LIGO

Making LIGO Possible: A Technical History

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Goal of Talk

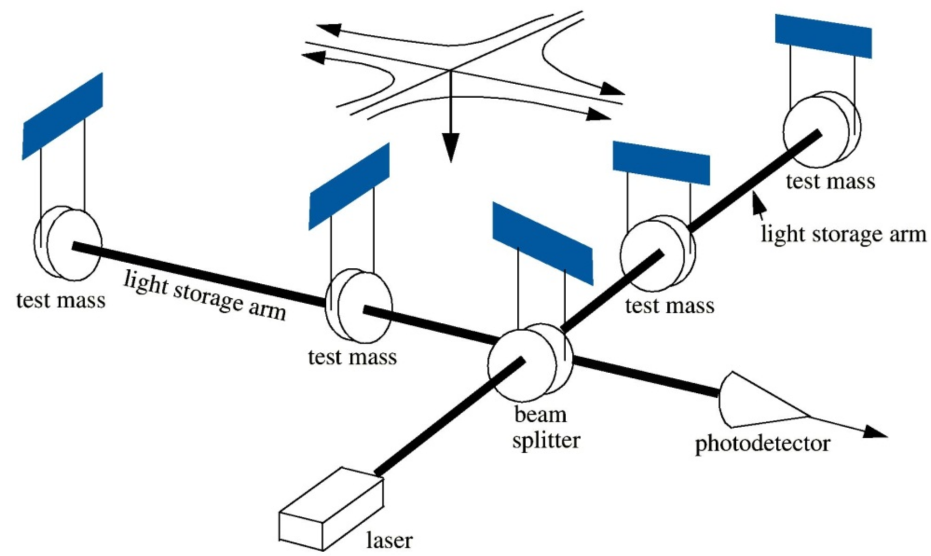
- Review a few of the technical developments that enabled LIGO, with emphasis on pre-construction era
  - “Invention” of laser interferometry for GW detection
  - Residual gas noise (Vacuum requirement)
  - Thermal noise
  - Mirror figure requirements
  - Mirror orientation noise

- Disclaimer: LIGO has an equally “rich” socio-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

Detecting GWs with Interferometry

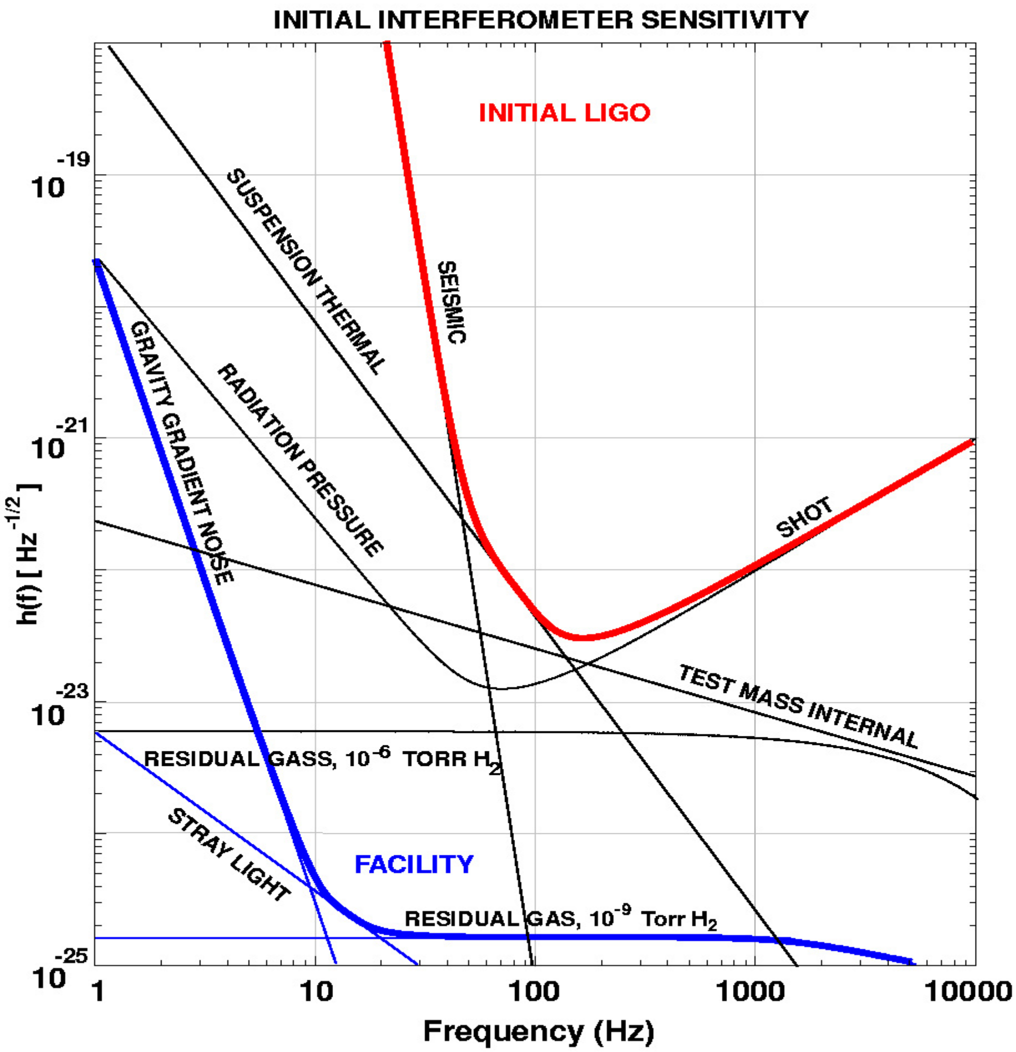
Suspended mirrors act as "freely-falling" test masses in horizontal plane for frequencies $f \gg f_{pend}$

$$\Delta L = hL/2$$



For a LIGO detector,
L ~ 4 km, $h \sim 10^{-21}$
$\Delta L \sim 10^{-18}$ m

The Core Principle Driving LIGO: Noise Reduction



- 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

Reference Documents

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

Rai's RLE Paper

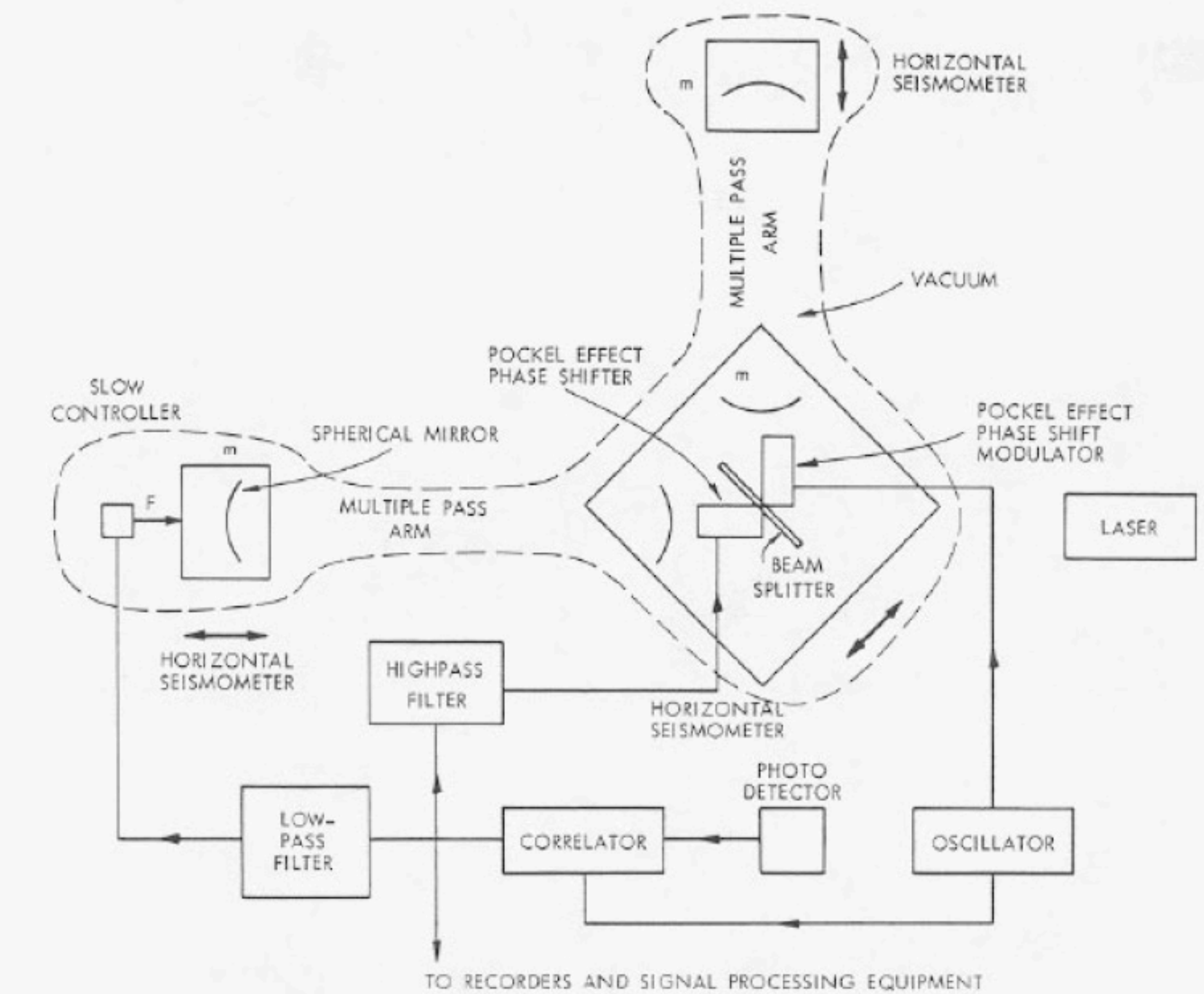


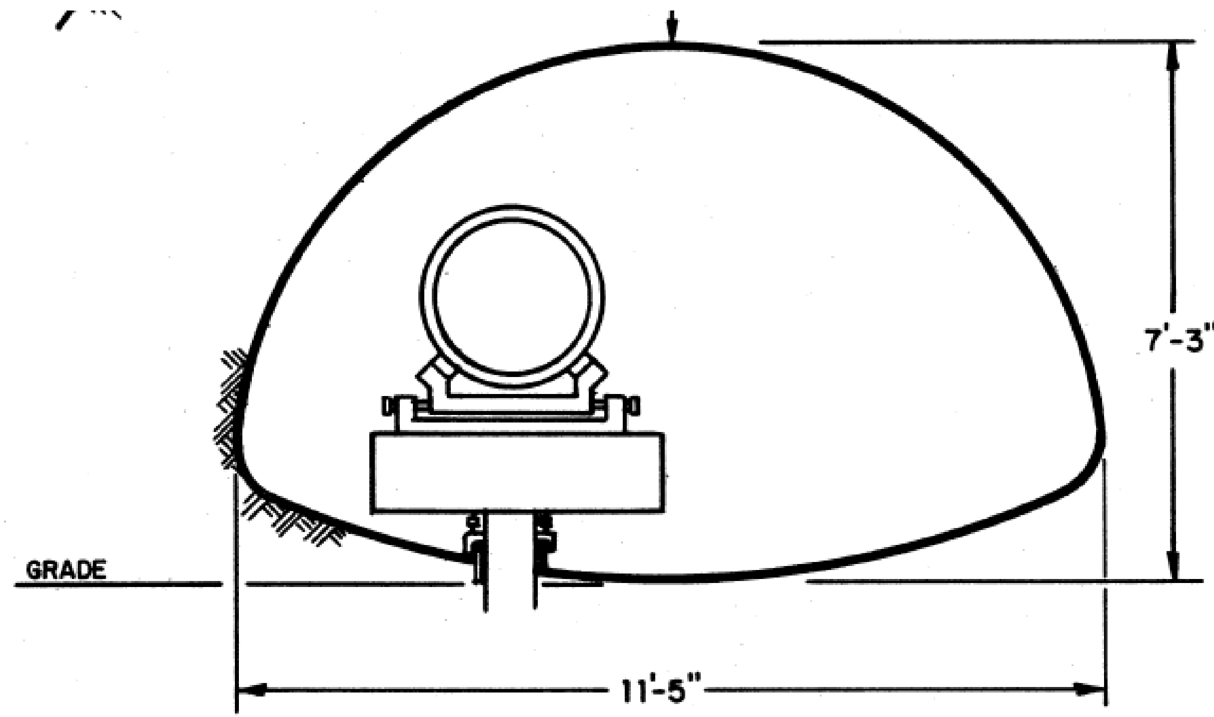
Fig. V-20. Proposed antenna.

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
- » …

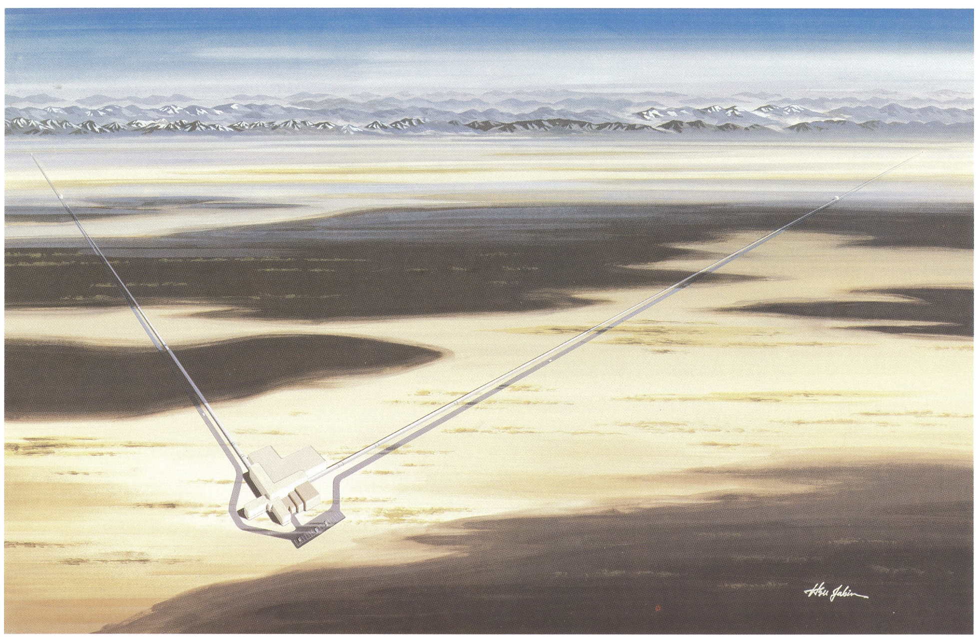
The Blue Book

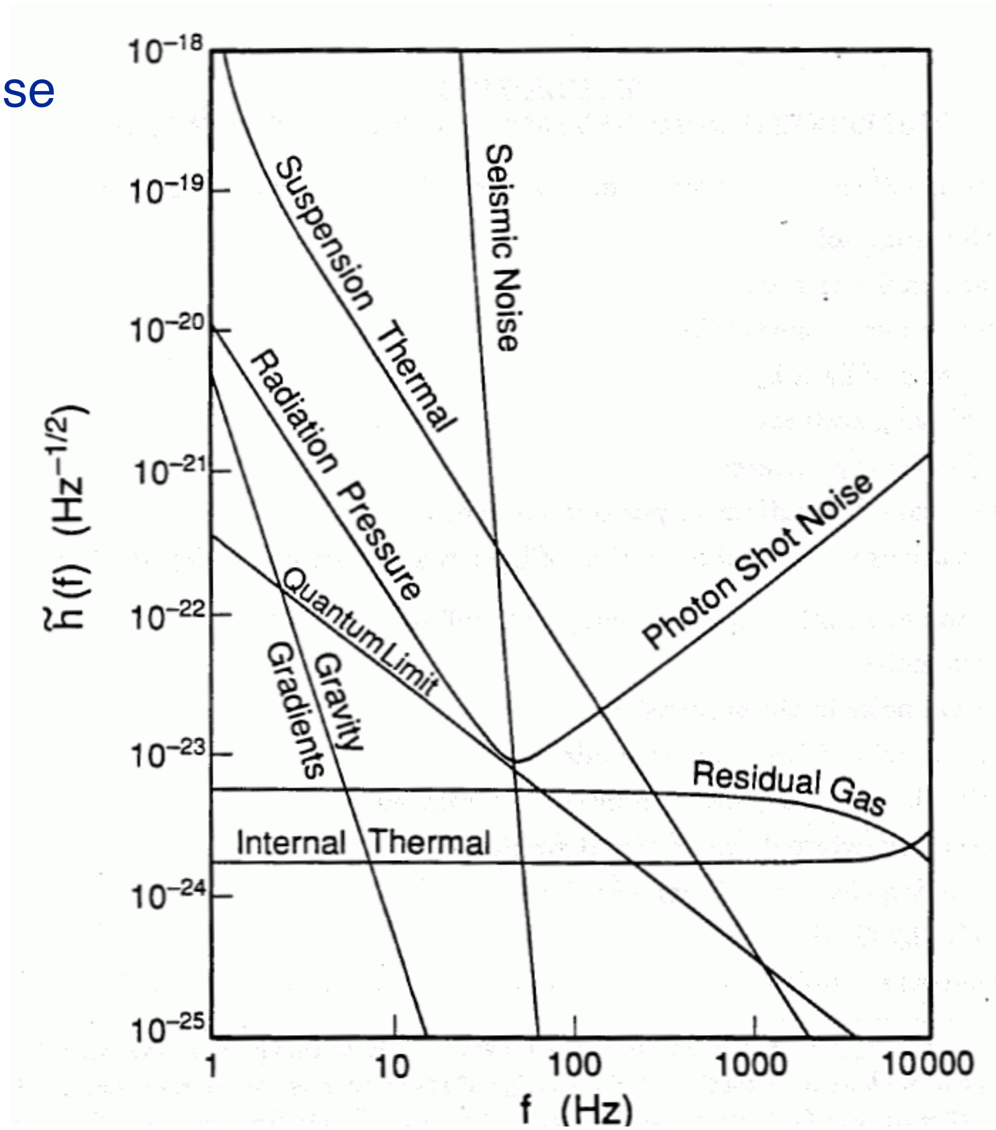
- Science and Engineering study of feasibility
- Comprehensive scope—Chapter titles
  - » Sources of Gravitational Radiation
  - » Physics and Detection
  - » Prototypes and Optical Concepts
  - » Noise sources
  - » Vacuum System
  - » Site survey
  - » Construction
  - » Proposed Design
- Important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



The '89 Proposal

- Two Volumes
  - » Science case, detector physics, noise analysis, prototype experience
  - » Engineering design and cost basis
- Defined sensitivity goals, phased approach, scope





Who Invented the Laser Interferometer Gravitational Wave Detector?

Because everyone asks this…

Multiple Independent Inventions

- (At least one) early gedanken experiment using interferometry to detect GWs:
  - » F.A.E. Pirani, *Acta Phys. Polon*. **15**, 389 (1956)
  - » (predates invention of laser by 4 years)
  - » Cited in Rai's RLE paper
- Often cited as first suggestion:
  - » M.E.Gertsenshtein and V.I. Pustovoit, Zh. Eksp. Teor. Fiz. **43**,605 (1962); Sov. Phys JETP,**16**, 433 (1063).
  - » Not cited in RLE paper, but was noted by Braginsky in "Gravitational radiation and the prospect of its experimental discovery," *Sov. Phys. Usp.* **8**, 513 (1966).
- Rai's RLE paper represented an independent invention ("several years" before 1972)
- RLE paper cites Philip Chapman (NASA) as having independently proposed technique

First Interferometer Prototype

- Started at Hughes Research Labs in 1966!
  - » Led by Robert Forward (former student of Joe Weber)
  - » Described in G.E. Moss, R.L. Miller and R.L. Forward, “Photon-noise-Limited Laser Tranducer for Gravitational Antenna” *Applied Optics* **10**, 2495 (1971).

> The idea of detecting gravitational radiation by using a laser to measure the differential motion of two isolated masses has been suggested often in the past.[5]
>
> 5. To our knowledge, the first suggestion was made by J. Weber in a telephone conversation with one of us (RLF) on 14 September 1964.

  - » Also acknowledges Weiss and Chapman
- First search result published in 1978
  - » “Wideband laser-interferometer gravitational-radiation experiment,” R.L. Forward, *Phys Rev* D, 17, 379 (1978)

Forward Interferometer

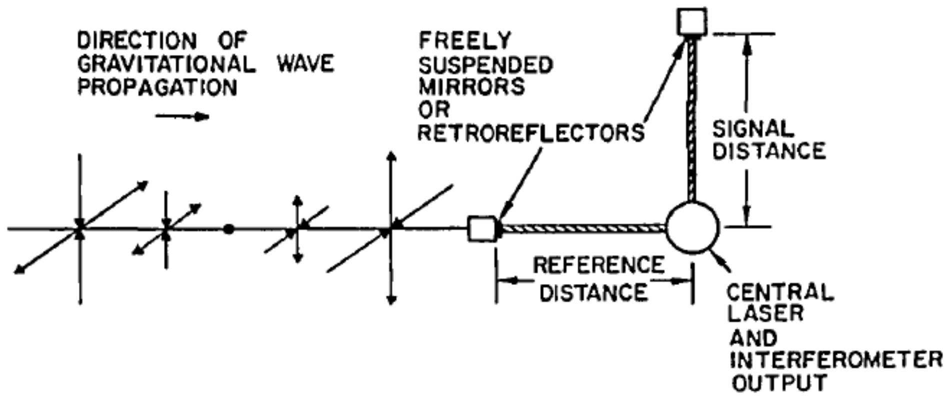


Fig. 1. Right angle interferometer antenna. The reference distance is not changed by gravitational radiation in the direction of propagation shown.

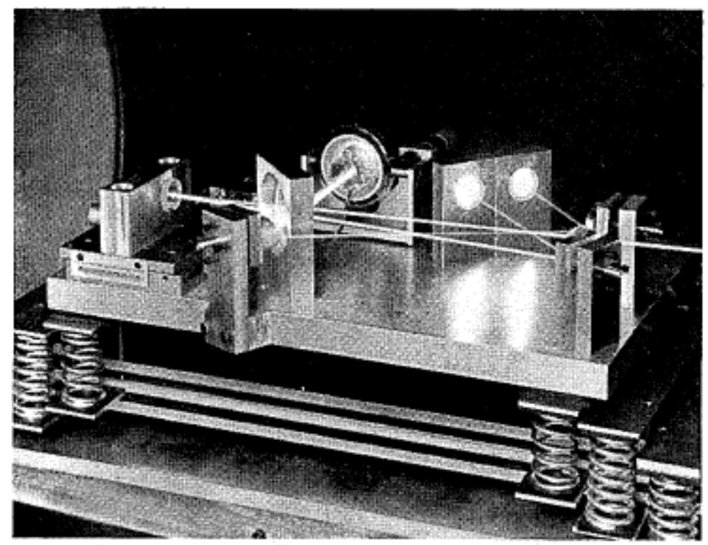


Fig. 4. Photograph of interferometer setup on 3-Hz isolation suspension.

Data Analysis section of 1978 paper:
"Calibration of the Ear"

Residual Gas Noise

- Not the most interesting noise source to typical physicist, but important because the vacuum system was the largest cost items in (initial) LIGO

Residual Gas Noise

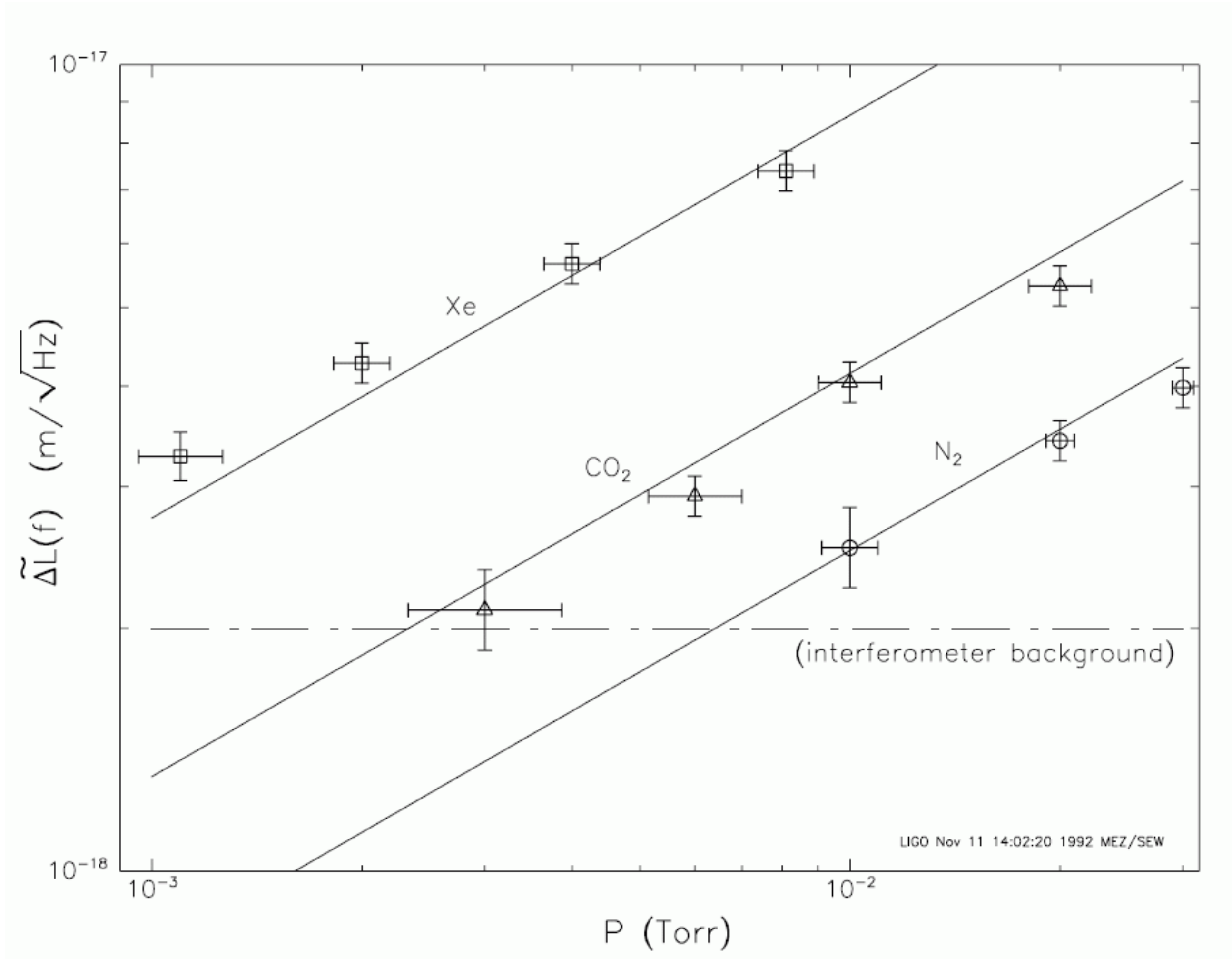
- Even though very small, the residual gas in the vacuum system contributes to index of refraction
- Not mentioned in Rai's RLE paper
- The Blue Book (1983)
  - » Has an essentially correct treatment of the noise due to residual gas—statistical fluctuations in the number of gas molecules in the beam causing fluctuations in refractive index
  - » Correct requirement for initial LIGO (~10^{-6} torr)
- Correct formulation independently published by the Munich/Garching group
  - » Referenced to Albrecht Rüdiger as unpublished derivation in paper on Munich 30 m prototype ("Noise behavior of the Garching 30-meter prototype gravitational wave detector," Shoemaker et al., *Phys Rev* **D 38**, 423 (1988))

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)

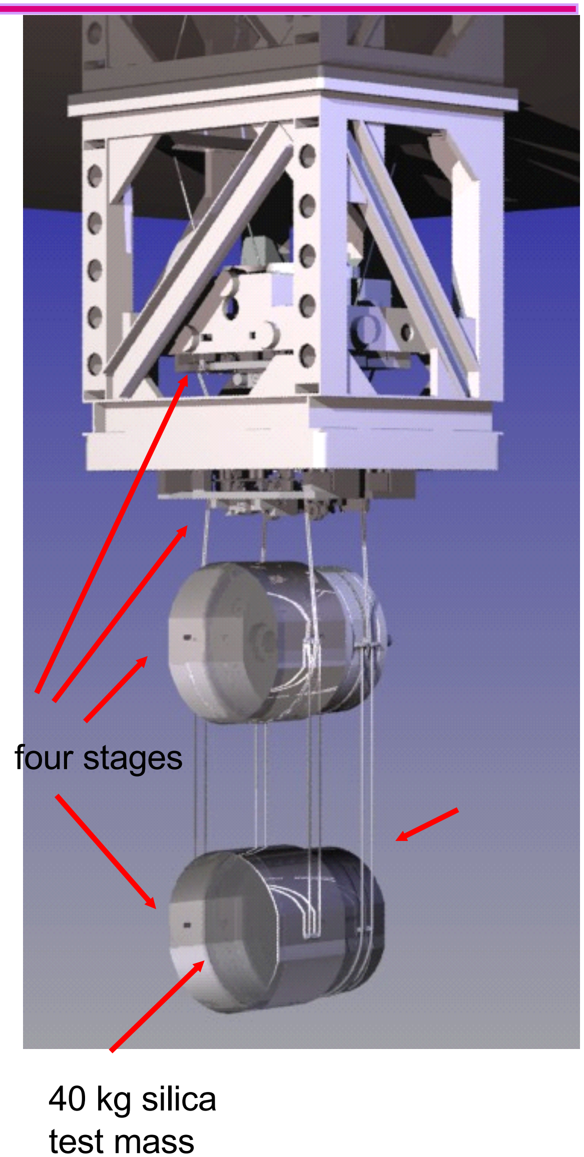
Residual Gas Noise Experiment

- Finally, definitively resolved (better than √2 level) and confirmed experimentally in 1994
  - » "Measurement of Optical Pathlength Fluctuations due to Residual Gas in the LIGO 40m Interferometer," M. E. Zucker et al., in *Proc. Of the Seventh Marcel Grossmann Conference*, (1994)
- Just prior to beginning construction (whew!)



Thermal Noise

- One of the most important and complex fundamental noise sources



Thermal Noise

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 RLE Paper

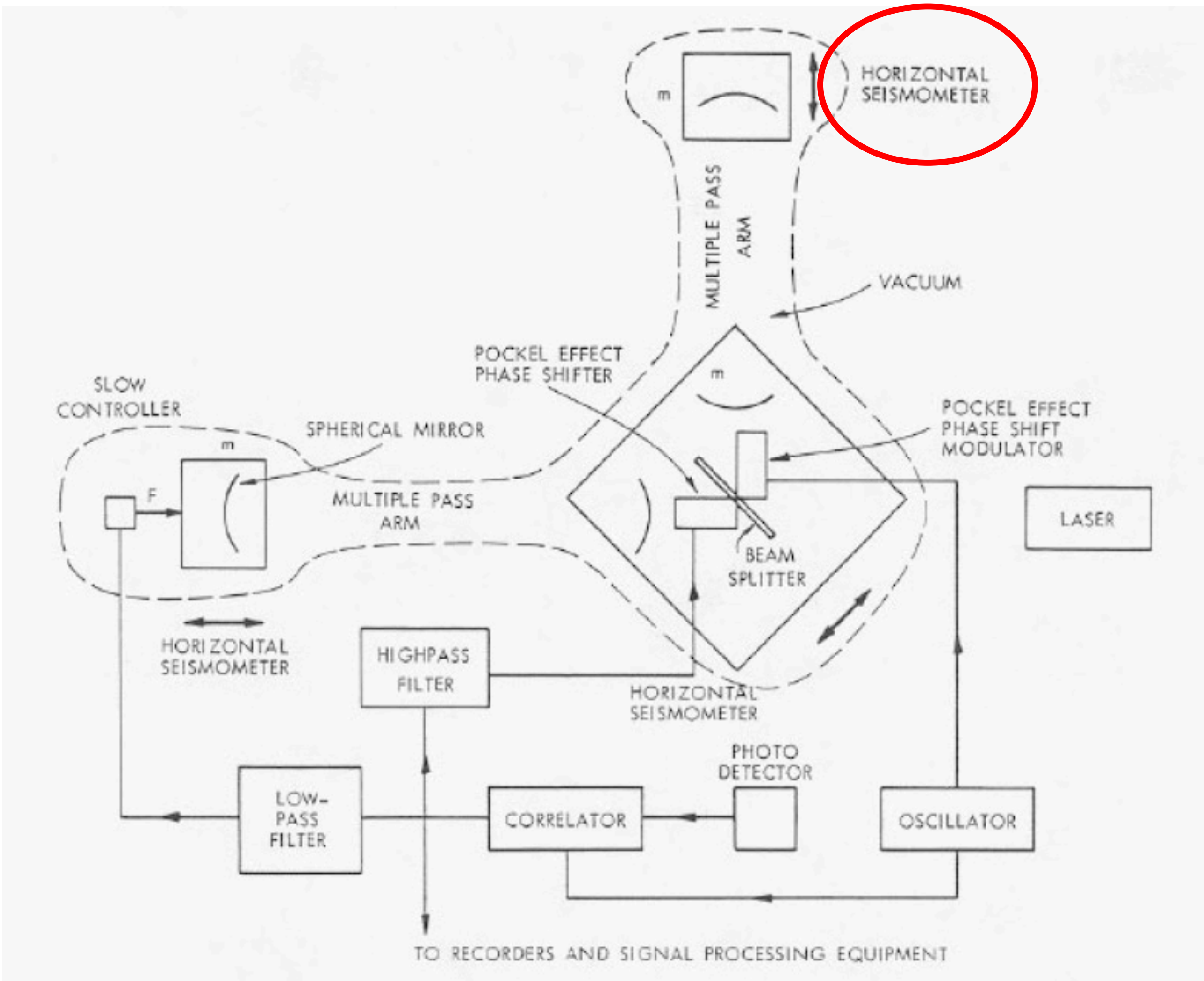


Fig. V-20. Proposed antenna.

LIGO

Thermal Noise

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 given as 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,…"

Thermal Noise

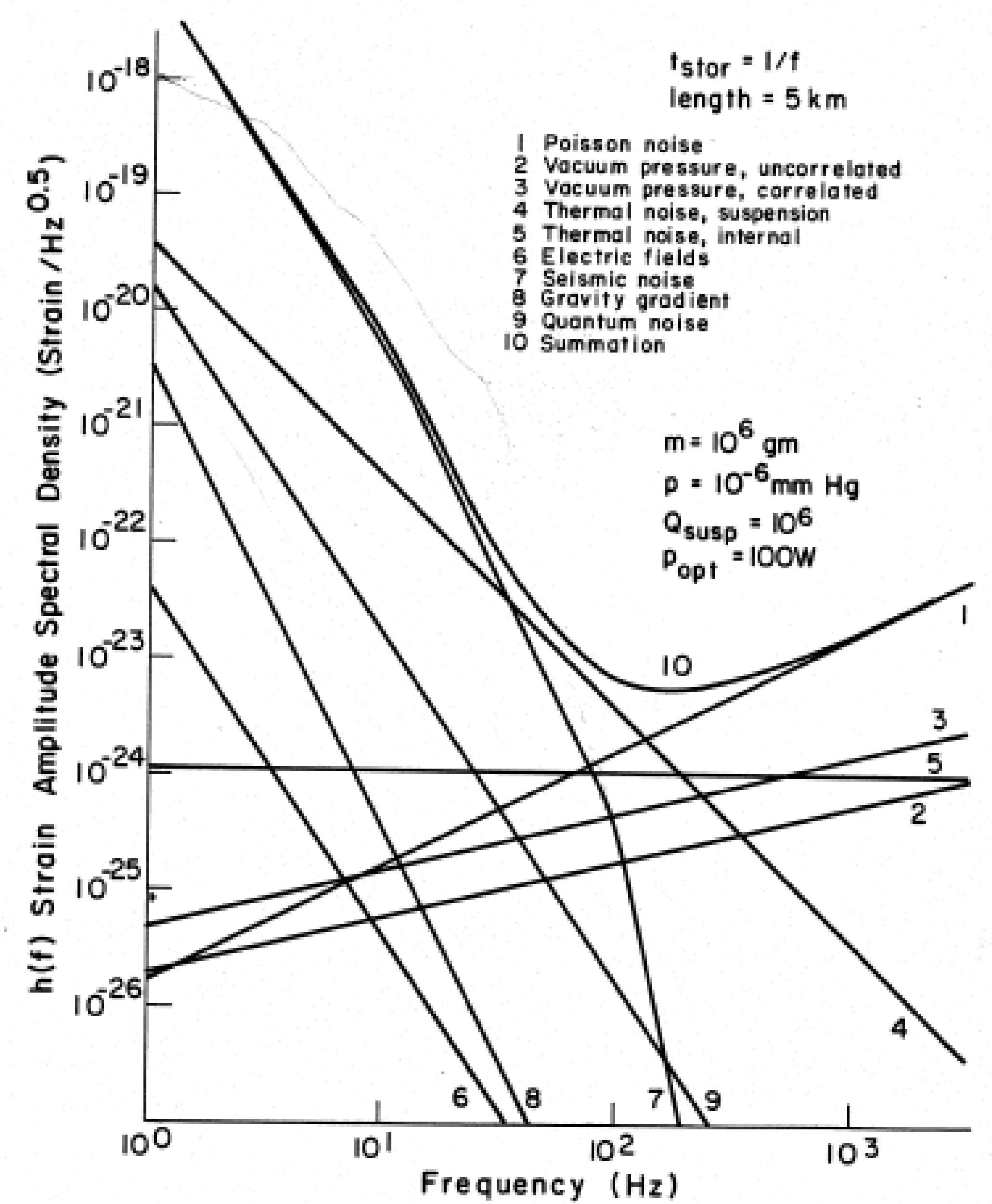
The "Blue Book"

- 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_{mat} given as $\sim 10^{4.}$ (actual $Q_{mat} \sim 10^{7}$)

Thermal Noise, cont

Blue Book

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



Thermal Noise, cont.

The ’89 proposal

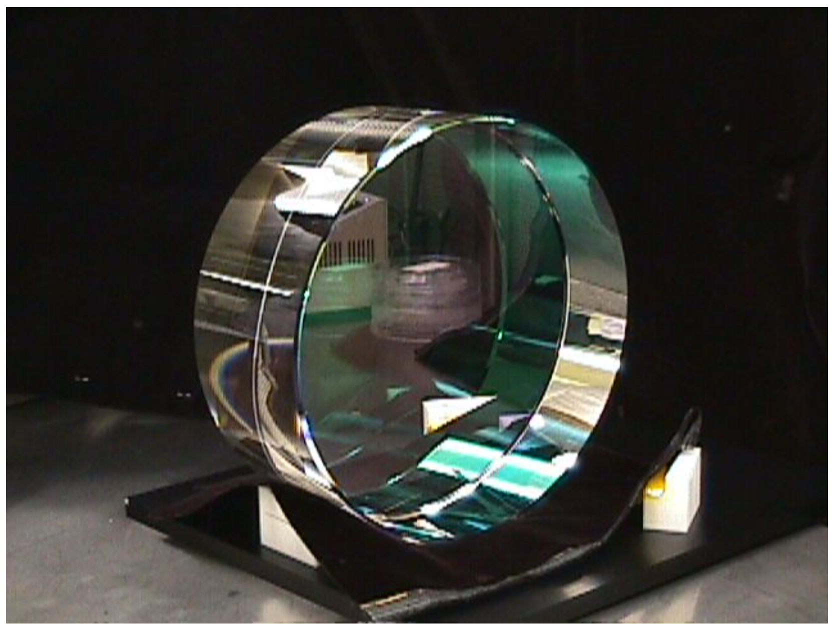
- First (?) mention of the Fluctuation-Dissipation Theorem (powerful theoretical tool)
  - Not really used, however
- Noise estimates still based on viscous damping, but
  - “…the damping can be frequency dependent so that a simple measurement of the Q of a resonance is not sufficient to predict the 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
  - "Thermal Noise in mechanical experiments," *Phys Rev* **D 42**, 2437 (1990)
  - 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 eventual initial LIGO requirement)

Mirror Figure Requirement, cont.

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

TABLE IV–B–3
PARAMETERS FOR MAIN OPTICAL CAVITIES

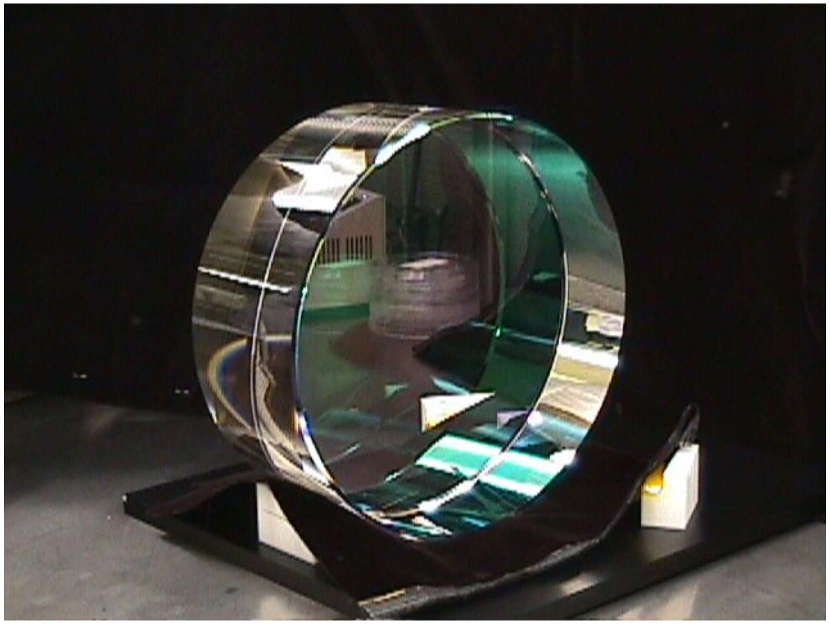
Parameter	Value	Notes[1]
Mirror Coatings		
Cavity storage time	2 msec	
Scattering + absorption	$\lesssim$ 50 ppm	
Surface microroughness	< 3 Å rms	for < 50 ppm scattering
Coating uniformity	$\lesssim$ 1.5%	rms variation of transmission coefficient over central 8 cm
Cavity length L	4.0 km	(2.0 km)
Mirror curvature R	3.0 km	(1.5 km)
Figure error	200 Å	rms over central 8 cm
Cavity stability parameter		
$g = 1 - \frac{L}{R}$	−0.33	(−0.33)

Mirror Figure Requirement, cont.

- 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 (Brett Bochner, Hiro Yamamoto, others)
- 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 (λ / 1600)
  - Radii of curvature matched < 3%
- Coating
  - Scatter < 50 ppm
  - Absorption < 2 ppm
  - Uniformity $<10^{-3}$



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

Mirror Orientation Noise

- Was a dominant source of noise in 40m prototype interferometer circa 1990
- Significant because (one of?) the first bi-linear noise mechanisms studied

Mirror Orientation Noise

- Not mentioned in RLE paper
- Mentioned, but not discussed as a serious noise source in Blue Book
  - » "These effects are only second order in the [angles.]"

$$\Delta d = -\,(R+D)^2\,\phi^2\left(\frac{1}{r} + \frac{1}{2(R+D)}\right)$$

- Not discussed in detail in '89 Proposal, but requirements indicate that it is still dismissed as second order

TABLE IV–B–6
STABILITY OF CAVITY BEAMS AND TEST MASSES

Parameter	Value	Notes
Test-mass stability		
Angular stability	$< 4 \cdot 10^{-7}$ rad	Peak motion at low frequency
Position stability	$\lesssim 0.7$ mm	Peak motion at low frequency
Beam stability		
Angular fluctuations	$< 10^{-12}$ rad/$\sqrt{\text{Hz}}$	$f \approx 1$ kHz
Position stability	$\lesssim 0.7$ mm	Peak motion at low frequency

Mirror Orientation Noise, first clue

- 1990: 40 m prototype interferometer noise was high, not understood
  - » LIGO construction proposal under review, and it was important for the prototypes to show steady progress on sensitivity
  - » Seiji Kawamura began investigations of orientation control systems, eventually engaged Mike Zucker
  - » Injection of dither peaks (to measure noise coupling) showed huge sidebands in addition to the expected peak—sideband structure mirrored low frequency orientation noise

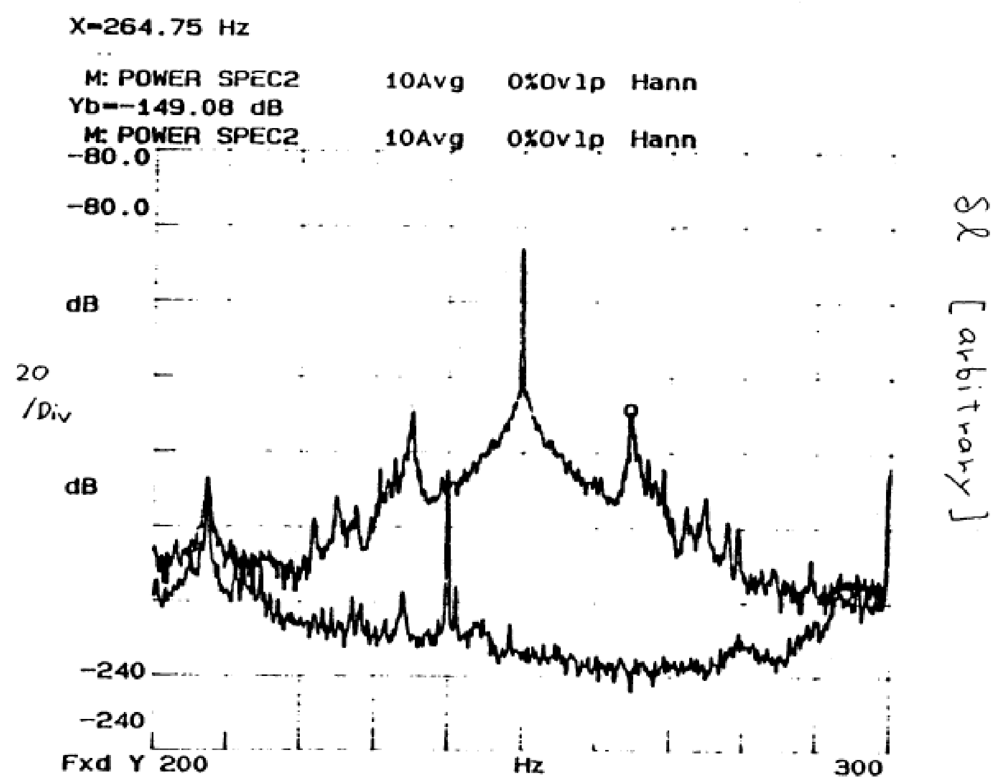


Fig. 3 Displacement spectrum.
Upper : with angle variations at 250 Hz
Lower : natural

Mirror Orientation Noise, continued

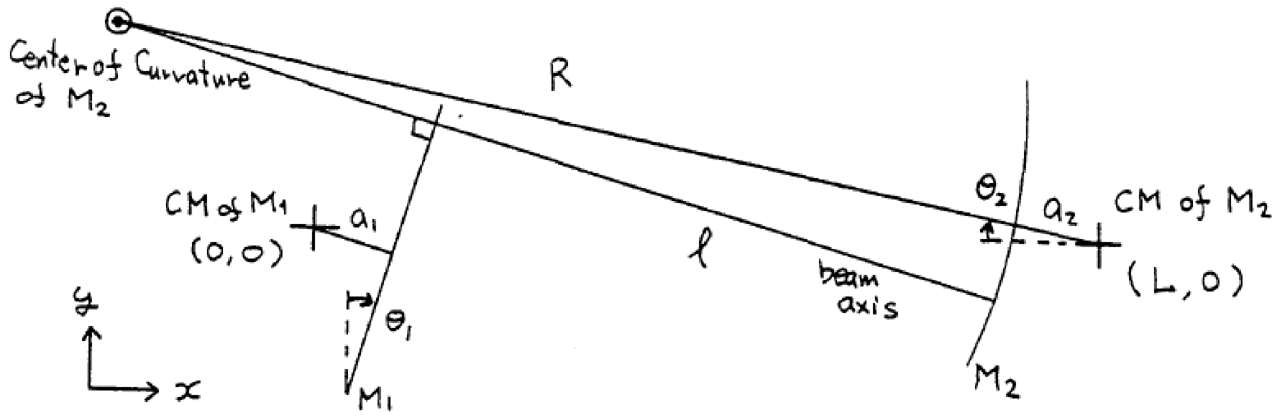


Fig. 1 Arm cavity of the 40m prototype

- Worked out the geometrical length of a misaligned cavity
- First interpretation was in terms of a static misalignment (displacement of the cavity spot from the center of rotation)

Evolution of Understanding

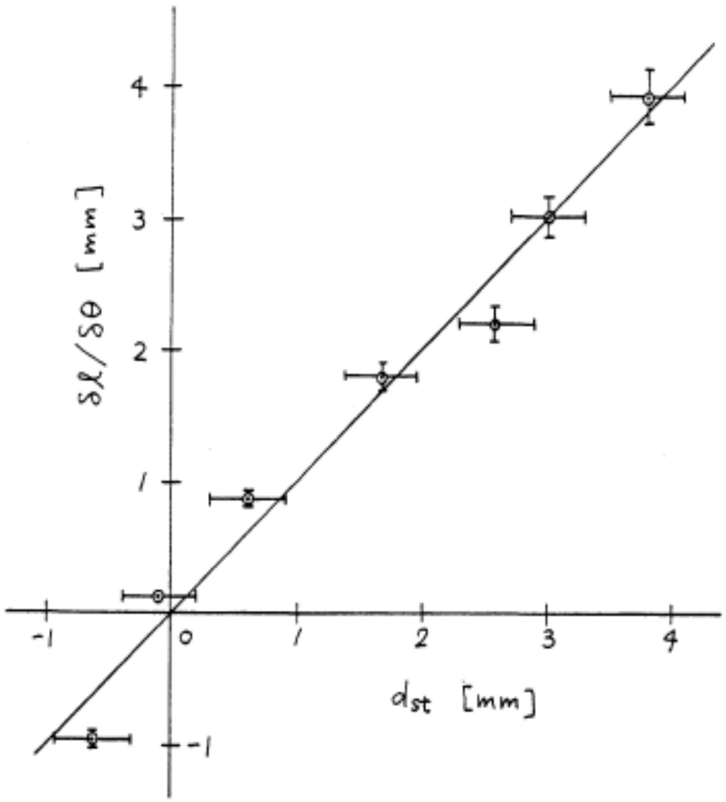
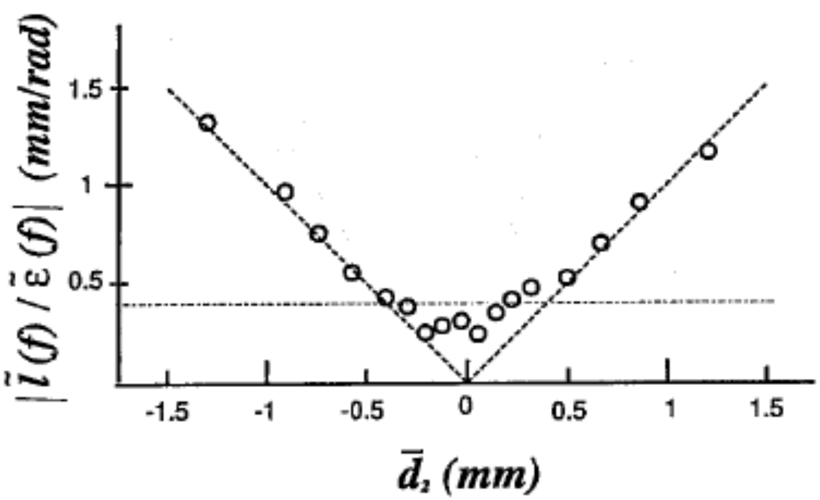


Fig. 2 Linear effect of mirror angle – displacement coupling as a function of static beam spot position. The solid line is $\delta\ell/\delta\theta = d_{st}$

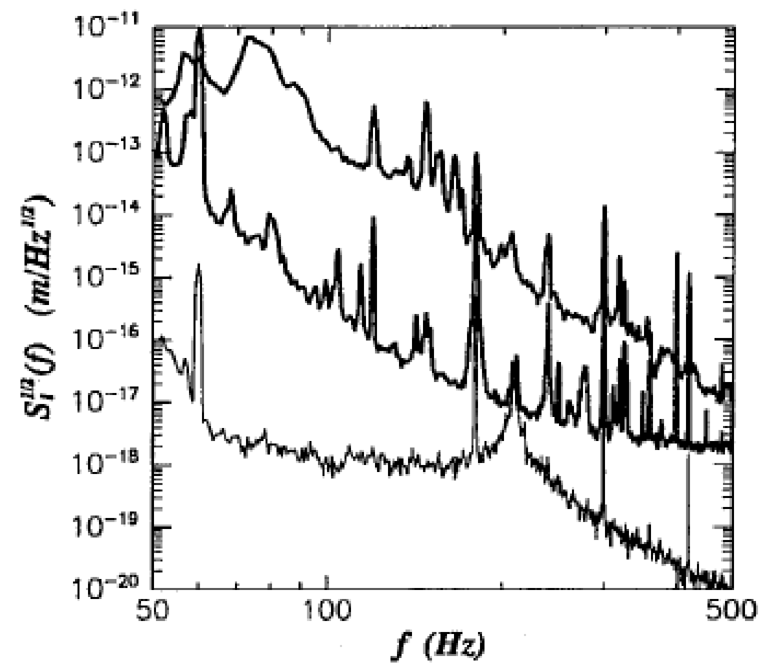
Important recognition was that the large amplitude low frequency mixes with in-band angular noise to create displacement noise



Improved 40 m performance

- Improved noise in 40 m at a critical time
  - » Published as "Mirror-orientation noise in a Fabry-Perot interferometer gravitational wave detector," S. Kawamura and M Zucker, *Applied Optics*, **33**, 3912 (1994).
  - » Obvious once it is pointed out, but under-appreciated (in my view)

- Opened many people's eyes to the large class of bi-linear noise sources



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.)

Extra Slides