Moving into the Laser Interferometer Gravitational-Wave Observatory (LIGO)*

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Abstract

The construction status of the LIGO Project is described. The construction of major facilities at the Hanford, Washington site, including the buildings and the long vacuum tubes for the laser beams, has been completed and the resident staff has begun setting up the laboratory infrastructure. Construction of a second observatory site in Livingston, Louisiana is well underway. Detector design has matured and fabrication of the detector hardware is underway. Installation of the first interferometer hardware at Hanford is scheduled to begin in Spring, 1998.

1 Introduction

The purpose of the Laser Interferometer Gravitational-Wave Observatory (LIGO) is to achieve the detection of gravitational waves of cosmic origin and to exploit these waves for astrophysical studies [1]. LIGO is a joint Caltech-MIT project, funded by the U.S. National Science Foundation (NSF), to construct laser interferometers at each of two observatory sites. Professor Kuroda asked me to give a status update on the LIGO Project. I have used the term "moving" in the title of my talk, because that best sums up our activities at the observatory sites in Hanford, Washington and Livingston, Louisiana. At Hanford, construction work has been completed on the 4-km-long beam tubes that make up the interferometer arms, the experimental halls that will house the lasers and optics, and the supporting laboratories and office space. Figure 1 is an aerial photo of the Hanford site, taken in October, 1997. As of November 1, 1997 the resident staff at Hanford was able to move into the new buildings. Construction in Louisianna, phased 6-9 months

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after Hanford to make best use of resources and experience, is also proceeding rapidly. All beam tubes are now under vacuum at Hanford and the large vacuum chambers that will house most of the interferometer hardware are being installed in the experimental halls. The design of most detector subsystems has been completed and fabrication of detector hardware is underway. We expect to begin installing our first interferometer components in Spring, 1998.

2 Basic Concepts

The physical layout of LIGO's interferometers is driven by a few simple facts about the gravitational waves we seek to detect. There is a fundamental similarity between gravitational waves and electromagnetic waves. In electromagnetism there are charges (+ and -) that respond by being accelerated in the same (for +) or the opposite (for -) direction as an applied electric field. When special relativity is taken into account, we find that accelerating charges produce a radiating electromagnetic field. An analogous picture exists for gravity, where the mass acts like the charge. As for the case of electromagnetism, we can expect that a treatment of gravity that properly takes special relativity into account will show that accelerating masses gives rise to gravitational radiation. However two distinctions between gravitational and electromagnetic forces will cause gravitational radiation to differ from electromagnetic radiation in two respects. One difference is that gravity obeys an equivalence principle: all objects in a gravitational field fall in the same manner. To the force-centered physicist this is because the "charge"-to-mass ratio for gravity is a universal constant; the more modern view that originated with general relativity is that gravity is ultimately a "geometrical" property of space-time. In an electromagnetic experiment, we might observe the passage of an electromagnetic wave by observing the motions of free charges as the wave passed. If we know the strength of the test charges and the amount of their motion, we could calculate the strength of the wave. If we similarly monitor the motion of an array of free masses under the influence of a gravitational wave, the equivalence principle implies that these motions must be independent of the masses themselves. Another difference is that gravity lacks the dual attractive and repulsive nature of the electric force - all masses attract. Whereas the electric force can define the DIRECTION in which charges are pushed or pulled, gravity can only define an AXIS along which charges move. The consequence of these distinctions is that passage of a gravitational wave through a collection of free masses produces a measurable strain: masses appear to move RELATIVE to each other in the plane transverse to the wave direction, such that masses appear to move closer together along one axis (shrink axis) while masses along an orthogonal axis (stretch axis) appear to move farther apart. The passage of a light beam between the free masses serves to define their separation.

A Michelson interferometer (or some variant thereof) is a natural device for measuring the passage of a gravitational wave. If the mirrors and beam splitter are suspended by fine wires, they behave as free test masses with regard to motions within the plane of the interferometer. The Michelson interferometer accurately measures differences in the time it takes for light beams to propagate along each arm. The method is to shine coherent light onto a beam splitter, where it is split into two separate beams. The light then illuminates the end mirrors in each arm of the interferometer and reflects back to the beam splitter. The interference of these reflected beams at the beam splitter depends on the propagation times along the two arms. When the propagation times are identical (modulo a half-period of the light wave), the returning light will be deflected by the beam splitter back toward the original light source. Small differences in propagation times along the two arms result in some fraction of this light being deflected at a right angle to this direction. A photodiode placed along this direction produces a signal that is fairly insensitive to any physics that affects both interferometer arms in the same way (a common-mode signal), but is very sensitive to differential changes.

Expected sources of gravitational waves that LIGO may see [1] [2] include the inspiral and coalescence of compact binary star systems made up of neutron stars and/or black holes, supernovae that develop non-axisymmmetric instabilities in the process of collapse and rotating neutron stars that are non-axisymmetric. LIGO will also search for stochastic gravitational waves that are remnants of the big bang. Estimating the strength of sources, such as black-hole inspirals or suitable supernovae is difficult, given present electromagnetic-based astronomical data. Probably the best source estimates are based on available data for the inspiral of binaries where both companions are neutron stars. Direct observations of pulsars provide guidance and the volume of space searched for such objects can be readily estimated [3] [4]. Even with this source, there can be significant questions about how uncertainties in stellar evolution and the observability of electromagnetic emissions from pulsars affect the number and strength of sources that LIGO might observe. It is expected that a strain sensitivity between 10^{-21} and 10^{-22} will be required to detect three such inspirals a year. The initial LIGO interferometers have been designed to extend the volume of space-time that has been previously searched for gravitational waves by $> 10^9$, with a strain sensitivity of $\simeq 10^{-21}$. R&D into technological upgrades to these interferometers is now underway aimed at increasing strain sensitivity by an additional order of magnitude, or a volume increase of 10^3.

3 Sensitivity Issues

In units of displacement these strains correspond to measuring differential changes in the 4-km lengths of LIGO's arms that are of the order of a millifermi (10^{-18} m). Using a typical optical wavelength, the transition from complete darkness at the photodiode to complete brightness has a period of order 1 micron (10^{-6} m) in the length difference between the two arms [5]. We can further improve our sensitivity to displacement by having light traverse the arms N times, resulting in an N-fold narrowing of the fringe. Multiple traversals can be accomplished by making each of the arms a resonant optical cavity. In LIGO these cavitites are Fabry-Perot cavities, each formed by a mirror situated near the beam splitter and another mirror at the other end of the arm. Multiple traversals will only improve sensitivity if the storage time for light in the arms is much less than the period of the gravitational wave. This limits the fringe-narrowing effect from the cavities to be of order 100 for LIGO. The resulting fringe width, of order 10^{-8} m, must now be monitored with a signal-to-noise ratio of order 10^{10}, in order to resolve the small displacements expected from gravitational waves. Fluctuations in the interference of photons at the beam splitter, governed by Poisson statistics, contribute to this noise [6], thereby setting a requirement on the photon flux in the arms needed for such a displacement measurement.

LIGO will use a configuration known as a power-recycled, Fabry-Perot-Michelson interferometer, shown schematically in Figure 2. Light arriving at the beam splitter from the laser is split into beams that resonate in the two long Fabry-Perot cavities with a typical storage time $\tau_E \simeq 2$ ms. This is achieved using an almost totally reflecting end mirror in each cavity and partially reflecting input mirrors. Servo systems hold the mirrors and the beam splitter in proper position and alignment, so that the long Fabry-Perot cavities remain optically resonant with the laser light and interference at the beam splitter directs returning light from the cavities back toward the laser. The photodiode, shown in Figure 2 at the so-called "dark port", provides the principal error signal that enforces this interference condition. This signal is amplified, filtered and fed back [7] to control the difference in length of the Fabry-Perot cavities. Any gravitational-wave effect is recorded on this signal, while the feedback allows the interferometer to be held at its most stable and sensitive operating point at all times. This null technique also allows the signal to be extracted with minimal absorption of photons in the photodetector. The use of a recycling mirror allows the light returned toward the laser to be re-used for subsequent measurements [8] [9].

The basic optical properties [10] and the length [11] and alignment [12] servo issues for the initial LIGO detectors have been investigated in small, "table-top" interferometers. Using results of these studies and extensive modeling based on metrology results from LIGO optics in fabrication, we expect to obtain power recycling factors exceeding 30. For arbitrary laser power, this provides more than 30 times the photon flux inside the interferometer compared to operating without recycling.

Experiments using a power-recycled Michelson interferometer [13] allow us to study and eliminate processes that might degrade the optical phase sensitivity achievable when using the high optical flux at the beam splitter. At frequencies above 500 Hz, phase sensitivities of 2×10^{-10} rad/$\sqrt{\mathrm{Hz}}$ have been achieved, consistent with predictions of the Poissonian noise expected with $\simeq 150$ W of light incident on the beam splitter. Excess noise at lower frequencies, possibly resulting from laser fluctuations and light scattered from mechanically excited optical components, is still under investigation.

The laser system for the initial LIGO interferometers will be a 10-W Nd:YAG laser, developed by Ligthwave Electronics for LIGO [14]. The laser system uses a master-oscillator, power-amplifier (MOPA) configuration. A prototype of this laser system has been delivered to LIGO for final testing. Installation of the first laser system at Hanford is expected in Spring, 1998. Fused silica substrates for the LIGO mirrors have been procured from Corning and Hereaus and polishing is under way at CSIRO in Australia and at General Optics in the U. S. The critical parameters for these mirrors are substrate absorption (for transmissive mirrors) of ≤ 5 ppm/cm and surface figure accuracy to approximately 0.5 nm over the beam spot size (~ 10 cm). Test results from early production substrates show that these challenges have been met. LIGO has been working with Research Electro-optics (REO) to develop high-homogeneity, large-aperture, low-loss, dielectric coatings for these substrates, using ion-beam coating techniques. Results from coating runs on test plates indicate that the coated mirrors will achieve the required surface homogenity for this wavefront accuracy. The first coated mirrors are expected to be completed by Spring, 1998.

4 Background Effects

Detection of gravitational waves requires not only a high sensitivity to displacements but also the reduction of background displacements that are not related to gravitational radiation. The sensitivity of LIGO's interferometers to displacements is largely determined by the quality of the lasers, optics and control systems used. Background displacements occur principally due to transmission of seismic motion and vibration to the mirrors and due to the random motions of the atoms that make up the interferometer. The seismic isolation system for the initial LIGO consists of an actuation system outside the vacuum chambers, a mechanical support structure that penetrates the vacuum chamber walls, passive layers of mass elements and springs inside the vacuum system [15] that support the optical tables, and a final pendulum suspension for each mirror. The external actuators allow for alignment and drift compensation of the optical tables and cancellation of the relative motions of the separate buildings containing the mirrors, due to the earth tides and the microseism. The earth-tide effect, with diurnal and semidiurnal components, can be as large as 4×10^{-4} m over the 4-km arm lengths. The microseism, driven by ocean-wave activity, has a typical period of from 5-7 s and is variable in magnitude but of order 10^{-5} m.

The passive layers of mass elements and springs for the initial LIGO are designed to provide filtering against transmitted noise above a few Hz. At frequencies above 35 Hz, the filtering is sufficiently effective that thermal noise [16][17], arising from the random thermal agitation of atoms in the mirrors, suspension fibers and mechanical structures of the interferometer, is larger than the externally transmitted displacements. Surprisingly, it is these atomic motions that set the length scale for laser interferometers. The interferometer length must be sufficiently large that displacements due to the gravitational-wave strain exceed background displacements from thermal noise. Immunity from thermal noise is achieved by designing critical interferometer components so that mechanical resonances, at which the thermal energy is peaked, lie outside the frequency band for gravitational-wave detection. This eliminates all but the small fraction of the thermal energy in the wings of the mechanical resonance from being confused with any gravitational-wave displacement. Very low loss (i.e., typical Q's $\geq 10^6$) structures are used to concentrate thermal energy at the resonant frequencies, further reducing the background in the wings of the resonances.

Sources of background noise have been studied using a 40-m-long interferometer as a test bed for vibration isolation, mirror suspensions and control systems [18]. Figure 3 compares the observed noise-equivalent displacement (shown in green) to a number of estimated sources of noise. The displacement spectrum consists of a broad background with a number of sharp spectral features. Our expectation is that the broad background should arise due to shot noise (i.e., Poission statistics on the light) at high frequencies, transmitted seismic noise at low frequencies and thermal noise in the mid-frequency range. From the measured optical parameters of the laser light, we can calculate the shot noise and we can estimate the thermal noise from measurements of the quality factors (Q's) of various mechanical resonances of the mirrors and suspension fibers. This produces the estimates, labelled "Shot + Wire Thermal Noise" and "Internal Thermal" in Figure 3. The combination of these two curves are consistent with the broad background to well below 1000 Hz. Many narrow features above 500 Hz are explained by thermal noise in the violin resonances of the many suspension fibers used to hang the mirrors. Using mechanical shakers and accelerometers at the base of a vibration isolation stack, the effect of vibrations on the interferometer has been measured at low frequencies. An estimate of the transmitted seismic noise under quiet conditions, shown by the stippled bar in Figure 3, gives a reasonable explanation for the noise below 100 Hz. There are several known mechanisms that can contribute to background noise in the mid-frequency region. The lines marked "L" correspond to power-line harmonics. At 80 Hz and 109 Hz, the mirrors exhibit pitch resonances that cause a background signal when the light does not strike the mirror at its center [19]. The dashed curve labelled "Pitch-Mode Thermal Noise" is an estimate for the thermal noise that would arise from a few mm of decentering. There are also symmetric pairs of narrow features that appear centered on the line harmonics at 180 Hz and 300 Hz. It is known that these line spikes appear on the laser amplitude. Small fringe offsets (e.g., when the servo gain does not sufficiently suppress seismic noise) can allow the laser amplitude variations to appear as a false background. Thus low-frequency mirror displacements will modulate the laser amplitude noise to produce a pattern of sidebands about the peaks in the laser noise spectrum. The dashed curve labelled "Excess Laser Intensity Noise" illustrates this effect near the 180-Hz power-line harmonic. A similar curve could be constructed near the 300-Hz harmonic. The curve labelled "Standard Quantum Limit" indicates the limit imposed by the Heisenberg uncertainty principle, applied to the 1.6-kg suspended masses used in this interferometer.

The 40-m interferometer has now been reconfigured to more closely resemble the initial LIGO interferometers. The interferometer was first reconfigured as a Fabry-Perot-Michelson interferometer without recycling and used to study apsects of lock acquisition, noise mechanisms and optical properties [20]. The first operation of the interferometer with power-recycling was achieved in early November,1997 and similar studies are now underway.

5 System Integration

A significant modeling and experimental program has been examining the highly nonlinear process by which the interferometer is brought from a state with swinging mirrors into the stable operating point, with six critical mirrors holding their positions in resonance with the laser light. Simulation code has been developed that describes this process as one cavity after another drops into its resonant state (referred to as “lock acquisition”). An early experimental application of this code was the successful demonstration of a “smart” lock-acquisition system [21]. This digital device read the optical transient produced by an uncontrolled Fabry-Perot cavity, computed and applied a force transient that reduced the relative velocity between the mirrors, and turned over control to a simple analog system that could then easily acquire lock. Work is also underway to include alignment degrees of freedom into simulation code.

The lessons learned from work on the various test interferometers are now being applied in the design and fabrication of the LIGO interferometers. An example is the development of metal springs with constrained layers of damping material by HYTEC Inc. (of Los Alamos, NM), arising from the desire to reduce the frequency at which seismic isolation limits interferometer sensitivity. With these new springs the 100-Hz seismic wall observed in the 40-m interferometer will be reduced to near 35 Hz in LIGO. Taking advantage of the reduced seismic noise places higher demands on other subsystems such as the electronics, which now need to achieve lower noise at lower frequencies. Another example is the development of servos for the critical alignment of optical surfaces, needed to achieve stable operation with high recycling factors, whose importance was demonstrated in protoptyping work.

The recently completed LIGO facilities at Hanford also were designed to stringent specifications to support interferometer operation at high strain sensitivity with low displacement backgrounds. Reducing thermal noise, associated with stretching of the suspension wires, required that the beam lines be perpendicular to vertical at the ends and corner of each interferometer to $\leq 10^{-3}$, which set requirements on the levelness of the site. Reducing optical phase shifts, caused by fluctuating densities of molecules in the beam paths, required that pressures $< 10^{-9}$ Torr be achievable in the 4-km beam tubes. A bake out of the beam tubes will be needed to achieve the even lower pressures required for polarizable molecules such as water vapor and hydrocarbons. To preserve the low vibration environment at the site, compressors and similar mechanical equipment were located approximately 100 m from all buildings containing suspended optics and special precautions were taken in the design of ventilation equipment for these buildings.

Interferometer installation at the two sites will occur between 1998 and 2000, followed by a significant shakedown period. Initial gravitational-wave searches are scheduled for 2002-2003. During this period, other interferometer projects, including VIRGO, GEO600 and TAMA300 are expected come on line, providing the initial components of an international detector network. The LIGO Science Collaboration, comprised of numerous research groups from around the world, is already researching technological upgrades to the initial interferometers. The development path of this field will likely depend both on these technological advances and what is seen with this initial generation of laser interferometers.

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Figure 1: Aerial view of the LIGO Hanford Observatory.

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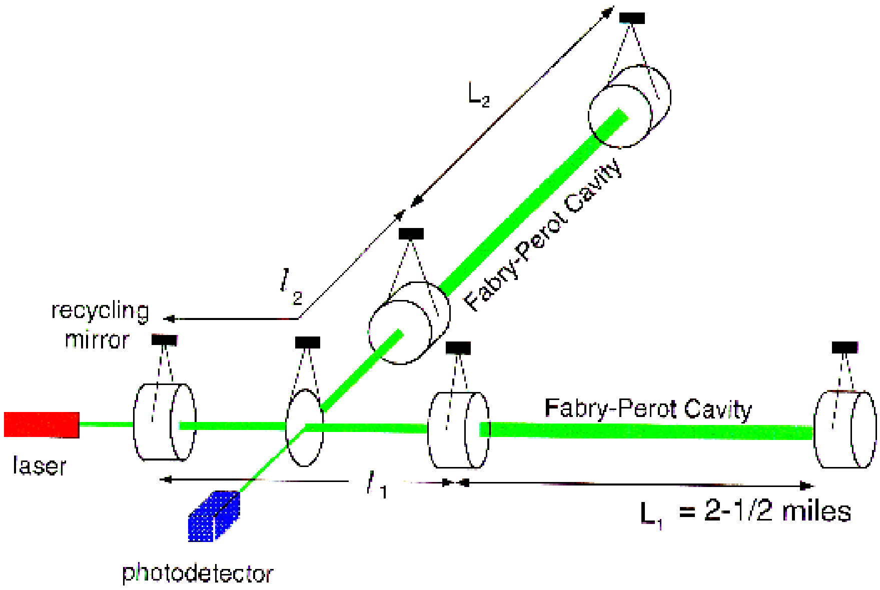

Figure 2: Schematic layout of a LIGO interferometer.

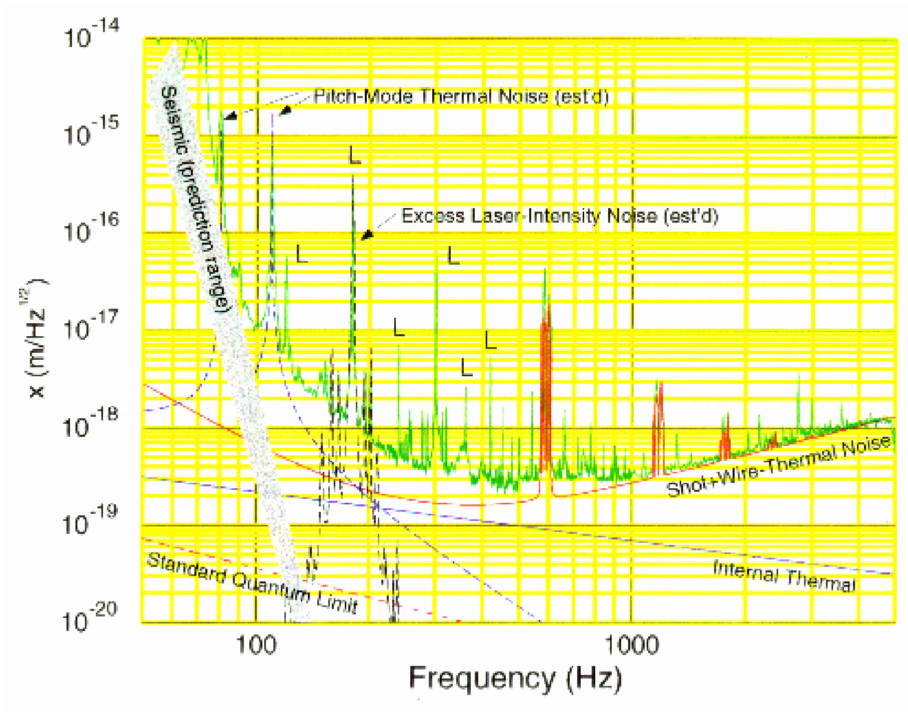

Figure 3: Displacement data from 40-m test interferometer (green) and estimated noise conributions (labelled). The narrow features marked "L" correspond to the first several power-line harmonics.