Measuring Gravitational Waves
Discussion of the Technology which has made the Detection of Gravitational Waves a weekly event.

Brian Lantz
Aug 12, 2020
SLAC Summer Institute
G201269
The LIGO concept

It’s sort of like this, except spacetime is stretching, and the mirrors don’t move.

\[ \text{Time } 0 = T_{\frac{P}{4}} = T_{\frac{P}{2}} = T_{\frac{3P}{4}} = T_{1 \text{ Period}} \]

\[ h_+ \]

\[ h_x \]

input light

4km arm cavity

output light, containing gravitational wave signal
Gravitational waves are hard to measure because space doesn’t like to stretch.

Our signal strain \( h = 10^{-21} \),
\[ dL = 4 \times 10^{-18} \text{ meters} \]

(that’s why it’s taken so long, Einstein 1916, Weiss 1973)
The LIGO concept
How it really works

Gravitational waves are hard to measure because space doesn’t like to stretch.

Our signal strain \( h = 10^{-21} \),
\[ dL = 4 \times 10^{-18} \text{ meters} \]

(that’s why it’s taken so long, Einstein 1916, Weiss 1973)

1. Long arms
2. Quiet mirrors
3. Precise measurement
4. Network
Long arms

Since $h = \frac{dL}{L}$, more $L$ gives you more $dL$ of signal (below cavity pole).
Many low frequency noise sources are fixed $dL$ of noise.
More $L$ = better signal to noise at low frequency.
World’s largest UHV system - each arm is 4 km long, 4 ft. diameter.
LIGO Beamtube

- 9000 m³ volume/site
- 30000 m² area/site
- 50 km of spiral welds
- ~1e-9 torr
- budget ~ $40M (1997)
LIGO Beamtube

9000 m$^3$ volume/site
30000 m$^2$ area/site
50 km of spiral welds
$\sim 1 \times 10^{-9}$ torr
budget $\sim$ $40$M (1997)
Advanced LIGO Noise budget is useful when describing mirror motion and sensing noise.

- **Newtonian**
- **Suspension Thermal**
- **Coating Brownian**
- **Coating Thermo-optic**
- **Substrate Brownian**
- **Excess Gas**
- **Total noise**

**Graph Details:**
- Y-axis: Strain [1/√Hz]
- X-axis: Frequency [Hz]
- Frequency range: $10^1$ to $10^3$ Hz
- Strain range: $10^{-24}$ to $10^{-22}$

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**Legend:**
- Green: Newtonian
- Blue: Suspension Thermal
- Red: Coating Brownian
- Cyan: Coating Thermo-optic
- Orange: Substrate Brownian
- Yellow: Excess Gas
- Black: Total noise
Detector Noise (design)

aLIGO new design curve: NSNS (1.4/1.4 $M_\odot$) 173 Mpc and BHBH (30/30 $M_\odot$) 1606 Mpc

Strain [1/\sqrt{Hz}]

- Quantum
- Seismic
- Newtonian
- Suspension Thermal
- Coating Brownian
- Coating Thermo-optic
- Substrate Brownian
- Excess Gas
- Total noise

Mirror motion

radiation pressure

seismic & newtonian

coating thermal

LIGO-T1800044

4e-19 m/\sqrt{Hz}
Detector Noise (design)

aLIGO new design curve: NSNS (1.4/1.4 $M_\odot$) 173 Mpc and BHBH (30/30 $M_\odot$) 1606 Mpc

[Graph showing various noise contributions such as quantum, seismic, Newtonian, suspension thermal, coating Brownian, coating thermo-optic, substrate Brownian, excess gas, and total noise with specific values for strain and frequency.]
Detector Noise (actual)

LIGO Sensitivity

- Strain noise (h/Hz)
- Freq (Hz)

Graph showing LIGO sensitivity across different frequencies with various markers and labels.
Watch for changes…

Spectrogram - 1 day at LLO

L1 gravitational-wave strain \([h(t), \text{GDS}]\)

Frequency [Hz]

10^3

100

10

Locked

Time [hours] from 2017-08-17 00:00:00 UTC (1186963218)

GW amplitude spectral density [strain/\sqrt{Hz}]

10^{-19}

10^{-20}

10^{-21}

10^{-22}

10^{-23}

10^{-24}
Watch for changes…

Normalized Spectrogram - 1 day at LLO

L1 gravitational-wave strain $[h(t), \text{GDS}]$
Changes suggesting a BNS as the source of the gravitational-wave signal, as the total masses of known BNS systems are between $2.57 M_\odot$ and $2.88 M_\odot$, with components between $1.17$ and $<1.6 M_\odot$. Neutron stars in general have precisely measured masses as large as $2.01 \pm 0.04 M_\odot$, whereas stellar-mass black holes found in binaries in our galaxy have masses substantially greater than the components of GW170817 [49–51].

Gravitational-wave observations alone are able to measure the masses of the two objects and set a lower limit on their compactness, but the results presented here do not exclude objects more compact than neutron stars such as quark stars, black holes or more exotic objects [52–56].

The detection of GRB 170817A and subsequent electromagnetic emission demonstrates the presence of matter. Moreover, although a neutron star–black hole system is not ruled out, the consistency of the mass estimates with the dynamically measured masses of known neutron stars in binaries, and their inconsistency with the masses of known black holes in galactic binary systems, suggests the source was composed of two neutron stars.

**DATA**

At the time of GW170817, the Advanced LIGO detectors and the Advanced Virgo detector were in observing mode. The maximum distances at which LIGO-Livingston and LIGO-Hanford could detect a BNS system (SNR = 8), known as the detector horizon [58–60], were 218 Mpc and 107 Mpc, while for Virgo the horizon was 58 Mpc. The GEO600 detector [61] was also operating at the time, but its sensitivity was insufficient to contribute to the analysis of the inspiral. The configuration of the detectors at the time of GW170817 is summarized in [29].

A time-frequency representation [57] of the data from all three detectors around the time of the signal is shown in Figure 1. The signal is clearly visible in the LIGO-Hanford and LIGO-Livingston data. The signal is not visible in the Virgo data due to the lower BNS horizon and the direction of the source with respect to the detector’s antenna pattern. Figure 1 illustrates the data as it was analyzed to determine astrophysical source properties. After data collection, several independently-measured terrestrial contributions to the detector noise were subtracted from the LIGO data using Wiener filtering [66], as described in [67–70]. This subtraction removed calibration lines and 60 Hz AC power mains harmonics from both LIGO data streams. The sensitivity of the LIGO-Hanford was particularly improved by the subtraction of laser pointing noise; several broad peaks in the 150–800 Hz region were effectively removed, increasing the BNS horizon of that detector by 26%.

Additionally, a short instrumental noise transient appeared in the LIGO-Livingston detector 1.1s before the coalescence time of GW170817 as shown in Figure 2. This transient noise, or glitch [71], produced a very brief saturation in the digital-to-analog converter of the feedback signal controlling the position of the test masses. Similar glitches are registered roughly once every few hours in each of the LIGO detectors with no temporal correlation between the LIGO sites. Their cause remains unknown. To mitigate the effect on the results presented in the Detection section, the search analyses applied a window function to zero out the data around the glitch [64, 72], following the treatment of other high amplitude glitches used in the O1 analysis [73]. To accurately determine the properties of GW170817 (as reported in the Source Properties section) in addition to the noise subtraction described above, the glitch was modeled with a time-frequency wavelet reconstruction [65] and subtracted from the data, as shown in Figure 2.
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https://www.ligo.caltech.edu/video/ligo20160211v6
http://mediaassets.caltech.edu/gwave
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Gravitational waves are hard to measure because space doesn’t like to stretch.

Our signal strain, $h = 10^{-21}$, $dL = 4 \times 10^{-18}$ meters

How do we get from $10^{-6}$ meters to LIGO sensitivity?
From 1 micron to aLIGO

From $10^{-6}$ meters to a signal of $h = 10^{-21}$, $dL = 4 \times 10^{-18}$ meters

Simple Michelson can do
Much Better than 1 micron.

$L = 1$ meter, $P = 1$ watt,
count photons , expect $N$,
quantum error $\sim \sqrt{N}$

$$dx = \sqrt{\frac{hc\lambda}{2\pi^2 P}} \text{ m/\sqrt{Hz}}$$

$$dL/L = h \text{ (noise)} = 1e-16/\sqrt{Hz}$$

output light, containing gravitational wave signal
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output light, containing gravitational wave signal
From 1 micron

From $10^{-6}$ meters to a signal of
$h = 10^{-21}$, $dL = 4 \times 10^{-18}$ meters

1. Simple Michelson does
   Much Better than 1 micron.

2. Really Long Arms.

![Graph of aLIGO noise curves](image)
From 1 micron

From $10^{-6}$ meters to a signal of $(h) = 10^{-21}$, $dL = 4 \times 10^{-18}$ meters

1. Simple Michelson does Much Better than 1 micron.
2. Really Long Arms.
3. Interesting Interferometry
3. Interesting Interferometry (measure length change accurately)
- Fabry-Perot arm cavities
3. Interesting Interferometry
(measure length change accurately)
- Fabry-Perot arm cavities

![Interferometer diagram](image)

- About 300 bounces
Interferometry

3. Interesting Interferometry (measure length change accurately)
- Fabry-Perot arm cavities

The 4k arms must be aligned to 1 nrad and controlled in length to ±10^{-14} m RMS.

https://dcc.ligo.org/LIGO-T070236/public
3. Interesting Interferometry (measure length change accurately) - Fabry-Perot arm cavities

- Interferometry

![Interferometry Diagram]

- Laser
- Input Mode Cleaner
- PRM
- PR2
- PR3
- BS
- ITM
- ERM
- SR2
- SR3
- ERM

- Power recycling mirror (SRM)
- Signal recycling mirror (SRZVM)
- Power recycling cavity mirror (ZVM)
- Faraday isolator
- Phase modulator

- The power levels shown correspond to full power operation; the interferometers can also be operated at much lower powers with good strain sensitivity.

- About 300 bounces

- aLIGO noise curves

- Strain noise, $h/\sqrt{\text{Hz}}$

- Freq (Hz)

- 1e-18
- 1e-16
- 1e-14
- 1e-12
- 1e-10
- 1e-08
- 1e-06
- 1e-04
- 1e-02

- 4 km

- 200 kW

- 5.2
Interferometry

3. Interesting Interferometry (measure length change accurately)
- Fabry-Perot arm cavities
- More Power
  (23 W for O1, 120 W ultimate)
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Interferometry

3. Interesting Interferometry (measure length change accurately)
   - Fabry-Perot arm cavities
   - More Power
     (23 W for O1, 120 W ultimate)
   - Power Recycling

- Power Recycling

800 W in PRC for O1

5.2 kW in PRC

5.2 kW in PRC for O1

200 kW
3. Interesting Interferometry
(measure length change accurately)
- Fabry-Perot arm cavities
- More Power
  (23 W for O1, 120 W ultimate)
- Power Recycling
- Signal Recycling/ Extraction

Interferometry
Quiet mirrors

Test Masses: fused silica, 34 cm diam x 20 cm thick, 40 kg

Input Mode Cleaner

Output Mode Cleaner

Laser

PRM

BS

CP

SRM

ETM

ERM

HEPI

4 km

4e-19

few e-10

Laser → \( \Phi_m \) → Input Mode Cleaner → FI → 125 W → PRM → T = 3%

PR2

PR3

T = 20%

SRM

SR2

SR3

T = 1.4%

ITM

Cavity mirrors

\( \Phi_m \)

Photodetector

GW readout

T = 20%

Suspended test mass

Power recycling mirror

Signal recycling mirror

Power recycling cavity mirror

ZV

Signal recycling cavity mirror ZV

Qaraday isolator

\( \Phi_m \)

T = 3%

\( \Phi_m \)

T = 20%

 few e-10

Quiet mirrors

The power levels shown correspond to full power operation. The interferometers can also be operated at much lower powers with good strain sensitivity.
The LIGO vacuum equipment

drawing courtesy of Oddvar Spjeld
Isolation

optics table - stage 2
stage 1
support - stage 0
optics table - stage 2

stage 1

support - stage 0
Isolation

Feedback Damping
Blended Isolation
Sensor correction
Feedforward

4e-19
four * e-10
Isolation

(a)

ISO†ATION LEVELS BSC-ISI

Arnaud Pèle, G1900949
Isolation

Feedback Damping

(a)

![Diagram of isolation system]

- Ground
- PASSIVE - no controls -
- DAMPED

Arnaud Pèlé, G1900949
Isolation

Feedback Damping
Blended Isolation

(a)
Isolation

Feedback Damping
Blended Isolation

(a)
Isolation

Feedback Damping
Blended Isolation
Sensor correction

(a)

ISOLATION LEVELS BSC-ISI

Ground
PASSIVE - no controls -
DAMPED
ISOLATED ST1
+ST1
+ SENSOR CORRECTION

Arnaud Pèle, G1900949
Pendulum Suspension

LIGO Mirrors:
Synthetic fused silica,
40 kg mass
34 cm diameter
20 cm thick

Suspended as a
4 stage pendulum

Silicate bonding creates a monolithic final stage
Pendulum Suspension

LIGO Mirrors:
Synthetic fused silica,
40 kg mass
34 cm diameter
20 cm thick

Suspended as a
4 stage pendulum

Best coatings available

Motion at 10 Hz set by thermal driven vibration

Silicate bonding creates a monolithic final stage
Pendulum Suspension

Parameters for suspension

- Test and penultimate masses: each 40 kg, 34 cm (diam) x 20 cm, silica
- Other masses: 22 kg, 22 kg
- Final stage: 60 cm silica ribbons, 1.1 mm x 0.11 mm
- Vertical bounce mode: 8.8 Hz
- First violin mode: ~490 Hz

Overall length (suspension point to optic centre): 1.63 m

MATLAB model used to compute transfer functions (update from MBarton not yet implemented - longitudinal TF will be unaffected, vertical TF will be slightly (<10%) larger than shown overleaf)

SUS requirements taken from SUS DRD document T010007-02

(Based on GEO600 design)

Arnaud Pèle, GI900949
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(Based on GEO600 design)
SUS: Quadruple Suspension for ETM/ITM

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(Pendulum Suspension)

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O1 to O3

LIGO Sensitivity

Lots of technical things

More power, squeezing
Events!

Cumulative Count of Events and (non-retracted) Alerts

O1 = 3, O2 = 8, O3a = 33, O3b = 23, Total = 67

Credit: LIGO-Virgo Collaboration
What’s next?

Timeline from: Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA

https://doi.org/10.1007/s41114-018-0012-9
LIGO A+ (for O5)

LIGO Sensitivity

Strain noise (h/Hz)

Freq (Hz)

O1 - LLO @ GW150914
O2 - LLO, Aug `17
O3 - LLO, Jun `19
aLIGO design
LIGO A+

‘frequency dependent’ squeezing
more power & squeezing
new coatings
3G detectors

Cosmic Explorer

Image Credit: Evan Hall
3G detectors

![Graph of frequency vs. strain for different detectors](https://doi.org/10.1088/1361-6382/aa51f4)

- aLIGO
- A+
- Voyager
- Einstein Telescope
- Cosmic Explorer

Strain $[1/(\text{Hz}^{1/2})]$

Frequency $[\text{Hz}]$

Better, Longer, Wideband CE curve

Exploring the sensitivity of next generation gravitational wave detectors (2017) CQG 34, 044001
How much could we see?

Reach of 3G Detectors

Credit: Evan Hall
We are not alone…

LISA (Laser Interferometer Space Antenna)
NanoGrav & IPTA (International Pulsar timing array)
others are proposed (see J Hogan talk tomorrow!)

http://GWplotter.com, C. Moore, R. Cole and C. Berry, see also arXiv:1408.0740
LISA
Laser Interferometer Space Antenna

- ESA led mission (L3), planned launch in 2034
- Enables new GW astronomy
- 100 µHz to 100 mHz req. (goal of 20 µHz - 1 Hz)
LISA Pathfinder mission
Launched Dec. 2015 to demonstrate key LISA technology

- measure 2 proof masses on the same spacecraft
- Performance better than LISA req’s
LISA mission highlights

- orbits yield ~stable triangle
- motion and inclination allow localization of long-lived sources
- optical ‘phase-meter’ compares the location of proof masses at the end of each arm
- re LIGO: longer arms, less power

https://sci.esa.int/web/lisa/-/59239-lisa-concept
https://www.elisascience.org/multimedia/image/lisa-payload
LISA Science

LISA will see lots of new sources

- Galactic binaries (white dwarfs)
  - known sources *
  - many estimated new sources

- unresolved sources (SNR<7) form a noise floor for the observatory.

<table>
<thead>
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<th></th>
<th>6 mo</th>
<th>1 yr</th>
<th>2 yr</th>
<th>4 yr</th>
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<td># detected</td>
<td>6,590</td>
<td>11,142</td>
<td>18,281</td>
<td>29,059</td>
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<tr>
<td>2D mapped</td>
<td>104</td>
<td>1,065</td>
<td>4,138</td>
<td>6,304</td>
</tr>
<tr>
<td>3D mapped</td>
<td>19</td>
<td>129</td>
<td>1,010</td>
<td>2,373</td>
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<tr>
<td>M measured</td>
<td>233</td>
<td>737</td>
<td>4,432</td>
<td>10,770</td>
</tr>
</tbody>
</table>

N. Cornish, T. Robson, “Galactic binary science with the new LISA design”, arXiv:1703.09858v2
LISA Science

LISA will see lots of new sources

- Galactic binaries
- ‘Early phase’ merger of LVK events
  - monitor and predict events well before LIGO observes the merger
LISA Science

LISA will see lots of new sources

- Galactic binaries
- ‘Early phase’ merger of LVK events
- Massive Black Hole Binaries
  - how often? where?
  - hierarchal formation of BHs at the center of galaxies?
  - coordinate with X-ray observatories to monitor the accretion discs?
LISA Science

LISA will see lots of new sources

- Galactic binaries
- ‘Early phase’ merger of LVK events
- Massive Black Hole Binaries
- Extreme Mass Ratio Inspiralrs
  - map out the spacetime of large BHs by tracking 100s of orbits of stellar mass BHs as they fall in…
Final thoughts

- Era of gravitational wave astronomy has begun
- Hopefully you have a sense for how we peer into the nearly invisible universe
- The field is moving rapidly to see more, heavier, and more distant sources
- There is a lot to see, and a lot to learn