# LIGO

## LASER INTERFEROMETER GRAVITATIONAL -WAVE OBSERVATORY

# PROGRESS AND PROSPECTS

**JAMES KENT BLACKBURN**

**LIGO PROJECT**

**CALTECH**

MATHEMATICAL ASPECTS OF THEORIES OF GRAVITATION

26 FEBRUARY - 30 MARCH 1996

INTERNATIONAL STEFAN BANACH CENTER

INSTITUTE OF MATHEMATICS

POLISH ACADEMY OF SCIENCE

WARSAW, POLAND

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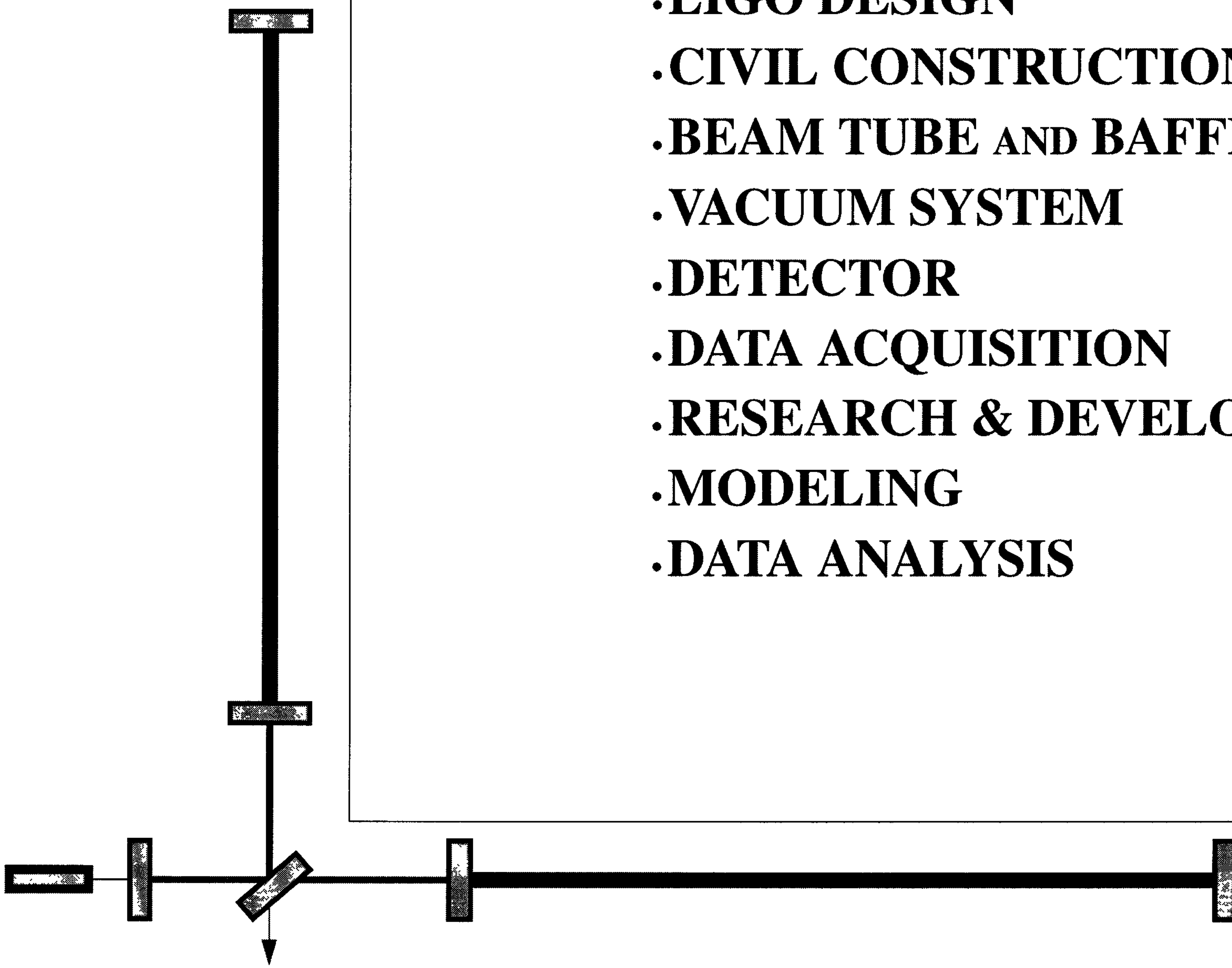
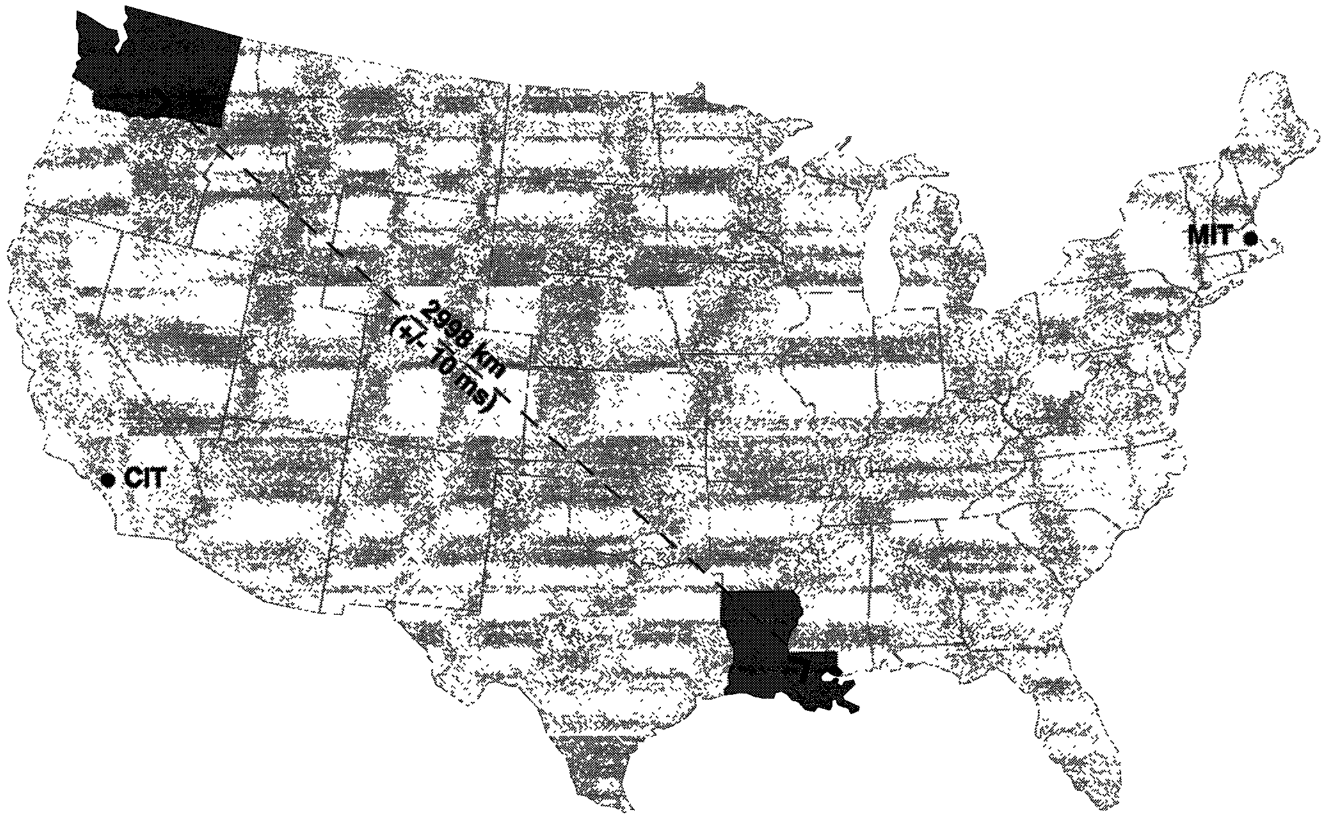
# OVERVIEW

- LIGO DESIGN
- CIVIL CONSTRUCTION
- BEAM TUBE AND BAFFLES
- VACUUM SYSTEM
- DETECTOR
- DATA ACQUISITION
- RESEARCH & DEVELOPMENT
- MODELING
- DATA ANALYSIS



# LIGO SITES




## Hanford, Washington

- Located on U.S. DOE reservation
- Treeless, semi-arid high desert
- ~ 25 km from Richland, WA
- Initially one 4km & one 2km IFO

## Livingston, Louisiana

- Located in forested rural area
- Low-lying; Poor drainage
- ~ 50 km from Baton Rouge, LA
- Initially a single 4km IFO

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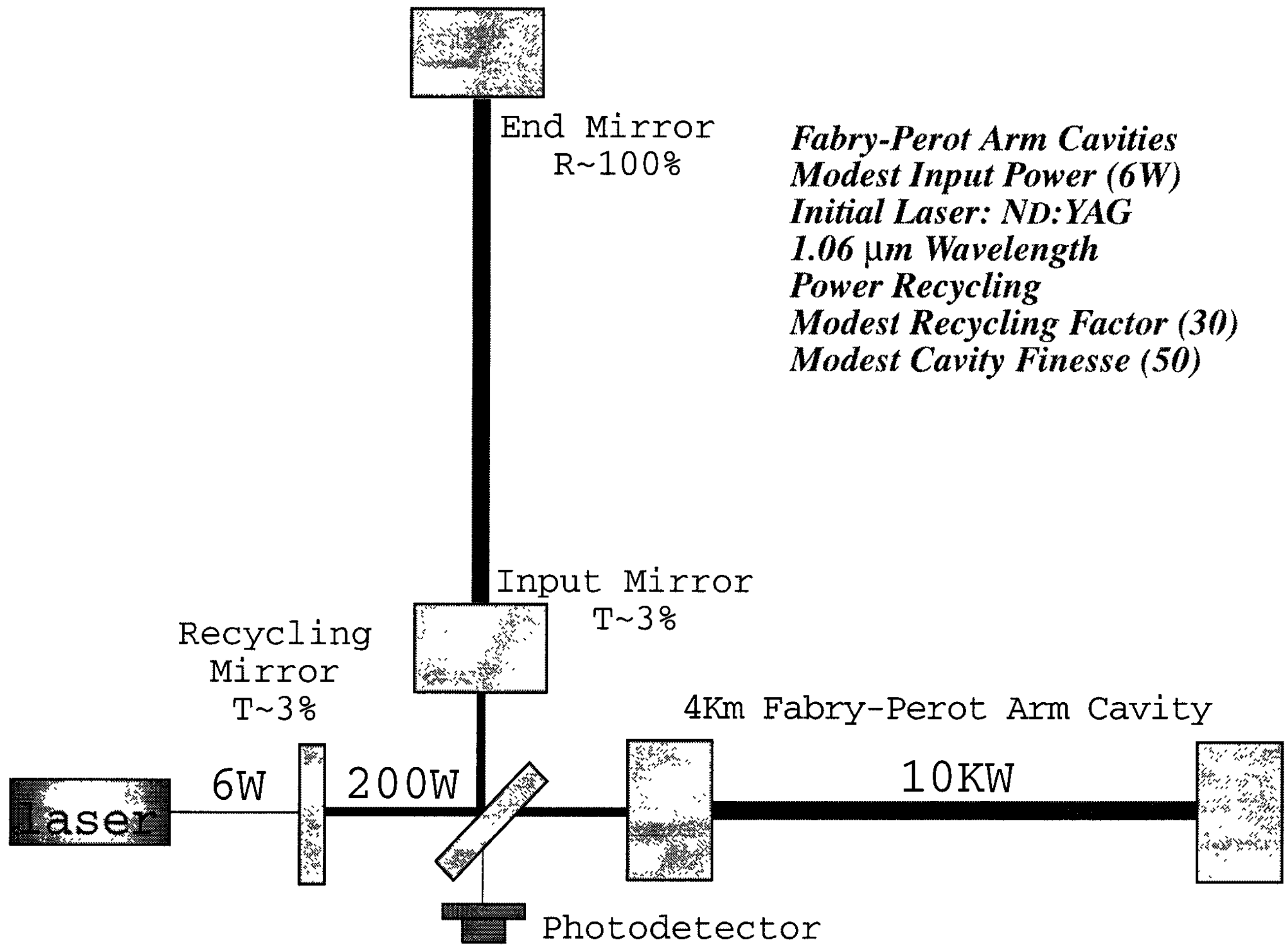
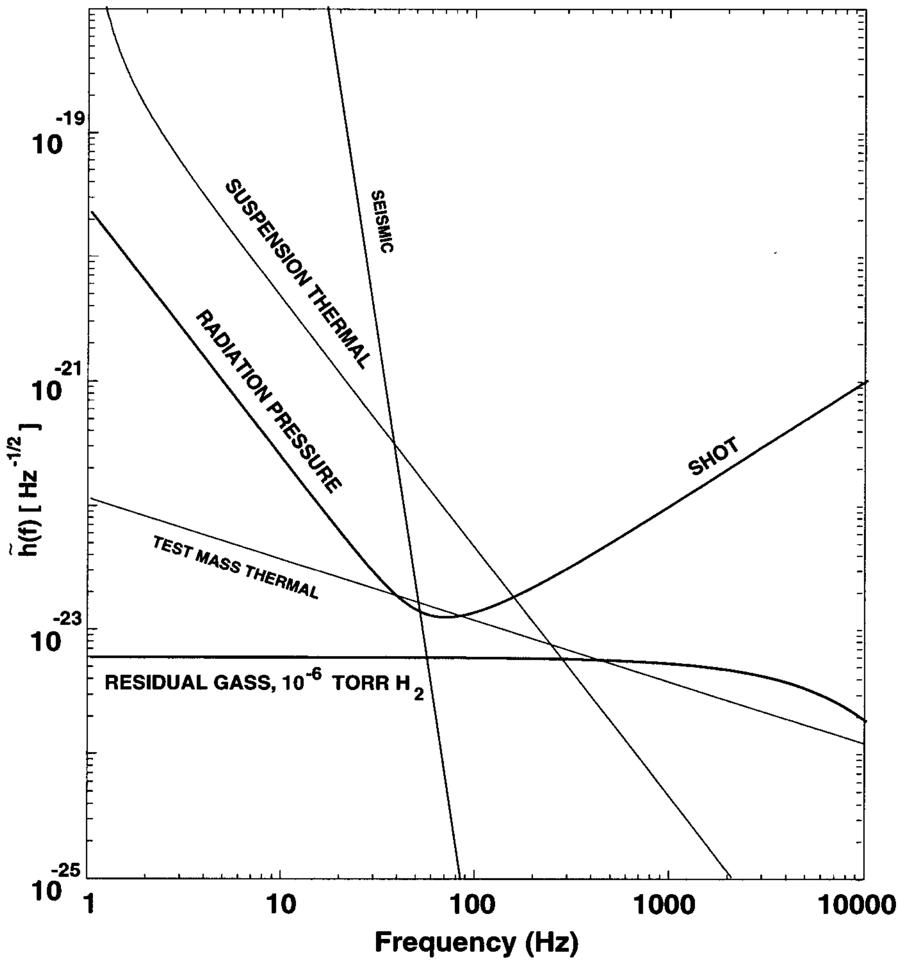
# INITIAL INTERFEROMETER CONFIGURATION



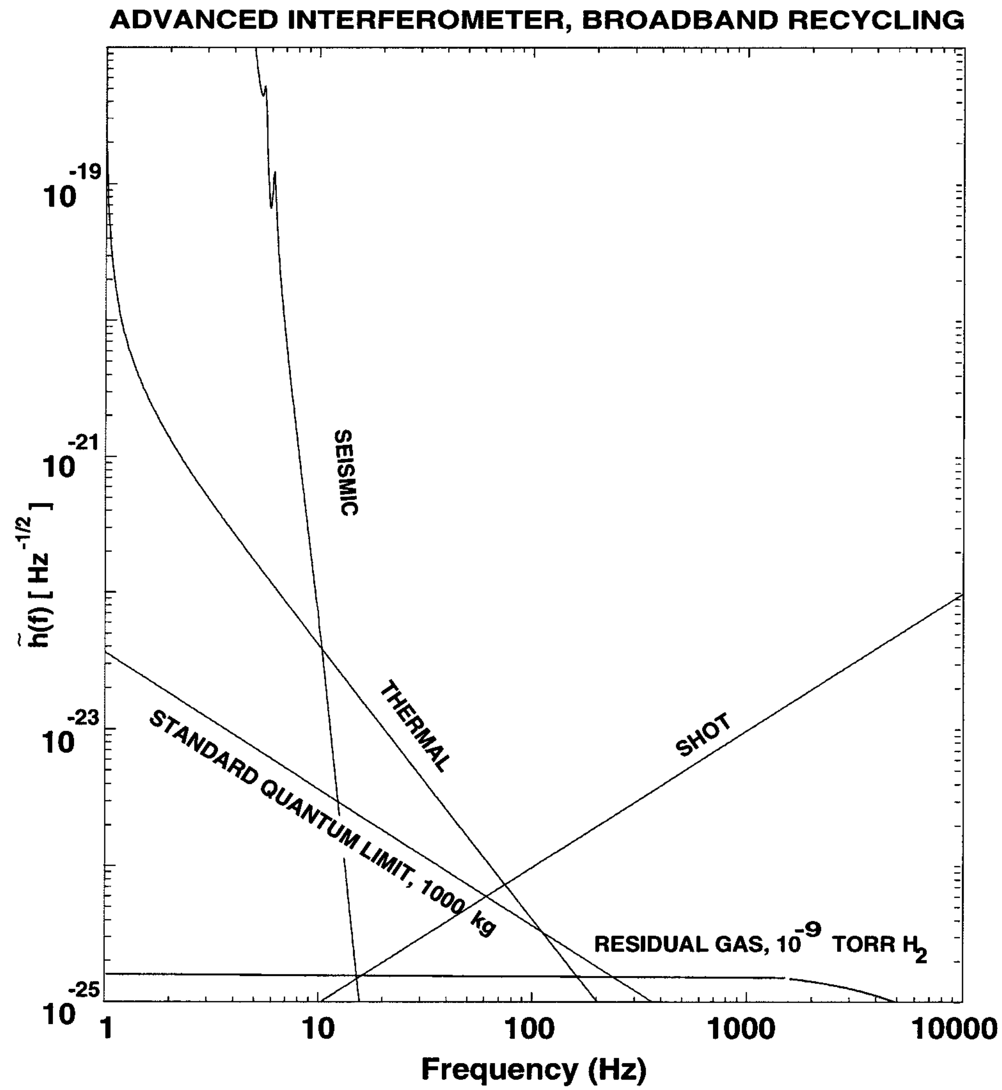

*Fabry-Perot Arm Cavities*
*Modest Input Power (6W)*
*Initial Laser: ND:YAG*
*1.06 µm Wavelength*
*Power Recycling*
*Modest Recycling Factor (30)*
*Modest Cavity Finesse (50)*

# INITIAL INTERFEROMETER DESIGN PERFORMANCE GOAL

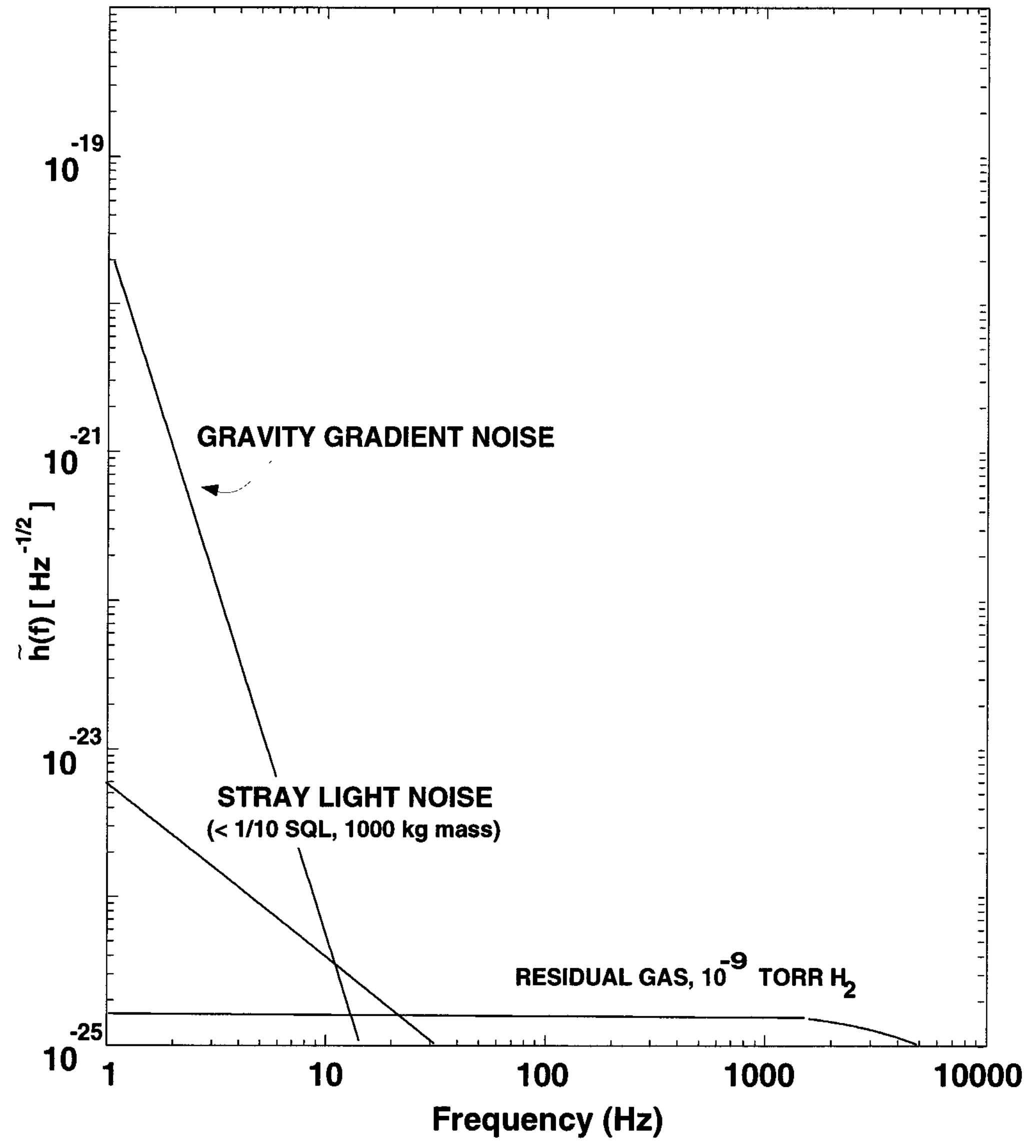
**INITIAL INTERFEROMETER SENSITIVITY**



# ADVANCED INTERFEROMETER DESIGN PERFORMANCE GOAL



# LIMITING PERFORMANCE DUE TO FACILITIES



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# OPERATIONAL CONSIDERATIONS

## PURPOSE: ASTROPHYSICAL RESEARCH

- HIGH ON-LINE AVAILABILITY
  - reliability studies currently underway with JPL
- MULTIPLE MODES OF OPERATION
  - 3X: $T_{online} > 75\%$
  - 2X (WA-LA): $T_{online} > 85\%$
  - 1X: $T_{online} > 90\%$
- ALLOCATION OF OBSERVING TIME
- TIME FOR DEVELOPMENT OF IMPROVED DETECTORS
- EXTREME CARE IN DESIGNING QUIET FACILITIES
- DATA FORMAT COMPATIBILITY WITH OTHER GW & PARTICLE DETECTORS
- LONG TERM DEVELOPMENT OF ADVANCED DETECTORS

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# CIVIL CONSTRUCTION

- BOTH SITES UNDER CONSTRUCTION
  - Infrastructure: large clean lab, high bay (9m hook height), beam tube enclosure for protection, office & lab space to accommodate staff and visitors, roads, foundations, structures, etc.
  - Requirements: remote sites with seismic stability, thick slab, isolated foundations, separated buildings, few internal noise sources such as EMI/EMF backgrounds, remotely operable facilities, cleanliness.
- WASHINGTON SITE
  - graded to final topography; soil settlement completed
  - beam tube slab/roads/enclosure under construction
- LOUISIANA SITE
  - logged and cleared (ground breaking took place 7/95)
  - being graded to interferometer plane
- PRELIMINARY DESIGN OF THE LIGO FACILITIES COMPLETED 12/95
  - laser & vacuum equipment areas (LVEA/VEA)
  - operations and support buildings (OSB)
  - mechanical equipment room, chilled water plant
- FINAL DESIGN SCHEDULED FOR 4/96

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# BEAM TUBE AND BAFFLES

- MODULE LENGTHS OF 2KM (*16KM TOTAL; 140KM OF WELDS*)
- TUBE DIAMETER 1.22M (*1M CLEAR APERTURE*)
- VERY LOW ALLOWED AIR LEAKAGE
  - $\mathcal{F} < 10^{-9}$ Atm cc/s He; (demonstrated $\mathcal{F} < 10^{-11}$ Atm cc/s)
- VERY LOW OUTGASSING (*DEMONSTRATED IN PROTOTYPE*)
  - $P_{ADVANCED} < 10^{-9}$ torr (all residuals)
  - $J[H_2]$: $< 10^{-13}$ torr-liter/cm2/s; (demonstrated $J[H_2]$: $< 10^{-13}$ torr-liter/cm2/s)
  - $J[H_2O]$: $< 10^{-15}$ torr-liter/cm2/s; (demonstrated $J[H_2O]$: $< 10^{-15}$ torr-liter/cm2/s)
  - Partial pressures for $CO + CO_2 + H_{2N}C_{2N}$ + ... must be even lower (demonstrated)
- BAFFLING TO REDUCE SCATTERED LIGHT PHASE NOISE
- BAFFLES GIVE PSEUDORANDOM SERRATION PATTERN
  - 8mm P-P serrations @ 6mm pitch
  - 25% variation in P-P to minimize coherence effects
- BAFFLES COATED WITH OPTICAL BLACK GLASS ENAMELED GLAZE
  - R < 0.1 averaged over S & P polarizations
  - $P_{BACKSCATTER} = 10^{-3}$ sr$^{-1}$

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# VACUUM SYSTEM

- CLEAR APERTURE FOR THE INTERFEROMETER
- CLEAN ENVIRONMENT FOR THE PRECISION OPTICS
- LOW PRESSURE IN ORDER TO MINIMIZE DIFFRACTION AND ACOUSTIC COUPLING
- EXTENSIVE CONTROLS AND MONITORING EQUIPMENT TO ENSURE SAFE OPERATIONS
- LARGE PUMPING SPEEDS AND VOLUMES
- WORLD'S LARGEST HIGH PERFORMANCE VACUUM SYSTEM WITH A PUMPED VOLUME OF ~20,000 CUBIC METERS
- USES MOSTLY CONVENTIONAL VACUUM HARDWARE
- FINAL DESIGN REVIEW SCHEDULED FOR 4/96

# DETECTOR

## CHARACTERISTICS

- BASELINE CONFIGURATION EMPLOYS PROVEN TECHNIQUES
  - 40m and 5m scale systems at CIT and MIT
  - optics experiments on recombination and recycling being performed in R&D
  - precision engineering
  - baseline changed 8/95 from $Ar^{+}$ (0.5145 m) laser to $Nd^{3+}$:YAG laser (1.064 m)
- COLLABORATIVE STUDIES WITH INDUSTRY TO DEVELOP MIRROR COATING AND POLISHING TECHNOLOGIES
- BUILT-IN DESIGN FLEXIBILITY FOR LATER IMPROVEMENTS AS R&D RESULTS BECOME AVAILABLE
  - passive and active seismic isolation
  - sensing and controls
  - advanced controls & data system using state of the art LAN/WAN architectures

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# DETECTOR

## STATUS

- DETECTOR DESIGN UNDER WAY
- INITIAL DESIGN REVIEWS HELD

- prestabilized laser subsystem (PSL)

- alignment control system design readiness review held 5/95

- suspension subsystem design readiness review held 6/95

- core optics component design readiness review held 2/96

- CDS control and monitoring design readiness review held 2/96

- mode-cleaner prototype available for use in 40m interferometer

- PSL prototype installed for use in 40m interferometer

- active seismic isolation (STACIS system from Barry Controls, Inc.) successfully demonstrated at MIT

- seismic isolation system (passive) being optimized by HYTEC, Inc. (Los Alamos, N.M.)

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# DATA ACQUISITION

## INTERFEROMETER DATA ACQUISITION DESIGN

- all data relevant to the operation of the interferometer, strain data stream plus large number of internal data from feedback signals and status information
- number of channels per interferometer: ~1400
- sample rates: 2Hz to 20kHz
- data rate per interferometer: ~2850 ksamples per second (5.7 MBytes/second)

## PHYSICS MONITORING DATA ACQUISITION DESIGN

- monitoring for seismic noise, acoustic noise, magnetic fields, RF interference, cosmic ray muons, power line fluctuations, residual gas, vacuum contamination, temperatures in vacuum chambers and beam tubes, relative humidity, wind speed and direction
- number of channels: 345 @ WA; 223 @ LA
- sample rates: 0.1Hz to 2500 Hz
- data rate at Washington site: 658 ksamples/second (1.3 MBytes/second)
- data rate at Louisiana site: 405 ksamples/second (0.82 MBytes/second)

**TWO 12 MBYTE/SEC/IFO TAPE DRIVES USED FOR CONTINUOUS RECORDING**

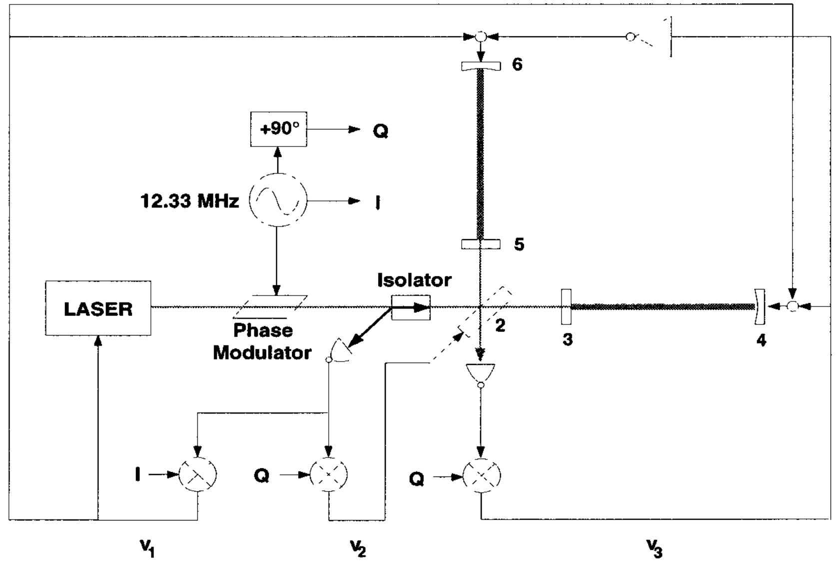
# RESEARCH AND DEVELOPMENT

## OBJECTIVES

- PROVIDES TIME LAG BETWEEN R&D EFFORTS WHICH DEMONSTRATE ENABLING TECHNOLOGIES AND DETAILED TASKS FOR LIGO DETECTOR DESIGNS
  - Nd:YAG laser
  - sensitivity limiting noise sources
  - optical configuration definition studies
  - phase noise studies at high recycling power
  - alignment, sensing and control
  - active/passive seismic isolation
  - data acquisition and analysis
- VALIDATES DESIGN PROTOTYPES
  - triangular mode cleaner
  - prestabilized laser subsystem
  - test mass suspension subsystem
- SUPPORTS INITIAL DETECTOR TECHNOLOGY
- ESTABLISHES FOUNDATION FOR FUTURE INTERFEROMETER ADVANCES
- FORMS LIAISONS WITH OTHER INTERESTED RESEARCH GROUPS

# CALTECH 40-METER INTERFEROMETER

## PRESENT CONFIGURATION



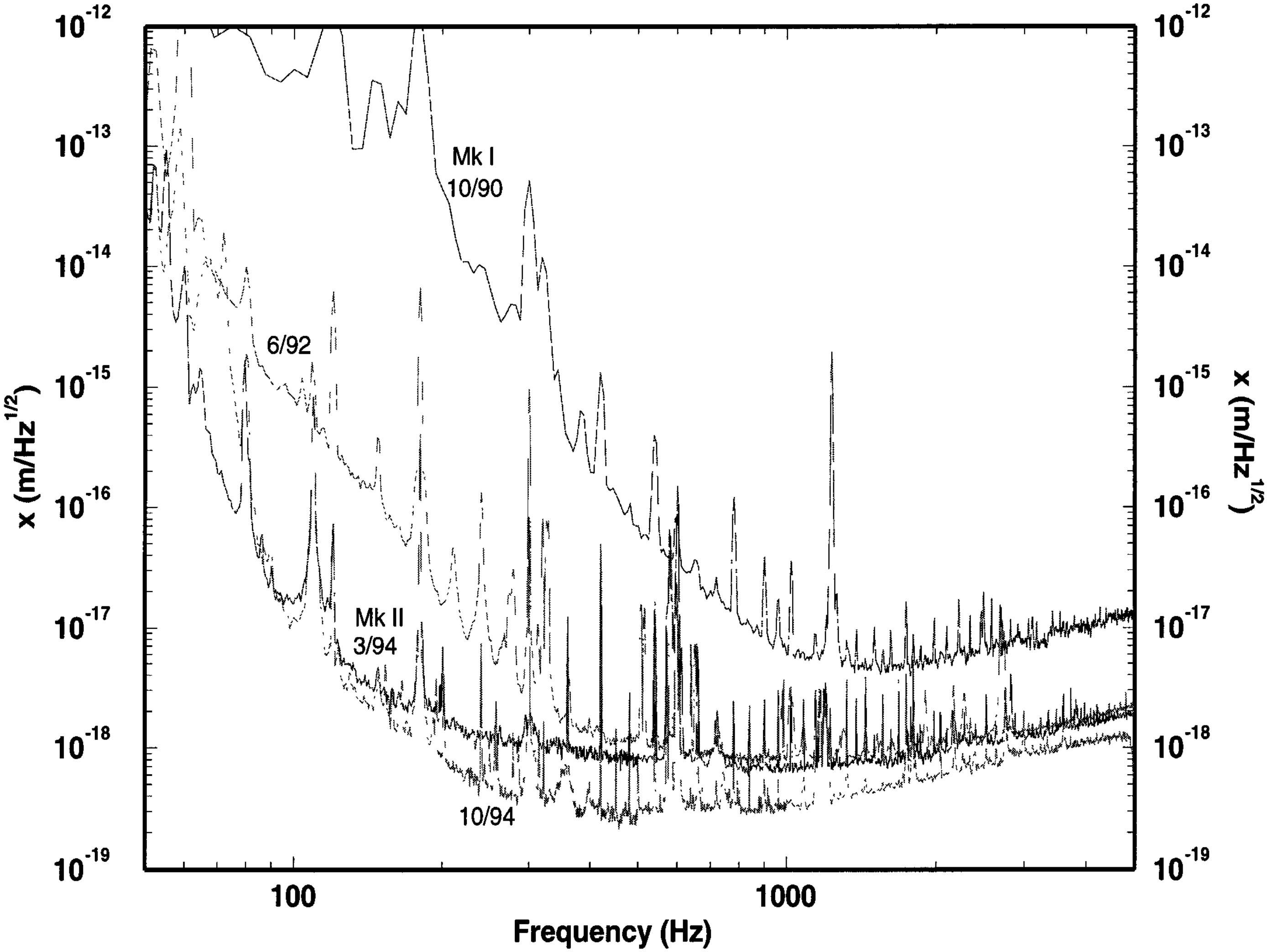

- gain experience with suspended, recombined interferometer
- characterization of sensing system, error signals, imperfections

## PLANS FOR 1996

- implement prestabilized laser
- addition of recycling mirror and new input mirrors
- incorporate EPICS based “Slow Parameter Monitoring System”
- characterize both small and large signal dynamics

# IMPROVEMENTS IN 40-METER SENSITIVITY

**Displacement Sensitivity of Caltech 40 m Interferometer**



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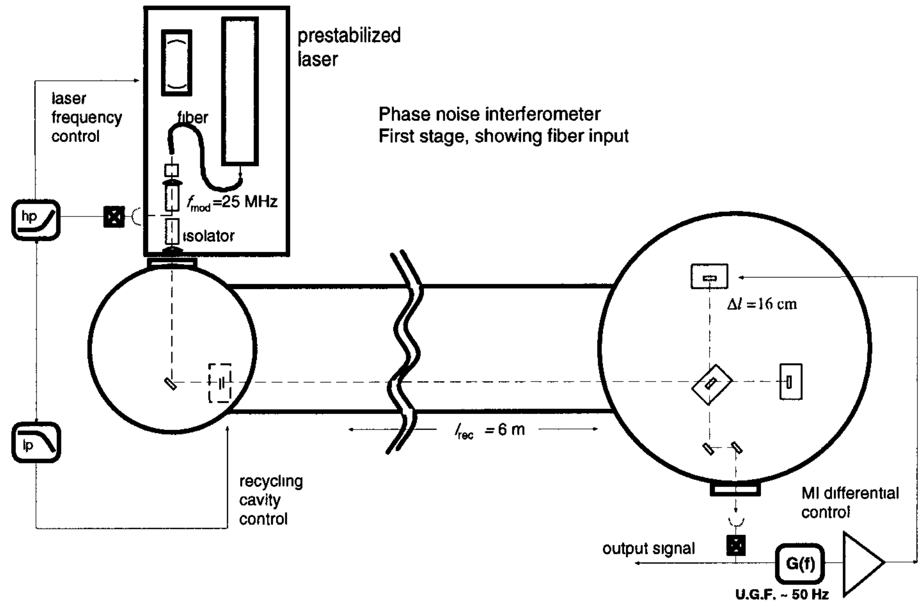
# MIT PHASE NOISE INTERFEROMETER

## PRESENT CONFIGURATION

### (Non-Recycled Michelson)




- demonstrate initial LIGO phase sensitivity (~$10^{-10}$ RAD/√HZ)
- develop sensors, electronics, scattering controls needed
- beta test of commercial "Active Isolation Unit" from Barry, Inc.

## PLANS FOR 1996

- addition of recycling mirror

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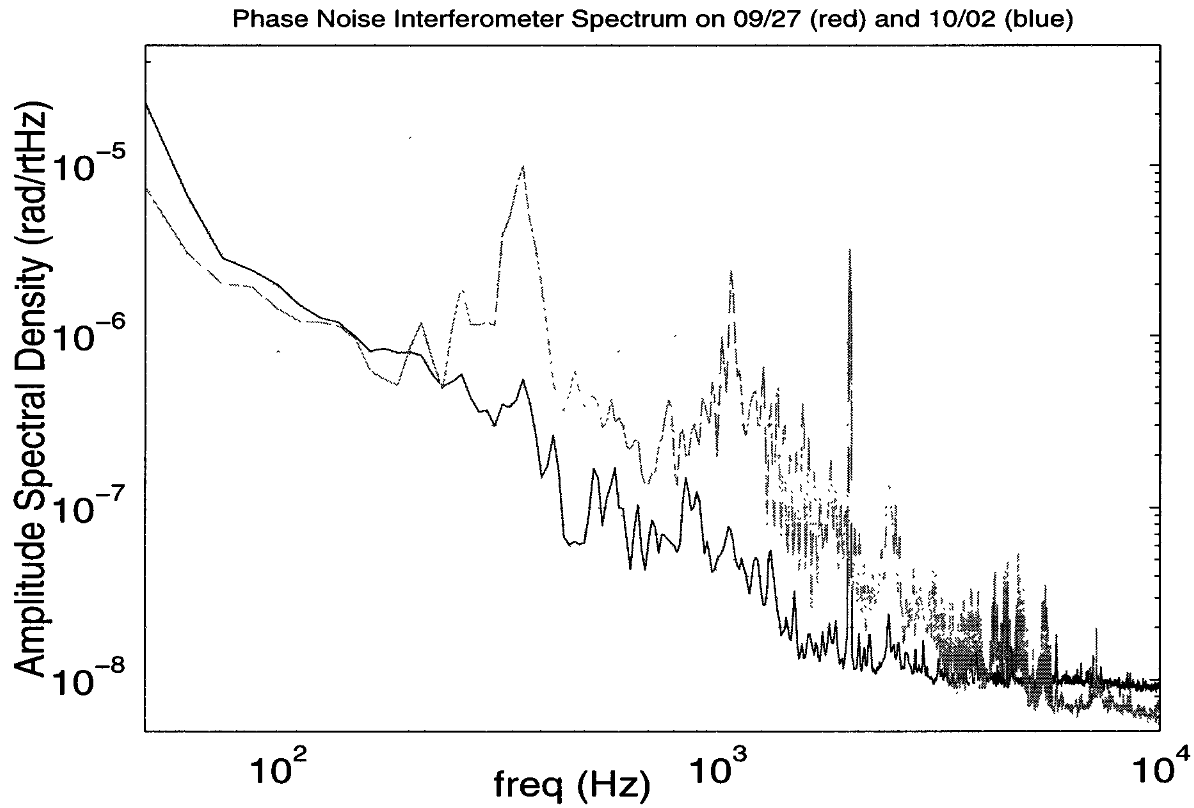
# IMPROVEMENTS IN MIT PN-IFO SENSITIVITY




- INITIAL SHAKEDOWN UNCOVERED CONTRAST VARIATIONS
  - correlated with passing subways, trucks and magnetic fields (not seismic noise)
  - resolved by reworking suspended optics controllers
  - demonstrated shot noise limited phase noise at high frequencies: $5\times10^{-9}$ RAD/√Hz

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# MODELING LIGO

- **LIGO END-TO-END MODEL:** Currently developing an integrated modular environment to model LIGO.
- **GOALS:** To design, develop, understanding, explore LIGO in software.
- **SOFTWARE:** Software development based on commercial data visualization environment (AVS5 & Express) from Advanced Visualization Systems. Code development in C, C++, and FORTRAN.
- **HARDWARE:** Unix workstations (Sun) and massively parallel computers (Intel Paragon) used for computation.
- **PHYSICS MODELS:** Building blocks are interferometer, noise sources, control loops and gravitational wave sources.
- **DOMAIN:** Present effort has focused on frequency domain models. Time domain models desirable and planned for near future.
- **SUPPORT:** Modeling provides direct support to the Detector and R&D effort within LIGO by answering design questions and allowing trade studies.
- **DATA ANALYSIS:** END-TO-END MODEL will be able to calculate response of LIGO to gravitational waves and produce simulated data streams for use in data analysis development.

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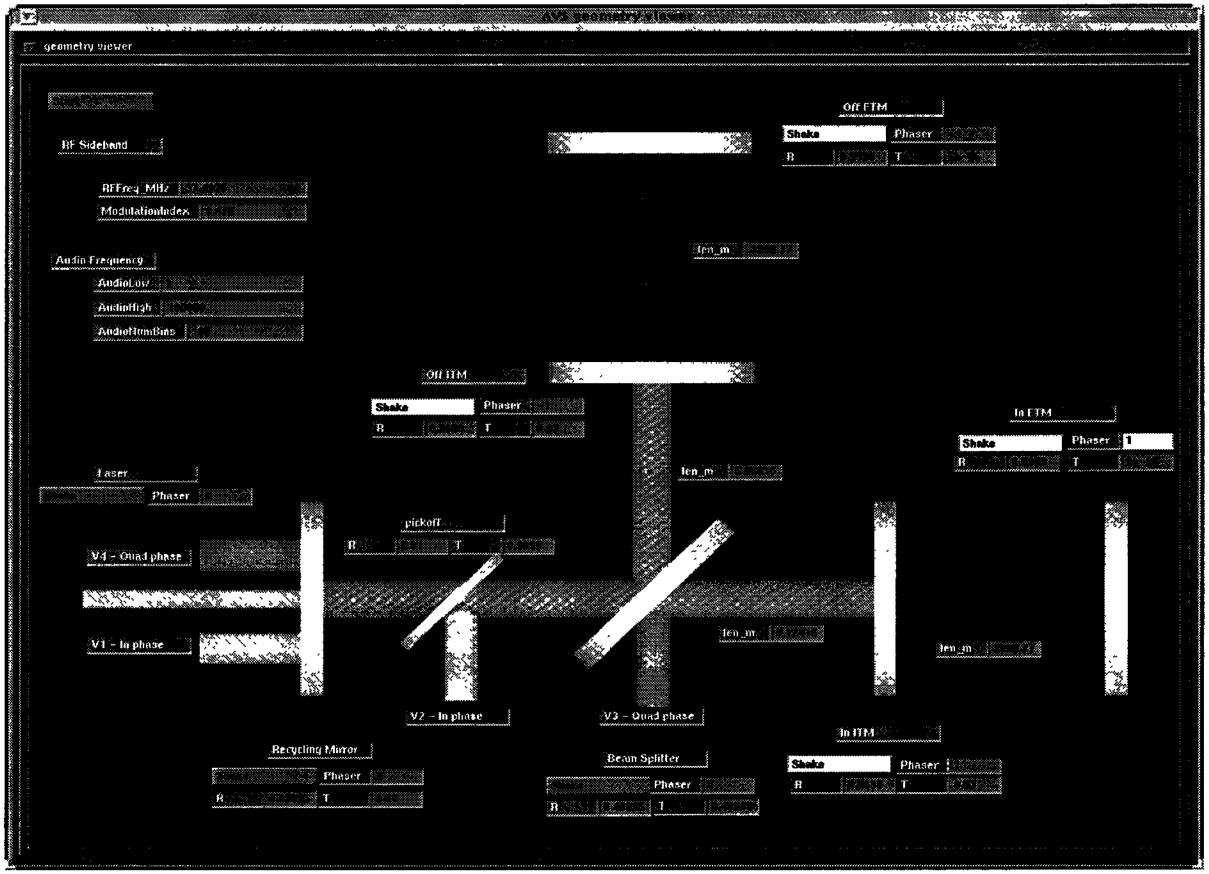
# INTERFEROMETER MODELING

- **<u>FREQUENCY DOMAIN</u>:** FFT, MODAL, TWIDDLE
  - static design, alignment, response
- **<u>TIME DOMAIN</u>:** SINGLE MODE, SPACIAL MULTI-MODE
  - lock acquisition, small to large misalignment



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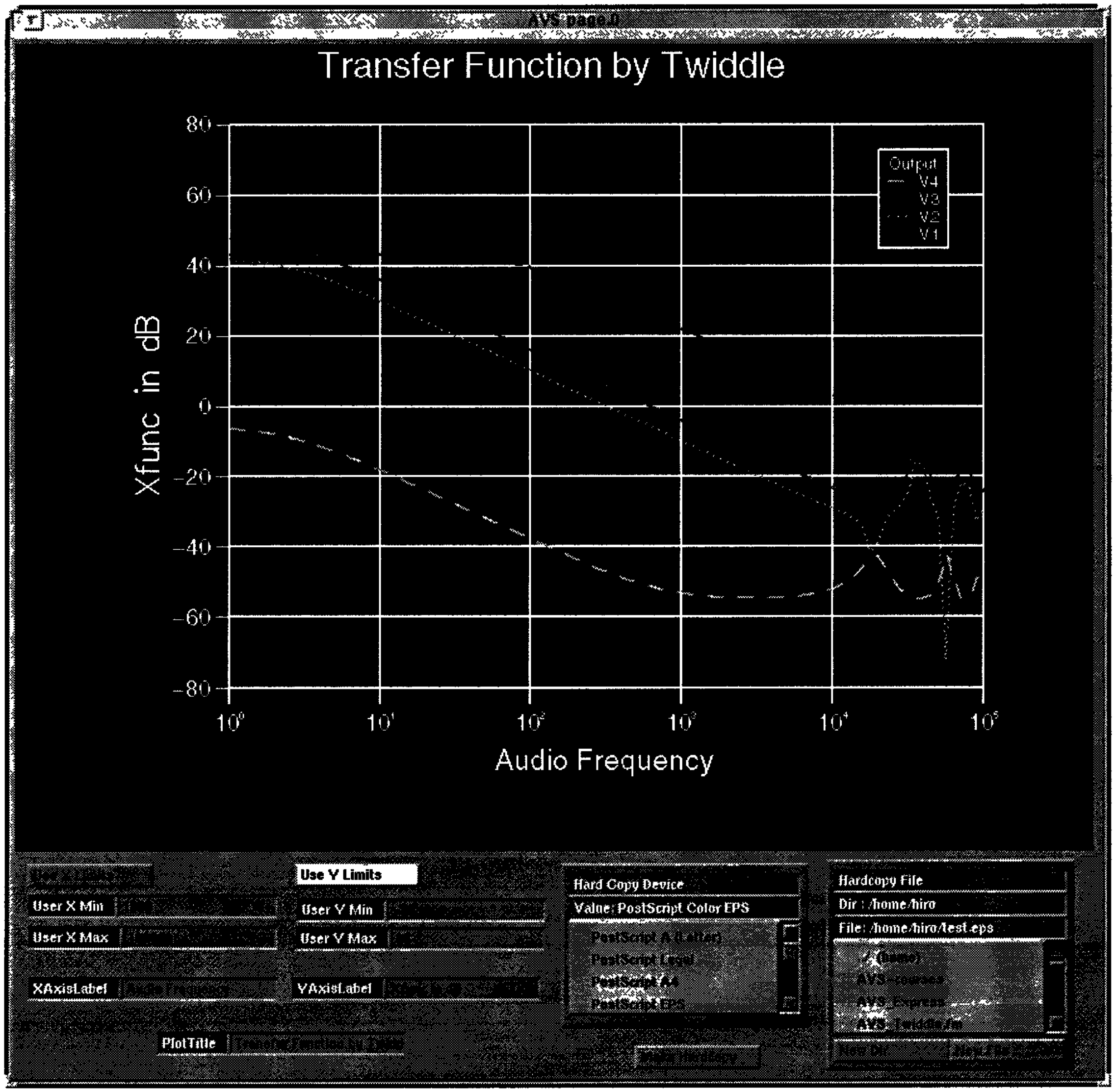
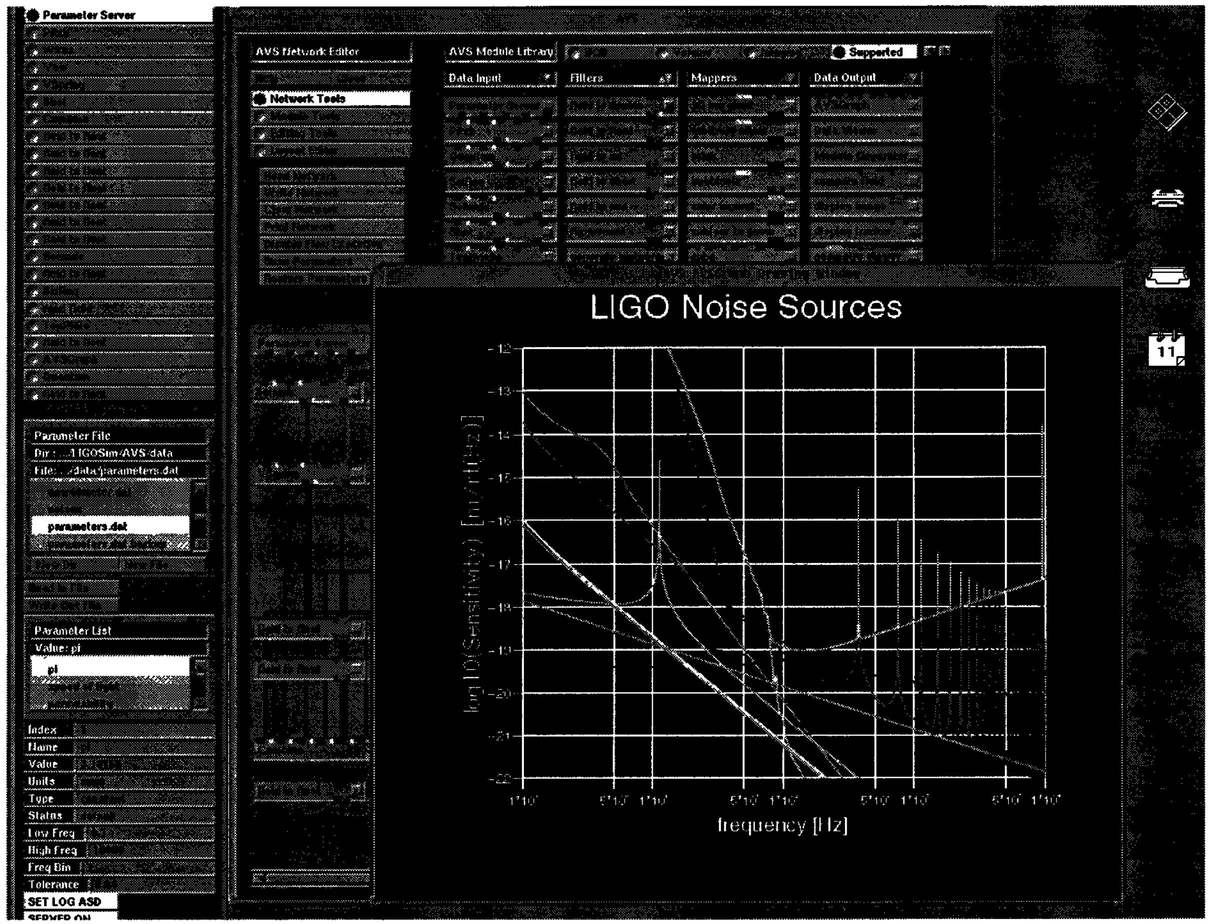
# IFO TRANSFER FUNCTION CALCULATED WITH TWIDDLE



# NOISE MODELING

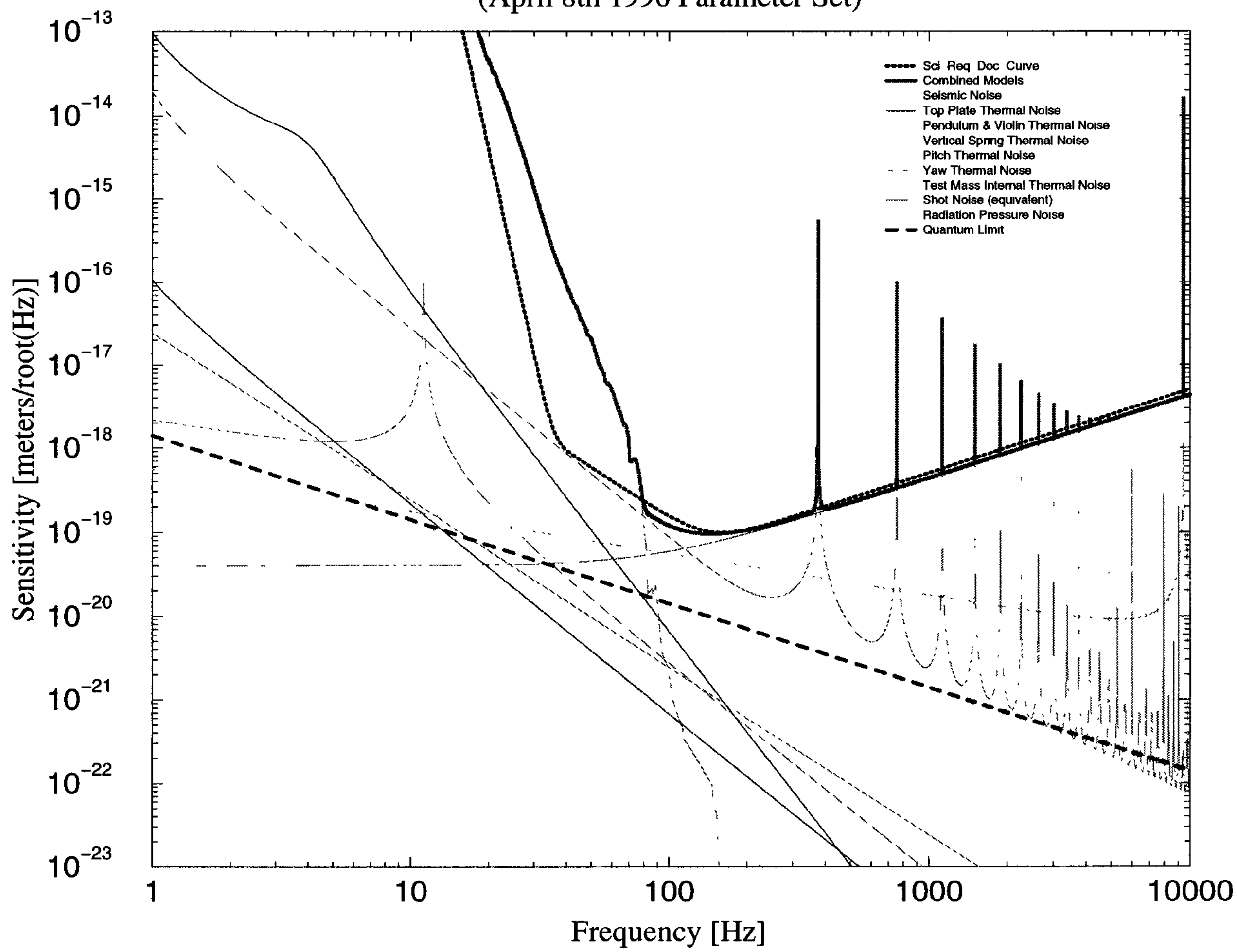
- **<u>PRIMARY NOISE SOURCES</u>:** Seismic Noise, Thermal Noises, Shot Noise
- **<u>SECONDARY NOISE SOURCES</u>:** Gravity Gradient Noise, Laser Noise, Residual Gas Noise, Radiation Pressure, Phase Noise Due To Scattering, Magnetic & Electric Field Noise, Technical Noises



# INITIAL LIGO NOISE CHARACTERIZATION

## Initial LIGO Noise Sources

(April 8th 1996 Parameter Set)



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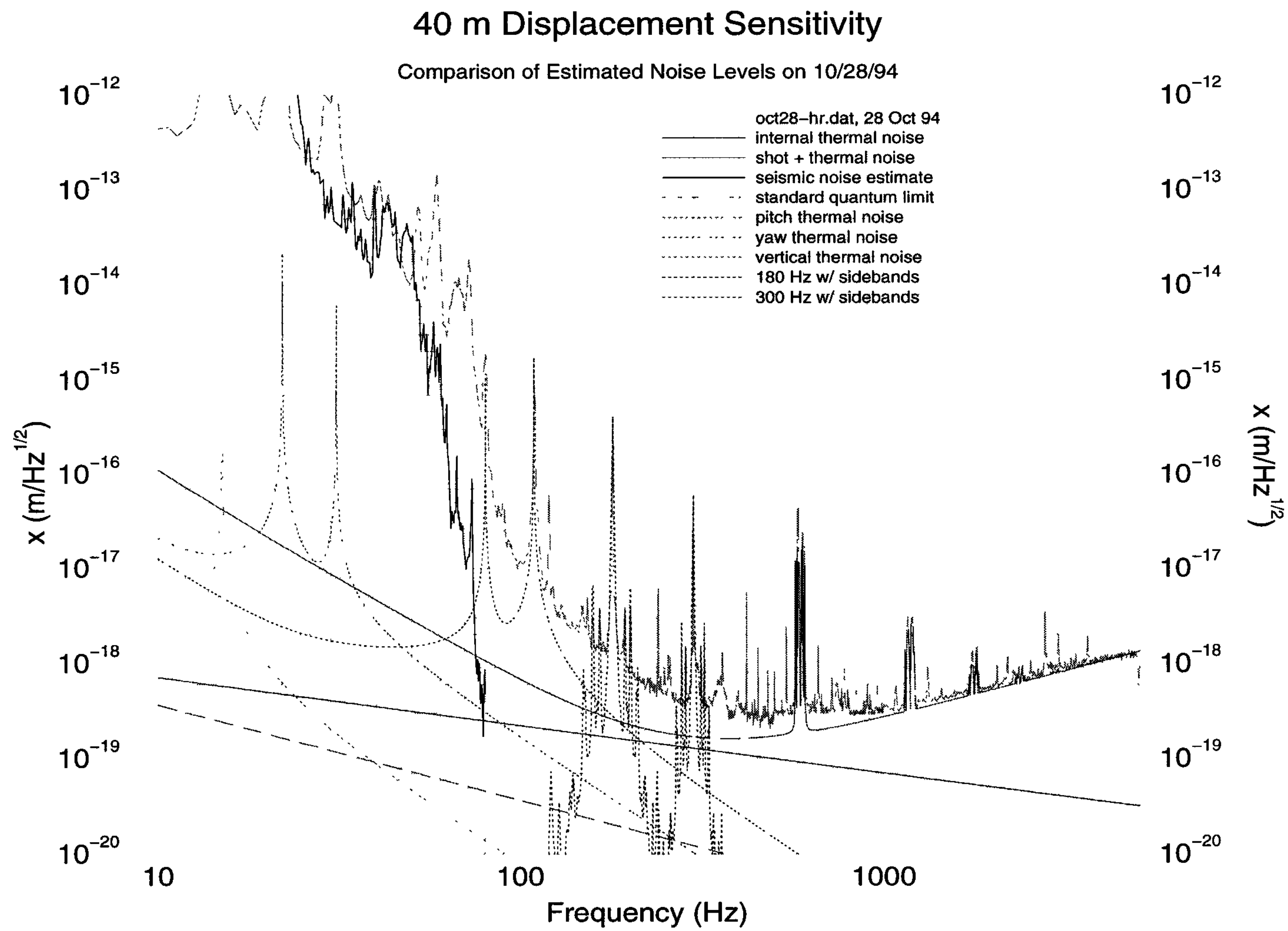
# NOISE CHARACTERIZATION IN 40-METER




Fri Feb2 10:48 1996

~fjr/fort/science_theory/newmodel7.xvgr

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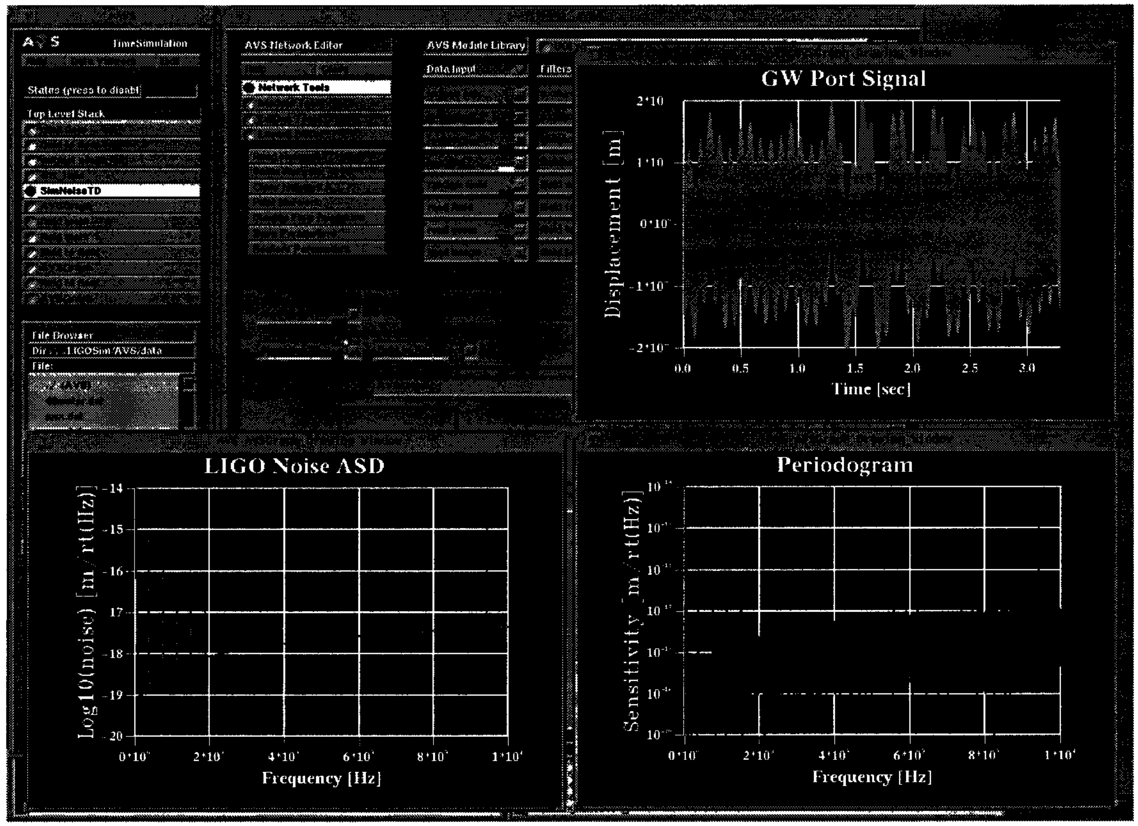
# SIMULATED TIME DOMAIN NOISE MODEL




- Model under development - based on Gaussian statistics
- Generates data that can be used in studying effects of companding, filtering and digitization of signals by data acquisition system
- Simulated data can be combined with astrophysical source waveforms for studying data analysis methods

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# DATA ANALYSIS

## DATA ANALYSIS STUDIES (KIP THORNE'S GROUP AT CALTECH)

- BINARY INSPIRAL
  - generation of high order post-Newtonian waveforms
  - calculations of density of templates and computational needs of grid search
    - 30 gigaflops for initial LIGO
    - 400 gigaflops for Advanced LIGO
  - investigation of non-linear methods (genetic algorithms, simulated annealing)
- PERIODIC SOURCES
  - calculations of number of patches/templates needed to search for pulsars based on all sky doppler shifts and spin down rates
    - $10^{24}$ templates would be needed for 4 month stretches of data!!
    - $10^{10}$ templates would be needed for 1 week stretches of data
- STOCHASTIC BACKGROUND (BRUCE ALLEN)
  - requires coincidence measurements between WA-LA for success
- WAVELETS & ADAPTIVE FILTERING
  - potentially useful techniques for sources without detailed waveforms
- 40 METER INTERFEROMETER DATA: 28 HRS TAKEN / 13.5 HRS ANALYZED

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# SIMULATING STOCHASTIC DATA ANALYSIS WITH AVS

## Stochastic GW Analysis Using Two Detectors Located at WA and LA Sites