Gravitational wave detection

Sam Waldman
LIGO MIT
June 25, 2010

GWPAW @ UWM
“What detector and network capabilities will maximize the science?”

-- Patrick Brady, 2011
LISA

Position noise ~ 20pm/√Hz, including shotnoise

acceleration noise ~ 3×10^{-15} m/(√Hz s^2)

Armlength penalty

Strain (1 year integration time)

GW frequency (Hz)
Measurement S/C to test mass

S/C to S/C measurement

Measurement S/C to test mass

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Extending the phase-locked scheme to include a phase-locked loop (PLL) between the two lasers on one spacecraft, it is obvious that all six lasers can be phase-locked to one arbitrarily chosen master laser. Such a scheme requires nine individual phase measurements: two for each arm and one each between the two lasers on a single spacecraft. In addition, each measurement of the test masses with respect to the optical bench requires another six phase measurements, so that a total of 15 phase measurements carry the complete information on the gravitational waves.

### 2. Optical system

The optical system of LISA contains all the optical components and their support that are needed for the interferometry. More specifically, each spacecraft comprises one optical assembly (Figure 6) with lower row, each made up from the optical bench, the telescope, and the gravitational reference sensor, as well as the associated mounting structures. The optical bench is mounted parallel to the primary mirror of the telescope, requiring a non-planar beam path, where the light from the optical bench to the telescope has to be directed "up" to the telescope. The Gravitational Reference Sensor (GRS) is mounted behind the optical bench so that the light from the optical bench to the GRS has to pass through the optical bench ("down"), resulting in a non-planar beam path as well.

#### 2.1. Optical bench

The required functionality of the optical bench (Figure 7) causes a relatively complex optical bench (Figure 8). The primary laser (~2W at end of life, see section 3) provides the light to be sent to the far spacecraft, the reference beam for the science interferometer, and the measurement beam to the local interferometer. The reference interferometer and the metrology for the point-ahead mechanism (PAAM) (see section 3) use a small portion of the beam. The optical bench comprises both stationary and moving parts, and allows for an accurate positioning of the optical elements to ensure the desired beam path. The optical bench is designed to be compact and lightweight, with a mass of approximately 200 kg, including all necessary components. The optical elements are mounted on a 3D printed, aluminum structure, which is fixed to the spacecraft via rigid mountings. The optical bench is designed to be highly stable and resistant to vibrations, with a vibration isolation of better than 10-13 m/s².
LISA Pathfinder

Graph showing relative acceleration noise (ms$^{-2}$/Hz) versus frequency (Hz) for different missions:
- **GRACE**
- **GOCE**
- **Microscope**
- **LISA Pathfinder**
- **LISA**
- **LPF Projected**

The graph compares the performance of these space missions in terms of relative acceleration noise.
LISA Pathfinder

Flight hardware at Astrium UK

- Caging mechanism key critical path for LTP
- Micro-thrusters
- Same flight hardware as LISA

Colloidal Thrusters mounted on s/c during magnetic test
GRACE-C

Gravity Recovery And Climate Explorer
Satellite to Satellite Interferometry

Launch 2015!

- GRACE residuals
- GRACE FO ifo requirement
- LISA single-link requirement
- LTP local Interferometer (AEI)
Ground Based Network

LHO

LLO

Virgo/AdV

GEO

LIGO-Australia

LCGT
Inspiral rate definition

\[ \rho_c = \Theta \left( (1 + z) M_C \right)^{5/6} \frac{D_l}{D_{ISCO}} \left( \frac{1}{f_{ISCO}} \int df \frac{d^2S_{\ell h}(f)}{f^{7/3}S_{\ell h}(f)} \right)^{1/2} \]

\[ 0 < \Theta(\theta, \phi, \psi, \iota) < 4 \]

Horizon = 2.26 x Range

Hanford
Livingston
Pisa
The GW decade

LIGO

eLIGO

aLIGO

Virgo

V+

AdVirgo

GEO

GEO-HF

LCGT

LIGO-Au
+ Detectors

**Enhanced LIGO (2008-2010)**
- In-vacuum, seismically isolated DC readout
- Increased laser power to 35W
- New magnets, EQ stops, aLIGO DAQ system, thermal compensation

**Virgo+ (2010-2011)**
- Increased laser power, higher finesse
- Monolithic suspension

**GEO-HF (2010+)**
- Increase laser power
- High frequency tuning
- Squeezed light injection
eLIGO + Virgo

S6: July 4, 2009 to Oct. 20, 2010
VSR2: Joint with Virgo thru Jan. 8 2010
VSR3: Joint with Virgo+ Aug. 11 to Oct. 20 2011
Virgo+

Virgo+ (run thru July 2011)
Increased laser power
New optics, higher finesse (50 to 150)
Monolithic suspension

violin Q ~ 3e7

https://wwwcascina.virgo.infn.it/DataAnalysis/Calibration/Sensitivity/
GEO-HF

Uses squeezed vacuum, high power, and new SRM for High Frequency tune
Returning to night / weekend mode

LIGO-Virgo (H. Grote Sept. 2010)
LCGT Funded

Project led by ICRR @ U Tokyo

3 km, cryogenic, underground detector coincident with aLIGO

Proposal based on experience with L=100m, T=20K CLIO prototype
http://gw.icrr.u-tokyo.ac.jp/lcgt/
Advanced LIGO
Advanced LIGO

- Increased power

125 W

750 kW

5 kW
Advanced LIGO

- Increased power
- Improved isolation

125 W

5 kW

Active isolation & quad pendulum

750 kW

Increased power
Improved isolation
Advanced LIGO

- Increased power
- Improved isolation
- Stable recycling cavities

Active isolation & quad pendulum

125 W

5 kW
Advanced LIGO

- Increased power
- Improved isolation
- Stable recycling cavities
- Signal recycling

Active isolation & quad pendulum

125 W

750 kW

5 kW
Advanced LIGO

- Increased power
- Improved isolation
- Stable recycling cavities
- Signal recycling
- DC readout

Active isolation & quad pendulum

125 W

5 kW
Advanced LIGO

- Increased power
- Improved isolation
- Stable recycling cavities
- Signal recycling
- DC readout

**Installation began October 20, 2010**
seismic isolation

Frequency

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

$0.9 \times 10^{-19} \text{ m} / 100 \text{ Hz}$
seismic isolation

suspension

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

Frequency

$0.9 \times 10^{-19} \text{ m} / 100 \text{ Hz}$
seismic isolation

LIGO-G1100101-V1

0.9 x 10^{-19} \text{ m / 100 Hz}
LIGO/Virgo/GEO

- **2005**
  - Oct. 20, 2010: Detector handoff

- **2010**
  - Summer 2011: H2 Single arm
  - Fall 2011: LLO Vertex; H1 squeezing
  - Oct. 2011: LIGO Australia go / no-go

- **2011**
  - Spring 2012: L1 installation complete
  - Fall 2013: H2 installation complete
  - Fall 2014: H1 installation complete

- **2015**
  - Spring 2015: Project complete
Speculative!

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Strain [1/Hz^{1/2}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^1</td>
<td>10^{-24}</td>
</tr>
<tr>
<td>10^2</td>
<td>10^{-23}</td>
</tr>
<tr>
<td>10^3</td>
<td>10^{-22}</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Horizon</th>
<th>NS-NS</th>
<th>BH-BH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early</td>
<td>135 Mpc</td>
<td>270 Mpc</td>
</tr>
<tr>
<td>OK</td>
<td>340 Mpc</td>
<td>2260 Mpc</td>
</tr>
<tr>
<td>BlackHole</td>
<td>310 Mpc</td>
<td>4350 Mpc</td>
</tr>
<tr>
<td>Design</td>
<td>460 Mpc</td>
<td>2780 Mpc</td>
</tr>
</tbody>
</table>

8W, no SRM, Noise
8W, no SRM
25W, NS/NS tune
125W, NS/NS tune
Speculative!

Detect 40 NS/NS, 20 BH/BH inspirals in 12 month science run

(Based on “realistic” values from Abadie et al. 2010 CQG 173001)
LIGO-T0900288-v3


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Optimal NSNS: optimized for 1.4 solar mass neutron star. This is slightly more difficult from a control system point of view. The NSNS case gives ~200 Mpc reach for a single interferometer, SNR 8, averaged over directions and polarizations.

BHBH 20deg: optimized for 30-30 solar mass black hole binary inspirals. This is slightly more difficult from a control system point of view.

High Freq: The "High frequency" case is an example of a narrowband tuning at 1kHz. Note though that, unlike all the other tunings, it needs a recycling mirror with a higher reflectivity.

Finally, we omitted the optimal BHBH curve that appears in the ISC CDD - it is technically a lot harder and offers only a very small increase in BHBH sensitivity, while giving very poor mid- and high-frequency performance.

Note that the plot in the ISC CDD was obtained with bench62. GWINC has an updated thermal noise estimate and supersedes bench62. Thus the curves are slightly different from the ones in the ISC CDD.

aLIGO progress

On target to meet NSF interferometer acceptance milestones

2.7 years in, we’re 40% complete and on budget

Most subsystems in fabrication, starting installation
Advanced Virgo Baseline Design

VIR-027A-09

Issue 1

The Virgo Collaboration
May 16, 2009
Advanced Virgo procurement has started

Some design decisions to be finalized

Installation to begin July 2011

Return to operation in 2015
LIGO Australia

3rd aLIGO detector in Western Australia at Gingin

Australia (ACIGA) provides all the infrastructure - buildings, vacuum, clean rooms and staff

No new cost or delay to NSF/LIGO project

Approved by NSF, under consideration by Australian funding agencies

LIGO Australia could be online 2017
Future is bright

LISA technology on orbit in 2013, space interferometry in 2015

Virgo+ and GEO-HF online, commissioning and taking data

aLIGO 40% complete and on schedule. Earliest science run conceivable late 2014

Chance for 6 (!!!) advanced interferometric detectors online in 2018
Bonus Time
Applying inverse wavelet transform

Estimate source direction

Use of wavelet transform

waveform of Gaussian

This could for work 50%

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Linear

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SGCQ9 HF

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3 LIGO sites

Ad Hoc LSC review Committee

Sam Finn             Pennsylvania State
Peter Fritschel      LIGO-MIT
Sergey Klimenko      University of Florida
Fred Raab            LIGO-Hanford
B. Sathyaprakash     Cardiff University
Peter Saulson        Syracuse University
Rainer Weiss         LIGO-MIT (chair)

Charge:

Enabled by improved analysis

Removal of H2 does not significantly impact network sensitivity

C. Capano et al. Syracuse
eLIGO is aLIGO

Have already commissioned aLIGO systems:

- DC readout (OMC alignment)
- Thermal Compensation System
- aLIGO DAQ and control
- HAM seismic isolation system
- 35 W of upgraded laser power
- High-power modulator and Faraday
- Feedforward seismic isolation
Standing army

Mode Cleaner mirror substrates (UF)
LISA Pathfinder
GWADW, 16th - 21st May 2010

EQM has now passed vibration test – However, pressure sensors of hydraulic launch lock failed

New sensors have been procured and FM manufacture is now under way

CM EQM

UV Lamp unit

Bi-polar discharge demonstrated on torsion pendulum

Rendered UV light intensity

Other LTP units

Optical Bench

ISS Front End Electronics

Sensing noise at Board Level

Sensing noise after board integrated

Other LTP units

Other LTP units

Other LTP units