LIGO Commissioning and Initial Science Runs: Current Status

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http://www.ligo.org
New Window on Universe

GRAVITATIONAL WAVES PROVIDE A NEW AND UNIQUE VIEW OF THE DYNAMICS OF THE UNIVERSE.

EXPECTED SOURCES:
1. BURST & TRANSIENT SOURCES - SUPERNOVAE
2. COMPACT BINARY SYSTEMS - INSPIRALS
3. ROTATING COMPACT STARS - "GW" PULSARS
4. STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

POSSIBILITY FOR THE UNEXPECTED IS VERY REAL!
Einstein’s Theory of Gravitation

- a necessary consequence of Special Relativity with its finite speed for information transfer

- gravitational waves come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light

gravitational radiation

binary inspiral

of

compact objects
“Indirect” detection of gravitational waves

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves.

Direct Detection

Gravitational Wave Astrophysical Source

Terrestrial detectors
LIGO, GEO, TAMA, Virgo, AIGO

Detectors in space
LISA
An International Network of Interferometers

Simultaneously detect signal (within msec)

- detection confidence
- locate the sources
- decompose the polarization of gravitational waves
Detecting a passing wave ....

Free masses
Detecting a passing wave ....

Interferometer
Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms
- Arms in LIGO are 4km
- Measure difference in length to one part in $10^{21}$ or $10^{-18}$ meters

...causing the interference pattern to change at the photodiode

As a wave passes, the arm lengths change in different ways....
LIGO sites

LIGO (Washington)

LIGO (Louisiana)

(“The evergreen state”)
Core Optics Suspension and Control

Shadow sensors & coil actuators provide damping and control forces.

Optics suspended as simple pendulums.

Mirror is balanced on 30 micron diameter wire to 1/100th degree of arc.
Some Commissioning Challenges

• Understand displacement fluctuations of 4-km arms at the millifermi level (1/1000\textsuperscript{th} of a proton diameter)
• Control arm lengths to $10^{-13}$ meters RMS
• Detect optical phase changes of $\sim 10^{-10}$ radians
• Hold mirror alignments to $10^{-8}$ radians
Interferometer Length 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
- Employs adaptive control system that evaluates plant evolution and reconfigures feedback paths and gains during lock acquisition
Tidal Compensation Data

Tidal evaluation on 21-hour locked section of S1 data

Predicted tides

Feedforward

Feedback

Residual signal on coils

Residual signal on laser
Controlling angular degrees of freedom

DC light level in recycling cavity

ongoing effort!

DC light level in long arms

WFS1, WFS2A, WFS3, WFS4 not engaged (alignment controls)

WFS1, WFS2A, WFS3, WFS4 engaged

Trend Ch 1: HI:LSC-LA_PRTT_NORM
Calibration of the Detectors

• Combination of DC (calibrates voice coil actuation of suspended mirror) and Swept-Sine methods (accounts for gain vs. frequency) calibrate meters of mirror motion per count at digital suspension controllers across the frequency spectrum

• DC calibration methods
  » fringe counting (precision to few %)
  » fringe stepping (precision to few %)
  » fine actuator drive, readout by dial indicator (accuracy to ~10%)
  » comparison with predicted earth tides (sanity check to ~25%)

• AC calibration measures transfer functions of digital suspension controllers periodically under operating conditions (also inject test wave forms to test data analysis pipelines)

• CW Calibration lines injected during running to monitor optical gain changes due to drift
LIGO Sensitivity Over Time

Livingston 4km Interferometer

May 2001

S1

~S2
The S1 Run

Hanford control room
The S1 run: In-Lock Data Summary

- **August 23 – September 9, 2002**: 408 hrs (17 days).
  - **H1** (4km): duty cycle 57.6% ; Total Locked time: 235 hrs
  - **H2** (2km): duty cycle 73.1% ; Total Locked time: 298 hrs
  - **L1** (4km): duty cycle 41.7% ; Total Locked time: 170 hrs

- **Double coincidences**:
  - **L1** && **H1**: duty cycle 28.4%; Total coincident time: 116 hrs
  - **L1** && **H2**: duty cycle 32.1%; Total coincident time: 131 hrs
  - **H1** && **H2**: duty cycle 46.1%; Total coincident time: 188 hrs

- **Triple Coincidence**: **L1**, **H1**, and **H2**: duty cycle 23.4% ;
  - Total coincident time: 95.7 hrs
Sensitivity during S1

LIGO S1 Run

“First Upper Limit Run”

- 23 Aug–9 Sept 2002
- 17 days
- All interferometers in power recycling configuration

GEO in S1 RUN

Ran simultaneously in power recycling Lesser sensitivity

Strain Sensitivities for the LIGO Interferometers for S1

23 August 2002 - 09 September 2002

LIGO-G020461-01-E

Frequency [Hz]
Potential gravity wave sources

- **Bursts**: supernovae, black hole mergers, unknown, {triggered burst search}
- **Binary inspirals**: NS-NS, {BH-BH, NS-BH, Macho}
- **Stochastic background**: big bang, weak incoherent source from more recent epoch
- **Continuous waves**: known EM pulsars, {all-sky search for unknown CW sources, LMXRB (e.g. Sco-X1)}
- **Analysis emphasis**:
  - Establish methodology, no sources expected.
  - End-to-end check and validation via software and hardware injections mimicking passage of a gravitational wave.
Search methods (generic, no templates):

- **Time domain** algorithm identifies rapid increase in amplitude of a filtered time series (threshold on ‘slope’).
- **Time-Frequency domain** algorithm: identifies regions in the time-frequency plane with excess power (threshold on pixel power and cluster size).

**Single interferometer:** noisy data epochs were excluded

**essential:** use temporal coincidence of the 3 interferometers

**correlate frequency** features of candidates (time-frequency domain analysis).
PRELIMINARY results of the Burst Search

- End result of analysis pipeline: **number of triple coincidence events.**
- Use **time-shift** experiments to establish number of **background events.**
- Use **Feldman-Cousins** to set 90% confidence upper limits on rate of foreground events (preliminary results):
  - Time domain: <5.7 events/day
  - Time frequency domain: <1.6 events/day
Search for Inspirals

- **Sources**: orbital-decaying compact binaries: neutron star known to exist and emitting gravitational waves (Hulse&Taylor).
- **Search method**: system can be modeled, waveform is calculable:

  - use optimal matched filtering: correlate detector’s output with template waveform
Inspiral algorithm

- Use LLO 4k and LHO 4k
- Matched filter trigger:
  - Threshold on SNR, and compute $\chi^2$
  - Threshold on $\chi^2$, record trigger
  - Triggers are clustered within duration of each template
- Auxiliary data triggers
  - Vetoes eliminate noisy data
- Event Candidates
  - Coincident in time, binary mass, and distance when H1, L1 clean
  - Single IFO trigger when only H1 or L1 operate
- Use Monte Carlo simulations to calculate efficiency of the analysis
  - Model of sources in the Milky Way, LMC, SMC
Results of the Inspiral Search

• Upper limit on binary neutron star coalescence rate
• Use all triggers from Hanford and Livingston: 236 hours
  » Cannot accurately assess background (be conservative, assume zero).
  » Monte Carlo simulation efficiency $\varepsilon = 0.53$
  » Effective no. MWEG: $N_G = \varepsilon(L_{\text{pop}}/L_G) = 0.53 \times 1.13 = 0.60$
  » 90% confidence limit = $2.3/ (\text{time} \times N_G)$.
  » Express the rate as a rate per Milky Way Equivalent Galaxies (MWEG).

$$R < 2.3/ (0.5 \times 236 \text{ hr}) = 170/\text{yr}/(\text{MWEG})$$

• Compare with:
  ➢ Previous experimental results:
    – LIGO 40m ‘94: 0.5/hr (25hrs, $D<25\text{kpc}$, Allen et al., PRD 1998)
    – TAMA300 ’99: 0.6/hr (6 hr, $D<6\text{kpc}$, Tagoshi et al., PRD 2001)
    – TAMA300 DT6: 82/yr (1,038 hr, $D<33 \text{kpc}$, GWDAW 2002)
  ➢ Expected Galactic rate: $\sim 10^{-6}$ - $5 \times 10^{-4}$/yr (Kalogera et al)
Search for Stochastic Radiation

- **Analysis goals**: constrain contribution of stochastic radiation’s energy $\rho_{GW}$ to the total energy required to close the universe $\rho_{critical}$:

  $$\int_{0}^{\infty} \frac{1}{f} \Omega_{GW}(f) df = \frac{\rho_{GW}}{\rho_{critical}}$$

- Optimally filtered **cross-correlation** of detector pairs: L1-H1, L1-H2 and H1-H2.

- Detector **separation and orientation** reduces correlations at high frequencies ($\lambda_{GW} \geq 2 \times \text{BaseLine}$): **overlap reduction function**
  - H1-H2 best suited
  - L1-H1(H2) significant <50Hz
Results of Stochastic Search

<table>
<thead>
<tr>
<th>Interferometer Pair</th>
<th>90% CL Upper Limit</th>
<th>$T_{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHO 4km-LLO 4km</td>
<td>$\Omega_{\text{GW}}(40\text{Hz} - 314 \text{ Hz}) &lt; 55$</td>
<td>64.0 hrs</td>
</tr>
<tr>
<td>LHO 2km-LLO 4km</td>
<td>$\Omega_{\text{GW}}(40\text{Hz} - 314 \text{ Hz}) &lt; 23$</td>
<td>51.3 hrs</td>
</tr>
</tbody>
</table>

- Non-negligible LHO 4km-2km (H1-H2) cross-correlation; currently being investigated.
- Previous best upper limits:
  - Measured: Garching-Glasgow interferometers:
    - $\Omega_{\text{GW}}(f) < 3 \times 10^5$
  - Measured: EXPLORER-NAUTILUS (cryogenic bars):
    - $\Omega_{\text{GW}}(907Hz) < 60$
• Detectable amplitudes with a 1% false alarm rate and 10% false dismissal rate by the interferometers during S1 (colored curves) and at design sensitivities (black curves).

• Limits of detectability for rotating NS with equatorial ellipticity $\varepsilon = \delta l/l_{zz}: 10^{-3}, 10^{-4}, 10^{-5} @ 8.5 \text{ kpc}$.

• Upper limits on $\langle h_o \rangle$ from spin-down measurements of known radio pulsars (filled circles) if observed spin-down all due to GW emission.

**S1: NO DETECTION EXPECTED**
Algorithms for CW Search

• **Central parameters** in detection algorithms:
  
  » *frequency modulation* of signal due to Earth’s motion relative to the Solar System Barycenter, intrinsic frequency changes.
  
  » *amplitude modulation* due to the detector’s antenna pattern.

• Search for **known pulsars** dramatically reduces the parameter space:
  
  *computationally feasible.*

• **Two search methods** used:
  
  » **Frequency-domain** based: fourier transform data, form max. likelihood ratio ("F-statistic"), frequentist approach to derive upper limit
  
  » **Time-domain** based: time series heterodyned, noise is estimated. Bayesian approach in parameter estimation: result expressed in terms of posterior pdf for parameters of interest
Results of Search for CW

- No evidence of continuous wave emission from PSR J1939+2134.

- Summary of preliminary 95% upper limits on $h$:

<table>
<thead>
<tr>
<th>IFO</th>
<th>Frequentist FDS</th>
<th>Bayesian TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO</td>
<td>$(1.9 \pm 0.1) \times 10^{-21}$</td>
<td>$(2.2 \pm 0.1) \times 10^{-21}$</td>
</tr>
<tr>
<td>LLO</td>
<td>$(2.7 \pm 0.3) \times 10^{-22}$</td>
<td>$(1.4 \pm 0.1) \times 10^{-22}$</td>
</tr>
<tr>
<td>LHO-2K</td>
<td>$(5.4 \pm 0.6) \times 10^{-22}$</td>
<td>$(3.3 \pm 0.3) \times 10^{-22}$</td>
</tr>
<tr>
<td>LHO-4K</td>
<td>$(4.0 \pm 0.5) \times 10^{-22}$</td>
<td>$(2.4 \pm 0.2) \times 10^{-22}$</td>
</tr>
</tbody>
</table>

- LLO upper limit on $h_o < 1.4 \times 10^{-22}$ constrain ellipticity $< 2.7 \times 10^{-4}$ (assuming $M=1.4M_{\odot}$, $r=10$km, $R=3.6$ kpc)

- Previous results for PSR J1939+2134: $h_o < 10^{-20}$ (Glasgow, Hough et al., 1983), $h_o < 3.1(1.5) \times 10^{-17}$ (Caltech, Hereld, 1983).
LIGO science has started

- LIGO has started taking data, completing a **first science run** (“S1”) last summer
- **Second science run** (“S2”) 14 February - 14 April:
  - Sensitivity was ~10x better than S1
  - Duration was ~ 4x longer
    - Bursts: rate limits: 4X lower rate & 10X lower strain limit
    - Inspirals: reach will exceed 1Mpc -- includes M31 (Andromeda)
    - Stochastic background: limits on $\Omega_{gw} < 10^{-2}$
    - Periodic sources: limits on $h_{max} \sim \text{few } 10^{-23} (\epsilon \sim \text{few } 10^{-6} @ 3.6 \text{ kpc})$
- Commissioning continues, interleaved with science runs
- **Ground based interferometers are collaborating internationally:**
  - LIGO and GEO (UK/Germany) during “S1”
  - LIGO and TAMA (Japan) during “S2”