadband Noise Limit



Derivation of the Requirement:

Acoustic measurements[3] in the LVEA and VEA for Initial LIGO indicate that a broadband acoustic power spectral density level of 10^{-4} Pa/√Hz, for frequencies > 40 Hz, is marginal (i.e. just adequate) to achieve the Initial LIGO Science Requirements Document (SRD) sensitivity. Given that:

- Advanced LIGO is expected to achieve a sensitivity that is a factor of up to 15 better than Initial LIGO and up to a factor of 4 lower in frequency, and

[3] R. Schofield, et. al., S4 Environmental Disturbances, LIGO-G050217-00

- technical noise sources should be a factor of 10 below the level which compromises the interferometer noise floor

then a simple linear scaling for Advanced LIGO yields a broadband acoustic noise level requirement of 7 x 10^{-7} Pa/√Hz, for frequencies > 10 Hz. However, in Advanced LIGO the sensitive readout optics and electronics are planned to be in vacuum and so not sensitive to acoustic noise levels in the LVEA & VEA areas. There may still be some readout optics in air (and acoustically shielded as is the case for Initial LIGO). Consequently this level is overly conservative.
At LLO where all of the electronics racks (fan noise) were removed from the LVEA, the ambient noise level varies linearly from 10^{-4} Pa/√Hz at 40 Hz to 10^{-6} Pa/√Hz at 1 kHz. Advanced LIGO Detector equipment should not compromise on this building/facility background acoustic level[4]. Since on the order of 10 subsystems can contribute to this overall acoustic noise in a root-sum-squared sense, the acoustic noise limit for each subsystem is set to 1/3 the above facility level.

N.B.: The derivation of acceptable electronic rack acoustic noise specification for Initial LIGO[5] does not apply for advanced LIGO.

9.2 Emission in the MSR and CDS Rack Areas

Requirement:

Racks and crates in the CDS Rack Area shall be no noisier than the EMI-tight Dawn crate and Knurr Rack currently used at LLO.TBD.

Derivation of the Requirement:

Some electronics can exhibit microphonic sensitivity. As a consequence the acoustic noise level in the rack areas of the LIGO facility should be held to a reasonable limit. In addition, these areas are not far from optics in the LVEA and VEA areas, which are acoustically sensitive. Measurements[6] after the Science #4 run indicated that at the initial LIGO interferometer sensitivity level, acoustic noise at a level much higher than the (considerable) fan noise associated with the LLO EMI-tight racks and crates, does not present a problem. Since we may use these (or similar) crates (Dawn) and racks (Knurr) for advanced LIGO, we'll assume that the acoustic noise emission from these crates and racks are acceptable, or that they can be made acceptable for advanced LIGO with some added sound dampening to the walls. The acoustic emission levels of the Dawn VME crates[7] are documented in T030075-00.

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[4] Note that this level is not precisely the facility/building background level in the LVEA and VEA areas, since Detector electronic racks in the adjacent CDS Rack Room may still be contributing to the ambient acoustic level.

[5] A. Lazzarini, Derivation of CDS Rack Acoustic Noise Specifications, LIGO-T960083-A.

[6] R. Schofield, LLO elog Entry: Acoustics, LVEA Electronics Room, 25 Mar 2005.

[7] S. Marka, Notes on the Acoustic Emission of VME Crates at LIGO, 25 Apr 2003, LIGO-T030075-00.

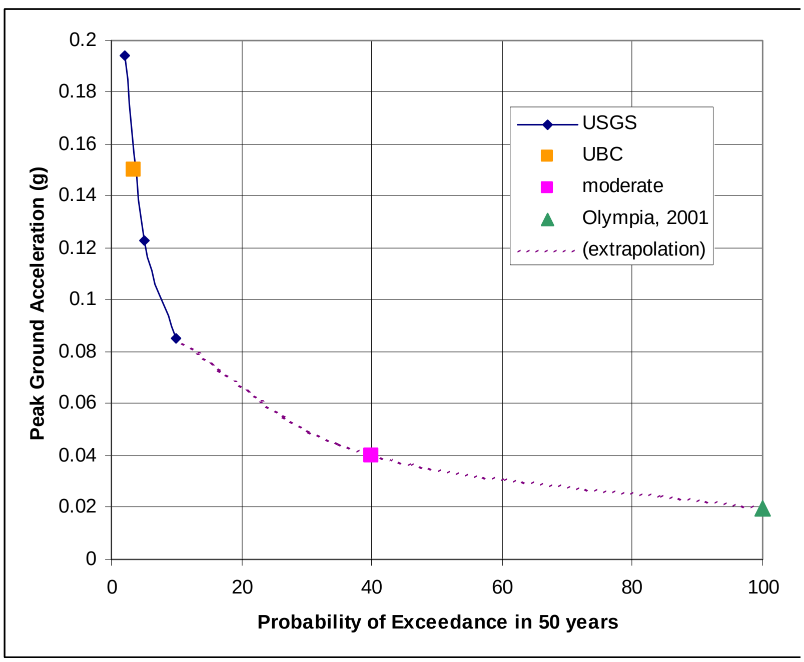
10 Earthquake Requirements

The LIGO interferometers are subjected to earthquakes of varying magnitudes. The interferometers are subjected to small micro-tremors and low amplitude accelerations, due to distant high magnitude earthquakes, as frequently as daily. Moderate and severe earthquakes are rare events. Requirements are defined in the following sections for three levels of earthquake motion: (i) Severe, (ii) Moderate and (iii) Minor.

A plot of the approximate probability of exceeding a peak ground acceleration (PGA) is shown below. The PGA associated with the severe motion design requirement from the Uniform Building Code (UBC) is 0.15 g and has a probability of exceedance of 3.5% in 50 years. The moderate earthquake PGA level chosen for design criteria is 4% of g and (very roughly) has a probability of ~40% in 50 years (or ~8% in the approximate 10 year lifetime between major detector changes).

Figure 2: Peak Ground Velocity Probability

Values for high Peak Ground Acceleration (PGA) versus the probability of exceedance for Hanford WA are from the USGS[8]. Strong ground motion is much less likely to occur at the LIGO Livingston site. Data was not found in the literature (with a limited time search) on the probability of moderate to low amplitude ground motion (though it seems likely that such data exists). In fact an anlysis of the LIGO seismometer data form the Observatories might be able to establish the low to moderate ground motion probabilities. The Olympia, WA 28 Feb 2001 event, which caused extensive "minor" damage to the Initial LIGO Detector and many months of Observatory downtime[9], had a PGA of 2% of g; For the purpose of approximate extrapolation the Olympia event assumed to be a 1 in 50 year event. The moderate ground motion level for design requirements was set to be 4% and it is guessed that the probability of exceeding this level is about 8% in 10 years. The PGA level associated with the UBC design criteria is also indicated in the plot.



[8] Frankel, Arthur, Mueller, Charles, Barnhard, Theodore, Perkins, David, Leyendecker, E.V., Dickman, Nancy, Hanson, Stanley, and Hopper, Margaret, 1997, Seismic-hazard maps for the conterminous United States, U.S. Geological Survey Open-File Report 97-131-F.

[9] D. Coyne, Earthquake Risk & Recovery: Lessons from the 28 Feb 2001 Olympia, WA Quake, G010208-00

10.1 Severe Earthquake Motion: Maintaining Structural & System Integrity

The high magnitude earthquake load requirement imposed on the detector equipment is modeled on the civil construction requirements which were applied to the design of LIGO buildings and derive from the Uniform Building Code (UBC).

10.1.1 Failure Levels

Each system, subsystem, assembly and component shall be designed to resist severe earthquake motion (at the magnitude defined in the next section) without "castastrophic damage"; In this context castastrophic damage is defined to be:

- fracture of structural members (exceeding ultimate strength), or
- failure of high value components or assemblies (assemblies or components whose replacement cost exceeds $250K (2005 USD) each or whose replacement time exceeds 1 year), or
- failure of the integrity of the vacuum system.

Acceptable levels of damage are as follows:

- fracture or yielding (plastic deformation) of components which can be repaired or replaced with a cost of less than $250K (2005 USD) for each instance and a replacement time (including vacuum and cleanroom operations, preparation staging and procurement activities, installation, alignment and integrated test) of less than 1 year

Examples of unacceptable levels of damage:

- Fracture of a core optic component (COC), for example by failure of it's caging structure which causes the optic to fall
- Failure of the SEI support structure which in turn would (could) lead to failure of the support tube bellows and compromise the vacuum system

Examples of acceptable levels of damage:

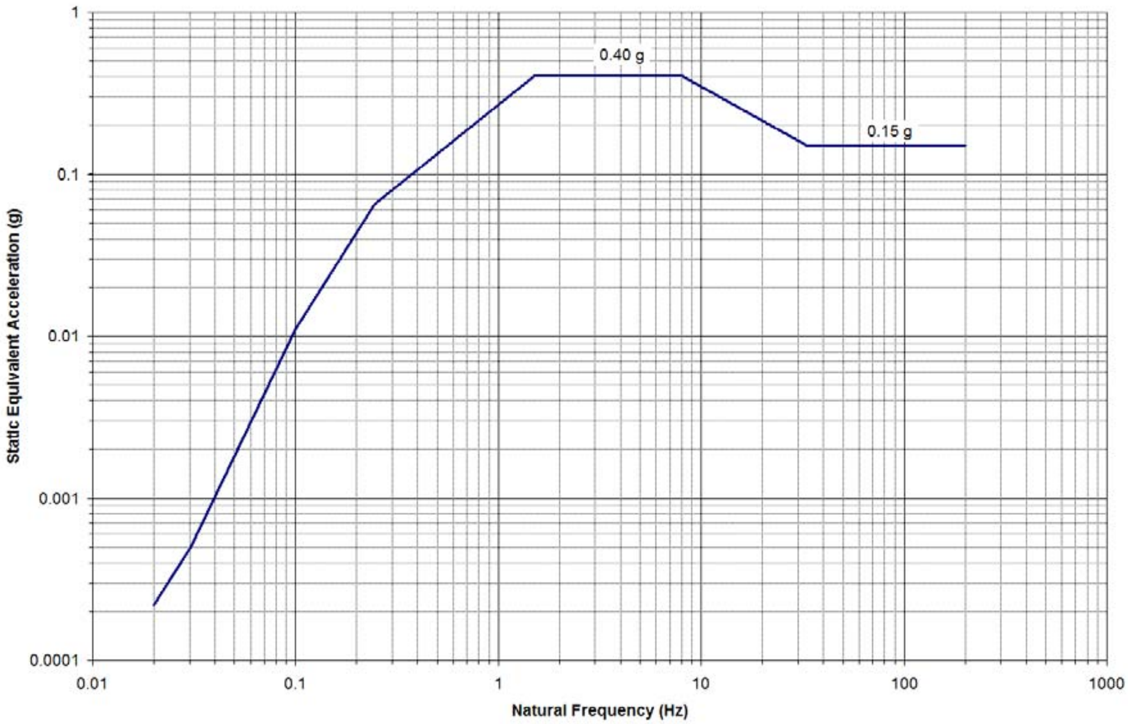
- Failure of a suspension fiber/ribbon or wire
- Failure of a bonded magnet/standoff from a suspended mass
- Ear to COC bond failure if the COC is re-usable, or if the probable number of non-re-usable COC is covered by acceptable delivered spares
- Failure of an SEI actuator

It is the responsibility of each subsystem to perform a failure effects and modes (FEMA) study and to propose the acceptable levels of damage in the event of a high magnitude earthquake. The susbsystem should, if appropriate, plan for adequate delivered spares to be consistent with the proposed damage mitigation strategy. Recovery from the damage defined as acceptable above, could take a year or more of observatory downtime.

10.1.2 Base Shear

Requirement: All LIGO Detector assemblies must meet the failure criteria defined in section 9.1.1 when subjected to the static-equivalent, horizontal load indicated in Figure2 as a function of the lowest natural frequency of the structural system that couples to horizontal motion. This load applies to any horizontal direction.

Figure 3: Elastic Design Response Spectrum for Severe Ground Motion
The design response spectra gives the static equivalent load that a structural system, with the indicated first natural frequency, must sustain in terms of the gravitational acceleration, g. The methodology given in A. Chopra[10] was used to develop this elastic design spectrum.



If meeting this requirement is difficult for a particular structural assembly, then assumptions with regard to allowable plasticity and inherent damping may be used to reduce the static equivalent loading (see derivation below) with review and approval. Another alternative to this static equivalent load, is a transient dynamic analysis with a time series realization of a canonical event with the equivalent peak ground motion.

Derivation of the Requirement: The static equivalent base shear (horizontal lateral force), V_b, that the system must survive is defined in the Uniform Building Code (UBC)[11], 1994 edition, as:

$$V_b = \left(\frac{ZIC}{R_W} \right) W$$

where

[10] A. Chopra, Dynamics of Structures: Theory and Applications to Earthquake Engineering, Prentice Hall, 1995, pg. 220-224.

[11] Uniform Building Code (UBC), Vol. 2, 1994. There have been a number of revisions to the UBC culminating in the 1997 version. The UBC is now superceded by the International Building Code (IBC).
Note: Tthe latest International Building Code (IBC) should be reviewed to insure that the strong earthquake base shear load herein is still applicable.

- W = the total dead load
- Z = the seismic zone factor; Z = 0.15 for zone 2B (Hanford,WA; it is zero for Livingston, LA)
- I = the structure importance factor; I = 1 for LIGO detector components
- R_w = the structural system coefficient and accounts for the ductility capacity and inelastic performance of the materials and system. In building wall design Rw might vary from 4 to 12; R_w is 6 for the LIGO buildings. For a completely elastic system, R_w =1. Since the Detector designs are typically stiffness critical designs, and have no detailing for ductile connections, the default for LIGO Detector components should be R_w =1.
- C = elastic seismic coefficient; $C = \frac{1.25S}{T_1^{2/3}} \leq 2.75$ The upper limit of 2.75 corresponds to the elastic amplification factor for acceleration for a structure with 5% damping (Q = 20) typical of bolted, welded or riveted construction.
- T1 = fundamental natural vibration period of the structure (sec)
- S = site soil coefficient; S = 1.2 (CHECK!) for the Hanford, WA LIGO site[12]

The UBC does not specify a vertical motion (load) requirement.

For the default assumptions that there is no plastic deformation to absorb the seismic loading (R_w = 1), the first natural frequency is greater than 2.5 Hz, and damping is 5%, then C = 2.75 and the base shear, V_b = 0.4 W, or the static equivalent base shear acceleration is 0.4 g (where g is the gravitational acceleration).

Using the methodology given in A. Chopra to define an elastic design spectrum, with a Z = 0.15 g as the peak ground acceleration, results in Figure 2. The maximum static equivalent acceleration is 0.4 g, consistent with the UBC result above.

[12] REF Parsons Engineering Report for LIGO

10.2 Moderate Earthquake Motion: No Damage Threshold

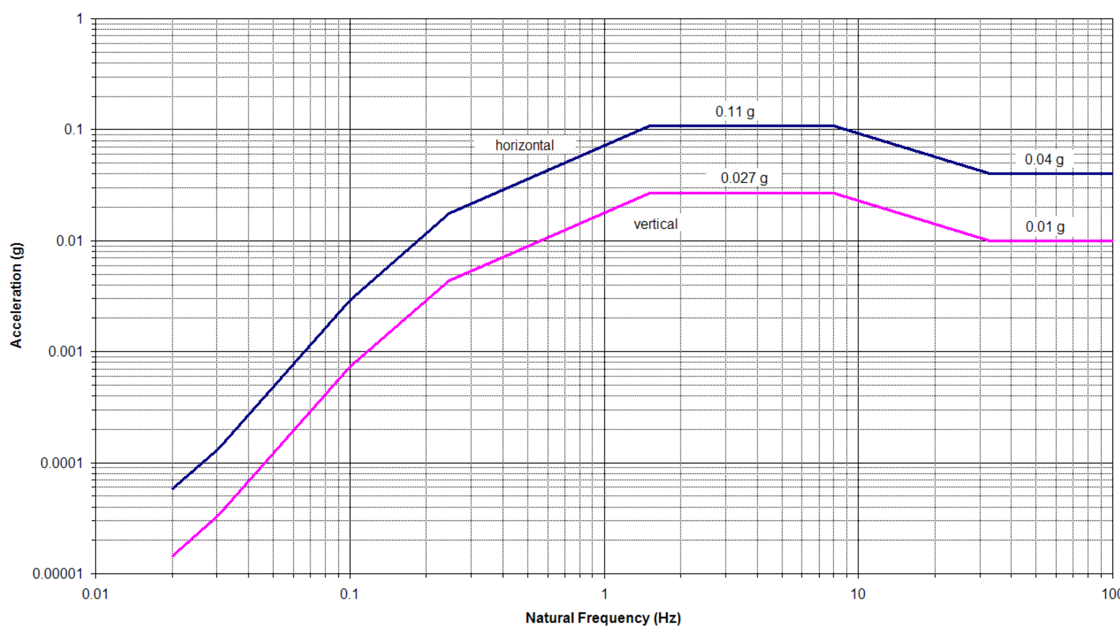
Requirement: No damage should occur to any Detector structural assemblies when subjected to the static-equivalent, horizontal load indicated in Figure 3 as a function of the lowest natural frequency of the structural system that couples to horizontal motion. This load applies to any horizontal direction.

In addition to this horizontal motion, a simultaneous vertical motion equal to ¼ of the horizontal motion must also be sustained without damage.

It is recognized that misalignment of the interferometer optics may occur at this level (without damage) and this is considered acceptable. The expected time to recover interferometer alignment is on the order of 4 months.

Figure 4: Elastic Design Response Spectrum for Moderate Ground Motion

The design response spectra gives the static equivalent load that a structural system, with the indicated first natural frequency, must sustain in terms of the gravitational acceleration, g.



Derivation of the Requirement: More frequent, though still rare, moderate magnitude motion should not cause long term downtime for the observatories. As indicated in the discussion in Section 9.1, we choose to set the no-damage threshold at the ground motion level for which the probability of exceedance in 10 years (the approximate lifetime between major upgrades) is about 8%. Based on available data the corresponding peak ground acceleration (PGA) at this probability level for the Hanford, WA site is about 0.04 g. The methodology in A. Chopra was used to define the elastic design response spectrum consistent with this PGA level which appears in Figure 3.

The USGS and the UBC do not define vertical ground motion for earthquake hazard definition. However, it seems prudent to consider a non-zero vertical acceleration level acting simultaneously with the horizontal acceleration for the purpose of defining the no-damage threshold criteria. Based on the 95 percentile r.m.s velocity values for the Hanford site in the 1-3 Hz band from E. Daw's study[13], the vertical motion might be expected to be about ¼ the magnitude of the horizontal motion. It is recognized that the sources of the ground noise in E. Daw's study is a mixture of anthropogenic and (micro)seismic events and may not apply to the moderate ground motion level under consideration. No source for better data was found in a limited time search.

10.3 Minor Ground Motion: Maintaining Operation

All Detector systems must be able to operate through the 95th percentile limits of ground motion defined in E. Daw's long term study of the LIGO seismic[6].

[13] E. Daw, Long Term Study of the Seismic Environment at LIGO, Class. Quantum Grav., 11 Mar 2004, P040015-00

11 Quality Assurance

This section includes all of the examinations and tests to be performed in order to ascertain if the product, material or process conforms to the requirements.

11.1 Quality conformance inspections

Design and performance requirements identified in this specification and referenced specifications shall be verified by inspection, analysis, demonstration, similarity, test or a combination thereof per the Verification Matrix (Section 10.2). Verification method selection shall be specified by individual specifications, and documented by appropriate test and evaluation plans and procedures. Verification of compliance to the requirements of this and subsequent specifications may be accomplished by the following methods or combination of methods:

11.1.1 Inspections

Inspection shall be used to determine conformity with requirements that are neither functional nor qualitative; for example, identification marks.

11.1.2 Analysis

Analysis may be used for determination of qualitative and quantitative properties and performance of an item by study, calculation and modeling.

11.1.3 Demonstration

Demonstration may be used for determination of qualitative properties and performance of an item and is accomplished by observation. Verification of an item by this method would be accomplished by using the item for the designated design purpose and would require no special test for final proof of performance.

11.1.4 Similarity

Similarity analysis may be used in lieu of tests when a determination can be made that an item is similar or identical in design to another item that has been previously certified to equivalent or more stringent criteria. Qualification by similarity is subject to Detector management approval.

11.1.5 Test

Test may be used for the determination of quantitative properties and performance of an item by technical means, such as, the use of external resources, such as voltmeters, recorders, and any test equipment necessary for measuring performance. Test equipment used shall be calibrated to the manufacture's specifications and shall have a calibration sticker showing the current calibration status.

11.2 Quality Conformance Verification Matrix

TBD

Table 1 Verification Matrix

Paragraph	Title	I	A	D	S	T

12 Reliability

12.1 Reliability Requirements

Each subsystem shall derive requirements on the reliability of their subsystems from system level imposed availability requirements. These derived requirements shall further be compared to the expected reliability of the subsystem designs by assessing the reliability of the components which are likely to limit availability of the subsystem. A complete failure effects and modes analysis (FEMA) is not required, as long as simple bounding analyses indicate that the required subsystem availability is adequate.

12.2 Reliability Testing

Reliability evaluation/development tests shall be conducted on items with limited reliability history that will have a significant impact upon the operational availability of the system.

13 Maintainability

TBD

14 Transportability

TBD

15 Safety

15.1 FEMA

A Failure Effects and Modes Analysis (FEMA) is required from every subsystem. For subsystems, comprised of multiple, non-interacting systems or assemblies, separate FEMAs on each system or assembly may be more suitable.

15.2 Personnel Safety

15.3 Laser Safety

LIGO Livingston Observatory Laser Safety Plan, M040112-07

LIGO Hanford Observatory Laser Safety Plan, M020131-01

LIGO LASTI Laser Safety: Kavli Institute/MIT safety plan

15.4 Machine Safety

15.4.1 Design Factor of Safety (FS)

see section ?

15.4.2 Proof Testing

see section ?

15.4.3 Overcurrent and Overvoltage Protection