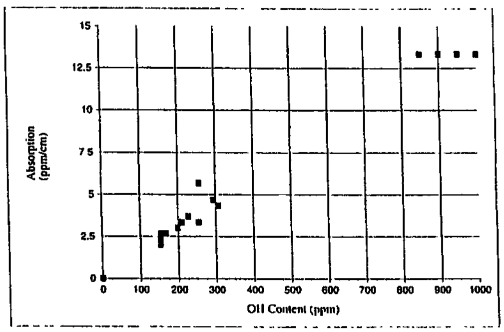
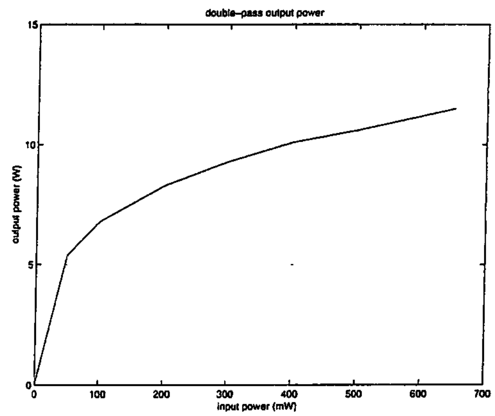
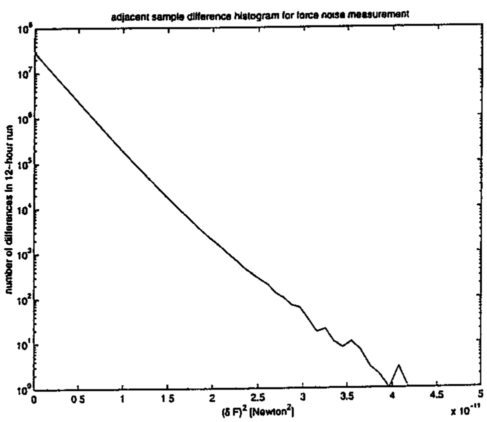
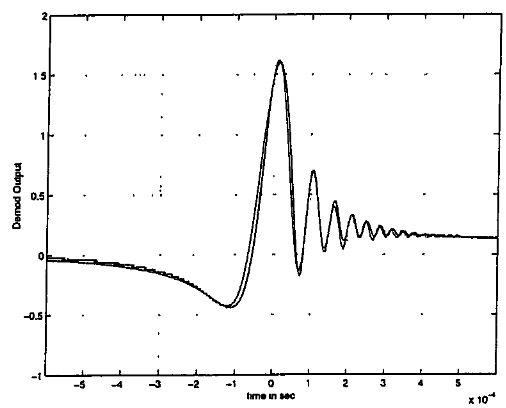
LIGO PROJECT

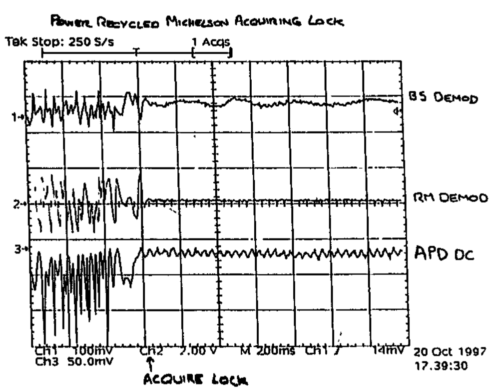
California Institute of Technology / Massachusetts Institute of Technology

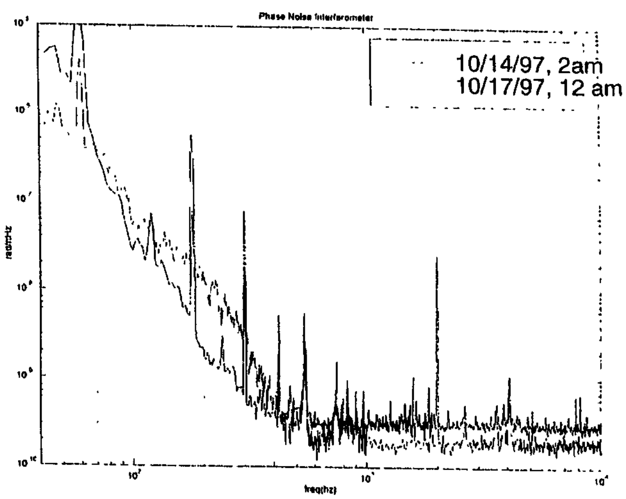












National Science Foundation Technical Review

October 28-30, 1997 - California Institute of Technology-Pasadena, California 91125

LIGO G970253-00-M

Laser Interferometer Gravitational Wave Observatory

LIGO PROJECT

California Institute of Technology / Massachusetts Institute of Technology

NSF Technical Review - October 28-30, 1997

Table of Contents

Charge
NSF Committee to Review Technical Progress on LIGO

October 28 - 30, 1997

Provide an in-depth review of the LIGO project. The principal thrust of the review will be the technical aspects of the project.

Assess the progress since the last review held in April 1997. In particular consider the risks to the project from the delay in the schedules of the interferometer sensing and alignment and of the 40 m interferometer program.

In your review, also include an assessment of progress in the following areas: the seismic isolation and suspension system; the optical system including the effects of the absorption of light and the input optics; the laser performance and phase modulation; the simulation of the interferometers; the beam tube and vacuum equipment; and the civil construction.

The final report of the review by the committee should be available to the Foundation by November 20, 1997.

National Science Foundation Technical Review of the LIGO Project
October 28-30, 1997
112-114 East Bridge
California Institute of Technology

Agenda

Tuesday October 28, 1997:

8:00: Executive session

9:00: Welcome - Dr. David Baltimore, President, Caltech

9:15: LIGO Project Introduction and Status - Gary Sanders

9:45: Hanford Site Status - Fred Raab

10:15: Livingston Site Status - Mark Coles

10:45: Break

11:00: Data Format/Analysis/Modeling - Albert Lazzarini

Noon: Lunch break, 112 East Bridge

1:00: Detector Status/R&D Status - Stan Whitcomb/David Shoemaker

3:00: Committee Executive Session

3:30: Parallel groups

A. Conventional Facilities, Beam Tube and Vacuum Equipment-39 Bridge Annex
Reviewers: Paul Gilbert and Rudy Damm
Subjects: Construction progress, beam tube performance, baffles, integration, etc.

B. Laser/Optics-351 West Bridge (Large SCR)
Reviewers: Roger Falcone, Marc Levenson, and Daniel Coulter
Subjects: Laser performance, lifetime, noise characteristics, and modulation scheme and its interaction with laser output stabilization

C. Seismic Isolation/Suspension-351 West Bridge (Small SCR)
Reviewers: Paul Reardon and Jim Bergquist
Subjects: technical performance, cost & schedule, creak effects, and long thermal time constant effects on high Q system in thermal isolation

D. 40M and Phase Noise Interferometer (PNI)-57 West Bridge
Reviewers: Don Hartill and Jerrold Zimmerman
Subjects: Present program, roles as R&D testbeds, and future plans

5:00: Executive Session followed by dinner at the Athenaeum.

<u>Wednesday October 29, 1997:</u>

8:00: Executive Session

9:00: Parallel sessions resume

A. Conventional Facilities, Beam Tube and Vacuum Equipment-39 Bridge Annex
Reviewers: Paul Gilbert and Rudy Damm
Subjects: Construction progress, beam tube performance, baffles, integration, etc.

B. Laser/Optics-351 West Bridge (Large SCR)
Reviewers: Roger Falcone, Jerrold Zimmerman, and Jim Bergquist
Subjects: Optics- Transmission optics - absorption and thermal lensing
Coatings - uniformity and testing
Polishing - quality assurance and variability
Metrology
System aspects of Input optics
Thermal time constant effects - excess noise due to high Q material's long relaxation time, thermal isolation and radiation effects

C. Interferometer Sensing and Control/Simulation-351 West Bridge (Small SCR)
Reviewers: Don Hartill, Paul Reardon, Daniel Coulter and Marc Levenson
Subjects: Comments on FMI final results, PNI experience
proposed scheme for LIGO,
progress on simulation effort and its prediction of 40M performance, noise tolerance of system, power handling of diodes, computing plans and template issues for data analysis

Noon: Lunch, 112-114 East Bridge

1:00: Executive Sessions
Reports from the Subgroups
Formulation of Recommendations and Executive Summary

Thursday October 30, 1997:

8:30: Committee Executive Sessions
Discuss Draft Report
Complete Executive Summary

11:00: Close-Out Session with LIGO Staff

Noon: Working Lunch (If needed)

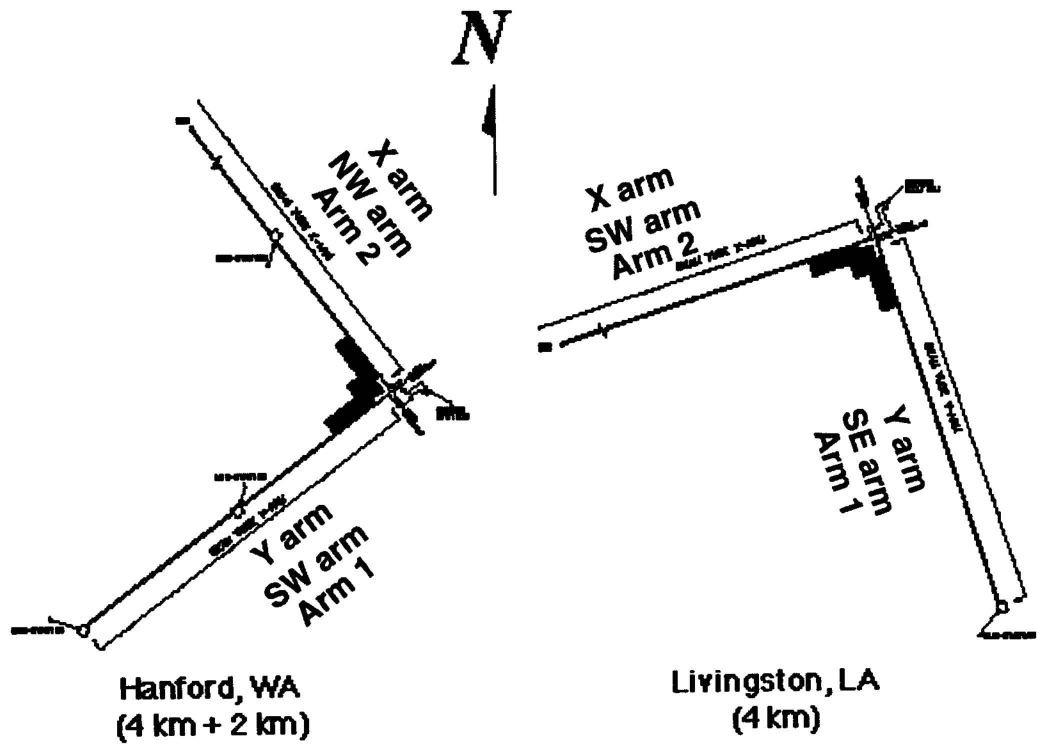
3:00: Adjourn

Glossary of Acronyms and Abbreviations

1x/2x/3x	Notation for single, double, and three-fold coincidence operational modes of the LIGO detector comprised of 3 IFOs
100BT	One hundred base T - 100Mb/s communications rate; also implies an electrical/mechanical interface
10BaseT	Telephone type Ethernet cable
ADC	Analog-to-Digital Converter
AMU	Atomic Mass Unit
ANSI	American National Standards Institute
API	Application Programmer Interface
ARO	After Receipt of Order
AS	Alignment System
ASC	Alignment Sensing and Control
ASCII	American Standard Code Information Interchange
ATM	Asynchronous Transfer Mode (inter-processor communications prot
AVS	Advanced Visual Systems (graphical development software package
BAC	Budget At Completion
BCU	Beam Control Unit
BNWL	Battelle Northwest Laboratories
BS	Beam Splitter
BSC	Beam Splitter Chamber
BT	Beam Tube
BTD	Beam Tube Demonstration
BUDG	Budget
C++	Object oriented computer language
CA/NS	Control Area and Networking System
CACR	Center for Advanced Computing Research (Caltech)
CAM	Control Account Manager
CAP	Control Account Plan
CBI	Chicago Bridge & Iron
CCB	Change Control Board
CCD	Charge Coupled Device
CDF/HDF	Common/Hierarchical Data Format
CDR	Conceptual Design Review
CDRL	Contract Data Requirements List
CDS	Control and Data System
CDS/DAQ	Computer & Data Systems Data Acquisition System
CNTR	beam Centering Alignment System
COC	Core Optics Components
COS	Core Optics Support
COTS	Commercial Off-The-Shelf software
CPU	Central Processing Unit
CSIRO	Commonwealth Scientific & Industrial Research Organization
CSR	Center for Space Research (MIT)
DAC	Digital-to-Analog Converter
DAQS	LIGO CDS Data Acquisition System
DCC	Document Control Center
DCCD	Design Configuration Control Document
DCU	Data Collection Unit
DEC/SUN	Computer Manufacturers: Digital Equip.Corp/SUN Microsystems, Ir
DMA	Direct Memory Access
DoD	Dept. of Defense
DoE	Dept. of Energy
DOF(s)	Degree(s) of Freedom
DRD	Data Requirement Description
DRR	Design Requirements Review
DSP	Digital Signal Processor
EAC	Estimate At Completion
EFINISH	Early Finish
EMC	Electro-magnetic Control

LIGO	Laser Interferometer Gravitational-Wave Observatory
LN2	Liquid Nitrogen
LNT2	Liquid Nitrogen Trap No. 2
LNS	Laboratory for Nuclear Science (MIT)
LOS	Large Optic Suspension
LRC	LIGO Research Community
LSC	Length Sensing and Control
LSU	Louisiana State University
LT	Long Term
LVDT	Linear Variable Differential Transducer
LVEA	Laser/Vacuum Equipment Area
MATLAB	Control system modeling environment
Mb/s	Unit information exchange rate: of 10^6 bits of information per
MB/s	8 Mb/s: 10^6 Bytes per second
Mbps	Megabits per second
MBps	Megabytes per second
MICS	DOE Mathematics, Information, & Computer Sciences
MIMO	Multiple Input, Multiple Output
MFLOPS	Million Floating Point Operations Per Second
MOPA	Master Oscillator, Power Amplifier
MPE	Message Passing Extensions
MPI	Message Passing Interface
MSFC	NASA Marshall Space Flight Center
NPACI	Nat'l Partnership for Advanced Computational Infrastructure
NPRO	Nonplanar Ring Oscillator
NIM	Nuclear Instrumentation Module
NIST	National Institute of Standards and Technology
NS	Neutron Star
NSB	National Science Board
NSF	National Science Foundation
OC3	Communication bandwidth designation: 155Mb/s
OC12	Communication bandwidth designation: 640 Mb/s=4X OC3
OOP	Object Oriented Programming
OPI	Operator Interface
OptLev	Optical Lever Alignment System
OSEM	Integrated Optical Position Sensor/ElectroMagnetic driver
OSIX	Platform Operating System Independent Standard for software/har interfaces
PAC	(LIGO) Program Advisory Committee
PAW	Data analysis package developed and distributed by CERN
PC	Pockels Cell
PD	Photo-Detector
PDR	Preliminary Design Review
PDRR	Preliminary Design Requirements Review
PEM	Physical Environment Monitoring System
PERF	Performance
PLC	Programmable Logic Controller
PM	Project Manager
PMB	Performance Measurement Baseline
PMCS	Project Management Control System
PMDAQ	Physical Environment Monitor Data Acquisition
PNI	Phase Noise Interferometer
PNNL	Pacific Northwest Nat'l Laboratory
POSIX	established industry standard for software/hardware interfaces
PSI	Process Systems International
PSL	Prestabilized Laser
PZT	Piezo-electric Transducer
QT	Qualification Test
QTR	Qualification Test Review
RAID	Redundant Array of Inexpensive Disks
RAM	Responsibility Assignment Matrix
RANCOR	vessel subcontractor to PSI
RCM	Recycling Mirror
RDIAG	Remote Diagnostics
REO	Research Electro-Optics (Company Name)

LIGO Site Layouts.



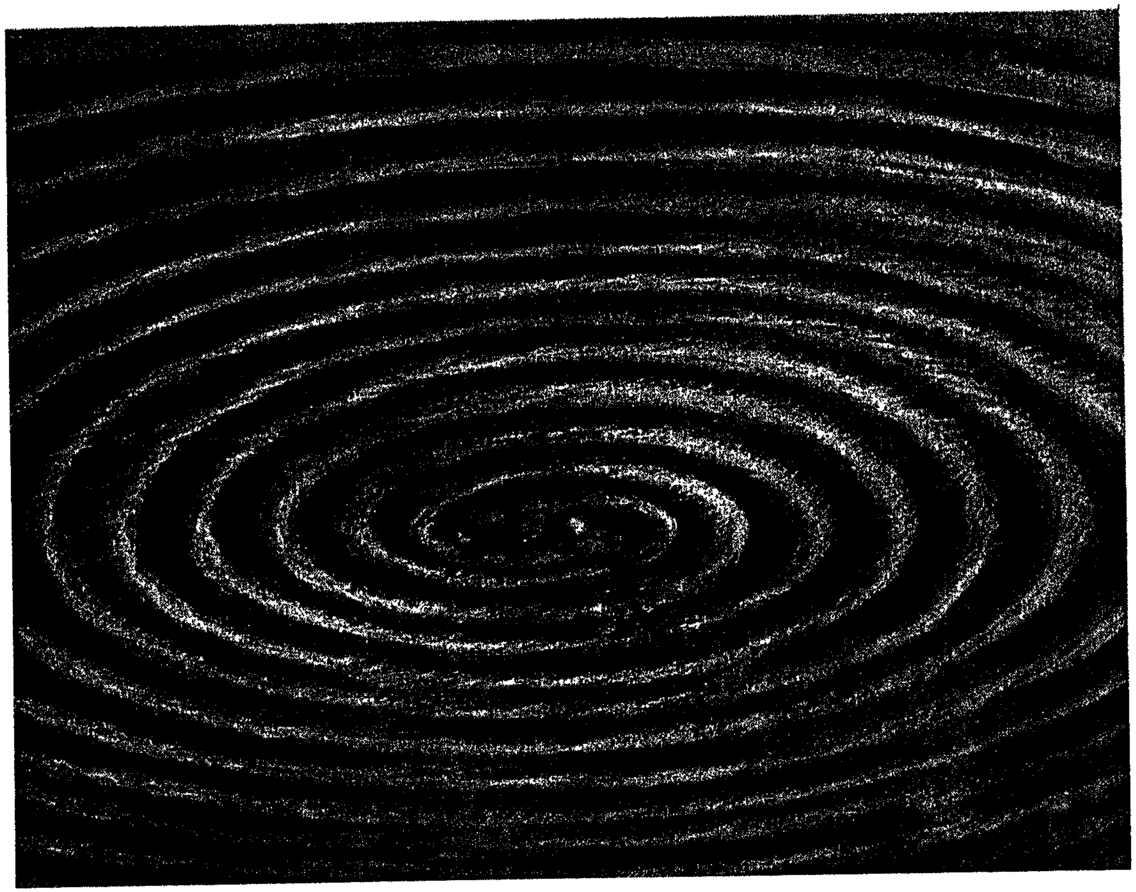
LIGO Project Status

Gary Sanders

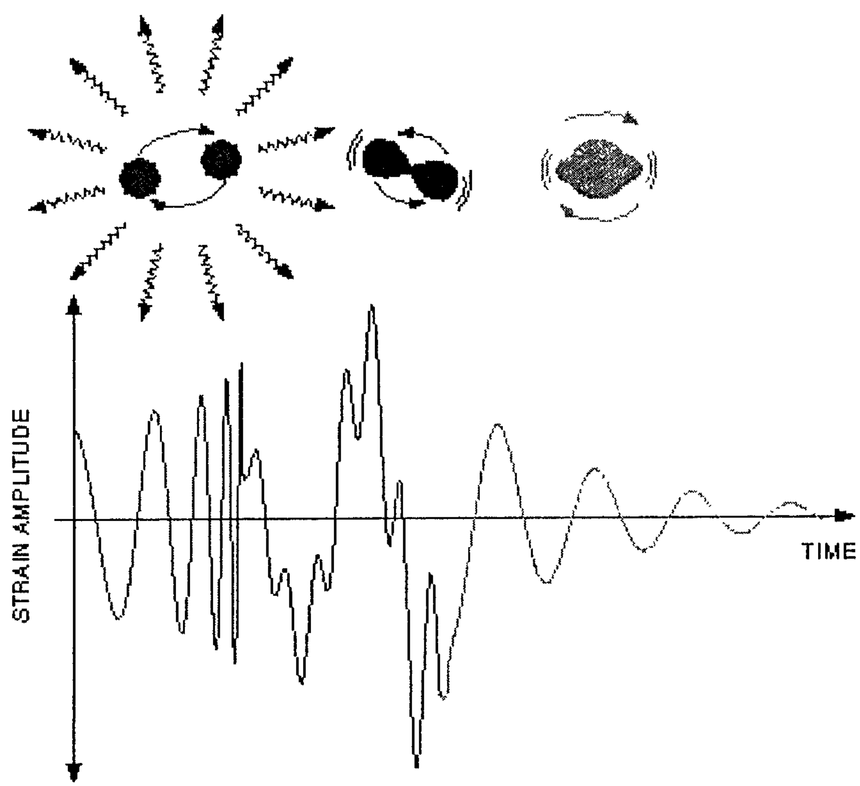
NSF Technical Review

October 28 - 30, 1997

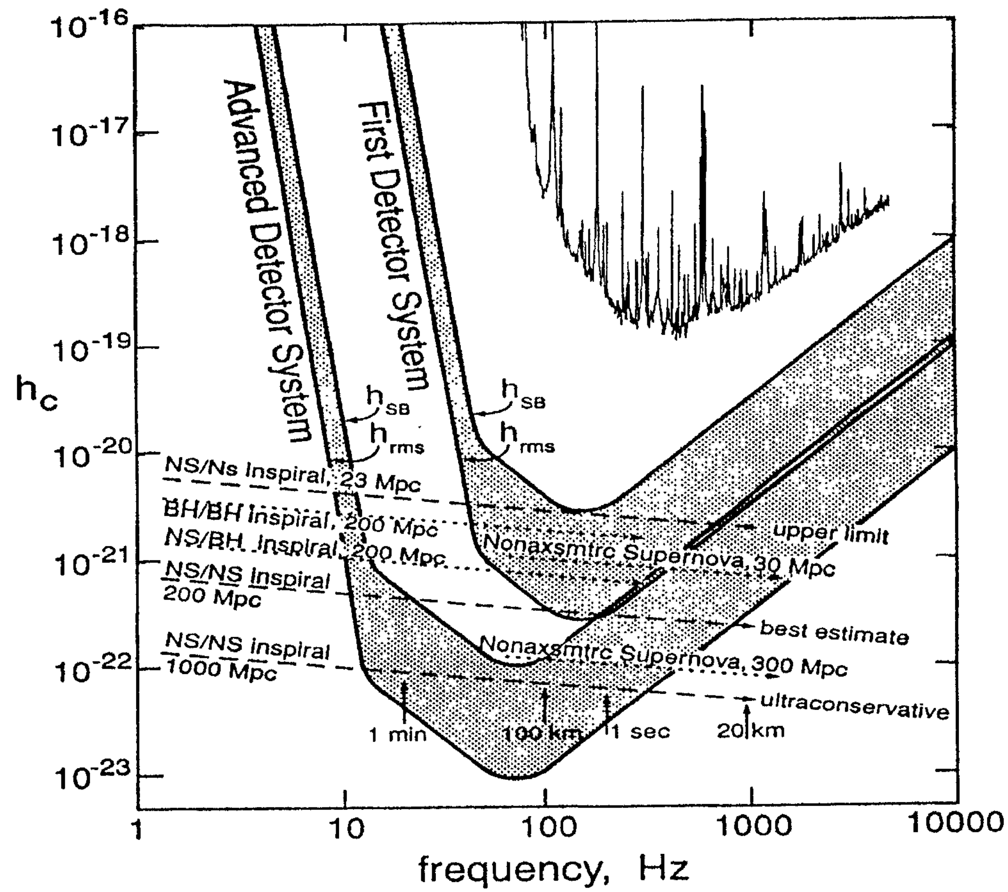
Gravitational Waves



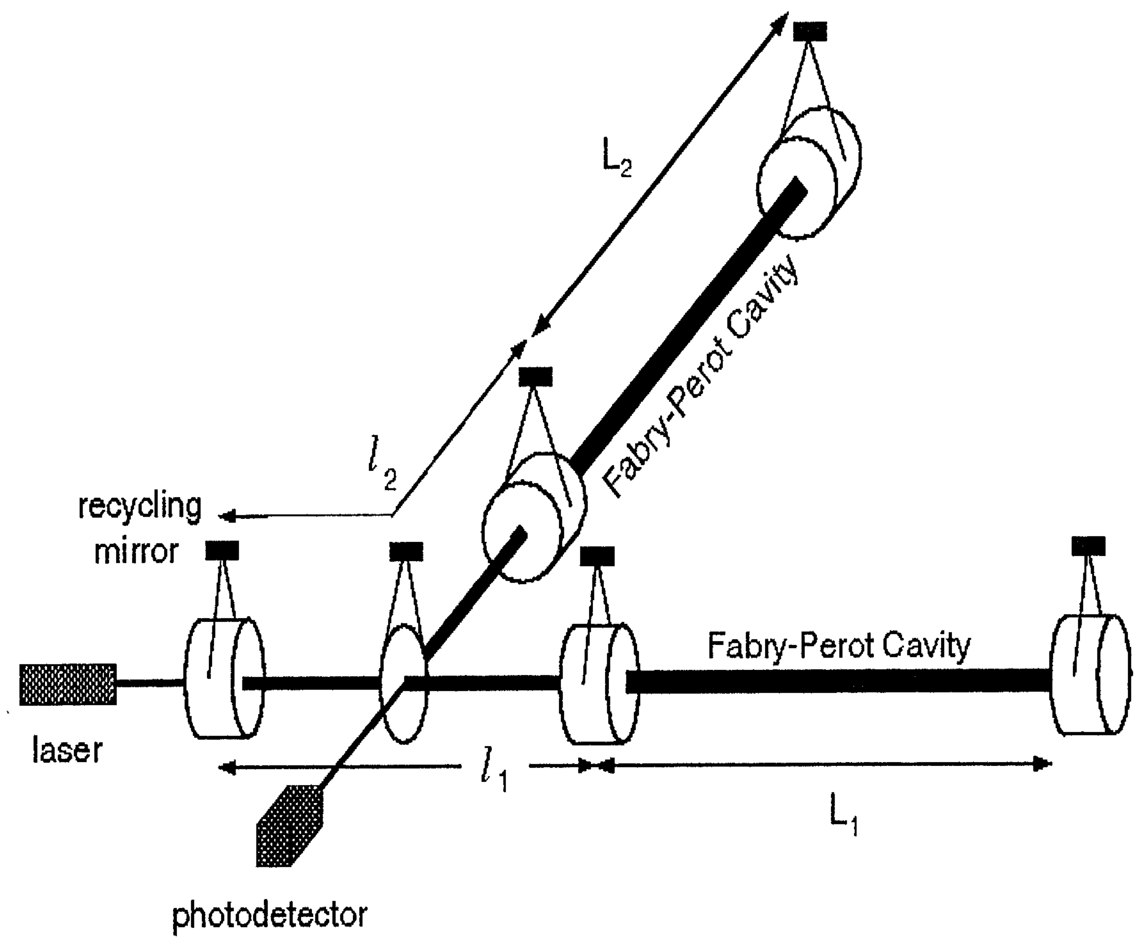
Inspiral Signal



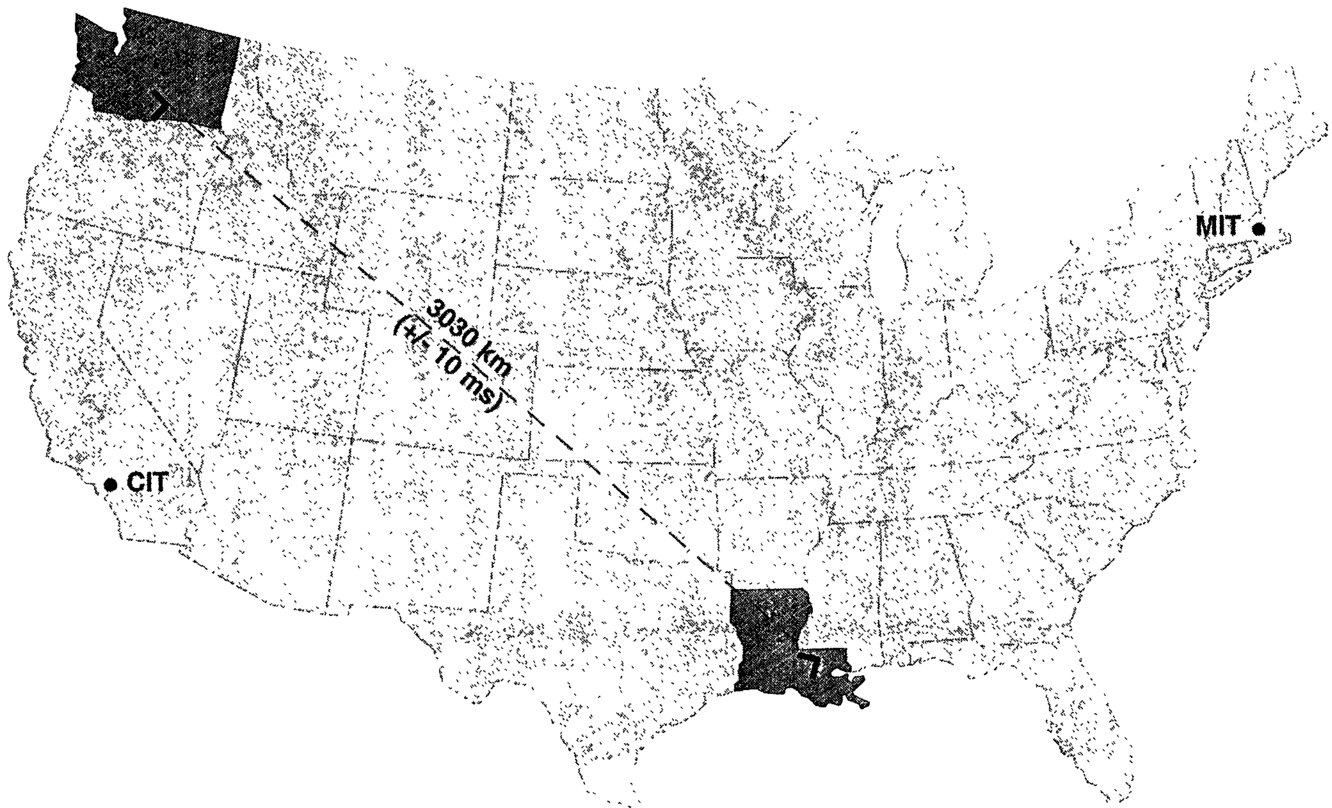
LIGO Detector Spectral Noise Density



LIGO Interferometer Configuration



Two LIGO Observatory Sites



This Talk

- Technical Status
- Cost/Schedule Status
  - ››covered mainly in this talk as emphasis in this review is technical
- Evolution of LIGO Organization
  - ››LIGO Scientific Collaboration and LIGO Laboratory
    - – Hanford Observatory operating organization is functioning
  - ››LIGO Program Advisory Committee

LIGO Construction is 65% complete!

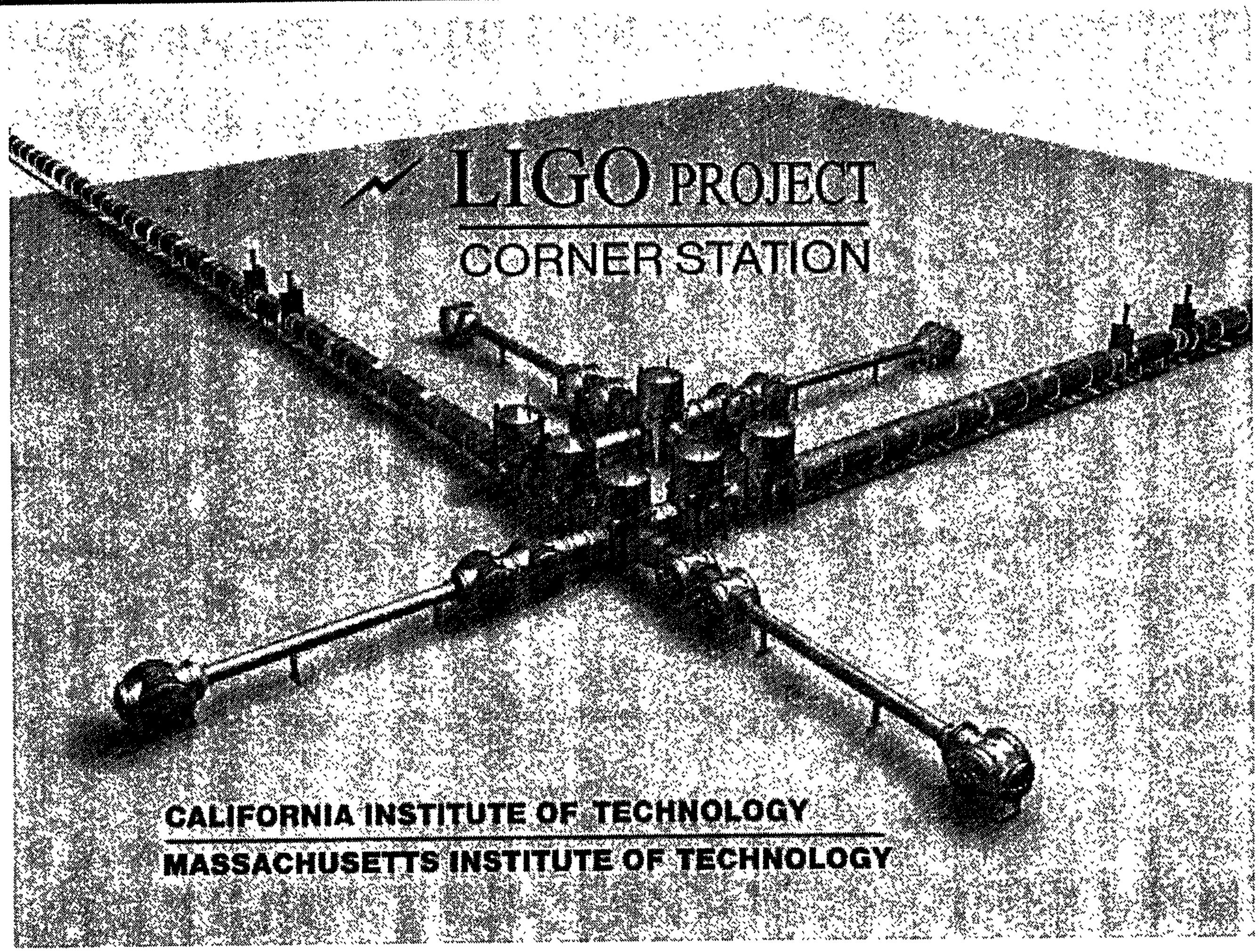
Project Manager's View: Status of the Project

- LIGO Project performance close to baseline cost/schedule
- Facility bid jeopardy passed at time of last review
- Technical risks in facility construction have been managed
- Facility/Integration Groups have managed many "workarounds"
- Hanford site entering Operations phase
- Detector design reaching firm definition
- Industrialization of detector is underway
- Many technical risks in design have been resolved
- Remaining technical risks and bid jeopardy resolved by next review - readiness for detector installation

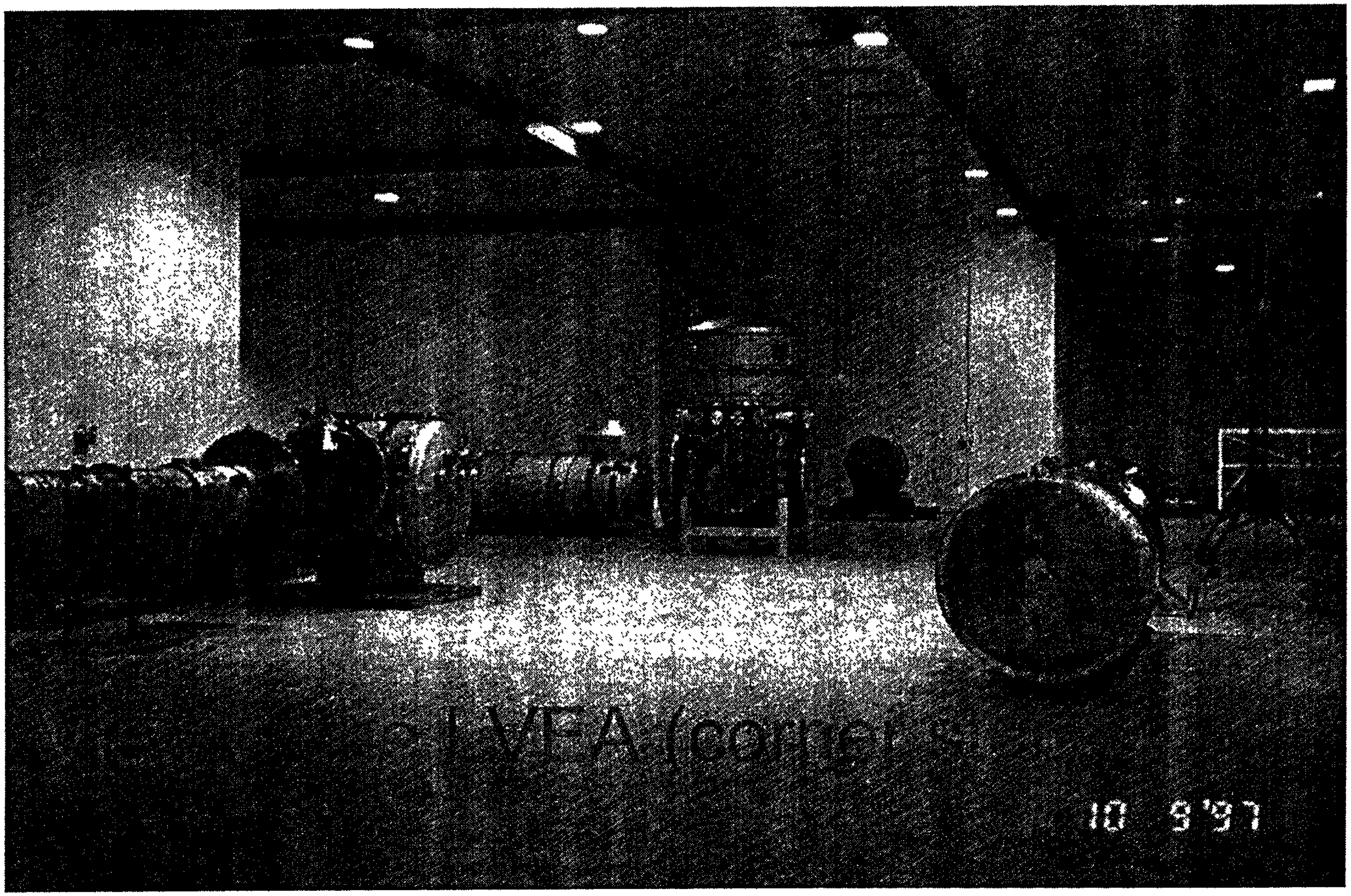
Technical Highlights - Vacuum Equipment

- Vacuum Chambers
  - ›› Hanford vacuum equipment complete and being installed on site
  - ›› Livingston vacuum equipment complete early in 1998
- Gate Valves
  - ›› Hanford valves installed
  - ›› First Livingston valves installed
    - – others awaiting shipment when buildings are ready
- Pump sets in use to pump beam tube acceptance tests

Vacuum Equipment System Cartoon



Vacuum Equipment Is At Hanford



Technical Highlights - Beam Tube

- Hanford Beam Tube Complete
  - ›› X arm 2 km modules passed prebake outgassing and alignment
    - —Viton outgassing appears to provide limit to leak detection sensitivity, but well below our requirements
  - ›› Y arm acceptance test underway
- All baffles installed at Hanford after resolving glass coating and weld cracking problems
- Livingston beam tube fabrication underway
- Livingston Installation is ready to proceed
  - ››Installation Readiness Review successfully completed last week

Outgassing Result From First 2 km Module

Table 1: Prebake Outgassing Rates (torr liters/sec cm^2)

gas	measured at 1100 hrs	assumed 1/t	comments
H_2	**$< 7.4 x 10^{-14}$**		larger than QT by 2 max correction for ordinary 304 SS 2.7×10^5 cm^2 at $J(H_2) = 1 \times 10^{-11}$ $J_{equiv}(H_2) < 3.5 \times 10^{-14}$
CO	6.9×10^{-15}	7.6×10^{-12} / t(hr)	smaller than QT by 10
CO_2	1.9×10^{-14}	2.1×10^{-11} / t(hr)	smaller than QT by 2
CH_4	5.2×10^{-16}	5.6×10^{-13} / t(hr)	larger than QT by 4
H_2O		8.0×10^{-9} / t(hr)	*see table 7 and 8* smaller than QT by 2
Hydrocarbons $\sum 41, 43, 55, 57$		$8 \times 10^{-3} * J(H_2O)$	larger than QT by 2

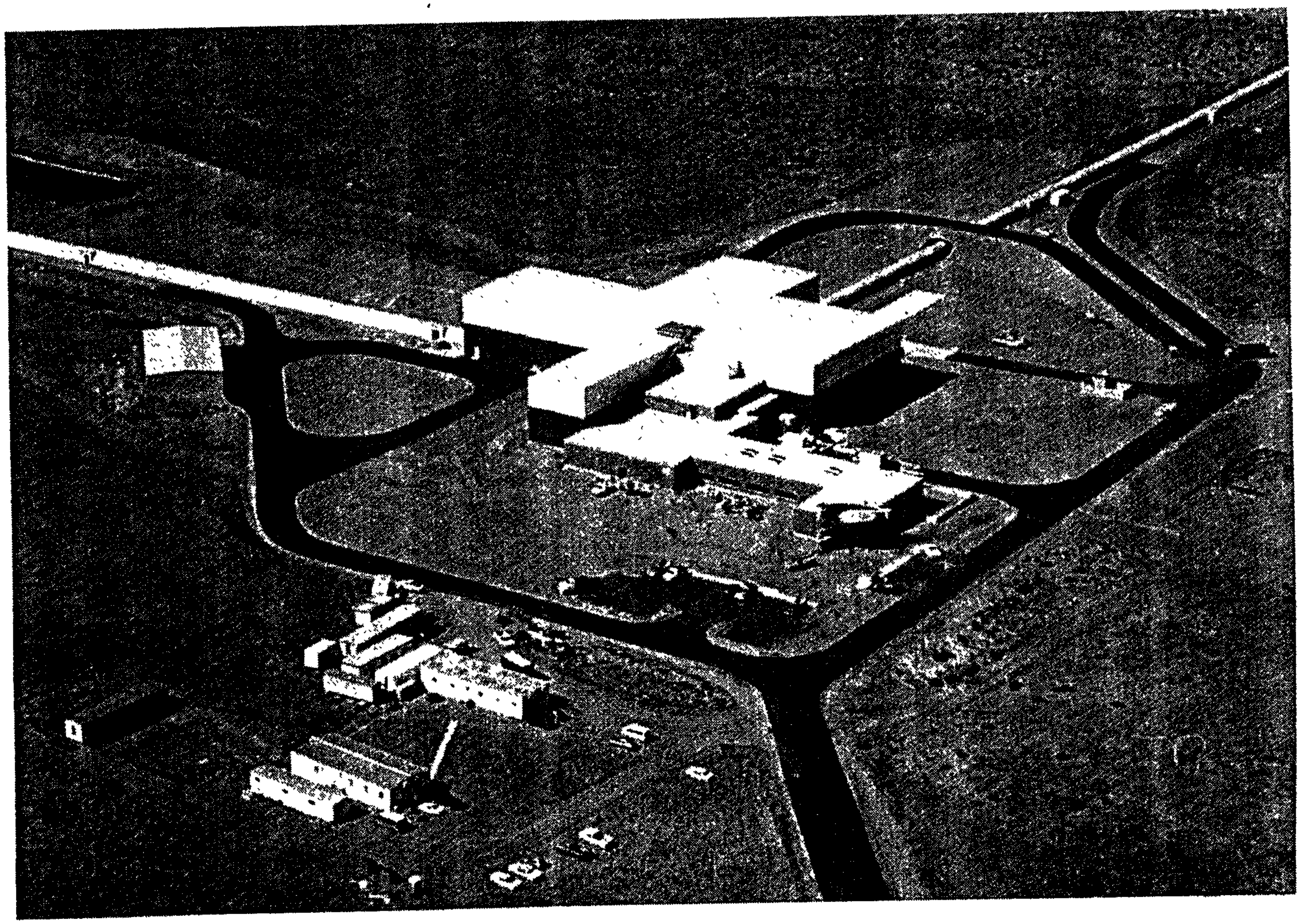
Technical Highlights - Hanford Civil Construction

- Hanford beam tube enclosures construction complete
- Hanford site buildings are complete, testing is underway
- Hanford buildings are all in joint occupancy or beneficial occupancy.
- Followon contractors now working in buildings
  - Beam tube bakeout insulation contractor working in enclosure for module X1 - kickoff last week
  - Vacuum equipment installation contractor is working in LVEA and several other buildings
  - Office Support Building (OSB) furniture is inside and offices are being occupied
  - Computer network is being brought online

Artists Concept of Corner Station - Aerial View

PHOTO SHOWN HERE

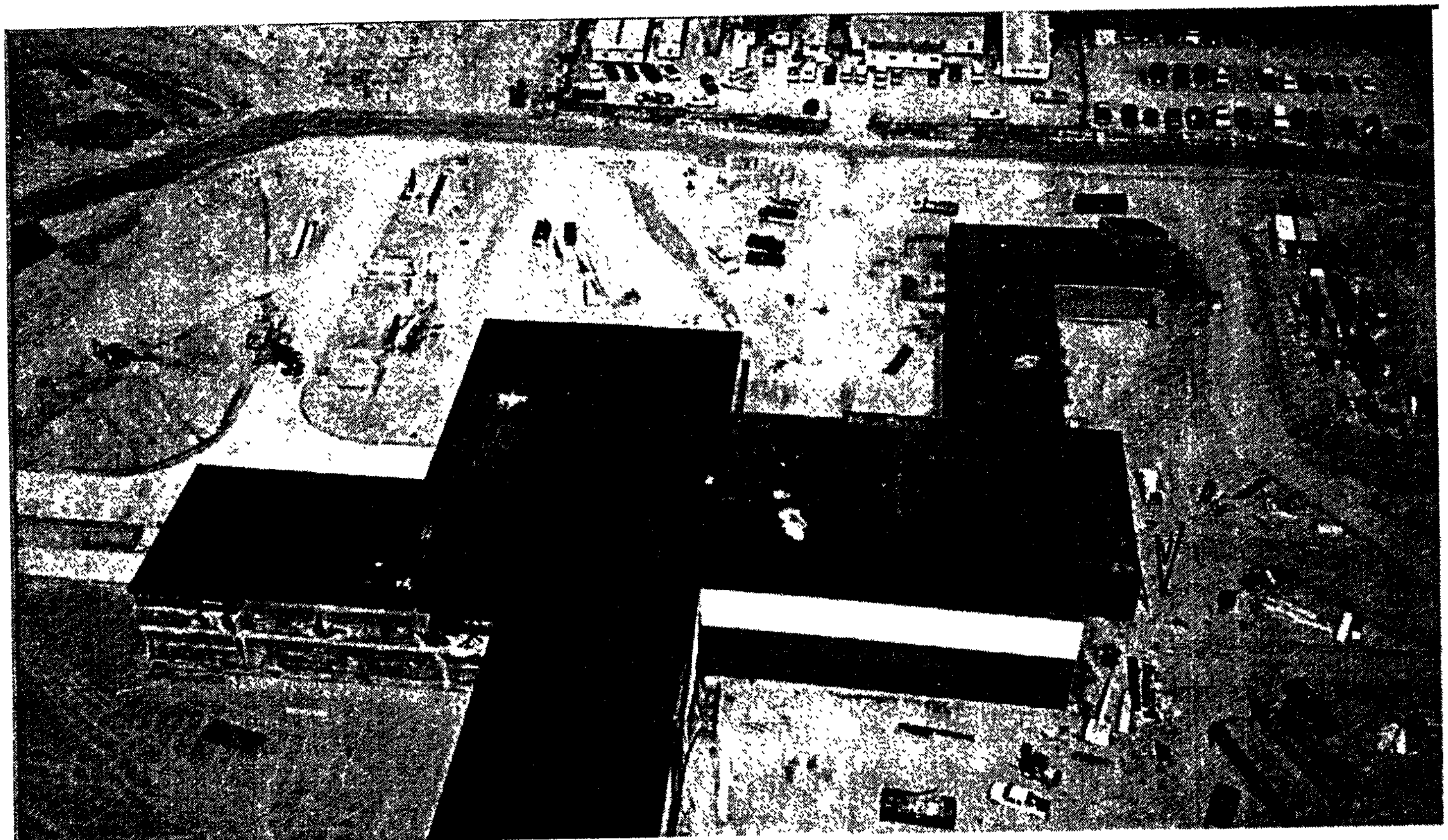
Hanford Corner Station Aerial View



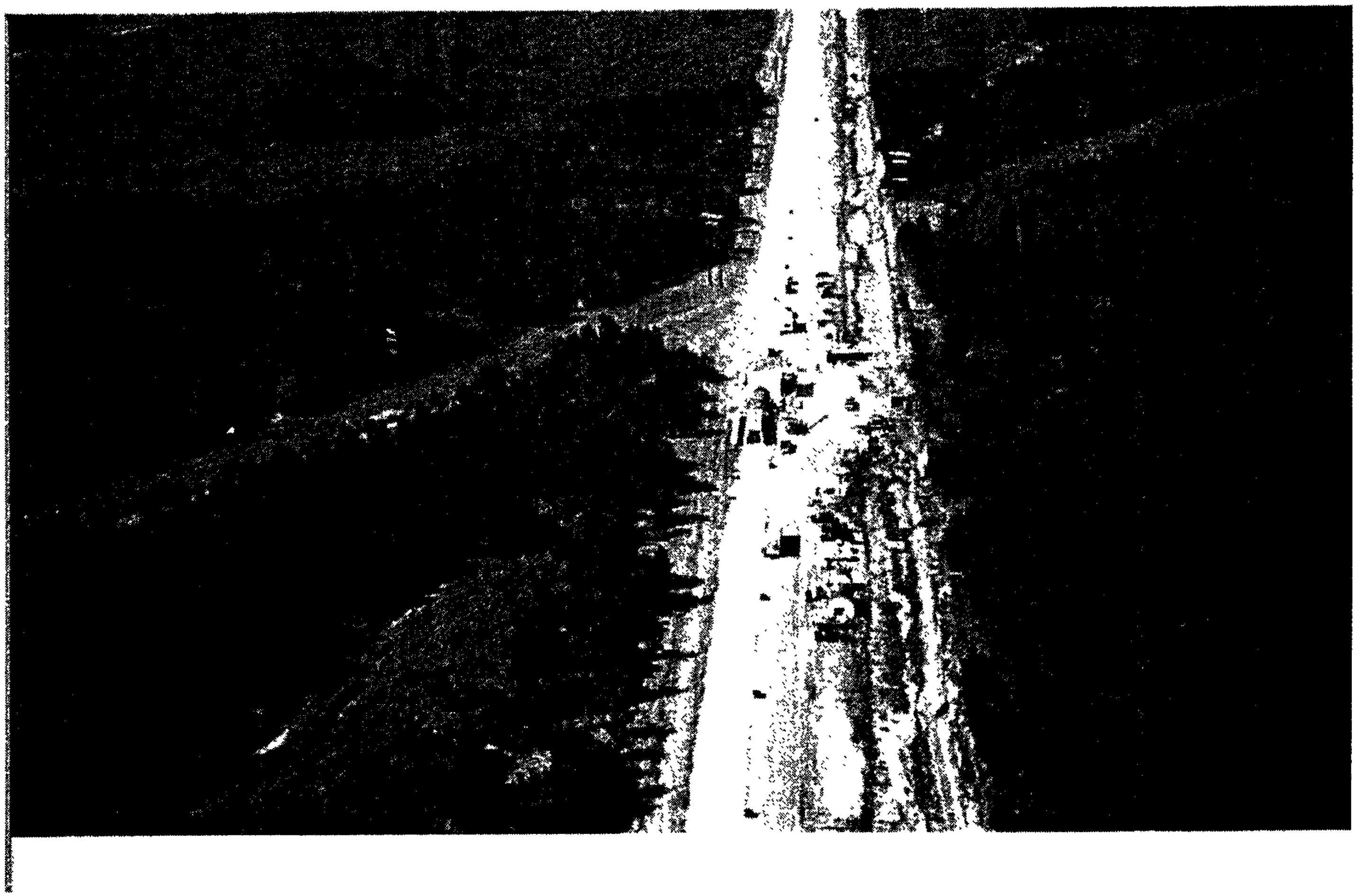
Technical Highlights - Livingston Construction

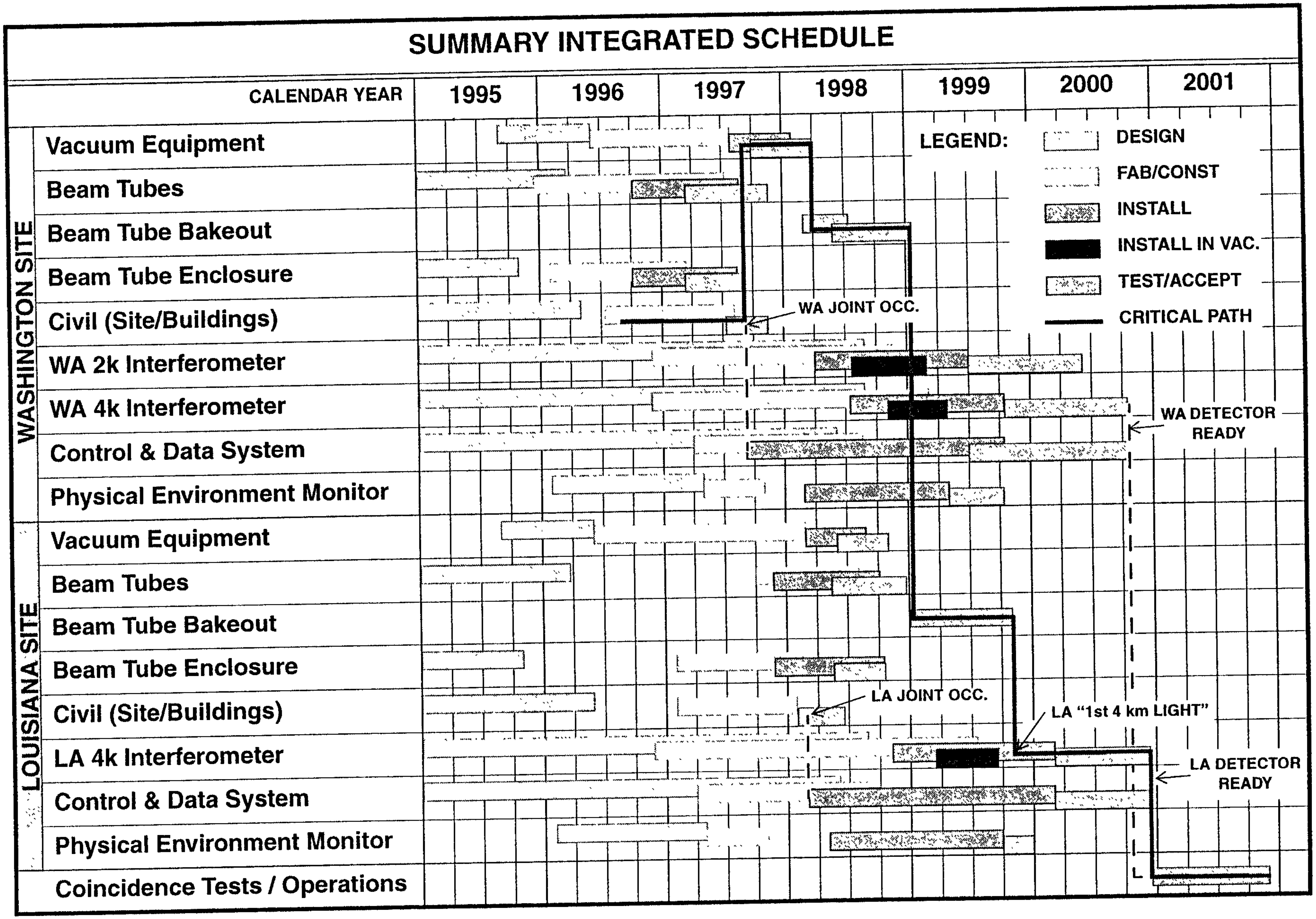
- First arm slab is complete
- Second arm slab is under construction
- Livingston buildings are in advanced stages of construction and are ahead of schedule
- Site access road problems have been successfully managed
- Site schedule coordination has dealt with several schedule disconnects and conflicts, preserving schedule

Livingston Corner Station



Livingston Beam Tube Installation




SUMMARY INTEGRATED SCHEDULE
CALENDAR YEAR
1995
1996
1997
1998
1999
2000
2001
WASHINGTON SITE
Vacuum Equipment
Beam Tubes
Beam Tube Bakeout
Beam Tube Enclosure
Civil (Site/Buildings)
WA 2k Interferometer
WA 4k Interferometer
Control & Data System
Physical Environment Monitor
LOUISIANA SITE
Vacuum Equipment
Beam Tubes
Beam Tube Bakeout
Beam Tube Enclosure
Civil (Site/Buildings)
LA 4k Interferometer
Control & Data System
Physical Environment Monitor
Coincidence Tests / Operations
LEGEND:
DESIGN
FAB/CONST
INSTALL
INSTALL IN VAC.
TEST/ACCEPT
CRITICAL PATH
WA JOINT OCC.
WA DETECTOR READY
LA JOINT OCC.
LA "1st 4 km LIGHT"
LA DETECTOR READY

Technical Highlights - R&D

- MIT Phase Noise Interferometer

  ››Demonstration of phase sensitivity *~2 x* 10^{-10} *rad/√Hz,* with 150 W circulating 1064 nm light power

- CIT 40 Meter Interferometer

  ››Power recycled Michelson is running with recycling gain ~4

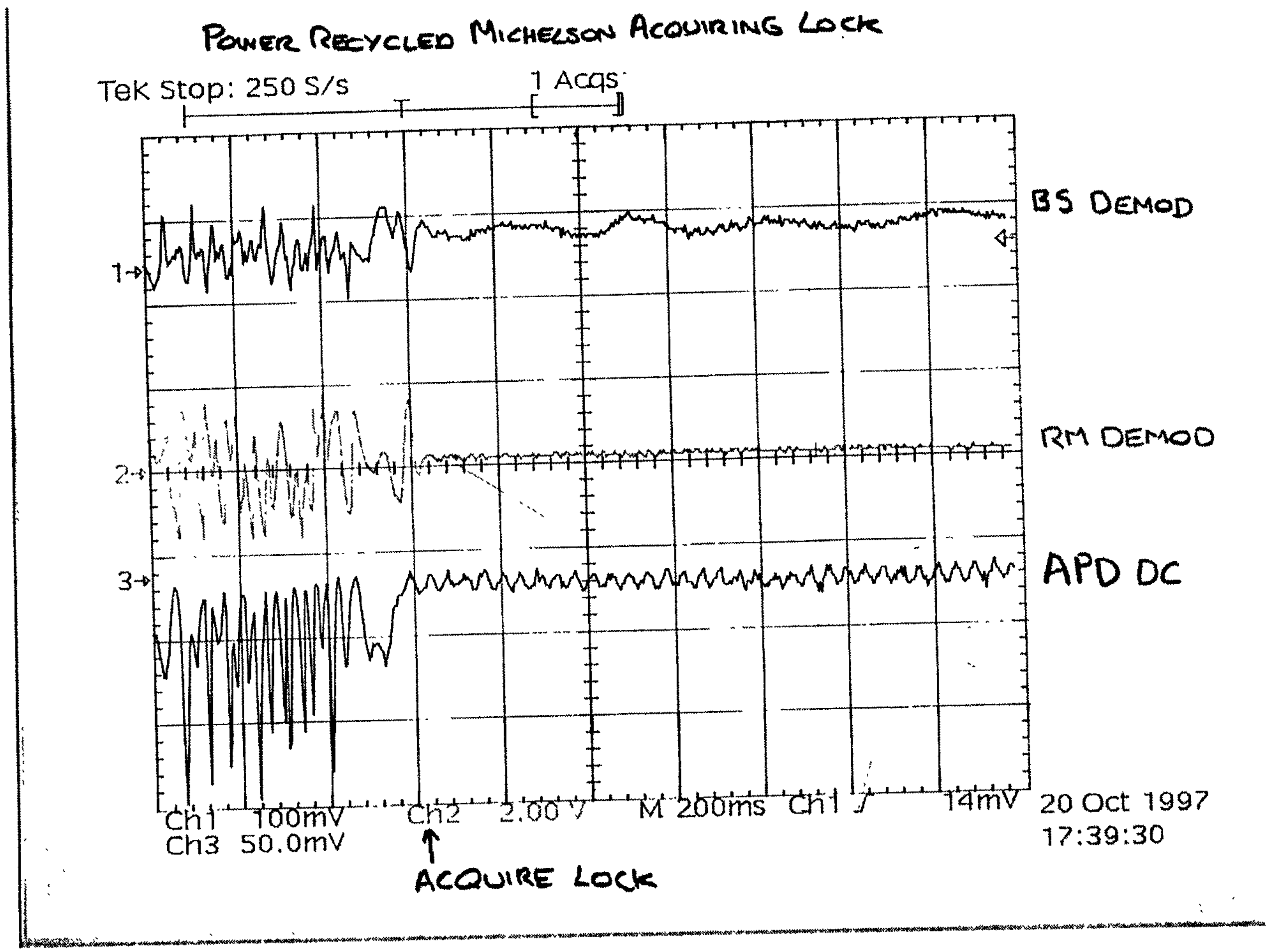
  —Lock acquisition guided by LIGO modeling

  —Fabry Perot cavities to be added next

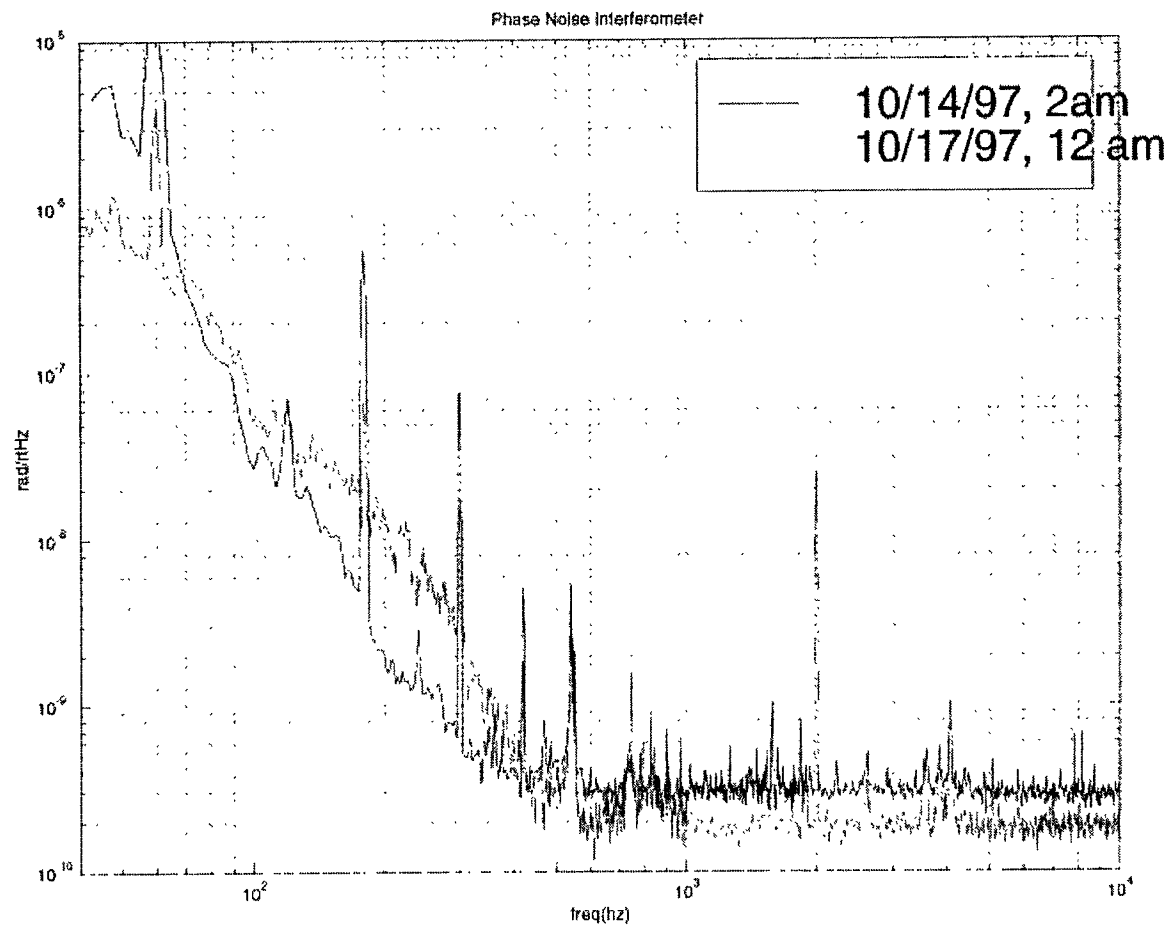
  ››LIGO end-to-end model has successfully reproduced single cavity response

  — more modeling tests planned

Power Recycled Michelson Acquiring Lock



Phase Noise Sensitivity From MIT Interferometer



Technical Highlights - Detector

- 10 W laser delivered by Lightwave Electronics; meets our power and noise requirements
- Most Corning and Heraus glass for core optics is delivered
  - ›› absorption requirements met
- Polishing and coating underway
- Seismic isolation fabrication contracts are being initiated
  - ››“creak” testing of springs carried out with encouraging results
  - ››“First Article” fabrication initiated

Technical Highlights - Detector

- Final designs for Length and Alignment Sensing and Control Systems underway
- Small Optics Suspension fabrication initiated
- Large Optics Suspension ready to bid mechanical fabrication
- Final design of Control and Data System global achitecture nearing completion
- Vacuum Control and Monitoring System complete and being readied for use in Hanford

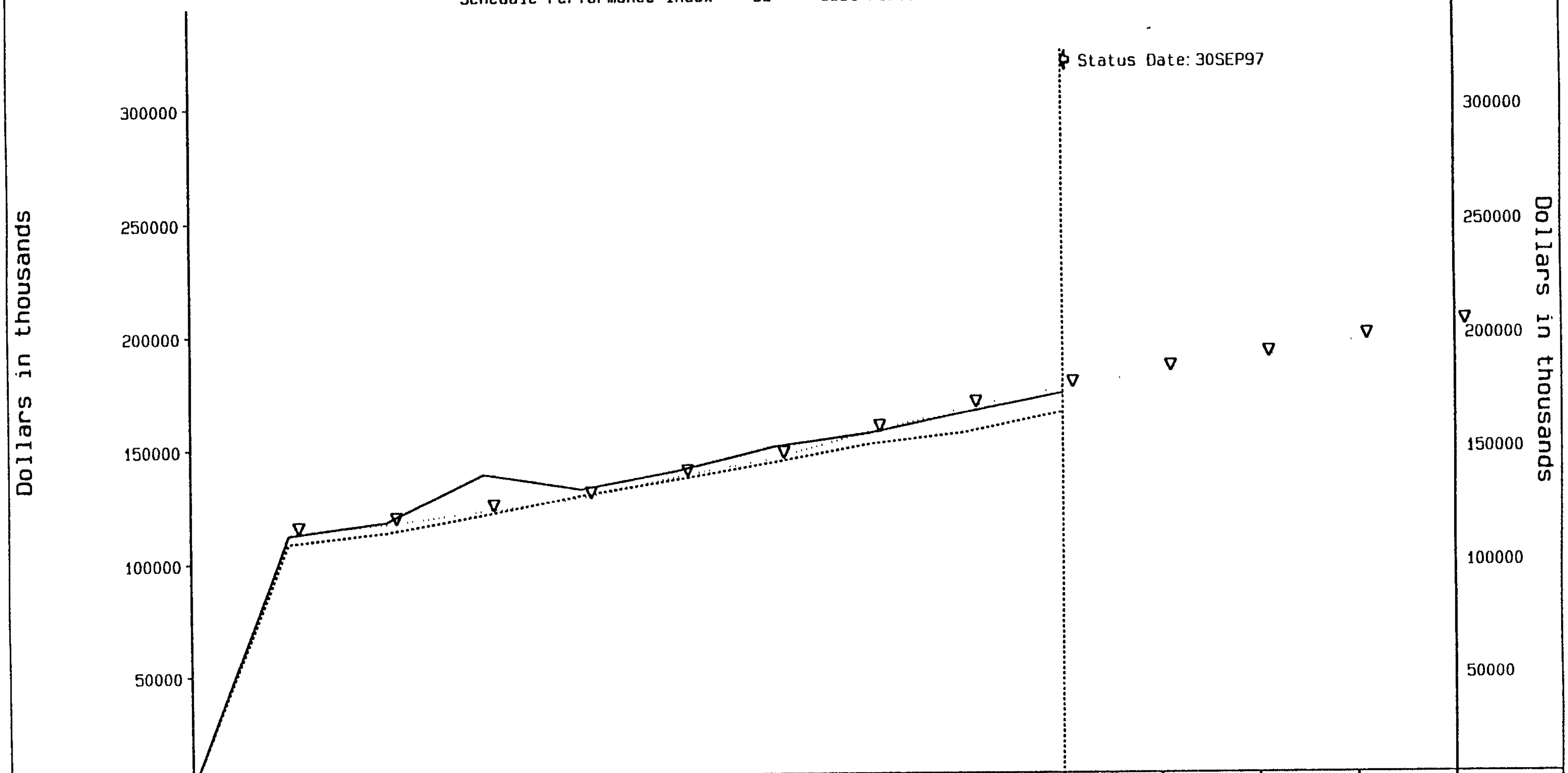
LEGEND	
Bud	▽ ▽ ▽
Per	————
Act	········

LIGO PROJECT
1 LIGO Construction

Date: 24OCT97
Program PMB_0997
Report. LIGOSPA
COBRA (R)

Budget vs Performance vs Actual

Schedule Performance Index = 99   Cost Performance Index = 105



	JAN97	FEB97	MAR97	APR97	MAY97	JUN97	JUL97	AUG97	SEP97	OCT97	NOV97	DEC97	JAN98	SCALE
Planned Budget	113,141	117,209	122,895	128,420	137,769	145,508	156,655	167,074	175,737	182,857	189,105	196,722	203,020	K$
Performance	112,153	118,208	139,121	132,413	140,321	150,487	156,277	165,098	173,375					K$
Actuals	108,646	113,436	121,244	129,596	136,466	143,809	151,490	156,355	165,063					K$
Schedule Variance	- 988	999	16,226	3,993	2,552	4,979	- 378	-1,976	-2,362					K$
Cost Variance	3,507	4,772	17,877	2,817	3,855	6,678	4,787	8,743	8,312					K$

Schedule Variance = Perf-Budg   Cost Variance = Perf-Actual   Schedule Performance Index = Perf/Budg   Cost Performance Index = Perf/Actual

Run Date: 23OCT97 COST / SCHEDULE STATUS REPORT (CSSR)

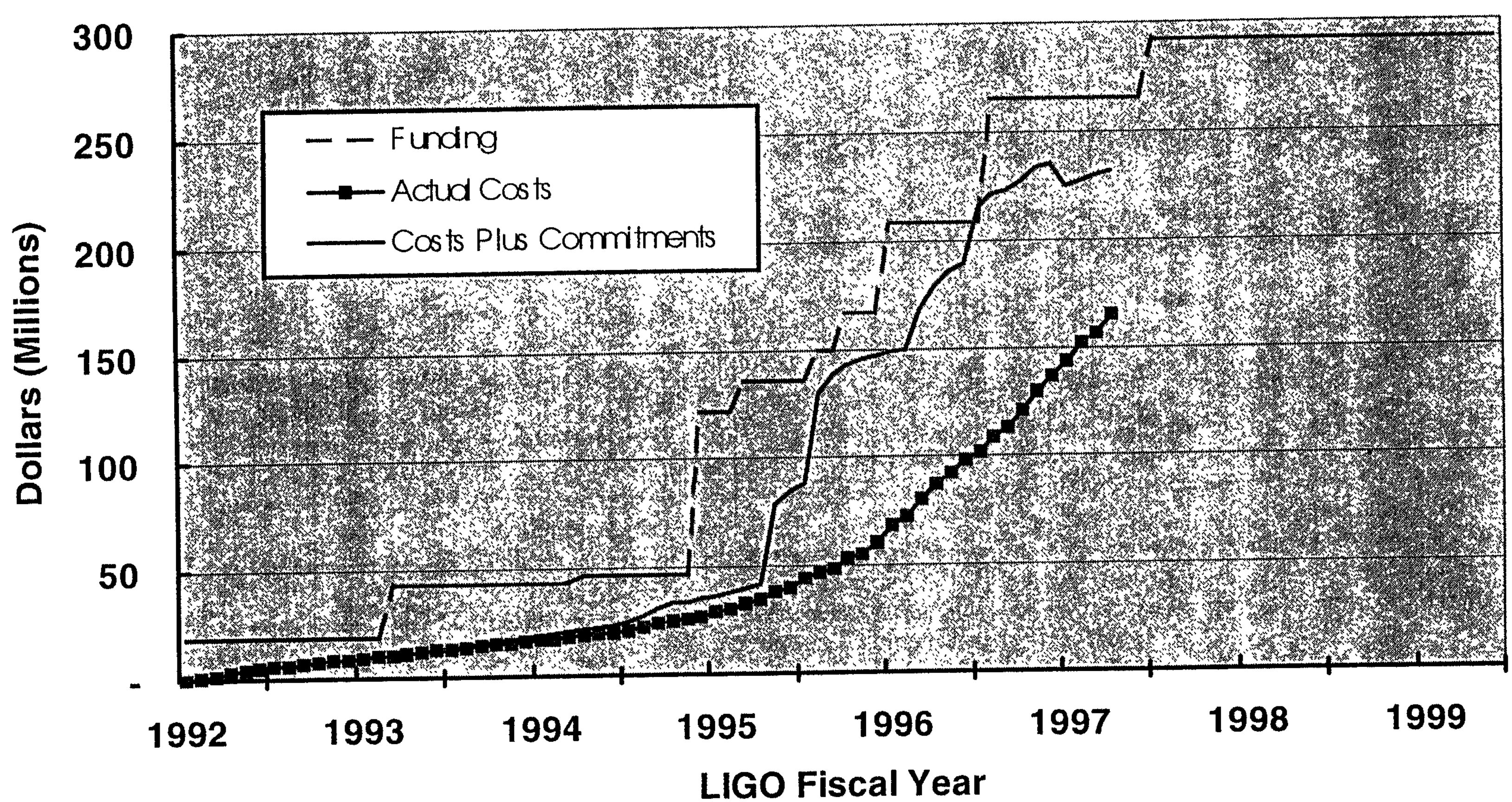
CONTRACTOR: Caltech LOCATION: Pasadena, CA	CONTRACT NUMBER: PHY-9210038	CONTRACT BUDGET BASELINE 292,100,000	REPORTING PERIOD: 31AUG97-30SEP97	PROJECT FILE NAME: LIGO Master Merged PMB - WBS 1.0

PERFORMANCE DATA (K$s)

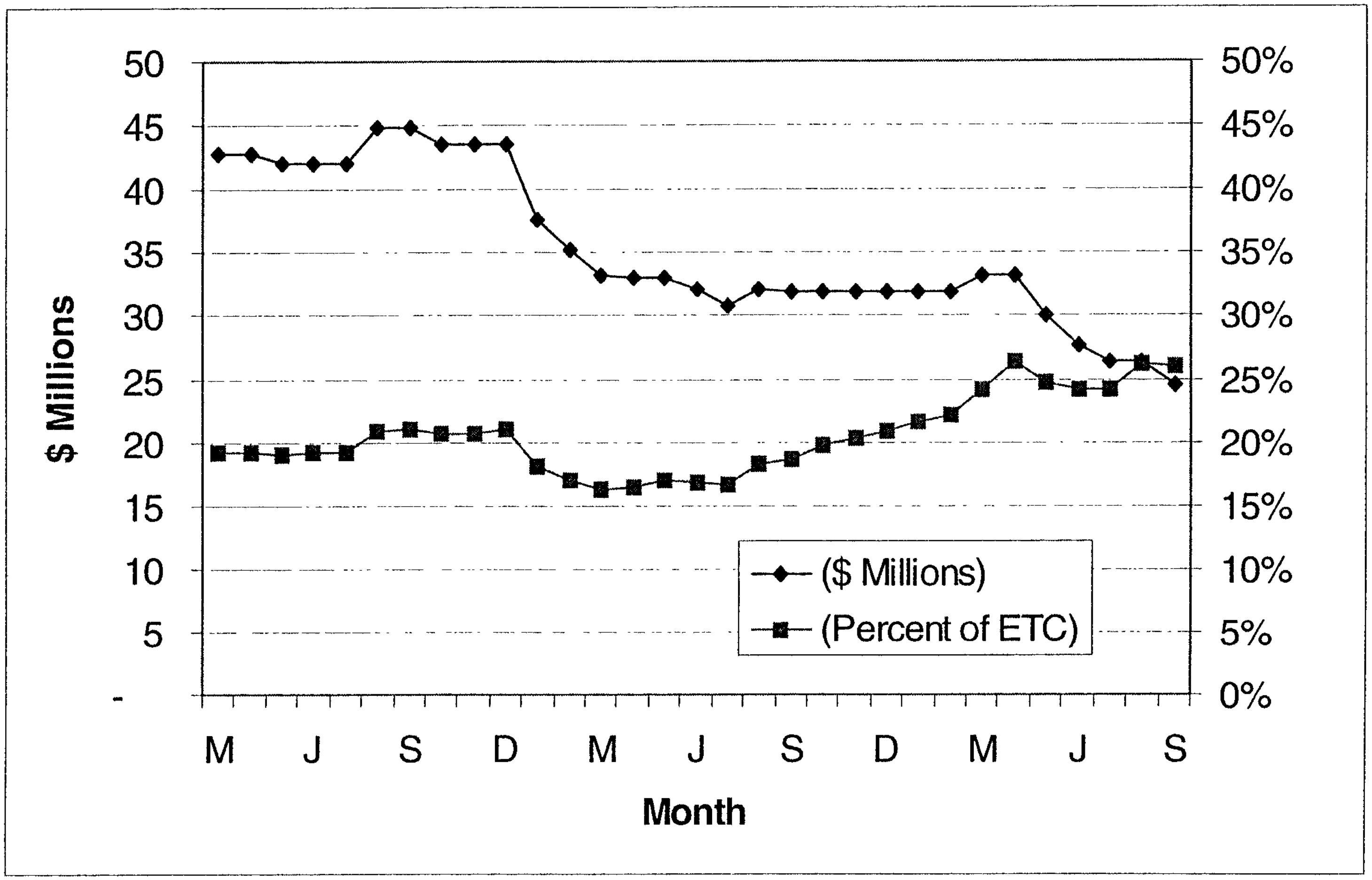
REPORTING LEVEL	CUMULATIVE TO DATE					AT COMPLETION		
MPR LEVEL	BUDGETED COST		ACTUAL COST	VARIANCE		BUDGET	ESTIMATE	VARIANCE
	WORK SCHEDULED	WORK PERFORMED	WORK PERFORMED	SCHEDULE (2-1)	COST (2-3)	(BAC)	(EAC)	(6-7)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.1.1 : Vacuum Equipment	31032	32099	28066	1067	4033	42763	42763	0
1.1.2 : Beam Tubes	31302	30924	30290	(378)	634	45047	45047	0
1.1.3 : Beam Tube Enclosur	14623	14109	14038	(513)	72	19796	19796	0
1.1.4 : Facility Design &	39631	39810	38427	180	1383	48581	48581	0
1.1.5 : Beam Tube Bake	0	0	0	0	0	4005	4005	0
1.2 : Detector	17394	14855	12825	(2539)	2030	54957	54957	0
1.3 : Research & Developme	20526	20348	19457	(178)	891	23490	23490	0
1.4 : Project Office	21229	21229	21960	0	(732)	27074	27074	0
SUBTOTAL	175737	173375	165063	(2362)	8311	265714	265714	0
CONTINGENCY						0	26386	(26386)
MANAGEMENT RESERVE						26386	0	26386
TOTAL	175737	173375	165063	(2362)	8311	292100	292100	0

COBRA (R) by WST Corp.

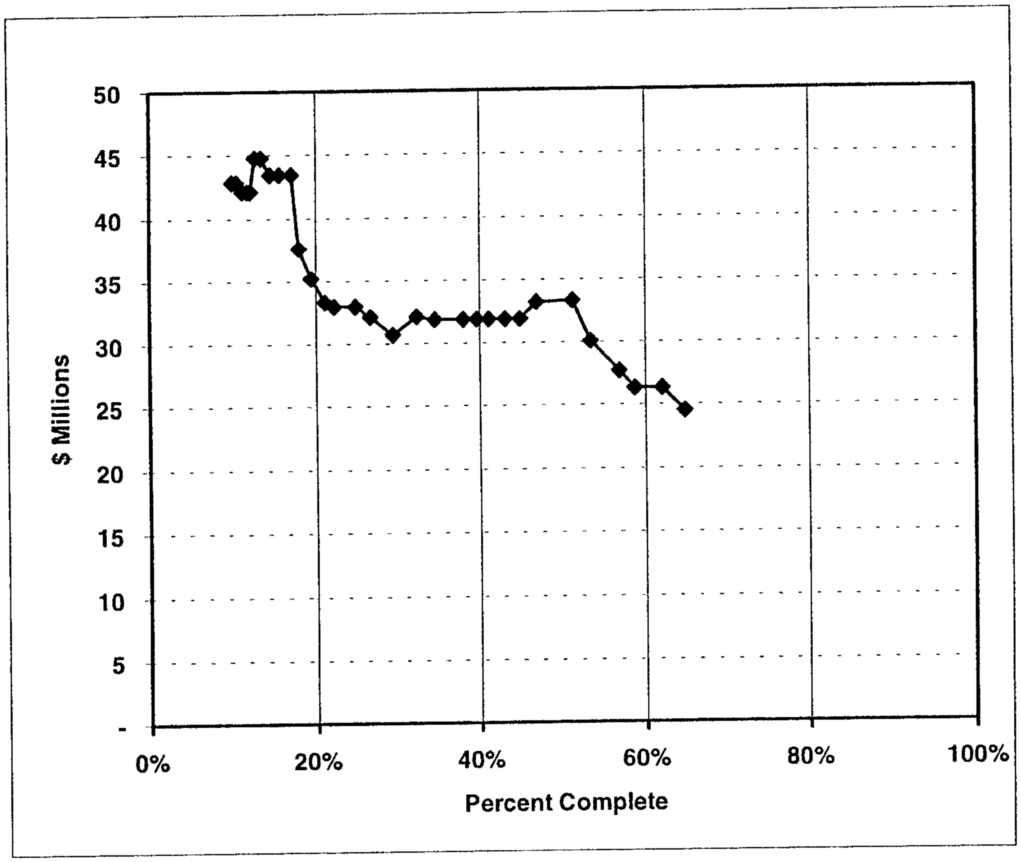
Funds, Commitments, Costs



Contingency vs. Estimate to Complete



Contingency vs. Percent Complete (through September 1997)



LIGO Funding by NSF Task and by Year

Fiscal Year	*Construction*	*R&D*	*Operations*	*Advanced R&D*	*Total*
Thru 1994	35.9	11.2			47.1
1995	85.0	4.0			89.0
1996	70.0	2.4			72.4
1997	55.0	1.6	0.3	0.8	57.7
1998	26.2	0.9	7.3	2.7	37.0
1999			20.9	2.8	23.7
2000			21.1	2.9	24.0
2001			19.1 (10 months)	2.9	22.0
Total	272.1	20.0	68.7	12.1	372.9
All funds shown in 'then-year' $M					

Costs and Commitments through September 1997

(All Entries are $ Thousands)

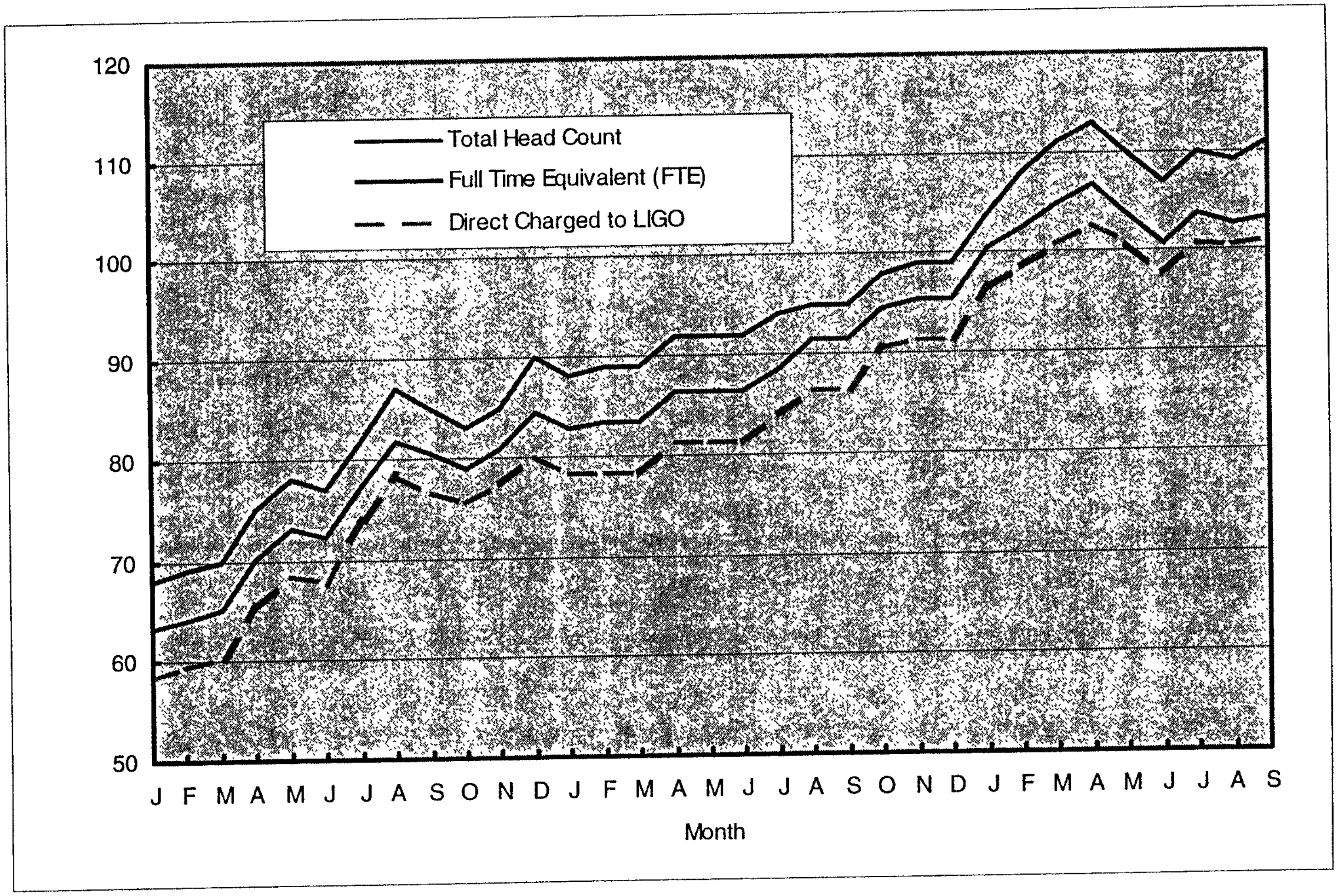
WBS	Costs Thru Nov 1996	First Quarter LFY 1997	Second Quarter LFY 1997	Third Quarter LFY 1997	Sep-97	Cumulative	Open Encumbrances	Total Cost Plus Commitments
1.1.1	21,254	956	3,646	1,758	452	28,066	17,787	45,853
1.1.2	17,262	4,795	3,687	3,796	777	30,316	16,062	46,378
1.1.3	6,237	958	2,933	1,747	2,162	14,038	7,383	21,421
1.1.4	14,117	4,705	7,555	8,659	3,391	38,427	13,555	51,982
1.2	6,270	1,521	2,267	1,720	1,072	12,850	8,062	20,912
1.3	16,816	845	802	732	261	19,457	1,442	20,899
1.4	16,288	1,452	2,102	1,543	576	21,960	2,084	24,044
7LIGO	2	(0)	8	(2)	(9)	(1)	16	15
TOTAL	98,246	15,231	23,000	19,954	8,682	165,113	66,392	231,505
Cumulative Actual Costs	98,246	113,477	136,477	156,431	165,113			
Open Commitments	91,492	109,800	98,775	73,606	66,392			
Total Costs plus Commitments	189,738	223,277	235,252	230,037	231,505			
NSF Funding	$ 208,468	$ 265,389	$ 265,389	$ 265,389	$ 265,389			

Note: Unassigned costs have not been assigned to a LIGO WBS, but are continually reviewed to assure proper allocation.

Major Detector Subcontracts

Subcontract	Award Date	Award Amount	Selection Basis
Nd3+ Lasers - Lightwave Electronics	May 1996	$735K	Competitive
Fused Silica Mirror Blanks - Heraeus Amersil	August 1996	$1230K	Competitive
Fused Silica Mirror Blanks - Corning, Inc.	August 1996	$360K	Competitive
Seismic Isolation Stack Development - Hytec	August 1996	$1865K	Change Order
Optics Polishing	October 1996	$65K	Competitive FFP
Full Service Polishing	December 1996	$1250K	Change Order
Optics Coating	Spring 1997	$1700K	Change Order
Detector Stack Fabrication	Winter 1997	$8000K	Competitive FFP
10W Lasers	Winter 1997	$500K	Change Order
Suspension System Fabrication	Winter 1997	$2900K	Competitive FFP
IOO Fabrication (University of Florida)	Winter 1997	$1300K	Change Order
Optical Modeling	Winter 1996	$200K	Change Order NTE
Metrology (NIST)	Winter 1996	$200K	Change Order NTE
Suspension System Fabrication	Winter 1997	$2900K	Competitive FFP
COS Telescopes	Spring 1998	$150K	Competitive FFP
In Vacuum Cables	Winter 1997	$100K	Competitive FFP
Network Installation - Hanford, Washington	Winter 1997	$100K	Competitive FFP

Staffing History



LIGO-G970249-00-M

Summary of Technical Status

- 40 Meter program is still behind schedule (X) but has achieved power recycled Michelson lock with SMAC model agreement ✔
- Input Optics subsystem appears to be progressing under University of Florida leadership ✔
- Heraus glass absorption okay for LIGO low OH glass ✔
- Load tests of springs indicate no “creaking” ✔
- Data simulation program has program schedule ✔
- Data analysis program has schedule and requirements ✔
- Baffle installation/retrofit in Hanford is complete ✔

Summary of Technical Status

- Beam tube vibration measurement will be repeated. In preparation.
- System startup and shutdown safety plans initiated.
- Beam tube bakeout design has progressed through PDR.✔
- Gate valve bakeout plan developed. ✔
- Detector support hardware plan is progressing. ✔
- Modulation scheme changed to series modulation. ✔
- In-house optical measurement capability in preparation. ✔
- 10 W laser has arrived. Prestabilized laser integration has begun.

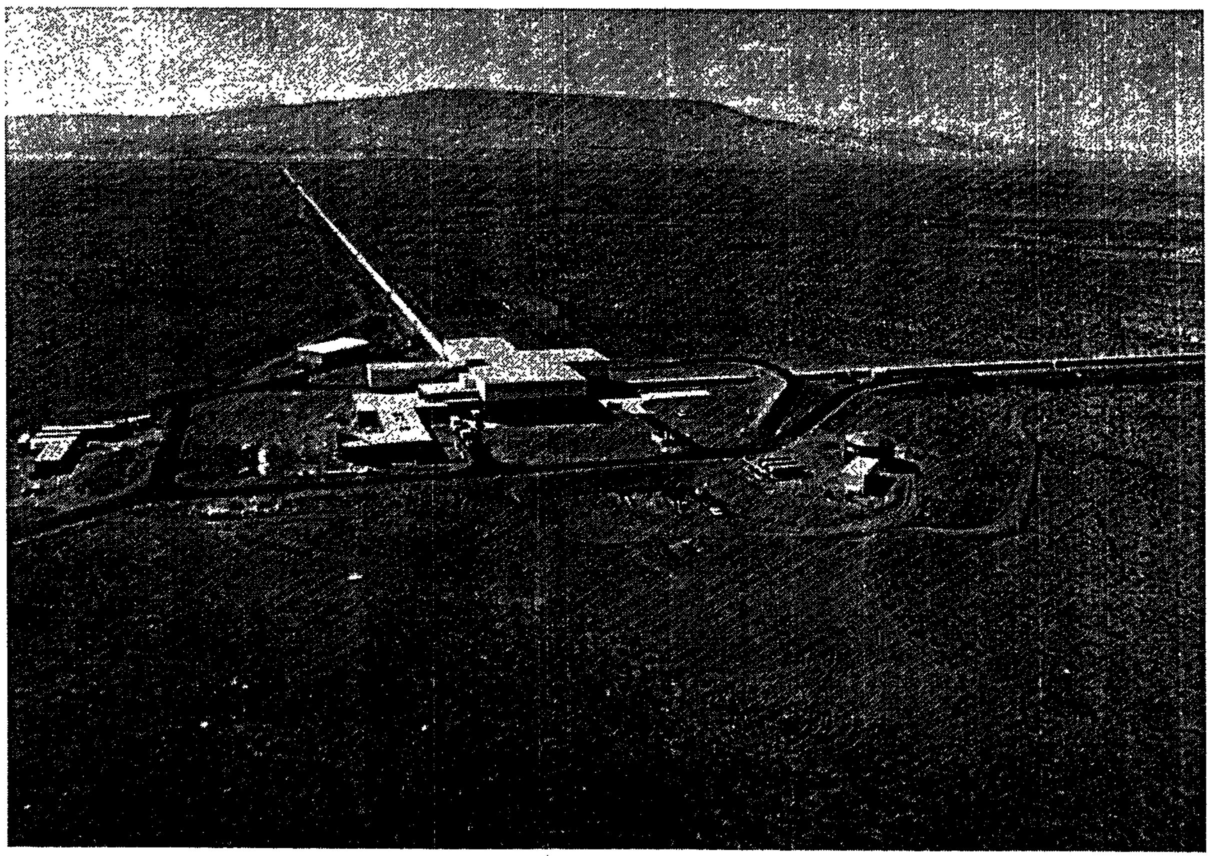
Summary of Technical Status

- 40 Meter Interferometer is operating with power recycling and is being used as an operational testbed and training ground. ✔
- Phase Noise measurement has set a lower record in the infrared and noise sources are being studied carefully. ✔

LIGO Construction is 65% complete!

Status of the LIGO Hanford Observatory (LHO)

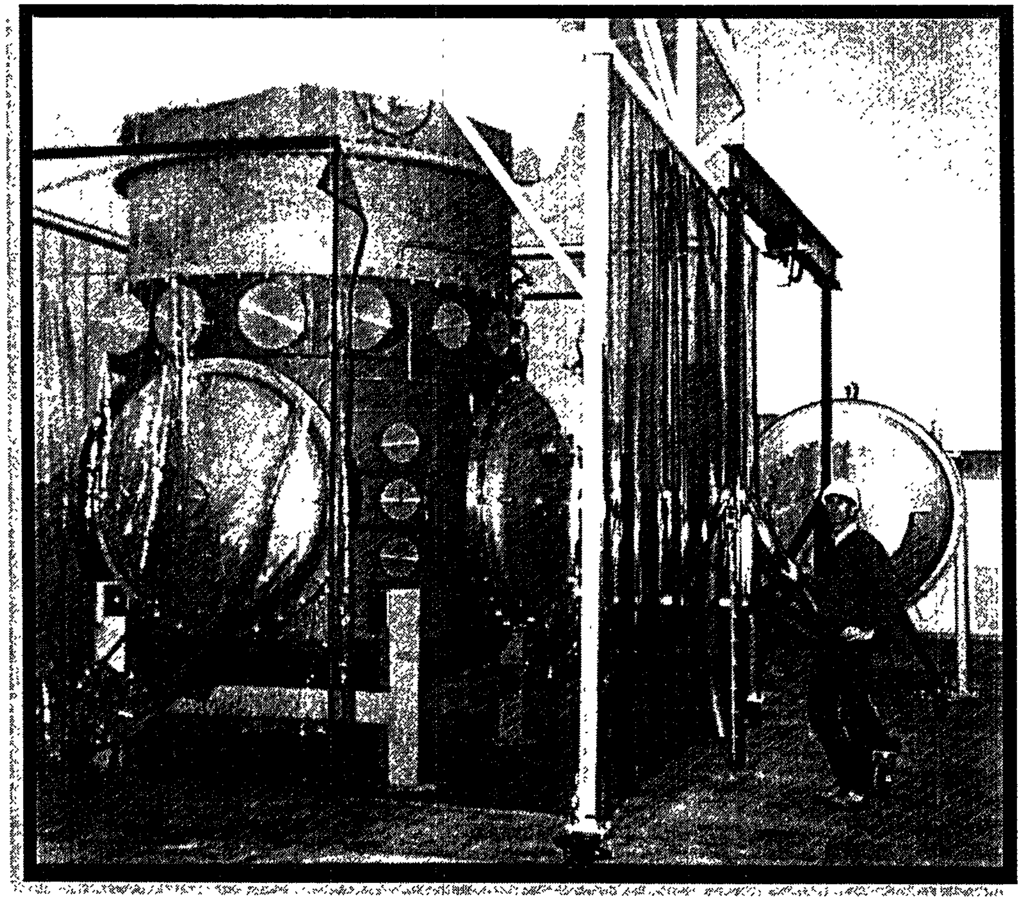
Fred Raab; October 28, 1997



LHO is Now a Real Address

- scientists have begun moving in
- civil construction largely completed
- beam-tube installation & evacuation completed
- vacuum equipment installation underway
- beam-tube bake out preparations underway
- building of the operations staff underway
- focus shifting toward future operations

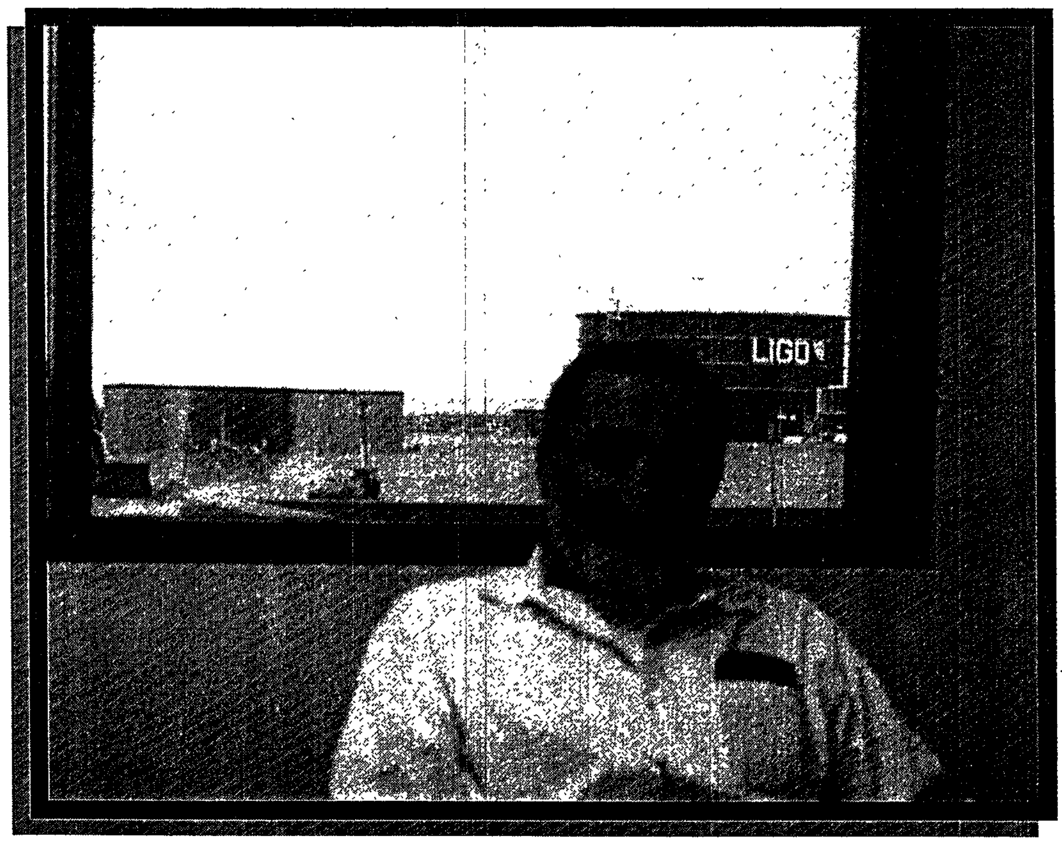
View From Inside LHO Y-End Station



LHO Civil Construction Status

- Y-End Station joint occupancy began 9/8/97
- Y-Mid Station joint occupancy began 9/10/97
- Corner-Station LVEA joint occupancy began 9/8/97
- X-End Station joint occupancy begins today
- X-Mid Station joint occupancy begins today
- Corner-Station OSB joint occupancy begins today; offices are assigned, phones are in and 1st furniture delivery installed
- General Computing Phase 1 Network installation expected by 11/5/97
- LIGO Program Advisory Committee meets at LHO Nov 6,7

Photo of Otto in New OSB Office



Status of LHO Beam Tube

- CB&I completed last beam-tube section 7/97 and moved factory
- CB&I completed beam-tube installation 10/97 and moved office
- all tubes baffled, aligned
- all tubes have held vacuum
- some held better than others
  - ››X2 was leak free
  - ››X1 leak at mid-station gate valved found and repaired
  - ››Y1 found to leak; initiating leak finding routine
  - ››Y2 evacuated and setting up for leak test

Status of LHO Vacuum Equipment

- all X-End Station equipment delivered
- all X-Mid Station equipment delivered
- all Corner-Station equipment delivered for both interferometers, except for WHAM9, WHAM13 and 1 cryopump/bellows assembly
- all LN2 tanks erected; plumbing started
- 2 soft-wall clean rooms commissioned
- clean-air skids for two buildings commissioned
- expect to start bolting chambers down this week
- vacuum-controls system ready, subject to cleaning

Photo of John & Kyle with LVEA Vacuum Equipment

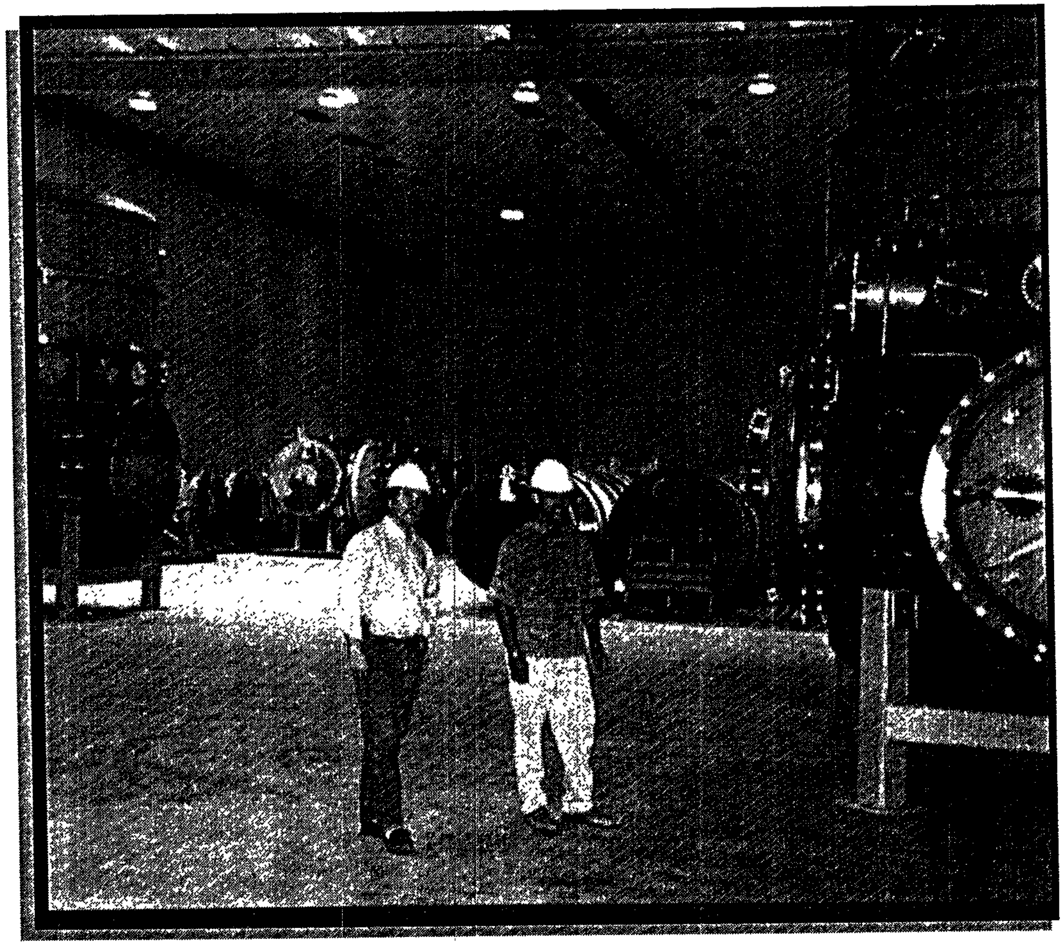
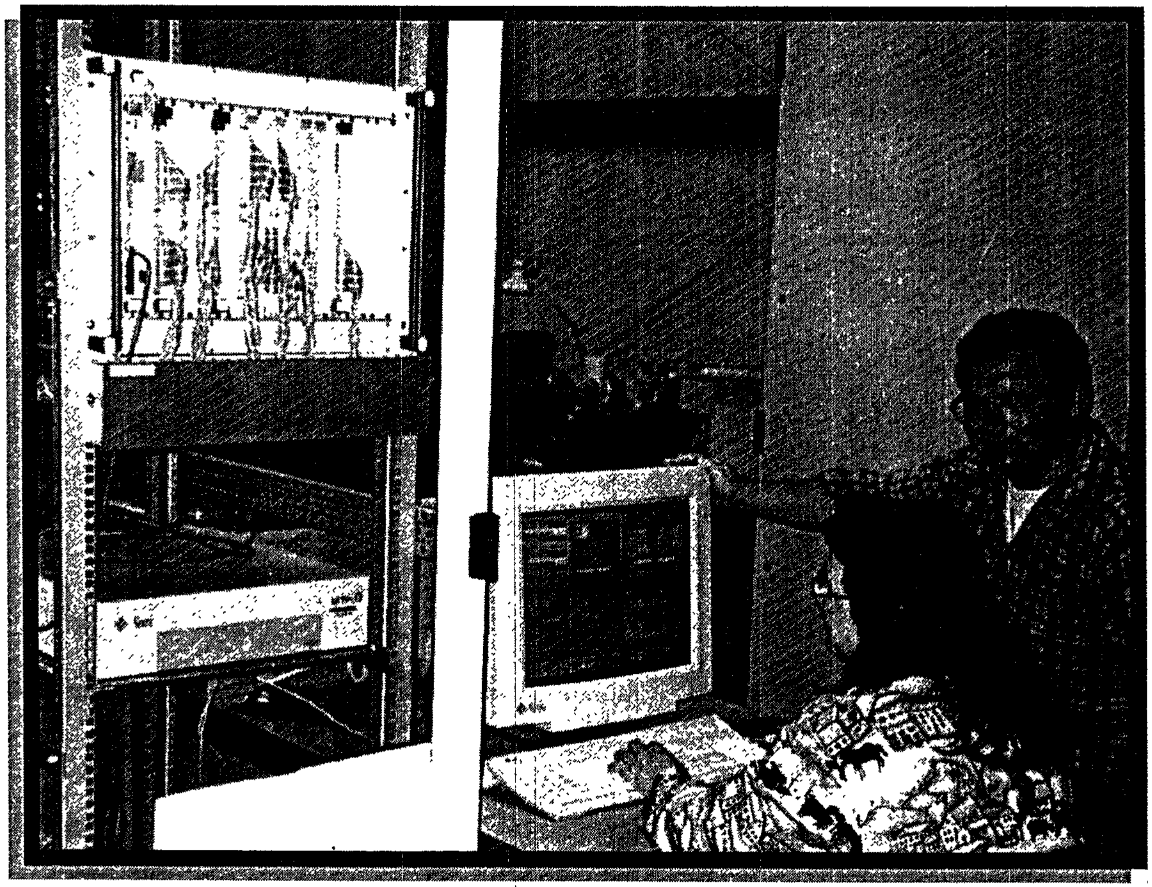


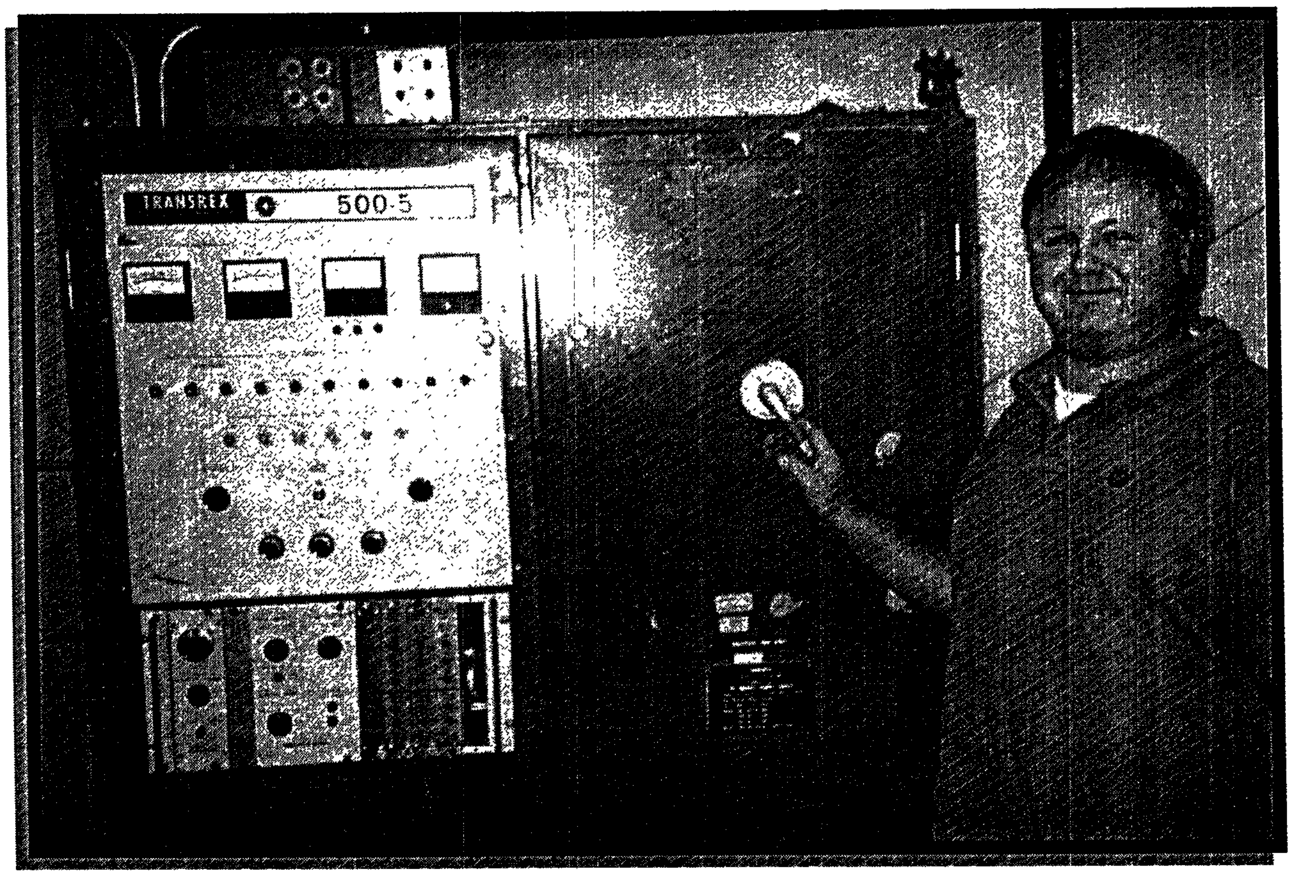
Photo of Dave Barker & Christine Patton with Vacuum Control Racks



Status of LHO Beam-Tube Bake Out

- Preliminary Design completed & reviewed
- Largest major contract (for insulation) signed and work has begun
- Bake-out power supplies (borrowed from Fermi Lab) delivered and stored on site
- 500 KVA transformers for power supplies expected 11/97
- Cooling plant for power supplies expected starting in 12/97
- Other major equipment items (RGAs, cryopumps and data acquisition system) nearing end of specification phase

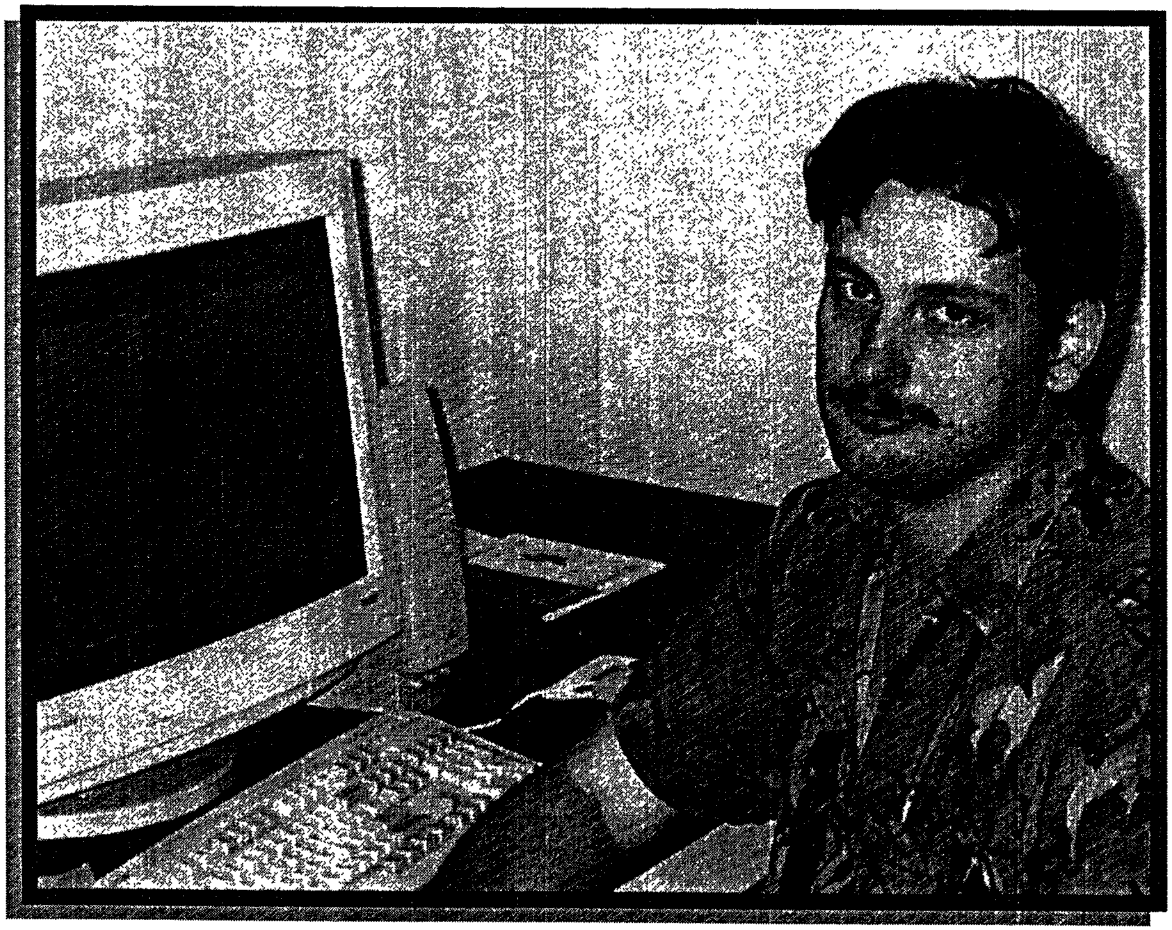
Photo of 'Ski with Bake-out Power Supplies



LHO Staffing Status

Position	Status	Position	Status
Head	Fred Raab	Senior Scientist-2	open
Facilities Manager	Otto Matherny	Scientist-2	open
Vacuum Engineer	John Worden	Scientist-3	open
Senior Scientist	Rick Savage	Ops Specialist -2	open
Scientist	Daniel Sigg	Ops Specialist -3	open
Software Engineer	Dave Barker	Ops Specialist -4	open
Electr. Engineer	Richard McCarthy	Ops Specialist -5	open
Vacuum Specialist	Kyle Ryan	Ops Specialist -6	open
Ops Specialist	Mark Lubinski	Ops Specialist -7	open
Administrative Sec.	open	Ops Specialist -8	open
Optics Specialist	open	Ops Specialist -9	open
Electr. Specialist	open		

Photo of Daniel Sigg



Front-Burner Issues at LHO

- establish General Computing network & infrastructure
- acquire site instrumentation & furnishings
- guide acceptance of facilities
- set up labs & shops to support detector installation
- plan & coordinate detector installation
- staff accordingly

Summary of LHO Status

- Faclities largely constructed and poised for operations
- Construction hand off to Operations peaks in Spring 98
  - ››completion of vacuum equipment installation - March 98
  - ››arrival of prototype laser - April 98
- Significant challenges in next six months
  - ››understand physics of the site & structures
  - ››set up labs & shake down facilities
  - ››hire staff (one position a month)
  - ››coordinate detector installation at sites
  - ››begin beam-tube bake out

NSF Review 10/28/97

LIGO-Livingston Site Status and Plans

Mark Coles

Civil Construction Schedule

- Building construction is within overall site schedule envelope of completion by March 9, 1998

- Hensel-Phelps (Bldg. Contractor) anticipated joint-occupancy dates:

Left Arm end	10/24/97
LVEA	12/31/97
OSB	12/31/97
Right Arm end	1/25/98

Beam tube

- CBI has accelerated the beam tube fabrication and installation schedule.

Activity	*Planned*	*Accelerated*
Start Fab	10/14/97	8/23/97
Start Right arm	12/18/97	10/13/97
Start Left arm	5/21/98	Jan/Feb 98

Beam Tube Factory Status

- Factory demobilized from Pasco in May, 97.
- New 800 foot long building leased by CBI in Magnolia Beach, approximately 23 miles from LIGO site
- Equipment installation began July, 97.
- First tube formed in La on Aug. 20
- Number of tubes fabricated ~ 90 (10 per week)
- Number of tubes leak checked ~ 60 (10 per week)
- Initial cleaning results are acceptable
  - FTIR results about 10% higher than Hanford, on the average ~ 70% of max

Beam Tube Installation Status

- Installation equipment on site ~ Oct 1
- Survey work
  - brass markers at BT-VE interface points installed and measured.
- IRR Review held 10/23/97
- First beam tube welded to valve on 10/17/97

BT Issues

- Good overlap of key staff between Hanford and Livingston, resulting in faster startup.
- Initial CBI concern about skill level of local hires in La -
  - CBI now says they are satisfied with the quality available - it is comparable to Hanford.
- Site access
  - no parallel roads like Hanford.
  - Need to be a good traffic cop

Beam Tube Slab Schedule

- Contract modified to accommodate CBI BT acceleration

Item	WWC contract	Revised	Actual	CBI required
Right arm slab	11/30/97	9/1/97	9/1/97	9/1/97
Left arm slab	5/1/98	1/1/98	12/10/97* (planned)	1/1/98

Note: $160 K acceleration incentive to complete X-arm by 9/1

Left arm detail:

- prepare base course 10/24
- place rebar 10/31
- slab paving 11/25

Beam tube slab

- Flatness - design specs are:
    - +/- 1″ over 100′
    - +/- 1/8″ over 10′
- Right arm meets specs
    - some remedial cutout and replacement was required

Beam Tube Enclosures

- Enclosures manufacturing is on schedule -
  - 900 cast
- Acceptance is behind schedule - this has not been a priority item with Parsons until recently
  - 150 accepted

Vacuum Equipment

- 3 of 5 BSC's mechanically complete ready for cleaning and testing
- 2 of 6 HAM's ready for cleaning and testing
- All four 80K pumps about half complete mechanically
- Manufacturing is comfortably on schedule
- Anticipate VE installation in LVEA in March 98

Issues

- Blistering of foam insulated exterior panels
  - Plan to install shorter length replacement panels with an exterior horizonal joint, subject to demonstration by contractor that this is acceptable/durable. Contractor is proceeding on their own risk in the meantime.

- Fence
  - required to go to CCB for contingency to install cow fencing to keep the livestock off our site. Needed primarily to maintain BT slab elevation (survey string)

- State Access Road
  - Louisiana State was late in their road construction for the LIGO access road. This required us to accept an "unfinished" construction road. State will now finish the road AFTER the construction of LIGO is complete.

Staffing

- 5 full time LIGO staff on site at present for civil construction and beam tube fabrication and installation oversight.
- 2 full time Parsons CM staff plus one additional 2/3 time.
- Plan to make the first scientific staff appointments during 1998, to assist with preparation of lab infrastructure.

LSU Connections

- Beginning to receive some site infrastructure support for computer networking, LSU is providing Internet service to the Livingston site via ISDN
- T1 upgrade next year
- Plans for T3 and links to Illinois NCSA site via SEPSCOR (NSF)
- Exploratory dialog developing on LIGO related educational outreach programs

Summary

- On schedule
  - Livingston is benefitting from Hanford learning curve.

- Tighter site access will be a critical issue that requires close monitoring throughout beam tube installation.

- Development of site staff and utilization of potential LSU resources will be important tasks for the next year.

Data Formats

Data Analysis

and

Modeling Activities

Albert Lazzarini

NSF Fall Review
28 - 30 October 1997

LIGO-G970248-00-E

OUTLINE

- Data Formats for LIGO Detector
  - Status & update
  - New specification and frame software library
  - Implementation at LIGO 40m prototype
  - C++ redesign of library -- user interface(s)

- LIGO Data Analysis System (LDAS) for the Initial LIGO Detector
  - Status & update
  - Design requirements/functional requirements
  - Implementation concept
  - Ongoing activities
  - Planned task; schedule, staffing, etc.

- Modeling & Simulation
  - Status & update
  - 40m modeling activities
  - LIGO modeling activities
  - Planned tasks; schedule, staffing, etc.

LIGO
DATA FORMAT

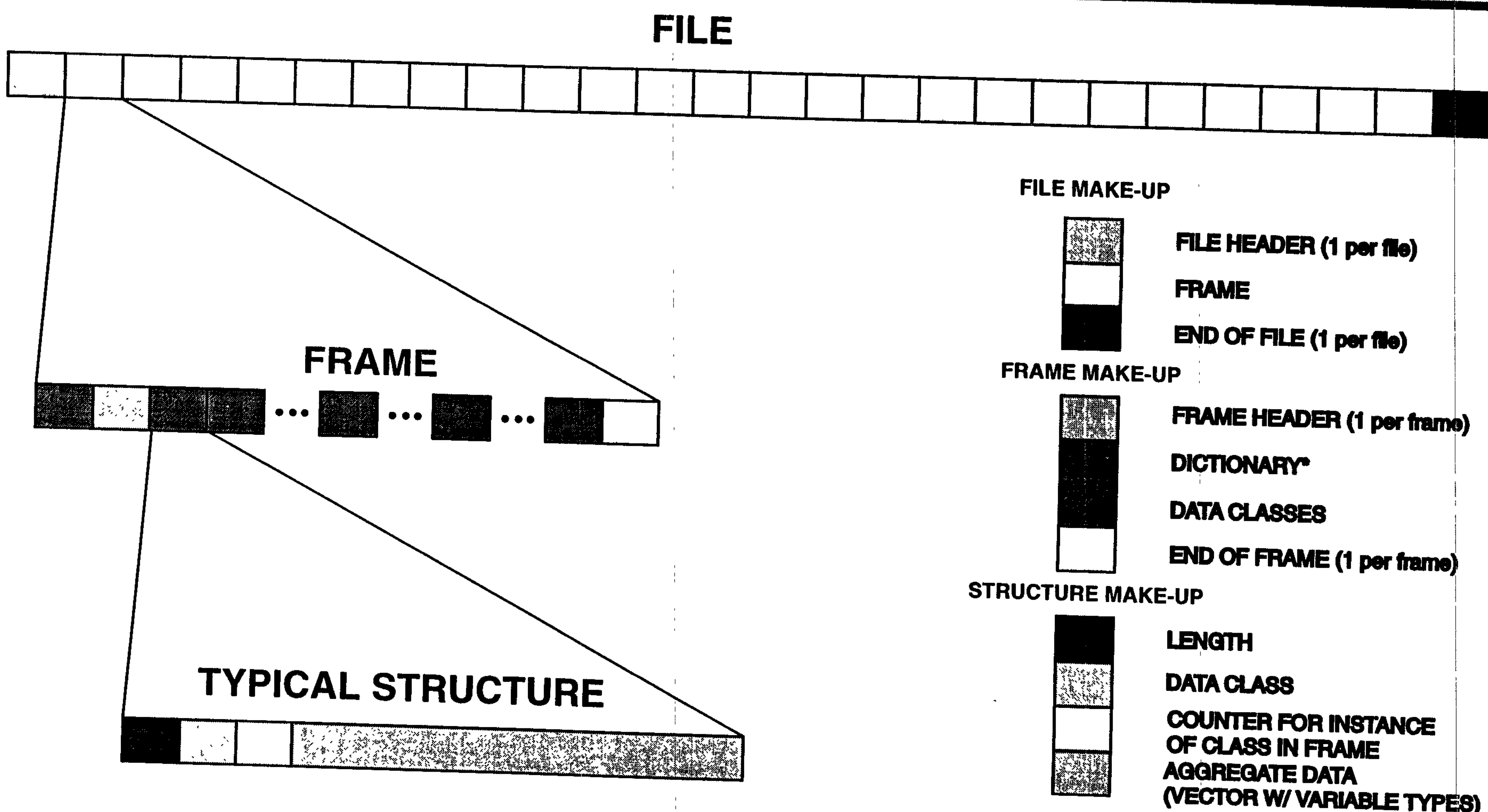
DATA FORMAT
Update & Status

- Meeting with VIRGO/Annecy group in June:
  - ›› Generated a specification for the frame format
  - ›› Platform independent implementation
  - ›› Scope:
    - data acquisition and archival;
    - common format with VIRGO/GEO/TAMA/...
  - ›› Introduced software standards: POSIX / ANSI
  - ›› Control evolution of frame after initial approved release through consortium of participating laboratories/projects
    - ftp sites to distribute/control software & documentation
- Planning a follow-up meeting in November

LIGO has established a close (weekly) working rapport with the VIRGO/Annecy group.

DATA FORMAT

Compositional relationships



* Dictionary structure behavior is unique in that:
1. It preceeds header for first frame of file;
2. Dictionary is built up incrementally as addititional structures are incorporated into frame
3. It is valid for entire file (persistent)

LIGO

DATA FORMAT
Ongoing activities

- New release of frame library by VIRGO
  - 3 1/2 month effort culminating in Rev 3.4, consistent with Rev. B of specification
  - Released to GEO & TAMA via ftp sites
  - Software validation is a collaborative effort among a number of groups:
    - VIRGO - code development
    - LIGO - code implementation in hardware
      - DAQS/40m
      - debugging new features
    - Univ. of Wisconsin (B. Allen)
      - incorporation into prototype analysis software (GRASP)
    - CACR (Center for Advanced Computing Research)
      - computational resources for testbeds/analysis
  - Plan to target frame I/O interfaces with commercial analysis environments
    - MATLAB
    - Mathematica
    - IDL
    - ...

DATA FORMAT
Ongoing activities

- Data compression (lossless) incorporated into frame library software (& specification)
  - SINGLE WORKSTATION IMPLEMENTATION
  - ~ 2X reduction in volume of files

- Direct savings in media per year

Results of GZIP compression on Frame Translation of 40m Data (16472 s)

GZIP Level	Differentiation	Translated Frame Size	Frame Size vs. Raw Data Size	Time (% cpu) to Translate	% Real-time
None	No	1282532 kB	97.67%	975s (7.4%)	5.9%
1	Yes	667693 kB	50.85%	1461s (75%)	8.9%
1	No	726269 kB	55.31%	1494s (72%)	9.1%
3	Yes	640549 kB	48.78%	1799s (78%)	10.9%
3	No	706373 kB	53.80%	1863s (77%)	11.3&
6	Yes	621157 kB	47.31%	3951s (91%)	24%
6	No	697533 kB	53.12%	3187s (83%)	19.3%
9	Yes	619965 kB	47.21%	4940s (91%)	30%
9	No	696613 kB	53.05%	4401s (87%)	26.7%

DATA FORMAT

- Future plans (1997/1998)
  - Object Oriented Implementation in C++
    - **Separation of Frame I/O -- User Application Programmer Interface (API)**
  - VIRGO/LIGO participation in redesign effort
    - **Continue design of Frame I/O classes**
    - **Develop a Frame API specification**
  - Implementation
    - **Continue testing with 40m DAQS (important!)**

LIGO DATA ANALYSIS SYSTEM (LDAS)

Data Analysis for Initial LIGO

Status & Update

- Presented an overview of LIGO plan for initial LIGO analysis system ("LDAS") at June PAC Meeting at MIT.
  - ›› White paper presented
  - ›› General approach endorsed
  - ›› Issues:
    - – Requirements/goals
    - – Schedule
    - – Magnitude of data archival
    - – Definition of reduced data sets
- Efforts from June to present focused on defining LDAS requirements and implementation concept
  - ›› LIGO Design Requirements Review by 1 December
  - ›› Review committee to include experts from outside

Data Analysis for Initial LIGO

Status & Update (continued)

- Benchmarking (Allen in collaboration with CACR and LIGO)

- Software prototyping

- Derived cost estimate

- Developed implementation plan for general computing infrastructure at observatories

- Developed a schedule to develop LDAS for LIGO I commissioning

Demonstrated LIGO I data analysis (on line) component feasible

LIGO Data Analysis System (LDAS)
Requirements

- Mission-critical services:
  - Provide on-line analysis at the observatories.
  - Process and reduce the raw LIGO datasets at the off-line center to prepare the data for archival storage and retrieval.
  - Provide computational and storage resources for off-line analysis using the archived data
  - Provide a flexible design which can be reconfigured to reflect new analysis or computational requirements as they evolve.
  - Provide access to LIGO data from all LIGO Laboratory sites and also from member institutions of the LIGO Scientific Collaboration for the LIGO I search.

LIGO Data Analysis System (LDAS)
Requirements

- Two LDAS components
  - ›› On-line LDAS (@ observatories)
    - Two systems, one for Hanford, and one for Livingston
    - Hanford system handles 2 interferometers
  - ›› Off-line LDAS (@ CACR/CIT/MIT)
    - Collaborative arrangement with CACR
      - Dedicated LIGO hardware within CACR on scale of observatory systems
      - Database archive
      - Strategic use of other CACR facilities as available
    - Transparent access for off-line analysis of archived data
      - LIGO Laboratory -- CIT/MIT
      - LIGO Scientific Collaboration

- Wide area network (WAN) to enable inter-site communications
  - ›› University scientific and engineering support to Observatories
  - ›› Access to archive database
  - ›› Access to real-time data from observatories
  - ›› Inter-observatory event sharing

LIGO Data Analysis System (LDAS)
Requirements

- Implementation attributes:

  ›› Flexibility => No (or very little) custom hardware with custom software interfaces

  ›› Extensibility => Modular (not function specific) component design

  ›› Portability => Upgradable hardware under same software or vice-versa => POSIX compliance, software standards, etc.

  ›› Maintainability => Object oriented programming design ("reusable software components")

Design reflects current approaches to large-scale software/hardware development efforts

LIGO Data Analysis System (LDAS)
Functions

- On-line component

  » diagnostics support
  - regression and cross-correlations
  - tests w/o closed loop feedback to interferometers

  » characterization of sensitivity
  - noise stationarity

  » signal processing for detection
  - best estimate strain
  - reduced data sets
  - share candidate events

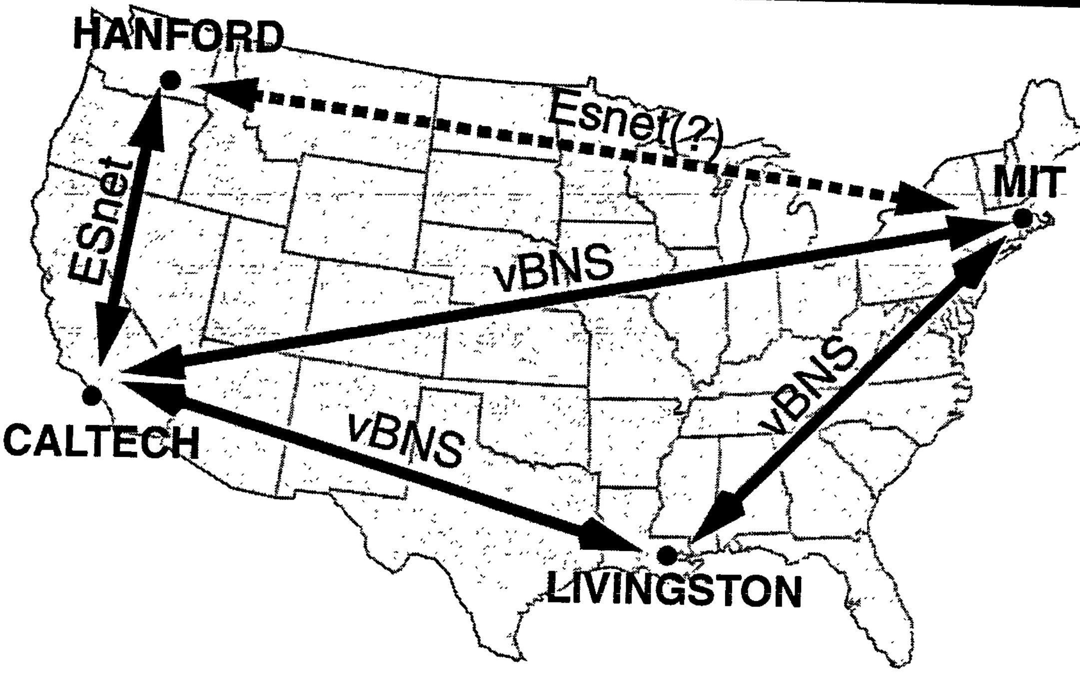
  » data distribution (limited)
  - near real-time data available across LIGO Laboratory

LIGO Data Analysis System (LDAS)
Functions

- Off-line component

  - ›› data ingestion/data reduction
    - process, reduce, and incorporate recent data into archive
  - ›› data distribution
    - retrieve, filter, and deliver data to LIGO researchers
  - ›› large scale searches
    - expanded searches (multiple interferometers, deeper, lighter masses, etc.)
    - extended searches for periodic sources (larger search area, greater parameter space)
  - ›› non-time critical searches
    - stochastic background
    - data mining
    - refined analyses, etc.
  - ›› algorithm prototyping and development
  - ›› hardware upgrade/prototyping testbeds

LIGO Wide Area Network



- LIGO drafted proposed MOU between NSF/DOE to establish access to ESnet at Hanford -- presently @ NSF for review.
- Working with LSU to set up link to Livingston; access to vBNS when available @ LSU

WAN/LAN Connectivity among LIGO Laboratory Sites

Site	*Livingston, LA*	*Hanford, WA*	*MIT*	*Caltech*
Caltech	vBNS/OC3	ESnet (3 X T1) <-> vBNS/OC3	vBNS/OC3	OC3/ATM 100BT
MIT	vBNS/OC3	ESnet (3 X T1) <-> vBNS/OC3	100BT OC3(?)	
Hanford, WA	ESnet (3 X T1) <-> vBNS/OC3	OC3 100BT		
Livingston, LA	OC3 100BT			

LDAS Prototyping Results

- DATA ANALYSIS
  - Inspiraling binary detection data flow
    - **40m data**
    - **Used 5 different systems/architectures**
      - **CACR Intel paragon - supercomputer; dated**
      - **CACR IBM SP2 - MPI multinode w/ fast switch -- CACR**
      - **CACR Beowulf (linux) cluster - experimental system composed of 200 MHz PCs w/ fast ethernet interconnections**
      - **LIGO Sun Ultra Cluster - high end WS w/ slow ethernet**
      - **SGI Origin 2000 - shared memory multi-node; latest technology -- (at vendor)**
- Archive retrieval and transmission of data
  - Throughput from archive prototype (CACR HPSS) achieved at LIGO bandwidths:
    > 7 MB/s for 100GB files with ATM
- Spreadsheet model of LIGO LDAS data flow to project costs/system size using expected technology growth

Results demonstrate feasibility of implementing LIGO LDAS concept

LDAS Prototyping Results

PRELIMINARY Benchmarks

- Wiener (optimal) filtering to detect short templates in data
- **Very parallel:** look for each of ~ *34,000 templates* in each data segment.

Number of CPU's to keep up with data stream (1997 technology)

	"small" data segments	"medium" data segments	full LIGO (extrapolated)
Intel Paragon	4	33	205
SGI Origin	1	3	90
Sun Ultra2	-	3	116
Beowulf Pentium Pro	**2**	**-**	**96**

Optimized FFT: Kuck for Paragon, SGI/Cray, Sun Performance, FFTW for Beowulf

- All these systems can provide
  - **parallel debuggers, profilers, optimizing compilers, assembler FFT libraries.**
- MPI code can be improved significantly;
  - ***Relative* performance figures expected to change little.**
- Results are representative for
  - **generic problem of searching for "short" templates in signals.**

Expect performance by 1999 to improve
~ 2X - 3X as technology improves
(higher clock speeds, etc.)

LDAS Prototyping Results

40m data analysis

- HARDWARE:
  - Developed a Client-Server Frame IO package using UNIX sockets (with TCP/IP communication -- ethernet)
  - Unix to vxWorks with Fast Ethernet link meets DAQS requirements: 5.9 MB/s
  - UNIX Socket I/O Implementation
    - **Will allow 2X (to 32) the number of fast channels acquired @ 40m with DAQS**
- Next:
  - Install client server package on Reflective Memory network
  - Add more bookkeeping

LDAS Prototyping Efforts

40m data analysis

- SOFTWARE: Use of PAW with Frame IO
  - ›› Exploit availability (and experience of newly arrived postdocs) to use CERN library tools for data visualization
    - – Tools primarily for discrete, tagged, events characterized by a number of simultaneous channels (HEP)
    - – Need to incorporate signal-processing (FFTs, spectral cross-correlations, etc.) into PAW --> extract/improve upon some GRASP package(s).
  - ›› Multiple channels of data can be viewed at a time

- SOFTWARE: Metadata - collateral information required to analyze GW time series, etc.
  - – In definition/design stage -- working with VIRGO
- CDS-generated information:
  - – configurational databases (the "settable parameters")
  - – health/status information
  - – trend summaries
  - – etc.
- Detector diagnostics information:
  - – test results
  - – parameters/fits

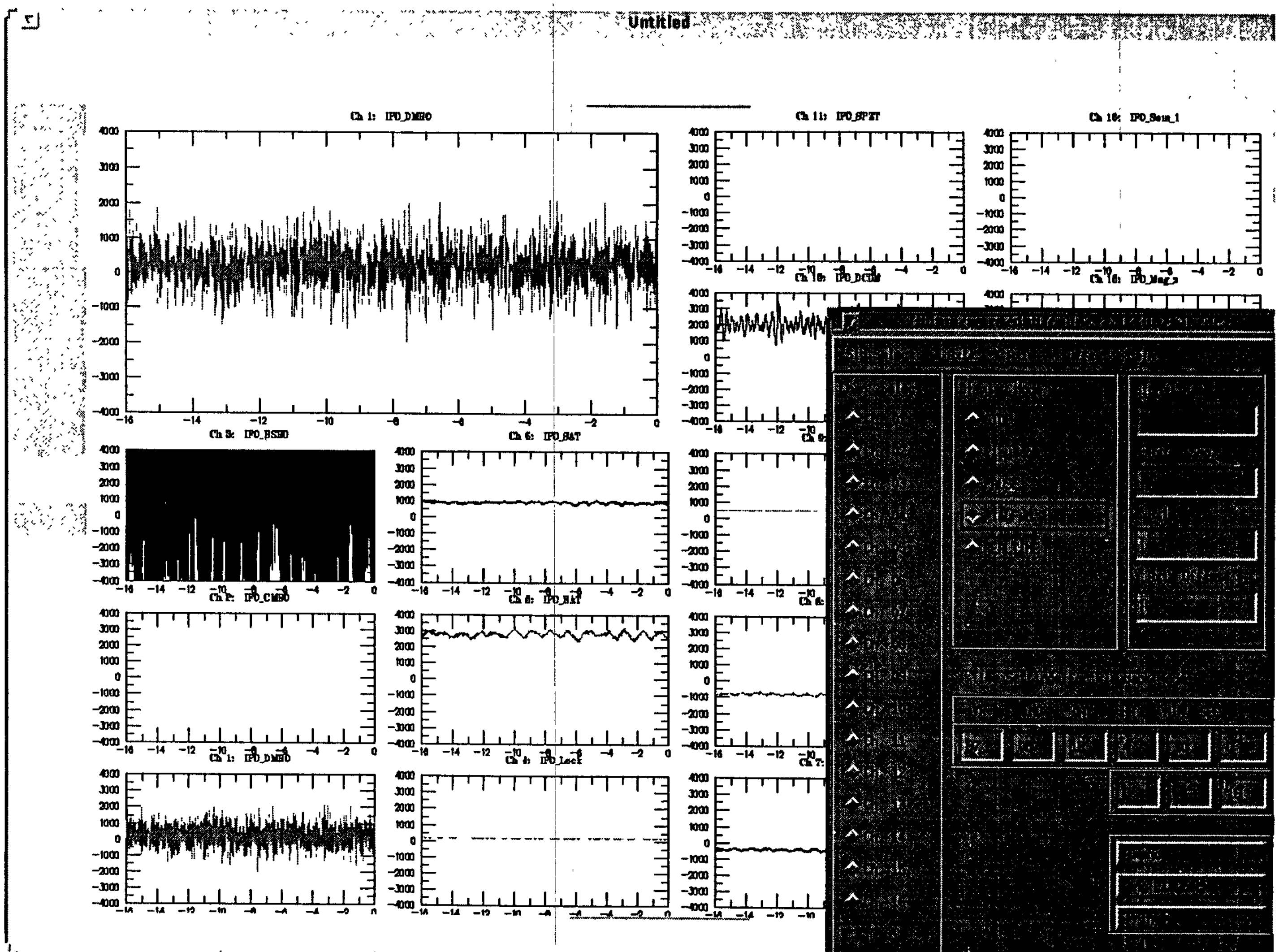
LDAS Prototyping Efforts

40m data analysis

- SOFTWARE: Metadata - collateral information required to analyze GW time series, etc.
- Detector diagnostics information:
  - in general, "the measurable parameters" defining the interferometer characteristics --
  - optical quantities;
  - transfer functions;
  - etc.
- Data analysis information:
  - non-LIGO data/events;
  - frame data tape summary data (index into the archived data)
  - LIGO events summaries (TBD)
- Data searches/queries
  - Frame files by time/date/etc.
  - Metadata about frames: calibrations/anomalies reported/etc.
  - External (non-LIGO events): earthquakes/storms/etc.
  - Candidate events from previous analyses of LIGO database
  - Calibrations/settings/states of hardware/etc.
  - ...

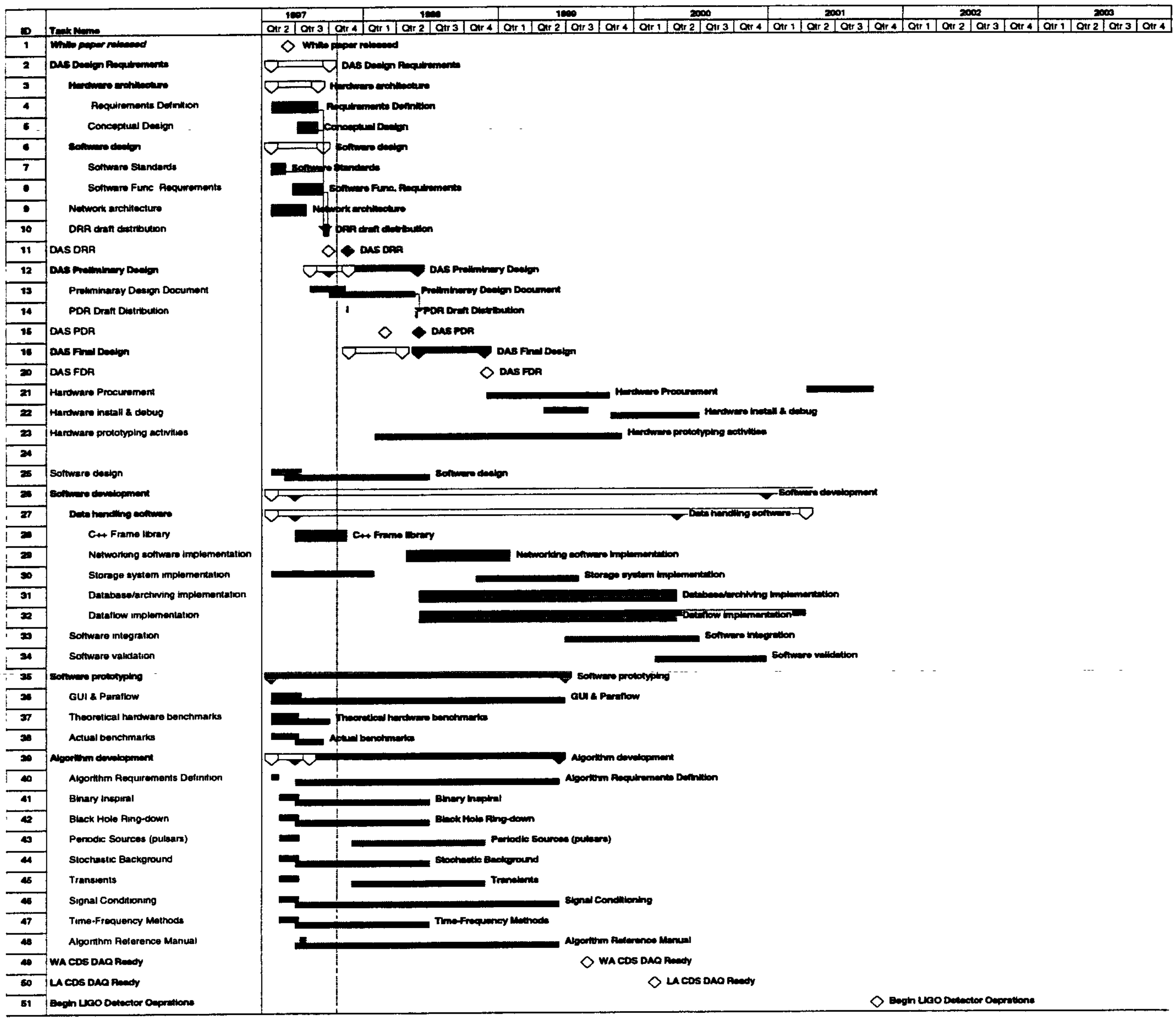
LDAS Prototyping Results

40m data analysis



LDAS Development

Schedule



Summary

- LIGO Data Analysis System design in the Design Requirements Review phase
- LIGO WAN plan is moving forward
  - » NSF-DOE interaction to grant access to LIGO of ESnet @ Hanford
  - » Working with LSU to set up link from Livingston to campus for vBNS access
- Prototyping and benchmarking activities are crucial to completing design
  - » Feasibility -- benchmarking
  - » Improvement of concepts - utilization of 40m prototype DAQS and CACR to developing data analysis concept
    - Compression/signal conditioning/reduction studies
  - » Validation of software
    - Frame library software
    - Data server software
    - GRASP
  - » **Pulsar Search** benchmarking: different problem
    - Communication fabric is heavily stressed by gigapoint FFTs.
    - <u>*NOT*</u> an on-line search, however

MODELING & SIMULATION

Modeling and Simulation

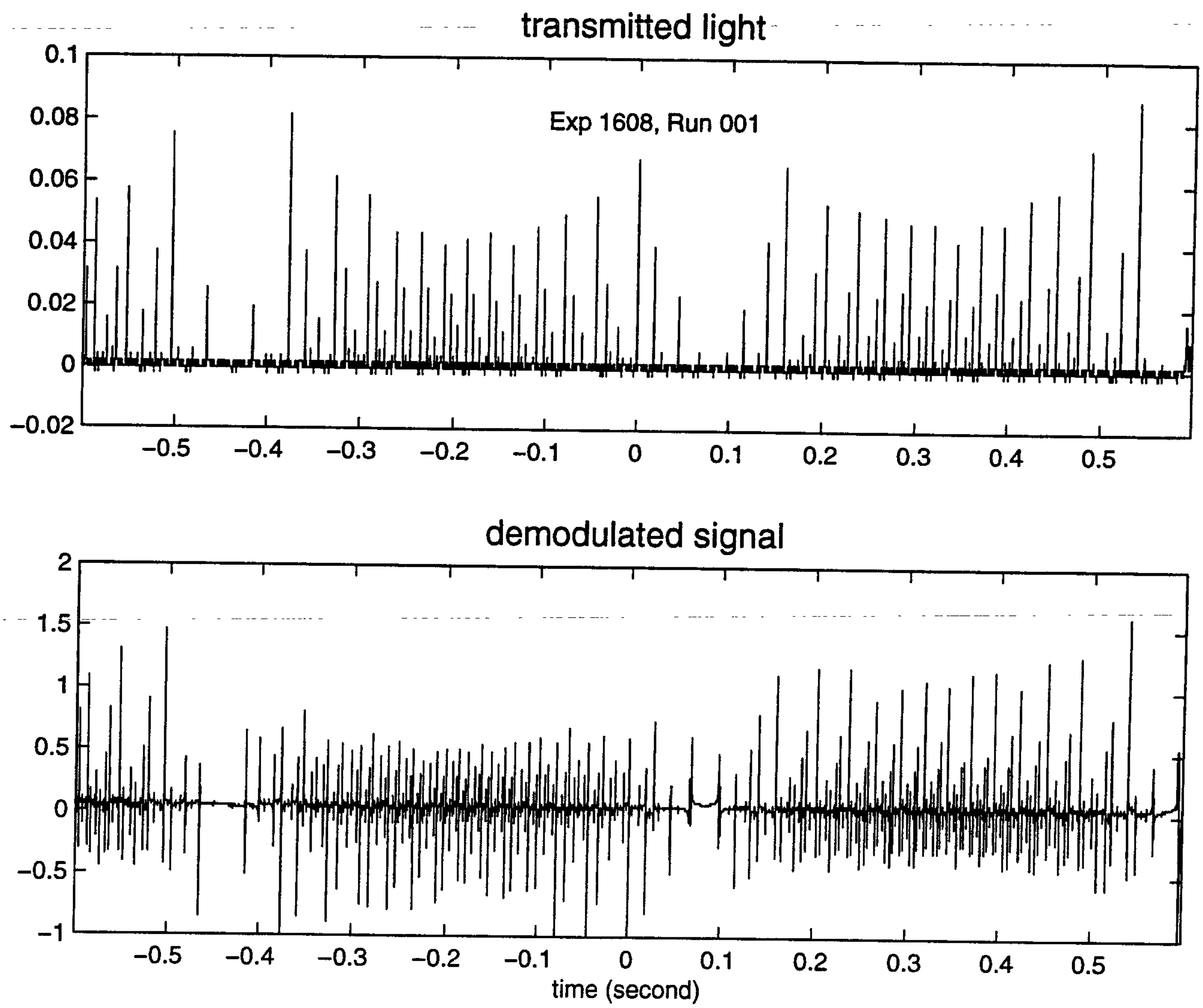
Status & Update

- Took data for a single cavity and started model comparison and validation with 40m prototype
  - Used multi-mode time domain model for qualitative comparison of scans
- Single mode (TEM_{00}) time domain model integrated into end-to-end environment
- Continuation with end-to-end model foundation
  - GUI interface to engine
  - Subsystem models under development
- Interface to data analysis at the Frame IO level
- Developed a schedule for the end-to-end model

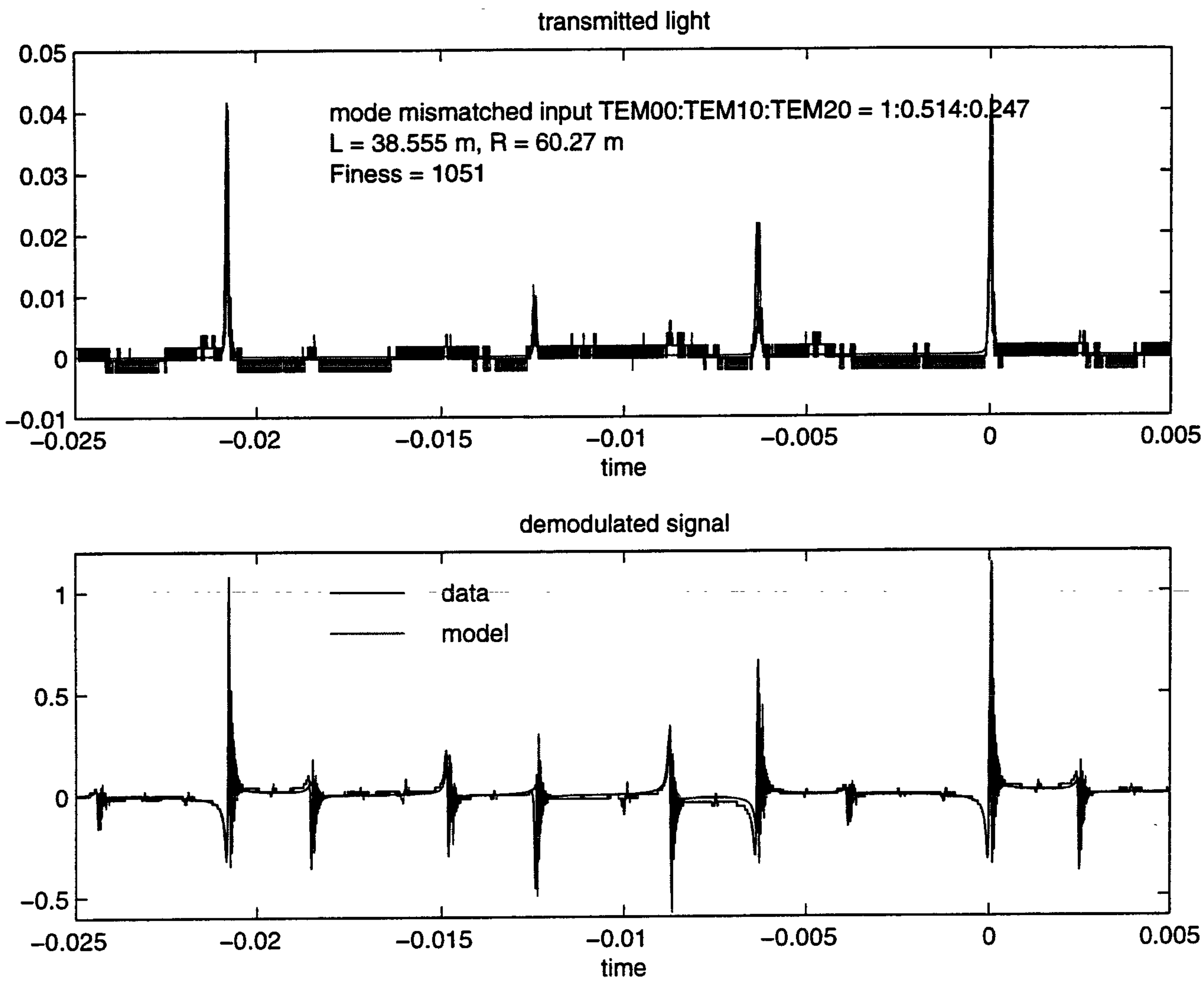
Modeling & Simulation

40m measurement & analysis results

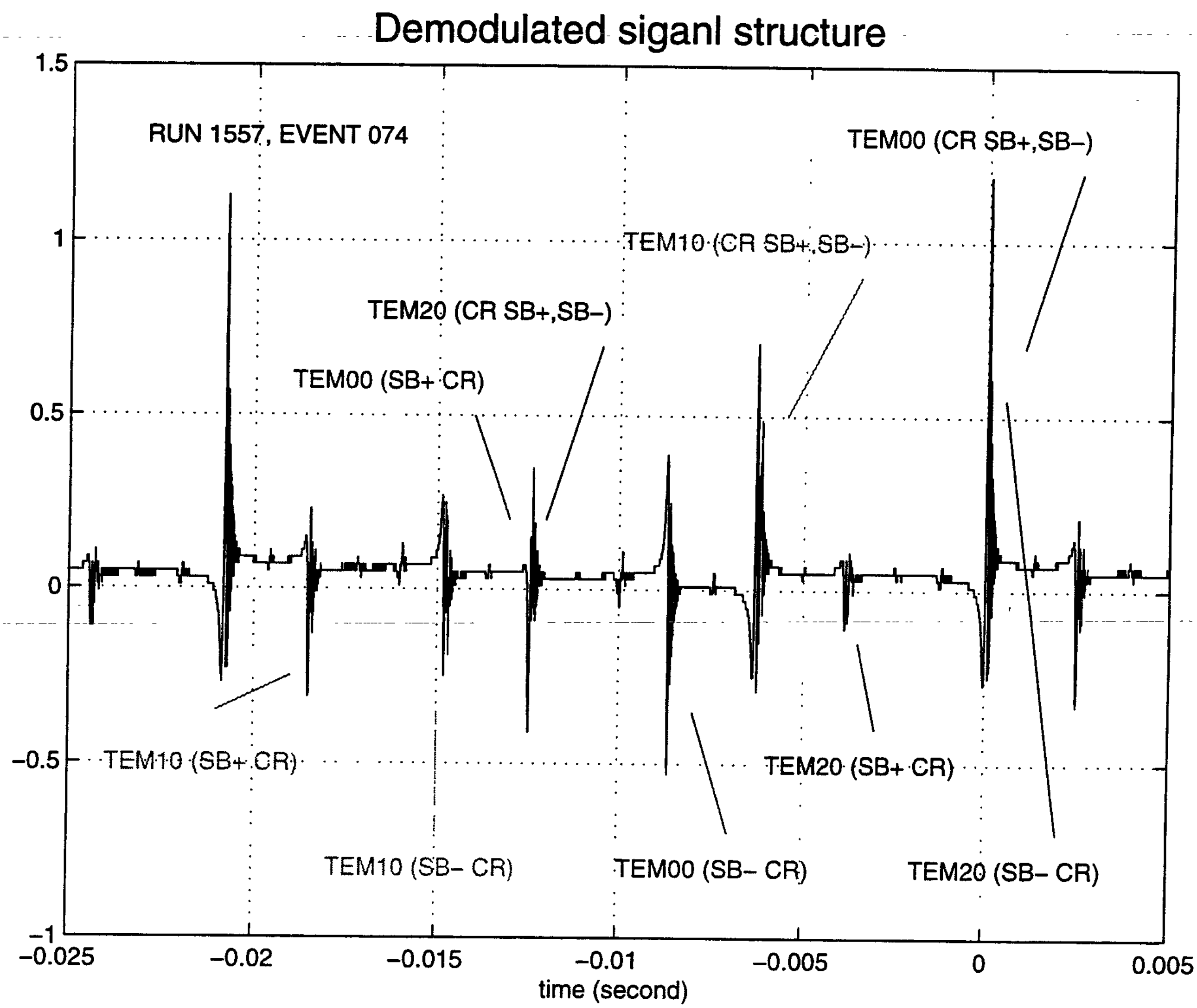
- Measured a large set of time-domain fringe sweeps of a single cavity
  - ›› measurement of opportunity between recycling installation activities
  - ›› asymmetric port photodiode demodulated signal
    - richness of structure, including higher order modes, side bands
  - ›› measured simultaneously transmitted intensity
    - simpler trace
      - sensitive primarily to TEM_{00} carrier
      - no interference
    - useful to identify components of the reflected demodulated signal for further interpretation and analysis
  - ›› time domain signals allow measurement of cavity physical parameters for comparison
    - mode spacings -> g factor
    - decay time -> finesse
    - order spacing (free spectral range) -> cavity length
    - fringe microstructure -> mirror velocity
    - quality of fit -> RF demodulation phase (nominally 0°)
    - overall structure -> model validation

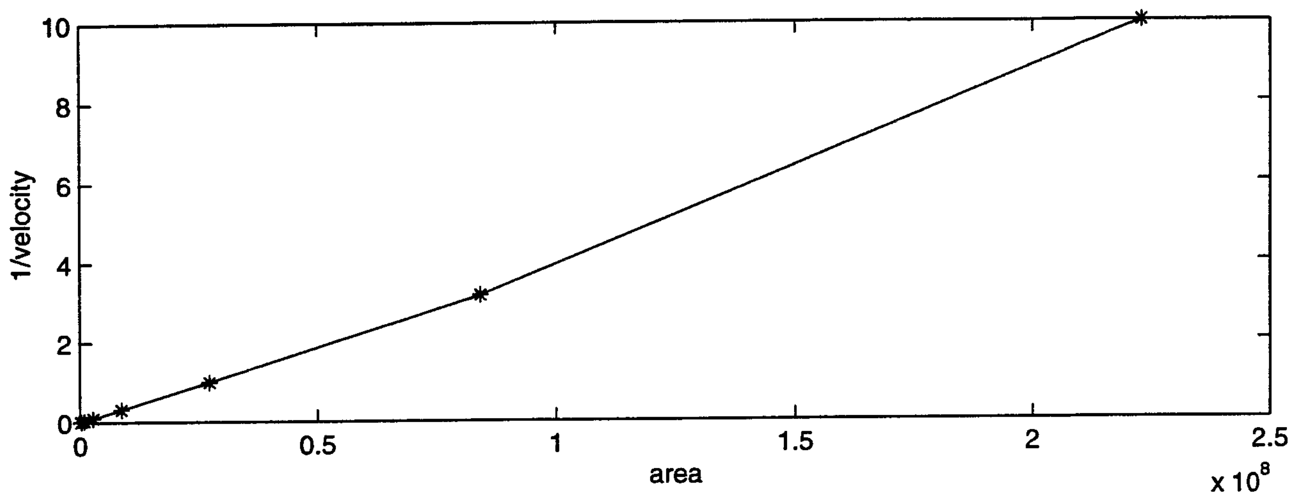


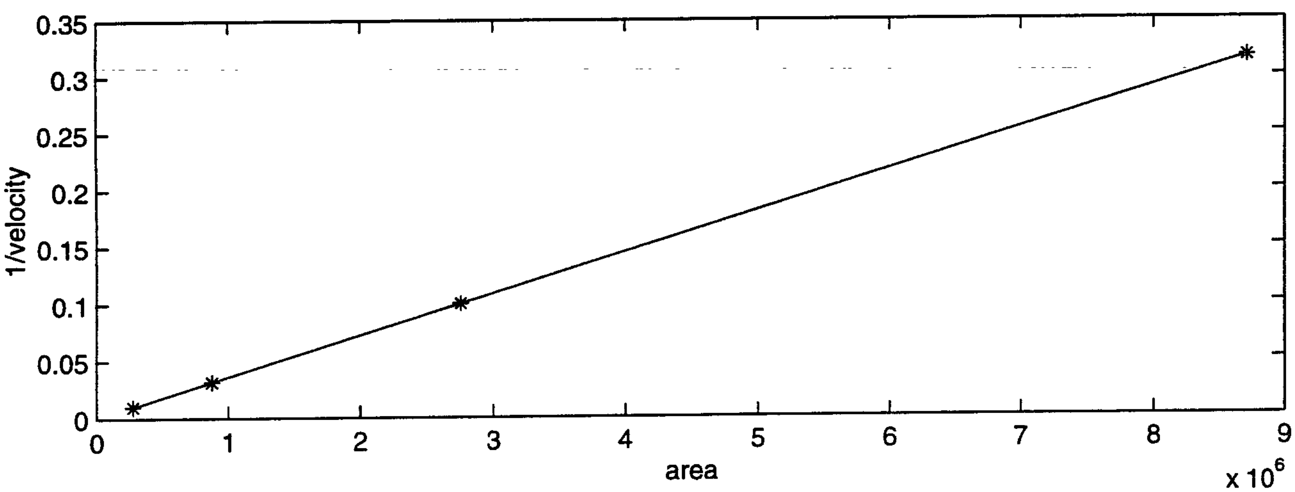
transmitted light
Exp 1608, Run 001
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.5
−0.4
−0.3
−0.2
−0.1
0
0.1
0.2
0.3
0.4
0.5
demodulated signal
2
1.5
1
0.5
0
−0.5
−1
−0.5
−0.4
−0.3
−0.2
−0.1
0
0.1
0.2
0.3
0.4
0.5
time (second)

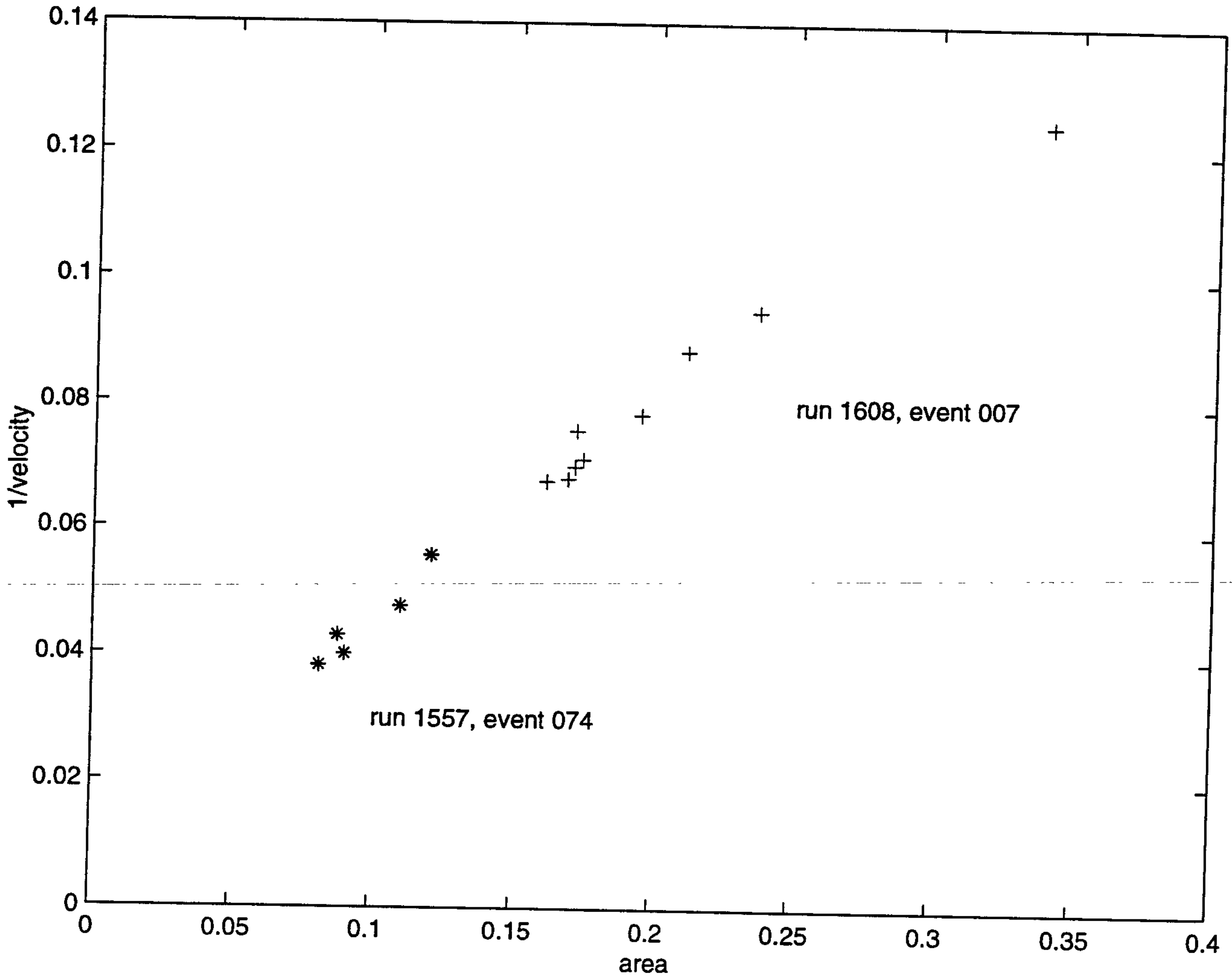


transmitted light
mode mismatched input TEM00:TEM10:TEM20 = 1:0.514:0.247
L = 38.555 m, R = 60.27 m
Finess = 1051
0.05
0.04
0.03
0.02
0.01
0
−0.01
−0.025
−0.02
−0.015
−0.01
−0.005
0
0.005
time
demodulated signal
data
model
1
0.5
0
−0.5
−0.025
−0.02
−0.015
−0.01
−0.005
0
0.005
time

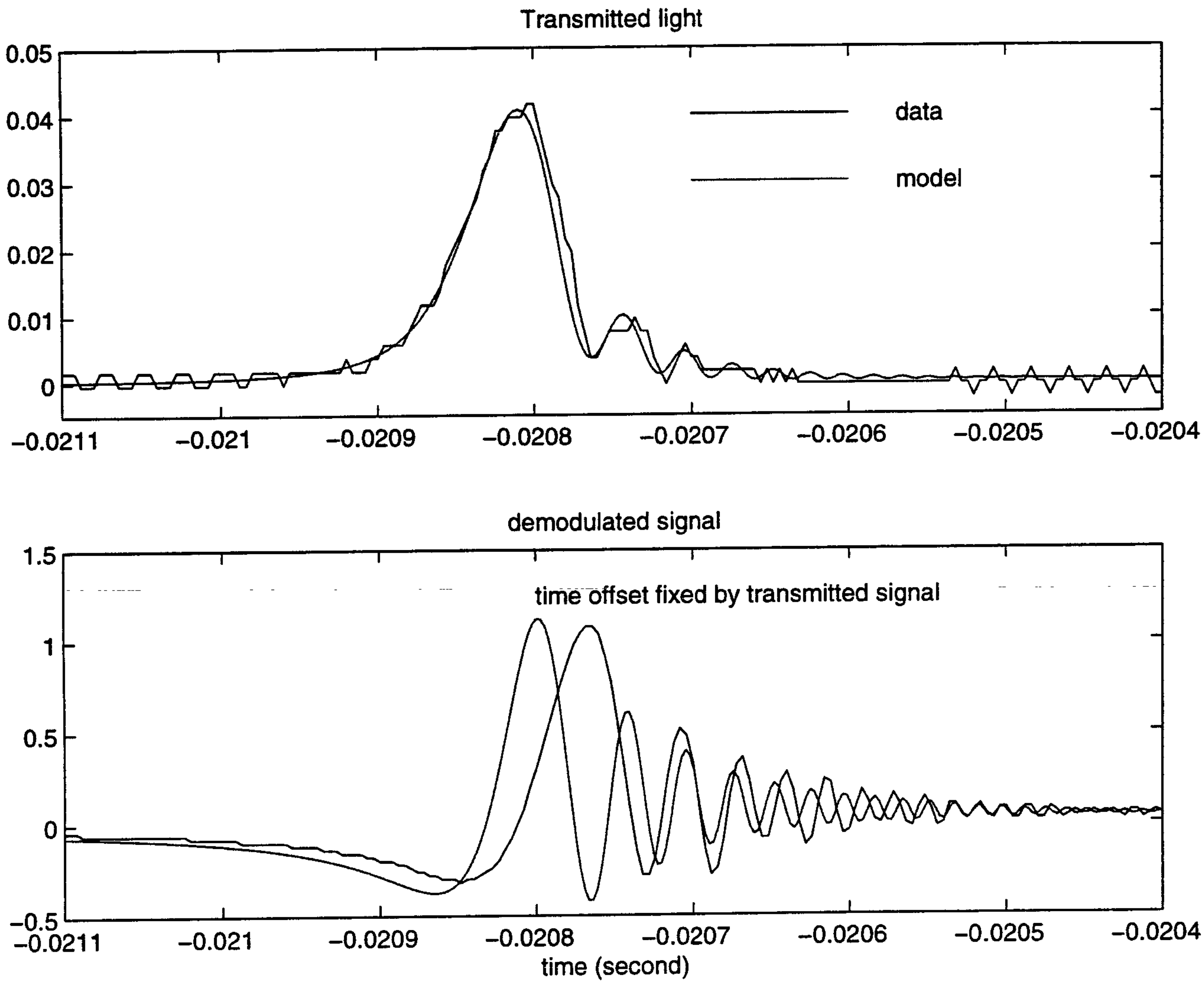

Demodulated siganl structure
RUN 1557, EVENT 074
TEM00 (CR SB+,SB-)
TEM10 (CR SB+,SB-)
TEM20 (CR SB+,SB-)
TEM00 (SB+ CR)
TEM10 (SB+ CR)
TEM20 (SB+ CR)
TEM10 (SB- CR)
TEM00 (SB- CR)
TEM20 (SB- CR)
1.5
1
0.5
0
-0.5
-1
-0.025
-0.02
-0.015
-0.01
-0.005
0
0.005
time (second)


1/velocity
area
x 10^8
0
2
4
6
8
10
0
0.5
1
1.5
2
2.5


1/velocity
area
x 10^6
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
1
2
3
4
5
6
7
8
9



0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1/velocity
run 1608, event 007
run 1557, event 074
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
area


Transmitted light
data
model
0.05
0.04
0.03
0.02
0.01
0
-0.0211
-0.021
-0.0209
-0.0208
-0.0207
-0.0206
-0.0205
-0.0204
demodulated signal
time offset fixed by transmitted signal
1.5
1
0.5
0
-0.5
-0.0211
-0.021
-0.0209
-0.0208
-0.0207
-0.0206
-0.0205
-0.0204
time (second)

Modeling & Simulation
End-to-end modeling results

- Reorganized computational engine for optical cavity time-domain model
  - 10X improvement in speed for few element systems
  - made data type passing interface between C++ modules less general
  - speed up possible because source code developed in-house; commercial simulators could not be modified
- Began development of the application user interface (API)/graphical user interface (GUI) to allow for “user-friendly” front end
  - migrate from script-based configuration
  - designing interpreter/translator to read/create scripts from graphical (“block diagram”) representations of hardware
  - still to consider: how to absorb modeling results and outputs from user presentation: visualization, analysis, display, ...
  - need: run time control of model to allow parameter changes/variation to be input without recompilation

Modeling & Simulation
End-to-end modeling results

- Modules developed:

  ›› digital filter
  - simulates feedback & control
  - simulates noise sources
  - simulates plant dynamics (state space representation)
  - mechanical elements -- pendulum/suspended optics,...

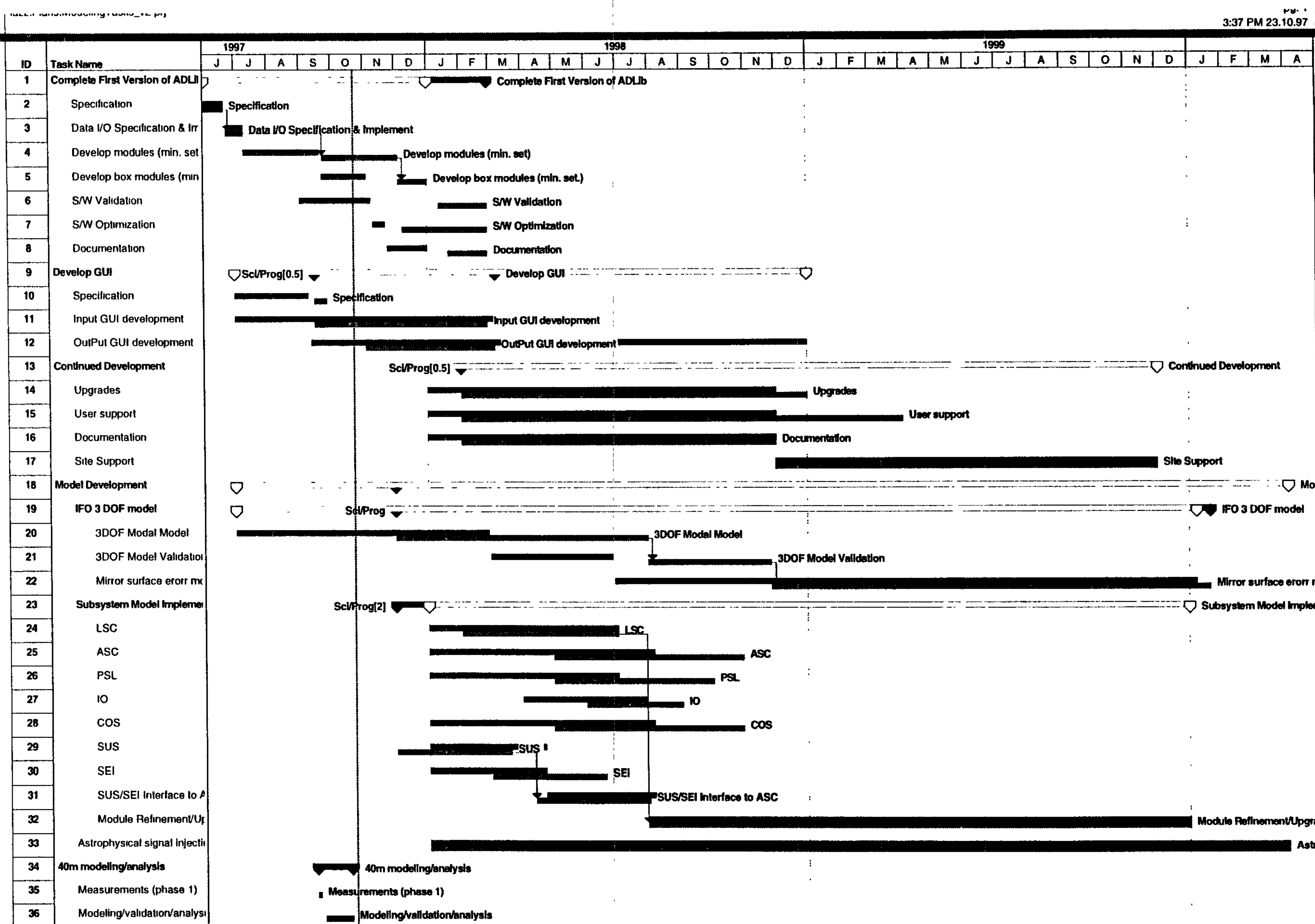
  ›› optical elements
  - free space propagator
  - mirrors & beamsplitters (4-port devices)
  - electro-optical components
    - phase shifters
    - detectors, demodulators
    - ...

Modeling activities

- Still needed
  - » seismic isolation system
    - – exists as MATLAB model being used for detector design
    - – needs to be implemented into end to end (C++) environment
  - » prestabilized laser system
    - – plan to begin working with PSL team to identify/develop components needed for model
    - – a body of measurements exist (e.g., frequency, intensity noise behavior in open/closed loop) against which validation can proceed
  - » length sensing control loop topology
    - – will incorporate final product developed by Detector LSC/ASC group
  - » Multi-mode time domain model
    - – elements of model, physics equations delivered as a parallel task (R. Beausoleil, consultant) -- useful for open-loop cavity dynamics
    - – extension of single mode model under development by D. Redding -- likely to become basis for end-to-end multiple mode engine (including closed loop control of alignment and length DOFs)

Modeling & Simulation

Schedule



ACRONYMS

ANSI	- American National Standards Institute
API	- Application Programming Interface
ASCII	- American Standard Code Information Interchange
C++	- Object oriented computer language
CACR	- Caltech's Center for Advanced Computing Research
CDS	- Computer and Data Systems (LIGO Detector subsystem)
CPU	- Central Processing Unit: a computer
DAQS	- LIGO CDS Data Acquisition System
DOE	- Department of Energy
DOF(s)	- Degree(s) of Freedom
ESnet	- Energy Sciences Network - DOE WAN infrastructure
FFT	- Fast Fourier Transform
GB	- Unit of data volume, 10^9 Bytes of information: 1 "CD" contains approximately 0.64 GB or 640 MB.
GEO	- Anglo-German gravitational wave detector project
GUI	- Graphical User Interface
GW	- Gravitational Wave(s)
GZIP	- UNIX standard lossless data compression algorithm
IDL	- Data analysis programming environment
I/O or IO	- Input / Output
LAN/WAN	- Local or Wide Area Networks
LDAS	- LIGO Data Analysis System
LSU	- Louisiana State University
MATLAB	- Control system modeling environment
Mb/s	- unit information exchange rate: of 10^6 bits of information per second
MB/s	- 8 Mb/s: 10^6 Bytes per second
MPI	- Message Passing Interface. A software protocol to use in a massively parallel manner a (large) number of independent CPUs to perform a single large computing task.
NSF	- National Science Foundation
OC3	- One of several communications bandwidth designations: 155 Mb/s
OC12	- One of several communications bandwidth designations: 640 Mb/s = 4X OC3
OOP	- Object Oriented Programming
OSIX	- Platform Operating System Independent Standard for software/hardware interfaces
PAC	- Program Advisory Committee
PAW	- Data analysis package developed and distributed by CERN

ACRONYMS - continued

RF	- Radio frequency
TAMA	- Japanese gravitational wave detector project
TCP/IP	- Transmission Control Protocol/Internet Protocol
TEM	- Mode of the electromagnetic field: transverse magnetic and electric fields
T1	- One of several communications bandwidth designations: 1.55 Mb/s = 1% of OC3
vBNS	- Very High Bandwidth Network System (NSF WAN infrastrcuture)
100BT	- One hundred base T - 100 Mb/s communications rate; also implies an electrical/mechanical interface.

NSF Review -

Detector/R&D Status

S. Whitcomb / D. Shoemaker

28 October 1997

LIGO-G970252-00-D

Outline

- Cost/schedule status
- Lasers and Optics (Whitcomb)
- Suspensions and Isolation (Whitcomb)
- Interferometer Sensing/Control (Shoemaker)
- Physics Environment Monitoring/Control and Data System (Shoemaker)
- Summary

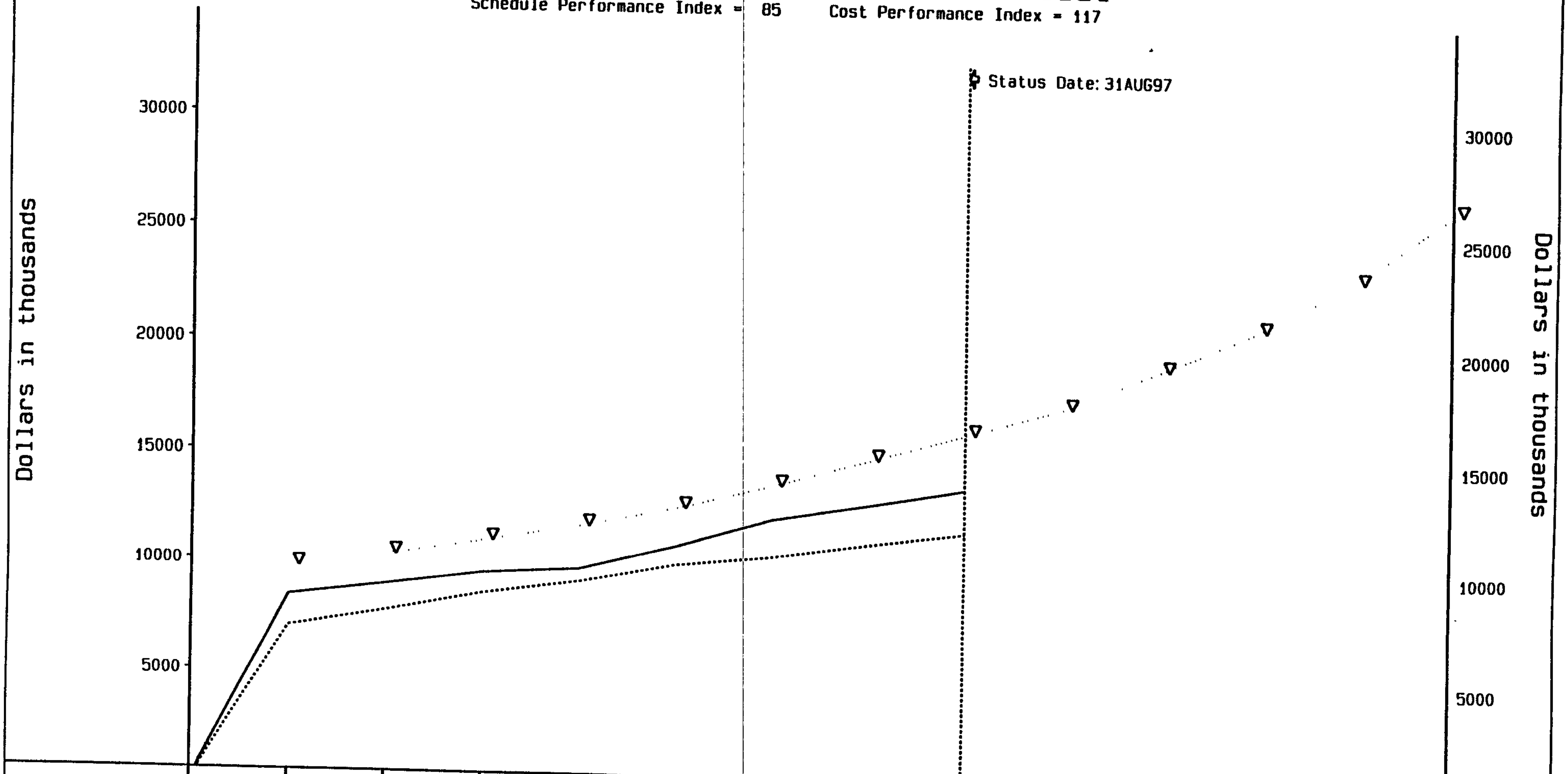
LEGEND	
Bud	▽ ▽ ▽
Per	———
Act	....

LIGO PROJECT
1.2 Detector

Date: 2OCT97
Program: PMB_0897
Report: LIGOSPA
COBRA (A)

Budget vs Performance vs Actual

Schedule Performance Index = 85 Cost Performance Index = 117



	JAN97	FEB97	MAR97	APR97	MAY97	JUN97	JUL97	AUG97	SEP97	OCT97	NOV97	DEC97	JAN98	SCALE
Planned Budget	9,660	10,279	10,987	11,736	12,639	13,733	14,951	16,147	17,394	19,152	20,979	23,209	26,300	K$
Performance	8,379	8,928	9,528	9,782	10,903	12,202	12,939	13,710						K$
Actuals	6,991	7,752	8,602	9,200	10,058	10,497	11,147	11,728						K$
Schedule Variance	-1,281	-1,351	-1,459	-1,954	-1,736	-1,531	-2,012	-2,437						K$
Cost Variance	1,388	1,176	926	582	845	1,705	1,792	1,982						K$

Schedule Variance = Perf-Budg Cost Variance = Perf-Actual Schedule Performance Index = Perf/Budg Cost Performance Index = Perf/Actual

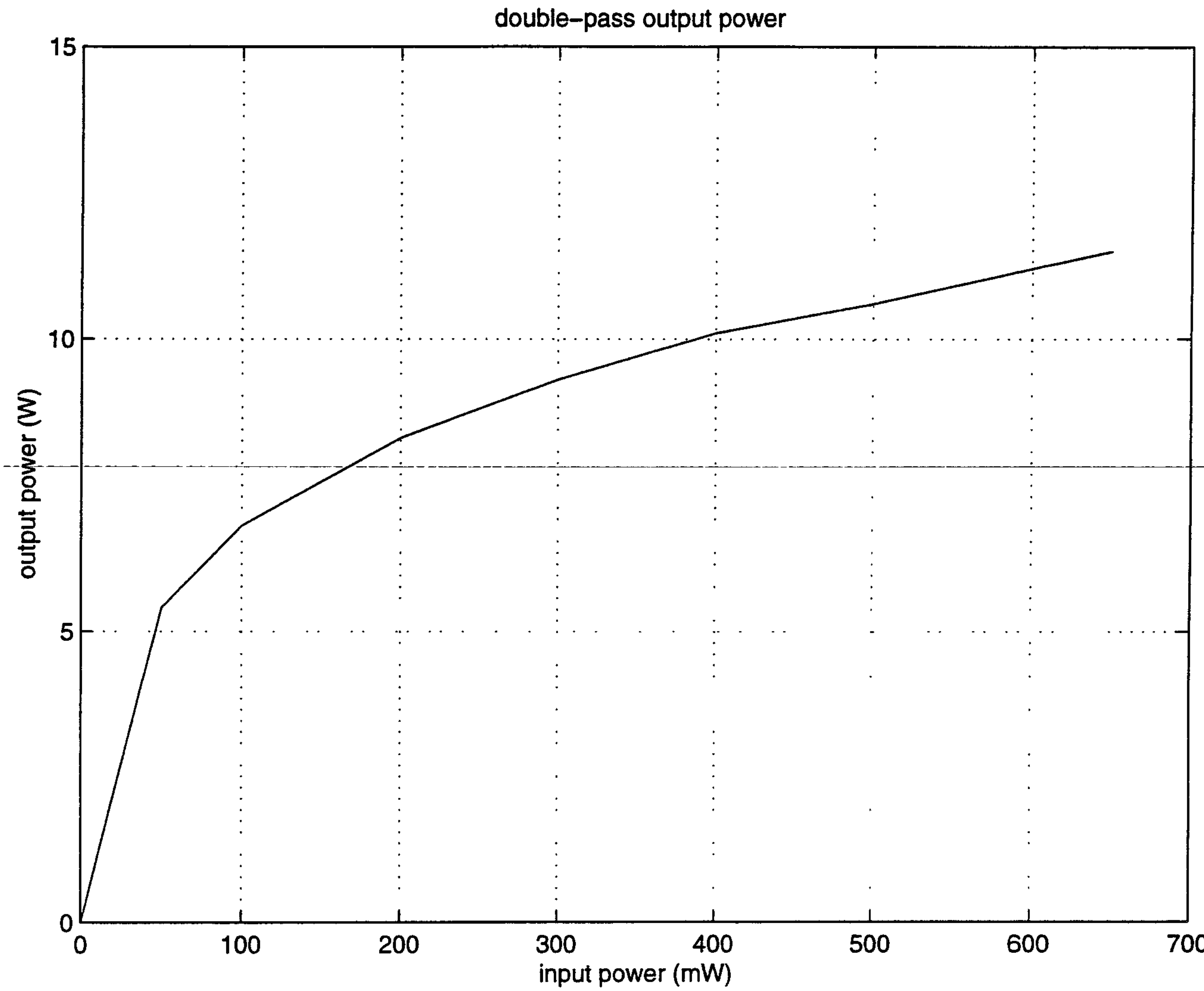
Detector Milestones

Milestone	PMP Date	Proposed PMP Date	Projected
BSC Seismic Isolation FDR	7/97	4/98	4/98
HAM Seismic Isolation FDR	7/97	4/98	4/98
Core Optics Support FDR	7/97	2/98	2/98
Suspension FDR	-	-	9/97 (Act.)
Core Optics Components FDR	7/97	12/97	12/97
Input Optic FDR	4/98	4/98	4/98
Prestabilized Laser FDR	8/98	8/98	8/98
Alignment S&C FDR	4/98	4/98	4/98
Length S&C FDR	5/98	5/98	5/98
Detector System PDR	12/97	12/97	12/97
CDS Network Installation	9/97	4/98	4/98
Data Acquisition System FDR	4/98	4/98	4/98
Physics Environ. Mon. FDR	6/98	6/98	10/97 (Act.)
Initiate Interferometer Installation	7/98 (WA) 1/99 (LA)	7/98 (WA) 1/99 (LA)	7/98 (WA) 1/99 (LA)
Begin Coincidence Tests	12/00	12/00	12/00

Prestabilized Nd:YAG Laser: Lightwave Contract

- **Goal: Develop 10 W diode-pumped Nd:YAG laser suitable for LIGO**
  - ››Single Frequency
  - ››Diffraction-Limited, Single Transverse Mode
  - ››Intensity and Frequency Stabilization
- **Double pass MOPA configuration adopted**
  - ››Commercial 700 mW NPRO used as master oscillator
  - ››Very good beam profile
  - ››Moderate efficiency and saturation
- **Final Design Review 7/97**
  - ››Brassboard results demonstrated key optical performance parameters (power, beam quality, frequency noise)
- **Alpha unit brought to LIGO this month**
  - ››preliminary testing at Lightwave at or near all output specifications, including demanding limits on intensity noise at 60 Hz harmonics

Prestabilized Nd:YAG Laser: MOPA Performance



Prestabilized Nd:YAG Laser: PSL Design

- **Prototype Prestabilized NPRO tested on Phase Noise Interferometer at MIT**
- **Conceptual design for Prestabilized 10 W Laser reviewed and approved**
  - Frequency stabilization based on system tested on PNI
  - Intensity stabilization will use amplifier pump diode current (with AOM as back-up approach)
- **"Pre-mode Cleaner" tested with NPRO**
  - Passive cavity to reduce intensity noise at modulation frequency (factor of ~5)
  - Collaborative effort with Stanford group
- **Table, enclosure design nearing completion (required by April 1998)**

Prestabilized Nd:YAG Laser: Issues

- **Have observed significant rate of power degradation (>1 mW/day) in some 700 mW NPRO's**
  - ››Power degradation due to decreasing pump power from laser diode, but underlying cause still uncertain
    - — Contamination?
    - — Defective laser diodes?
  - ››Changes made in Lightwave build process to reduce possible contamination sources; not sufficient data (yet) to evaluate effect
  - ››Some units show long life
    - — MO's for LIGO lasers will be tested and selected to have acceptable rate of degradation
  - ››Continuing to urge Lightwave to find and fix the problem

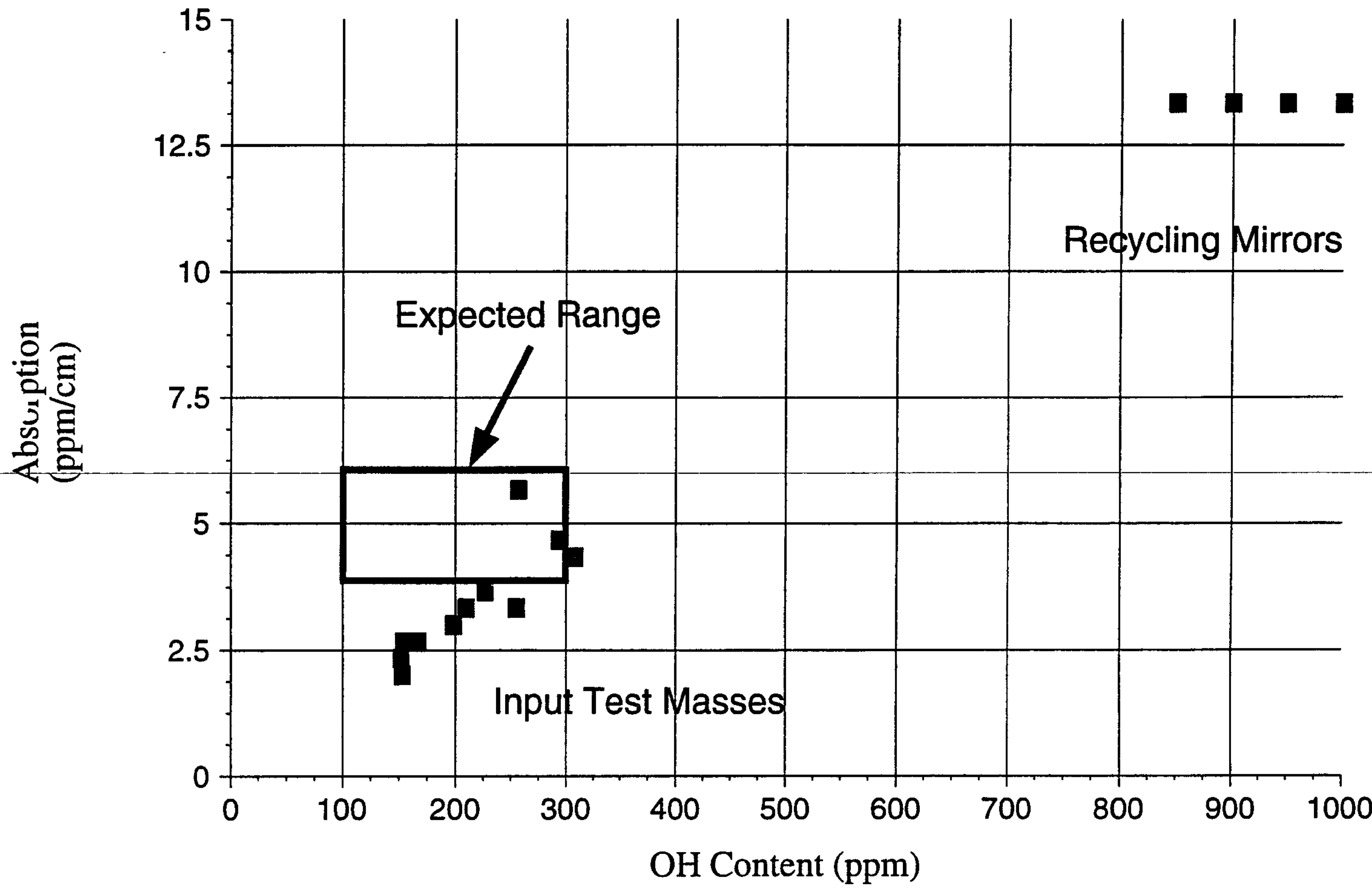
Input Optics: Progress and Status

- **Includes modulators, beam expanding telescope, suspended mode cleaner cavity**
- **University of Florida group taking responsibility for Input Optics**
- **Modulation scheme reconsidered and changed to (simpler) series modulation**
- **Preliminary Design Review held Aug '97**
- **Optical analysis of mode-matching telescope completed**
- **Optical layout of in-vacuum components underway**
- **Long-lead procurements underway**
  - ››Bids for optics blanks received
  - ››Fabrication of Small Optics Suspensions started

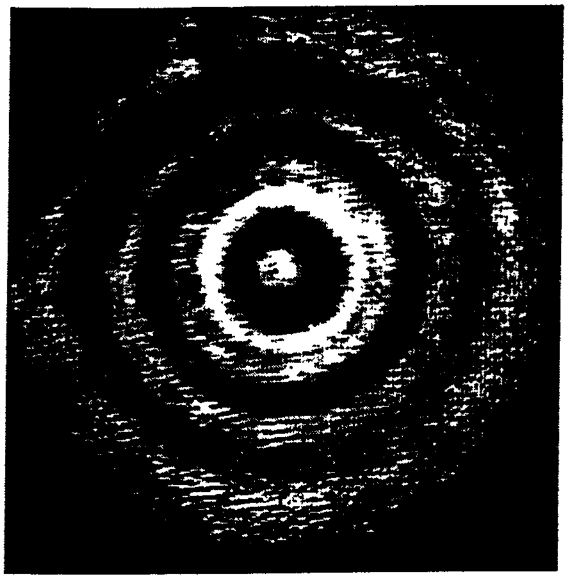
Core Optics: Procurement Status

- **Fused silica blanks for core optics**
  - ››Corning (21 ordered): 17 delivered (ETM's, FM's RCM's)
  - ››Heraeus (18 ordered): 11 delivered (ITM's, BS's)
- **Thermal lensing in Input Test Masses**
  - ››Witness samples have absorption 2-5 ppm/cm versus expected 4-6 ppm/cm
  - ››Analysis indicates sensitivity degradation ~few %
- **Polishing contracts moving forward**
  - ››General Optics: 6 ETM's completed, 2 in work
  - ››CSIRO: 4 ETM's completed, 4 FM's completed, 4 RCM's in work
  - ››Contract to polish 12 Input Test Masses awarded to CSIRO
- **Coating uniformity meets LIGO req'ts**
  - ›› Full-sized optic fabricated at REO and tested at NIST

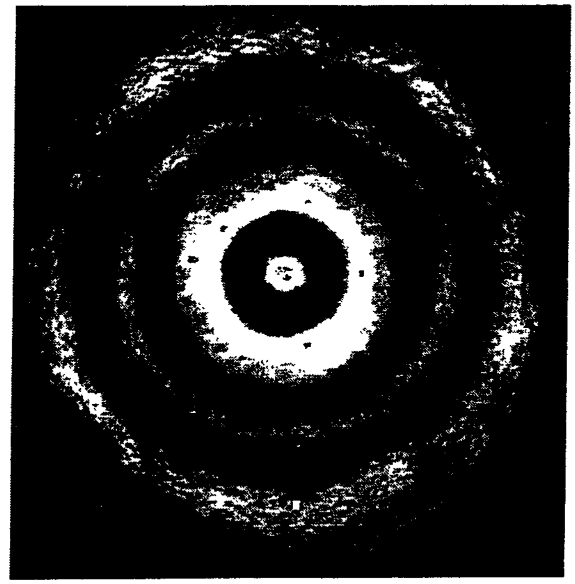
Lasers and Optics
Core Optics: Substrate Absorption



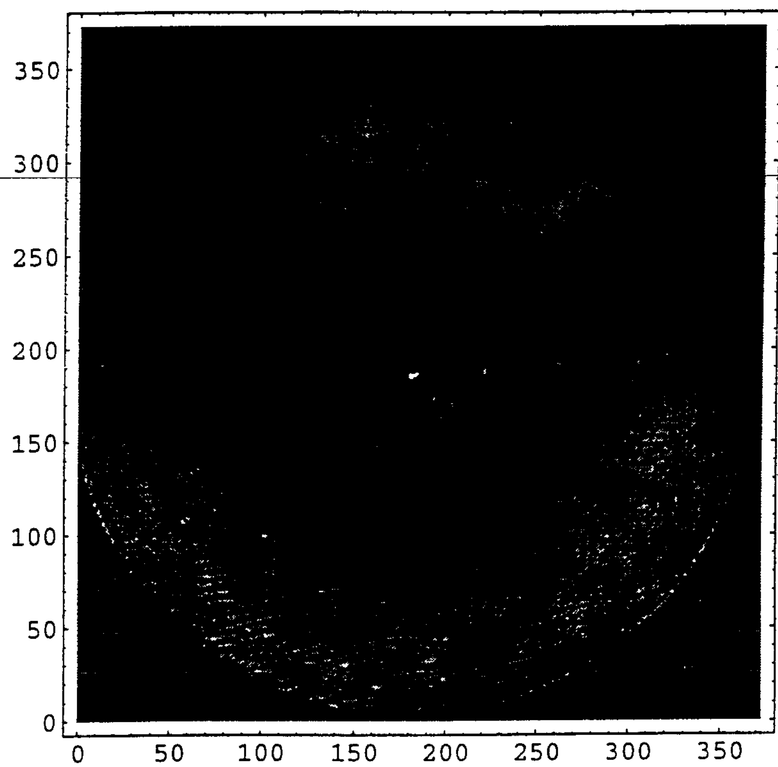
Uncoated



Coated



Difference



Core Optics: Issues

- **Delay of Heraeus fused silica blanks uses all schedule contingency for core optics**
  - ››Aggressive procurement schedule had built ~4 month float
  - ››Heraeus material used for BS and ITM's (logically the first core optics to be installed)
- **Coating scheduling needs to be defined**
  - ››Requires significant block of coating chamber time which must be scheduled with other REO production
  - ››Original plan (involving 3 coating blocks) may need to be modified
- **Optics for 2 km interferometer still scheduled to be delivered on time for installation**
  - ››If any delays occur, we can rearrange the installation sequence to minimize impact on full interferometer operation

LASERS AND OPTICS

Core Optics Support: Progress and Status

- **Responsible for:**
  - ››Telescopes and beam steering optics to extract light for LSC/ASC from vacuum system
  - ››Baffles and beamdumps in vacuum chambers
- **Recent emphasis on design of in-vacuum beam-reducing telescopes**
  - ››16 cm diameter off-axis reflector with 8x demagnification
  - ››Total number required ~20 => significant cost driver
  - ››Key issue is effects of aberrations on alignment wavefront sensing system
  - ››Preliminary conclusion: ~λ/3 telescope optics adequate
- **Preliminary Design Review planned for November**

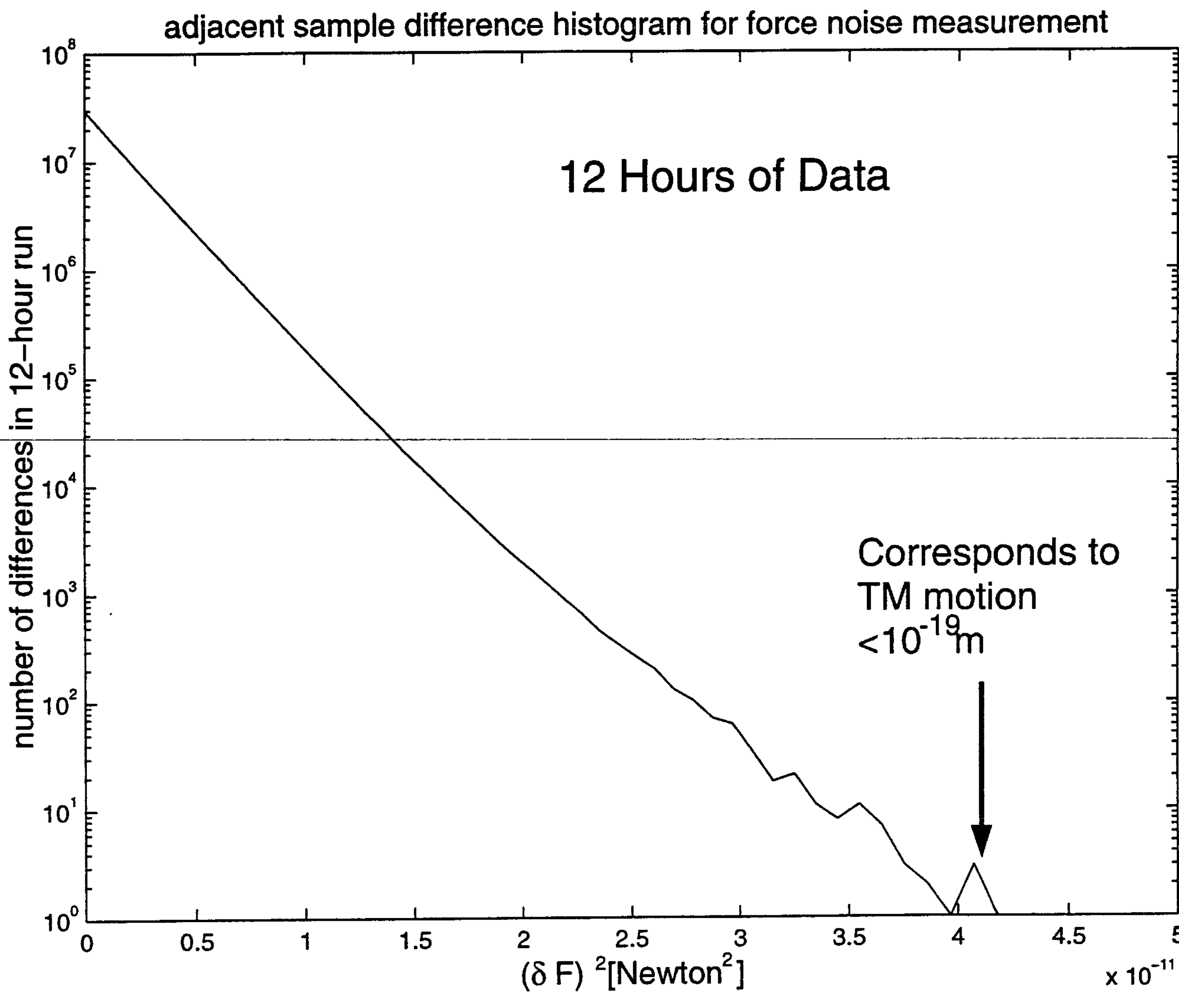
Suspensions: Status

- **Small Optics Suspension**
  - ››Mechanical design complete, prototype installed in 40 m interferometer for performance testing
  - ››Mechanical fabrication for Input Optics underway
- **Large Optics Suspension**
  - ››Mechanical design complete (multiple variants required for different Core Optics)
  - ››Prototype mechanical fabrication, testing complete
  - ››RFQ for fabrication ready to release
- **Electronic circuit invented which meets range/noise requirements**
  - ››Simulation and breadboard verify design concept
  - ››Final design in progress

Seismic Isolation: Status

- **First Article Fabrication Underway**
  - First Article fabrication drawings for mechanical structures finalized and reviewed (June-September)
  - Expect HAM First Article assembly to begin February 1998
- **Creak tests of constrained-layer-damped metal springs performed at Caltech**
  - 12 hours of data showed no evidence for large impulsive events; meets LIGO req't for nongaussian noise
- **Installation sequence for seismic isolation system reviewed in preparation for design of assembly fixtures and tooling**
- **Actuators**
  - Coarse actuator design reviewed; mechanical drawings being finalized, discussions with vendors for commercial components underway
  - Fine actuator range/noise tests being started (for compensation of tidal motion and microseismic peak)

Seismic Isolation: Creak Test Results



Seismic Isolation: Issues

- **Fabrication schedule is tight**
  - ››Need to have 3 HAM seismic isolation systems ready for installation April 1998, 3 BSC systems by late summer
  - ››Some raw materials with lead times up to 12 weeks
  - ››Schedule can be met, but with no allowance for major changes based on First Article testing
- **Cost**
  - ››Some items quoted above our budget, some below -- Net likely to be 5-10% above budget (Fab budget ~$8.7 M
  - ››Fabrication using fixed price contracts, will be managed like facilities fixed price contracts

Interferometer Sensing and Control

Principal Functions:

- Interferometer Length and Alignment sensing
  - Fiducial references/tooling for optics installation, length & angle setup
  - Low-noise sensors for detection-mode alignment and cavity length
- Length & alignment control system design
  - Electronics & networks implemented by Control/Data System partners
- Strain signal readout & calibration
- End-to-end interferometer diagnostics

ISC has three Modes of operation:

- Initial alignment (all mirrors within 0.5 μrad)
- Acquisition (acquire resonance)
- Detection (hold lengths/angles to < 0.1 pm /10 nrad; provide readout)

Operational sensors use interferometric sensing

- length relies on RF-modulation-demodulation techniques, null servos
  - Pound-Drever-Hall for common mode ('reflection locking')
  - asymmetric interferometer for differential mode (not white-light ifo)
- alignment similar; uses quadrant diodes, measures shear between carrier and sidebands
  - near- and far-field to separate angles from displacements

Alignment Sensing/Control

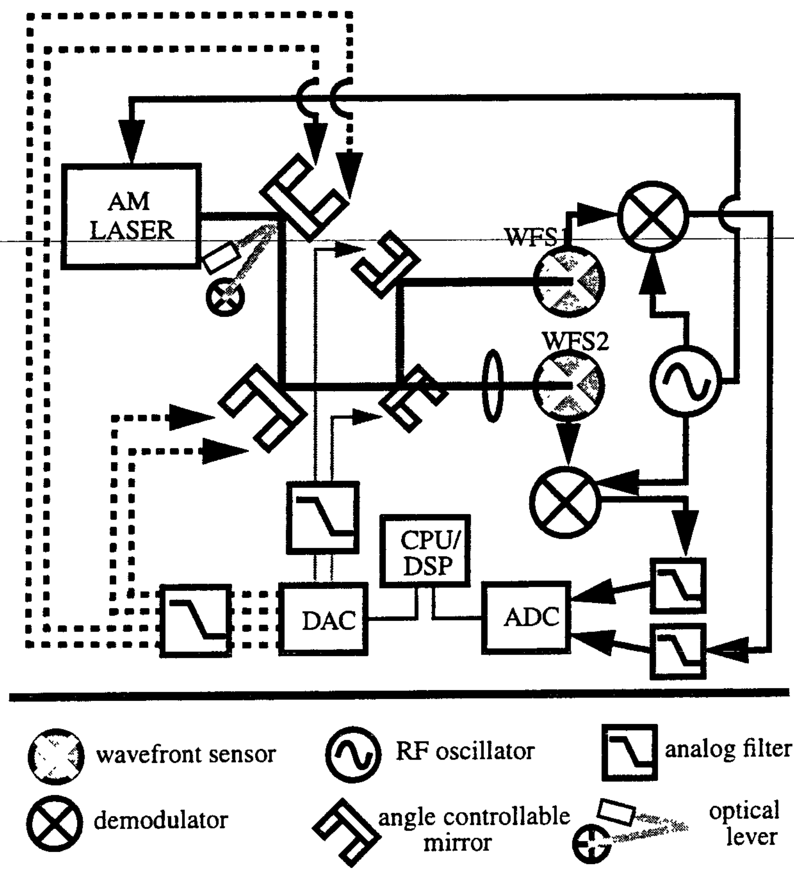
Basic system design and prototyping of sensor well advanced

- Fixed Mass Interferometer verified sensing model, control concepts
- also, tests on Wavefront Sensor head and demodulator concept

Further sensor hardware tests in preparation or underway

- Phase Noise Interferometer uses autoalignment (but with analog servo)
- 40m use (re-use of FMI parts) imminent

Test bench for test of digital controller in construction

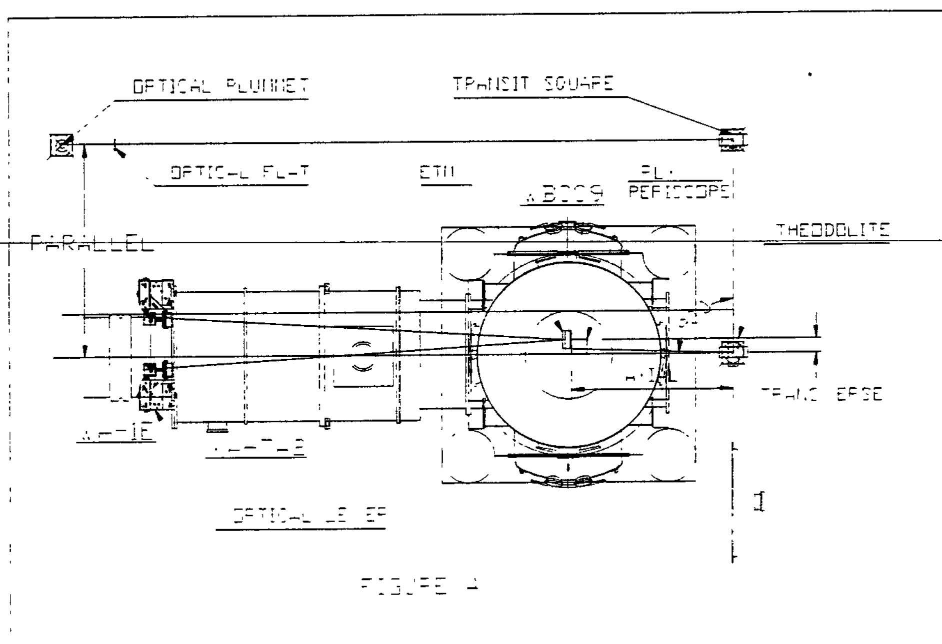


- end-to-end test of a simple cavity; prototype for Mode Cleaner controls

Alignment Sensing/Control

Significant Activity this last half year: Initial Alignment

- must bring components from non-aligned to $<10^{-6}$ rads
- length control system not well-defined 'plant' for larger initial angles
- theodolites and precision monuments used to establish initial pointing
    - > initial articles of the surveying tools acquired
    - > test at Hanford planned in coming months
    - > complete procedures drafted, circulated to impacted systems



- maintaining pointing during acquisition using optical levers
    - > complete prototype constructed and in long-term test

Alignment Sensing/Control

Diagnostics for Alignment and Length

- special role in interferometer diagnosis: most subsystems rely on Align/ Length for diagnostic functions
  - example: tests of cross coupling from intended simple translation of a test mass to accidental rotations; transfer functions of isolation system;...
- both Alignment and Length use digital signal processing, unique in LIGO
  - many interesting test points are never analog
  - requires re-thinking diagnostic procedures, access, and thus design

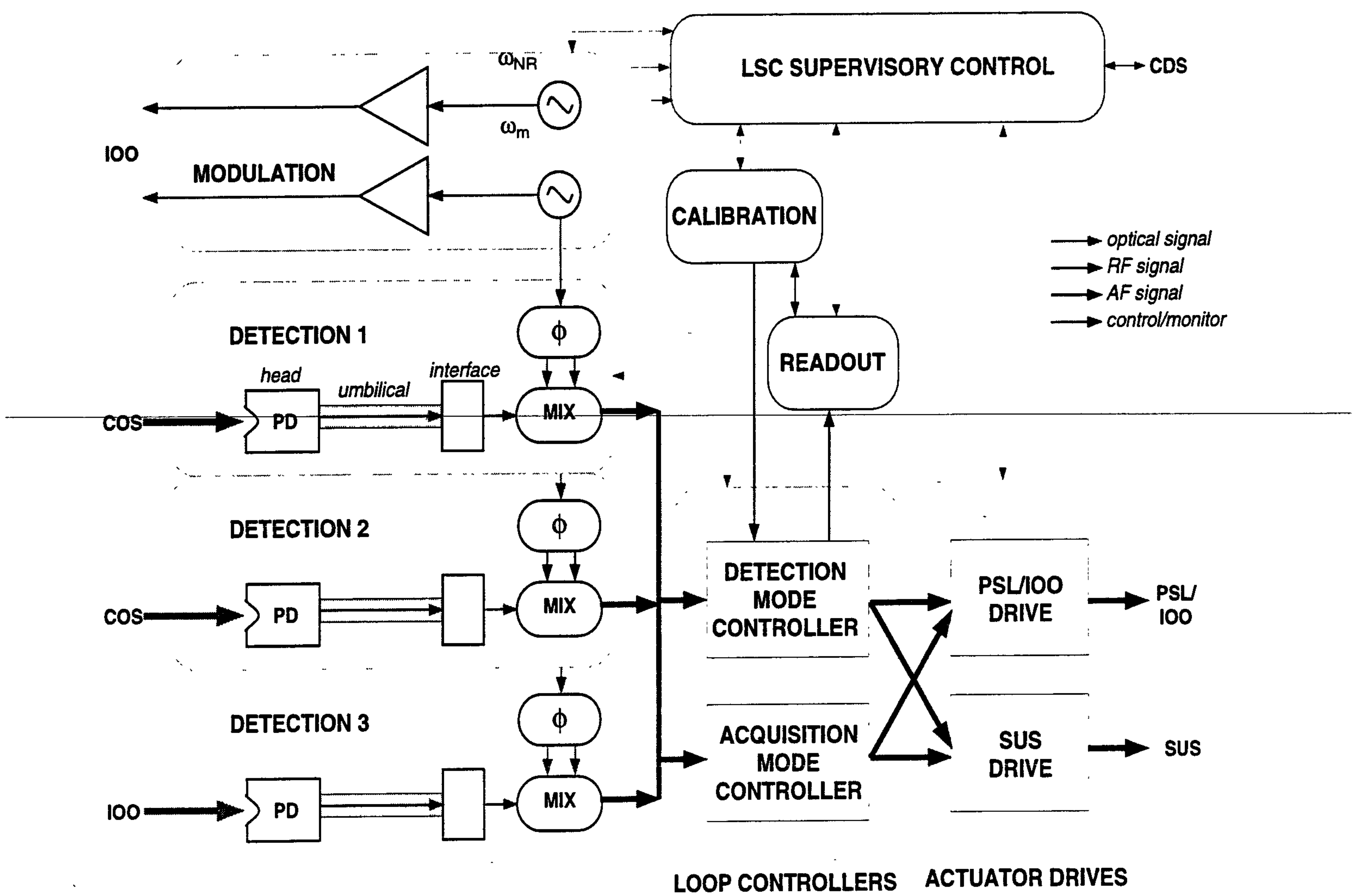
Requirements: capability to

  - extract and display any (digital) signal, including internal servo signals
  - add a stimulus to every error and/or control signal using predefined waveforms (in band and out of band, up to several kHz).
  - store all important Length/Align signals on disk for ~1 h.
  - correlate the diagnostics read-outs with PEM signals (off-line).
  - data formats of data acquisition and diagnostics to be identical
- Presently in conceptual design; test Length aspects on Phase Noise Interferometer (after phase demonstration)

Length Sensing/Control

Preliminary Design completed

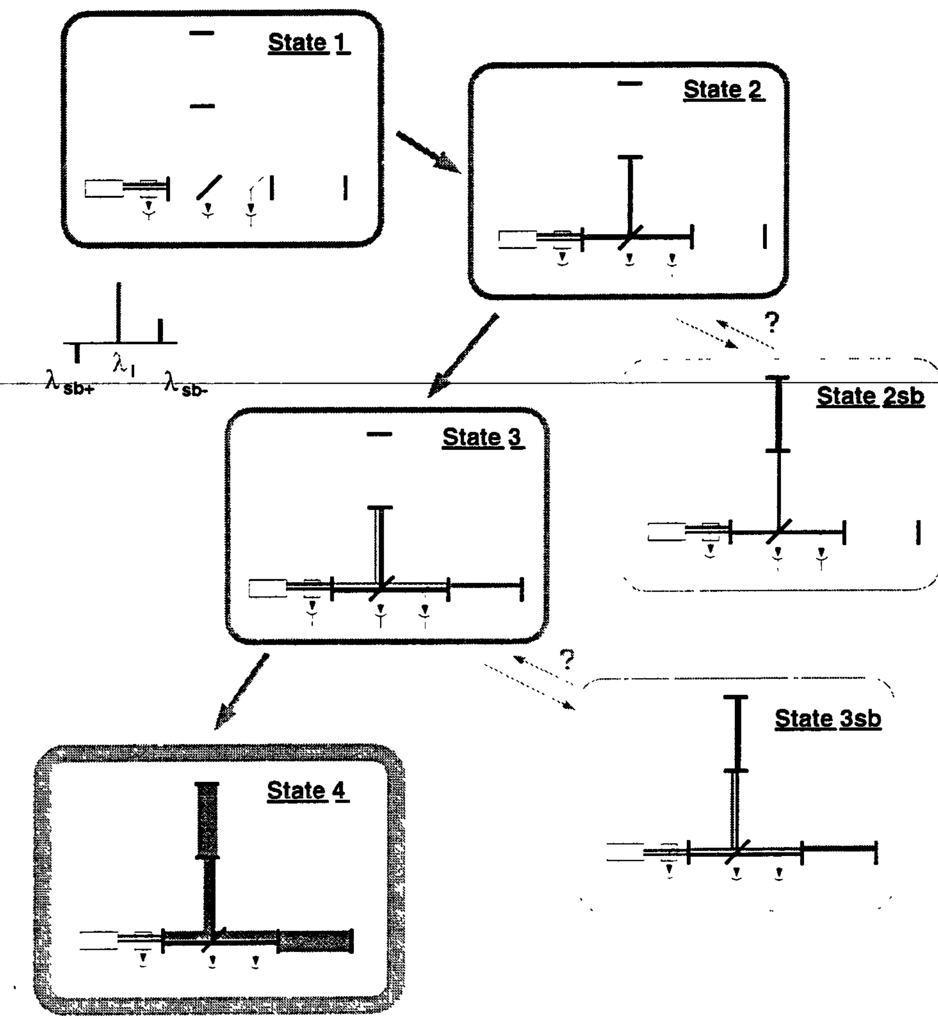
- Subsystem functional block with principal interfaces



Length Sensing/Control

Lock Acquisition

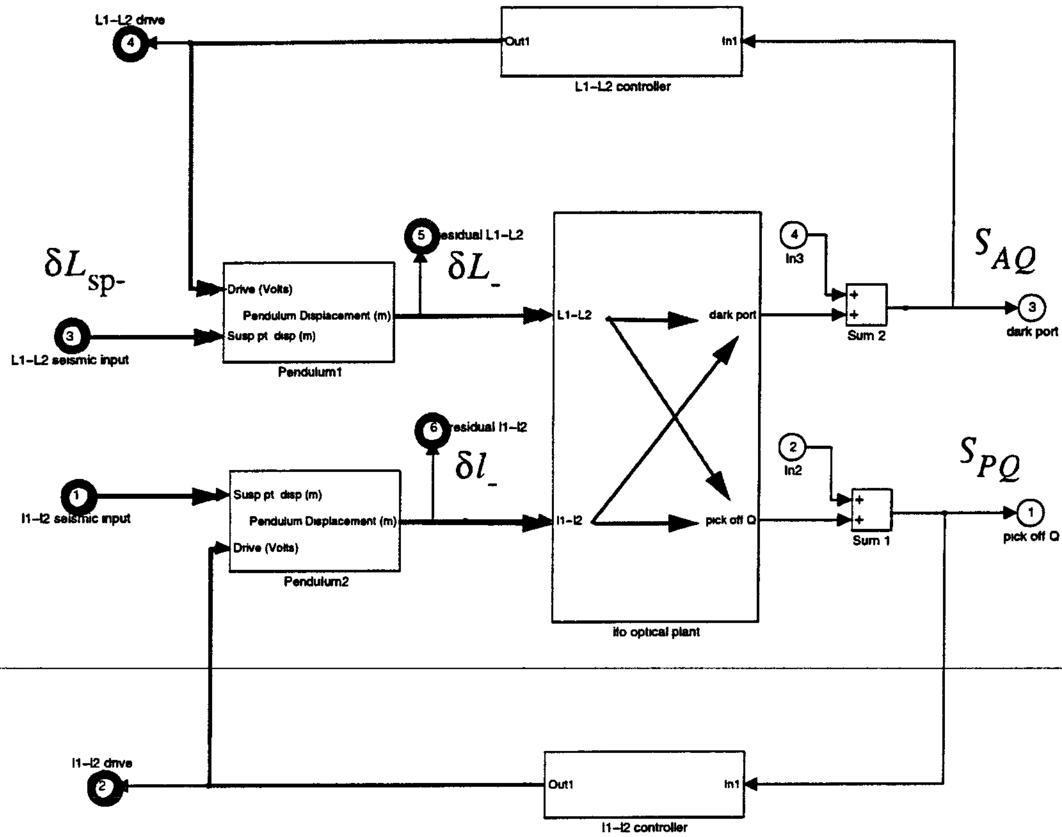
- states identified; stable servoloops developed for each state
- two 'tricks' needed:
  - guided lock acquisition, with intelligent deceleration of masses
  - high gain servo in intermediate state (briefly while test mass 'rings up')



- productive interaction with 40m to test models/aid labwork

Length Sensing/Control

Example: Schematic of differential length control system



Requirements:

- hold arm cavities on resonance to limit laser amplitude noise coupling ($\sim 10^{-13}$ m rms): requires high loop gains at microseismic peak (0.16 Hz) and isolation system resonances (1-10 Hz)
- hold Michelson at minimum without corrupting GW sensing due to limited shot noise sensitivity in Michelson; requires high gain (~100) at ~2 Hz, unity gain at 30 Hz, 0.1 at 47 Hz.

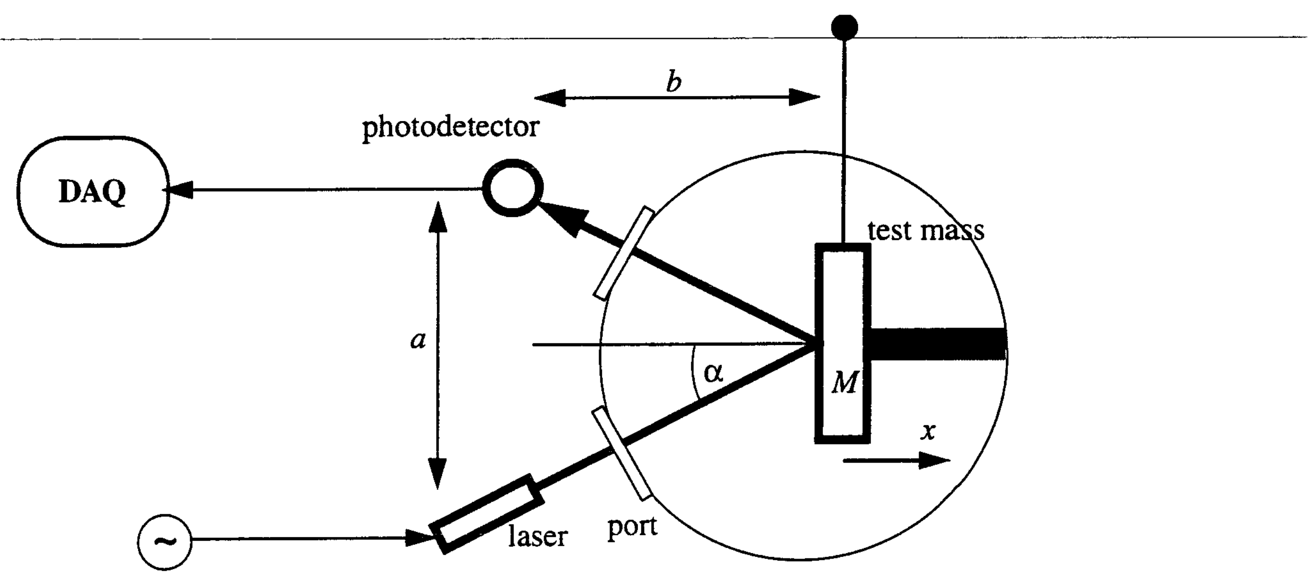
Length Sensing/Control

Requirements for calibration of absolute strain sensitivity

- Absolute strain amplitude: 5%
- Timing of incident GW: ±50 μsec relative to world time

Two systems to be employed

- calibration of coil currents to force, leading to known displacement
  - developed/used on 40m, PNI; requires some care
- Photon Actuator
  - several mW of power sufficient for reasonable measurement durations
  - measurement of power biggest uncertainty (~2%)
  - test planned on Phase Noise Interferometer



Length Sensing/Control

Photodetectors

- InGaAs devices have undergone additional testing
  - surface measurements for comparison with backscatter
  - lifetime at high currents (>80 mA photocurrent per 2mm dia device)
- Additional commercial sources identified
  - Hamamatsu, GPD, EG&G
- photodetector 'head' (diode, resonant circuit, preamplifier, monitor) designed
  - in test on the Phase Noise Interferometer (right test of dynamic range)

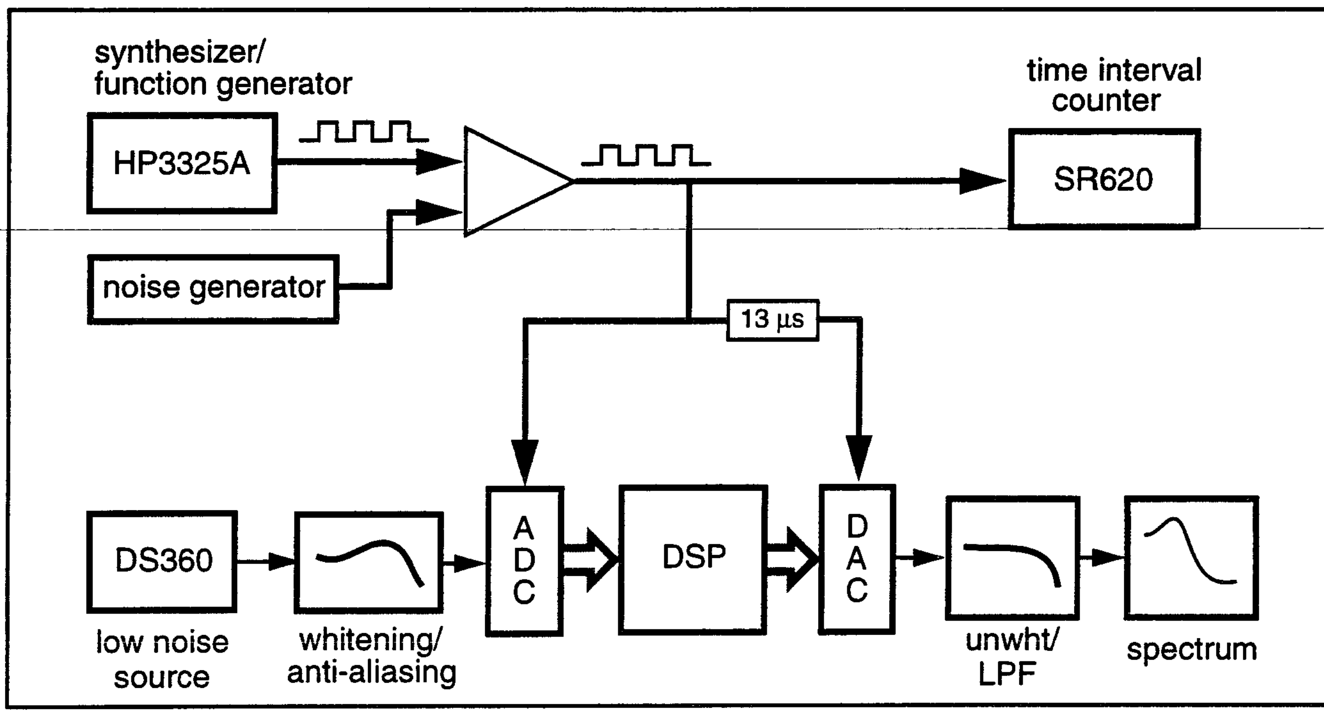
Length Sensing/Control

Digital transmission of test-mass control signals

- required to send signals down 4km length
- puts entire system in digital domain: flexibility abounds

Requirements on dynamic range severe

- control signals to test mass span from tidal motions (hundreds of microns) to instrument shot-noise limited sensitivity (10^{-19} $\mathrm{m}/\sqrt{\mathrm{Hz}}$)
- test starting; open loop, closed loop, then application to Phase Noise Interferometer



- many similarities in gains, dynamic range requirement (no 4km delay, arm storage time though)

Length/Alignment Sensing/Control

issues identified at time of Length Preliminary Design Review (July 97)

- technical
  - operational servo designs are not yet finalized; robustness difficult to achieve given large low-frequency gain requirements and very severe out-of-band performance requirements
  - acquisition requires 'tricks'; has undesired states which are presently simply left to occur at will (lengthens locking time); no real tests of full storage time possible
  - digital signal systems new for scientists, challenging for engineers
- schedule
  - technical problems more challenging than 'planned'
  - subcritical design teams (1.something people per task)
  - ~~some lost/re-deployed staff~~
  - and: shared staff with Phase Noise and 40m Interferometers

Difficult choice: reduce 40m effort, regroup/strengthen Length/Align

- control systems must be in place for debugging of entire interferometer
- build in flexibility to allow late information from 40m to be incorporated
- place more reliance on modeling
- some increased risk, but best path from here to operations

40m program remains important and vital

- longer schedule for same goals

40m Interferometer

Objectives

- demonstrate acquisition and operational control systems on a complete LIGO-configuration interferometer
- serve as a testbed for LIGO electronics subsystems

Planned activities during last half year

- incorporation of recycling mirror
- shakedown of recycled Michelson system
- shakedown of complete recycled interferometer

Technical problems

- Argon Ion Laser: 3 tubes (various defects, various delays), power supply
- instrumentation: power supplies, more interesting problems (modulation system phase shifter, suspension controller)
- optics: Pockels Cells with anomalous 'clouding', also failures of vacuum bakeout controls

Staffing

- limited number of experienced interferometer physicists

40m Interferometer

Accomplishments

- installation procedures on optics/suspensions
- input to suspension design (cross-coupling of suspensions sensors)
- testing of data acquisition system
- tests of dynamic and static models
- **successful operation of recycled Michelson**

In preparation

- installation of wavefront sensors, associated (analog) servo
  - aid to operations of 40m (some critical degrees of freedom)
  - test on long-baseline, suspended system with coupled cavities
- servocontrols for complete recycled Fabry-Perot configuration

---

Schedule

- shakedown of recycled Michelson in process; installation of wavefront sensors
- November: add one Fabry-Perot arm
- December: second arm, thus complete configuration
- January '98: use of wavefront sensor
- April '98: stable operation, noise studies; data taking, analysis

Phase Noise Interferometer

Objectives

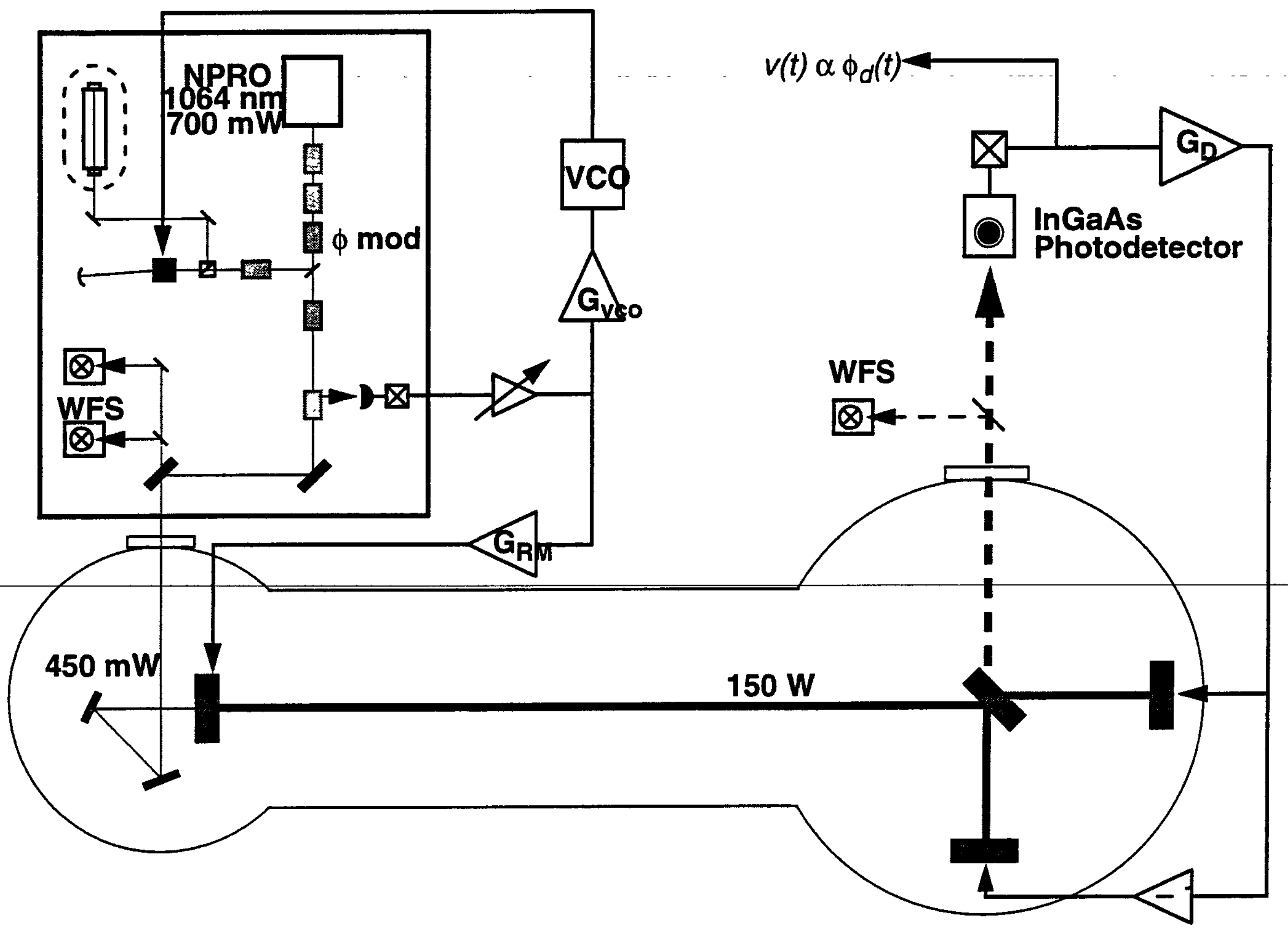
- demonstrate ability to sense phase as required for LIGO (8×10^{-11} $\mathrm{rad}/\sqrt{\mathrm{Hz}}$)
- test photodetector/amplifier designs
- explore sensing limitations in general; e.g., scattered light, frequency noise...
- new: demonstrate a closed-loop digital control loop with prototype hardware

Conversion to Nd:YAG

- incorporation of 700 mW IR Pre-Stabilized Laser
  - changes in servo-system configuration, parameters
- change of optics to 1064 nm
- trimming of alignment, length control systems
- operational at the end of September

Phase Noise Interferometer

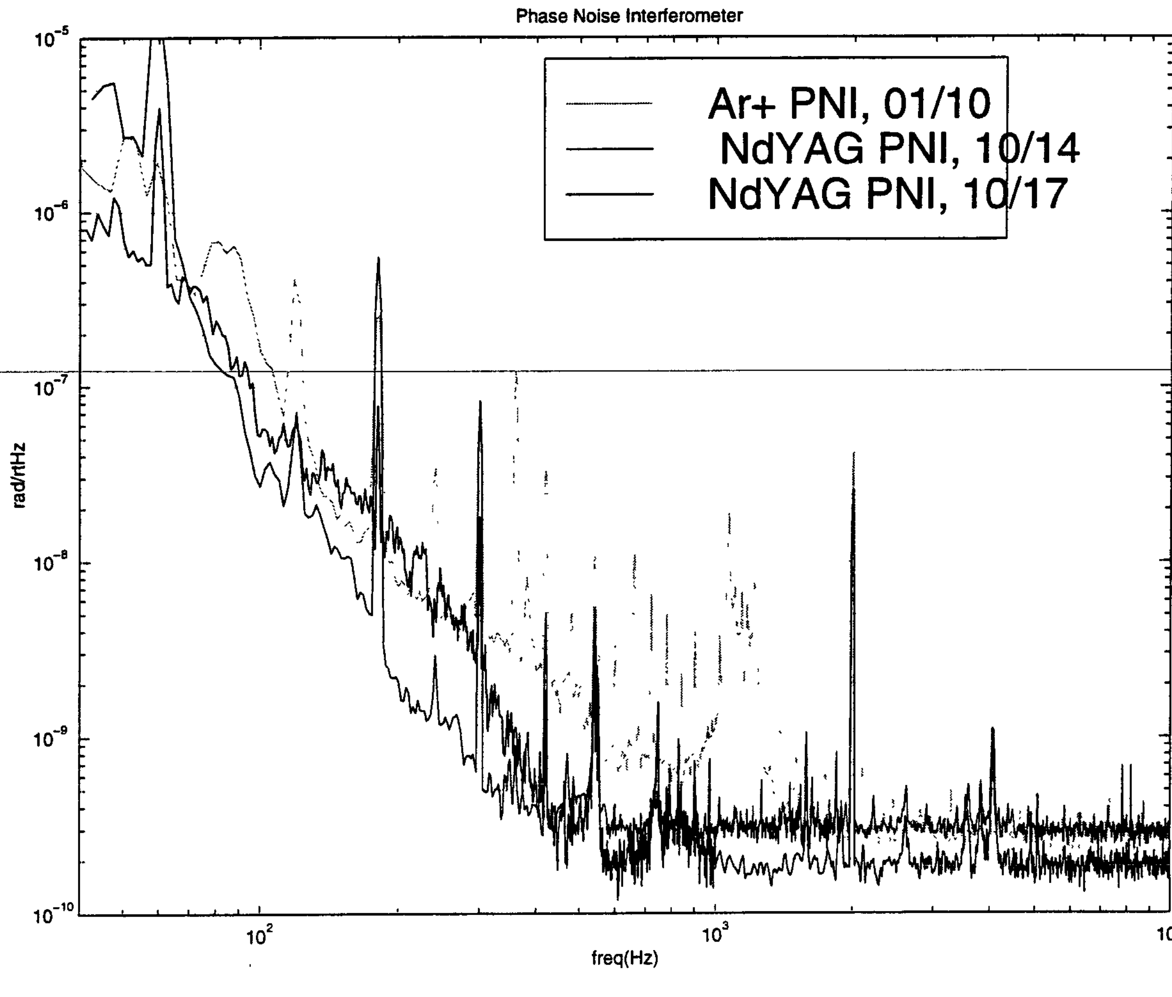
Schematic layout



Phase Noise Interferometer

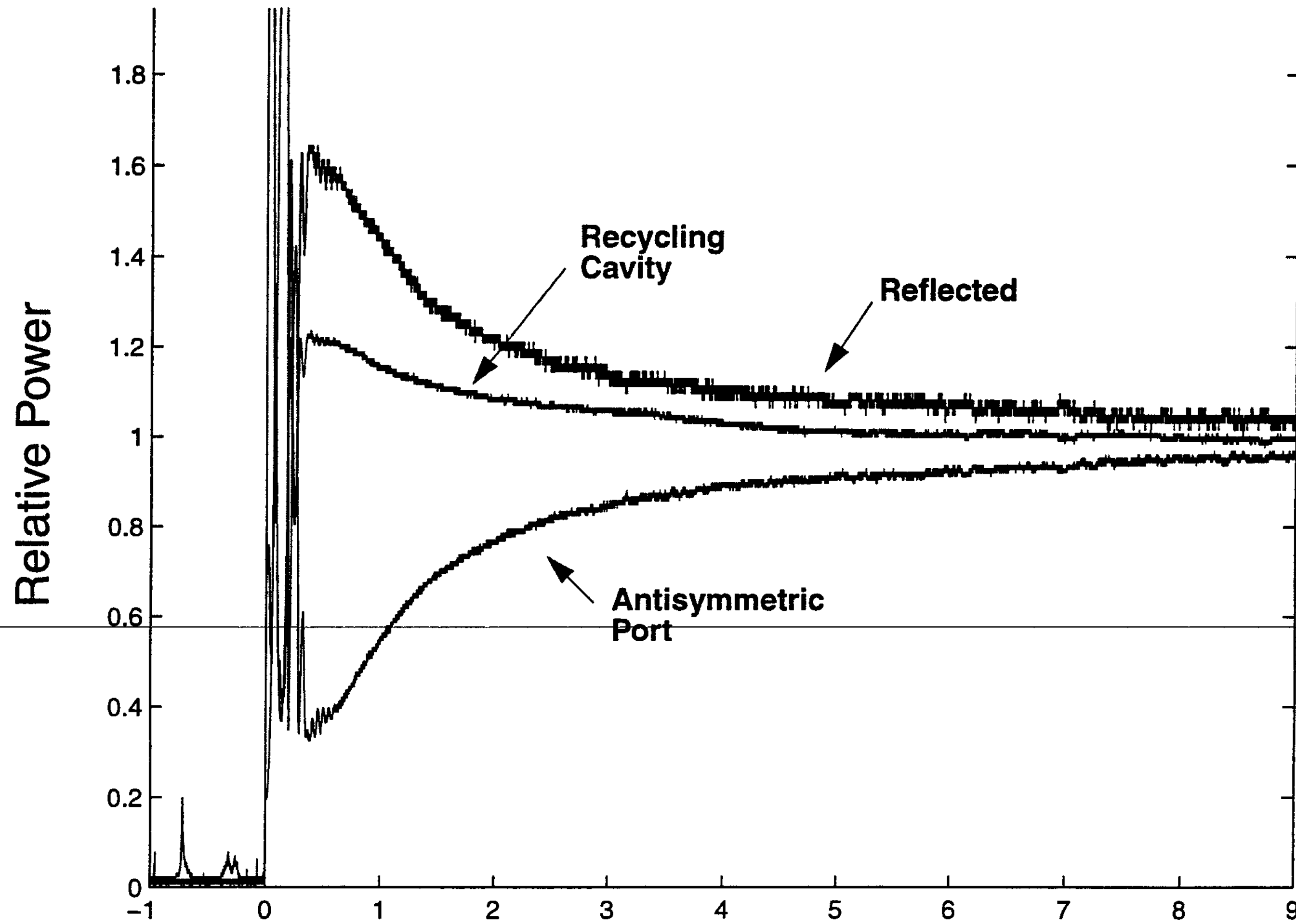
System works well, looking at noise sources carefully

- Low frequencies: variable, related to seismic noise, probably accidental backscatter from output table components
- High frequencies: shot noise limited at ~150 W circulating, $2\times10^{-10}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$, limited by thermal lensing



Phase Noise Interferometer

Thermal lensing identified by time evolution of interferometer parameters



- Contrast degrades from ~10^{-4} to ~4×10^{-4} in matter of seconds
- had also observed with Argon laser Phase Noise Ifo, but changing beam position reduced effect --> mirror contamination; for Nd:YAG, this effect independent of beam position
- roughly explained by 15 ppm/cm absorption in Beamsplitter substrate, to be confirmed by measurements on similar pieces

Phase Noise Interferometer

High frequency research thus at a natural limit

- close enough to LIGO requirements to show photodiode performance, scattering paths, stress dynamic range of detection/control system

Low frequency research now focus

- search for backscatter paths
- excitation of probable contributors

Parallel development of closed-loop digital servo tests on system

- to follow understanding of noise spectrum and tests of analog detection elements

Have to finish everything by May, when Building 20 is slated for destruction.

Physics Environment Monitor

Purpose: to understand environmental impact on interferometer

- obvious linear couplings (e.g., seismic noise in GW band)
- non-linear couplings (e.g., upconversion from large motions at a few Hz)
- dynamic range issues (e.g., correlation of microseismic peak)
- unanticipated couplings (e.g., RFI saturating amplifier front ends)
- characterization of observatories (e.g., weather monitoring)

Sensors:

- accelerometers, seismometers, microphones, magnetometers, RF receivers, thunderstorm monitor, muons detector, power line monitors, dust monitors, residual gas analyzers, weather monitors

Sources of excitation:

- piezo-electric and electro-magnetic 'shakers', loudspeakers, magnetic and electric field generators

Implementation

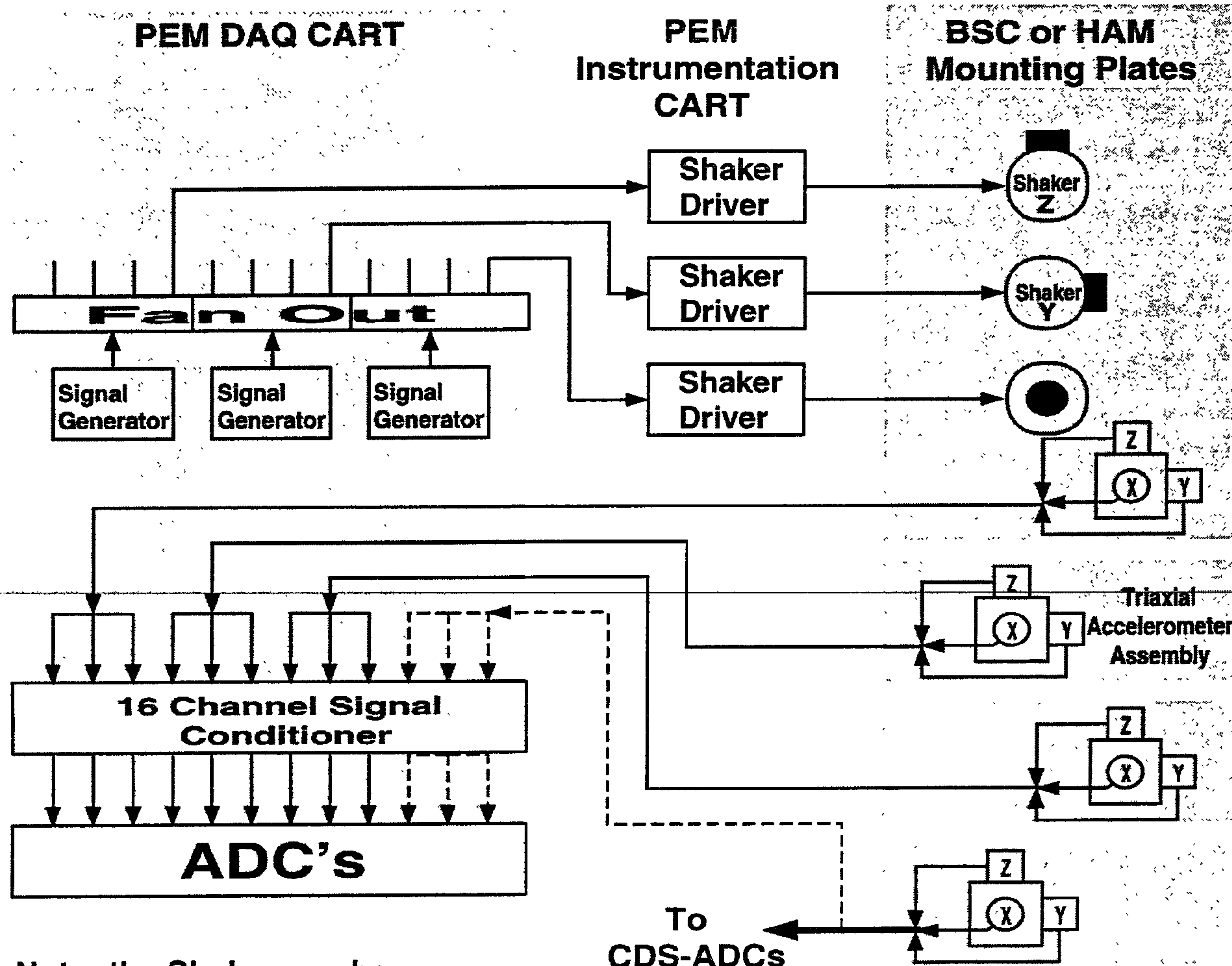
- fixed equipment associated with interferometer
- portable excitation/sensing equipment for special tests
- central acquisition system for global diagnostic tests, or stand-alone

Status

- Final Design completed; fabrication/procurement underway
    - principally commercial instruments
- Field measurements (for early site correlation studies) in November

Physics Environmental Monitor

Example: Transfer function of a seismic isolation system
Mechanical Excitation System



Note: the Shaker can be PZT or Electromagnetic Shaker

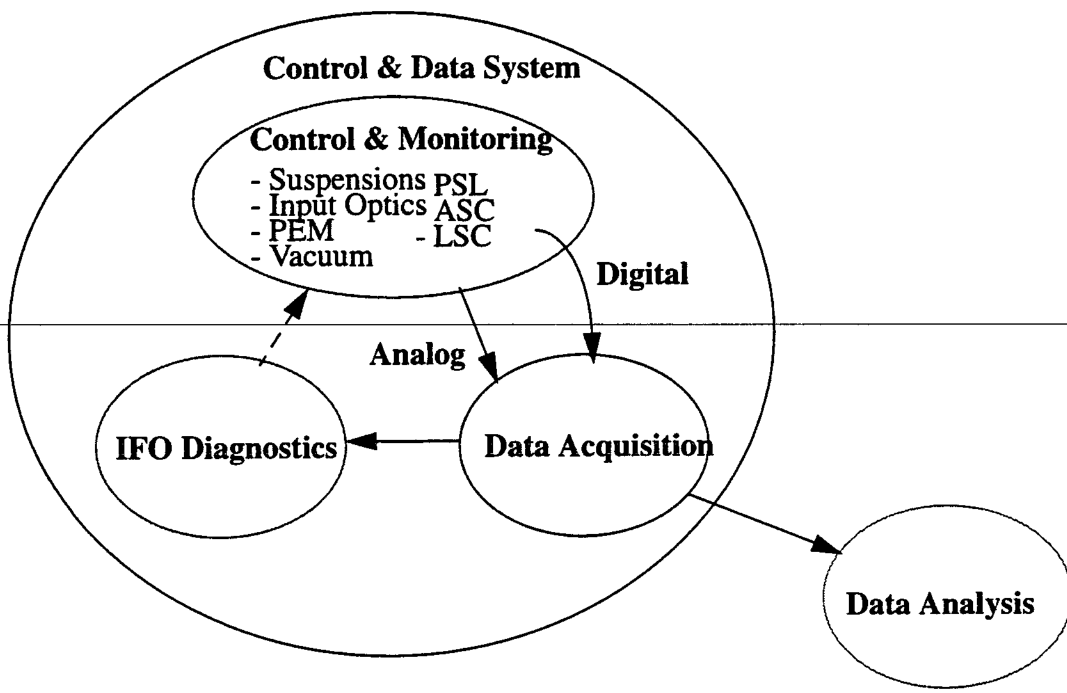
Control and Data System

Group very active in all detector subsystems

- those actions reported with subsystem activities
- hardware and software in preliminary or final design

Global Control and Data System activities

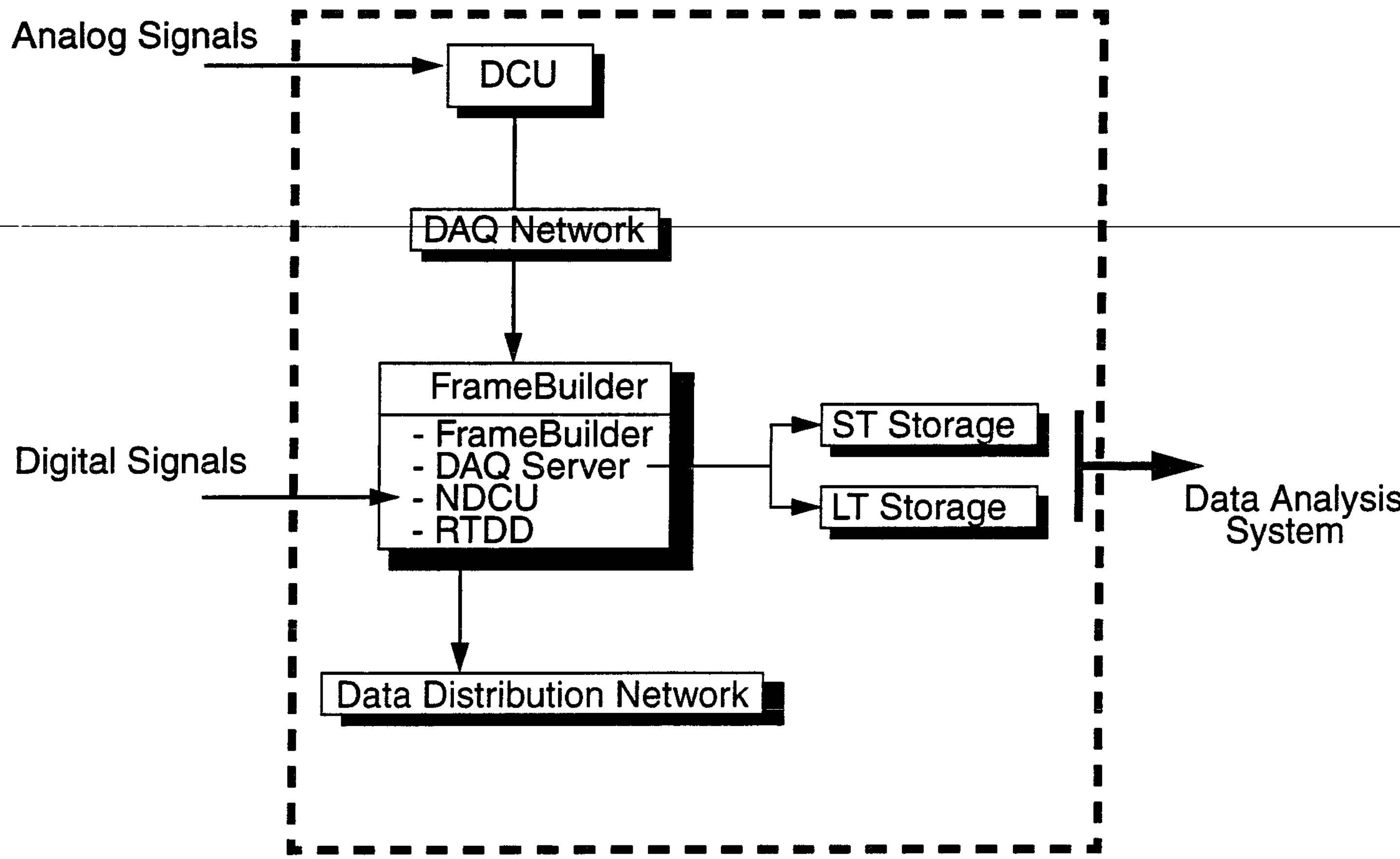
- Data Acquisition Preliminary Design completed
-



Control and Data System

Requirements for Data Acquisition system:

- Acquire analog signals provided by control and monitoring subsystems
  - Provide anti-alias filtering and overrange detection
  - 16 bit digitization, to 16384 samples/sec
- Format acquired data into LIGO/VIRGO standard frame formats.
- Save formatted data to short and long term storage.
- Provide data display capabilities data distribution capabilities



Control and Data System

Design issues resolved:

- Anti-aliasing and sampling approaches
- time-stamping system, GPS receiver deployment
- network and frame-builder hardware tests
-

Final Design underway

- Procure and install VME UltraSparc in prototype and verify system meets specs of >6MBytes/sec
- Work with others to develop specifications for LIGO database
    - Instrument Configuration
    - Operator entries
    - Tape storage information
- Add additional data display features
    - Faster graphics packages (XRT Graph / Open GL)
    - Add DSP engine into FrameBuilders to present FFTs in realtime
- Finalize initial system layout based on actual control system designs

Control and Data System

Vacuum Controls

- CDS carries responsibility for coordination and remote control of vacuum system
- ~700 analog interface signals, 7 control racks
- software to lockout illegal states
- display systems to track status and indicate errors
- system complete September 20
- testing/commissioning with PSI in December/January
- **first 'detector' hardware on sites, much more to follow**

Where are we?

Significant accomplishments

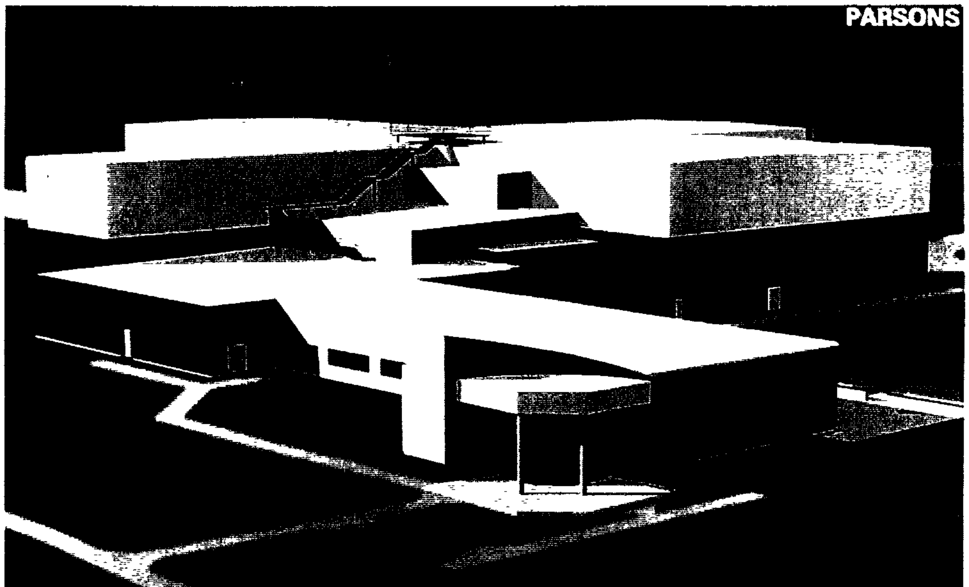
- Verified low absorption of Heraeus fused silica, completed polishing of 14 Core Optics, verified coating uniformity
- Received first 10 W Nd:YAG laser, verified LIGO performance of servocontrols in Phase Noise Interferometer test
- Placed comfortable limit on spring creaking, started first article Seismic Isolation fabrication
- Invented circuit to meet range/noise requirements for suspension drive, completed suspension design
- Verified that InGaAs photodiodes can operate at power and frequency required, demonstrated near-LIGO phase sensitivity
- Started digital servo implementation test, established length control design basis
- PEM final design complete, ordering deliverable equipment

Overall status

- ~1/2 of all subsystems have initiated fabrication
- A number of issues to watch but no major technical problems

Major Challenge

- To move the fabrication along in time to support installation
- To remain flexible to adapt to (inevitable) changes in plan



LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

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