Gearing up for Gravitational Waves: the Status of Building LIGO

Frederick J. Raab, LIGO Hanford Observatory
LIGO’s Mission is to Open a New Portal on the Universe

In 1609 Galileo viewed the sky through a 20X telescope and gave birth to modern astronomy

» The boost from “naked-eye” astronomy revolutionized humanity’s view of the cosmos
» Ever since, astronomers have “looked” into space to uncover the natural history of our universe

LIGO’s quest is to create a radically new way to perceive the universe, by directly sensing the vibrations of space itself
LIGO Will Reveal the “Sound Track” for the Universe

LIGO consists of large, earth-based, detectors that will act like huge microphones, listening for cosmic cataclysms, like:

» Supernovae
» Inspiral and mergers of black holes & neutron stars
» Starquakes and wobbles of neutron stars and black holes
» The Big Bang
» The unknown
The Laser Interferometer Gravitational-Wave Observatory

Sponsored by the National Science Foundation; operated by Caltech and MIT; the research focus for about 350 LIGO Science Collaboration members worldwide.
LIGO Observatories
Configuration of LIGO Observatories

- 2-km & 4-km laser interferometers @ Hanford
- Single 4-km laser interferometer @ Livingston
Part of Future International Detector Network

Simultaneously detect signal (within msec)

detection confidence
locate the sources
decompose the polarization of gravitational waves
What Are Some Questions LIGO Will Try to Answer?

- What is the universe like now and what is its future?
- How do massive stars die and what happens to the stellar corpses?
- How do black holes and neutron stars evolve over time?
- What can colliding black holes and neutron stars tell us about space, time and the nuclear equation of state?
- What was the universe like in the earliest moments of the big bang?
- What surprises have we yet to discover about our universe?
Regardless of what you see on Star Trek, the vacuum of interstellar space does not transmit conventional sound waves effectively.

Luckily General Relativity provides a work-around! General relativity allows waves of rippling space that can substitute for sound if we know how to listen!
John Wheeler’s Summary of General Relativity Theory
Gravitational waves are ripples in space when it is stirred up by rapid motions of large concentrations of matter or energy.
Gravitational waves shrink space along one axis perpendicular to the wave direction as they stretch space along another axis perpendicular both to the shrink axis and to the wave direction.
In 1974, J. Taylor and R. Hulse discovered a pulsar orbiting a companion neutron star. This “binary pulsar” provides some of the best tests of General Relativity. Theory predicts the orbital period of 8 hours should change as energy is carried away by gravitational waves. Taylor and Hulse were awarded the 1993 Nobel Prize for Physics for this work.
Spacetime is Stiff!

- \( K \sim [G/c^4] \) is lowest order combination of \( G \), \( c \) with units of \( 1/N \)

  \[ h \sim (G/c^4) \left( E_{NS}/r \right) \]

\[ G_{\mu\nu} = K T_{\mu\nu} \]

Units of \( 1/m^2 \)

Units of \( 1/N \)

Units of \( N/m^2 \)
What Phenomena Do We Expect to Study With LIGO?
"Since I first embarked on my study of general relativity, gravitational collapse has been for me the most compelling implication of the theory - indeed the most compelling idea in all of physics. . . It teaches us that space can be crumpled like a piece of paper into an infinitesimal dot, that time can be extinguished like a blown-out flame, and that the laws of physics that we regard as 'sacred,' as immutable, are anything but."

– John A. Wheeler in Geons, Black Holes and Quantum Foam

Photograph by Robert Matthews, Courtesy of Princeton University (1971)
Do Supernovae Produce Gravitational Waves?

- Not if stellar core collapses symmetrically (like spiraling football)
- Strong waves if end-over-end rotation in collapse
- Increasing evidence for non-symmetry from speeding neutron stars
- Gravitational wave amplitudes uncertain by factors of 1,000’s

Credits: Steve Snowden (supernova remnant); Christopher Becker, Robert Petre and Frank Winkler (Neutron Star Image).
Catching Waves From Black Holes

Sketches courtesy of Kip Thorne
Sounds of Compact Star Inspirals

Neutron-star binary inspiral:

Black-hole binary inspiral:
Searching for Echoes from Very Early Universe

Sketch courtesy of Kip Thorne
How does LIGO detect spacetime vibrations?
Sketch of a Michelson Interferometer
Some of the Technical Challenges

- Typical Strains $\sim 10^{-21}$ at Earth $\sim 1$ hair’s width at 4 light years
- Understand displacement fluctuations of 4-km arms at the millifermi level
- Control arm lengths to $10^{-13}$ meters, absolute
- Detect optical phase changes of $\sim 10^{-10}$ radians
- Provide clear optical paths within 4-km UHV beam lines
Fabry-Perot-Michelson with Power Recycling

Recycling Mirror

Beam Splitter

Laser

Optical Cavity

Photodetector

4 km or 2-1/2 miles
What Limits Sensitivity of Initial LIGO Interferometers?

- Seismic noise & vibration limit at lowest frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels
Beam Tube Bakeout Ensured Good Vacuum for Good “Seeing”

- Method: Insulate tube and drive ~2000 amps from end to end
Beam Tube Bakeout
### Postbake measurements of module X1 at Hanford

March 11-12, 1999

**Table 1: Results from gas model solution of 16.9 hour postbake accumulation ending March 12, 1999 at 10:00AM.**

<table>
<thead>
<tr>
<th>molecule</th>
<th>Outgassing rate @ 10C (torr liters/sec/cm²)</th>
<th>pressure@ 10C (torr)</th>
<th>outgassing rate @ 23C (torr liters/sec/cm²)</th>
<th>pressure@ 23C (torr)</th>
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<tr>
<td>H₂</td>
<td>1.6 x 10^{-14}</td>
<td>1.0 x 10^{-9}</td>
<td>5.2 x 10^{-14}</td>
<td>3.4 x 10^{-9}</td>
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<tr>
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<tr>
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<tr>
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<td>&lt; 2.9 x 10^{-19}</td>
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</table>
Vacuum Chambers Provide Quiet Homes for Mirrors

View inside Corner Station

Standing at vertex beam splitter

Raab: Gearing up for Gravitational Waves
HAM Chamber Seismic Isolation
HAM Seismic Isolation Installation
HAM Seismic Isolation Measured in Air at LHO

Seismic Design Model
Transfer Function Measurements
BSC Chamber Seismic Isolation
Frequency Stabilization of the Light

- Pre-stabilized laser delivers light to the long mode cleaner
  - Frequency fluctuations
  - In-band power fluctuations
  - Power fluctuations at 25 MHz

- Actuator inputs provide for further laser stabilization
  - Wideband
  - Tidal

Diagram:
- PSL
- 10-Watt Laser
- IO
- Interferometer
- 15m
- 4 km
Prestabilized Laser Optical Layout
Washington 2k PSL
Frequency Servo Performance

PSL Frequency Noise as measured by the MC

Frequency Noise (Hz/rtHz)

Frequency (Hz)

- Green: PSL requirement
- Blue: Jan. 2000
- Red: June 2000

N. Mavalvala
P. Fritschel
Suspended Mirrors

initial alignment

test mass is balanced on 1/100th inch diameter wire to 1/100th degree of arc
ITMx Internal Mode Ringdowns

9.675 kHz; Q \sim 6e+5

14.3737 kHz; Q = 1.2e+7
Single-Arm Tests

- Alignment of 2-km arms worked for both arms!
- The beam at 2-km was impressively quiet
- Stable locking was achieved for both arms by feeding back to arms
- Measured optical parameters of cavities
- Characterized suspensions
- Characterized Pre-Stabilized Laser & Input Optics

Swinging through 2-km arm fringes
Interferometer Control System

- Multiple Input / Multiple Output
- Three tightly coupled cavities
- Ill-conditioned (off-diagonal) plant matrix
- Highly nonlinear response over most of phase space
- Transition to stable, linear regime takes plant through singularity
- Requires adaptive control system that evaluates plant evolution and reconfigures feedback paths and gains during lock acquisition
- But it works!
Digital Interferometer Sensing & Control System

PHOTODETECTOR

WHITENING/ANTI-ALIAS FILTER

ADC

CPU VAXWORKS

GPS

VMEbus

100bT

SUN

OPTICAL FIBER

Reflective Memory

COIL DRIVER

TEST MASS

DEWHITENING/ANTI-IMAGE FILTER

DAC

CPU VAXWORKS

VMEbus

Reflective Memory

LIGO-G010189-00-W

Raab: Gearing up for Gravitational Waves
Digital Phase Control Test on Phase Noise Interferometer
Steps to Locking an Interferometer

Laser

Y Arm

X Arm

signal

Composite Video
Watching the Interferometer Lock

![Diagram of an interferometer setup with labeled parts: Laser, X Arm, Y Arm, and signal output.](image)
Why is Locking Difficult?

One meter, about 40 inches

- \( \div 10,000 \)  
  Earhtides, about 100 microns

- \( \div 100 \)  
  Microseismic motion, about 1 micron

- \( \div 10,000 \)  
  Precision required to lock, about \( 10^{-10} \) meter

- \( \div 100,000 \)  
  Nuclear diameter, \( 10^{-15} \) meter

- \( \div 1,000 \)  
  LIGO sensitivity, \( 10^{-18} \) meter
Earth Tide is Largest Source of Interferometer Drift

Data from Engineering Run E3
Earth Tides: Freshman Physics to the Rescue
Commissioning of Full Interferometer Underway

For Example: Noise-Equivalent Displacement of 40-meter Interferometer (ca1994)
When Will It Work?
Status of LIGO in Spring 2001

- Initial detectors are being commissioned, with first Science Runs commencing in 2002.
- Advanced detector R&D underway, planning for upgrade near end of 2006
  - Active seismic isolation systems
  - Single-crystal sapphire mirrors
  - 1 megawatt of laser power circulating in arms
  - Tunable frequency response at the quantum limit
- Quantum Non Demolition / Cryogenic detectors in future?
- Laser Interferometer Space Antenna (LISA) in planning and design stage (2015 launch?)
LIGO, Built to Last