Gravitational Waves and LIGO: A Technical History

Stan Whitcomb
IEEE SV Tech History Committee Event
11 October 2018
Goal of Talk

- Review a few of the technical developments that enabled LIGO, with emphasis on pre-1995 era
  - Residual Gas Noise (Vacuum requirement)
  - Thermal noise
  - Mirror figure requirements

- Disclaimer: LIGO has an equally “rich” political history—NOT covered in this talk
  - See e.g., Janna Levin, *Black Hole Blues*
  - Caltech Archives--search for “LIGO Oral Histories” at [http://archives.caltech.edu/search/index.html](http://archives.caltech.edu/search/index.html)
• Einstein (in 1916) recognized gravitational waves in his theory of General Relativity
  » Necessary consequence of Special Relativity with its finite speed for information transfer
  » Most distinctive departure from Newtonian theory

• Time-dependent distortions of space-time created by the acceleration of masses
  » Propagate away from the sources at the speed of light
  » Pure transverse waves
  » Two orthogonal polarizations

\[ h = 2\Delta L / L \]

~10^{-21} for plausible astrophysical sources
Detecting GWs with Interferometry

Suspended mirrors act as “freely-falling” test masses in horizontal plane for frequencies $f >> f_{\text{pend}}$

For a LIGO detector, $L \sim 4 \text{ km, } h \sim 10^{-21}$

$\Delta L \sim 10^{-18} \text{ m}$
Laser Interferometer Gravitational-wave Observatory (LIGO)
The Core Principle Driving LIGO: Noise

- Sensing Noise
  - Photon Shot Noise
  - Residual Gas

- Displacement Noise
  - Seismic motion
  - Thermal Noise
  - Radiation Pressure

- Noise sources add
  - All noise sources have to be identified, understood and controlled
Three documents so central to the technical history of LIGO that they must be introduced immediately

• “Rai’s RLE paper”
  » “Electromagnetically Coupled Broadband Gravitational Antenna”
  R. Weiss, Quarterly Reports of the Research Laboratory of Electronics MIT 105, p. 54 (1973).
  » Paper “… grew out of an undergraduate seminar that I ran at M.I.T. several years ago…”

• The “Blue Book”
  » “A Study of a Long Baseline Gravitational Wave Antenna System”
  » Authors: Paul Linsay, Peter Saulson, Rai Weiss
  » Dated October 1983, but not really published

• NSF Proposal for LIGO Construction (’89 proposal)
  » Proposal team: Robbie Vogt, Ron Drever, Rai Weiss, Kip Thorne, Fred Raab, but with contributions from many others
Not first suggestion of a laser interferometer to measure GWs, but first detailed noise/sensitivity analysis

- Shot noise/radiation pressure
- Thermal noise
- Seismic noise
- Gravity gradient
- ...
The Blue Book

- Science and Engineering study of feasibility
- Comprehensive scope—Chapter titles
  » Sources of Gravitational Radiation
  » Physics and Detection
  » Prototypes and Optical Concepts
  » Noise sources
  » Vacuum System
  » Site survey
  » Construction
  » Proposed Design
- Important because of first engagement of engineering firms
The ‘89 Proposal

• Two Volumes
  » Science case, detector physics, noise analysis, prototype experience
  » Engineering design and cost basis

• Defined sensitivity goals, phased approach, scope
Residual Gas Noise

• Not the most interesting noise source to typical physicist, but important because the vacuum system is one of the largest cost items in LIGO
Residual Gas Noise

- Even though very small, the residual gas in the vacuum system contributes to index of refraction
- Not mentioned in Rai’s RLE paper
- The Blue Book (1983)
  - Has an essentially correct treatment of the noise due to residual gas—statistical fluctuations in the number of gas molecules in the beam causing fluctuations in refractive index
  - Correct requirement for initial LIGO (~10^-6 torr)
- Correct formulation independently published by the Munich/Garching group
Residual Gas Noise, cont.

- Not entirely a straight line progression
- 1987 LIGO R&D proposal
  - Initial LIGO requirement quoted (at least one place) as $10^{-3}$ torr, three orders of magnitude too high
- LIGO ’89 proposal
  - A new formulation of the problem, in terms of the forward scattering matrix for individual gas molecules
  - Simple mathematical error ended up with incorrect formula
  - Gave approximately correct vacuum requirement (probably why the incorrect formula was not noticed)
Residual Gas Noise Experiment

- Finally, definitively resolved (better than $\sqrt{2}$ level) and confirmed experimentally in 1994

- Just prior to beginning construction (whew!)
Thermal Noise

• One of the most important and complex fundamental noise sources
Rai’s RLE paper

• Importance clearly recognized (third noise source mentioned after shot noise and laser frequency noise)

• Single mode analysis for thermal noise, assuming viscous damping (suspension modes and internal modes)

• Suspension not defined as a pendulum
  » Described as a “long-period seismometer suspension”
Fig. V-20. Proposed antenna.
Rai’s RLE paper

• Importance clearly recognized (third noise source mentioned after shot noise and laser frequency noise)

• Single mode analysis for thermal noise, assuming viscous damping (suspension modes and internal modes)

• Suspension not defined as a pendulum
  » Described as a “long-period seismometer suspension”
  » “The suspensions are critical components in the antenna, and there is no obvious optimal design”
  » Suspension mode Q \( \sim 10^4 \) (actual requirement for Advanced LIGO \( \sim 10^9 \))

• Multimode nature recognized
  » “The general problem with suspensions in the real world is that they have not one degree of freedom but many,...”
The “Blue Book”

- Still single mode analysis of thermal noise for estimating noise
- Beginning to recognize the complexity:
  - “…a frequency independent stochastic force is at this time still only a conjecture.”
  - “There are situations where a blithe application of the model will give the wrong results.” (coupled oscillators and servo damping)
- Largely unreferenced, so source of incorrect aspects hard to pin down
  - Fused silica $Q_{\text{mat}}$ given as $\sim 10^4$. (actual $Q_{\text{mat}} \sim 10^7$)
Blue Book

- Noise Budget
  » Thermal noise from the suspensions (4) estimated to dominate in mid-frequency band
The ’89 proposal

• First (?) mention of the Fluctuation-Dissipation Theorem (powerful theoretical tool)
  » Not really used, however

• Noise estimates still based on viscous damping, but
  » “…the damping can be frequency dependent so that a simple measurement of the Q of a resonance is not sufficient to predict the thermal noise off resonance.”

• Recognized importance of overlap between internal mechanical modes and optical modes
  » “Estimates of the equivalent gravitational wave strain … depend upon the overlap integral of the optical mode shape with the mechanical mode of the mass.”
Thermal Noise

• Peter Saulson’s paper
  » Complete set of references!

• Began while Peter was at MIT, during writing of ’89 proposal, completed during a sabbatical at JILA

• First (?) presentation in the GW literature of:
  » Structural damping on an equal basis with viscous damping
  » Thermoelastic damping
  » Clear discussion of Fluctuation-Dissipation Theorem
  » Multi-mode systems, systems with localized losses, etc.

• Set the stage for progress in several areas: Yuri Levin’s work, modern appreciation of coating thermal noise, etc.
Mirror Figure Requirement

- One of the biggest challenges in initial LIGO
- Requirement for Initial LIGO detectors: 0.6 nm rms
Mirror Figure Requirement

- Not mentioned in RLE paper
- Not mentioned in Blue Book
- 1987 LIGO R&D Proposal:
  - “Mirror specifications (substrate material, surface polish, figure and slope errors) have been developed with industry.”
  - No clear discussion of where those requirements came from
  - Requirement given as 20 nm (for laser wavelength ~500 nm)
    (Correcting for wavelength difference, ~60 times poorer than requirement for initial LIGO detectors)
Mirror Figure Requirement, cont.

- Same requirement repeated, without elaboration in '89 proposal (still for wavelength ~500 nm)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror Coatings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity storage time</td>
<td>2 msec</td>
<td></td>
</tr>
<tr>
<td>Scattering + absorption</td>
<td>≤ 50 ppm</td>
<td>for &lt; 50 ppm scattering</td>
</tr>
<tr>
<td>Surface microroughness</td>
<td>&lt; 3 Å rms</td>
<td>rms variation of transmission</td>
</tr>
<tr>
<td>Coating uniformity</td>
<td>≤ 1.5%</td>
<td>coefficient over central 8 cm</td>
</tr>
<tr>
<td>Cavity length $L$</td>
<td>4.0 km</td>
<td>(2.0 km)</td>
</tr>
<tr>
<td>Mirror curvature $R$</td>
<td>3.0 km</td>
<td>(1.5 km)</td>
</tr>
<tr>
<td>Figure error</td>
<td>200 Å</td>
<td>rms over central 8 cm</td>
</tr>
<tr>
<td>Cavity stability parameter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$g = 1 - \frac{k}{R}$</td>
<td>−0.33</td>
<td>(−0.33)</td>
</tr>
</tbody>
</table>
• Began to realize challenge as a result of effort to define specification of the substrate uniformity
  » Mike Burka (MIT postdoc) undertook a program of measurements and modeling to study effects of mirror substrate inhomogenities on the dark port contrast (to assure adequate recycling gain)

• Slowly the requirement began to tighten
  » Developed optical modal model for full interferometer
  » First FFT models for interferometer a few years later

• By 1995, when construction of detectors began
  » Requirement had tightened to $\lambda/400$
  » Laser type changed from Ar+ laser to Nd:YAG (wavelength from 500 nm to 1064 nm)
  » “Discovered” the AXAF Test Flat (LIGO sized optic polished by Perkin-Elmer for NASA x-ray satellite—approximately 1 nm rms)
Test Mass/Mirror Specification

• Detailed optical modelling led to final specification (another factor of ~4)

• Polishing
  » Surface uniformity < 0.6 nm rms ($\lambda / 1600$)
  » Radii of curvature matched < 3%

• Coating
  » Scatter < 50 ppm
  » Absorption < 2 ppm
  » Uniformity <10^{-3}

• The final challenge was to convince industry that not only could they do it, they were already doing it
Take-Aways

• Some of the challenges facing LIGO were recognized early, and the path to overcoming them was steady, even if difficult (thermal noise)

• Some of the challenges were recognized early, and the path to overcoming them involved both positive and negative progress (residual gas noise)

• Some of the challenges were not recognized until rather late in the project, and had to be overcome under intense pressure (mirror figure reqt.)