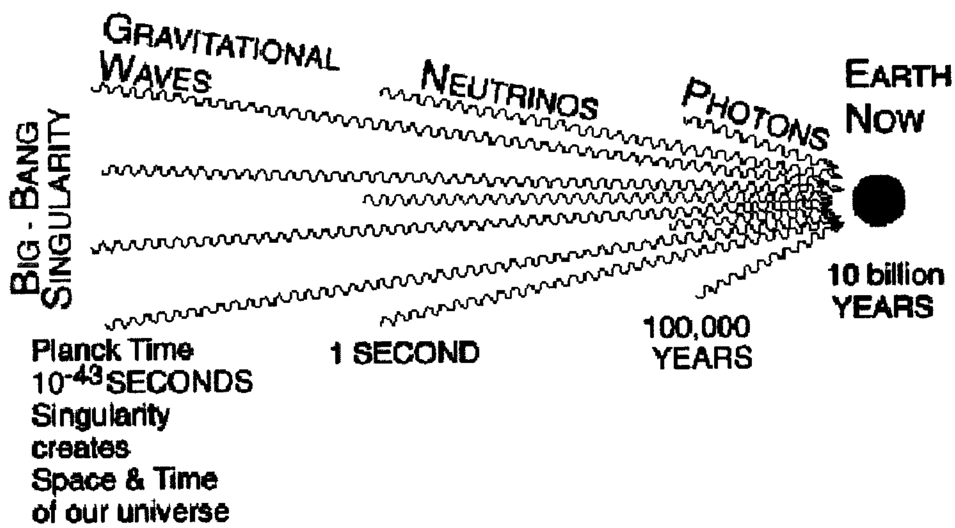
National Science Foundation Review
of
LIGO

February 26 – March 1, 2001

Hanford, Washington



LIGO-G010041-00-M

LIGO PROJECT
California Institute of Technology/Massachusetts Institute of Technology

National Science Foundation Review
February 26 – March 1, 2001
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Charge to the LIGO Review Panel

February 26 – March 1, 2001

The NSF Grant Proposal Guide (http://www.nsf.gov/pubs/2001/nsf()12/toc.html) contains instructions and guidelines for individual investigator proposals. The National Science Board approved review criteria are included in the section from the Proposal Guide reproduced below and they should be followed in this review:

III. NSF Proposal Processing and Review

Proposals received by the NSF Proposal Processing Unit are assigned to the appropriate NSF program for acknowledgement and, if they meet NSF requirements, for review. All proposals are carefully reviewed by a scientist, engineer, or educator serving as an NSF Program Officer, and usually by three to ten other persons outside NSF who are experts in the particular fields represented by the proposal. Proposers are invited to suggest names of persons they believe are especially well qualified to review the proposal and/or persons they would prefer not review the proposal. These suggestions may serve as one source in the reviewer selection process at the Program Officer's discretion. Program Officers may obtain comments from assembled review panels or from site visits before recommending final action on proposals. Senior NSF staff further review recommendations for awards.

A. REVIEW CRITERIA

The National Science Board approved revised criteria for evaluating proposals at its meeting on March 28, 1997 (NSB 97-72). The criteria are designed to be useful and relevant across NSF's many different programs, however, NSF will employ special criteria as required to highlight the specific objectives of certain programs and activities.

On September 20, 1999, the NSF Director issued Important Notice 125, Merit Review Criteria. This Important Notice reminds proposers of the importance of ensuring that, in addition to the criterion relating to intellectual merit, the criterion relating to broader impacts is considered and addressed in the preparation and review of proposals submitted to NSF. The Important Notice also indicates NSF's intent to continue to strengthen its internal processes to ensure that both criteria are appropriately addressed when making funding decisions.

The merit review criteria are listed below. Following each criterion are considerations that the reviewer may employ in the evaluation. These considerations are suggestions and not all will apply to any given proposal. While reviewers are expected to address both merit review criteria, each reviewer will be asked to address only those considerations that are relevant to the proposal and for which he/she is qualified to make judgments.

What is the intellectual merit of the proposed activity?

How important is the proposed activity to advancing knowledge and understanding within its own field or across different fields? How well qualified is the proposer (individual or team) to conduct the project? (If appropriate, the reviewer will comment on the quality of prior work.) To what extent does the proposed activity suggest and explore creative and original concepts? How well conceived and organized is the proposed activity? Is there sufficient access to resources?

What are the broader impacts of the proposed activity?

How well does the activity advance discovery and understanding while promoting teaching, training, and learning? How well does the proposed activity broaden the participation of underrepresented groups (e.g., gender, ethnicity, disability, geographic, etc.)? To what extent will it enhance the infrastructure for research and education, such as facilities, instrumentation, networks, and partnerships? Will the results be disseminated broadly to enhance scientific and technological understanding? What may be the benefits of the proposed activity to society?

PIs should address the following elements in their proposal to provide reviewers with the information necessary to respond fully to the above-described NSF merit review criteria. NSF staff will give these elements careful consideration in making funding decisions.

Integration of Research and Education

One of the principal strategies in support of NSF's goals is to foster integration of research and education through the programs, projects and activities it supports at academic and research institutions. These institutions provide abundant opportunities where individuals may concurrently assume responsibilities as researchers, educators, and students, and where all can engage in joint efforts that infuse education with the excitement of discovery and enrich research through the diversity of learning perspectives.

Integrating Diversity into NSF Programs, Projects, and Activities

Broadening opportunities and enabling the participation of all citizens -- women and men, underrepresented minorities, and persons with disabilities -- are essential to the health and vitality of science and engineering. NSF is committed to this principle of diversity and deems it central to the programs, projects, and activities it considers and supports.

Specific Charge to the LIGO Review Panel.

The proposal includes three major activities; operations of the LIGO facilities; scientific research; detector research and development. To address this wide range of activities, the Review Panel will be divided into two sub-panels. The first will concentrate on detector research and development. The second will concentrate on operation of the LIGO facilities and scientific research. The broader issues of scientific merit and the overlap in manpower and other resources assigned to the three activities will require both sub-panels to consider the total proposal in their evaluations.

A. Detector Research and Development Sub-Panel

This sub-panel will concentrate on detector research and development to improve the science reach of the LIGO observatories. A major contribution to this R&D program is provided by members of the LSC at institutions other than Cal Tech and MIT. Funds to support those LSC member research programs are provided directly to the LSC institutions.

- While this sub-panel is not charged with reviewing each of the LSC proposals, it is asked to evaluate the total detector R&D plan as presented by the LIGO Laboratory in this proposal. Are the LSC R&D activities (including Cal Tech and MIT) appropriate to achieve the scientific goals of the proposal and are they well-coordinated?

- The Sub-Panel should review the schedule and milestones for progress in the detector R&D program. Is the schedule achievable with the available and proposed resources and are there sufficient significant milestones provided?

- The sub-panel is asked to review the LIGO Laboratory R&D program (Cal Tech and MIT) in detail, including manpower allocation and budget.

The final report of this Sub-Panel is to be completed at this meeting so that it can be made available to the Operations and Scientific Research Sub-Panel before the meeting of that sub-panel.

B. Operations and Scientific Research Sub-Panel

The activities to be reviewed by this sub-panel include completion of installation and commissioning of the interferometers, operation of the facility for engineering and science runs, creating and maintaining the infrastructure for data acquisition and analysis by the LIGO Scientific Collaboration (LSC), and scientific research proposed by the LIGO Laboratory. The Sub-Panel is asked to review and evaluate the proposal with regard to each of the following items:

- Is the proposed budget for LIGO Laboratory operations and the scientific research program justified and adequate to carry out the activities listed above?
- Is the proposed LIGO Laboratory infrastructure, including manpower and facilities, adequate for effective participation in the science by the LSC members?
- Are the schedule and milestones for LIGO Laboratory commissioning and for proposed engineering and scientific running achievable with the available and proposed resources. Are there sufficient significant milestones provided?
- Is the proposed outreach and education plan well-designed and are proposed manpower and funds adequate to carry out the plan?
- What is the status of international collaboration between LIGO and other gravity wave centers around the world?
- Is the plan for public access to LIGO data appropriate?

The final report of the Detector Research and Development Sub-Panel will be provided as input to the Operations and Scientific Research Sub-Panel which is requested to determine if there are issues involving allocation of manpower or other resources between the major activities presented in the proposal. If there are, a teleconference will be arranged during the meeting of the Operations and Scientific Research Sub-Panel and members of the Detector Research and Development Sub-Panel to discuss these issues.

LIGO Operations and Scientific Research Sub-Panel
AGENDA

Monday February 26, 2001

8:30 - 9:00	Panel Executive Session
9:00 - 9:15	Introduction of Panel and Reading of Panel Charge
9:15 -10:45	LIGO Presentations
10:45 -11:00	Break
11:00 -12:30	LIGO Presentations
12:30 - 1:30	Lunch /Panel Exec. Session; formulate requests for info. from LIGO/LSC staff
1:30 - 2:30	LIGO Presentations
2:30 - 4:00	Laboratory Tour
4:00 - 6:00	Panel Exec. Session—Formulate questions for LIGO/LSC Staff.
6:30	Dinner

Tuesday February 27, 2001

8:30 - 9:00	Panel Exec. Session.
9:00 -12:30	Response of LIGO/LSC—break-out or full panel presentation.
12:30 - 3:00	Lunch and Panel Exec. Session; discuss R&D Report; formulate questions
3:00 - 5:00	Panel-LIGO/LSC parallel sessions or full panel discussion as needed; sub-groups begin writing report.
5:00 - 6:00	Panel Exec. Session—Formulate questions for LIGO/LSC staff-continue writing
6:30	Dinner

Wednesday February 28, 2001

8:30 - 9:00	Panel Exec. Session
9:00 -10:15	Break-out sessions or full Panel presentations by LIGO/LSC
10:15 -10:30	Break
10:30 -12:30	Discussion with R&D Panel chair (Roger Falcone)
12:30 - 1:30	Lunch; Exec. Session
1:30 - 6:30	Panel completes report; Draft Exec. Summary; discuss close-out presentation.
6:30	Dinner

Thursday March 1, 2001

9:00 -10:00	Panel Executive Session—final discussion of close-out presentation.
10:00 -11:00	Close-out session with Panel and LIGO/LSC Staff. Adjourn.

Parallel Meetings

1. Budgets, Schedules and Milestones (Kirk, Oddone, Baltay)
2. LIGO Lab Infrastructure, LSC Participation in LIGO Science, Manpower (Wolff, Mountain)
3. LIGO I Science, Outreach, International Collaboration (Teukolsky, Gates, Hogan)

Acronyms and Abbreviations

Acronym	
ACIGA	Australian Consortium for Interferometric Gravitational Astronomy
ACWP	Actual Cost of Work Performed
ADC	Analog-to-Digital Converter
AMU	Atomic Mass Unit
ANU	Australian National University
API	Application Programmer Interface
BAC	Budget at Completion
BCWP	Budgeted Cost of Work Performed
BCWS	Budgeted Cost of Work Scheduled
BH	Black Hole
BSC	Basic Symmetric Chamber
BSC	Beam Splitter Chamber
CACR	Center for Advanced Computer Research (Caltech)
CAD	Computer-Assisted Design
CB&I	Chicago Bridge & Iron
CDS	Control and Data System
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
CSSR	Cost Schedule Status Report
DAC	Data Analysis and Computing
DAC	Digital-to-Analog Converter
DcAPI	Data Conditioning Application Programmer Interface
DMRO	Differential Mode Read-Out
EAC	Estimate at Completion
EPICS	Experimental Physics and Industrial Control System
ER1	LIGO Engineering Run, April 2000
ER2	LIGO Engineering Run, November 2000
ETF	Engineering Test Facility
ETM	End Test Mass
FDR	Final Design Review
FFT	Fast (Discrete) Fourier Transform
FTE	Full Time Equivalent
GASF	Geometrical Anti-Spring Filter
GEO	British-German Cooperation for Gravity Wave Experiment
GFLOPS	1000 MFLOPS
GRB	Gamma-Ray Burst
GWADW	Gravitational Wave Data Analysis Workshop
GWIC	Gravitational Wave International Committee
HAM	Horizontal Access Modules
HPSS	High Performance Storage System (IBM)
HVAC	Heating, Ventilation and Air Conditioning
IDE	Integrated Drive Electronics (disk standard)
IFO	Interferometer
InGaAs	Induim-Gallium-Arsenide

INSA	French National Institute for Applied Science
IO	Input Optics
IP	Inverted Pendulum
ISC	Interferometer Sensing and Control
ITM	Input Test Mass
IV&V	Integration, Verification, and Validation
kpc	Kiloparsec
LASTI	LIGO Advanced System Test Interferometer
LDAS	LIGO Data Analysis System
LHO	LIGO Hanford Observatory
LIGO	Laser Interferometer Gravitational-Wave Observatory
LLO	LIGO Livingston Observatory
LMXB	Low-Mass X-Ray Binary
LSC	LIGO Scientific Collaboration also Length Sensing and Control System
LVDT	Linear Variable Differential Transducer
LVEA	Laser and Vacuum Equipment Area
LZH	Laser Zentrum Hannover
MB	Megabytes
MC	Mode Cleaner
MDC	Mock Data Challenges
MFLOPS	Million Floating Point Operations Per Second
MGASF	Monolithic Geometrical Anti-Spring Filter
MIMO	Multiple Input, Multiple Output
MOPA	Master Oscillator-Power Amplifier
MOU	Memorandum of Understanding
Mpc	Megaparsec
MPI	Message Passing Interface
MSU	Moscow State University
NBI	Neutron Star Binary Inspiral
NPRO	Non-Planar Ring Oscillator
NS	Neutron Star
OSB	Operations Support Building
OSEM	Optical Shadow Sensor and Magnetic Actuator
PEM	Physics and Environmental Monitor
PM	Project Management
PMP	Project Management Plan
Ppm	Parts per million
PSL	Prestabilized Laser
QND	Quantum Non-Demolition
R&D	Research and Development
RAID	Redundant Array of Inexpensive Disks
REO	Research Electro-Optics (Company Name)
REU	Research Experience for Undergraduates
RF	Radio Frequency
RMS	Root mean square
RSE	Resonant Sideband Extraction
s	Second

s/s	Samples/second
SAS	Seismic Attenuation System
SEI	Seismic Isolation
SEM	Secondary Emission Monitor
SIOM	Shanghai Institute of Optical Materials
SOS	Small Optics Suspensions
SURF	Summer Undergraduate Research Foundation
TAMA	Japanese Interferometric Gravitational-Wave Project
TB	Terabytes
TES	Technical and Engineering Support
TNI	Thermal Noise Interferometer
TRW	Company Name
UHV	Ultra high vacuum
VME	Versa Modular Eurocard (IEEE 1014)
WAN	Wide Area Network
WBS	Work Breakdown Structure

LIGO
Introduction

Barry Barish

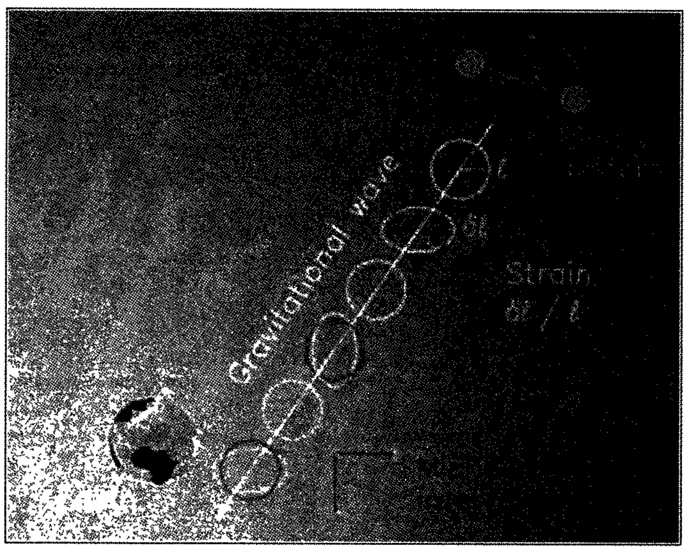
Operations Proposal Review
NSF Operations Subpanel
February 26, 2001

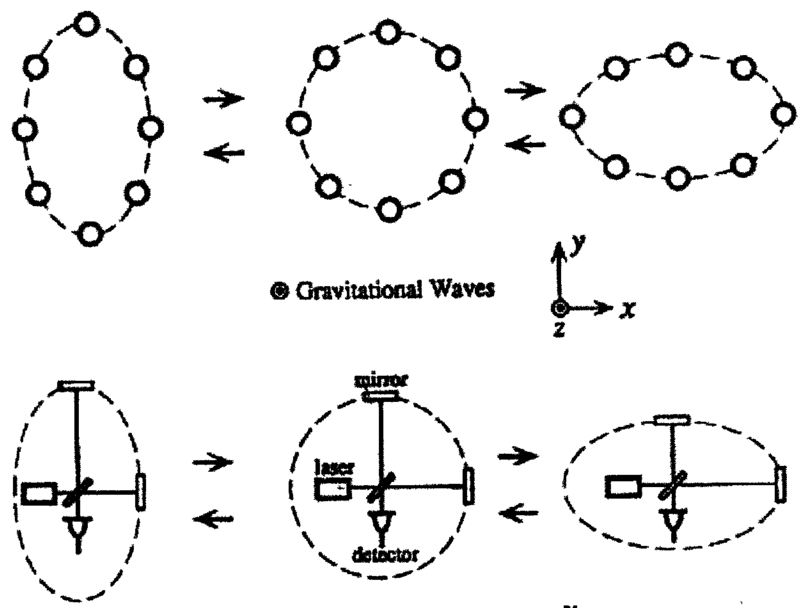
LIGO-G010036-00-M

Interferometers
terrestrial

Suspended mass Michelson-type interferometers on earth's surface detect distant astrophysical sources

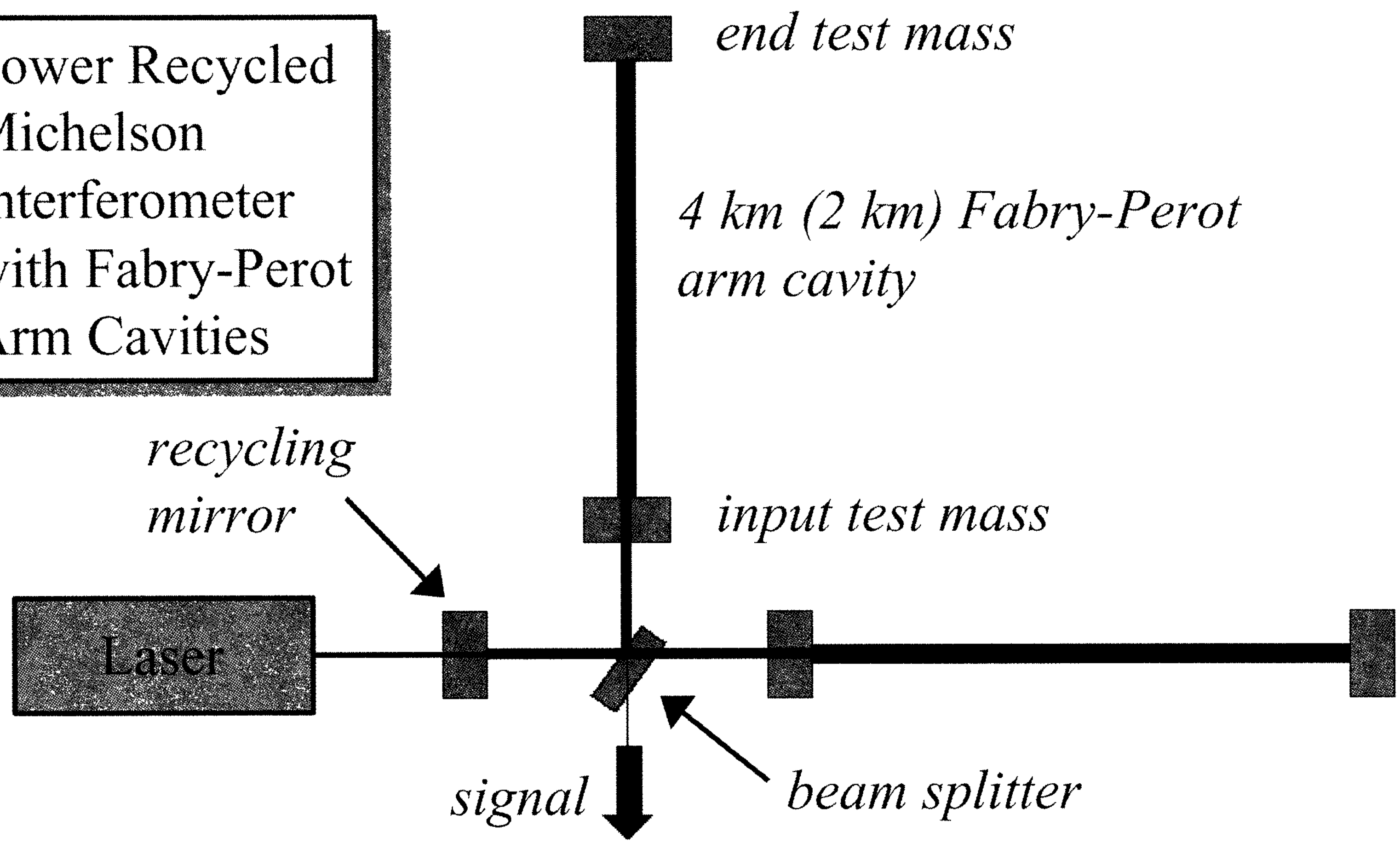
International network (LIGO, Virgo, GEO, TAMA) enable locating sources and decomposing polarization of gravitational waves.





LIGO Interferometers

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities

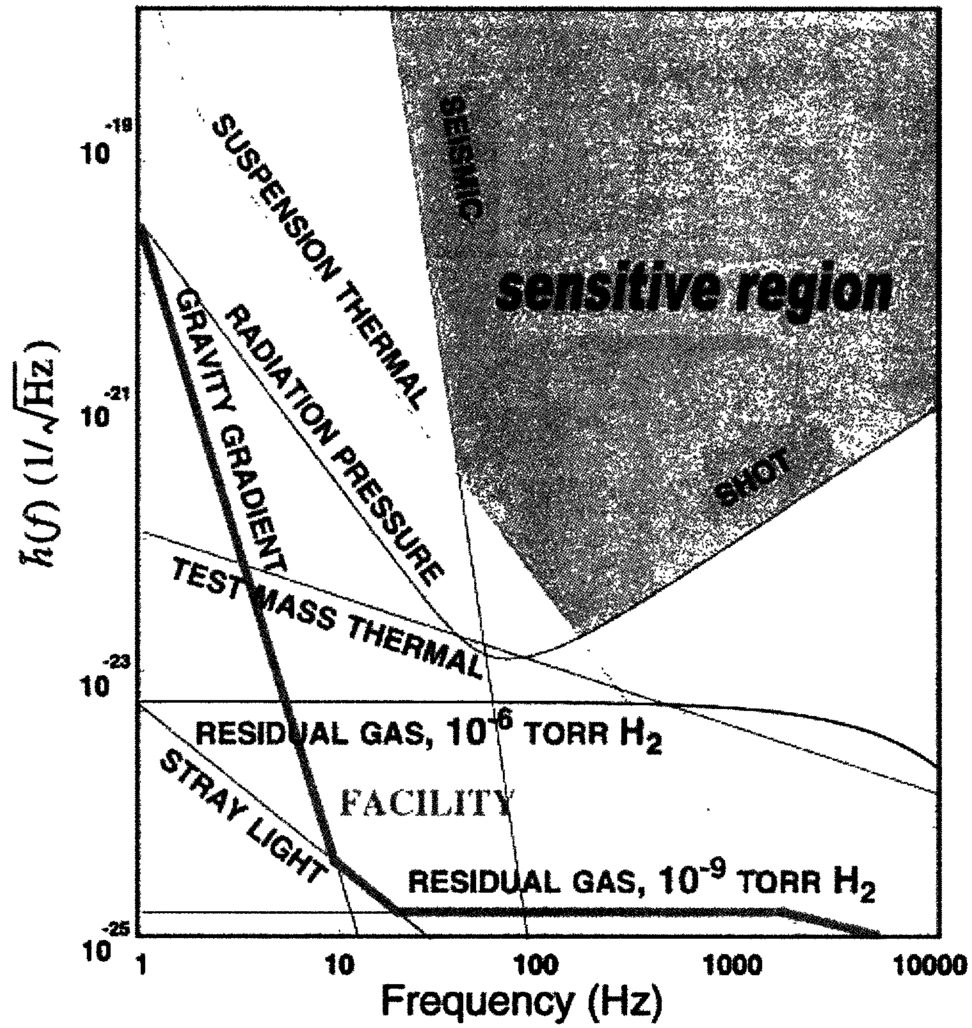


LIGO I

the noise floor

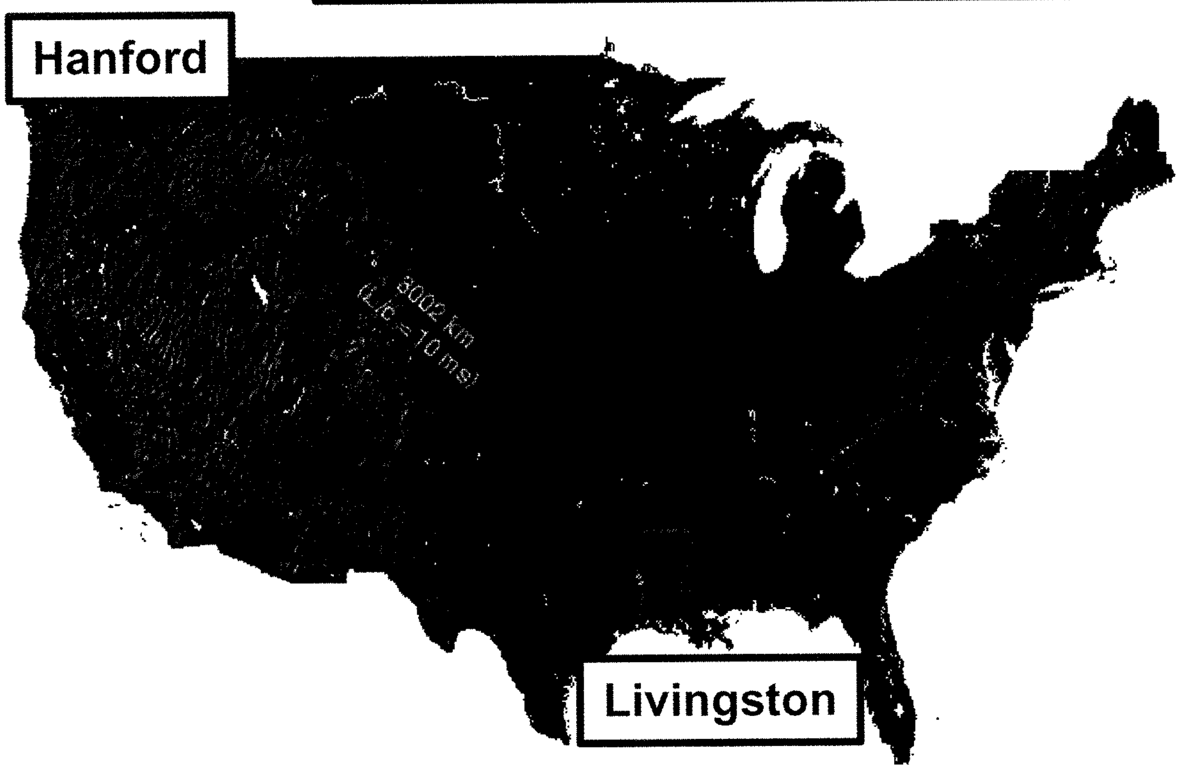
- **Interferometry is limited by three fundamental noise sources**
  - ➢ **<u>seismic noise</u> at the lowest frequencies**
  - ➢ **<u>thermal noise</u> at intermediate frequencies**
  - ➢ **<u>shot noise</u> at high frequencies**

- **Many other noise sources lurk underneath and must be controlled as the instrument is improved**



LIGO

- **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)**



Coincidences between LLO & LHO

LIGO Plans
schedule

1996	**Construction Underway** (mostly civil)
1997	**Facility Construction** (vacuum system)
1998	**Interferometer Construction** (complete facilities)
1999	**Construction Complete** (interferometers in vacuum)
2000	**Detector Installation** (commissioning subsystems)
2001	**Commission Interferometers** (first coincidences)
2002	**Sensitivity studies** (initiate LIGO I Science Run)
2003+	**LIGO I data run** (one year integrated data at $h \sim 10^{-21}$)
2006+	**Begin 'advanced' LIGO installation**

Budget History

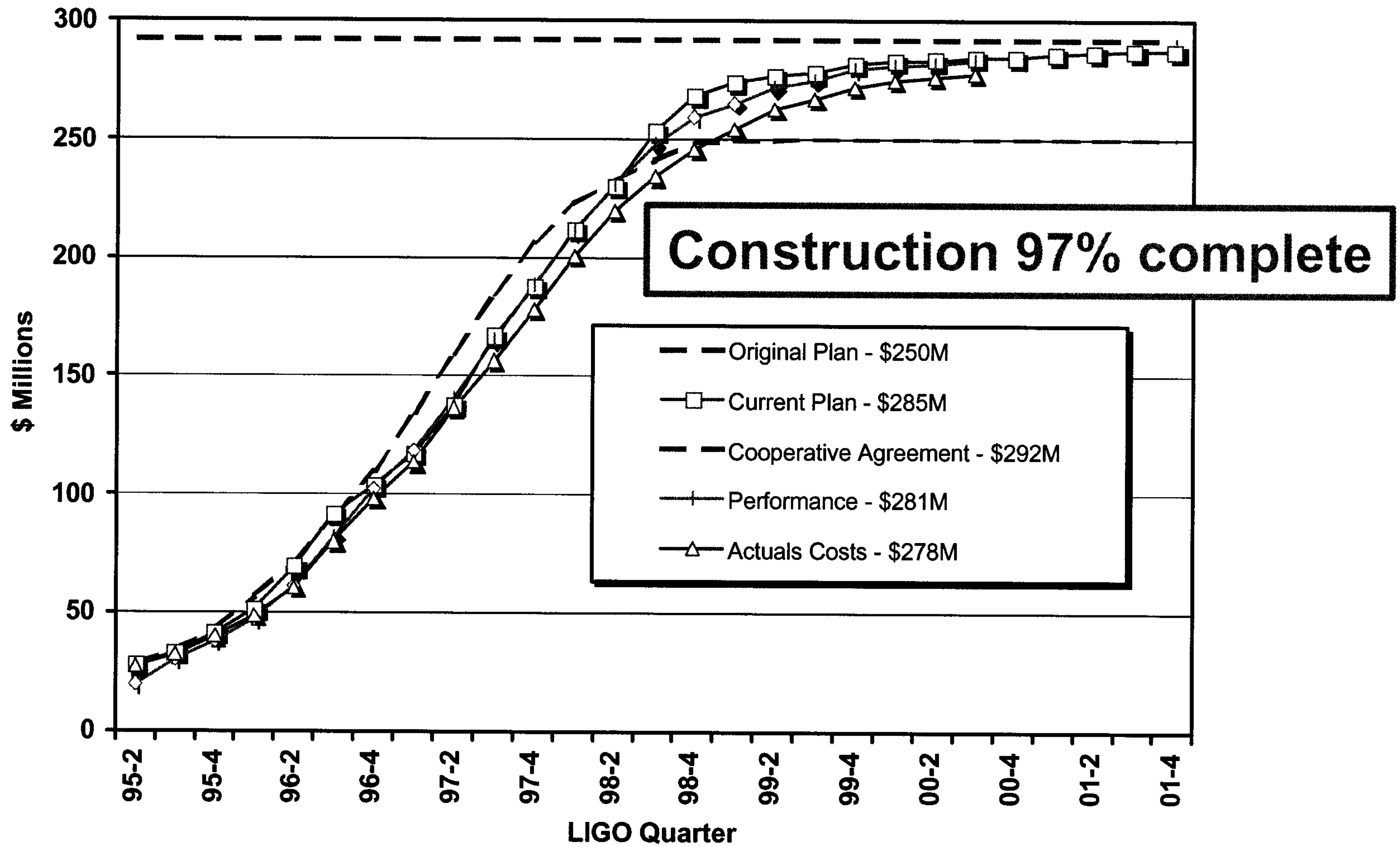
MRE Funds

Fiscal Year	Construction ($M)	R&D ($M)	Operations ($M)	Advanced R&D ($M)	Total ($M)
1992 - 94	35.90	11.19	-	-	47.09
1995	85.00	3.95	-		88.95
1996	70.00	2.38	-		72.38
1997	55.00	1.62	0.30	0.80	57.72
1998	26.00	0.86	7.30	1.82	35.98
1999	0.20	-	20.78	2.28	23.26
2000	-	-	21.10	2.60	23.70
2001	-	-	19.10 (10 Months) **22.92 (12 Months)**	**2.70**	21.80 **25.6 (12 Months)**
Total	**272.10**	**20.00**	**68.58**	**10.20**	**370.88**

Construction Project **Operations**

LIGO Project

construction and related R&D costs



Budget History

MRE Funds

Fiscal Year	Construction ($M)	R&D ($M)	Operations ($M)	Advanced R&D ($M)	Total ($M)
1992 - 94	35.90	11.19	-	-	47.09
1995	85.00	3.95	-		88.95
1996	70.00	2.38	-		72.38
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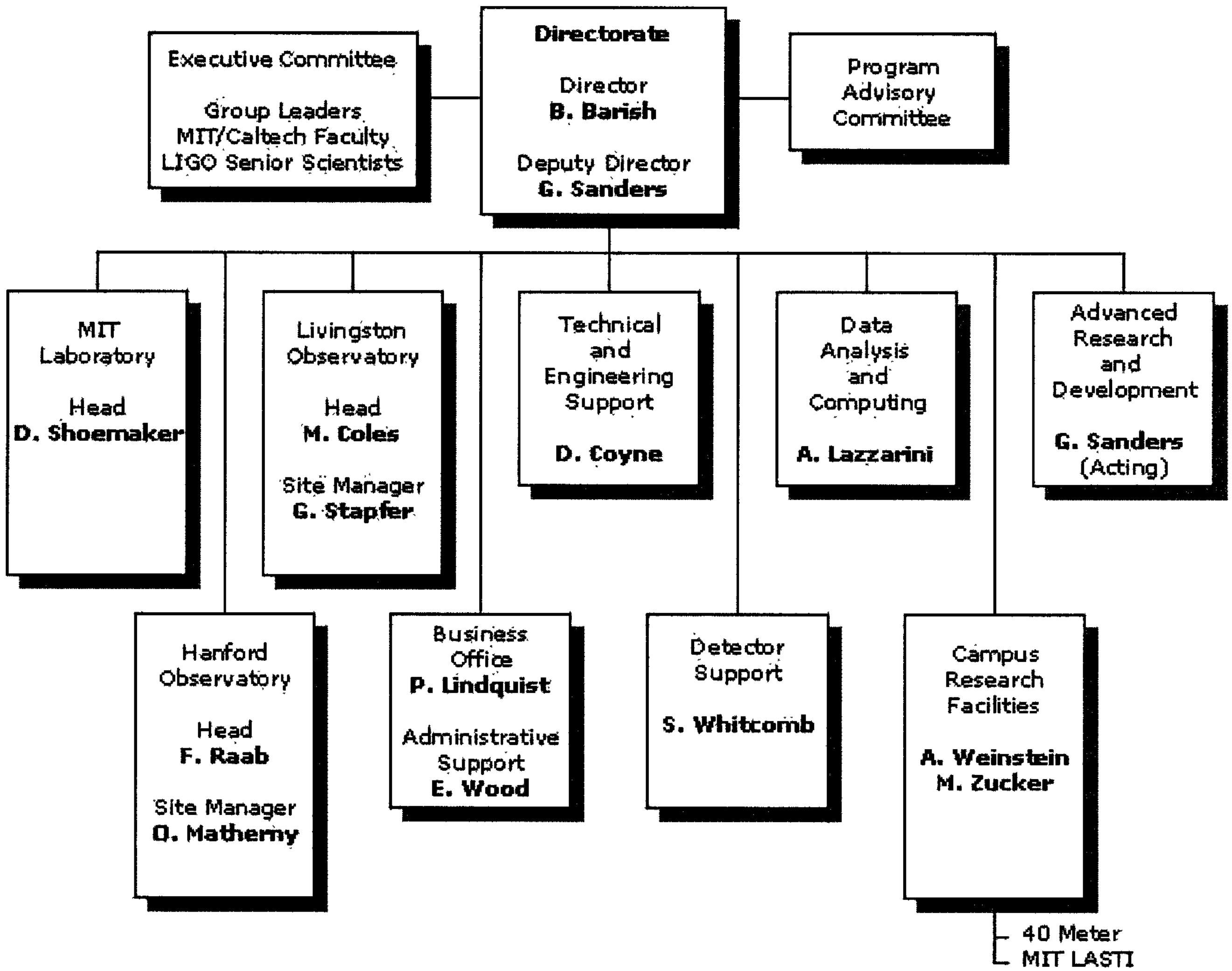
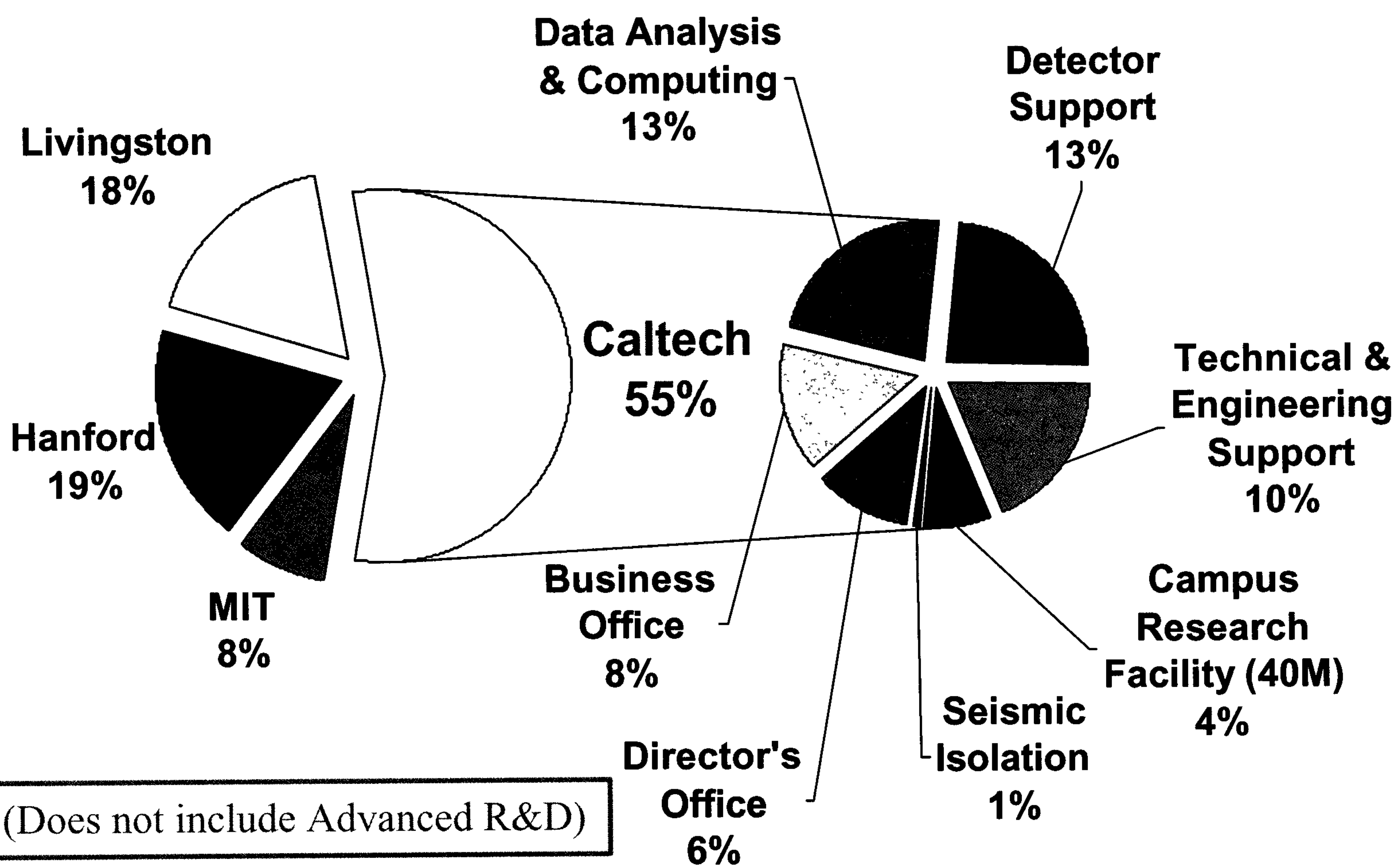
Construction Project **Operations**

LIGO Laboratory Organization

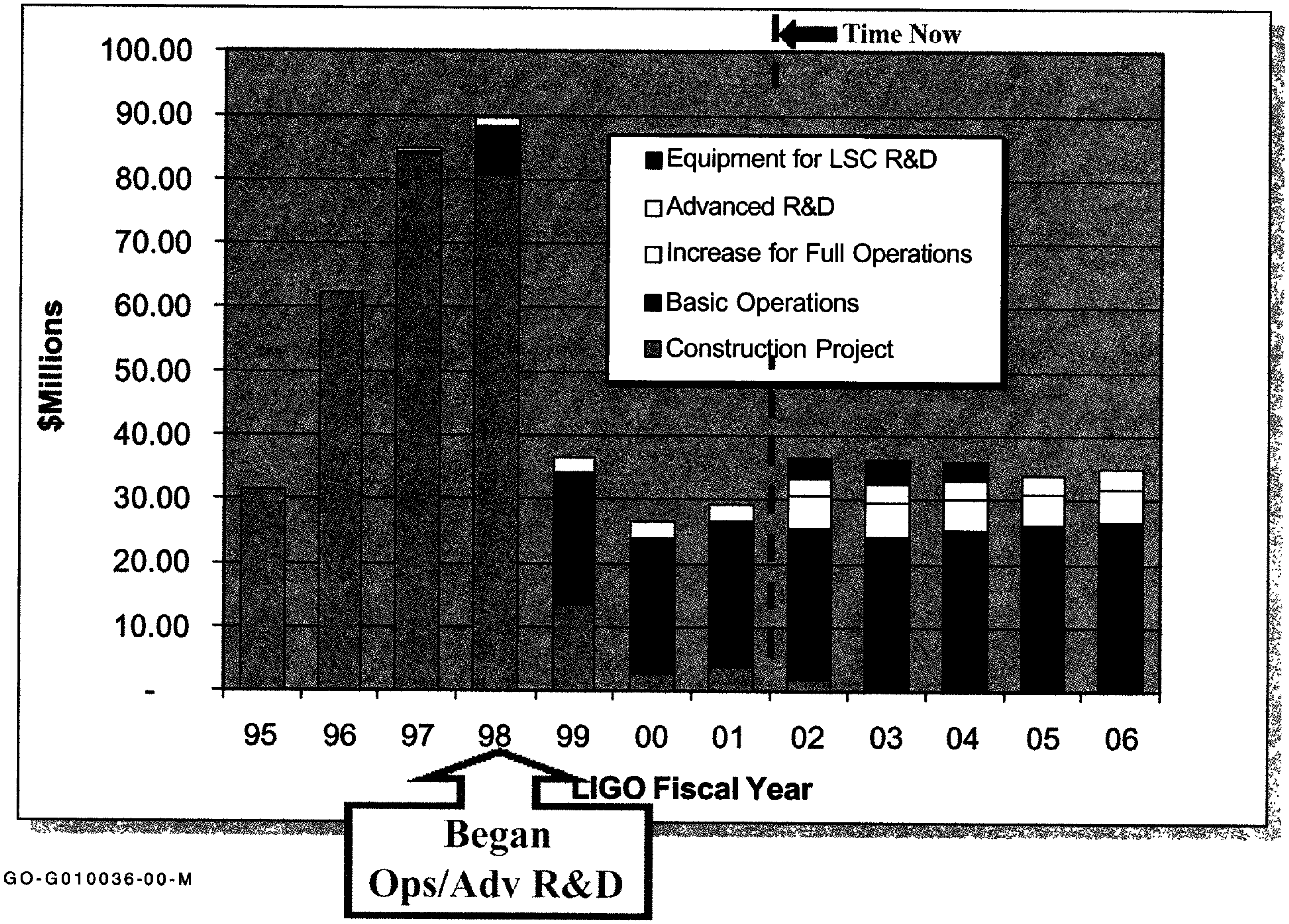


FY 2000 Expenses



(Does not include Advanced R&D)

Funding History and Request



LIGO
funding request

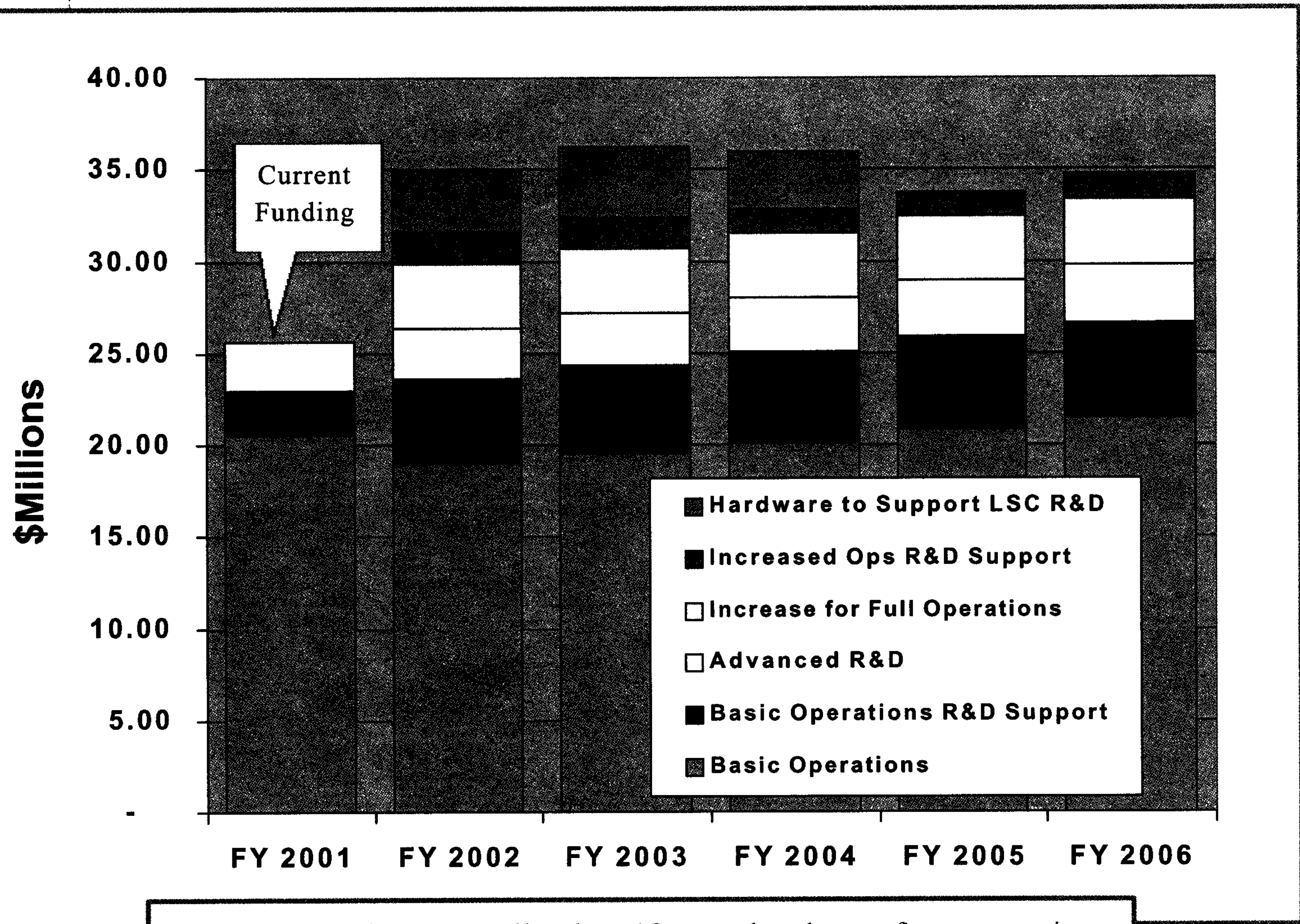
	FY 2001 ($M)	FY 2002 ($M)	FY 2003 ($M)	FY 2004 ($M)	FY 2005 ($M)	FY 2006 ($M)	Total 2002-6 ($M)
Currently funded Operations	22.92	23.63	24.32	25.05	25.87	26.65	125.52
Increase for Full Operations		**5.21**	**5.20**	**4.79**	**4.86**	**4.95**	**25.01**
Advanced R&D	2.70	2.77	2.86	2.95	3.04	3.13	14.76
R&D Equipment for LSC Research		**3.30**	**3.84**	**3.14**			**10.28**

FY 2001 currently funded Operations ($19.1M for ten months) is normalized to 12 months and provided for comparison only and is not included in totals.

Increase for Full Operations

Budget Category		Increase	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Basic Operations							
	*	CDS Hardware Maintenance	513,800	502,434	517,507	533,032	549,023
	*	LDAS Maintenance	1,378,728	1,378,728	1,322,235	1,303,163	1,303,163
		Outreach	249,848	257,343	265,063	273,015	281,206
	*	Site Operations	558,485	575,240	592,497	610,272	628,580
		Telecommunications / Networking	540,500	542,200	542,200	539,500	539,500
		Staff for Site LSC Support	254,678	262,318	270,187	278,293	286,642
Basic Operations Totals			**3,496,039**	**3,518,263**	**3,509,689**	**3,537,275**	**3,588,114**
Operations Support of Advanced R&D							
		Seismic Development	506,300	434,574			
	*	Engineering Staff	920,868	948,494	976,949	1,006,257	1,036,445
		Simulation & Modeling Staff	282,485	293,949	305,614	317,772	330,617
R&D Total			**1,709,652**	**1,677,017**	**1,282,562**	**1,324,029**	**1,367,062**
Grand Total			**5,205,691**	**5,195,280**	**4,792,252**	**4,861,304**	**4,955,176**

* Need recognized by NSF panel



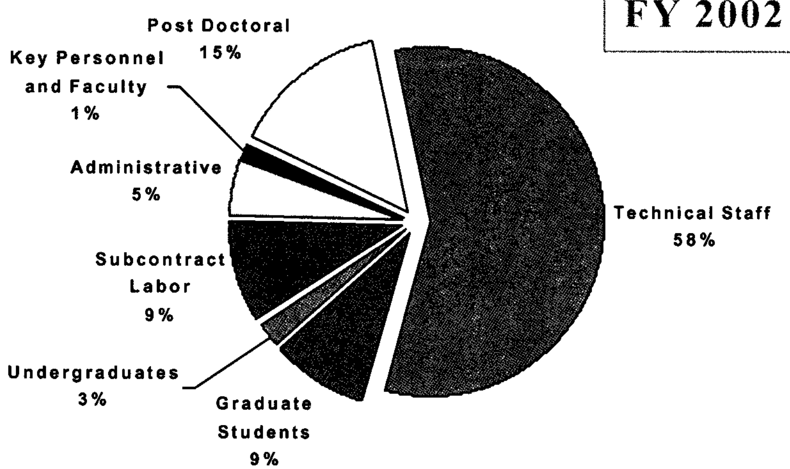
FY 2001 funding normalized to 12 months shown for comparison

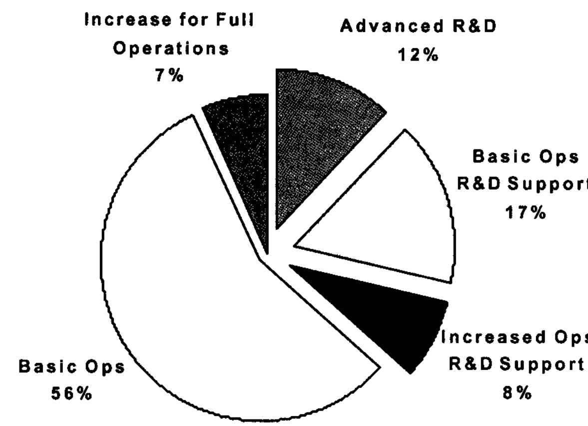
Staffing

Category	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Key Personnel / Faculty	2.6	2.6	2.6	2.6	2.6
Post Doctoral	27.0	27.0	26.0	26.0	26.0
Technical Staff	104.7	105.7	101.7	102.7	102.7
Graduate Students	18.0	17.0	17.5	17.5	17.5
Undergraduate	4.9	4.9	4.9	4.9	4.9
Subcontract Labor	17.0	17.0	17.0	16.0	16.0
Administrative	9.9	9.9	9.9	9.9	9.9
Grand Total	**184.1**	**184.1**	**179.6**	**179.6**	**179.6**

Numbers shown Are Full Time Equivalent Employees (FTEs) actually charged

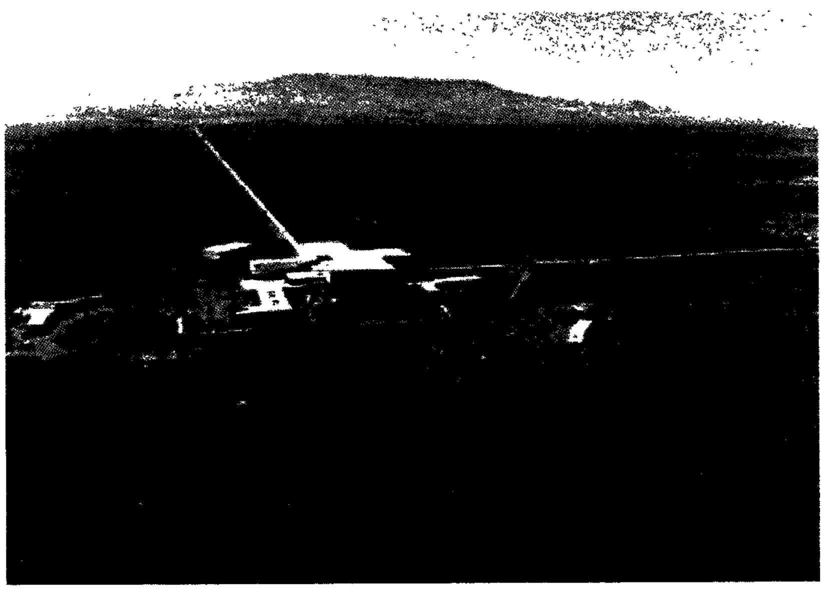
FY 2002



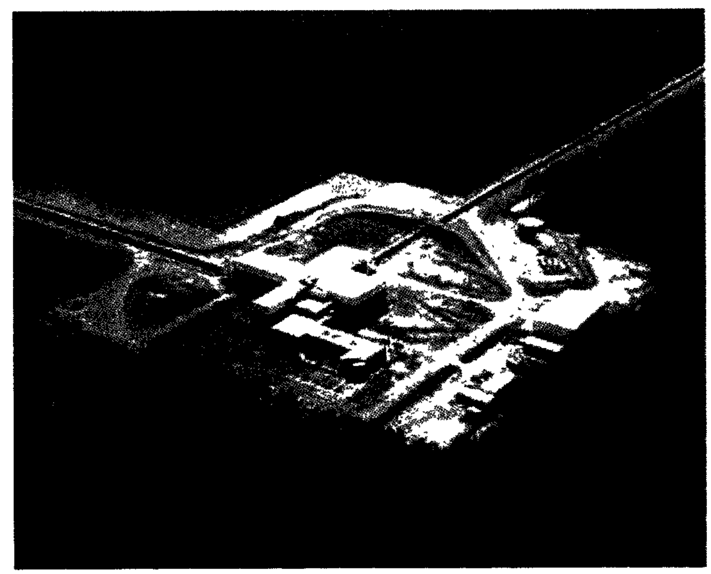


LIGO
civil construction

LIGO (Washington)

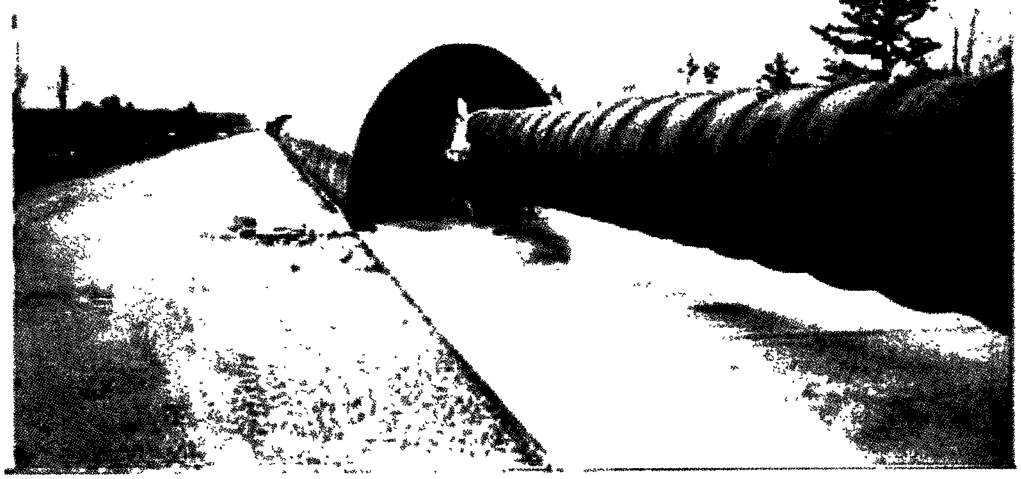


LIGO (Louisiana)



LIGO
vacuum chambers

LIGO
beam tube



- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

1.2 m diameter - 3mm stainless
50 km of weld

NO LEAKS !!

LIGO Facilities

beam tube enclosure

- minimal enclosure
- reinforced concrete
- no services

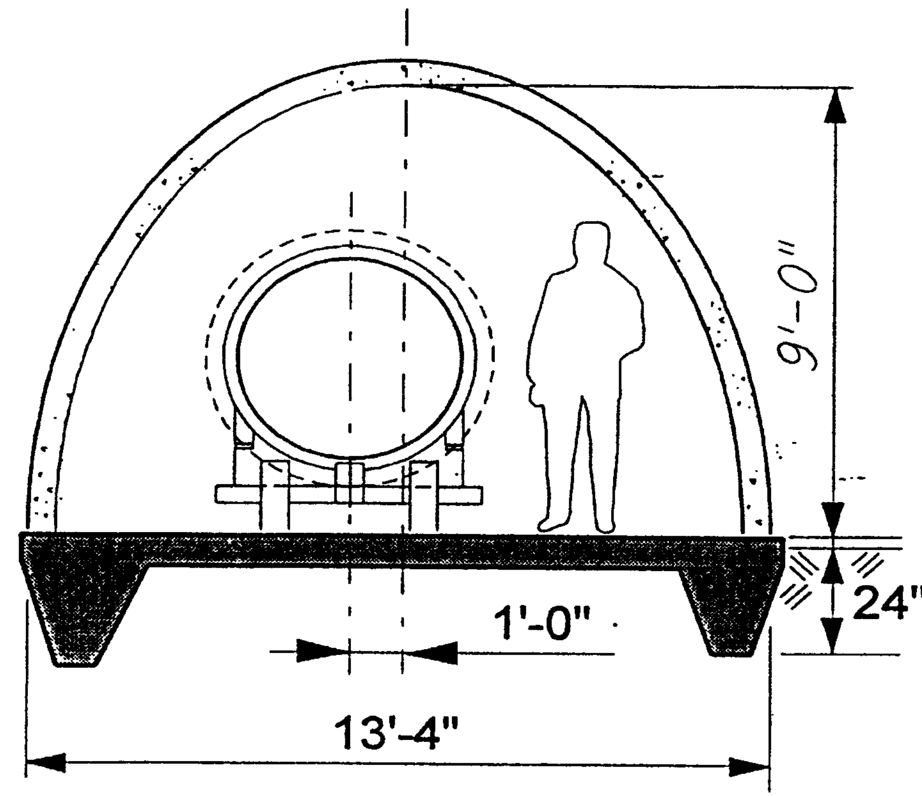
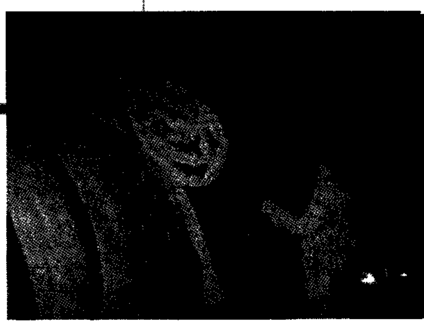
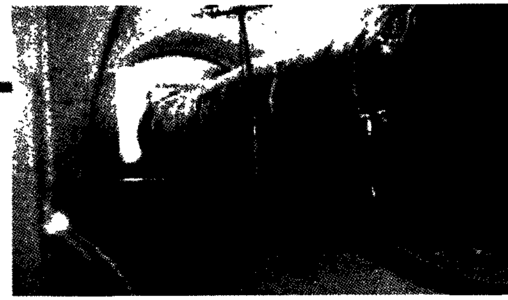
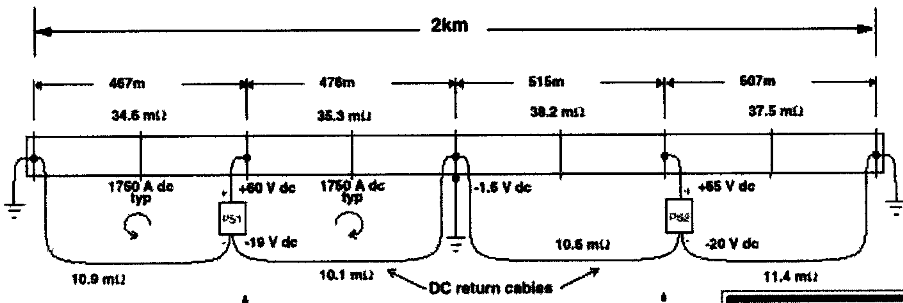


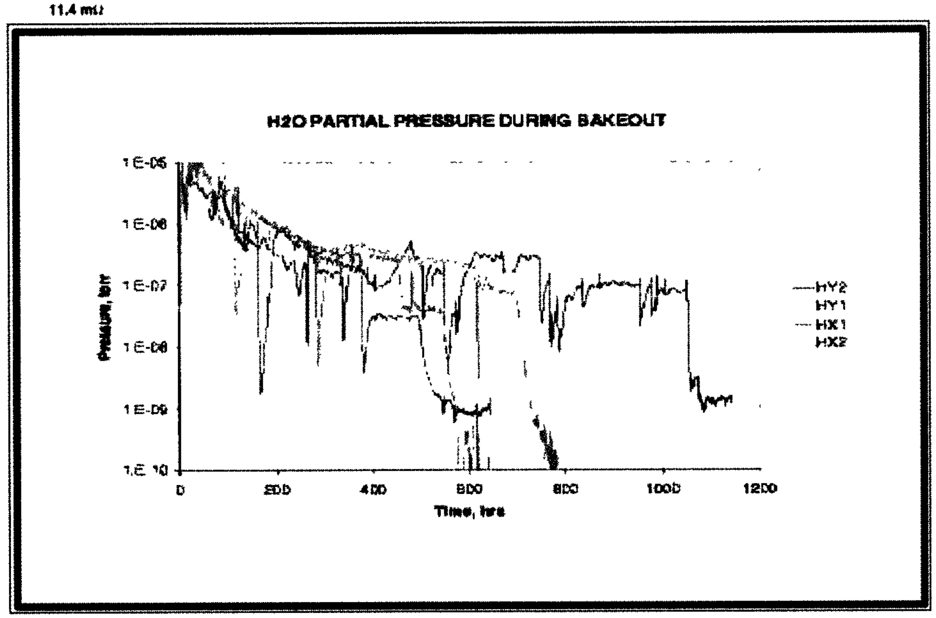
Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

Beam Tube *bakeout*



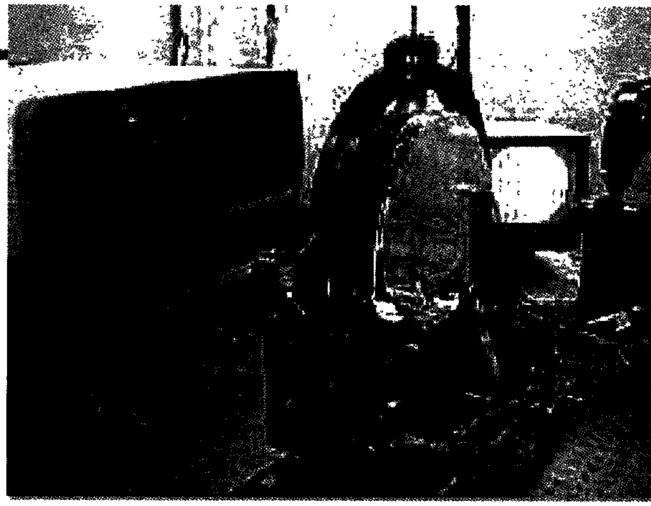






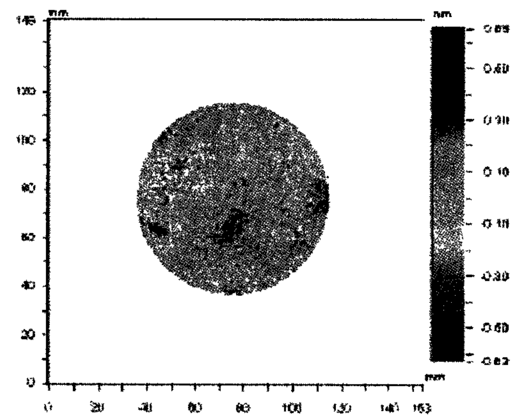
- I = 2000 amps for ~ 1 month
- no leaks !!
- final vacuum at level where it is not source of limiting noise (even future detectors)

Core Optics
fused silica



LIGO requirements

- Surface uniformity < 1 nm rms
- Scatter < 50 ppm
- Absorption < 2 ppm
- ROC matched < 3%
- Internal mode Q's > 2 x 10^6



Date: 10/17/2000	X Center: 283.00
Time: 09:26:37	Y Center: 244.00
Wavelength: 1.064 um	Radius: 160.00 pix
Pupil: 100.0 %	Terms: Tilt Power Astig
PV: 1.2818 nm	Filters: None
RMS: 0.1620 nm	Masks: Analysis 4.0 Sigma Masks
Rad of curv: 14.053 km	Ref Sub:
	Averages:

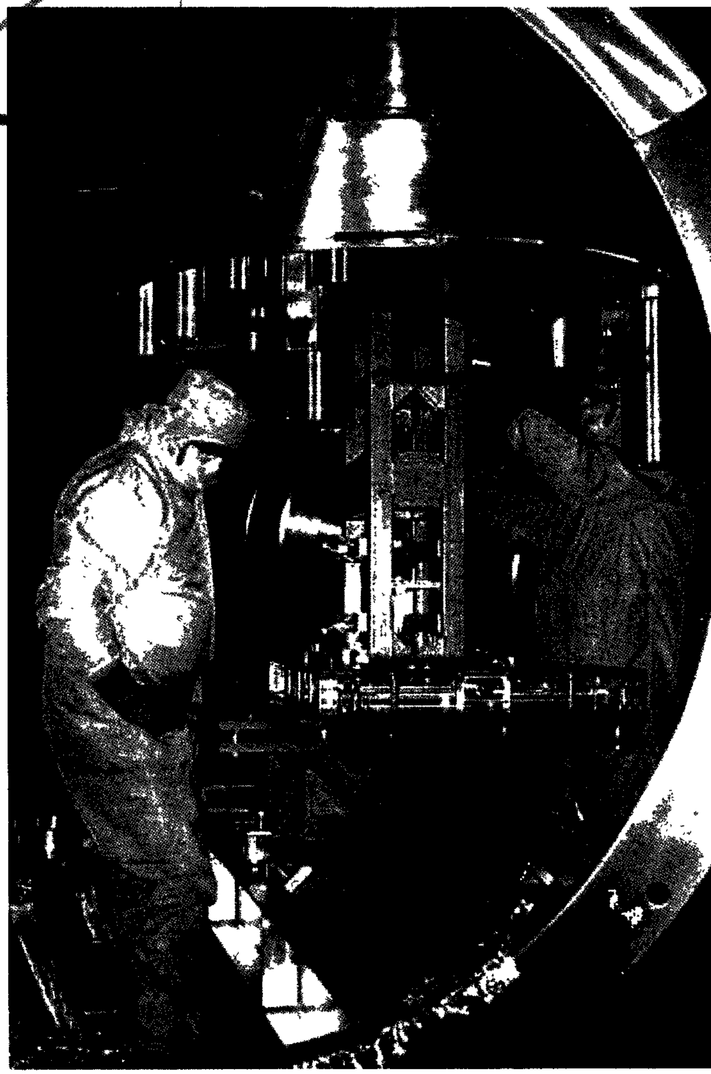
LIGO measurements

- central 80 mm of 4ITM06 (Hanford 4K)
- rms = 0.16 nm
- optic far exceeds specification.

Surface figure = λ/ 6000

Core Optics

installation and alignment



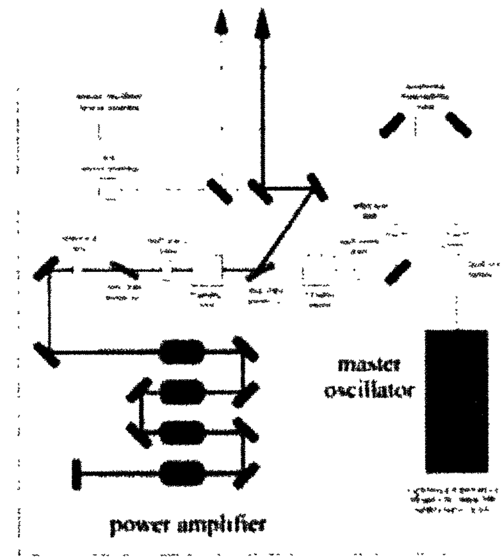
Commissioning
configurations

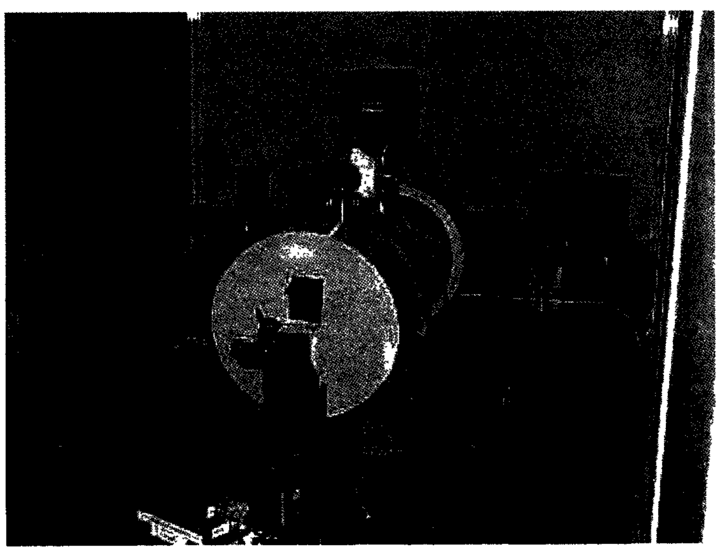
- Mode cleaner and Pre-Stabilized Laser
- 2km one-arm cavity
- short Michelson interferometer studies

- Lock entire 2km Michelson Fabry-Perot interferometer with Power Recycling (Hanford)
  - » First lock – Oct 00
  - » Robust locking – Jan 01
- Lock one 4km arm (Livingston)
  - » First single long arm – Jan 01

LIGO
laser

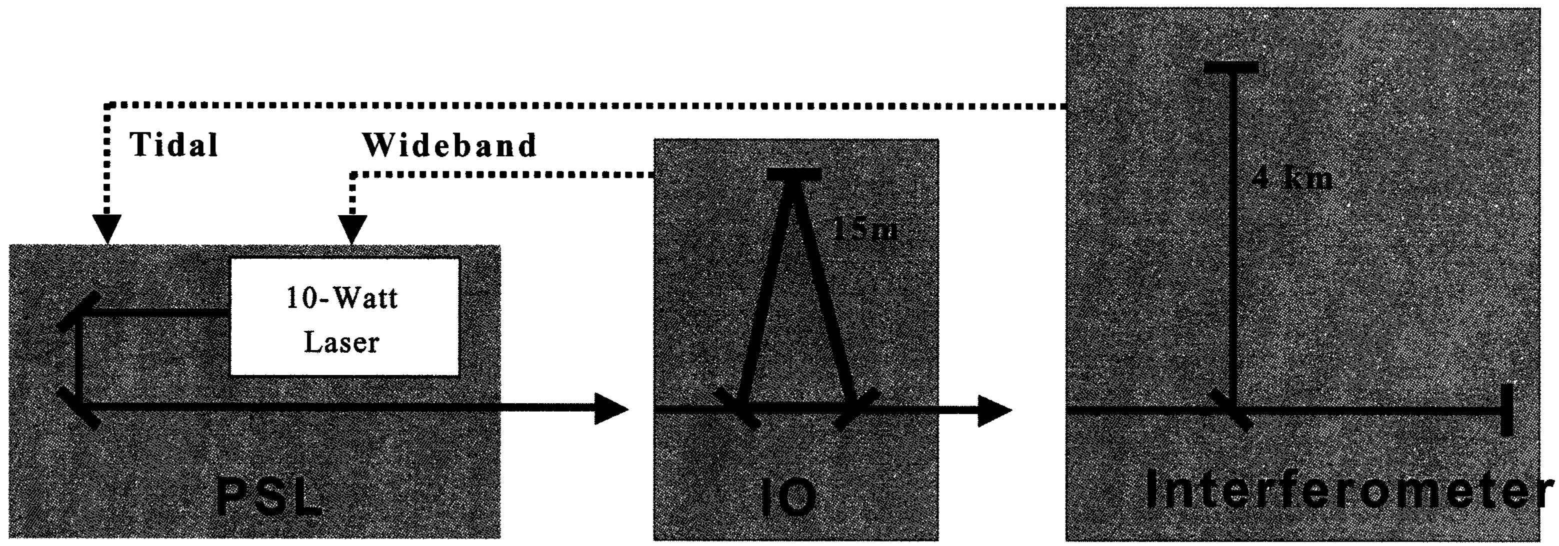
- Nd:YAG
- 1.064 μm
- Output power > 8W in TEM00 mode





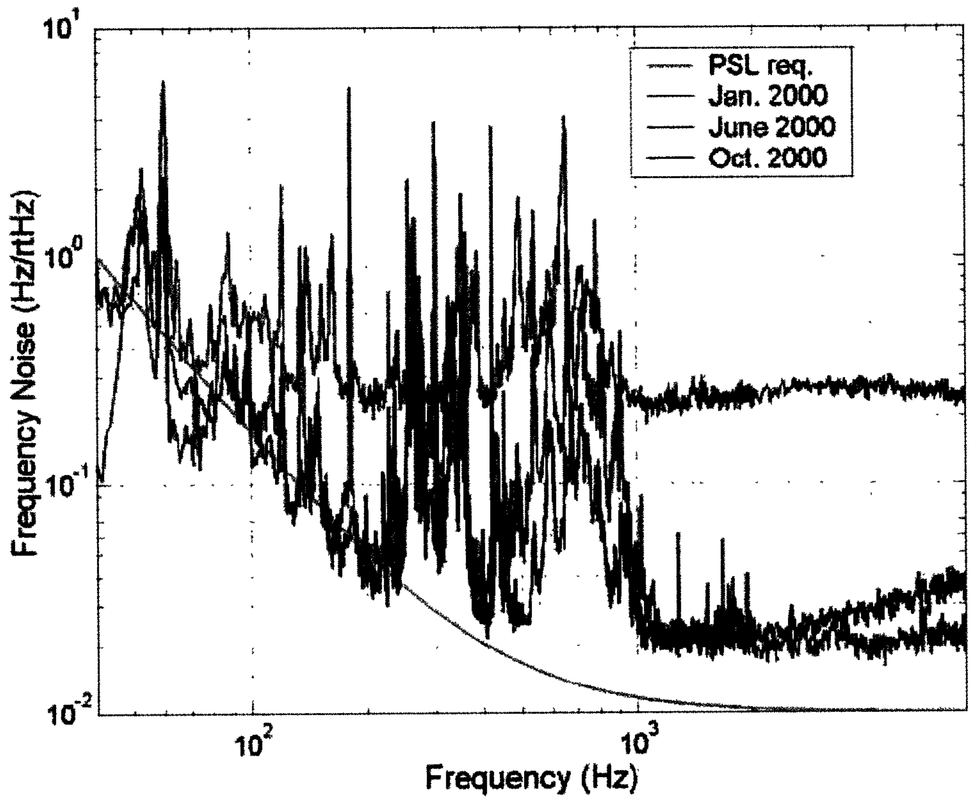
Laser *stabilization*

- Deliver pre-stabilized laser light to the 15-m mode cleaner
  - Frequency fluctuations
  - In-band power fluctuations
  - Power fluctuations at 25 MHz
- Provide actuator inputs for further stabilization
  - Wideband
  - Tidal



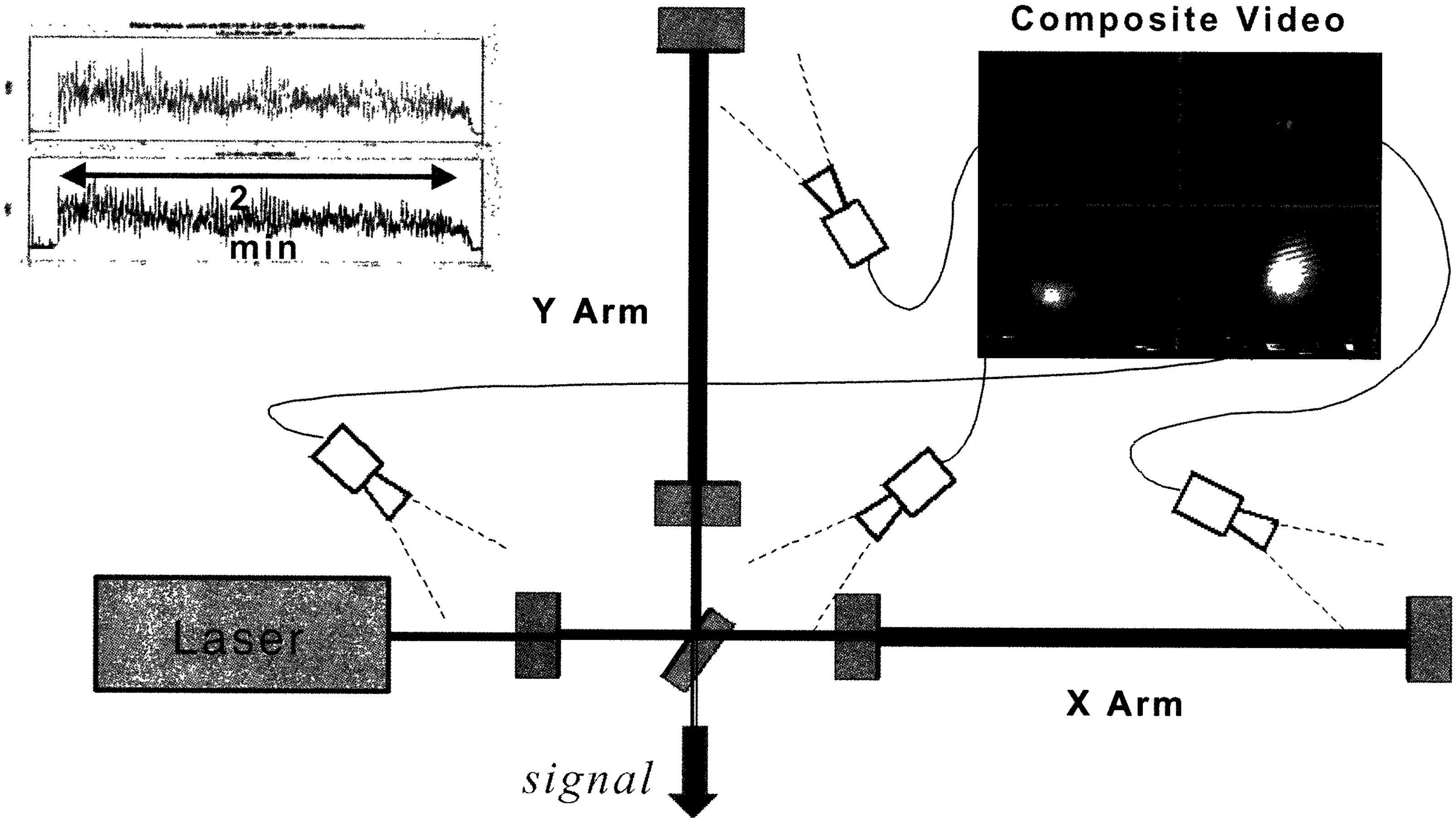
10^{-1} Hz/Hz$^{1/2}$ 10^{-4} Hz/ Hz$^{1/2}$ 10^{-7} Hz/ Hz$^{1/2}$

Pre-stabilized Laser
performance



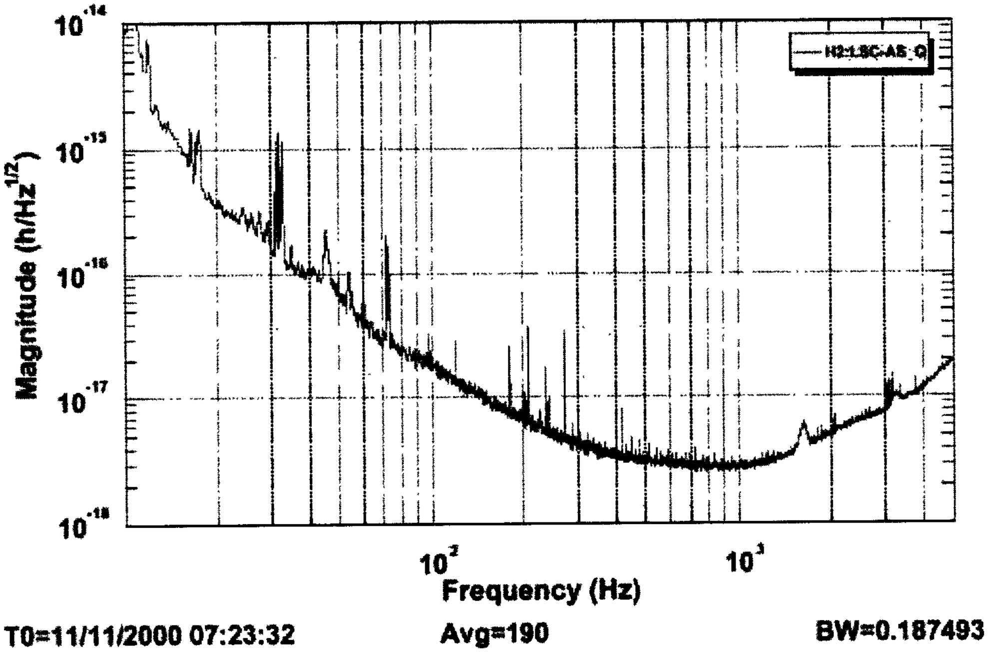
- > 18,000 hours continuous operation
- Frequency and lock very robust
- TEM_{00} power > 8 watts
- Non-TEM_{00} power < 10%

LIGO
first lock



Strain Sensitivity
Nov 2000

2-km Hanford Interferometer



- operating as a Michelson with Fabry-Perot arms
- reduced input laser power on the beam splitter (about 3 mW)
- without recycling
- noise level is a factor of 10^4-10^5 above the final specification
- sources of excess noise are under investigation

Significant Events

Hanford 2km interferometer	➢ Single arm test complete ➢ installation complete ➢ interferometer locked ➢ robust locking	6/00 8/00 10/00 1/01
Livingston 4km interferometer	➢ Input Optics completed ➢ interferometer installed ➢ short Michelson locked ➢ interferometer locked	7/00 10/00 1/01 3/01
Coincidence Engineering Run Hanford 2km& Livingston 4km	➢ Initiate (Upper Limit Run) ➢ Complete Engineering Runs	9/01 7/02
Hanford 4km interferometer	➢ All in-vacuum seismic installed ➢ interferometer installed ➢ interferometer locked	1/00 6/01 8/01
LIGO I Science Run (3 interferometers)	➢ Initiate ➢ Complete(obtain 1 yr @ $h \sim 10^{-21}$)	7/02 1/05

LIGO I
steps prior to science run

- commissioning interferometer
  - » robust locking
  - » three interferometers
  - » sensitivity
  - » duty cycle

- interleave engineering runs (LSC)
  - » implement and test acquisition and analysis tools
  - » characterization and diagnostics studies
  - » reduced data sets
  - » merging data streams
  - » upper limits

LIGO Scientific Collaboration
LSC

- The LIGO Laboratory
  - **MIT, Caltech, LHO and LLO groups operating as one integrated organization.**
  - **maintains the fiduciary responsibility for LIGO and is responsible for operations and improvements.**

- The LIGO Scientific Collaboration
  - **The underlying principle in the organization is to present "equal scientific opportunity" to all collaborators.**
    - LSC has developed its own governance, elects its own leadership, and sets its own agenda.
    - The LSC has an elected spokesman, has an executive committee, collaboration council and several working groups in different research areas and generally operates independently of the LIGO Laboratory management..
    - The scientific research of the LIGO Laboratory staff is carried out through the LSC.

LIGO Scientific Collaboration
LSC

- LIGO is available to all interested researchers through participation in the LSC, an open organization.
  - » a research group defines a research program with the LIGO Laboratory through the creation of a Memorandum of Understanding (MOU) and relevant attachments
  - » When the group is accepted into the LSC it becomes a full scientific partner in LIGO

LIGO Scientific Collaboration
Member Institutions

LSC Membership

35 institutions > 350 collaborators

University of Adelaide ACIGA	LIGO Livingston LIGOLA
Australian National University ACIGA	LIGO Hanford LIGOWA
California State Dominquez Hills	Louisiana State University
Caltech LIGO	Louisiana Tech University
Caltech Experimental Gravitation CEGG	MIT LIGO
Caltech Theory CART	Max Planck (Garching) GEO
University of Cardiff GEO	Max Planck (Potsdam) GEO
Carleton College	University of Michigan
Cornell University	Moscow State University
University of Florida @ Gainesville	NAOJ - TAMA
Glasgow University GEO	University of Oregon
University of Hannover GEO	Pennsylvania State University Exp
Harvard-Smithsonian	Pennsylvania State University Theory
India-IUCAA	Southern University
IAP Nizhny Novgorod	Stanford University
Iowa State University	University of Texas@Brownsville
Joint Institute of Laboratory Astrophysics	University of Western Australia ACIGA
	University of Wisconsin@Milwaukee

International

India, Russia, Germany, U.K, Japan and Australia.

The international partners are involved in all aspects of the LIGO research program.

GWIC

Gravitatational Wave International Committee

Science in LIGO I
LSC data analysis

- Compact binary inspiral: *"chirps"*
  - » NS-NS waveforms are well described
  - » BH-BH need better waveforms
  - » search technique: matched templates
- Supernovae / GRBs: *"bursts"*
  - » burst search algorithms – excess power; time-freq patterns
  - » burst signals - coincidence with signals in E&M radiation
  - » prompt alarm (~ 1 hr) with ν detectors [SNEWS]
- Pulsars in our galaxy: *"periodic"*
  - » search for observed neutron stars (freq., doppler shift)
  - » all sky search (computing challenge)
  - » r-modes
- Cosmological Signals *"stochastic background"*

Inspiral Sources

LSC
Upper Limit
Group

Inspiral Sources	Co-chair P Brady, G Gonzalez
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Data & Computing Group

engineering & science runs

- » **Simulation & Modeling:**
  - – detector support
  - – data analysis
- » **Data Management**
  - – movement of large volumes of data
  - – archive
- » **Data Analysis**
  - – pipeline analyses running
  - – participation in analysis teams
- » **Software**
  - – maintenance/improvements/enhancements
- » **LSC support**
- » **LIGO Lab IT support**

LIGO I Science Run
Data Analysis Model

- Astrophysical searches : follow plan in the LSC Data Analysis White Paper – http://www.ligo.caltech.edu/LIGO_web/lsc/lsc.html
  - » organized around teams as in near-term upper limit studies
  - » open to all LSC members contributing to LIGO I
- LDAS resources to be shared among the teams
- LSC institutional resources used by individuals
- Longer term
  - » distributed computing LIGO/LSC Tier 2 centers – GriPhyN
  - » LSC open to researchers wanting access to LIGO data

LIGO I
science run

- Strategy
  - » initiate science run when good coincidence data can be reliably taken and straightforward sensitivity improvements have been implemented (~ 7/02)
  - » interleave periods of science running with periods of sensitivity improvements

- Goals
  - » obtain 1 year of integrated data at $h \sim 10^{-21}$
    - – searches in coincidence with astronomical observations (eg. supernovae, gamma ray bursts)
    - – searches for known sources (eg. neutron stars)
    - – stand alone searches for compact binary coalescence, periodic sources, burst sources, stochastic background and unknown sources at $h \sim 10^{-21}$ sensitivities
  - » Exploit science at $h \sim 10^{-21}$ before initiating ‘advanced’ LIGO upgrades

LIGO Science
physics schedule

- LIGO I (~2002-2006)
  - » **LIGO I Collaboration of LSC**
  - » **obtain data for one year of live time at $h \sim 10^{-21}$ (by 2005)**
  - » **one extra year for special running or coincidences with Virgo**

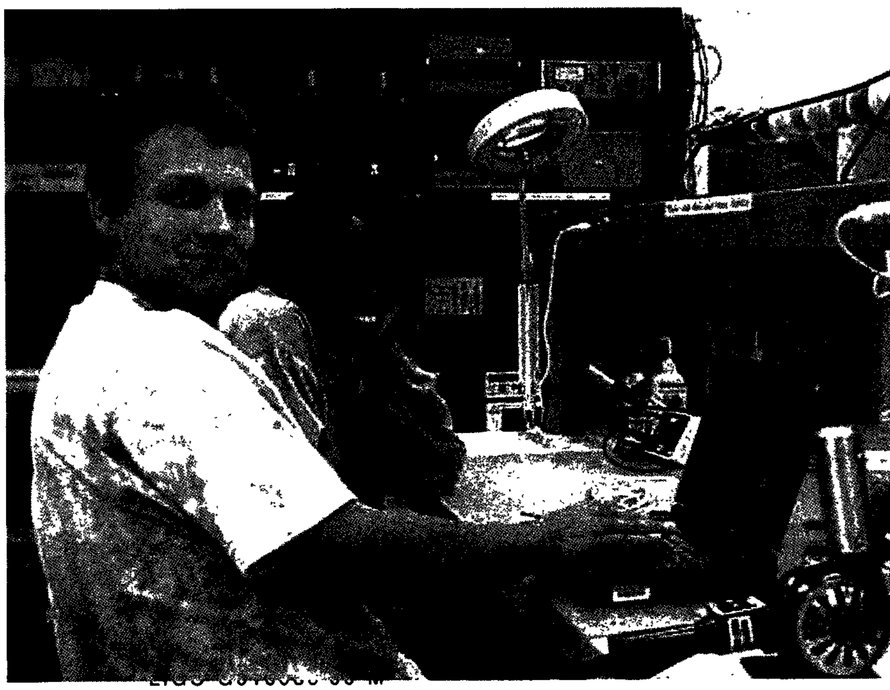
- Advanced LIGO (implement ~2006+)
  - » **broad LSC participation in R&D, design and implementation**
  - » **design sensitivity $h \sim 10^{-22}$** (or better)
  - » 2.5 hr will exceed <u>all</u> LIGO I (rate increase $\propto$ sensitivity cubed)

- 'Facility Limited' Detectors (> 2010 +)
  - » **new optical configurations, new vacuum chambers, cryogenic, QND, etc**
  - » **sensitivity $h \sim 10^{-23}$**

LIGO

Outreach and Education

REU, teacher training, student researchers, minority programs, public lectures and educational materials

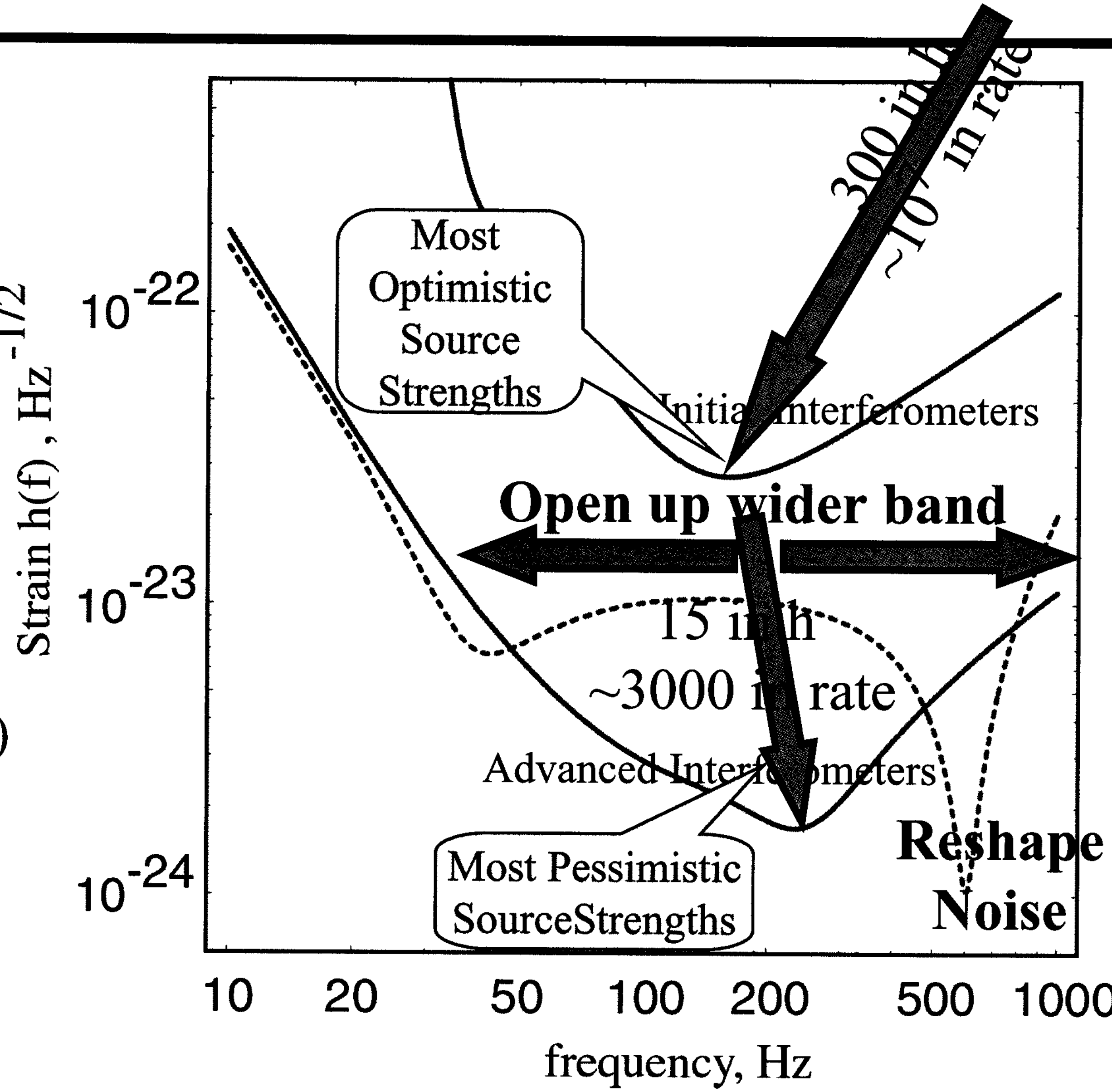


LIGO SCIENCE

Kip S. Thorne
CaRT, California Institute of Technology

NSF LIGO Operations Panel
Hanford - 26 February 2001

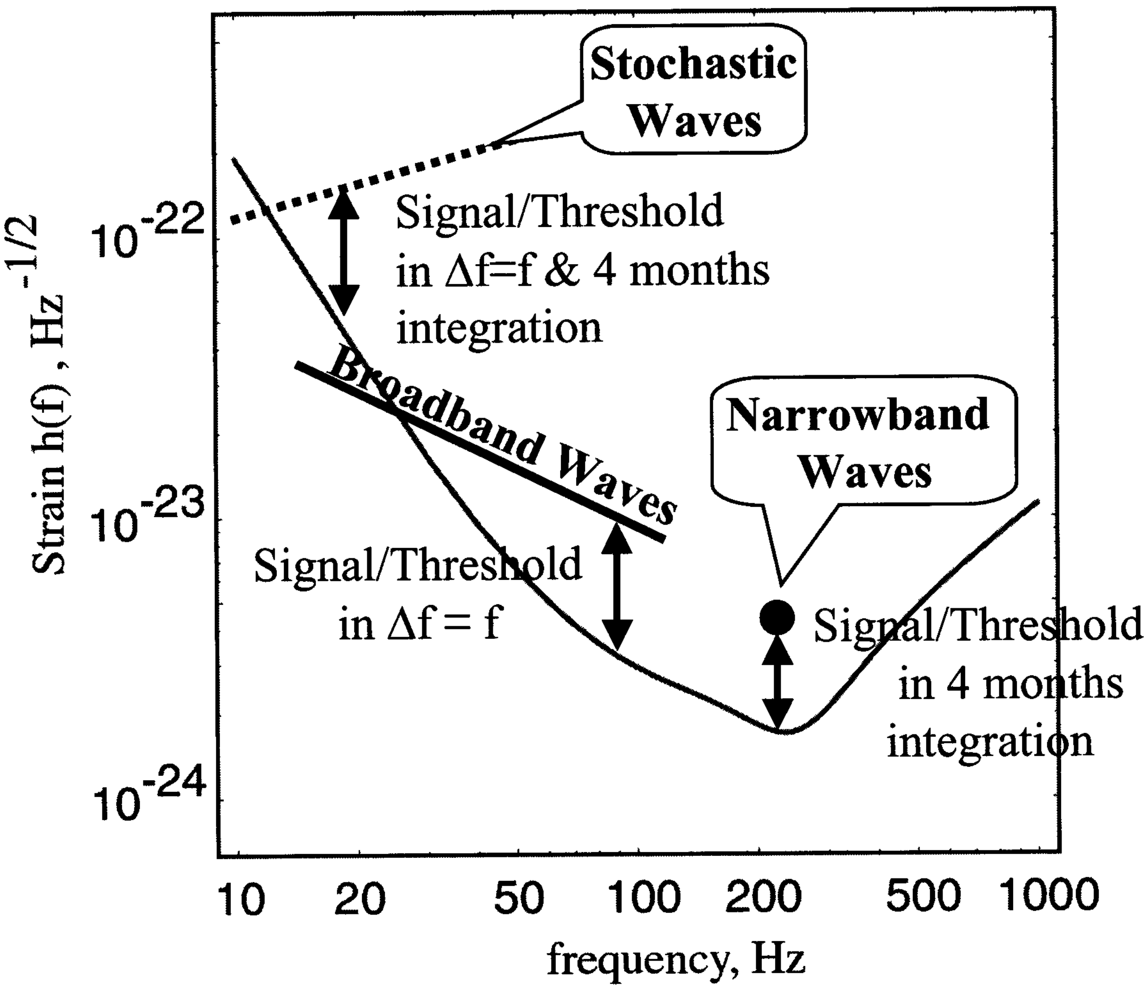
From Initial Interferometers to Advanced



$h_{rms} = h(f)\,\sqrt{f} \sim 10\, h(f)$

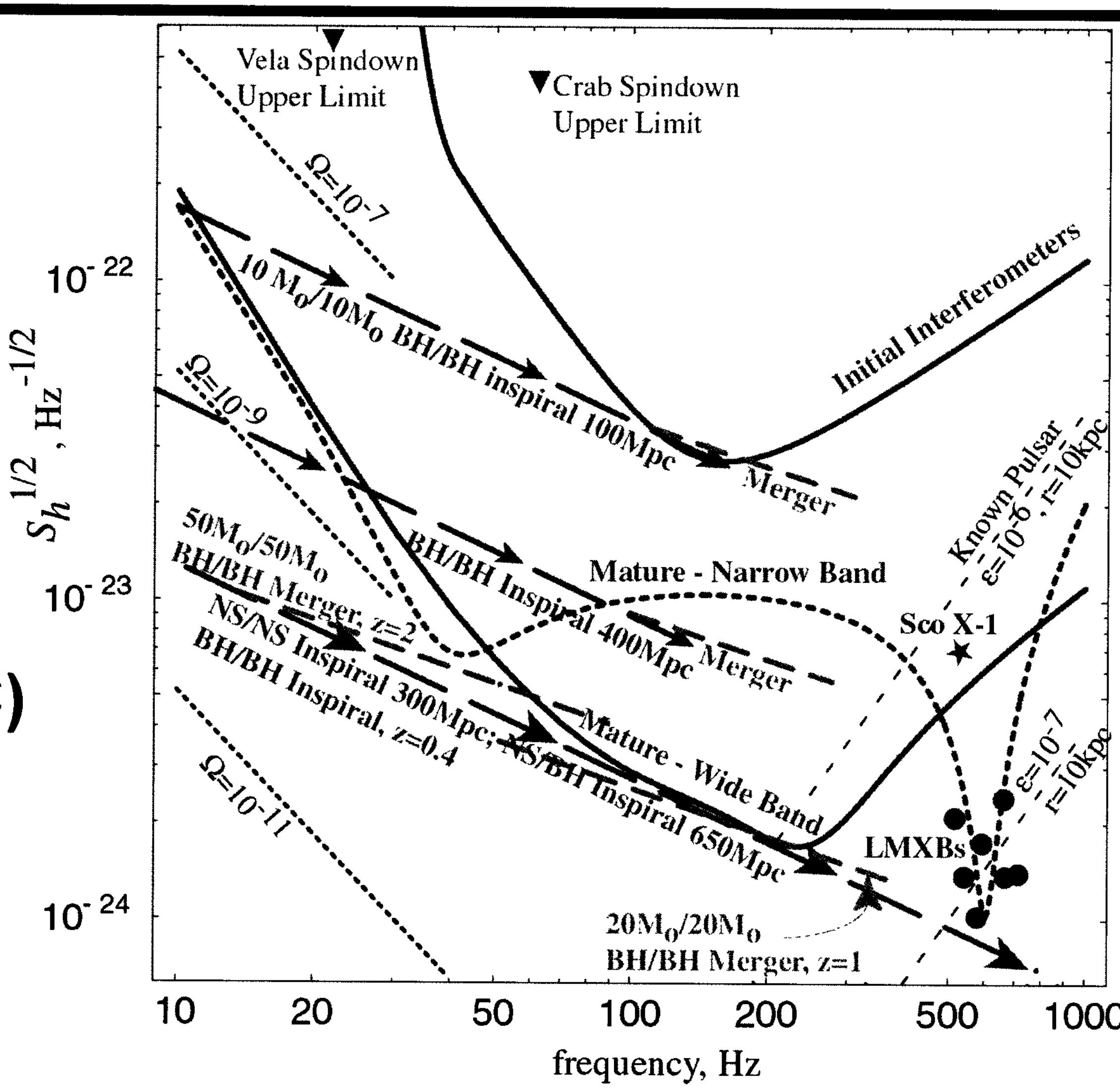
Conventions on Source/Sensitivity Plots

- Assume the best search algorithm now known
- Set Threshold so false alarm probability = 1%

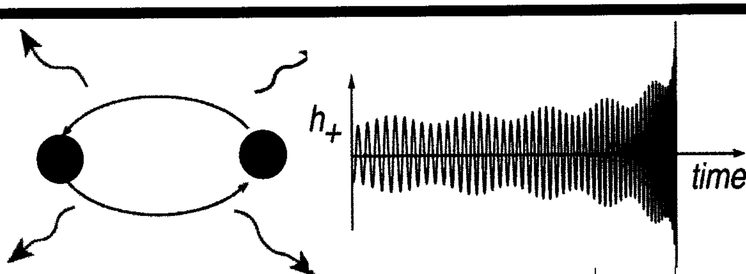


Overview of Sources

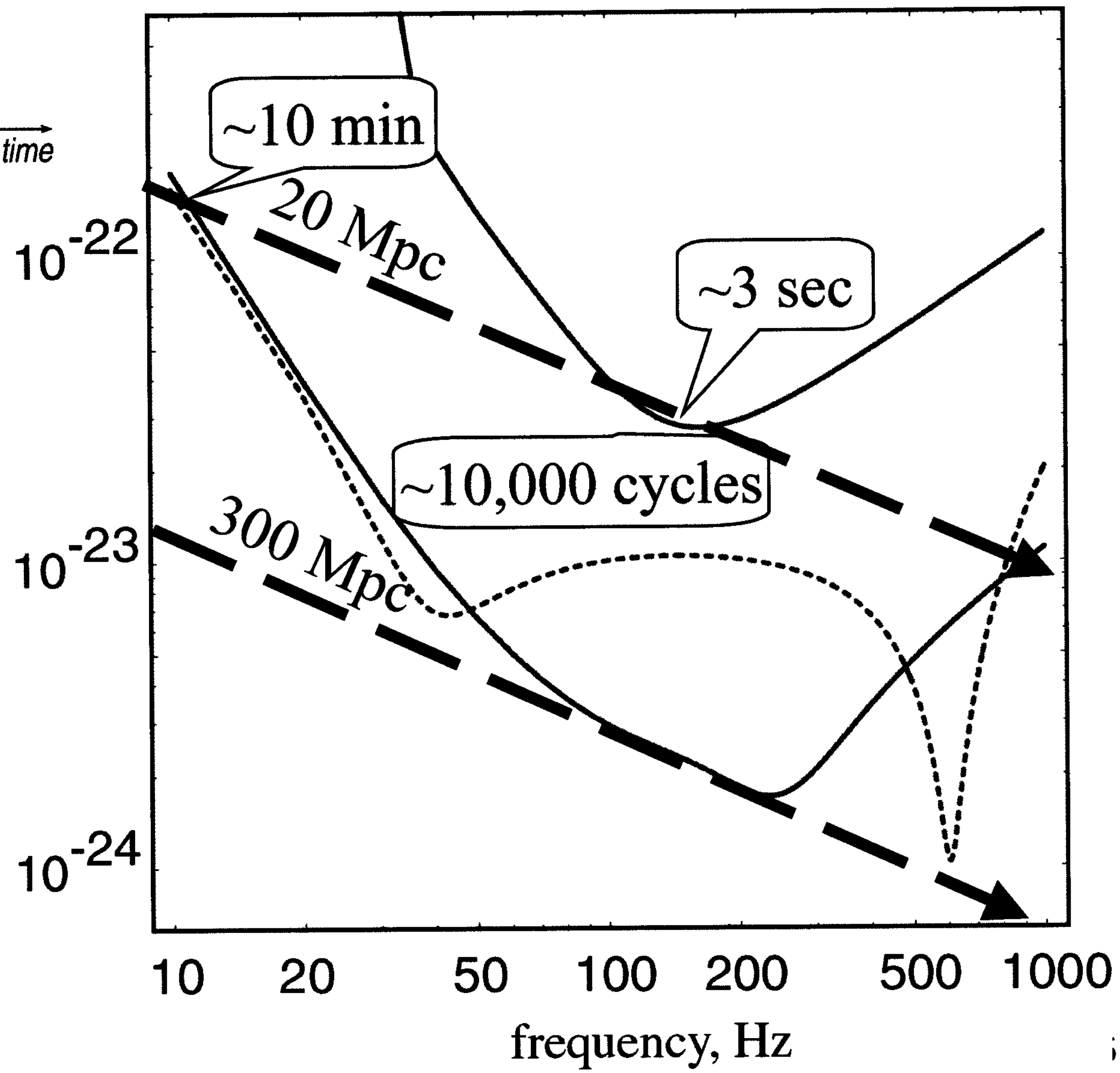
- **Neutron Star & Black Hole Binaries**
  - » inspiral
  - » merger
- **Spinning NS's**
  - » LMXBs
  - » known pulsars
  - » previously unknown
- **NS Birth (SN, AIC)**
  - » tumbling
  - » convection
- **Stochastic background**
  - » big bang
  - » early universe



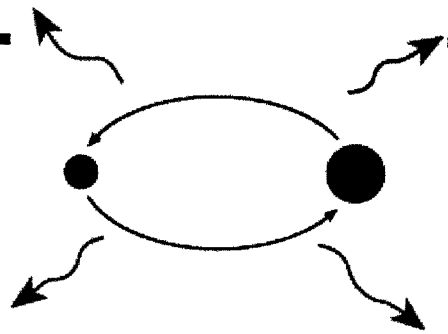
Neutron Star / Neutron Star Inspiral (our most reliably understood source)

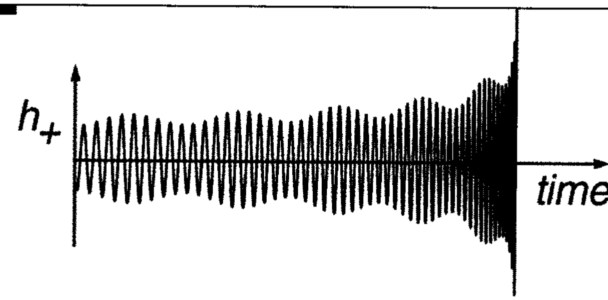


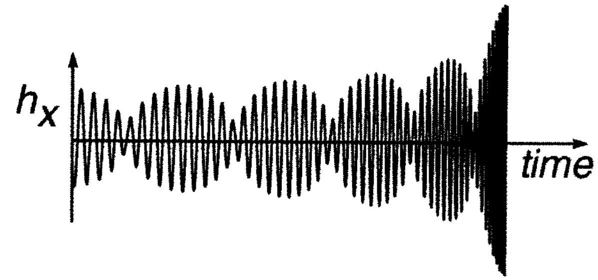
- **1.4 Msun / 1.4 Msun NS/NS Binaries**
- **Event rates**
  - » V. Kalogera, R. Narayan, D. Spergel, J.H. Taylor astro-ph/0012038
- **Initial IFOs**
  - » Range: 20 Mpc
  - » 1 / 3000 yrs to **1 / 3yrs**
- **Advanced IFOs -**
  - » Range: 300Mpc
  - » **1 / yr to 2 / day**



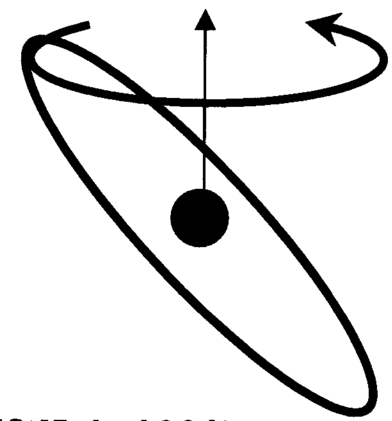
Science From Observed Inspirals: NS/NS, NS/BH, BH/BH





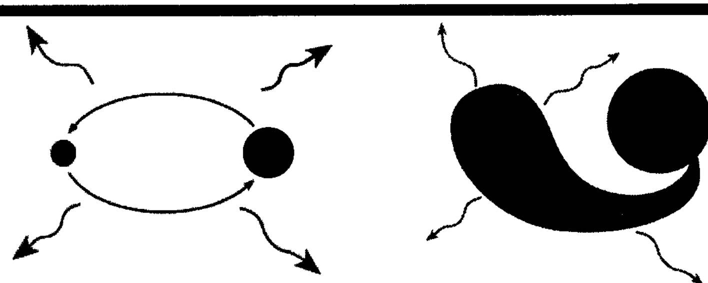


- Relativistic effects are very strong -- e.g.
  - » ***Frame dragging by spins $\Rightarrow$ precession $\Rightarrow$ modulation***
  - » ***Tails of waves modify the inspiral rate***



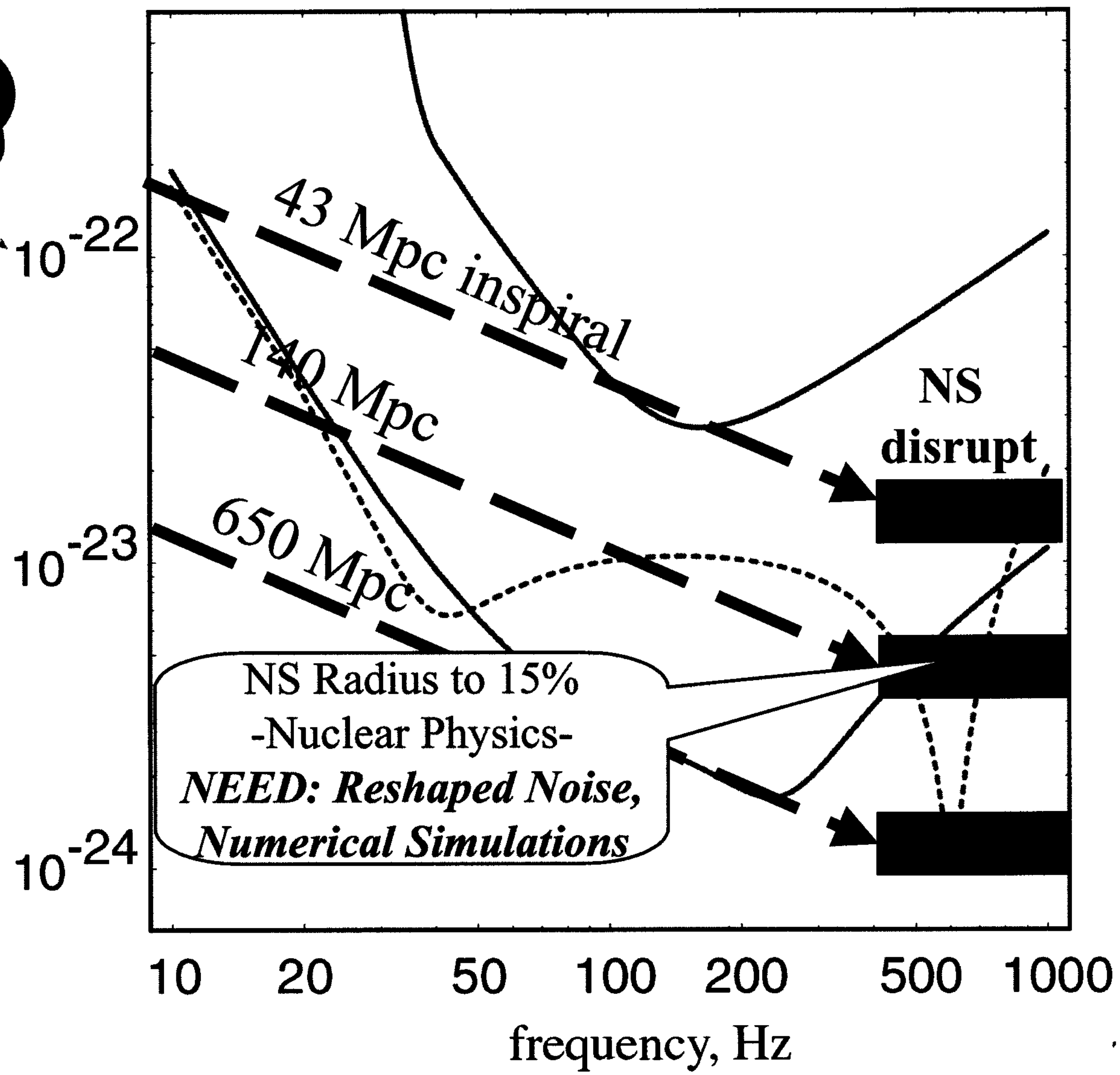
- Information carried:
  - » ***Masses (a few %), Spins (?few%?), Distance [not redshift!] (~10%), Location on sky (~1 degree)***
    - – $M_{\mathbf{chirp}} = \mu^{3/5} M^{2/5}$ to $\sim 10^{-3}$
- Search for EM counterpart, e.g. γ-burst. If found:
  - » ***Learn the nature of the trigger for that γ-burst***
  - » ***deduce relative speed of light and gw's to ~ 1 sec / 3x10^9 yrs ~ 10^{-17}***

Neutron Star / Black Hole Inspiral and NS Tidal Disruption



1.4Msun / 10 Msun NS/BH Binaries

- **Event rates**
  - » Population Synthesis [Kalogera's summary]
- **Initial IFOs**
  - » Range: 43 Mpc
  - » ≲1 / 2500 yrs to **1 / 2yrs**
- **Advanced IFOs**
  - » Range: 650 Mpc
  - » **≲1 / yr to 4 / day**

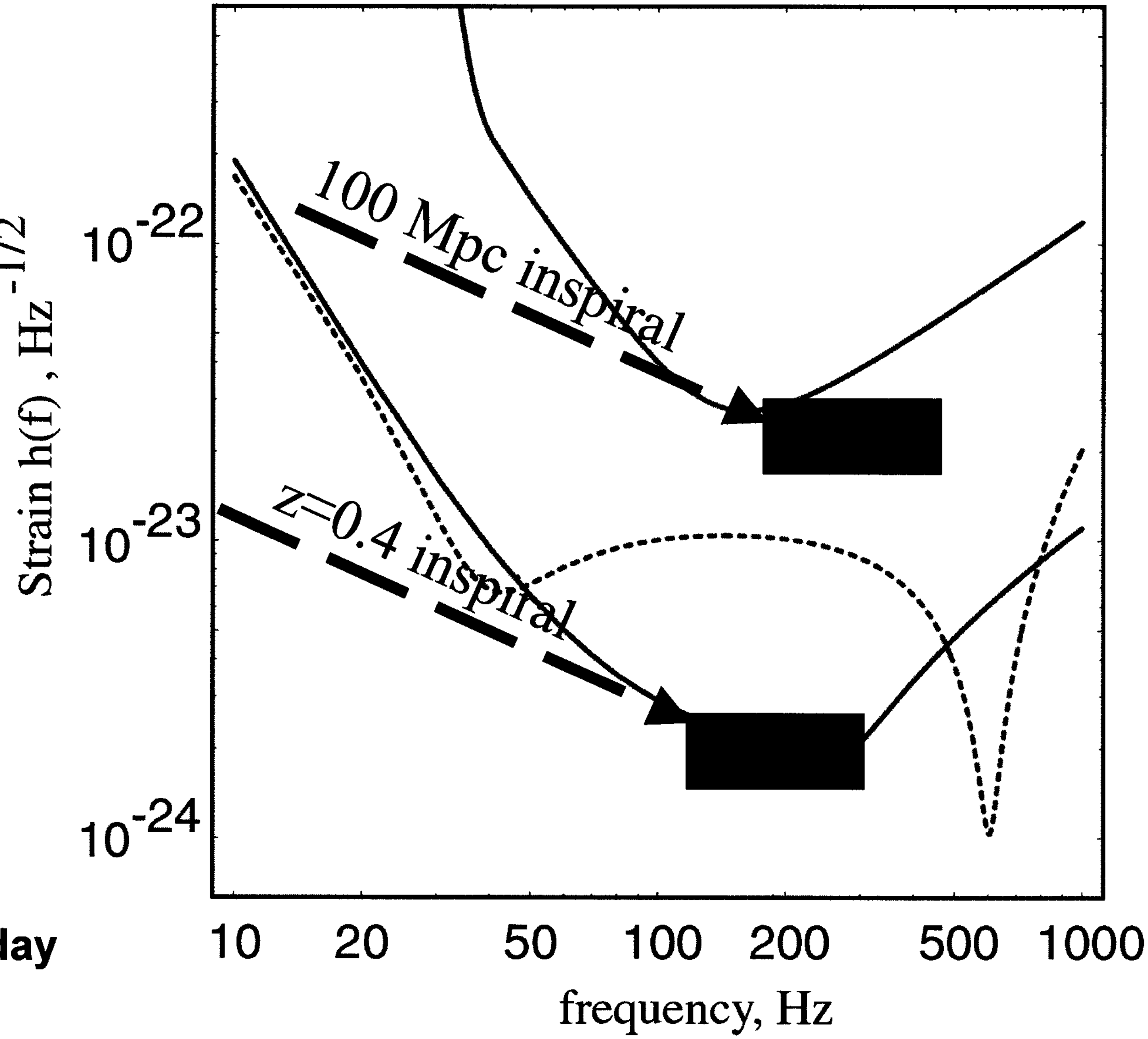


Black Hole / Black Hole Inspiral and Merger

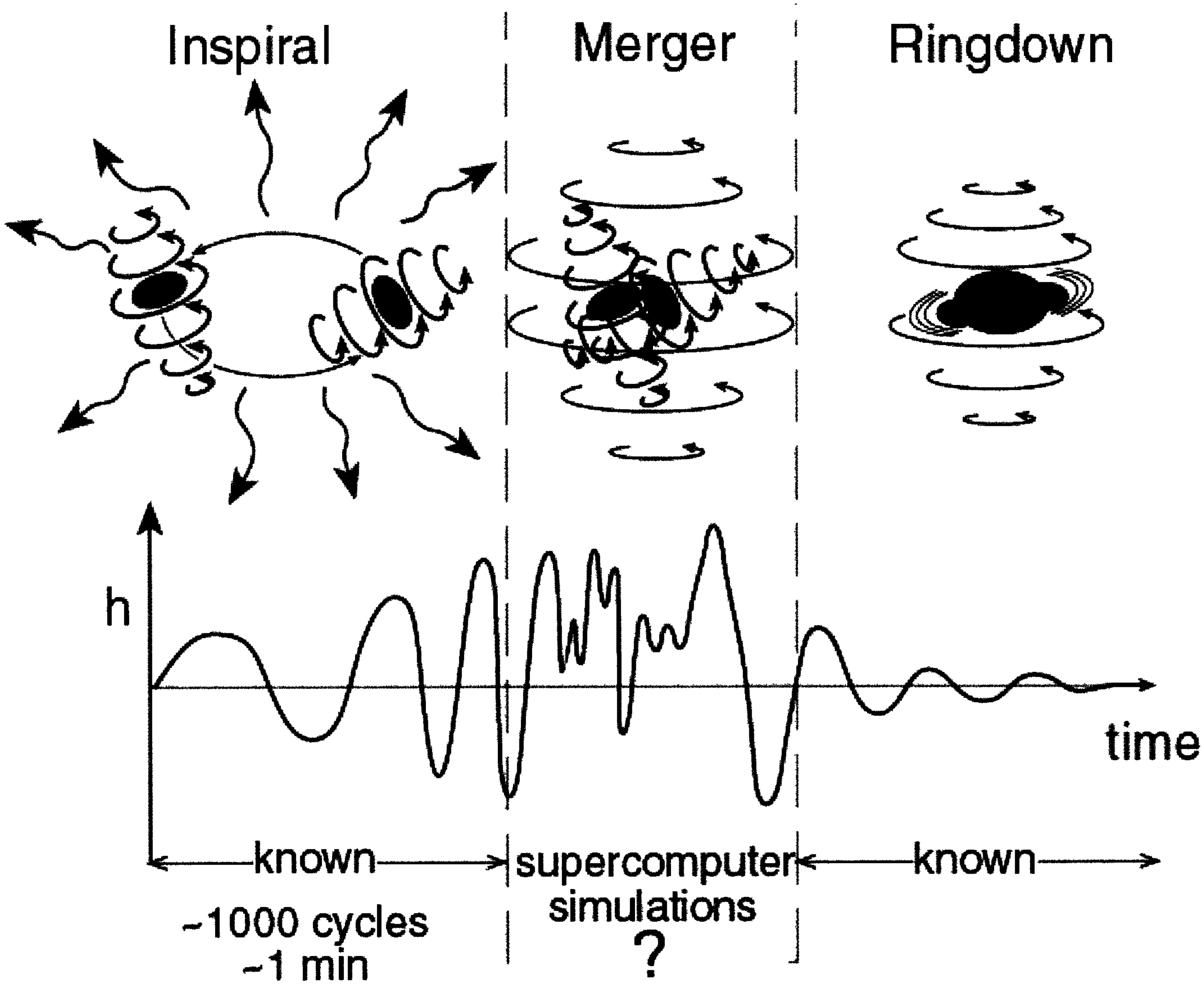
- **10Msun / 10 Msun BH/BH Binaries**
- **Event rates**
  - » Based on population synthesis [Kalogera's summary of literature]

Initial IFOs
  - » Range: 100 Mpc
  - » ≲1 / 300yrs to **~1 / yr**

- **Advanced IFOs -**
  - » Range: z=0.4
  - » ≲**2 / month to ~10 / day**

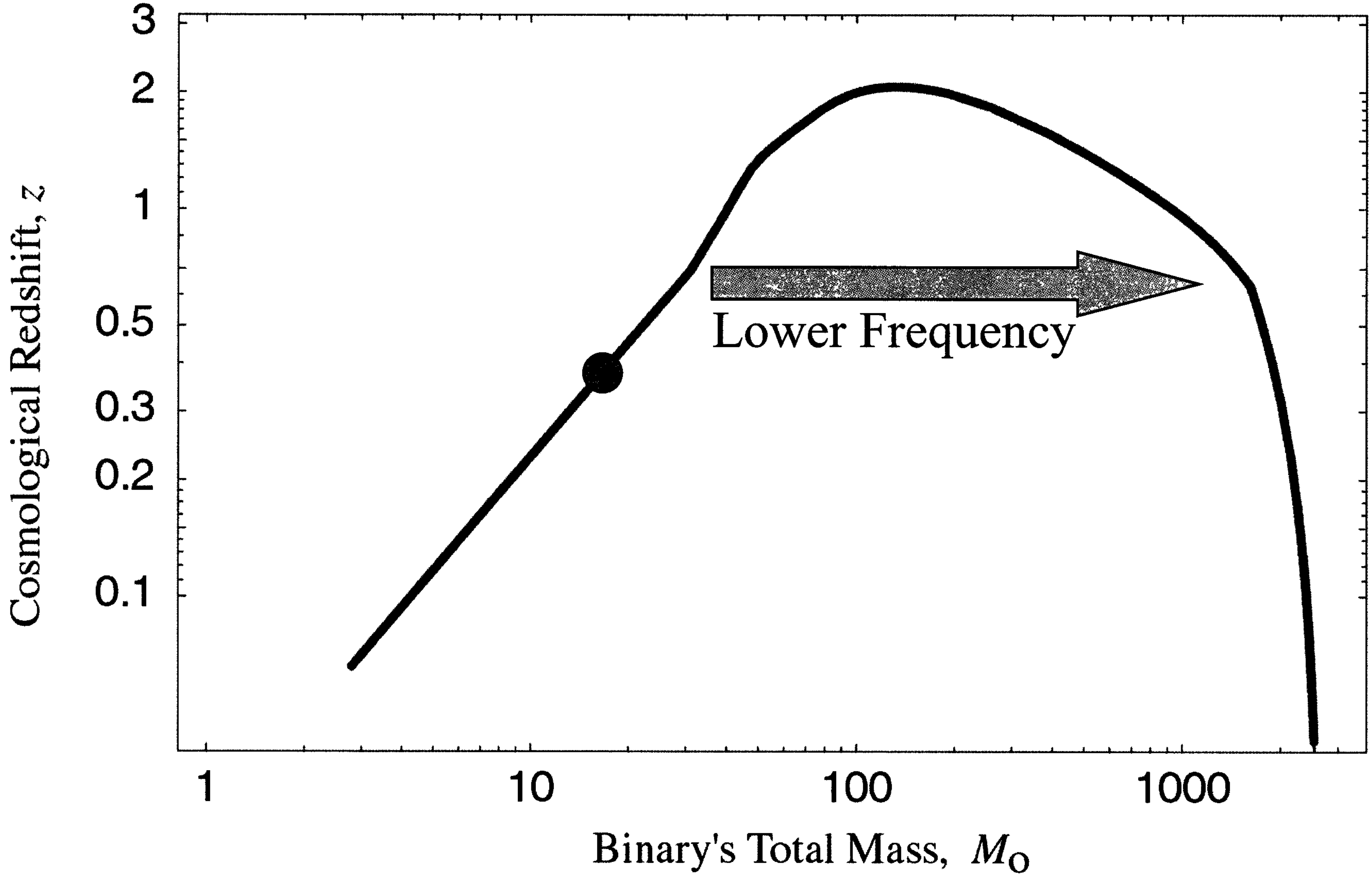


BH/BH Mergers: Exploring the Dynamics of Spacetime Warpage



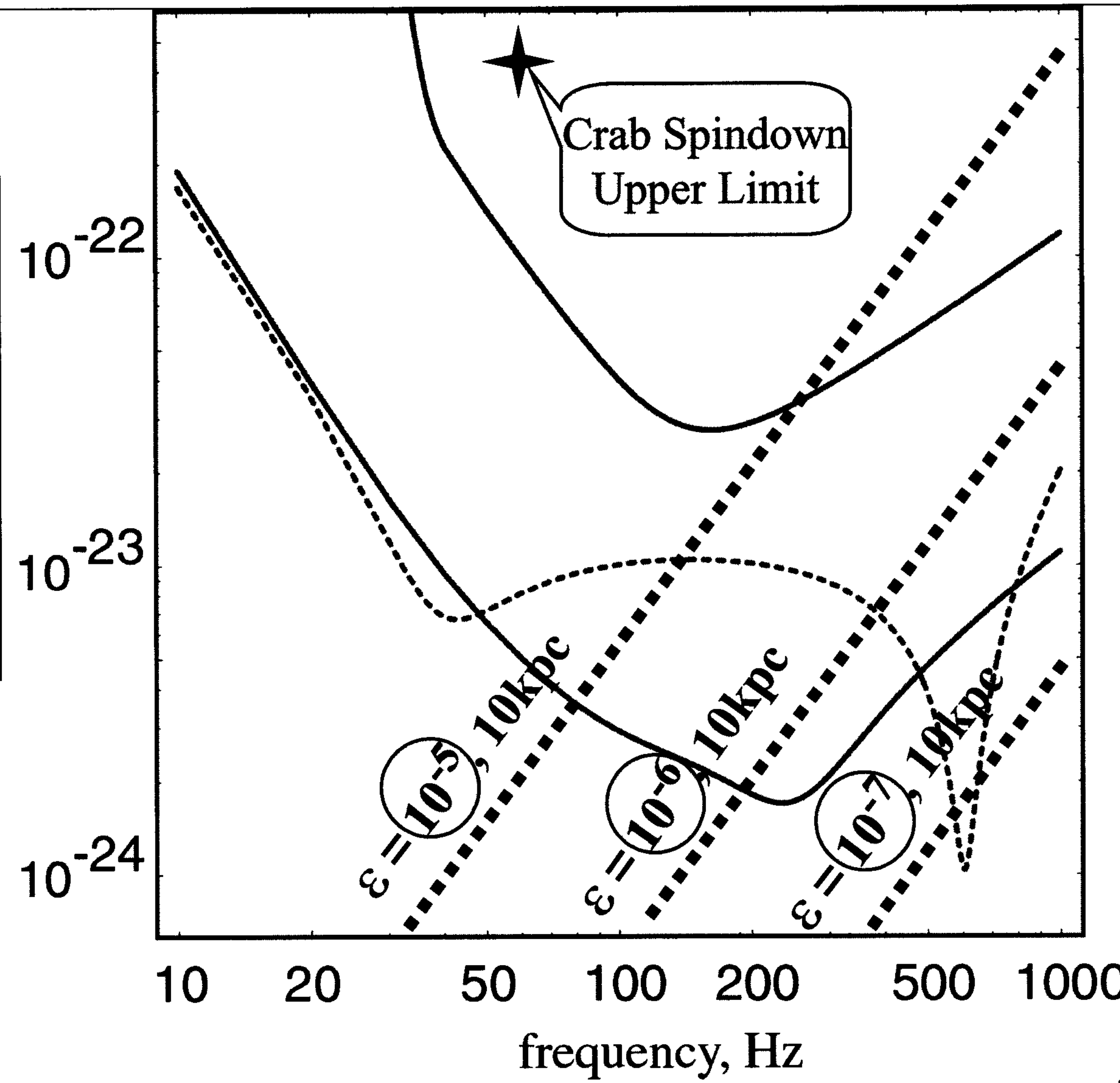
Numerical Relativity Simulations Are Badly Needed!

Massive BH/BH Mergers with Fast Spins - Advanced IFOs



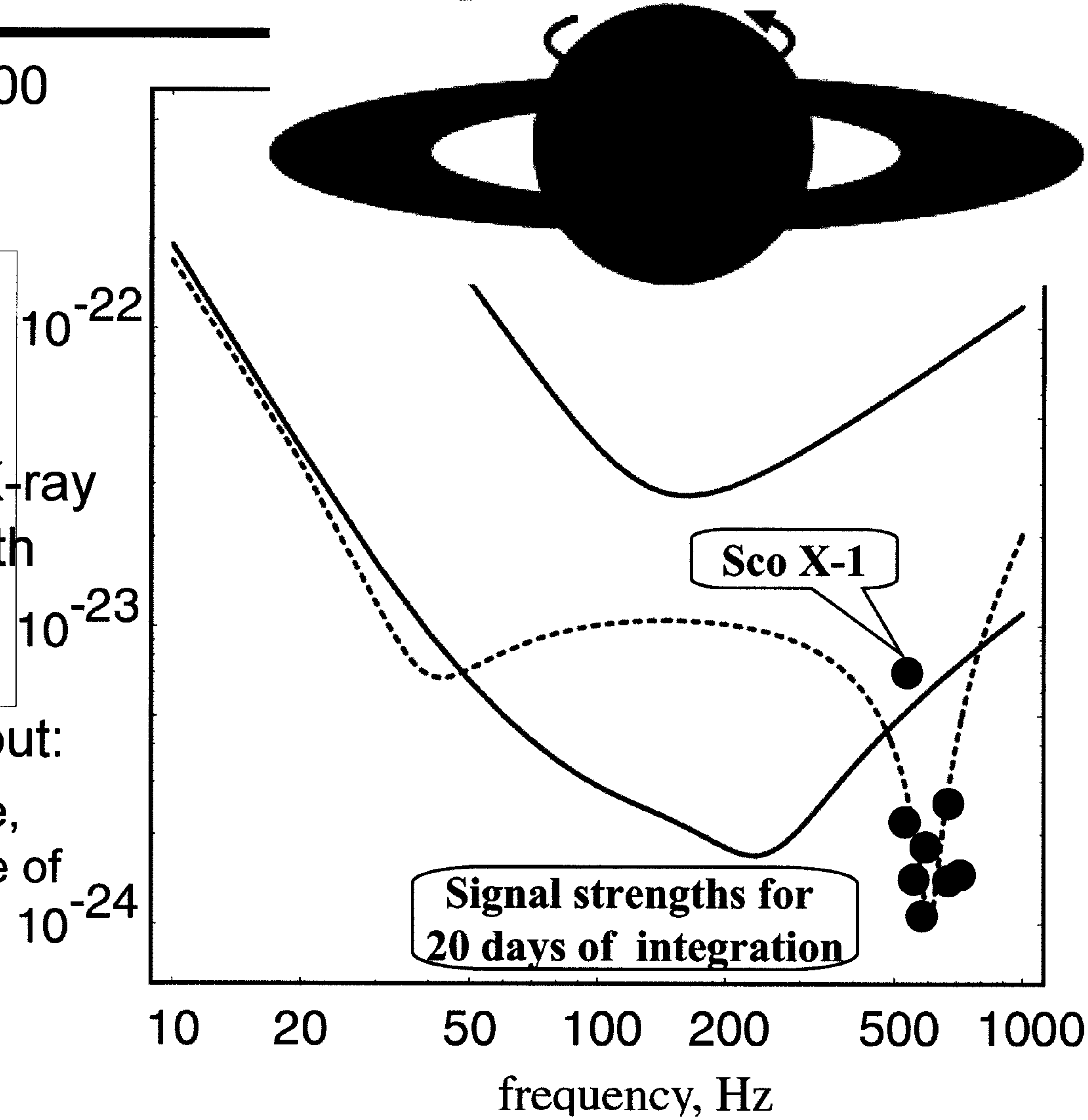
Spinning NS's: Pulsars

- NS Ellipticity:
  - » Crust strength Γ
    $\varepsilon \lesssim 10^{-6}$; possibly 10^{-5}
- Known Pulsars:
  - » First Interferometers:
    $\varepsilon \gtrsim 3\text{x}10^{-6}$ (1000Hz/f) x (distance/10kpc)
  - » Narrowband Advanceδ
    $\varepsilon \gtrsim 2\text{x}10^{-8}$ $(1000\text{Hz/f})^2$ x (distance/10kpc)
- Unknown NS's - All sky search:
  - » Sensitivity ~5 to 15 worse



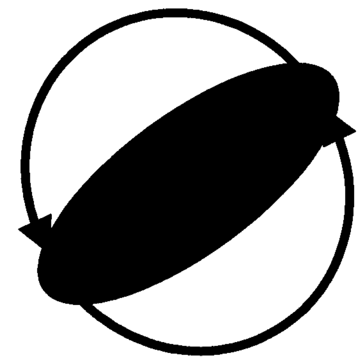
Spinning Neutron Stars: Low-Mass X-Ray Binaries

- Rotation rates ~250 to 700 revolutions / sec
  - » Why not faster?
  - » **Bildsten**: Spin-up torque balanced by GW emission torque
- If so, and steady state: X-ray luminosity ⇒ GW strength
- Combined GW & EM obs's ⇒ information about:
  - » crust strength & structure, temperature dependence of viscosity, ...



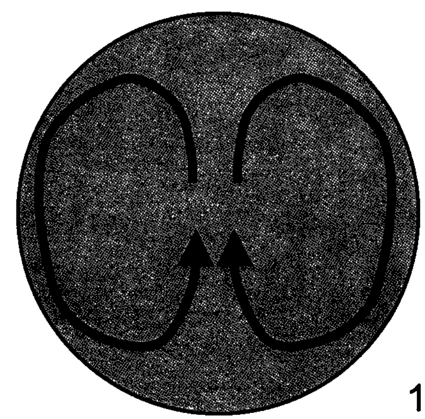
NS Birth: Tumbling Bar; Convection

- **Born in:**
  - » Supernovae
  - » Accretion-Induced Collapse of White Dwarf
- **If very fast spin:**
  - » Centrifugal hangup
  - » **Tumbling bar** - episodic? (for a few sec or min)
  - » ***If modeling gives enough waveform information,*** detectable to:
    - – Initial IFOs: ~5Mpc (M81 group, ~1 supernova/3yr)
    - – Advanced IFOs: ~100Mpc (~500 supernovae/yr)



If slow spin:

- » **Convection** in first ~1 sec.
- » Advanced IFOs: Detectable only in our Galaxy (~1/30yrs)
- » GW / neutrino correlations!

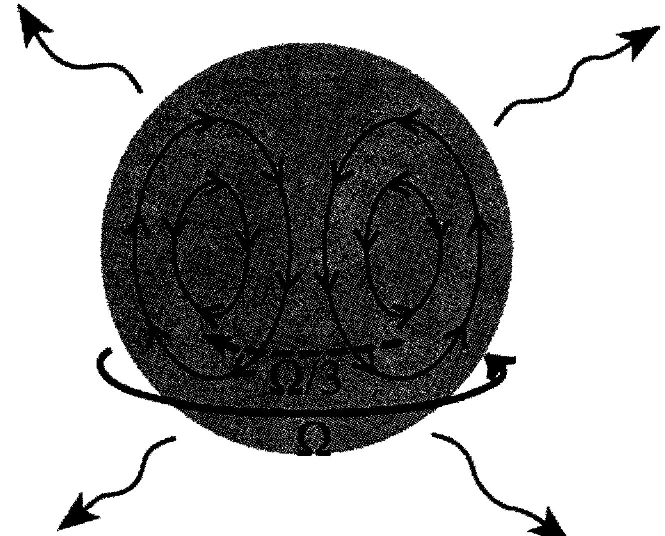


Neutron-Star Births: R-Mode Sloshing in First ~1yr of Life

NS formed in supernova or accretion-induced collapse of a white dwarf.

» *If* NS born with P_{spin} < 10 msec: ***R-Mode instability:***

» Gravitational radiation reaction drives sloshing



- **Physics complexities: What stops the growth of sloshing & at what amplitude?**
  » Crust formation in presence of sloshing?
  » Coupling of R-modes to other modes?
  » Wave breaking & shock formation?
  » Magnetic-field torques?
  » ....

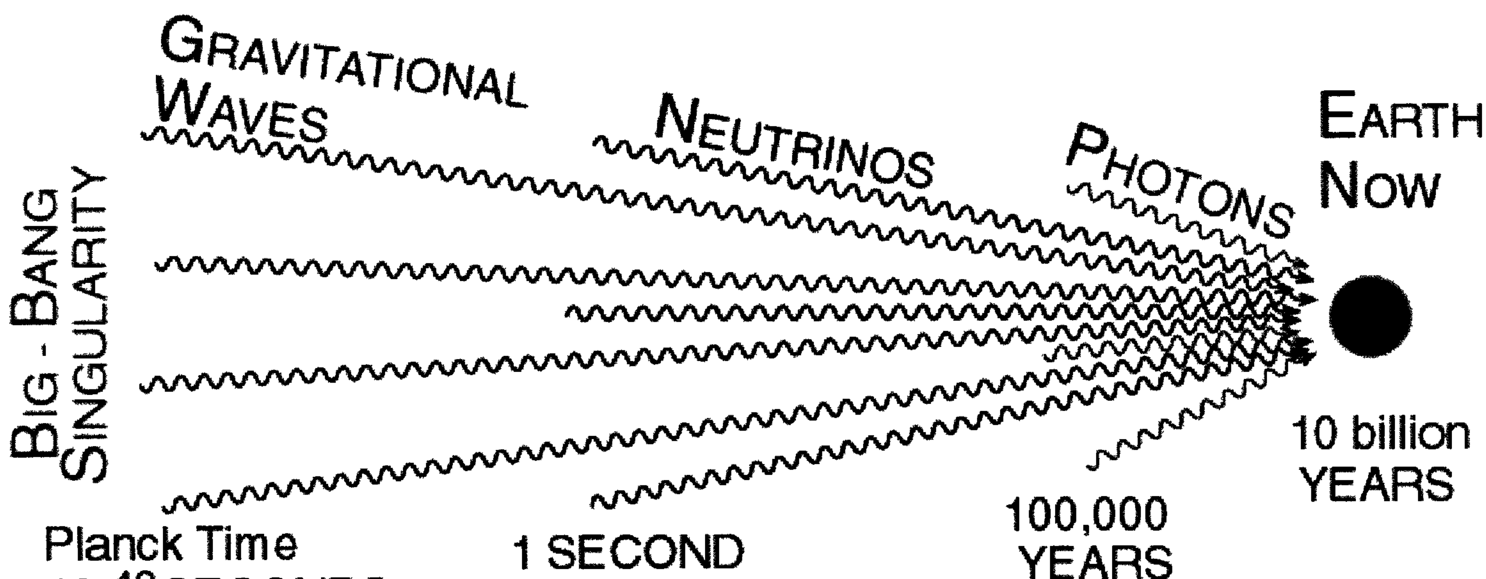
Depending on this, Initial IFOs detect to 1 Mpc (Local Group, ~1 SN/15yr) Advanced IFOs detect to 20 Mpc (Virgo, ~5 SN/yr)

GW's carry information about these

LIGO

Stochastic Background from Very Early Universe

- **GW's are the ideal tool for probing the very early universe**

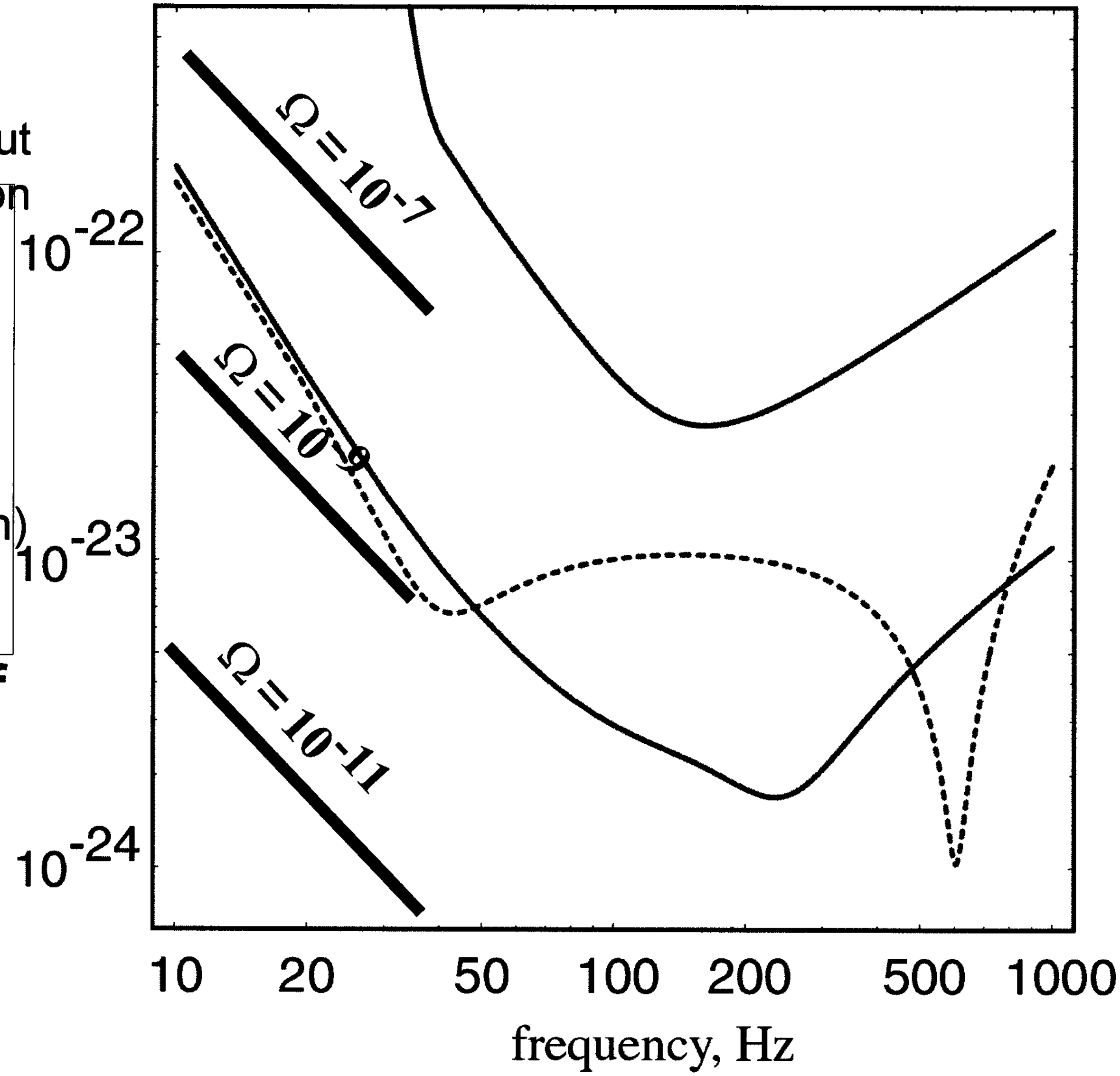


Planck Time
10^{-43} SECONDS
Singularity creates Space & Time of our universe

- **Present limit on GWs**
  - » From effect on primordial nucleosynthesis
  - » $\boxed{\Omega = \text{(GW energy density)/(closure density)} \lesssim \mathbf{10^{-5}}}$

Stochastic Background from Very Early Universe

- **Detect by**
  - » cross correlating output of Hanford & Livingston 4km IFOs
- **Good sensitivity requires**
  - » (GW wavelength) $\gtrsim$ **2x**(detector separation)
  - » f $\lesssim$ 40 Hz
- **Initial IFOs detect if**
  - » $\boldsymbol{\Omega \gtrsim 10^{-5}}$
- **Advanced IFOs:**
  - » $\boxed{\boldsymbol{\Omega \gtrsim 5\text{x}10^{-9}}}$



Grav'l Waves from Very Early Universe. ***Unknown Sources***

- Waves from standard inflation: $\Omega \sim 10^{-15}$: much too weak
- ***BUT:*** Crude superstring models of big bang suggest waves ***might be strong enough*** for detection by Advanced LIGO
- GW bursts from cosmic strings: possibly detectable by Initial IFOs
- Energetic processes at (universe age) ~ 10^{-25} sec and (universe temperature) ~ 10^{9} Gev $\Rightarrow$ GWs in LIGO band
  - » **phase transition at 10^{9} Gev**
  - » **excitations of our universe as a 3-dimensional "brane" (membrane) in higher dimensions:**
    - **Brane forms wrinkled**

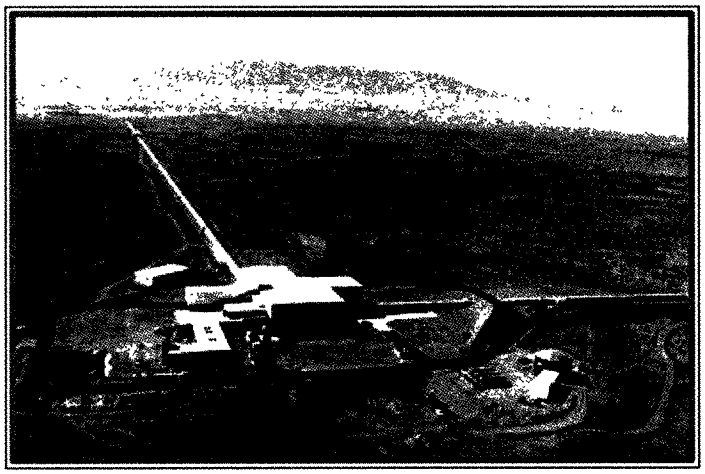
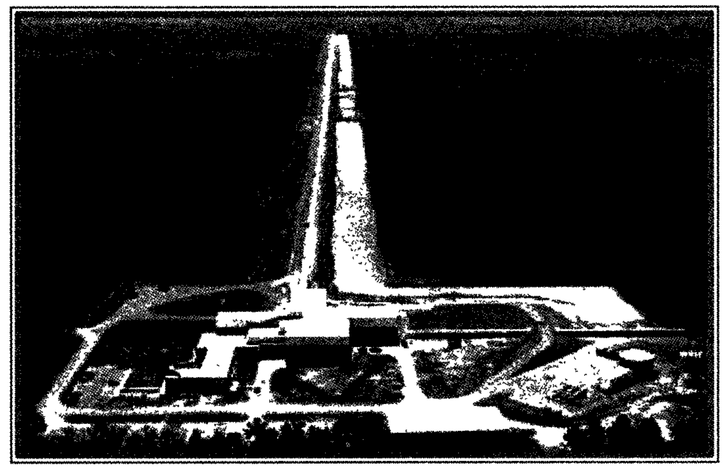
    - **When wrinkles "come inside the cosmological horizon", they start to oscillate; oscillation energy goes into gravitational waves**
    - **LIGO probes waves from wrinkles of length ~ 10^{-10} to 10^{-13} mm**
    - **If wave energy equilibrates: possibly detectable by initial IFOs**
- Example of hitherto $\boxed{\textit{UNKNOWN SOURCE}}$

Conclusions

- **LIGO's Initial Interferometers bring us into the realm where it is plausible to begin detecting cosmic gravitational waves.**
- **With LIGO's Advanced Interferometers we can be confident of:**
  - » detecting waves from a variety of sources
  - » gaining major new insights into the universe, and into the nature and dynamics of spacetime curvature, that cannot be obtained in any other way

Detector Installation and Commissioning

Stan Whitcomb

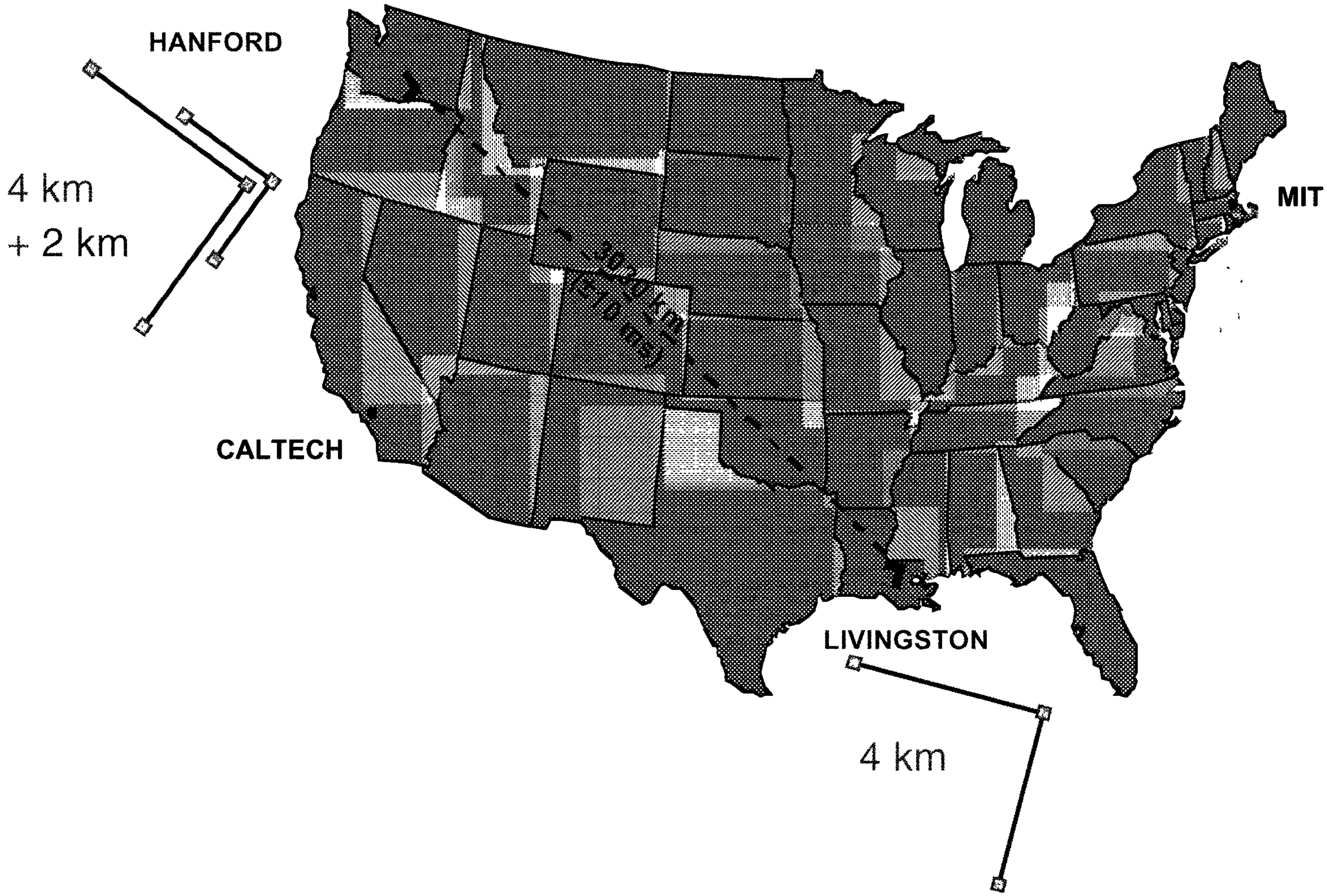
NSF Operations Review

26 February 2001

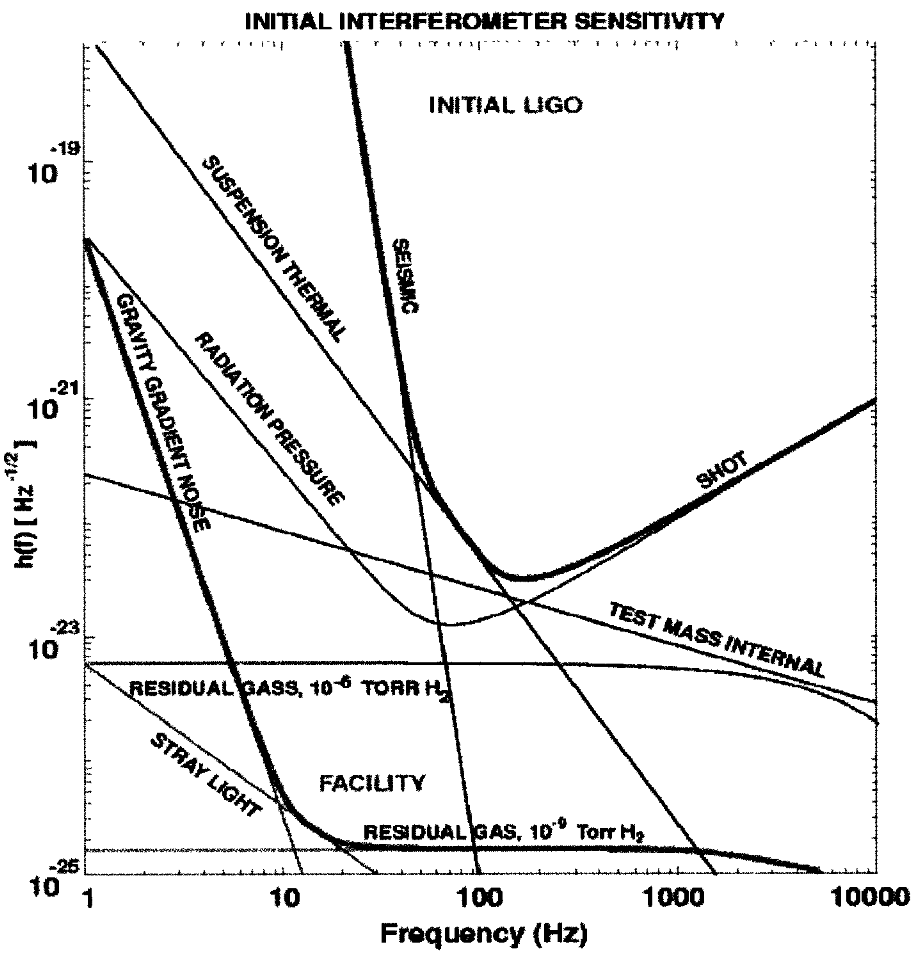
LIGO Hanford Observatory

LIGO-G010035-00-D

LIGO Observatories



Initial LIGO Sensitivity Goal



- Strain sensitivity $<3\times10^{-23}$ 1/Hz$^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

Installation/Commissioning Philosophy

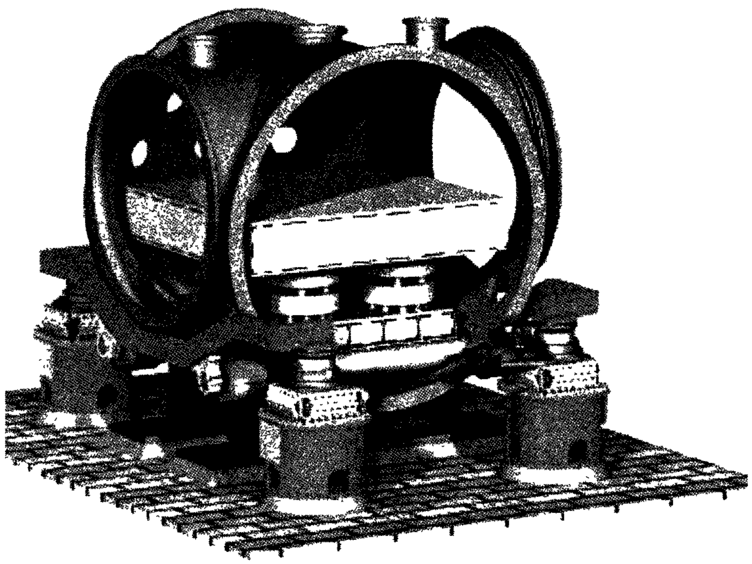
- Each interferometer has a specific role in commissioning
  - 2 km Interferometer: "Pathfinder", move quickly, identify problems, move on
  - LLO 4 km Interferometer: Systematic characterization, problem resolution
  - LHO 4 km Interferometer: Scheduled so that all fixes can be implemented prior to installation
- Stagger the installation and commissioning activities to make optimal use of available staff

Installation Status

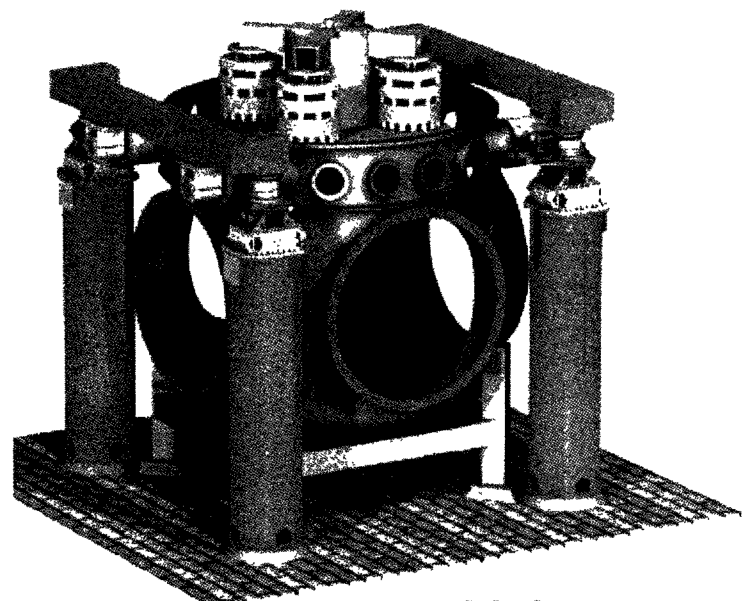
- All installation complete for LHO 2km and LLO 4km interferometers
  - » Commissioning underway
- LHO 4km interferometer
  - » Seismic isolation complete
  - » Prestabilized laser installation underway
  - » In-vacuum optics installation currently underway
- Data Acquisition/Control Network infrastructure complete at both sites
  - » Basic functionality all in place; still working on reliability, enhancements

Vibration Isolation Systems

» Reduce in-band seismic motion by 4 - 6 orders of magnitude
» Large range actuation for initial alignment and drift compensation
» Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation



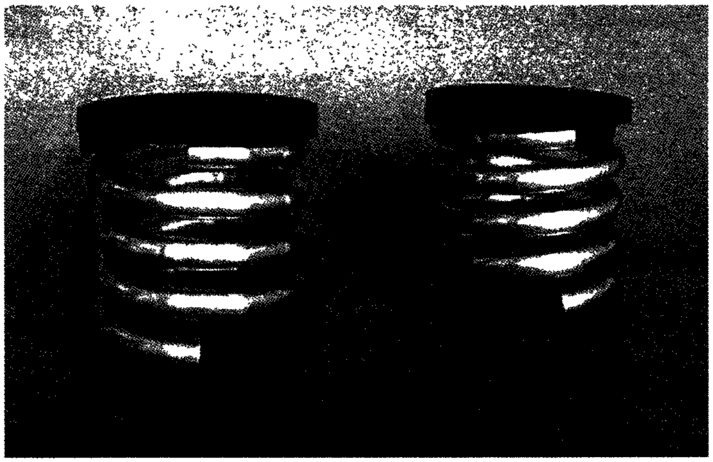
HAM Chamber



BSC Chamber

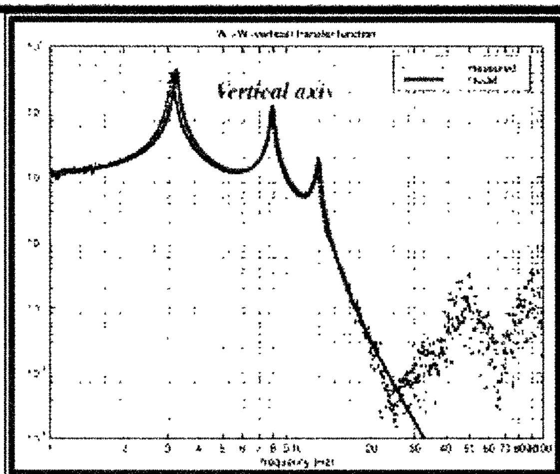
LIGO

Seismic Isolation – Springs and Masses



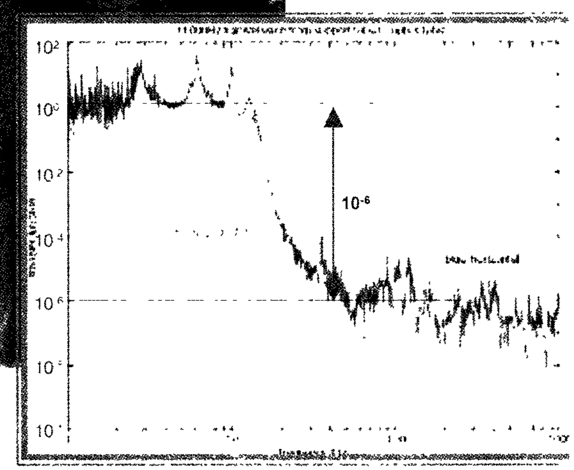
damped spring
cross section

Seismic System Performance



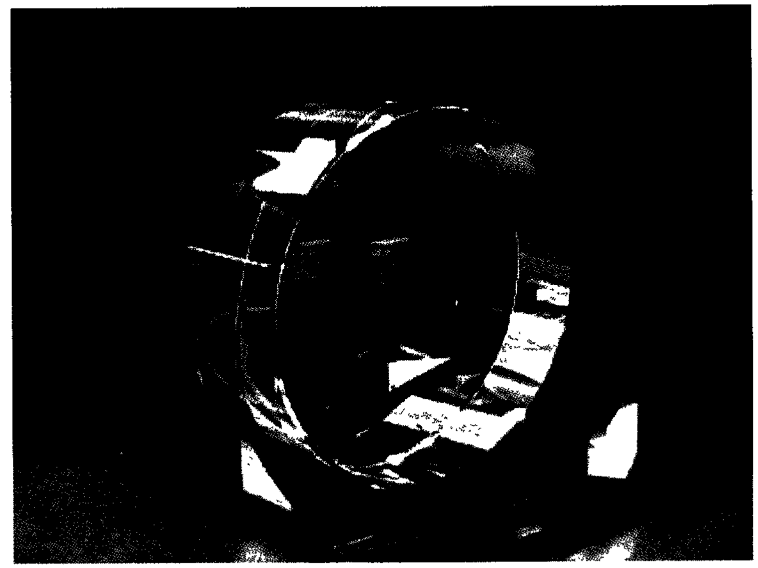
HAM st
in air

BSC stack
vacuum



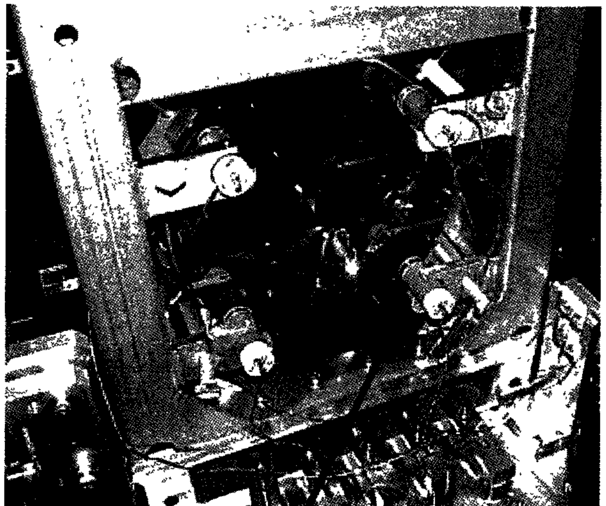
Core Optics

- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity < 5 x 10^{-7}
  - » Internal mode Q's > 2 x 10^{6}
- Polishing
  - » Surface uniformity < 1 nm rms
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity <10^{-3}



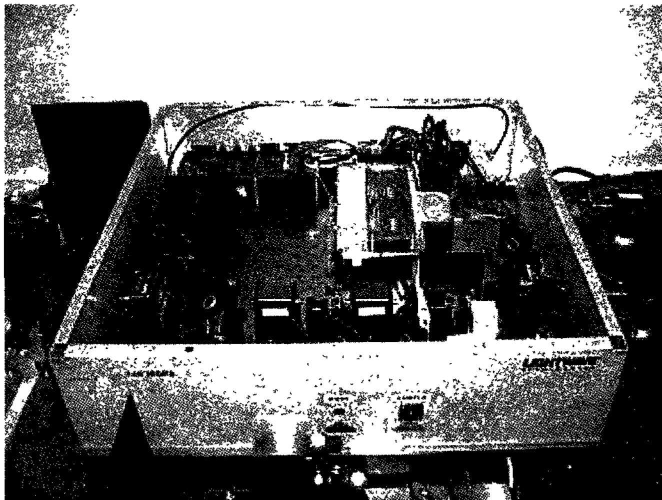
- Successful production involved 6 companies, NIST, and the LIGO Lab
- All optics for three interferometers delivered to sites

Core Optics Suspension and Control

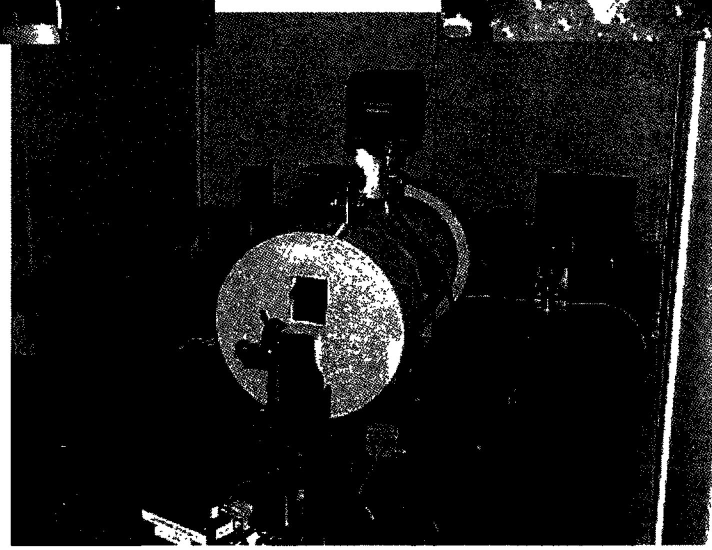


- Optics suspended as simple pendulums
- Local sensors/actuators for damping and control
- Problem with local sensor sensitivity to laser light

Pre-stabilized Laser



Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics
(now commercial product)

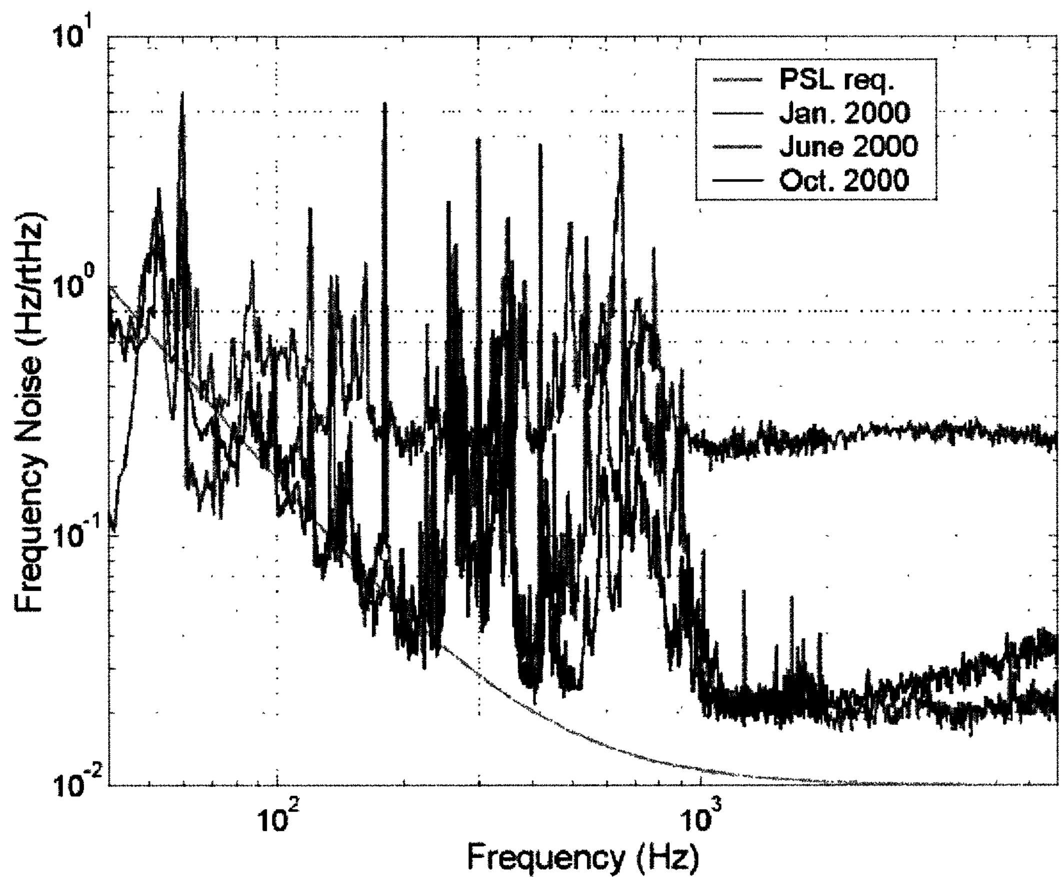


Cavity for
defining beam geometry,
joint development with
Stanford

Frequency stabilization
cavity

WA 2k Pre-stabilized Laser Performance

- > 20,000 hours continuous operation
- Frequency lock typically holds for months
- Improvement in noise performance
  - » electronics
  - » acoustics
  - » vibrations



Control and Data System

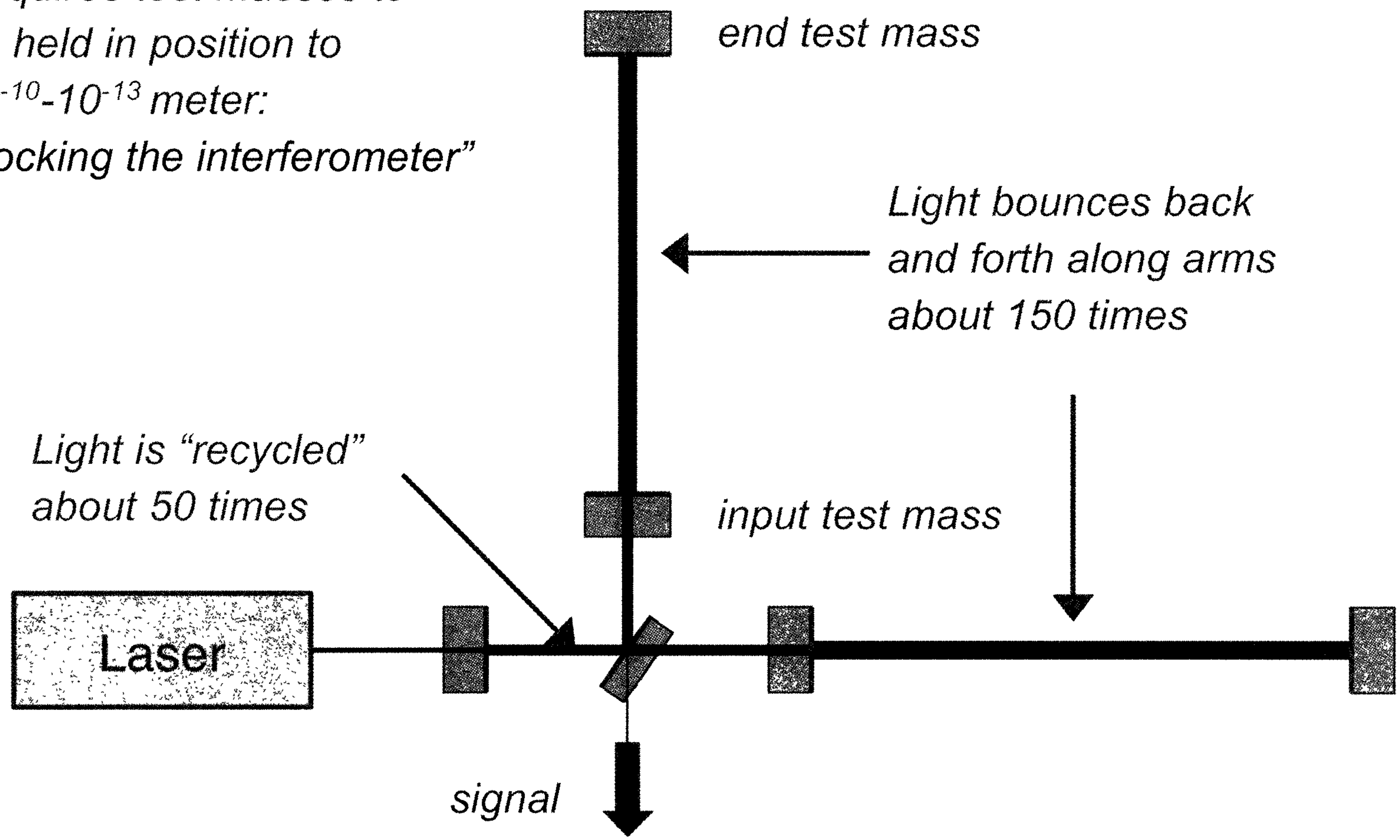
- EPICS-based distributed realtime control system
  - » ~50 realtime processors, ~20 workstations per site
  - » ~5000 process variables (switches, sliders, readings, etc) per interferometer
  - » Fiber optic links between buildings
- Data acquisition rate of 3 MB/s per interferometer
  - » Reflective memory for fast channels, EPICS for slow ones
  - » Synchronized using GPS
  - » Data served to any computer on site in realtime or playback mode using same tools
- Multiplexed video available in control room and next to the interferometer

Commissioning Status

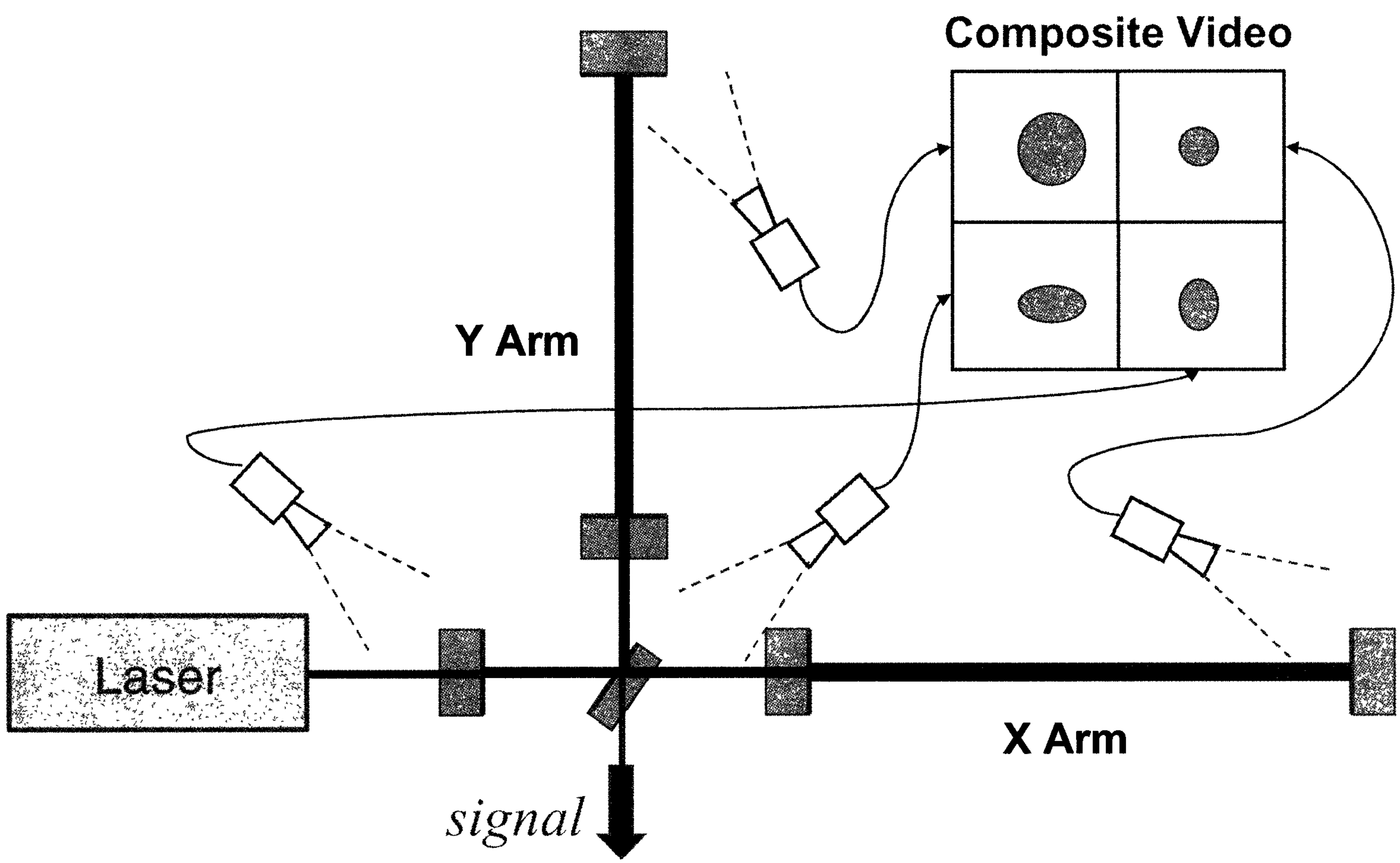
- LHO 2 km interferometer
  - » Identified problem with scattered light in suspension sensors during modecleaner testing – moved to lower power and continued on
  - » Early test of individual arm cavities performed before installation was complete
  - » Full interferometer locked at low input power (100 mW)
    All longitudinal degrees of freedom controlled
    Partial implementation of wavefront-sensing alignment control
  - » Still tuning servo loops to get design performance
- LLO 4 km interferometer
  - » Careful characterization of laser-modecleaner subsystems
  - » Single arm testing underway (discovered that there was no need for separate single arm configuration for hardware)
  - » Repetition of 2 km integrations taking much less time than (I) expected (20 times shorter to date, but probably can't continue)

Locking an Interferometer

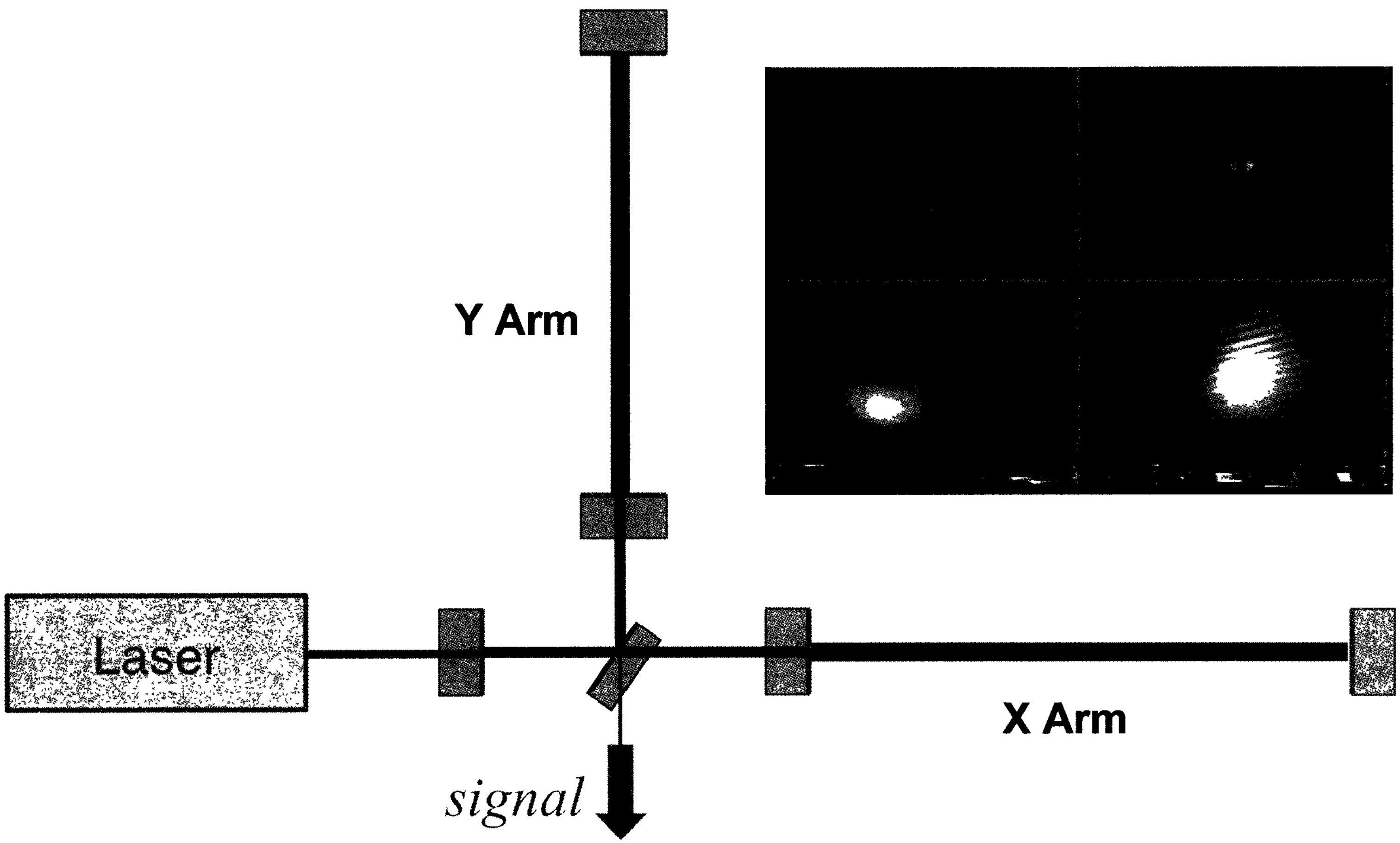
Requires test masses to be held in position to 10^{-10}-10^{-13} meter: "Locking the interferometer"



Steps to Locking the Interferometer



Watching the Interferometer Lock

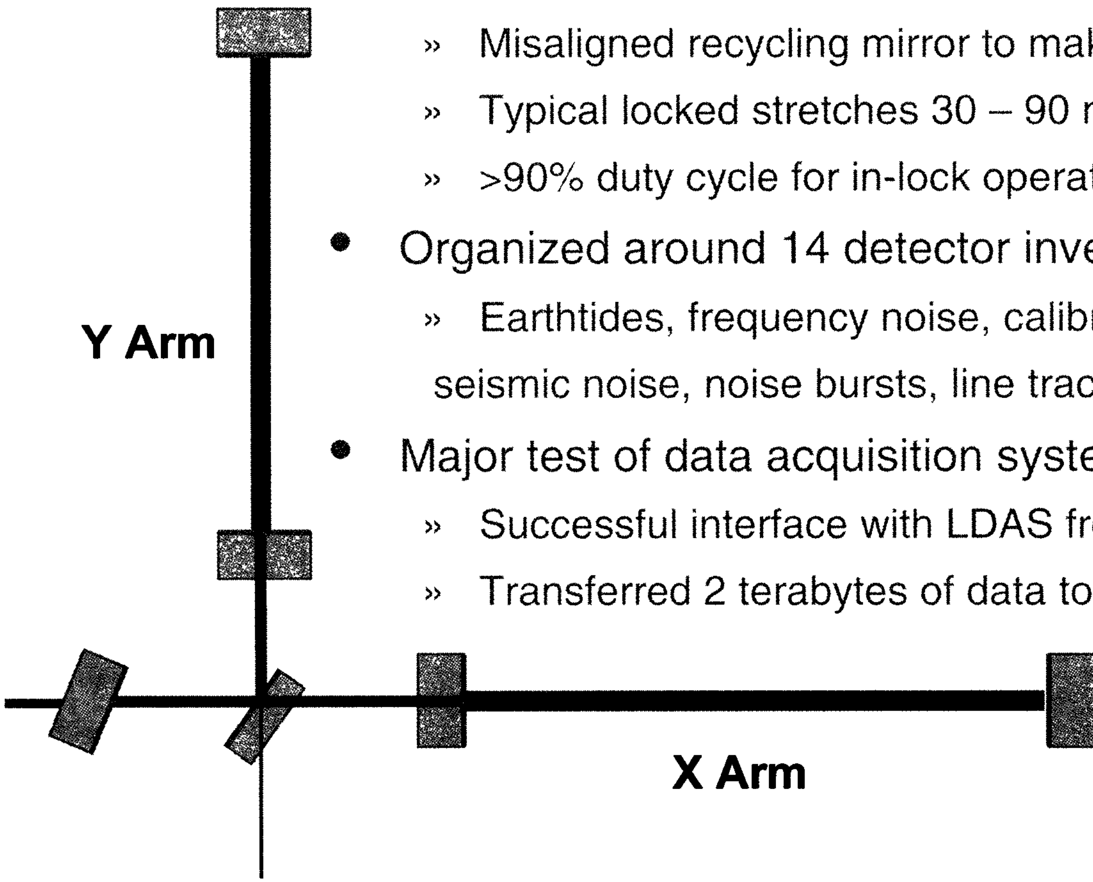


Engineering Runs

- Means to involve the broader LSC in detector commissioning
- Engineering Runs are a key part of our commissioning plan
  - » Test interferometer stability, reliability
  - » Well-defined dataset for off-site analysis
  - » Develop procedures for later operations
- First Engineering Run (E1) in April 2000
  - » Single arm operation of 2 km interferometer with wavefront sensing alignment on all angular degrees of freedom
  - » 24 hour duration
  - » Lots of interest, seven LSC groups made arrangements for data access

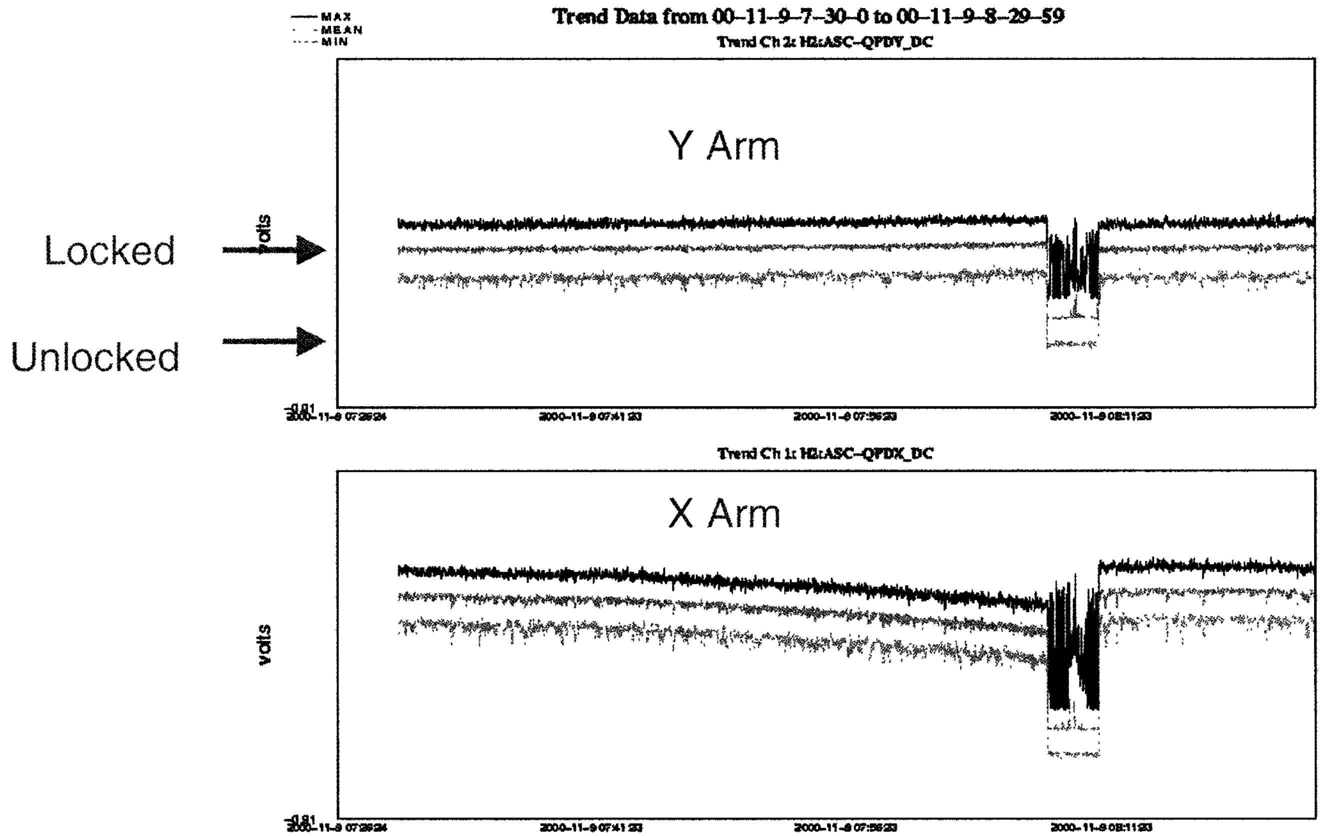
Second Engineering Run (E2)

- November 2000
  - » One week of 24/7 operation of 2 km interferometer
  - » Approximately 35 scientists participated on site
- Recombined Michelson with Fabry-Perot arms
  - » Misaligned recycling mirror to make for more robust locking
  - » Typical locked stretches 30 – 90 minutes (longest ~ 3 hours)
  - » >90% duty cycle for in-lock operation
- Organized around 14 detector investigations
  - » Earthtides, frequency noise, calibration, noise stationarity, seismic noise, noise bursts, line tracking, …
- Major test of data acquisition system
  - » Successful interface with LDAS front-end
  - » Transferred 2 terabytes of data to Caltech archive



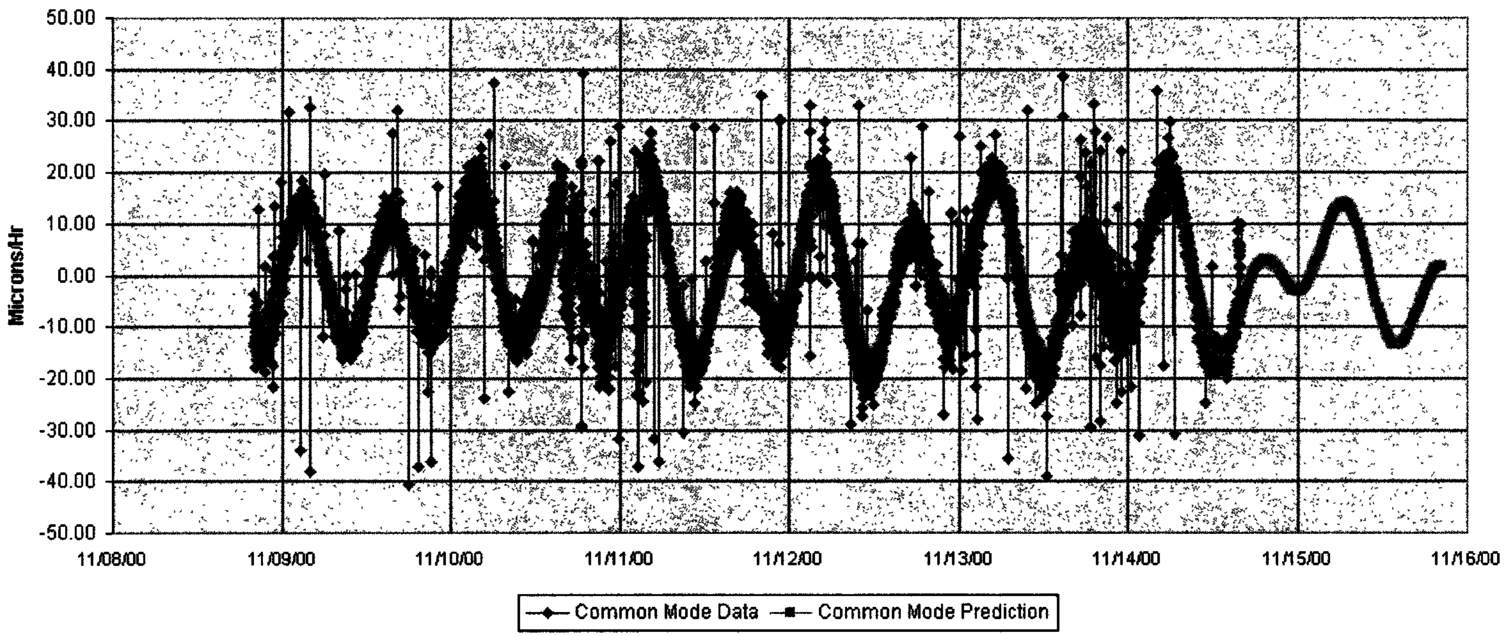
E2: Recombined Michelson Robustness

Randomly chosen hour from recent engineering run

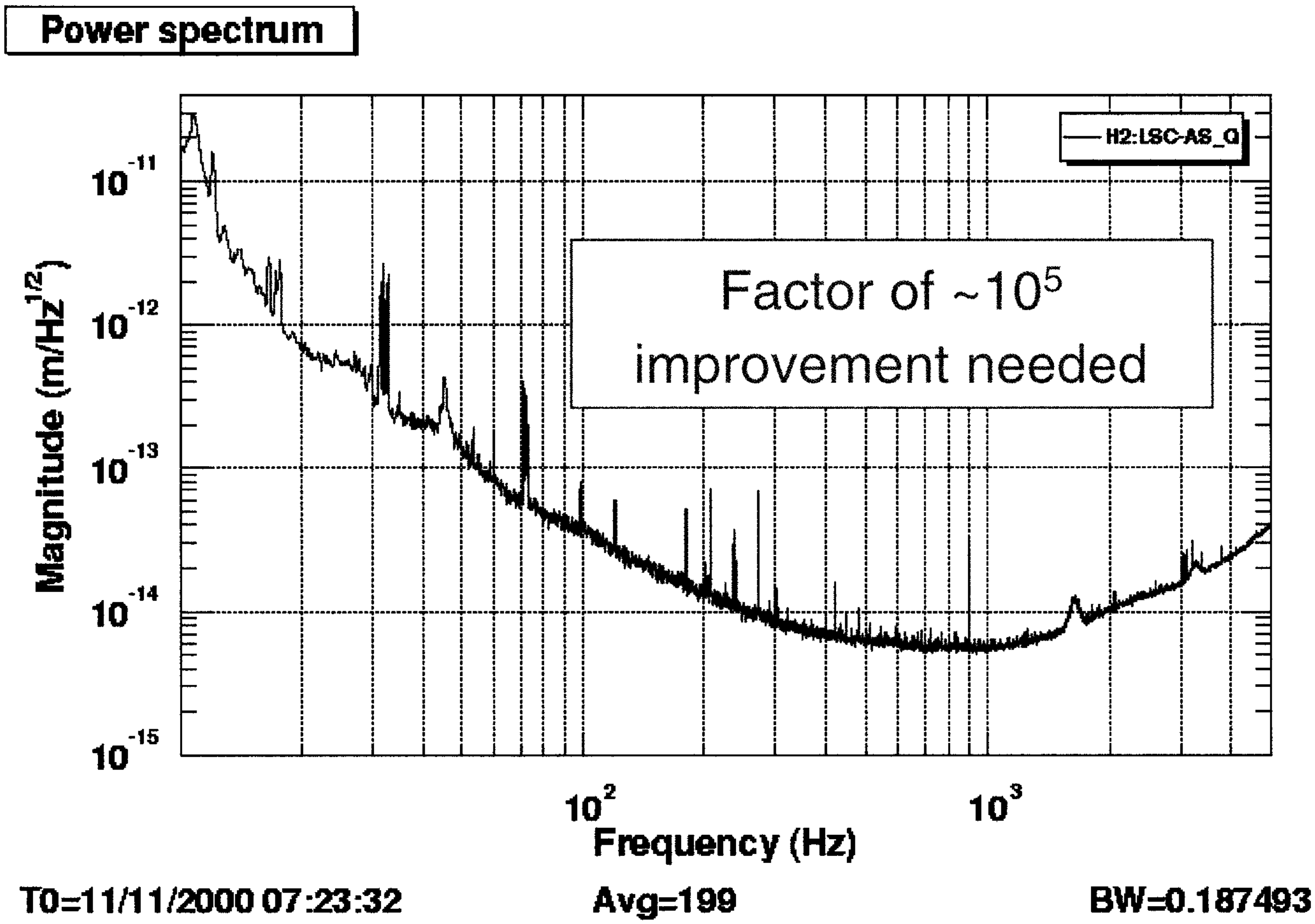


E2: Earthtide Investigation

- Observed in earlier E1 Run
- Main cause of loss of lock in E2 run: ~200 microns p-to-p
- Tidal actuator being commissioned for continuous lock
- Common mode (both arms stretch together) and differential mode (arms stretch by different amounts)



E2: Recombined Interferometer Spectrum



First differential arm spectrum, Nov. 2000

E3 Engineering Run

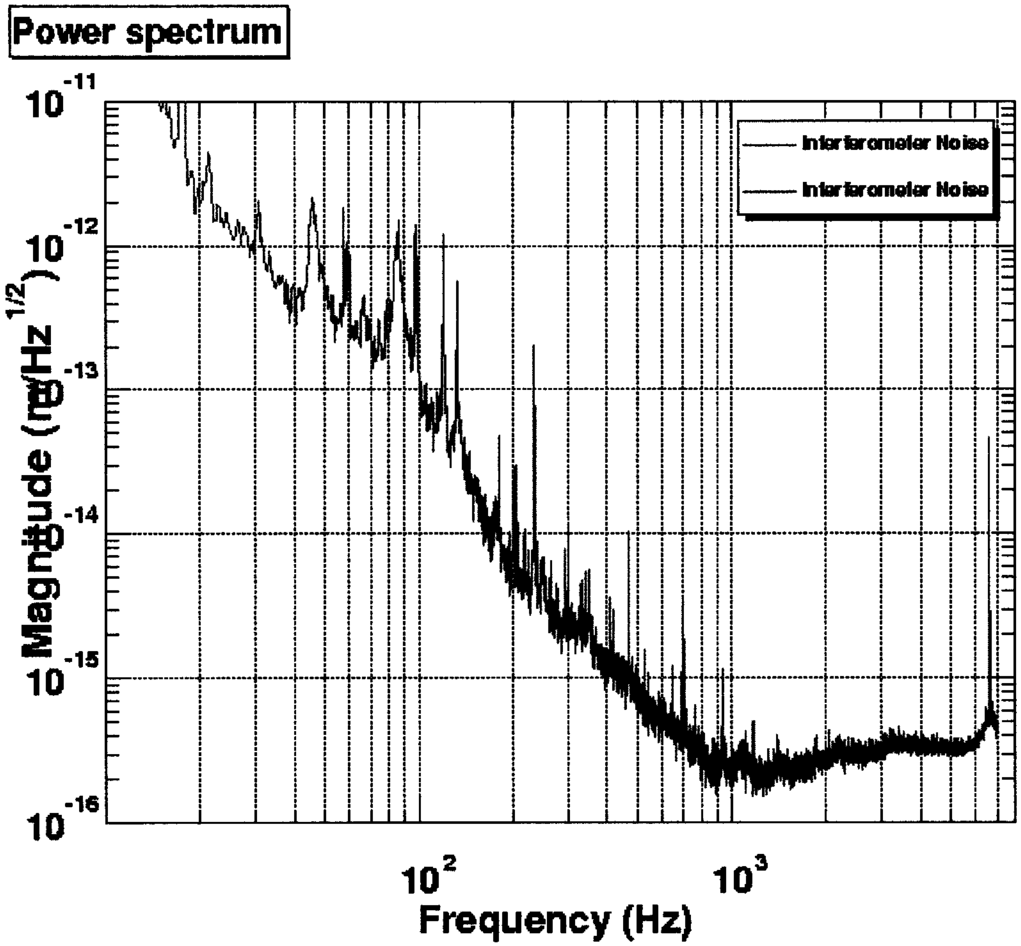
- Scheduled for March 9-12
- First coincidence run between LHO 2 km interferometer (full recycled configuration) and LLO
  4 km interferometer (recombined F-P Michelson)
- Again organized around investigations
- Specific goals
  - » Correlations between environmental signals
  - » Integration of data streams from two sites
  - » First operation of full recycled F-P Michelson interferometer

Work on Interferometer Noise

Pretty much what we expected from first noise spectrum:

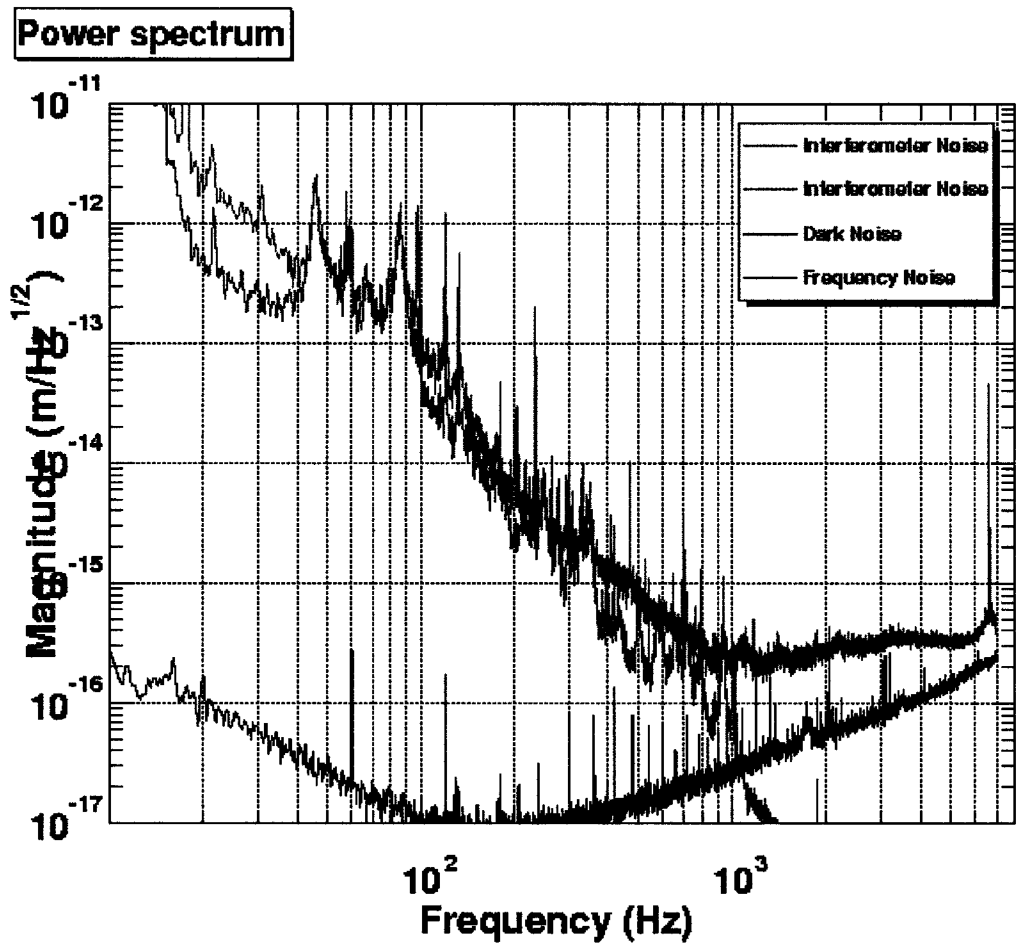
- Electronics noise dominant at high frequencies in E2 spectrum (due to low input power)
- Laser frequency noise dominates in mid frequency band (stabilization servos still being tuned up)
- Low frequencies seismic noise?
- Many resonant features to investigate and eliminate
- No showstoppers!

Current Noise Spectrum



Factor of 20 improvement:
- Recycling
- Reduction of electronics noise
- Partial implementation of alignment control

Known Contributors to Noise

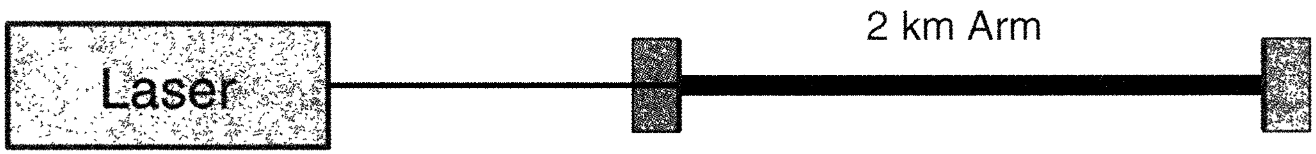


Identification and reduction of noise sources underway using well-established noise-hunting techniques developed on prototype interferometers

Progress Toward Robust Operation

- Different measure of interferometer performance (in contrast with sensitivity)
  - » Interferometer lock duration goal is 40 hours
- 2 km Prestabilized Laser
  - » Two years continuous operation with ~20% loss in power (recovered in recent tune-up)
  - » Locks to reference cavity and premodecleaner for months
- Mode Cleaner
  - » Locks for weeks at a time, reacquires lock in few seconds
- Data Acquisition and Control
  - » Data Acquisition and Input Output Controllers routinely operate for days to months without problems
  - » Tools in place for tracking machine state: AutoBURT, Conlog

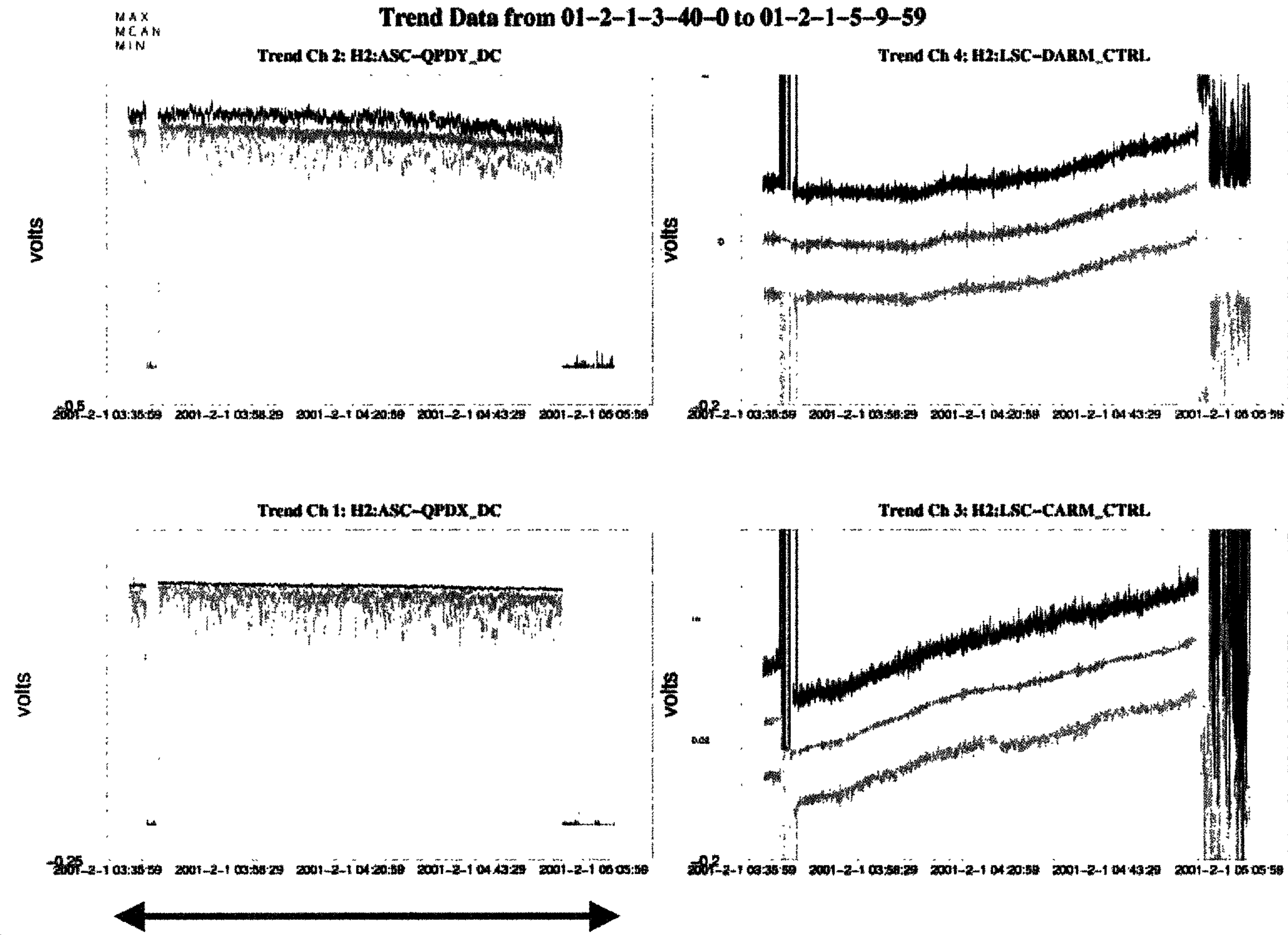
Extending the Lock on a Single Arm



- Start with Y Arm
  - » 12/1/99 Flashes of light
  - » 12/9/99 0.2 seconds lock
  - » 1/14/00 2 seconds lock
  - » 1/19/00 60 seconds lock
  - » 1/21/00 5 minutes lock
- Change to X Arm
  - » 2/12/00 18 minutes lock
  - » 3/4/00 90 minutes lock
  - » 3/26/00 10 hours lock

Result of: -automatic alignment system
-tuning electronics
-reduction of noise sources

Full Interferometer Locking



90 Minutes

Plan to Reach Science Run

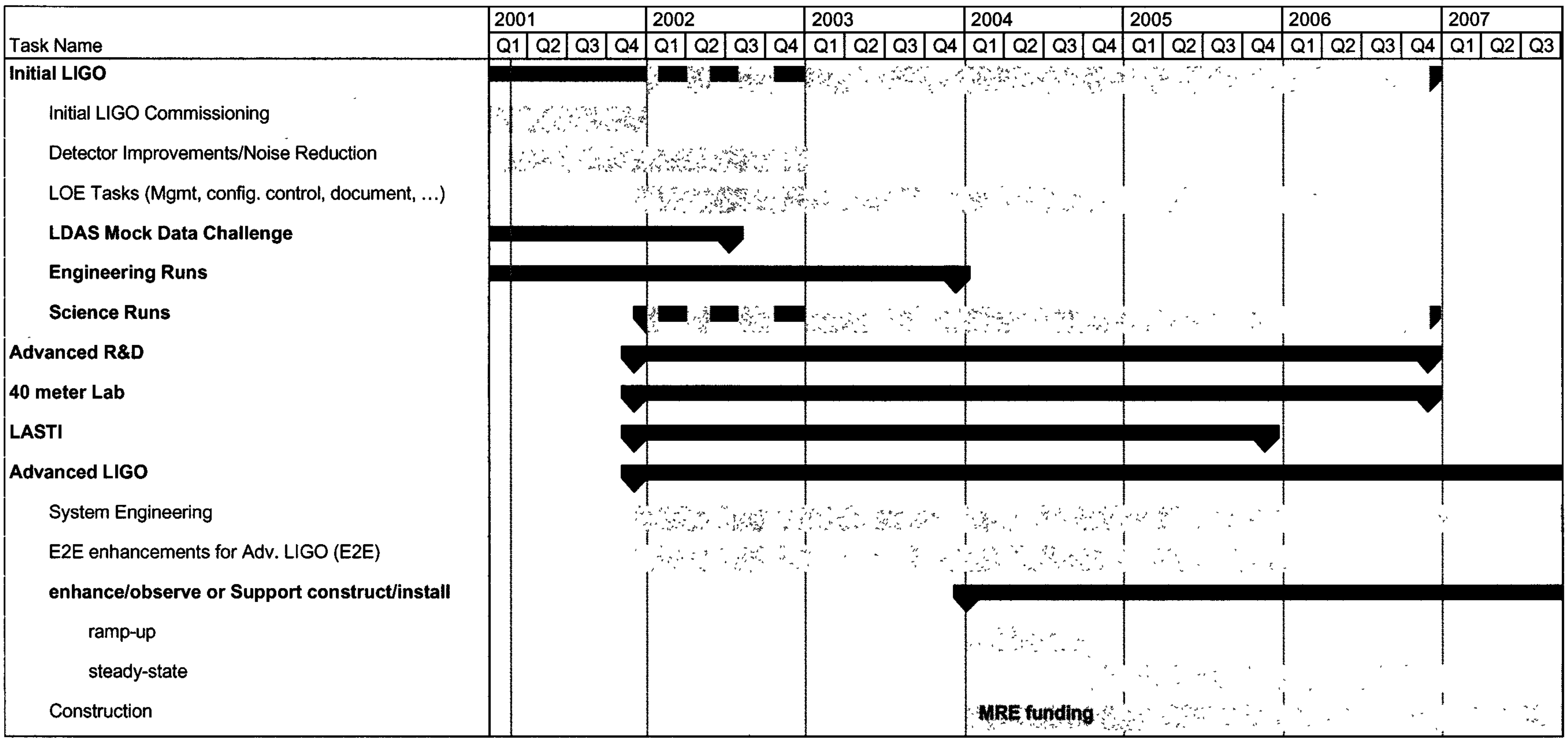
- Jan to mid-March
  - » LHO 2k, continued work on improving robustness of lock, some work on sensitivity
  - » LLO 4k, Lock single arm, recombined Michelson with Fabry-Perot (F-P) arms, Power Recycled Michelson (PRM)
  - » LHO 4k, installation
- March 9-12
  - » E3 (engineering run): coincidence run between full 2km interferometer and recombined Michelson with F-P arms (possibly single arm) at LLO
- mid-March to mid-May
  - » LHO 4k, complete installation, lock modecleaner
  - » LHO 2k, suspension sensor replacement, PRM studies
  - » LLO 4k, lock full interferometer, sensitivity/robustnessearly
- May
  - » E4 run: LLO 4 km only, operating in recombined mode (possibly recycling)

Plan to Reach Science Run, Part 2

- May - June
  - » LHO 2k, bring full interferometer back on-line, sensitivity studies
  - » LLO 4k, improve full interferometer lock, sensitivity studies
  - » LHO 4k, PRM locking (no arms yet)
- late June - early July
  - » E5 LHO 2k and LLO 4k in full recycled configuration, LHO 4k in PRM mode
- July - Sept
  - » LLO 4 k suspension sensor replacement, bring back on-line
  - » LHO 2km sensitivity studies, 4k lock full interferometer
- late Sept
  - » E6 triple coincidence run with all 3 interferometers in final optical configuration (“upper limit run”)
- Oct – early 2002
  - » Improve sensitivity and reliability
  - » Alternate diagnostic testing with engineering runs

LIGO

Overall Proposed Schedule



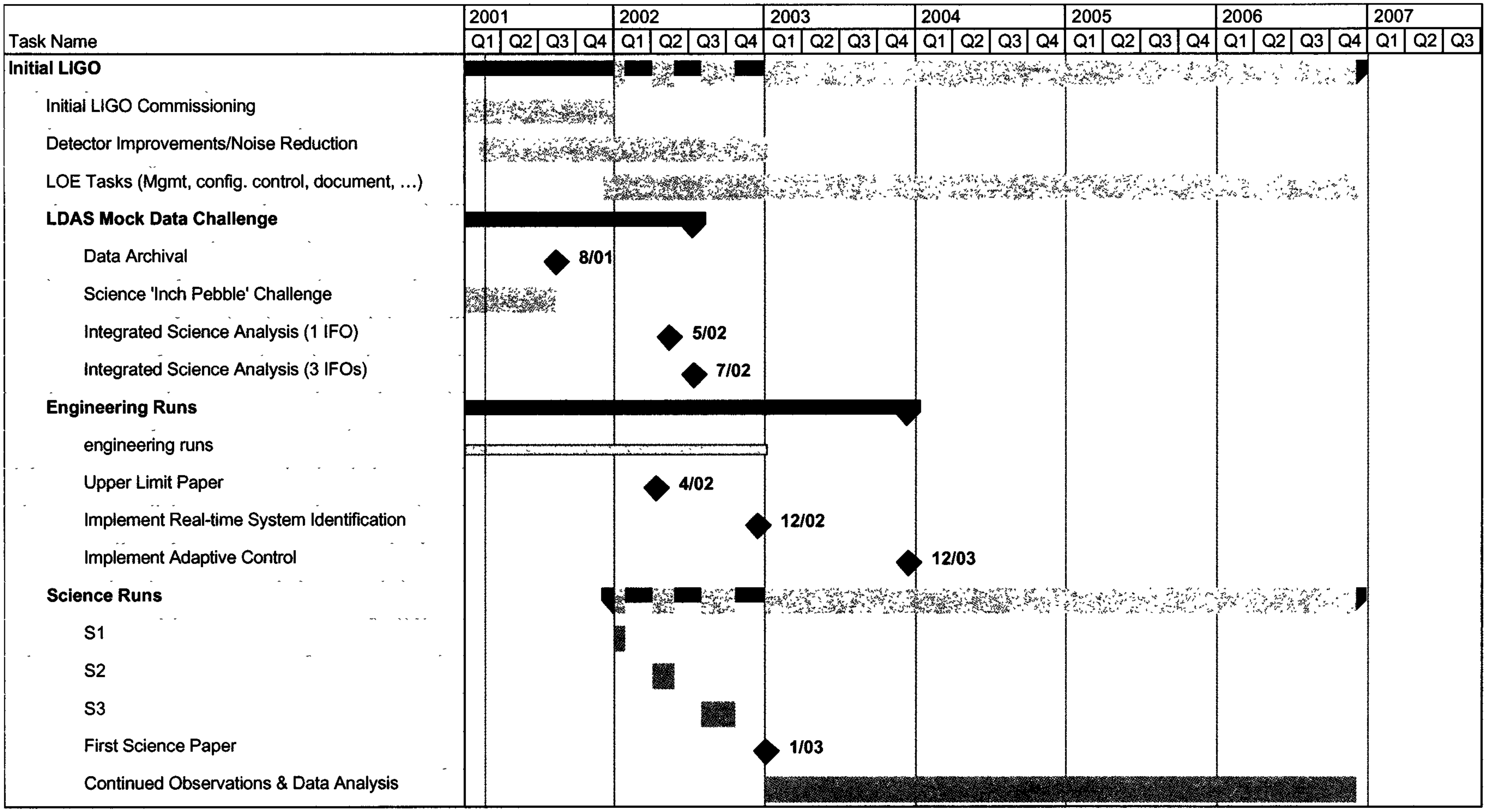
Detector Upgrades

- Planned Detector Upgrades
  - » Redesigned Damping Sensor/Actuator Heads (increased immunity from the laser light)
  - » Digital Suspension Controllers (frequency dependent diagonalization)
  - » Servo-control and diagnostic software modifications (continuous)
  - » On-line system identification (enable controls improvement)
  - » Adaptive interferometer control (for improved control robustness)

Detector Upgrades (continued)

- Possible Future Detector Upgrades
  - Modulated damping sensor electronics (increased immunity to laser light)
  - Improved laser frequency stabilization servo electronics (noise reduction)
  - Improved interferometer sensing & control servo electronics (noise reduction)
  - Redesigned pre-mode cleaner (enable higher bandwidth control)
  - additional physics environment monitoring (PEM) sensors (after correlation analyses indicate useful deployment)
  - TBD -- as commissioning and characterization studies determine needs

Initial Detector Milestones



Increase for Full Operations

Increases for initial LIGO Detector Operations

Budget Category	Increase	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Basic Operations						
	CDS Hardware Maintenance	513,800	502,434	517,507	533,032	549,023
	LDAS Maintenance	1,378,728	1,378,728	1,322,235	1,303,163	1,303,163
	Outreach	249,848	257,343	265,063	273,015	281,206
	Site Operations	558,485	575,240	592,497	610,272	628,580
	Telecommunications / Networking	540,500	542,200	542,200	539,500	539,500
	Staff for Site LSC Support	254,678	262,318	270,187	278,293	286,642
Basic Operations Totals		**3,496,039**	**3,518,263**	**3,509,689**	**3,537,275**	**3,588,114**
Operations Support of Advanced R&D						
	Seismic Development	506,300	434,574			
	Engineering Staff	920,868	948,494	976,949	1,006,257	1,036,445
	* Simulation & Modeling Staff	282,485	293,949	305,614	317,772	330,617
R&D Total		**1,709,652**	**1,677,017**	**1,282,562**	**1,324,029**	**1,367,062**
Grand Total		**5,205,691**	**5,195,280**	**4,792,252**	**4,861,304**	**4,955,176**

Covered in Observatory Operations Talk

* Need recognized by NSF Review Panel

Increases for Initial LIGO Detector Operation

- Computer & Data System (CDS) Hardware Maintenance
  - » Annual replacement and maintenance of the control room data acquisition and control hardware plus overhead
  - » installed detector computer and network infrastructure at both sites is ~$3M; estimate 10% maintenance and replacement costs per year
  - » installed custom electronics and embedded computers is also ~$3M; estimate 5% maintenance and replacement costs per year
- LIGO Data Analysis System (LDAS) Equipment Maintenance
  - » ~ $4M of computing equipment for LDAS
  - » assume 25 percent replacement rate per year plus over-head
  - » missing budget was recommended by an NSF review panel

Initial Detector Operations Staffing

Group	Roles	Proposed Staff	Incremental Staff
Hanford Observatory & Livingston Observatory	Maintain up-time & peak performance (continuous operator coverage)	14 Scientists 18 operations specialists 14 engineers 2 administrators	+ 4 operations specialists
	Ensure quality of detector operation & data stream		
	Maintain detector support infrastucture (computer network, labs, instruments, spares, ...)		+1 Computer Admin
	Maintain installed detector & LDAS equipment		+2 Scientist, +2 Engineer
	Physical configuration control of detector & LDAS equipment		
	Assist in software configuration control		
	Participate in detector characterization studies		
	Support subsystem upgrade installation & commissioning		
	visiting LSC observatory liaison		+2 Scientist
Data & Computing Group (LDAS & Simulation subgroups)	Maintain, enhance & configuration control LDAS software	9 Scientists 4 Graduate Students 9 Software Engineers	
	Data QA, distribution & archival		
	Provide LSC community with processed & QA'd data		
	Pipeline analysis of data stream		
	Astrophysics searches		
	Simulation & modeling		
Detector Support (CIT)	Lead commissioning	8 Scientists	
	Lead detector characterization studies		
	Instrumentation support to LDAS & Simulation		
	Train Observatory Staff		
Detector Support (MIT)	Lead commissioning	4 Scientists 2 Graduate Students	
	Lead detector characterization studies		
	Instrumentation support to LDAS & Simulation		
	Train Observatory Staff		
Technical & Engineering Support (CIT)	Lead installation	4 Engineers & Technicians	
	Support comissioning		
	Support detector characterization		
	Centralized design documentation & configuration control (HW & SW)		
	Lead re-dsign for upgrades & fixes		
	Totals:	35 Scientists 18 Operations Specialists 27 Engineers 6 Graduate Students 2 Adminstrators	4 Scientists 4 Operations Specialists 2 Engineers 1 Administrator

Summary

- Detector installation is nearly complete
- Commissioning is proceeding well
- 2001
  - » Improve sensitivity/reliability
  - » First coincidence operation
  - » Initial data run ("upper limit runs")
- 2002
  - » Begin Science Run
  - » Interspersed data taking and machine improvements
- 2003-2006
  - » Minimum of one year of integrated data at 10^{-21} sensitivity

First Lock in the Hanford Observatory control room

Overview of LIGO R&D and Planning for Advanced LIGO Detectors

David Shoemaker

NSF Operations Review

Hanford, 26 February 2001

LIGO-G010034-00-M

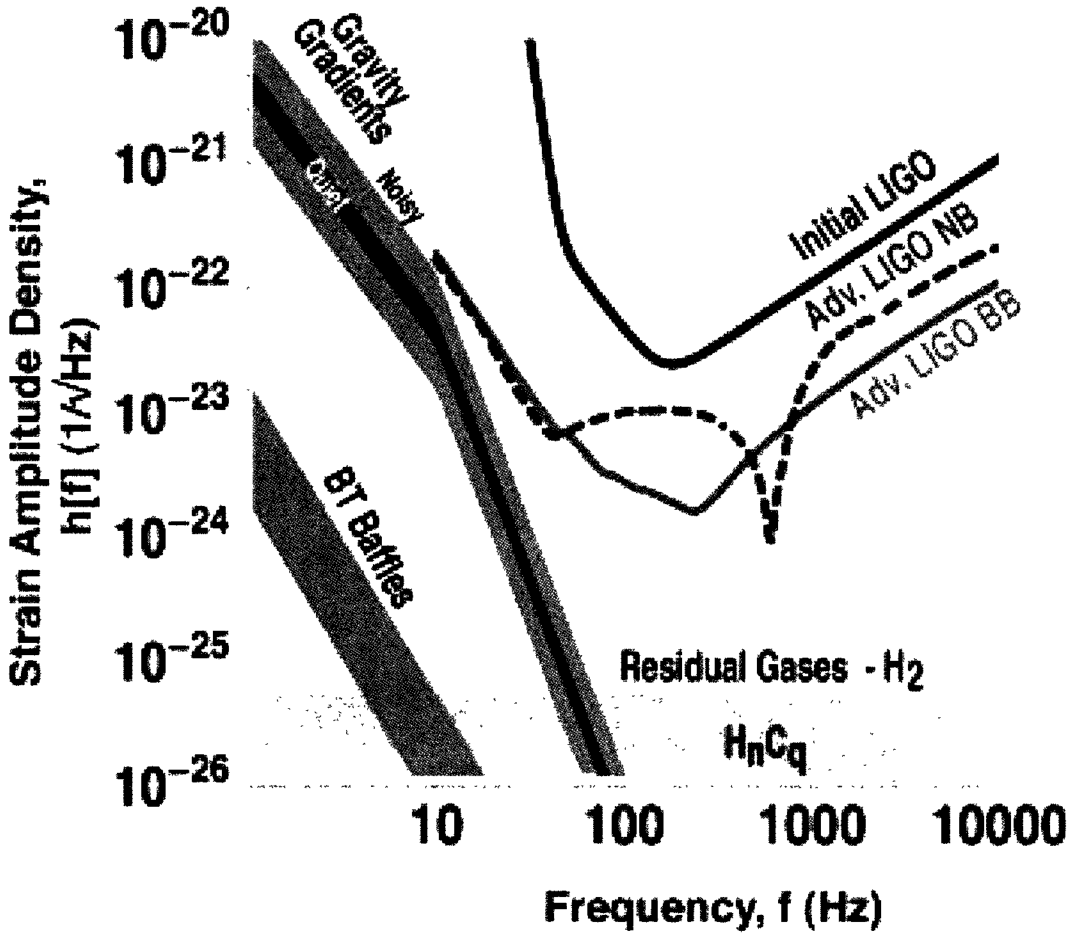
Program and Mission of the LIGO Laboratory

- **observe gravitational wave sources**;
- operate the LIGO facilities to support the national and international scientific community;
- and support scientific education and public outreach related to gravitational wave astronomy.
- develop advanced detectors that approach and exploit the facility limits on interferometer performance

The Vision for Research and Development in LIGO

- LIGO was conceived as a **program** to detect gravitational waves; From the NSF Review of the LIGO II Conceptual plan (1999): "Since its inception, the LIGO Project was authorized by the NSF to pursue the development of the technology of advanced gravitational wave detectors."
- LIGO construction was approved to provide an initial set of feasible detectors and a set of facilities capable of supporting much more sensitive detectors
- It was planned that the initial detectors would have a **plausible** chance to make direct detections
- It was planned that more sensitive detectors would be required to enable **confident** detection

LIGO Facilities planned to support detector upgrades



History of LIGO R&D

- Early R&D leading to initial LIGO took place during the 1970's and 1980's
- Preconstruction R&D for initial LIGO was included in the award for the LIGO construction
  - » LIGO construction $272 million
  - » Preconstruction R&D $20 million (addressing final issues)
  - » Early operations $69 million
- NSF invited proposals for R&D in support of more advanced detectors in 1996
- LIGO Laboratory has been receiving $2.7 million/year of a ~$6.9 million program

Request for LIGO R&D

- This proposal requests funds for the R&D program for Advanced LIGO

1) Continuation of the present R&D funding level ($2.77M in 2002)
2) Increase of funding of R&D engineering support for the Lab <u>and</u> greater LSC ($1.71M in 2002)
3) Funding of ‘big ticket’ R&D items for the LSC community ($3.30M in 2002)

Reference Design and the LIGO Scientific Collaboration

- Serious R&D coordination started in 1996, resulting in Reference Design in 1999 in LSC White Paper
- Reference design established through LSC Working Groups, shared research and decision making
- e.g., Seismic Isolation
  - » Key ideas from JILA, Caltech; teams at JILA, Stanford, LSU, MIT, Caltech, LLO, Pisa brought ideas to maturity through prototypes at Caltech and MIT; continued prototyping at Stanford, then MIT
- e.g., Interferometer Configuration
  - » Key ideas from Glasgow, MIT; tabletop experiments in Australia, Caltech, Garching, Univ. Florida to explore different approaches; continued prototyping at Glasgow, then Caltech

Major International Roles in Advanced LIGO

- GEO (UK, Germany) project has joined the LSC
  - » advanced LIGO involvement includes leading roles in suspensions, configurations, prestabilized laser.
  - » GEO is proposing a capital contribution/partnership in construction of advanced LIGO
- ACIGA project has joined LSC
  - » advanced LIGO involvement includes laser development, sapphire development and high power issues
- Recent discussions have begun with Virgo on collaboration in coating development and in joint data taking and data analysis

Role of Lab in the LIGO Scientific Collaboration

- Peoples report: Lab should coordinate R&D direction and major investments, provide infrastructure
  - » "…the Panel urges the NSF to take the necessary steps to strengthen the integration of the R&D tasks carried out by the LSC partners into the Lab's planning and reporting process."
- The Lab's plan follows this lead:
  - » all R&D tasks are defined in MOU's with the Laboratory
  - » program is conducted as the early stages of a construction project
  - » systems trades and engineering are carried out by the Lab
  - » the R&D across the LSC is organized with a detailed cost estimate and schedule carried by the Lab
  - » monthly coordinating meetings with LSC working groups are held to monitor progress

Approach to Interferometer Upgrades

- **substantial** improvements in performance are very inefficient to achieve with incremental upgrades
  - » Gravitational wave interferometers are “point” designs
  - » lowering one noise floor encounters another
  - » changing the performance of one subsystem causes system mismatch with other subsystems
- Installing, and commissioning, an interferometer system is a major effort – typically 1-2 years in duration
  - » much of the campaign overhead is encountered even with subsystem upgrades
- Upgrading an interferometer has a high cost in missed scientific opportunity – thus,

Upgrade must yield a major increase in sensitivity

Timing of R&D for interferometer upgrades….

- A 'major increase in sensitivity' requires a major R&D effort on many fronts
- In addition, long-lead items (optics) provide a 2-3 year 'strut' from order to installation
- The LIGO Science Run with the initial detector will be completed 2006
- Now is the appropriate time for a high-level of pre-construction R&D

…Timing of R&D for interferometer upgrades

- The LSC and Lab submitted a White Paper and a Conceptual Project plan in late 1999; reviewed by the NSF Special Emphasis Panel chaired by John Peoples in Oct 1999
- From the Review report, "The panel recommends….
  - » that the Lab proceed with the preparation of a full proposal for the Preconstruction R&D for LIGO II
  - » that the Lab and the LSC submit an integrated R&D Plan for 2000 and 2001 in order to ensure that the Adv R&D goals are well matched to the Pre-construction R&D plan for 2002 through 2005
  - » that the laboratory be authorized to prepare a complete proposal for the LIGO II Project, including cost and schedule before the end of 2000
  - » that meaningful LIGO I data analyses results be in hand prior to turn off of the LIGO I observing system"

Advanced LIGO Program Assumption

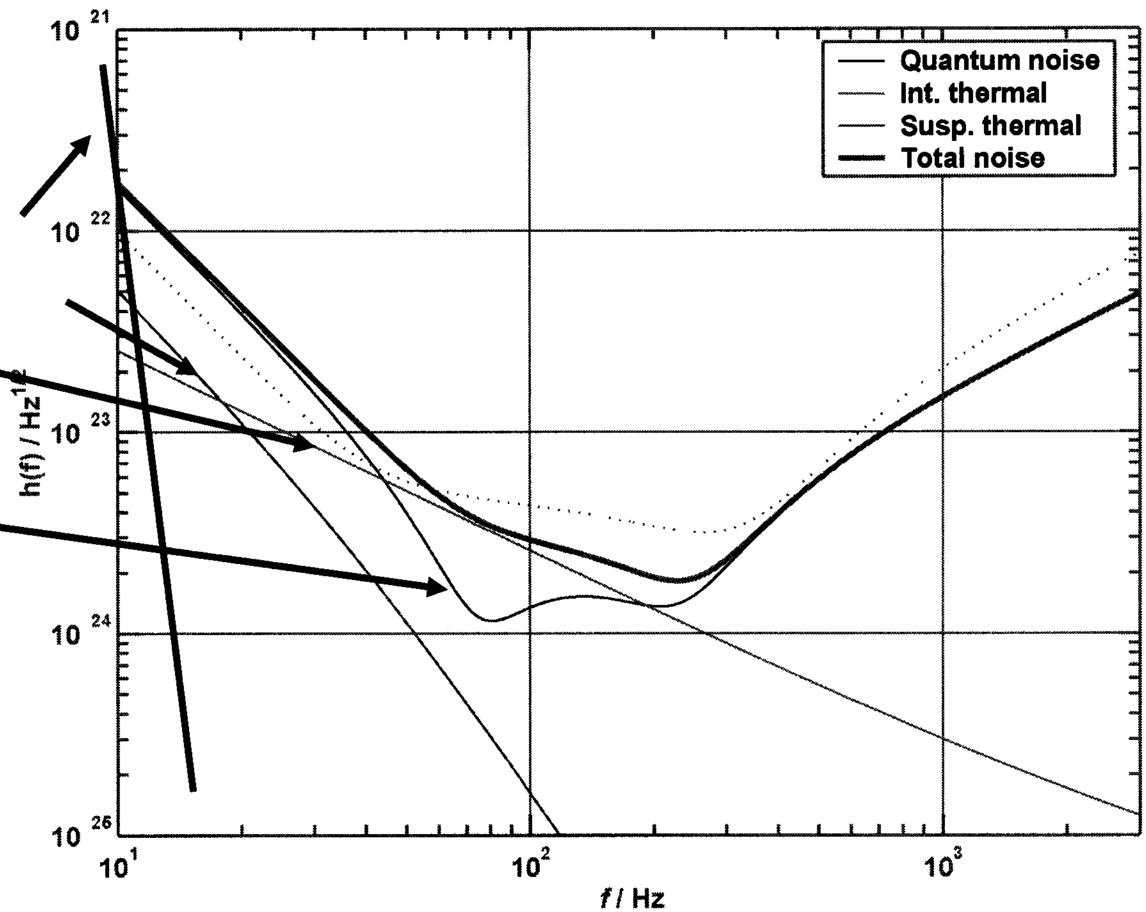
- R&D in progress now
  - » major equipment expenditures in 2001, 2002-2004
- R&D is substantially completed in 2004
  - » some tests are completed in 2005
- Construction funds will be requested for 2004 start
  - » some long lead purchases occur as early as 2003
  - » assembly outside vacuum system takes place in 2005
- Advanced interferometers will be installed beginning in early 2006
  - » when LIGO Science Run I is producing published results
  - » Coordinated shutdowns with other detectors worldwide

The Advanced LIGO Detector concept

- Fabry-Perot Michelson interferometers
- Power recycling AND signal recycling
- 180 W Nd:YAG laser
- possible sapphire core optics
- much better isolation through the use of a fully active seismic isolation system, and a multiple pendulum suspension with silica suspension fibers
- …Estimate that 2.5 hours of operation of Advanced LIGO will be equivalent in observation ‘reach’ to the entire initial LIGO data run

Anatomy of the projected detector performance

- Sapphire test mass baseline system
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Internal thermal noise
- Unified quantum noise dominates at most frequencies
- 'technical' noise (e.g., laser frequency) levels held in general well below these 'fundamental' noises
- Silica test mass dotted line



R&D Challenges
(Quotes from January NSF Review Report)

» Advanced LIGO will require a level of **control system complexity** that considerably exceeds that required for initial LIGO. Recent locking of the Michelson Fabry-Perot 2–km detector at Hanford represents a significant demonstration of a multi-dimensional control system, and builds confidence in the ability of the LIGO team to deal with its even more complex design challenge in advanced LIGO.

» A critical path item for advanced LIGO is a set of **new optics**. Advanced LIGO requires increased size of the test masses, dealing with the absorptivity of optical coatings, and better mechanical Q optimization of the mirrors. This part of the R&D program will require new partnerships with vendors. The availability of increased expertise for the LIGO program, especially in optical materials and system integration in the optics area, is crucial to the success of this effort.

R&D Challenges
(Quotes from January NSF Review Report)

» The requirement for stable, single-mode, **80 - 180 W lasers** for advanced LIGO represents a significant challenge to the state-of-the-art. Attention should be given to the tradeoffs between a potentially more reliable but lower power laser system (or a phased-locked ensemble of lower power laser systems), and the potentially increased high-frequency performance of the detector at higher power.

» Higher average power on the input optics of advanced LIGO presents a challenge to the current technology of crystal **modulators and isolators**. An aggressive testing program will be required to understand the limitations and potential of these important optical elements.

R&D Challenges
(Quotes from January NSF Review Report)

» **Forces exerted on the mirrors due to the higher average power** stored in advanced LIGO cavities may introduce alignment instabilities. The planned inclusion of these effects in the end-to-end model and the planned testing program are essential elements of the program.

» Success of advanced LIGO will be (in part) measured by its uptime. The **reliability of the in-vacuum components** (such as the active seismic isolation system) is crucial, and design for reliability should be kept at the forefront of the R&D effort.

» **Suspension of test masses by [fused silica] ribbons** represents a novel solution to test mass suspension noise. However, effects such as creep (leading to potential excess noise) in the expected load regime, should be carefully evaluated.

R&D Program Approach to Risk Reduction

- All significant risks are planned for measurement or verification during the proposed program
- Faithful prototypes of advanced LIGO subsystems are fully tested in parallel to operating LIGO
- Goal is to fully qualify all designs before installing in LIGO vacuum system
  - » 40 Meter test interferometer (Caltech) qualifies controls system
  - » LASTI test interferometer (MIT) qualifies the isolation/suspension system and the prestabilized laser/input optics systems
- Installation into LIGO vacuum system occurs when new systems are fully ready and qualified

The R&D Program Budget

- Most work supports Advanced LIGO realization, both science ('R&D') and engineering ('Ops')
- Some far reaching research
- All work highly collaborative, coordinated with and supportive of the LSC at large
- Three budgetary elements, each with a distinct role:

1) Research and Development activities *per se*
2) Engineering, infrastructure, and some senior effort supported from Lab Operations
3) Big ticket equipment items for LSC program in Lab proposal

1) R&D Effort: Subsystem science (snapshot 2002)

Stochastic Noise. LASTI integrated system tests of the advanced seismic isolation and suspension prototypes.	**$275,222**
Thermal Noise Interferometer. Direct measurement of test mass thermal noise for initial and advanced LIGO designs.	**$176,697**
Advanced Core Optics including sapphire optics.	**$283,937**
Advanced Interferometer Sensing and Control including Photodetector Development.	**$298,779**
Stiff Seismic Isolation Development.	**$46,353**
Auxiliary Optics Systems including Active Thermal Control.	**$366,088**
Advanced Suspensions including Fiber Research.	**$208,725**
Improved Low Frequency Strain Sensitivity.	**$345,637**
40-Meter Advanced R&D. Tests of controls and electronics for a signal and power recycled configuration with read-out scheme and control topology intended for advanced LIGO.	**$235,075**
Advanced Controls and System Identification. Research on application of advanced system identification and control concepts to LIGO.	**$188,677**
Advanced (highly stabilized) Input Optic Systems.	**$347,423**

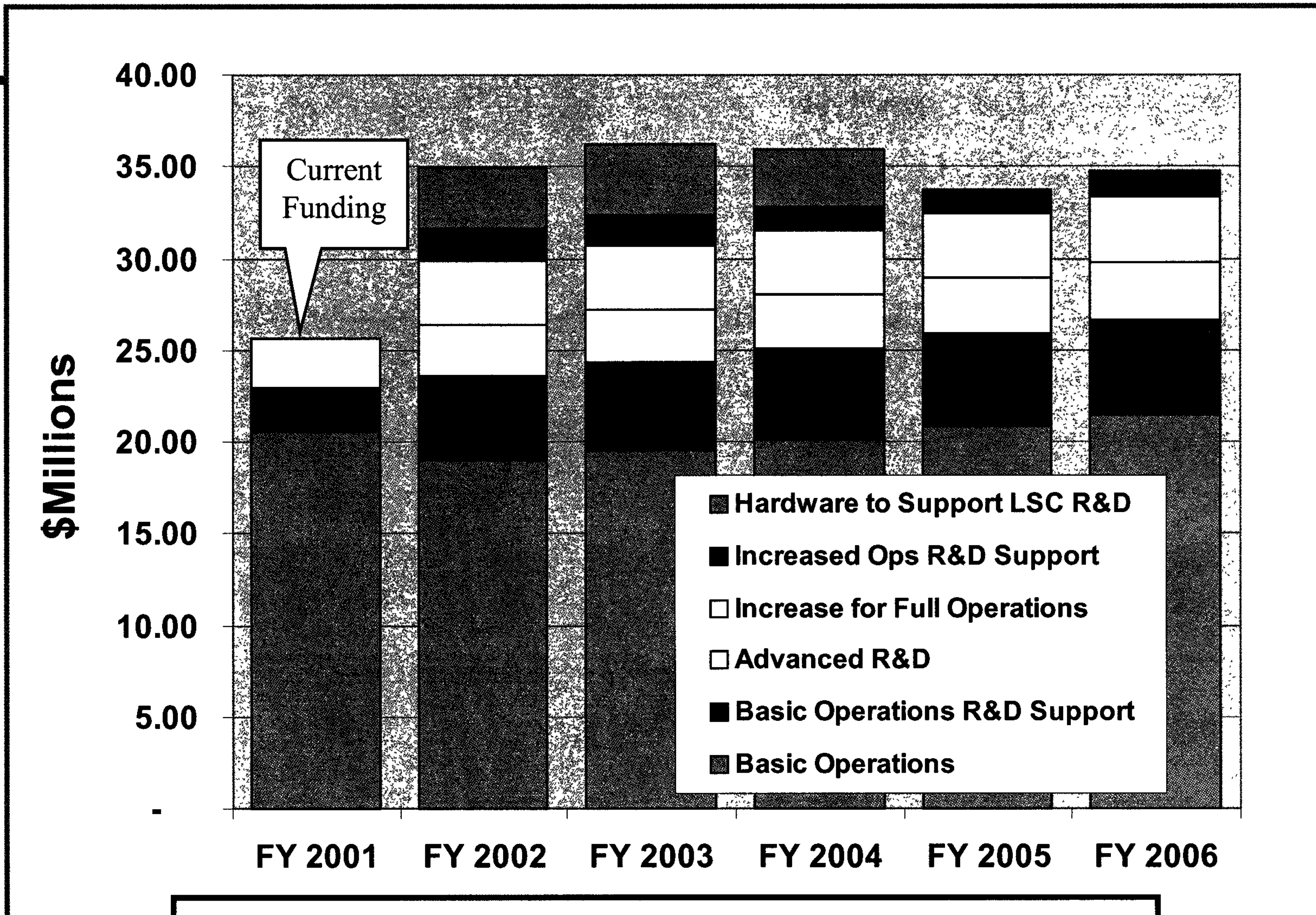
2) Increased Staffing in Ops to Support R&D and Modeling

- Increased staff in the Technical and Engineering Support and Detector Support Groups to perform Advanced LIGO R&D engineering $921k
- Increment for engineering and technician labor (4 FTEs) in Livingston to support the Seismic Isolation LSC team (2 years, non-recurring) $506k
- Increased staff for Modeling and Simulation (end-to-end model) $282k

3) R&D Equipment in Support of LSC Research Program

- Equipment costs for the development of advanced seismic isolation prototypes. $934k
- Equipment costs for the development of multiple pendulum, fused silica fiber suspension prototypes. $2,257k
- Materials and manufacturing subcontracts to support the development of sapphire test masses and high Q test mass materials and coatings research. 5,585k
- Investment and non-recurring engineering costs for a large coating chamber and its commissioning. $1,500k
    - » study of coating strategy in progress

LIGO Budget Proposal…



FY 2001 funding normalized to 12 months shown for comparison

...LIGO Budget Proposal

	FY 2001 ($M)	FY 2002 ($M)	FY 2003 ($M)	FY 2004 ($M)	FY 2005 ($M)	FY 2006 ($M)	Total 2002-6 ($M)
Currently funded Operations	22.92	23.63	24.32	25.05	25.87	26.65	125.52
Increase for Full Operations		5.21	5.20	4.79	4.86	4.95	25.01
Advanced R&D	2.70	2.77	2.86	2.95	3.04	3.13	14.76
R&D Equipment for LSC Research		3.30	3.84	3.14			10.28
Total Budgets	25.62	34.91	36.21	35.93	33.77	34.74	175.57

FY 2001 currently funded Operations ($19.1M for ten months) is normalized to 12 months and provided for comparison only and is not included in totals.

Isolation Research

(STO, SUS, TNI, SEI)

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
ISOLATION						
Sci & PD	MIT	1		2.4	3.4	8.1
	CIT	3		1.7	4.7	
UG & Grads	MIT	3		0.0	3.0	5.0
	CIT	2		0.0	2.0	
Eng & Techs	MIT	0		2.8	2.8	14.2
	CIT	0		6.9	6.9	
	LLO	0		4.5	4.5	
Totals (FTE):		9		18.3	**27.3**	
Equip. & Supplies		$54	$1,595	0.0	**$1,649**	

N.B.: Does not include LSC research staff.

Lasers & Optics Research
(LAS, OPT, IOS, AOS)

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
LASERS & OPTICS						
Sci & PD	MIT	0		0.1	0.1	3.3
	CIT	1		2.3	3.3	
UG & Grads	MIT	1		0.0	1.0	2.0
	CIT	1		0.0	1.0	
Eng & Techs	MIT	0		0.0	0.0	2.0
	CIT	0.5		1.5	2.0	
Totals (FTE):		3.5		3.8	**7.3**	
Equip. & Supplies		$755	$1,706	0.0	**$2,461**	

N.B.: Does not include LSC research staff.

Advanced Interferometer Systems, Sensing & Control (ISC, 40m, SID, SYS)

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
Advanced Interferometer Systems, Sensing & Control (ISC)						
Sci & PD	MIT	0		1.7	1.7	6.9
	CIT	2		3.2	5.2	
UG & Grads	MIT	1		1.0	2.0	5.0
	CIT	3		0.0	3.0	
Eng & Techs	MIT	0		0.8	0.8	10.2
	CIT	0		9.5	9.5	
Totals (FTE):		6		16.1	**22.1**	
Equip. & Supplies		$313	$0	0.0	**$313**	

N.B.: Does not include LSC research staff.

Total LIGO Laboratory R&D

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
TOTAL for advanced LIGO R&D (including CRY)						
Sci & PD	MIT	1		4.2	5.2	20.3
	CIT	8		7.2	15.2	
UG & Grads	MIT	5		1.0	6.0	13.0
	CIT	7		0.0	7.0	
Eng & Techs	MIT	0		3.5	3.5	26.4
	CIT	0.5		17.9	18.4	
	LLO	0		4.5	4.5	
Totals (FTE):		21.5		38.2	**59.7**	
Equip. & Supplies		$1,139	$3,301	0.0	**$4,440**	
				MIT	14.7	
				CIT	40.5	
				LLO	4.5	

N.B.: Does not include LSC research staff.

...Advanced LIGO Chronology

- The proposal under review lays the path for installing advanced interferometers beginning in early 2006
  - » when LIGO Science Run I is producing published results
  - » Coordinated shutdowns with other detectors worldwide

Commissioning, then observation,
starting in 2007-2008

R&D for Advanced LIGO
(Quotes from January NSF Review Report)

- The proposal for research and development regarding an advanced LIGO detector contains a set of **significant technical challenges** that, if met, will provide a design for a gravitational wave detector that should be **capable of yielding extremely exciting science**.

- We believe that the **LIGO Laboratory, in consort with the LSC, is capable of carrying out, and is ready to carry out, the R&D program** described in the proposal.

R&D for Advanced LIGO
(Quotes from January NSF Review Report)

- The review panel finds that the proposed **balance between operation of initial LIGO and R&D on advanced LIGO**, as described during the review, is **appropriate for optimizing the probability of programmatic success**.

- The Panel did not validate budgetary items in detail. However, the Panel notes that **the total request, the continuity** of the funding request, the clarification of R&D costs actually contained within "operations manpower," **and the proposed balance between operation of initial LIGO and R&D on advanced LIGO** as described during the review, seem appropriate for **optimizing the probability of programmatic success**.

THE LSC AND ITS ROLE

LIGO Operations and Scientific Research Sub-Panel

Rainer Weiss

Hanford, WA February 26, 2001

LIGO Scientific Collaboration Member Institutions

University of Adelaide ACIGA
Australian National University ACIGA
California State Dominquez Hills
Caltech LIGO
Caltech Experimental Gravitation CEGG
Caltech Theory CART
University of Cardiff GEO
Carleton College
Cornell University
University of Florida @ Gainesville
Glasgow University GEO
University of Hannover GEO
Harvard-Smithsonian
India-IUCAA
IAP Nizhny Novgorod
Iowa State University
Joint Institute of Laboratory Astrophysics
LIGO Livingston LIGOLA
LIGO Hanford LIGOWA
Louisiana State University
Louisiana Tech University
MIT LIGO
Max Planck (Garching) GEO
Max Planck (Potsdam) GEO
University of Michigan
Moscow State University
NAOJ - TAMA
University of Oregon
Pennsylvania State University Exp
Pennsylvania State University Theory
Southern University
Stanford University
University of Texas@Brownsville
University of Western Australia ACIGA
University of Wisconsin@Milwaukee

LSC Membership and Function

- Recommended by Barish and McDaniel Committee
- Founded in 1997, now includes 35 research groups with 355 members
- Membership and roles determined by MOU between Project and Institution
- MOU updated yearly and posted
- Agreement by LSC

LSC functions

- Determine the scientific needs of the project
- Set priorities for the research and development
- Present the scientific case for the program
- Carry out the scientific and technical research program
- Carry out the data analysis and validate the scientific results
- Establish the long term needs of the field

LIGO

Additional LSC roles during operations

- Maximize scientific returns in the operations of LIGO Laboratory facilities
- Determine the relative distribution of observing and development time
- Set priorities for improvements to the LIGO facilities.
- Actively participate in operations and provide scientific guidance at the sites.

Mechanisms

- LSC White Paper on Detector Research and Development
  - describes near term program and goals
  - areas of research for long range program
  - iterated as new results become available
  - second iteration
- LSC Data Analysis White Paper
  - algorithm development for astrophysical sources
  - techniques for detector characterization
  - validation and test of software
  - long range goals for software and hardware
  - first iteration

Mechanisms

- Publications and presentations policy
  assure integrity of scientific and technical results
  provide recognition of individual and institutional contributions

- Proposal driven data analysis
  formation of groups to make specific analysis proposals
  proposals posted and open to the entire collaboration
  proposals reviewed by LSC executive committee

ORGANIZATION

- **LCS working committees**

Technical development committees

- Suspensions and isolation systems - control of stochastic forces
  David Shoemaker MIT
- Optics - reduction in sensing noise / thermal noise
  David Reitze University of Florida
- Lasers - reduction in sensing noise
  Benno Willke University of Hannover GEO
- Interferometer configurations - detector control and response
  Ken Strain University of Glasgow GEO

ORGANIZATION

Software and data analysis committees

- Astrophysical sources and signatures
  Bruce Allen University of Wisconsin @ Milwaukee
  Barry Barish LIGO lab liaison

- Detector characterization and modelling
  Keith Riles University of Michigan
  Daniel Sigg LIGO lab liaison

- Software coordination committee and change control board
  Alan Wiseman Data analysis and software coordinator
  University of Wisconsin @ Milwaukee

LIGO

GOVERNANCE and OPERATIONS

- LSC meetings in March and August

  LSC Council meeting (membership, governance.....)

- Executive committee meetings monthly

  Spokesperson, data and software Coordinator, committee chairs, Director and Deputy Director of the LIGO Laboratory

- Working committees meet monthly or more frequently

LIGO

Astrophysical source upper limit groups

- Combined groups of experimenters and theorists
- Develop data analysis proposals

Purpose:

- Test the LIGO Data Analysis System
- Set scientifically useful upper limits using engineering data
- Publish first astrophysically interesting results from LIGO

Groups:

Burst sources : Sam Finn Penn State, Peter Saulson Syracuse

Inspiral sources: Pat Brady Univ of Wisc., Gabi Gonzalez Penn State

Periodic sources: Stuart Anderson Caltech, Michael Zucker MIT

Stochastic backgrd.: Joe Romano, UT Brownsville, Peter Fritschel MIT

- *Coincidence engineering data runs fall 2001*

Mock Data Challenges

- Test and validation of the LDAS pipeline
- Joint Laboratory and LSC function

Accomplished

8/2000: Data conditioning and pre-processing common to all searches
Sam Finn *chair* Caltech, PSU, UTB, ANU

1/2001: Binary inspiral template search using MPI
Pat Brady *chair* Caltech, UWM, UTB

Planned

3/2001: Use of relational databases to store/access/mine LIGO event data

9/2001: Use of archival system to store/access LIGO raw frame data

>5/2001: Test algorithms for all major types of searches

Examples of LSC Activities

- Process to formulate conceptual design of the LIGO advanced detector
- Upper limit to binary inspiral events from 40m prototype data
- Kalman filter string mode removal
- Time frequency technique to search for transients

More examples in breakout sessions

Conceptual design of LIGO advanced detector

- Continuing program outlined in 1989 LIGO proposal
- Initial Laboratory concept
  - reduced sensing noise -- 100 watt laser
  - reduced thermal noise and improved test mass control -- multi stage suspension
  - reduced seismic noise --- external active isolation
  - Projected result: sensitivity gain of 5 @ 100 Hz, sensitive bandwidth increase factor of 2
- LSC committee deliberations and White Paper iteration
  - Technical assessment, experience across LSC, schedule impact of change
    - change in interferometer configuration --narrow and broad band operation
    - major change in seismic isolation -- improve control and bandwidth
    - tested multi stage suspension with improved thermal noise
    - sapphire test mass option
- Projected result: sensitivity gain 15@100Hz, sensitive bandwidth increase factor of 10
- Major commitments in R&D and implementation by LSC institutions

Organization and Budget

Gary Sanders

NSF Operations Review

Caltech, February 26, 2001

LIGO-G010033-00-M

LIGO Program and Mission of the LIGO Laboratory

- *observe gravitational wave sources;*
- develop advanced detectors that approach and exploit the facility limits on interferometer performance; ✓
- operate the LIGO facilities to support the national and international scientific community;
- and support scientific education and public outreach related to gravitational wave astronomy.

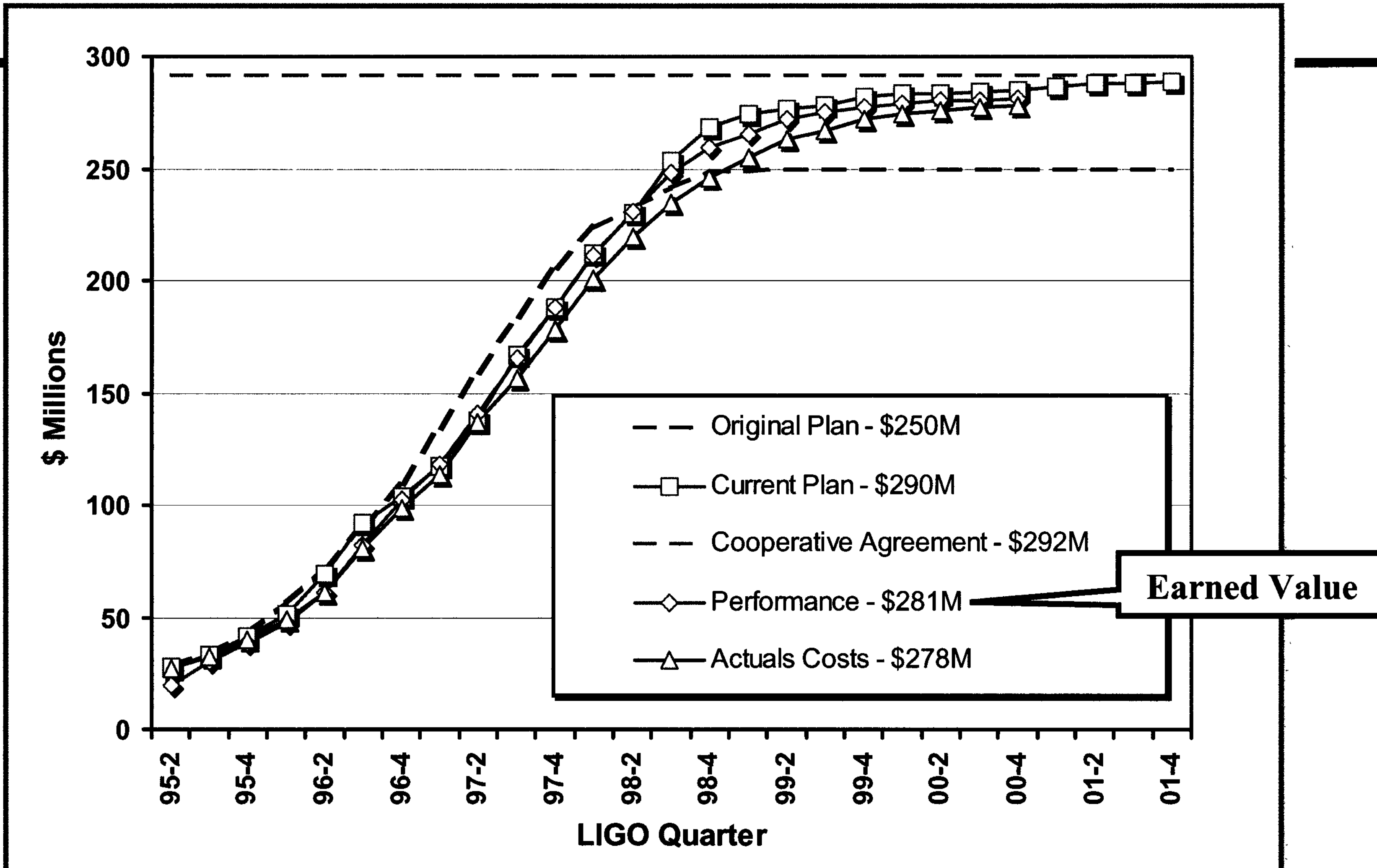
LIGO Proposes To:

- Complete commissioning of the initial LIGO interferometers;
- operate the LIGO interferometers for the initial LIGO Science Run;
- process and analyze the Science Run data and publish the results of the first scientific searches for gravitational wave sources;
- characterize and improve the sensitivity and availability of the operating interferometers;
- define interferometer upgrades and carry out a research and development program to underpin future upgrade proposals;
- support the development and research of the LIGO Scientific Collaboration;
- support the development of the international network of gravitational wave detectors;
- interpret the LIGO program to the public;
- leverage LIGO in educational settings;
- and address new industrial technologies and applications stimulated by the requirements of gravitational wave observation.

LIGO Construction (1995 – 2001)

- Organization mirrored the construction project WBS
  - » Deliverable oriented
- Budget defined by the integrated cost and schedule baseline
  - » Tasks defined
  - » Labor resources defined
  - » Commitments and costs defined
- Construction delivered the Facilities (buildings and vacuum systems) and the interferometer components *ready for installation*
  - » Installation/commissioning supported with early operations funding

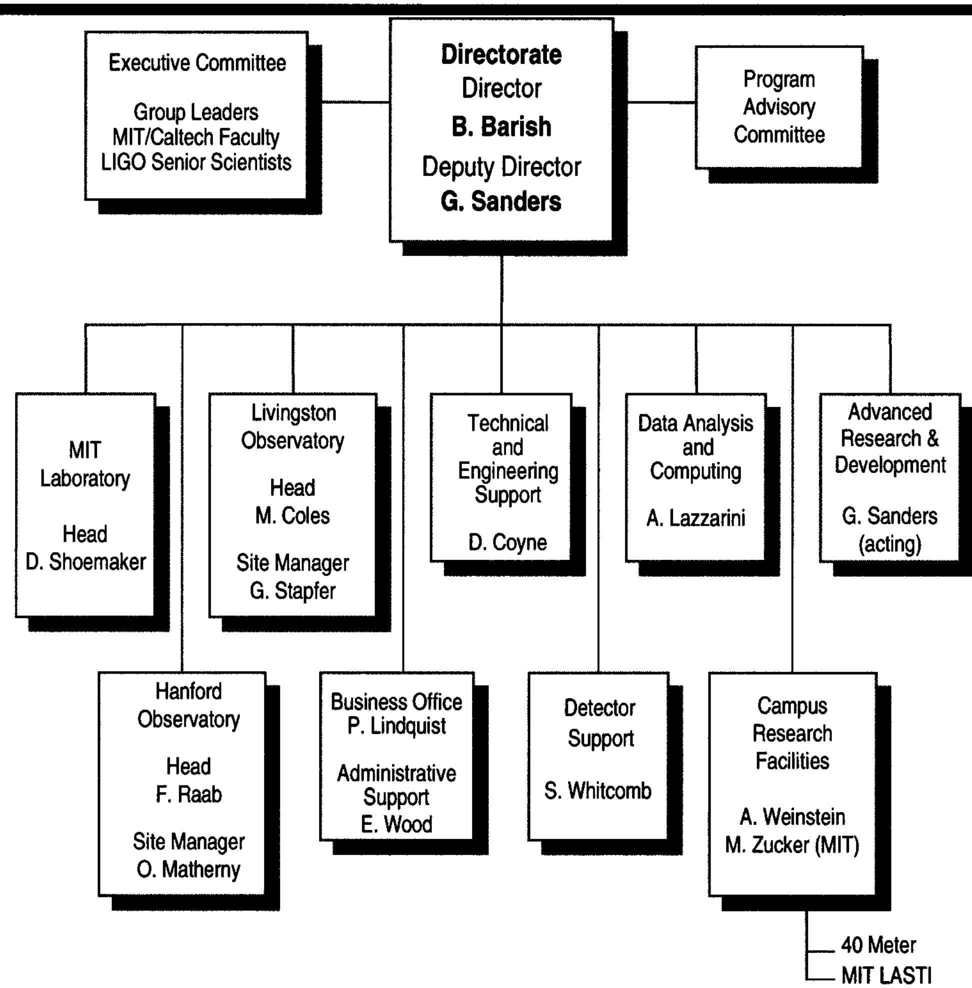
Cost Schedule Performance



Operations (1997 – 2001)

- *Early operations* phase activities include:
  - » Installation and commissioning of interferometers
  - » Operation and stewardship of facilities
  - » Developments of data analysis with LSC
  - » Support of LSC
  - » Outreach
- Budgets based upon 1994 estimate
  - » No prior large interferometer laboratories for comparison
  - » Data analysis with LSC is a larger activity than original scope
  - » R&D for future detectors is increased as well
    - – Supported by separate award and support from Operations
- Budget development has been *empirical and iterative*
  - » *Experience with costs has been applied to successive budgeting*

LIGO Laboratory Organization



Work Breakdown Structure – Caltech

Operations

WBS	WBS Element
1.1	Director's Office (DIR)
1.2	Business Office (BUS)
1.3	Technical and Engineering Support (TEC)
1.4	Detector Support (DET)
1.5.1	Data Analysis
1.5.2	Modeling & Simulation
1.5.3	General Computing
1.6	Campus Research Facilities (40M)
1.7	Seismic Prototype (Livingston)
0.4.2.1	Seismic Isolation R&D Equipment
0.4.3.1	Suspensions R&D Equipment
0.4.6.1	Core Optics R&D Equipment

Equipment in support of LSC R&D

Advanced R&D

WBS	WBS Element
A.2	Thermal Noise Interferometer (TNI)
A.3	Advanced Stabilized Lasers (LAS)
A.4	Advanced Core Optics (Including Sapphire)
A.6	Advanced ISC (Including Photodetectors)
A.8	Seismic Isolation System (Livingston)
A.9	Auxiliary Optics and Thermal Control
A.10	Advanced Suspensions and Fibers
A.11	Low Frequency Noise Suppression
A.12	Resonant Sideband Extraction (40M)
A.13	Advanced Controls and System Identification
A.14	Advanced Input Optics System
A.15	New Advanced R&D CIT

Work Breakdown Structure - Observatories

Hanford

WBS	WBS Element
2.1	Site Office
2.2	Facility Maintenance
2.3	Vacuum Equipment
2.4	Optics
2.5	Data Analysis and Computing
2.6	Electronics
2.7	Administration
2.8	Installation Support
2.9	Stockroom
2.10	Outreach
2.11	CDS Maintenance
2.12	LDAS Maintenance

Livingston

WBS	WBS Element
3.1	Site Office
3.2	Facility Maintenance
3.3	Vacuum Equipment
3.4	Optics
3.5	Data Analysis and Computing
3.6	Electronics
3.7	Administration
3.8	Installation Support
3.9	Stockroom
3.10	Outreach
3.11	CDS Maintenance
3.12	LDAS Maintenance

Work Breakdown Structure - MIT

WBS	WBS Element
4.1	MIT Project Office
4.2	MIT Business Office
4.3	MIT LSC Support
4.4	MIT Detector Support
4.5	MIT Data Analysis & Computing
4.6	MIT Campus Research (LASTI)
A.1	MIT Stochastic Noise R&D
A.6	Advanced ISC (Including Photodetectors)
A.9	Auxiliary Optics and Thermal Control
A.16	New Advanced R&D MIT

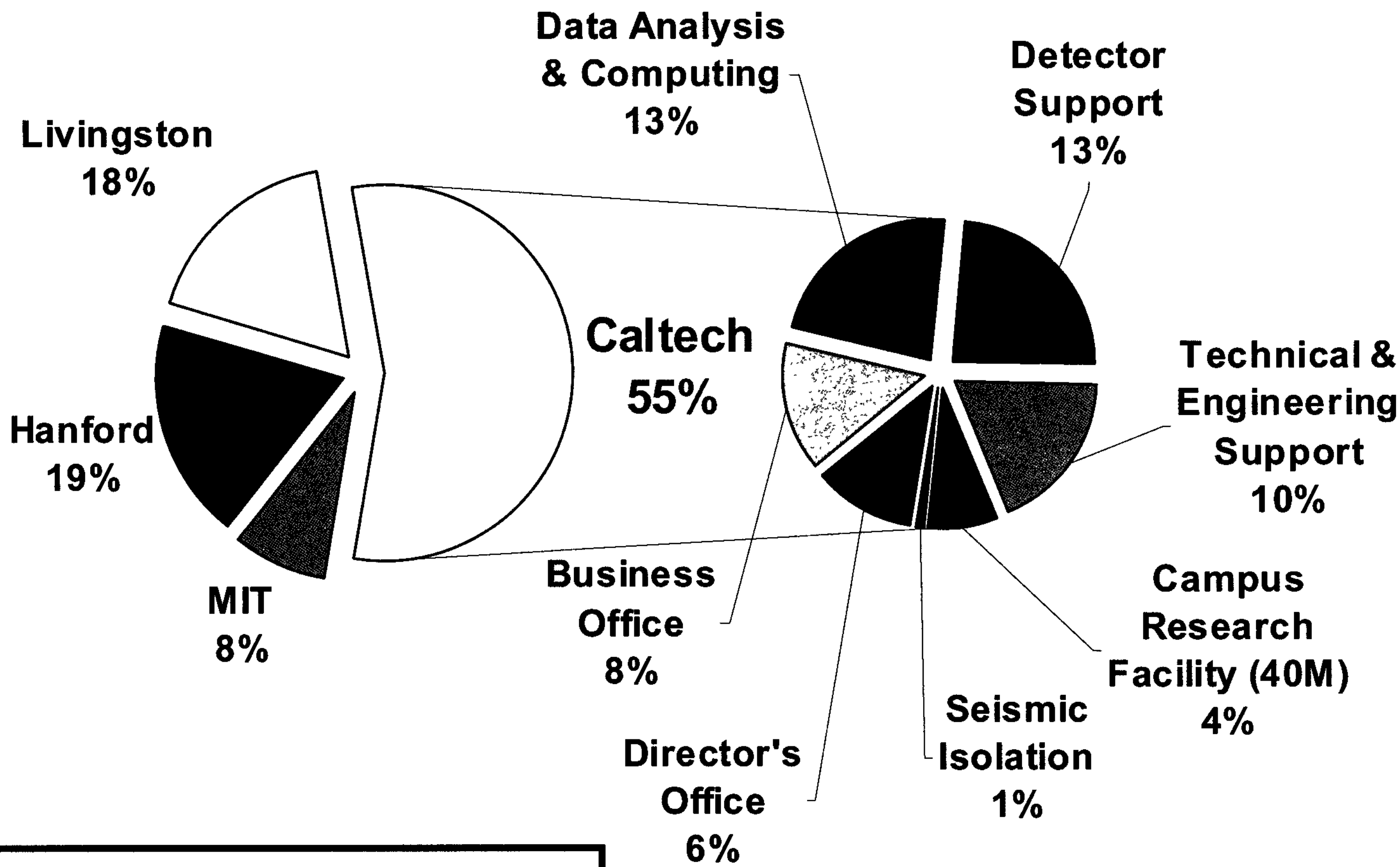
Funding History

MRE Funds

Fiscal Year	Construction ($M)	R&D ($M)	Operations ($M)	Advanced R&D ($M)	Total ($M)
1992-94	35.90	11.19	-	-	47.09
1995	85.00	3.95	-	-	88.95
1996	70.00	2.38	-	-	72.38
1997	55.00	1.62	0.30	0.80	57.72
1998	26.00	0.86	7.30	1.82	35.98
1999	0.20	-	20.78	2.28	23.26
2000	-	-	21.10	2.60	23.70
2001 (10 mo.)	-	-	19.10 (10 mo.)	2.70	21.80 (10 mo.)
2001 (12 mo.)			22.92 (12 mo.)	2.70	25.62 (12 mo.)
Total (10 mo.)	272.10	20.00	68.58	10.20	370.88

Construction Project | Operations

FY 2000 *Expenses*



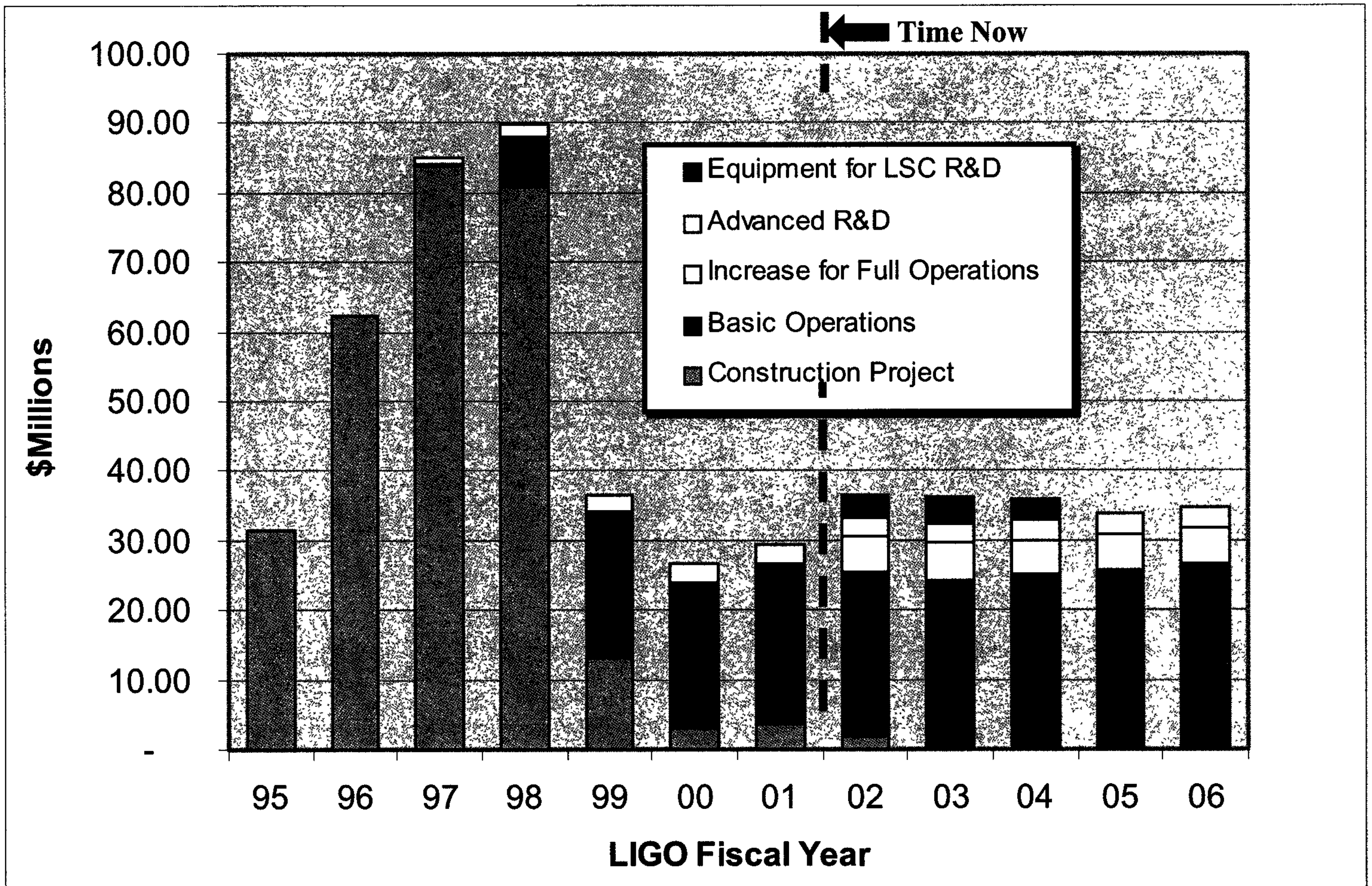
(Does not include Advanced R&D)

Methodology of Budget Estimate

- R&D budget is based upon bottom up estimate of R&D tasks as in a project estimate
  - » Initial LIGO cost experience supported this
- Operations budget was estimated by the managers for each major WBS
  - » Initial budget estimate was based upon
    - – ***Cost experience*** for existing tasks
    - – Estimate for new and desired tasks
  - » Initial budget estimate was too high and a set of exercises was carried out to scrub each WBS
    - – ~$10 million increase in 2002 became ~$5.2 million in this exercise
  - » Scrubbed estimate was organized into four broad budget categories for analysis and presentation in the proposal

LIGO

Budget History and Request



Internal Review by LIGO Program Advisory Committee…

- Reviewers:
  - » Abe Seiden (SCIPP)
  - » John Domingo (Jefferson Lab)
  - » Tom Nash (FNAL)
  - » P. Saulson (Syracuse)
- PAC commented that operating budgets were tight
  - » “Judging from the detailed presentation of the operating budget for the Livingston and Hanford sites, this budget appears extremely tight. In particular the staffing level for these sites is so lean…”
  - » “The maintenance and replacement costs for the control room data acquisition and control hardware are based on a very modest replacement rate…”
  - » “A continuous [computing] replacement cycle is, therefore, not an option or a luxury, but mandatory during this period of dynamic change...”

Future Operations Proposal Budget

	FY 2001 ($M)	FY 2002 ($M)	FY 2003 ($M)	FY 2004 ($M)	FY 2005 ($M)	FY 2006 ($M)	Total 2002-6 ($M)
Currently funded Operations	22.92	23.63	24.32	25.05	25.87	26.65	125.52
Increase for Full Operations		5.21	5.20	4.79	4.86	4.95	25.01
Advanced R&D	2.70	2.77	2.86	2.95	3.04	3.13	14.76
R&D Equipment for LSC Research		3.30	3.84	3.14			10.28
Total Budgets	25.62	34.91	36.21	35.93	33.77	34.74	175.57

FY 2001 currently funded Operations ($19.1M for ten months) is normalized to 12 months and provided for comparison only and is not included in totals.

LIGO

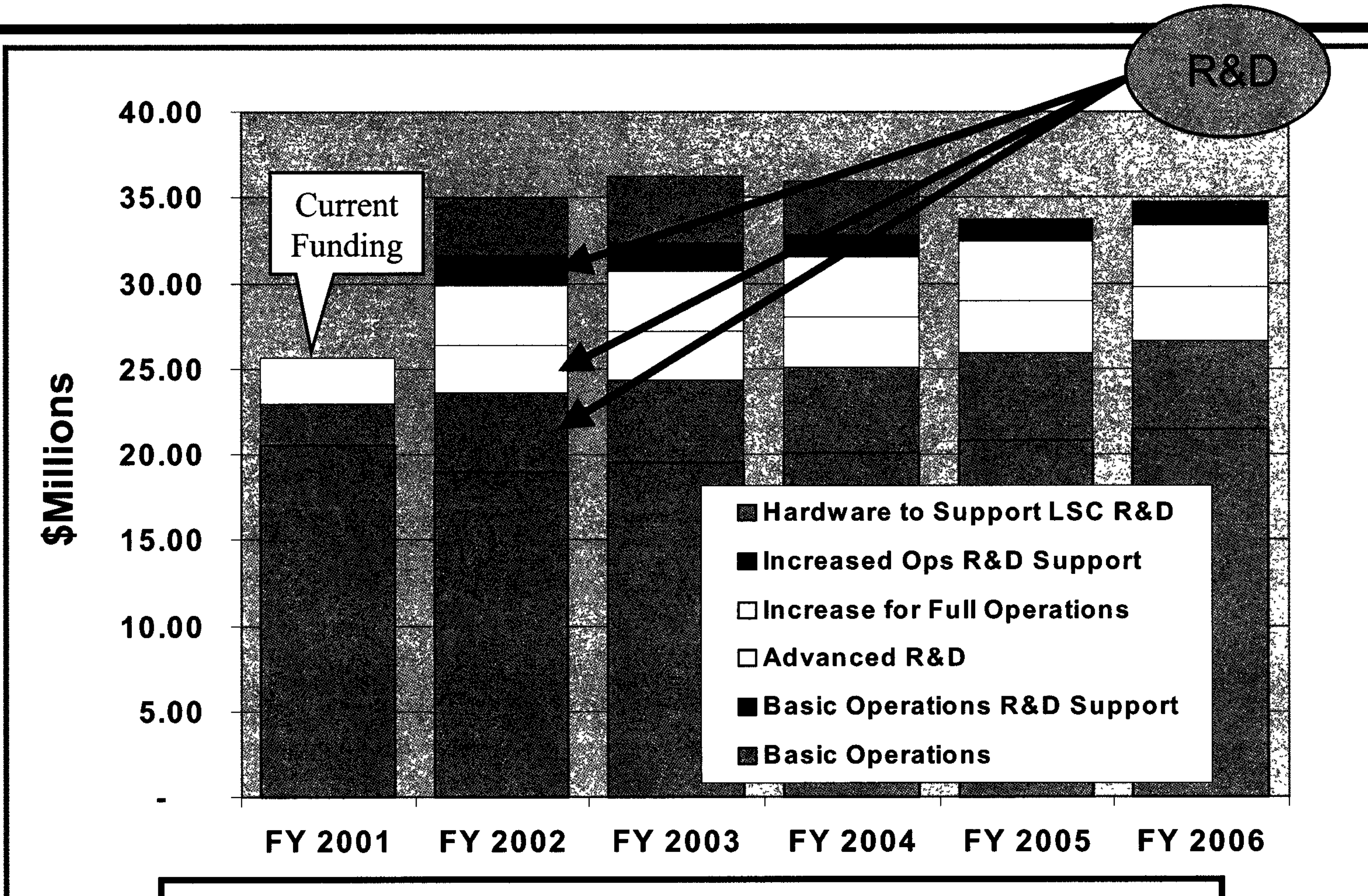
Increase for Full Operations

Budget Category	Increase	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Basic Operations						
*	CDS Hardware Maintenance	513,800	502,434	517,507	533,032	549,023
*	LDAS Maintenance	1,378,728	1,378,728	1,322,235	1,303,163	1,303,163
	Outreach	249,848	257,343	265,063	273,015	281,206
	Site Operations	558,485	575,240	592,497	610,272	628,580
*	Telecommunications / Networking	540,500	542,200	542,200	539,500	539,500
	Staff for Site LSC Support	254,678	262,318	270,187	278,293	286,642
Basic Operations Totals		**3,496,039**	**3,518,263**	**3,509,689**	**3,537,275**	**3,588,114**
Operations Support of Advanced R&D						
	Seismic Development	506,300	434,574			
	Engineering Staff	920,868	948,494	976,949	1,006,257	1,036,445
*	Simulation & Modeling Staff	282,485	293,949	305,614	317,772	330,617
R&D Total		**1,709,652**	**1,677,017**	**1,282,562**	**1,324,029**	**1,367,062**
Grand Total		**5,205,691**	**5,195,280**	**4,792,252**	**4,861,304**	**4,955,176**

R&D

*** Need recognized by NSF review panels**

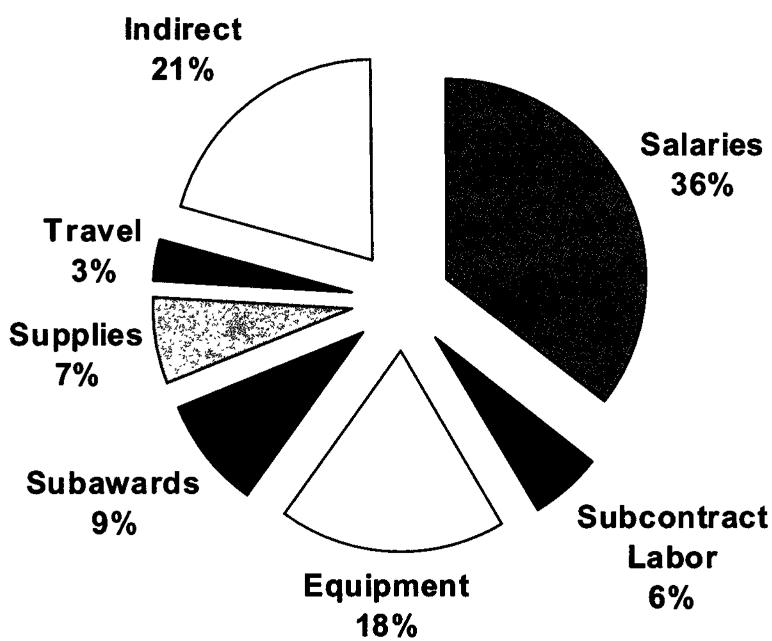
Future Operations Proposal



FY 2001 funding normalized to 12 months shown for comparison

Proposal Budget by Cost Category

Cost Category	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Salaries	12,451,415	12,826,004	12,858,588	13,356,635	13,829,893
Subcontract Labor	2,038,000	2,104,870	2,173,680	2,162,816	2,233,769
Equipment	6,362,448	7,206,883	7,057,561	4,155,678	4,136,905
Subawards	3,207,223	2,994,144	3,002,745	3,073,862	3,149,893
Supplies	2,459,296	2,464,861	2,170,455	2,034,321	2,092,037
Travel	1,118,600	1,134,605	1,082,299	1,130,594	1,180,000
Indirect	7,273,884	7,483,522	7,585,321	7,856,542	8,116,886
Grand Total	**34,910,865**	**36,214,889**	**35,930,651**	**33,770,448**	**34,739,382**



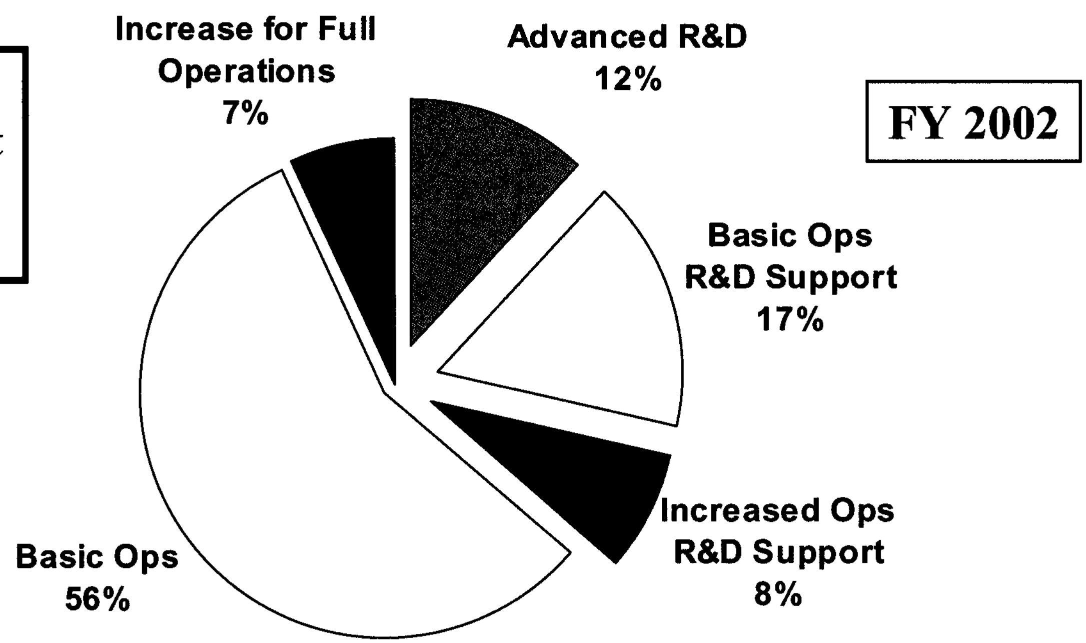
FY 2002

Operations
including Advanced R&D

Staffing by Funding Source

Funding Issue	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Advanced R&D	21.8	21.8	21.8	21.8	21.8
Basic Ops R&D Support	30.9	30.9	30.9	30.9	30.9
Increased Ops R&D Support	14.3	14.3	9.8	9.8	9.8
Basic Ops	104.2	104.2	104.2	104.2	104.2
Increase for Full Operations	13.0	13.0	13.0	13.0	13.0
Grand Total	**184.1**	**184.1**	**179.6**	**179.6**	**179.6**

Numbers shown are Full Time Equivalent Employees (FTEs) actually charged



Increase for Full Operations

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Basic Operations						
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*** Need recognized by NSF review panels**

LIGO Proposes To:

- Complete commissioning of the initial LIGO interferometers;
- operate the LIGO interferometers for the initial LIGO Science Run;
- process and analyze the Science Run data and publish the results of the first scientific searches for gravitational wave sources;
- characterize and improve the sensitivity and availability of the operating interferometers;
- define interferometer upgrades and carry out a research and development program to underpin future upgrade proposals;
- support the development and research of the LIGO Scientific Collaboration;
- support the development of the international network of gravitational wave detectors;
- interpret the LIGO program to the public;
- leverage LIGO in educational settings;
- and address new industrial technologies and applications stimulated by the requirements of gravitational wave observation.

Operating the Observatories

Mark Coles

LIGO-G010032-00-L

Goals of Presentation

- Describe scope of work undertaken at sites
- Describe allocation of staff and budget needed to perform this work
- Describe changes as sites transition from installation and commissioning to scientific operation

FY2001 Site Operations 12 Month Budget ~ $9M

	FY01	FY02
Site labor	50%	50%
Building and site maintenance, utilities	20%	18%
Vacuum system operation, liquid nitrogen	5%	4%
Computer and network operations, supplies, maintenance	4%	12%
Electronics, optics, administrative supplies, telephone	3%	3%
Other miscellaneous – travel by site staff, repairs, etc.	3%	4%
Outreach	0%	2%
Installation and commissioning related: supplies, fixturing, travel from campus, etc.	15%	6%

FY02 Budget ~ $10.7M

Scope of site based responsibilities for maintenance:

Electrical power	Sewage treatment plant maintenance and inspection
Electrical maintenance	Water system maintenance and certification
Crane service	Sump cleanout
HVAC service, supplies, repairs	Road maintenance
Landscaping maintenance	Vehicle fuel and maintenance
Fence maintenance	Vehicle lease
Brush clearing	Property leases
Custodial service	Security patrol
Trash collection	Safety Equipment inspections
Pest control	Fire detection equipment service and inspection
	Telephone

FY01 annual cost of ~$1.9 M

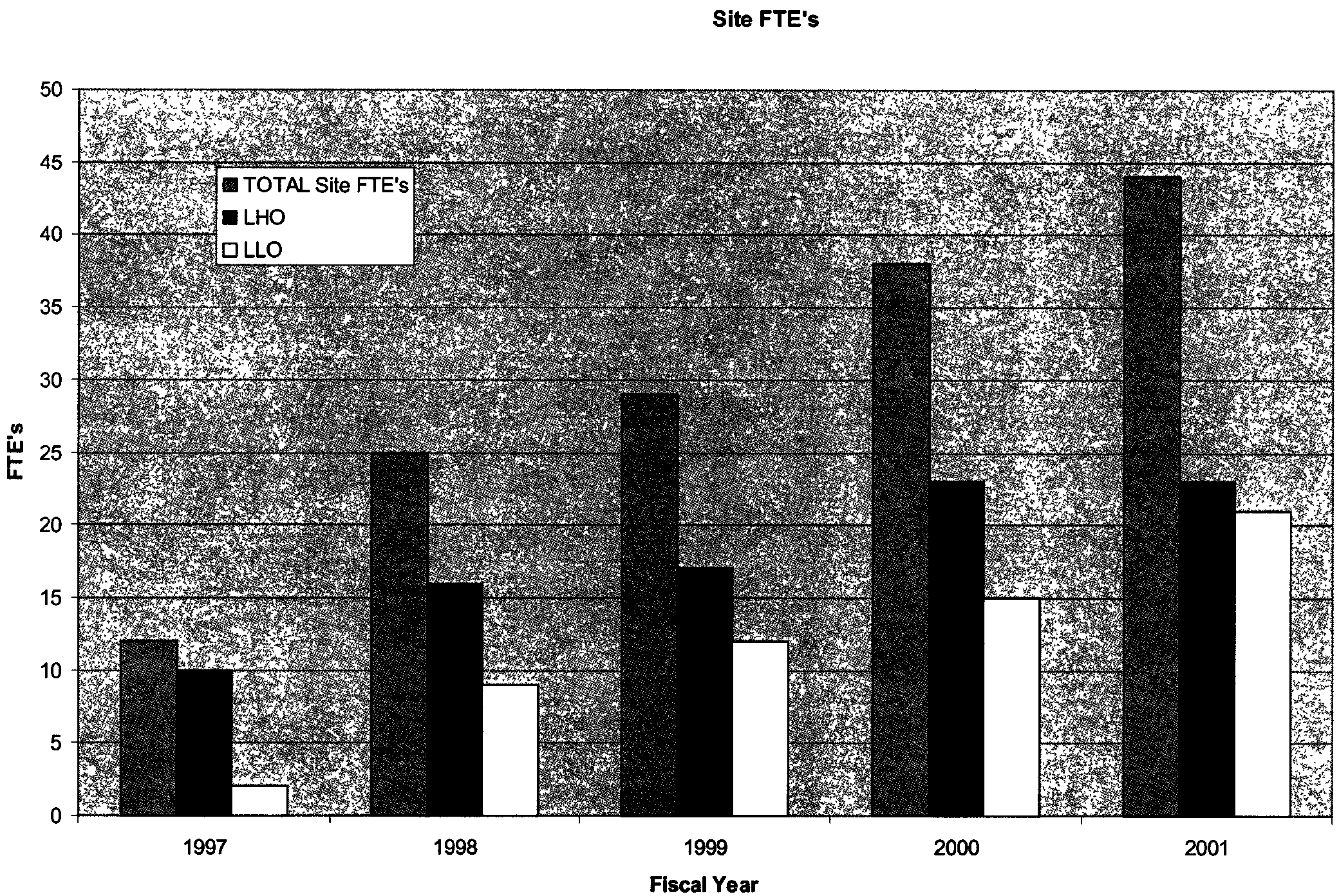
Site Staff Role 1996-2001

- Management and quality control during construction and installation of facilities
- Site maintenance
- Installation of interferometer, *in partnership with campus staff*
- Initial interferometer commissioning, *in partnership with campus and LSC staff*
- We have augmented regular staff with temporary contract labor as needed

Composition of Present Staff at Each Site

- 7 Scientific staff positions available
- 7 Engineering and technical support staff
  - » Facilities maintenance, vacuum, electrical, control and data acquisition software, optics, network and computing
- 9 Operations specialists (mixture of technical skill backgrounds to support installation,maintenance, and control room operation)
- 1 site administrator
  - » Campus provides in-depth engineering and scientific support, administrative support for contracts, purchasing, travel
- Contract labor utilized to augment staff as required while maintaining flexibility

Site Staffing History



- Staff placed at both sites to participate in installation and commissioning of the interferometers, and to maintain the sites.
- Additional staffing will be required to support full operation and maintenance.

Staffing Responsibilities

Professional scientific and technical staff participate in LIGO Scientific Collaboration

- Scientific staff
  - » Participate in detailed studies of interferometer and subsystem performance
  - » Responsible for “quality control” of interferometer operation and data collection
  - » Operation of on-site Data Analysis System (LDAS)
- Engineering support staff
  - » Participate in installation and commissioning
  - » Maintain operation of installed systems
  - » Provide on-site technical support, in partnership with Caltech and MIT staff
- Operations Specialists
  - » Mix of junior engineering and scientific staff
  - » Support installation and commissioning activities
  - » Provide operations support during commissioning, control room operation

Scientific Staff Development

- Stagger 3 year term appointments for 3 staff members, replace one per year
- Look for opportunities to “leverage” scientific staff positions:
  - » Agreements on joint appointments between LLO and Southeastern Louisiana University – Hammond, LA
    - one half-time faculty position filled beginning January ’01,
    - search in progress to fill second position in fall ’01
  - » Agreement with U Florida to share cost of basing two UF staff at LLO
  - » Cost sharing to place U of Oregon and U of Michigan staff at LHO

Operations Staff Training

- We are broadly training staff in interferometer operation:
  - » Hands-on installation and commissioning activities
  - » Some formal lectures
  - » Evolving and expanding list of daily shift duties:
    - Monitoring DCU operations
    - Inspecting laser beam spots
    - PSL and mode cleaner locking
    - PEM data monitoring – do things look OK?
    - Checking configurations and values of servos
    - Vacuum system monitoring
  - » Trouble-shooting with expert staff when faults occur
- Control room staffing is presently Mon-Fri with day and evening shifts, plus additional shifts as necessary

Configuration Control

- Maintain tight configuration control so the sites do not diverge technically:
  - » Installation oversight led by Caltech/MIT campus staff
  - » Site staff technical liaisons assigned for each sub-system
  - » Joint commissioning meetings involving both sites and Caltech/MIT to insure common effort, equipment, and configurations
  - » Software and data acquisition and control electronics design files maintained on campus
  - » Site LDAS system activities directed from Caltech/MIT

Site Activities 2002-2006

- Interferometer operation and support
- Facility support and maintenance
- Related research and development activities based at sites
- Educational outreach

Interferometer Staffing During Operation

- 2 operations specialists per hour shift, plus scientific staff
  - » *at least one* scientist per shift for initial operation
  - » Role of scientist is to be "eyes and ears" of scientific community analyzing data – identify unique features of interferometer, environment, configuration, etc
- 24x7 operation requires ~ minimum 10 operations specialists vs 9 in current budget – assuming normal operation, no training courses, flu epidemics, etc
- Additional operating staff needed to make operation robust, ability to handle exceptional conditions, also maintenance and calibration, etc
- Accommodate staff turnover

Site Staffing Increases From 47 ➡ 60

FTE's

LDAS operation, maintenance, data management	2 scientists, 2 engineers
24x7 interferometer operation	4 engineers
LSC liaison with LSC	2 scientists
Computer and network systems administration	1 engineer
Educational outreach	1 technical, 1 admin/educator

Annual cost ~$1,063K

Site Related Budget Augmentation FY2002-2006

- Annual equipment maintenance and replacement of LIGO Data Analysis and Computing hardware on 4 year cycle:
  - » ~$1,380K annually
  - » *recognized by NSF review panel*
- Networked data distribution via OC3:
  - » ~$540K annually
  - » *recognized by NSF review panel*

These items can be discussed by Albert Lazzarini in breakout session

LIGO

Site Related Budget Augmentation FY2002-2006

- Annual maintenance and replacement of control room data acquisition and control hardware, custom electronics, and embedded controllers
  - » ~$514K annually
  - » Represents about 10% of total value of control room computers and 5% of total value of custom electronics and VME controllers

Long Term Major Repairs

- LIGO has *not* included a budget request for major facility and infrastructure repairs that will be needed as the sites age
- We do *not* expect to need funds for this during 2002-6
  - » The buildings and supporting infrastructure are new
- We want to raise the issue now, so that proper planning can be done in advance of future need

Discuss in breakout session

Intellectual Atmosphere at the Sites

- We are trying to create an intellectual center at each site, not an outpost
  - » Conduct LIGO related research on-site where feasible
  - » On-site Seminars
  - » Encourage participation and interaction with regional universities and with K-12 education – become valuable resource to regional education infrastructures
  - » Maintain strong connection to the campuses
    - – ~10 visitors/day from LSC or Caltech/MIT
    - – Weekly teleconferences with both sites and campuses
    - – Site staff visit each other to share experiences, lessons learned, and to give “quick start” to new activities

On-site Research Activities During FY2002-6

- Characterization of seismic environment at LHO and LLO:
  - » “TriNet” real-time earthquake information system – Caltech, USGS, State of Calif
  - » Louisiana Tech Univ collaboration to operate seismometers, collect and analyze data
  - » Seismometers and data recorders loaned by: IRIS PASSCAL Instrument Center (NSF supported center) at New Mexico Tech U
- Advanced seismic isolation system development:
  - » reduce ground motion at 10 Hz by 3-4 orders of magnitude
  - » Develop two stage active seismic isolation platform on hydraulic actuators
  - » LLO provides lab and office space, project management, site infrastructure
- Operation of high power laser test facility at LLO:
  - » Anticipate upgrade in LIGO laser power to 100-200 W (from 6 watts)
  - » Measure thermal lensing, thermally induced bi-refringence, component selection, of core optics, modulators, isolators
  - » Facility jointly utilized by LLO, UF, Southern Univ., and SLU staff

Educational Outreach

- SST - Scientist, Student, Teacher program at LHO
  - » Collaboration with Pacific Northwest National Laboratory
  - » moves components of LIGO research to high school curricula through summer internships and academic-year research programs
- Classroom resource: "The Scientific Method at Work" video taped at LHO and distributed by The School Company as a classroom resource for Middle/High School science education

Educational Outreach

- Distance Learning: LHO developed interactive program for 8th grade science for broadcast over the the WA state K-20 teleconferencing network. Program involves discussion and experiments on the law of falling bodies to demonstrate the process of science
- LIGO Public Lecture: LHO sponsored a free lecture by Kip Thorne and John Archibald Wheeler, detailing Wheeler's contributions to local and global science - from the first production nuclear reactor at Hanford to LIGO
  - » Cooperative ventures during the Wheeler visit included B-Reactor Museum Society reunion and book signing at Columbia River Exhibition of History, Science and Technology

Educational Outreach

- Field trips by community and professional groups at both sites
- More than 3,000 visitors in last year at LLO (mostly school classes), 750 during public open house
- Teacher open houses in summer and winter, more than 100 middle and high school science teachers in Livingston Parish have toured LIGO as part of teacher in-service
- LLO hosted more than 100 African-American high school science students participating in Southern University's Timbuktu Academy
- Development of hands-on activities and educational resource materials at each site

Optical Telescope

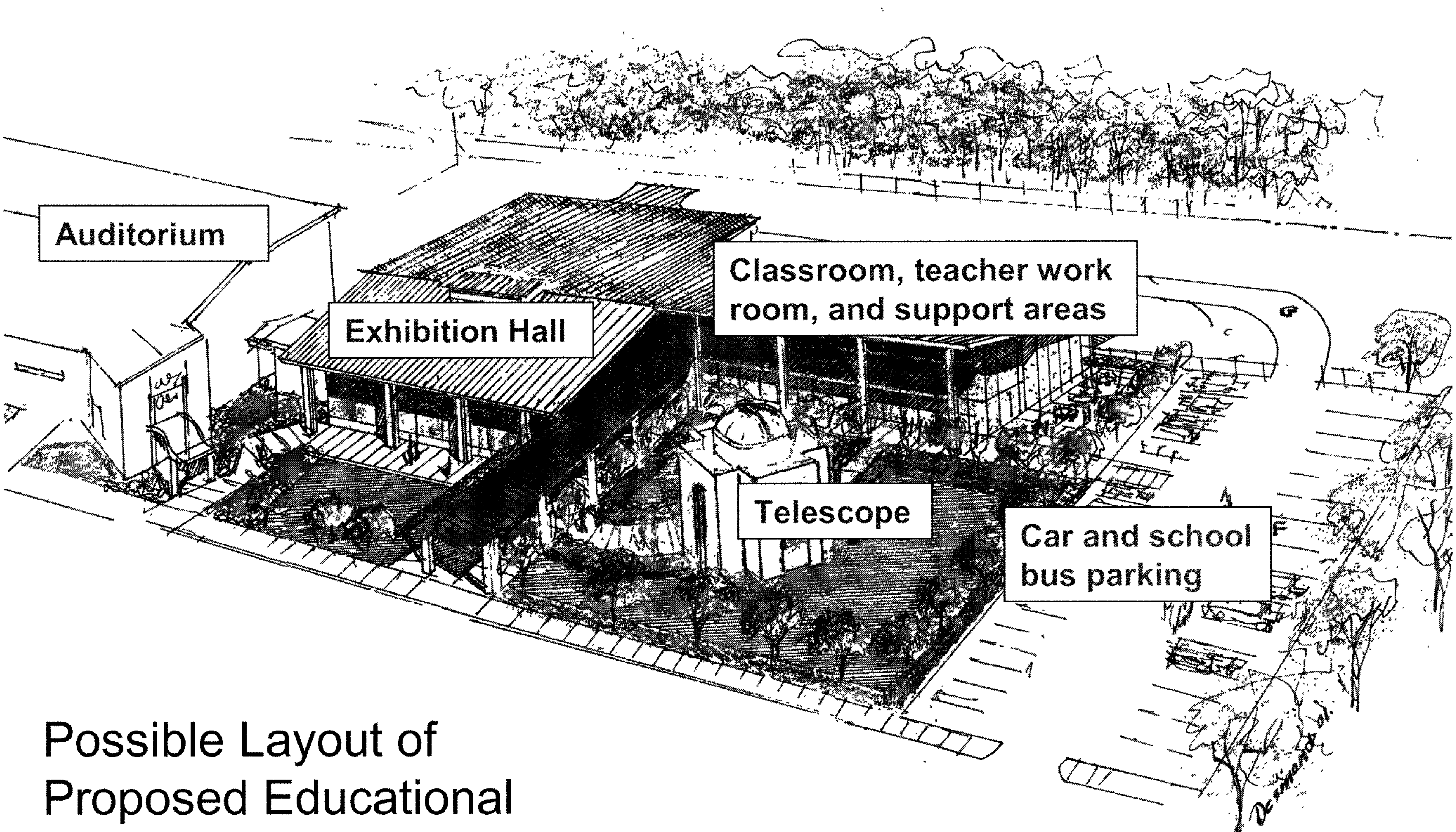
- Funded through Prof. Greg Guzik at LSU via Louisiana Technical Innovation Fund and Louisiana Board of Higher Education (only state employees are eligible to apply)
- Endorsed by LIGO and to be located at LLO site
- $98K in state funds for 16 inch robotic telescope, dome, controls
- Web accessible for remote use by classrooms
- LLO to provide:
  - » Site, internet connection, staffing
- Opportunities for outreach and possibly a modest science program in association with community organizations
  - » Monitoring variable stars, supernovae searches, etc
  - » Opportunity to attract staff with formal backgrounds in astronomy and interests in LIGO science

Educational Outreach

- Plan for formally budgeted outreach activities as part of future operations
- Possible extension of LIGO-SST (Scientist – Student – Teacher) program now underway at LHO to LLO
- Possible partnerships with professional K-12 educators
  - » Northwestern State University Space Science Education Program for middle school science enrichment
  - » Plan to submit NSF-IPSE program proposal to involve teachers in development of educational materials for schools
- Concentrate on sites-specific opportunities for outreach since needs and resources are different at each site

Educational Outreach Center

- Hope to establish Education Outreach Centers at both sites
  - » Host site visitors with hands-on exhibits and science classes (like NSF-funded Arecibo and Lowell Observatory centers)
  - » Teacher in-service training and support for classroom enrichment (also like Arecibo and Lowell Centers)
  - » Host a modest school-to-work program for vocational training
- In the past the NSF has financially supported the development of program content and start-up labor costs, but has not provided funds for infrastructure such as building, parking lots, etc
- Discuss plans for LLO and LHO in detail during breakout session



Possible Layout of Proposed Educational Outreach Center at LLO

LIGO Future Operations (FY 2002-2006)

Budgets, Schedules, and Milestones

NSF Review February 26, 2000
Hanford, Washington
Operations Sub Panel

Objectives

- Describe the methods used to manage the LIGO Construction Project and the concurrent Operations.
- Present financial data demonstrating these processes and the current status.
- Describe the the process used to develop the proposal budgets for “Future Operations,” FY 2002-2006.
- Present the “budget model” and various views of the cost estimate and staffing plans.

LIGO Funding History

<u>Revised cost estimate – presented to NSF September 1994</u>

- NSB review and resolution – November 1994
- LIGO Construction Project (NSF PHY-9210038) $272,100,000
- Construction related R&D (NSF PHY-9210038) $20,000,000
- Operations (NSF PHY-9210038) $68,700,000 ($68,580,000 actually funded)
- Advanced R&D (NSF PHY-9700601, PHY-9801158) $10,200,000

<u>Subsequent Funding</u>

- REU Program (NSF PHY-9210038) $48,000
- LIGO Visitor's Program (NSF PHY-99528300) $34,245 (1996)
- LIGO Visitor's Program (NSF PHY-9603177) $656,025 (1997-99)
- LIGO Visitor's Program (NSF PHY-9986274) $280,000
- 1999 Edoardo Amaldi Conference (NSF PHY-9972068) $25,000

Funding History (Continued)

MRE Funds

Fiscal Year	Construction ($M)	R&D ($M)	Operations ($M)	Advanced R&D ($M)	Total ($M)
1992-94	35.90	11.19	-	-	47.09
1995	85.00	3.95	-	-	88.95
1996	70.00	2.38	-	-	72.38
1997	55.00	1.62	0.30	0.80	57.72
1998	26.00	0.86	7.30	1.82	35.98
1999	0.20	-	20.78	2.28	23.26
2000	-	-	21.10	2.60	23.70
2001 (10 mo.)	-	-	19.10 (10 mo.)	2.70	21.80 (10 mo.)
2001 (12 mo.)			22.92 (12 mo.)	2.70	25.62 (12 mo.)
Total (10 mo.)	272.10	20.00	68.58	10.20	370.88

Construction Project

Operations

Construction Project (PHY-9210038)

- Project management approach – LIGO implemented a full cost schedule reporting and control system
  - » Budget baseline reviewed by NSF May 1995
  - » Early focus on budgets and performance measurement baseline
  - » Focus shifted to ETC and contingency management
- Reporting, internal and external – cost schedule status report and performance charts
  - » Budget, earned value, actual costs, budget-at-completion, estimate-at-completion
- Change requests, change control board, and change log
  - » Threshold for approval required set at $50,000
- Contingency tracking, contingency needs forecasting
- Weekly project controls meetings attended by PI, PM, group heads, key personnel as required

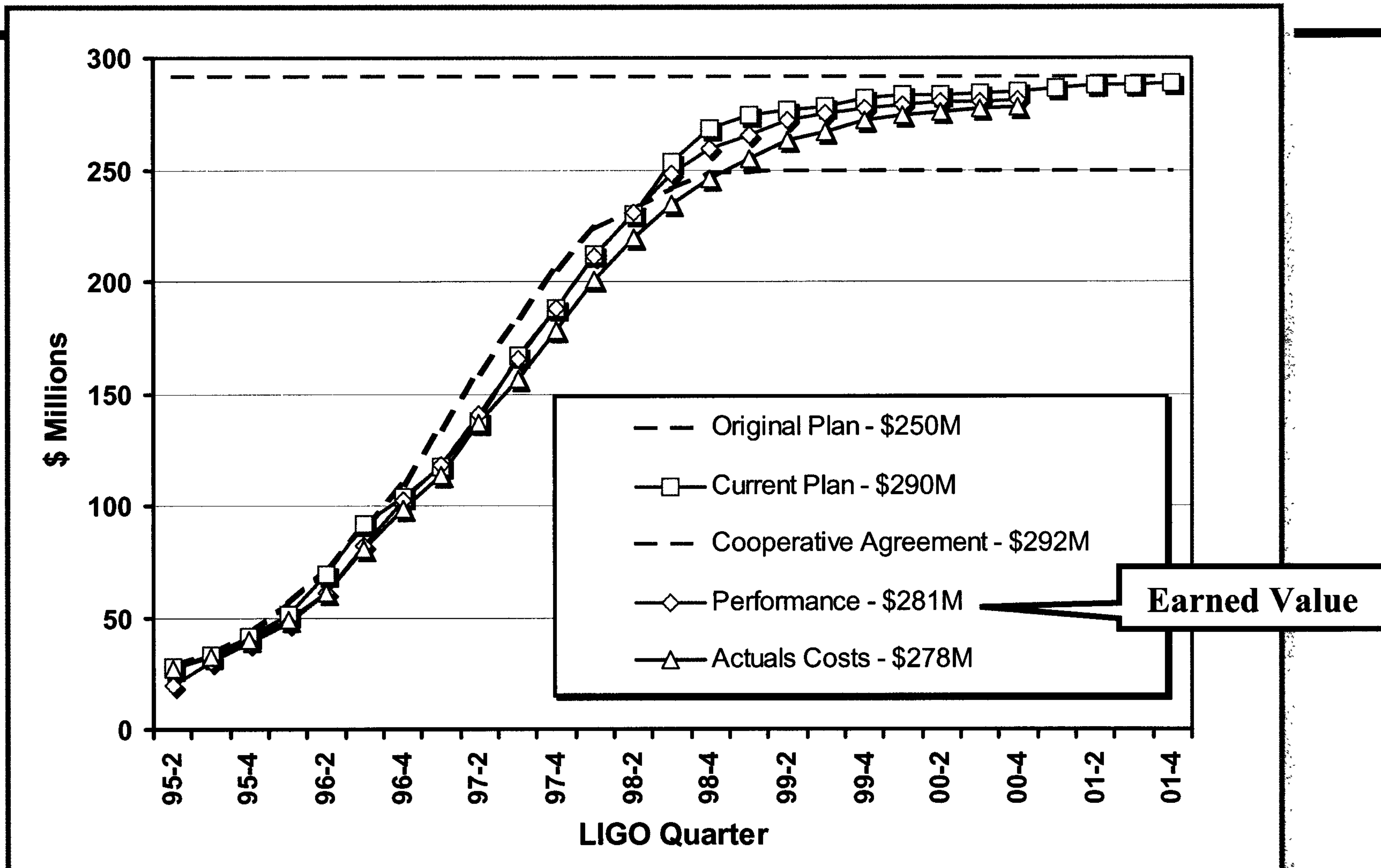
Cost Schedule Status Report

End of November 2000

Reporting Level	Cumulative To Date					At Completion		
Work Breakdown Structure	Budgeted Cost of Work Scheduled (BCWS)	Budgeted Cost of Work Performed (BCWP)	Actual Cost of Work Performed (ACWP)	Schedule Variance (2-1)	Cost Variance (2-3)	Budget-at-Completion (BAC)	Estimate-at-Completion (EAC)	Variance-at-Completion (6-7)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.1.1 Vacuum Equipment	43,970	43,970	44,047	-	(77)	43,970	44,047	(77)
1.1.2 Beam Tubes	46,967	46,967	47,004	-	(37)	46,967	47,004	(37)
1.1.3 Beam Tube Enclosure	19,338	19,338	19,338	-	-	19,338	19,338	-
1.1.4 Facility Design & Construction	53,722	53,656	53,580	(66)	76	56,226	55,775	451
1.1.5 Beam Tube Bake	5,695	5,695	5,559	-	136	5,695	5,559	136
1.2 Detector	60,252	59,698	56,390	(554)	3,308	60,252	59,752	500
1.3 Research & Development	22,089	22,089	22,100	-	(11)	22,089	22,100	(11)
1.4 Project Office	32,597	29,934	29,934	(2,663)	-	35,509	35,509	-
Subtotal	284,630	281,347	277,952	(3,283)	3,395	290,046	289,084	962
Contingency							3,016	(3,016)
Management Reserve						2,054		2,054
Total	284,630	281,347	277,952	(3,283)	3,395	292,100	292,100	-

<u>All values in $K</u>

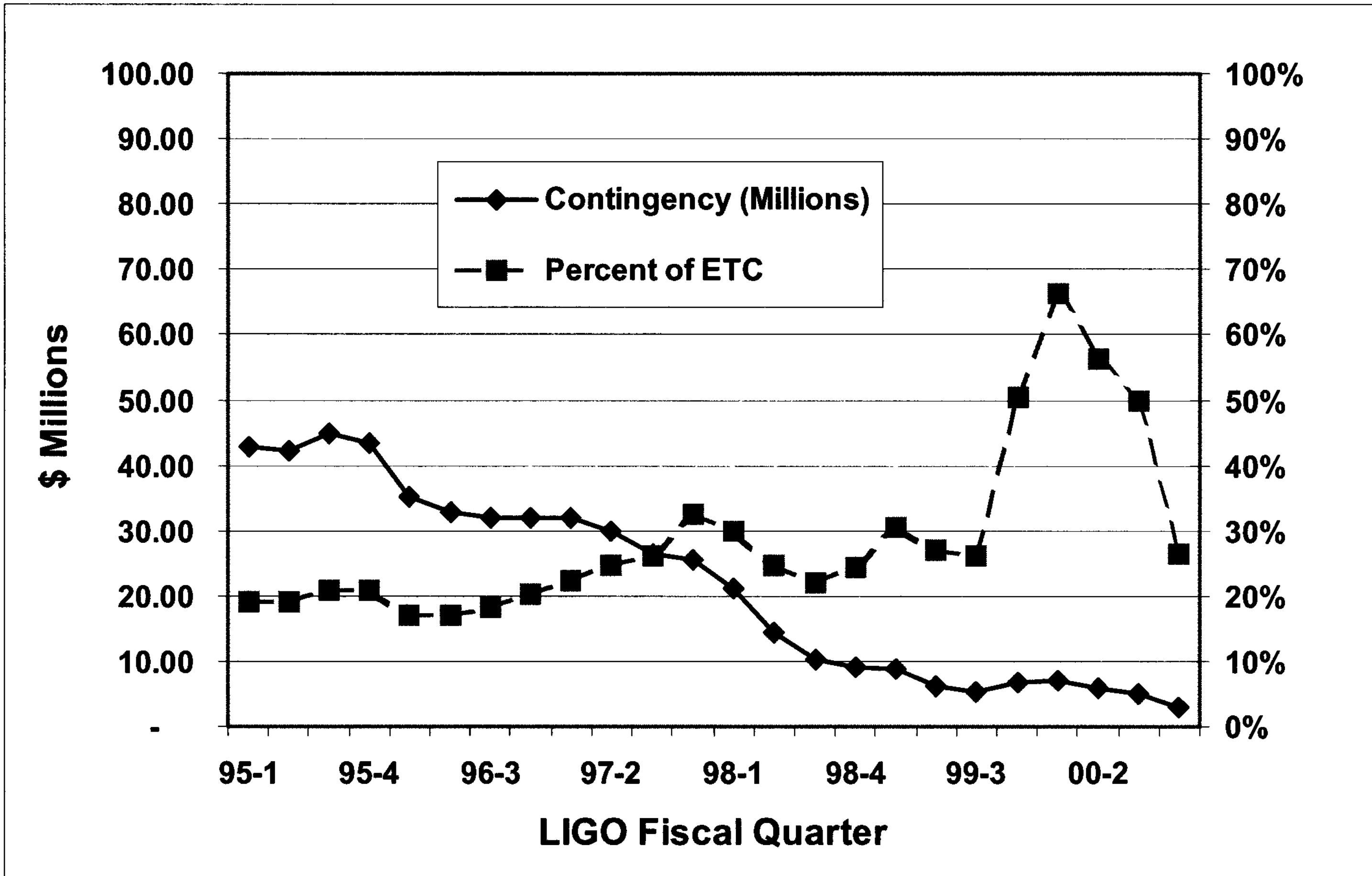
Cost Schedule Performance



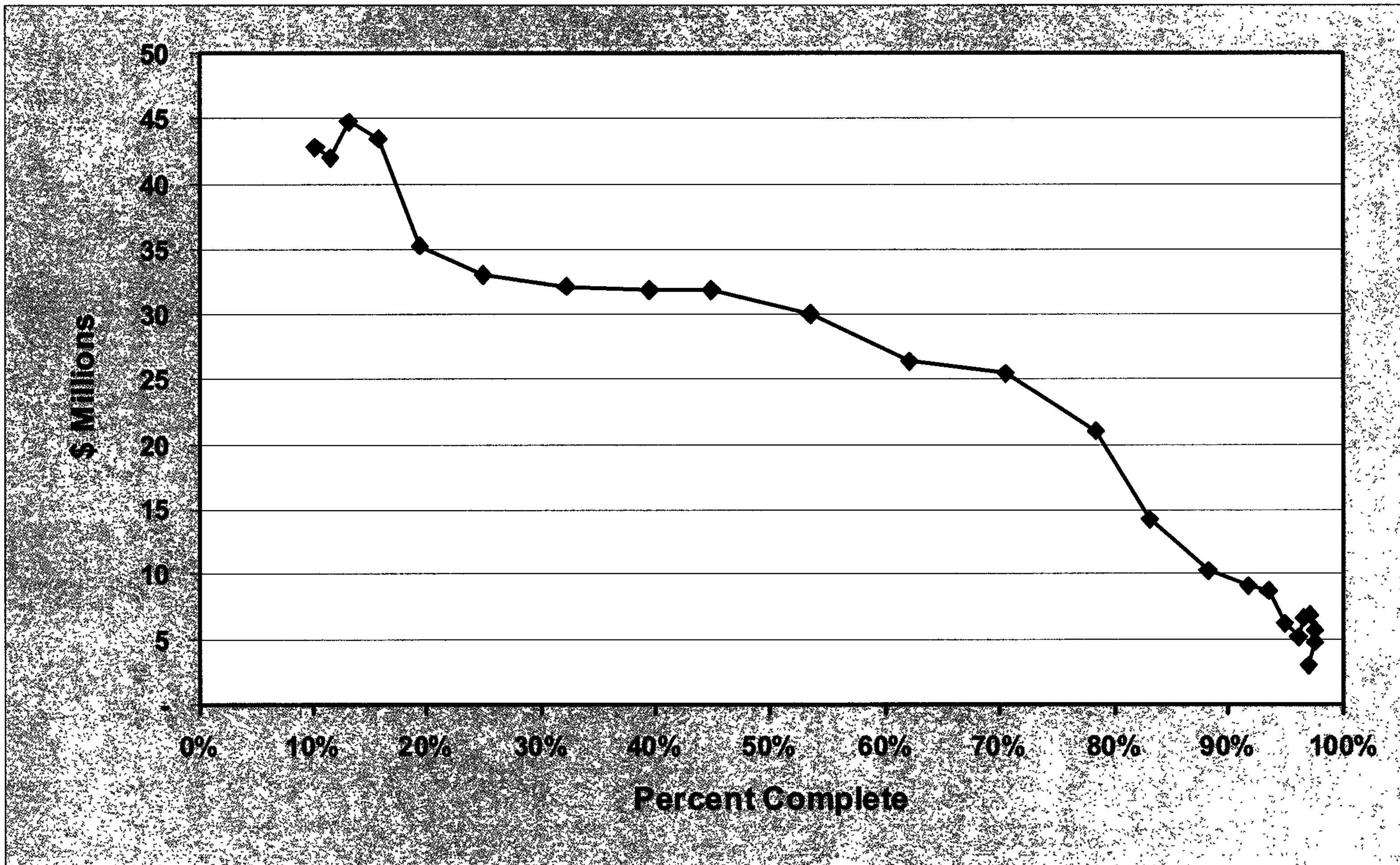
Change Request Log

Change Request No.§	Description§	Submitted By§	Submittal¶ Date§	Current¶ Status§	Disposition Date§	Baseline Date§	Net¶ Contin-gency§
CR-000004§	1.1.4--LVEA Concrete Floor Protection at Hanford§	O. Math-emy§	April 4, 2000§	Approved $86,500 (to be paid from OPs)§	April 11, 2000 M000142§	NA§	$4,619,301§
CR-000005§	1.2.1--Upgrade Prestabilized Lasers§	S. Whit-comb§	April 21, 2000§	Approved $215,000§	August 1, 2000 M000237§	July 2000§	$4,404,301§
CR-000006§	1.2.1--Repolish Core Optics Components§	S. Whit-comb§	April 21, 2000§	Approved $25,200 (to be paid from OPs)§	August 1, 2000 M000237§	NA§	$4,404,301§
CR-000007§	1.2.1--Replace Optical Lever Lasers§	S. Whit-comb§	May 8, 2000§	Approved $120,000 (to be paid from OPs)§	August 1, 2000 M000237§	NA§	$4,404,301§
CR-000008§	1.1.4--Cameras and Projec-tion System for LIGO Liv-ingston Observatory§	F. Asiri§	June 6, 2000§	Approved $26,000§	August 1, 2000 M000237§	July 2000§	$4,378,301§
CR-000009§	1.1.4--Cameras and Projec-tion System for LIGO Han-ford Observatory§	F. Asiri§	June 6, 2000§	Approved $26,000§	August 1, 2000 M000237§	July 2000§	$4,352,301§
CR-000010§	1.2.2--Redesign Suspension Controllers (Large Optics Suspensions)§	S. Whit-comb§	June 2, 2000§	Approved $356,000 (to be paid from OPs)§	August 1, 2000 M000237§	NA§	$4,352,301§

Contingency vs. Time



Contingency vs. Percent Complete

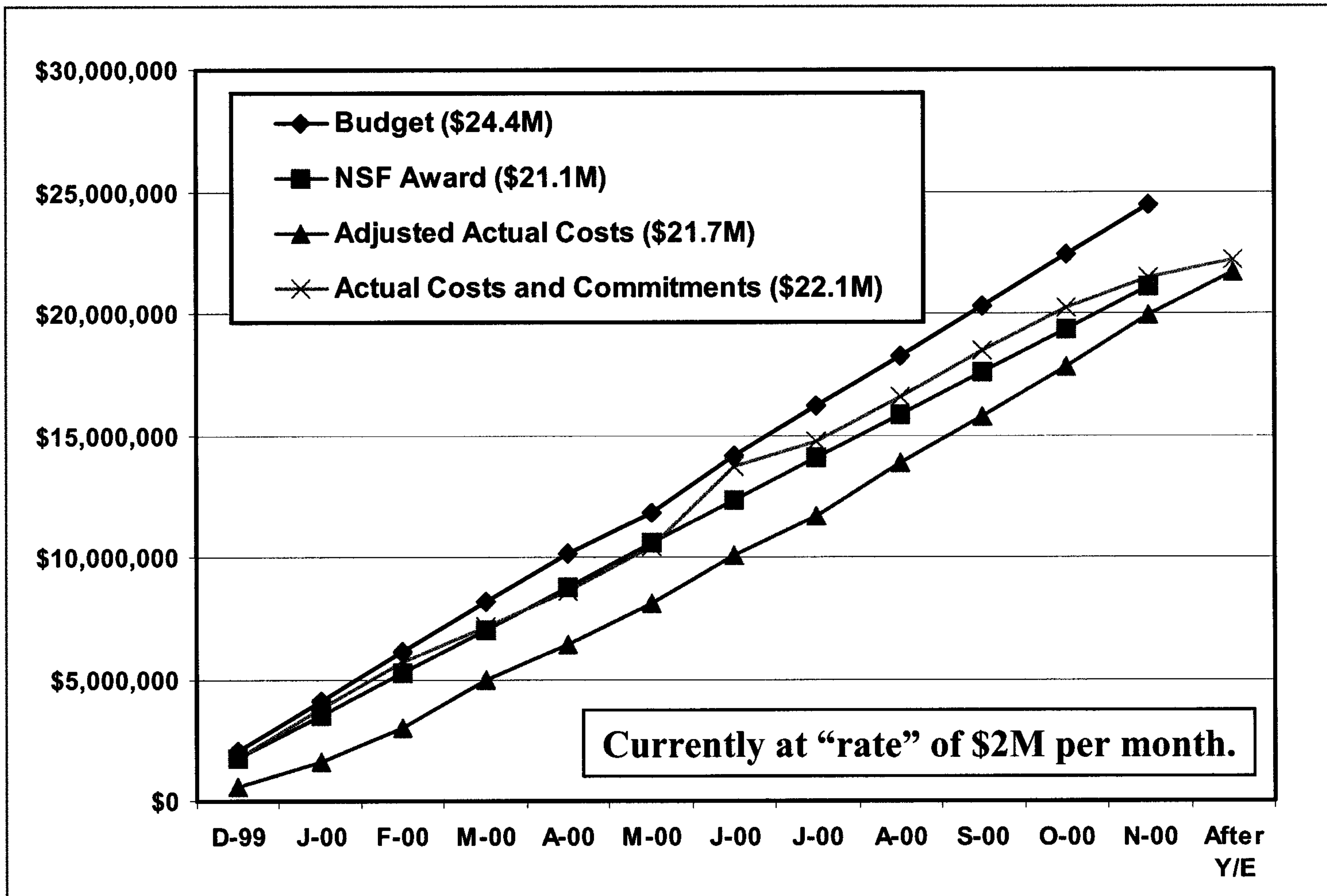


Operations and Advanced R&D

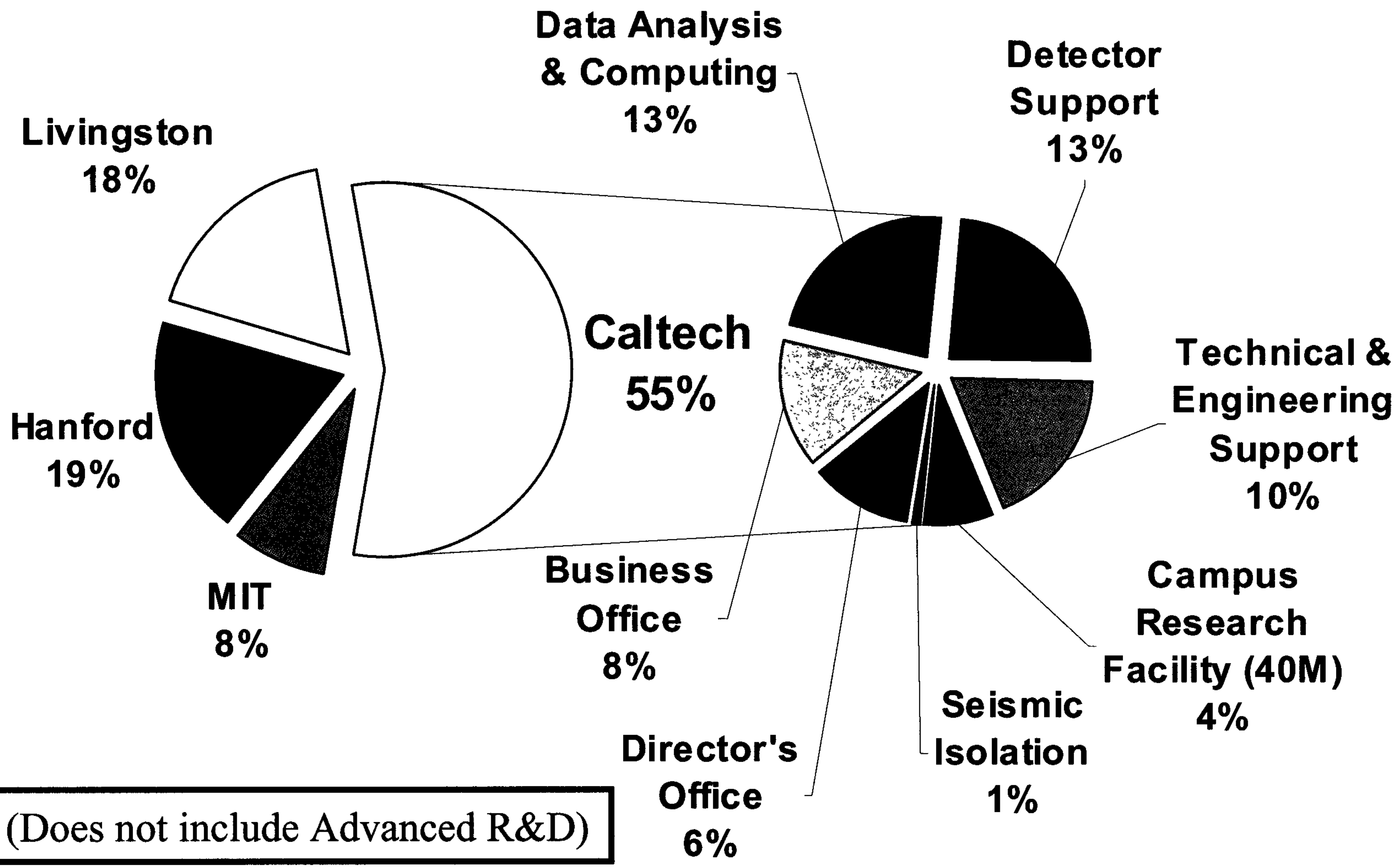
Approach

- Tracking actual costs and commitments vs. Budgets (we make no attempt to measure earned value)
- Budgets prepared and negotiated with group leaders prior to the beginning of the fiscal year
- The Change Control Board (CCB) is used to modify budgets and allocate management reserve as required; threshold requirements same as Construction Project ($50,000)
- Actual cost data derived directly from Caltech's ORACLE financial systems
- Costs and commitments tracked closely within LIGO organization and adjustments made to enhance comparisons, e.g., accruals for known costs that have not yet been booked
- Monthly reports prepared and distributed (see examples)
- Weekly site teleconferences (Caltech, MIT, Hanford, Livingston)

FY 2000 Operations Costs Summary



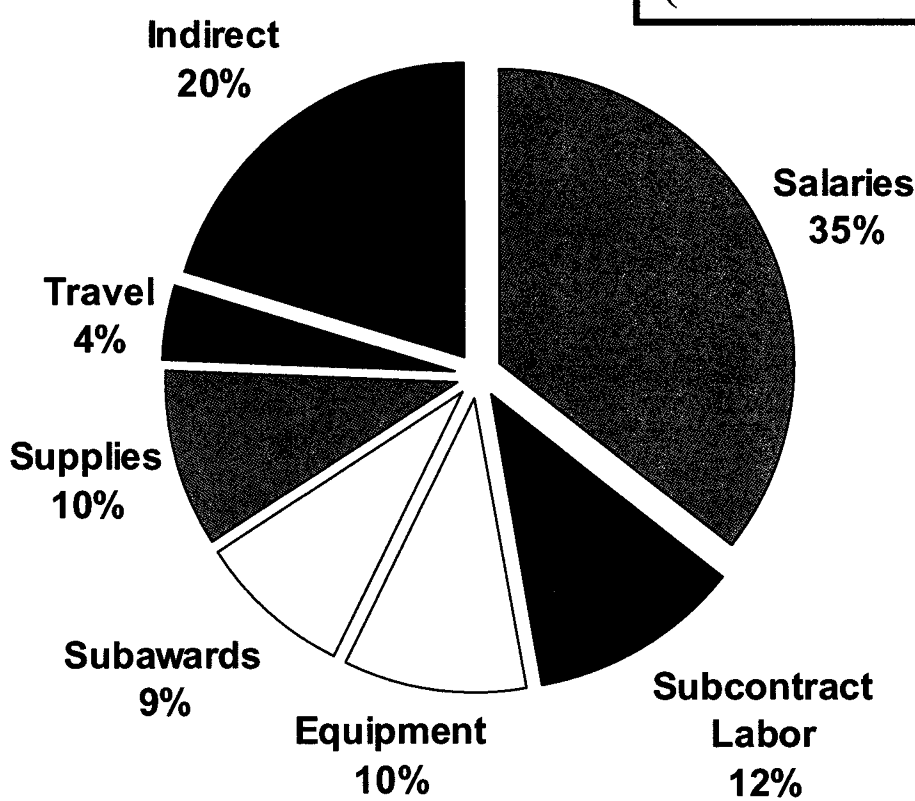
FY 2000 Expenses



(Does not include Advanced R&D)

FY 2000 Expenses (cont.)

(Does not include Advanced R&D)



Proposed Management Approach

- LIGO Operations and Advanced R&D
  - Continuation of systems developed above (e.g., will continue to establish budgets at the beginning of the year and report costs against the budget)
- LSC Advanced R&D
  - Use different management approaches to control the broad community effort
  - Establish Memoranda of Understanding (MOU) with each participant updated every six months http://www.ligo.caltech.edu/LIGO_web/mou/mou.html
  - Initiate Monthly Working Group teleconferences
- Future Proposed Construction (MRE)
  - Full cost schedule control system
  - Integrate with Advanced R&D deliverables (directed R&D)

Future Operations Cost Estimates

<u>How developed</u>

- Based on current operating experience and costs
- Based on WBS
- Separate line item for each cost element
  - » Labor - each position identified
  - » Equipment
  - » Domestic and foreign travel
  - » Participant costs
  - » Other direct costs include materials and supplies, subawards, contract labor
- Burden application
  - » Approved Caltech structure

<u>Also developing Cost book</u> (Web-Based Cost Estimating Tool)

Work Breakdown Structure – CIT

Operations

WBS	WBS Element
1.1	Director's Office (DIR)
1.2	Business Office (BUS)
1.3	Technical and Engineering Support (TEC)
1.4	Detector Support (DET)
1.5.1	Data Analysis
1.5.2	Modeling & Simulation
1.5.3	General Computing
1.6	Campus Research Facilities (40M)
1.7	Seismic Prototype (Livingston)
0.4.2.1	Seismic Isolation R&D Equipment
0.4.3.1	Suspensions R&D Equipment
0.4.6.1	Core Optics R&D Equipment

Equipment in support of LSC R&D

Advanced R&D

WBS	WBS Element
A.2	Thermal Noise Interferometer (TNI)
A.3	Advanced Stabilized Lasers (LAS)
A.4	Advanced Core Optics (Including Sapphire)
A.6	Advanced ISC (Including Photodetectors)
A.8	Seismic Isolation System (Livingston)
A.9	Auxiliary Optics and Thermal Control
A.10	Advanced Suspensions and Fibers
A.11	Low Frequency Noise Suppression
A.12	Resonant Sideband Extraction (40M)
A.13	Advanced Controls and System Identification
A.14	Advanced Input Optics System
A.15	New Advanced R&D CIT

Work Breakdown Structure Hanford and Livingston

Hanford

WBS	WBS Element
2.1	Site Office
2.2	Facility Maintenance
2.3	Vacuum Equipment
2.4	Optics
2.5	Data Analysis and Computing
2.6	Electronics
2.7	Administration
2.8	Installation Support
2.9	Stockroom
2.10	Outreach
2.11	CDS Maintenance
2.12	LDAS Maintenance

Livingston

WBS	WBS Element
3.1	Site Office
3.2	Facility Maintenance
3.3	Vacuum Equipment
3.4	Optics
3.5	Data Analysis and Computing
3.6	Electronics
3.7	Administration
3.8	Installation Support
3.9	Stockroom
3.10	Outreach
3.11	CDS Maintenance
3.12	LDAS Maintenance

Work Breakdown Structure - MIT

WBS	WBS Element
4.1	MIT Project Office
4.2	MIT Business Office
4.3	MIT LSC Support
4.4	MIT Detector Support
4.5	MIT Data Analysis & Computing
4.6	MIT Campus Research (LASTI)
A.1	MIT Stochastic Noise R&D
A.6	Advanced ISC (Including Photodetectors)
A.9	Auxiliary Optics and Thermal Control
A.16	New Advanced R&D MIT

Example Cost Elements

WBS	Line	Labo Category	Description	FY 2002 FTEs	FY 2002 Amount	FY 2003 FTEs	FY 2003 Amount	Budget Code
1.3	B2	Engineer	Abbott	1.00	[redacted]	1.00	[redacted]	BOP
1.3	B2	Engineer	Billingsley	1.00	[redacted]	1.00	[redacted]	BOP
1.3	B2	Senior Engineer	Bork	1.00	[redacted]	1.00	[redacted]	BOP
1.3	B2	Senior Engineer	Coyne	1.00	[redacted]	1.00	[redacted]	BOP
1.3	B2	Senior Engineer	Heefner	1.00	[redacted]	1.00	[redacted]	BOP
1.3	B2	Engineer	Romie	1.00	[redacted]	1.00	[redacted]	BOP
1.3	B2	Technician	Russell	1.00	[redacted]	1.00	[redacted]	BOP
1.3	B2	Engineer	Mageswarean	1.00	[redacted]	1.00	[redacted]	BOP
1.3	B2	Technician	Hoang	1.00	[redacted]	1.00	[redacted]	BOP
1.3	B2	Technician	Cardenas	1.00	[redacted]	1.00	[redacted]	BOP
1.3	B2	Engineer	Mailand	1.00	[redacted]	1.00	[redacted]	BOP
1.3	B2	Engineer	Nocero	1.00	[redacted]	1.00	[redacted]	BOP
1.3	C	Benefits	Benefits (22.5 percent)		[illegible]		230,707	BOP
1.3	D1	Equipment	Equipment under $5000		[illegible]		12,360	BOP
1.3	D2	Equipment	Equipment over $5000		[illegible]		41,200	BOP
1.3	E1	Travel Domestic	Domestic Travel		[illegible]		12,360	BOP
1.3	E2	Travel Foreign	Foreign Travel		[illegible]		16,480	BOP
1.3	G1	Supplies	Supplies		65,000		66,950	BOP
1.3	G5C	Senior Engineer	Karwoski	1.00	[redacted]	1.00	[redacted]	BOP
1.3	I	Indirect	Campus Overhead (58 percent)		768,203		791,249	BOP
1.3	B4	Undergraduate	Undergraduate (Robinson)	0.40	[redacted]	0.40	[redacted]	DSE
1.3	B4	Undergraduate	Undergraduate (Lopez)	0.40	[redacted]	0.40	[redacted]	DSE
1.3	B2	Engineer	Liu	1.00	[redacted]	1.00	[redacted]	DSE
1.3	C	Benefits	Benefits (22.5 percent)		16,313		16,802	DSE
1.3	G5C	Senior Engineer	Senior Electronic Engineer	1.00	[redacted]	1.00	[redacted]	DSE
1.3	G5C	Technician	Senior Electronic Technician	1.00	[redacted]	1.00	[redacted]	DSE
1.3	I	Indirect	Campus Overhead (58 percent)		61,255		63,093	DSE

LIGO uses contract labor for flexibility

Basic Operations

Increase For Engr Support

Indirect Cost Rate Agreement

Cognizant Agency & Date:	**Office of Naval Research, 08/31/00**
On Campus Overhead Rate[1]:	**58% MTDC**
Off Campus Overhead Rate[1]:	**26% MTDC**
Staff Benefits Rate[2]:	**22.5%**
GRA Benefit Rate:	**60% of GRA Stipend[3]**
MIT:	**Numbers provided by MIT based on MIT negotiated rates**

Modified Total Direct Costs

1. Excludes: Equipment, Caltech transfers (funds from campus to JPL), subcontract amounts over $25,000, GRA Benefit and participant support costs.
2. Excludes: Undergraduate and Graduate Student salaries.
3. Applicable to all federal grants and contracts, and all other awards that provide full indirect cost recovery. The GRA Tuition Remission Benefit for all non-federal awards (gifts, grants, contracts) that do not provide full overhead is 80% of GRA salary.

Future Operations Proposal Budget

	FY 2001 ($M)	FY 2002 ($M)	FY 2003 ($M)	FY 2004 ($M)	FY 2005 ($M)	FY 2006 ($M)	Total 2002-6 ($M)
Currently funded Operations	22.92	23.63	24.32	25.05	25.87	26.65	125.52
Increase for Full Operations		5.21	5.20	4.79	4.86	4.95	25.01
Advanced R&D	2.70	2.77	2.86	2.95	3.04	3.13	14.76
R&D Equipment for LSC Research		3.30	3.84	3.14			10.28
Total Budgets	25.62	34.91	36.21	35.93	33.77	34.74	175.57

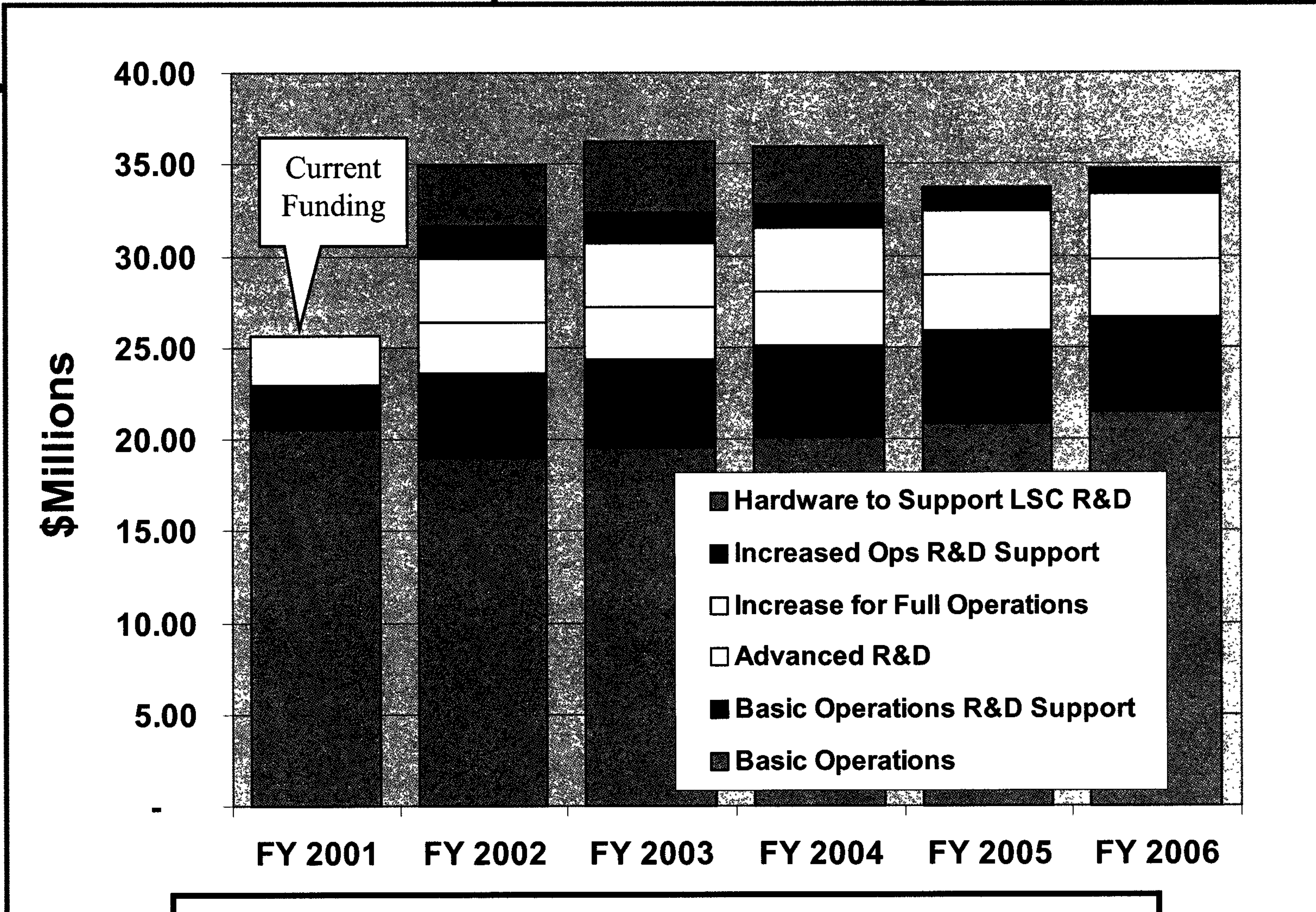
FY 2001 currently funded Operations ($19.1M for ten months) is normalized to 12 months and provided for comparison only and is not included in totals.

Future Operations Proposal (cont.)

- Advanced R&D Subpanel requested a breakout of all costs associated with the support of Advanced R&D.

Budget Category	Funding Issue	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
R&D						
	Advanced R&D	2,772,611	2,864,430	2,950,363	3,038,874	3,130,040
	Basic Ops R&D Support	4,663,972	4,796,151	4,932,296	5,072,525	5,216,961
	Increased Ops R&D Support	1,709,652	1,677,017	1,282,562	1,324,029	1,367,062
R&D Total		**9,146,235**	**9,337,598**	**9,165,221**	**9,435,428**	**9,714,062**
Ops						
	Basic Operations	18,967,517	19,523,471	20,115,396	20,797,746	21,437,206
	Increased Basic Operations	3,496,039	3,518,263	3,509,689	3,537,275	3,588,114
Ops Total		**22,463,555**	**23,041,734**	**23,625,085**	**24,335,020**	**25,025,319**
LSC						
	Equipment in Support of LSC R&D	3,301,075	3,835,556	3,140,345		
LSC Total		**3,301,075**	**3,835,556**	**3,140,345**		
Grand Total		**34,910,865**	**36,214,889**	**35,930,651**	**33,770,448**	**34,739,382**

Future Operations Proposal (cont.)



FY 2001 funding normalized to 12 months shown for comparison

Advanced R&D Effort (FY2002)

Stochastic Noise. LASTI integrated system tests of the advanced seismic isolation and suspension prototypes.	**$275,222**
Thermal Noise Interferometer. Direct measurement of test mass thermal noise for initial and advanced LIGO designs.	**$176,697**
Advanced Core Optics including sapphire optics.	**$283,937**
Advanced Interferometer Sensing and Control including Photodetector Development.	**$298,779**
Stiff Seismic Isolation Development.	**$46,353**
Auxiliary Optics Systems including Active Thermal Control.	**$366,088**
Advanced Suspensions including Fiber Research.	**$208,725**
Improved Low Frequency Strain Sensitivity.	**$345,637**
40-Meter Advanced R&D. Tests of controls and electronics for a signal and power recycled configuration with read-out scheme and control topology intended for advanced LIGO.	**$235,075**
Advanced Controls and System Identification. Research on application of advanced system identification and control concepts to LIGO.	**$188,677**
Advanced (highly stabilized) Input Optic Systems.	**$347,423**

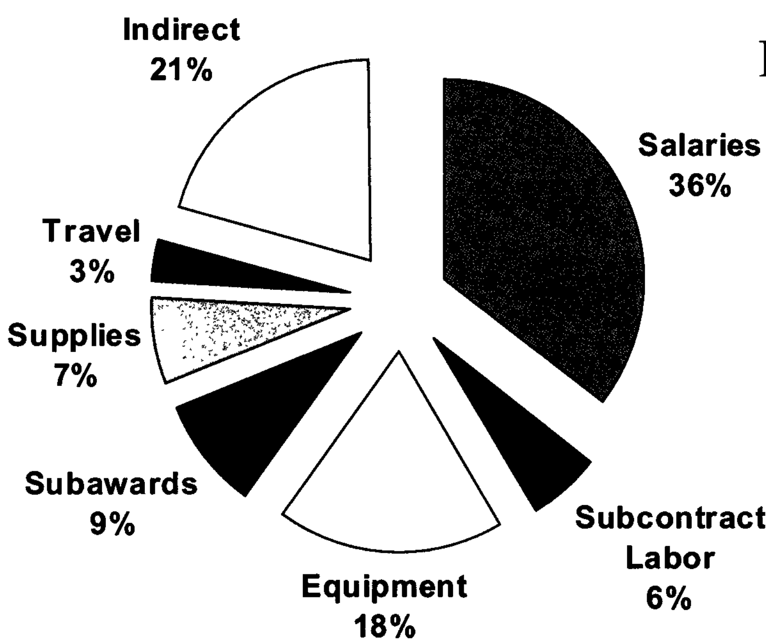
Increase for Full Operations

Budget Category	Increase	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Basic Operations						
	* CDS Hardware Maintenance	513,800	502,434	517,507	533,032	549,023
	* LDAS Maintenance	1,378,728	1,378,728	1,322,235	1,303,163	1,303,163
	Outreach	249,848	257,343	265,063	273,015	281,206
	Observatory Operations	558,485	575,240	592,497	610,272	628,580
	* Telecommunications / Networking	540,500	542,200	542,200	539,500	539,500
	LIGO Staff for LSC	254,678	262,318	270,187	278,293	286,642
Basic Operations Total		**3,496,039**	**3,518,263**	**3,509,689**	**3,537,275**	**3,588,114**
Operations Support of Advanced R&D						
	Seismic Development	506,300	434,574			
	Engineering Staff	920,868	948,494	976,949	1,006,257	1,036,445
	* Simulation & Modeling Staff	282,485	293,949	305,614	317,772	330,617
Advanced R&D Support Total		**1,709,652**	**1,677,017**	**1,282,562**	**1,324,029**	**1,367,062**
Grand Total		**5,205,691**	**5,195,280**	**4,792,252**	**4,861,304**	**4,955,176**

*** Need recognized by NSF Review Panel**

Proposal Budget by Cost Category

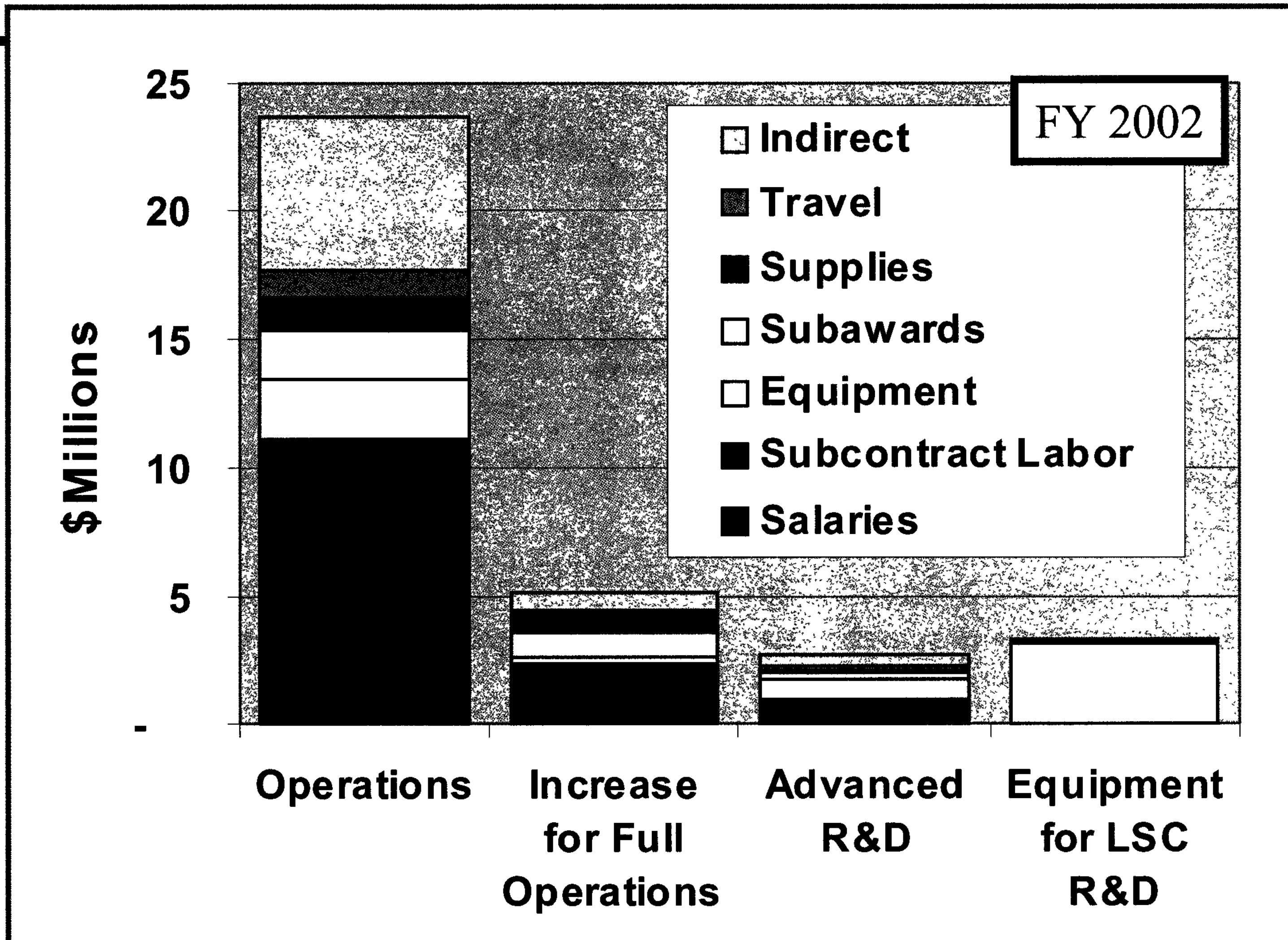
Cost Category	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Salaries	12,451,415	12,826,004	12,858,588	13,356,635	13,829,893
Subcontract Labor	2,038,000	2,104,870	2,173,680	2,162,816	2,233,769
Equipment	6,362,448	7,206,883	7,057,561	4,155,678	4,136,905
Subawards	3,207,223	2,994,144	3,002,745	3,073,862	3,149,893
Supplies	2,459,296	2,464,861	2,170,455	2,034,321	2,092,037
Travel	1,118,600	1,134,605	1,082,299	1,130,594	1,180,000
Indirect	7,273,884	7,483,522	7,585,321	7,856,542	8,116,886
Grand Total	**34,910,865**	**36,214,889**	**35,930,651**	**33,770,448**	**34,739,382**



FY 2002

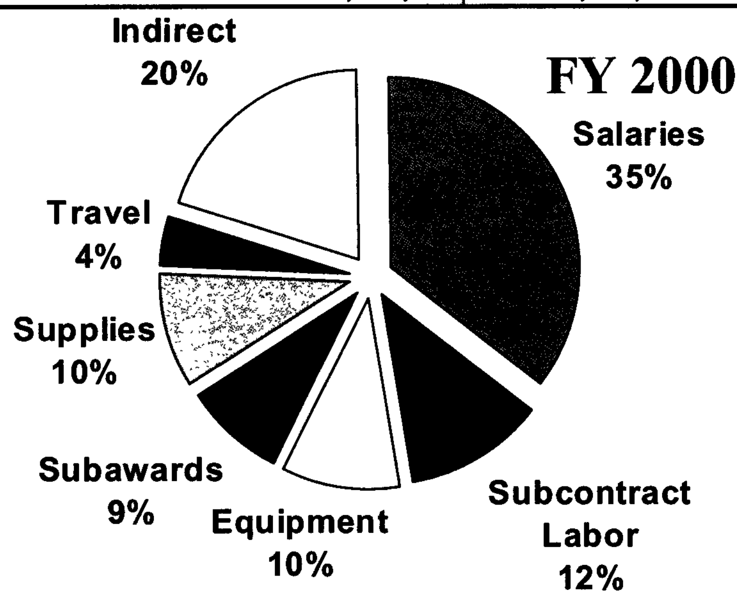
Operations
including Advanced R&D

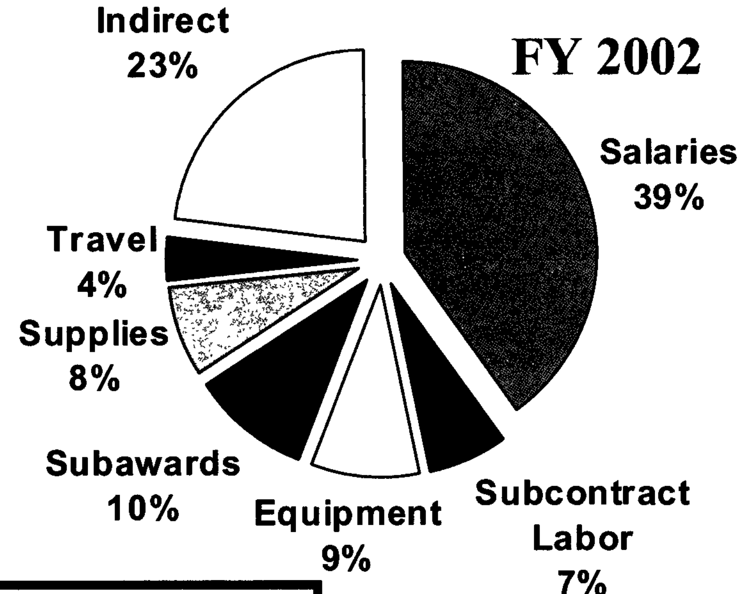
Proposal Budget by Cost Category



Proposal Budget by Category (2)

Cost Category	FY 2000 Actual Costs	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Salaries	$7,657,911	11,511,859	11,804,699	11,809,411	12,184,066	12,570,548
Subcontract Labor	$2,499,533	1,963,000	2,027,620	2,094,113	2,162,816	2,233,769
Equipment	$2,162,367	2,569,771	2,604,437	2,923,586	3,110,967	3,158,532
Subawards	$1,846,189	2,859,800	2,931,079	3,002,745	3,073,862	3,149,893
Supplies	$2,052,735	2,239,018	2,272,304	2,035,805	1,983,807	2,035,264
Travel	$908,740	1,044,500	1,062,136	1,023,450	1,054,154	1,085,778
Indirect	$4,368,267	6,649,232	6,812,627	6,950,832	7,161,903	7,375,558
Grand Total	**21,495,742**	**28,837,180**	**29,514,903**	**29,839,943**	**30,731,574**	**31,609,342**





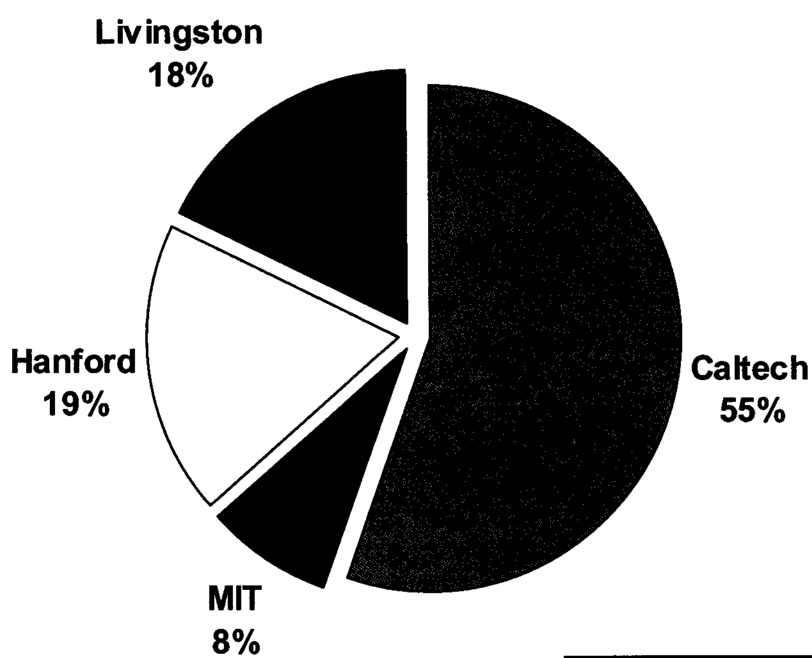
Operations excluding Advanced R&D

Proposal Budget by Location

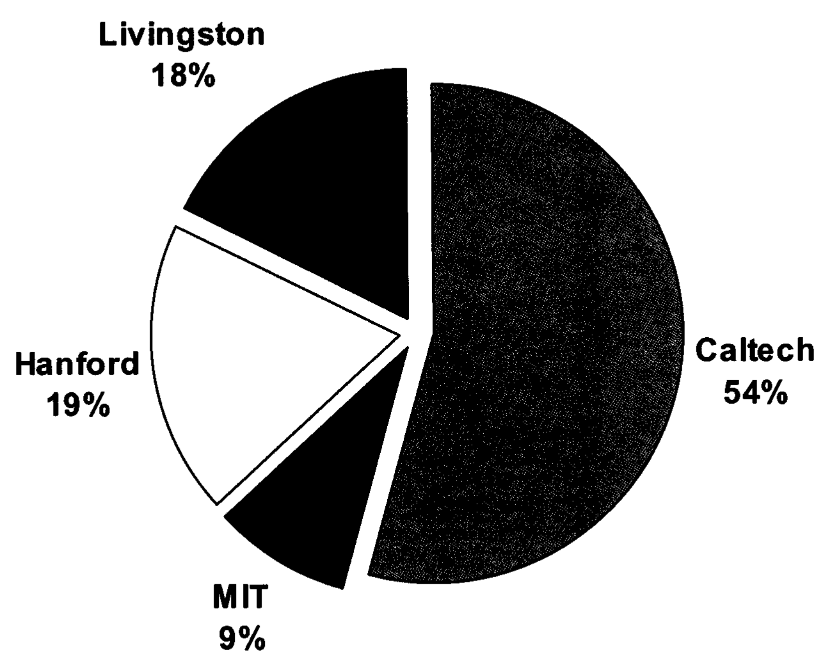
	FY 2002 ($M)	FY 2003 ($M)	FY 2004 ($M)	FY 2005 ($M)	FY 2006 ($M)	Total ($M)
Caltech	21.21	22.14	21.47	18.90	19.44	102.23
MIT	3.02	3.11	3.20	3.30	3.39	16.01
Hanford	5.57	5.72	5.87	6.04	6.21	29.42
Livingston	5.11	5.24	5.38	5.54	5.70	26.97
Total	34.91	36.21	35.93	33.77	34.74	175.57

Proposal Budget by Location

FY 2000 actual costs



FY 2002 proposal budget



Excludes Advanced R&D

Proposal Budget Summary for Caltech

1.1	Director's Office	1.33	2.23	2.30	2.37	2.44	2.51
1.2	Business Office	1.76	1.60	1.65	1.70	1.75	1.80
1.3	Technical and Engineering Supt	2.15	2.79	2.88	2.96	3.05	3.14
1.4	Detector Support	2.86	2.22	2.29	2.36	2.43	2.50
1.5	Data and Computing	2.74	5.50	5.62	5.71	5.91	6.06
1.6	40-Meter Facility	0.92	0.74	0.76	0.77	0.79	0.80
1.7	Seismic Facility	0.12	0.51	0.43			
	Subtotal	11.87	15.60	15.92	15.87	16.37	16.83
0.	LSC R&D Support		3.30	3.84	3.14		
A.	Advanced R&D	(est.) 1.87	2.31	2.39	2.46	2.53	2.61
	Total	**13.74**	**21.21**	**22.15**	**21.47**	**18.90**	**19.44**

Balancing Administrative Activities Across Sites

<u>Advantages for administrative functions at Caltech</u>

- Large number of administrative functions provided as part of the Caltech infrastructure
- Efficiency of scale (no duplications at the sites)
- Close interaction required with Caltech-provided support functions

<u>Advantages for administrative functions at sites</u>

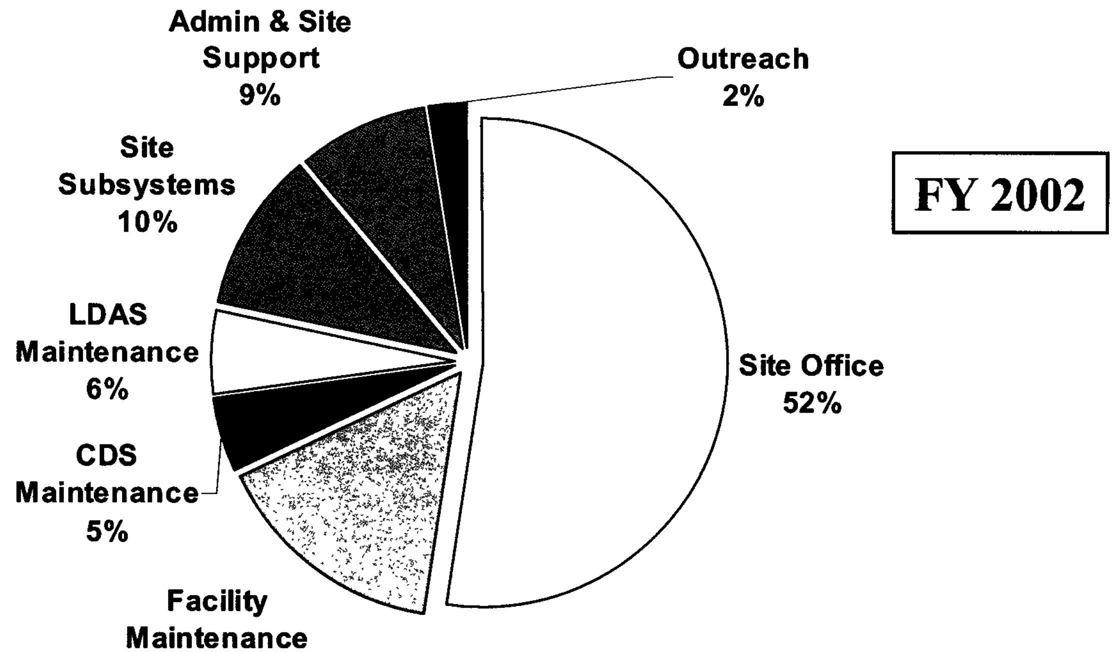
- Reduced overhead
- Provides a measure of autonomy for site operations
  - » Caltech has issued purchasing cards for use at sites
  - » Petty cash checking accounts have been established
  - » Blanket purchase orders have been established for supplies and temporary labor

Administrative Activities at CIT

- Procurement, subcontracts management
- Accounts Payable, Invoice Processing
- Account and Cost Reporting
- Project Financial Reporting and Data Audit
- Property Management
- Human Resources
- Payroll and Benefits
- Legal
- Travel
- Document Control Center
- Safety
- Web Development

Proposal Budget Summary for Hanford

WBS Group	FY 2000 Actual Costs	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Site Office	2,066,265	2,912,987	3,000,376	3,090,387	3,183,099	3,278,592
Facility Maintenance	652,085	864,840	890,785	917,509	945,034	973,385
CDS Maintenance		281,900	276,967	285,276	293,834	302,649
LDAS Maintenance		314,218	314,218	307,531	304,638	304,638
Site Subsystems	468,071	574,130	591,354	609,095	627,367	646,188
Admin & Site Support	797,700	491,400	506,142	521,326	536,966	553,075
Outreach	34,817	134,831	138,875	143,041	147,332	151,753
	4,018,938	**5,574,305**	**5,718,718**	**5,874,165**	**6,038,271**	**6,210,280**



Lower Level Budgets at Hanford

WBS Group	Cost Category	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Hanford						
Site Office						
	Salaries	2,081,275	2,143,713	2,208,025	2,274,265	2,342,493
	Equipment	150,000	154,500	159,135	163,909	168,826
	Subawards	10,000	10,300	10,609	10,927	11,255
	Supplies	3,000	3,090	3,183	3,278	3,377
	Travel	80,000	82,400	84,872	87,418	90,041
	Indirect	588,712	606,373	624,564	643,301	662,600
Site Office Total		**2,912,987**	**3,000,376**	**3,090,387**	**3,183,099**	**3,278,592**
Facility Maintenance						
	Equipment	36,000	37,080	38,192	39,338	40,518
	Subawards	552,000	568,560	585,617	603,185	621,281
	Supplies	216,000	222,480	229,154	236,029	243,110
	Indirect	60,840	62,665	64,545	66,482	68,476
Facility Maintenance Total		**864,840**	**890,785**	**917,509**	**945,034**	**973,385**
Hanford Total		**3,777,827**	**3,891,161**	**4,007,896**	**4,128,133**	**4,251,977**

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Proposal Budgets by Location and WBS

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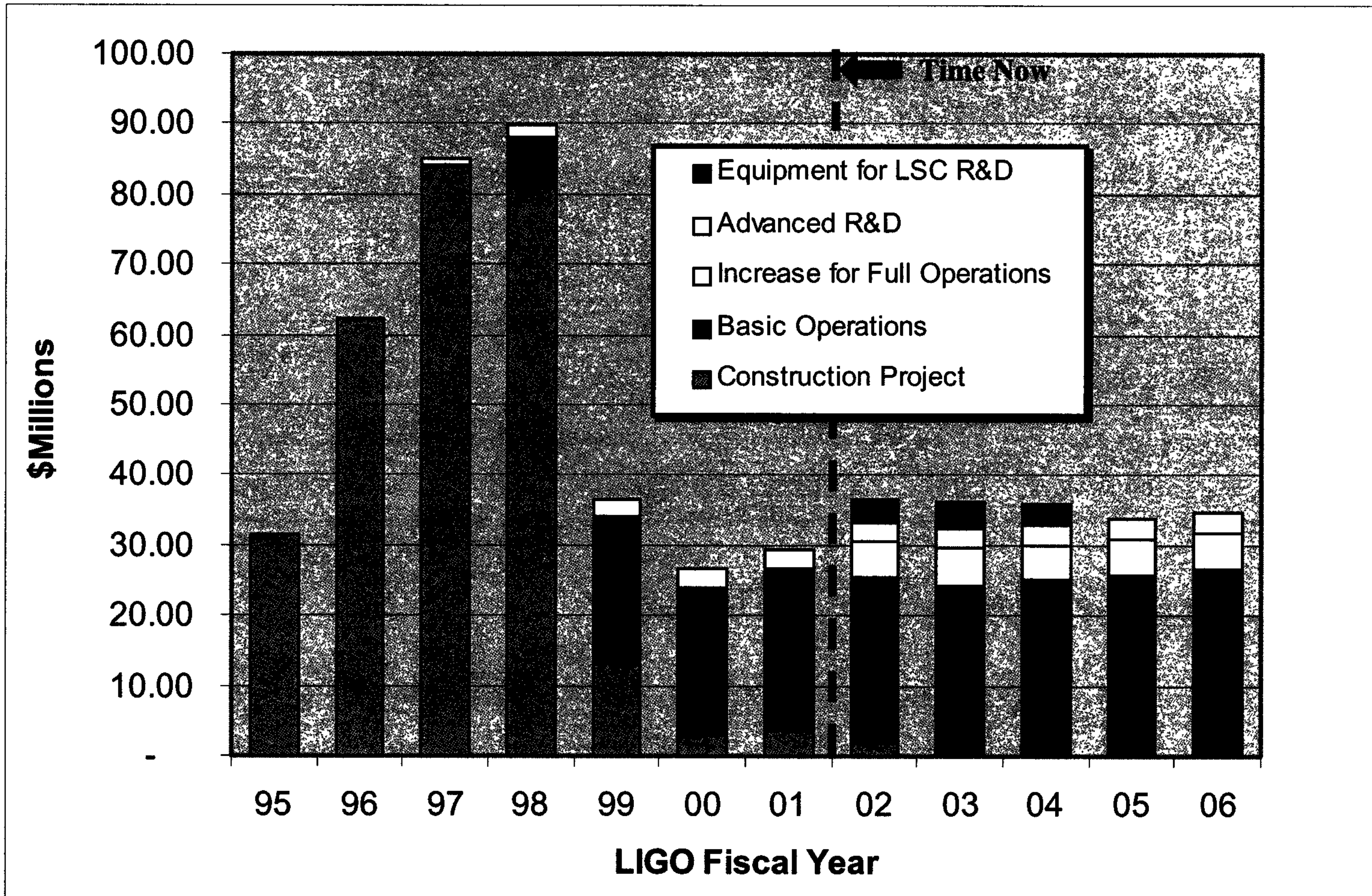
Proposal Budgets by NSF Cost Code

Budget History and Request

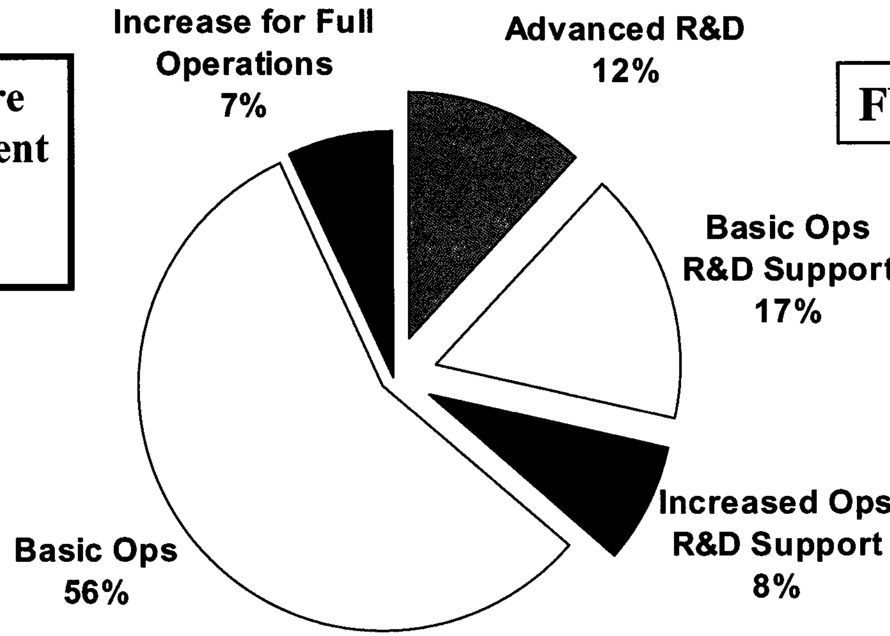


Staffing by Funding Source

Funding Issue	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Advanced R&D	21.8	21.8	21.8	21.8	21.8
Basic Ops R&D Support	30.9	30.9	30.9	30.9	30.9
Increased Ops R&D Support	14.3	14.3	9.8	9.8	9.8
Basic Ops	104.2	104.2	104.2	104.2	104.2
Increase for Full Operations	13.0	13.0	13.0	13.0	13.0
Grand Total	**184.1**	**184.1**	**179.6**	**179.6**	**179.6**

Numbers shown are Full Time Equivalent Employees (FTEs) actually charged

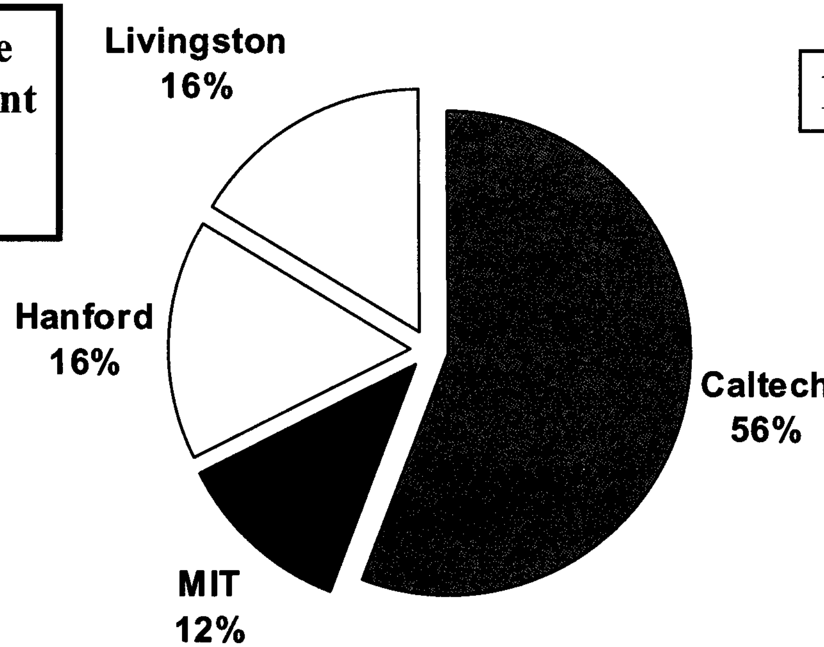
FY 2002



Staffing by Location

Location	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Caltech	102.3	102.3	97.8	97.8	97.8
Hanford	30.0	30.0	30.0	30.0	30.0
Livingston	30.0	30.0	30.0	30.0	30.0
MIT	21.8	21.8	21.8	21.8	21.8
Grand Total	**184.1**	**184.1**	**179.6**	**179.6**	**179.6**

Numbers shown are Full Time Equivalent Employees (FTEs) actually charged

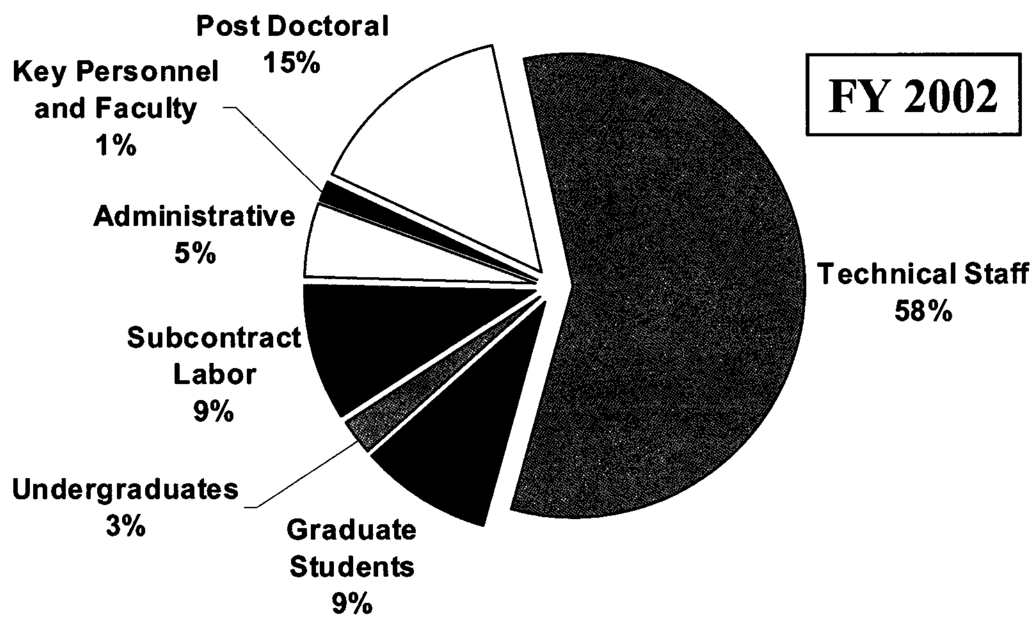


FY 2002

Staffing by Labor Category

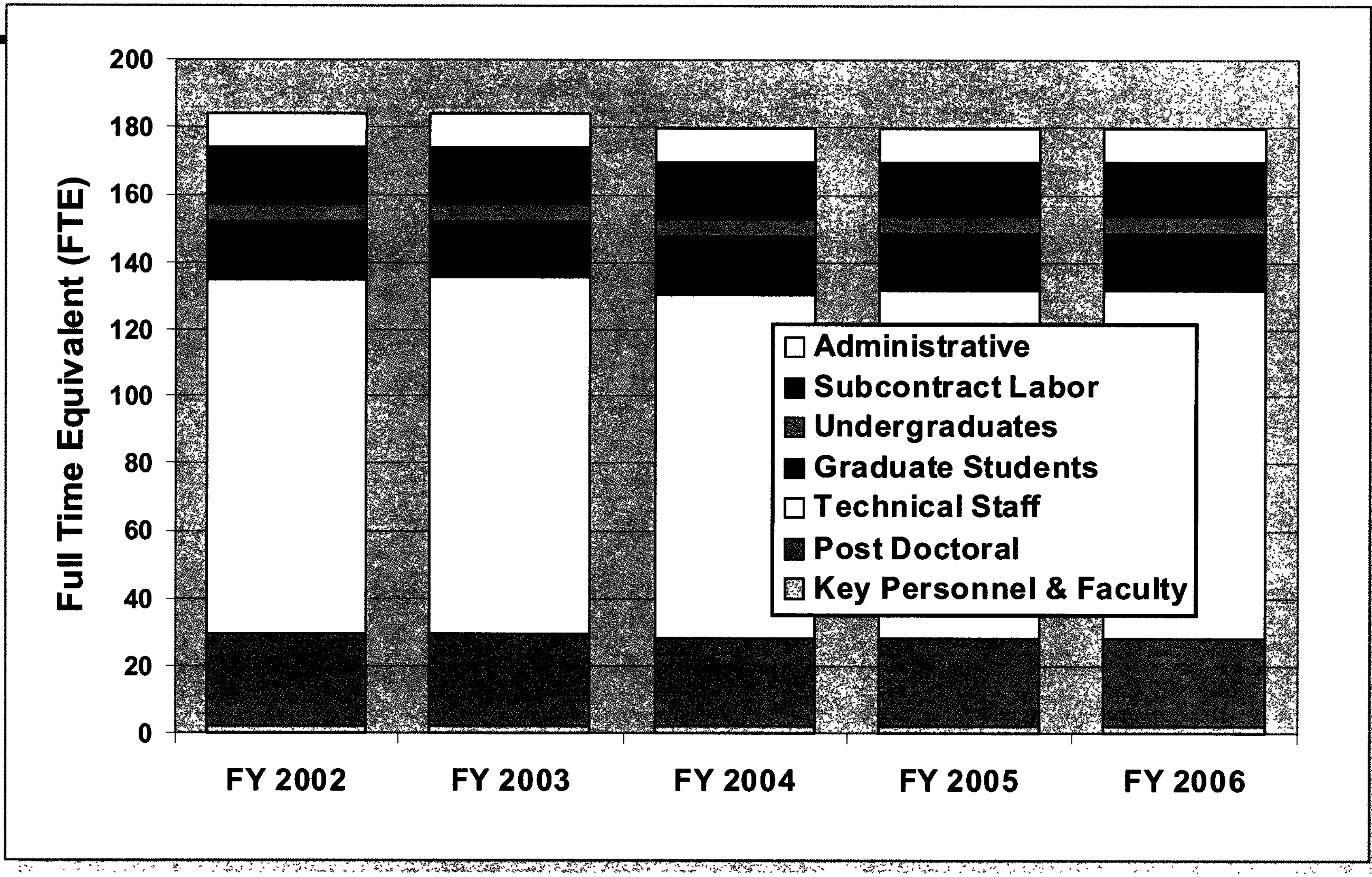
Category	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006
Key Personnel / Faculty	2.6	2.6	2.6	2.6	2.6
Post Doctoral	27.0	27.0	26.0	26.0	26.0
Technical Staff	104.7	105.7	101.7	102.7	102.7
Graduate Students	18.0	17.0	17.5	17.5	17.5
Undergraduate	4.9	4.9	4.9	4.9	4.9
Subcontract Labor	17.0	17.0	17.0	16.0	16.0
Administrative	9.9	9.9	9.9	9.9	9.9
Grand Total	**184.1**	**184.1**	**179.6**	**179.6**	**179.6**

Numbers shown Are Full Time Equivalent Employees (FTEs) actually charged

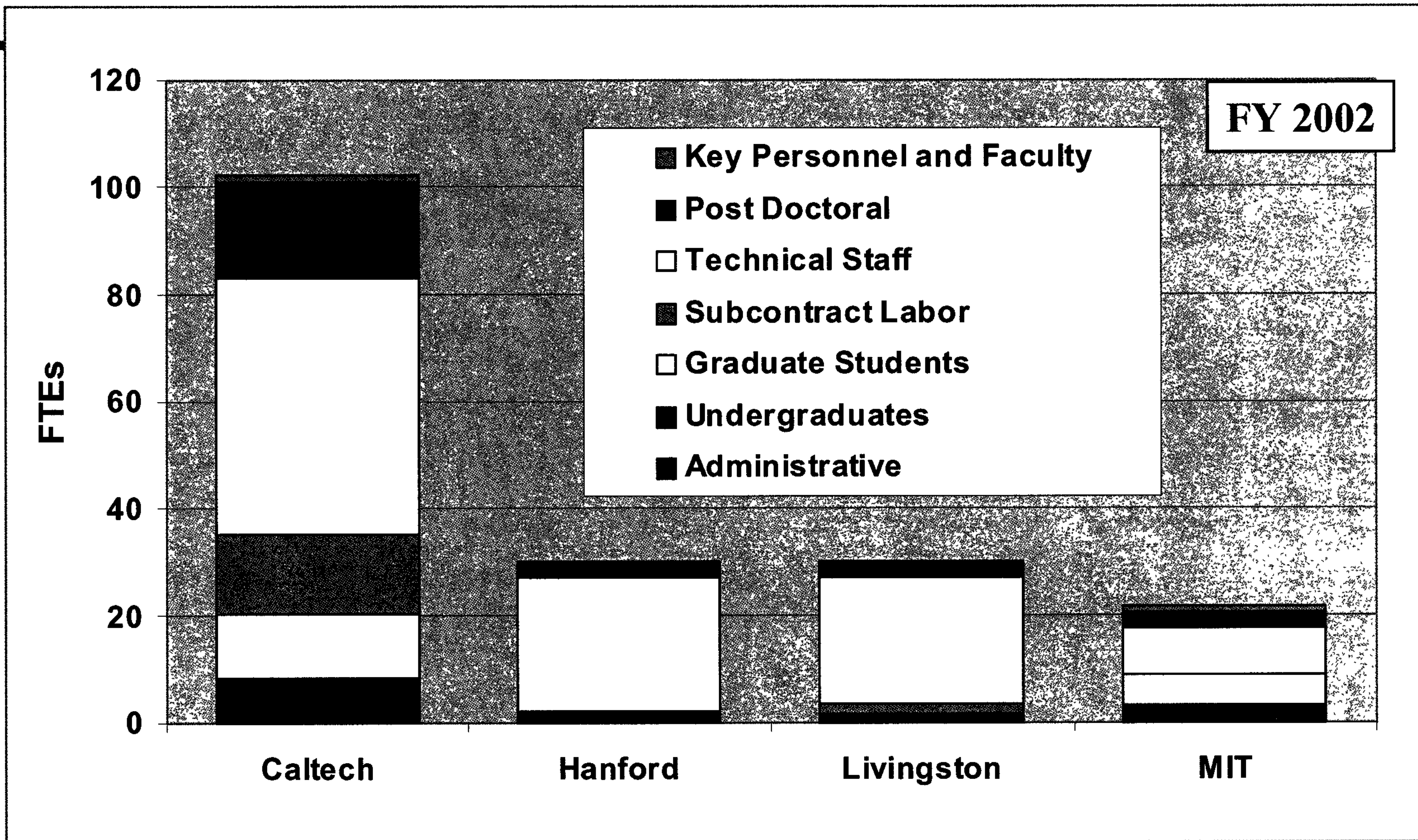


LIGO

Staffing by Fiscal Year



Labor Category by Site



Staffing by WBS - Caltech

WBS	WBS Description	FY 2002 FTEs	FY 2003 FTEs	FY 2004 FTEs	FY 2005 FTEs	FY 2006 FTEs
1.1	Director's Office (DIR)	5.4	5.4	5.4	5.4	5.4
1.2	Business Office (BUS)	11.5	11.5	11.5	11.5	11.5
1.3	Technical and Engineering Support (TEC)	16.8	16.8	16.8	16.8	16.8
1.4	Detector Support (DET)	16.0	16.0	16.0	16.0	16.0
1.5.1	Data Analysis	16.6	16.6	16.6	16.6	16.6
1.5.2	Modeling & Simulation	7.0	7.0	7.0	7.0	7.0
1.5.3	General Computing	4.0	4.0	4.0	4.0	4.0
1.6	Campus Research Facilities (40M)	5.0	5.0	5.0	5.0	5.0
1.7	Seismic Prototype (Livingston)	4.5	4.5			
A.2	Thermal Noise Interferometer (TNI)	2.0	2.0	2.0	2.0	
A.3	Advanced Stabilized Lasers (LAS)				1.0	
A.4	Advanced Core Optics (Including Sapphire)	0.5				
A.6	Advanced ISC (Including Photodetectors)					
A.9	Auxiliary Optics and Thermal Control	2.0				
A.10	Advanced Suspensions and Fibers	2.5	3.0	3.0		
A.11	Low Frequency Noise Suppression	3.0	3.0	3.0	3.0	3.0
A.12	Resonant Sideband Extraction (40M)	3.0	3.0	3.0	3.0	3.0
A.13	Advanced Controls and System Identification	2.0	2.0	2.0	2.0	2.0
A.14	Advanced Input Optics System		2.0	2.0		
A.15	New Advanced R&D CIT			0.5	4.5	7.5
Total		102.3	102.3	97.8	97.8	97.8

AR&D Does not Include LSC Support

Staffing by WBS
Hanford and Livingston

WBS	WBS Description	FY 2002 FTEs	FY 2003 FTEs	FY 2004 FTEs	FY 2005 FTEs	FY 2006 FTEs
Hanford						
2.1	Site Office	29.0	29.0	29.0	29.0	29.0
2.10	Outreach	1.0	1.0	1.0	1.0	1.0
Hanford Total		30.0	30.0	30.0	30.0	30.0
3.1	Site Office	29.0	29.0	29.0	29.0	29.0
3.10	Outreach	1.0	1.0	1.0	1.0	1.0
Livingston Total		30.0	30.0	30.0	30.0	30.0

- 2.10, 3.10 is incremental support for Outreach

LIGO

Staffing by WBS - MIT

WBS	WBS Description	FY 2002 FTEs	FY 2003 FTEs	FY 2004 FTEs	FY 2005 FTEs	FY 2006 FTEs
4.1	MIT Project Office	1.3	1.3	1.3	1.3	1.3
4.2	MIT Business Office	1.0	1.0	1.0	1.0	1.0
4.3	MIT LSC Support	1.3	1.3	1.3	1.3	1.3
4.4	MIT Detector Support	7.5	7.5	7.5	7.5	7.5
4.5	MIT Data Analysis & Computing	4.5	4.5	4.5	4.5	4.5
A.1	MIT Stochastic Noise R&D	4.3	4.3	4.3	4.3	
A.6	Advanced ISC (Including Photodetectors)	1.0	1.0	1.0		
A.9	Auxiliary Optics and Thermal Control	1.0	1.0	1.0		
A.16	New Advanced R&D MIT				2.0	6.3
Total		**21.8**	**21.8**	**21.8**	**21.8**	**21.8**

FTEs do not reflect support provided by LIGO Scientific Collaboration.

Schedule and Milestones

- Schedules and Milestones will be discussed in the subsequent presentations
- The only remaining NSF milestone for the Construction Project is "Begin Coincidence Tests"
  - » Project Management Plan – 12/00
  - » Current Projection – 03/01
- Level of Effort for Operations – remaining milestones include (*see D. Coyne's presentation*):
  - » Initiate LIGO Science Run –2002
  - » Complete Initial LIGO Science Run –2006
- Directed R&D tasks will be matrixed into any future Construction (MRE) schedule.

LSC Data Analysis White Paper
Draft IV

Bruce Allen, Sam Finn, Tom Prince, Keith Riles, Rainer Weiss

October 30, 1999

Contents

1 Executive Summary

The LSC Data Analysis White Paper provides an overview of the data analysis program planned for the LIGO I data runs and outlines a baseline strategy for the future. The White Paper will be updated yearly as the results of the research become available.

The scientific program of the LSC is to test relativistic gravitation and to open the field of gravitational wave astrophysics. The initial effort is designed to understand the detector and execute searches for astrophysical sources of all types: impulsive, periodic and a stochastic background. The analysis is designed to make detections as well as to set upper limits.

The analysis program has the basic components:

- calculation of parametrized source waveforms from the astrophysics
- characterization of the detector: calibration, sensitivity to the environment
- estimation of the detector noise
- design of optimal filters and efficient detection algorithms
- modeling of the detector and the source to establish detection efficiency and errors
- generation of triggers and vetoes from ancillary and environmental measurements
- tests for confidence using multiple LIGO (and worldwide) detector coincidence

The data analysis will be carried out by collaborating groups within the LSC that propose to take on specific scientific projects. A communal LSC software development and test program will be organized and guided by the LSC Software Coordinator. The LSC Spokesperson will work with the LSC Data Analysis Committee composed of the Laboratory Directorate, the Software Coordinator and the LSC committee chairs to organize the data analysis program.

The large quantity of data collected by the LIGO detector, defined as all three interferometers and the ancillary instrument and environmental channels, needs to be reduced to intellectually manageable levels. A function of the LSC is is to design useful reduced data sets for various scientific and technical purposes. One classification of reduced data sets is described in the White Paper.

The LSC Software development is being carried out at many of the collaborating institutions. The ability for software generated by different groups to be compatible rests on setting guidelines as described in the LIGO/LSC Specification and Style Guide which establishes software structure and testing standards. A LIGO/LSC Analysis Library is being developed which consists of both elemental and more complex modules to be used in the analysis. The library and tests of its programs are maintained and organized by the LSC Software Coordinator.

The overall data analysis pipelines will be tested in "Mock-Data Challenges" carried out by teams of LSC members organized by the LSC Software Coordinator. The "Mock-Data Challenges" are coordinated with major releases of LIGO Data Analysis System (LDAS) and LSC software.

The LIGO Laboratory plan for computational infra-structure and network utilization assumes

- on-line and real time analysis will take place at the Hanford and Livingston sites.
- sufficient computing capability exists at the sites to carry out impulsive searches to establish triggers.
- the major tape archive will be at Caltech which supports a limited number of external users
- reduced data sets will be directly available by network to remote LSC users
- a user is expected to have a minimum hardware capability.

Advances in the data analysis program for the longer range include

- New detection software and source modeling to improve the sensitivity of the searches and, thereby, the event rate and depth of the search in the universe.
- Software development and hardware changes (evolution) to allow a larger search range of the parameters for inspiral sources and ultimately an unprejudiced all-sky search for periodic sources.
- Utilization of improved blind-search techniques to help in the detection of unmodeled sources.

The anticipated advances in network speed and in storage technology allow contemplation of

- Full transmission of and fast access to the entire LIGO data set.
- The on-line coupling of the world-wide gravitational-wave network.

2 Science Overview

Introduction

The science goals of the LIGO Science Collaboration are:

- to test relativistic gravity, and
- to develop and exploit gravitational wave detection as an astronomical probe, both by itself and in conjunction with other astronomical observations.

Neither of these goals can be accomplished without a major effort to understand the detectors.

In planning for LIGO I data analysis, we assume that

1. there are no known gravitational wave sources whose "best-guess" rates and strengths are sufficiently large that we can be sure of detections during the first several years of LIGO operation;
2. there are great uncertainties associated with either or both the rates and strengths of all conjectured sources;
3. LIGO, GEO and VIRGO will extend our sensitivity to gravitational wave sources in a new frequency regime by two to three decades in amplitude and bandwidth.

Consequently, the LIGO I data analysis strategy is opportunistic, emphasizing breadth over depth (*i.e.,* range of "covered" sources over in-depth focus on a single source). Particular attention is paid to the detection of serendipitous sources (*i.e.,* sources entirely unanticipated). Recognizing current theoretical prejudice, the data analysis approach is capable of placing upper limits on signal strengths or rates in the event of non-detection; however, it is also sufficiently flexible to recognize and permit the characterization of strong, serendipitous signals.

Testing Relativity

The existence of gravitational radiation is not a unique property of general relativity; nevertheless, general relativity makes several unambiguous predictions about the character of gravitational radiation, which can be tested by observations with LIGO and other gravitational wave detectors providing there are high signal to noise detections.

Black holes and strong-field gravity. The radiation associated with the violent formation of a black hole reflects the detailed nature of strong-field gravity. In general relativity, the late-time radiation is a superposition of several damped normal modes, whose frequency and damping constants are determined entirely by the final black hole's mass and spin. Observation of any single overtone gives, in the context of general relativity, a measurement of the black hole mass and spin. Observation of a pair or more overtones must yield the same masses and spins: any inconsistency is evidence of non-Einsteinian strong-field gravity.

Spin character of the radiation field. General relativity makes a specific prediction for the polarizations of the gravitational wave field. LIGO can detect this polarization as well as components associated with other relativistic theories of gravity (scalar, vector, non-metric tensor). By using the radiation from long-lived (*e.g.*, CW) sources it is possible to distinguish between different polarization components and thereby set limits on alternate gravitational theories.

Gravitational wave propagation speed. In general relativity gravitational radiation travels at the speed of light. The measurement of burst gravitational-wave sources associated with distant astronomical events (*e.g.*, supernovae or gamma-ray bursts) also observed by electromagnetic channels can be exploited to limit a difference between the actual propagation speed and the speed of light. (This can also be characterized as a measurement of the mass of the graviton.)

Gravitational Wave Astronomy

The gravitational-wave "sky" is entirely unexplored. Since many prospective gravitational wave sources have no corresponding electromagnetic signature (*e.g.*, black hole interactions), there are good reasons to believe that the gravitational-wave sky will be substantially different from the electromagnetic one. Mapping the gravitational-wave sky will provide an understanding of the universe in a way that electromagnetic observations cannot. Being a new field of astrophysics it is quite likely that gravitational wave observations will uncover new classes of sources not anticipated in our current thinking, hence data analysis strategies need to be broad based and flexible.

Discrete gravitational wave signals detectable by LIGO will most likely involve stellar mass compact objects undergoing relativistic motion. Observed gravitational wave signals can tell us about the characteristics of underlying sources while their statistics can tell us about the broader character of the source population and can be used as markers for cosmological measurements.

Some gravitational-wave signals will be accompanied by a electromagnetic, neutrino or cosmic ray signal. For example, core-collapse supernovae are strong electromagnetic and neutrino sources. Still other electromagnetic sources *may* have a substantial gravitational radiation component: examples include pulsars, quasi-periodic oscillators and low-mass x-ray binaries, nascent neutron stars in the year following their birth in a supernova explosion, and gamma-ray bursts. For these sources, multi-channel (electromagnetic, neutrino, particle and gravitational) observations of the signals will provide important information regarding the physics of the underlying sources and, in some cases, may be the only way to differentiate between different source models.

LSC analysis goals are organized by source:

Compact binary inspiral: to measure or place an upper limit on the rate of compact binary inspiral, and to characterize the source of detected binary inspiral radiation. With strong signals to test strong field dynamics and, if neutron stars, to study the supernuclear equation of state of the matter comprising the star.

Gravitational waves and gamma-ray bursts: to measure or set limits on the in-band gravitational wave power associated with gamma-ray bursts.

Black hole formation: to observe stellar mass black hole formation, or set limits on its rate as a function of the black hole mass and energy radiated gravitationally. If the radiation associated with the formation of a black hole is observed, the black hole mass and angular momentum will be quantified and, to the extent possible, general relativistic predictions tested.

Supernovae: to observe the gravitational radiation arising from core-collapse supernovae or place upper limits on the gravitational-wave power radiated in-band. For sufficiently strong signals, an analysis goal is to provide early-warning to astronomical observatories, allowing those observatories to capture the early part of the supernova light curve. Should radiation from core-collapse supernovae be observed, it will be used together with neutrino observations to test theories of supernova dynamics.

Nascent neutron stars: to search for neutron stars formed in supernovae. The stars are born rapidly rotating and may have a gravitational-radiation driven instability that carries away the bulk of the angular momentum during the first year following birth. The greatest contribution to the S/N occurs in the last several weeks before cooling of the neutron star damps-out the instability. An LSC analysis goal is to be prepared to search for this radiation, testing this conjecture and possibly characterizing the evolution of the supernova remnant.

General gravitational wave bursts: to search for bursts whose source or detailed character (*i.e.,* waveform) is not known in advance. Such bursts might arise during compact binary coalescence (following inspiral but before the black hole ringdown), during "optically silent" stellar core collapse (failed supernovae); however, other, unimagined sources might also be responsible for observable bursts. The analysis of the data from multiple detectors is essential for this type of investigation.

Pulsars and rapidly rotating neutron stars: to observe or set limits on the power radiated by known, young pulsars and by previously unidentified rapidly rotating neutron stars at certain, fixed locations in the sky. Should gravitational radiation associated with a pulsar be observed, it will be used to determine the ellipticity of the neutron star and characterize the stress supported by its crust. A longer range goal is to develop the techniques to observe or set limits on the power radiated by unknown rapidly rotating neutron stars throughout the sky, the so called unprejudiced search for periodic sources.

QPOs and LMXBs: to search for gravitational wave power radiated by certain quasi-periodic oscillators and low-mass x-ray binary systems, either bounding or setting upper limits on the radiated power.

Stochastic Signals: to search for the presence of a cosmological stochastic gravitational wave signal, either bounding or setting an upper limit on the in-band signal power.

3 Detector Characterization

Introduction

Data analysis requires a systematic understanding and characterization of the detector: its response function, noise behavior and sensitivity to the environment. The confidence associated with source detection or upper limits for detection depend on detector performance characteristics, including: power spectra, the probability distribution of the detector output, stationarity of the noise and the statistics of transients. Detector characterization is also critical to improving the detector's performance and in designing new detectors.

Detector characterization involves both invasive (*e.g.*, stimulus-response) and passive (*e.g.*, monitoring) techniques and is carried out at several levels. The Global Diagnostic System (GDS) is closest to the detector monitoring all data channels online and before archiving. GDS will establish rudimentary performance diagnostics and will have the unique ability to stimulate the detector and measure its transfer functions between different input and output ports.

The second level is represented by the Data Monitor Tool (DMT) which operates off-line and monitors the detector and environmental sensors in real-time using dedicated workstations at the observatories. The DMT's primary function is to update the LIGO meta-database with information on interferometer performance and identified instrumental/environmental transients. Selected transient types (triggers) will also cause alarm messages to be sent to the control room. It should be noted that many offline monitoring tasks are expected to migrate upstream to online diagnostics, as experience and confidence in the algorithms increase. The DMT is also likely to provide the first level of data reduction.

The third level is offline monitoring which includes detailed performance characterization, transient analysis and statistics and trend analysis. An associated activity is instrument and noise modeling in which an end to end model of the detector, built up from its various sub systems, is driven with both astrophysical signals and the observed noise. This is one of the principal tools to carry out Monte Carlo calculations of the system to establish the confidence of a detection.

Detector characterization will be carried out mainly at the observatories, using the full data set. The algorithm development and testing will take place at many locations in the collaboration. In addition, it may be necessary to carry out more refined characterization in periodic "reruns" over the archived, reduced data at Caltech, and it will be useful to carry out limited detector characterization at LSC member's institutions, using customized reduced data sets. It is important that all LSC groups have a means of receiving these reduced data sets, a requirement that affects data storage formats and network bandwidths, as described in the chapter below on the Usage Model.

Online Diagnostics / Environmental Monitoring

Online diagnostics allow a rapid measure of data quality and verification of the instrument's current state, information that can be fed back to the control room and recorded for later use in offline analysis. In addition, diagnostics include invasive measurements, such as applying known waveforms at different inputs to the interferometers (*e.g.*, swept-sine transfer functions) and changing the state of the interferometers (*e.g.*, measurement of optical loss in arms via single-arm-lock

Detector Characterization
Summary of task categories, priorities & active institutions

Task Category	Priority	Institutions
Online Diagnostics & Measurements	1, 3	CIT LSU MIT Mich
Offline Monitoring Infrastr.	1	CIT
Environ. Monitoring (hardware)	1, 2, R	CIT LSU MIT LaTech Oreg PSU
Line Noise Identification	1	AEI ANU Dublin Flor LSU Mich PSU Wisc
Instrumental Correlations	1	Dublin PSU Wisc
Enviromental Correlations	1, R	LSU LaTech Oreg PSU Syr
IFO State Summaries	1, 2, 3	ANU CIT LSU Flor Mich PSU Wisc
IFO–IFO Correlations	3	PSU
Transient ID / Analysis (instr.)	1, 2, 3	AEI IUCAA MIT Mich PSU
Transient ID / Analysis (instr.)	2, 3	CIT Oreg
Time / Frequency Analysis	2, 3	CIT Flor
Data Set Reduction	1, 2	Flor Oreg
Phenomenological Modelling	2	MIT PSU
End-To-End Modelling	1, 2	CIT Flor PSU Pisa

Only institutions with firm task commitments shown in summary table
Priority 1 ≡ Needed at start of 2-km commissioning (10/99)
Priority 2 ≡ Needed during 2-km commissioning (5/00)
Priority 1 ≡ Needed by six months before science run (6/01)
Priority R ≡ Research aread for advanced LIGO

A much more detailed version of the table with task breakdowns, estimated FTE-months requirements and the names of individual scientists responsible for the effort can be found at
`http://wwwmhp.physics.lsa.umich.edu/~keithr/lscdc/tasktables.html`

visibility). Most of the initial work in online diagnostics is being carried out as part of instrument installation & commissioning. This work is extensive, requiring low-level software for hardware control (*e.g.*, control of D/A converters via VME reflective memory modules), medium-level software for implementing specific algorithms (*e.g.*, stimulus-response) and high-level software for control and display of diagnostics results.

Offline Performance Characterization

The goal of offline performance characterization is primarily to establish average noise properties of the system, identify correlations between signals and to gain statistics on recurring transient phenomena, especially, those with a small duty cycle. Studies that will be needed include the influence and reduction of narrow spectral peaks in the data such as electrical line contamination (60 Hz & harmonics), suspension fiber violin modes, internal mirror resonances and isolation stack normal modes. A particularly interesting study is the variation of the amplitude and frequency of these narrow features as a means of enhancing their removal from the data. To understand the rms instrument noise, studies of the broad band seismic and thermal noise will be carried out. Techniques need to be developed to identify and remove non-Rayleigh spectral components in the data such as wandering oscillators.

It is also necessary to describe the operating state of the instrument. Examples of such studies include: the operation of the servos (*e.g.*, full/partial/poor lock), linear interchannel correlations (including frequency dependence), and non-linear cross couplings. It is also desirable to provide immediate measures of astrophysical sensitivity, *e.g.*, summary metrics such as strain sensitivity at particular representative frequencies, maximum viewing distance for an inspiral standard "candle", and the rate of single-IFO transients matching astrophysical templates.

The above measurements of stationary or quasi-stationary behavior rely primarily upon analysis tools in the frequency domain,such as: power spectra, band-limited rms, matched filters and principal value decomposition. More general methods will use time-frequency analysis.

Offline Transient Analysis

It is necessary to identify and record transients due purely to the instrument or to its terrestrial environment. Identifying such waveforms prevents possible confusion with astrophysical burst sources, but more important, allows for correction of the data and may provide diagnosis of curable problems.

Examples of anticipated transients include a large variety of instrumental and environmental impulses such as: suspension wire relaxation, dust particles dropping through the beam, flickering optical modes, ringdown of violin modes after lock acquisition, onset of servo instability or of out-of-band line excitation, onset of analog or digital saturation in the controls system, data acquisition malfunctions, lightning and wind gusts. Some of these may be recognized immediately in the dark port signal. Others require correlation with one or more instrumental or environmental channels. Detection methods for transients include sudden increases in band-limited RMS, matched filters, threshold triggers on time-domain or frequency-domain amplitude and more general time-frequency analysis (*e.g.*, wavelet analysis). As experience with the interferometers grows, it should be possible to classify the vast majority of the transients via an event catalog.

Data Set Simulation

Simulation includes both near-term phenomenological modeling to test monitoring algorithms and far-term *a priori* Monte Carlo modeling for comparison with actual instrument response. The former includes modeling of random noise, lines (*e.g.*, violin modes) and other parameterized waveforms and allows superposition of these waveforms. The latter falls under the heading of the ongoing LIGO End-to-End modeling and attempts a bottoms-up model of full interferometer response in the time or frequency domain. The End-to-End Model is meant to simulate LIGO optics, servo control loops, suspensions, ambient environmental noise, time delays, misalignments, thermal lensing, and other effects. It includes a user-friendly graphical user interface and data visualization tools. One of the functions of the end to end model will be to test the recovery of astrophysical waveforms injected into the simulated data stream.

4 Astrophysical Source Detection

Overview

Each type of astrophysical search will have a data analysis pipeline, whose input is data and diagnostic information from the detector(s), and whose output is a list of potential source candidates. Each stage of the pipeline makes cuts and selections, passing smaller amounts of data to the next stage. Some of the events which pass the cuts and selections will also be recorded in a 'metadata' database .

The different data analysis pipelines will have many common elements, particularly at the input end, where measures of data quality and detector performance are most important. The later stages contain more specialized discriminators, which make cuts and selections based on how well the signals match the posited sources. The design and characterization of these filter pipelines and discriminators is an optimization problem (for example minimizing false dismissal rates for a given false alarm rate). This will be done using Monte Carlo simulations on a mixture of real and simulated data.

In general, the most effective means of gaining detection confidence is the observation of a signal in two or more independent detectors. While the beam patterns, polarization sensitivities, and frequency response of the non-LIGO detectors differ significantly, the LSC hopes to work with them to gain increased confidence and sensitivity.

The near-term program in source detection is divided into four main categories: inspiral, uncharacterized, CW, and stochastic background. The goal is to have basic searches in place and working when the instruments reach a 10^{-20} strain sensitivity in November 2000. The CW and stochastic background searches will be carried out offsite; the other two searches will be distributed between onsite and offsite. During the following year, while the instrument sensitivity reaches the design goal of 10^{-21}, the focus will be on testing, characterizing, and improving the methods.

This program is summarized in a set of four tables, which prioritize the necessary work and divide it into tasks. One or more research groups will work on each task. In each case, one group will be identified as having the ultimate responsibility to ensure that the task is completed on schedule, and to coordinate other groups participating in the development. The organization indicated in the tables is not designed or intended to be exclusive, new members are welcome to join any of the working groups.

The development and implementation work will be carried out at the individual LSC sites, using the resources available at those sites. When the development has reached the stage where it needs to be run on CACR/LIGO hardware, the group will, through the LSC, obtain access to the necessary resources for development, testing, and production.

Inspiral/Merger/Ringdown Signals

Coalescing binary systems can produce both known and unknown waveforms. The parts of the waveform arising from the merger phase cannot presently be calculated; techniques to search for these signals are described in the section on unmodeled sources. Matched filters may be used for the known waveforms, including:

- Inspiral of systems with masses of a few $M_\odot$ (visible in the sensitive band below $\sim$ 300 Hz for $\sim$ 90 sec).
- The characteristic ring-down after formation of a black hole horizon (exponentially damped sinusoids with $2 \lesssim Q \lesssim 10$.) Since such waveforms could also be produced by other sources such as stellar core collapse, this search must be independent of the inspiral one.

Filtering methods to search for the inspiral and ringdown signals at a single site are well understood: searches of this sort have already been carried out on data from prototype instruments, so the work required is primarily development. For a reasonable range of masses the search can be carried out on-line. The plan is shown in

Templates for the expected gravitational waveforms are the main theoretical input to the inspiral and ringdown detection process. The literature contains time-domain template approximations that are sufficiently accurate for detection work,

Inspiral Source Searches

	Hierarchical	Coincident Event List	Discriminator	Combined Inspiral, Merger, Ringdown	Noise Power Spectrum Changes	Multi-Detector Analysis	Template Generation and Bank	Temples Generation nonzero eccentricity	Template Generation nonzero precession
Priority	1	1	1	2	2	1	1		
FTE (Code+Test)	6+3	2+2	1+4	1+1	2+3	3+4	2+2		
FTE (Science)		2		2	1				
AEI						I			
Cardiff	I	I					L		
Penn State	I					L	I		
TAMA	I								
UWM	L	I					I		

Table 1: Tasks and group assignments for inspiral source searches. FTE's are shown in person-months. L=lead group, I=interested group.

Priority 1 tasks are essential and must be completed by November 2000.

Priority 2 tasks are useful, and should be completed by November 2001.

but potentially better methods of approximation have been proposed. The efficiency with which templates can be computed determines whether templates are computed once and used many times, or computed as needed. Efficient means of computing the templates can greatly reduce the computational demands of this search technique. These require development.

Templates vary significantly depending on the source characteristics (for example, binary masses, spins, and orbital eccentricity); consequently, the detector output must be correlated against many templates to detect a signal. Template spacing in parameter space depends on the detector's performance: templates and their spacing will need to be recomputed if the detector noise power spectrum changes shape significantly during the time-scale of the data segments being filtered. Practical ways of determining when this is necessary, and of re-locating the templates, need to be developed.

Hierarchical searches should be the most computationally efficient means of filtering the detector data through the bank of filters. The first pass uses a large, coarsely spaced grid of filters, identifying segments of data passing a low SNR threshold. A second pass uses a smaller, finely spaced grid of filters near the region of interest, and a higher SNR threshold. Studies assume that the detector noise is Gaussian, derive optimal values for the two thresholds, and predict computational gains in the range from 5 to 30 compared to a one-pass filtering scheme. A flexible implementation of this method and the experimental determination of optimal thresholds for real instrument noise are now needed. Additional study of correlations between nearby filters, and of methods of constructing robust rather than optimal filter banks would be useful.

Discriminators are statistical tools which help distinguish between large filter outputs arising from instrument artifacts and those arising from potential gravitational wave sources. In this way they reduce the sizes of final event lists. Specialized χ^2 statistics developed for analysis of interferometric data and for resonant mass detectors have proved useful in reducing false alarm rates. Discriminators which see if the postulated waveform is consistent with the frequency and time distribution of a signal in a given filter and with the registration of the signal across the filter bank need further development and characterization.

Coincident event lists are produced by (automatically) comparing event lists produced by a filtering process at different sites , and selecting those which match certain criteria. These include arrival time differences less than the light travel time, best fit source parameter differences smaller than some threshold, SNR ratios within certain bounds, and so on. While somewhat less sensitive than optimal filtering (or maximum likelihood analysis) of all signal streams simultaneously, it yields greater confidence. The criteria for combining and comparing these event lists still need to be determined.

Combined searches use output from different filter banks or lists of metadata to look for signals coming from all three stages (inspiral, blind search, ringdown) of binary coalescence. This can be done at either the single or multidetector level. The tools for such a search need to be developed.

The final stage in a search will probably be the use of multidetector statistics from a 2- or N-detector data stream to estimate the likelihood that a source is present. The scientific work on these methods is complete, and only implementation work remains.

Establishing detection confidence.

Methods of establishing confidence include the detection of the ringdown associated with black hole formation juxtaposed after an inspiral waveform, and simultaneous observation of the signal in two or more detectors but not in the various environmental and instrument monitoring channels. Unfortunately there is only a small range of masses for which both the inspiral and ringdown signals can be observed with significant SNRs. It may also be possible to observe the harmonic structure (overtones) of these signals of black hole formation. Establishing confidence for ringdown signals will require a thorough understanding of the instrument, since such signals can easily arise from from electrical and mechanical control loops.

Upper limits.

The effective volume of space surveyed for binary inspiral by LIGO varies as the $5/2$ power of the system mass up to a mass of approximately 25 $M_{\odot}$. For NS/NS binaries, the volume corresponds to a sphere of $\approx$ 15 Mpc radius which includes the Virgo cluster of galaxies. Better modeling of this dependence of source number as a function of radius in our cosmological neighborhood for $R \lesssim 50$ Mpc is required. Once an analysis pipeline is operating, it can be thoroughly characterized using Monte Carlo simulations. In this way the most efficient operating point can be determined for setting upper limits on the rate.

Unmodeled Sources

There are many sources for which waveforms are not calculated, including supernovae, and the merger phase of binary coalescence. Since sources for which waveforms *are* accurately predicted probably do not have rates/amplitudes large enough to see with LIGO I, a substantial effort to search for sources with generic characteristics is desirable. Here, matched filtering cannot be used and more general techniques are needed. These methods may also be useful for identifying periods of unusual instrument behavior, and should be carried out on-line. In some cases (for example, supernovae) it is desirable to identify the source location quickly enough to alert electromagnetic observatories, so some analysis must be in real time on-site. The development of real-time N-detector techniques is crucial for this purpose.

In general, knowledge gained from numerical and analytical studies of poorly understood signals such as the neutron star or black hole merger waveform makes it possible to construct more efficient and sensitive search techniques.

It may also be possible to detect unmodeled sources using statistical correlation techniques, for example using gamma ray bursts or other triggers to identify short time windows in which a significant gravitational wave flux may be present. These correlation techniques require further development. They are low bandwidth but will be carried out offline due to the need for external astrophysical trigger data. The near term program for detection of unmodeled sources is shown in Table 2.

Pulse matching techniques use a bank of filters designed to look for generic pulses with $\lesssim 20$ cycles. Typically the set of filters consists of a Gaussian and (say 20) derivatives of it, similar to a wavelet analysis Since the time-scale is not known, Gaussian pulses of different widths are required. The techniques used to generate banks of optimal filters can be applied here to construct an efficient bank of such filters. Time domain thresholding is a variation of this method, which looks looks for signal amplitudes exceeding a certain threshold in the whitened data stream.

Unmodeled Source Searches

	Time/ Frequency	Power Monitoring	Time Domain Thresholding	Pulse Matching	Two-site Correlation
Priority	1	1	2	1	1
FTE (Code+Test)	3+1	1+1	1+1	2+2	1+1
AEI	I				I
Cardiff	L				
Cornell		L			I
UWM	I	I			
Penn State					L

Table 2: Tasks/group assignments for unmodeled source searches. FTE's shown in person-months. L=lead group, I=interested group.

Priority 1 tasks are essential and must be completed by November 2000.

Priority 2 tasks are useful, and should be completed by November 2001.

Time-frequency methods locate statistically-significant excesses of power in particular frequency bands. The best-studied method was developed to search for line-like features in the T/F plane. This method needs to be ported to the LDAS environment. A related technique uses short FFTs to monitor energy in particular frequency intervals.

Power-monitoring is a variation on this technique, which looks for excess power in the outputs of a set of filters designed to cover specific frequency ranges. A good example is supernovae. Their waveforms can probably never be accurately characterized, since they probably depend sensitively upon initial conditions. Despite this uncertainty, numerical simulations suggest that the radiation power spectrum is a power-law, with $|\tilde{h}(f)|^2 \propto f^{-2}$, between 10 Hz and 1 KHz.

Correlation techniques look for unusual correlations between the outputs of two or more detectors, and correlation between other types of signals, such as gamma-ray and neutrino bursts. They can be applied to event lists generated using the above methods, or to a simultaneous data stream. Special filters could be developed for coincident detection of supernovae and other source types.

Establishing detection confidence

Until environmental and detector noise-burst artifacts are completely understood, the only way of establishing detection confidence for unmodeled signals is through correlation with other detectors (gravitational, neutrino, and electromagnetic) and by veto from the environment and instrument monitoring channels.

Upper limits.

A method for setting upper-limits on in-band signal strength for the trigger population has been developed.

Continuous Wave (CW) and Pulsar Signals

Rapidly rotating neutron stars are the most likely sources of continuous gravitational waves in the observable band. The signal from a CW source will be nearly sinusoidal at twice the rotational frequency of the underlying neutron star (plus weaker harmonic and sub-harmonic components). The signal amplitude from these sources will be sufficiently weak that observations over periods of months or years are required to accumulate enough signal power to detect the source or to set astrophysically interesting upper limits. During this period, the frequency and phase of the detected signal will change due to the diurnal and annual motion of the Earth and also due to evolution of the source. Variations arising from the motion of the Earth depend on the source position on the sky; slow variations arising from source evolution may be observable electromagnetically for some sources.

The computational complexity of a CW signal search varies dramatically depending on the amount of prior knowledge about the source parameters. If the position and intrinsic spin evolution are unknown, the search entails looking through a discretized parameter space with a huge number of mesh points. Since such searches are computer limited, there is a premium on the development of efficient algorithms. When the source position is known (a *directed search*) a search to the limit of instrument sensitivity is possible. For an unprejudiced search, instrument-limited sensitivity requires more computing power than is practical, because the signals are modulated by the earth's motion, and have unknown intrinsic frequency drifts. The near-term program is shown in Table 3.

Directed searches for known phase pulsars may be carried out using folding, in which the time-series is added together with a time shift equal to the period of oscillation. This technique is widely used to search for radio pulsars. Some further development may be required to produce the optimal SNR if the instrumental noise levels are drifting with time. The search in a known direction for **pulsars of unknown phase** is more difficult, but should be feasible if the intrinsic frequency drift of the source is not too large.

Searches for unknown pulsars require substantial computation. Since an all-sky search at the instrumental limit of sensitivity is not currently possible, the goal is to make the most sensitive search constrained by the available computational power. The most efficient known techniques are a two- or three-stage **FFT-based stack-slide or Hough-transform hierarchical** search. The methods have similar

CW Source Searches

	Directed known phase	Data base	FFT stack/slide Hierarchical	Hough Transform Hierarchical	Robust Algorithms	Discriminators	Multiple Detector Analysis
Priority	1	1	1	1	3	1	2
FTE (Code+Test)	2+2	?	6+6			TBD	
FTE (Science)			1		TBD		1
AEI		L		L			
Cardiff			I				
Caltech	L		I				
Michigan	I					L	
Stanford					L		I
UWM			L				

Table 3: Tasks and group assignments for CW (pulsar) source searches. FTE's in person-months. L=lead group, I=interested group.

Priority 1 tasks are essential and must be completed by November 2000.

Priority 2 tasks are useful, and should be completed by November 2001.

Priority 3 tasks are research.

computational efficiency for Gaussian detector noise, but they may have different performance digging signals out from non-Gaussian instrumental noise. These methods share many common features and work is underway to implement both of them within a single code.

Robust algorithms are specialized methods capable of searching for waves from poorly modeled sources (e.g.,accreting x-ray binaries, r-modes in nascent neutron stars). Methods are also needed to search for emission from wobbling neutron stars, where significant energy is present in sidebands of the main "carrier" signal. Searches for pulsars in binary systems should also be possible, but algorithms don't yet exist.

Discrimination techniques will be needed as a way of verifying that signals which are found are gravitational in origin and not instrumental. These techniques should be capable of identifying wandering oscillators, and should also test for amplitude modulation consistent with the time-dependent detector response. These methods do not yet exist.

Multiple interferometer search techniques for both the detection and the confirmation stages of discovery do not yet exist.

Establishing detection confidence.

CW gravitational wave signals will become apparent only after long integration times, so techniques may be needed to discriminate these from instrumental artifacts. These techniques should be capable of identifying wandering oscillators, and should also test for amplitude modulation consistent with the time-dependent detector response.

Stochastic Background Detection

Stochastic backgrounds are signals produced by many weak incoherent sources. They are non-deterministic and can only be characterized statistically. Such signals can arise from early-universe processes (analogous to the electromagnetic CBR) and from present-day phenomena. They give rise to a (probably stationary and Gaussian) signal which is correlated between the two detectors. It will have the same spectrum in each detector, and is differentiated from detector noise by its inter-detector correlation, which depends in a known way on the signal spectrum and the detector separation and orientation. The greatest risk is that similar correlations may be produced by the (electromagnetic) environment.

Stochastic signals are expected to be quite weak compared to the intrinsic noise of an individual LIGO interferometer; consequently, detecting or placing a limit on a stochastic gravitational wave signal will require long observation periods over a bandwidth a few times the inverse light travel time between the interferometers.

Detection of a stochastic background signal requires fairly simple analysis of long stretches of data. This is well-suited to off-line analysis. Two detection techniques have been extensively studied, one based on combining cross-correlations of pairs of detectors, and the other based on a likelihood formed from N-detector data. The near-term program is shown in Table 4.

Stochastic Background Searches

	Correlation Statistic	Robust	Maximum Likelihood	Non Gaussian Sources
Priority	1	1	1	3
FTE (Code+Test)	2+2	1+2	3	
FTE (Science)		3	1	
AEI	I			
Cornell	I	L		
Penn State			L	
UT-Brownsville	L			
UWM	I	I		I

Table 4: Task/group assignments for stochastic-background searches. FTE's in person-months. L=lead group, I=interested group.

Priority 1 tasks are essential and must be completed by November 2000.

Priority 2 tasks are useful, and should be completed by November 2001.

Correlation statistic analysis combines the data streams from pairs of detectors in an optimal fashion and has been shown to perform as expected with Gaussian detector noise. Additional work is needed to design tests to search for similar correlations between environmental channels at the different sites.

Robust correlation statistics. Correlation analysis appears to be badly affected by non-stationary and non-Gaussian detector noise. Recent work indicates that more robust methods which carry out a form of limiting should give about the same performance in the case where the noise is Gaussian, and are optimal or near-optimal in the non-Gaussian case.

Maximum likelihood techniques are an alternative to the correlation statistic analysis. In principle they are the most sensitive search technique, but in practice, if there are many unknown parameters (i.e. the detector's noise spectrum at every frequency) in which to maximize the likelihood function, they may not perform well. Further work is needed to determine the utility of this technique.

Establishing detection confidence.

Since stochastic background detection requires a pair of detectors, finding a signal with two detectors is not enough to establish confidence. Terrestrial effects, particularly correlated electromagnetic noise at the two sites, can mimic a gravitational stochastic background signal. LIGO can place an upper bound on the amplitude of a stochastic gravitational wave signal, but it will be extremely difficult to assert confident detection. This will probably require another baseline. Many tests may prove useful as diagnostics: including correlation between nearby resonant-mass detectors and the LIGO interferometers, studies of the correlation matrix between gravitational strain and electromagnetic signals at the sites and the correlation analysis of the 4km and 2km interferometers at the same site.

5 Data Products: Reduced Data Sets and Artifacts

LIGO will collect data at a rate of 15 MB/s. The planned duty cycle for triple-coincident lock is 50%; correspondingly, we anticipate a minimum of 500 Tbytes of raw data during the first two years of operation. Most of this rate is of ephemeral value: except for immediate use in instrument diagnosis or characterization, few LSC scientists will work with significant quantities of the raw detector data.

As it is collected the LIGO data stream will be reduced in volume in a three stage process. The intermediate data product at each stage will be archived, either as FRAMES or in a relational database. Most analysis activities are expected to access either the end product or one of the intermediate data products through the relational database, either in FRAME or LIGO Lightweight XML format.

Archival and Reduced Data Sets

The LIGO data set is acquired as a collection of several thousand channels at rates up to 16 KHz. Coincident with its acquisition the LIGO data stream will be reduced in volume through through three successive steps. At each stage some channels will be discarded, some will be reduced in resolution (either dynamic range or bandwidth), and others combined into new, summary channels. We identify four data sets, corresponding to the raw data and the product of each stage or data reduction:

Level 0: Full IFO Data Stream. Level 0 data will be available only on-site and in FRAME format for approximately 16 hours after acquisition, during which time it will be processed into the Level 1 data set (see below). Level 0 data will not, except for short epochs recorded for diagnostic purposes, be archived after it is processed into Level 1 data.

Level 1: Archived Reduced Data Set. Level 1 data, which will be maintained in the LIGO data archive, consists of all important IFO and PEM data channels storied in FRAME format, together with regression, whitening, calibration, and instrument state data. Like Level 0 data, Level 1 data will be used principally for detector diagnostic studies. The Level 1 data set will be approximately 10% of the full data stream, corresponding to a minimum of 50 TB of triple-coincidence data during the first two years of operation.

Level 2: IFO Strain plus Data Quality Channels. For more detailed science analyses a further reduced data set containing basic IFO strain data plus a variety of quality channels will be provided. Quality channels will include calibration, whitening, and regression coefficients, as well as the most important auxiliary IFO and PEM channels. The total Level 2 data set will be about 1% of the full data stream, or a minimum of 5 TB of triple coincidence data during the first two years of operation.

Level 3: Whitened GW Strain Data. Level 3 data will consist of the best estimate of the (whitened) GW strain. The reported strain will be as free as possible from instrumental artifacts and reduced to a 500 Hz bandwidth. The Level 3 data set will include all the relevant whitening filter coefficients, regression and calibration information used in its production from the Level 2 data. At a nominal 1 kHz sampling rate, a 2 year, 50% duty cycle data stream from the three interferometers will occupy 200 GB.

Metadata and Event Data

Most LIGO data will be selected for analysis on the basis of some distinguishing characteristic, e.g. coincidence in time with an astrophysical event, period of high seismic activity, or anomalous behavior of a control system. The LDAS system includes a database system for searching and making queries on summary information (called metadata). The following types of information will be available from the database:

Frame Data Information. This includes tables of locations of sets of frames, as well as statistics and spectra derived from sets of frames.

Trigger, Veto, and Instrumental Artifacts. This includes information about the triggers and vetoes generated by Global Diagnostics System (GDS) and Data Monitoring Tool (DMT) filters, including information about the filters themselves. It also includes "astrophysical artifact" triggers, such as those generated by the binary inspiral, ringdown, burst, and periodic source analyses performed by LDAS. Artifacts are considered a particularly interesting form of LIGO data and can be delivered to the user in LIGO Light-Weight format.

Non-LIGO-Generated Event Information. The metadatabase will include information environmental and astrophysical information in addition to those artifacts identified by by LIGO analyses of IFO and PEM data sources. These include seismic alerts from external monitoring networks, electromagnetic storms, -ray burst events, neutrino events, UVOIR (UV, optical, IR) events such as supernovae, and events generated by other GW detectors.

CDS and LDAS Log Information. Information normally kept in logs will be available electronically via the database.

6 LSC Organization of Data Analysis

The obligations that LSC members have made to the data analysis effort and the rights to access of the LIGO I data are defined in the Memoranda of Understanding between the LIGO Laboratory and the LSC member's institution. Broadly, rights to the LIGO I data are gained by making a substantial and recognized contribution to LIGO 1 construction, commissioning and or software development. The LIGO Scientific Collaboration is responsible for the data analysis, validation and scientific interpretation of the LIGO data. The intent is that LSC members will organize group efforts to study specific scientific problems with the LIGO data. The spokesperson of the collaboration will coordinate the data analysis effort. Analysis efforts will be initiated by proposal made to the collaboration by individuals or a group of members or organized by the spokesperson. The proposals will include:

- the scientific problem to be addressed
- the computational and analysis methods to be used
- the logistics to carry out the analysis:
  - an estimate of the laboratory resources required
  - the division of responsibility between the proposers
  - students assigned to the effort and PhD theses expected
  - an estimated schedule for completion
- an outline of the publication(s) that are expected to arise from the analysis

The LSC software development, test and maintenance will be organized by the LSC Software Coordinator. The functions of the Coordinator include:

- define and manage the software development across the LSC
- maintain the LIGO/LSC analysis library
- chair the LSC software change control board

The LSC Spokesperson will work with a committee consisting of the Laboratory Directorate, the LSC committee chairs and the LSC Software Coordinator in evaluating proposals and in receiving advice to guide the LSC data analysis program. Publications resulting from the analysis will be reviewed and authorized by the entire collaboration as described in the LSC Publications Policy.

7 LSC Software Development

Overview

The LSC science analysis pipeline will be implemented from modular components that are validated and controlled as part of the LIGO/LSC Analysis Library

(LLAL). All delivered software will conform to a standard that has been defined jointly by the LIGO Lab and the LSC.[1]

The LSC Software Coordinator has the principal responsibility for defining and managing the LSC software development effort. Verification and validation of LLAL components will take place at three levels: *(i)* compliance to standards, *(ii)* piecewise component tests and *(iii)* integrated tests of the analysis pipeline through Mock-Data Challenges.

The LIGO/LSC Analysis Library

The LLAL configuration is managed by the LSC Software Coordinator, who coordinates regular releases of the LLAL library with and between LDAS releases. Major releases will be scheduled to coincide with major LDAS releases (α-1 in Q2'99, α-2 in Q4'99, β in Q4'00 and V1.0 in Q4'01). These will test LDAS functionality and support the development and testing of analysis pipelines. Intermediate releases will take place quarterly to correct bugs and provide incremental increases in functionality and performance.

All LIGO data analyses involve filtering operations — either linear or nonlinear — on time series consisting of weak signals in the presence of additive noise. These analyses can all be described as compositions of "atomic" operations on a small number of rigidly structured data types. Typical atomic operations include linear algebra and filtering, signal processing methods and descriptive statistics; typical data types are time series, frequency spectra and linear filter transfer functions. LLAL consists of these atomic operations acting on these structured data types.

All LLAL software development will conform to style specified in T990030, which describes coding rules, documentation standards, software diagnostic and test requirements.

We expect that LLAL will evolve and grow with accrued data analysis experience. Changes to LLAL will be authorized by a Change Control Board whose members are appointed by the LSC and the LIGO Lab. Proposed changes will be weighed for relevance, impact on existing systems and resource, and benefits offered.

Software Verification and Validation

Software verification tests the behavior of individual components. LSC component software verification involves documentation, component tests, and run-time diagnostics. Documentation describes in detail what the component is supposed to

[1]LIGO-T9900030.

do, how it is supposed to do it, error conditions and how they are handled, and accuracy requirements or guarantees. Each LLAL software component will include documented test code which tests the component for fault tolerance, accuracy and correctness of implementation as described in the documentation. Finally, each component is required to return at run time a status structure, which reports on the component's current functioning and provides diagnostic information in the event of an error condition. All these components — the documentation, the test suite, and software status reporting and error handling — are the responsibility of the LSC member(s) who supply the software component.

Software Validation test that the software components can be integrated into analysis pipelines that can perform that analyses described in the science goals (§1 of this document) with the requisite speed on the target hardware platform (*i.e.,* the on-site and off-site LIGO Beowulfs).

Software system integration is tested at several levels. The LLAL has a hierarchical, modular design, with increasingly sophisticated analyses built upon a base of more primitive library calls: *e.g.,* power spectrum estimation by Welch's method involves sub-division of a time series into sequential overlapping components, the generation and application of a window function, discrete Fourier transform of the windowed sub-sequence, term-by-term modulus of the DFT results, and summing and normalizing the resulting frequency series. Each of these operations is a low-level library function that must properly integrate to compute successfully a power spectrum estimate.

At higher levels, system integration, performance and analysis goals are tested through "Mock-Data Challenges" (MDCs). In a MDC data of known character (*e.g.,* noise of known statistical properties possibly superposed with a signal of known character) is passed through the system, whose response is observed and compared to the expected response. MDCs of increasing sophistication are carried out first on sub-systems and finally on the full system in different configurations.

System integration and performance testing will involve a single LSC/LDAS team that both generates test data and characterizes the system's performance. End-to-end tests of an analysis pipeline will be carried-out single-blind by two teams: one team generates data, which may include signals, and a second team analyses the data and reports back the conclusions. The two teams operate independently, with only the data (but no details of its character) passing between them. The system's ability to handle the analysis goals will be verified statistically by comparing the conclusions reached by the second team with the known character of the input data, generated independently by the first team.

These final MDCs require the ability to generate data streams with the statistical character of LIGO data. This characterization comes from the LSC detector characterization effort, described above, and involves the LIGO End-to-End modeling effort.

MDCs will be performed on an incremental basis. MDCs will be coordinated with each of LLAL and LDAS major release; additionally, there will be MDCs in between major releases, continually testing the software in different configurations. MDCs are organized by the Software Coordinator in collaboration with the LIGO Laboratory LDAS team.

8 Computational Infrastructure and Usage Model

The computational infrastructure required for data analysis is determined by the LIGO/LSC user/usage model. This model defines several different physical locations where data analysis must be supported and the types of usage supported at each location.

Data analysis computations will take place at three distinct types of sites:

- **IFO Lab Sites** (LIGO/WA and LIGO/LA);
- **Non-IFO Lab Sites** (CIT and MIT); and
- **Non-Lab LSC Sites.**

Non-lab LSC sites may eventually number in the tens.

Three broad categories of usage are also defined:

- **Local Processing/Local Data/Low-bandwidth WAN.** This type of usage involves workstation-based analysis and analysis development activities using local data files. Typical activities will involve requesting small (1-10 MB) data files from the archive over the net, or larger ones (1-10 GB) via tape, and analysis using programs running on local workstations. The analysis environment may or may not involve the LDAS software environment. It is expected that a large fraction of the LSC software development and instrument characterization will fall under this model.
- **Remote Processing/Remote Data/Low-bandwidth WAN.** This model describes development and analysis using significant LSC resources accessed via the net through a browser or X-window interface. A typical example would be a LSC scientist connecting from their home institution to the LDAS system at the CIT archive and performing an analysis on a multi-gigabyte data set using the LIGO/CIT Beowulf cluster. Analysis will take place principally within the LDAS software environment. Code validation, Monte Carlo analyses, as well as a large fraction of the computational intensive science analysis are expected to fall under this model.

- **Local Processing/Remote Data/High-bandwidth WAN.** This usage model encompasses analysis on a local workstation or supercomputer using remote data files provided via high-bandwidth (OC-1 or greater) from the LIGO archive. Usage under this model is not expected initially; however, it is expected to play an increasingly large role in the future as high-bandwidth network connections and increasingly powerful local computing resource become more common.

Usage at sites

IFO Sites

Operation of the interferometers and reduction of data from Level 0 to Level 1 is the highest priority activity at the IFO sites. Correspondingly, the on-site computing infrastructure is oriented toward local-access, with access from off-site strictly controlled. Three LANs will be supported: CDS/GDS, LDAS and general computing.

Non-IFO Lab Sites

Two sites — CIT and MIT — are supported under this category. The CIT site is home to the LIGO data archive. Its principal role is to provide access to archival data and support detailed science analysis on the combined IFO data set. Remote user support will include searching the archive and selecting archival data for analysis. Analyses may be carried-out on the LIGO/CIT workstations or Beowulf cluster, or transferred to a remote site via network or tape. The LIGO/CIT LDAS is scoped to provide support for five simultaneous high-bandwidth users, assuming a mix of tape and disk data transfers.

The principal usage model for the MIT site is currently TBD. MIT will be equipped with a Beowulf cluster for software development and local data analysis. MIT may act as a mirror for the Level 2 data product, in which case it will support use in the Remote Processing/Remote Data/Low-bandwidth WAN mode using the LDAS software environment.

Non-Lab LSC Sites

Non-Lab LSC sites will operate in either the Local Processing/Local Data/Low-bandwidth WAN or the Remote Processing/Remote Data/Low-bandwidth WAN mode. High-bandwidth connection to Lab sites is not currently a requirement; however, efficient remote access to data and LSC computational resources for code validation and data analysis is.

Some non-Lab LSC sites may obtain or have access to significant computing resources for LIGO analyses. These resources should be available for scheduled use by remote LSC users, operating in the Remote Processing/Remote Data/Low-bandwidth WAN mode.

Infrastructure requirements

The LIGO/LSC usage model determines the network, computing, storage and support personnel at each type of site.

LIGO Lab IFO and non-IFO sites

To support data pipeline activities at Laboratory IFO sites, LIGO/LA and LIGO/WA will each have a Beowulf cluster providing a minimum of 20 Gflop/s.

To support science data analysis the LIGO/CIT site is allocated a Beowulf cluster providing a minimum of 40 Gflop/s. To support data archive activities, the LIGO/CIT site will be equipped with a 100 TB tape robot, 1 TB disk storage, and an OC-3 network connection.

LIGO/MIT computing, storage and network connections are TBD.

Processor improvements are expected to boost computing performance at all sites by a factor of 2–3 over the course of the first two-year science run; additionally, disk storage at LIGO/CIT should be increased by a factor of at least 2 by the end of the LIGO I science run.

Non-Lab LSC sites

The LIGO/LSC usage model involves computing and data storage at Non-Lab LSC sites. To support science analysis at Non-Lab LSC sites we define an LSC minimum workstation configuration:

- 0.5 Gflop/s processor speed;
- 50 GB disk;
- TBD WAN connection; and a
- TBD tape drive.

This workstation configuration is expected to support a standard software environment, consisting of

- The LDAS software environment, which is supported only on Linux systems;

- a DB2 client for database access; and
- other TBD software.

Computing infrastructure acquired for LIGO data analysis substantially beyond the LSC minimum configuration are to be accessible to LSC researchers as LSC resources, providing access under remote-usage models described above.

9 Long Range Program and Anticipated Needs

The near-term research program ensures that within the limitations of the available manpower and computing resources, LIGO can carry out reasonably sensitive searches for the primary categories of expected sources. The most pressing need is to begin these activities early, so that during the commissioning phase of the LIGO detectors, the data analysis systems can be tested, debugged, and optimized.

In the longer term, LIGO's program will evolve toward increasing detection sensitivity and bandwidth and in the ability to widen the scope of the search. Eventually, when detections are made, the program will transform into a study of the nature of the signals and the properties of their sources.

Elements in a long range program are both in the intellectual development of improved understanding and software and in the exploitation of the improvements in the hardware.

1. **Development of improved detection algorithms**

    - *Improved sensitivity* Because the LIGO measures the amplitude of the gravitational wave, even small increases in sensitivity result in significant changes in event rate. For example, a 25% improvement in sensitivity through improved algorithms can increase the event rate by a factor of 2 or make a corresponding change in an upper limit.
    - *Extended searches* Development of advanced algorithms for binary inspiral and periodic sources will open more of the gravitational wave sky in this branch of the research which is both software and hardware limited. A relevant study is the influence on the data analysis of the improvements at low frequencies being projected for LIGO II which will extend the search at low frequencies by about a decade, to approximately 10Hz.
    - *Modeling of astrophysical sources* Research into predicting gravitational waveforms of astrophysical sources will continue to play a critical role in the design of search filters. Two examples are: a program

to bound the waveforms of the recently hypothesized r-mode sources and NS-BH and BH-BH systems and the completion of the program to determine the waveforms from colliding black holes with orbital and spin angular momentum.

- *The inverse problem* Research is required in the development of the computational techniques to fully utilize the dynamical information in the gravitational wave time series in a high signal to noise observation. The detected gravitational waves signals are field amplitudes rather than intensities and retain detailed information of the dynamics at the source. The full inversion will most likely require both position and polarization information determined from detections at multiple sites.
- *Improved visualization techniques* Automated pattern recognition as has been developed for speech recognition and oceanographic research may provide new methods to diagnose the detectors as well as to search for unmodeled gravitational wave sources.

2. **Improved hardware**

- *Broader band inspiral binary systems* Searches for inspiraling binary systems over a wider range of system masses and spins would be enabled by faster computation. The amount of computation power required grows as a rapid power of the lower-mass limit of the search: currently LIGO's data analysis facilities are scoped to carry out a search down to 1 solar mass (10 Gflops). A search for objects to a lower mass limit (0.1 solar mass) would require $\approx$ 1 Tflop.
- *Unprejudiced search for periodic sources* $\approx$ 1 Tflop computer could carry out an all sky searches for CW/pulsar signals to within about a factor of three of the limit of instrument sensitivity. Additional computational power would make it possible to approach the instrument sensitivity, and also consider larger ranges of spin-down parameters.

These longer-term activities should develop naturally out of the LSC's near-term research program but will require a greater concentration of effort in software and theoretical development. A well placed investment is in the support of additional scientists interested in the software and data analysis of gravitational wave astrophysics.

Improvements in computer hardware and the bandwidth of communications networks will enhance the effectiveness of the LSC data analysis activities. The rapidly-decreasing price of commodity computer hardware and the concurrent development of very cost-effective parallel computing architectures such as Beowulf systems should make it feasible for different LSC groups to make timely and effective contributions to the overall computing infrastructure needed to analyze LIGO data. These efforts will benefit from development efforts in other fields to create software and hardware configurations that can handle these enormous data sets. In common with some of the data from other fields, (most notably, high-energy physics) much of LIGO data has an *event independence* which allows the data to be efficiently analyzed in parallel. This suggests that the databases and tools which are used or might be developed for these fields have substantial overlap with GW detection.

Because LIGO's data rates are fixed at around 15 Mbytes/sec, and the speed of the national and international networking infrastructure continues to improve exponentially, easy access to LIGO data should become available in the long term. But the next five years are crucial ones, and during this time the LSC needs to make a continued effort to improve access to the data and resources. For example, by the end of the first science run it may be possible to put all the LIGO data onto spinning media, and make it available anywhere within the US, at reasonable cost.

These improvements in networking and facilities will enable another critical step in the field's evolution by the full use of the international network of gravitational wave detectors (GEO, VIRGO, TAMA, ACIGA, bar detectors) to gain position and polarization information on the observed sources. Improved networks will also enhance the ability of the gravitational wave detectors to provide a trigger to other astrophysical observations after an impulsive event has been detected. A model for this is the Supernova Neutrino Network (SNNET) which has been set up to provide alerts if neutrino bursts associated with supernovae are detected.

We strongly endorse the LIGO visitor's program. This has proved to be an effective way of reaching out for expertise and assistance from the scientific and engineering community. Data analysis problems comparable to those encountered in gravitational wave detection occur in several research areas such as speech analysis, oceanography and other branches of observational astrophysics. The visitor's program is an effective way to bring individuals who have developed particular methods and abilities into close contact with the LIGO detectors and data.

It is our expectation that gravitational wave observations will become a standard part of astrophysical measurements in the next decade and add new and complementary insight into the nature of the universe. The most promising direction in which the field will develop is not easy to predict. It is, however well known, that those best prepared will be most likely to discover something new and enduring.

WHITE PAPER

A PROPOSAL TO ESTABLISH A SCIENCE EDUCATION CENTER AT THE LIGO LIVINGSTON OBSERVATORY

Mark W. Coles
LIGO Document M010017-00-L

Summary

LIGO proposes to establish a Science Education Center at the LIGO Livingston Observatory. The programs of the education center will be a direct extension of the scientific mission of LIGO. They will facilitate the involvement of K-12 teachers and students directly into the LIGO research program, host school-to-work vocational training programs that utilize LIGO operations to provide on-the-job experience, and communicate to the general public the scientific mission of LIGO.

LIGO, the Laser Interferometer Gravitational-wave Observatory, is a major scientific initiative by Caltech and MIT, with funding provided by the National Science Foundation, to directly observe gravitational radiation. The detection of this phenomenon, whose characteristics are described by Einstein's General Theory of Relativity, will open an entirely new and exciting observational window on the universe. Public interest in LIGO is already very high, so effective means are needed to communicate the science and technology associated with LIGO to the public. The Center will host site visits by students, provide LIGO related resources for science teacher education, and provide an exhibit hall through which the science and technology of LIGO can be conveyed to the visitors.

A centerpiece of the outreach center will be an optical telescope, funded through the Louisiana Technology Innovation Council. This will be an integral part of the center. During the day, visitors will be able to view the sun through a solar filter, while evening programs for visitors will use the telescope for stellar and planetary viewing. The telescope will have remote control capability using the internet so that students can utilize it from their classrooms. Additionally, "hands-on" exhibits within the outreach center will explain LIGO's scientific mission and the technology it utilizes. The exhibits will be developed by a collaboration of LIGO scientific and technical staff, regional educators participating in the development of the Center, and a nationally prominent advisory board of science museum advisors. We will seek opportunities for teachers and community groups to become involved in exhibit development as an additional way of conveying information about how LIGO works. We would also like to involve the colleges of education at local universities so that teachers-in-training with interest in science education can serve as docents in the exhibit area.

A teacher resource center located within the Outreach Center will house a collection of educational materials about LIGO and related science. The outreach center will seek opportunities to provide internships to teachers so they can participate with LIGO scientists in research projects at the Observatory and, as a result of this experience, prepare educational materials that can be

incorporated into their classroom curriculum. We also plan to conduct enrichment science education classes for children on the LIGO site. Teachers and prospective teachers would be involved as partners in curriculum planning and the implementation of this program.

We also recognize the importance of vocational/technical education and will seek opportunities for students to participate in cooperative work-study programs at LIGO in areas with strong industrial demand such as vacuum technology, laser technology, and computer and network systems administration.

The LIGO Livingston Observatory is located in a region that has traditionally been underserved in access to science education centers. The regional population has median levels of income and educational attainment that are well below the national average and it has a high proportion of the population that is African-American - a historically disadvantaged segment of the population that is also underrepresented in the physical sciences. The impact of a science education center established in this area can be profound.

Outreach Center Goals

The LIGO Education Outreach Center will be a natural extension of the research programs of the observatory, making LIGO accessible to students, educators, and the public. The Observatory, its staff, and its visiting scientists are unique educational resources which we intend to integrate into the regional education infrastructure. We see the proposed Outreach Center, its programs, exhibits, and staff as key elements needed to achieve this goal. We propose to establish within the outreach center a hall with exhibits that describe the scientific motivation and goals for building LIGO as well as the technology that makes it work. Exhibits will be updated as LIGO progresses, to reflect new results and new experimental techniques. Detailed exhibit designs and implementations will be developed with the consultation of LIGO's science museum advisory board. We plan to include, as part of our goals for what the exhibits should convey, the Science Education Goals of the Louisiana Systemic Initiative as well as the National Research Council's National Science Education Standards.

Education programs. We plan to establish a number of educational outreach programs that will be operated from the center. These programs will address the needs of K-12 students, provide for pre-service and in-service teacher training, and we will create a vocational education program which provides technical training through direct participation in the operating programs of the LIGO Livingston Observatory.

In partnership with LIGO's scientific staff, teachers will prepare curriculum materials that they can use in their home districts when they return to the classroom. Another opportunity will involve student teachers from the local colleges of education as docents within the exhibit hall, leading children's science education classes, and participating in the preparation of exhibits. We also plan to explore opportunities to work with Southern University's graduate program in science education (Southern University is the largest historically black university system in the United States and offers the only graduate science education program in Louisiana) as part of the process of development of curriculum materials for teachers to use in their classrooms. We will also seek opportunities to partner with other regional university level teacher education programs at institutions such as Southeastern Louisiana University, Louisiana State University, Northwestern State University, etc.

Teacher education. The impact of the educational outreach activities of the center can be multiplied greatly by educating teachers as well as students. Teacher involvement will span a broad range of activities. For example, we intend to establish a strong connection with the NSF's Internships in Science Education (IPSE) program, since the objectives and scope of this program appear to be ideally matched to aims of the Outreach Center. The development of a teacher internship program will provide opportunities for teachers to work directly with LIGO scientists as participants in the LIGO science program. This will bring teachers into frequent contact with the scientific community of LIGO as summer employees or on leave from their home districts to work as part of a LIGO science team. Those participating in this program will spend part of their time developing classroom curriculum materials relating to their experiences which they can use to enhance their classroom teaching. Copies of the materials will be maintained in the Outreach Center library and at the Louisiana Energy and Environmental Resource Information Center (LEERIC). LEERIC will make these materials available to requesting institutions state-wide using existing funds made available by the State of Louisiana. The outreach center will provide the teacher workshop teacher training classroom space needed for these activities. We will create opportunities, through partnerships with teacher certification programs in regional colleges and universities, for pre-service teachers to participate as docents in the outreach center as part of their practical science training.

Student education. We plan to utilize classroom space within the outreach center to offer science classes for students, taught by Outreach Center staff, members of the LIGO staff and scientific collaborators, and by qualified volunteers associated with the outreach center. We plan to obtain guidance from the Caltech Pre-College Science Initiative and participating local school districts to offer hands-on science education classes to students. We have the beginnings of this program already in place. More than 2,000 students have visited LLO in the past year and many of these students have participated in "hands-on" science classes taught by LIGO staff. Included in this group were 120 minority high school students from across the nation that participated in Southern University's Timbuktu Academy (a program to promote physical science education among disadvantaged minorities). LLO staff have also visited several schools regionally to teach science lessons relating to LIGO in the classroom. Requests for school groups to visit LIGO are becoming increasingly frequent as word spreads, further motivating the construction of a dedicated facility to host these visitors.

Vocational/technical education and "school-to-work" programs. A further goal of LLO's outreach is the development of a vocational/technical program as a direct extension of the operation of the observatory. This will provide work/study opportunities for students as they participate in the operation of the LIGO site and learn technical skills that lead directly to job opportunities. This program is expected to have particularly strong local support. The Capital Region Planning Commission Overall Economic Development Plan for 1995 lists the promotion of vocational/technical education as a priority for Livingston and surrounding parishes. Examples of areas where students can learn and apply technical skills to the operation of the interferometer are areas such as vacuum technology, computer network operation and systems administration, and lasers and optics. The outreach center will host technology classes in these areas and participating students will work at LLO under the guidance of the operational staff to apply these skills as a direct extension of the LIGO program.

Description of the Outreach Center Facilities

This section describes the conceptual design of the Outreach Center and a room-by-room description of the features of the facility and their specific uses. The overall layout indicating the relationship of the outreach center to other buildings on the LIGO site is shown in figure 1. An exterior view is shown in figure 2, and a conceptual floor plan of the proposed center is shown in figure 3. The site plan is designed to allow the natural integration of the Outreach Center with the LIGO Observatory while maintaining traffic at a safe distance from vibration sensitive components of the interferometer.

It is envisioned that visitors will arrive in the parking area east of the center. Roads and parking will be designed to accommodate school groups arriving by bus. A typical school group will come to see the exhibits and view a presentation in the existing auditorium accessible through the visitor center, and then walk approximately 150 feet south to the main entrance of LIGO to view the observatory.

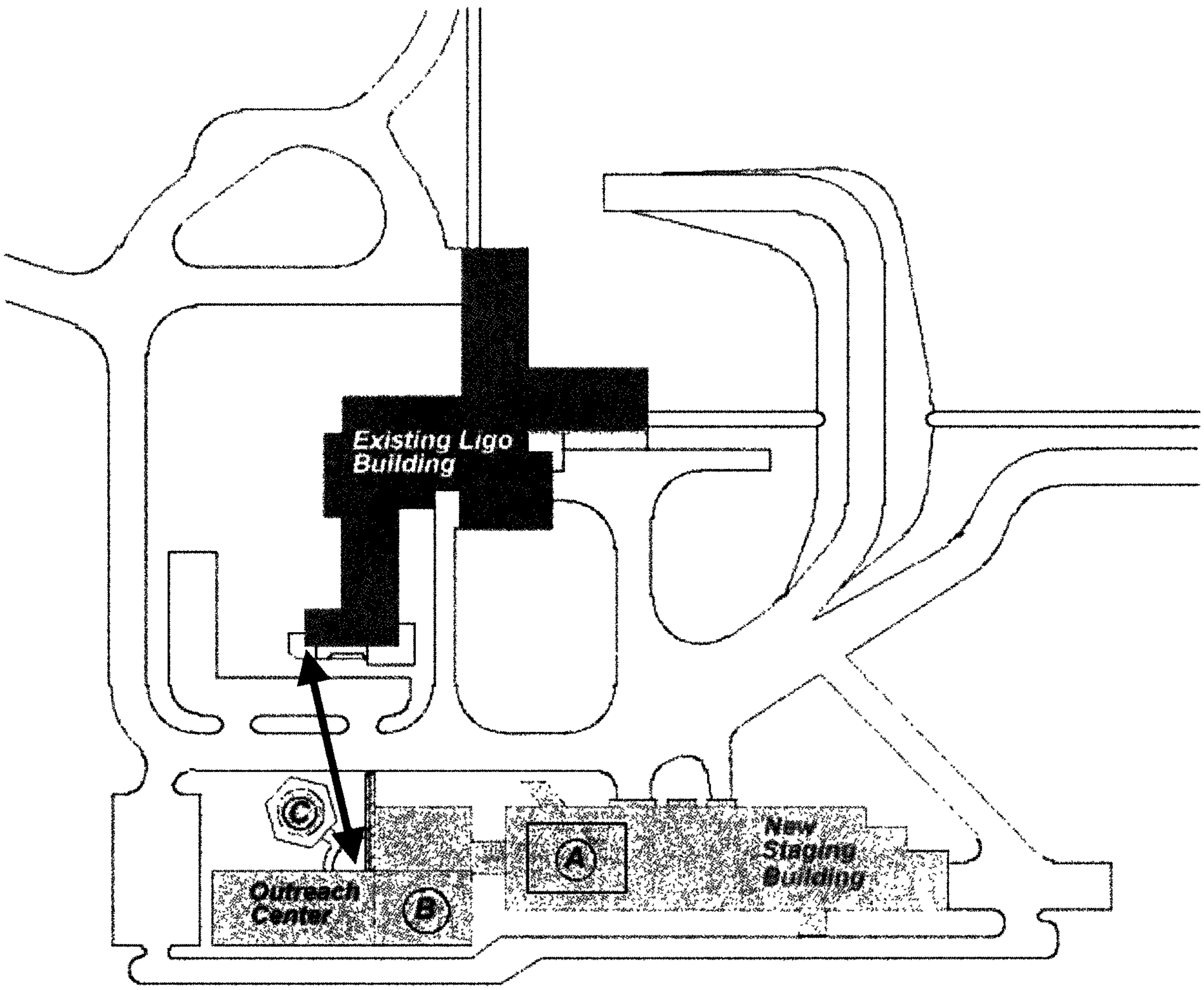


Figure 1. *The location of the proposed Outreach Center is shown at lower left. The red arrow indicates the path that visitors will take to go from the outreach center to the main entrance of the LIGO Livingston Observatory. The layout also allows easy access to the site auditorium located on*

the left side of the New Staging Building and designated by the letter A on the drawing. B is the location of the teacher workshop space to be located within the Outreach Center, and C indicates the location of the telescope.

The main exhibition hall will have an open exhibition area with high ceilings. This will allow the accommodation of exhibits that require a lot of space and will also make it possible for the room to be flexibly configured. Using portable room dividers, exhibits can be easily added while still leaving ample room for visitors to interact with the exhibits on display. The circulating space will be wide enough to allow a forklift to deliver or remove an exhibit. Directional lighting will be used to highlight exhibits and graphics. The hall will be located adjacent to the main entrance to allow controlled access to the hall via the visitors' desk. Computer ports will be spread throughout the exhibit hall, as some exhibits will make use of networked computers. Access to the LIGO site auditorium (175 seat capacity, located in existing space adjacent to the left hand side of the floor plan shown in figure 3) from within the center will allow it to be regularly used for outreach. The auditorium will have movie and projection TV capabilities, and a raised stage.

Located adjacent to the exhibition hall will be a large workshop and storage area that will be used to create new exhibits. It will provide ample bench space, carpentry tools, and material storage areas for these activities. This space will also serve as a teacher workshop space for the creation and storage of curriculum materials to be used in school classrooms. A combination educational materials library and workroom will hold educational books and supplies for the outreach center. It will also serve as a teacher workroom for the preparation of posters, worksheets, and other curriculum materials to be used by teachers in their classrooms. It will provide computers and a printer, paper, posters, copy machine, laminating machine, and bins of supplies to support these activities.

The classroom adjacent to the exhibition hall will be used for informal science classes with small groups of students, for teacher in-service training, and as a classroom setting to support the vocational/technical education program.

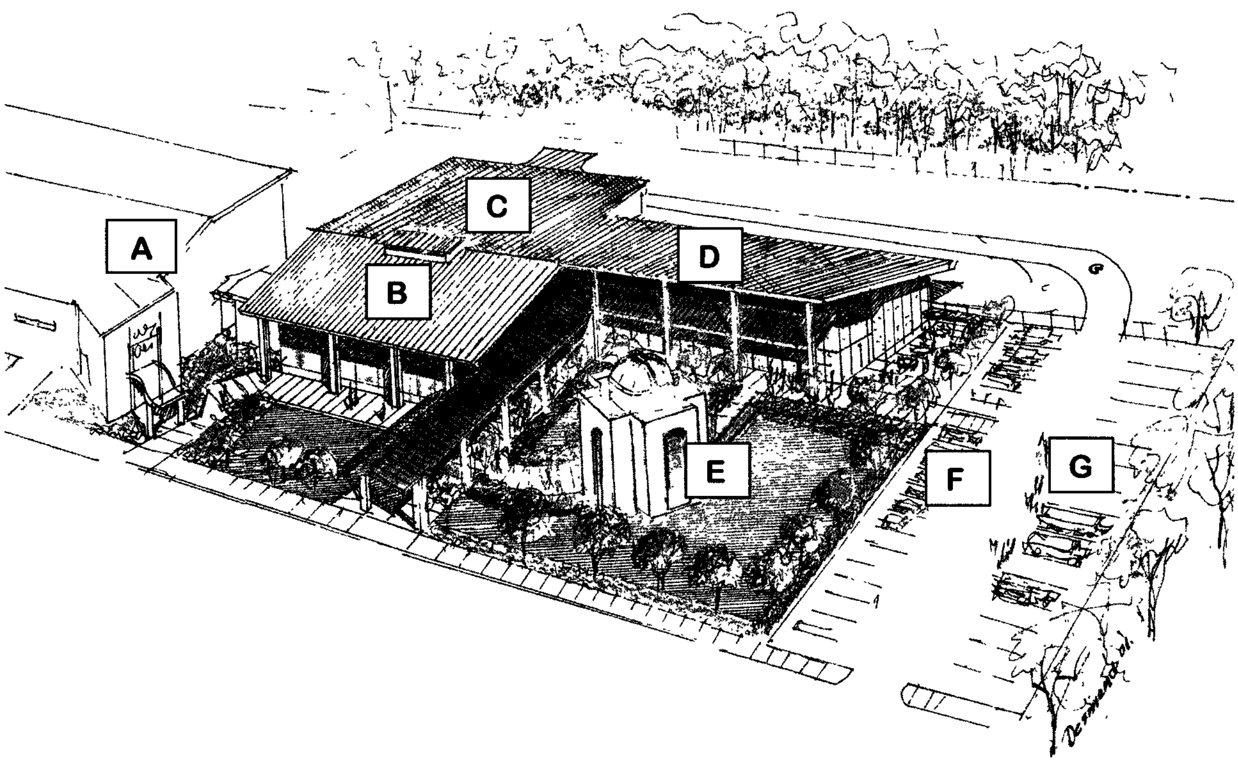


Figure 2. *The outreach center is shown in relationship to the auditorium, designated "A" at left in the plain white area on the drawing. Other designation letters on the drawing indicate the following features of the center: B- exhibition hall; C- teacher workshop and support area;D- main entrance, restrooms, gift shop, and snack bar; E- optical telescope; F- car park; G- bus parking.*

The telescope will be located in a separate building on a raised pedestal. This will allow it good viewing of the sky without the need to look across a hot roof or parking lot when viewing at low elevations. The prime direction for viewing is to the south (in the foreground in figure 2), and the placement as shown on the site layout in figure 1 gives unobstructed access in that direction. Equipping the telescope for daytime solar observations as well as night-time use will further enhance its utility as a focal point of the outreach center. (The outdoor lighting strategy for the center will take into account the needs of the telescope for dark skies.) We propose to devote about half of the available night-time viewing with the telescope to a modest scientific program carried out by LLO staff. We feel that this will further integrate the outreach center into the programs of the observatory.

A small museum shop, a snack bar/vending and patio area, rest rooms, and two offices for operating staff dedicated to the Outreach Center activities will also be provided.

Analysis of Low-frequency Seismic Vibrations at LIGO

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Abstract

LIGO (the Laser Interferometer Gravitational-wave Observatory) is located near the Hanford site outside of Richland, WA. As part of the Scientist-Student-Teacher Enhancement Program (SST) program which is administered by the Pacific Northwest National Laboratory, students at Gladstone High School are examining low-frequency ground vibration data from seismometers that are located at LIGO. Accurate characterization of these microseism vibrations will assist the LIGO staff as they seek to optimize the performance of the interferometer in its quest to detect gravitational waves.

This report describes methods that we are using to characterize the nature of the microseism at LIGO. We have learned that the microseism amplitude is relatively steady from one 15-minute period to the next. On a scale of one to two days, however, the amplitude can shift by as much as a factor of five. Another branch of our research deals with the influence of global earthquakes on vibrations in the microseism frequency band. Preliminary results have failed to show a significant earthquake contribution to the microseism data other than from high-magnitude events.

Introduction

Gladstone High School is currently participating in the Scientist-Student-Teacher Enhancement Program (SST), which is administered by the Educational Programs Division of the Pacific Northwest National Laboratory (PNNL) in Richland, Washington. The goal of SST is to incorporate research into high school classrooms by involving teams of high school students and a science teacher in an active, professional research program. PNNL and LIGO are the institutions that are partnering with high school teams in the SST endeavor.

LIGO's mission is to search for gravity waves, which are thought to be ripples in space-time produced by highly energetic events in the universe. Einstein predicted the existence of gravity waves in his General Theory of Relativity, and astrophysicists now hope to detect the presence of these waves through the use of enormously long interferometers such as LIGO. Upon passing through the earth, a gravity wave would create an extremely small and short-lived difference in the lengths of the light path of the interferometer arms. Typical ground vibrations at the site will far exceed the magnitude of detectable gravity wave activity, so these ground vibrations must be factored out of the interferometer's gravity wave data. One of Gladstone's tasks in the SST program is to analyze and characterize a particular type of low-frequency ground vibration called the microseism.

Through the work of a four-person Gladstone team at LIGO in the summer of 1999 plus the efforts of a larger group of students during the current academic year, we have developed the means of collecting low-frequency data from LIGO seismometers and analyzing these data at our school. We have been able to lift seismometer data from a Web page (which originates from a LIGO computer) and plot it using Microsoft Excel. We have also monitored the statistics of the data stream. Our work to this point has been focused on developing the computing mechanisms that are described in this report. Our examination of the data has revealed the basic characteristics of the microseism at LIGO, and the preliminary results we describe in this report have prompted questions for further research.

The Microseism

What we refer to as the microseism is really a family of seismic processes. Microseisms are low frequency, small vibrations in the surface of the earth from sources other than earthquakes. It is believed that they are caused by disturbances in the earth and atmosphere. They are extremely common in seismograph readings. Possible sources of microseisms include the surf pounding against the shore, trade winds, atmospheric oscillations found in storm centers (hurricanes and monsoons), volcanic eruptions, and strain in the earth's crust. Human activity such as traffic and machinery can also create microseisms.

Amplitudes of standing waves at sea directly affect the ground amplitude of one class of microseisms. Longuet-Higgins discovered that these microseismic periods are equivalent to half the periods of standing ocean waves. Amplitudes of ground movement can be less than 10^{-8} centimeters or as large as 10^{-2} centimeters for processes in this class. Periods of microseisms are dependent upon the amplitude, and regardless of origin, microseisms all have about the same periods – between five and nine seconds[1]. Ever present, microseisms can create problems for facilities such as LIGO that are exceedingly sensitive to the most miniscule perturbations of the earth's crust.

Accessing LIGO Seismometer Data at the High School

The microseism is detected by a collection of seismometers at the LIGO Hanford Observatory (LHO), each of which outputs a data channel for north-south, east-west, and up-down vibrations. This is time series data, meaning that a graph would show vibration magnitudes versus time. This is the most common representation of seismometer measurements. Instead of delivering time-based output directly from the instrument, however, LIGO's acquisition system collects and digitizes the data. The digitized measurements enter a computer, where they are manipulated through software. First the data is filtered. We then instruct the computer to perform a Fourier transform to convert our time series into a frequency series, and the signal information from one frequency band (0.1 to 0.2 Hz) is extracted from the entire data set. Each transform is constructed from 15 minutes of time series data. This data is velocity versus frequency. For our purposes, displacement—or the amplitude of shaking—of the microseism is more useful than the velocity. Therefore, the data is integrated. Then the displacement of the microseism band is determined. This number represents the average amount of ground movement caused by the microseism during that 15-minute period. It is then posted to a text file on a Web server for each channel. After posting, the numbers are multiplied by calibration terms that account for the slightly different response factors of the seismometers. This data allows the general trend of the microseism's activity to be tracked over days and weeks.

Characterization of the Microseism at LIGO

After the data is posted to the Web site we transfer it to an Excel spreadsheet in weekly increments. Ongoing installation work on the hardware and software systems at LIGO occasionally interrupts our data stream, and we collect the measurements on an as-available basis. Figure one shows the output from one LIGO seismometer over a period of three days during a time when the data stream was continuous. Each data point represents the average amplitude of ground displacement during the previous 15 minutes, but we are only monitoring vibrations that have frequencies between 0.1 and 0.2 Hz.

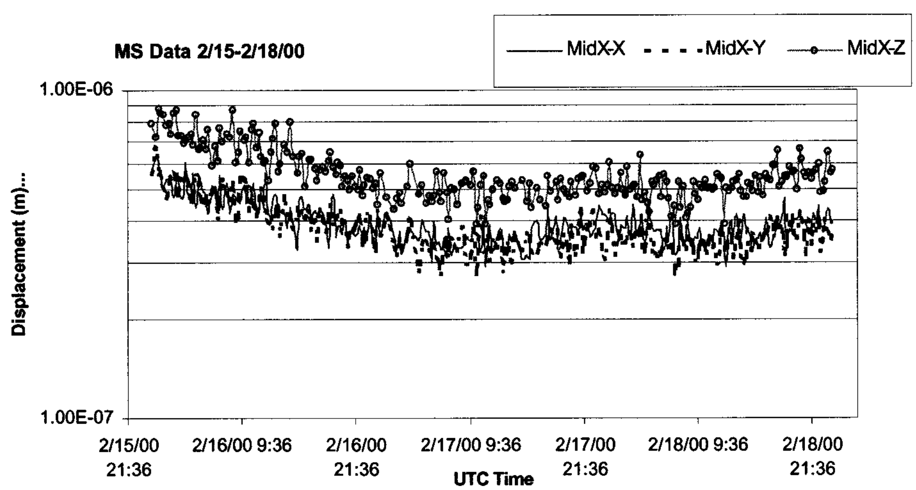

Figure 1
A three-day plot of the microseism signal from one LIGO seismometer

Figure one shows that the signals stay fairly constant from one 15-minute increment to the next. However one notes a drop in the amplitude of the Z (vertical) channel vibrations by a factor of two over the span of 1.5 days, with similar but somewhat smaller shifts in the other channels. Variations of this type appear frequently in the data. In looking at data that has been accumulated since Nov. 1999, we can see movements over periods as short as a day that are as large as a factor of five. One of the main tasks of future work is to identify the forces that move the amplitudes up and down over these time frames.

Statistical measures such as mean and standard deviation have been important tools in our effort to characterize the microseism signal. The means for the data from figure one exceed the corresponding standard deviations by factors of 8.5, 7.0, and 7.4 for the X, Y and Z channels respectively. These results are indicative of a relatively quiet data set. Values for this ratio have ranged from 3 to 10 since Oct. of 1999. We commonly observe that the vertical channels of the instruments show higher means and standard deviations than the horizontal channels. The same is true for the data from figure one. The Z-channel mean was nearly 15% larger than the X-channel mean, and the standard deviation for Z was almost 25% larger than the corresponding value for X.

We have also calculated the correlation coefficients between the data sets of various channels. A coefficient of 1 represents a complete correlation, while a value of (-1) indicates a complete anti-correlation. A value of zero implies that there is no association between the sets. Correlation coefficients for the three channels from figure two are shown in the table 1. Our expectation is that a seismic vibration that affects one channel of an instrument should similarly affect the other two channels, and so the size of the coefficients should help us discern the extent to which ground vibrations are present in the baseline, as opposed to random electronic noise.

Table 1
Correlation coefficients for three channels from one LIGO seismometer

	MidX-X	MidX-Y	MidX-Z
MidX-X	1		
MidX-Y	0.75	1	
MidX-Z	0.74	0.81	1

Graphs that display the difference between the signal in two channels provide another way of assessing the similarity between the two data sets. Figure two is a graph of the absolute difference between two channels of the same seismometer. If the two signals were completely identical, the difference plot would show displacement values of zero. Random fluctuations in the signals preclude this outcome, and one can see that the difference value undergoes considerable variation across the graph. However the differences are typically at least five times smaller than the channel means themselves, which suggests a reasonable correlation between the channel signals.

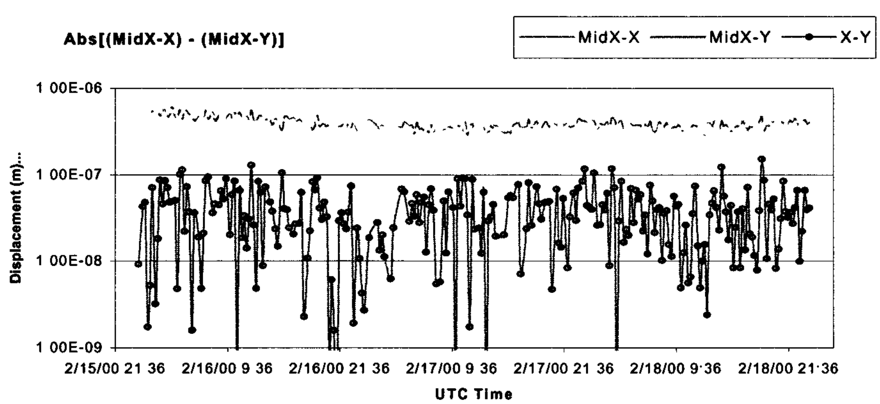

Figure 2
Two horizontal seismometer channels are shown, as well as the absolute difference between them

The Influence of Earthquakes in the Microseism Baseline

The microseism baseline often shows spikes that seem potentially significant. In the fall of 1999 we clearly saw evidence of major quakes in Turkey and Mexico in all channels of the low-frequency signal. Given that hundreds of 3(+) quakes occur across the globe each month, we began questioning the extent to which earthquakes might make a persistent contribution to our data stream. The method used to pursue this question was to align USGS earthquake data to our microseism data, to see if significant events in the baseline showed any relation to earthquake activity[2]. We used a five-day data sample from February 2000 for the test.

The first step in the earthquake analysis was to identify unusual points in the microseism data. A formula was applied to the spreadsheet that picked out data points that lay at least three standard deviations above the mean for a given set. A list of earthquakes was then included in the spreadsheet, and we used a macro to place the earthquakes next to the closest microseism data point (taking into account the travel times of the earthquake waves). We then graphically looked for matches between earthquakes and the high baseline events. During the five days there were no baseline events that occurred simultaneously in all three channels of the instrument that could be attributed to earthquakes. The USGS data showed no major quakes during this time, so we are now examining other portions of data as we pursue the question of earthquake influence.

Conclusion

We are developing a basic understanding of the average magnitude of the microseism at LIGO. We are also developing a clearer sense of the variations that typically occur in the microseism data. Our work so far has produced several questions for further research. Two of these are listed below.

- What are the factors that cause the level of the signals to change as they do over periods of hours and days? Gladstone students are looking at weather patterns as possible contributors to these undulations.
- How do seismic waves move through the roughly 10-square mile site? Does microseism activity ripple through the ground under the interferometer in any predictable way? This question will require exacting scrutiny of the data, and will be one of the major thrusts of our efforts over the next several months.

Another team from Gladstone will travel to LIGO for the summer of 2000, and the research program will continue through the next school year. As the interferometer starts accumulating data, we will be furthering our characterization of the microseism, and we will begin analyzing the effects of earth tides on ground movement at the site.

[1] *This summary of the microseism was taken from a larger work which can be found in its entirety at http://www.ghs.gladstone.k12.or.us/~physics*

[2] *Earthquake data was taken from http://www.earthquake.usgs.gov/neis/bulletin/bulletin.html*

Comments and questions can be addressed to Dale Ingram at ingramd@gladstone.k12.or.us

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