LIGO

A View of & from the Bulldozers

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Caltech

May 9, 1996

LIGO
Introduction

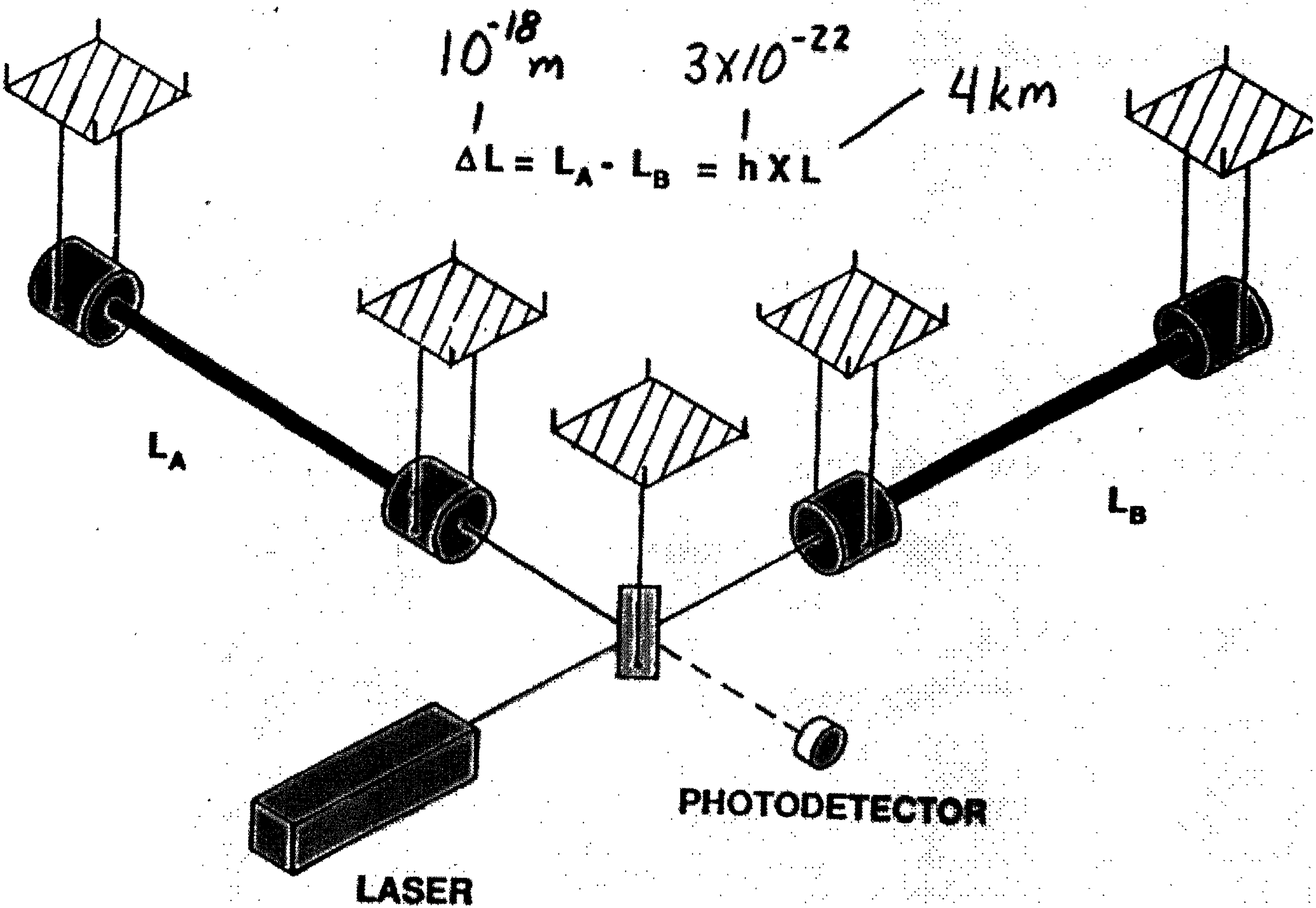
- Laser Interferometer Gravitational Wave Observatory
  - » **DIRECT** Detection of Gravitational Waves
- Joint Caltech/MIT Project funded by the National Science Foundation
- Under Construction
  - » Two Sites -- Louisiana and Washington

LIGO
Perspectives

- Views of LIGO

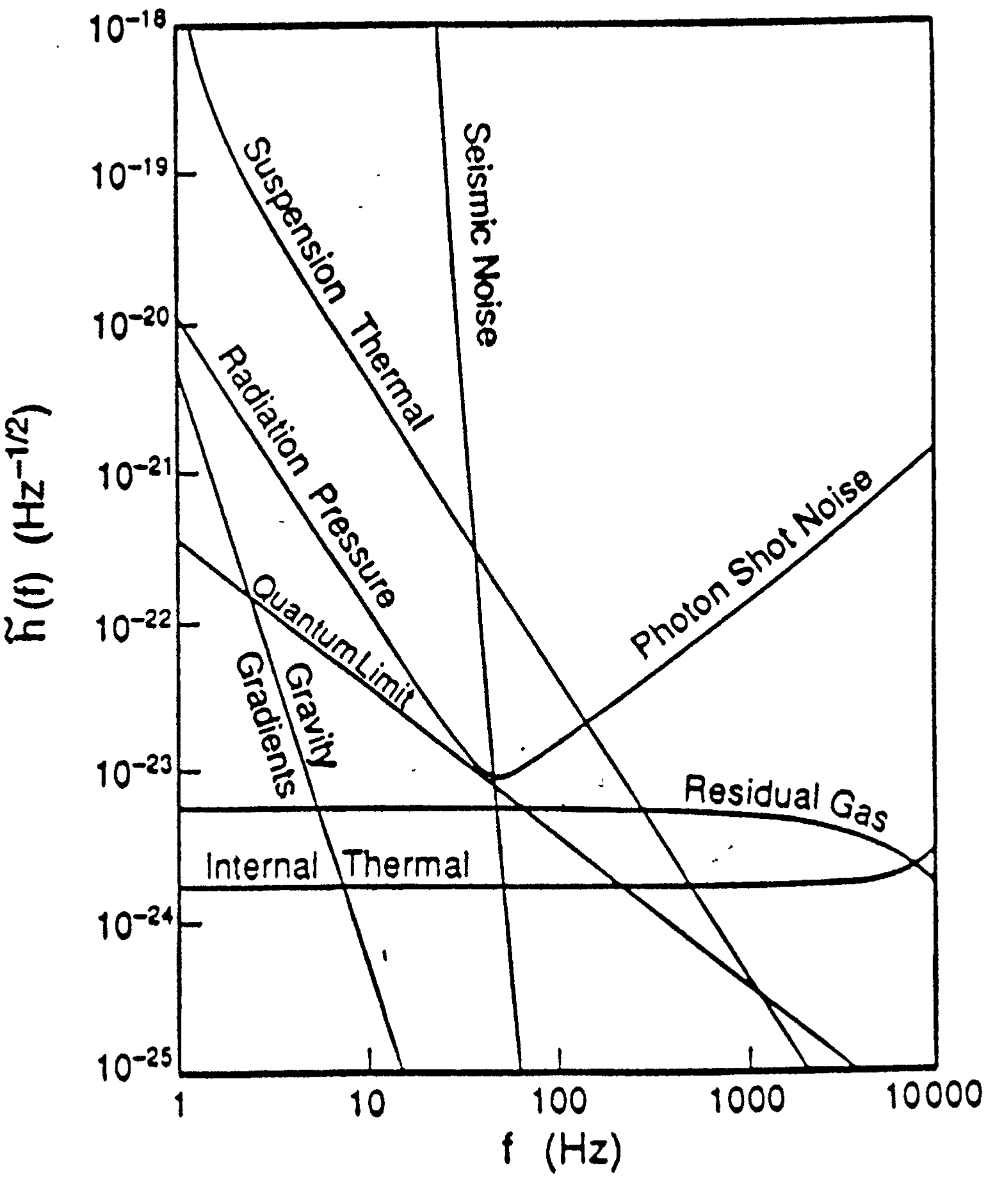
1975-85	Drever	The Concept
1989	Vogt	The Project
1992	Raab	Noise
1994	Thorne	Sources
1996	Barish	Bulldozers
1998	?	Detectors
2000	?	'First Light'
2002	?	Initial Data

SCHEMATIC INTERFEROMETRIC DETECTOR



Noise Budget For First LIGO Detectors

- 5 Watt Laser
- Mirror Losses 50 ppm
- Recycling Factor of 30
- 10 kg Test Masses
- Suspension $Q=10^7$



LIGO

Gravitational Wave Strength

Strain Sensitivity

$$h \approx \frac{G(E_{kin}^{ns}/c^2)}{r}\frac{1}{c^2}$$

for $E_{kin}^{ns}/c^2 \sim M_\Theta$

$h \sim 10^{-20}$ for Virgo Cluster of Galaxies

$h \sim 10^{-23}$ at Hubble Distance

LIGO Goal: $h \sim 10^{-22}$

Detector $\Delta L = hL$

$L = 4km \Rightarrow \Delta L = 10^{-16} cm$

This leads to Stringent Specifications:

Vacuum

Seismic and Acoustic Isolation

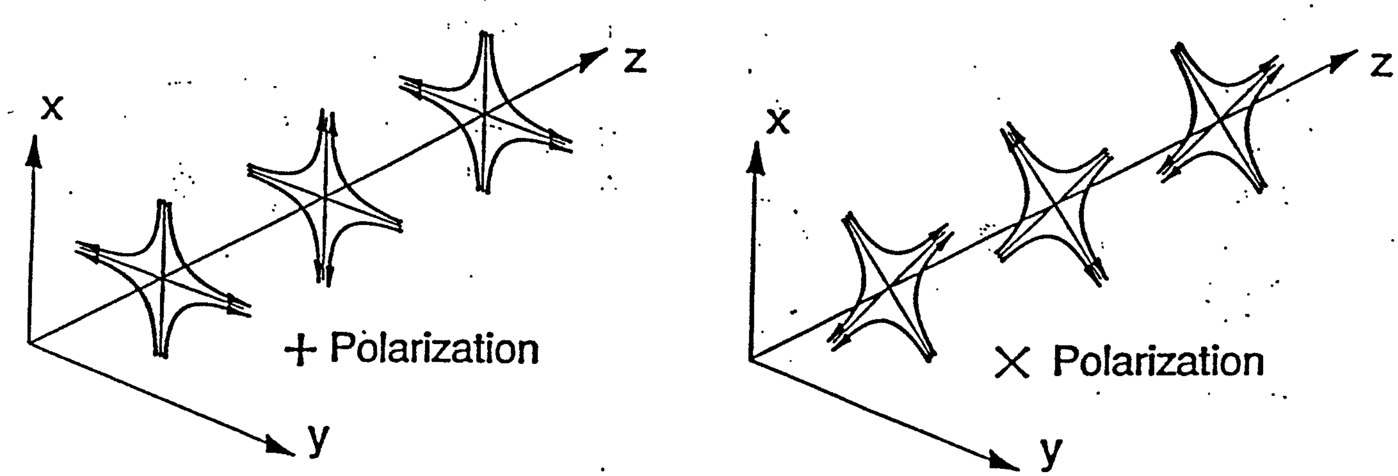
Test Mass Suspensions

Optics

etc.

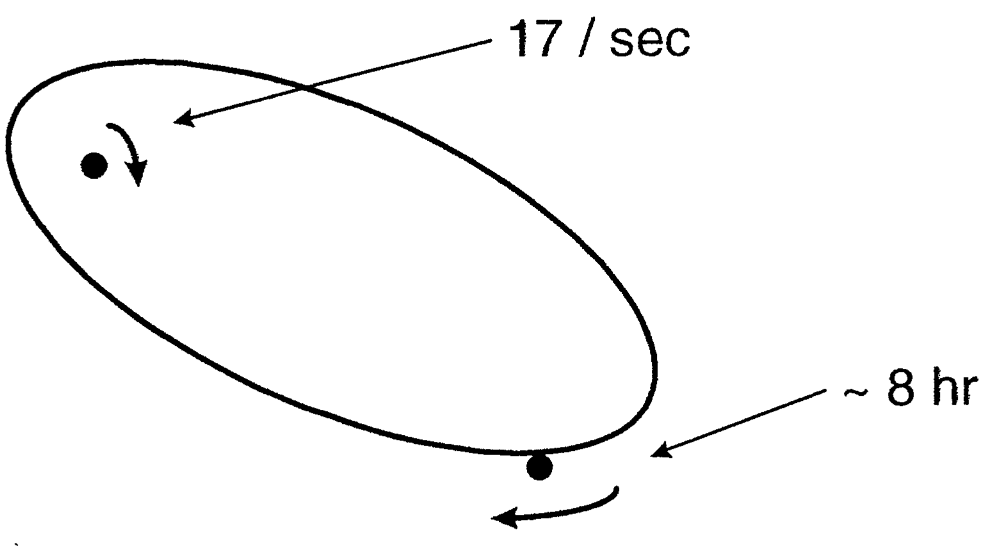
Gravitational Waves
General Relativity

- Non-spherically symmetric accelerations of mass
- main term - time dependence of quadrupole moment
  - » binary systems always radiate
  - » non-sherically symmetric supernova collapse
- types of waves
  - » bursts, periodic or quasi-periodic waves
  - » stochastic background from compact binaries, primordial waves and cosmic strings or phase transitions



Gravitational Waves
Evidence

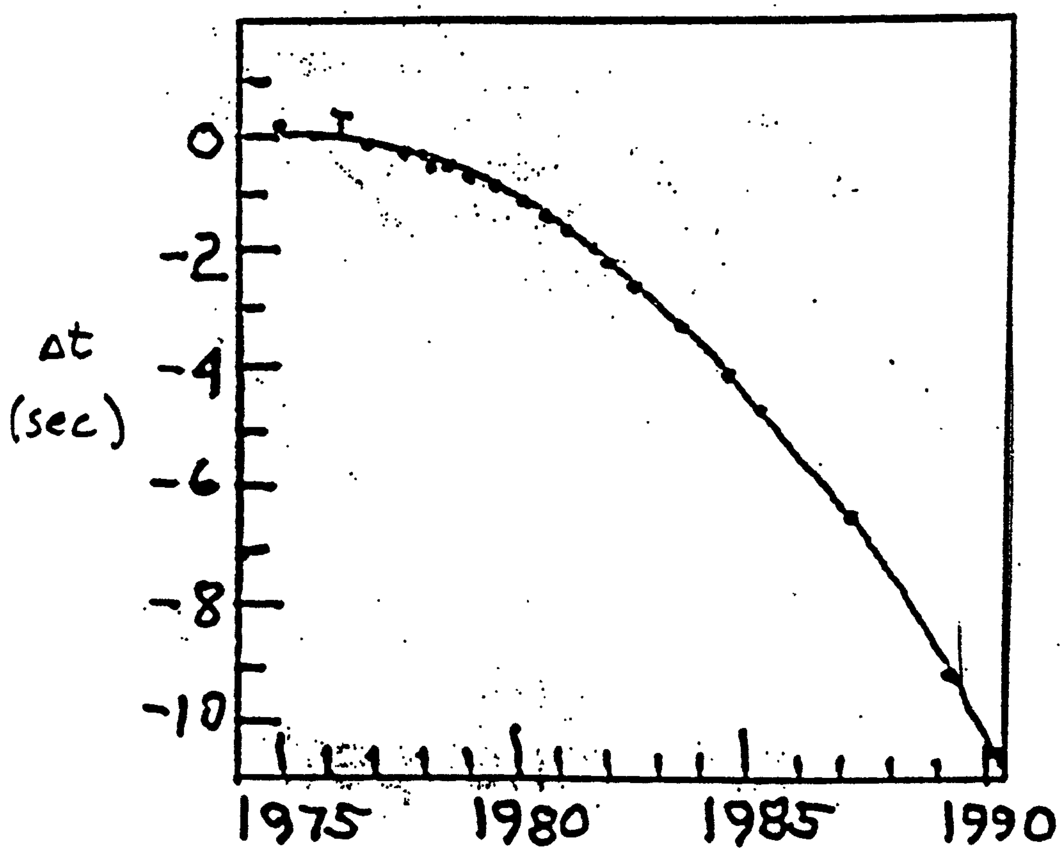
- **Russell Hulse and Joseph Taylor**
- Neutron Binary System
  - » PSR 1913 + 16 -- Timing of Pulsars



Hulse and Taylor

Timing of Orbit

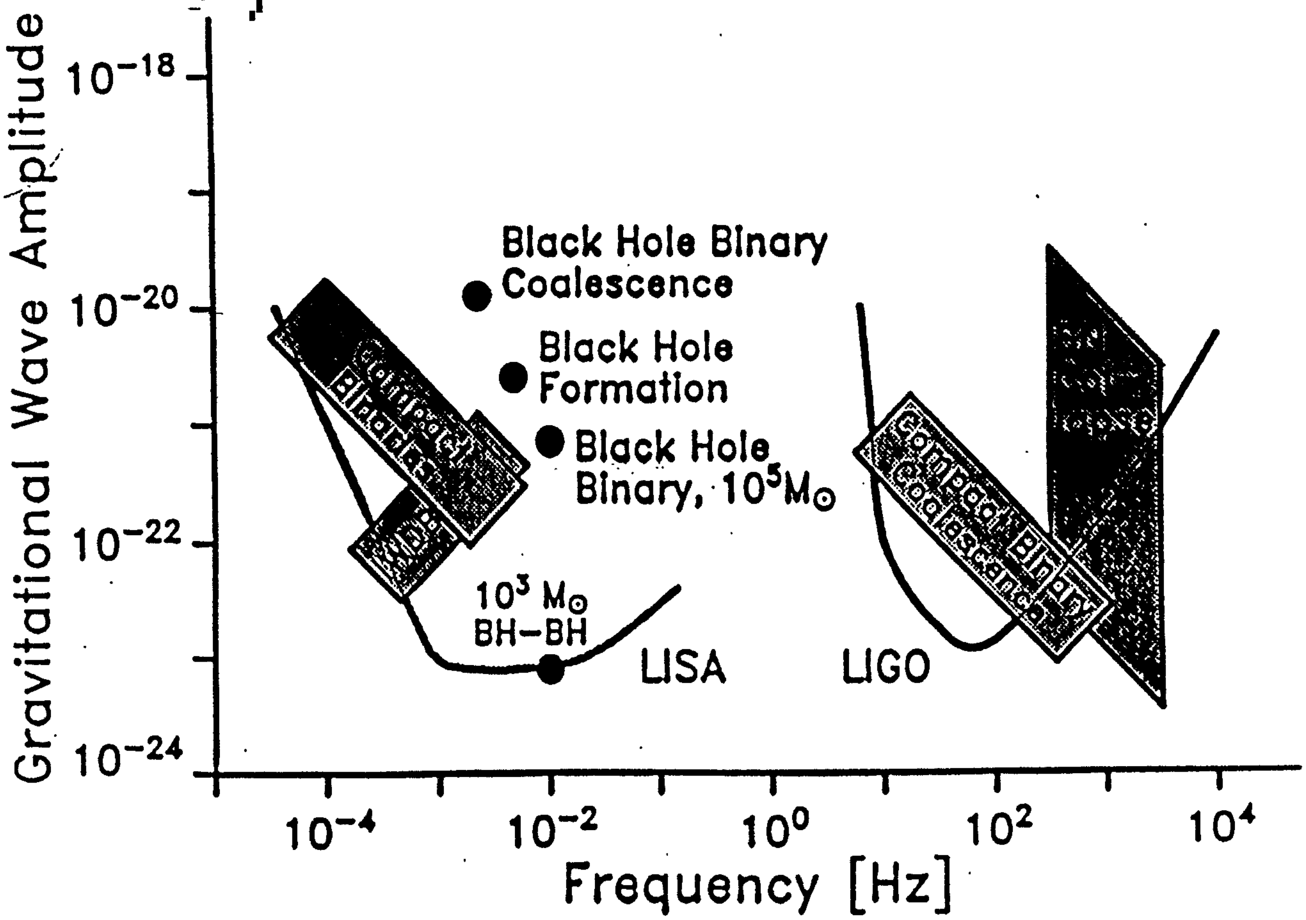
- Speed up 10 sec in 15 years
  - » measured to ~50 µsec accuracy
- Deviation grows quadratically in time



- Due to loss of orbital energy, from emission of gravitational waves

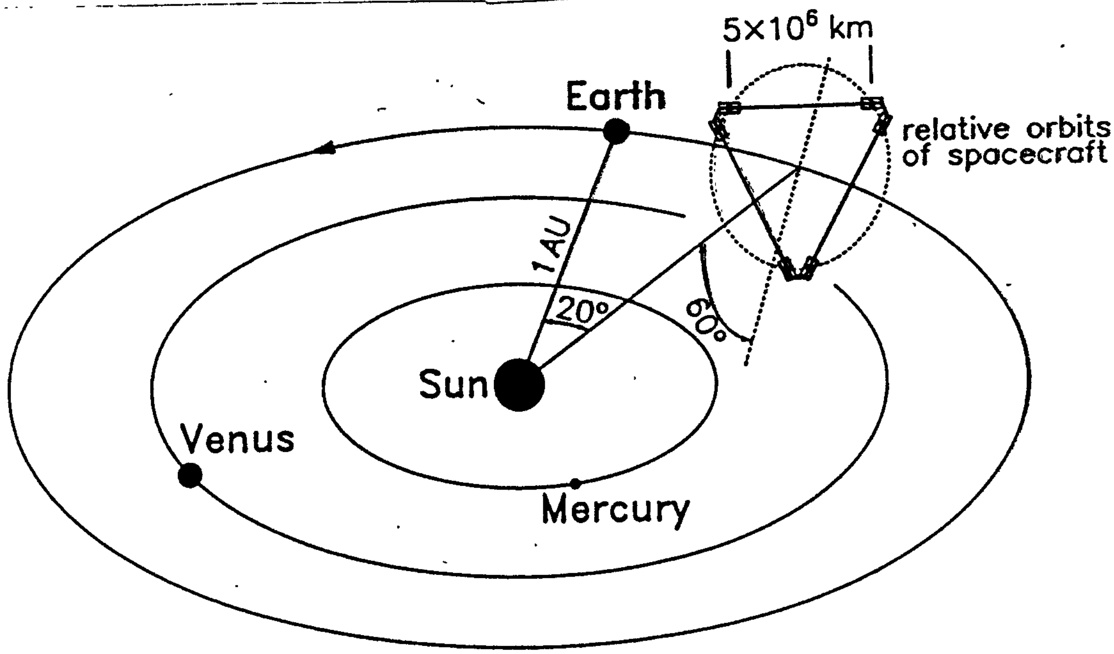
Astrophysical Sources
Frequency Range

- Electromagnetic Waves - ~ 20 orders of magnnitude (ULF radio -> HE γ rays)
- Gravitational Waves - ~ 10 orders of magnitude
- Combination of terrestrial and space experiments



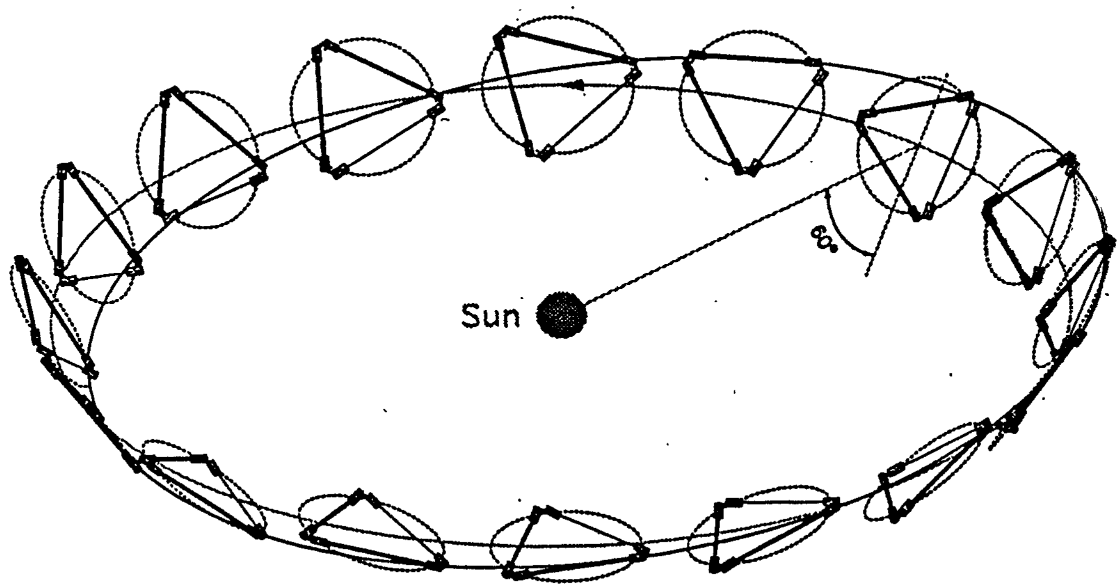
Gravitational Waves
Space Experiment

- LISA - Laser Interferometer Space Antenna
  - » six spacecraft in triangle (four needed)
  - » pair at each vertex



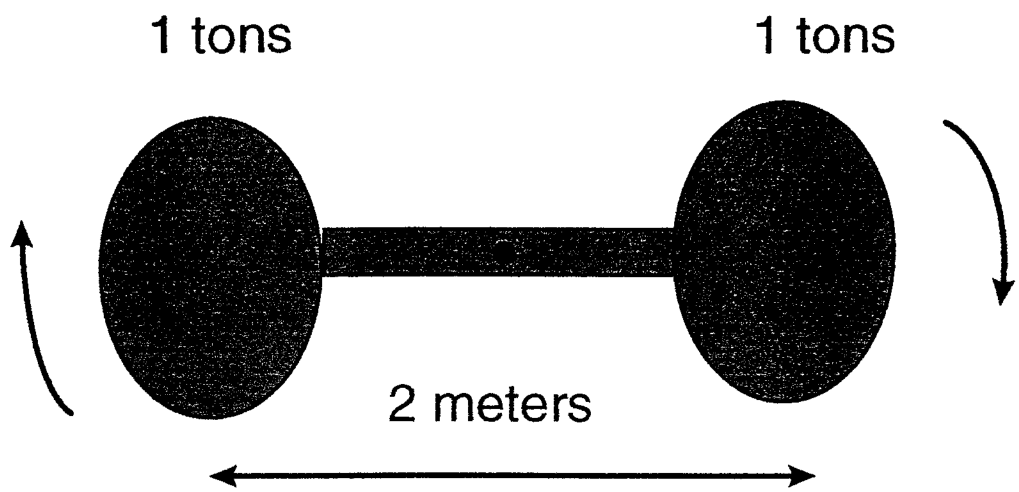
LISA
Annual Revolution

- 60 degree half opening angle
- 'tumbling' allows determination of position of source and polarization of wave



Laboratory Experiment
(a la Hertz)

Laboratory Dumbbell System



f_{rot} = 1 kHz

h_{lab} = 2.6 10^{-33} m x 1/R

R = detector distance (> 1 wavelength) = 300 km

h_{lab} = 9 10^{-39}

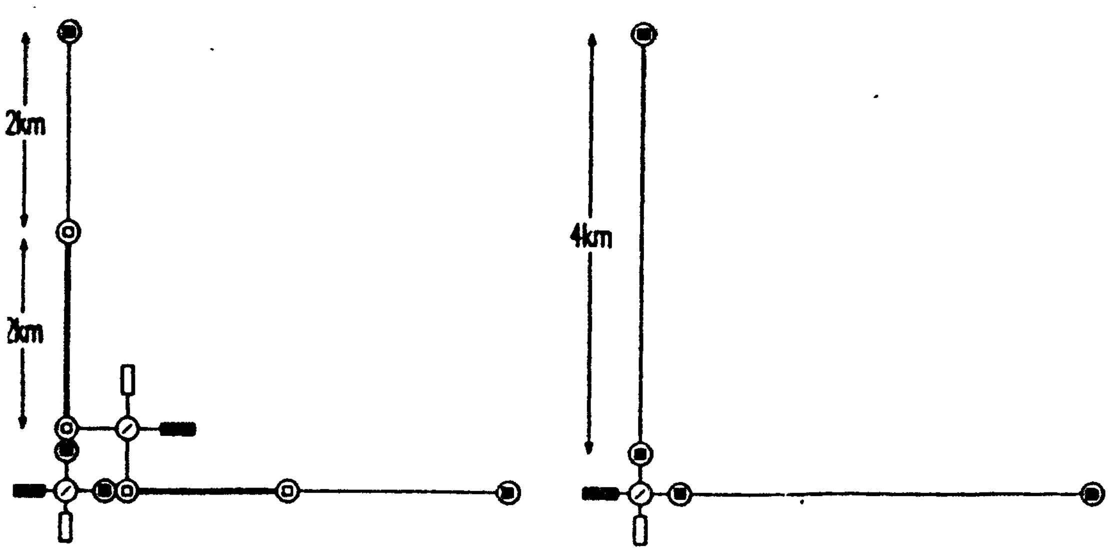
This is too weak by about 16 orders of magnitude!

Gravitational Waves
International Effort

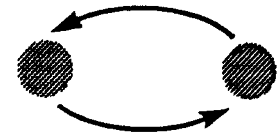
- Techniques
  - » Resonant Bar Detectors (LSU, Rome, etc)
    - – narrow band
  - » Large Scale Interferometers
    - – broad band
- International Interferometer Effort
  - » U.S. -- LIGO (Two Sites)
    - – Caltech & MIT (Wash and Louisiana)
  - » Europe -- VIRGO (One Site)
    - – French and Italian (near Pisa)
  - » Smaller efforts
    - – Germany, Japan, Australia
- Time Scale (Interferometers)
  - » Approximately year 2000

Description of LIGO

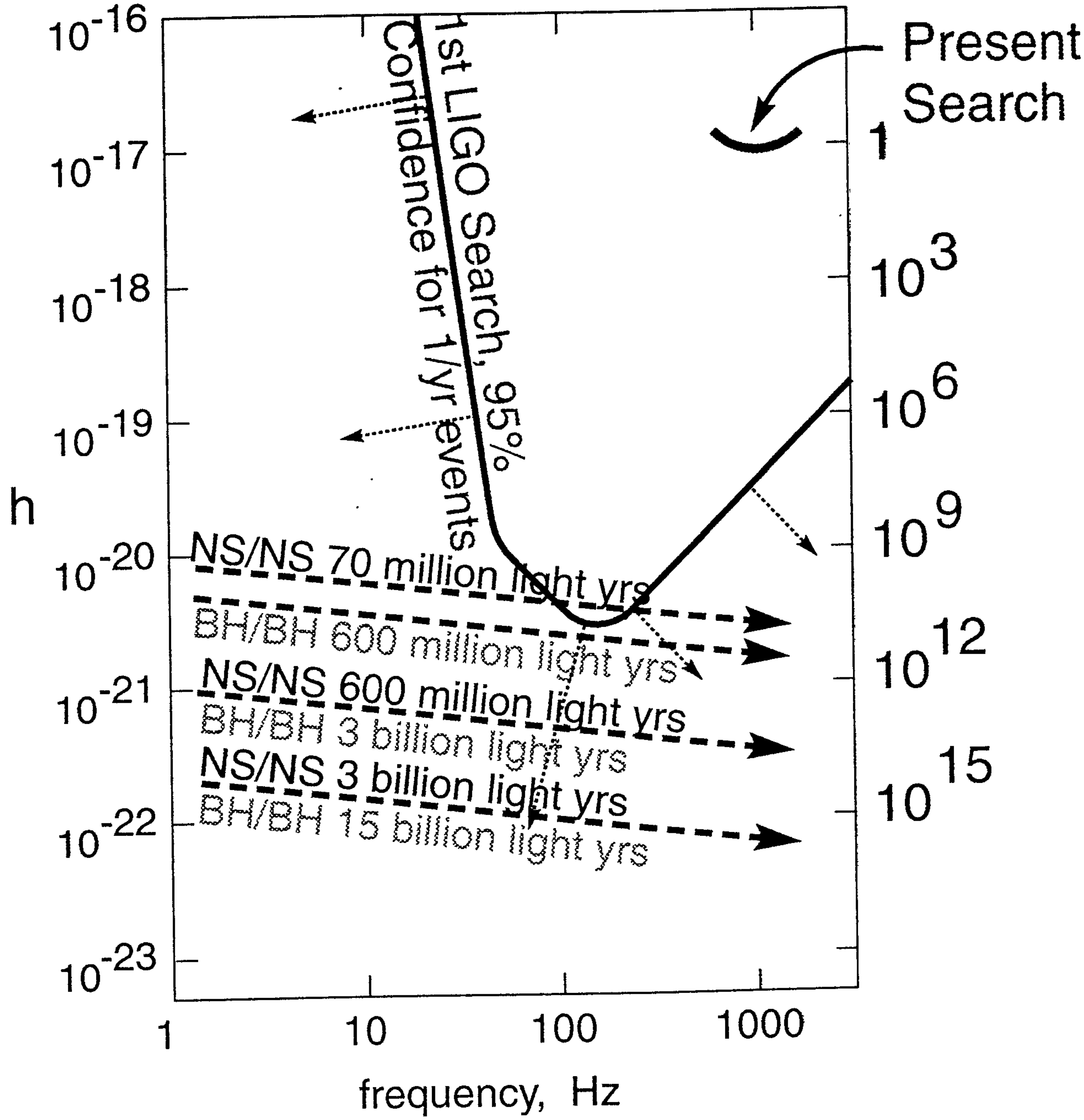
- Two Sites - Widely Separated
- Hanford, Washington
  - 4km and 2km Interferometers
- Livingston, Louisiana
  - 4 km Interferometer
- Expansion for Advanced Detectors



NEUTRON STAR BINARIES



["Near-Guaranteed" source]



- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

LIGO
Scientific Mission

- Direct Detection of Gravitational Waves
  - Benchmark Source: Neutron Binary Coalescence
    - Detect the last 15 minutes of Hulse/Taylor type binary system (eg. 100 million years)
    - Sensitivity -- detection rate >3 year
  - Other Sources

- Fundamental Physics (GR)
  - » Test General Relativity in Strong Field and High Velocity Limit
  - » Measure Polarization and Propagation Speed

Neutron Star Binary Coalescence

Method	*Our Galaxy*	*Distance for 3/yr*
Progenitor Death Rate	~1/1000 yr	130 M.L.yr
Binary Pulsar Searches and Discoveries	~1/$10^{5\pm1}$ yr	600 M.L.yr.
Ultra-conservtive Limit from Binary Pulsar Searches	~1/10^{7} yr	3000 M.L.yr

LIGO

Long Range Goals

- Final Coalescence of Binary Systems
  - » Neutron Star/Neutron Star
    - – Design Benchmark: last 15 min, 20,000 cycles, 600 MLyr
  - » Black-hole/Black-hole
  - » Black-hole/Neutron Star

- Supernovae
  - » Axisymmetric in our galaxy
  - » Non-axisymmetric ~300MLyr

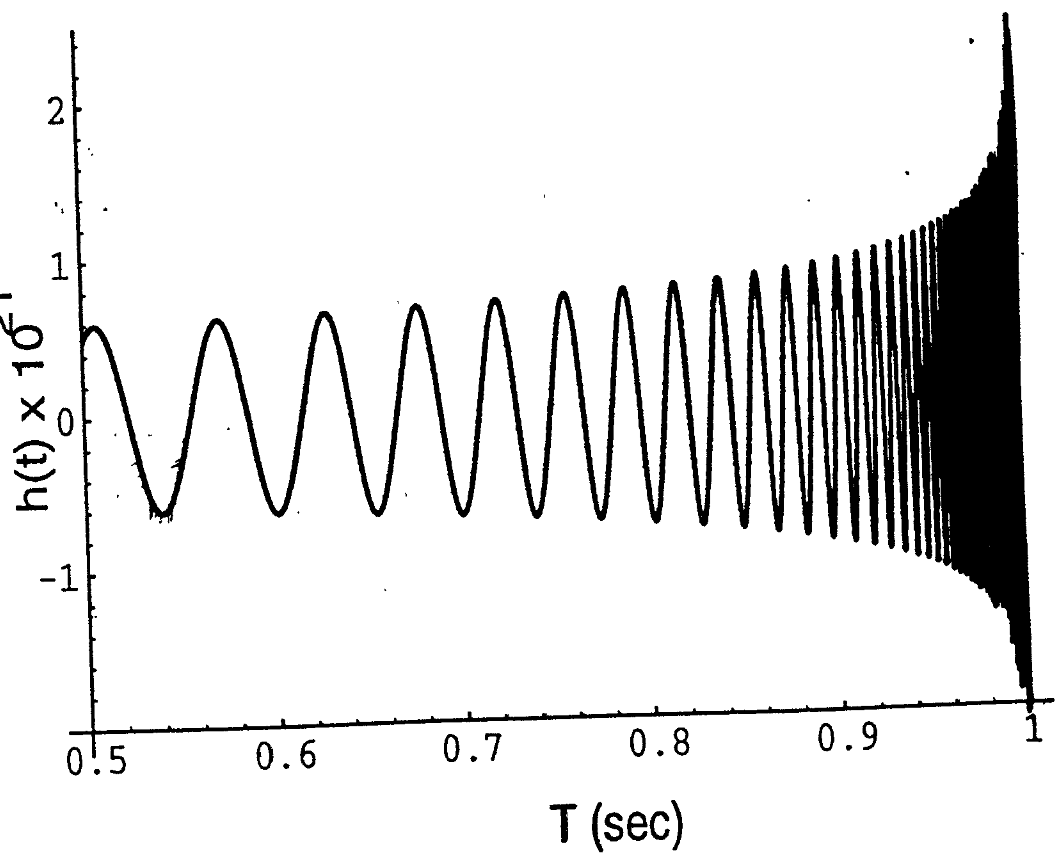
- Early Universe
  - » Vibrating Cosmic Strings
  - » Vacuum Phase Transitions
  - » Vacuum Fluctuations from Planck Era

- Unknown Sources

Neutron Binary Systems

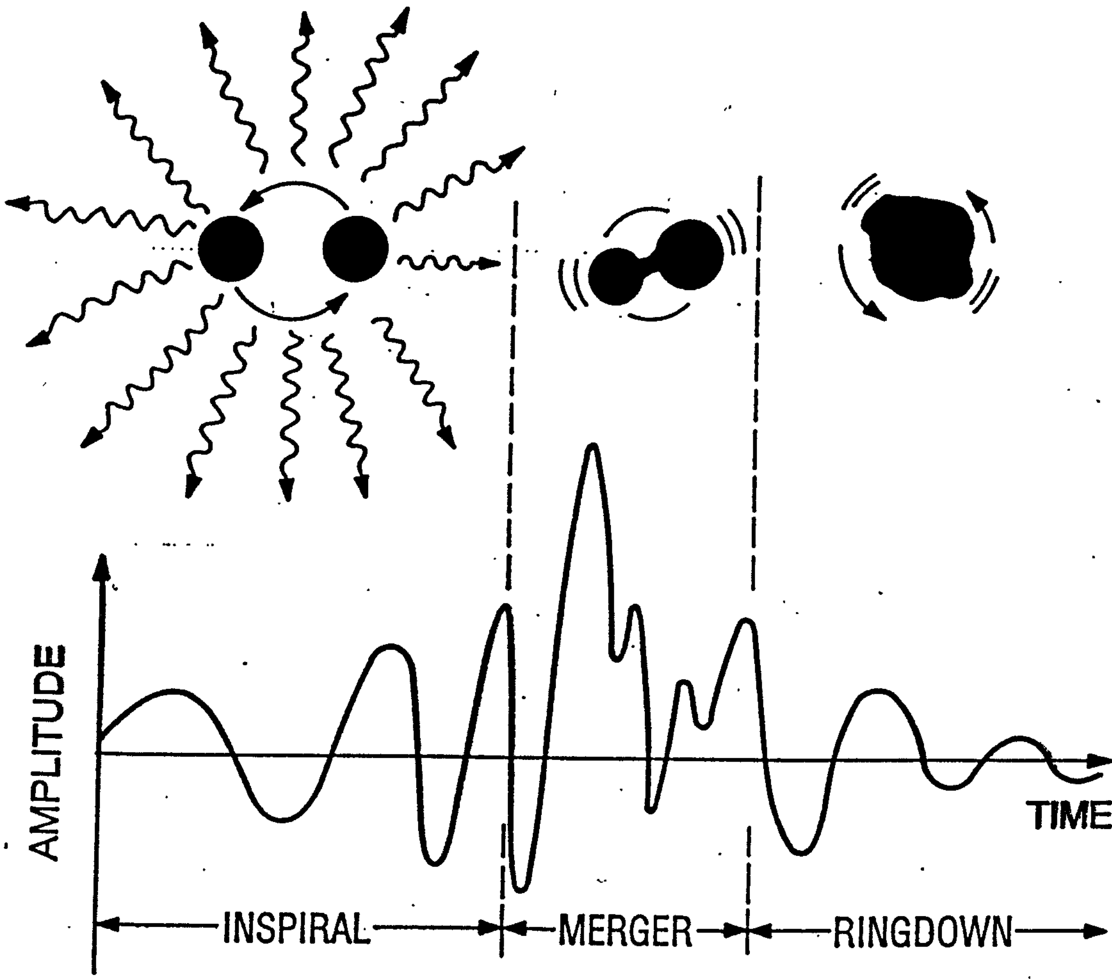
Inspiral

- LIGO frequency band
  - » last 15 minutes (~10^4 cycles)
- 'Chirp Signal'
- Detailed waveform gives masses, spins, distance, eccentricity of orbit, etc



Binary Sources

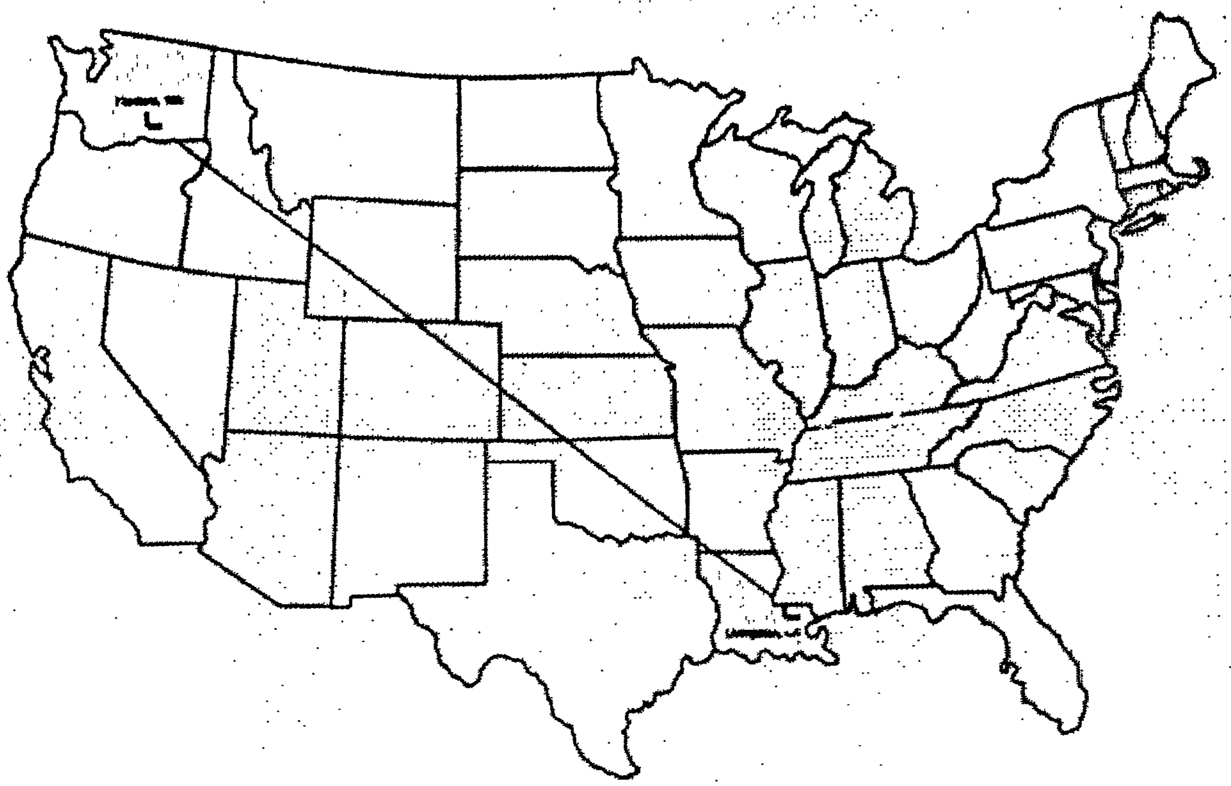
Inspiral and Coalescence



LIGO

LIGO-G960108-00-M

LIGO Site Pair



- Hanford, Washington
  - Located on U.S. Dept. of Energy Reservation
  - Treeless, Semi-arid Desert
  - Approx. 25 km from Richland (Metropolitan Pop. 140,000)

- Livingston, Louisiana
  - Located in Forested Rural Area
  - Approx. 50 km from Baton Rouge (Pop. 450,000)

BB
CGM

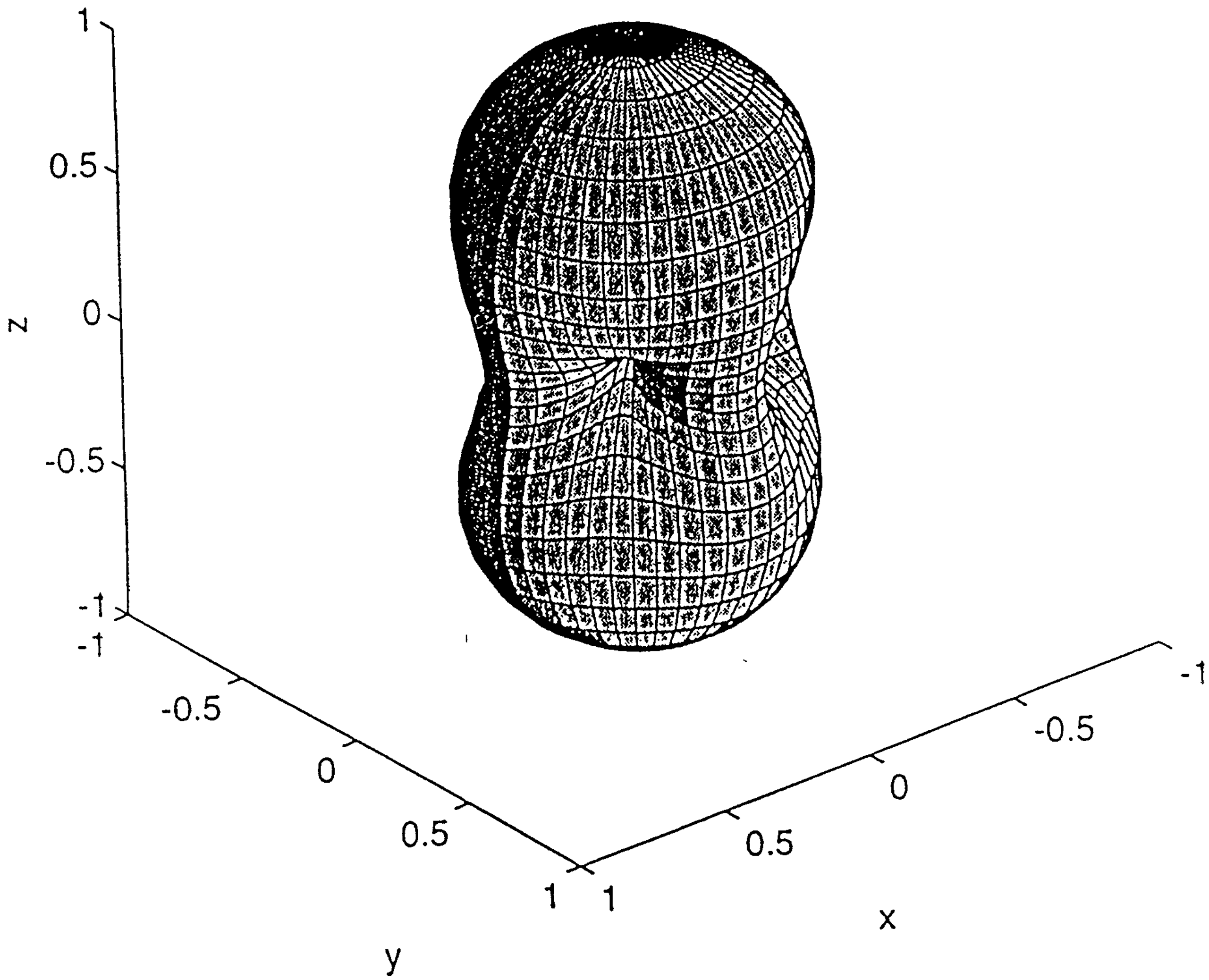
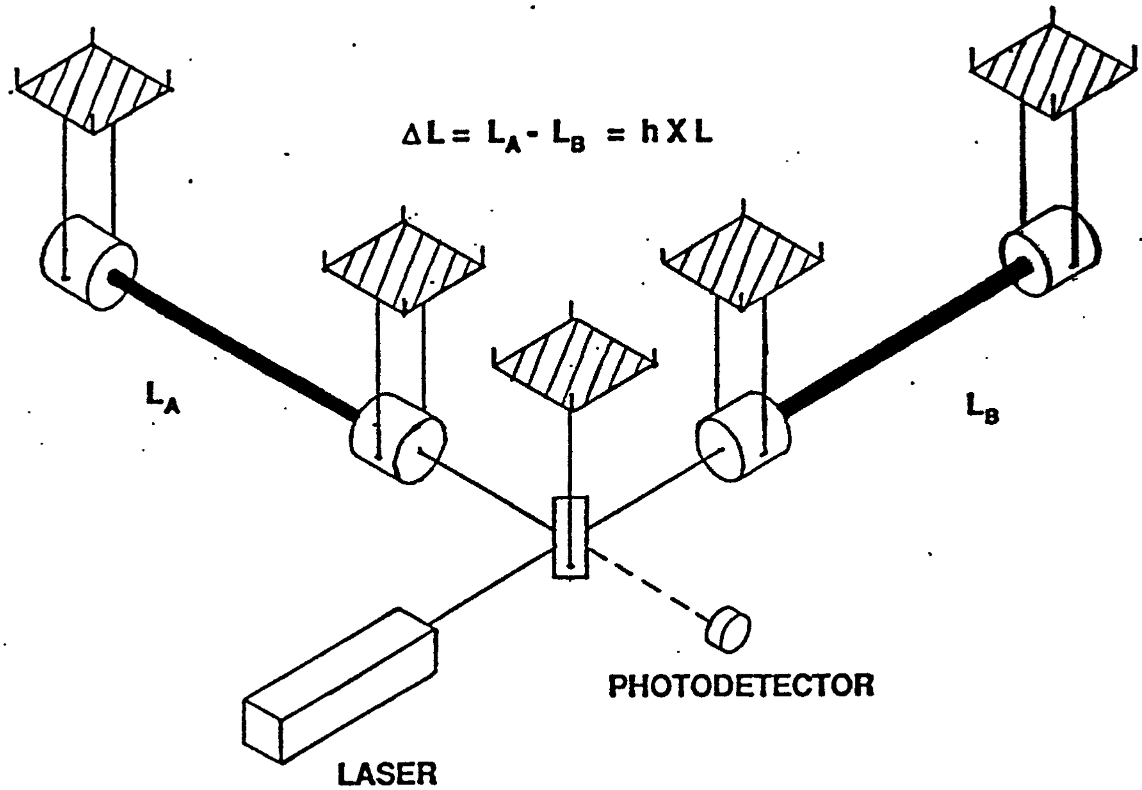


Figure 2.7 The sensitivity, as a function of direction, of an interferometric gravitational wave detector to unpolarized gravitational waves. The interferometer arms are oriented along the x and y axes.

Interferometers

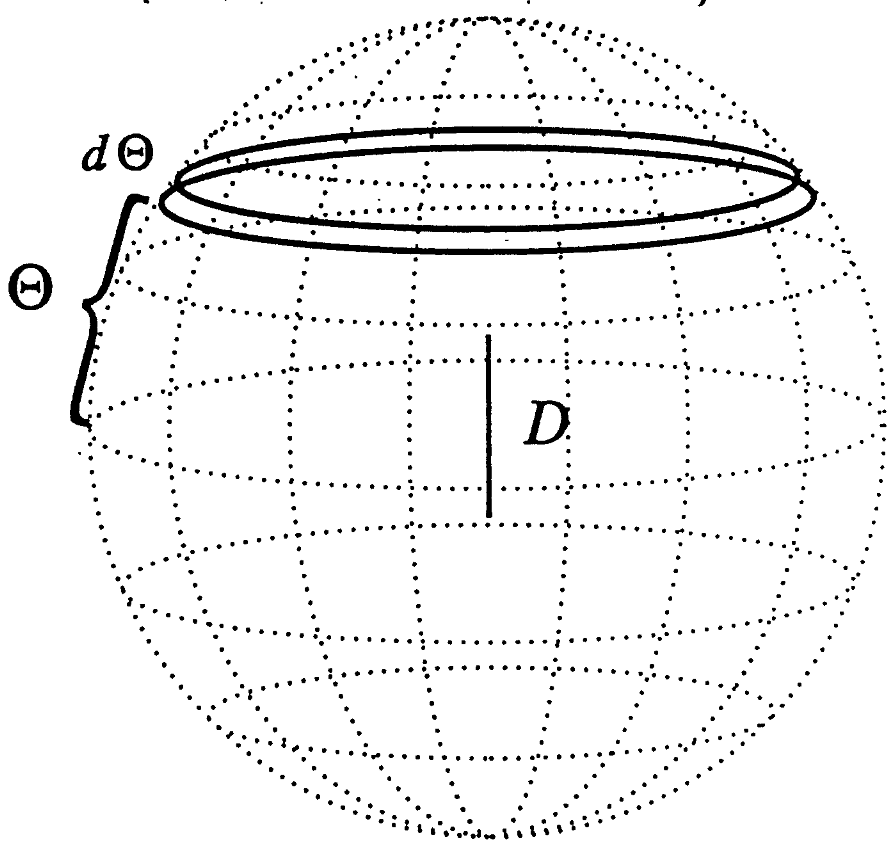
- $\Delta L/L = h = F_+ h_+(t) + F_x h_x(t)$



- LIGO Measures ***one*** waveform
  - » orientation aligned (Washington & Louisiana)
  - » direction(timing) determined ~10' to ~ 1^0 on ring
- LIGO + VIRGO(Italy)
  - » decompose waveforms $(h_+(t), h_x(t))$
  - » direction 10' to 1^0

Source Positions

- Celestial Sphere position location from LIGO (two interferometers)

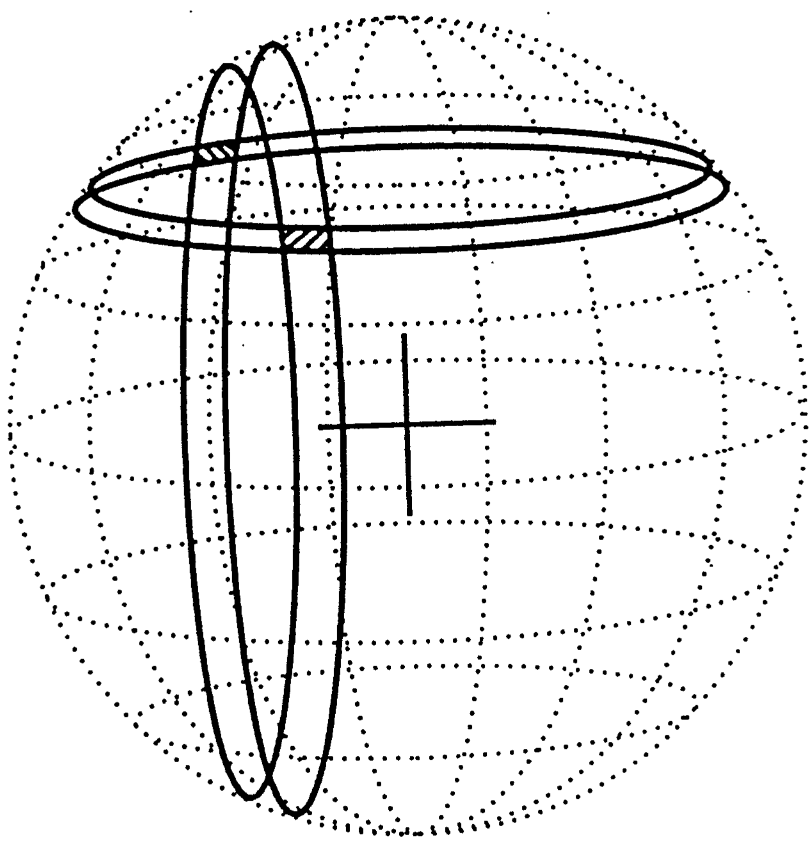


- determine from time shift between detectors (~.1 msec accuracy)
- 'declination angle' of circle (ring)

$$\Theta = \arcsin \frac{c\Delta t_{sig}}{D}$$

Source Positions
LIGO + VIRGO

- LIGO (2 det) + VIRGO (1 det)
- decomposition of waveforms
  - » $h_x(t)$, $h_+(t)$
- position on sky (two positions)



Gravitational Wave
Forces

IF

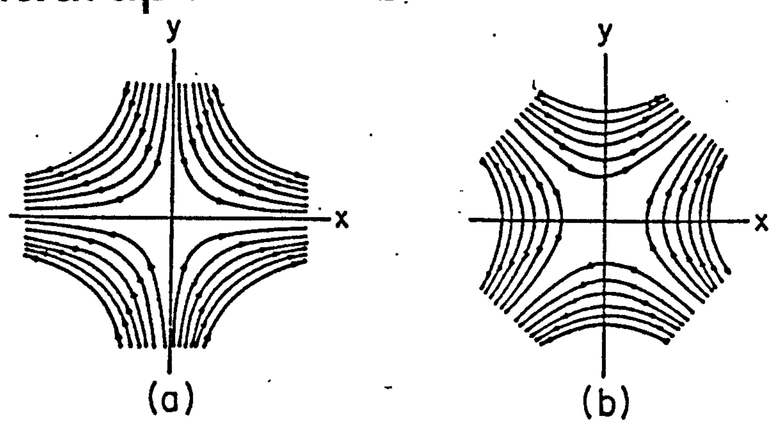
- Detector Size << Wavelength

  (4 km) (300-30,000km)

  (10 kHz - 10 Hz LIGO)

THEN

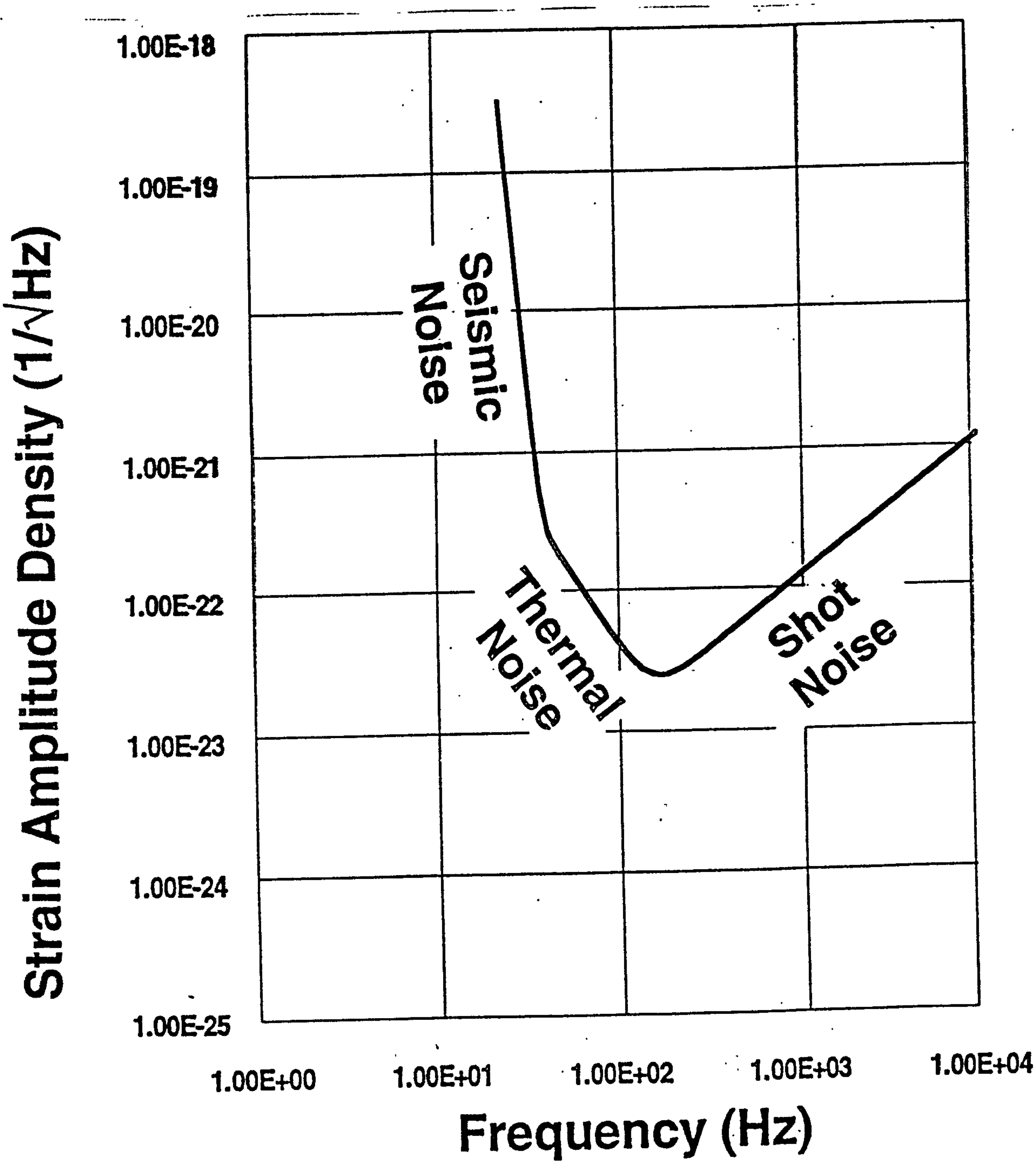
- Free Masses
- Quadrupolar Lines of Force



+ Polarization x Polarization

Initial Interferometers

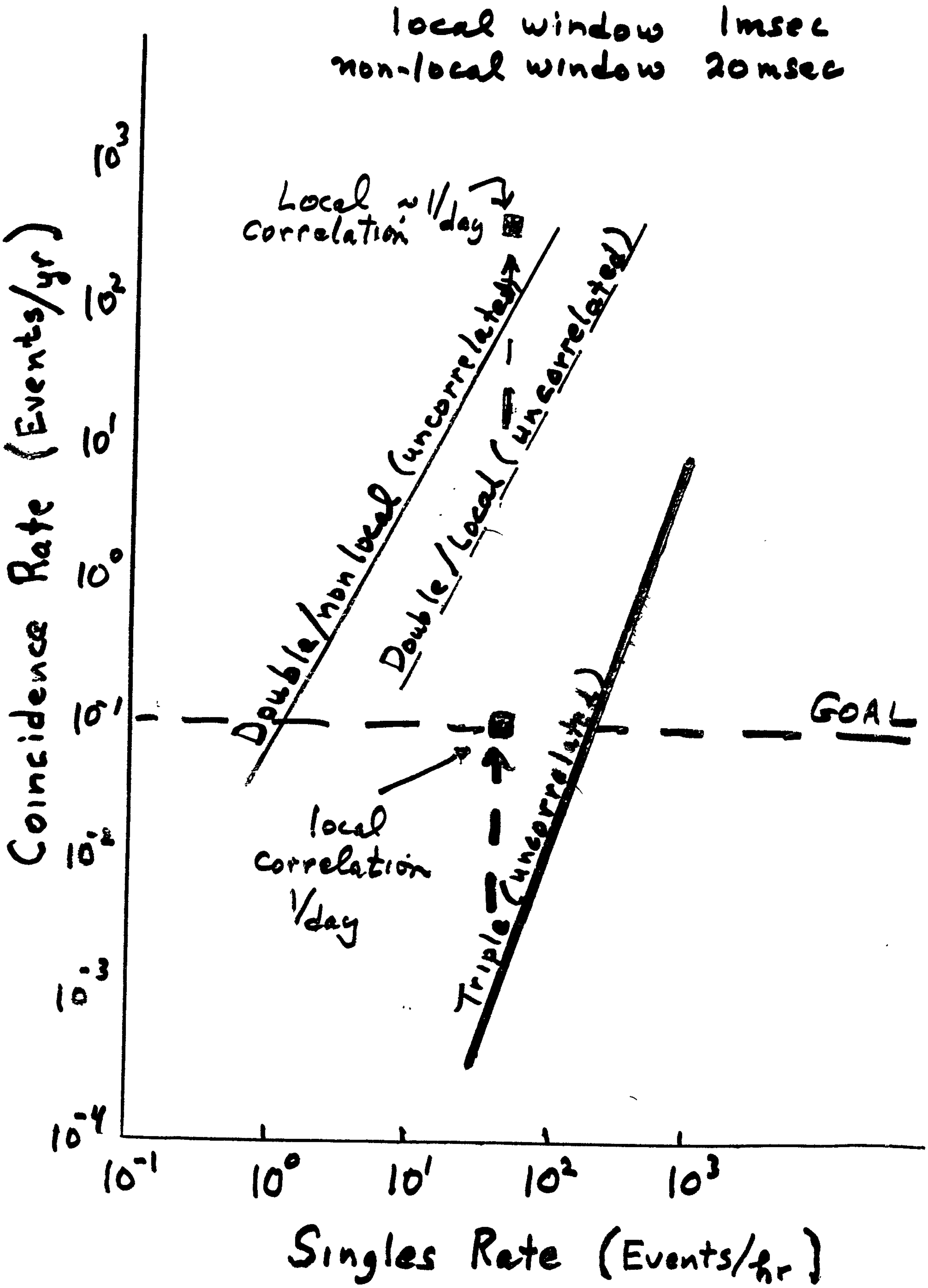
Noise Floor



Gravitational Wave Detection Strategy

- Interferometer Sensitivity
  - ⇒ R&D Program
    - Technology Development
    - Demonstration Experiments
  - ⇒ Engineering Implementation
    - Precision Engineering Design
    - Quality Control
- Two Sites - Three Interferometers
  - ⇒ Single Interferometer ~50/hr
    - non-gaussian level
  - ⇒ Hanford (Doubles) ~1/day
    - correlated rate (x1000)
  - ⇒ Hanford + Livingston <0.1/yr
    - uncorrelated (x5000)

MULTIPLE COINCIDENCES



LIGO Project
Technical

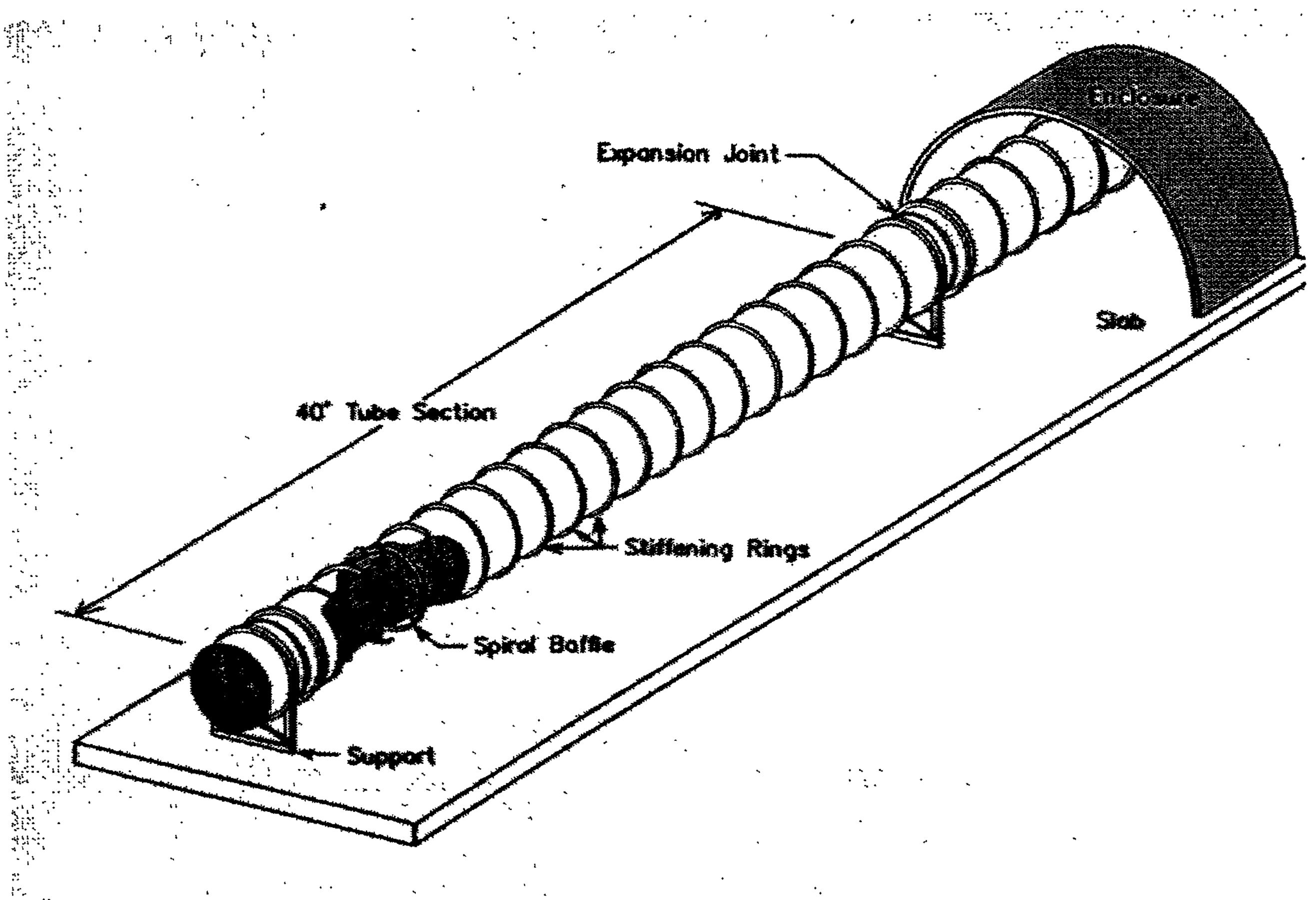
- Major Facilities
  - » Beam Tube
  - » Vacuum Systems
  - » Civil Construction
- Detector
  - » Detection Strategy
  - » Interferometers
- R&D
  - » Noise Sources and Sensitivity
  - » Demonstration Experiments
- Status and Plans

Beam Tube

- Characteristics
  - ⇒ Arm Lengths - 4km
  - ⇒ Tube Diameter - 4 ft
  - ⇒ Initial Detector
    - 10^{-6} torr Hydrogen; 10^{-7} torr Water
  - ⇒ Advanced Detectors
    - 10^{-9} torr Hydrogen; 10^{-10} torr Water
  - ⇒ Quality Control
    - (materials, welding, cleaning, etc)

- Status and Plans
  - ⇒ Design Contract was with CBI
    - Final Design Report Accepted (6/94)
  - ⇒ Qualification Test
    - 130 ft Section - success (4/95)
  - ⇒ Contract Options

Beam Tube


Enclosure
Expansion Joint
Slab
40' Tube Section
Stiffening Rings
Spiral Baffle
Support

LIGO Facilities

Beam Tube Enclosure

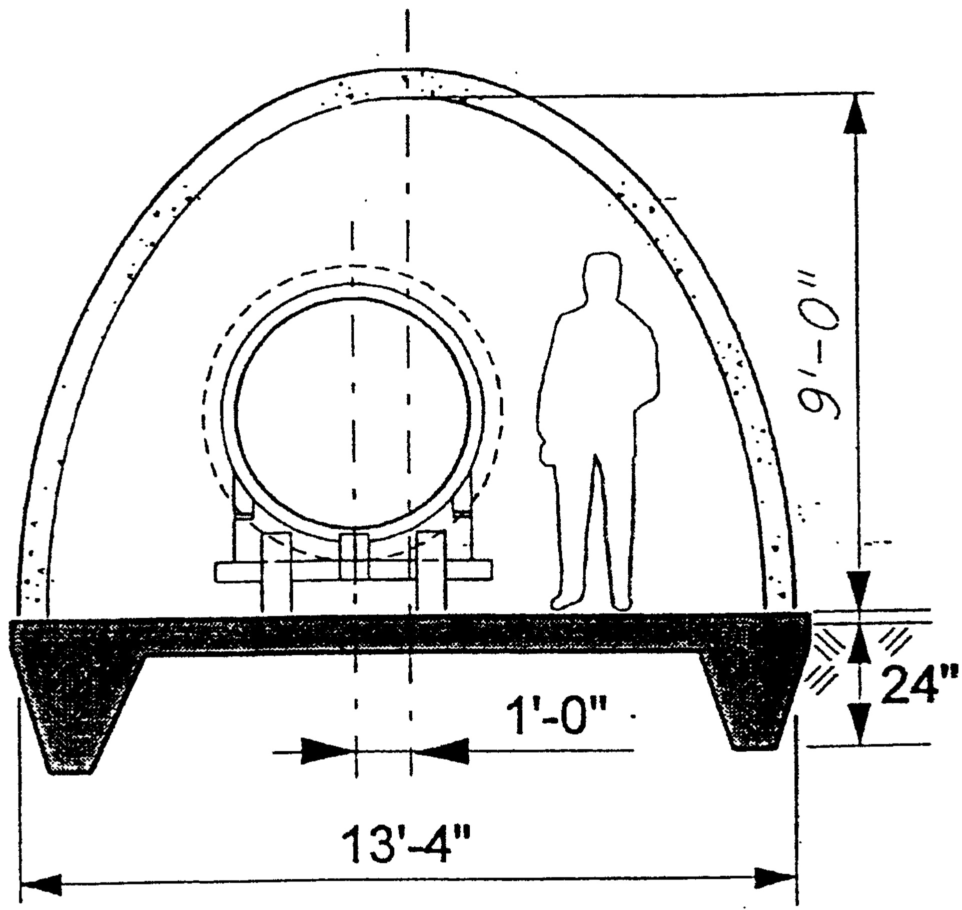
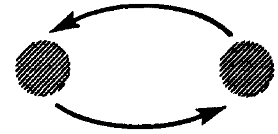
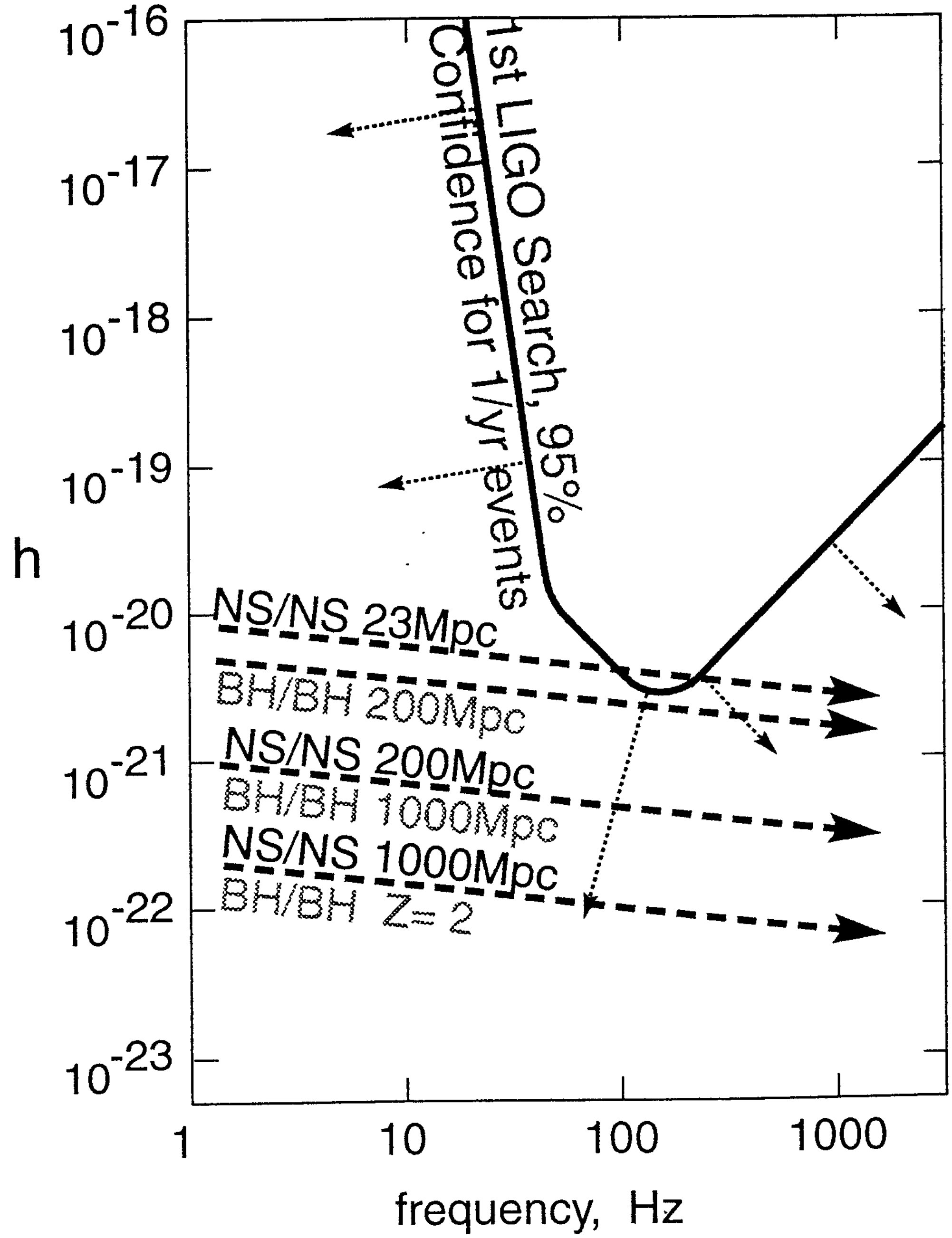


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

NEUTRON STAR BINARIES

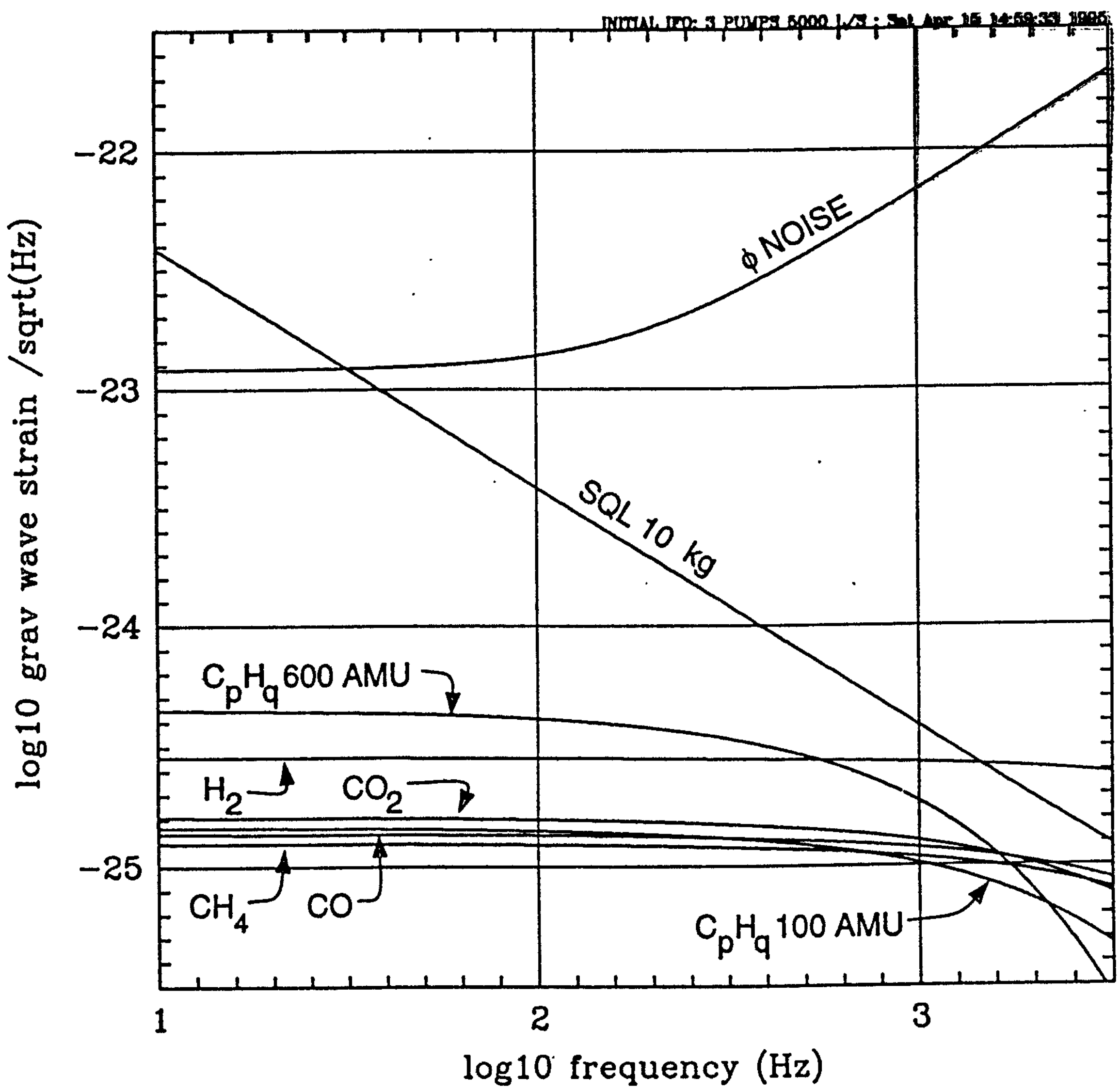


[“Near-Guaranteed” source]

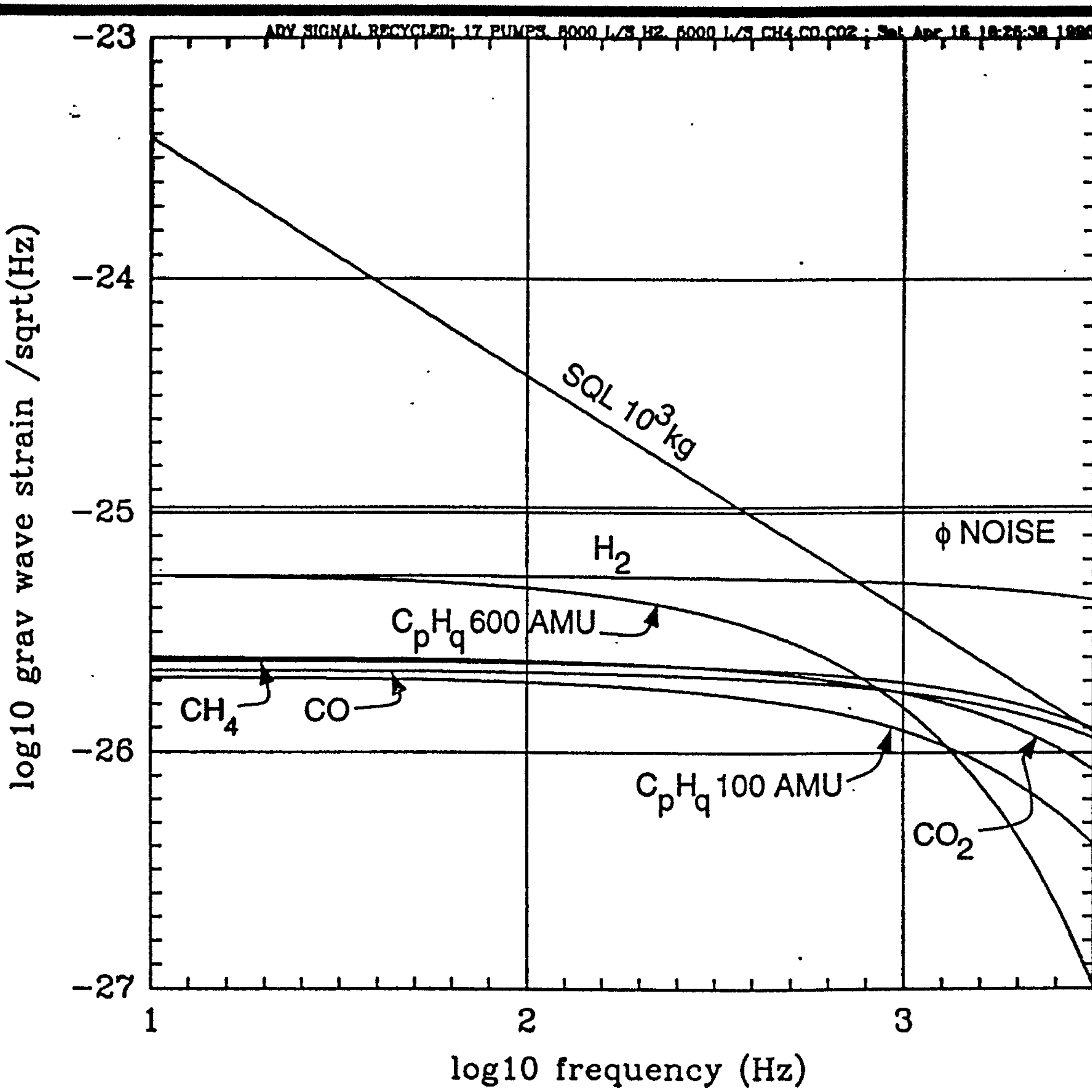


- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

Initial Interferometer Noise Budget



Advanced Interferometer Noise Budget



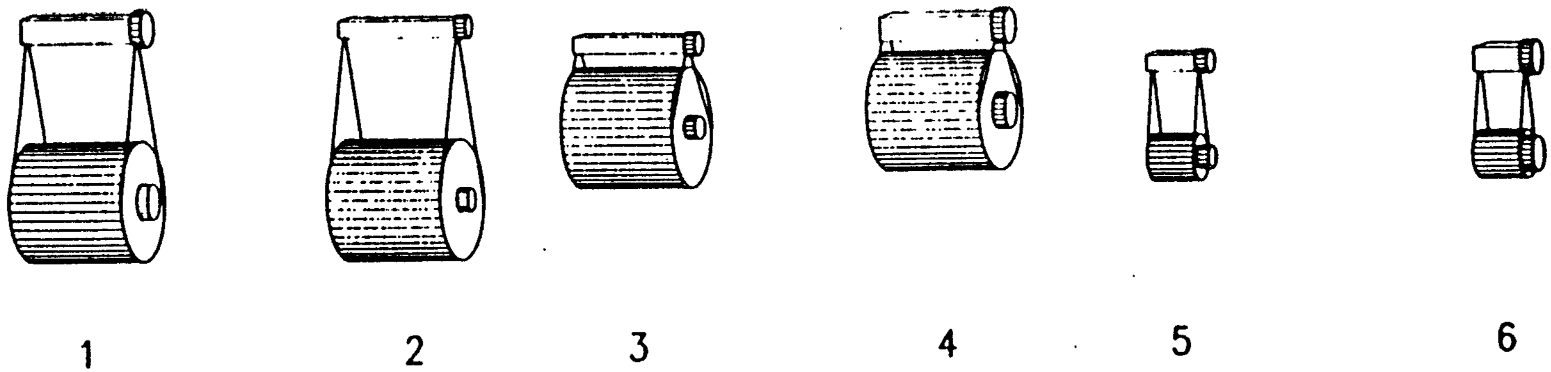
Advanced amplitude recycled interferometer parameters:

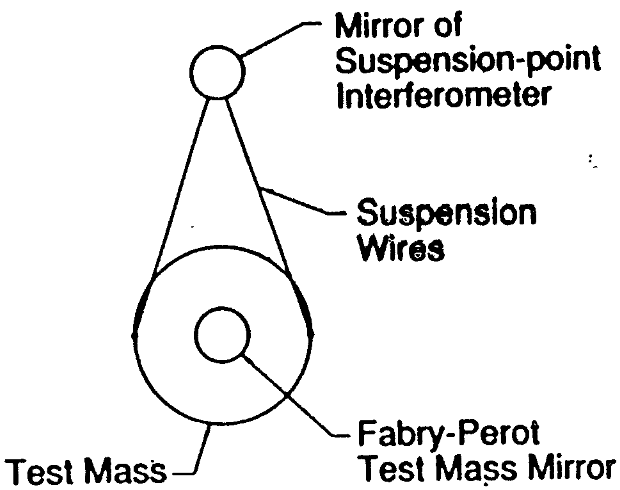
$A_m = 10^{-5}$

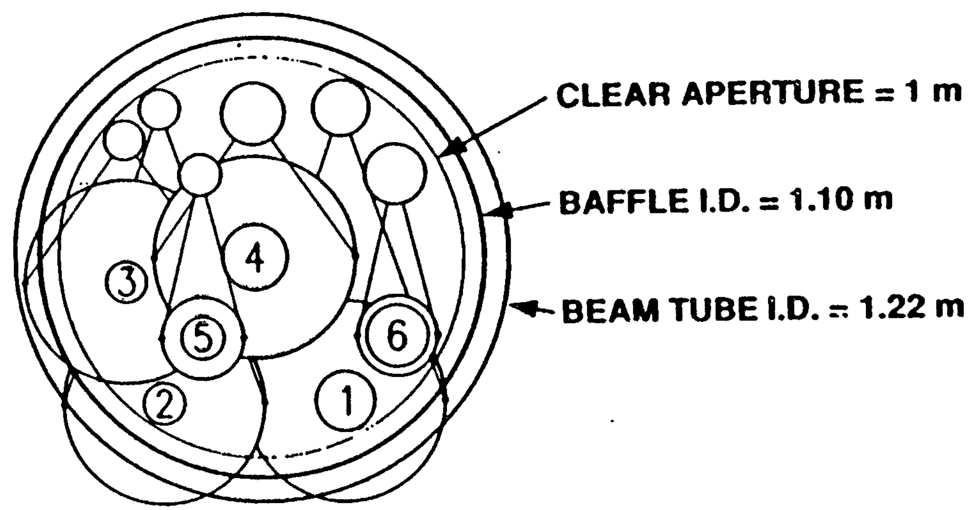
P_{in} = 100 W $\qquad$ P_{circ} ~ 1 MW

$\varepsilon_{opt} = 0.3$

$\lambda = 1.06\ \mu$


1
2
3
4
5
6


Mirror of Suspension-point Interferometer
Suspension Wires
Fabry-Perot Test Mass Mirror
Test Mass


CLEAR APERTURE = 1 m
BAFFLE I.D. = 1.10 m
BEAM TUBE I.D. = 1.22 m
1
2
3
4
5
6

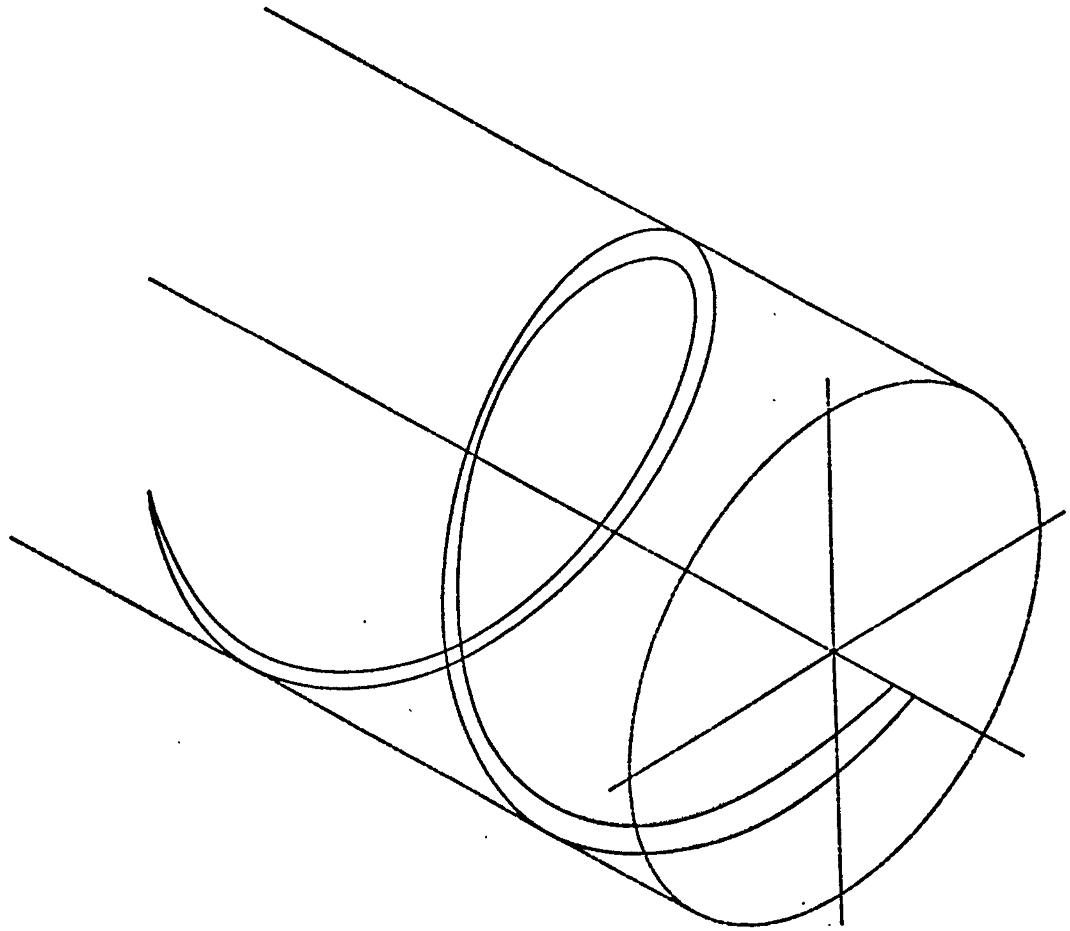
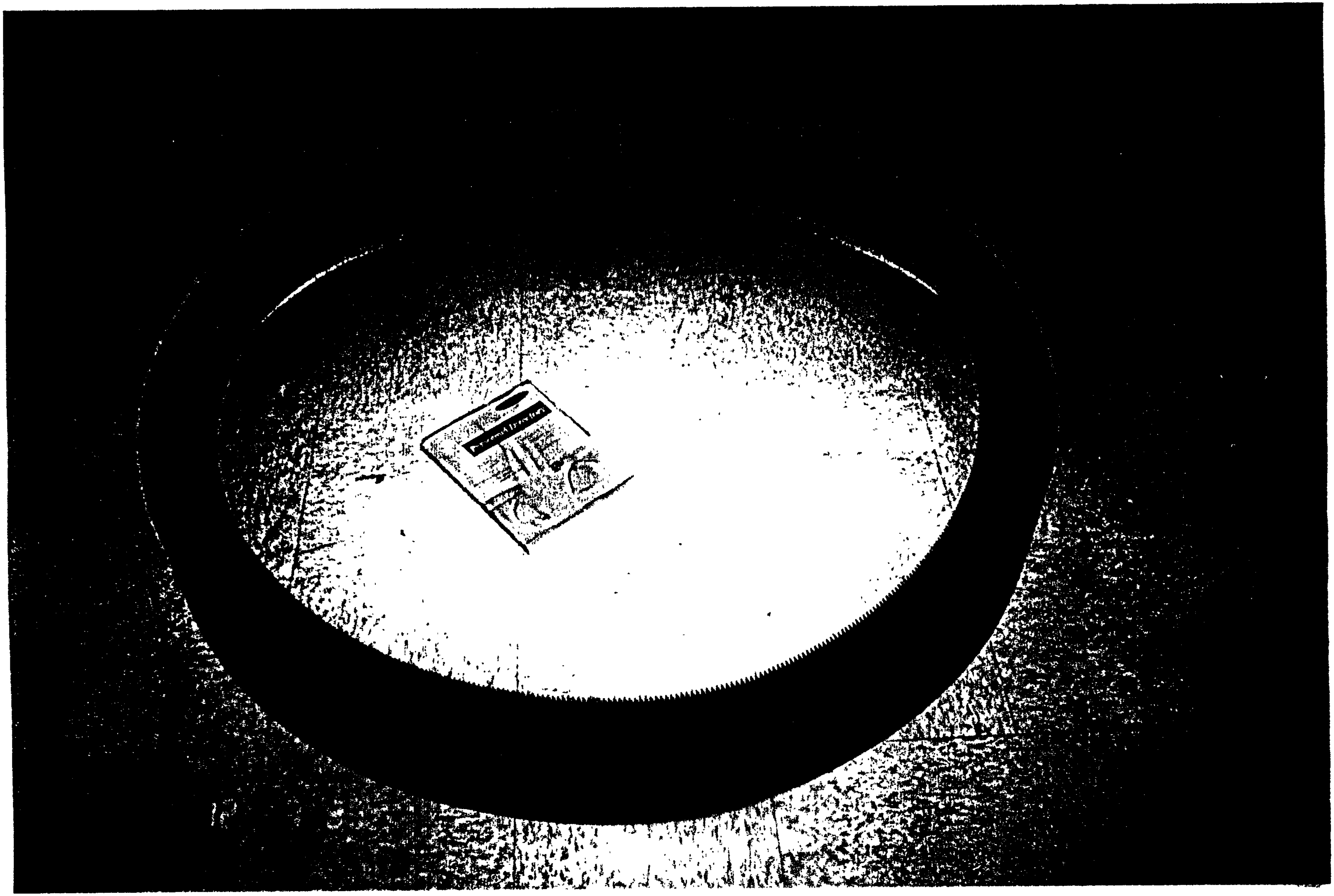


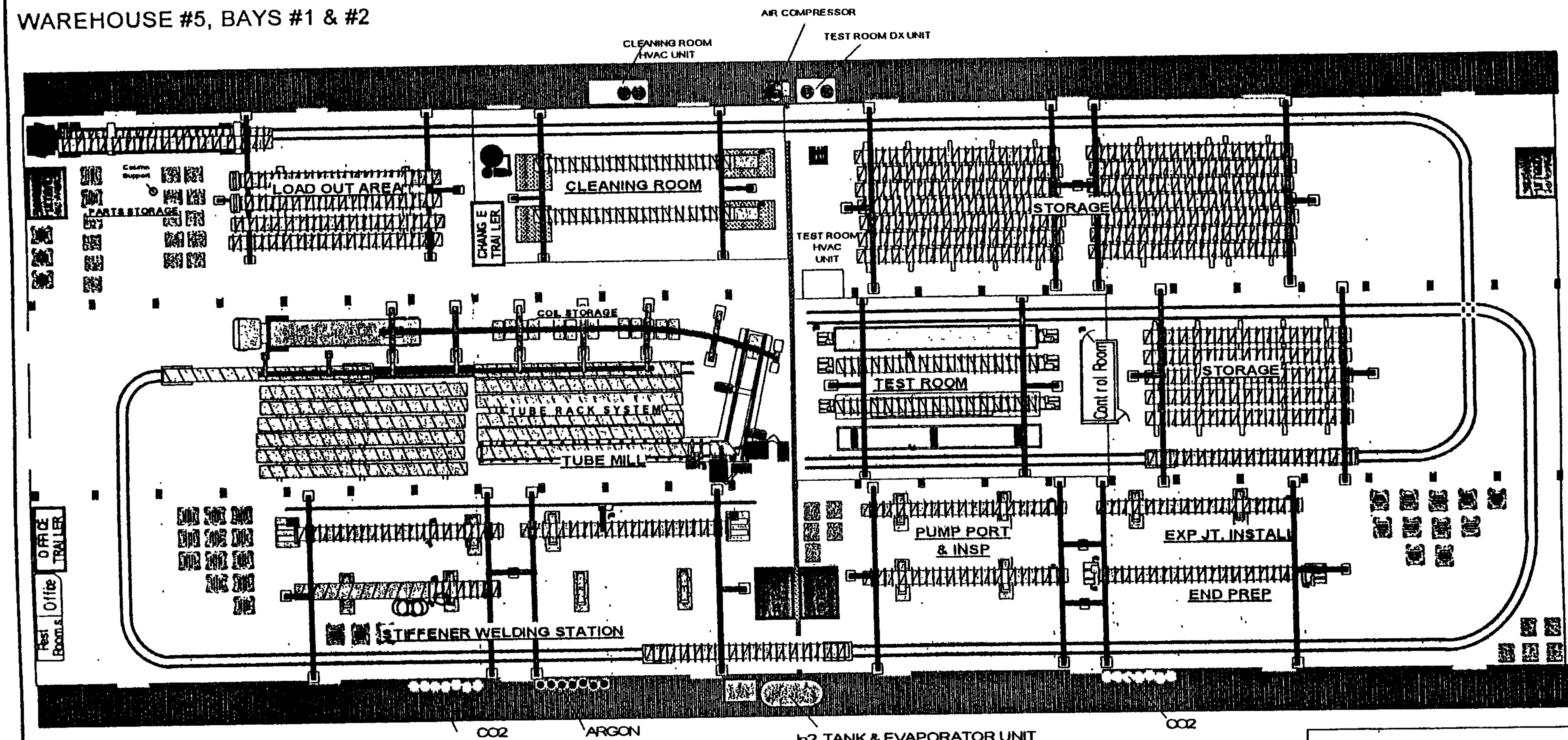
FIGURE1.1.2 #4 BAFFLE SCHEMATIC

L.T



BIG PASCO

WAREHOUSE #5, BAYS #1 & #2



LIGO LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

HANFORD LOCATION

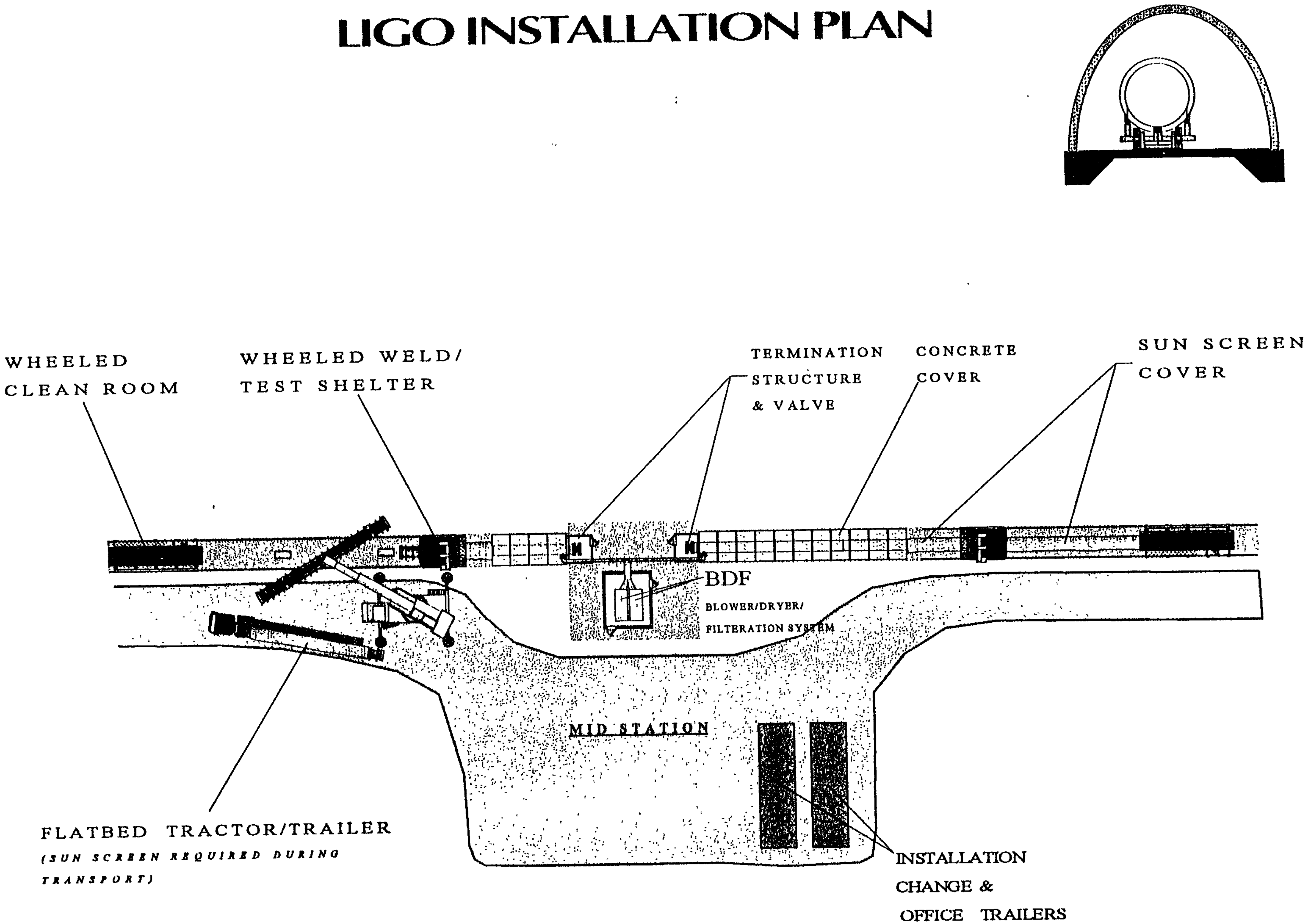
FABRICATION FACILITY

BIG PASCO WHSE #5, BAYS 1 & 2

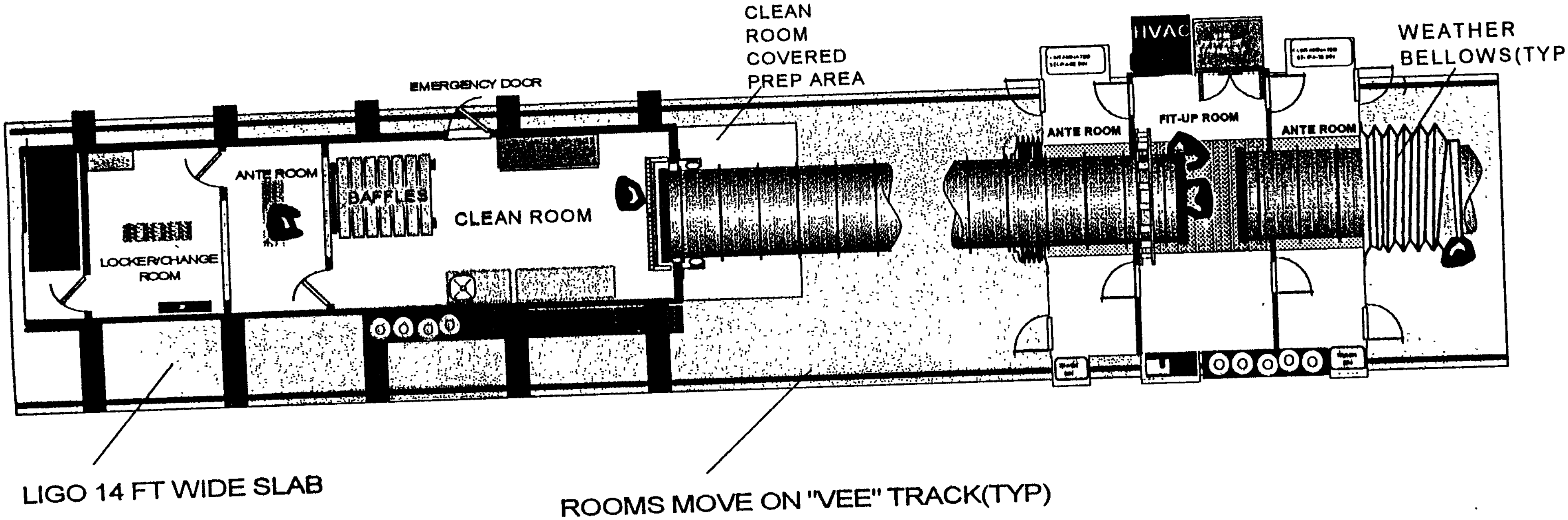
PC181520

BIGPASO1.CVS

LIGO INSTALLATION PLAN



INSTALLATION PLAN



LIGO Facilities

Vacuum Equipment

- Characteristics
  - » mostly standard vacuum equipment
    - – 1st stage roughing atm -> 0.1 torr
    - – 2nd stage roughing 0.1 torr -> 10^{-6} torr
    - – steady state - ion/getter pumps
  - » large gate valves (4 ft diam)
    - – access and flexibility
  - » controls and monitoring

- Status
  - » Science requirements and review 6/94
  - » RFP issued for design contract only
  - » Two competitive contracts awarded (CB&I, PSI)
  - » Final design and manufacturing
    - – down select (6/95) to PSI
    - – CDR approved 10/95
    - – FDR May 96; some prototype/acquisitions now

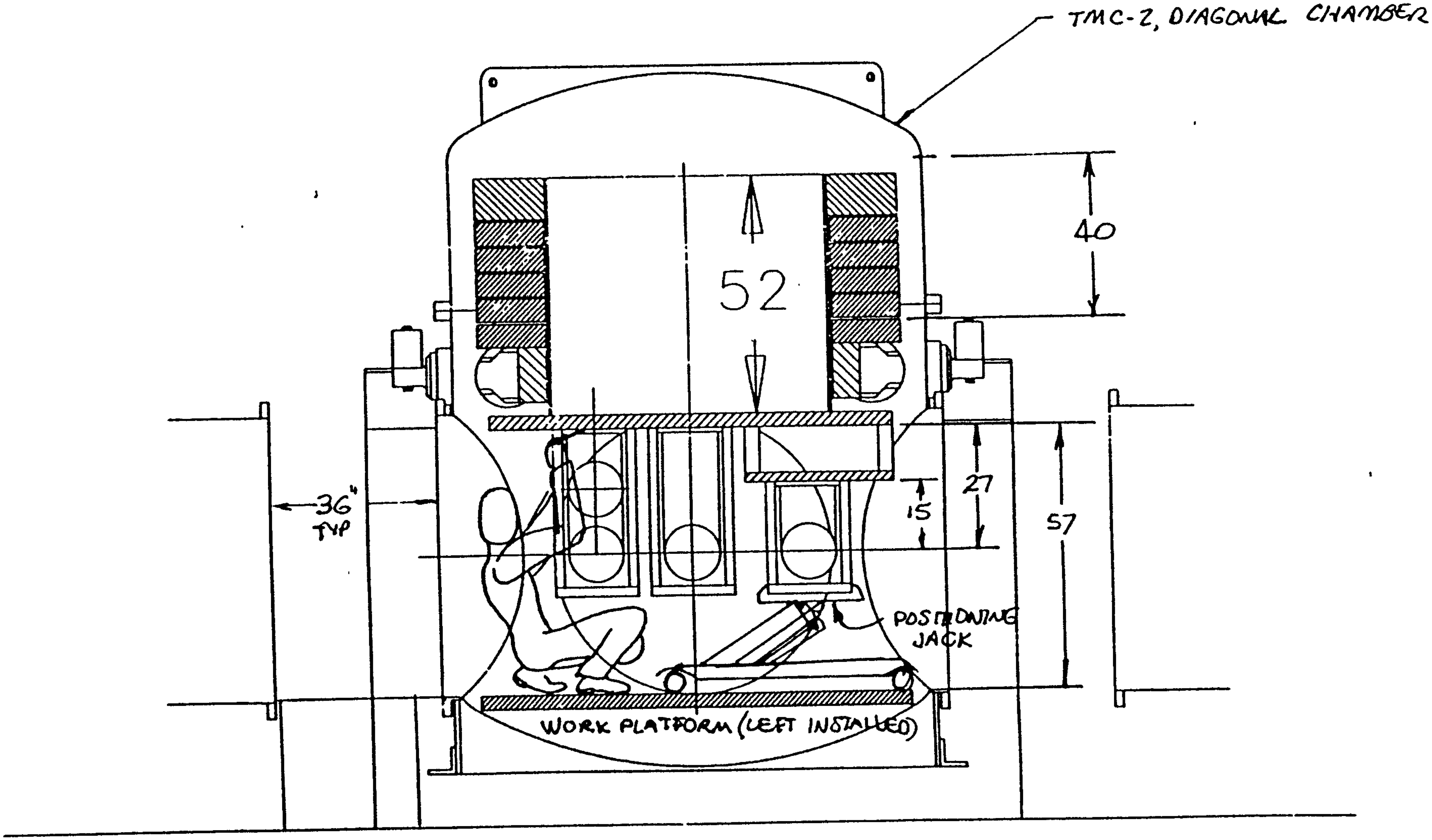
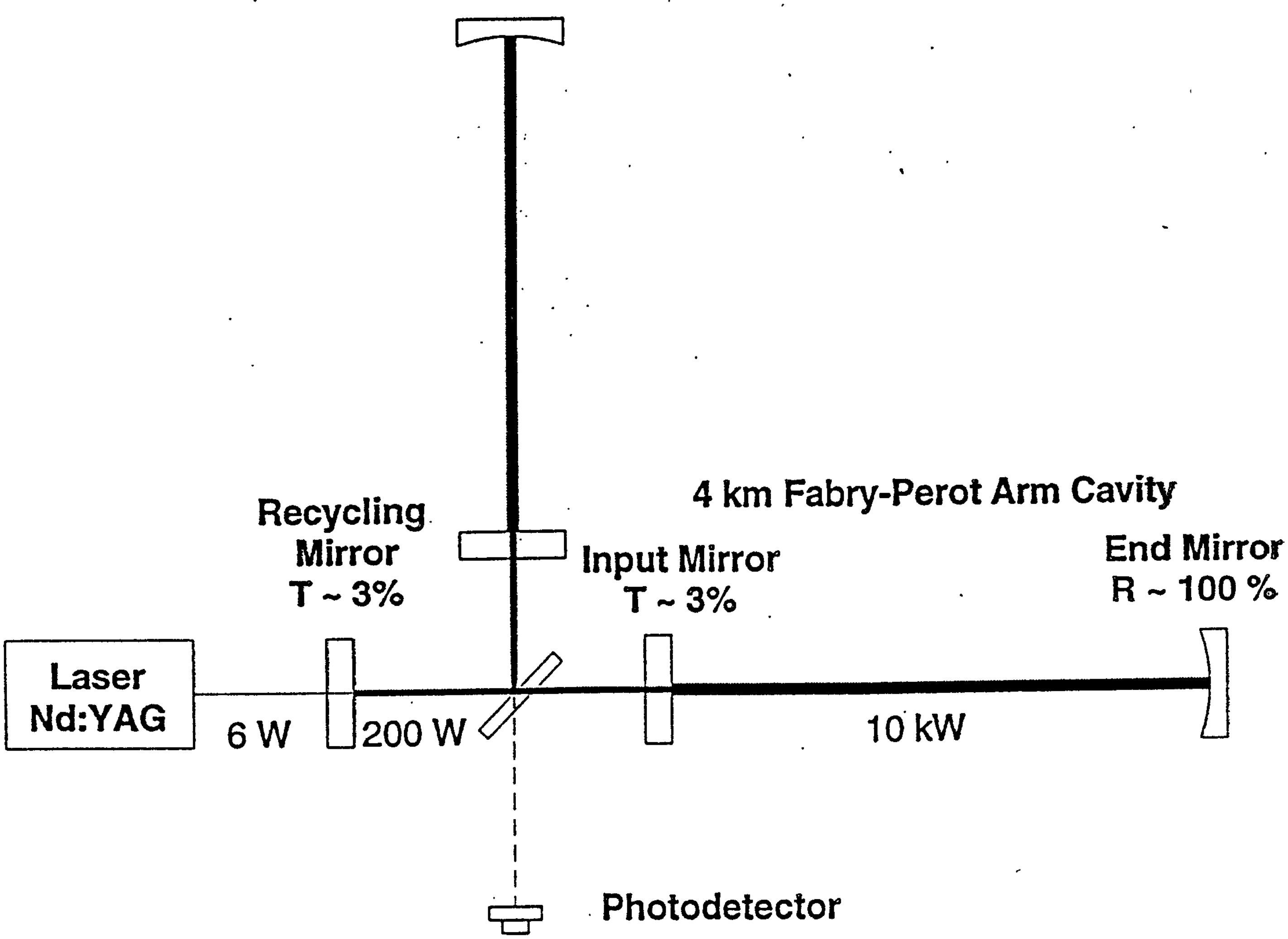


FIG. 3 INTERNAL ACCESS

9-2-92

Initial Interferometers
Configuration



LIGO
R&D Program

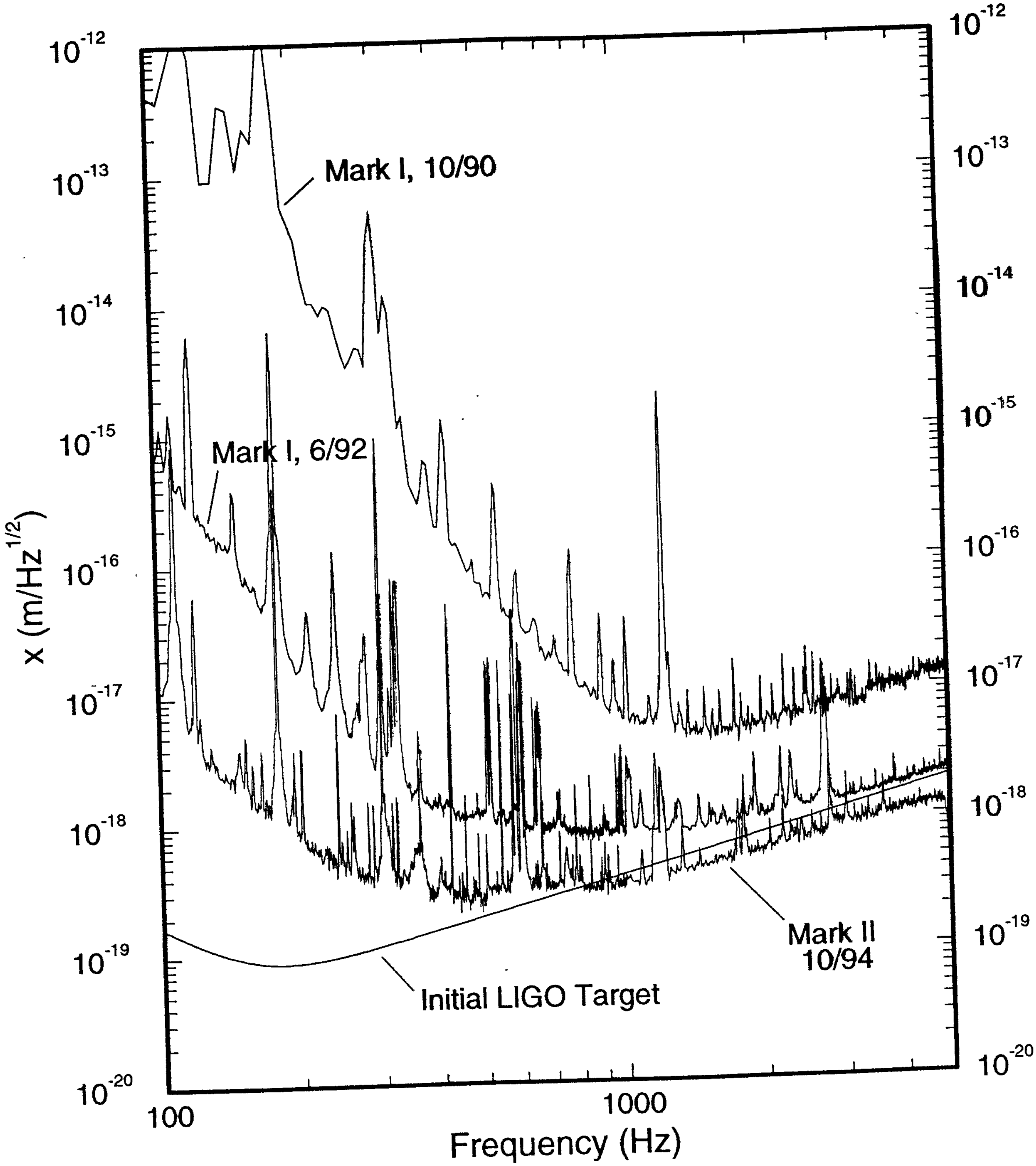
- Sensitivity
  - » main features of 40 m spectrum understood
  - » monolithic test masses improve sensitivity

- Demonstration Experiments
  - » optical recombination demonstrated on 40 m
  - » acquisition locking with LIGO controls
  - » MIT phase noise experiments

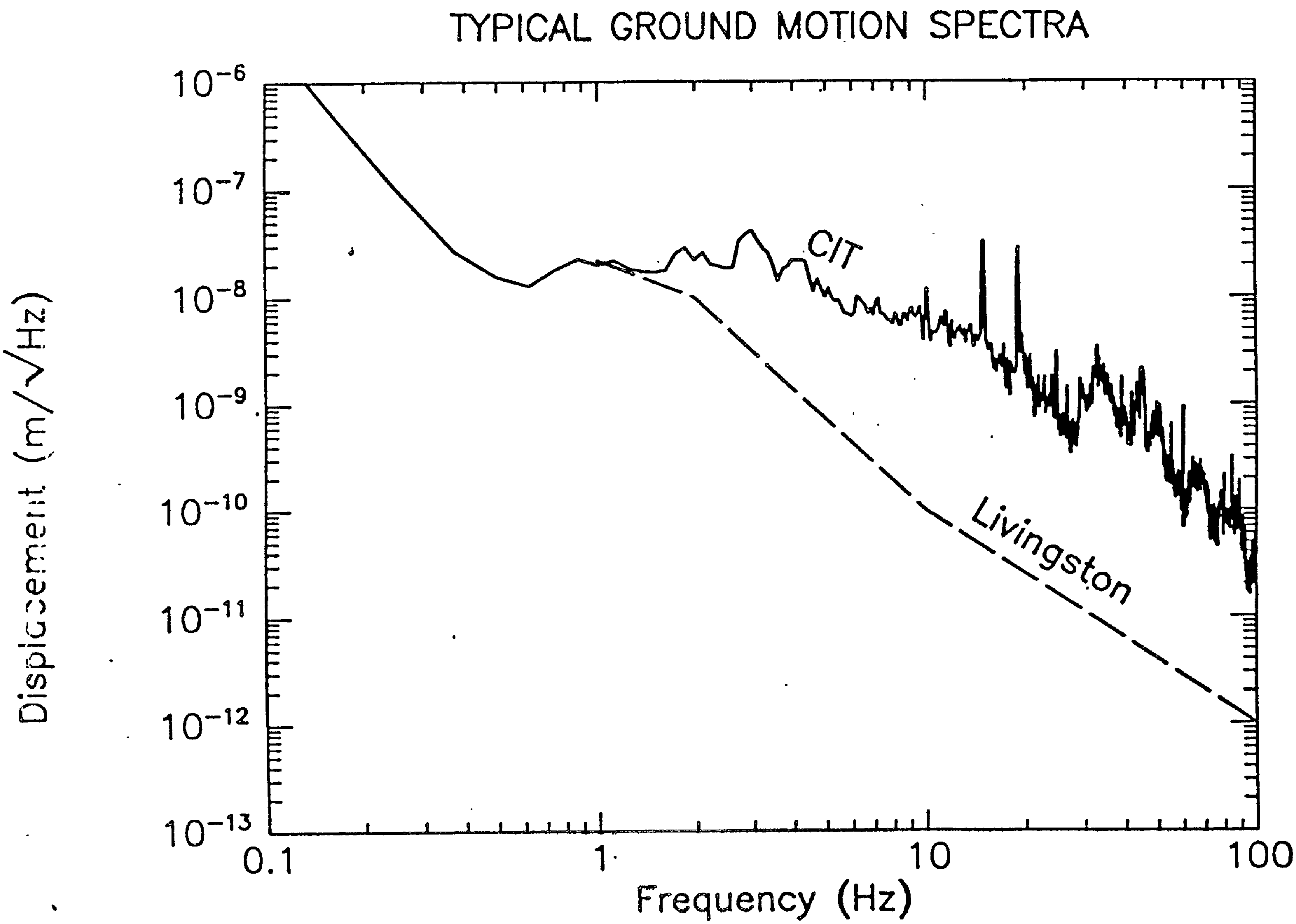
- Pre- [detector design freeze][<1998]
  - » Program testing directed at tasks that could effect design over the next two years

- Post- [detector design freeze][>1998]
  - » Advanced R&D program on techniques for improved sensitivity;
  - » understand performance - initial interferometer
  - » gain experience running an interferometer facility (perform search)

Displacement Sensitivity of 40-Meter Interferometer

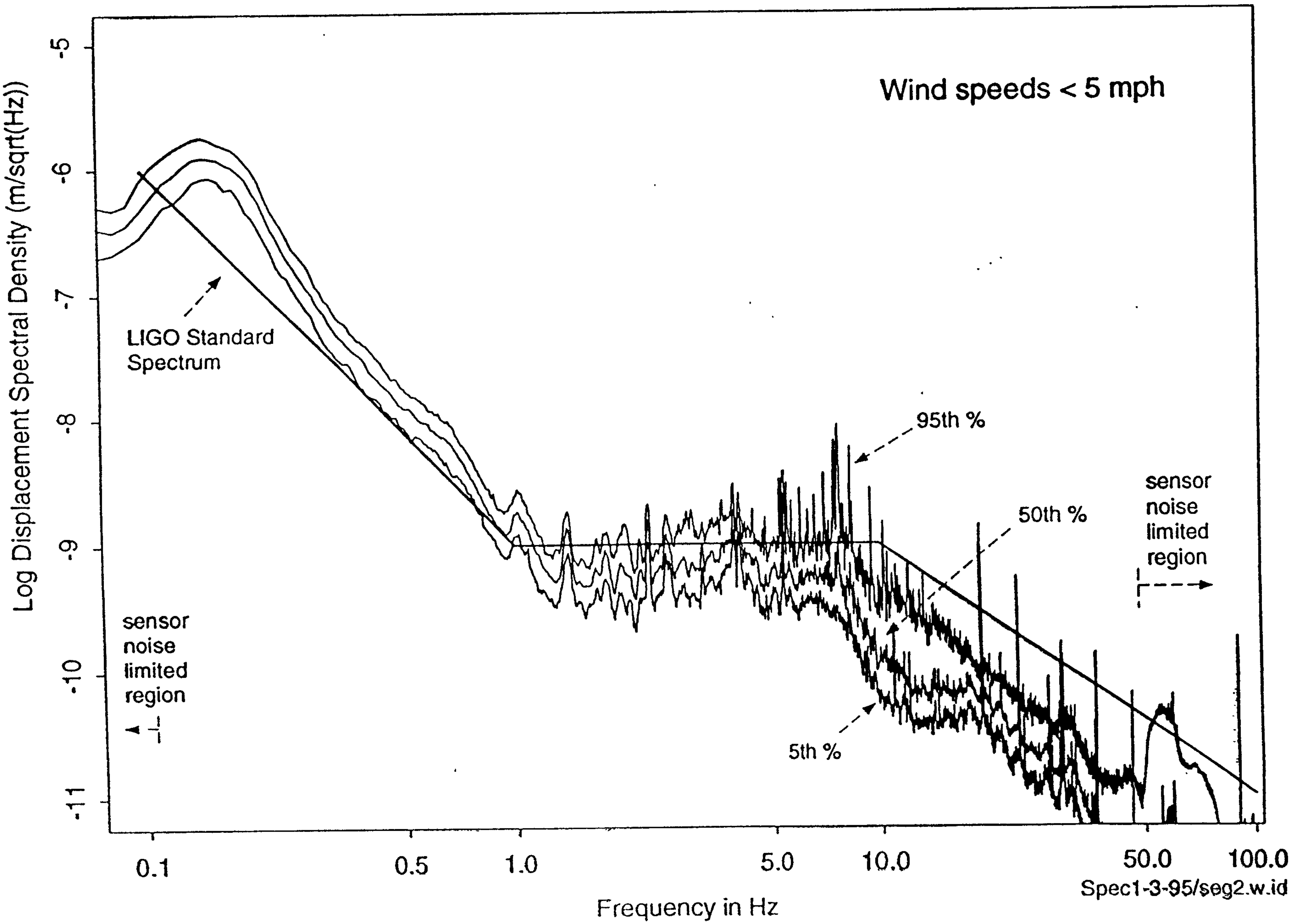


~fjr/fort/mk2/port_90_94.xvgr

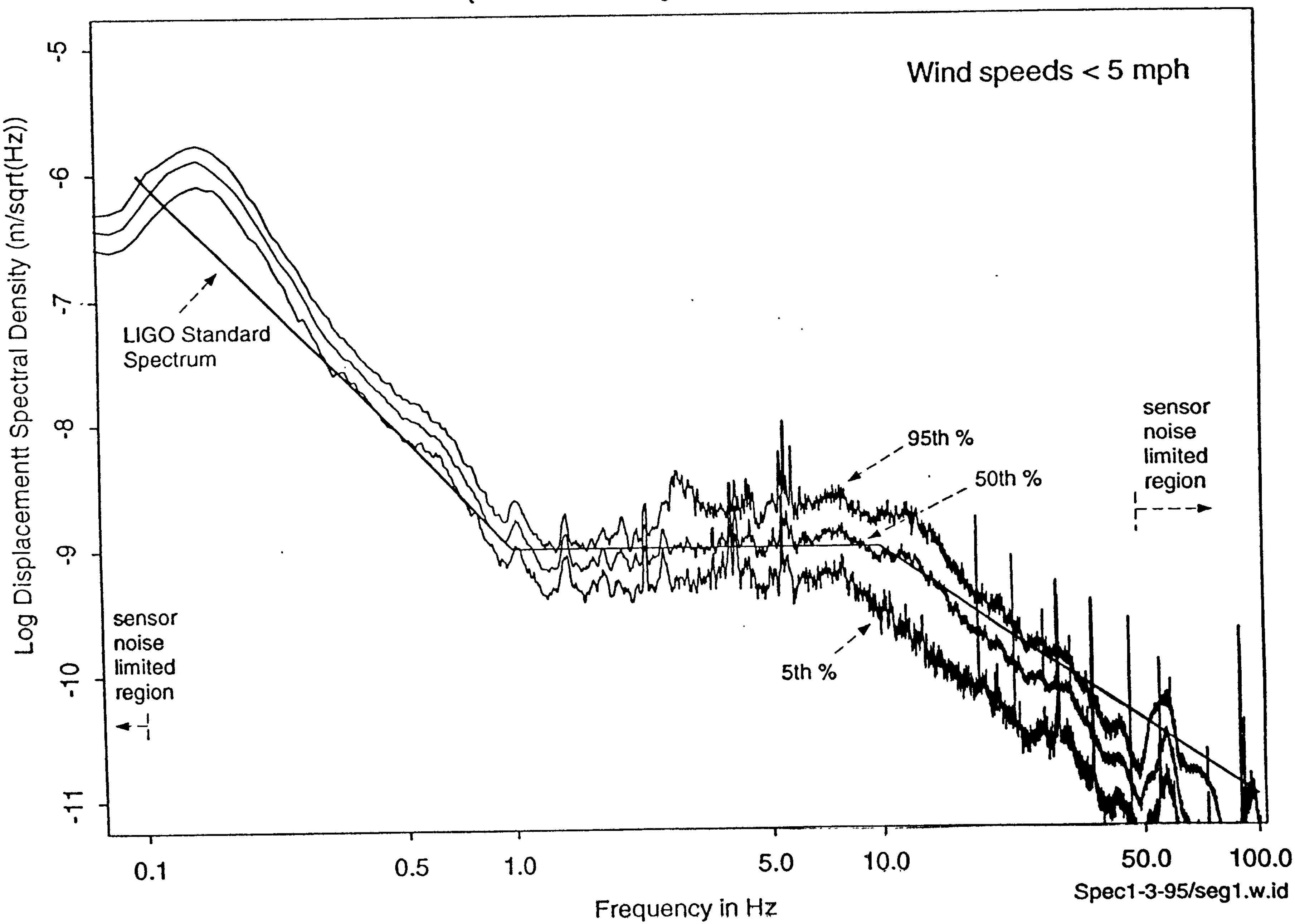

TYPICAL GROUND MOTION SPECTRA
Displacement (m/√Hz)
Frequency (Hz)
CIT
Livingston
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
0.1
1
10
100

7B

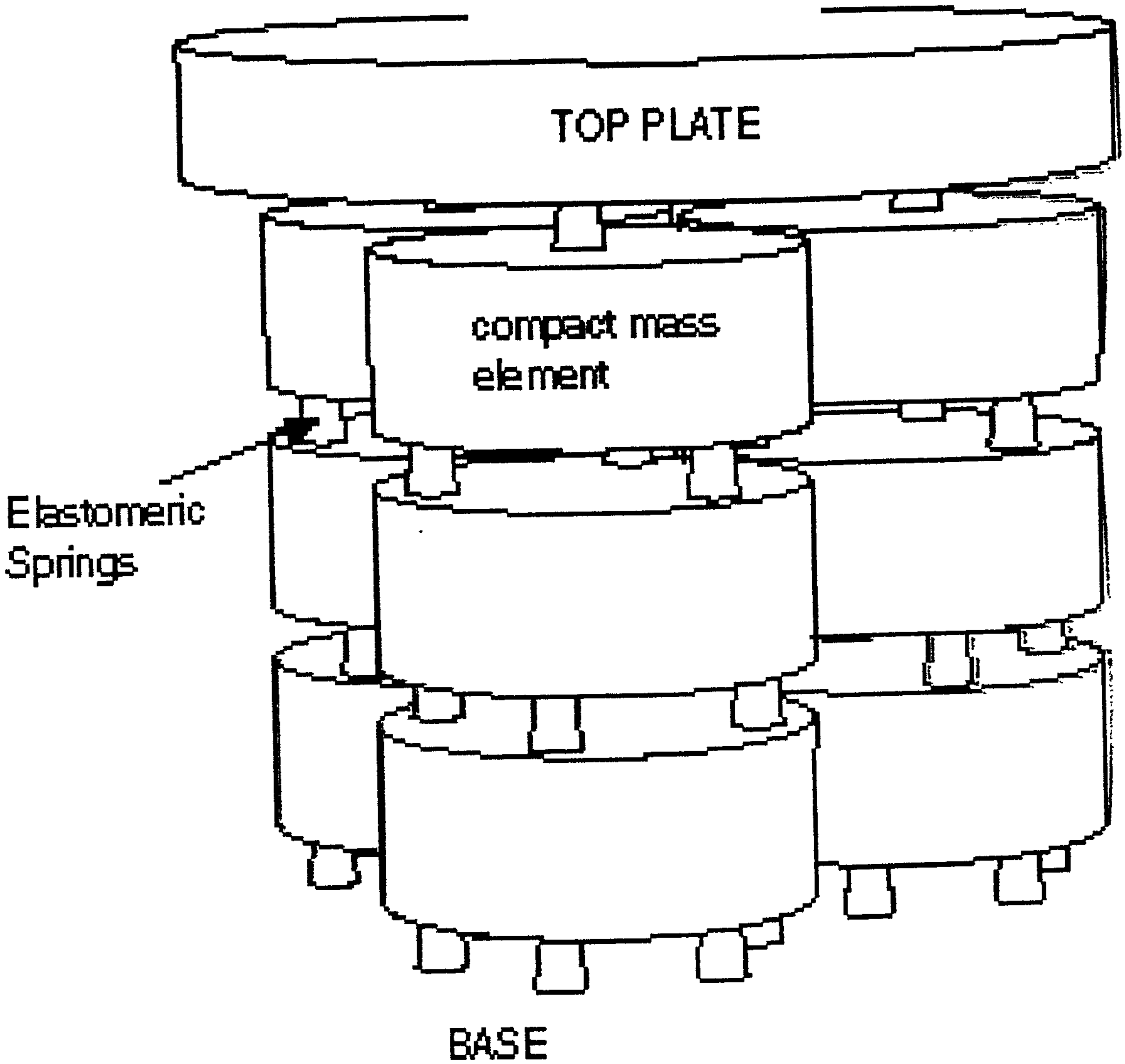
Hanford Corner Station SW Arm Axis, Late Night December 12,1994
(Preliminary Data)



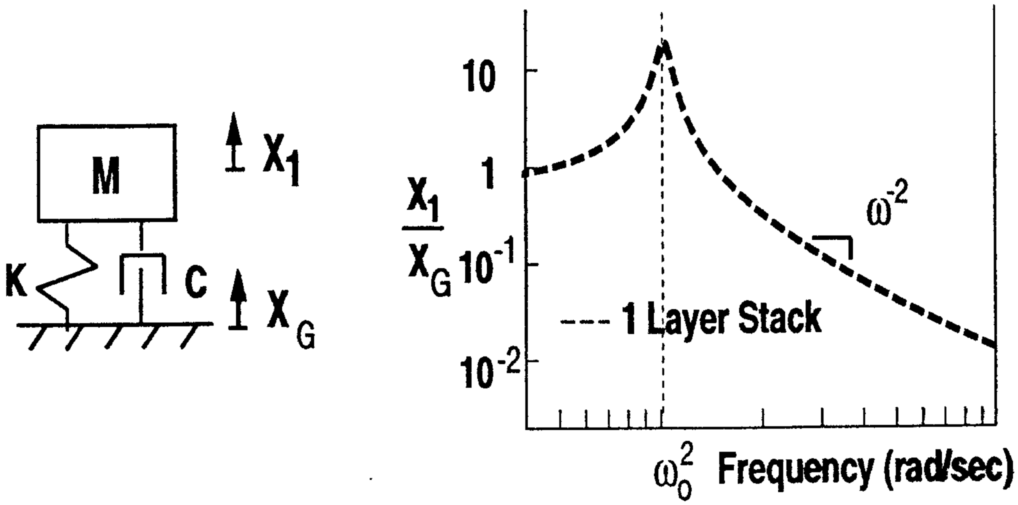
Hanford Corner Station SW Arm Axis, Morning Traffic December 13,1994
(Preliminary Data)

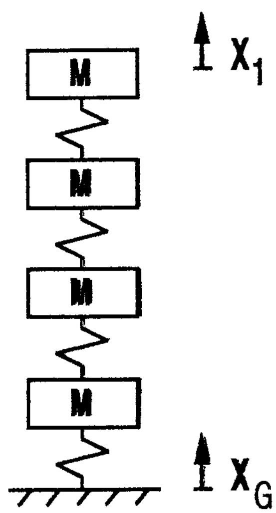


7c

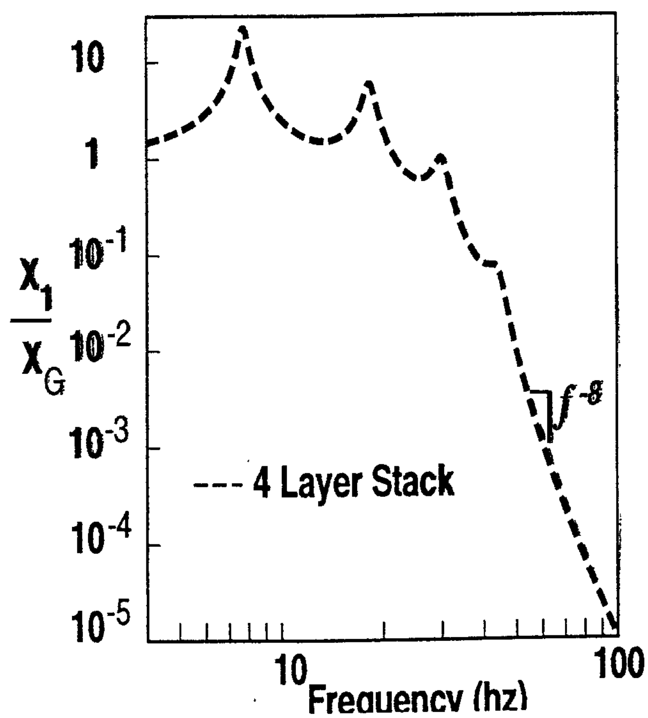


PROTOTYPE ISOLATION STACK





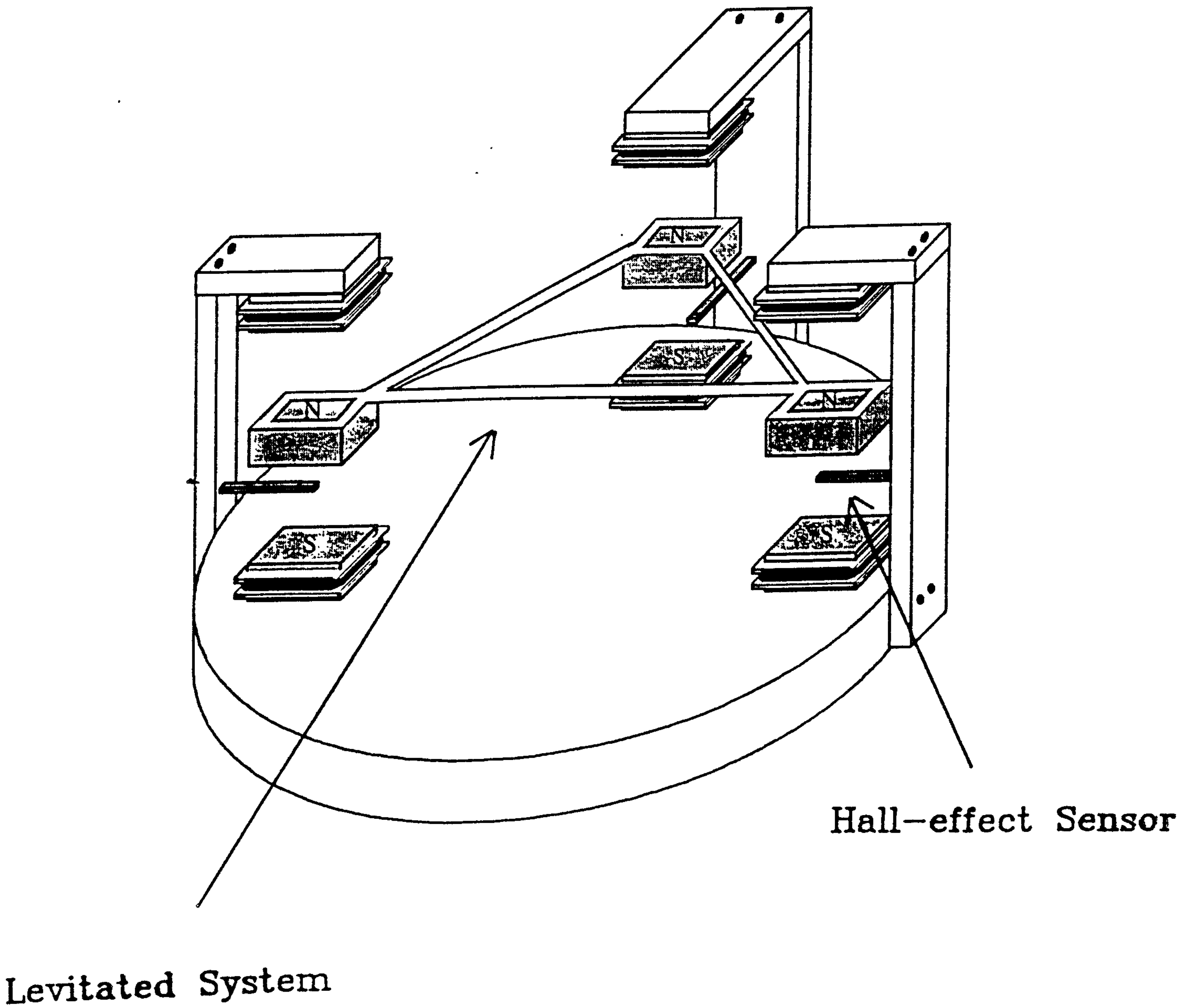
Simple Model of Mark 2 Stack Isolation (vertical)



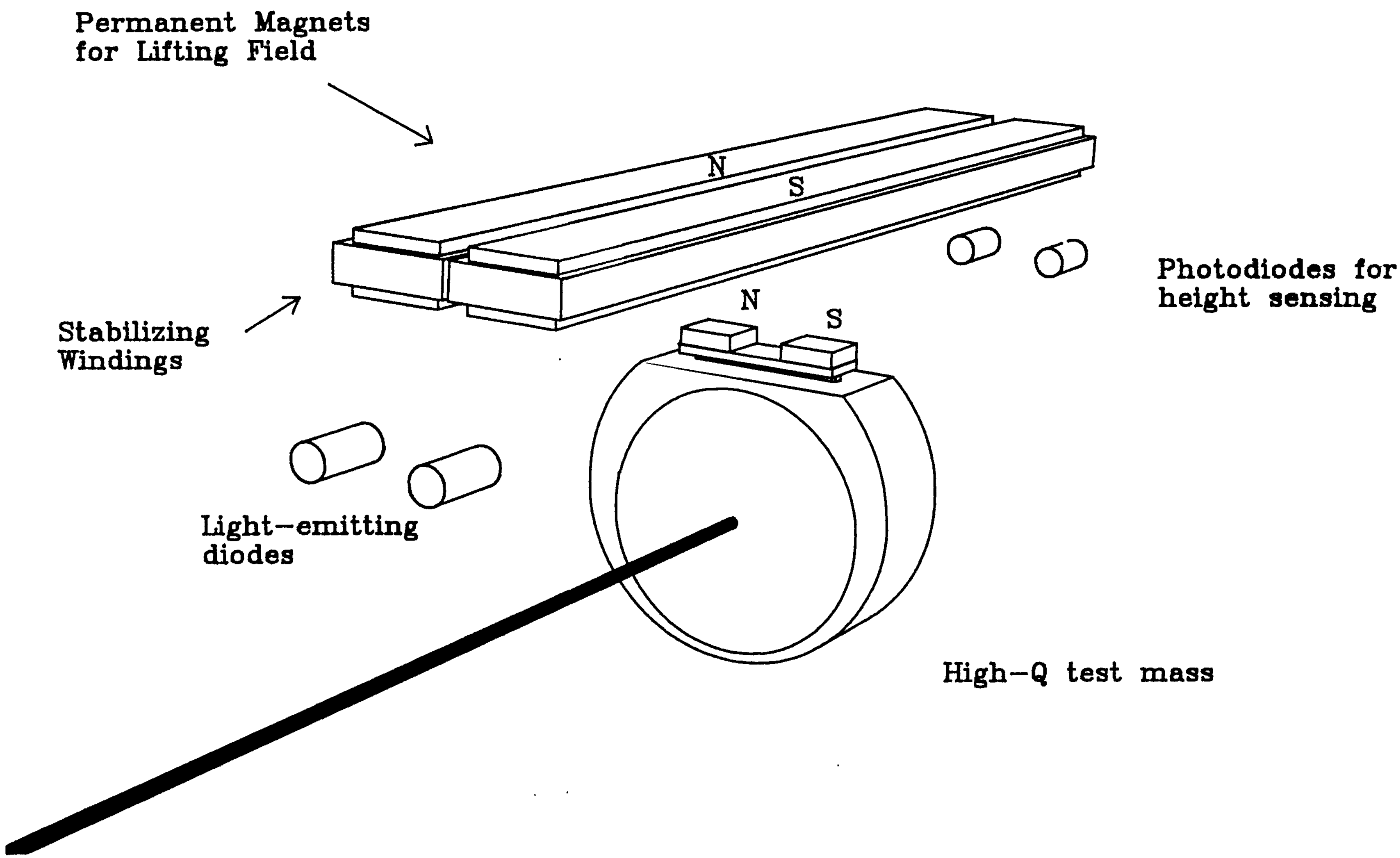
PASSIVE ISOLATION CONCEPT

DREVER + AUGST

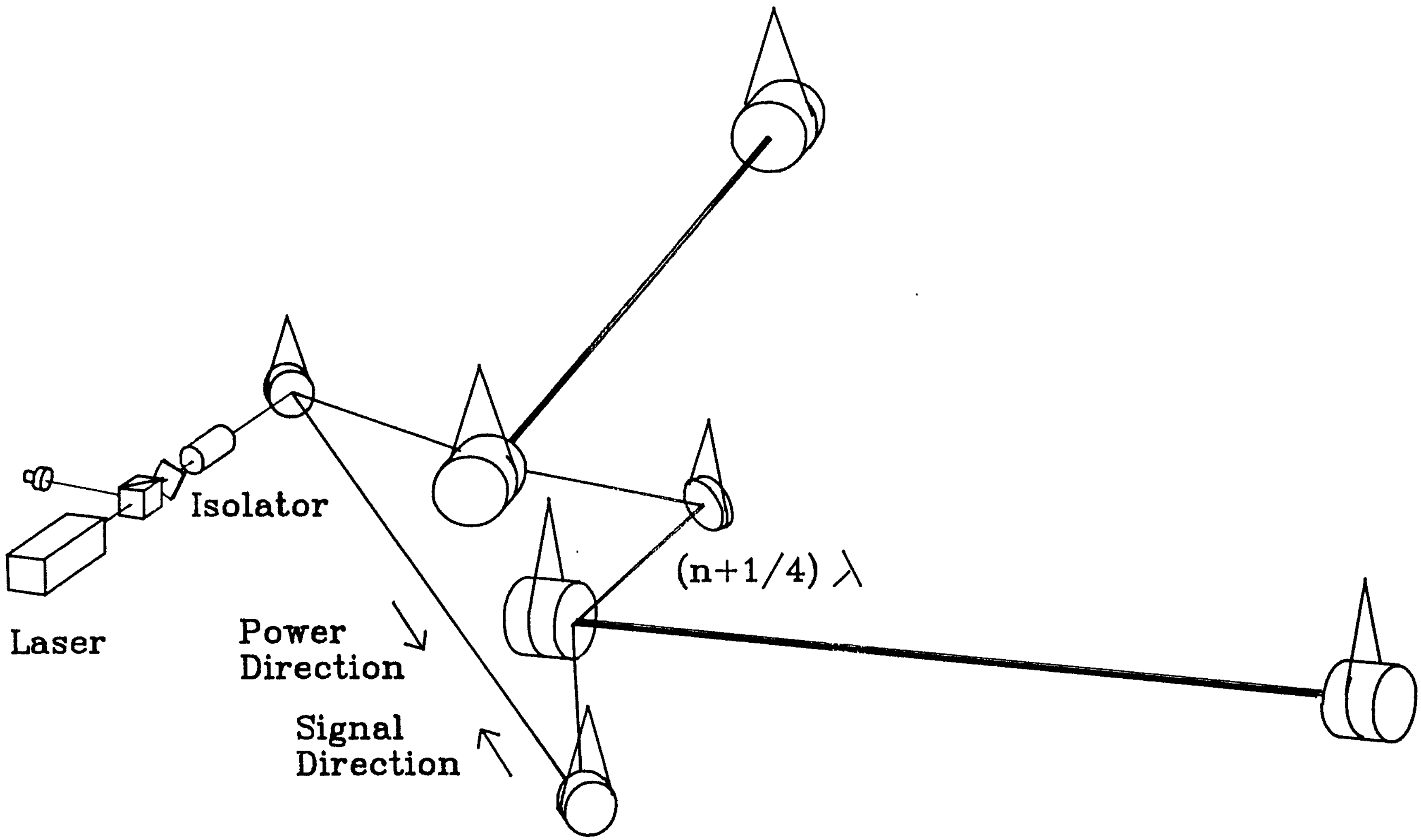
Magnetic Levitation Seismic Isolation Stage



Magnetically Levitated Test Mass



Diffractive–Coupled Recycling Interferometer



(Diagram shows main beams only)

DIFFRT1
5/8/96 RD

Initial Interferometer
Specifications

Strain Sensitivity [rms, 100 Hz band]	10^{-21}
Displacement Sensitivity [rms, 100 Hz band]	4×10^{-18} *m*
Fabry-Perot Arm Length	4000 *m*
Vacuum Level	$< 10^{-6}$ *torr*
Laser Wavelength	1064 *nm*
Optical Power at Laser Output	10 *W*
Optical Power at Interferometer Input	5 *W*
Power Recycling Factor	30
Input Mirror Properties	Reflectivity = 0.97
End Mirror Properties	Reflectivity > 0.9998
Arm Cavity Optical Loss	≤ 3%
Light Storage Time in Arms	1 *ms*
Test Masses	Fused Silica, 11 *kg*
Mirror Diameter	25 *cm*
Test Mass Period Pendulum	1 *sec*
Seismic Isolation System	Passive, 4 stage
Seismic Isolation System Horizontal Attenuation	$\geq 10^{-7}$ (100 *Hz*)
Maximum Background Pulse Rate	1 *per minute*

LIGO Interferometers

Optical Parameters

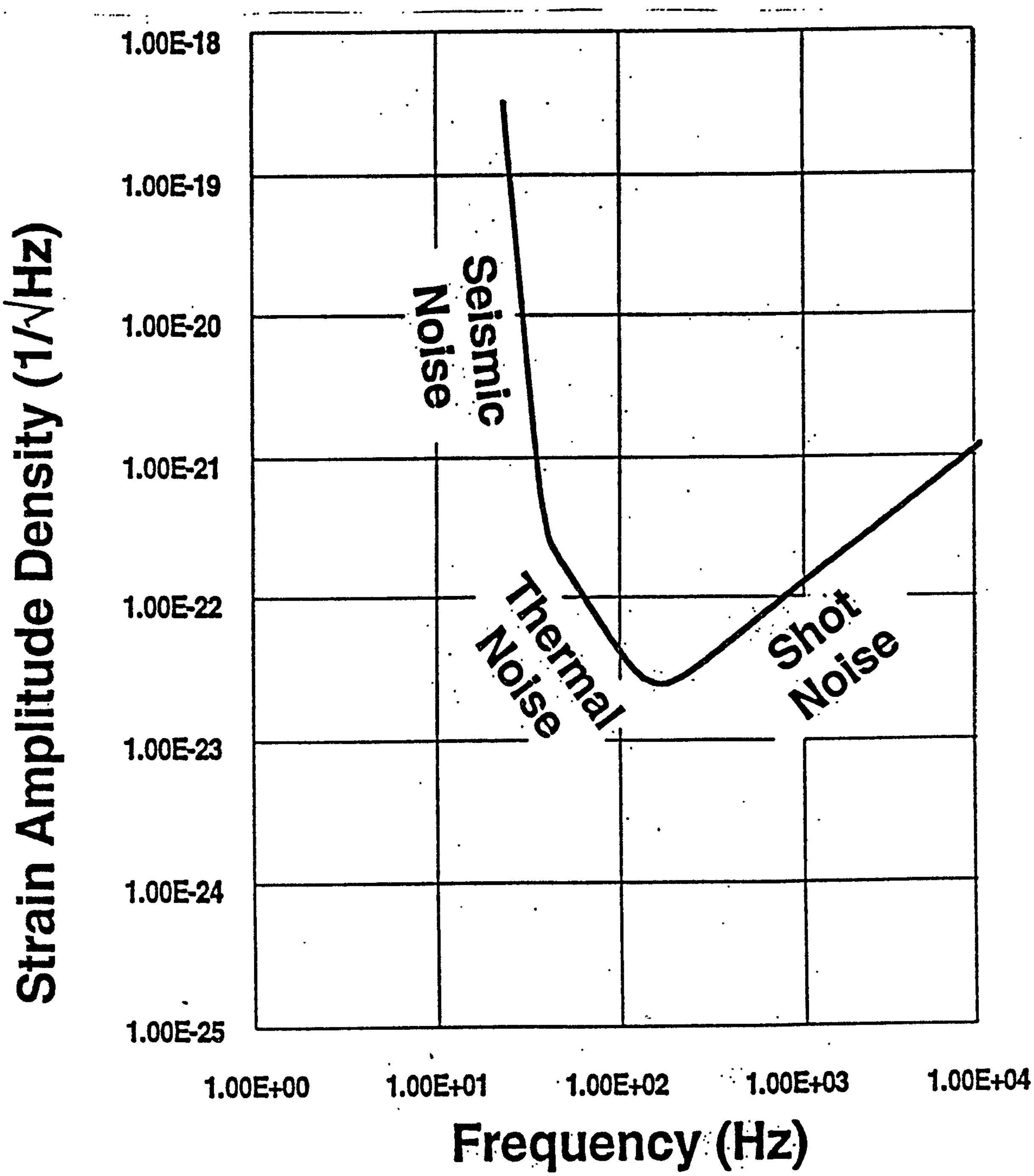
Optical Characteristics	Nominal Initial Interferometer	Sample Enhanced Interferometer
Arm Length	4000 m	4000 m
Laser Type & Wavelength	Nd:YAG, $\lambda = 1.064\ \mu m$	Nd:YAG, $\lambda = 1.064\ \mu m$
Input Power into Recycling Cavity, P	6W	100W
Contrast Defect, 1-c	3×10^{-3}	3×10^{-3}
Mirror Loss, L_M	1×10^{-4}	1.3×10^{-5}
Power Recycling Gain	30	380
Arm Cavity Storage Time, τ_{Arm}	8.8×10^{-4} s	1.3×10^{-3}s
Cavity Input Mirror Transmission, T	3×10^{-2}	2×10^{-2}
Total Optical Loss, L_T = (Absorption + Scattering)	4×10^{-2}	3×10^{-3}

LIGO Interferometers
Mechanical Parameters

Mechanical Characteristics	Nominal Initial Interferometer	Sample Enhanced Interferometer
Mirror Mass, M_M	10.7 kg	40 kg
Mirror Diameter, D_M	0.25 m	0.40 m
Mirror Internal Q_M	1×10^6	3×10^7
Pendulum Q_P(damping mechanism)	1×10^5 (material)	1×10^8 (material)
Pendulum Period, T_P	1 s (Single)	1 s (Double)
Seismic Isolation System	T(100 Hz) = -100 dB	T(10 Hz) = -100 dB

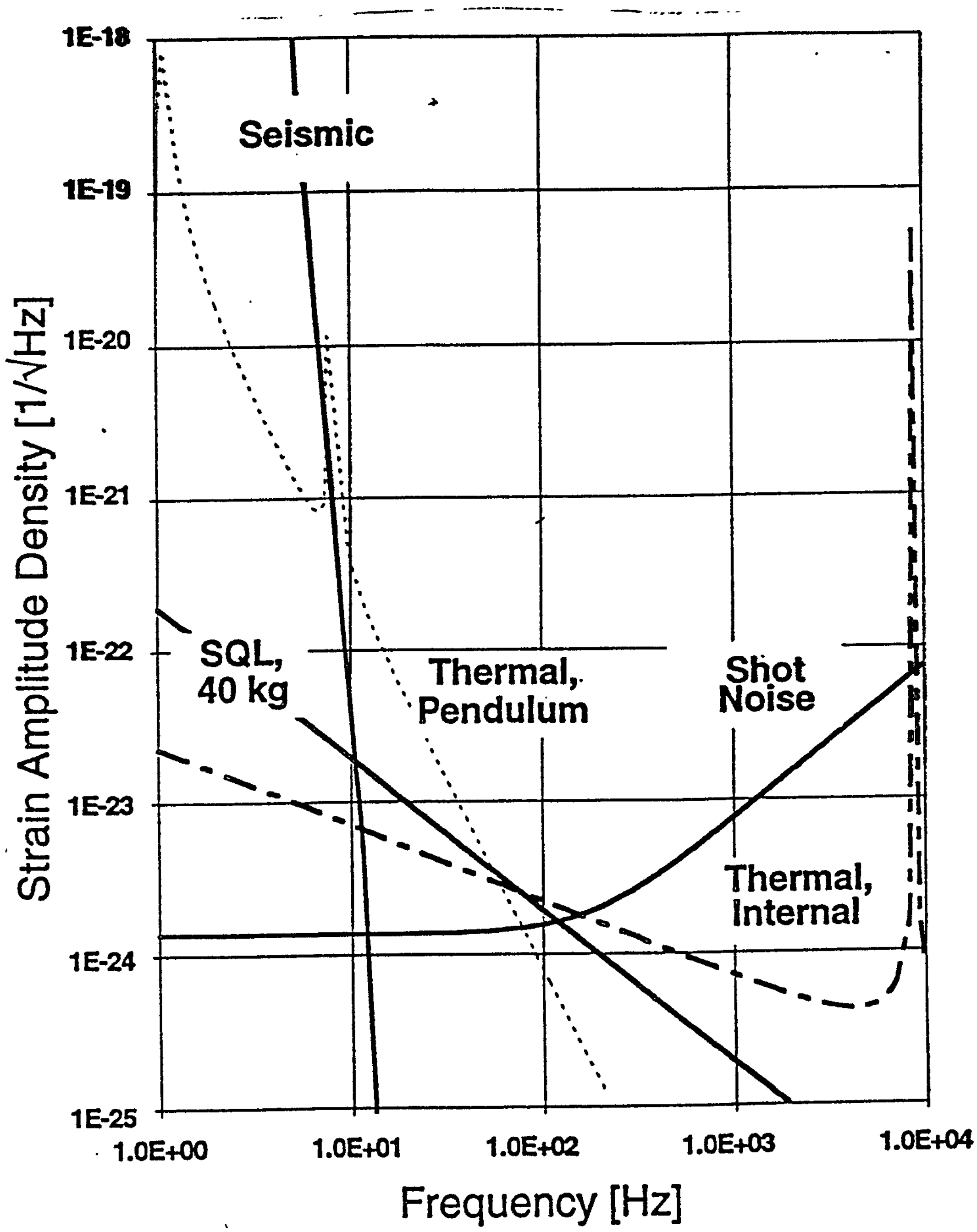
Initial Interferometers

Noise Floor



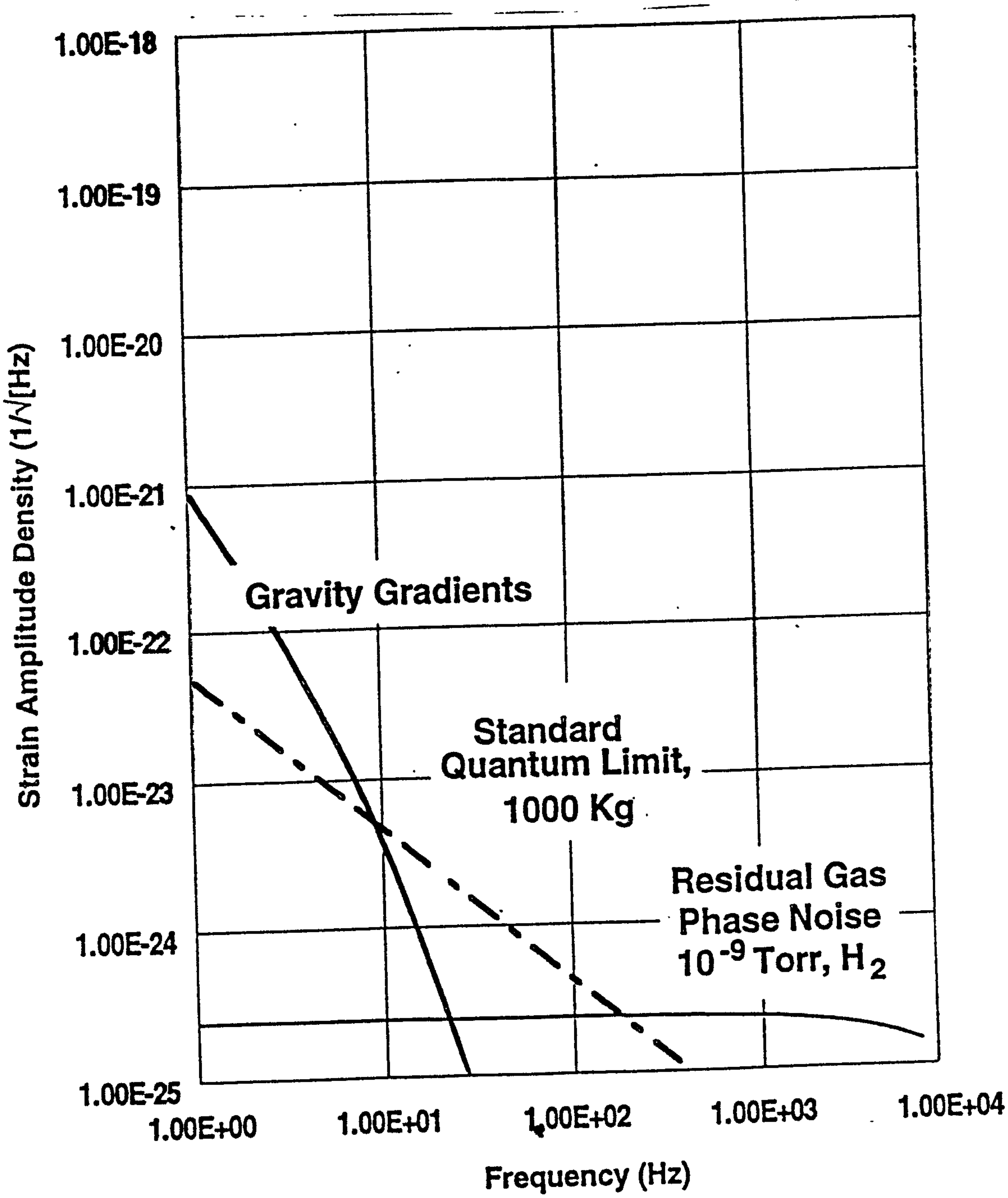
Enhanced Interferometer

Noise Budget



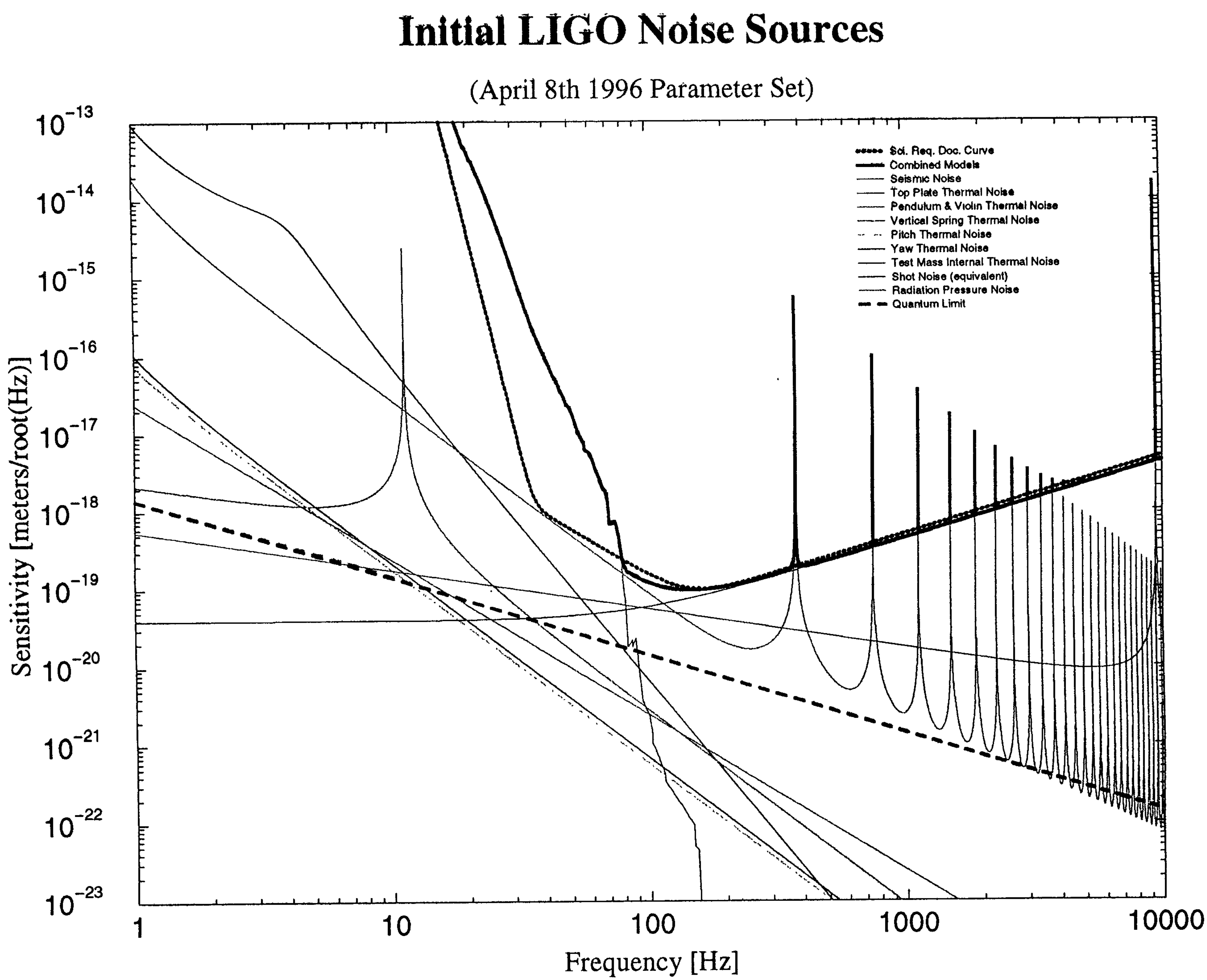
LIGO Facilities

Limiting Noise Floor



LIGO

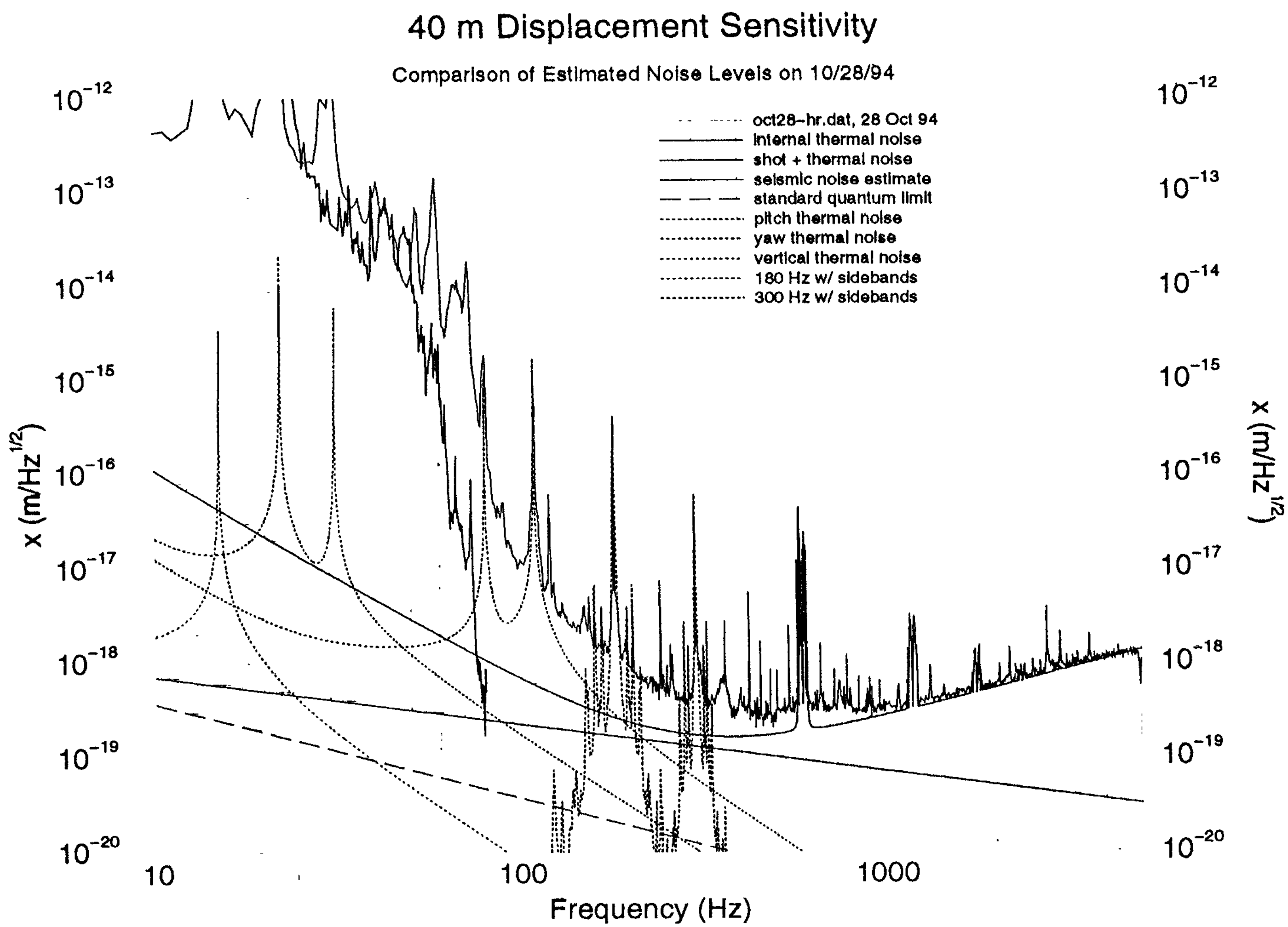
LIGO-G960108-00-M

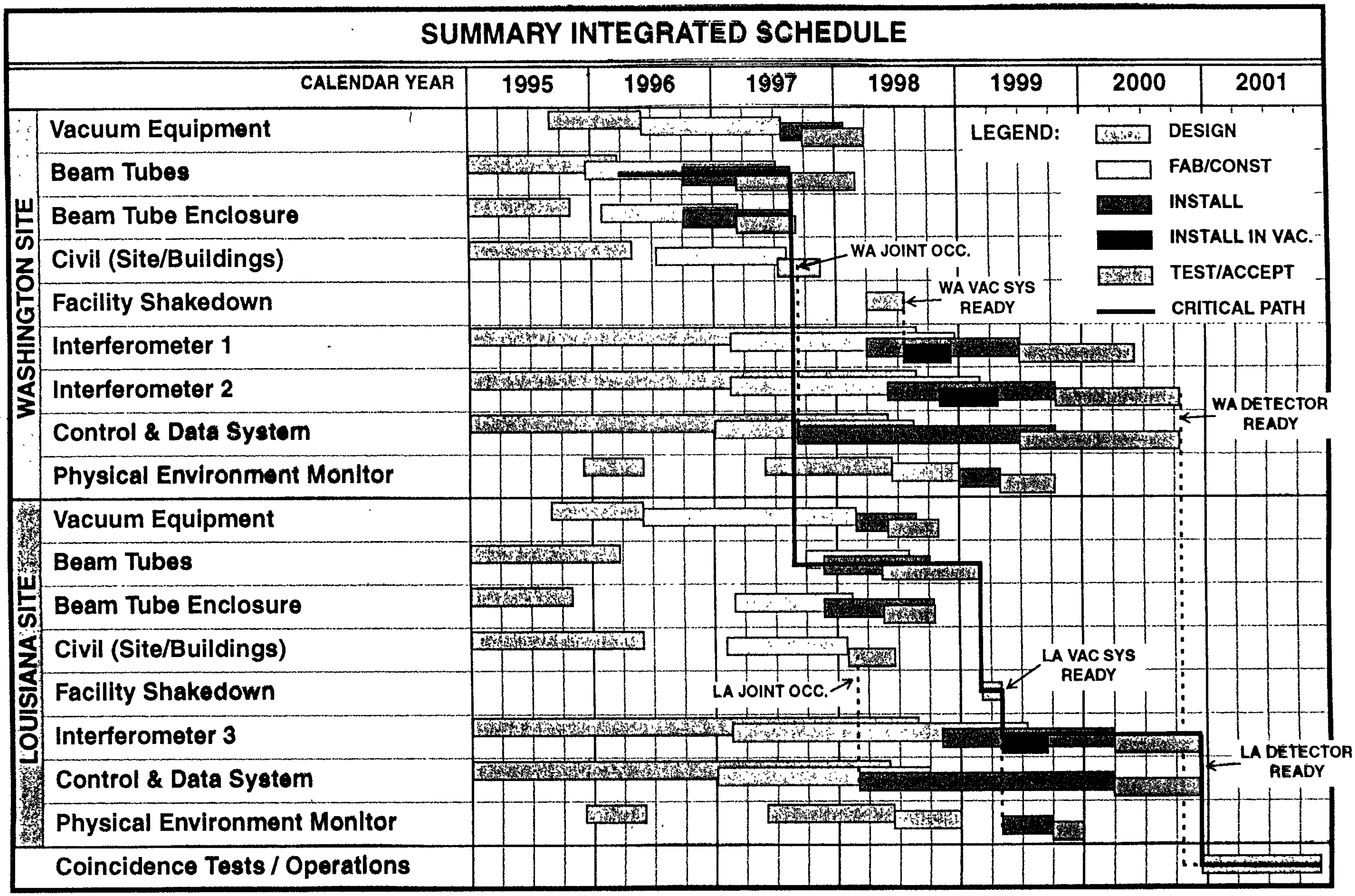


Initial LIGO Noise Sources
(April 8th 1996 Parameter Set)
Sci. Req. Doc. Curve
Combined Models
Seismic Noise
Top Plate Thermal Noise
Pendulum & Violin Thermal Noise
Vertical Spring Thermal Noise
Pitch Thermal Noise
Yaw Thermal Noise
Test Mass Internal Thermal Noise
Shot Noise (equivalent)
Radiation Pressure Noise
Quantum Limit
Sensitivity [meters/root(Hz)]
Frequency [Hz]

LIGO Systems Engineering and Integration

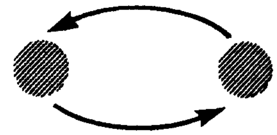
40 m Lab



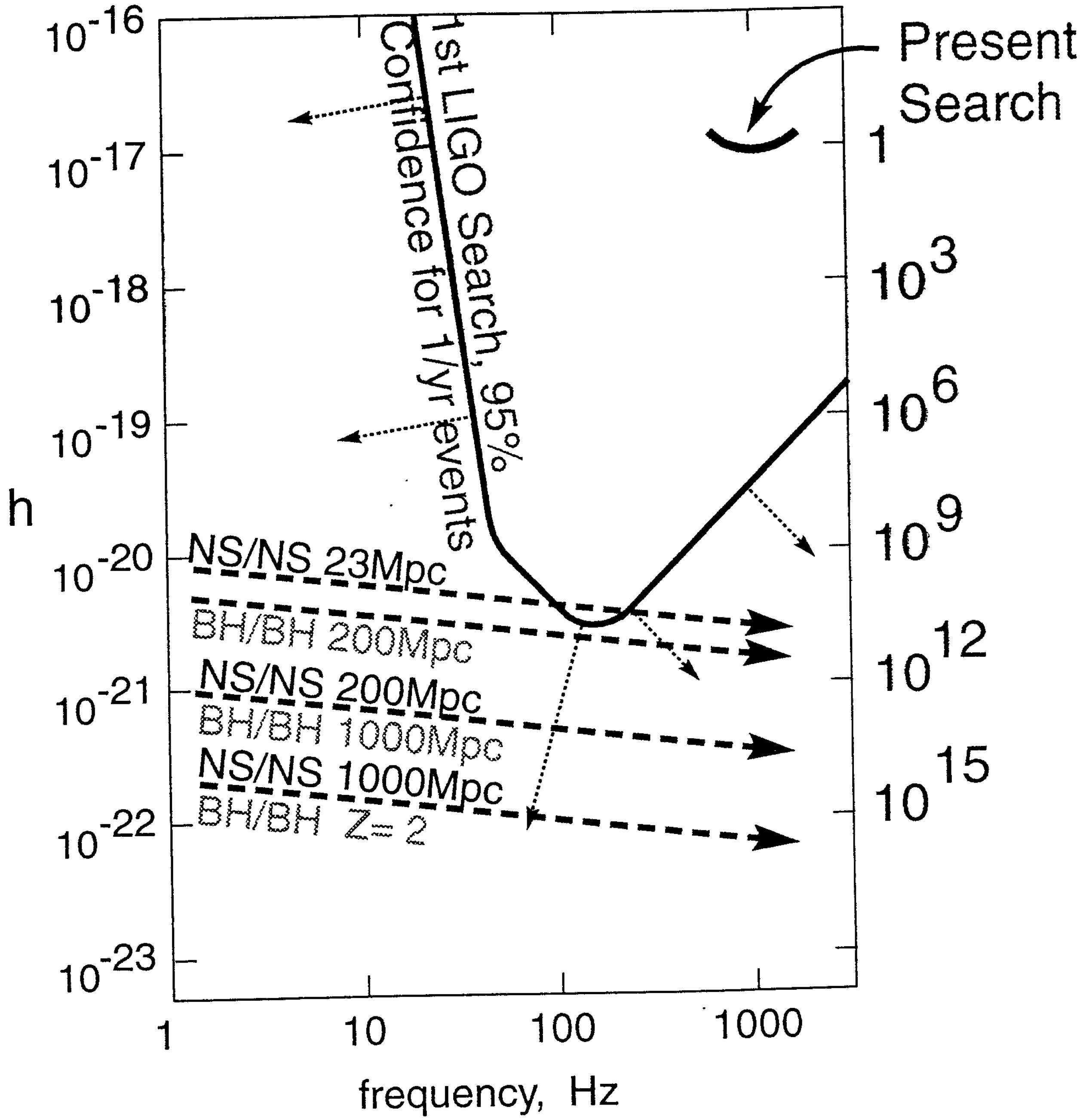


SUMMARY INTEGRATED SCHEDULE
CALENDAR YEAR
1995
1996
1997
1998
1999
2000
2001
WASHINGTON SITE
Vacuum Equipment
Beam Tubes
Beam Tube Enclosure
Civil (Site/Buildings)
Facility Shakedown
Interferometer 1
Interferometer 2
Control & Data System
Physical Environment Monitor
LOUISIANA SITE
Vacuum Equipment
Beam Tubes
Beam Tube Enclosure
Civil (Site/Buildings)
Facility Shakedown
Interferometer 3
Control & Data System
Physical Environment Monitor
Coincidence Tests / Operations
LEGEND:
DESIGN
FAB/CONST
INSTALL
INSTALL IN VAC.
TEST/ACCEPT
CRITICAL PATH
WA JOINT OCC.
WA VAC SYS READY
WA DETECTOR READY
LA VAC SYS READY
LA JOINT OCC.
LA DETECTOR READY

NEUTRON STAR BINARIES



["Near-Guaranteed" source]



- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

G960025-02-0-V

Conclusions

- LIGO Construction is well Underway
- Direct Detection of Gravitational Waves Appears Realistic within 10 years
- Ultimate Sensitivities Capable of Opening a New Field of Observational Astronomy with Gravitational Waves is the Long Term Goal.