LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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LIGO Science Requirements Document (SRD)

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A. Lazzarini
R. Weiss
Authors(s)

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of the LIGO Project

California Institute of Technology
LIGO Project - MS 51-33
Pasadena CA 91125
Phone (818) 395-2129
Fax (818) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

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

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Facilities Group: ________________________________ Date: ________

Detector Group: ________________________________ Date: ________

Systems Engineer: ________________________________ Date: ________

Integration Scientist: ________________________________ Date: ________

Project Manager: ________________________________ Date: ________

Principal Investigator: ________________________________ Date: ________

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LIGO PROJECT SCIENCE REQUIREMENTS DOCUMENT

1 SCOPE

1.1 IDENTIFICATION

This Science Requirements Document establishes the scientific requirements and goals for the Laser Interferometer Gravitational-Wave Observatory (LIGO). These requirements flow down to all other system- and subsystem-level requirements and specifications for LIGO.

1.2 PURPOSE

The LIGO project is intended to open the field of gravitational wave astrophysics. The detection technique is to measure the strains induced in space by gravitational waves using laser interferometry between nearly free masses. The project is designed to permit phased incorporation, at later dates, of improvements in the technology of laser gravitational wave detection to further improve the instrumental sensitivity and bandwidth. LIGO will be part of an international network of long baseline interferometric detectors to establish the polarization of the waves and the location of the astrophysical sources.

The observations carried out by LIGO are expected to provide fundamental and new information concerning the gravitational interaction including:

- direct measurement of strong field gravity through the observation of the gravitational waves from black holes. The waves will convey information about
    - the normal modes of black holes
    - inertial frame dragging by rotating black holes
- the observation of compact stellar systems such as neutron star/neutron star, black hole/black hole and black hole/neutron star binaries thereby providing detailed information of the relativistic equations of motion.
- the direct measurement of the polarization states of gravitational waves in conjunction with other interferometric gravitational wave detectors.
- a direct measurement of the speed of propagation of gravitational waves.

The astrophysical information derived from LIGO observations includes:

- the spatial and mass distribution of neutron star binary systems in the universe.
- the spatial and mass distribution of black holes and black hole binary systems in the universe.
- a new and independent method of determining the Hubble expansion using compact binary systems as standard objects.

- the equation of state of neutron stars from the gravitational waveforms at the final coalescence of neutron star binaries.
- the internal dynamics of asymmetric supernova explosions.
- limits to or measurements of the gravitational multipole moments of pulsars.
- limits or observations of the gravitational wave background from the earliest epoch of cosmic evolution.
- a new view of the universe with a high probability of uncovering phenomena not observed by electromagnetic astronomy.

2 APPLICABLE DOCUMENTS

Information and requirements appearing in the Document are derived from previously published LIGO technical and scientific documents. The relevant documents are listed in Table 2-1. The requirements presented here form the basis of various other LIGO specifications, principally the LIGO System Design Requirements Document.

Table 2-1: Documents relevant to LIGO Science Requirements

DOCUMENT TITLE	ID NUMBER
Construction, Operation, and Supporting Research and Development of a Laser Interferometer Gravitational-Wave Observatory	LIGO-M890001-00-M (Vols. I & II)
LIGO: The Laser Interferometer Gravitational-Wave Observatory	LIGO-P920002-00-M (April, 1992; *Science*, Vol. 256, p325)
Technical Supplement to the LIGO Construction Proposal	LIGO-M930002-00-M
LIGO Project Management Plan	LIGO-M950001

3 REQUIREMENTS

3.1 LIGO DETECTOR REQUIREMENTS

The LIGO detector shall have the capability of making a confident detection of gravitational waves alone. The LIGO detector shall also be capable of providing angle-of-arrival information for detected signals.

These requirements can be met by a detector which consists of three independent laser interferometers, at least one of which is located remotely from the other two. One interferometer shall be located at sufficient distance from the other two to enable angle-of-arrival measurement from temporal correlation of coincident signals.

Two instruments shall be colocated and be designed to have different sensitivities to gravitational wave strain (2:1). The operation of a full length and a half length interferometer at one site serves several functions: [i] it improves the rejection of accidental coincidences by imposing a triple coincidence for a valid burst event; [ii] it is a diagnostic for gravitational waves by demanding that coincident displacement signals scale with interferometer length; [iii] it enables a broad-band search for a stochastic gravitational wave background limited by the environmental correlations at a single site.

The data from the detector shall be analyzed for impulsive, chirp, periodic and stochastic background gravitational waves. Accurate and precise absolute timing shall be provided by the Global Positioning System (GPS). The precision will permit operating with narrow coincidence gates among the interferometers and the accuracy permits correlation of LIGO data with other detector systems, such as resonant bar detectors, particle (neutrino) detectors, and electromagnetic (γ-ray, x-ray, visible, infrared, and radio) astronomical observatories. The two sites have been chosen to be sufficiently separated so that environmental perturbations to the interferometers are expected to be minimally correlated. The gravitational waves signals will be correlated and this property is used in making the observation. At both sites an environmental monitoring system is used to measure the environmental perturbation to the interferometers to reduce the singles rate in a burst search, to measure the background perturbations that could influence a periodic and stochastic gravitational wave measurement, and as a diagnostic for interferometer development. In addition, all relevant interferometer and system parameters that can potentially affect the noise budget shall be recorded for subsequent diagnostic studies.

To obtain the maximum scientific return, LIGO is also planned to be operated as an element of an international network of gravitational wave detectors involving other long baseline interferometric detectors and acoustic detectors. Long baseline interferometric detectors are expected to be operated by the VIRGO Project at Pisa, Italy and by the GEO600 project at Hannover, Germany. Plans are also underway to establish long baseline interferometric detectors in Japan and Australia. A global network of detectors will be able to provide full information from the gravitational waves, in particular, the wave polarization and the source position on the sky. Simultaneous observations in several systems also improves the confidence of a detection. Acoustic detectors that are expected to be operating at the inception of the LIGO are in: Frascati, Italy; Baton Rouge, Louisiana; and Perth, Australia.

3.2 LIGO DEFINITION

The Laser Interferometer Gravitational Wave Observatory comprises two remotely located observatory sites where the detector system(s) and all support facilities are located and also includes laboratories, prototype interferometer facilities, research and development, and design facilities at the associated Universities.

The initial detector shall consist of three independent laser interferometers operating in coincidence or correlation. Interferometers shall be built on two scales, two interferometers shall have arm lengths of 4 km and the third shall have arm lengths of 2 km. The lengths are constrained by considerations of site topography and associated costs of additional earth removal. Each interferometer is in a Michelson ("L") configuration with resonant Fabry-Perot cavities in the arms.

The two LIGO observatory sites selected are (i) at the DOE Hanford Nuclear Facility in Washington State (denoted "Hanford"), and (ii) in Livingston Parish, Louisiana (denoted "Livingston").

The Hanford site shall house two instruments in the same vacuum envelope: a full length (4 km) and the half length (2 km) interferometer. The site at Livingston shall contain a single 4 km interferometer. The vertex of the Hanford instrument is at elevation 162.5 m above mean sea level (AMSL) and at geographic coordinates 46° 27′ 18.5″ N, 119° 24′ 27.1″ W, with arms oriented toward the northwest at a bearing N36.8° W and the southwest at a bearing S53.2° W. The vertex of the Livingston Louisiana site is at elevation 18.9 m AMSL and at geographic coordinates 30° 33′ 46.0″ N, 90° 46′ 27.3″ W, with arms oriented southeast at a bearing S18° E, and southwest at a bearing S72° W. The separation of the sites is approximately 3000 km, which corresponds to a maximum time difference for the arrival of gravitational waves at the two sites of approximately +/- 10 ms. The interferometer arms at the two sites are oriented for maximum coincidence sensitivity for a single gravitational wave polarization. This is achieved by orienting one arm of each interferometer at the same angle relative to the great circle passing through the two interferometer sites while the other arms are held parallel to each other. At a single site, the two arms of an interferometer are perpendicular and lie within 6.2×10^{-4} radians of the local horizontal plane at the intersection of the arms.

3.3 CONFIGURATION

The initial LIGO interferometer configuration (Figure 3-1) is a power recycled Michelson interferometer with optically resonant Fabry - Perot cavities in the 4km (2km) arms. All the optical components in the phase sensitive part of the interferometer are suspended as pendula to reduce the coupling to seismic and thermal noise and to provide a means to control the optical path lengths in the interferometer. The path lengths are maintained by servo systems to hold the light incident on the detector, placed at the antisymmetric port of the beamsplitter, at a dark fringe. A gravitational wave disturbs this condition by inducing an antisymmetric path length change in the two orthogonal Fabry - Perot cavities thereby increasing the intensity at the photodetector. When the interferometer is operated in this manner, the light not absorbed or scattered by the optical components, or lost via contrast defects at the dark port, is reflected by the interferometer and returned to the laser at the symmetric port of the beamsplitter. In the initial LIGO detector a mirror is placed between the laser and the interferometer to enclose the entire interferometer into an optical cavity. The position and reflectivity of this mirror is chosen so that the light from the laser is added constructively with that circulating in the interferometer while the light reflected by the mirror back to the laser is combined destructively with light emerging from the interferometer. The net result is that little light is returned to the laser and the optical power circulating in the interferometer is increased by the reciprocal of the interferometer optical loss. The increase in shot noise limited sensitivity is equivalent to using a more powerful laser. Tables 3-1 and 3-2 present the design parameters of the presently planned (initial) interferometers. Also presented in the table are sample parameters for an enhancement contemplated for the initial interferometer. In later phases of LIGO more radical changes in the interferometer configurations are expected such as signal recycled, resonant and frequency agile systems leading to advanced detectors.

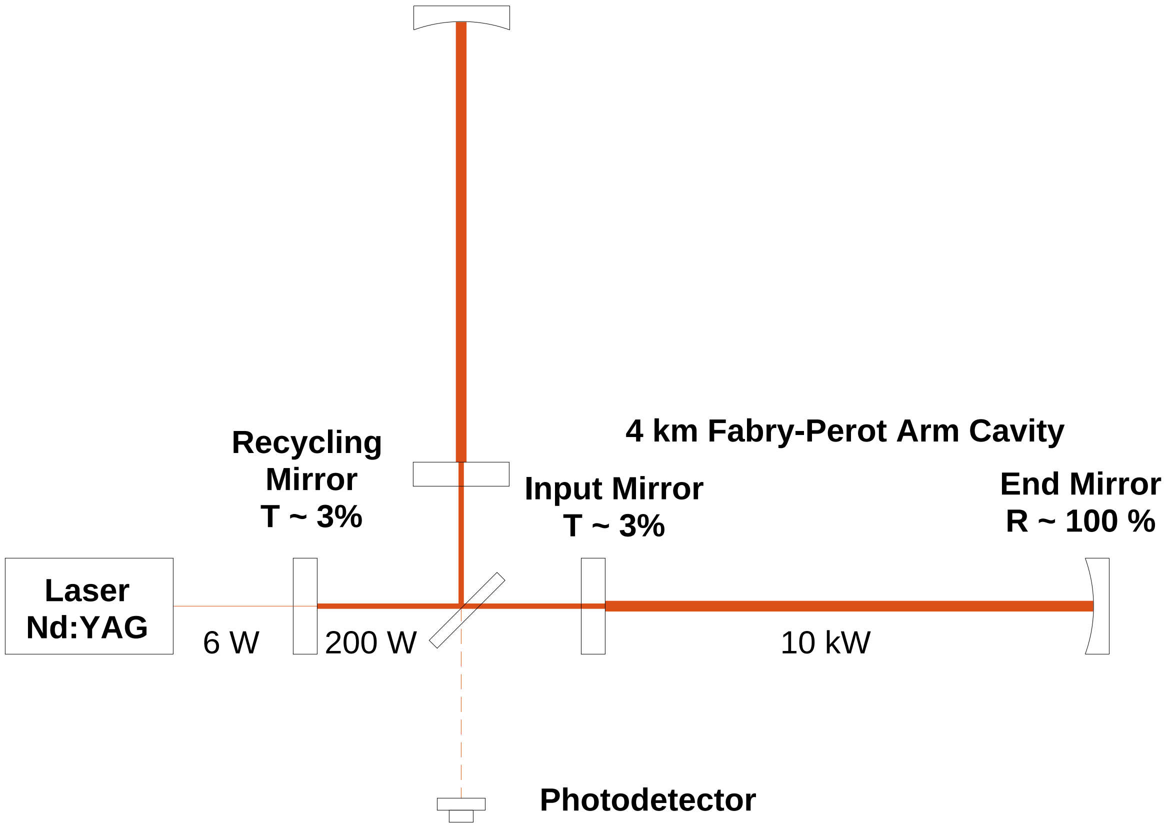
Table 3-1: LIGO Interferometer Optical Parameters

OPTICAL CHARACTERISTICS	NOMINAL INITIAL INTERFEROMETER	SAMPLE ENHANCED INTERFEROMETER
Arm Length	4000 m	4000 m
Laser Type & Wavelength	Nd:YAG, $\lambda = 1.064\ \mu$m	Nd:YAG, $\lambda =1.064\ \mu$m
Input Power into Recycling Cavity, P	6W	100W
Contrast Defect, 1-c	3×10^{-3}	3×10^{-3}
Mirror Loss, L_M	1×10^{-4}	1.3×10^{-5}
Power Recycling Gain	30	380
Arm Cavity Storage Time, τ_{Arm}	8.8×10^{-4} s	1.3×10^{-3}s
Cavity Input Mirror Transmission, T	3×10^{-2}	2×10^{-2}
Total Optical Loss, L_T = (Absorption + Scattering)	4×10^{-2}	3×10^{-3}

Table 3-2: LIGO Interferometer Mechanical Parameters

MECHANICAL CHARACTERISTICS	NOMINAL INITIAL INTERFEROMETER	SAMPLE ENHANCED INTERFEROMETER
Mirror Mass, M_M	10.7 kg	40 kg
Mirror Diameter, D_M	0.25 m	0.40 m
Mirror Internal Q_M	1×10^6	3×10^7
Pendulum Q_P(damping mechanism)	1×10^5 (material)	1×10^8 (material)
Pendulum Period, T_P	1 s (Single)	1 s (Double)
Seismic Isolation System	T(100 Hz) = -100 dB	T(10 Hz) = -100 dB

Figure 3-1: LIGO Configuration for the initial interferometers



3.4 SENSITIVITY

3.4.1 Instrument Noise Floor

The initial LIGO detector with three interferometers operating in coincidence shall have a strain sensitivity adequate to provide confident detection of gravitational waves generated by astrophysical objects and processes discussed in Section 1.2. As an example, the gravitational strain near 100 Hz produced by the coalescence of two 1.4 solar mass neutron stars at a distance of the Virgo cluster has a characteristic magnitude at Earth of 6×10^{-21}. An initial LIGO detector strain sensitivity goal of 10^{-21} RMS, integrated over a 100 Hz bandwidth centered at the minimum noise region of the strain spectral density, is comensurate with this sensitivity. At this threshold of sensitivity, the false signal rate (i.e., triple coincidences not due to astrophysical sources) shall be held to less than 0.1 events per year. The design strain spectral densities of the initial instruments and an example enhanced instrument are shown in Figures 3-2 and 3-3.

Figure 3-2: Envelope of the broadband strain spectral density noise floor of the initial LIGO detector. Different spectral regions of the noise floor are dominated by the indicated noise mechanisms.

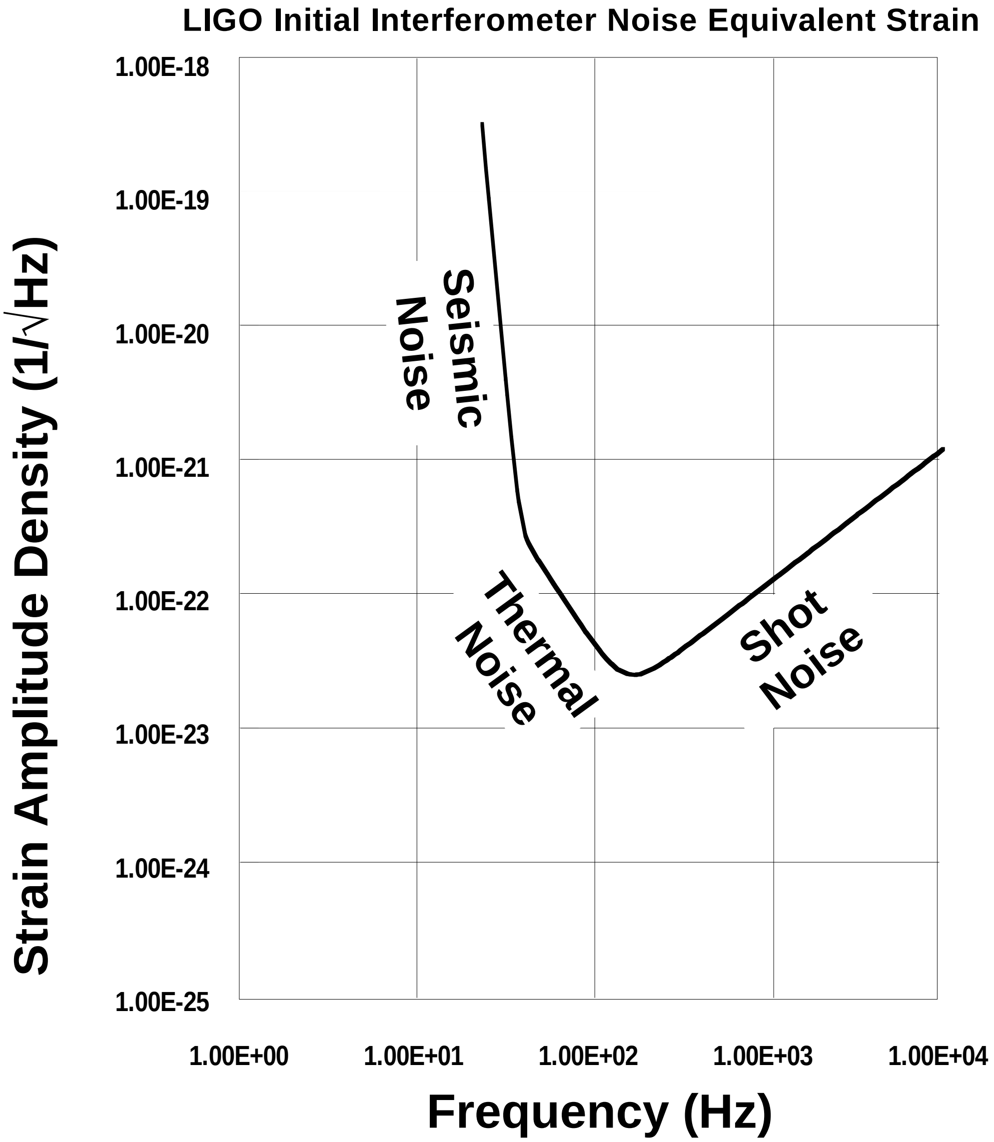
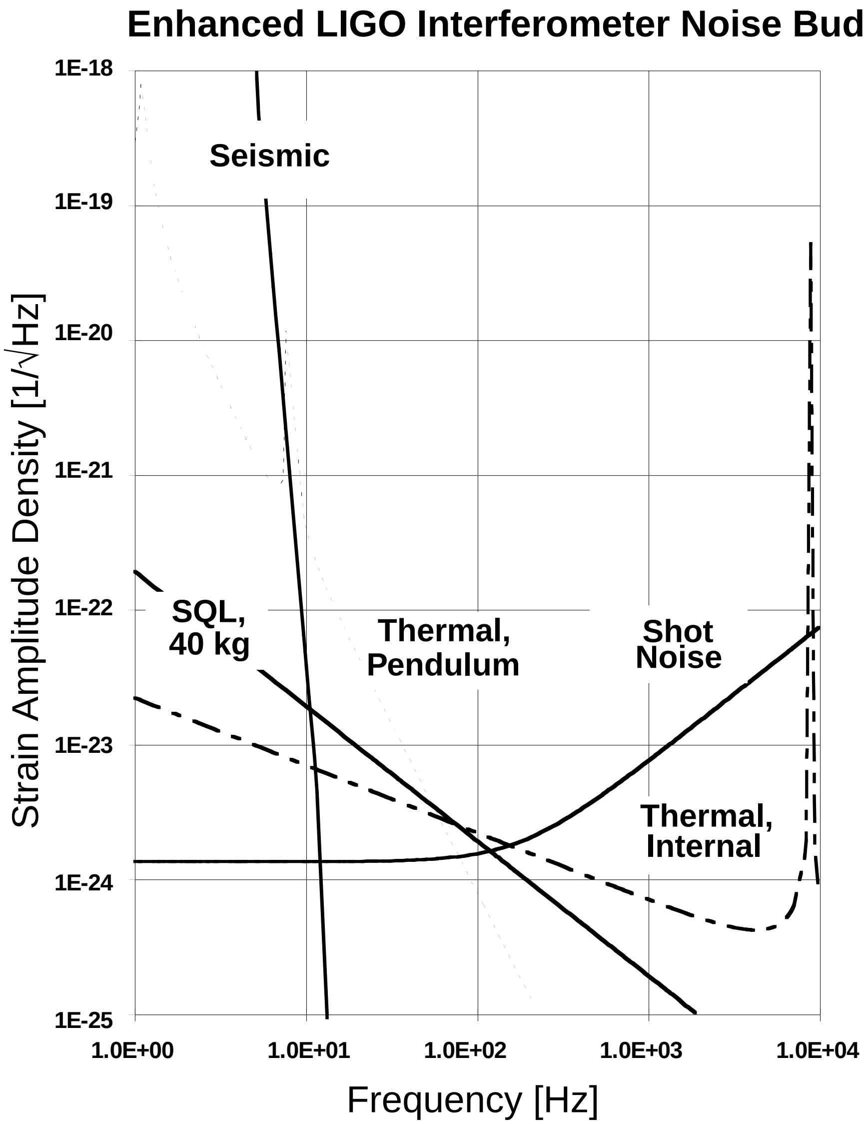


Figure 3-3: Dominant contributions to the strain spectral density noise floor of an example Enhanced LIGO detector

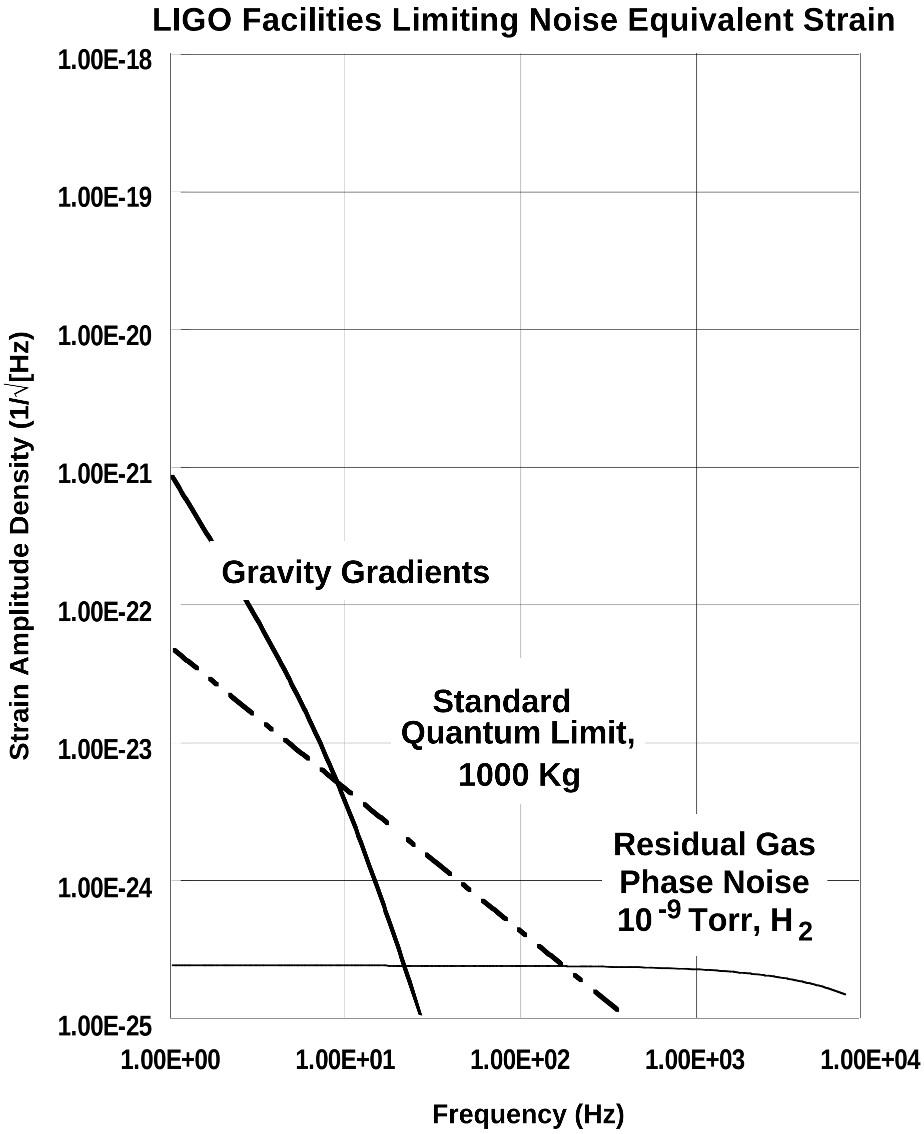
[The Standard Quantum Limit (SQL) shown in Figure 3-3 represents the limiting strain sensitivity arising from radiation pressure fluctuations (producing momentum uncertainty) and shot noise (producing measurement uncertainty). It depends on the mass, sensing frequency, and arm length of the interferometer. The curve shows the locus of points where sensing noise, which varies as $P^{-1/2}$, and radiation pressure, which varies as $P^{1/2}$, are minimized simultaneously].



3.4.2 Natural and Facility Sensitivity Limits

The facilities design permits the ultimately attainable strain sensitivity limits indicated in Figure 3-4. The limiting sensitivity is set at low gravitational frequencies (f < 20 Hz) by the naturally occurring gravitational gradients due to density variations from the ground and atmosphere. The design goal for the facilities is to not increase the naturally occurring environmental perturbations, such as mechanical vibrations, acoustic noise, electromagnetic fields and gravitational gradients, by more than a factor of two in the gravitational wave detection band.

Figure 3-4: Limiting interferometer performance attributable to the facilities



The ultimate LIGO vacuum levels are derived from the need to maintain optical phase noise due to fluctuations in the residual gas column density in the beam tubes and vacuum chambers at a level at or below an equivalent strain noise of 2 x 10^{-25} $Hz^{-1/2}$. This is expected to be the limiting noise source at the highest frequencies (100 Hz < f < 1 kHz).

The clear aperture of the beam tubes and vacuum chambers is in part determined by the requirement to maintain optical phase noise produced by scattered light to an acceptable level. The stray light requirement must be satisfied between 0.5 to 1.1 micron wavelengths, which is the range of laser wavelengths contemplated for LIGO interferometers. Stray light is produced by imperfections in mirror surfaces, is rescattered within the beam tubes and vacuum chambers, and is modulated by motion of the scattering surfaces. Scattered light is expected to be the limiting noise source in the mid-frequency range of operation and will be controlled by suitable optical baffling. The design goal for stray light phase noise is that it be no greater than 0.1X the standard quantum limit for a 1 ton mass. This allocation allows for uncertainties in both the stray light estimates as well as in the estimates of beam tube wall and other scatterer motions which are excited by seismic and acoustic disturbances.

3.5 SYSTEM EXTENSIBILITY

LIGO is planned to accommodate multiple interferometers at Hanford and Livingston in the advanced phase. These later instruments will have sensitivities representing reasonable extrapolations of the state of the art of interferometric detection over the 30 year lifetime of the facilities. Hence the design and construction of the facilities shall permit (i) eventual operation at higher sensitivity and bandwidth and (ii) eventual expansion and upgrade to more interferometers than are in the initial phase.

Because beam tubes cannot be easily upgraded or replaced, beam tube assemblies and vacuum chambers shall have clear aperture diameters of at least 1 meter in order to be capable of accommodating multiple interferometers operating simultaneously. Stray light attenuation must be sufficient to permit advanced instrument operation at the limits outlined above. Similarly, beam tube vacuum levels shall be low enough to support measurement at these same physical limits.

The layout and design of LIGO facilities constructed in the initial phase shall allow further expansion, as required at a later date, to accommodate multiple interferometers with minimum interference during installation and operation. Where possible, the construction of the initial phase shall provide for extensible infrastructure requiring a minimum of later alteration and replacement other than facility additions.

3.6 OBSERVATORY OPERATIONS

Observatory operations must satisfy a range of scientific requirements to further the field of gravitational wave astrophysics. The facility needs to support operations allowing:

- reliable searches for gravitational wave impulsive, chirp, periodic and stochastic background sources at the level of detector sensitivity current at the time;
- retain high enough duty cycle to give a reasonable probability that rare gravitational wave events observable by other gravitational detection techniques or astrophysical measurements shall be detected by the LIGO;
- time for the development of improved detectors.

The allocation of operations time shall be made by the LIGO Principal Investigator in consultation with the LIGO Program Advisory Committee and the National Science Foundation to balance the conflicting scientific priorities. The LIGO research community is represented in these decisions as described in the LIGO Management Plan.

3.6.1 Single Interferometer Operations

The goal for the initial detector is the ability to maintain at least one interferometer in operation at an annually integrated availability of 90% with minimum continuous operating periods of 40 hours, allowing for short term loss of lock. Such loss of lock may occur in order to accommodate long-term, low frequency drift (i.e., out of the GW measurement band) by shifting resonant operation from one longitudinal mode to another.

3.6.2 Multiple Coincidence Operations

As a goal, LIGO shall have the ability to operate in triple coincidence mode for an annually averaged availability of 75%. As a goal, operation in double coincidence mode (defined as operation of the Livingston interferometer with either of the two Hanford interferometers) shall be possible with an annually averaged duty cycle of 85%. For both these modes, the minimum period of continuous operation shall be 100 hours. The same allowances as in §3.6.1 are permitted for short term loss of lock.

3.7 DATA FORMATS

Data collected with the LIGO detector shall be available in a format which is compatible with other gravitational wave detectors world wide. This is to enable ease of data interchange and coincidence analysis. Data formats shall be defined after consultation with the LIGO Research Community, other interferometer groups, and acoustic and particle detector groups involved in astrophysical research relevant to gravitational wave searches.

LIGO shall also provide long-term data archival and analysis capabilities at Caltech and MIT. Analysis capabilities shall also be provided at the observatories. Data processing services involving removal of instrument-specific signatures and normalization (if required) from the raw data stream shall be provided by the project. Observatory-based analyses shall include the ability, as a minimum, to provide immediate-response data for correlation with other (non-interferometric) detectors and also on-line detection of interesting signatures using real-time or near-real-time filtering of the data stream.

The gravitational wave signal shall be collected with a dynamic range and precision consistent with the LIGO scientific missions. Collateral data involving LIGO system state and environmental data for veto analysis shall be collected at rates and precisions to be specified later. These additional signals shall be recorded along with the gravitational-wave signals.

3.8 ENABLING RESEARCH AND FACILITIES

The LIGO project is intended to begin a long term program of research in gravitational wave astrophysics. The elements of this program are:

- high duty cycle searches for gravitational wave sources.
- a continuing development program to improve the sensitivity and detection bandwidth of the interferometers.
- a development program to respond to the new discoveries by tailoring detector responses.
- continuous development of improved data analysis and diagnostic techniques.

The facilities and personnel dedicated to the development include:

- suspended mass interferometers and special purpose test facilities on the Caltech and MIT campuses.
- gravitational astrophysics research groups at Caltech, MIT and at the LIGO sites to develop data analysis procedures.
- the LIGO Research Community, a broadly based consortium of groups at universities and research laboratories, who participate collaboratively or independently in observations, detector development and the data analysis.

3.9 USEFUL OBSERVATORY LIFE

All durable infrastructure shall be capable of providing for a facility lifetime of no less than 20 years.