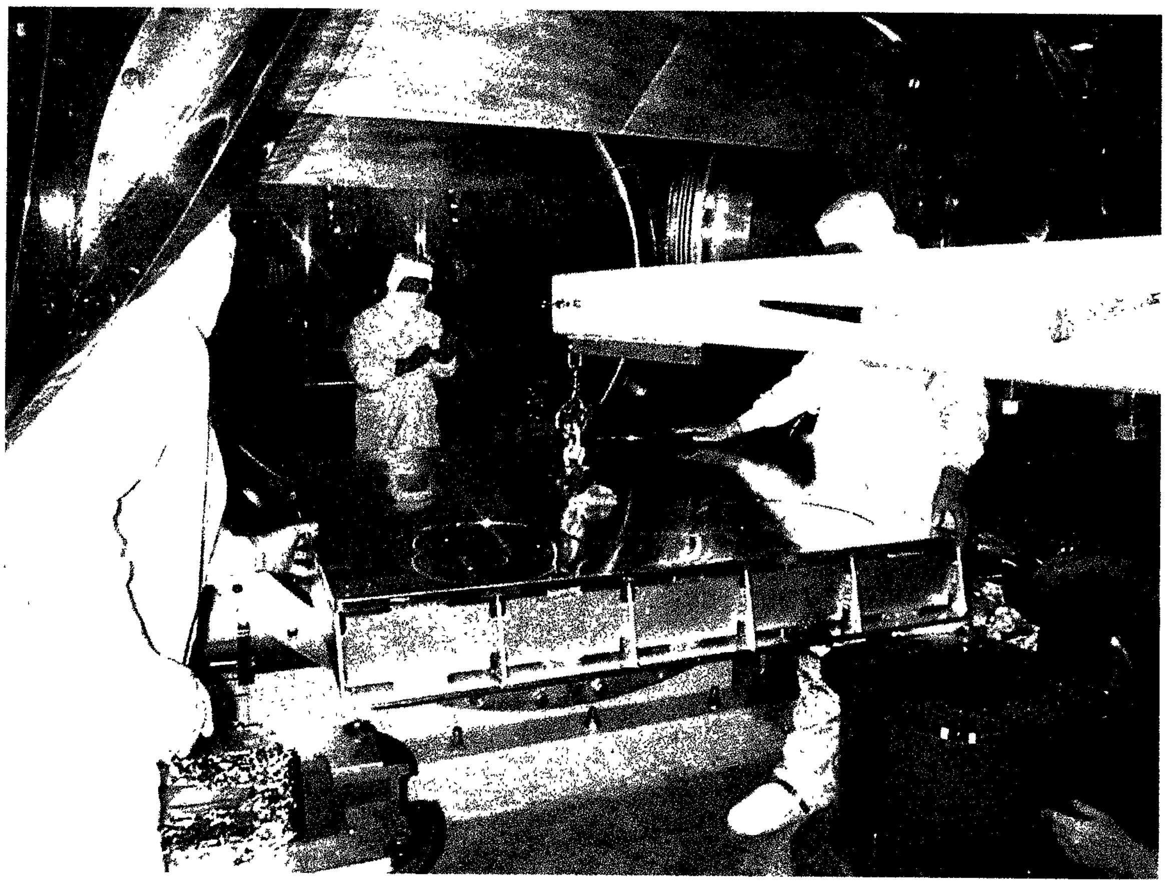
National Science Foundation
Technical Review of the LIGO Project

October 27-29, 1998

LIGO Hanford Observatory
Washington



Laser Interferometer Gravitational Wave Observatory

LIGO - G980126-00-M

LIGO Project
California Institute of Technology/Massachusetts Institute of Technology

National Science Foundation
Technical Review of the LIGO Project
October 27–29, 1998
Hanford, Washington

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INTRODUCTION

Charge to the Committee

Charge
NSF Committee to Review Technical Progress on LIGO

October 27 - 29, 1998

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

Include in your report, reviews of progress on:

> The procurement and installation of the detector systems; the beam tube; the vacuum equipment, and the civil construction,
>
> The LIGO Data Acquisition System, the software development and the plans to specify the hardware, and
>
> The first year of the advanced R&D program, and the plans for and status of the 40m interferometer.

Consider the effect on the detector installation and on the 40m interferometer program from a possible shortfall in the operations budget.

A summary of the recommendations should be available by the time of adjournment of this meeting and the final report of the review by the committee should be available to the Foundation by November 20, 1997.

Agenda

LIGO Project
California Institute of Technology/Massachusetts Institute of Technology

National Science Foundation
Technical Review of the LIGO Project
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TUESDAY OCTOBER 27, 1998

8:00 Executive session

9:00 LIGO Project Introduction and Status — Gary Sanders

9:45 Livingston Site Status — Mark Coles

10:15 Hanford Site Status — Fred Raab

10:45 Break

11:00 Detector Status/R&D Status — Stan Whitcomb/David Shoemaker

Noon Lunch break

1:00 Detector Installation — Dennis Coyne

2:00 Tour of Hanford Observatory site for committee and NSF (in two groups)

3:30 Committee Executive Session

4:00 Parallel groups

A. Detector Installation and Integration — Multi-use Room
Reviewers: Rohrer, Berquist, Hartill, Marx

B. Laser/Optics Status and R&D summary — Small Conference Room
Reviewers: Falcone, Kirk, Levenson, Butler
Subjects: Lasers and Optics

C. Bakeout, Conventional Construction, Vacuum Systems — Main Conference Room
Reviewers: Damm, Reardon

5:30 Executive Session

6:30 Depart for Dinner

WEDNESDAY OCTOBER 28, 1998

8:00 Executive Session

9:00 LIGO Data Analysis, Modeling, Computing — A. Lazzarini

10:00 Parallel sessions resume

- **A.** Continued — Multi-use room
  Reviewers: Rohr, Kirk, [Damm, Reardon, if available]
- **B.** Continued — Small Conference Room
  Reviewers: Falcone, Levenson, Hartill
  Subjects: 40M and R&D
- **C.** Continued — Main Conference Room
  Damm, Reardon
- **D.** LIGO Data Analysis, Modeling, Computing — Control Room
  Reviewers: Butler, Marx, Levine

12:30 Lunch

1:30 Executive Sessions
Reports from the Subgroups
Formulation of Recommendations and Executive Summary

THURSDAY OCTOBER 29, 1998

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

Table 1: LIGO Acronyms and Abbreviations

Acronym	Definition
1x/2x/3x	Notation for single, double, and three-foldcoincidence operational modes of the LIGOdetector comprised of 3 IFOs
1D/2D/3D	One, two, three dimensions (dimensional)
10/100BaseT	Telephone type Ethernet cable (10/100 Mpbs)
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
ATM	Asynchronous Transfer Mode (inter-processorcommunications protocol)
AVS	Advanced Visual Systems (graphical development software package)
BAC	Budget At Completion
BCU	Beam Control Unit
BH	Black hole
BNWL	Battelle Northwest Laboratories
BSC	Beam Splitter Chamber
BT	Beam Tube
BTD	Beam Tube Demonstration
BUDG	Budget
BW	bandwidth
CA/NS	Control Area and Networking System
CACR	Center for Advanced Computing Research (Caltech)
CAM	Control Account Manager
CAP	Control Account Plan
CBI, CB&I	Chicago Bridge & Iron
CCB	Change Control Board
CCD	Charge Coupled Device

Acronym	Definition
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
CIT	Caltech
CNTR	beam Centering Alignment System
COC	Core Optics Components
CONT.	Continued (from previois page)
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)
CW	Continuous wave (periodic) source
DAC	Digital-to-Analog Converter
DB, DBMS	DataBase Management System
DCC	Document Control Center
DCCD	Design Configuration Control Document
DEC/SUN	Computer Manufacturers:Digital Equipment Corp/SUNMicrosystems, Inc
DMA	Direct Memory Access
DoD	Dept. of Defense
DoE, DOE	Dept. of Energy
DOF	Degree of Freedom
DRD	Data Requirement Description
DRR	Design Requirements Review
DSP	Digital Signal Processor
E2E	"End to End", LIGO Modeling & Simulation Environment
EAC	Estimate At Completion
EM	Electromagnetic

Acronym	Definition
EFINISH	Early Finish
EMC	Electro-magnetic Control
EMI	Electro-magnetic Interference
EMSL	Environmental Molecular Sciences Lab (Battelle)
EPICS	Experimental Physics and Industrial Control System
ESnet/DoE	Energy Sciences Network/Dept. of Energy
ESTART	Early Start
ETC	Estimate to Complete
FAB	Fabrication
Fcl	Frame Class Library, suite of routines which create, read, process LIGO framed data objects.
FDR	Final Design Review
FFT	Fast (Discrete) Fourier Transform
Fiber Channel	255 Mbit per second communications network
FIFO	First In, First Out Method of reading data written to dynamic memory
FMI	Fixed Mass Interferometer
FO, F/O	Fibre optic (cable)
FP	Fabry-Perot
FSSC	Frequency-Shifted Subcarrier generator
GCDS	Global CDS Functions
GEO	British/German Cooperation for Gravity Wave Experiment
GFLOPS	1000 MFLOPS
GO	General Optics (Company Name)
GPIB	General Purpose Interface Bus
GPS	Global Positioning System
GUI	Graphical User Interface
GW	Gravitational Wave
HAM	Horizontal Access Module
HDOS	Hughes Danbury Optical Systems (Company Name)
HEP	High Energy Physics

Acronym	Definition
HNR	Hanford Nuclear Reservation (LIGO Site)
HiPPI	High Performance Perfipheral Interface, networking protocol for supercomputer mainframes
HPSS	High Performance Storage System, high volume tape robot system for mass data storage
HR	High Reflector (mirror)
HTML	HyperText Markup Language, language for creating web pages
HWP	Half-Wave Plate
HYTEC	Company Name
Hz, kHz, MHz	1, 10^3, 10^6, etc. Hertz or cyles per second
I/O	Input/Output
IAS	Initial Alignment System
IFO	Interferometer
IFODAQ	Interferometer Data Acquisition
Internet II	Consortium of Universities (Formed Fall 1996)
IPAC	Infrared Processing and Analysis Center (Caltech research center)
I/O	Input/Ooutput (computer data)
IOC	Input/Output Controller
IOO	Input/Output Optics
IPAC	Image Processing & Analysis Center (Caltech)
IPS	Integration Project Schedule
IR	Infrared
ISC/ASC/LSC	Interferometer/Alignment/Length Sensing & Control Systems
JPL	Jet Propulsion Laboratory
kB/MB/GB/TB	10^3/10^6/10^9/10^12 bytes
kbps	Kilobits per second
kBps	Kilobytes per second
km	kilometer
kFLOP/MFLOP/GFLOPS	kilo/Mega/Giga Floating Point Operations per second
kpc	3 x 3^3 lightyear (kiloparsec)
LA	Louisiana

Acronym	Definition
LAN	Local Area Network
LaSERnet II	Louisiana Southeast Regional net
LBL	Lawrence Berkeley National Lab
LDAS	LIGO Data Analysis System
LIGO	Laser Interferometer Gravitational-Wave Observatory
LigoLW	LIGO LightWeight Data format (complements framed data)
LN2	Liquid Nitrogen
LNT2	Liquid Nitrogen Trap No. 2
LNS	Laboratory for Nuclear Science (MIT)
LOS	Large Optic Suspension
LOTS	Laser Optical Tape Storage, a company developing alternative to magnetic media for tape storage.
LRC	LIGO Research Community
LSC	Length Sensing and Control
LSU	Louisiana State University
LVDT	Linear Variable Differential Transducer
LVEA	Laser/Vacuum Equipment Area
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
MOU	Memorandum of understanding
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

Acronym	Definition
NIST	National Institute of Standards and Technology
NS	Neutron Star
NSB	National Science Board
NSF	National Science Foundation
OC3/OC12	Fiber-optic data bandwidth specifications: 155/622 Mbps
OO, OOP	Object Oreinted Programing
OPI	Operator Interface
OptLev	Optical Lever Alignment System
OSEM	Integrated Optical PositionSensor/ElectroMagnetic driver
PAC	(LIGO) Program Advisory Committee
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 forsoftware/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

Acronym	Definition
RAM	Responsibility Assignment Matrix
RANCOR	vessel subcontractor to PSI
RDIAG	Remote Diagnostics
REO	Research Electro-Optics (Company Name)
RF	Radio Frequency
RFP	Request for Proposal
RFPD	Radio-Frequency Photo-Detector
RGA	Residual Gas Analyzer
RMP	Ralph M. Parsons, LIGO Architect/Engineer Contractor
ROM	Relative Order of Magnitude or Read-Only Memory
ROOT	CERN's C++ (object oreinted) event and data analysis package
s	Second
SDSC	San Diego Supercomputing Center (UCSD)
SC	Supercomputer(ing) Center(s)
SEI	Seismic Isolation
SEPSCOR	South East Partnership for Shared Computational Resources
SI	Seismic Isolation
SNR	Signal-to-Noise Ratio
SOS	Small Optic Suspension
SPARC	Scaled Processor Architecture
SS20	SunSparc 20 workstation
SUR	IBM's Sponsored University Research Grants Program
SQL	Standard Quantum Limit or Standard Query Language (databases)
SQRT	Square Root
STACIS	(Product Name)
SUP	Support Equipment
SUS	Suspension System
SW, S/W	Software
SYS	Systems Engineering

Acronym	Definition
T	Time
T3	Telecommunications standard, 45 Mbps
TAMA	Japanese Interferometric Gravitational-WaveDetector Project
TBD	"To be determined"; presently undefined or unknown
Tcl/Tk	Tool Control Language - scripting high level language for controling porcesses in computer environments
TCP/IP	Transmission Control Protocol/Internet Protocol
TEM	Transverse Electromagnetic
TF	Total Float
TFP	Thin Film Polarizer
TLA	Three-letter Acronym
TFLOPS	1000 GFLOPS
TMC	Test Mass Chamber
Triana	GEO's Data Analysis and Visualization Package
TWIDDLE	name of a particular modelling code within LIGO
U. Fl.	University of Florida
UNIX (linux)	Operating systems for computers
UTC	Universal Time Code
VAC	Vacuum System Controls
vBNS	very high-speed Backbone Network Service (NSF)
VCO	Voltage Controlled Oscillator
VE	Vacuum Equipment
VEA	Vacuum Equipment Area
VFC	Vacuum Feedthroughs and Cabling
VIRGO	Italian-French Laser Interferometer Collaboration
VME	Versa Modular Eurocard (IEEE 1014)
VXI	VME eXtensions for Instrumentation
VxWorks	A real time operating system for VME based systems
WA	Washington
WAN/LAN	Wide/Local Area (Computer) Network

Acronym	Definition
WBS	Work Breakdown Structure
WFS	Wavefront Sensing
WP	Work Package
WVFNT	Wavefront Alignment System
WWW	World Wide Web
XCVR	Transmitter/Receiver
XME	eXtensible Markup Language a textual markup language (generalized HTML)

PRESENTATIONS

LIGO Project Introduction and Status

LIGO Project Status

Gary Sanders

NSF Technical Review

October 27 - 29, 1998

This Talk

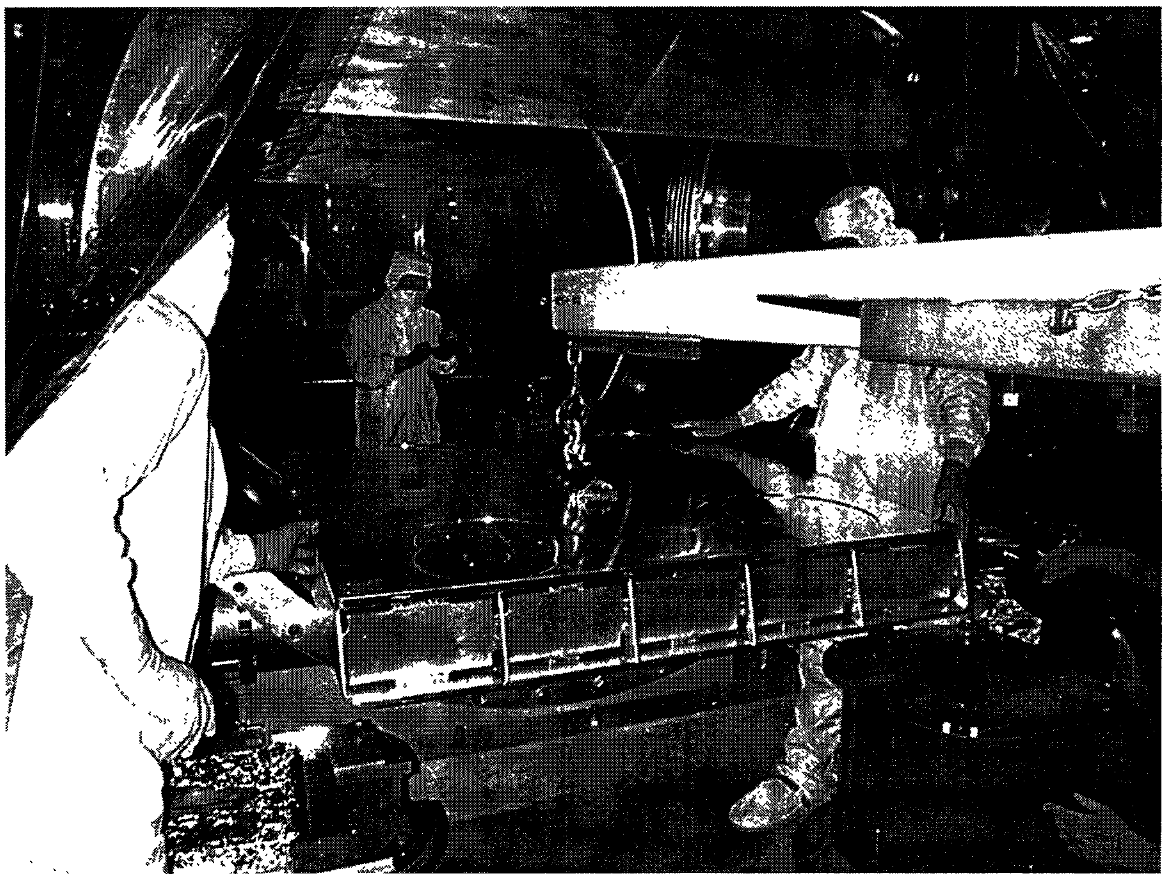
- Technical Status
- Status of LIGO Organization
  - » LIGO Scientific Collaboration
  - » Gravitational Wave International Committee (GWIC)
  - » LIGO Laboratory
    - – Both observatories are functioning as operating organizations
  - » LIGO Program Advisory Committee
- Cost/Schedule Status
  - » covered mainly in this talk as emphasis in this review is technical

LIGO Construction is 88% complete!

Project Manager's View: Status of the Project

- Project performance close to baseline cost/schedule
- Facility construction, including vacuum systems, near completion at both sites
- Buildings accepted, occupied and in use
- Detector design is essentially complete
- Detector fabrication in full swing with major bid jeopardy passed and many items being delivered for installation
- Installation of detector at Hanford is underway
- Data analysis and modeling systems being implemented

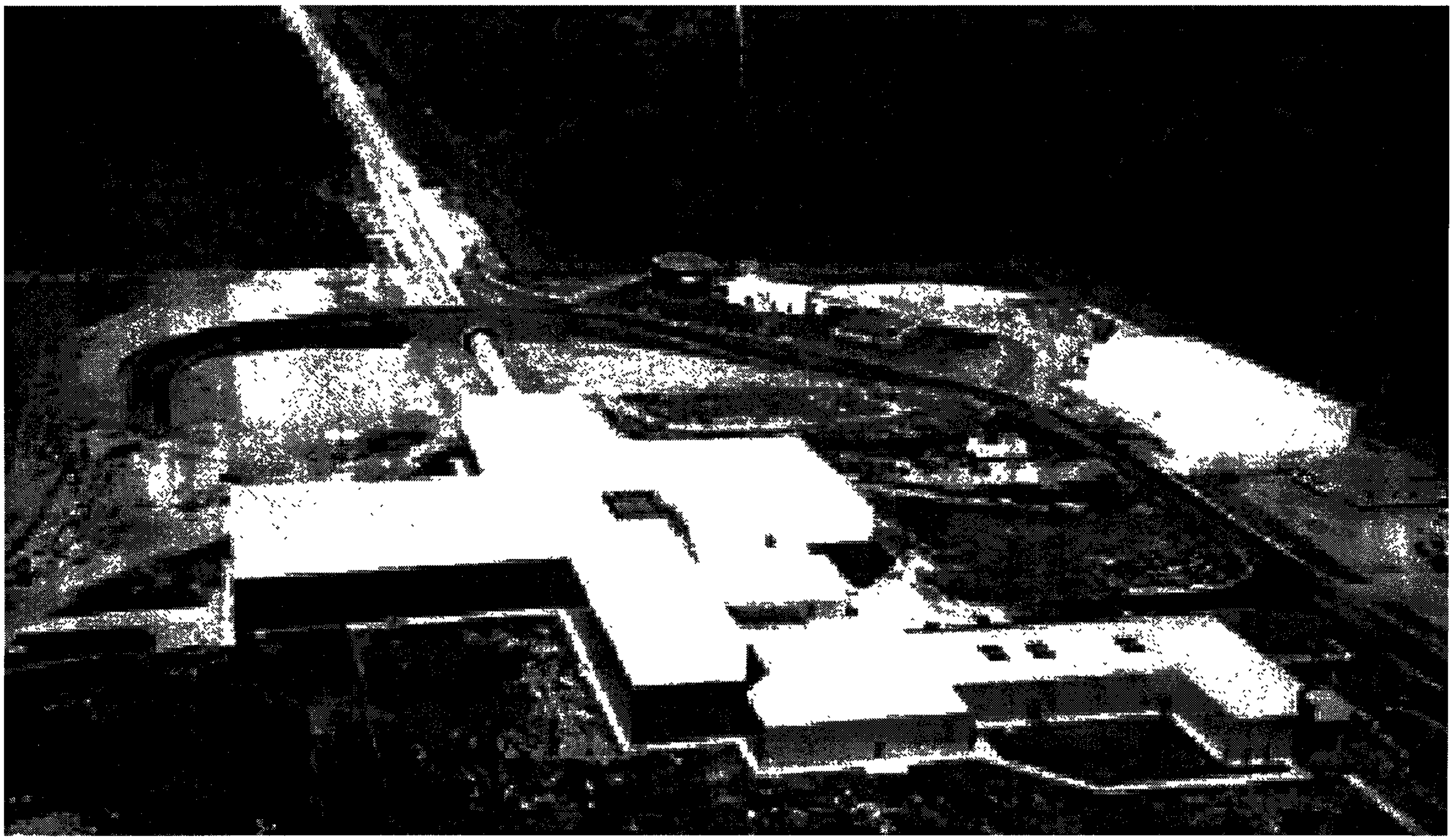
Picture of the Month: Installing Detector in the Vacuum System



Technical Highlights - Livingston Observatory

- Beam Tube Fabrication and Installation complete
  - » X arm vacuum performance accepted, Y arm essentially accepted
- Vacuum equipment installation essentially complete
- Commissioning of vacuum system volumes is underway
  - » Right end station accepted, others in progress
  - » Gate valve inspection and rework/repairs underway
- All buildings in use and undergoing shakedown
  - » Electrical substation provided by DEMCO cured power instability
  - » Punchlist and building QA items being worked or reworked
- Preparations begun for early '99 detector installation

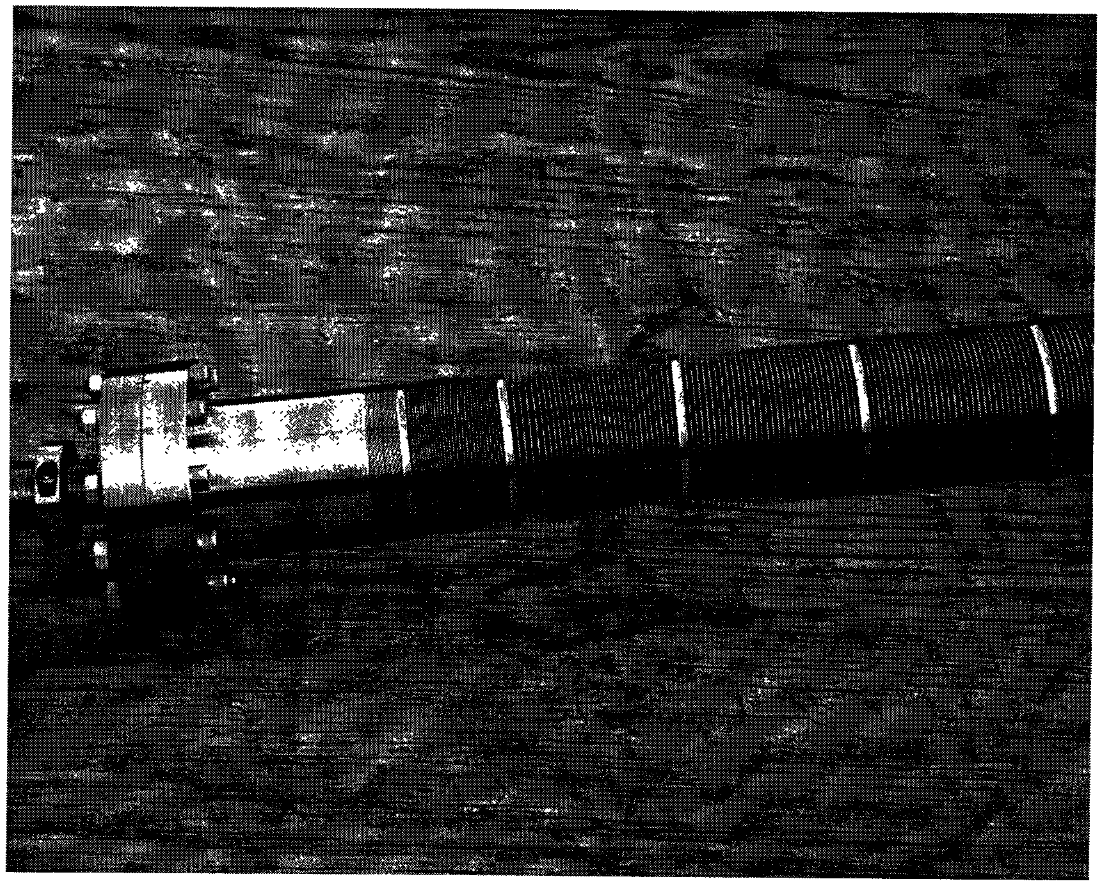
Livingston Aerial View



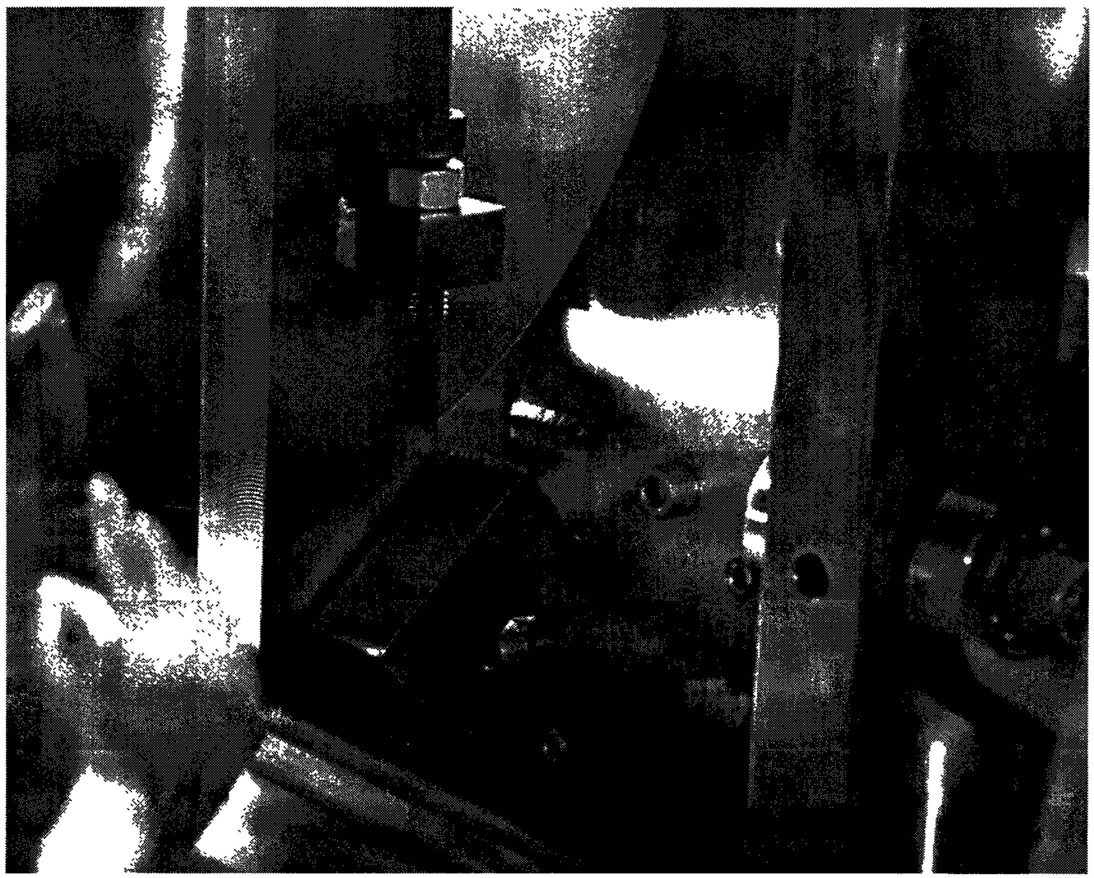
Livingston Corner Station

Mid-Station Gate Valve Repair

Gate Valve Lead Screw Bellows



Livingston Mid-Station Sheared Gate Valve Stop



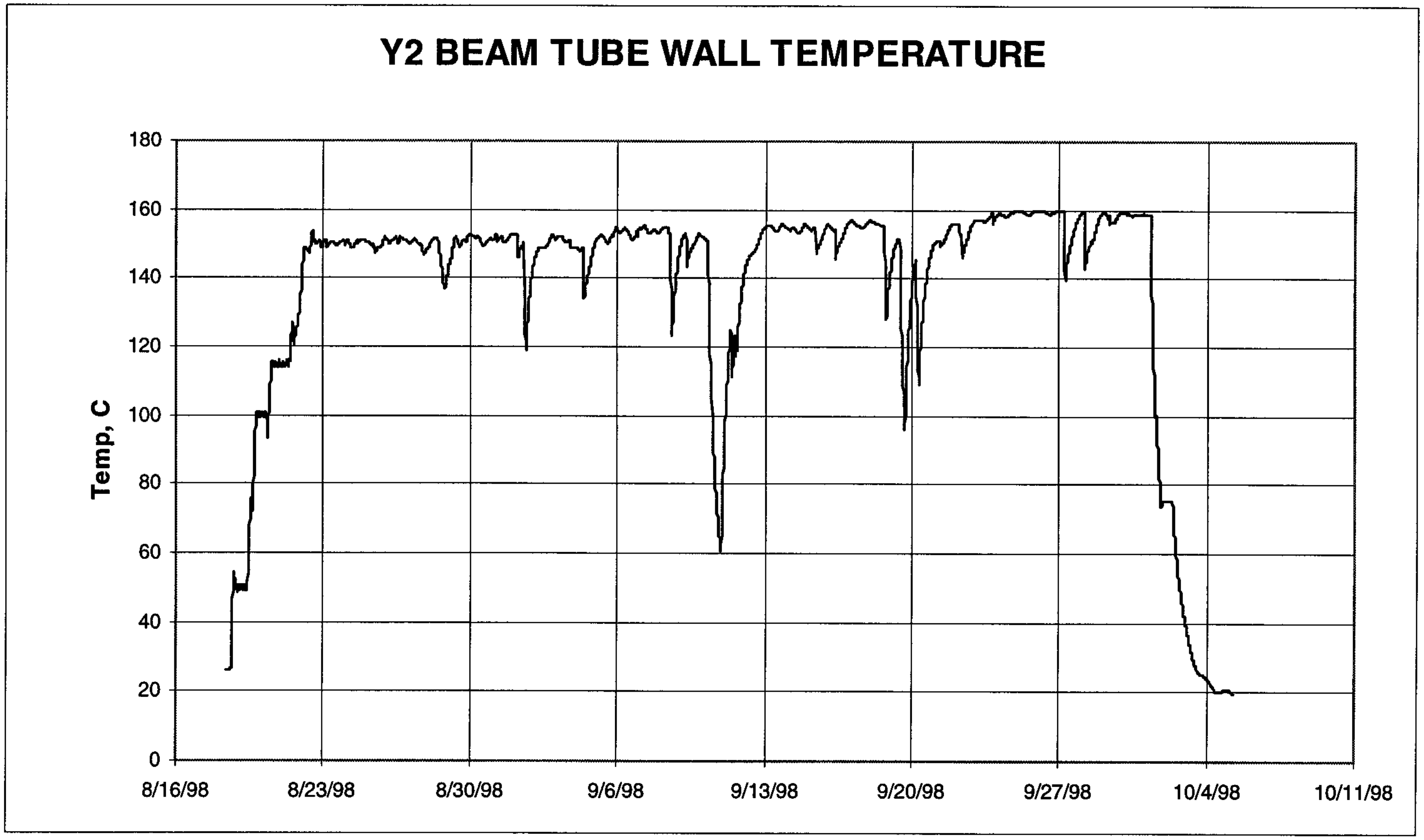
LIGO

Technical Highlights - Hanford Observatory

- Buildings and vacuum systems essentially complete
- About 50% staff on board
- Technical site characterization underway
- First beam tube module successfully baked
- Detector installation is underway

LIGO Hanford Observatory has transitioned from a construction site to a Laboratory!

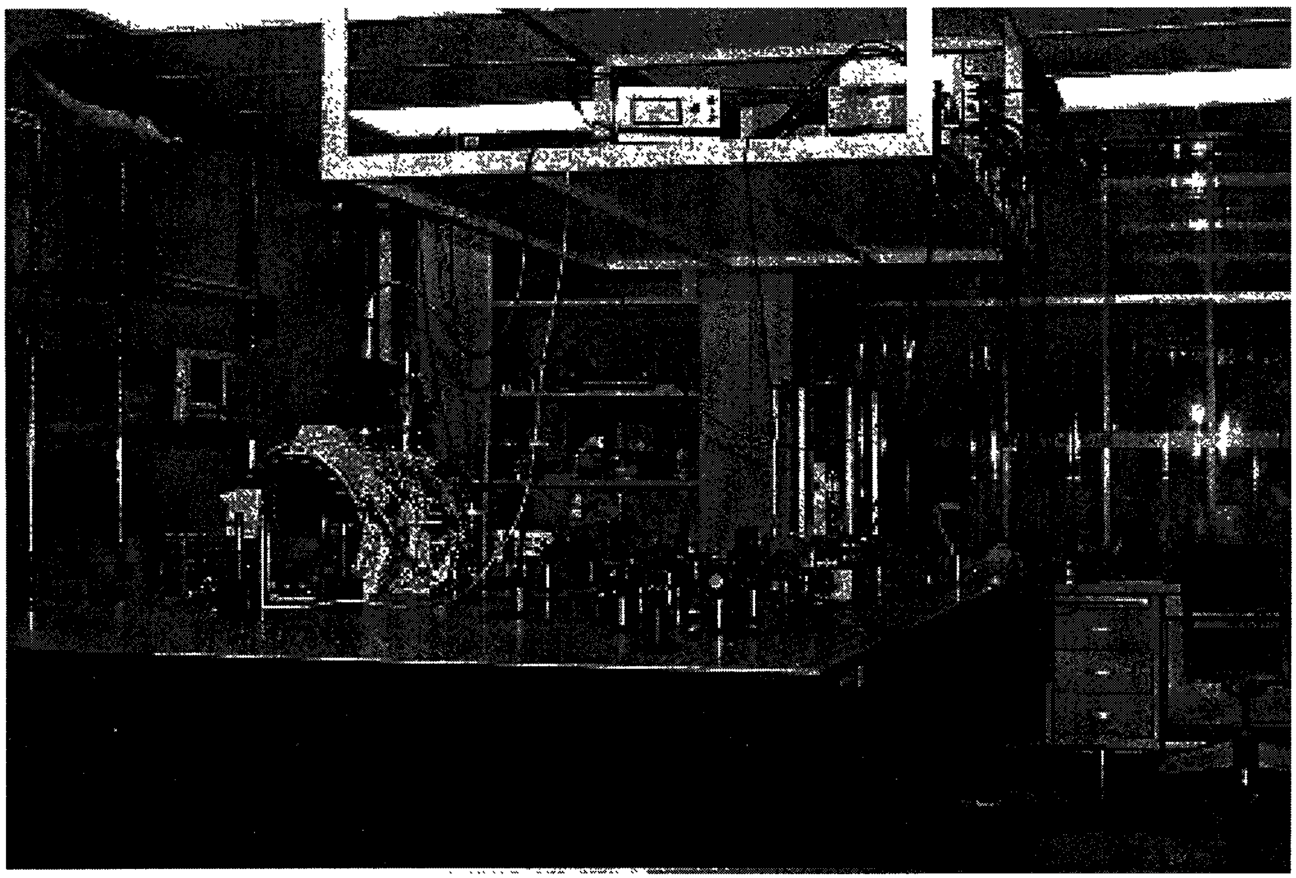
First Module Bakeout



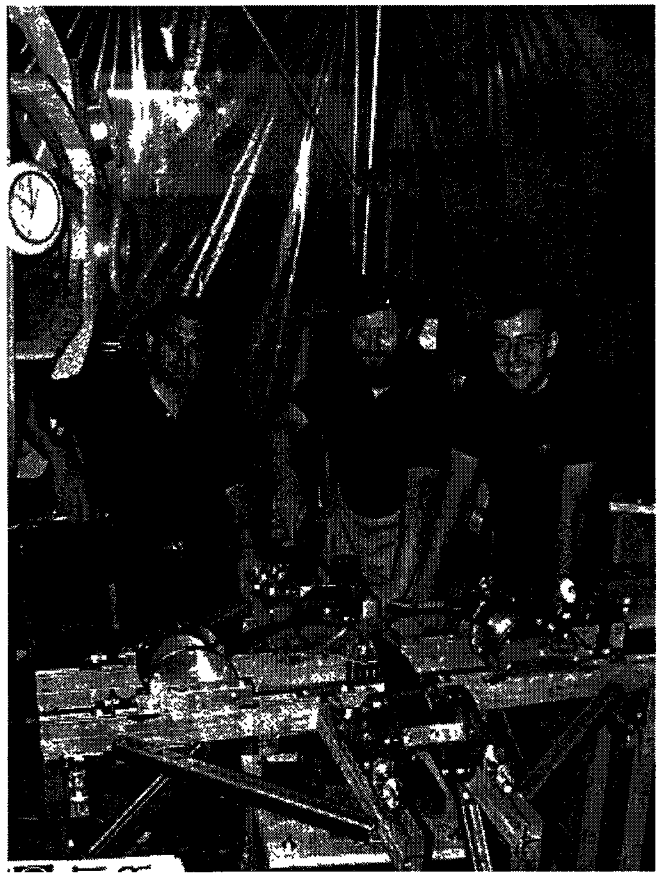
Technical Highlights - R&D

- Construction related R&D
  - » MIT Phase Noise Interferometer
    - Phase Noise experiment successfully completed
    - Completed digital loop test of suspension controller
    - Carried out prototype diagnostics testing
  - » Caltech 40 Meter Interferometer
    - Has successfully achieved stable lock in power recycled configuration
    - Detailed characterization underway
    - Data taking planned by year end
- Advanced R&D activities initiated
  - » Thermal noise, Resonant Sideband Extraction, sapphire, vertical isolation studies already underway
  - » Multiyear funding just received to initiate other activities

Thermal Noise Interferometer



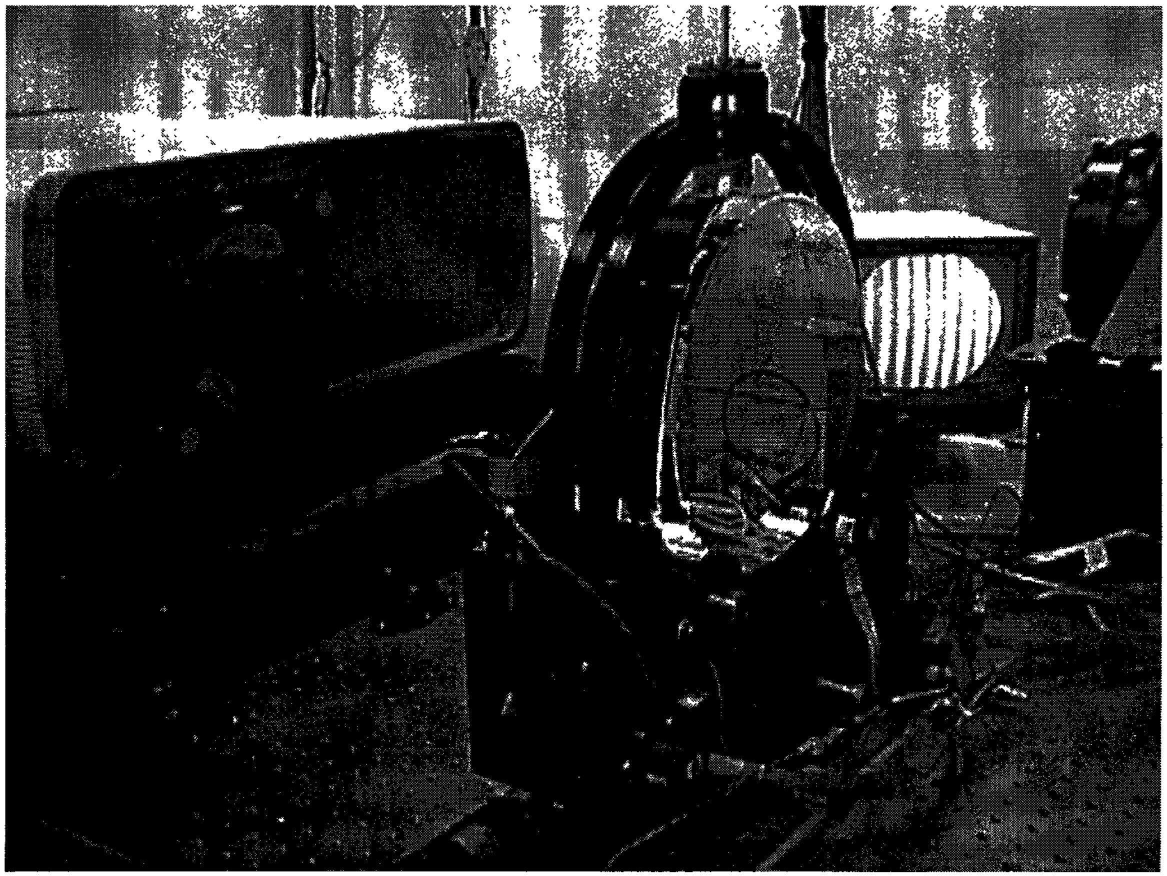
Vertical Isolation Research



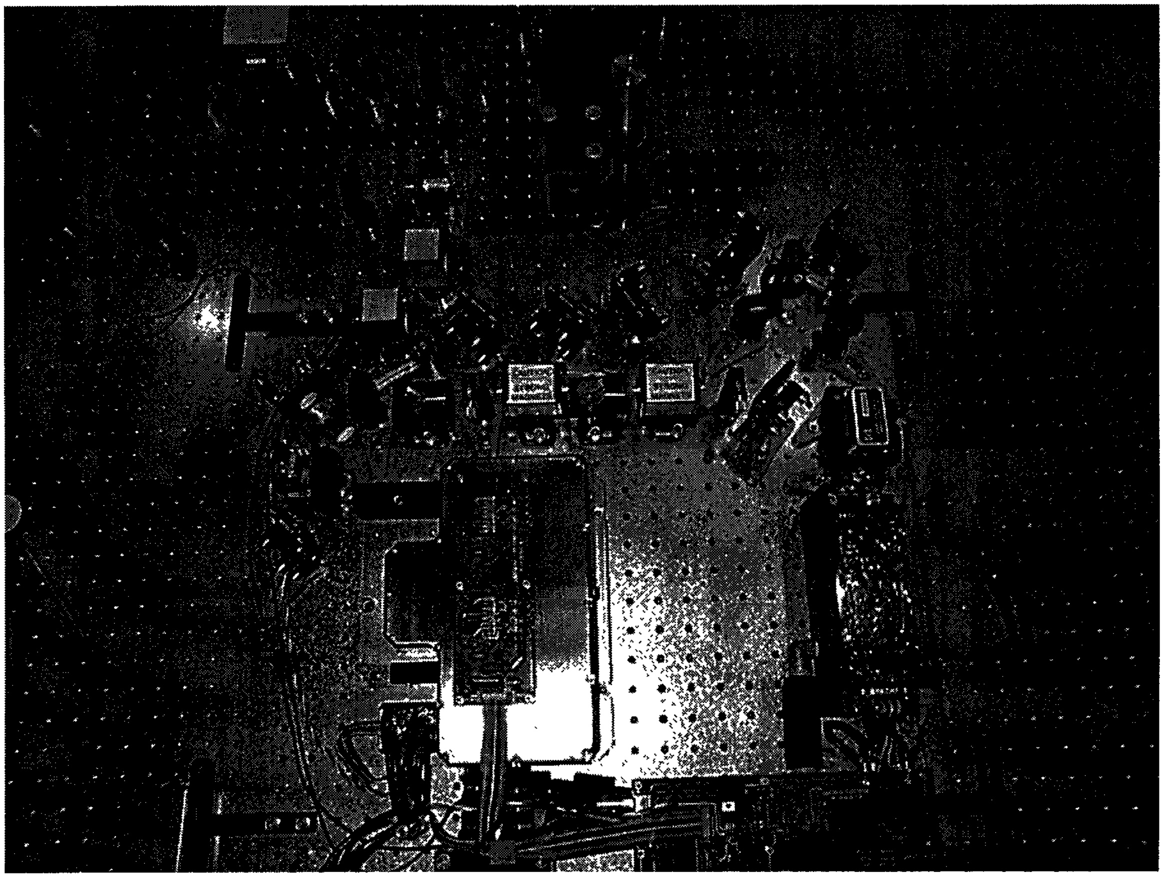
Technical Highlights - Detector Design and Fabrication

- 2 km IFO Prestabilized Laser installing at Hanford
  - » other lasers are being delivered
- Input Optics installation in early stages
- CDS DAQ/backbone/networks running at Hanford
- Core Optics nearly all fabricated
- Core Optics Support systems essentially designed
- Alignment Sensing system in use on prototypes
- Large Optics Suspension in production
- Seismic System first article tests successful and real installation is underway

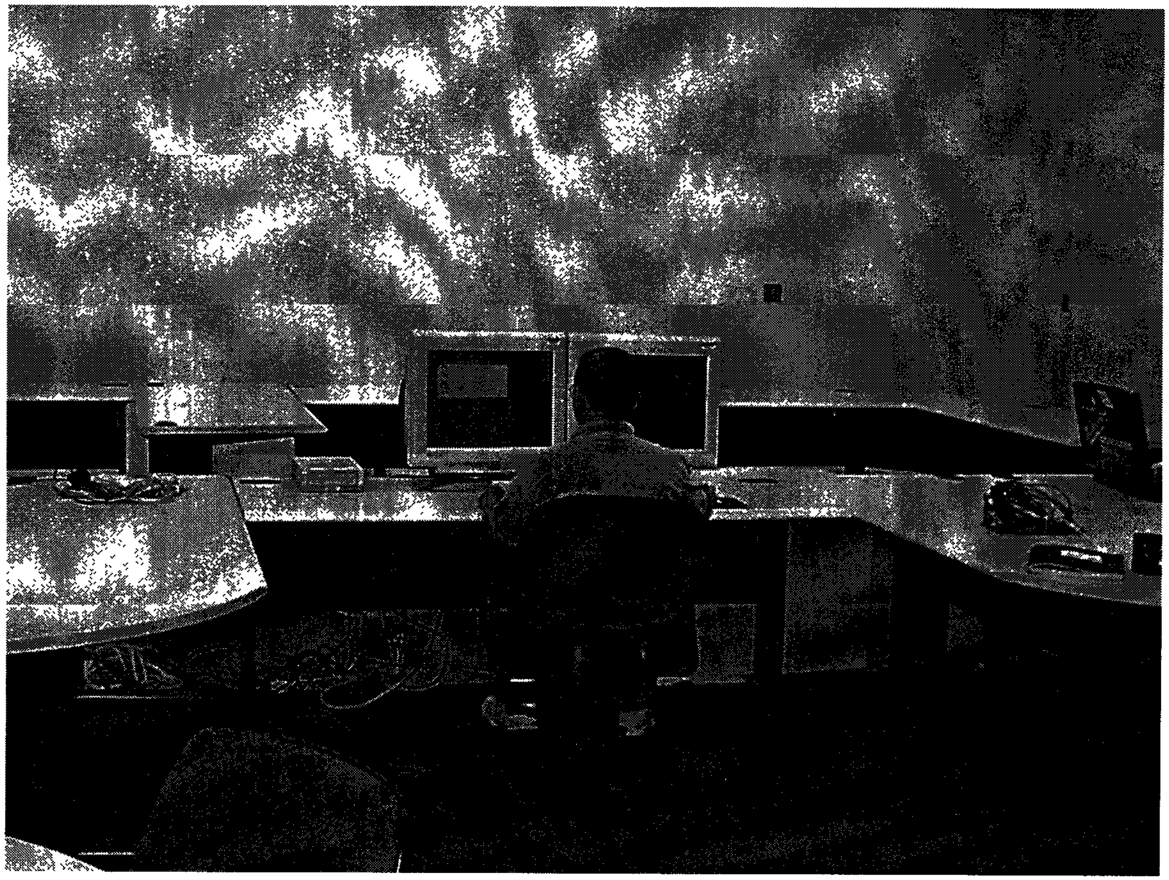
IR Interferometer at Caltech Is In Use



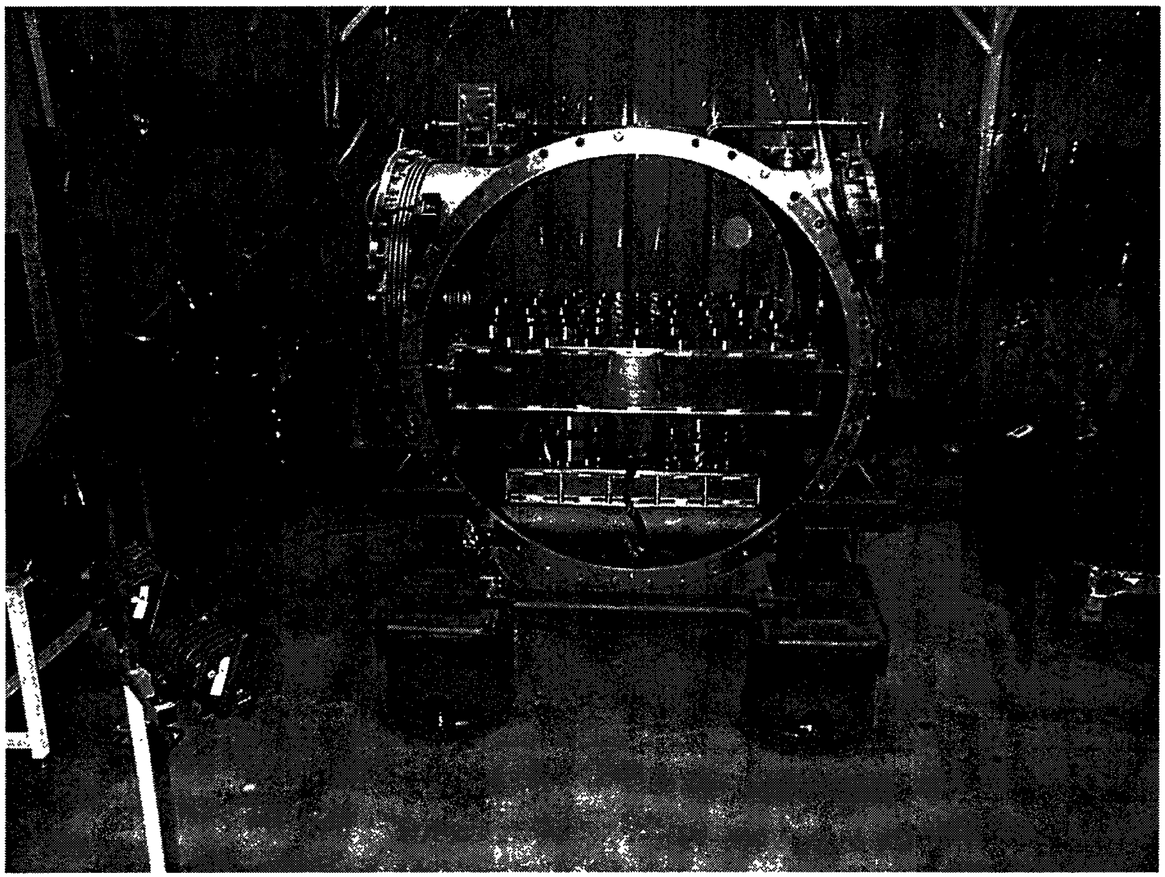
Hanford 2 km IFO PSL



CDS Starts Up in the Control Room



HAM First Article Test at Hanford



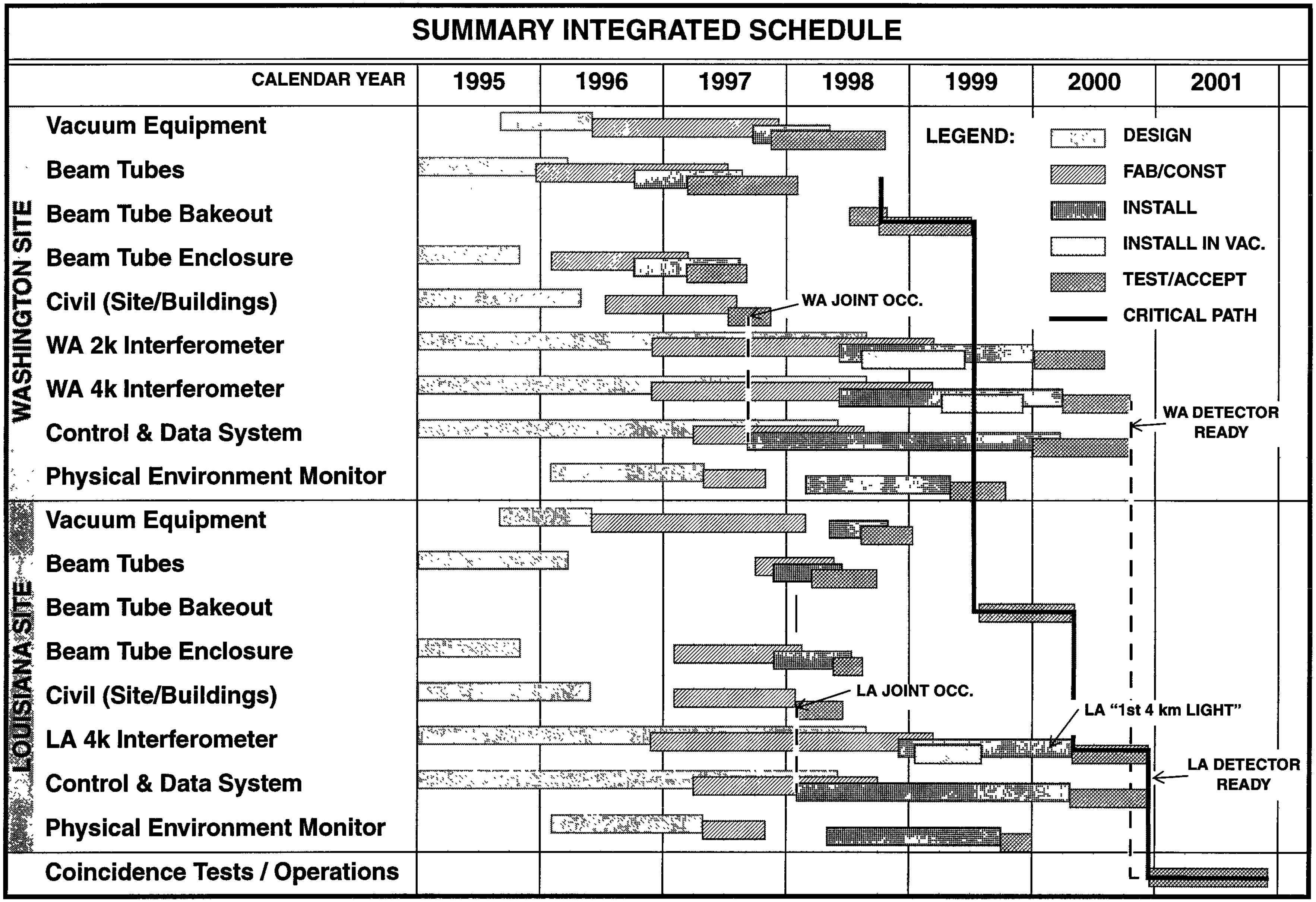
Detector Status

- Detector installation is underway and buildup of effort is following our plan
- Detector delivery and implementation has not slipped significantly since the 2 - 3 month delay presented at the Spring 1998 review
  - » Seismic design and fabrication is still the pacing item
    - – Some delay caused by beam tube valve difficulties and this delay was applied to completing first article tests
  - » Core optics coating failures fall within our plan
  - » IR interferometer procurement has followed its recovery plan with a second vendor

Status of LIGO Organization

- LIGO Scientific Collaboration is now an autonomous organization
  - » Boulder meeting in August
  - » Recent White Paper draft issued to describe R&D program of LSC
- Gravitational Wave International Committee (GWIC)
  - » GWIC #2 April 1998 in Livingston
  - » GWIC #3 December in Paris
- LIGO Laboratory observatories are functioning
- Program Advisory Committee
  - » next meeting in November
- Education and Outreach programs being established

OCTOBER 1998



LIGO

LIGO Construction Project

Cost/Schedule/Contingency (End of August 1998)

NSF Review

October 27th, 1998

Overview (as of end of August 1998)

- $236 million actual (booked) costs
- $256 million committed
- 88 percent complete (physical completion)
- 83 percent "costed" (actual costs relative to estimate-at-completion)
- $10.3 million contingency remaining relative to estimate-at-complete
- 22 percent contingency relative to estimate-to-complete

LIGO Funding by NSF Task and Year

Fiscal Year	Construction	R&D	Operations	Advanced R&D	Total
Through 1994	35.9	11.2			47.1
1995	85	4			89
1996	70	2.4			72.4
1997	55	1.6	0.3	0.8	57.7
1998	26	0.9	7.3	1.6	35.8
1999	0.2		19.8	2.5	22.5
2000			21.1	2.6	23.7
2001			20.2 (10 months)	2.7	22.9
Total	272.1	20	68.7	10.2	371.1

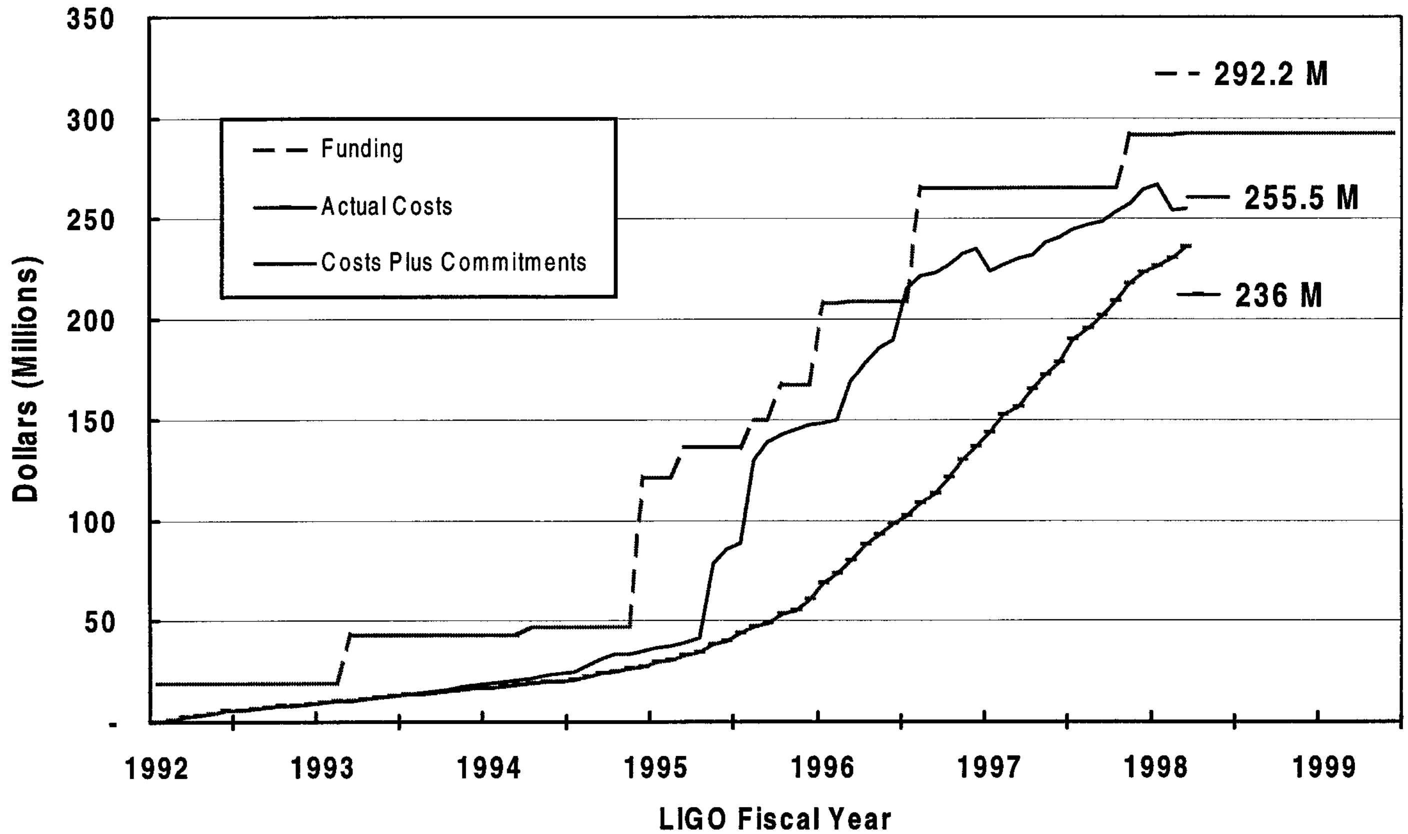
(All funds shown in "then year" $ Millions)

Actual Costs and Commitments

(All values $ Thousands)

WBS		Costs Thru Nov 1997	First Quarter LFY 1998 Costs	Second Quarter LFY 1998 Costs	Jun-98	Jul-98	Aug-98	Cumulative Actual Costs	Open Commitments	Total Cost Plus Commitments
1.1.1	Vacuum Equipment	30,517	3,389	5,192	(11)	74	1,408	40,569	3,193	43,762
1.1.2	Beam Tube	32,978	5,703	5,565	205	178	1,038	45,667	1,425	47,092
1.1.3	Beam Tube Enclosure	13,274	1,987	1,648	1,054	1,184	(7)	19,140	302	19,442
1.1.4	Civil Construction	44,681	4,249	1,933	220	(947)	441	50,577	896	51,473
1.1.5	Beam Tube Bake	75	704	836	197	375	138	2,325	803	3,128
1.2	Detector	14,340	4,363	4,104	1,786	1,684	2,311	28,588	10,375	38,963
1.3	Research & Development	19,681	670	216	118	317	93	21,095	807	21,902
1.4	Project Management	22,649	1,459	1,424	53	535	369	26,489	1,672	28,161
7LIGO	Unassigned	1	6	4	1	2	3	17	19	36
	Installation and Commissioning	330	840	258	57	8	9	1,502	60	1,562
TOTAL		178,526	23,370	21,180	3,680	3,410	5,803	235,969	19,552	255,521
Cumulative Actual Costs		178,526	201,896	223,076	226,755	230,165	235,967			
Open Commitments		62,510	47,085	43,458	40,332	24,342	19,552			
Total Costs plus Commitments		241,036	248,981	266,534	267,087	254,507	255,519			
NSF Funding - Construction		$ 208,468	$ 265,089	$ 291,948	$ 291,948	$ 291,948	$ 291,948			
NSF Funding - Facilities		$ 300	$ 300	$ 7,600	$ 7,600	$ 7,600	$ 7,600			

Costs and Commitments As a Function of Time



Project Management Plan Milestones Status Facilities

Milestone Description	PMP *	Current Projection	PMP *	Current Projection
Facilities	**Hanford**		**Livingston**	
Initiate Site Developemnt	Mar-94	Complete	Aug-95	Complete
Beam Tube Final Design Review	Apr-94	Complete	Apr-94	Complete
Select A&E Contractor	Nov-94	Complete	Nov-94	Complete
Complete Beam Tube Qual Test	Feb-95	Complete	Feb-95	Complete
Select VE Contractor	Mar-95	Complete	Nov-94	Complete
Complete Performance Baseline	Apr-94	Complete	Apr-94	Complete
Initiate Beam Tube Fabrication	Oct-95	Complete	Oct-95	Complete
Initiate Slab Construction	Oct-95	Complete	Jan-97	Complete
Initiate Building Construction	Jun-96	Complete	Jan-97	Complete
Joint Occupancy	Sep-97	Complete	Mar-98	Complete
Accept Tubes and Covers	Mar-98	Complete	Mar-99	Oct-98
Beneficial Occupancy	Mar-98	Complete	Sep-98	Sep-98
Accept Vacuum Equipment	Mar-98	Sep-98	Sep-98	Dec-98
Initiate Facility Shakedown	Mar-98	Sep-98	Mar-99	Dec-98

* Project Management Plan Revision C submitted to NSF October 1997

Project Management Plan Milestones Status Detector

Milestone Description	PMP *	Current Projection
Detector		
Beam Splitter Chamber Stack FDR	Apr-98	Complete
Core Optics Support FDR	Feb-98	Oct-98
Horizontal Access Module FDR	Apr-98	Complete
Core Optics Components FDR	Dec-97	Complete
Input/Output Optics FDR	Apr-98	Complete
Pre-Stabilized Laser FDR	Aug-98	Oct-98
Alignment Sensing FDR	Apr-98	Complete
Length Sensing Control FDR	May-98	Complete
WA Controls Area Net Ready to Install	Apr-98	Complete
CDS Data Acquisition FDR	Apr-98	Complete
Physics Environment Monitoring FDR	Jun-98	Complete
Detector System PDR	Dec-97	Sep-98
Begin WA Interferometer Installation	Jul-98	Complete
Begin LA Interferometer Installation	Jan-99	Jan-99
Begin Coincidence Tests	Dec-00	Dec-00

* Project Management Plan Revision C submitted to NSF October 1997

Cost Schedule Status Report (CSSR)

- The Cost Schedule Status Report is provided each month to the NSF
- Similar report (the Cost Performance Report) is used internally at a lower level of detail to monitor the status of the Project
- The report shown is for the end of August 1998
- ***BAC*** - sum of the budgets established to accomplished the approved scope
- ***BCWS*** - sum of the budgets established for work scheduled to have been accomplished to date
- ***BCWP*** - sum of budget for tasks that have been completed (Earned Value)
- ***EAC*** - recently began to focus on monthly reporting of the Estimate-at-Completion EAC = ACWP + ETC (Estimate-to-Complete)

Cost Schedule Status Report (CSSR)

End of August 1998

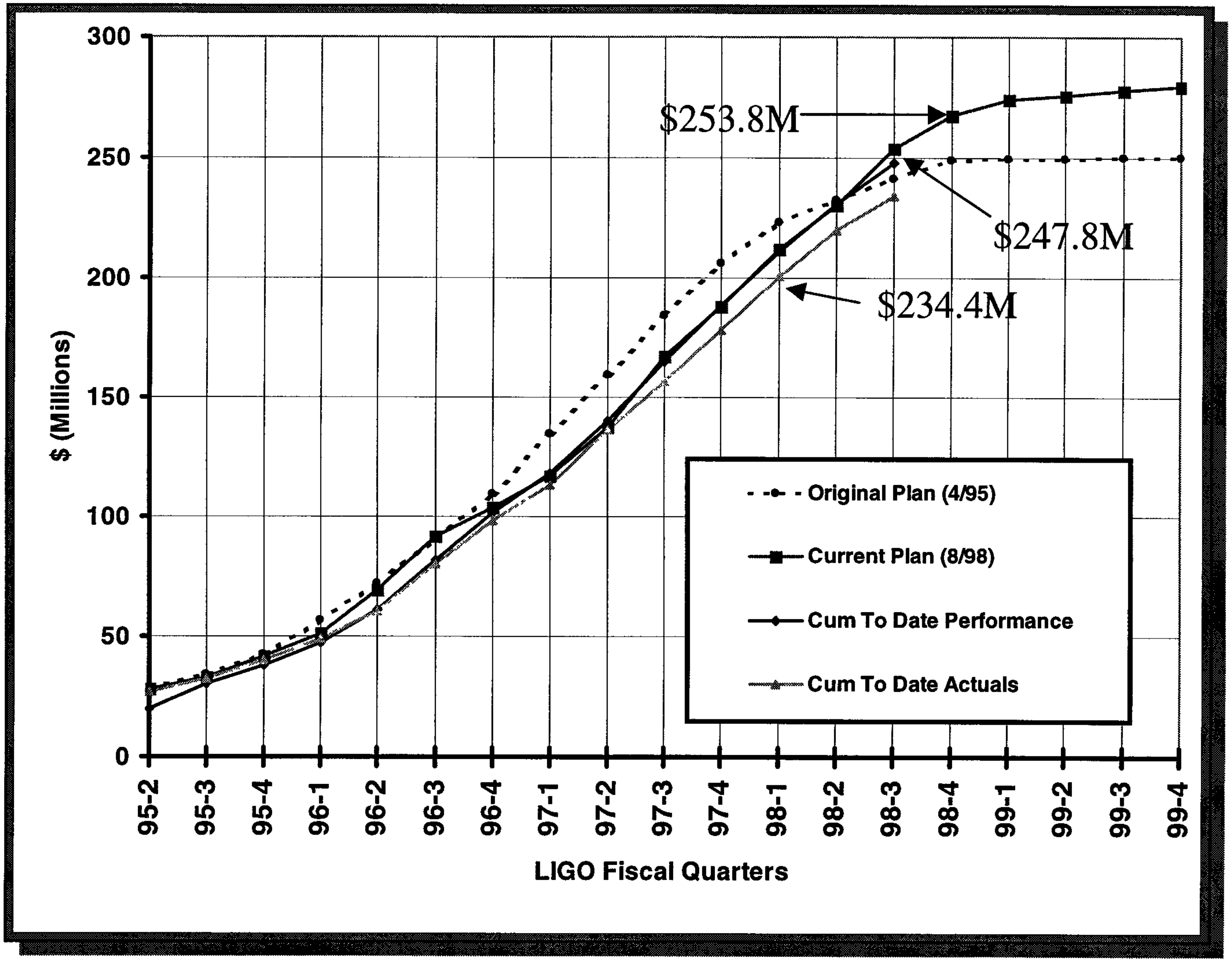
Reporting Level	Cumulative To Date					At Completion		
	Budgeted Cost of Work Scheduled	Budgeted Cost of Work Performed	Actual Cost of Work Performed	Schedule Variance	Cost Variance	Budget-at-Completion	Estimate-at-Completion	Variance-at-Completion
Work Breakdown Structure	(BCWS)	(BCWP)	(ACWP)	(2-1)	(2-3)	(BAC)	(EAC)	(6-7)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.1.1 Vacuum Equipment	42,511	41,892	40,567	(619)	1,325	43,424	43,812	(388)
1.1.2 Beam Tubes	44,939	45,807	45,667	868	140	47,185	47,284	(99)
1.1.3 Beam Tube Enclosure	18,658	19,842	19,139	1,184	703	19,991	19,349	642
1.1.4 Facility Design & Construction	50,905	51,731	50,576	826	1,155	52,010	52,183	(173)
1.1.5 Beam Tube Bake	2,595	2,874	2,325	279	549	4,879	4,989	(110)
1.2 Detector	43,779	35,264	28,587	(8,515)	6,677	56,411	56,360	51
1.3 Research & Development	23,490	23,490	21,095	-	2,395	23,490	23,484	6
1.4 Project Office	26,920	26,920	26,488	-	432	33,760	34,296	(536)
								-
Subtotal	253,797	247,820	234,444	(5,977)	13,376	281,150	281,757	(607)
Contingency							10,343	(10,343)
Contingency (MR)						10,950		10,950
Total	253,797	247,820	234,444	(5,977)	13,376	292,100	292,100	-

Performance Summary

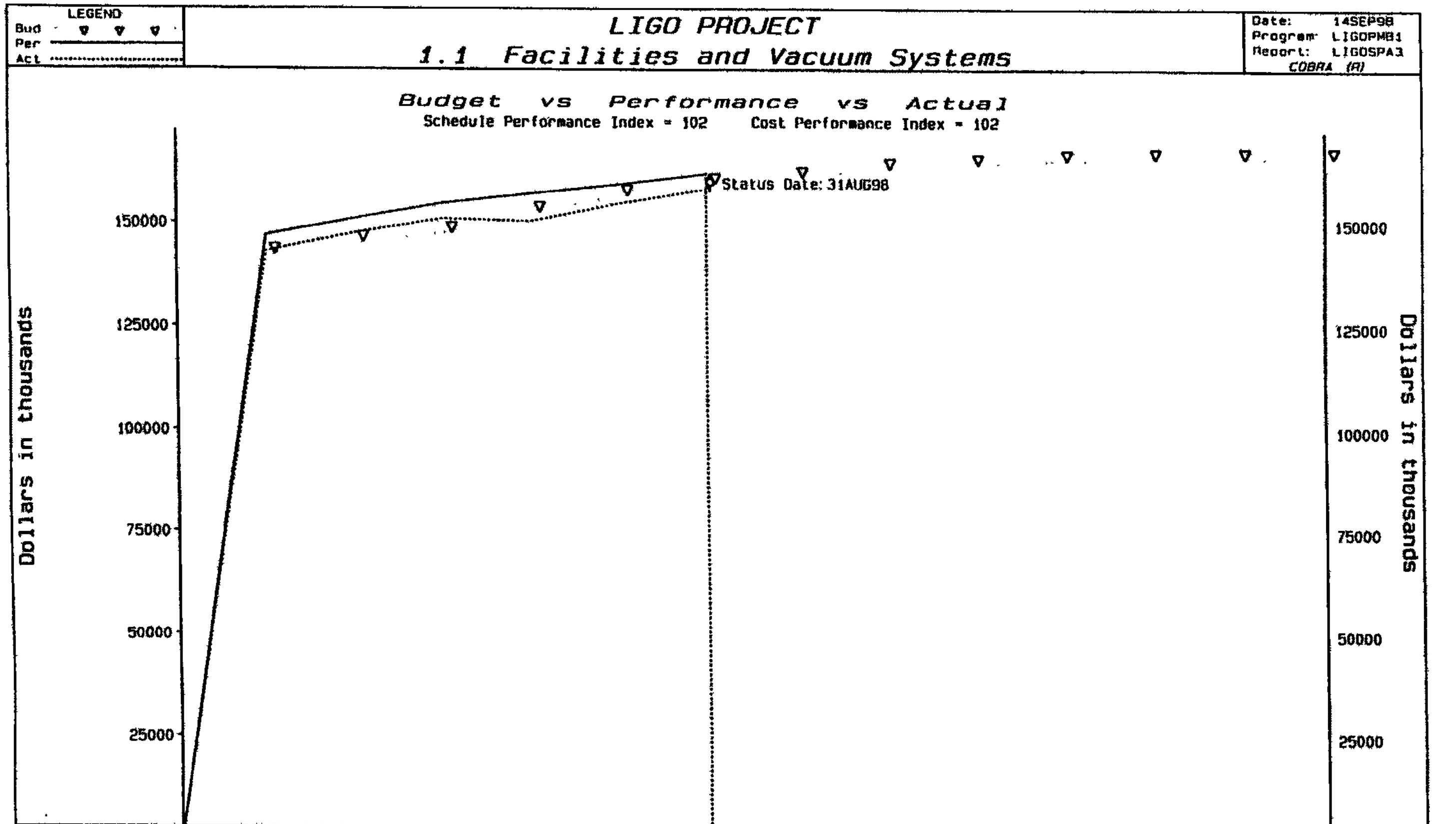
End of August 1998 data

- Total Budget Scheduled - $253.8 million
- Total Budget of Work Performed - $247.8 million
- Schedule Variance - Unfavorable $5.9 million
- Actual Costs - $234.4 million
- Cost Variance - $13.4 million favorable
- BAC - $281.1 million
- Contingency relative to BAC - $10.9 million
- EAC - $281.8 million
- At-completion Variance - Unfavorable $.6 million
- Contingency relative to EAC - $10.3 million

Top Level (WBS 1.0) Performance Chart (End Aug 98)



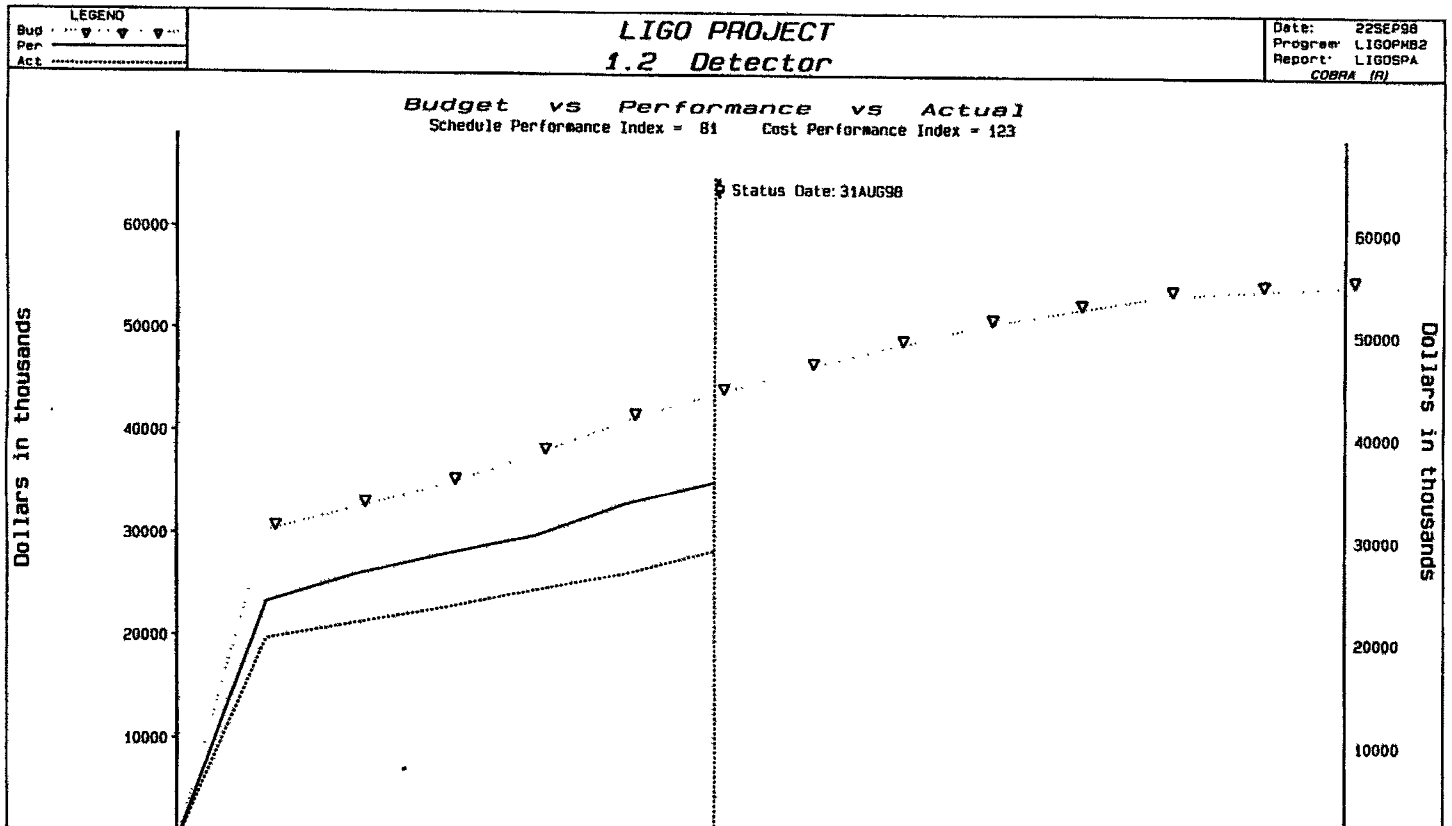
Facilities Performance Chart



	MAR98	APR98	MAY98	JUN98	JUL98	AUG98	SEP98	OCT98	NOV98	DEC98	JAN99	FEB99	MAR99	SCALE
Planned Budget	142,316	145,212	147,462	152,498	156,670	159,608	161,144	163,355	164,472	165,428	165,826	166,019	166,199	K$
Performance	146,899	150,943	154,723	157,079	159,479	162,144								K$
Actuals	143,105	147,469	150,902	150,304	154,683	158,274								K$
Schedule Variance	4,583	5,731	7,261	4,581	2,809	2,536								K$
Cost Variance	3,794	3,474	3,821	6,775	4,796	3,870								K$

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

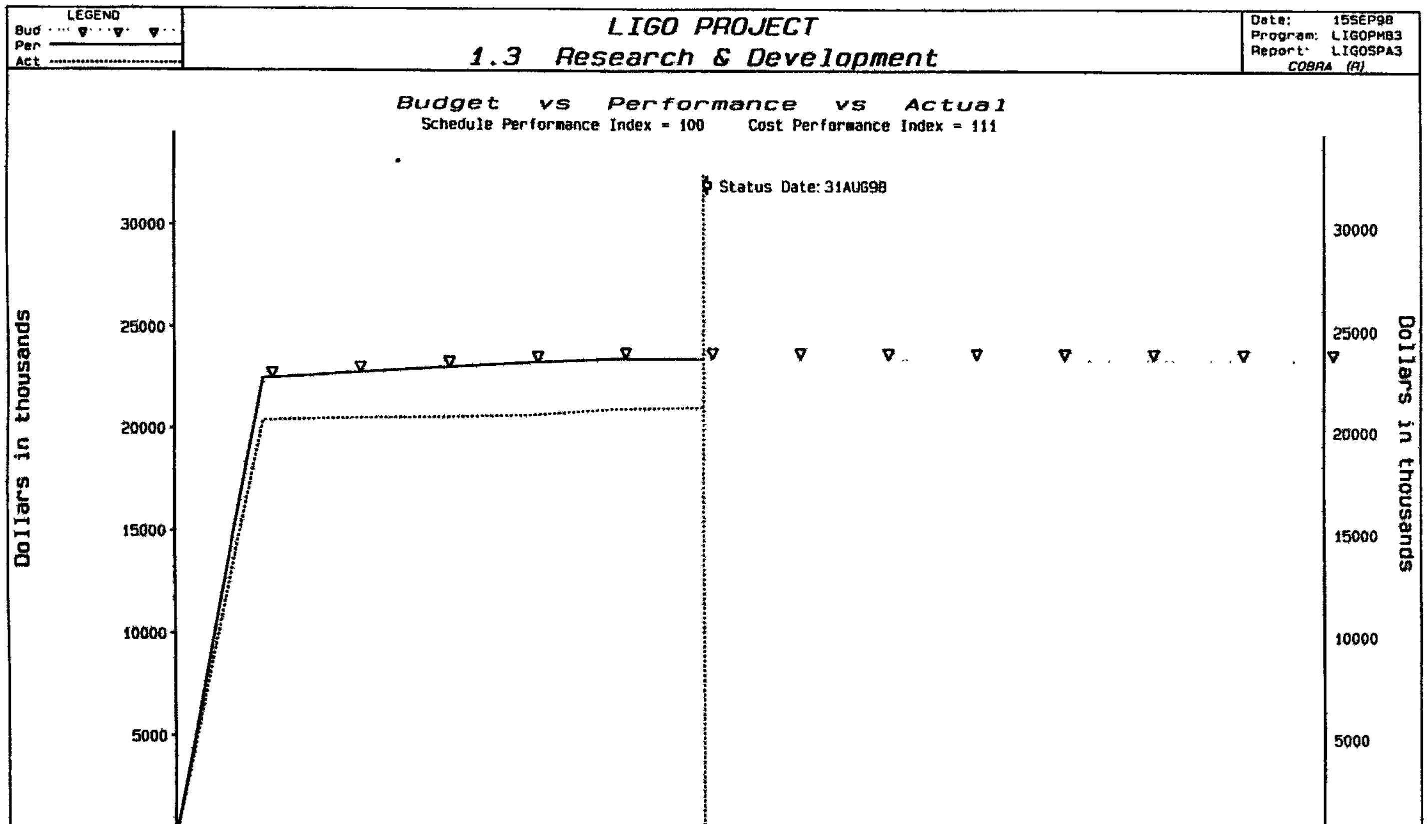
Detector Performance Chart



	MAR98	APR98	MAY98	JUN98	JUL98	AUG98	SEP98	OCT98	NOV98	DEC98	JAN99	FEB99	MAR99	SCALE
Planned Budget	30,257	32,605	34,876	37,900	41,264	43,779	46,344	48,662	50,740	52,214	53,673	54,236	54,768	K$
Performance	23,276	25,979	28,075	29,977	33,183	35,264								K$
Actuals	19,737	21,275	22,816	24,592	26,276	28,587								K$
Schedule Variance	-6,981	-6,626	-6,801	-7,923	-8,081	-8,515								K$
Cost Variance	3,539	4,704	5,259	5,385	6,907	6,677								K$

Sched Var = Perf-Budg Cost Var = Perf-Actual Sched Perf Index = Perf/Budg Cost Perf Index = Perf/Actual

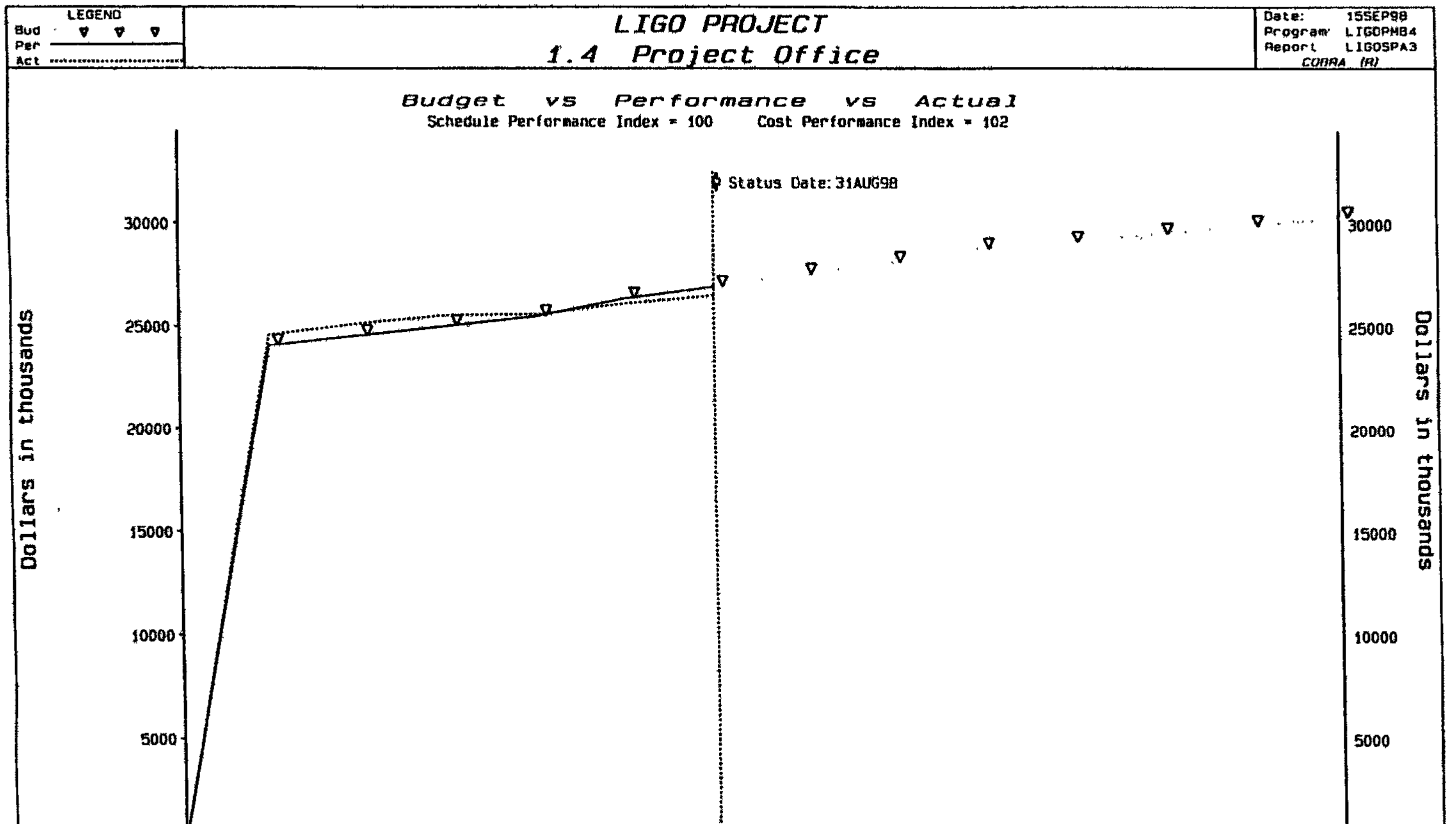
R&D Performance Chart



	MAR98	APR98	MAY98	JUN98	JUL98	AUG98	SEP98	OCT98	NOV98	DEC98	JAN99	FEB99	MAR99	SCALE
Planned Budget	22,485	22,758	23,030	23,294	23,490	23,490	23,490	23,490	23,490	23,490	23,490	23,490	23,490	K$
Performance	22,485	22,758	23,030	23,294	23,490	23,490								K$
Actuals	20,396	20,519	20,567	20,685	21,002	21,095								K$
Schedule Variance	0	0	0	0	0	0								K$
Cost Variance	2,089	2,239	2,463	2,609	2,488	2,395								K$

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

Project Office Performance Chart



	MAR98	APR98	MAY98	JUN98	JUL98	AUG98	SEP98	OCT98	NOV98	DEC98	JAN99	FEB99	MAR99	SCALE
Planned Budget	24,058	24,516	25,007	25,486	26,365	26,920	27,512	28,099	28,773	29,101	29,501	29,881	30,300	K$
Performance	24,058	24,516	25,007	25,486	26,365	26,920								K$
Actuals	24,579	25,114	25,530	25,585	26,113	26,487								K$
Schedule Variance	0	0	0	0	0	0								K$
Cost Variance	- 521	- 598	- 523	-99	252	433								K$

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

Change Control Board (CCB) Summary

Change Request activity since March 1998 Review

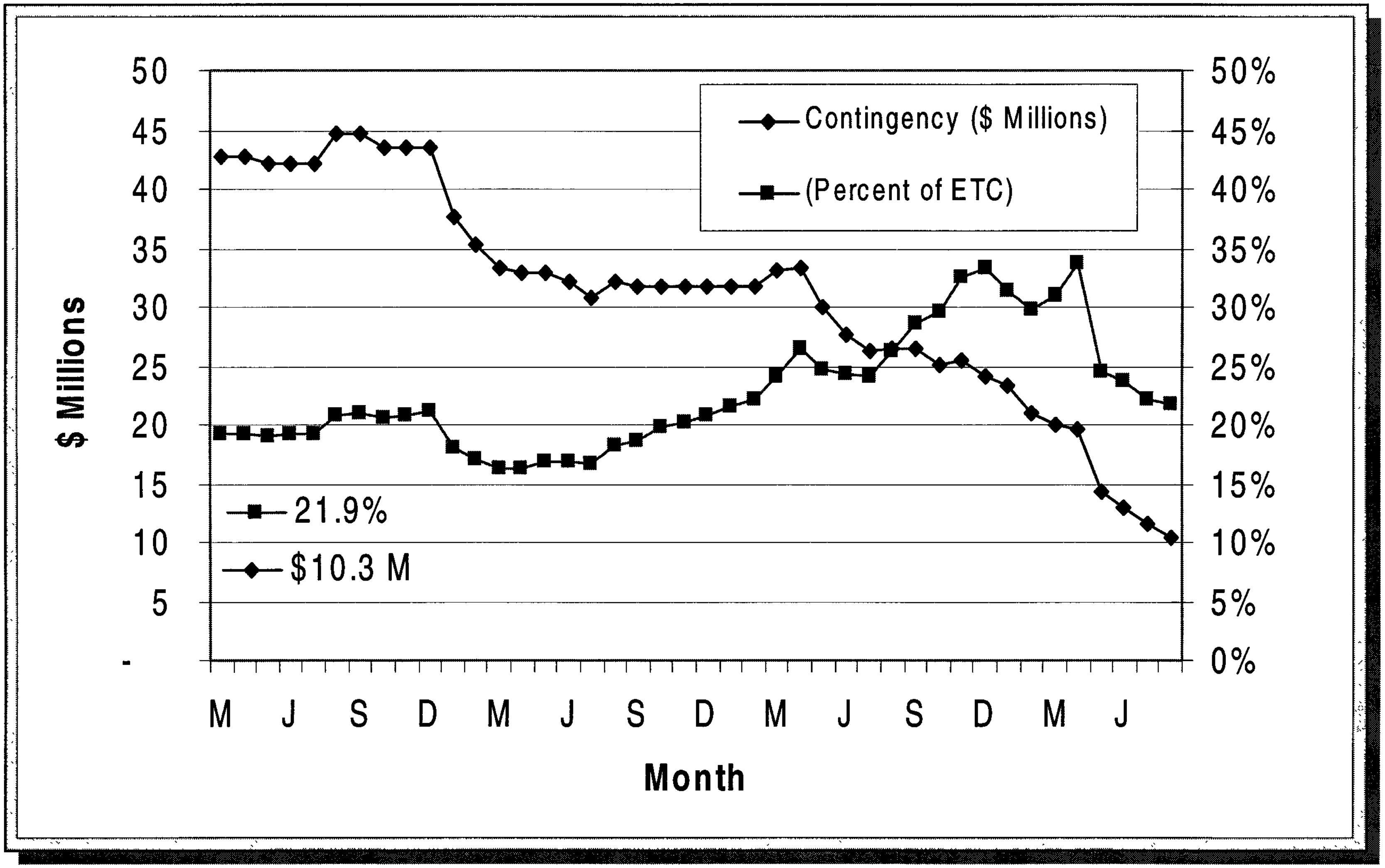
- 28 Change Requests submitted and approved - $11.922 million
- One Change Request for Information Only
- Change Requests Pending
  - Livingston Electrical Power Costs for FY 98 and 99
  - Vacuum Equipment Changes and Payment Milestone Modifications
  - Hanford Water System Irrigation
  - COC Beamspliter Repolishing
  - Seismic Isolation System, Left Handed Spring Seats
  - Beam Tube Module Testing and Equipment Purchase
  - Cancellation of Beam Tube Module Alignment Checks
  - Caltech General Computing

Change Control Log

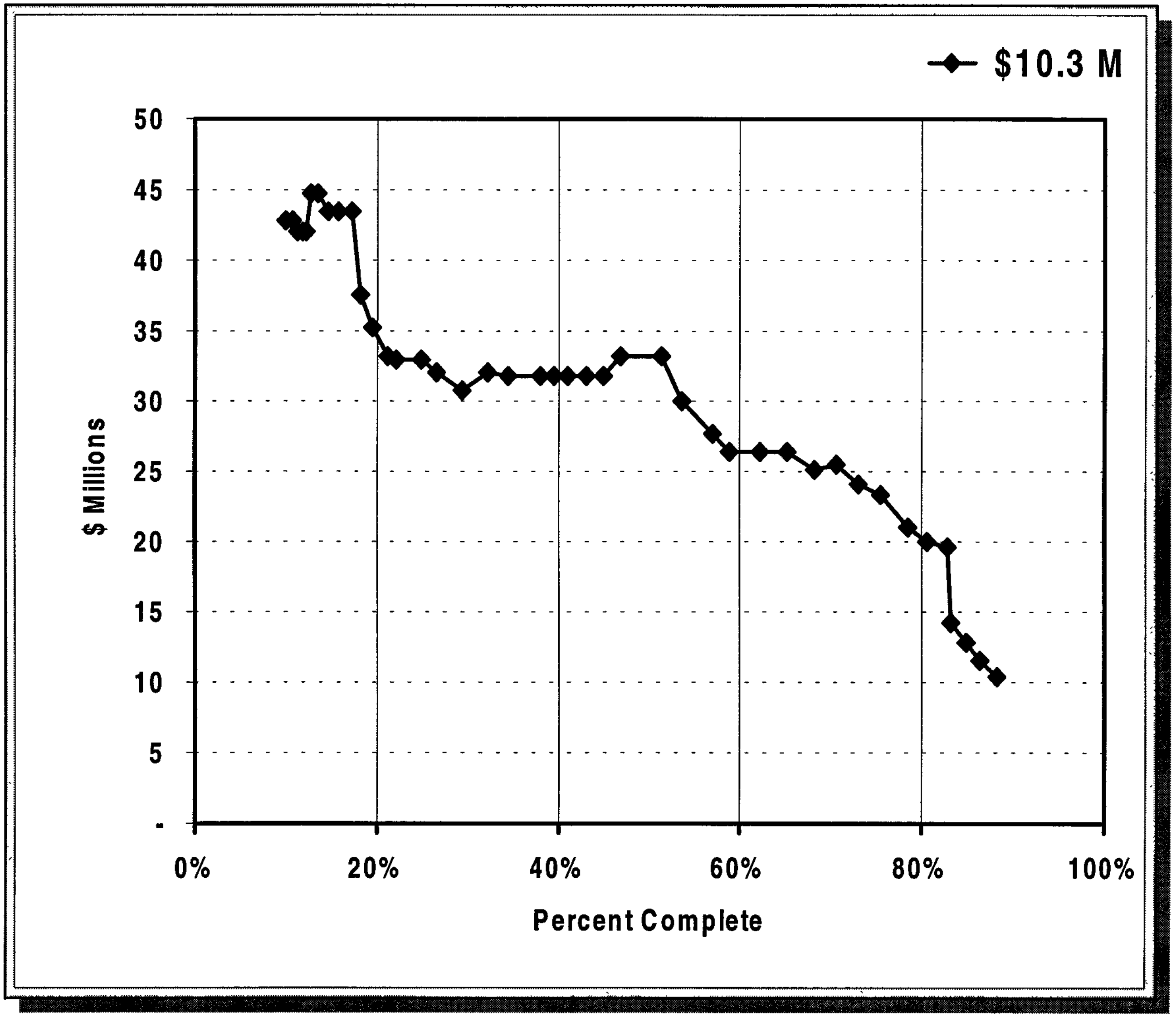
Change Requests approved since March 1997 Review

Change Request Number	WBS	Description	Submittal Date	Amount
CR980008	1.1.1	Miscellaneous Changes-5A511, 5A512, 5A513	Apr-98	$ 164,241
CR980009	1.1.1	VE Changes	Apr-98	$ 472,020
CR980010	1.1.2	BT Taxes and Module End Conditions	Apr-98	$ 59,574
CR980013	1.1.4	Field Work Directives at Hanford (5D532)	Apr-98	$ 272,430
CR980014	1.1.4	Field Work Directives at Hanford (5D522)	Apr-98	$ 139,645
CR970037	1.4.3	LIGO Data Analysis System	May-98	$ 5,579,000
CR980007	1.1.5	Beam Tube Bake Estimate to Complete	May-98	$ 959,000
CR980011	1.1.5	Beam Tube Bake Electrical Power	May-98	$ 307,000
CR980012	1.1.5	Beam Tube Bake Site Support Items	May-98	$ 49,000
CR980015	1.1.1	Miscellaneous Vacuum Equip Mods	May-98	$ 55,335
CR980016	1.1.4	On site telephones, Hanford	May-98	$ 60,000
CR980017	1.2.2	Test Stands, Spares and Travel	May-98	$ 265,580
CR980018	1.1.3	Asphalt Paving of Service Roads at Livingston	May-98	$ 95,351
CR980019	1.2.1	Develop and Qualiffy Cleaning Procedures- COC	Jul-98	$ 130,000
CR980020	1.2.1	Additional Lasers and Laser Support	Jul-98	$ 110,576
CR980021	1.2.1	Laser/Optics Staffing	Jul-98	$ 655,000
CR980022	1.4.1	Revised Staffing (5N502)	Jul-98	$ 538,576
CR980023	1.1.4	Electrical Power for Hanford	Jul-98	$ 130,000
CR980025	1.1.3	Negotiated Taxes for Livingston	Jul-98	$ 99,510
CR980026	1.1.4	Hensel Phelps Closeout	Jul-98	$ 481,366
CR980027	1.2.2	CDS Staffing	Jul-98	$ 500,000
CR980028	1.2.1	Seismic Isolation and Suspension Staffing	Jul-98	$ 235,000
CR980029	1.1.4	Modification for Parking at Livingston	Jul-98	$ 28,846
CR980030	1.4.3	DCC Staffing	Jul-98	$ 68,315
CR980031	1.1.2	Taxes, Clear Caps, FTIR's, Work Stoppages	Aug-98	$ 75,306
CR980032	1.1.2	Purchase of Left Over Equipment	Aug-98	$ -
CR980033	1.2	Installation Travel for 1998	Aug-98	$ 167,200
CR980034	1.1.4	Bldg. Plus Mezzanine at Hanford (Rev to CR-9803)	Aug-98	$ 224,000
		Total		$ 11,921,871

Project Contingency as a Function of Time



Project Contingency vs. Percent Complete



Analysis of Potential Contingency Needs for Facilities

Description	CR	WBS	Direct	Benefits	Overhead	Total
Unresolved PSI contract payments		1.1.1	140,000			140,000
QA Support and Travel		1.1.1	50,000		28,725	78,725
Miscellaneous Field Change Orders (PSI)		1.1.1	30,000			30,000
Central Vacuum System (Livingston)		1.1.1	15,000			15,000
Gate Valve - Livingston		1.1.1	100,000			100,000
Liguid Nitrogen Storage Tanks - Crow Elimination Hats		1.1.1	2,000			2,000
Shop Tools (Livingston)		1.1.1	28,000			28,000
Stiles/Scaffolding (Hanford)		1.1.1	18,000			18,000
Stiles/Scaffolding (Livingston)		1.1.1	18,000			18,000
Vacuum Cleaning System - Hanford		1.1.1	25,000			25,000
Purchase Leftover CB&I Equipment	CR-980032	1.1.2	14,000			14,000
Livingston Beam Tube Alignment Checks - Cancel	CR-980042	1.1.2	(30,000)			(30,000)
Additional Air Signature Measurements, Mid-Valve Issues	CR-980043	1.1.2	24,095			24,095
CB&I Spare VAT Valves	CR-980043	1.1.2	11,500			11,500
Leak Check Y Arm Mid-Station GNB Valve Bellows	CR-980043	1.1.2	2,430			2,430
Purchase Vacuum Pumping/Test Equipment	CR-980043	1.1.2	10,000			10,000
LA Baffle Installation Cleaning		1.1.2	20,000			20,000
Receive Reimbursement for LN2 Dewars		1.1.2	(180,000)			(180,000)
Reimburse CB&I for Y1, Y2 Leak Location Tests		1.1.2	169,000			169,000
Beam Tube Enclosure Lightning Protection, Hanford		1.1.3	158,000			158,000
Beam Tube Enclosure Lightning Protection, Livingston		1.1.3	158,000			158,000
Potential Gain of ACME Tax Reduction (under litigation)		1.1.3	-			-
Enclosure Contract Underruns (Unused Overtime, etc.)		1.1.3	(500,000)			(500,000)
Electric Power Livingston FY 1999	CR-980035	1.1.4	221,500			221,500
Electric Power Livingston FY 1998	CR-980036	1.1.4	100,000			100,000
Modifying Water Systems at Hanford	CR-980037	1.1.4	129,000		-	129,000
Bid Package Costs		1.1.4	50,000			50,000
Building Customization - both sites		1.1.4	60,000			60,000
Covers on Intakes on buildings at Livingston		1.1.4	5,000			5,000
In-House Labor Rate Variances		1.1.4	100,000	25,000	71,813	196,813
Lightning Rod Tripods		1.1.4	8,000			8,000
Oil Filled Motor Replacement		1.1.4	6,000		-	6,000
Site Cleanup (both sites)		1.1.4	200,000		28,725	228,725
Telephones- Livingston		1.1.4	50,000			50,000
Unidentified Contingency Needs for Beam Tube Bake		1.1.5	200,000			200,000
Facilities Total		**1.1**	**1,412,525**	**25,000**	**129,263**	**1,566,788**

Analysis of Potential Contingency Needs for Detector

Description	CR	WBS	Direct	Benefits	Overhead	Total
Re-Polish Beamsplitters	CR-980038	1.2.1	130,000			130,000
Left-handed Seismic Isolation Spring Seats	CR-980041	1.2.1	50,000			50,000
Absorption Measurements Labor and Materials		1.2.1	110,000	15,000	71,813	196,813
Cleaning Springs - CO2 Pre-cleaning		1.2.1	25,000			25,000
Extended ISC/ASC Fabrication		1.2.1	200,000	50,000	143,625	393,625
High Power Electro Optic Modulation/Faraday Isolation		1.2.1	130,000		74,685	204,685
High Powered Diode Protection		1.2.1	260,000	15,000	157,988	432,988
Higher Quality COS Telescope		1.2.1	200,000		14,363	214,363
Increased Baffling		1.2.1	300,000		172,350	472,350
Possible Gross Backscatter		1.2.1	180,000	15,000	112,028	307,028
Re-Coat Six Core Optics		1.2.1	100,000			100,000
Re-Polish Six Core Optics		1.2.1	70,000			70,000
Rework SEI First Article		1.2.1	400,000			400,000
Tidal Motion Actuator for SEI		1.2.1	300,000		14,363	314,363
Suspension Installation Fixture Rework		1.2.1	140,000		14,363	154,363
Air Bearing Rework		1.2.1	180,000			180,000
Seismic Isolation Design (Hytec Increase)		1.2.1	223,000			223,000
Seismic Isolation Scissors Table Second Source		1.2.1	130,000		14,363	144,363
Cable Trays Including Installation		1.2.2	200,000			200,000
Servo Electronics		1.2.2	280,000	32,500	179,531	492,031
Total			**3,608,000**	**127,500**	**969,470**	**4,704,970**

Analysis of Potential Contingency Needs for Project Office

Description	CR	WBS	Direct	Benefits	Overhead	Total
Support Services (Consulting)	CR-980024	1.4.2.3	(88,000)			(88,000)
Administration		1.4.4.1	100,000			100,000
General Computing		1.4.4.2	600,000			600,000
Infrastructure Computers for Hanford	CR-970035	1.4.4.2	245,000			245,000
Infrastructure Computers for Livingston	CR-970036	1.4.4.2	250,000			250,000
Travel		1.4.4.2	50,000		28,725	78,725
Total			**1,157,000**	**-**	**28,725**	**1,185,725**

Cost Schedule Status Report - Facilities

End of August 1998
(All values $ Thousands)

Reporting Level	Cumulative To Date					At Completion		
Work Breakdown Structure	Budgeted Cost of Work Scheduled (BCWS) (1)	Budgeted Cost of Work Performed (BCWP) (2)	Actual Cost of Work Performed (ACWP) (3)	Schedule Variance (2-1) (4)	Cost Variance (2-3) (5)	Budget-at-Completion (BAC) (6)	Estimate-at-Completion (EAC) (7)	Variance-at-Completion (6-7) (8)
1.1.1 Vacuum Equipment	42,511	41,892	40,567	(619)	1,325	43,424	43,812	(388)
1.1.2 Beam Tubes	44,939	45,807	45,667	868	140	47,185	47,284	(99)
1.1.3 Beam Tube Enclosure	18,658	19,842	19,139	1,184	703	19,991	19,349	642
1.1.4 Facility Design & Construction	50,905	51,731	50,576	826	1,155	52,010	52,183	(173)
1.1.5 Beam Tube Bake	2,595	2,874	2,325	279	549	4,879	4,989	(110)
Subtotal	159,608	162,146	158,274	2,538	3,872	167,489	167,617	(128)
Contingency						1,567	1,439	128
Total	159,608	162,146	158,274	2,538	3,872	169,056	169,056	-

Cost Schedule Status Report - Detector

End of August 1998

(All values $ Thousands)

Reporting Level	Cumulative To Date					At Completion		
	Budgeted Cost of Work Scheduled	Budgeted Cost of Work Performed	Actual Cost of Work Performed	Schedule Variance	Cost Variance	Budget-at-Completion	Estimate-at-Completion	Variance-at-Completion
Work Breakdown Structure	(BCWS)	(BCWP)	(ACWP)	(2-1)	(2-3)	(BAC)	(EAC)	(6-7)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.2.1 Interferometer Design and Fabrication	29,086	24,458	19,676	(4,628)	4,782	39,155	39,331	(176)
1.2.2 Control and Data Systems	11,974	8,322	7,636	(3,652)	686	13,497	13,409	88
1.2.3 Physics Environment Monitoring	1,780	1,774	720	(6)	1,054	2,195	2,053	142
1.2.4 Support Equipment	939	710	555	(229)	155	1,564	1,567	(3)
Subtotal	43,779	35,264	28,587	(8,515)	6,677	56,411	56,360	51
Contingency						4,705	4,756	(51)
Total	43,779	35,264	28,587	(8,515)	6,677	61,116	61,116	-

Cost Schedule Status Report - R&D

End of August 1998
(All values $ Thousands)

Reporting Level	Cumulative To Date					At Completion		
	Budgeted Cost of Work Scheduled	Budgeted Cost of Work Performed	Actual Cost of Work Performed	Schedule Variance	Cost Variance	Budget-at-Completion	Estimate-at-Completion	Variance-at-Completion
Work Breakdown Structure	(BCWS)	(BCWP)	(ACWP)	(2-1)	(2-3)	(BAC)	(EAC)	(6-7)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.3.1 Laboratory Operations	6,880	6,880	5,626	-	1,254	6,880	6,880	-
1.3.2 R&D Tasks	16,610	16,610	15,470	-	1,140	16,610	16,604	6
Subtotal	23,490	23,490	21,096	-	2,394	23,490	23,484	6
Contingency							6	(6)
Total	23,490	23,490	21,096	-	2,394	23,490	23,490	-

Cost Schedule Status Report - Project Office

End of August 1998
(All values $ Thousands)

Reporting Level	Cumulative To Date					At Completion		
	Budgeted Cost of Work Scheduled	Budgeted Cost of Work Performed	Actual Cost of Work Performed	Schedule Variance	Cost Variance	Budget-at-Completion	Estimate-at-Completion	Variance-at-Completion
Work Breakdown Structure	(BCWS)	(BCWP)	(ACWP)	(2-1)	(2-3)	(BAC)	(EAC)	(6-7)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.4.1 Project Management	13,980	13,980	13,909	-	71	14,747	14,747	-
1.4.2 Support Services	801	801	717	-	84	848	755	93
1.4.3 System Engineering	5,046	5,046	4,509	-	537	6,410	6,380	30
1.4.4 Office Operations	7,092	7,092	7,352	-	(260)	11,755	12,415	(660)
Subtotal	26,919	26,919	26,487	-	432	33,760	34,297	(537)
Contingency						1,186	649	537
Total	26,919	26,919	26,487	-	432	34,946	34,946	-

LIGO Project Contingency Analysis

End of August 1998
(Costs, Estimates, and Contingency in $ Thousands)

Work Breakdown Structure	Percent Complete (BCWP/ BAC)	Percent "Costed" (3) / (5)	Actual Costs (ACWP)	Estimate-to-Complete (ETC) (5) - (3)	Estimate-at-Completion (EAC) (EAC)	Contingency relative to Estimate-at-Completion)	Total (5) + (6)	Contingency as percent of Estimate-to-Complete (6) / (4)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.1 Facilities	97%	94%	158,274	9,343	167,617	1,439	169,056	15%
1.2 Detector	63%	51%	28,587	27,773	56,360	4,756	61,116	17%
1.3 Research and Development	100%	90%	21,096	2,388	23,484	6	23,490	0%
1.4 Project Management	80%	77%	26,487	7,810	34,297	649	34,946	8%
Contingency Reserve						3,492		
TOTALS	88%	83%	234,444	47,314	281,758	10,342	292,100	22%

- Facilities - 97 percent complete, $9.3 million ETC, 15 percent contingency
- Detector - 63 percent complete, $27.8 million ETC, 17 percent contingency
- Project Management - 80 percent complete, $7.8 million ETC, eight percent contingency

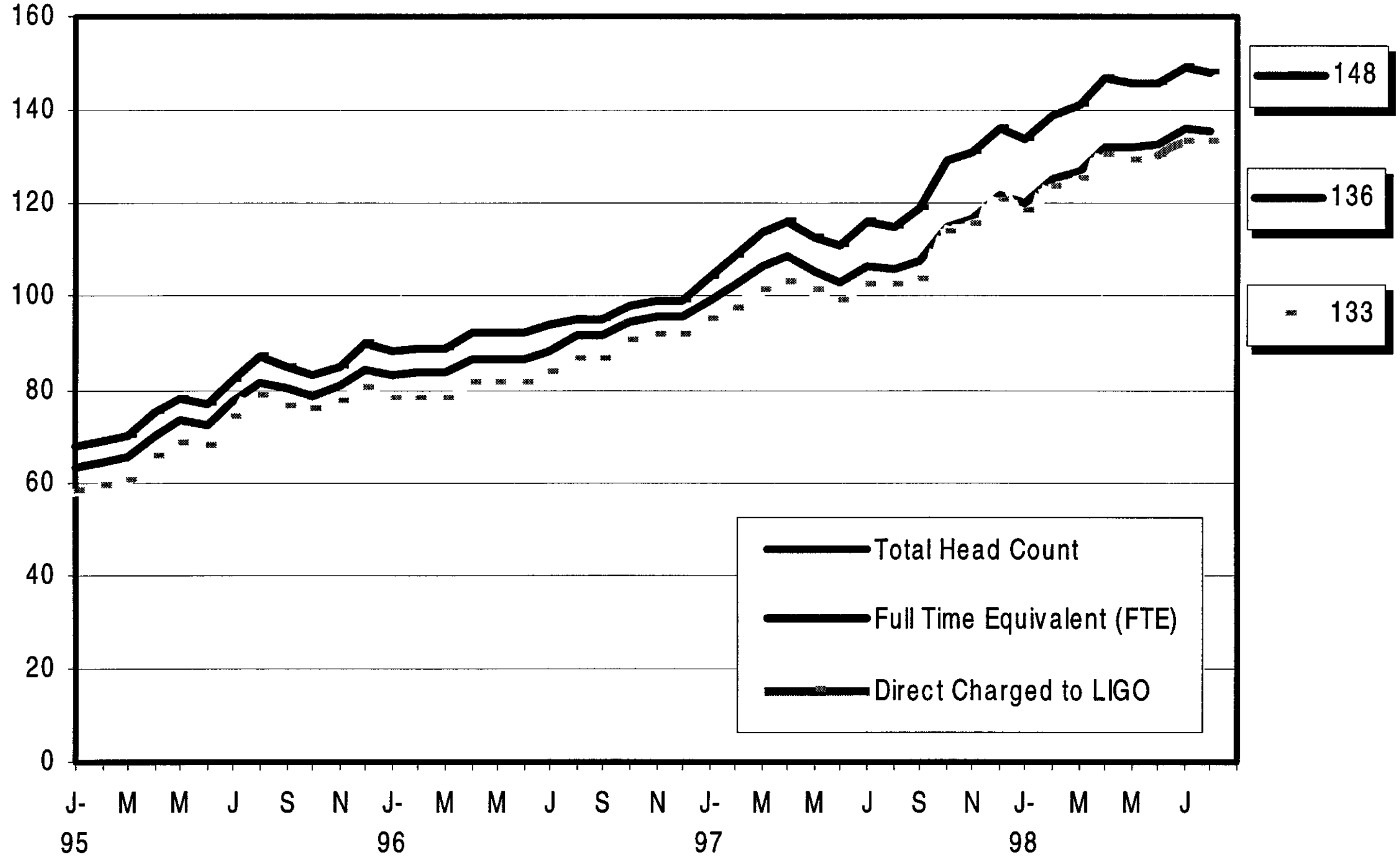
Staffing Summary

As of the end of August 1998
(Excluding Undergraduates)

		Caltech	MIT	Washington	Louisiana	Total
Direct	Headcount	65.0	20.0	17.0	8.0	110.0
	FTEs	55.0	18.0	17.0	8.0	98.0
Contract	Headcount	38.0				38.0
	FTEs	38.0				38.0
Total Headcount		103.0	20.0	17.0	8.0	148.0
Total FTEs		93.0	18.0	17.0	8.0	136.0

Graduate Students	Headcount	7.0	6.0	-	-	13.0
(included above)	FTEs	7.0	6.0	-	-	13.0

Staffing Chart



Summary

- LIGO Construction Project status supports the December 2000 and December 2001 Project milestones
- LIGO will complete the Construction Project within the $292.1 Approved Funding

Livingston Site Status

Topics Presented

- Status of facilities construction, installation, and commissioning
- Remaining work to be accomplished
- Staffing
- Plans and preparation for detector installation
- Educational outreach

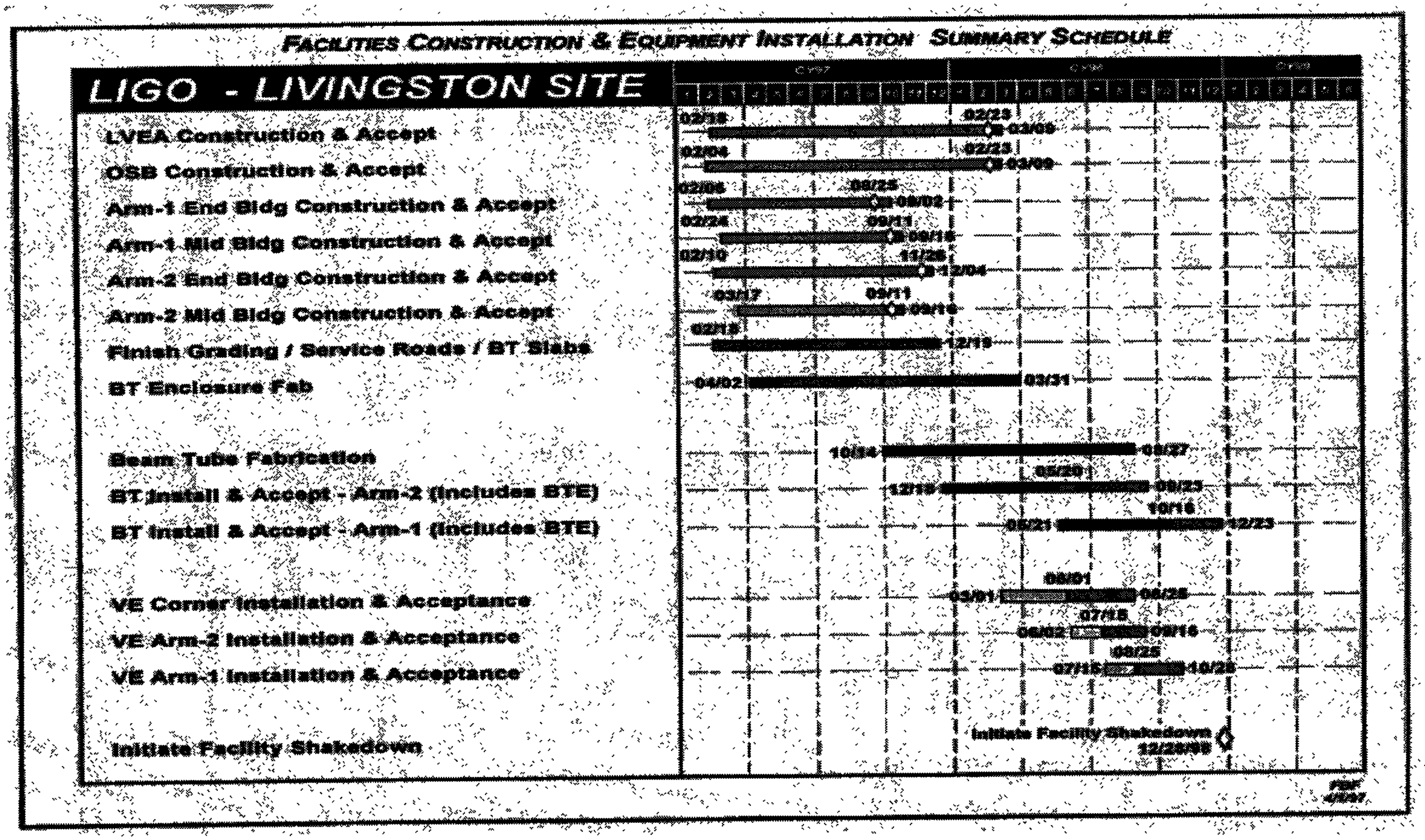
Status of the LIGO Livingston Observatory

Mark Coles

Introduction

- The LIGO Livingston Observatory (LLO) is just completing major facility construction and acceptance.
- Civil construction, beam tube work, and vacuum equipment should all be completed by year end or shortly after.
- Part of our effort is now directed toward preparation for detector installation.
- We are also expanding relationships with institutions in Louisiana to increase the scope of scientific collaboration and to develop educational outreach opportunities.

Construction Schedule - Livingston



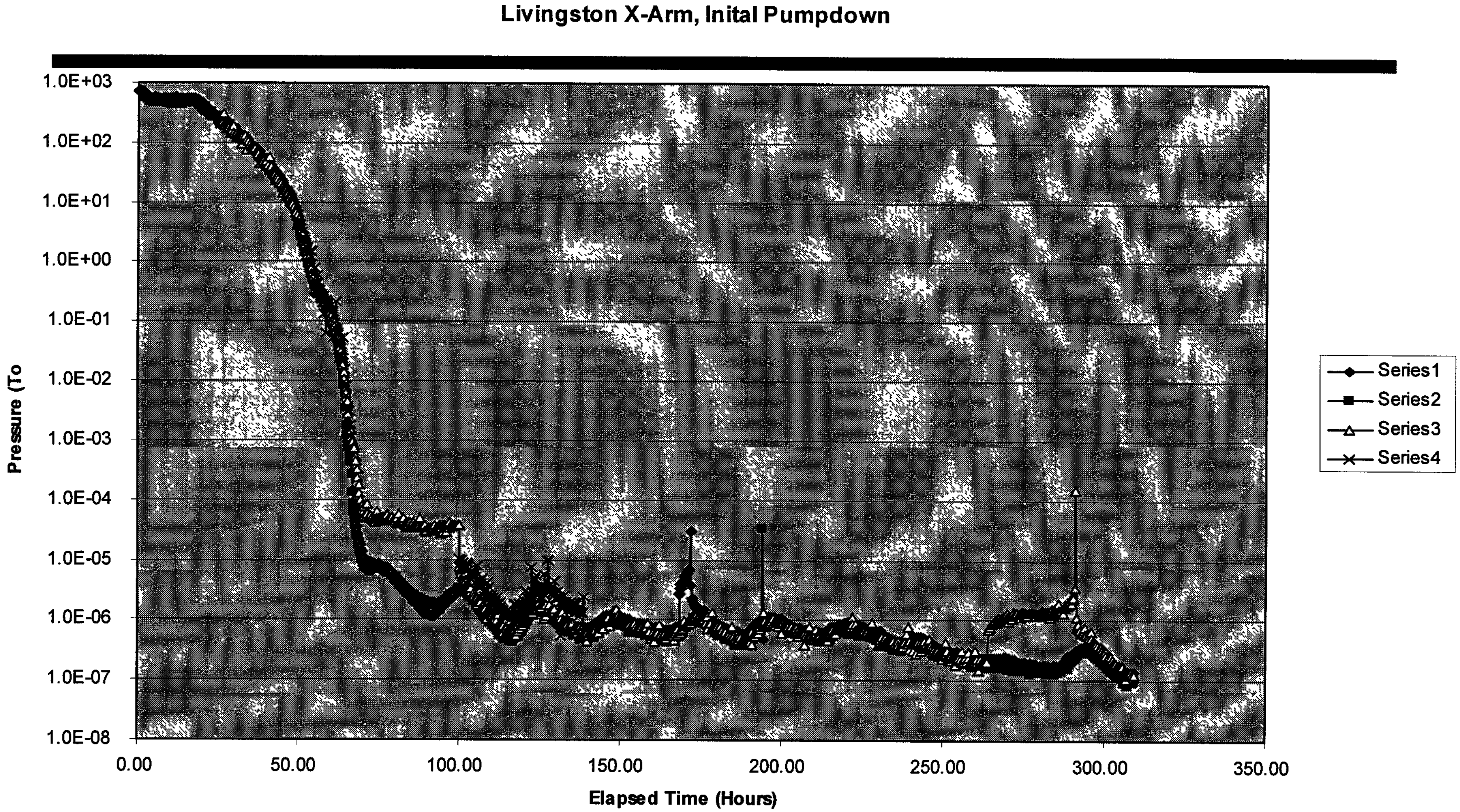
Beam Tube

- **Accomplishments since last review:**
  - Completion of all beam tube fabrication
  - Completion of Y arm installation
  - Alignment of X and Y arm
  - Installation of all beam tube enclosures
  - Pump down and acceptance of X arm
  - Pump down of Y arm - acceptance in progress
  - Vent of X arm using purge air system.

Beam tube acceptance

- **Right arm (X-arm) pumped down and accepted as an entire arm.**
- **Acceptance complicated by initial problems with site electrical power and X mid-station gate valve accident**
  - **Electrical power:**
    - **Initially phase imbalances of up to 10% caused trips of pumps and HVAC**
    - **Situation remedied by placement of substation close to site by utility provider (DEMCO). Now have phase imbalance of less than 0.5%**
  - **Gate valve:**
    - **gate accidentally freewheeled closed while electrical drive was being connected at right mid-station**

LLO Beam Tube Pump Down

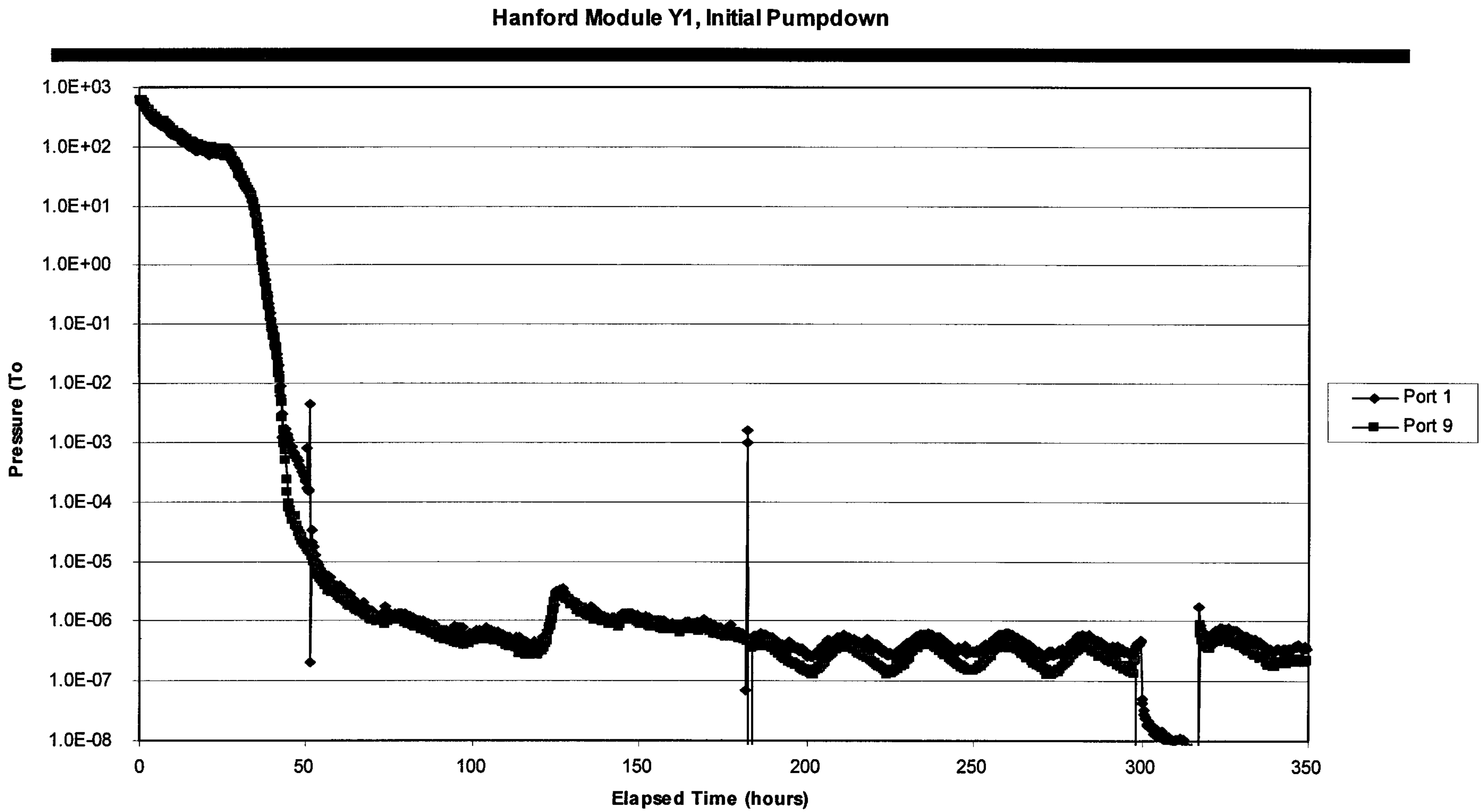


October 27, 1998
L980470-00-L

Mark Coles

LIGO

LHO Beam Tube Pump Down



October 27, 1998
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Mark Coles

Livingston X arm vacuum tests

Table 1: Gas model in the 4km volume of the Livingston x arm in 10^{-8} torr liters/sec

Gas	7/15/98	7/23/98	7/28/98	7/30/98
			2.66×10^{-6} air lk in x2	2.66×10^{-6} air lk in x1
H_2	1490±13	1020±3.8	1740±24	1840±35
CH_4	2.08 ±0.13	2.93 ±0.22	15.4 ±0.59	9.3 ±0.69
N_2	25.8±3.4	17.9±1.9	312±6.9	263±9.5
CO	29.9±3.0	15.4±2.4	39.2±7.9	99.0±9.1
O_2	7.9±0.3	1.5±0.2	28.5±0.8	31.7±0.9
A	0.13 ±0.01	0.016±0.007	0.52 ±0.03	0.75 ±0.04
CO_2	261±6.6	87±2.3	360±4.9	594±16
NO	179±3.2	102±1.4	374±9.2	690±12
C_2H_6	0.56 ±0.05	0.31±0.06	0.12 ±0.09	0.37 ±0.19
Temp C	28 (est)	29.1	32.2	34.5

Table 2: Estimated upper limits for air leak in entire arm

from	cracking fraction for air	air lk in 10^{-7} torr liters/sec
N_2	1.0	1.8
O_2	0.096	1.6
A	0.0021	3.4

Acceptance criteria

leak rate< 2x10-7

Table 3: Prebake outgassing rates at 23C

gas	T_0 K	J(296K) torr liters/sec cm^2
H_2	8000	6.0×10^{-14}
CO	10000	8.2×10^{-16}
CH_4	10000	9.1×10^{-17}
CO_2	10000	1.3×10^{-14}

Substation provided by utility (DEMCO)

Site Electrical Power

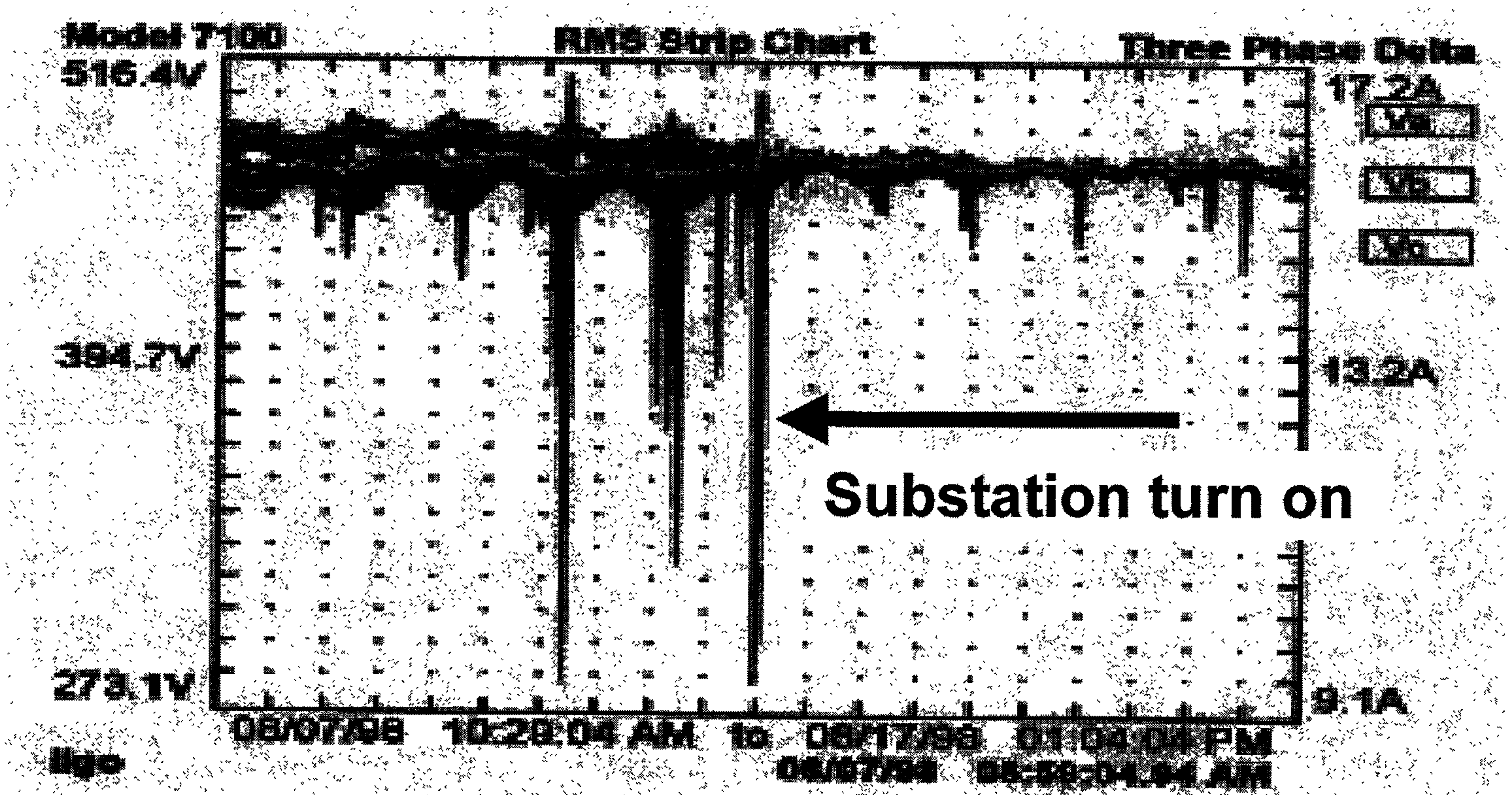
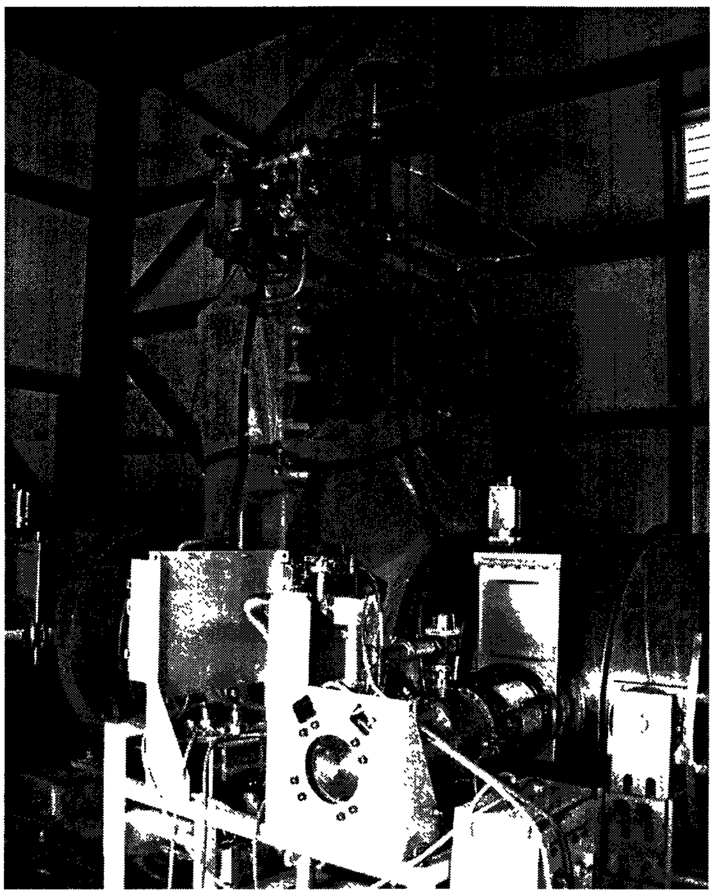
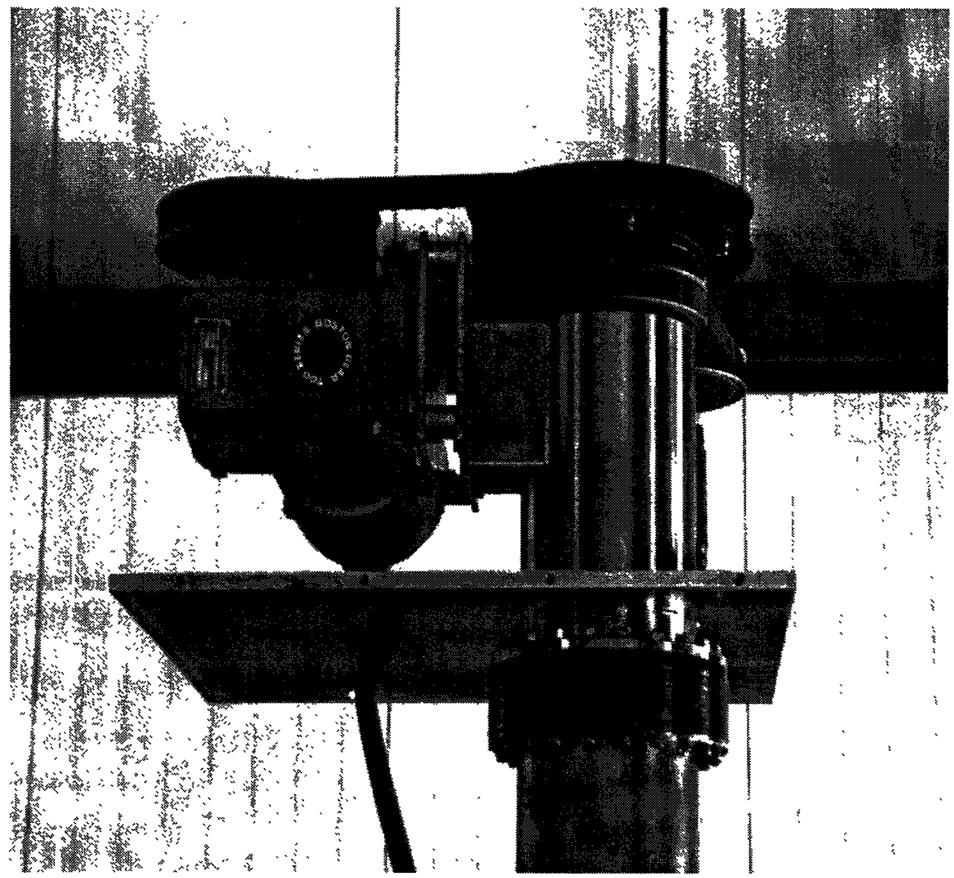
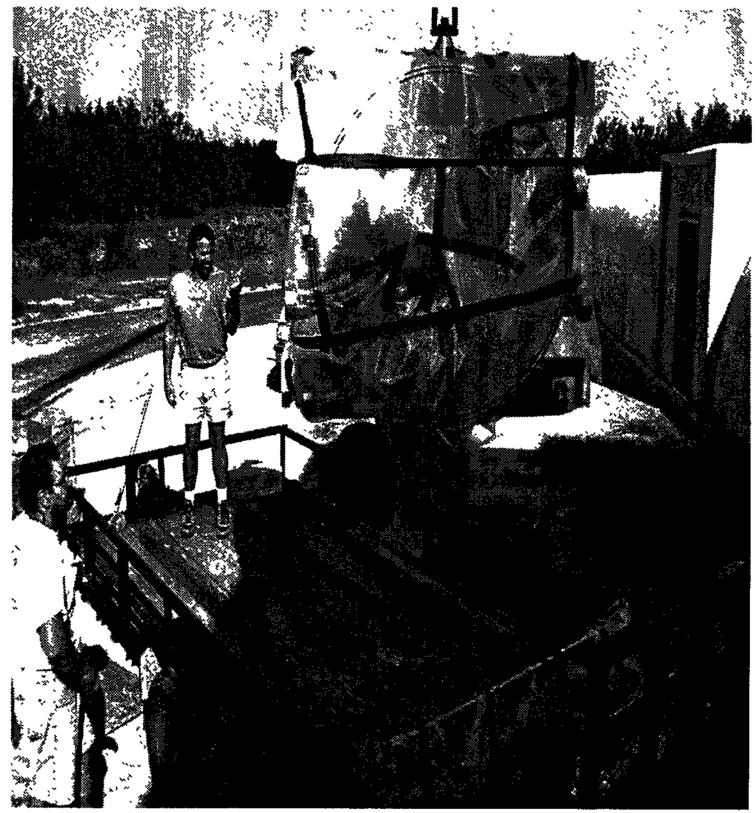


Photo of gate valve





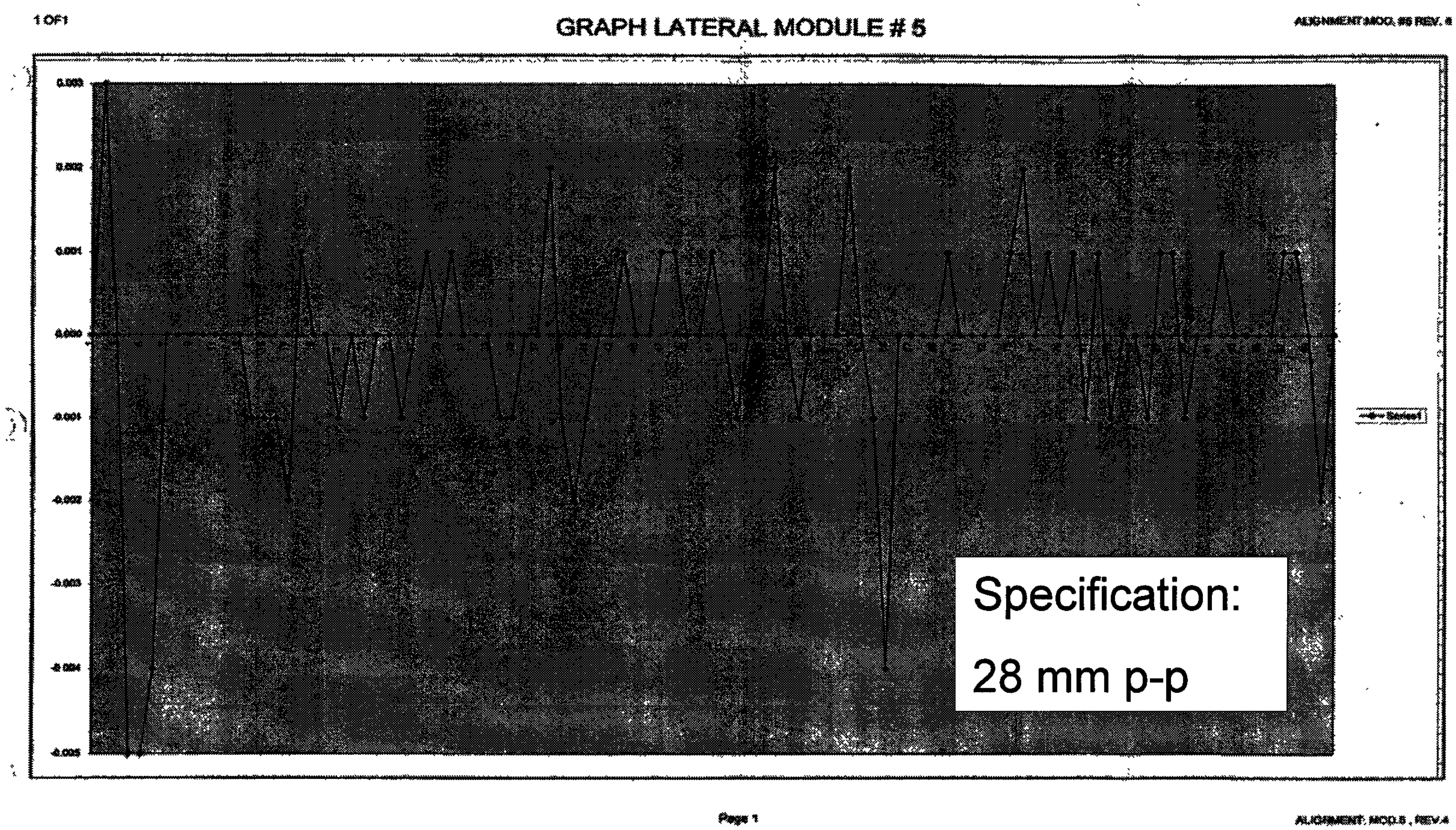
Gate valve removal



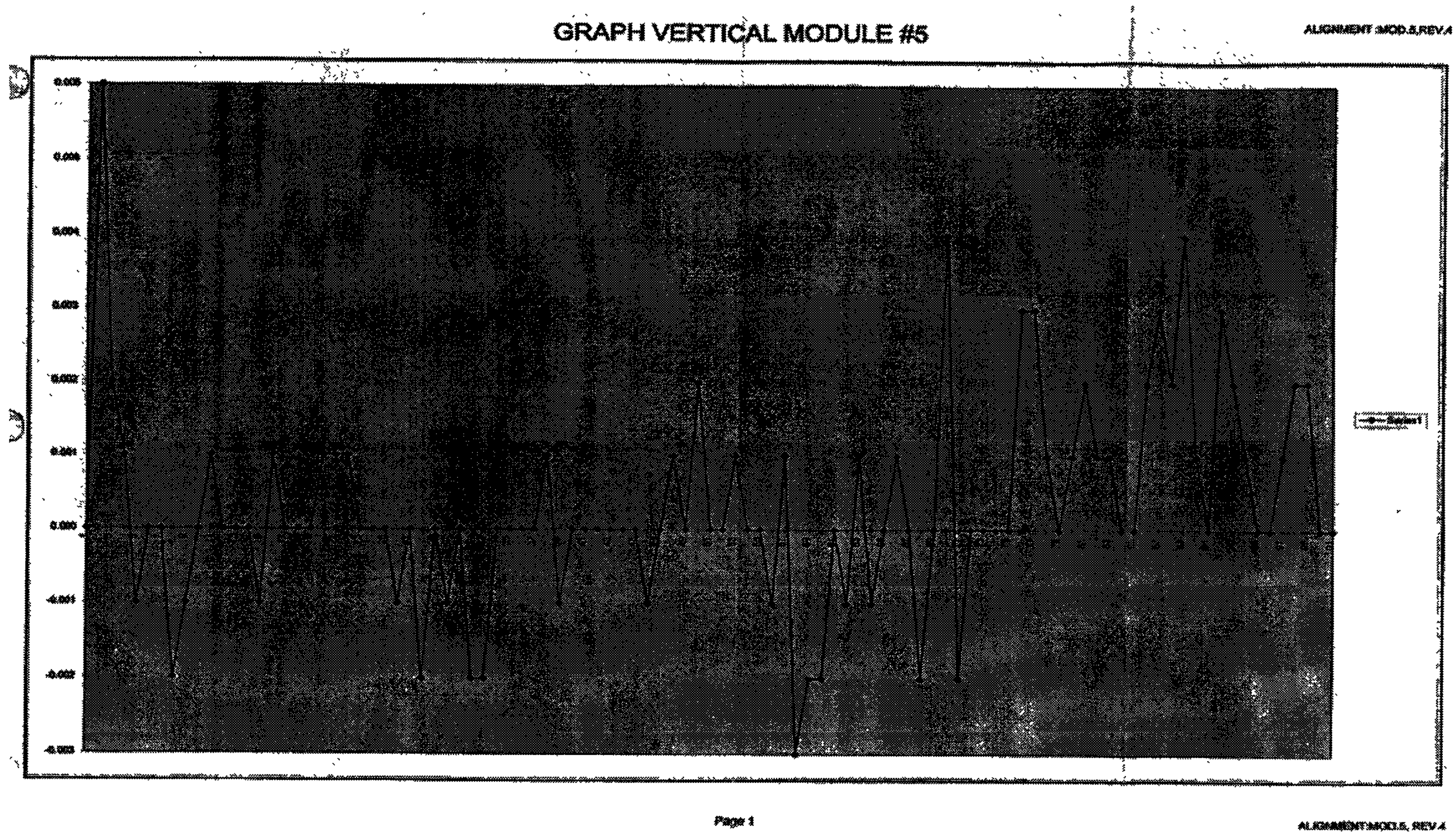
Lessons Learned

- Damaged gate valve (repair as part of planned inspection of all gate valves)
  - repair damaged stops and wheels
  - inspect gate
  - reinstall and adjust gate gap
- Implementation of work permit system:
  - identification of responsible authority
  - submission of procedures
  - use of lock-out tag-out
- regular permit meeting held to authorize all work
  - permits and procedures kept on file

Representative beam tube alignment data

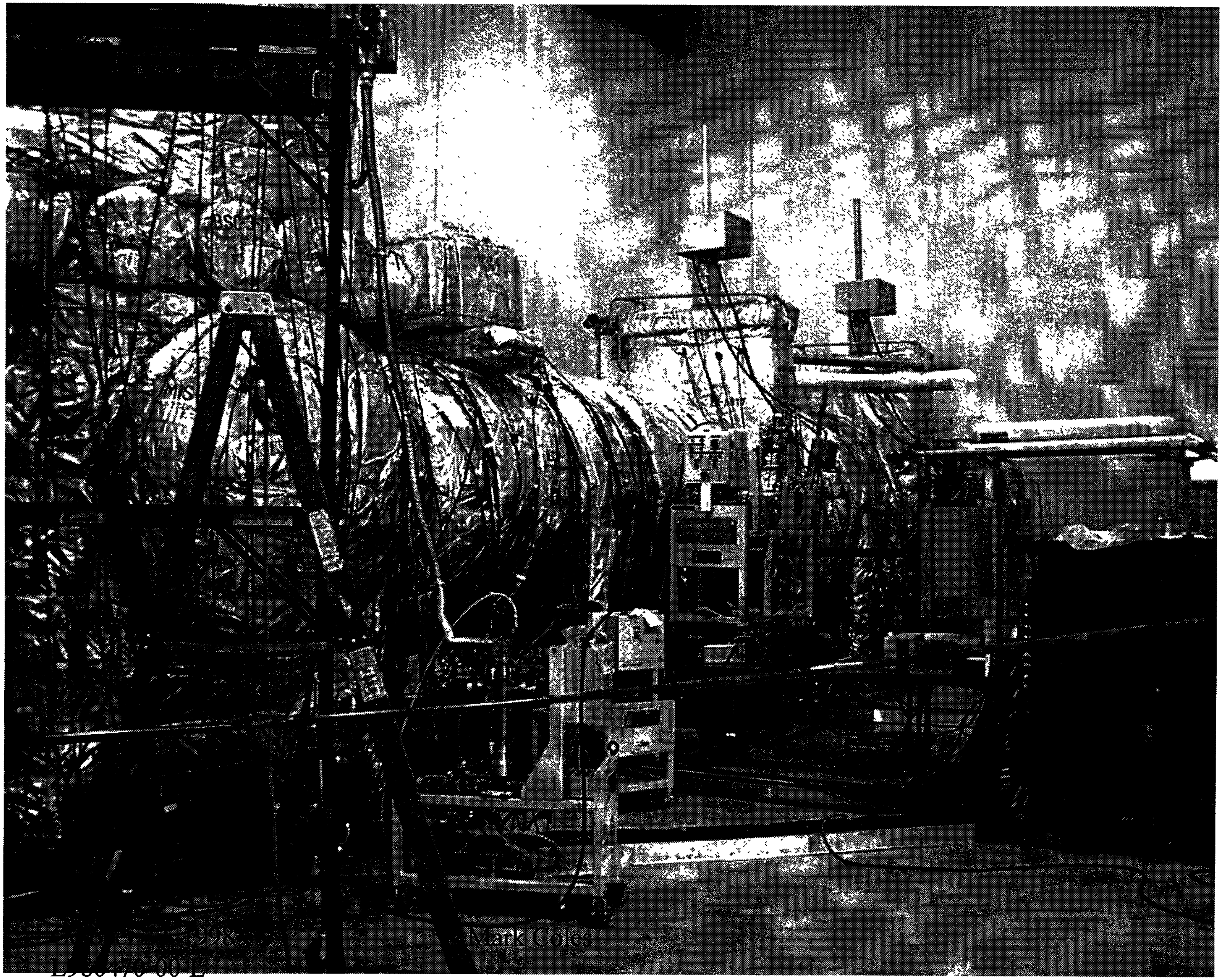


Vertical beam tube alignment data

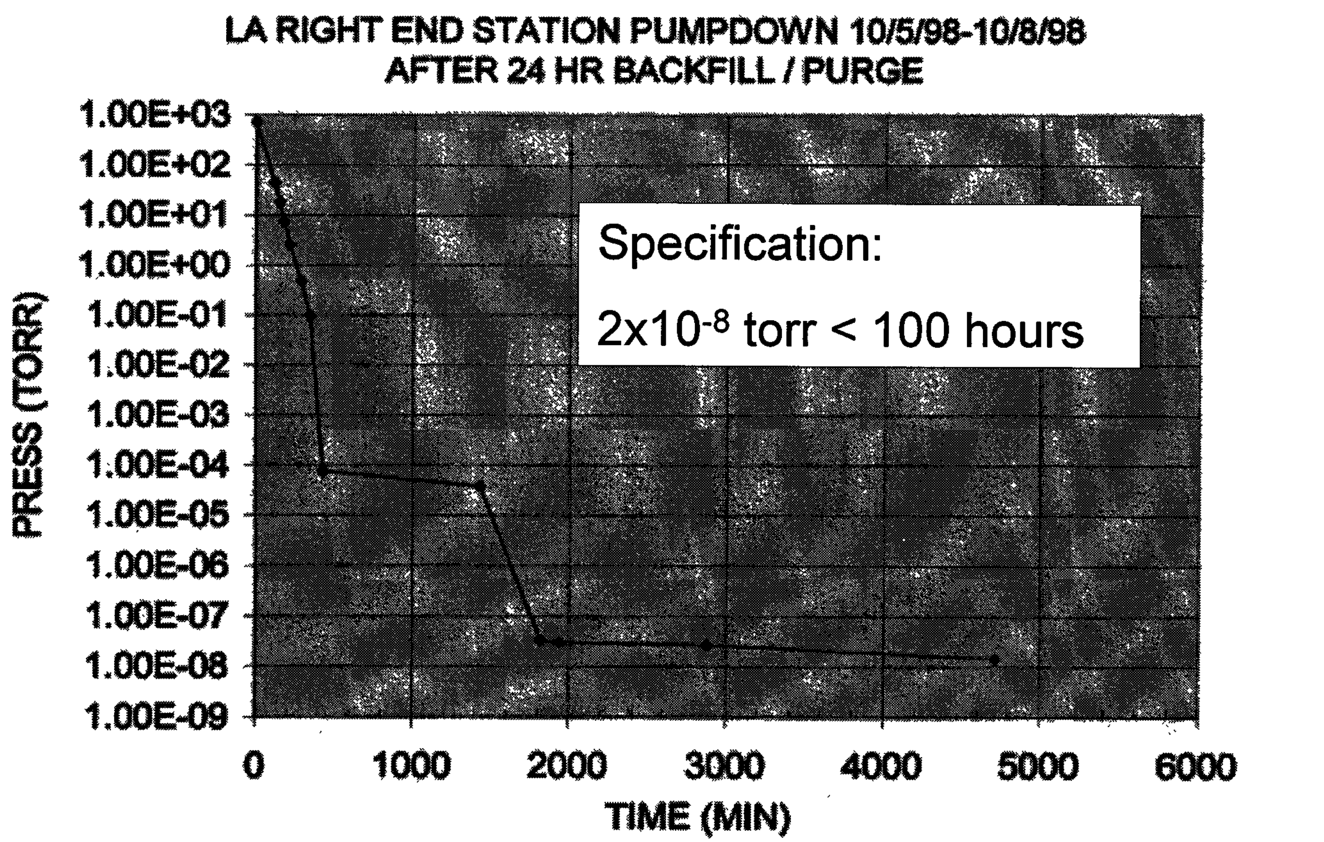


Vacuum Equipment

- **Summary of achievements since last review**
  - Delivery of all vacuum chambers, tanks, and pumps
  - Installation and grouting of chambers and tanks
  - Delivery and integration of CDS cryo control system
  - Bake out and acceptance of right end station
  - (Bake out of left end station in preparation)



End station pump down



First Test Results:
Right End Station Bake Out

- Interim report from PSI for each isolatable volume
- Final reports submitted at job closeout.
- Tests witnessed by cognizant LIGO engineer.

Partial Pressure Calculation

Acceptance of the Bakeout with respect to Air Signature and Partial Pressures

Date:9/23/98
Test ID:LA RIGHT END STATION
PSI Engineer:S.MOTEW

AMU	$F_{(amu)}$ transmission efficiency wrt N_2	$E_{(amu)}$ ionization efficiency wrt N_2	$S_{(p\_amu)}$ sensitivity (Torr/A)	$I_{(amu)}$ ion current (A)	$PP_{(amu)}$ (Torr)
2	-	-	12.94	4.00E-10	5.18E-09
16	0.57	1.60	17.00	5.00E-12	4.01E-11
18	0.64	1.12	17.00	8.20E-11	9.93E-10
28	-	-	17.00	4.70E-11	7.99E-10
44	1.57	1.42	17.00	1.40E-12	2.10E-11
all others	-	-	17.00	4.36E-11	7.41E-10

		LIGO Contract Limits	Actual	Pass
Primary Criteria -	Total Pressure:	2.00E-08 Torr	7.77E-09 Torr	Yes
Secondary Criteria -	Others except H_2 & H_2O:	3.00E-09 Torr	1.60E-09 Torr	N/A

LIGO:

PSI: 9/23/98

Right end station boil off test

- Contract requires > 90 days between fill for each cryopump system. (pump, tank, control system)
- Similar tests to be done for left end station and both corner station systems.
- Tests witnessed by LIGO cognizant engineer

LIQUID NITROGEN CONSUMPTION TEST
Ref. Spec. V049-2-208

Station	LA RIGHT END	Cryopump LCP4		
Test	Start	Finish		
Date	9/22/98	9/26/98		
Time	1200	1400		
Storage Tank	LDW4			
14400	gallons total volume			
13700	gallons at full trycock			
13700 x 0.95 =	13015	usable gallons		
300	in.H2O level indication at full trycock			
45.67	gallons / in.H2O			
Results				
Starting level=	260	in.H2O		
Ending level=	248	in.H2O		
Duration=	122	Hours		
Liquid consumed=	548.0	gallons		
Tank pressure=	12	psig		
Ave.consumption for test duration=			4.49	gal/hour
Required duration for usable gallons=			90.0	days
Projected duration for usable gallons=			120.7	days
Test status			PASS	

PSI [signature] /RW

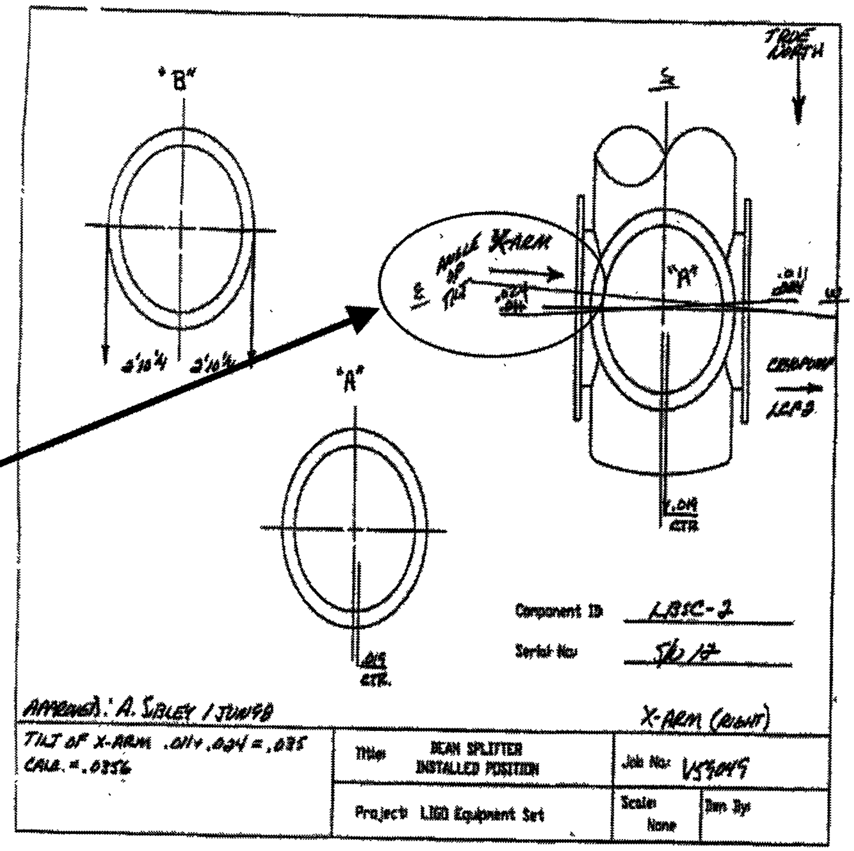
LIGO [signature]

October 27, 1998
L980470-00-L

Mark Coles

Chamber Alignment Data

- all chambers have been positioned by PSI and alignments have been checked.
- alignment documents are submitted for each chamber.
- spec = 0.080”



Remaining VE Activities

- Bakeout of Y end station (anticipate complete < 10/31)
- Bakeout of corner station
- Boil off tests
- Inspection/repair of all gate valves
- Formal submission and review of acceptance data

Building and site infrastructure

- **Beneficial occupancy since last review. Building Contractor (Hensel Phelps) is now offsite.**
- **Acceptance procedures - QA**
  - status
    - initiated a QA program prior to acceptance of the building to study:
      - Electrical,
      - mechanical,
      - building control,
      - power consumption and optimization of power factors

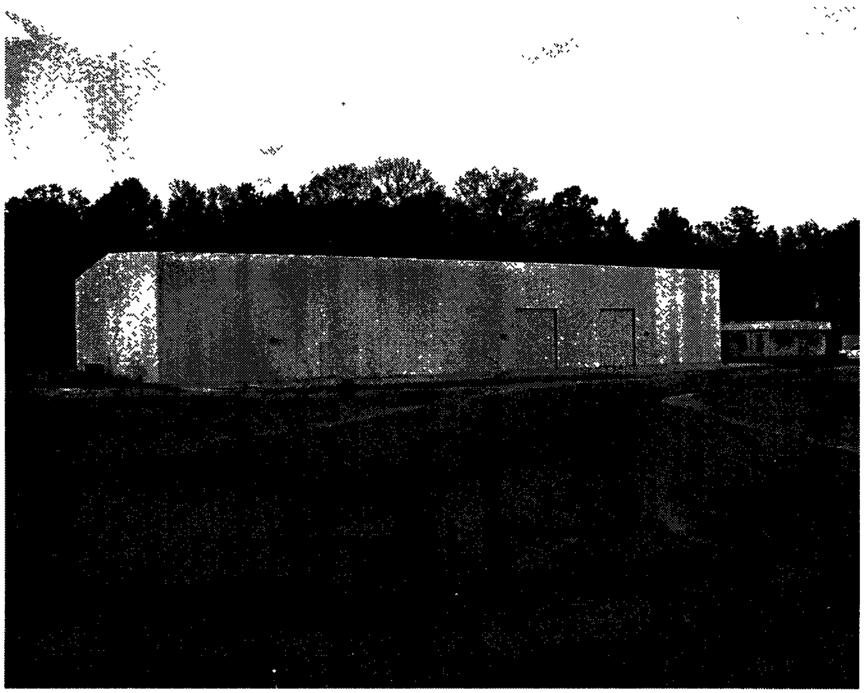
(Note that there are no building inspectors in Livingston parish, so QA needed to insure code requirements .)

  - Preliminary indications are that we have some deficiencies in the electrical work that need to be remedied.
  - Other outstanding issues on which we are working
    - Maintenance contract - bids received, expect to have in place < Dec. 1
    - panel blistering
    - vault leaks
    - Access road
    - Erosion control and landscaping

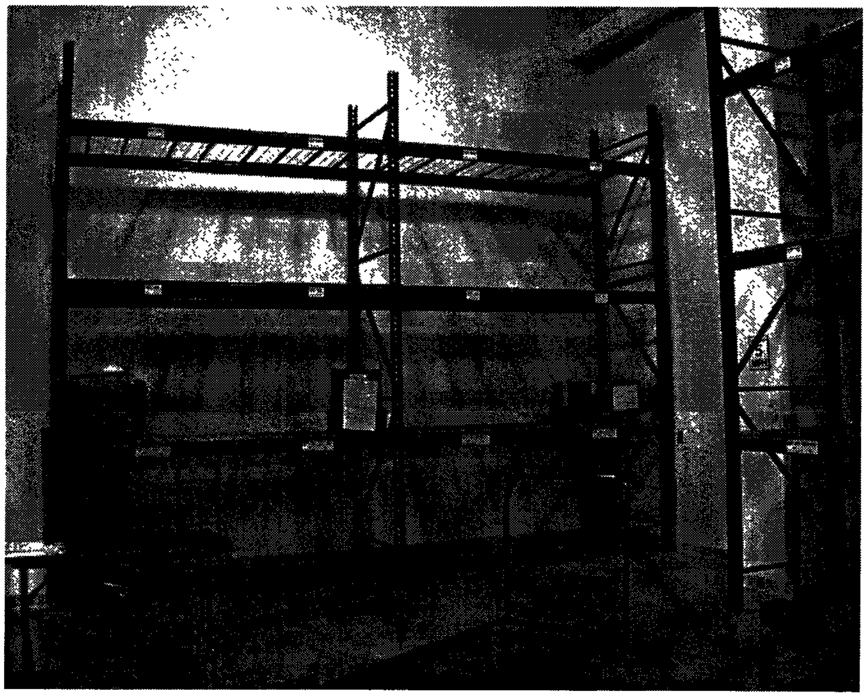
Preparations for detector installation

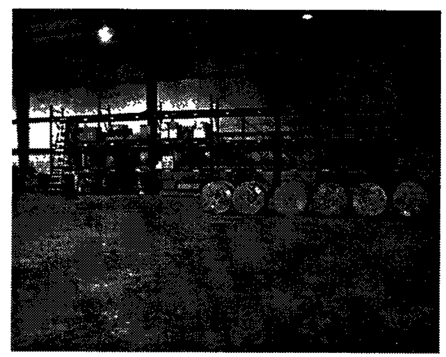
- Staffing Plan
  - Two scientists now resident (Coles, Rizzi)
  - Offer extended to one additional scientist
  - 50% of Site Manager (Gerry Stapfer) and 50% of Site Administrator (Bonnie Wascom) this FY
- 5 other resident staff now fulfilling construction related activities that will transition to detector installation and site sustaining activities.
- We plan two add 2 additional engineering staff in FY99
  - electrical engineer
  - software engineer
- We plan to add two scientific staff as joint appointments with the Univ. of Florida in FY99.

Staging building



Material handling



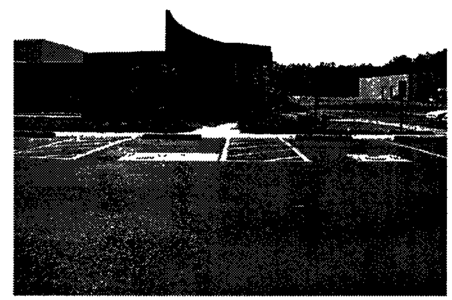


Mark Coles

LIGO

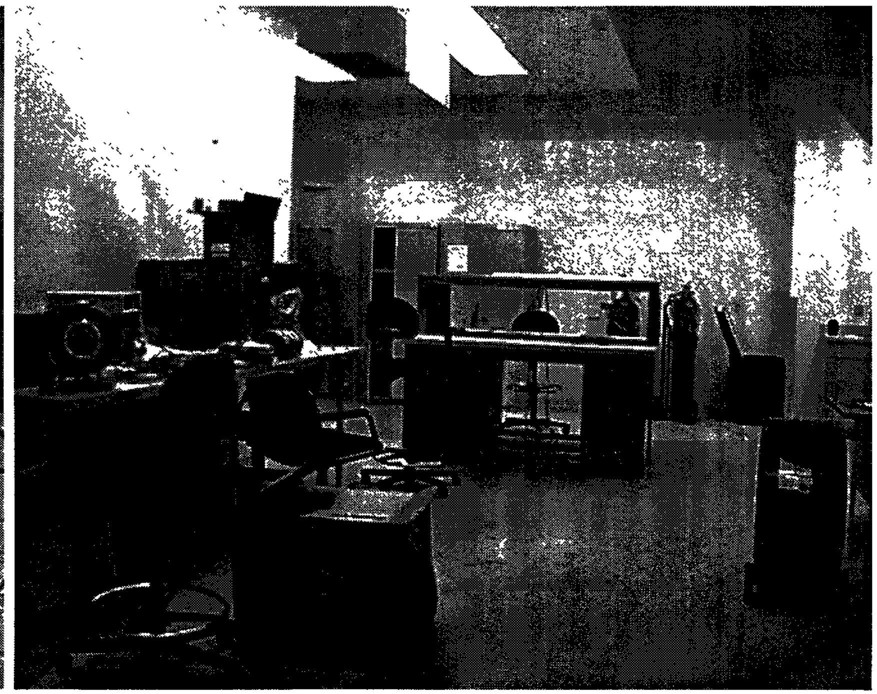
Multipurpose room

Asphalt roads along arms



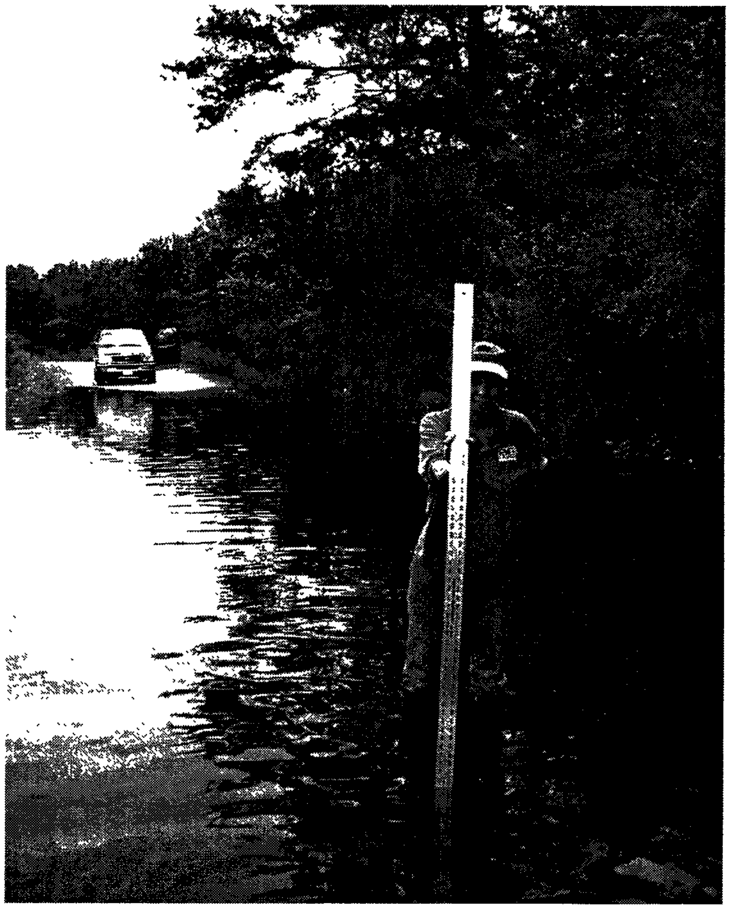
Lab set up

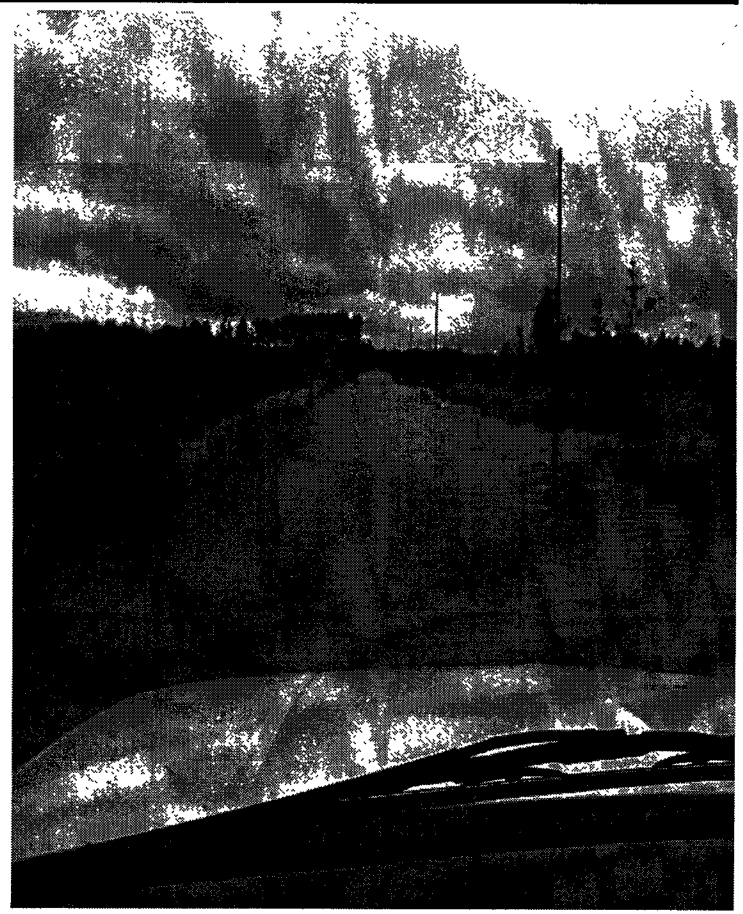

Electrical lab


Mechanical lab

State provided access road -

We are working with LSU and the La DOT to make sure that we get an all weather road.





FY 99 LLO Staffing Detail

Operations Staff	Name	FTE
Observatory Head	Coles	1
Senior Scientist	Offer extended	0.5
Staff Scientist	Rizzi	1
Staff Scientist	Shu (U of FL joint appt)	0.25
Staff Scientist	Yoshida (U of FL joint appt)	0.25
Observatory Manager	Stapfer	1
Administrator	Wascomb	1
Sr. Mechanical Engr.	Sibley	1
Electrical Engr	Open	0.5
Software Engr.	Open	0.5
Optics Specialist	Kern	0.67
Operations Specialist	Riesen	1
Operations Specialist	Svoboda	1
	TOTAL	*9.67*
Bakeout Staff	**Name**	**FTE**
Vacuum Specialist	Franklin	1
Operations Specialist	Stiff	1
Long term visitors		
Tom Evans	MIT	

Detector Installation Preparation Activities

- **Vacuum preparation and optics labs:**
  - **Clean areas**
  - **Install cabinets, optics tables, low conductivity water system, laser curtains, vacuum bake out oven, etc.**
- **Procure and set up electrical lab, mechanical lab**
  - **Install benches, test equipment, tools, parts, cables, consumable items, etc.**
- **Set up material handling, tracking, inventory systems**
  - **shelves, pallets, lifting eqpt, forklift, clean room handling eqpt and supplies, etc.**
- **Set up control room**
- **Set up open office areas for visiting staff**
- **We are learning from Hanford's experience so that when we do things in Livingston we benefit from that prior experience.**

Educational Outreach

- **Pursuing opportunities to provide educational outreach resources to the local community.**
  - Louisiana State University
  - Southeastern Louisiana University
  - Louisiana Tech University
  - Loyola University
  - East Baton Rouge, Livingston, and St. Tammany Parish schools
  - Louisiana School for Math and Science
  - LaSIP (Louisiana Systemic Initiative)
  - Louisiana Board of Regents
- **Plan to have on-site REU opportunities summer FY99**
- **Some student hiring during school year**

Summary of Activities Underway

- Completion of major subcontracts and remedy of remaining construction problems
- Preparation for detector installation scheduled to begin in January
- Development of educational outreach partnerships with the local community

LIGO Hanford Observatory (LHO) Status

Fred Raab
October 27,1998

Hanford Summary

- Infrastructure largely completed
- Approximately 1/2 the Operating Staff on board
- First Physics Meetings held (PAC & LSC)
- First Experimental Tests Performed (HAM 1st Article)
- First Student Projects (4 REU students)
- First Beam-Tube Module Baked out
- First 10-Watt Laser Installation Underway
- First HAM Seismic Installation Underway
- Building relationships with local universities, colleges, school districts & professional societies

Observatory Staffing

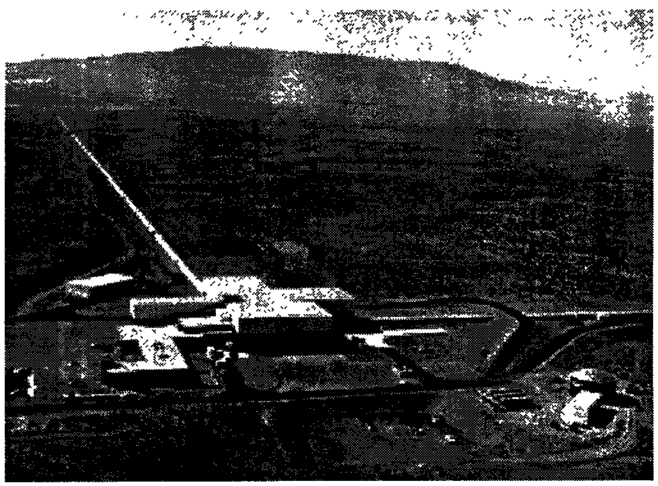
- Available manpower currently comprised of:
  - ››Resident Staff (~13 in operations; 2 in bakeout)
  - ››LIGO Laboratory Visitors (avg ~10 during installation & commissioning)
  - ››LIGO Science Collaboration (~2 members from UFI for input optics; ~ 4 members from JILA, LSU, PSU for HAM testing)
  - ››Contractors for ongoing non-technical services (e.g., maintenance, grounds, janitorial)
  - ››Temporary services for special jobs that do not carry over into steady-state operations (materials receiving/handling during installation; beam-tube bakeout; vacuum prep)
  - ››Special “installation” contractors for trades (electricians, grouters, etc.)
- Typically 30-40 people working on site

LIGO-G980091-01-W

Resident Staff at Hanford by Task

- Management/Administration: Berry, Matherny, Raab
- Scientific Staff: Rong, Savage, Sigg
- Vacuum Systems: Ryan, Worden
- Electrical & Electronics Systems: McCarthy, TBD
- Software & Systems Administration: Barker, Patton
- Optics & Lasers: Cook
- Seismic Systems: Gray, Radkins
- Beam -Tube Bakeout: Guenther, Lubinski

Status of Facilities



•Corner Station, Mid-Stations, End-Stations complete

•OSB (main laboratories & office space) complete

•Maintenance, grounds, janitorial services are established

•Water system mods underway

- Additional space under construction to provide laboratory/ staging space, fabrication shop, additional office and storage space and space for outreach programs

Status of Vacuum Equipment

- PSI installation completed
- System tests completed
- Vacuum chamber bakeout completed
- Valve problems were discovered and rework program was established
- All valve internals inspected and reworked as necessary
- Soft closure test completed

Status of Beam-Tube Bakeout

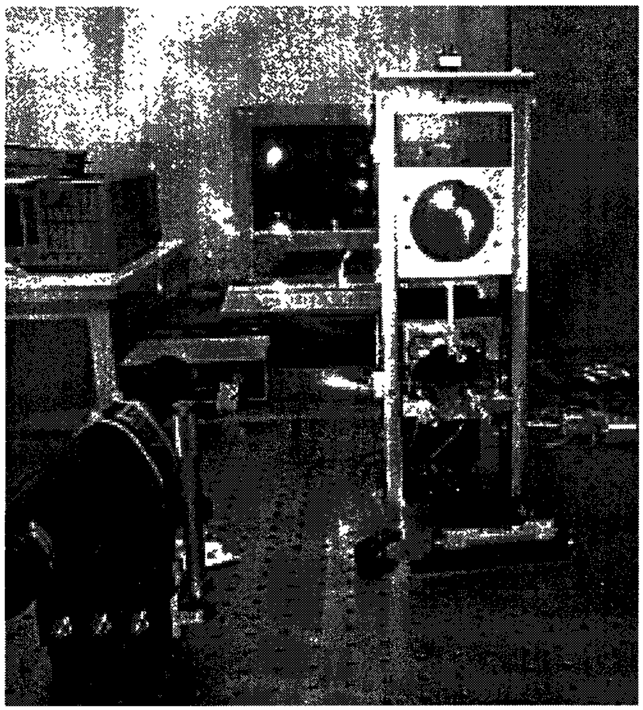
- Design, Procurement & Staging completed June 98
- Bakeout started August 98 following valve repairs
- First beam-tube module (Y2) successfully baked out!
  - $H_2O < 10^{-15}$ Torr-liter/s/cm^2
  - $H_2 = 10^{-13}$ Torr-liter/s/cm^2
  - CO_2, CO, CH_4, NO $< 10^{-15}$ Torr-liter/s/cm^2
  - Hydrocarbons $< 10^{-16}$ Torr-liter/s/cm^2
  - No Leaks $> 3 \times 10^{-9}$ Torr-liters/s
- Equipment moved to next module (Y1)
- Y1 Bakeout scheduled to start 2nd week in November

Water Behavior During Bakeout

Outgassing Before & After Bakeout

Laboratory Infrastructure

- Electronics lab in business
- Mechanical lab in business

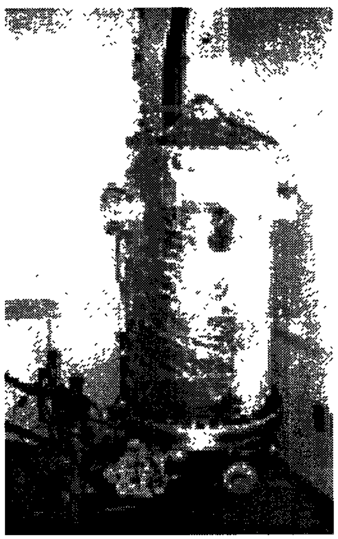


•Optics Lab in business; cleaning of input optics has begun

•Vacuum Assembly lab in business; suspension test stand used to check out 1st-article suspension assembly procedures using dummy mirror

•Clean-room practices in place in corner station labs and experimental halls

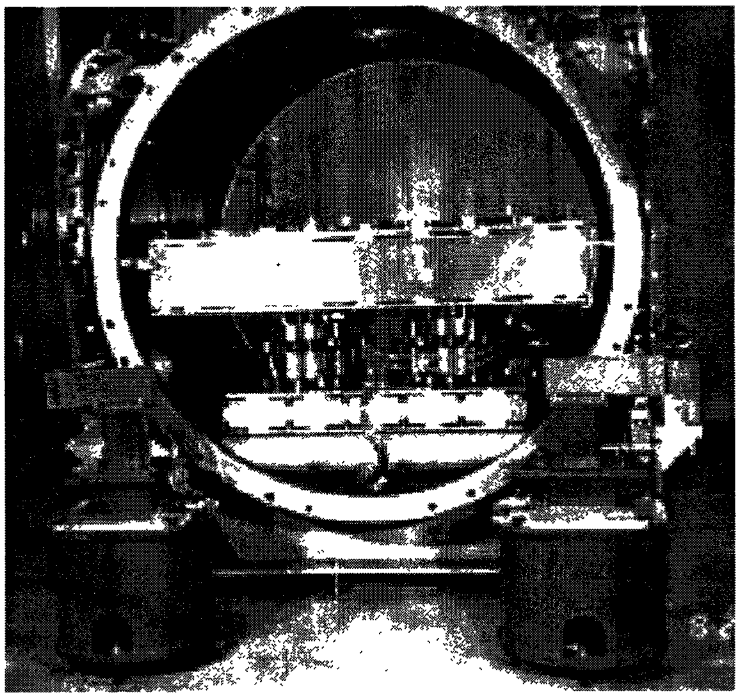
Laboratory Infrastructure - 2



- Vacuum Bake/Qualification Facility in business
- 2 of 3 LANs in business (CDSnet, GCnet)
- T1 WAN service through ESnet tested; use agreement signed; installation in progress
- General Computing system ~1/2 built
- Control Room presence growing: vacuum controls, facility controls & laser screens currently available at consoles

- Data Acquisition system installation has begun; first data written into frames; GRASP installed

HAM Seismic First-Article Test Program



- form, fit & function tests were successfully completed
- a number of improvements were incorporated into assembly fixtures and production drawings
- enabled resident staff to master stack assembly process and to develop detailed assembly procedures

HAM Seismic First-Article Test Program (continued)

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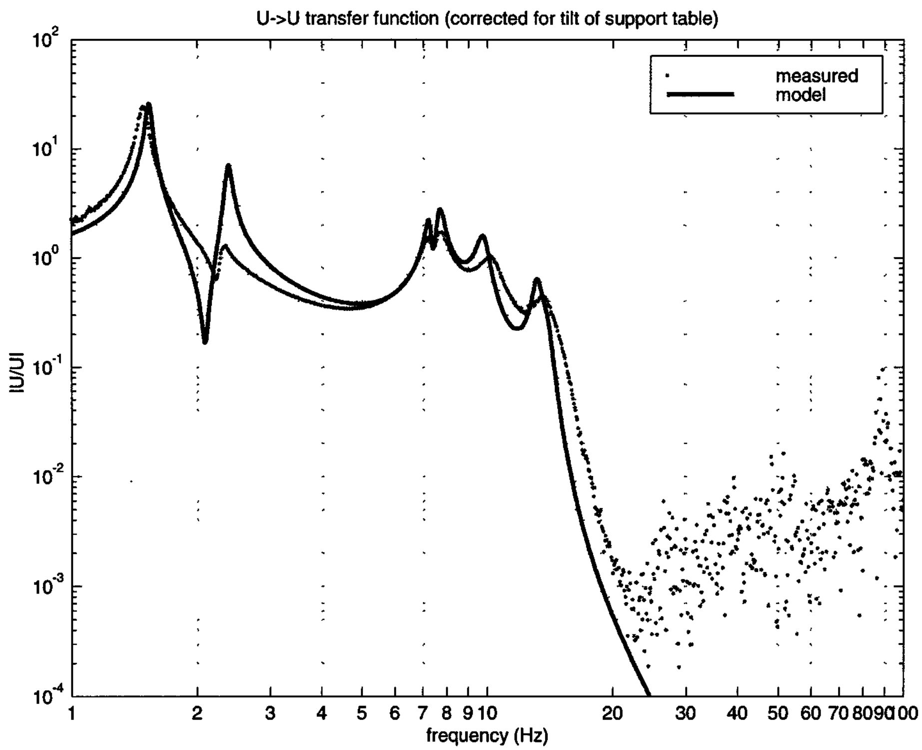
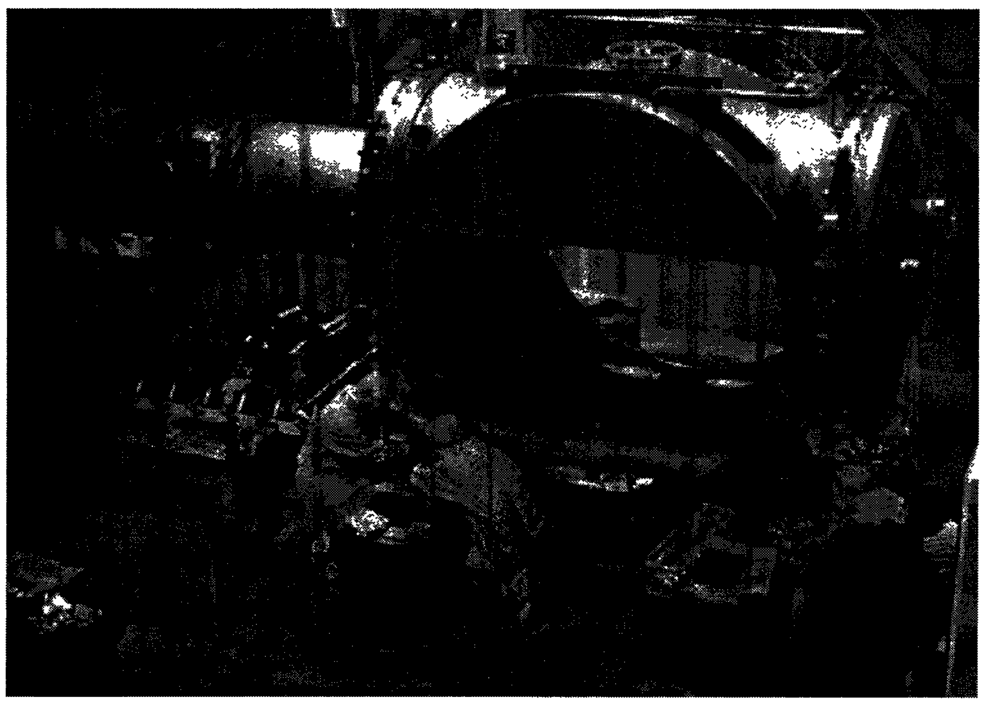


- performance testing of stack completed using LHO test systems
- stack performance well described by stack models
- drift rates generally within required range
- need for left-handed springs was confirmed by performance test

Interferometer Installation is in Progress

- Laser installed; pre-mode-cleaner locked
- Installation of seismic isolation into 1st Input HAM chamber in progress



Outreach Activities - Visitor's Area

- Visited heads of science/technology centers to learn museum business
  - ››Adler Planetarium
  - ››Lederman Institute
  - ››Exploratorium
  - ››Los Angeles Museum of Natural History
- Attended course on informal education & museum evaluation (needed for any NSF proposal)
- Prospects for NSF funding need to be worked out (currently a plan for long term financing is lacking), so emphasize low-budget activities as targets of opportunity arise

Outreach Activities in Local Area

- Met with superintendents of 6 local school districts to solicit advice on local educational needs & opportunities
- Held workshop with area teachers (supported by local school superintendents) to get advice on how LIGO can best interface to local needs and opportunities
- Discussions with PNNL to create internship opportunities for area high-school teachers and students for Summer 99
- Working with local high school teachers to establish science club and enrich content in current school programs
- Building bridges to local Universities: 4 REU undergrads from Caltech, Grinnel, Washington State U., & Whitman College interned at LHO during Summer 98

Summary

- Tremendous amount of work completed
- Upcoming events in 2K interferometer installation:
  - ››complete PSL & input HAM Seismic Systems in Nov98
  - ››install Input Optics in Dec98
  - ››begin BSC Seismic stack installation in Dec98
  - ››begin corner-station Core Optics installation in Jan99
  - ››complete Beam-Tube Bakeout by Jun99
  - ››complete mid-station installation work by Jul99
- Resident staff focused on installation

Detector Status

David Shoemaker

27 Oct 98

- Brief schedule/cost update
- Top-level status of each Detector subsystem
  - design, procurement, fabrication
  - technical highlights
- R&D activities for initial and advanced LIGO

Detector Milestones

<table>
<tr><th>Milestone Description</th><th colspan="2">Management Plan Date</th><th colspan="2">Completion Date</th></tr>
<tr><td>BSC Stack Final Design Review</td><td colspan="2">04/98</td><td colspan="2">08/98</td></tr>
<tr><td>Core Optics Support Final Design Review</td><td colspan="2">02/98</td><td colspan="2">11/98</td></tr>
<tr><td>HAM Seismic Isolation Final Design Review</td><td colspan="2">04/98</td><td colspan="2">06/98</td></tr>
<tr><td>Core Optics Components Final Design Review</td><td colspan="2">12/97</td><td colspan="2">05/98</td></tr>
<tr><td>Detector System Preliminary Design Review</td><td colspan="2">12/97</td><td colspan="2">10/98</td></tr>
<tr><td>I/O Optics Final Design Review</td><td colspan="2">04/98</td><td colspan="2">03/98</td></tr>
<tr><td>Prestabilized Laser Final Design Review</td><td colspan="2">08/98</td><td colspan="2">11/98</td></tr>
<tr><td>CDS Networking Systems Ready for Installation</td><td colspan="2">04/98</td><td colspan="2">03/98</td></tr>
<tr><td>Alignment (Wavefront) Final Design Review</td><td colspan="2">04/98</td><td colspan="2">07/98</td></tr>
<tr><td>CDS DAQ Final Design Review</td><td colspan="2">04/98</td><td colspan="2">05/98</td></tr>
<tr><td>Length Sensing/Control Final Design Review</td><td colspan="2">05/98</td><td colspan="2">07/98</td></tr>
<tr><td>Physics Environment Monitoring Final Design Review</td><td colspan="2">06/98</td><td colspan="2">10/97</td></tr>
<tr><td>Initiate Interferometer Installation</td><td>07/98 WA</td><td>01/99 LA</td><td>07/98 WA</td><td>01/99 LA</td></tr>
<tr><td>Begin Coincidence Tests</td><td colspan="2">12/00</td><td colspan="2">12/00</td></tr>
</table>

Detector Cost Status

Subsystem	Budget	Cost and commitment	Estimate at completion
Control and Data	13497	8787	13409
Physics Environ. Monitor	2196	1067	2052
Pre-Stabilized laser	3210	2728	3148
Input Optics	1860	1886	2149
Core Optics	8102	7517	7979
Core Optics Support	2021	812	1999
Alignment Sensing/Control	4820	2105	4589
Length Sensing/Control	1695	1013	2049
Suspensions	3443	1451	1714
Seismic Isolation	11762	9664	13488
Systems	2244	1886	2231
Support Equipment	1563	640	1566
TOTAL	56414	39556	56372

Control and Data System (CDS)

Function:

- communication infrastructure, data acquisition, individual subsystem control/monitoring (addressed with subsystem)

Status:

- Final Design Review for Length/Alignment sensing for early 99
- all other Final Design Reviews complete and successful
- detailed layout/engineering/fabrication underway
- installation underway at Hanford

LAN installed at Hanford

- system in use for scientific computing and facilities monitoring

Vacuum controls finished

- complete and in use at Hanford
- being exercised as part of Vacuum Equipment installation at Livingston

Data acquisition

- prototype complete and accepted

Physics Environment Monitor

Function:

- to monitor environment, provide veto and regression information; provide excitation to help characterize interferometer

Status:

- Final Design Review complete; design complete except for cosmic muon detector
- first articles installed for several elements (residual gas analyzer, weather, excitation, stand-alone DAQ)
- installation paced by other activities: vacuum equipment, seismic isolation; all elements ready when needed

Support for seismic isolation first article tests

- used to characterize dynamic performance
- sensors, excitation systems, DAQ employed/exercised

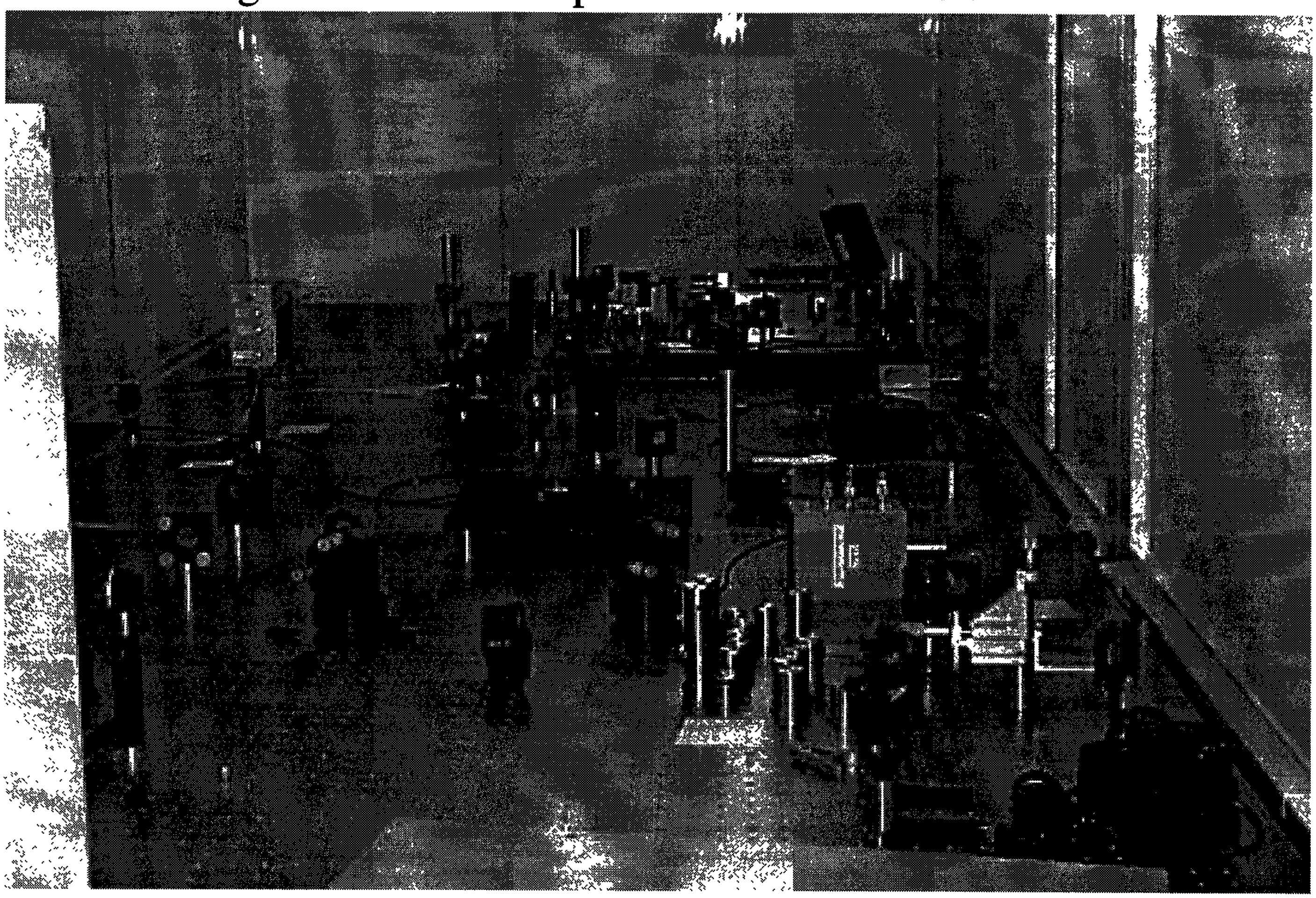
Pre-Stabilized Laser

Function:

- supplies the light to the interferometer, includes the 10W laser source; important element in the overall servocontrols approach

Status

- **first article installed at Hanford (initiated installation of Detector)**
- testing of prototypes completed
- Final Design Review to take place in November '98



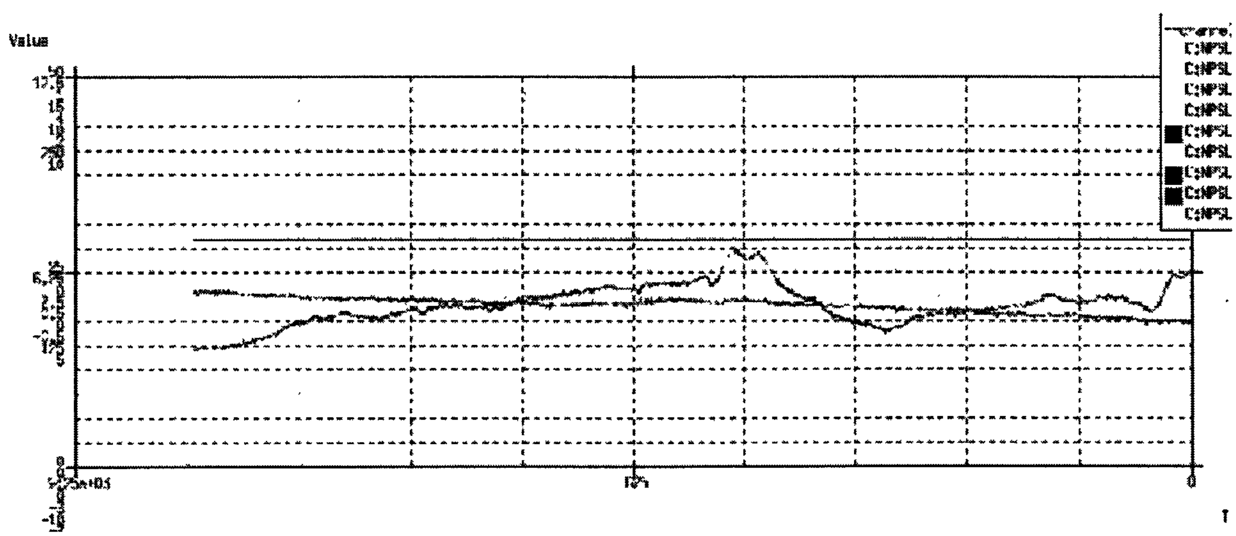
Pre-Stabilized Laser

Laser source

- source lasers showing good reliability
  - > 2000 hours, <3% drop in power
- now commercially available from Lightwave as '20 W laser'
- first 'option' laser in house - production running on schedule

Prototype tests

- good 'standalone' noise performance
- high availability --- days of continuous operation of servosystems
  - > frequency stabilization servo, the PMC servo, the intensity servo and the temperature stabilization servo
  - > robust against environmental changes

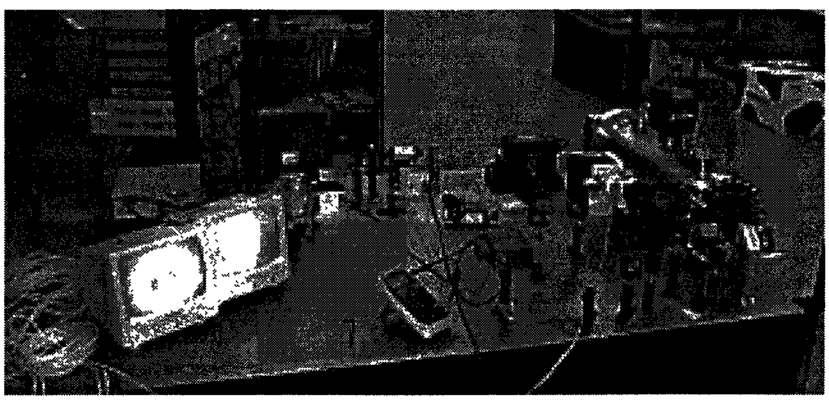


Input Optics

- temporal and spatial low-pass filtering of input light, matching of light into the interferometer; important element in servocontrol
- University of Florida has designed and is delivering/installing subsystem
- 2k suspensions completed, most optics in house
- installation for LHO 2k interferometer started, staging at Hanford

Detection system for matching prototyped/tested

- bulls-eye sensor for circularly-symmetric modes
- dithering system allows independent test, calibration of wavefront sensor

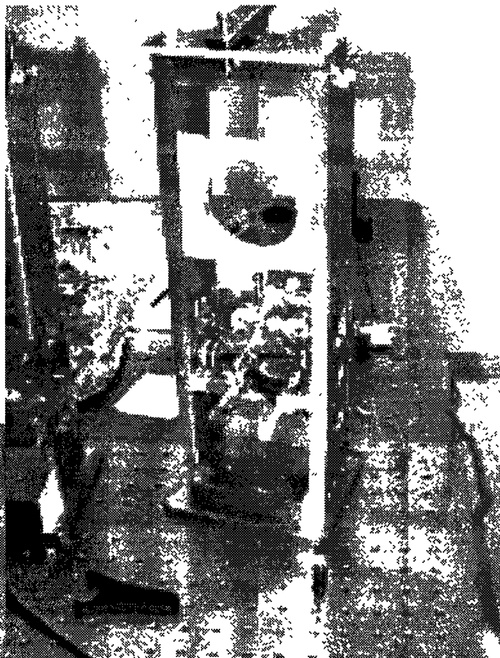


Large optics advancing nicely

- Test-mass sized last mirror presents manufacturing challenges
- long radius of curvature, usual size constraints
- polished, in-house, characterization in process

Input Optics

Setup of suspensions underway at Hanford



- Small Optics Suspension

- UFla and Hanford staff balancing one of the Input Optics

Core Optics Components

- optics for the interferometer, test masses for the strain detection
- all core optics substrates procured, ground; only 6 left to polish, 16 to coat (out of 40)
- testing commencing for figure, loss, point defects
  - 25-100 defects, >2.5 microns (~20ppm scatter)
- cleaning procedures in qualification

In-house metrology

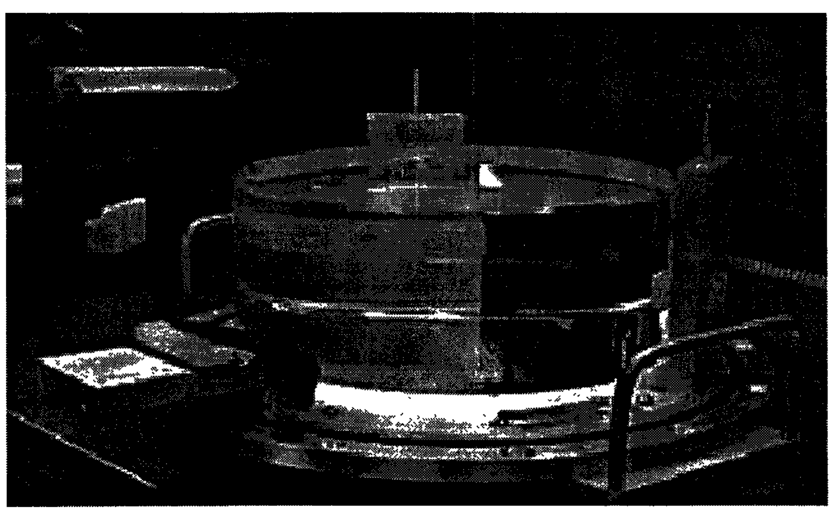
- initial interferometer vendor could not deliver, second vendor has had difficulty
- interferometer now in-house, accepted, and in tests/practice runs
  - best repeatability of 0.2 nm,

Some difficulties with coating

- improper cleaning at vendor, re-coating needed; improved QA now in place (LIGO personnel present for procedure)
- spares philosophy appears about right

Overall development effort a smashing success

- polishing, metrology, and coating technologies all advanced
- LIGO requirements met or exceeded



Core Optics Support

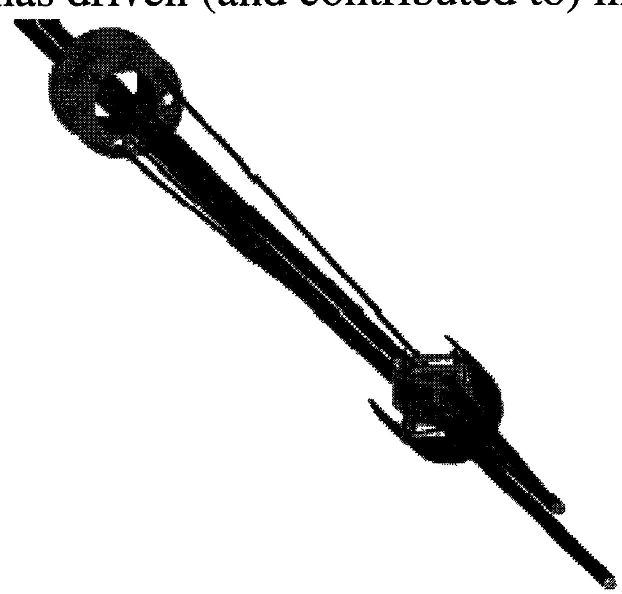
- Function: bring light out of interferometer for sensing/monitoring; contain scattered light; 'dump' unwanted beams
- Preliminary Design well advanced; Final Design Review in November
- detailed design of telescopes well advanced
- prototypes of parts installed in mock-ups

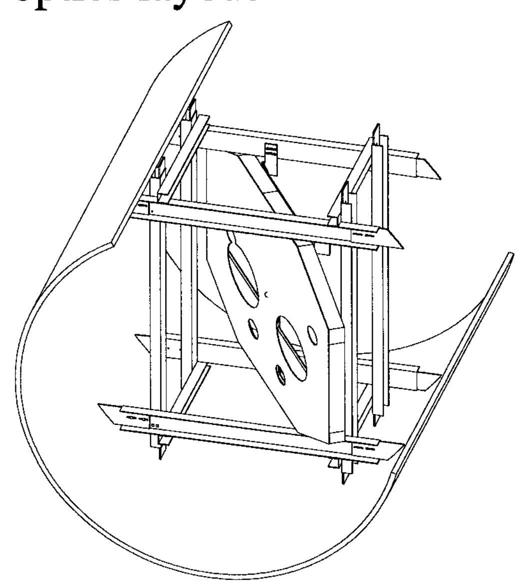
Wavefront flatness a challenge

- Alignment sensors require small astigmatism, other distortions
- places strong requirements on beam-reducing telescopes
  - 0.7λ peak-valley phase flatness

Strong interaction with overall optics layout

- baffling must accommodate pointing beams, ghost beams
- has driven (and contributed to) integrated optics layout





Initial Alignment

- establishes the position and angle of optical components at moment of installation; maintain external pointing references to allow quick bootstrap to operational alignment, ease servicing work
- equipment for initial surveying in-house and qualified
- tests of basic procedures exercised at MIT
  - 80 microrad initial alignment requirement easily fulfilled
- optical lever assemblies in fabrication or shipped

Prototype tests

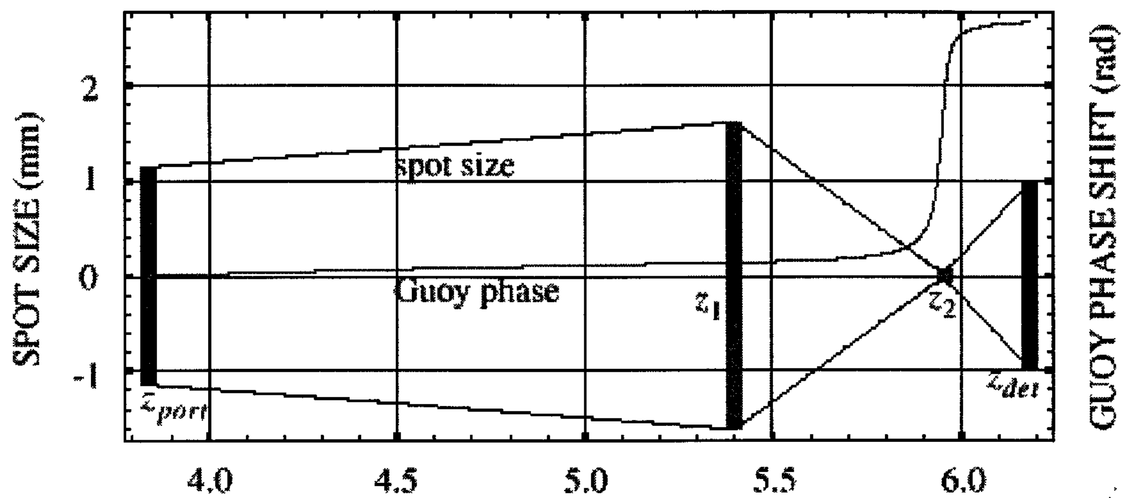
- stability of pointing system exceeds requirements
  - 50 microrad peak over weeks requirement

Interaction with facilities driven integrated layout

- Vacuum equipment: as-built viewports, deflections on pump-down
- Civil construction: placement of surveying markers, stability

Alignment Sensing/Control

- maintains operational alignment
- prototype tests of sensors completed
- detailed soft/Hardware engineering underway
- details of transformation optics in design



Use on suspended prototypes central to research

- Phase Noise Interferometer
- 40m Interferometer
- models confirmed quantitatively

Digital servo

- 10 degrees-of freedom to sense, control
- requires fully multiple-input multiple-output system
- low bandwidth, but state changes, saturation, sharp filters
- in prototype tests

Length Sensing/Control

- acquire, maintain the operational lengths for the interferometer; read out gravitational-wave strain
- now in detailed software development

Suspended interferometer test of digital control

- MIT Phase Noise Interferometer demonstration (details under R&D)
- proof-of-practice for critical dynamic range and servo questions

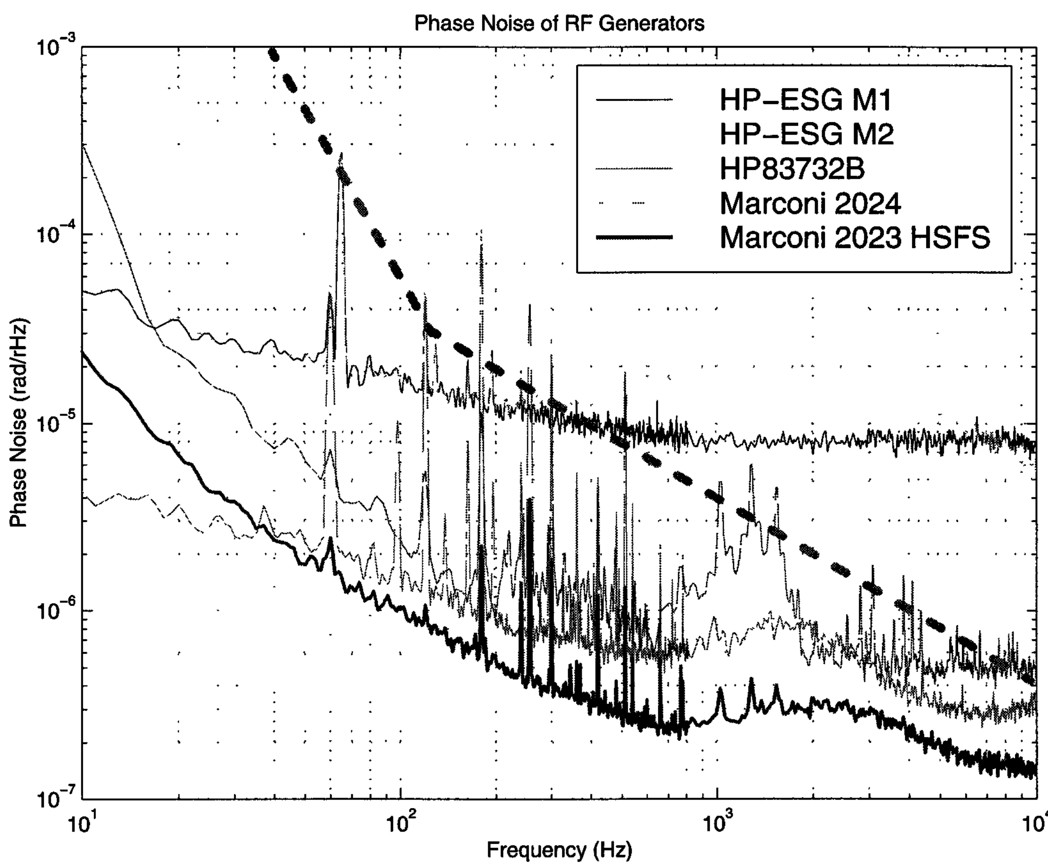
Acquisition modeling well advanced

- modifications but especially exploitation of dynamic model
- increases in calculated critical locking velocity of factor of 10
  - 3λ/sec; implies locking in several seconds
- also progress on determining initial alignment requirements, with results comparable to earlier expectations

Length Sensing/Control

Modulation source

- comparison of commercial systems for phase noise
  - best is not most expensive
- amplitude stabilization to below $10^{-8} 1/(\sqrt{\text{Hz}})$ requirement



Suspensions

- support test mass and other optics but not compromise thermal noise performance; provide actuators for positioning optics in angle and position
- Final Design Reviews and detailed design completed
- Small Optics Suspensions fabricated
  - mechanical parts by University of Florida (used in Input Optics)
  - electronics by Control and Data Systems
  - in installation at Hanford
- Large Optics Suspension prototype iterated, now in production

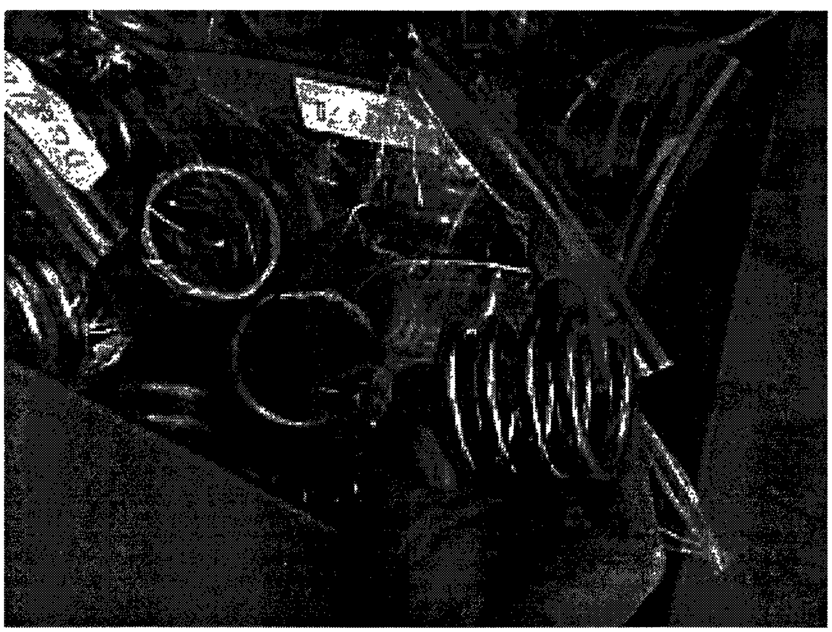
Alternative means for attachments investigated

- magnets attached to test masses, used as part of actuator system
- epoxy used to date; cleanliness and assembly time disadvantages
- exploring use of Indium
  - measurements indicate better thermal noise performance; roughly 10^{-7} for Indium, factors 3-10 greater loss for epoxy

- Suspension installation fixture in initial setup and test

Seismic Isolation

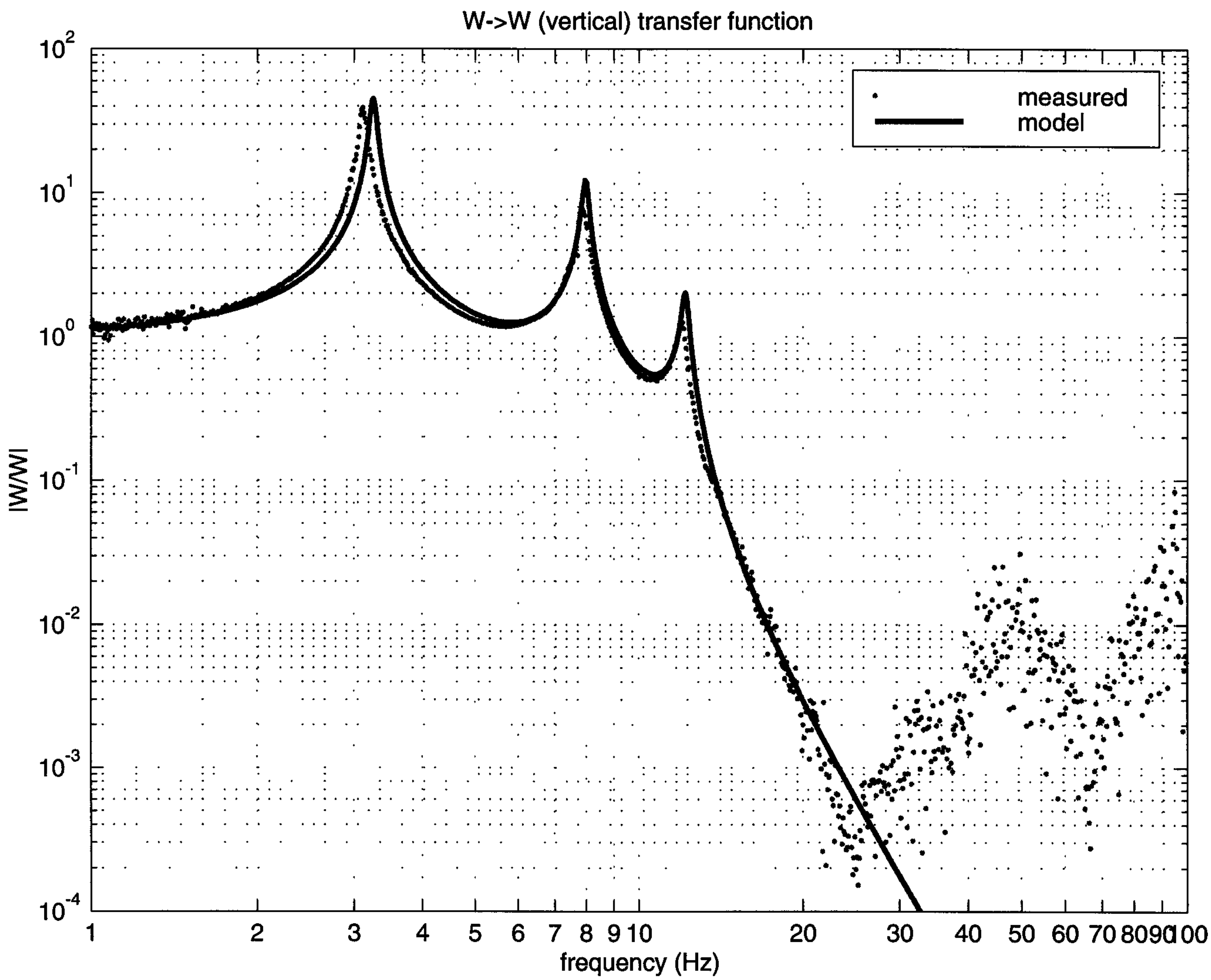
- provide attenuation of seismic noise in-band (>30 Hz); provide actuation at microseismic peak (0.16 Hz); provide coarse positioning, drift compensation
- Final Design Reviews complete
- First article fit-check tests of both basic designs complete
  - HAM (Horizontal Access Module - input optics)
  - BSC (Basic Symmetric Chamber - test masses)
- some remaining issues/tests
  - air-bearing (used as part of positioning)
  - fine actuator and coarse actuator linkage
- fabrication underway for most parts
  - complicated parts, complicated cleaning procedures
  - installation rate will be limited by production rate



Seismic Isolation

First article tests of great value

- in addition to fit checks, fixturing; screw thread clearance; need for left handed springs...
- training for installation and tests of integration approach



- dynamic tests --- comparison with models very good

Research and Development

R&D in support of the initial detector

- largely complete
- efforts to provide 'agile support' for problems discovered in fabrication or field, for example
  - tests of Indium bonding to test masses
  - prototyping of digital controls
- 40m interferometer and Phase Noise interferometer work

Advanced R&D for future improvements to LIGO detectors

- medium- and long-term research programs
- range from engineering obvious solutions to exploring inklings

40m Interferometer

Objectives:

- experience with LIGO configuration on a suspended interferometer
- tests of data acquisition soft/hardware and diagnostics approaches

Difficulties

- continued poor reliability of Argon laser
- recent loss of scientist leading effort
- re-focus on near term goals

Successes in automated alignment, using digital techniques

- alignment control a pre-requisite for operation
- digital loop used to ease matrix transformation

Exercise of the dynamic model for locking

- light storage time comparable to LIGO (high finesse cavities)
- allows comparisons with locking design code

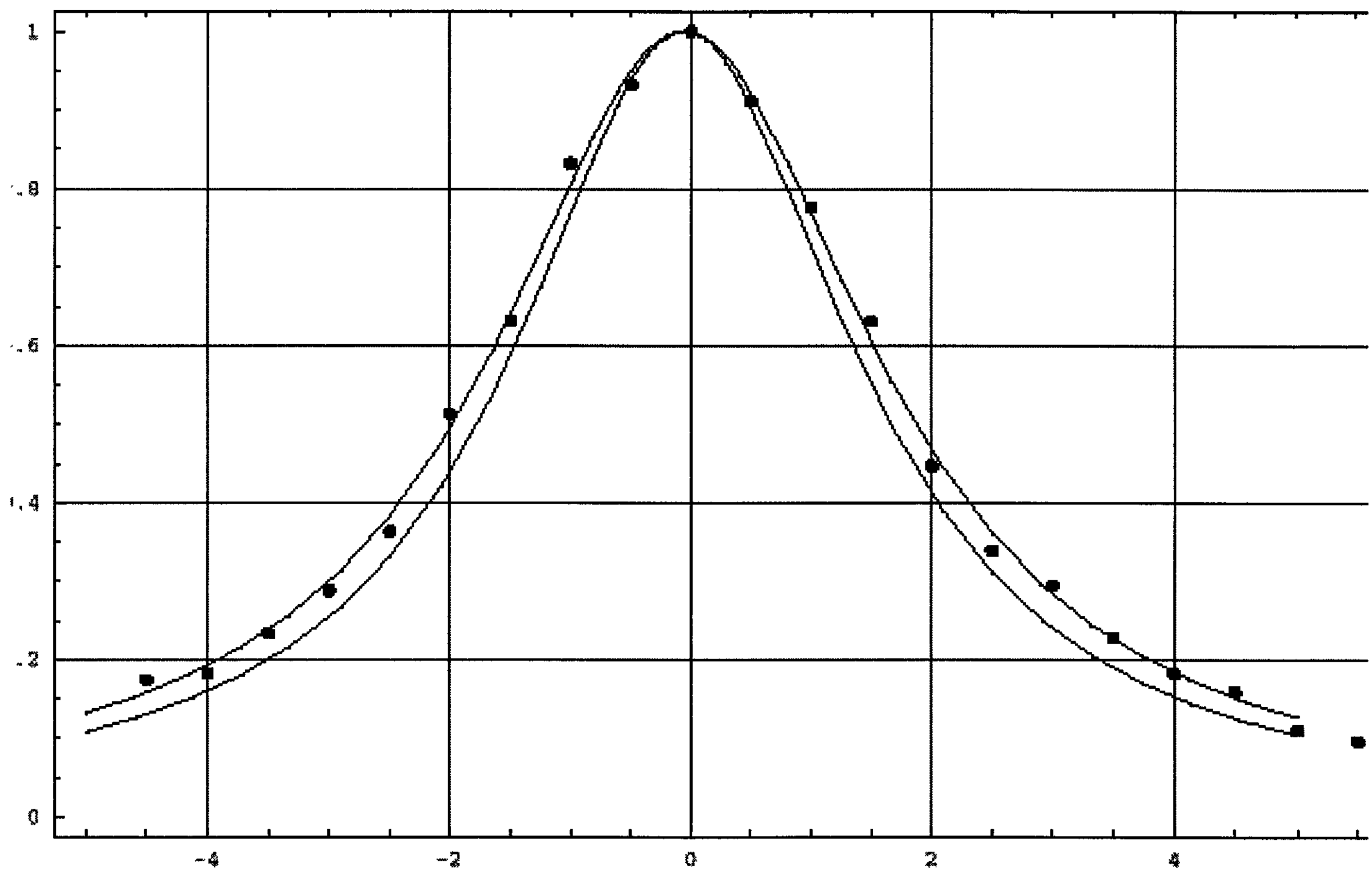
Development of diagnostic techniques on LDAS/DAQ prototype

- full LIGO data acquisition system
- real-time techniques as well as viewing/post-analysis tests created

40m Interferometer

Development of probes of optical performance

- new ways to examine the mode structure of the cavities
- sweeping of modulation frequency, transmission/reflection analyzed



- excellent match of data and model for resonance form
- indication of lack of competing nearby modes to pull error signal

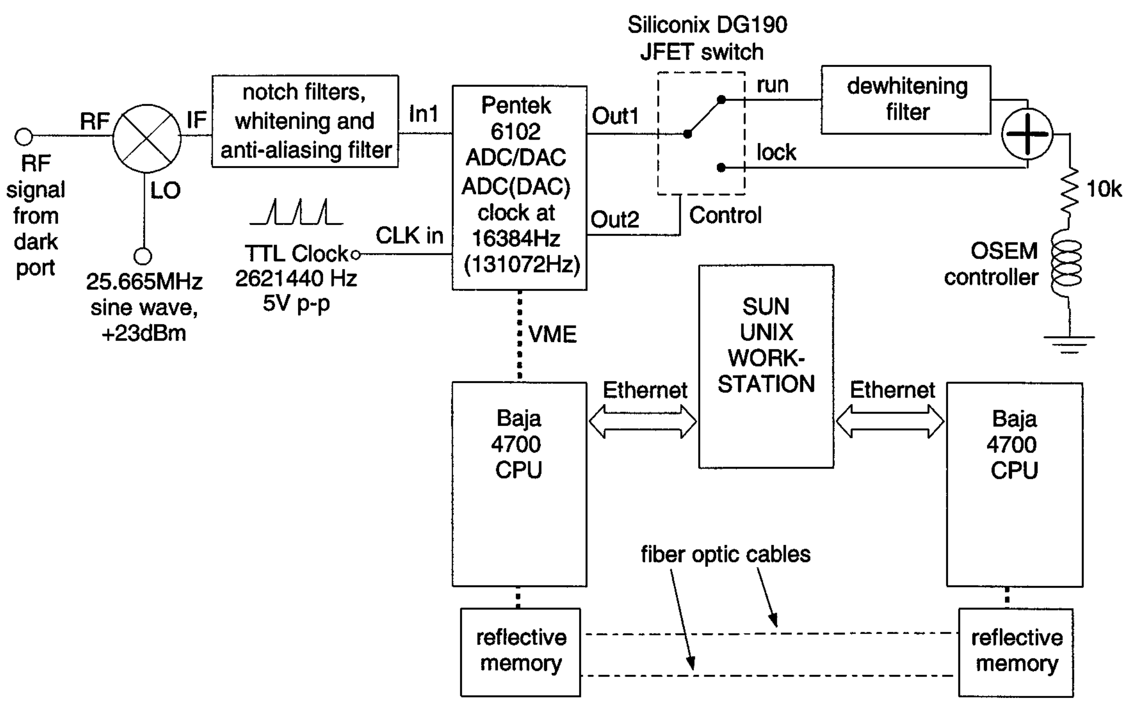
Phase Noise Interferometer

Objectives:

- phase noise demonstration: successfully completed
- tests of digital servoloop technology, real time diagnostics
- tests of photodetection system

Configuration

- power-recycled Michelson
- very similar dynamic range, intensity demands to those in LIGO
- digital filter function/gain replaces analog system
- second crate linked via reflective memory



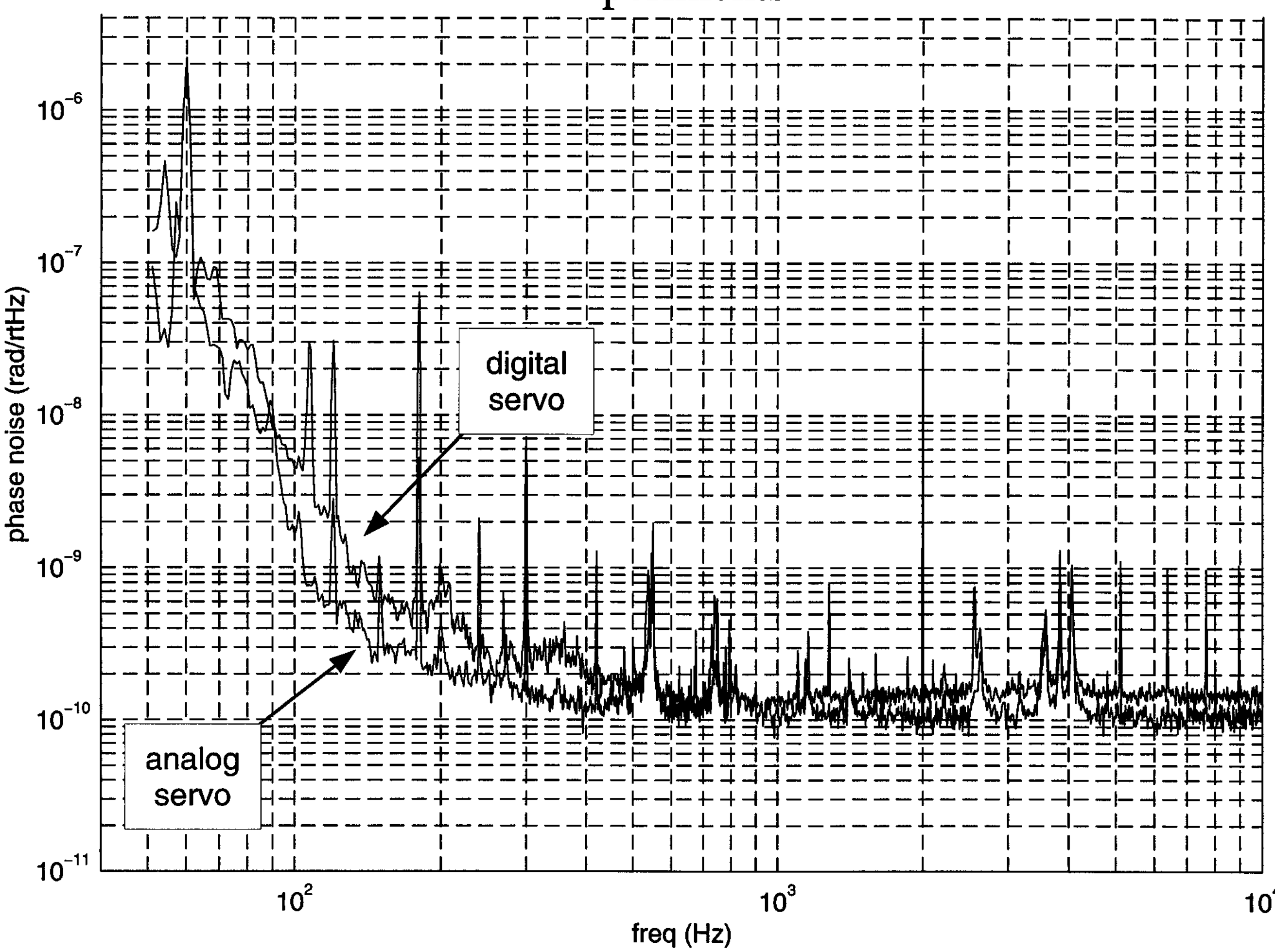
Phase Noise Interferometer

Servoloop tests

- similar loop gains, noise performance to (excellent) analog system
- resonant gains, adiabatic transfer function changes, state switching for acquisition tested successfully

Status

- demonstration complete, lessons learned passed on to design team
- system dismantled with MIT move in July
- chambers now used in other experiments



Advanced R&D

INTERFEROMETER CONFIGURATIONS

- Objective: explore means to tune the frequency response of advanced detectors to match instrument or astrophysical signatures
  - › demonstrate Resonant Sideband Extraction on a tabletop Technique: addition of output recycling mirror to make gravitational wave sidebands resonant or anti-resonant
- Experiment: table-top prototype experiment using a control scheme which could be employed in LIGO
- James Mason, CIT graduate student, leading experiment

Status:

- modeling complete; start of construction of system in June
- lab set up, mirror mounts/actuators built, electronics controls designed, built, and tested
- 3-mirror cavities locked, more components being added
- anticipated February '00 completion with planned outcome a recommended design for LIGO

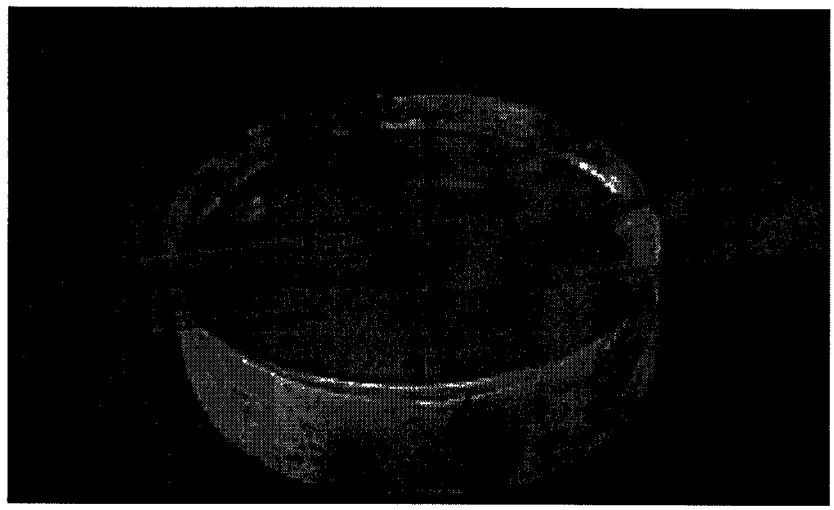
Advanced R&D

SAPPHIRE TEST MASS DEVELOPMENT

- Objective: to push technology of sapphire as optical and mechanical element for advanced LIGO designs
- Technique: international collaboration (VIRGO, ACIGA) to push fabrication techniques, characterize materials

Status:

- Materials procured from Crystal Systems, and China Institute of Optics (SIOM)



- Characterization of optical absorption losses in ACIGA, Stanford, VIRGO; range of values, but generally higher than anticipated (100 ppm/cm), feedback given to producers on some suspects
- General Optics polished a15cm dia surface; difficulties in obtaining a reasonable figure due to bulk fault(s), will try again with new sample
- Mechanical Q testing performed at Caltech
  - *Qs* greater than 1×10^7 seen, but many lower
  - iterating suspension technique, excitation system

Advanced R&D

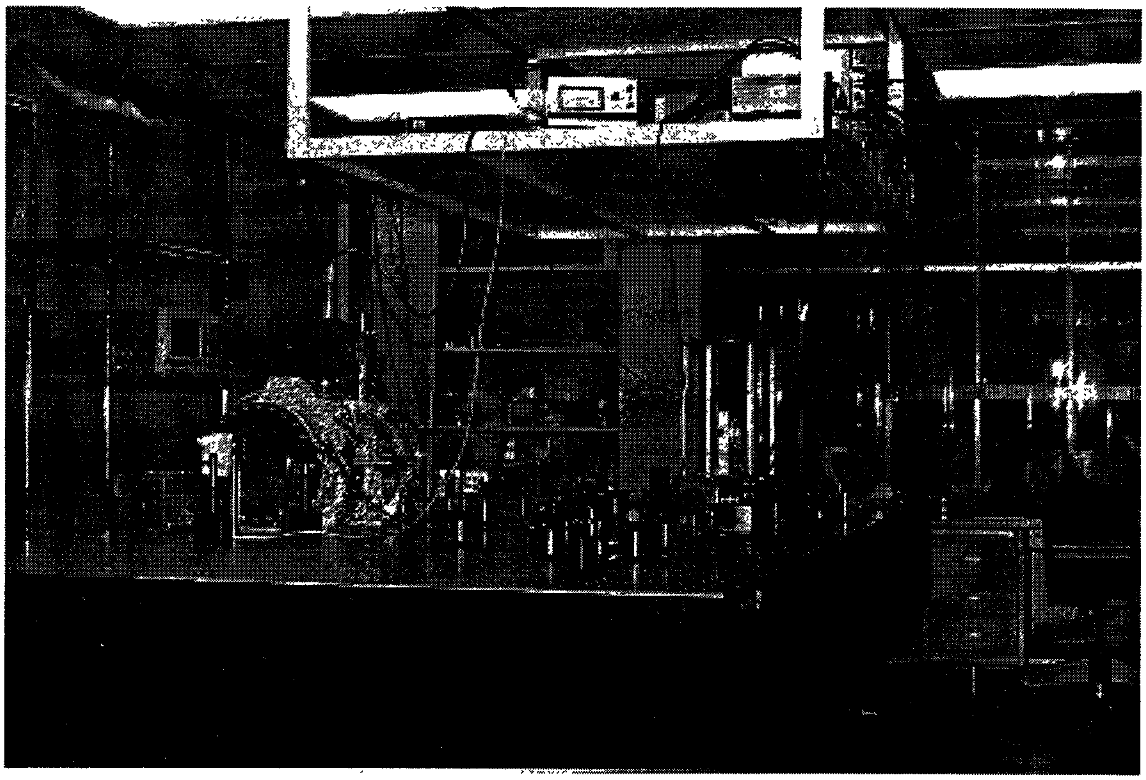
THERMAL NOISE INTERFEROMETER

- Objective: direct measurement of thermal and excesses in realistic suspension systems
- Technique: short-baseline special-purpose interferometer
  - › makes seismic noise 'common-mode'
  - › relaxes laser frequency-noise requirements
- first measurements on LIGO-I like suspensions
  - › allows learning curve with familiar wire loop
  - › can help debug LIGO-I problems
- later work with advanced LIGO components (fused quartz suspensions)

Advanced R&D

THERMAL NOISE INTERFEROMETER Status

- the pre-stabilized laser has been assembled and tested with a second reference cavity, and functions well



- vacuum chamber and stack (from the Phase Noise Interferometer) are in assembly;
- taken delivery of all the significant optics
- optics suspensions and controls in design/construction
- plan to collect first complete data by December '98

Advanced R&D

SUSPENSIONS

- Objective: reduced thermal noise and better isolation for near-term LIGO enhancements
- Technique: incorporation of a fused-quartz suspension, re-allocation of actuator authority
- Experiment: tests of prototypes; ultimately full-scale engineering tests
- Status: infrastructure coming together; design work underway
- Full-scale Advanced System Test Interferometer installation November 2

First tests in smaller vacuum system:

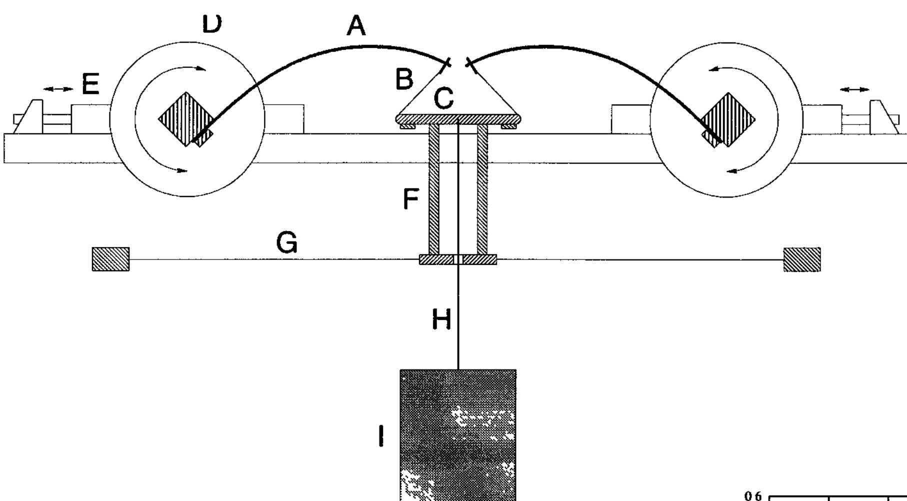
- tests of GEO suspension
- charge control
- tests of sample pre-isolator
- December start of shakedown/tests

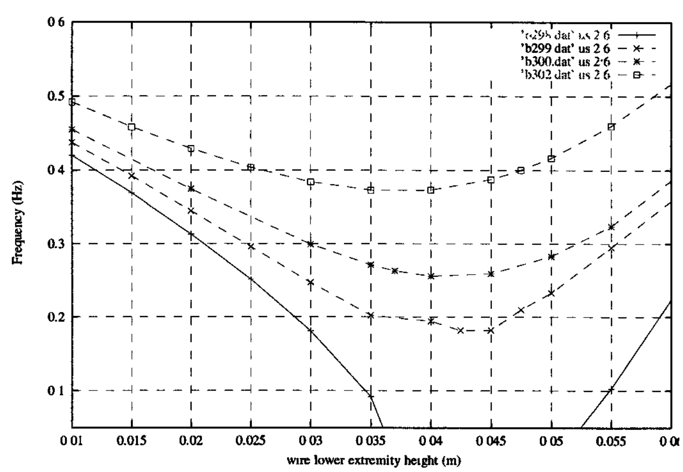
First results by March '99

Advanced R&D

ISOLATION

- Objective: exploration of techniques for advanced seismic isolation
- Technique: redesign and test of VIRGO-like isolation systems
- Experiment: tests of vertical isolation system
- Status: prototype designed, assembled, in first test
  - > low vertical resonant frequencies achieved
  - > sensitive parameters explored





Advanced R&D

FUSED QUARTZ SUSPENSION FIBER DEVELOPMENT

- Plan to develop means to produce reliable reproducible fibers
- 'lathe' on order, lab being set up, modeling underway

ADAPTIVE OPTICS

- Plan to develop correction for thermal lensing in test mass substrates, due to absorption of laser beam in substrate and on surface
- experiment in construction (in Phase Noise Interferometer vacuum tank), MIT Grad (Ryan Lawrence) leading effort
- first results in March '99

Detector: Summary

Design very nearly complete

Prototyping and first article testing very nearly complete

Fabrication started for most subsystems

Detector effort still (essentially) on schedule and no significant problems

The challenge, and excitement, is becoming the installation

Detector Installation

Dennis Coyne

27 Oct 98

- Progress Overview
- Organization
- Plan
- Schedule
- Subsystem Installation or Readiness Status

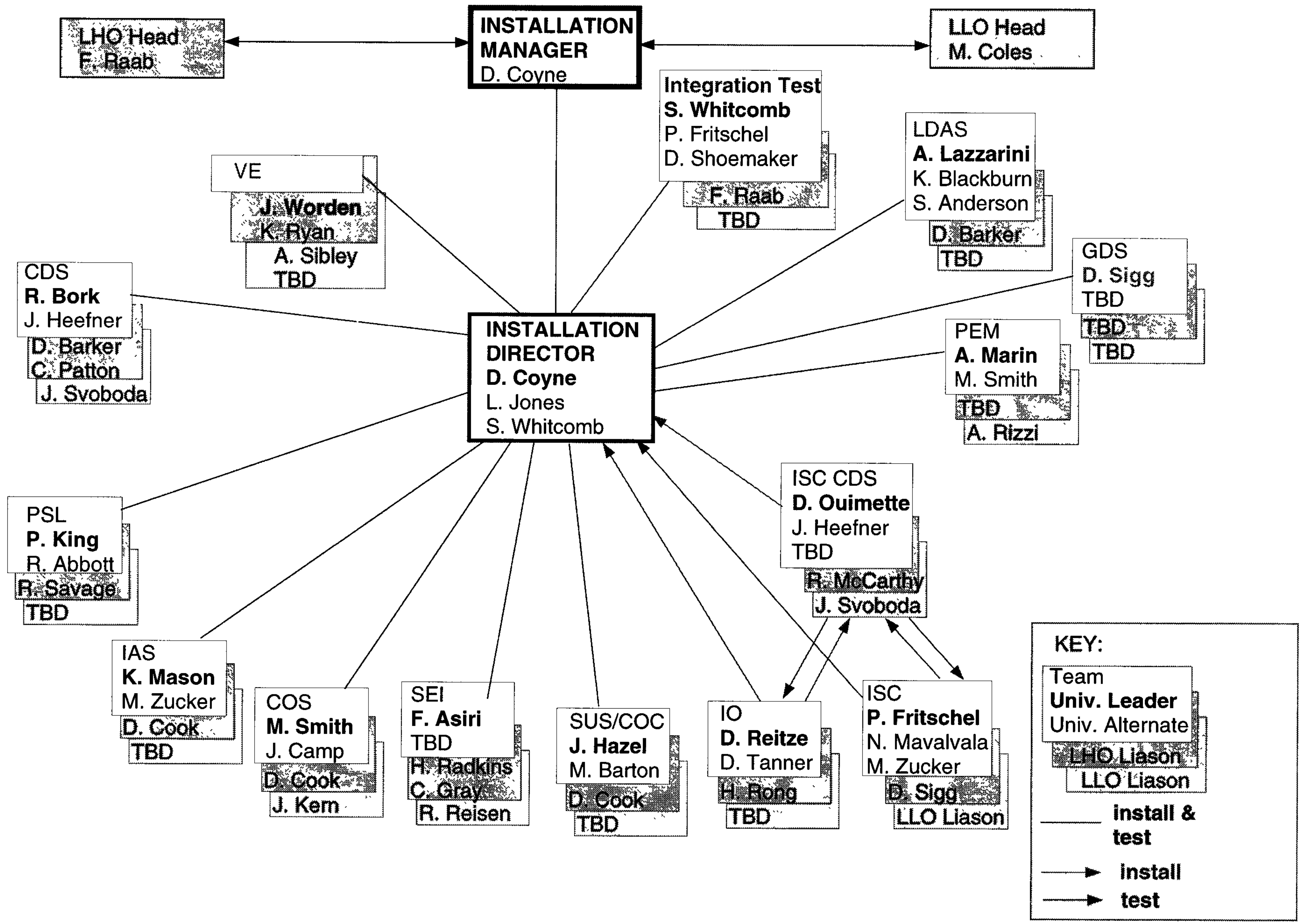
Installation Progress Overview

- Detector System PDR and Installation Readiness Review (9/98)
- Initiated Installation @ LHO!
  - ››Pre-Stabilized Laser (PSL)
  - ››Input Optics (IO)
  - ››Seismic Isolation System (SEI)
  - ››Physics Environment Monitoring (PEM)
  - ››Data Acquisition System (DAQS)
  - ››Control & Monitoring (CM) System
  - ››Cable Trays
- PSL Installation is Progressing Well!
  - ››Locked to pre-mode cleaner
  - ››Control Room Display is Functional
- Installing In-Vacuum Components!
  - ››WHAM7 SEI Bellows & All Diagonal Section Electrical Feedthrus are Leak Tight
- All HAM Piers are Installed!
  - ››Completed Virtually all Drilling for Embedded Bolts @ LHO

Installation Organization & Staffing

- EXECUTION:
  Day-to-Day On-Site Staff Direction & Tracking is the Designated Installation Director's Responsibility
- PLANNING/COORDINATION:
  Work-Around Planning & Technical/Scientific Support Staff Coordination is the Integration Manager's Responsibility
- Detector Design Staff Migrates to Support the Installation Effort
- Subsystem Teams (with Observatory members) Execute the Installation

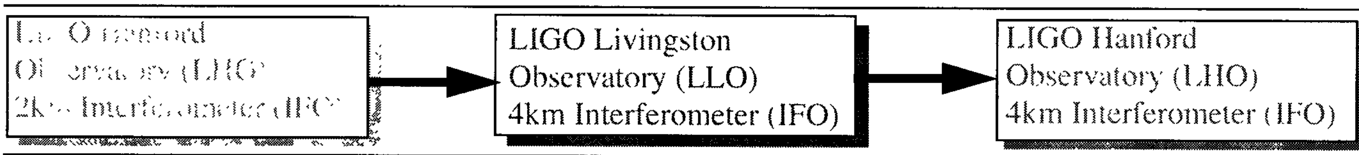
Installation Organization



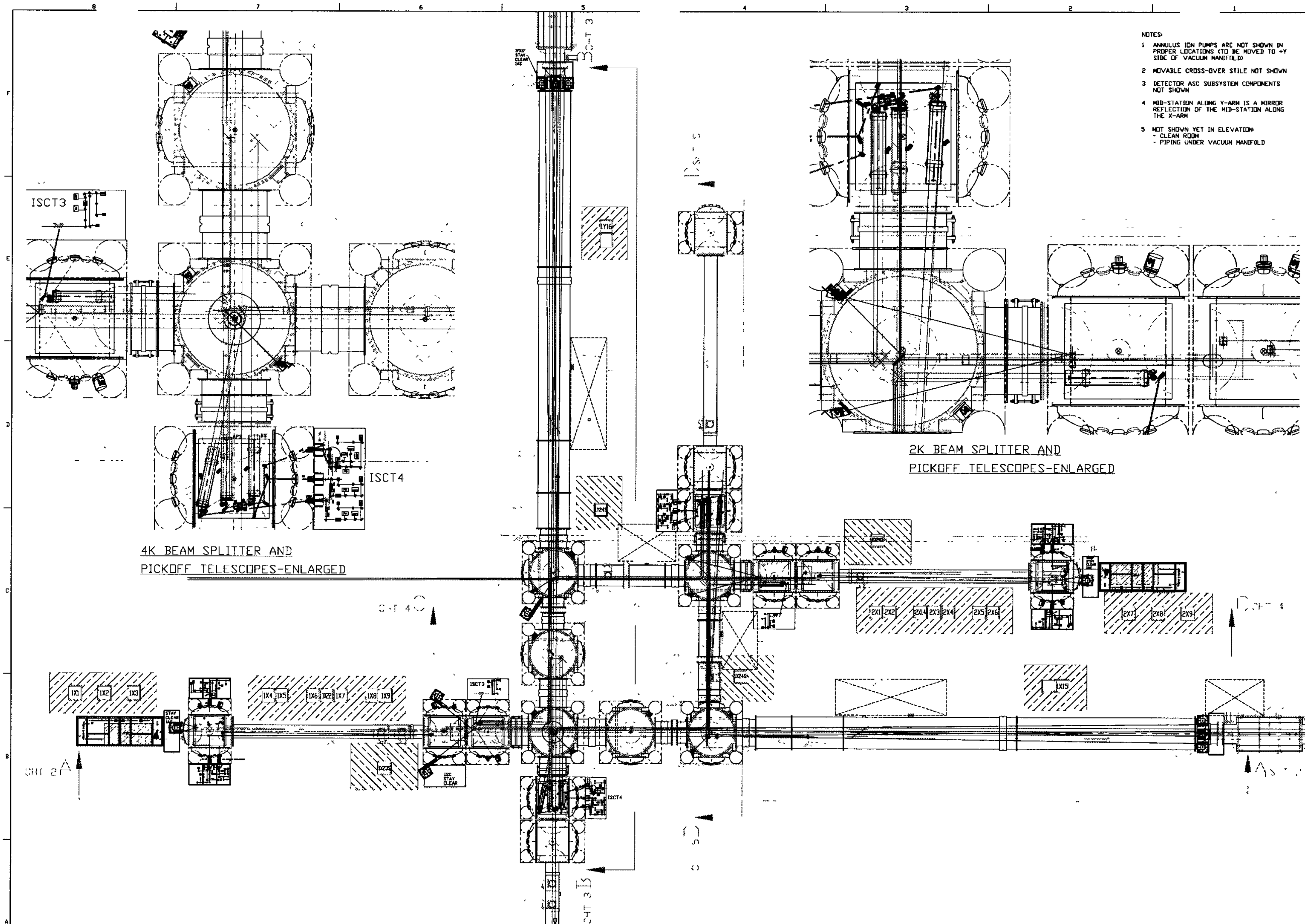
LIGO-G980119-00-D

Detector Installation Plan Overview

- Interferometer Sequence:



  - — 2km IFO is First Since It's Easier to Align & Can be Debugged in Parallel with 4km IFO Installation
  - — LLO 4km IFO is Second Since Facility and Staff are Available
  - — 2nd and 3rd IFOs benefit from Debug/Commissioning on the Earlier IFOs
- Initiate Interferometer Installation 07/98
- First Coincidence Run ($h < 10^{-20}$) 12/00
- Design Sensitivity ($h < 10^{-21}$) 11/01
- Need ~12 months for Debug & Commissioning of Interferometers (Operations Proposal)



NOTES:

1. ANNULUS ION PUMPS ARE NOT SHOWN IN PROPER LOCATIONS (TO BE MOVED TO +Y SIDE OF VACUUM MANIFOLD)
2. MOVABLE CROSS-OVER STILE NOT SHOWN
3. DETECTOR ASC SUBSYSTEM COMPONENTS NOT SHOWN
4. MID-STATION ALONG Y-ARM IS A MIRROR REFLECTION OF THE MID-STATION ALONG THE X-ARM
5. NOT SHOWN YET IN ELEVATION:
   - CLEAN ROOM
   - PIPING UNDER VACUUM MANIFOLD

REV	DESCRIPTION	DCN NUMBER	-	DRWN	DATE
A	RELEASE	E980260	-	KABOT	9/29/98
01	PRE-RELEASE	-	-	KABOT	3/6/98
00	PRE-RELEASE	-	-	KABOT	6/20/97

ISSUE DESCRIPTION

DO NOT SCALE THIS DRAWING

USED ON:

NEXT ASS'Y:

DWG. NO.	DESCRIPTION	DWG. NO.	DESCRIPTION

REFERENCE DRAWINGS

LIGO CALIFORNIA INSTITUTE OF TECHNOLOGY / MASSACHUSETTS INSTITUTE OF TECHNOLOGY

INTERFEROMETER OPTOMECHANICAL LAYOUT
HANFORD SITE
LASER VACUUM EQUIPMENT AREA (LVEA)
PLAN VIEW

CAD FILE: D970308-A | SIZE: E | DWG. NO.: D970308-A

SCALE: NTS | SHEET 1 OF 5

Installation Plan: Subsystem Prerequisites

- Configuration Controlled Drawings
- Assembly Procedure(s)
- Data Package
- Installation Procedure(s)
- Subsystem Component/AssemblyTraveler(s)
- Test Plan

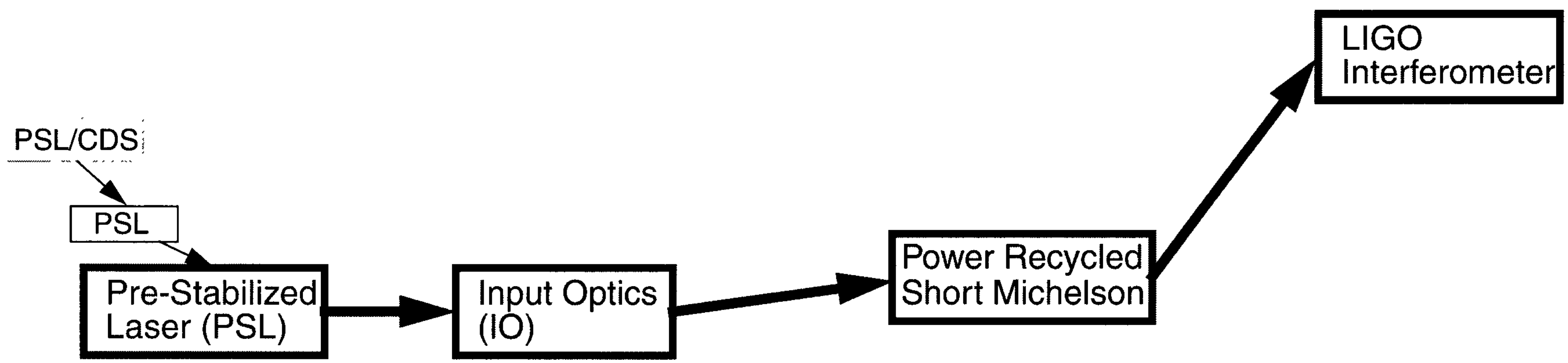
Installation Plan: Documentation

- Installation Logbook
  - ››Record of the system configuration as it is assembled
  - ››Maintained by the Installation Director
  - ››One logbook per Observatory
  - ››Completed installation procedures are incorporated
  - ››Record of daily activities
  - ››Record of all installed components/assemblies by Dwg # and Revision
  - ››Record all waivers
- As-Built Engineering Change Logbook
  - ››Capture as-built deviations, discrepancies (responsibility of the subsystem team leader)
  - ››Reviewed periodically by the Installation Manager for disposition (Technical Review Board, Material Review Board or Document Change Notice)

Installation Plan: Documentation (continued)

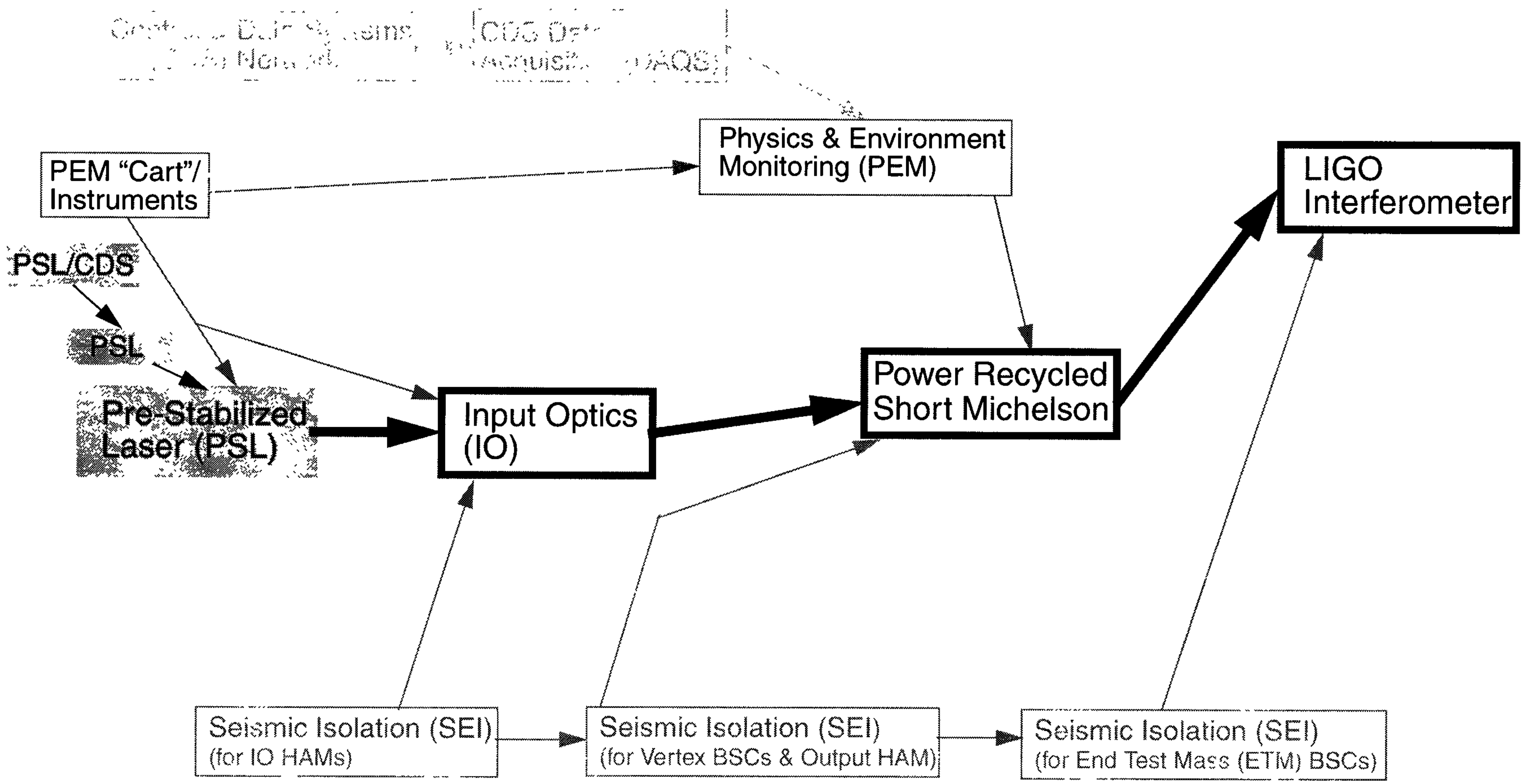
- Test Results
  - ›› responsibility of the test director/conductor(s)
  - ›› logbook or report
  - ›› presentation
- Schedule
  - ›› maintained at two levels by the Installation Director with input from the subsystem team leaders:
    - – overall per interferometer, and
    - – via task lists for current and near-term activities (~2-4 week span sliding window)
- Work Orders
  - ›› Maintained/managed by the Observatory Head (or designee)
  - ›› Process for obtaining permits by the observatory for work which has a safety impact/concern or could interfere with or limit other activities at the site

Detector Installation Sequence
Core Thread

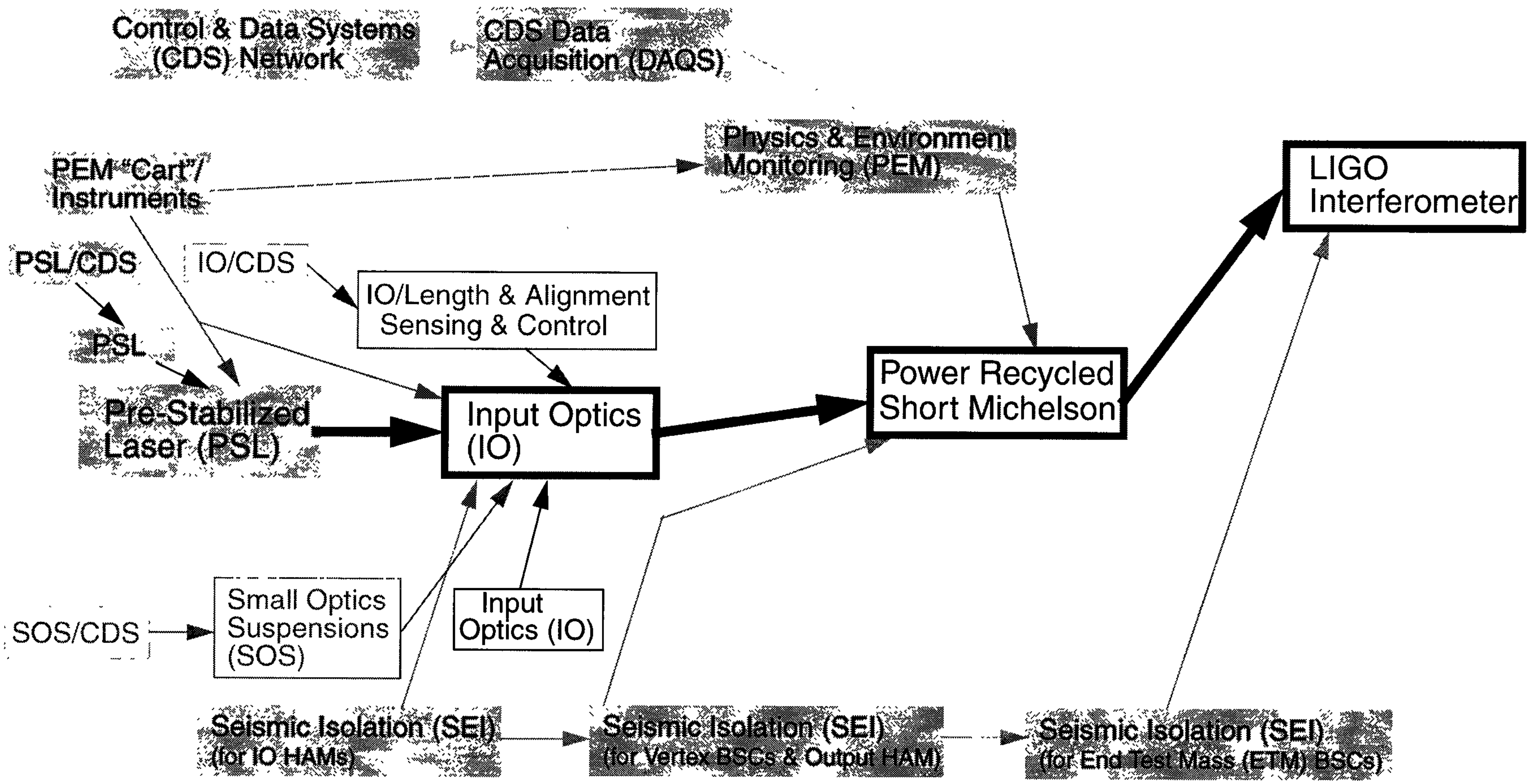


Detector Installation Sequence

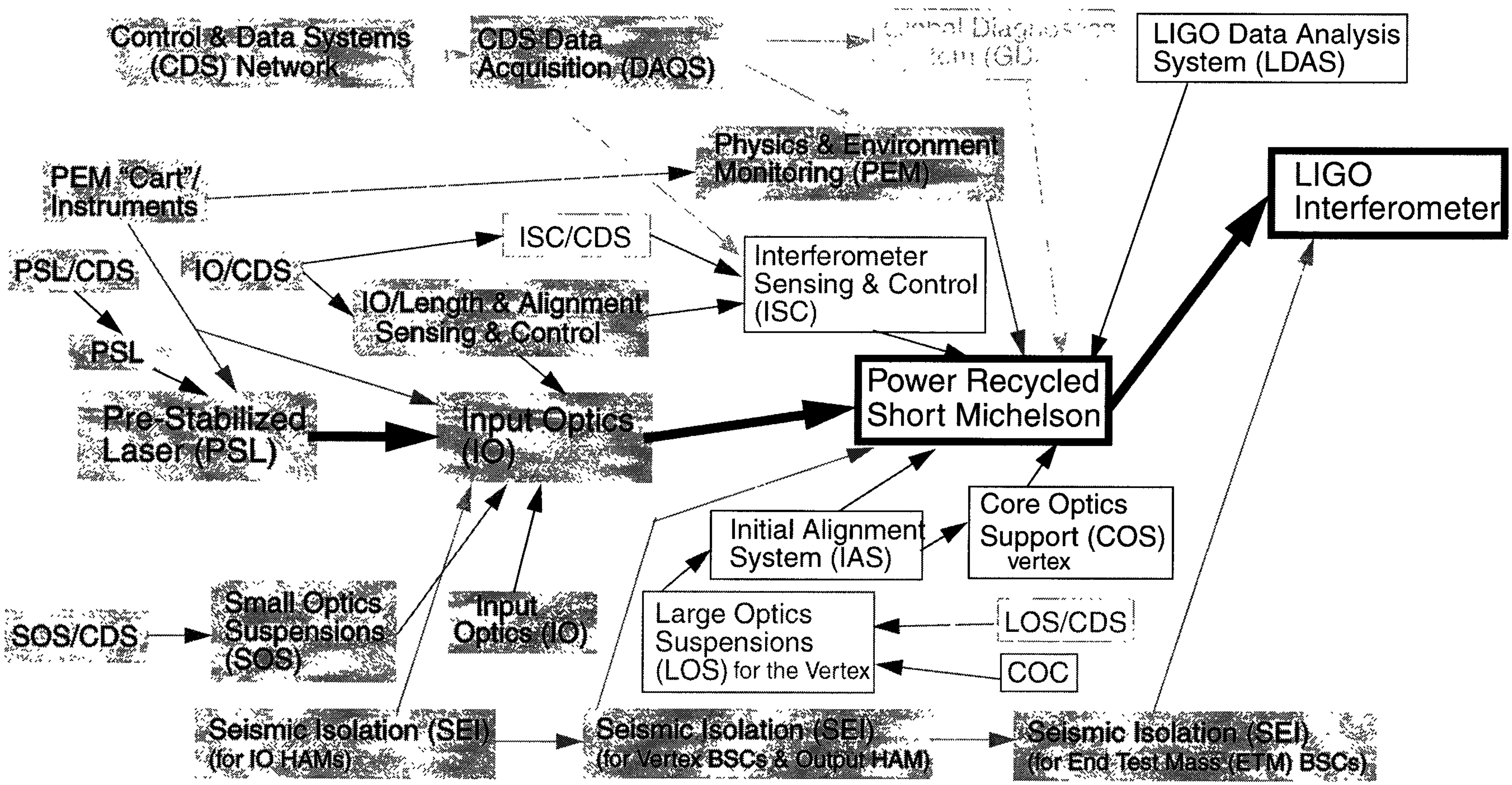
Infrastructure Threads



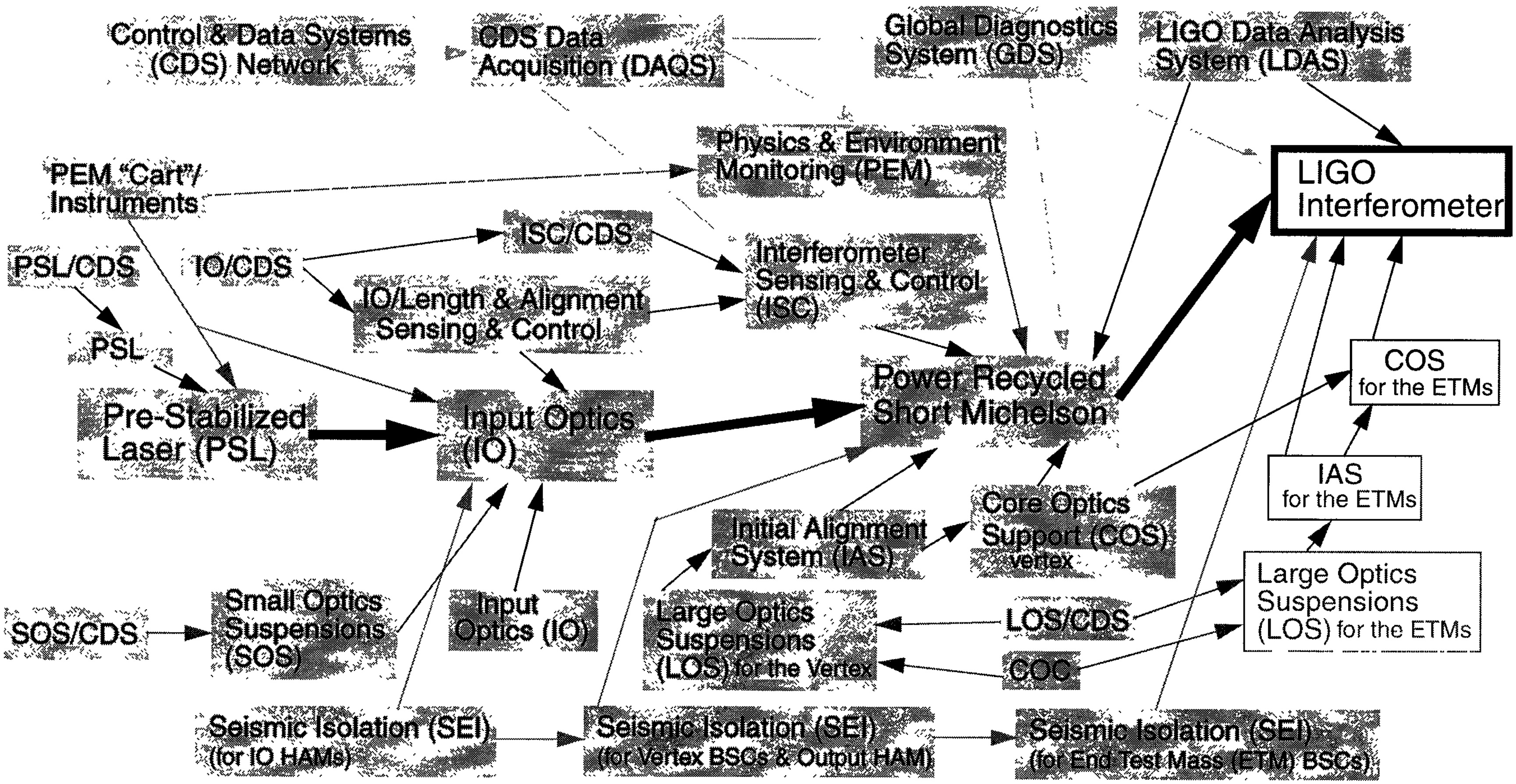
Detector Installation Sequence
Input Optics Threads



Detector Installation Sequence
Short Michelson Threads

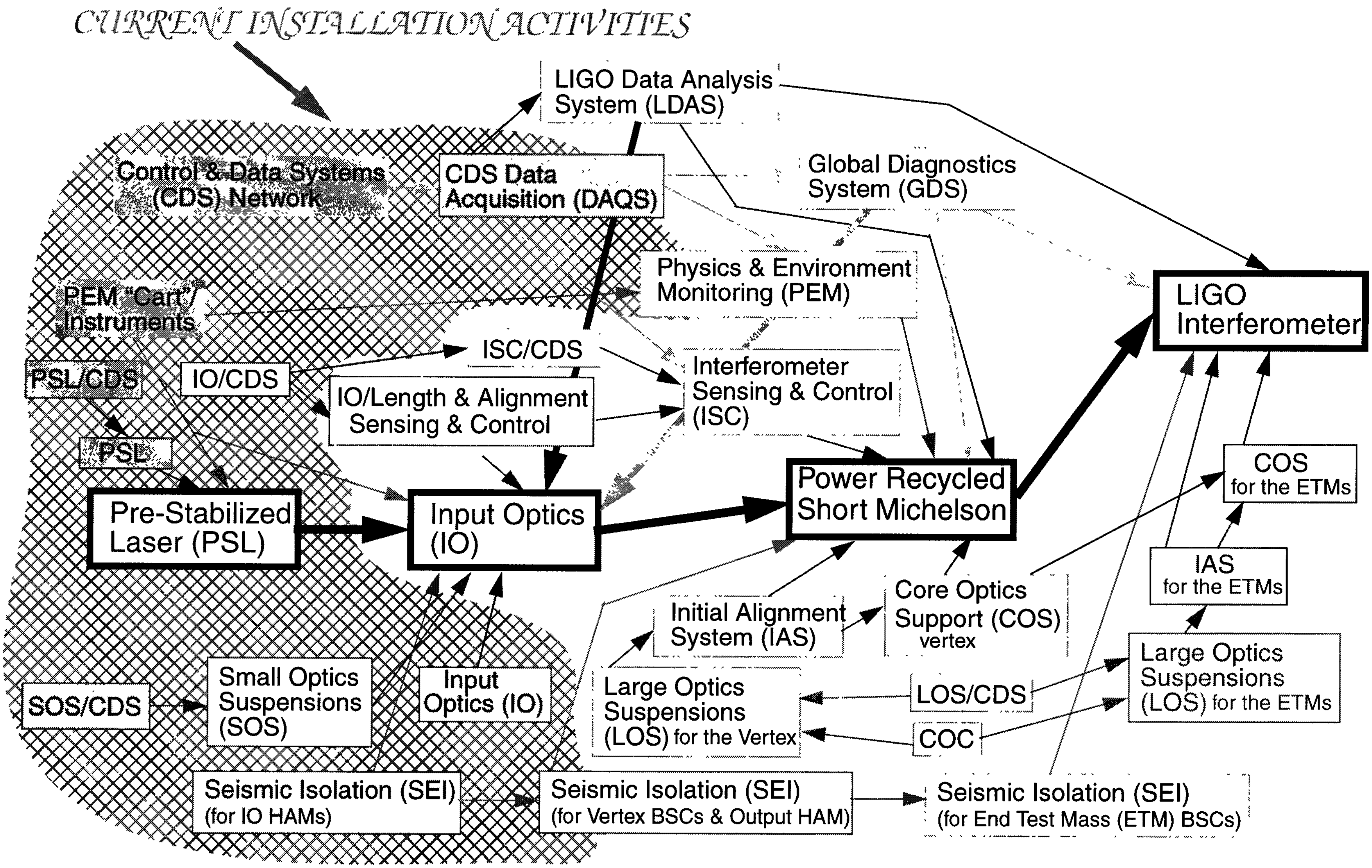


Detector Installation Plan
Sequence Threads



LIGO-G980119-00-D

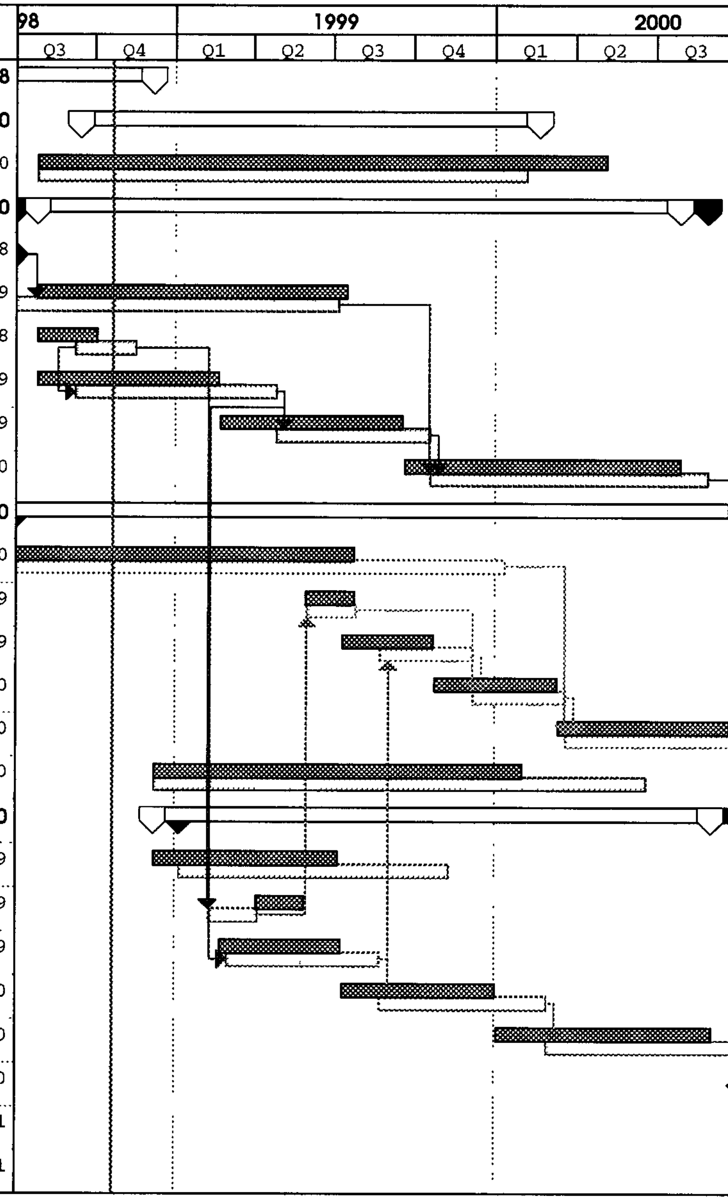
Detector Installation Status



10/21/98

LIGO DETECTOR INSTALLATION -- TOP LEVEL

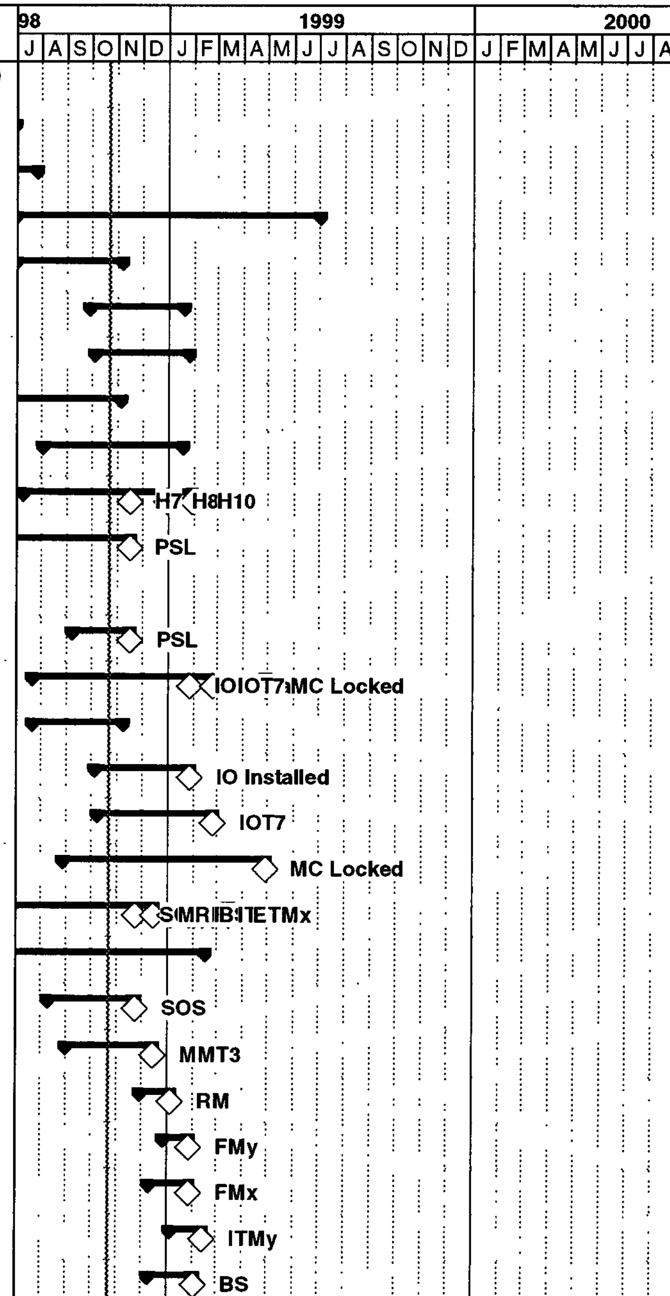
ID	Task Name	Duration	Start	Finish
1	**VE Completion**	**194 days**	**3/11/98**	**12/8/98**
11	**BT Bake Out**	**374 days**	**9/15/98**	**2/21/00**
21	**LHO Detector Infrastructure**	80 wks	7/27/98	2/4/00
22	**LHO 2km IFO**	**564 days**	**7/1/98**	**8/28/00**
23	Start Detector Integration	0 days	7/1/98	7/1/98
24	Install SEI, SUS, COS, ISC	53 wks	7/1/98	7/6/99
25	PSL	10 wks	9/8/98	11/16/98
26	Input Optics	33 wks	9/8/98	4/26/99
27	PR Near Michelson	25 wks	4/27/99	10/18/99
28	PR Michelson w/ FP Arms	45 wks	10/19/99	8/28/00
29	**LHO 4km IFO**	**599 days**	**7/1/98**	**10/16/00**
30	Install SEI, SUS, COS, ISC	80 wks	7/1/98	1/11/00
31	PSL	8 wks	6/1/99	7/26/99
32	Input Optics	15 wks	8/24/99	12/6/99
33	PR Near Michelson	15 wks	12/7/99	3/20/00
34	PR Michelson w/ FP Arms	30 wks	3/21/00	10/16/00
35	**LLO Detector Infrastructure**	80 wks	12/8/98	6/19/00
36	**LLO 4km IFO**	**489 days**	**1/6/99**	**11/20/00**
37	Install SEI, SUS, COS, ISC	44 wks	1/6/99	11/9/99
38	PSL	8 wks	2/9/99	4/5/99
39	Input Optics	25 wks	3/2/99	8/23/99
40	PR Near Michelson	27 wks	8/24/99	2/28/00
41	PR Michelson w/ FP Arms	38 wks	2/29/00	11/20/00
42	**Detector Commissioned (h<10^-20)**	0 days	11/20/00	11/20/00
43	Observatory Operations & improvemer	50 wks	11/21/00	11/5/01
44	**Design Sensitivity (h<10^-21)**	0 days	11/5/01	11/5/01



LIGO Hanford Observatory (LHO) 2km IFO Detector Installation Schedule

10/21/98

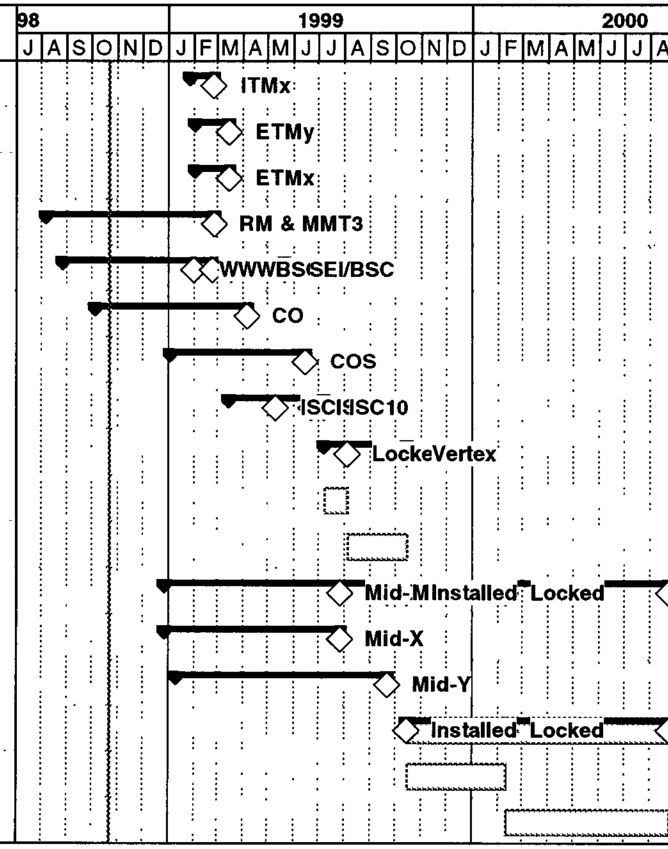
ID	Task Name	Duration	Start	Finish
1	1 2km PR Near-Michelson	575.9 days	7/1/97	10/14/99
2	1.1 Setup Labs	22 days	6/1/98	7/1/98
7	1.2 Accept Vacuum Equipment	96 days	3/11/98	7/27/98
16	1.5 PEM System Installation	252 days	7/1/98	7/1/99
34	1.6 Install SEI Phase 1	91 days	7/1/98	11/6/98
55	1.7 Cable Tray Installation	75 days	9/29/98	1/20/99
61	1.8 In-Vacuum Cable Assembly	75 days	10/5/98	1/26/99
68	1.9 Cleaning	341 days	7/1/97	11/5/98
75	1.10 Viewport & Feedthru Installation	113 days	8/3/98	1/18/99
84	1.11 SEI/HAM Phase 2&3 Installation	137.9 days	7/10/98	1/29/99
129	1.12 PSL INSTALLATION	153 days	4/13/98	11/16/98
130	1.12.1 Setup	16 days	4/13/98	5/4/98
135	1.12.2 PSL Installation	50 days	9/8/98	11/16/98
144	1.13 IO Installation & MC Lock	192.95 days	7/22/98	4/28/99
145	1.13.1 IO Deliveries	77 days	7/22/98	11/9/98
152	1.13.2 Install Input Optics (IO)	74.95 days	10/6/98	1/27/99
163	1.13.3 IO ISC Table Installation (IOT7)	91.95 days	10/9/98	2/24/99
168	1.13.4 Input OpticsCommissioning	165.95 days	8/28/98	4/28/99
180	1.14 SUS Assembly	229 days	4/15/98	3/15/99
181	1.14.1 SUS/COC Deliveries	209 days	4/15/98	2/16/99
204	1.14.2 SUSPEND Small Optics	75 days	8/10/98	11/23/98
210	1.14.3 SUSPEND MMT3	72 days	9/1/98	12/14/98
216	1.14.4 SUSPEND Recycling Mirror (RM)	21 days	11/30/98	1/4/99
221	1.14.5 SUSPEND Fold Mirror Y (FM-Y)	21 days	12/28/98	1/27/99
226	1.14.6 SUSPEND Fold Mirror X (FM-X)	29 days	12/11/98	1/27/99
231	1.14.7 SUSPEND Inner Test Mass-Y (ITM-Y)	29 days	1/5/99	2/12/99
236	1.14.8 SUSPEND Beam Splitter (BS)	34 days	12/10/98	2/2/99



LIGO Hanford Observatory (LHO) 2km IFO Detector Installation Schedule

10/21/98

ID		Task Name	Duration	Start	Finish
241		***1.14.9 SUSPEND Inner Test Mass X (ITM-X)***	***20 days***	***1/28/99***	***2/24/99***
246		***1.14.10 SUSPEND End Test Mass Y (ETM-Y)***	***29 days***	***2/3/99***	***3/15/99***
251		***1.14.11 SUSPEND End Test Mass X-Arm (ETM-X)***	***29 days***	***2/3/99***	***3/15/99***
257		***1.15 Install RM & MMT3***	***137.25 day***	***8/7/98***	***2/26/99***
290		***1.16 SEI/BSC Phase 2&3 Installation***	***183.2 days***	***8/27/98***	***5/21/99***
359		***1.17 Install & Align CO***	***123.9 days***	***10/6/98***	***4/6/99***
420		***1.18 INSTALL COS***	***115.9 days***	***1/4/99***	***6/15/99***
485		***1.19 ISC Installation***	***80.9 days***	***3/15/99***	***7/7/99***
508		***1.20 Vertex Michelson Shakedown***	***70 days***	***7/7/99***	***10/14/99***
510		1.20.2 Align/Lock Vertex Michelson	4 wks	7/7/99	8/4/99
512		1.20.4 Characterize Vertex Michelson	10 wks	8/4/99	10/14/99
516		***2 LIGO 2k PRM with F-P Arms***	***423.9 days***	***12/28/98***	***8/24/00***
517		***2.1 Install Detector in X-Arm Mid-Station***	***147.2 days***	***12/28/98***	***7/27/99***
554		***2.2 Install Detector in Y-Arm Mid-Station***	***178.2 days***	***1/11/99***	***9/21/99***
589		***2.3 Shakedown 2k PRM w/ F-P Arms***	***220 days***	***10/14/99***	***8/24/00***
591		2 3.2 Align/Lock 2k IFO	16 wks	10/14/99	2/10/00
593		2.3.4 Characterize 2k IFO	28 wks	2/10/00	8/24/00

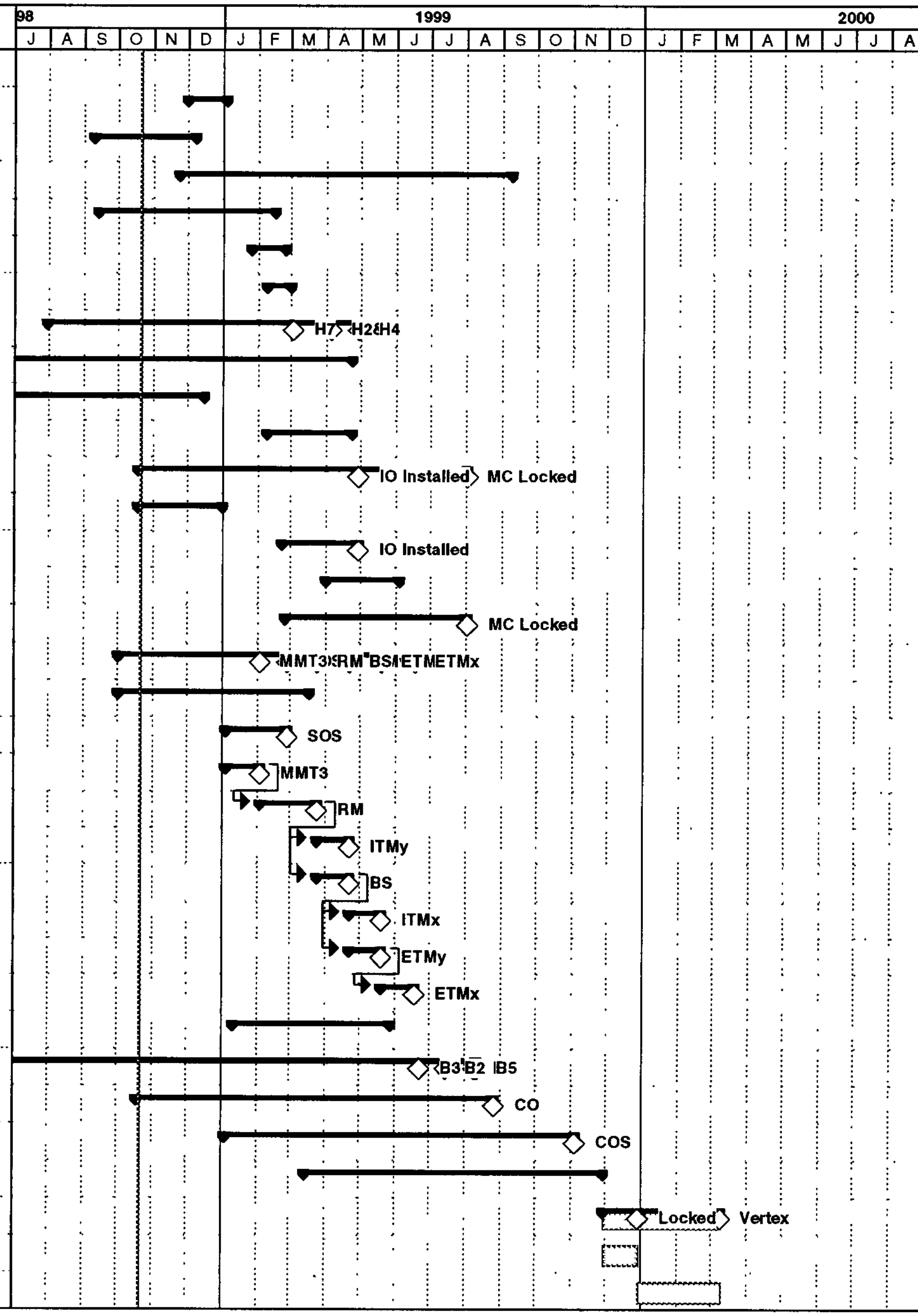


LLO_4dc.MPP non-milestone tasks

LIGO Livingston Observatory (LLO) Detector Installation Schedule

10/21/98

ID	Task Name	Duration	Start	Finish
1	1 LA 4km PR Near-Michelson	475.4 days	4/20/98	3/9/00
2	1.1 Setup Labs	19 days	12/1/98	1/4/99
7	1.2 Accept Vacuum Equipment	61 days	9/10/98	12/8/98
13	1.5 PEM System Installation	197.6 days	11/24/98	9/9/99
28	1.6 Install SEI Phase 1	104 days	9/14/98	2/15/99
52	1.7 Cable Tray Installation	22 days	1/26/99	2/24/99
60	1.8 Cleaning	15 days	2/9/99	3/1/99
66	1.9 SEI/HAM Phase 2&3 Installation	186.15 days	7/31/98	4/29/99
106	1.10 PSL Installation	255 days	4/20/98	4/23/99
107	1.10.1 PSL Deliveries	167 days	4/20/98	12/16/98
111	1.10.2 PSL Installation	54 days	2/9/99	4/23/99
121	1.11 IO Installation & Mode Cleaner (MC) Lock	196.4 days	10/19/98	8/2/99
122	1.11.1 IO Deliveries	48 days	10/19/98	1/1/99
127	1.11.2 Install Input Optics (IO)	48.4 days	2/22/99	4/29/99
140	1.11.3 IO ISC Table Installation (LIOTH1)	45.4 days	4/1/99	6/4/99
147	1.11.4 Mode Cleaner Commissioning	110.4 days	2/25/99	8/2/99
155	1.12 SUS/COC Assembly	177 days	10/1/98	6/17/99
156	1.12.1 SUS/COC Deliveries	112 days	10/1/98	3/18/99
174	1.12.2 SUSPEND Small Optics	40 days	1/4/99	2/26/99
179	1.12.3 SUSPEND Mode Match Telescope Mirror-	22 days	1/4/99	2/2/99
184	1.12.4 SUSPEND Recycling Mirror (RM)	36 days	2/3/99	3/24/99
189	1.12.5 SUSPEND Inner Test Mass-Y (ITM-Y)	20 days	3/25/99	4/21/99
194	1.12.6 SUSPEND Beam Splitter (BS)	20 days	3/25/99	4/21/99
199	1.12.7 SUSPEND Inner Test Mass X (ITM-X)	20 days	4/22/99	5/19/99
204	1.12.8 SUSPEND End Test Mass Y (ETM-Y)	20 days	4/22/99	5/19/99
209	1.12.9 SUSPEND End Test Mass X-Arm (ETM-X)	20 days	5/20/99	6/17/99
214	1.13 RM & MMT3 Installation	99.7 days	1/11/99	5/28/99
248	1.14 SEI/BSC Phase 2&3 Installation	286.6 days	6/22/98	8/11/99
314	1.15 Install & Align SUS/COC Assemblies	214.4 days	10/19/98	8/26/99
369	1.16 INSTALL COS	215.4 days	1/4/99	11/4/99
434	1.17 ISC Installation	180.4 days	3/15/99	11/29/99
459	1.18 Vertex Michelson Shakedown	70 days	11/29/99	3/9/00
461	1.18.2 Align/Lock Vertex Michelson	4 wks	11/29/99	12/29/99
463	1.18.4 Characterize Vertex Michelson	10 wks	12/29/99	3/9/00

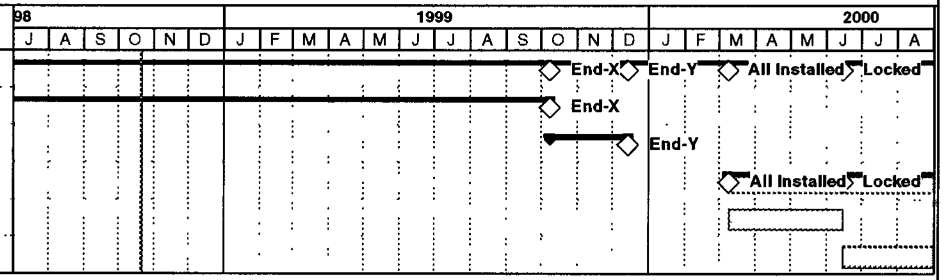


LLO_4dc.MPP non-milestone tasks

LIGO Livingston Observatory (LLO) Detector Installation Schedule

10/21/98

ID		Task Name	Duration	Start	Finish
465		***2 LA 4k PRM with F-P Arms***	***865.4 days***	***7/1/97***	***11/30/00***
466		***2.1 Install Detector in X-Arm End-Station***	***571.6 days***	***7/1/97***	***10/8/99***
502		***2.2 Install Detector in Y-Arm End-Station***	***45 days***	***10/8/99***	***12/14/99***
535		*2.3 Shakedown LA 4k PRM w/ F-P Arms*	*190 days*	*3/9/00*	*11/30/00*
537		2.3.2 Align/Lock LA 4k Michelson	14 wks	3/9/00	6/15/00
539		2.3.4 Characterize LA 4k Michelson	24 wks	6/15/00	11/30/00



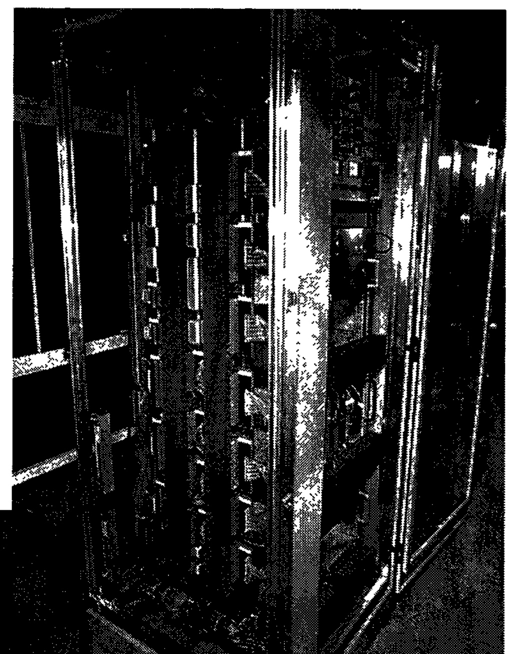
Subsystem Installation Status: Control & Data System (CDS)

- Network fiber installed @ LHO;
  LLO fibre optic bid awarded; installation to occur in Nov 98
- CDS network ATM switching system & Servers are installed and operational at both observatories
- CDS controls for Vacuum Equipment (VE) are operational at both observatories
- Control Room furniture & some CM computers are installed @ LHO
- DAQS Installation @LHO started 10/13/98

  Cabling:
  - All CDS racks located in the LVEA and VEAs early (unstuffed)
  - Cable Tray installation prior to SEI installation; started 10/1 @ LHO
  - Cabling pulled as needed to install subsystems as integration proceeds

Subsystem Installation Status: Pre-Stabilized Laser (PSL)

- Initial Assembly & Check-out at CIT; Dis-assembled and shipped to Obs.
- 2km Interferometer PSL installation started 9/7/98
- Completion expected by 12/98
- Characterization and Subsystem Testing in parallel with IO installation
- 4km LLO Interferometer Installation Begins 2/99



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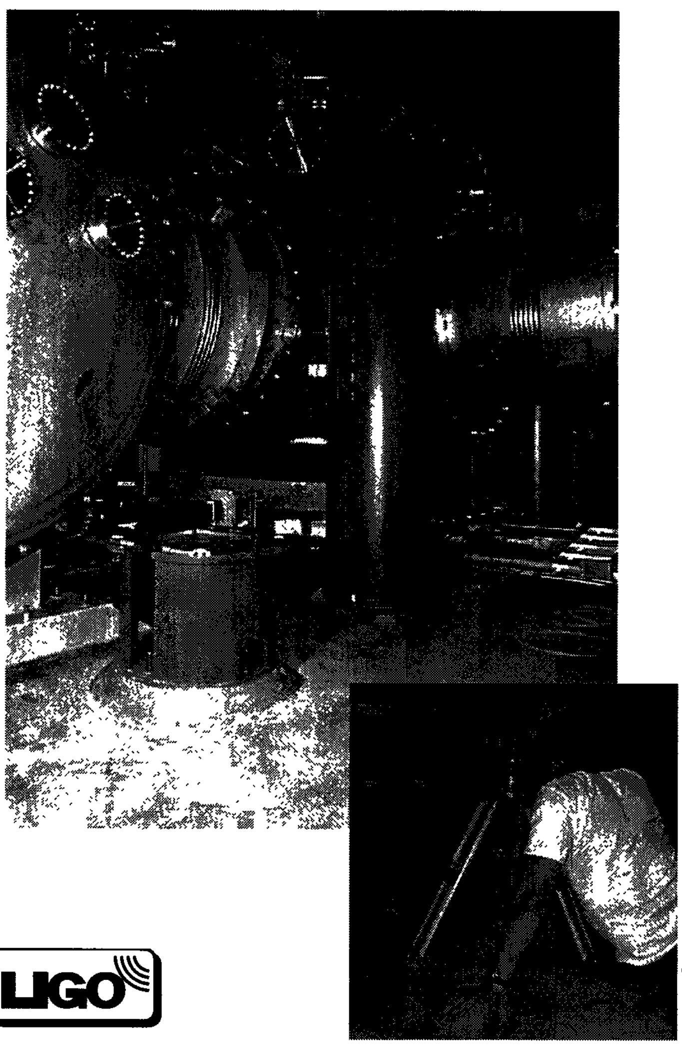
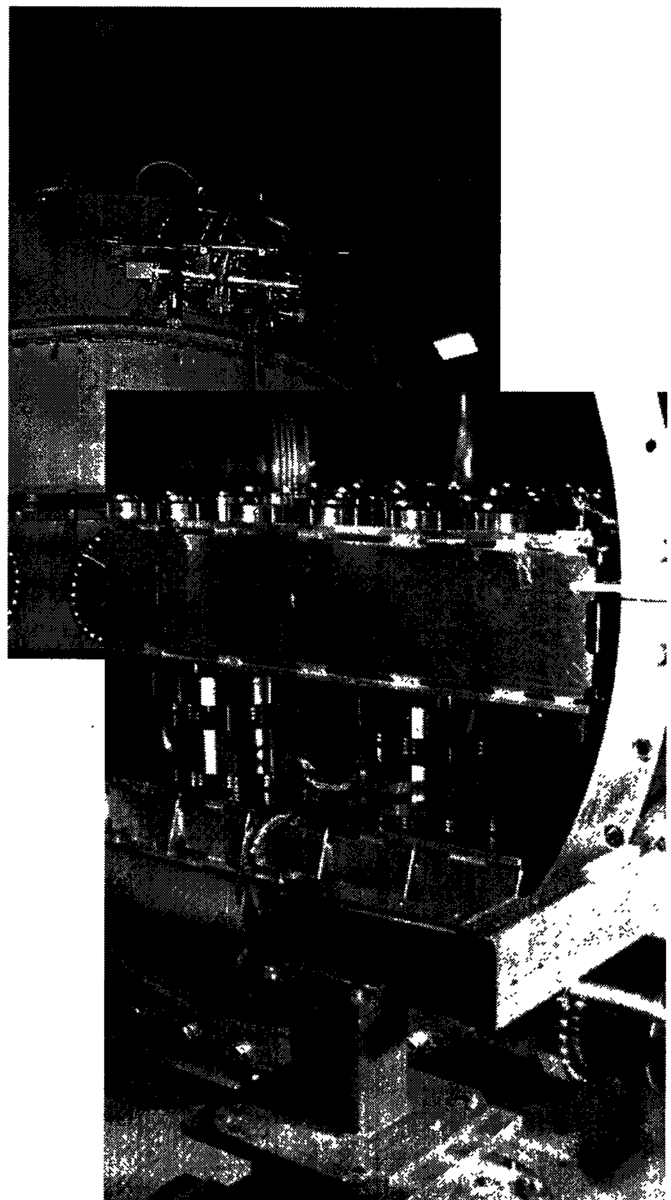
Subsystem Installation Status: Seismic Isolation System (SEI)

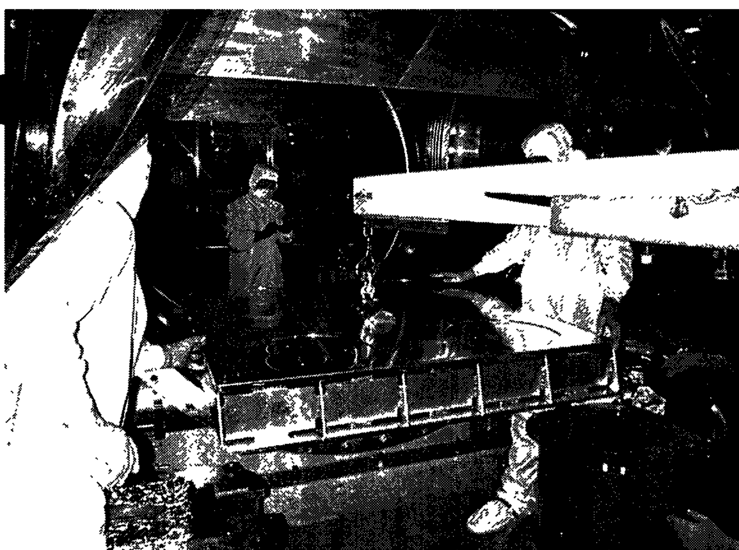
- First Article Testing:
  - SEI/HAM (without actuation system) @ LHO4/98-8/98
  - SEI/BSC (with coarse and then fine actuation) @ Hytec4/98-11/98
- Simultaneous Installation of Feedthrus & Viewports, in-vacuum cabling & cable clamps and counter-balance weights
- All HAM Piers Installed @ LHO; BSC Pier Installation Underway

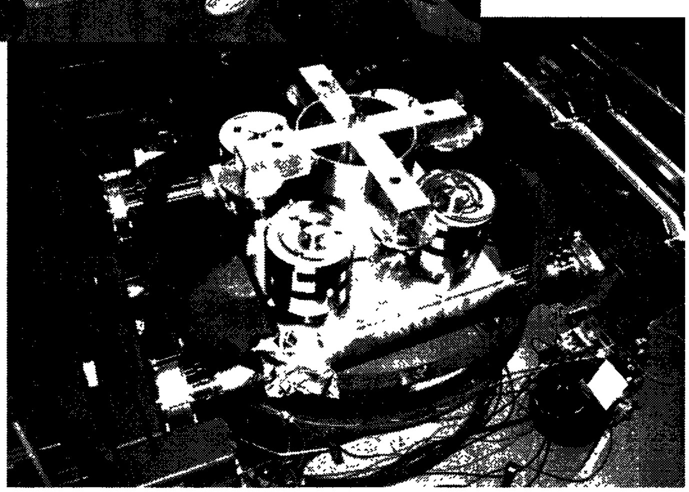


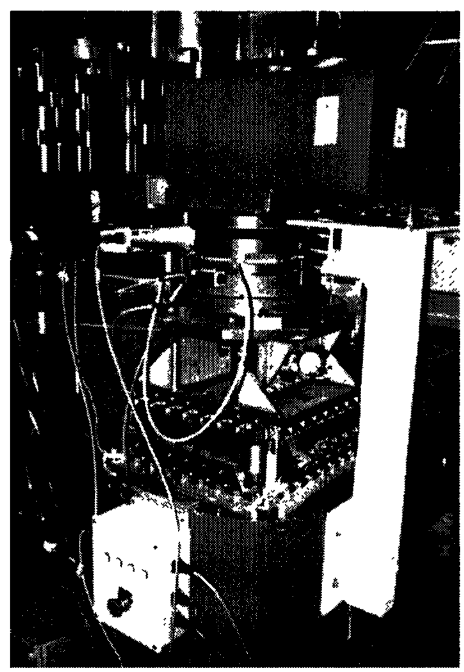


Subsystem Installation Status: Seismic Isolation System (SEI)

- First HAM Chamber (WHAM7)
  - — leak tested
  - — scissors tables, air bearings and cross beams about to be done (10/21)
  - — isolation stack to be installed early to mid-Nov
- Next HAM Chambers (WHAM8 and WHAM9) to have their support structures installed and leak tested by early Nov
- First SEI installation in a BSC chamber is scheduled for 1/99 in LHO







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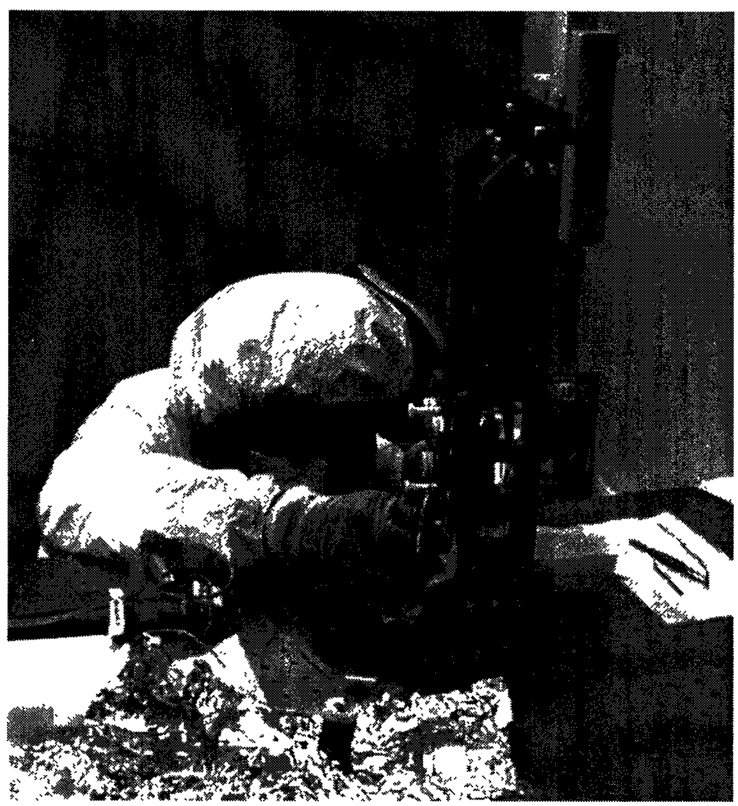
Subsystem Installation Status: Input Optics (IO)

- CDS SUS Test Stand Installed in the Optics Lab
- SOS Structures Assembled
- Small Optics Cleaning and Hanging/Alignment Training & Trials
- Staging UHV Parts and assemblies
- Some IOO components mounted on the PSL table
- in-vacuum, non-suspended mirrors to be cleaned and mounted week of 10/26



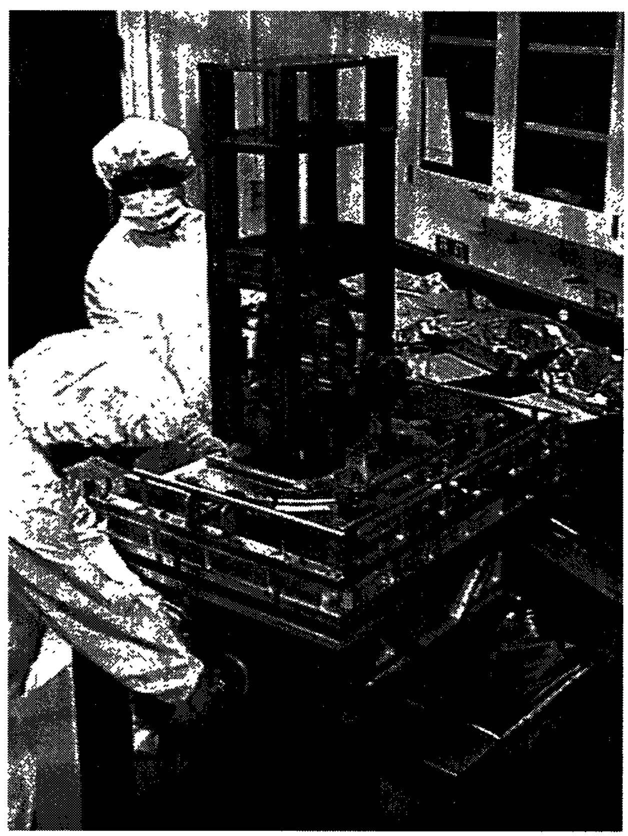
Subsystem Installation Status:
Interferometer Sensing & Control (ISC)

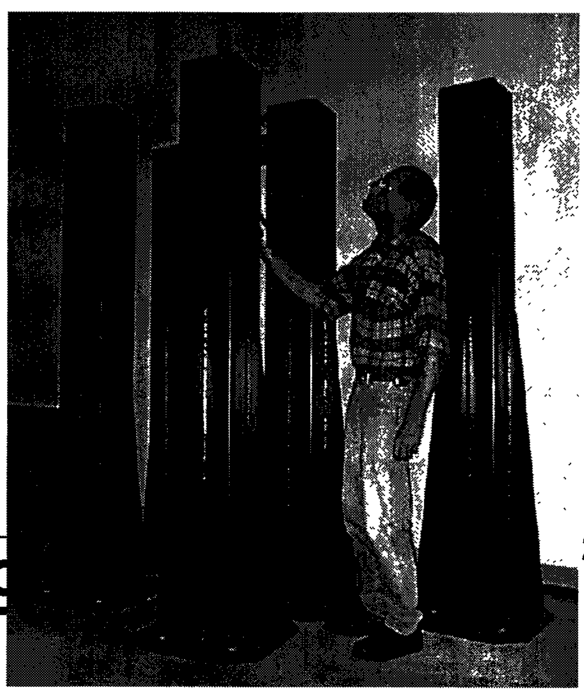
- IO/ISC:
  - Includes Integrated/Aligned Wavefront Alignment & Length Sensing Optics Table (IOT7 for the 2km IFO) & Optical Lever for the 3rd Mode Match Telescope Mirror (MMT3)
  - Installation occurs after basic optical elements have been installed by the IO group in the IO HAM chambers
  - FIRST MAJOR INTEGRATED SYSTEM TEST!
- ISC for CO (ASC and LSC):
  - Currently performing HW/SW test stand check-out
  - Includes Installation of Pre-Integrated Sensing Tables to Support ISC optical signals from COS (ISCT7, ISCT9 & ISCT10 for the 2km IFO)
  - To be Installed after CO/SUS and COS
  - Supporting electronics (demod, opt-lev, shutter control, digital servo control, etc.) to be installed in racks just prior to ISCTs

Subsystem Installation Status:

Suspension System (SUS), Core Optics Components (COC) and Initial Alignment System (IAS)

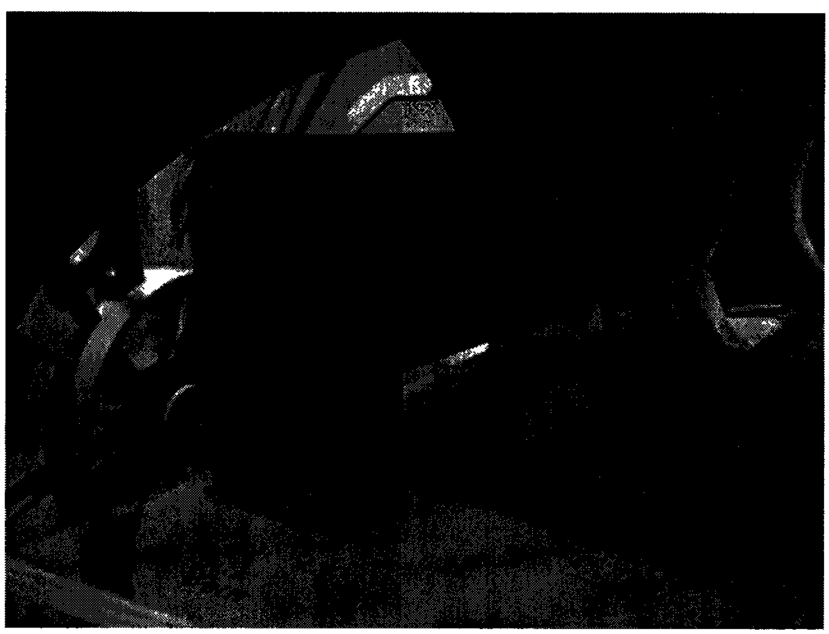
- Large Optics Suspension (LOS)/COC Assembly at the Observatories
- LOS/CDS Satellite Electronics Module & Controller Board Assembly & Check-out @ CIT
- Optical Lever Module Assembly & Check-out @ MIT
- Installation includes:
  - — physical placement & alignment (with IAS) of the LOS/COC
  - — physical installation of the SUS/CDS Satellite Electronics, Controller Board and interconnecting Cabling (exo-vacuum)
  - — Functional Check-out & tuning with SUS/CDS controller
  - — Optical Lever installation, cabling, alignment & check-out
  - — Requires simultaneous opening of 3 BSC chambers including interconnecting spools
- SUS & IAS Installation Field Trial to be Conducted in Y-End Station BSC week of 11/16





Subsystem Installation Status: Core Optics Support (COS)

- Fabrication Bids in Nov-Dec 98
- Installation enabled by vertex core optic installation & alignment
- IR Autocolimator used to generate ghost beams from the Core Optics
- Requires removal of manifoild spools for entry to install large baffles



LIGO Data Analysis, Modeling, Computing

LIGO Data Analysis and Simulation

Overview and Status

Albert Lazzarini

NSF Fall Review
28 October 1998

LIGO Hanford Observatory
Hanford, WA

Outline

- Datastream description
  - Datastream characteristics
  - Data analysis challenges
- Data types & data products
  - Framed data
  - Lightweight format
  - Metadata
  - Events
- LIGO Data Analysis System (LDAS)
  - Requirements
  - Software
  - Databases
  - Hardware
  - WAN
- Simulation environment
  - End-to-End (E2E)

LIGO Datastream Characteristics

- LIGO datastream consists of continuous broadband signals
  - Audio frequency (16384 samples/s, 16 bit) digitization & acquisition of key channels *(lower sample rates for ancillary channels)*
  - LIGO detection band: 40 Hz < f < 3 kHz

- No directionality
  - Require signal processing to deduce source locations
    - modulation of CW sources due to Earth motion
    - Time delay between coincident responses along 3000km baseline

LIGO Datastream Characteristics (cont.)

- LIGO signals expected to be at limits of detectability
  - Instantaneous SNR ~ 10^{-4}(strong chirp; pulsars) (weakest EM pulsars: SNR ~ 5 x 10^{-3}, require T_{int}~ hours to detect)
  - Need to integrate over entire (most) of the waveform to generate detectable SNRs (~ 10).
  - Requires coherent detection & signal processing
  - False alarms: validation of an "event" requires ability to preclude all other (terrestrial) interpretations -- vetoes

    [Ref. LIGO Sources charts, A1,2 at end of talk]
- LIGO acquisition data rates are high
  - Many parallel channels of instrumentation to monitor instrument behavior, environment, anthropogenic disturbances, ...
  - GW channel: 100kB/s for three interferometers (IFOs) -- 16384 samples/s @ 2bytes = 32kB/s per IFO
  - Data acquisition is ~ 10 MB/s for 3 IFOs
    - 573 channels *per* IFO (only 1 is GW channel)
    - 610 channels on physical environment monitors (PEM) (at each site)
  - Science (astrophysics) channels constitute as little as ~ [100 kB/s]/[10MB/s] ~ 1%

LIGO Data Analysis
Challenges

- Techniques are those for detecting the possible presence of weak signals embedded in noise (radar, sonar, pulsar searches, ...):
  - ›› Continuous processing of interferometer output
  - ›› Parallelization
  - ›› Frequency-domain spectral analysis (spectral cross-correlation)
    - – Optimal matched filtering; [1-3] x 10^4 physics-based templates; 90+% of CPU time spent of Fourier transformations.
    - – Frequency-time analyses (spectrograms, Wigner-Ville distributions, etc.); pattern/ridge detection (2-D)
  - ›› Wavelet analysis; novelty detection; phenomenology
  - ›› Kalman filtering to remove instrumental signatures -- data conditioning

[Ref. LIGO Data Flow chart, A3 at end of talk]

- Data archival & Distribution
  - ›› volume reduction by 10X => reduction/veto algorithms
  - ›› access to archived data => database engine/network tools
  - ›› 100% processing => computational power
    - – LIGO inspiral search requires ~300 kFLOP/Byte of data
    - – This is higher than typical processing requirements
      - – radar/sonar ~ 100 FLOP/Byte (many fewer templates, shorter durations!)
      - – directed EM pulsar searches ~ 1 kFLOP/Byte
    - – Compare: blind EM pulsar searches ~ 100 -1000 kFLOP/Byte

DATA TYPES & DATA PRODUCTS

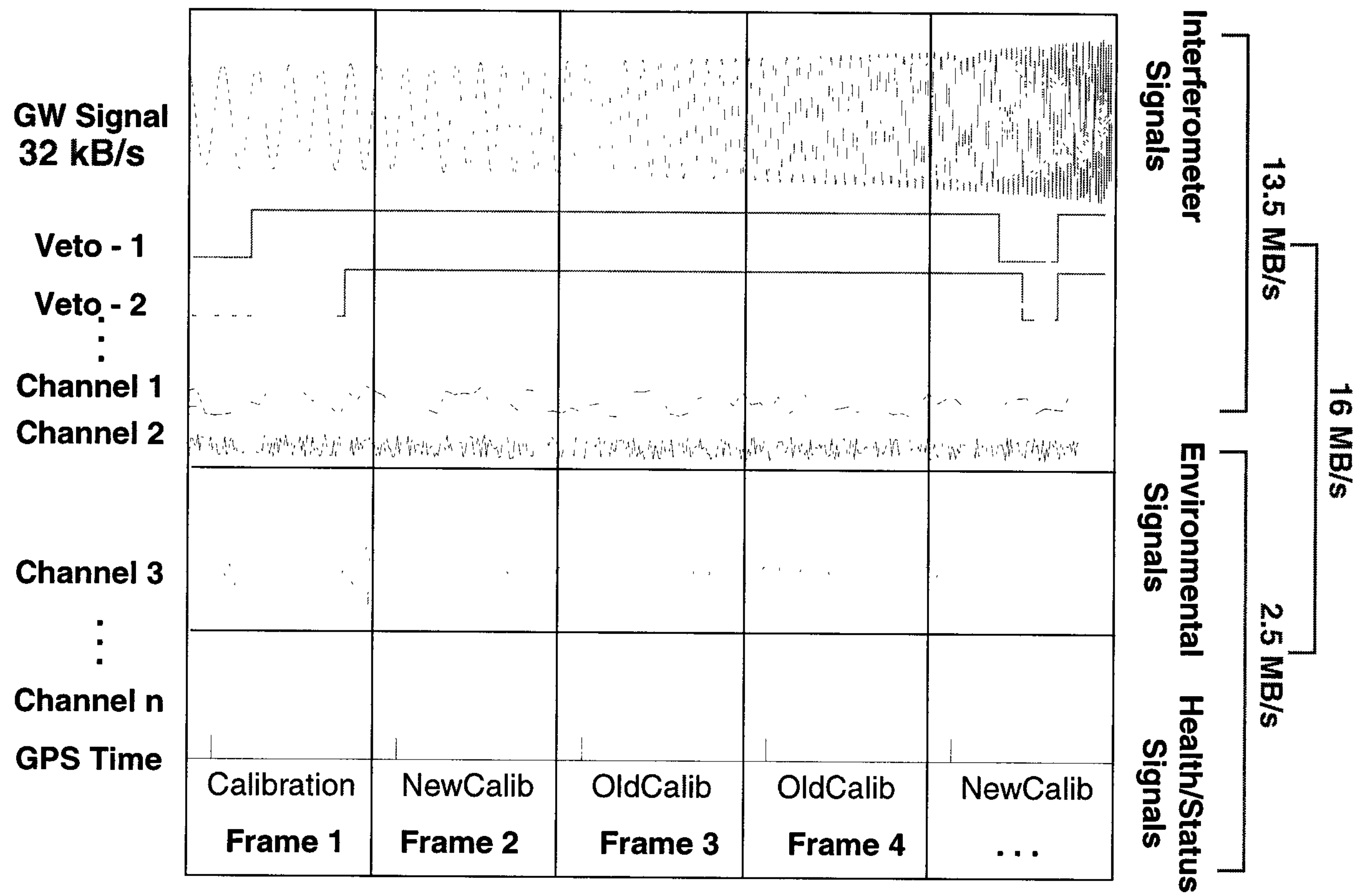
LIGO Data Products/Types

- The full [raw] detector datastream will be acquired and recorded as data frames.
  - ›› Format for data frames has been unified with VIRGO in anticipation of being able to share software (now) and data (at some future date)
  - ›› Other major interferometer projects have adopted standard
    - – GEO
    - – TAMA
- Frame Class Library (C++ implementation)
  - ›› Implements Frame Format Specification
  - ›› Progress to date:
    - – v1.01 released 98.10.16
    - – Documentation available on web (http://docuserv.ligo.caltech.edu/~wmajid/fcl/index.html):
    - – HowTo's, Sources
    - – Compatible and interfaced with CERN's ROOT package
    - – Fcl to LigoLW(XML) translation module completed
  - ›› Planned work (next quarter):
    - – Implement interface to Matlab
    - – Provide additional UNIX shell tools
    - – Develop Tcl level Frame API

LIGO Datastream

Frame Design

[Ref. LIGO Frame Format chart, B1 at end of talk]



- Frame is (structured) self-contained snapshot of data for a period of time
  - GW channel & ancillary IFO channels
  - Environmental monitoring (veto) channels
  - Facilities/Vacuum health & status
  - Hierarchical organization of data reflects IFO subsystems for more efficient veto utilization
- Full datastream could be ~ 300TB/yr
  - Plan to reduce (and compress) to ~ 50 TB/yr

Lightweight Data Format
XML

- Reduced, processed, or otherwise non-frame data will be recorded in a LIGO-standard lightweight data format (LigoLW)
  - Metadata (data about data: frame catalog indices, operator logs, textual data, etc.)
  - Event data [event specification still TBD]
  - Spectra, time series snippets, intermediate analyses performed with commercial/public-domain tools (MATLAB, Mathematica, ROOT, Triana, ...)
  - LigoLW is based on XML to anticipate web-distribution, network distributed processing
    - Metadata: tags, keywords, elements, attributes
    - Data: encoded binary; ASCII; raw binary(?); other objects; ...
- Need a lightweight format to complement frames:
  - interprocess data communications (@ socket level)
  - easily readable/parsable format for end users
    - quick-look products, single channels
    - spectra
    - plots
    - events
    - metadata
  - estimated data volume: ~600 GB/yr reduced data;
    ~135 MB/yr metadata

[Ref. LIGO Reduced & Meta Data Estimate charts, C1,2 at end of talk]

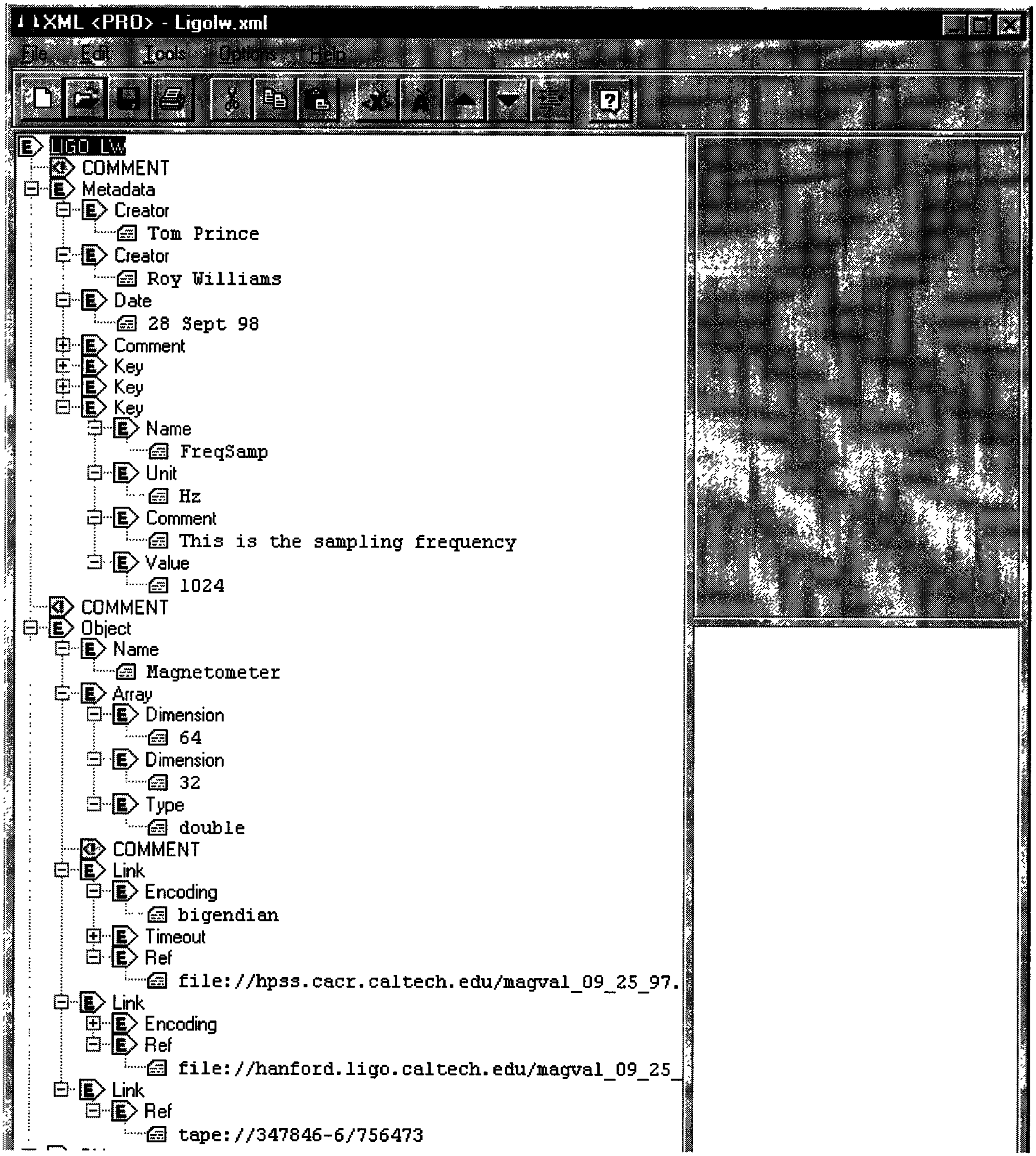
Lightweight Data Format
XML

- Status:
  - ›› Specification released
    - – LIGO-defined data objects with defaults enable simple utilization *[http://www.cacr.caltech.edu/ligo/ligolw]*
      - – tables (ntuplets: points in a hyperspace)
      - – arrays (indexed elements of data)
        - matrix
        - vector, time-series, power-spectrum, ...
  - ›› First implementations
    - – Directed pulsar search results from 40m dataset - summer student project
    - – Socket-to-socket and Tcl-C++ LDAS interprocess communications prototyped
  - ›› Parser built to extract metadata from frames and to create LigoLW metadata catalog
  - ›› Revise specification over next 3 months as experience dictates

[Ref. LigoLW XML example, D1,2 at end of talk]

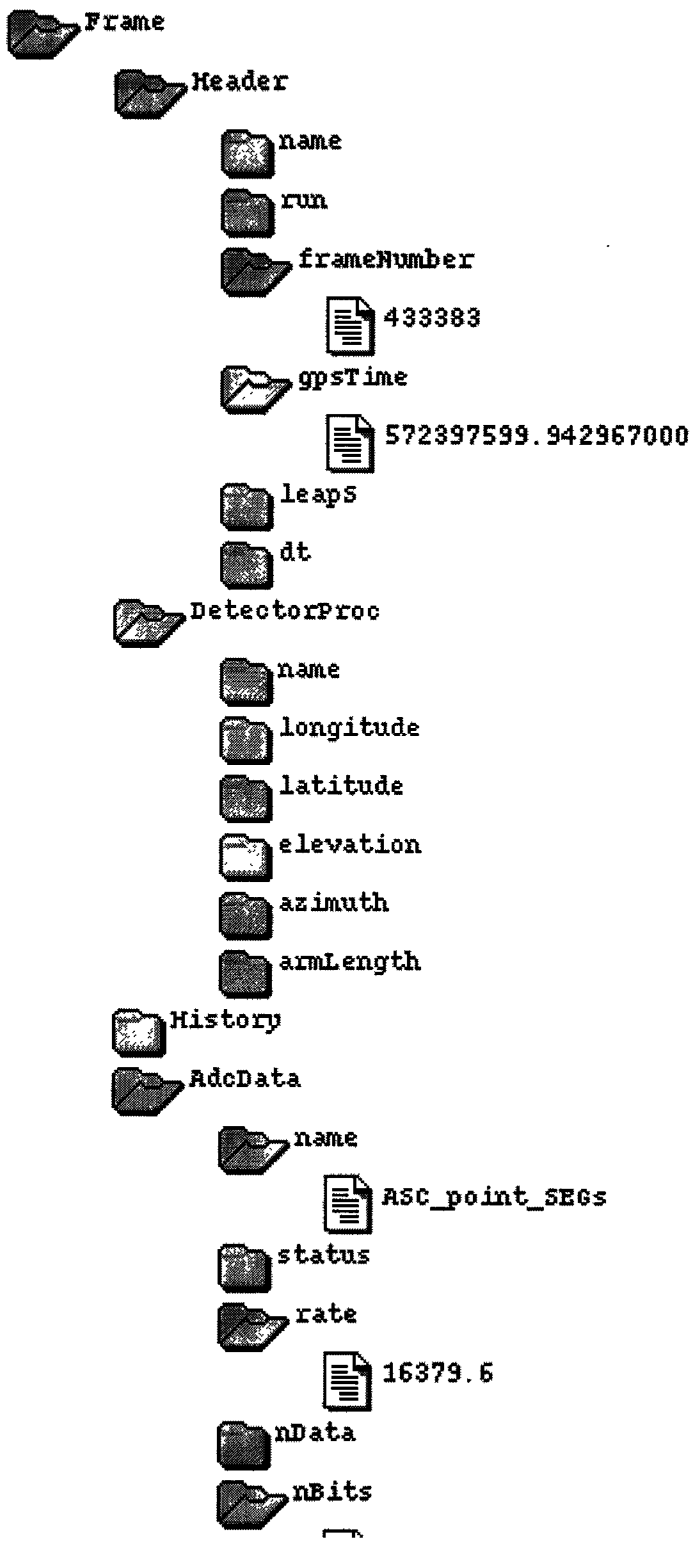
LigoLW

Parsed LW data object



Frame - LigoLW Conversion

Parsed frame object [XML <-> Fcl]



DATA ANALYSIS SYSTEM

LIGO Data Analysis System

LDAS Primary Requirements

EXPLOIT THE GW CHANNEL TO THE MAXIMUM EXTENT POSSIBLE TO DETECT GRAVITATIONAL WAVES FROM ASTROPHYSICAL PROCESSES

- Provide on-line analysis capability at the observatories; data distribution from on-line data cache -- astrophysics, diagnostics.
- 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.

LDAS Development
Timeline

- Highest priority: staged implementation of on-line systems to support detector testing:

Detector Milestone:	Date	LDAS Need
PSL/Input Optics	4/99	Min. data dist.
Vertex Michelson, “first light”	9/99	Full data dist.
2km operational	8/00	On-line system

- Staged installation at CACR of off-line system in period 9/99 - 12/01

LDAS Summary

- Software design complete -- design requirements review held 12/97
- Software components specification for Application Programmer Interfaces (APIs) complete
- Work under way to develop Generic (template) API, from which specific APIs may be extended
- Prototyping activities under way in several important areas:
  - Software module development
  - Data distribution using web tools
  - Interprocess communications, data transmission
  - Data flow for (directed) pulsar searches
- Hardware configuration definition complete
  - On-line systems at observatories
  - Off-line system at data repository (CACR/Caltech)
  - Wide area network for inter-site connectivity

Data Analysis System for LIGO I
Software Design

SOFTWARE DESIGN MUST SUPPORT A DISTRIBUTED NETWORK-BASED COMPUTING ENVIRONMENT

- **Software Specific Requirements:**
  - ›› Portability:
    - Portable Operating System Interface compliant (POSIX) on Unix Platforms
    - ANSI Languages Compliant Code (C++ Standard, 11/14/97! - http://www.research.att.com/~bs/iso_release.html)
  - ›› Extensible:
    - Object Oriented Programming Techniques in C++
    - Modular, Reusable Code Units elsewhere
    - Distributed Computing based on MPI
  - ›› Maintainability:
    - Source Code Management using Concurrent Version System (CVS configured in client-server mode using CVSH)
    - Expressly Coded in Object Oriented C++ Language whenever possible
    - Keep It Simple Style (KISS) Guidelines for Coding Constructs
  - ›› Flexibility:
    - Object Oriented Design (C++)
    - Modular Libraries (C, C++, others: e.g Fortran...)
    - Centralized Server-Client(s) paradigm for program control
    - Remaining infrastructure based on Standard Libraries (STL)

Data Analysis System for LIGO I
Software Design

LDAS SOFTWARE DESIGN FEATURES -- LAYERED DESIGN

Languages:

- ANSI C++
- ANSI C for wrappers to C, FORTRAN and TCL
- TCL (Tool Control Language) for control of resources.processes
- TK for Graphical User Interfaces
- Tclets (TCL/TK plug-ins) for web browser connectivity
- *TBD* database for data/metadata

Communications:

- TCL layer sockets to communicate commands and messages between processes
- C++ socket class library to communicate data between processes
- MPI (Message Passing Interface) for numerically intense parallel [scientific] computing.

Libraries:

- Shared C++ Class Libraries, numerical libraries and I/O libraries on supporting platforms for efficient use of hardware resources

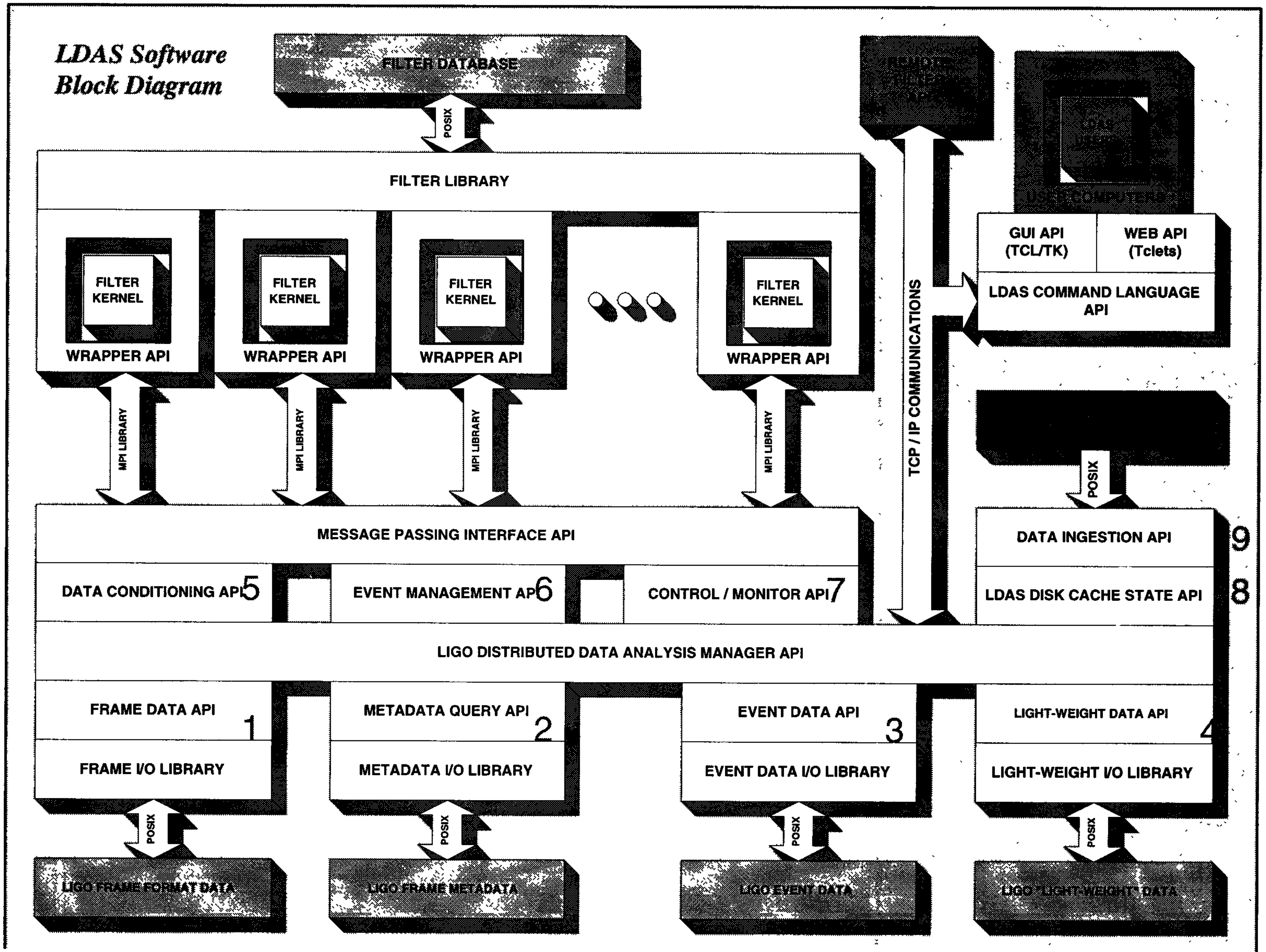
[Ref. LDAS Software Design chart, E1 at end of talk]

Data Analysis System for LIGO I
Software Design

›› Application Programmer Interfaces (APIs)

1. Frame Data
   - Manipulates framed data; I/O; channel extraction/ insertion; concatenation; ....
2. Metadata API
   - Interacts with the DB environment; data entry/extraction; data searches/sorts/queries.
3. Event Data API
   - Updates event lists; classifies events; searches on events;
4. LigoLW Data
   - Frame->LigoLW translator; data object extraction/ insertion.
5. Data Conditioning API
   - Data pre-processing; calibration; filtering; regression; computation either done using filter kernels or within this API (depends on complexity);
6. Event Management API
   - Receives output from the MPI based filter kernels; reports events; displays; ...
7. Control & Monitoring API
   - LDAS configuration, monitoring, exception handling, resource allocation; user interaction;
8. Disk Cache API
   - Stages data from archive/large disk farm to intermediate cache for efficient retrieval; queues data requests.
9. Data Ingestion API
   - Incorporates new data into archive; filter; reduce; compress.

LIGO Data Analysis System
Software Design



Data Analysis System for LIGO I
Software Development - Status

- GenericAPI [15 October status]:
  - Basis for all other APIs. Initial investment in prototyping and design will allow rapid diversification into specific APIs by extension of the generic class.
  - 90% complete

The first APIs to be developed will support Detector Installation milestones for the first interferometer

- FrameAPI [15 October status]:
  - Fcl I/O Library: complete
  - Fcl Specification: complete
  - FrameAPI 5% complete, expect mid-Nov completion date
- ManagerAPI:
  - FrameAPI 5% complete, expect mid-late Nov completion date
- DataConditioningAPI:
  - DataCondAPI 5% complete, expect mid-late Dec completion date
- Preliminary Design Review:
  - Develop prototype UserAPI by end of Dec.
  - Hold Preliminary Design Review Late December/Early January

Database Management Systems
DBMS

- LIGO has four data types that need to be managed:
  - ›› raw, framed data -- HPSS or equivalent network file system
  - ›› lightweight data -- HPSS or database management system (DBMS)
  - ›› events (as they are generated, cataloged) -- DBMS
  - ›› metadata -- DBMS
    - catalogs & indices
    - operator logs
    - trends and high-level descriptions of detector performance
- Still in process of deciding DBMS for LIGO
  - ›› Recent workshop (22,23 October) with representatives from CERN, SDSC, CACR, Astronomy(IPAC/CIT) to review LIGO needs, compare with other programs from HEP, Astronomy
  - ›› Choices being considered:
    - relational [deemed sufficient for LIGO needs]
      - ORACLE (CIT license for campus MIS)
      - PostgresSQL (INFORMIX precursor; public domain - 'free')
      - miniSQL (similar to above)
    - object-oriented DBMS
      - Objectivity
  - ›› Issues: Buy-in costs; operational costs; upgrades if we start too low; metadata only vs (metadata+data); ...
  - ›› Plan to have a decision by PDR

Database Management Systems
DBMS prototyping activities

- Ongoing BT Bakeout activity is generating 4 disparate DBs
  - temperature, current, pressure data along BT
    - Microsoft ACCESS DB
  - residual gas data from RGA
    - Proprietary SW from RGA vendor: spreadsheet compatible
    - partial pressure vs time scans
    - mass spectra
    - calibrations
  - weather station/environmental data: proprietary SW with station vendor: spreadsheet compatible
  - operator logs
    - text (ASCII) files
- Data arrive weekly as (~80MB files)
  - ›› 700 channels x 10000 rows
  - ›› data are ingested (transformed) and metadata produced for indexing into archive -- 3 hour ingestion process on NT server @ CACR
- Need to make data available at future dates for intercomparisons as bakeout progresses
  - ›› DB will eventually grow to ~ 2GB, indexed by timestamp
  - ›› Metadata+data co-located in DB

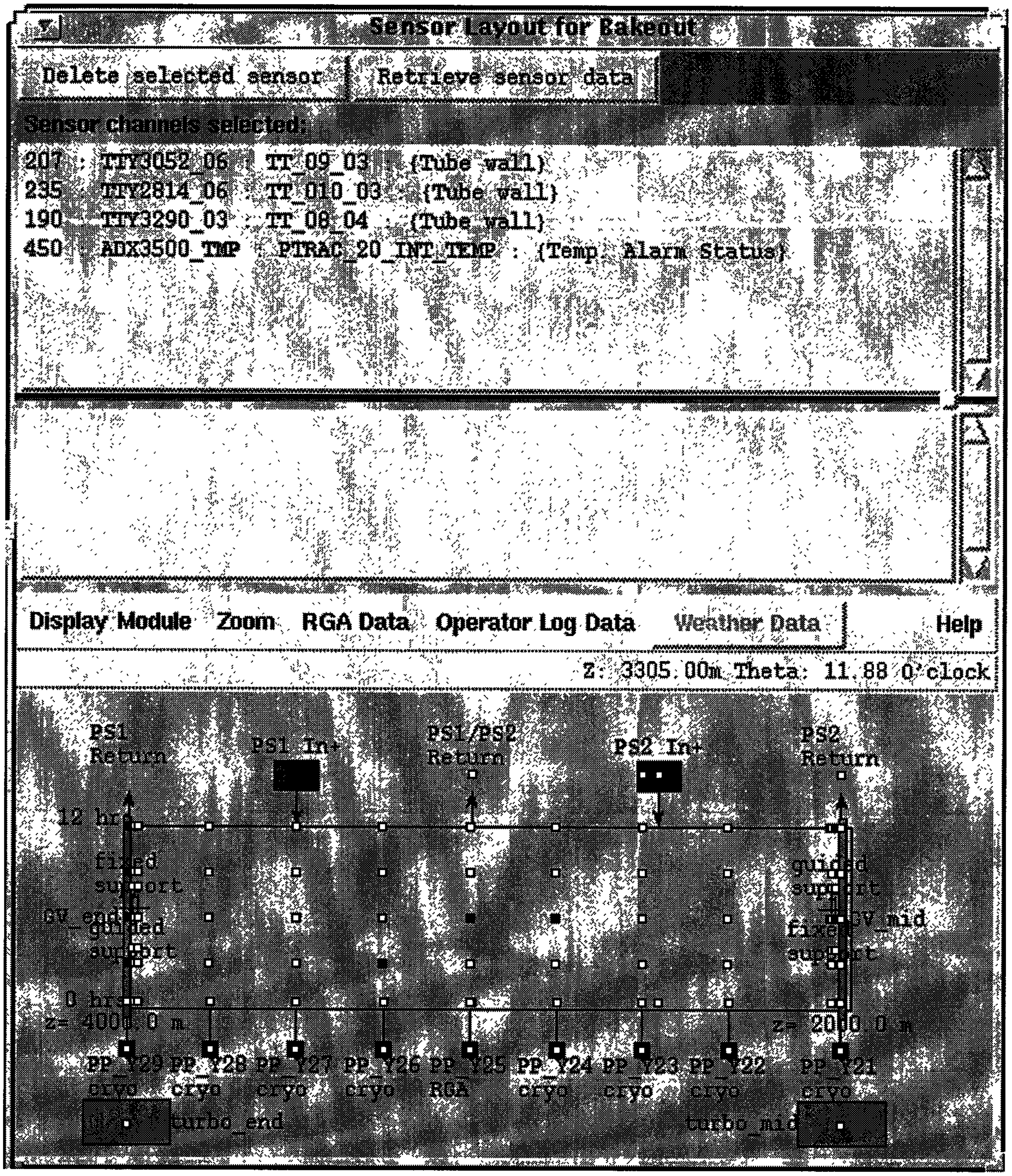
Database Management Systems

DBMS prototyping activities

- Developed a GUI using the tools being developed for LDAS to allow web-based (via browser-plus-plugins) access to DBs
- Data server independent of GUI
- Communications through query standard protocol
- Present: temperature data now available
- Next:
  - remaining datasets -- RGA data, weather data,operator logs
  - return LigoLW objects [XML]

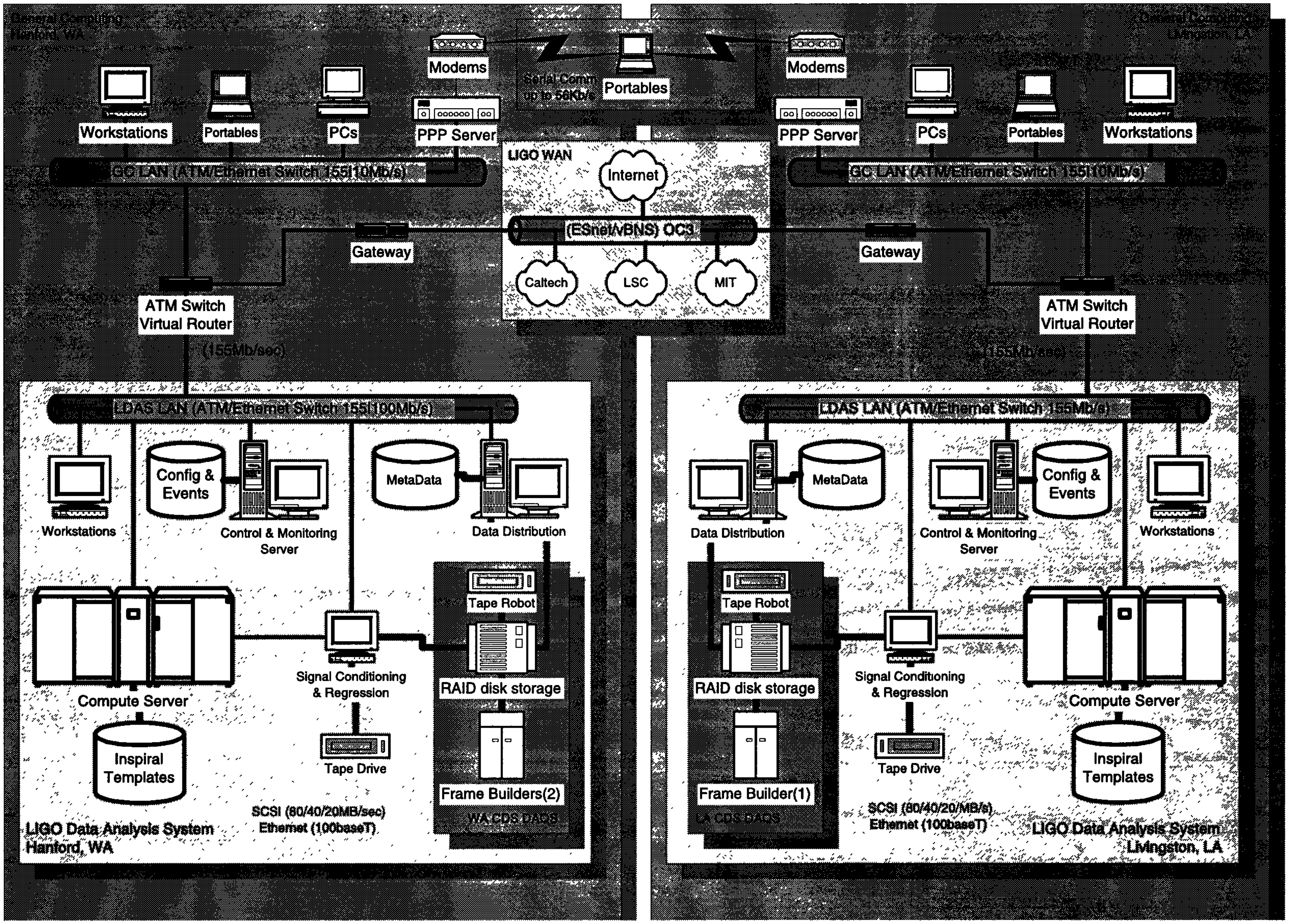
Database distribution tools

BT Bakeout Data Distribution Prototype



LIGO Data Analysis System
On-line architecture

[Ref. LDAS Off-line Hardware chart, F1, Hardware Spec. charts, F2-5 at end of talk]

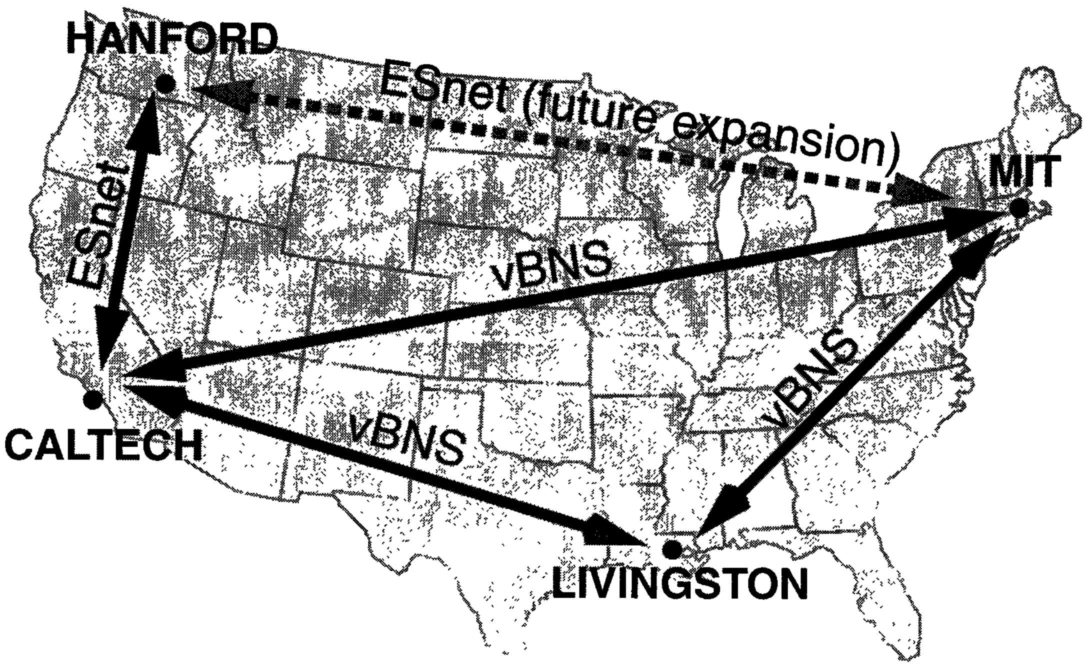


Hardware Status

- Network based data transmission at LIGO BW demonstrated
  - ATM<->ATM is adequate (6 - 15 MB/s; depends on platform, TCP/IP vs UDP).
  - 100BT<->100BT (needed for MPI, Beowulf cluster inter-node communications) is acceptable (>4.5 MB/s)
  - HIPPI<->HIPPI (with supercomputer mainframes) is superior (>30MB/s)
- Beowulf and MPI has been implemented on LIGO- scalable data flows for inspiral detection
  - Joint effort with CACR (Paragon) & Univ. Wisc. (PC/linux)
  - 8 node/16CPU integrated cluster ordered, due end October.
- Directed pulsar search prototype code has been developed using 40m data and CACR machines.
- Data archival technology choice deferred as late as possible (2001) - letting CACR lead way
  - Exploring optical tape technology replacement for magnetic media in HPSS (LOTS)
  - 1TB/cassette (same form factor as present IBM robot cassettes)
  - ~$250/cassette ($0.25/GB)
  - Optical heads replace magnetic tape heads in same cabinetry.

LIGO Wide Area Network

WAN Topology



WAN/LAN Connectivity among LIGO Laboratory Sites

Site	*Livingston, LA*	*Hanford, WA*	*MIT*	*Caltech*
Caltech	vBNS(OC3)	ESnet (4 X T1) <-> vBNS(OC3)	vBNS(OC3)	**OC3/ATM 100BT**
MIT	vBNS(OC3)	MIT<->Caltech<->Hanford ESnet (4 X T1) <-> vBNS(OC3)	**100BT OC3/ATM(?)**	
Hanford, WA	ESnet (4 X T1) <-> vBNS(OC3)	**OC3/ATM 100BT**		
Livingston, LA	**OC3/ATM 100BT**			

LIGO Wide Area Network

Status

- LIGO proposed & drafted an MOU between NSF/DOE to provide access to ESnet at Hanford
- Authorized as of October 1998
- Implementing initial (T1) capability; requested up to 4 x T1 BW (cost is an issue).
  - Routing: LHO-PNNL-SDSC-CACR-LIGO/Caltech
  - In Progress:
    - DNS in process of being turned over to Caltech ligo-wa.caltech.edu
    - T1 connectivity tested and working
    - Move workstations over to new IP addresses
    - Setup E-mail and Web services
  - Planned:
    - MOU covers 4 T1 connections -- may take advantage of contingency.
    - WSU/Pullman (~ 100km NE) awarded an NSF grant to establish a vBNS hook-up
    - UW/Seattle (~350 km W) has vBNS at present
    - PNNL is investigating future high speed connections via Seattle -- LIGO will participate if costs are acceptable.
- MIT may be added later as a separate addendum to MOU

[Ref. LDAS WAN Toplogy.charts, G1,2 at end of talk]

LIGO Wide Area Network

Status

- T1 link to Livingston Observatory is in place
  - ›› LSU awarded vBNS access in latest round of NSF awards -- includes LIGO access at Livingston
  - ›› LSU provides gateway service
    - – Caltech providing DNS services ligo-la.caltech.edu
    - – E-mail and Web services in process of being setup (last week)
  - ›› Planned:
    - – Finalize hardware logistics with LSC
    - – Install main server
    - – Establish modem services and contingency plan
    - – Establish OC3 Connectivity in the next 1-2 years depending on fiber availability (present connection is Cu)
      - – LIGO will have to install FO lines from Livingston to the Observatory
      - – Upgrade the routing equipment to accommodate new connectivity

END-TO-END
SIMULATION ENVIRONMENT

End-to-End (e2e) Simulation

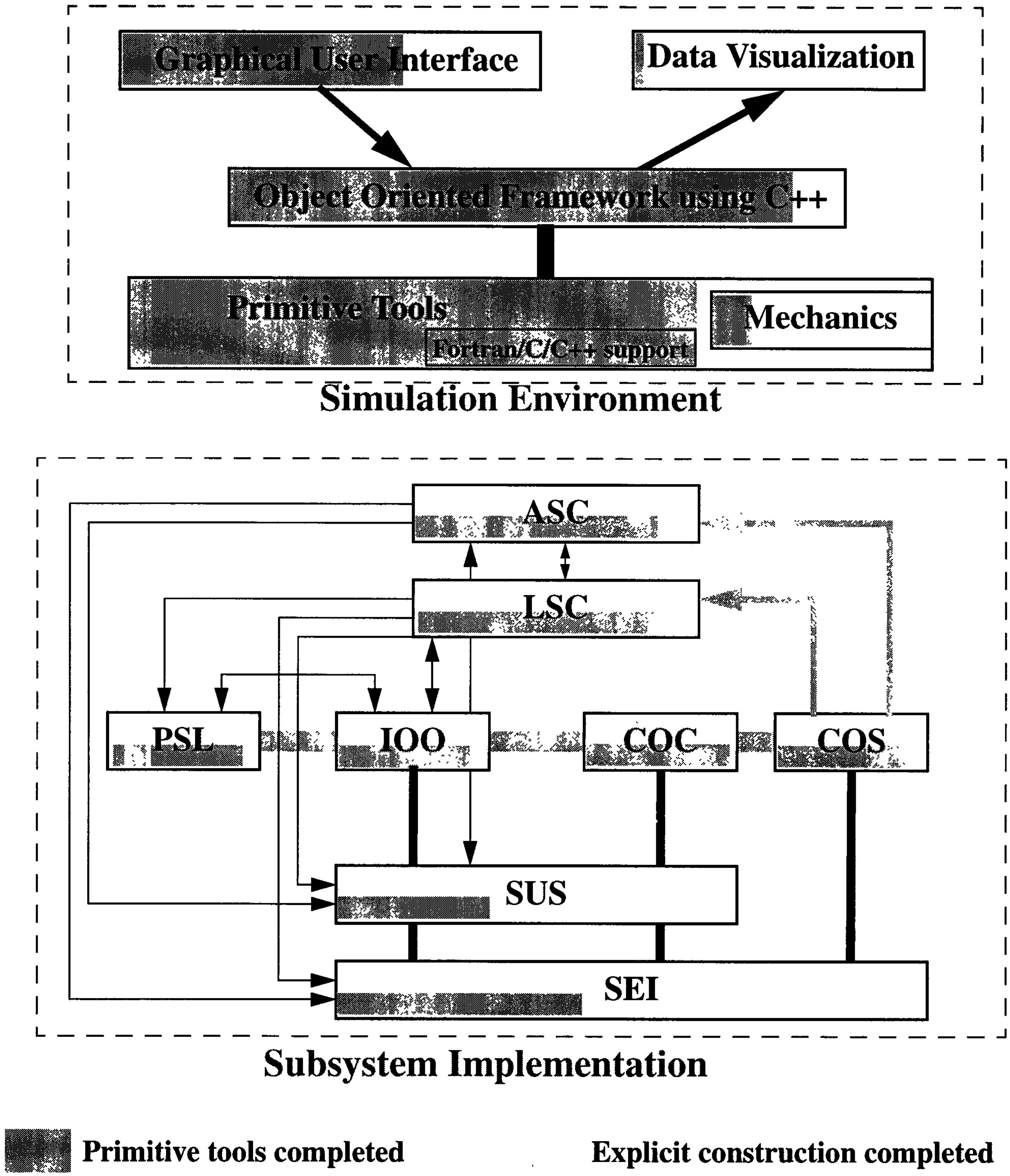
- Time domain simulation of LIGO interferometer output(s)
- Object Oriented structure using C++
  - Modular and expandable
  - Support for plug-ins using FORTRAN/C/C++
- No low level language (i.e., C++) needed to use
  - Easy to use high level language
  - GUI
- "Toolbox" Primitives
  - mirror - reflection, transmission, tilt, ...
  - field propagator - time delay, Guoy phase, ...
  - modulator and demodulator - arbitrary number of sidebands, ...
  - digital filter - models servos, electronics, linearized response, ...
  - mechanical components
    - test mass, beam, clamp...

Support to Detector Installation
e2e simulation

- Plan
  - When the vertex Michelson at Hanford is available, E2E will provide the minimum set of subsystems so that semi-quantitative comparison of performance can be made.
- Construct the simulation models to map into the real hardware
  - Implement phenomenological models for those parts which cannot be simulated using primitives.
  - PSL - 4/99
  - IOO - 7/99 [with UFl]
  - SUS/SEI - 7/99
- Collaborative participation [e.g., U. Fl.] to develop LIGO physics modules using available toolbox primitives
- Simulation team will participate in shakedown of hardware alongside detector subsystem teams

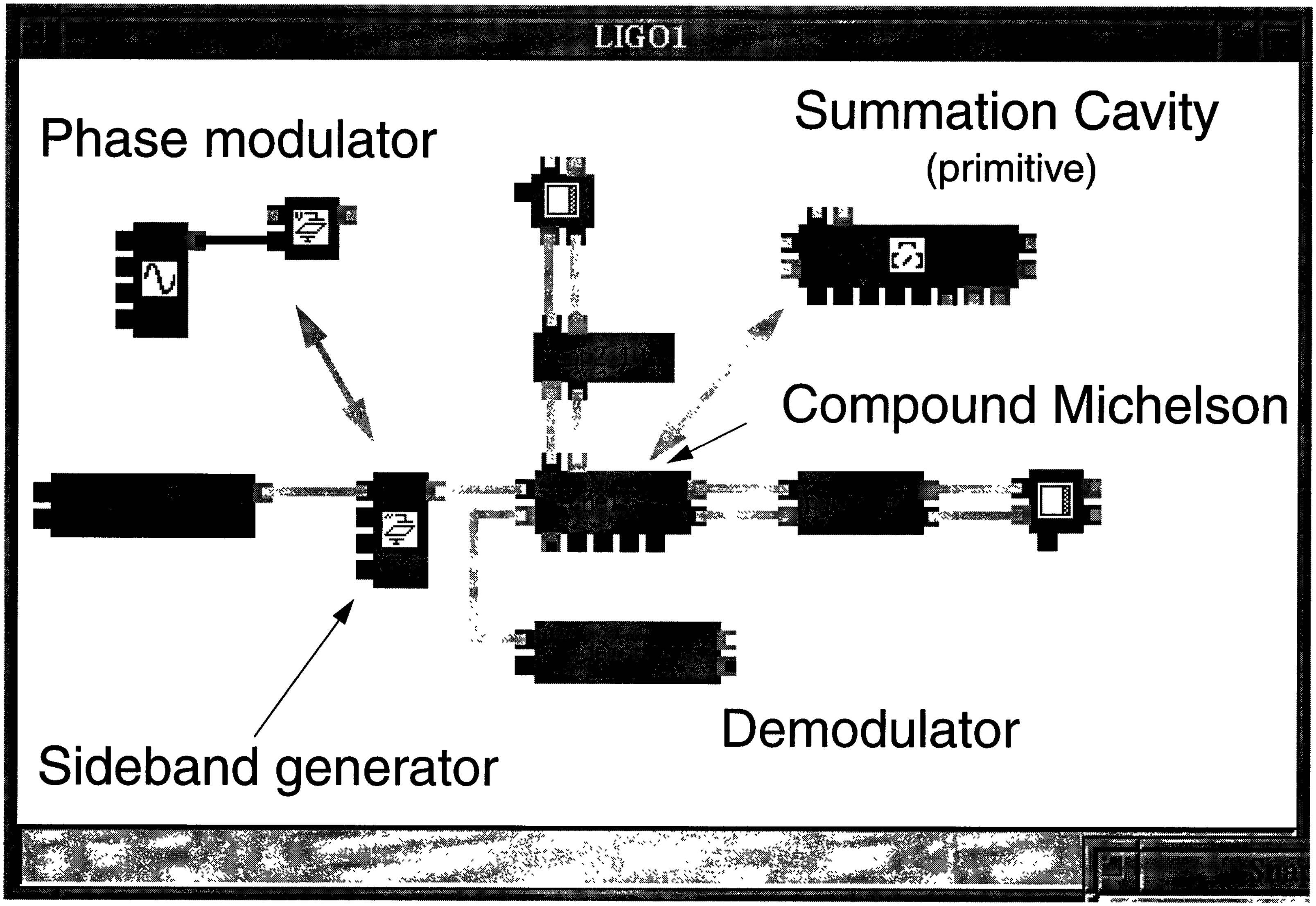
Status Overview

e2e simulation



Example

e2e simulation



Status
e2e simulation

- Single mode time domain model
  - Improved capabilities
  - Validation alost completed
- Modal model in time domain
  - Field expanded by finite Hermite-Gaussian modes
    - Mirror tilt and displacement
    - Mode mismatching
    - Thermal lensing
  - Implementation in progress
    - validation for FP case done
- Primitives (toolbox components) complete except for mechanical subsystems

Status
e2e simulation

- Mechanics module development
  - ›› Any simple linearized model can be built using Digital Filter
  - ›› A more detailed simulation needs physical model implementation
  - ›› S. Mohanty - Penn. State Univ. (visitor 1997/1998)
    - Formulation of dynamics of a mechanical structure
    - Self-consistent inclusion of thermal noise sources
    - Explicit formula for a single pendulum derived
  - ›› G. Cella - Pisa Univ. (formerly with VIRGO)
    - Author of simulation program of mechanics model for VIRGO
    - C++ based, modular and expandable
    - Similar syntax as e2e -- easily adapted to e2e environment
- E2E incorporation of mechanics models
    - Integrate framework of Cella into e2e framework
    - Include dynamics and thermal noise formulation developed by Mohanty as appropriate
    - Use the same GUI as LIGO e2e
  - ›› Short term implementation strategy
    - Implement single pendulum model by Mohanty
    - Validate dynamics of model
    - Use for simulating a simple SEI model
    - Validate modular model of Cella

APPENDIX
VIEWGRAPHS

Initial LIGO Sources - A1

Table 1: Initial LIGO Sources and Estimated Analysis Capability Requirements

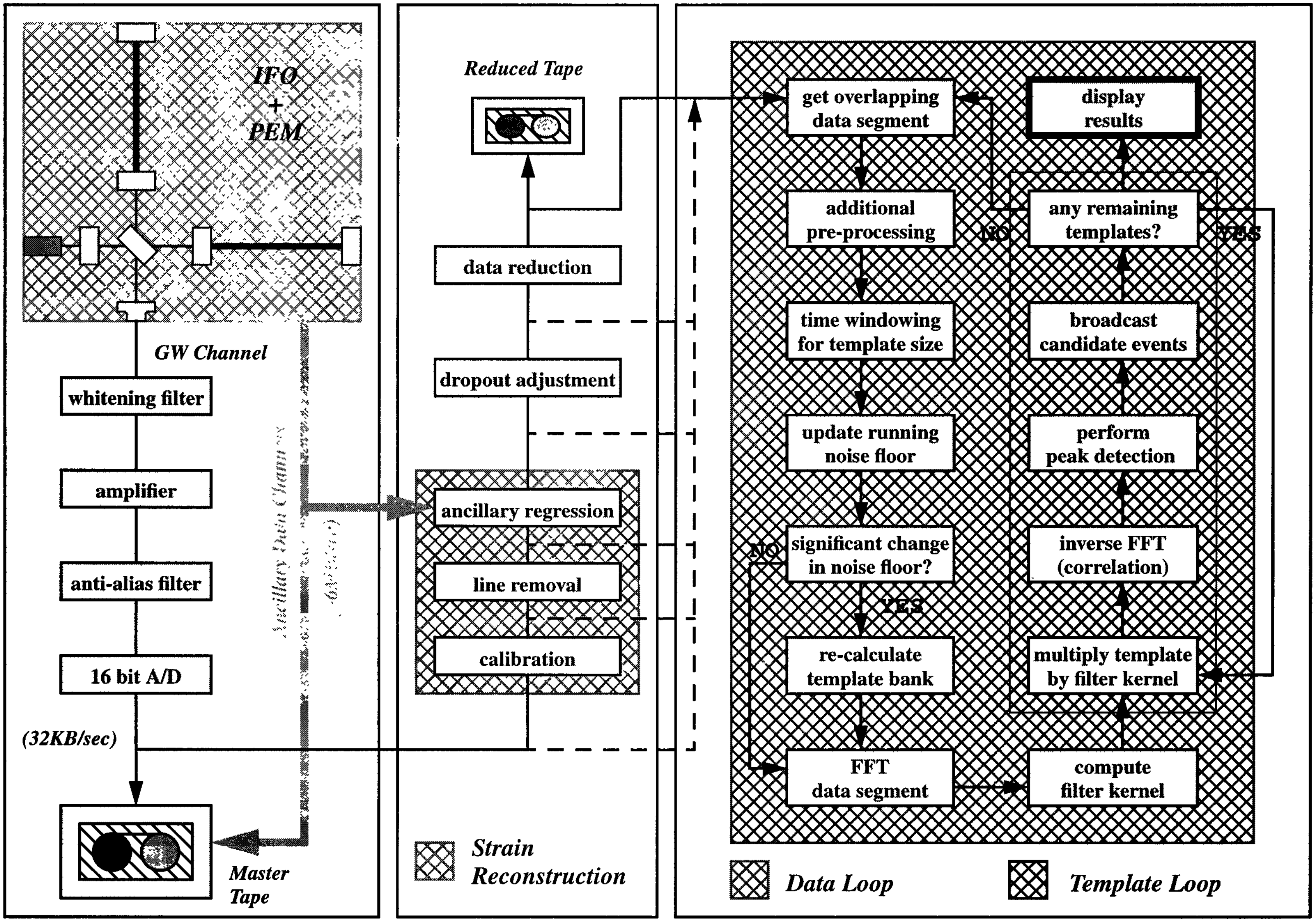
	Sources	Initial LIGO Performance Estimate	Data Analysis Requirements		
			CPU	Storage	Comments
Burst Signals $\Delta T < 1\,s$	Supernovae & Accretion-induced collapse of white dwarfs	$\Re_0 \sim 2-3/\ \text{yr}$ @ 15 Mpc If sufficiently asymmetric; however, ΔE_{GW} expected to be significantly less than $10^{-7}\ M_{solar}$	Minimal	Minimal Need PEM/houskeeping data for veto	• On-line analysis desirable for correlation with other astrophysics: **EW** • **visible/radio/γ** • ν Gravity • VIRGO/GEO • Resonant bars • Waveforms unknown • 2x/3x IFO correlation of events
	BH/BH Collisions	$\Re_0 \sim 1/\ \text{yr}(?)$ @ 500 Mpc;			
Chirped Waveform $10s < \Delta T < 1000s$	NS/NS Inspirals	$\Re_0 \sim 3/\ \text{yr}$ (?) @ 23 Mpc; for $M_{NS} \sim M_{solar}$ $\Delta T \sim 36 \times T_{inspiral} = 360s$	~ 7.2 GFLOPS (WA)	Templates/Data ~5 GB /~24 MB	• On-line analysis appears feasible down to $\sim 1\ M_{solar}$ • 1x/2x/3x correlations feasible depending on SNR. • Coalescence event may generate correlated (EW) signals as above. • PEM/housekeeping needed for vetoing • Template matching (Wiener filtering) or wavelet analysis in f-t domain.
	BH/BH & NS/BH Inspirals	$\Re_0 \sim 1/\ \text{yr}$ @ 150 Mpc; for $M_{BH} \sim 3M_{solar}$ $\Delta T \sim 36 \times T_{inspiral} = 60\ s$	~ 330 MFLOPS (WA)	~ 41 MB /~4 MB	

Initial LIGO Sources - A2

Table 2: Initial LIGO Sources and Estimated Analysis Capability Requirements

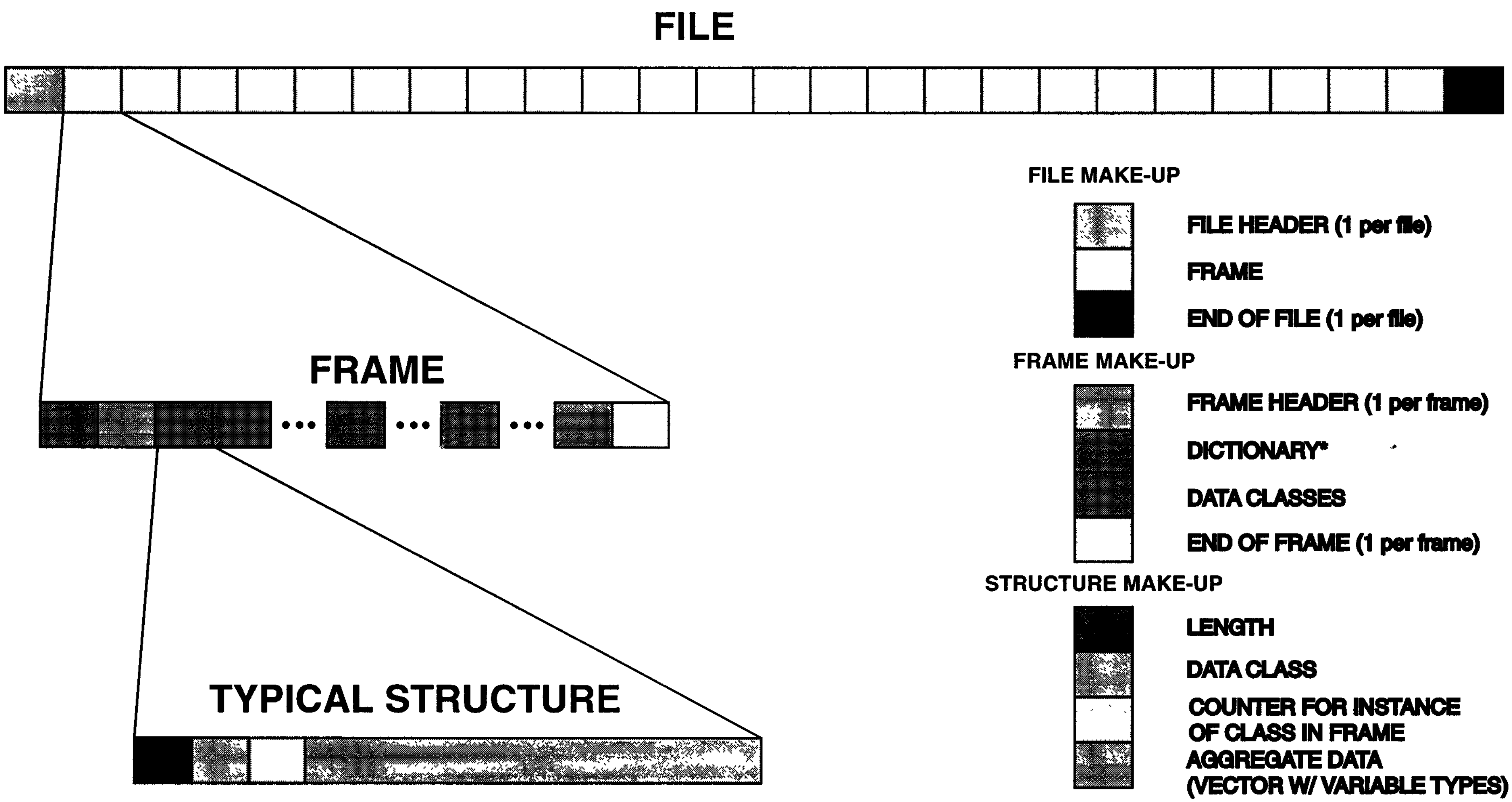
	Sources	Initial LIGO Performance Estimate	Data Analysis Requirements		
			CPU	**Storage**	**Comments**
Periodic Signal $\Delta T \sim 10^6 - 10^7$ s	Pulsars with mass asymmetry $\frac{S}{N} \approx 1.5\left(\frac{\varepsilon}{10^{-6}}\right)\left(\frac{10\text{kpc}}{r}\right)\left(\frac{1\text{ms}}{P}\right)^{\frac{5}{2}}\sqrt{\frac{T_{int}}{1\text{month}}}$ $\tau_{spindown} \sim 830\text{yr}\left(\frac{f_{rot}}{1\text{kHz}}\right)^{-4}\left(\frac{\varepsilon}{10^{-6}}\right)^{-2}$	$\frac{S}{N} \approx 8$ $\varepsilon = 10^{-5}$ r=10 kpc P=1 ms $T_{int} = 10^7$s	Only directed searches feasible for nearby sources	10 GB for 10^6s (GW waveform)	• Off-line analysis • Detection less sensitive to non-Gaussian noise; more sensitive to calibration drifts. • Detection techniques as for pulsars -- narrow line sources with modulated frequency. • Correlations among interferometers may be performed (if needed) after detection. • A 4π sr. search requires decomposition of the sky into a very large number of pixels. Exact number is sensitive details of stacking.
Broadband Signals $\Delta T \sim 10^6 - 10^7$ s	Stochastic Background $\zeta \equiv \frac{\Omega_g}{\Omega_0}$	$\zeta \geq 3\times10^{-6}$ $40\text{Hz} < f < 300\text{Hz}$ $T_{int} = 10^7$sec	Minimal requirements -- analysis may done on single workstations; study of systematic correlated noise effects may require significantly more processing.		• Off-line analysis • Requires multiple interferometers to be correlated

LIGO Data Flow (Model) -- A3



Frame Format Implementation - B1

Frame Composition



*** 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)

LDAS Reduced Data and Metadata - C1

SOURCE	Data	Data Types	Basis of size estimate #Parameters #Bins #Pixels #Samples	#Bytes/Unit	#/Hr	LW Data Volume/Year [GB]	MetaData Volume/Year [MB]
LIGO - Interferometer	Machine state vector	String[XML]	2048	1	10	0.0	90
		Binary	128	1	10	0.01	0.0
	Operator Logs	Strings	20480	1	20	0.0	180
		Graphics[JPEG]	32768	1	10	2.9	89.8
	Diagnostics	Video	4096	1	60	2.2	538.6
		Spectra/Fast Scopes	2048	2	20	0.7	179.5
		Calibrations - Spectra	2048	4	10	0.7	89.8
		Calibrations - Coefficients	4096	1	10	0.4	89.8
		Calibrations - Matrices	2048	4	10	0.7	89.8
		Triggers/Discrete Logic	128	2	60	0.1	538.6
	Frame Data Catalog	String[XML]	1024	1	3600	0.0	64630.0
LIGO - Environment [PEM]	Facilities state vector	String[XML]	512	1	10	0.0	134.6
	Seismometers	Spectra	1024	2	60	1.1	538.6
	Magnetometers	Spectra	1024	2	60	1.1	538.6
	Tiltmeters	Time Series@0.1 Hz Stored 1/Hr	16	1	360	0.1	9.0
	Acoustic Sensors	Spectra	8192	2	60	8.6	538.6
	Diagnostics - Calibrations	Matrices/coefficients	2048	1	0.41666667	0.01	3.7
	Diagnostics - Triggers	String[XML]: Model parameters	1024	1	0.41666667	0.004	7.5
		Discrete logic	128	2	60	0.1	538.6

LDAS Reduced Data and Metadata - C2							
SOURCE	Data	Data Types	Basis of size estimate #Parameters #Bins #Pixels #Samples	#Bytes/Unit	#/Hr	LW Data Volume/Year [GB]	MetaData Volume/Year [MB]
Non-LIGO	Seismic	String[XML]	512	1	10	0.0	89.8
	Electromagnetic storms	String[XML]	256	1	100	0.2	897.6
	Astrophysics - GRBs	String[XML]	256	1	0.04	0.0	0.4
	Astrophysics - neutrinos	String[XML]	256	1	0.00	0.0	0.0
	Astrophysics - visible	String[XML]	256	1	0.00011408	0.0	0.0
	Astrophysics - gravitational	String[XML]	2048	1	10	0.2	89.8
LDAS Events	Event Lists	String[XML]	2048	1	3600	64.6	32315.0
		Images/Graphics[GIF]	8192	2	3600	517.0	32315.0
			Total Database [GB]		**==>**	**600.8**	**134.5**

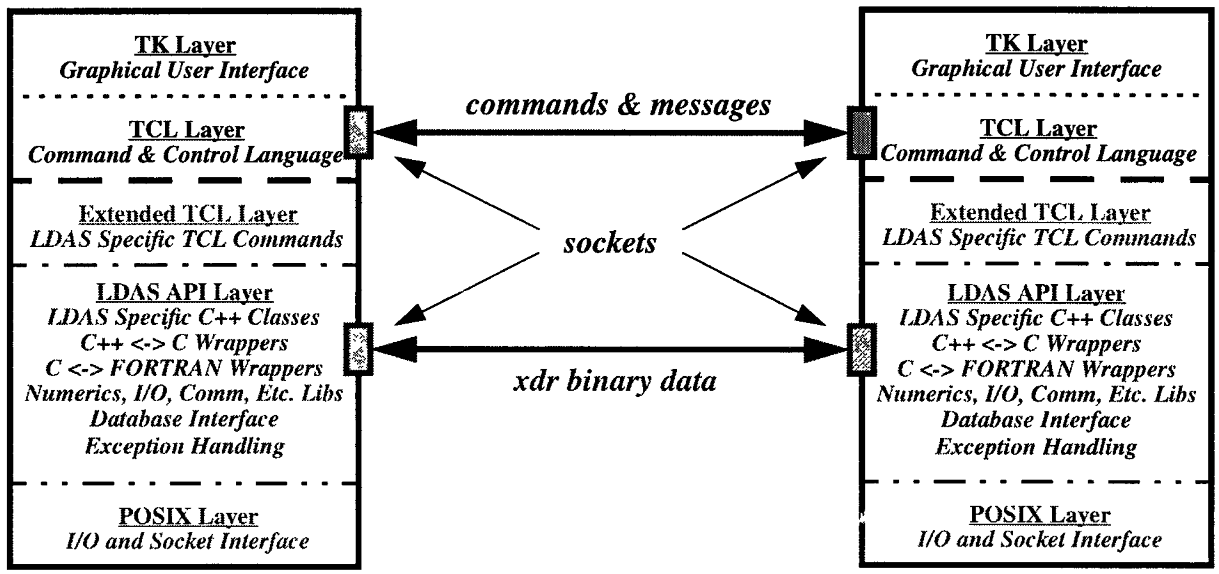
LigoLW - D1
Example -- Metadata

```
<?xml version="1.0"?>
<!DOCTYPE LIGO_LW SYSTEM "Ligolw.dtd">
<LIGO_LW>
<!-- First the Metadata ---------------------------- -->
 <Metadata>
  <Creator>Tom Prince</Creator>
  <Creator>Roy Williams</Creator>
  <Date>28 Sept 98</Date>
  <Comment>LIGO power spectrum of 32 magnetometers at 64 frequencies</Comment>
  <Key>
   <Name>LIGOType</Name>
   <Comment>The Ligo data type is defined here...</Comment>
   <Value>Power Spectrum</Value>
  </Key>
  <Key>
   <Name>StartDate</Name>
   <Comment>Can't remember exactly but this date is close!</Comment>
   <Value>03/21/97</Value>
  </Key>
  <Key>
   <Name>FreqSamp</Name>
   <Unit>Hz</Unit>
   <Comment>This is the sampling frequency</Comment>
   <Value>1024</Value>
  </Key>
 </Metadata>
```

LigoLW - D2
Example -- Data

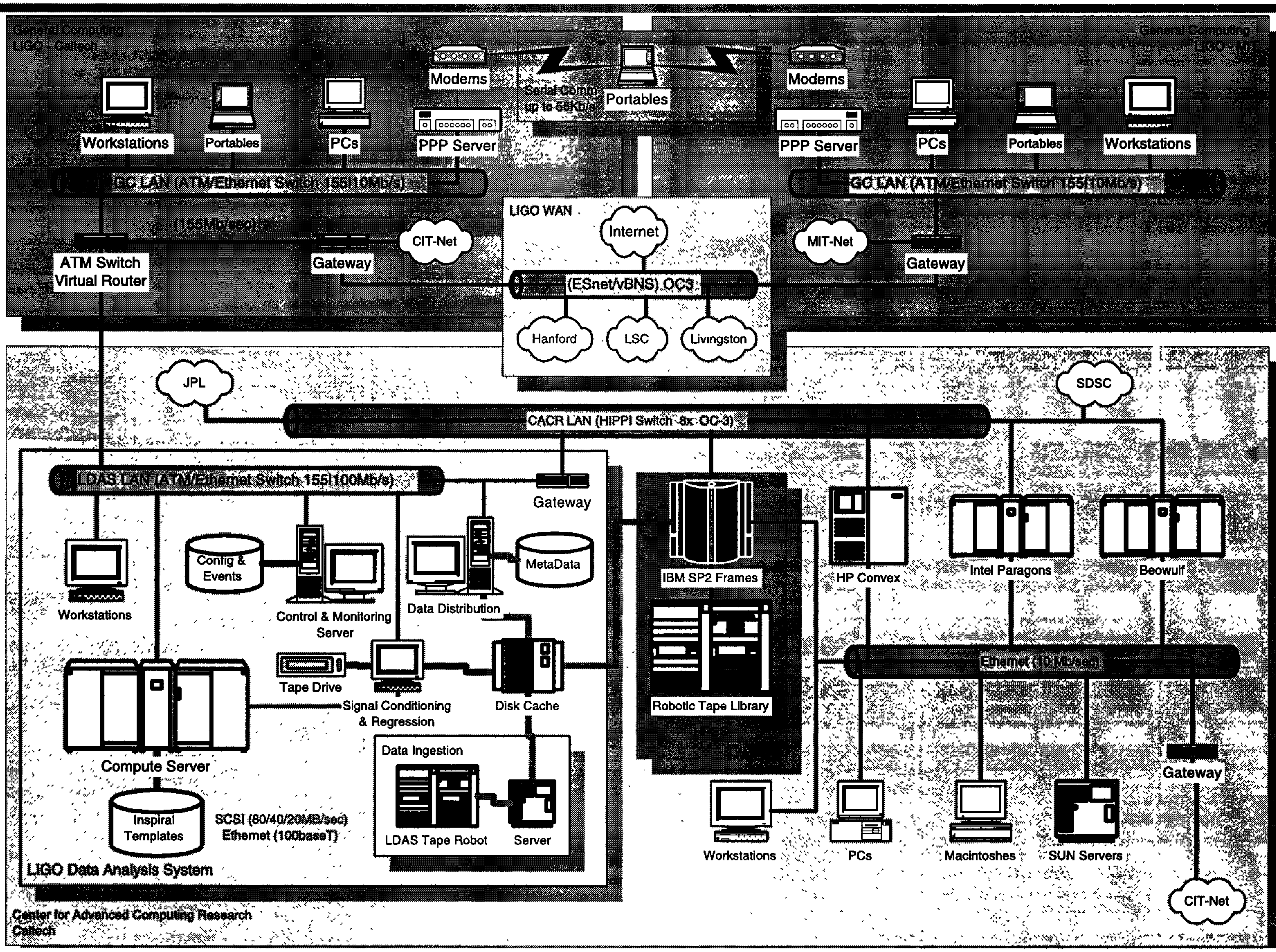
```xml
<!-- Now for the Data objects ------------------------ -->
  <Object>
    <Name>Magnetometer</Name>
    <Array>
      <Dimension>64</Dimension>
      <Dimension>32</Dimension>
      <Type>double</Type>
    </Array>
<!-- This Array is at Cacr, Hanford, and on a tape -->
    <Link>
      <Encoding>bigendian</Encoding>
      <Timeout>600</Timeout>
      <Ref>file://hpss.cacr.caltech.edu/magval_09_25_97.bin</Ref>
    </Link>
    <Link>
      <Encoding>base64</Encoding>
      <Ref>file://hanford.ligo.caltech.edu/magval_09_25_97.bin</Ref>
    </Link>
    <Link>
      <Ref>tape://347846-6/756473</Ref>
    </Link>
  </Object>
  <Object>
    <Name>Magscale</Name>
    <Array><Dimension>32</Dimension></Array>
<!-- Embedded data -->
    <Data>
      1.28374 1.23453 1.94847 2.148474 2.39484 2.84746 3.10928 4.92827
      5.28374 5.23453 5.94847 6.148474 6.39484 6.84746 7.10928 8.92827
      9.28374 9.23453 9.94847 10.18474 10.3984 10.8446 11.1928 12.9827
      13.2874 13.2453 13.9847 14.18474 14.3984 14.8446 15.1928 16.9827
    </Data>
  </Object>
  <Object>
    <Name>Magoffset</Name>
    <Comment>This is the magnetic offset</Comment>
    <Array><Dimension>32</Dimension></Array>
<!-- Data follows from the end of the previous Object in the same stream -->
    <Follows/>
  </Object>
</LIGO_LW>
```

APIs "*TWO-LEVEL*" SOCKET COMMUNICATIONS



API	FW	MPI	DC	EM	CM	FD	MD	ED	SDF	FK	COM	DI	DCS	MAN	RF
FW		mpi								inherit					
MPI	mpi	mpi	socket	socket	socket					inherit					
DC		socket			socket	socket	socket		socket					socket	socket
EM		socket		socket	socket			socket	socket					socket	socket
CM		socket	socket	socket		socket	socket	socket	socket					socket	socket
FD			socket		socket				socket				socket	socket	
MD			socket		socket		socket	socket	socket				socket	socket	
ED				socket	socket		socket	socket	socket					socket	
SDF			socket	socket	socket	socket	socket	socket					socket	socket	socket
FK	inherit	inherit													
COM														socket	
DI													socket		
DCS						socket	socket		socket			socket		socket	
MAN			socket	socket	socket	socket	socket	socket	socket		socket		socket		socket
RF			socket	socket	socket				socket					socket	

LIGO Data Analysis System
Off-line Architecture - F1



LIGO Data Analysis System Hardware Elements - F2

- Provides distributed computing and archival across the four laboratory sites

Hanford: Operations for 2 interferometers

Component	Specification	Cost (K$)
Data distribution system, On-line		
Servers	6ea @ 600MHz	
Disk system	RAID, Ultrawide/fast SCSI 4 ports; shared w/CDS	
	500GB	
Metadata storage system	50GB, Ultrawide/fast SCSI	
Computational engines, On-line		
Signal conditioning, regression engines	4ea @ 600MHz	
Compute server (BEOWULF system, 2 X 10 GFLOPS)	64 nodes @ 600MHz ea, local disk space + RAM	
Control & monitoring	2ea @ 600MHz	
Networking		
Networking switches/routers)	100BT/OC3(ATM)	
ESnet access, hardware required	4 x T1	
Off-line analysis		
Off-line analysis stations	10ea @ 600MHz	
SW & Peripherals	Licenses/printers/plotters/ tape drives/scanners/local SCSI disk/...	
Hanford, total estimated		**$925**

LIGO Data Analysis System Hardware Elements - F3

Livingston: Operations for 1 interferometer

Component	Specification	Cost (K$)
Data distribution system, On-line		
Servers	3ea @ 600MHz	
Disk system	RAID, Ultrawide/fast SCSI 4 ports; shared w/ CDS	
	375	
Metadata storage system	50GB, Ultrawide/fast SCSI	
Computational engines, On-line		
Signal conditioning, regression engines	2ea @ 600MHz	
Compute server (BEOWULF system, 2 X 10 GFLOPS)	32 nodes @ 600MHz ea, local disk space + RAM	
Control & monitoring	1ea @ 600MHz	
Networking		
Networking switches/routers)	100BT/OC3(ATM)	
vBNS access, hardware required		
Off-line analysis		
Off-line analysis stations	7ea @ 600MHz	
SW & Peripherals	Licenses/printers/plotters/ tape drives/scanners/local SCSI disk/...	
Livingston, total estimated		**$545**

LIGO Data Analysis System Hardware Elements - F4

MIT: Data analysis

Component	Specification	Cost (K$)
Off-line analysis		
Off-line analysis stations	10ea @ 600MHz	
Local disk cache	400 GB	
SW & Peripherals	Licenses/printers/plotters/ tape drives/scanners/local SCSI disk/...	
Networking		
Networking switches/routers	100BT/OC3(ATM)	
vBNS hardware/hookup	OC3/ATM	
MIT, total estimated		**$410**

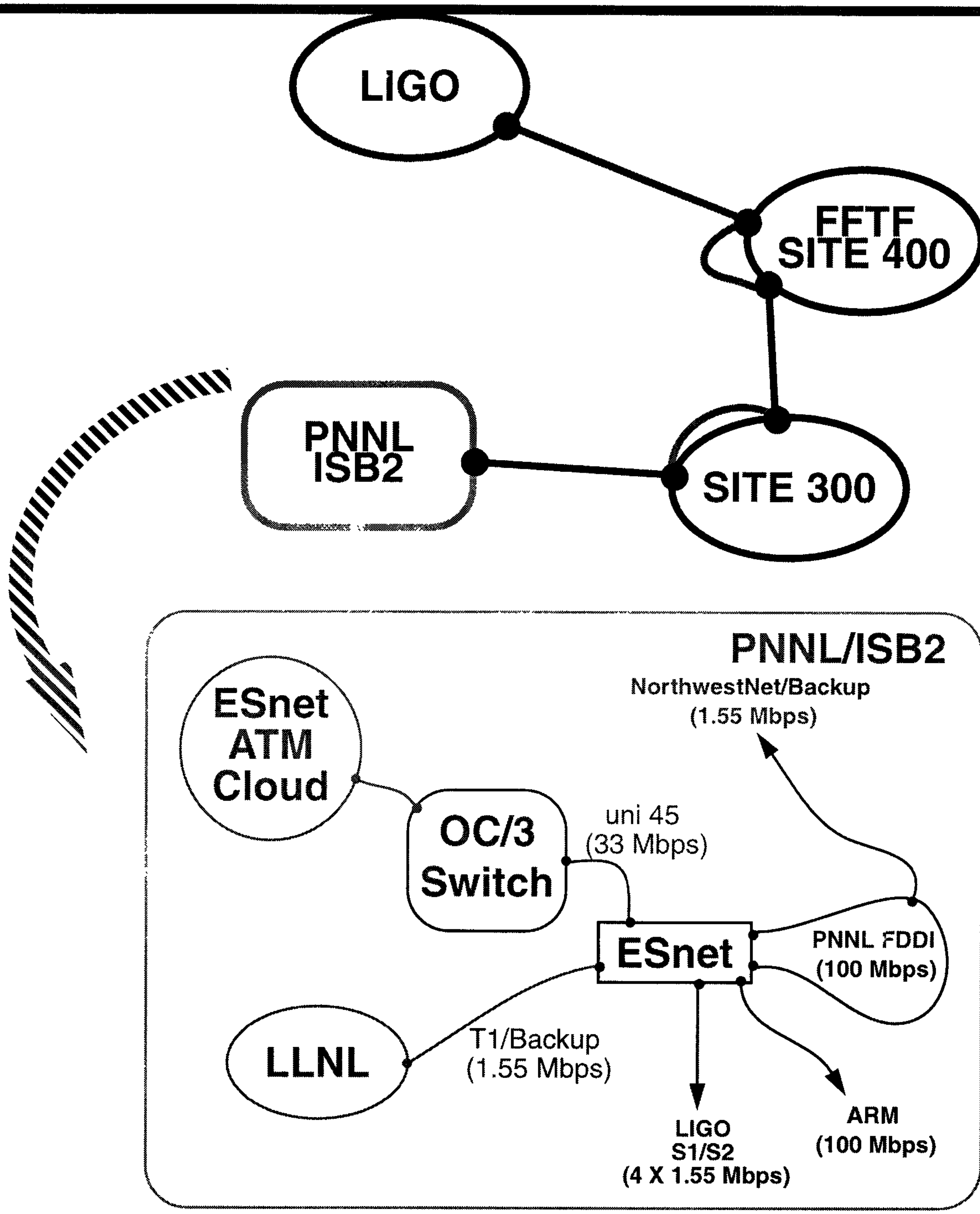
LIGO Data Analysis System Hardware Elements - F5

Caltech: Off-line operations & data analysis

Component	Specification	Cost (K$)
Data distribution system, Off-line		
Tape robots	8ea	
Cabinets	4ea	
Disk Cache	4000 GB, RAID	
Servers	10ea @ 600MHz w/extra memory kits/ATM	
Computational engines, Off-line		
Signal conditioning, regression engines	4ea @ 600MHz	
Compute server (BEOWULF system)	96 nodes @ 600MHz ea, local disk space + RAM	
Post-processing workstations	4ea @ 600MHz	
Networking switches for compute server	100BT/OC3(ATM)	
Networking		
vBNS access, hardware required		
Networking, LAN	100BT/OC3(ATM)	
Off-line analysis		
Off-line analysis stations	15ea @ 600MHz	
SW & Peripherals	Licenses/printers/plotters/ tape drives/scanners/local SCSI disk/...	
Caltech, Off-line total estimated		**$2504**

LIGO Hanford WAN Topology - G1

Link to ESnet



LIGO Livingston WAN Topology - G2

Link to LSU/vBNS