25 years ago ...

CALTECH/MIT PROJECT
FOR A
LASER INTERFEROMETER
GRAVITATIONAL WAVE OBSERVATORY

December 1987
LIGO-M870001-00-M
1987

Signing of the Intermediate Range Nuclear Forces Treaty

1st Visit of East Germany’s head of state in West German capitol
Signing of the Intermediate Range Nuclear Forces Treaty

1st Visit of East Germany’s head of state in West German capitol

Top Movie of the year

Fatal Attraction
By comparing the source strengths and benchmark sensitivities in Figure II-2 and in the periodic and stochastic figures A-4b,c (Appendix A), one sees that (i) There are nonnegligible possibilities for wave detection with the first detector in the LIGO. (ii) Detection is probable at the sensitivity level of the advanced detector. (iii) The first detection is most likely to occur, not in the initial detector in the LIGO but rather in a subsequent one, as the sensitivity and frequency are being pushed downward from the middle curve toward the bottom curve of Figure II-2.
25 Years Later: They were correct!

By comparing the source strengths and benchmark sensitivities in Figure II-2 and in the periodic and stochastic figures A-4b,c (Appendix A), one sees that (i) There are nonnegligible possibilities for wave detection with the first detector in the LIGO. (ii) Detection is probable at the sensitivity level of the advanced detector. (iii) The first detection is most likely to occur, not in the initial detector in the LIGO but rather in a subsequent one, as the sensitivity and frequency are being pushed downward from the middle curve toward the bottom curve of Figure II-2.
which leads us to the ‘subsequent one’:

Advanced LIGO

By comparing the source strengths and benchmark sensitivities in Figure II-2 and in the periodic and stochastic figures A-4b,c (Appendix A), one sees that (i) There are nonnegligible possibilities for wave detection with the first detector in the LIGO. (ii) Detection is probable at the sensitivity level of the advanced detector. (iii) The first detection is most likely to occur, not in the initial detector in the LIGO but rather in a subsequent one, as the sensitivity and frequency are being pushed downward from the middle curve toward the bottom curve of Figure II-2.
Advanced LIGO

- Design began in earnest in 1999 as a LIGO Scientific Collaboration concept paper
- Major Advanced LIGO R&D and design work during 1999-2006
- Final baseline review by NSF in November 2007
  - At this point, many aLIGO subsystem designs were far along
- Advanced LIGO Project officially began on April 1, 2008
**Advanced LIGO**

- Capital Partners: UK/DE/AU
- Installation started 2010
- First Science Run 2014
- Parallel VIRGO upgrade
- KAGR under development

- 10 times more sensitive > 60Hz
- Push low frequency limit to 10Hz
- Tunable detector
- **First Detection 2015/6**

Different Operational Modes

- Low Power: 25W
- High Power: 125W
- Different SRM

Thursday, May 24, 2012
Advanced LIGO

Dual-recycled, cavity-enhanced
Michelson interferometer

\[ h = \frac{\delta L}{L} \]

\[ L = 4000 \text{ m} \]

Measures changes in light travel time between free ‘falling’ mirrors

• Laser interferometry turns this into a phase comparison at the beam splitter

Free ‘falling’ mirrors

• Mirrors decoupled from environment via suspensions and seismic isolation systems
Key Improvements:

- Better Seismic Isolation
- Better Suspension
- Larger Mirrors
- Better Stray Light Control
- Better Mirrors/Coatings
- Higher Laser Power
- Signal Recycling (RSE)
- Better Sensing and Control
- Better Modeling Capabilities
- Stable Recycling Cavities
- *Cleaner* Vacuum ...

Helps mainly at

- Low Frequencies
- Mid Frequencies
- High Frequencies
- All Frequencies
Remove oxide layer from interior heat-treated surfaces
• Pneumatic tools used, all lubricants removed
  (contamination risk; tool failure rates thus high)

• LLO: All Chambers cleaned
• LHO: Last BSC chambers will be cleaned early summer

Installed larger mode cleaner beam tubes for larger beam diameter inside PR cavity
Vacuum System

New IMC-Tube

BSC6 Move at LHO
Seismic Isolation

For Main Optics

BSC:
- Suspensions hanging off the Internal Seismic Isolator (ISI)
- ISI placed on top of Hydraulic External Pre-Isolators (HEPI)
  - Both use a combination of active and passive damping mechanism to reduce seismic noise
Seismic Isolation

Active Isolation – The Basic Control Loop

Displacement Sensors
- CPSINF
- CPS2CART
- CPSALIGN

Blend Filters

Isolation Filters
- CART2ACT
- OUTF

Super Sensor

Damping Filters
- DAMP

Inertial Sensors
- GS13INF
- GS132CART

Analog Whitening

On Board Sensors

HAM ISI “Plant”

Actuators

Ground Motion

Software

Hardware

Courtesy of Jeff Kissel

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Seismic Isolation

Active Isolation – Successive Loop Closure

< 10pm/rtHz in Band

100 times smaller @ 1Hz

Courtesy of Jeff Kissel
Seismic Isolation

Ham Chambers for

- secondary optics
  (Recycling Cavities, Mode Cleaner, ...)

HEPI for HAM Chambers

PR2 & IMC2 on ISI Table

ISI Table in HAM Chamber

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Suspensions

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Suspensions

Installation of Quad Suspension in Hanford

Thursday, May 24, 2012
Installation of Quad UK-Suspensions in Hanford

Thursday, May 24, 2012
Better test masses:

10 kg $\rightarrow$ 40 kg

Higher Q

Lower Absorption ( < ppm/cm )

Better Surface profiles ( < nm )

Still issues with coating uniformity over large area

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Pre-stabilized Laser (PSL)

30 W → 200 W

Built and delivered by AEI-Hannover

• Operating at LLO since Summer 2011
• Operated in H2 since December 2012
  • Just moved to H1

Input Optics I:

Modulators

• Wedged to also act as polarizers
• High Power qualified

Power Control

Mode matching

Diagnostic
Advanced LIGO

Input Optics II (In Vacuum):

- Input Mode Cleaner
- Faraday Isolator
- Mode matching
- Diagnostic

**Faraday Isolator:**
(tested with PSL in air)
- Losses 3.3%
- eLIGO 7%
- iLIGO 14%

**Isolation Ratio:**
- > 34 dB up to 70W

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Suspended Optics in IO

- Input Mode Cleaner
- Mode Matching Optics
- Beam Steering Optics
Input Mode Cleaner 2

Baffles to control stray light missing

Power Rec. Mirror 2

Steering Mirrors + Black Glass
Next
HAM 2 @ LLO

Little crowded ...

• PR3, IMC 1 & 3 are chamber-side

• Final testing followed by installation early next week
Current Schedule:

• L1 (Livingston)
  • Short Michelson test Feb 2013
    • incl. Power Recycling
  • Full Interferometer Testing June 2013
  • Acceptance Tests May 2014

• H1 (Hanford)
  • Single Arm Test July 2012
  • Full IFO locked Dec 2013
  • Acceptance Tests July 2014
• Acceptance Tests:
  • Need ~2h of full interferometer lock
  • No requirement on Sensitivity
• Finishes Project Phase

• Followed by Operations Phase
  • Commissioning work to improve
    • sensitivity
    • duty cycle
    • understanding of the instrument
  • interspersed by science runs at (~50MPc, ~100MPc, >150MPc)
The Advanced GW Detector Network

- Advanced LIGO Hanford 2015
- Advanced LIGO Livingston 2015
- GEO 600 (HF) 2011
- Advanced Virgo 2015
- LIGO India 2020?
- LCGT (KAGRA) 2017

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Advanced LIGO
Prospects and Status

Move of H2 to India II

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LIGO India Master Plan:
• India provides vacuum system, infrastructure, S&H, Operations Costs and local staff
• LIGO sends 2nd Hanford interferometer to India
  • Design will change to an unfolded L1 interferometer
  • Requires some re-polishing of Input Optics mirrors
• LIGO-India would be operated as part of the LIGO Network
Advanced LIGO in India

- India provides vacuum system, infrastructure, S&H, Operations Costs and local staff
- LIGO sends the 2nd Hanford interferometer to India
- Design will change to an unfolded L1 interferometer
- Requires some re-polishing of Input Optics mirrors

LIGO-India would be operated as part of the LIGO Network.
Three phases to LIGO-India:

» Phase 1 (2012-2013)
   – Establish project office, site selection, facility design, vacuum system design update

» Phase 2 (2014-2016)
   – Site preparation, facility and vacuum construction

» Phase 3 (2017-2019)
   – Detector installation and commissioning
Directors of three institutions have agreed to serve as nodal institutions

» Institute for Plasma Research (IPR, Department of Atomic Energy autonomous institute), vacuum system and facility

» Raja Ramanna Centre for Advanced Technology (RRCAT, DAE laboratory), detector responsibilities

» Inter-University Centre for Astronomy and Astrophysics (IUCAA, University Grants Commission-funded centre), data analysis and astrophysics
Approval Status in India:

• IPR Governing Board has approved role in project

• Project presented to Atomic Energy Commission
  » All comments positive, prepared recommendation for Cabinet consideration

• Cabinet approval needed because project spans multiple 5-year plans
  » Cabinet approval can trigger seed funding by DAE
  » Scheduling uncertain, but should be possible within 2 months

• Continuing site visits and evaluations

• Beginning process of getting Visas for entry to US
  » Typically 2 month process » Will enable first visits from India by summer or fall
Approval Status in US:

Following successful review of recommendation to proceed, LIGO asked NSF for permission to cease H2 installation

» Granted immediately by Physics Division,

• NSF asked for “mini-Project Execution Plan”

• Replanning aLIGO installation and testing for two interferometer US configuration underway

• Submit both to NSF by June 1 for review June 12/13

• NSB information item May 2, action item July 17-18

• Beginning export license application
Approval Status in Europe/Australia:

UK, Germany and Australia are capital partners in LIGO who make significant financial contributions
• Suspensions from UK
• Laser from Germany
• Wavefront Sensing from Australia

Official requests for approval will be made following probably the NSB decision in the US
Advanced LIGO in India

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LIGO India is (very likely) coming ...
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## Binary coalescences rates

- Neutron star (NS) = $1.4 \, M_\odot$, Black Hole (BH) = $10 \, M_\odot$

<table>
<thead>
<tr>
<th>IFO</th>
<th>Source</th>
<th>$N_{low}$ yr$^{-1}$</th>
<th>$N_{re}$ yr$^{-1}$</th>
<th>$N_{pl}$ yr$^{-1}$</th>
<th>$N_{up}$ yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial LIGO</td>
<td>NS-NS</td>
<td>$2 \times 10^{-4}$</td>
<td>0.02</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>NS-BH</td>
<td>$7 \times 10^{-5}$</td>
<td>0.004</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BH-BH</td>
<td>$2 \times 10^{-4}$</td>
<td>0.007</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IMRI into IMBH</td>
<td></td>
<td></td>
<td>$&lt; 0.001^b$</td>
<td>0.01$^c$</td>
</tr>
<tr>
<td></td>
<td>IMBH-IMBH</td>
<td></td>
<td></td>
<td>$10^{-4}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Advanced LIGO</td>
<td>NS-NS</td>
<td>0.4</td>
<td>40</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>NS-BH</td>
<td>0.2</td>
<td>10</td>
<td>300</td>
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</tr>
<tr>
<td></td>
<td>BH-BH</td>
<td>0.4</td>
<td>20</td>
<td>1000</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td>$10^b$</td>
<td>300$^c$</td>
</tr>
<tr>
<td></td>
<td>IMBH-IMBH</td>
<td></td>
<td></td>
<td>0.1$^d$</td>
<td>1$^e$</td>
</tr>
</tbody>
</table>

The Message:

• Advanced LIGO is progressing fairly well
  • No major problems in sight right now
  • Have certainly seen our share of delays
    • Still within schedule and budget contingency

• Deliverable for Advanced LIGO Project:
  • 2h continuous lock of each interferometer in full configuration (that could mean: No SR)
    • No sensitivity requirement
  • LIGO Operations will do the follow-up optimization and noise hunting
Current Plan

3rd run: >6 months @ > 150 Mpc

2nd run: >3 months @ 100 Mpc, “likely” detection

1st run: 2 months @ 50 Mpc, we could be lucky!

LIGO

Thursday, May 24, 2012
Beyond Advanced LIGO:

- Improve sensitivity by another factor 10
- Reduce low frequency to around 1 Hz

R&D for 3G:

- Better suspensions
  - lower resonance freq.
  - less thermal noise
- Gravity gradient noise
  - Underground
  - Measure and subtract
- Lower thermal noise
  - Material research
- Squeezing
  - Modify the Vacuum
  - ...

Thursday, May 24, 2012
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- Modify the Vacuum
  - ...

Now it is getting really difficult ...

and we leave that for 'next week' ...

Thursday, May 24, 2012
Questions?
Comments?
or Coffee?
Seismic Isolation

SEI Sensors and Their Noise

- **IPS**
  - Kaman’s Inductive Position Sensors
  - Used On: HEPs
  - Used For: \( \leq 0.5 \text{ Hz} \) Control, Static Alignment
  - Used ‘cause: Reasonable Noise, Long Range

- **CPS**
  - MicroSense’s Capacitive Displacement Sensors
  - Used On: HAM-ISIs and BSC-ISIs
  - Used For: \( \leq 0.5 \text{ Hz} \) Control, Static Alignment
  - Used ‘cause: Good Noise, UHV compatible

- **STS2**
  - Strekheisen’s STS-2
  - Used On: HEPs
  - Used For: \( 0.01 \leq f \leq 1 \text{ Hz} \) Control
  - Used ‘cause: Best in the ‘Biz below 1 Hz, Triaxial

- **T240**
  - Nanometric’s Trillium 240
  - Used On: BSC-ISIs
  - Used For: \( 0.01 \leq f \leq 1 \text{ Hz} \) Control
  - Used ‘cause: Like STS-2s, Triaxial, no locking mechanism -> podded

- **GS13**
  - GeoTech’s GS-13
  - Used On: HAM-ISIs and BSC-ISIs
  - Used For: \( \geq 0.5 \text{ Hz} \) Control
  - Used ‘cause: awesome noise above 1Hz, no locking mechanism -> podded

- **L4C**
  - Sercel’s L4-C
  - Used On: All Systems
  - Used For: \( \geq 0.5 \text{ Hz} \) Control
  - Used ‘cause: Good Noise, Cheap, no locking mechanism -> podded

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