ADVANCED LIGO—THE NEXT GENERATION

PHILIP E. LINDQUIST
on behalf of the LIGO Scientific Collaboration
California Institute of Technology (MS 18-34)
Pasadena, CA 91125, USA

The initial LIGO gravitational-wave detectors have begun observations and are already yielding data that will establish new upper limits on the gravitational-wave flux. Direct detection is the primary LIGO goal. The initial LIGO instruments may be sensitive enough to achieve this goal. If they succeed, the community will demand improved sensitivity to increase the astrophysical information that can be extracted. There is a general consensus concerning the sensitivity required to assure that gravitational waves will be detected frequently and with high signal-to-noise ratios. If no discovery is made with the initial detectors, there will be no less urgency to improve to this sensitivity level. The development of a next generation LIGO should be pursued aggressively. A proposal has been submitted for an instrument that is ten times more sensitive over a broader frequency band than initial LIGO. This instrument will see a volume of space more than one thousand times that seen with initial LIGO and extends the range of compact masses that can be observed by a factor of four or more. Advanced LIGO will exceed the planned total integrated observations of initial LIGO during its first few hours of operation. We plan to start these observations in 2007.

1 The LIGO Mission

Gravitational waves offer an unprecedented opportunity to see the universe from a new perspective, providing astrophysical insights not available via any other interaction.

From the beginning LIGO was charged by the National Science Foundation to directly observe gravitational waves from cosmic sources and to establish the field of gravitational-wave astronomy. The complete mission statement also tasks the Laboratory to:

- Operate the facilities to support the national and international scientific community,
- Provide data archiving and contribute computational resources for data analysis,

- Develop software infrastructure for data analysis and participate in the search and analysis,
- Support scientific education and public outreach, **and**
- **Develop new advanced detectors that exploit facility limits for interferometer performance.**

The current LIGO facilities were designed and built to specifications intended to allow future interferometers to reach sensitivity levels approaching the ultimate limits of ground based interferometers limited by practical constraints imposed by size at specific sites.

The initial LIGO detectors are in operation. The sensitivity of LIGO detectors is improving rapidly as we install the final interferometer systems and resolve remaining technical challenges. We are interleaving periods of commissioning with science runs. The runs are timed to balance competing demands for performance improvements and data for exercising the search algorithms. To date, commissioning progress has been so successful that we are already performing some of the most sensitive searches ever undertaken for gravitational waves. The Livingston four-kilometer interferometer is now operating within a factor of ten of the design science requirements sensitivity.

The first science run began August 23, 2002 and lasted 17 days. All three interferometers at two sites ran in coincidence with the UK-German GEO600 interferometer, with some overlap with the Japanese TAMA detector. The LIGO instruments operated in their design configuration and accumulated roughly 100 hours of data in triple coincidence between the two sites. The LIGO Scientific Collaboration (LSC) "upper limits" groups are analyzing the data for chirp signals from binary "inspirals," periodic signals from neutron stars, burst signals from supernovae and gamma ray bursts, and from possible stochastic background. We are preparing publications describing the results and establishing new limits to the gravitational-wave flux.

The second science run began February 14, 2003. The objective during this run is to improve the upper limits measurement of the gravitational-wave flux by at least an order of magnitude compared with the first science run, and the current sensitivity of the detectors will permit us to achieve this goal[2]. The second science run was in progress at the time of the Moriond Conference and was completed on April 15, 2003. The data is now being analyzed.

Future improvements to reach the design sensitivity will involve modifications to the electronics and to the mechanical infrastructure, and optimization of control systems and filters. Substitute recycling mirrors, with a radius of curvature optimized for the observed optical properties, will be installed during favorable opportunities. These improvements will largely occur between the second and third science runs.

In the third science run, planned to begin early in 2004, we will transition to a mode where observation dominates commissioning at the observatories. The overall goal is to collect at least one year of integrated data with an RMS strain sensitivity of h $\sim 10^{-21}$ (integrated noise level in a 1 kHz band) during the first three years of observation ending in 2006. When that goal is reached and results have been extracted from the data, installation of improved interferometers can commence.

The initial LIGO design is expected to deliver the planned performance levels and will represent an advance over all previous searches by two or three orders of magnitude in sensitivity and bandwidth. Its "reach" will permit us, for the first time, to detect foreseeable signals due to neutron star binary "inspirals" from the Virgo Cluster (17 Mpc distant). At this level, it is plausible, though not certain, that we will make the first observations of gravitational waves. Small improvements in sensitivity may be possible, for example by modest increases in laser power. However, a large improvement will require a coordinated upgrade of the entire detector. Significant research and development by LIGO and the greater community has been completed or is in progress to enable this step.

The advanced LIGO interferometer that has been proposed to the NSF promises to improve sensitivity by more than a factor of ten over the entire initial LIGO frequency band. We also propose to increase the bandwidth to lower frequencies (from ∼40 Hz to ∼ 10 Hz) and implement signal recycling. This translates to an enhanced physics reach that during its first few hours of operation will exceed the integrated one-year observations of the initial LIGO science run. These improvements will enable the next generation of interferometers to study sources not accessible with initial LIGO and to extract detailed astrophysical information from the waveforms. The advanced LIGO detectors will be able to see in-spiraling binaries comprising two 1.4 solar mass neutron stars at a distance of 300 Mpc, 15 times further than initial LIGO, and providing an event rate 3000 times greater (event rates depend on population densities as well as volume). Neutron star-black hole binaries will be visible to 650 Mpc; and coalescing black hole systems up to 50 solar masses will be visible to a cosmological distance of z = 0.4. We will be able to pinpoint periodic signals from many known pulsars that radiate in the range from 500 to 1000 Hertz. Recent results from the WMAP[a] satellite show that the photon or infrared cosmic background provides a rich source of information originating from some 400,000 years after the Big Bang. We will be able to optimize Advanced LIGO to search for gravitational cosmic background radiation, providing tests of theories concerning the development of the universe at only 10^{-35} seconds after the Big Bang.

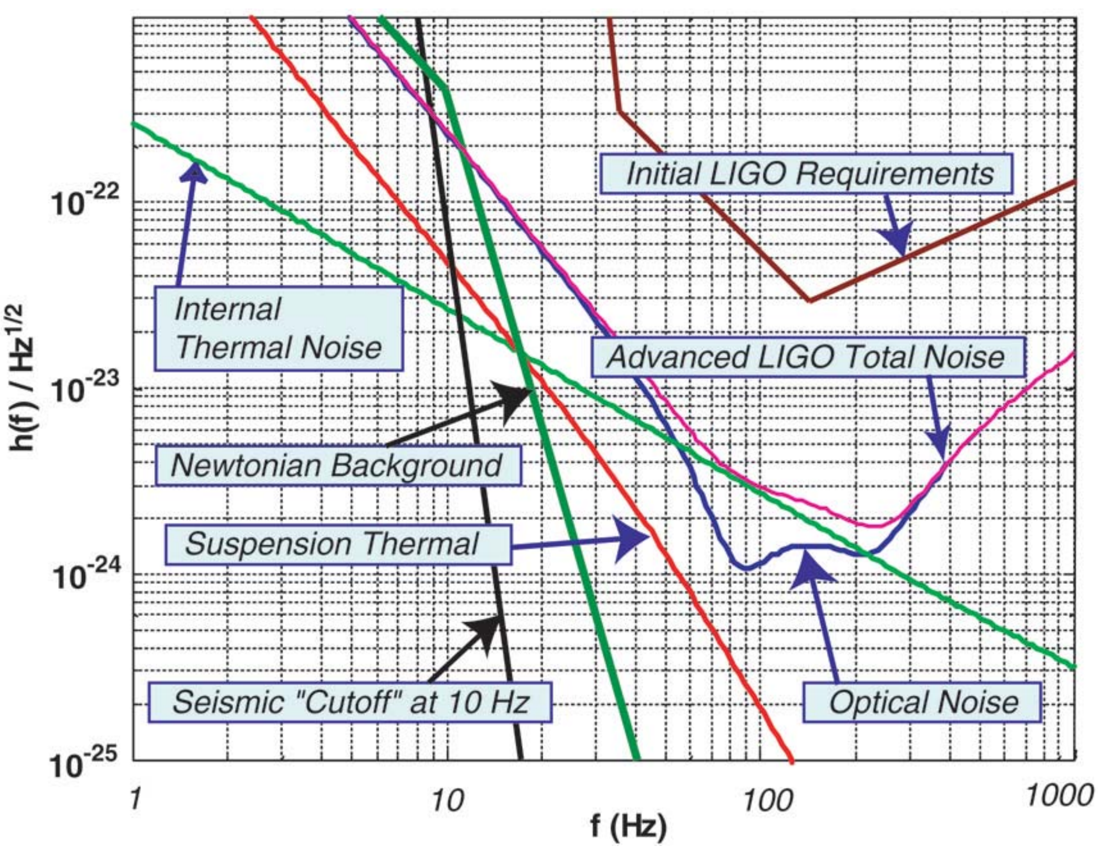

Figure 1: Projected Sensitivity Limits for the Advanced LIGO Design.

Figure 1 shows the projected limits to sensitivity for the Advanced LIGO design. Shot noise (counting statistics) limits sensitivity at higher frequencies and improves with the square root of the laser power. Radiation pressure fluctuations limit at lower frequencies and become worse with the square root of the laser power. These are coupled in a signal-recycled interferometer (shown

[a] Wilkinson Microwave Anisotropy Probe, http://map.gsfc.nasa.gov/m_mm.html

in the figure as the "optical" noise) and dominate at most frequencies for full-power operation and broadband tuning. The Newtonian background caused by the time varying distribution of mass in the vicinity of the test masses sets a low frequency limit for ground-based detectors. The estimate for the LIGO sites is shown in the figure. Space-based instruments are required for gravitational-wave astrophysics below 10 Hz.

Initial LIGO is a power-recycled configuration with Fabry-Perot arms to increase storage time. Table 1 summarizes the design parameters for the Advanced LIGO reference design. Advanced LIGO will have increased laser power (180 Watts instead of 10 Watts). Input optics must be modified to handle the higher power levels. We are developing sapphire or large silica core optics. We are also developing better mirror coatings, but the polish requirements will be similar to initial LIGO. Quad suspensions based on the GEO-600 design are being developed to lower the thermal noise and reduce the noise contribution from the control systems. We are designing active seismic isolation systems to reduce motion in the gravitational-wave band and also at low frequencies to reduce control requirements on the mirrors. Other improvements include an output mode cleaner to reduce the TEM100 light on the photodetectors, the increased number of servo loops related to the additional active controls, and increased requirements for data handling and calculations related to the increased number of servo loops. The design also features signal recycling to allow us to tune the interferometer to optimize the sensitivity to adjust for technical constraints or to look for specific astrophysical signatures. Signal recycling extends the sensitivity without increasing the circulating power at the beam splitter.

Table 1: Principal parameters of the Advanced LIGO reference design with Initial LIGO parameters provided for comparison.

Subsystem and Parameters	Advanced LIGO Reference Design	Initial LIGO Implementation
Observatory Instrument Lengths: LHO = Hanford, LLO = Livingston	LHO: 4km, 4km LLO: 4km	LHO: 4km, 2km LLO: 4km
Strain Sensitivity (rms, 100 Hz band)	8 x 10^{-23}	10^{-21}
Displacement Sensitivity (rms, 100 Hz band)	8 x 10^{-20}m	4 x 10^{-18}m
Fabry-Perot Arm Length	4000 m	4000 m
Vacuum Level in Beam Tube and Vacuum Chambers	$< 10^{-7}$ torr	$< 10^{-7}$ torr
Laser Wavelength	1064 nm	1064 nm
Optical Power at Laser Output	180 W	10 W
Optical Power at Interferometer Input	125 W	6 W
Optical Power on Test Masses	800 kW	30 kW
Input Mirror Transmission	0.5 percent	3 percent
End Mirror Transmission	15 ppm	15 ppm
Arm Cavity Power Beam Size	6 cm	4 cm
Light Storage Time in Arms	5.0 ms	0.84 ms
Test Masses	Sapphire, 40 kg	Fused Silica, 11 kg
Mirror Diameter	32 cm	25 cm
Test Mass Pendulum Period	1 sec	1 sec
Seismic/Suspension Isolation System	3 stage active, 4 stage passive	Passive, 5 stage
Seismic/Suspension System Horizontal Attenuation	$\geq 10^{-12}$ (10 Hz)	$\geq 10^{-9}$ (100 Hz)

2 Advanced LIGO Schedule and Cost

A structured R&D program for Advanced LIGO started in 1998 and is funded through 2006 under the current cooperative agreement with the NSF. Initial LIGO observations are also scheduled through 2006. The proposed project start for Advanced LIGO is 2005 with first installation in 2007 and observation commencing in 2009. We hope to initiate some long-lead procurements in 2004. We submitted the Advanced LIGO proposal to the NSF in February 2003 (NSF PHY-0328418).

We developed the cost estimate for this proposal at the lowest feasible level given the current status of the design (approximately 5000 separate line items). To provide a complete picture we included in this estimate the total for design, fabrication, installation, and commissioning labor and materials, even for items that will be contributed from other collaborators or funding sources.

The joint United Kingdom/German GEO Project[b] has proposed to provide a capital investment in the project. The UK proposal for the suspension subsystem including suspension assemblies, controls, installation, and commissioning is valued in our estimating system at approximately $11.5 million. The German proposal is for the design and fabrication of the prestabilized laser subsystem, and that contribution is also valued in our estimating system at $11.5 million. The GEO Project is a full partner in Advanced LIGO, participating at all levels.

The Australian Consortium for Interferometric Gravitational Astronomy (ACIGA)[c] is also proposing a significant role in Advanced LIGO. The Australian proposal is valued at approximately $2.5 million and will support part of the output mode filtering system and R&D to develop a variable transmission signal-recycling mirror.

Much of the remaining design and advanced R&D, installation, and commissioning effort will be performed by staff currently paid under the existing NSF cooperative agreement (NSF PHY-0107417) or the next cooperative agreement for operations as these personnel are freed up from their current installation and commissioning assignments, or operations staff who will become available as initial LIGO is shut down. There will be some additions to the staff for specialty engineering functions or to cover peak resource loading needs. The total cost estimate is $234 million. The proposed cost (request from the NSF) is for $122 million beginning in 2005.

3 Advanced LIGO Community

The fundamental LIGO goal is to become a true national facility for the scientific community. To accomplish this, LIGO has opened participation to encompass the total community of interested scientists by creating the LIGO Scientific Collaboration (LSC)[d]. There are now over 400 members from 44 institutions. The LSC has significant international participation including collaborating groups from India, Russia, Germany, the United Kingdom, Japan, and Australia. In the United States, these efforts, and in particular the LIGO Laboratory, are supported by the NSF.

The Advanced LIGO design, both in concept and in the ongoing R&D effort, is very much a product of the LSC. Technical working groups have been and continue to be central to the design, and the proposal was developed with the strong support of many participating institutions. As discussed above, several international partners have offered significant material participation. The LSC provides the impetus for Advanced LIGO, is the source of expertise, and participates in the development.

---

[b] http://www.geo600.uni-hannover.de/

[c] http://www.anu.edu.au/Physics/ACIGA/

[d] http://www.ligo.org/

4 Summary

Initial LIGO is in operation. We are preparing publications describing results from the first science run started in August 2002. The second science run was completed in April 2003. The third science run, representing a true transition in focus from commissioning to observation, is scheduled to begin early in 2004. It can be argued that discoveries with the initial LIGO detectors are plausible. However, whether or not there are discoveries, there will be a demand from the community for advanced detectors that push towards the technical limits of the LIGO facilities. R&D and design for Advanced LIGO subsystems are in progress. A strong international partnership has been established in the LIGO Scientific Collaboration. Current plans support the start of installation in 2007 with observations commencing in 2009.

Acknowledgments

The LIGO Observatories were constructed by the California Institute of Technology and Massachusetts Institute of Technology with funding from the National Science Foundation under Cooperative Agreement PHY 9210038. The LIGO Laboratory operates under Cooperative Agreement PHY-0107417. This paper has been assigned LIGO Document Number LIGO-P030019-00-R

The author gratefully acknowledges the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory and the Particle Physics and Astronomy Research Council of the United Kingdom, the Max-Planck-Society and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector. The author also gratefully acknowledges the support of the research by these agencies and by the Australian Research Council, the Natural Sciences and Engineering Research Council of Canada, the Council of Scientific and Industrial Research of India, the Department of Science and Technology of India, the Spanish Ministerio de Ciencia y Tecnologia, the John Simon Guggenheim Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

I would also like to thank Drs. G. Sanders, D. Shoemaker, B. Barish, S. Whitcomb, and A. Lazzarini for their encouragement and assistance as well as for source materials.

References

1. "Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO)," Proposal NSF 0328418 to the National Science Foundation (February 27, 2003).
2. P. Lindquist, "LIGO Is On" in *Proceedings for XXXVIIIth Rencontres de Moriond, Gravitational Waves and Experimental Gravity* , (2003).