LIGO-G940018-00-M

Parallel Session Agenda
R&D and Detector Fabrication Session

Wednesday, September 21, 1994
Room 360 W. Bridge

9:00 am	Experience Base from Past Work	S. Whitcomb
9:20 am	Lab Visits to View Relevant Set-Ups	
10:45 am	MIT Labs	D. Shoemaker
11:00 am	User Program Discussion (with PM Group, 114 E. Bridge)	
12:00 pm	Lunch	
1-3:00 pm	Detector Cost	
	Interferometer Cost Overview	F. Raab
	Subsystem Details: Optics	R. Savage
	Subsystem Details: Seismic	K. Reithmaier
	CDS Cost Overview	V. Schmidt
	Subsystem Detail	
	Physics Env. Mon/Support Equip.	D. Shoemaker
	Detector Implementation Plan	W. Althouse

Thursday, September 22, 1994

9:30 - 11:00 am	R&D Cost	
	R&D Cost Overview	S. Whitcomb
	Status of Major Tasks	D. Shoemaker & F. Raab

Experience Base for R&D and Detector Cost Estimate

S. Whitcomb

Experience Base for Cost Estimate

- 40–m Interferometer
- 5–m Interferometer
- LIGO-Scale Subsystems
- Tabletop Experiments
- Experience of Other Groups

40–m Interferometer

- Fully Functional Gravitational Wave Interferometer
  - Nominal Gravitational wave Sensitivity Comparable with Best Bar Detectors
- Incorporation of LIGO-Style and –Scale Components and Subsystems Has Been a Major Goal over past several Years
  - Rebuilt in Mark II Configuration
- Comparison with LIGO Interferometers
  - Size

Seismic Isolation Stacks	Approximately One-Half LIGO Scale
Test Masses and Suspension	40% of LIGO Diameter, Full LIGO Thickness
Laser	Full LIGO Power
Mode Cleaner	Currently Much Smaller than LIGO, Planned for Replacement in 1995

  - Complexity

Length Sensing and Control	Two Lengths Contolled vs. Four for LIGO
Alignment System	Includes Local and Optical Lever Sensing, No Wavefront Sensing
Control and Data System	Most Servo Loops Meet LIGO Requirements, Integration with Computer Monitoring and Data Acquisition System Just Beginning

5–m Interferometer

- Testbed for LIGO-Scale Seismic Isolation Stacks
- Test of Active Vibration Isolation System
- Suspended Cavity for Wavefront Sensing Alignment Test
- Reconfiguration for Phase Noise Demonstration In Progress
  - Pre-stabilized Laser
  - LIGO Length Sensing System
  - Next Generation of Optical Suspensions

LIGO-Scale Subsystems

- Pre-stabilized Laser
  - Designed to Meet All Requirements for Initial LIGO Interferometers
  - Stand-alone Tests Complete, Will Be Tested Further with Mode Cleaner
- Mode Cleaner
  - Designed to Meet All Requirements for Initial LIGO Interferometers (Except mounted on Lab-Scale Seismic Isolation Stacks)
  - Testing Underway
- Alignment System
  - Suspended Single Cavity Prototype (at MIT) Demonstrated on 5m Baseline
  - Directly Applicable to LIGO Mode Cleaner
- Optics Components
  - Fabrication and Test of Full-Scale Test Masses Underway
  - Modeling and Analysis of Data From Vendors

Tabletop Experiments

- Length Sensing and Control System
  - Demonstrated on Tabletop Experiments
  - Verified Stability of Servosystem in Operational Mode
  - Similar in Complexity to LIGO Operational Configuration
  - Not a Model for Lock Acquisition
- Alignment System
  - Local Sensors and Optical Levers Used on 40–mand 5–m Interferometers
  - Tabletop Experiments Verify Simplified Coupled Cavity Model for Wavefront Sensing System
  - Test of Full Interferometer Wavefront Sensing in Tabletop Experiment Beginning

Experience of Other Groups

- Stanford
  - Nd:YAG lasers
- Syracuse
  - Fundamental Thermal Noise Studies
- Colorado
  - Active Seismic Isolation
- MPQ Garching
  - Phase Noise
  - Advanced Interferometer Configurations
- VIRGO
  - Advanced Seismic Isolation
  - Control and Data System
- Glasgow
  - Wavefront Sensing
  - Double Pendulum Suspension
- Australian Groups
  - Advanced Seismic Isolation
  - Nd:YAG Lasers
- Japanese Groups
  - Optical Recombination
  - Wavefront Sensing

UNIVERSITY OF FLORIDA

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September 15, 1994

Professor Barry Barish
Caltech
Department of Physics
Pasadena, CA 91125

Dear Professor Barish:

We are writing to express University of Florida's interest in joining the LIGO collaboration. This is a research area which the Department is particularly interested in entering; it is also one where we can provide a strong group of supporting faculty.

We look forward to collaborating with Caltech and MIT in all aspects of the project including the construction phase, the development of hardware and software, and in the subsequent research program. At present we are particularly interested in developing software which could be used in the search for patterns of gravitational wave signals in the presence of various backgrounds.

We look forward to hearing your thoughts about how University of Florida participants can most effectively interact with LIGO.

Sincerely,

Neil Sullivan
Professor and Chair

Charles F. Hooper, Jr.
Professor

cc: G. Mitselmakher

LIGO COLLABORATIVE PROGRAM

Aims:

- Enhance the probability for detection of gravitational waves and the opening of a new field of astrophysics
- Increase the active participation of the scientific and engineering community
- Develop a LIGO user group
- Enhance the effectivness of the scientific constituency for the field

COMMUNICATION

Professional meetings:

- American Physical Society spring meeting (4/94)
- Snowmass APS Particle and Nuclear Astrophysics and Cosmology (7/94)
- Marcel Grossman Conference on Gravitation and Cosmology (7/94)
- International Astronomical Union Symposium (8/94)
- Optical Society of America annual meeting (10/94)
- International Meeting on General Relativity and Gravitation (7/95)

General Workshops:

- Aspen Winter Physics Conference (1/95)

Topical workshops:

- Thermal noise in suspensions and substrates (1/94)
- Coalescing-binary wavforms and data analysis (1/94)
- Optics modeling, fabrication and testing (95)
- Interferometer configurations (95)
- Laser sources (95)
- Data analysis (96)
- Applications of squeezed light to interferometry (96)

Special international collaborative workshops:

- VIRGO/LIGO joint meeting on optical technology (6/93)
- VIRGO/LIGO joint meeting on optical technology (95)

Publications:

- Publication of LIGO research results
- Online (WWW) LIGO publications and selected reports
- LIGO facilities interface document (96)

ORGANIZATION

LIGO Program Advisory Committee LPAC

- Temporary Pre-Program Advisory Committee

  Advise LIGO management on LPAC:

  - composition
  - charter
  - role
- Anticipated roles of LPAC:
  - Report to LIGO management
  - Review proposed internal LIGO scientific activities
  - Review proposed external scientific research in support of LIGO
  - Support review of overall project scientific progress
  - Advise project management on international collaborations and coordinated observations
  - Advise project management on time and beam line allocations in operations of LIGO
  - Advise project management on the collaborative data analysis program

LIGO External Research Coordinator

- Reports to LIGO management

Functions:

  - Point of contact for potential LIGO collaborators
  - Facilitates interaction of collaborator and LIGO team
  - Advises collaborator in formulating proposals

LIGO Research and User's Group

- Organization and charter to be formulated at Aspen workshop
- Includes LIGO collaborators, interested scientists and engineers, LIGO team members
- Chair of group is member of LPAC
- Expected to form subgroups in special disciplines: data analysis, thermal noise,....

International Gravitational-Wave Network

- LIGO to be part of international network
- Enhance science:
  - Source localization
  - Wave polarization
  - Improved detection confidence
- International efforts in long baseline interferometry
  - France/Italy (VIRGO Project)
  - United Kingdom/Germany (GEO Project)
  - Australia (AIGO Project)
  - Japan

MODES AND STYLES OF COLLABORATION

- LIGO opened to many types of collaborative arrangements

Examples:

  - Visitors to work with the LIGO team
  - Collaborators working at home institutions coupled through User's group and LIGO External Research Coordinator
  - Collaborations to develop deliverable hardware and software on project schedule
  - Collaborations to develop new detector systems to follow initial LIGO operations
  - Collaborations in the data analysis
  - Collaborations proposing coordinated astrophysical observations

- Specific collaborative mechanism to be determined by collaborating group and project management.
- Major efforts reviewed by LPAC

NATURE OF COLLABORATIVE RESEARCH

Examples:

- Basic research in physics related to LIGO technologies
- Development of enhancements to initial interferometer
- Development of new interferometer concepts
- Development of second generation detectors
- Development of data analysis algorithms and software
- Calculation of source waveforms and detection filters
- Interpretation of waveforms

CURRENT COLLABORATIONS

- **Experiment:**

P. Bender	Univ of Colorado	Active isolation systems
V. Braginsky	Moscow State Univ	Low loss suspensions
R. Byer	Stanford Univ	Laser sources
R. Drever	Caltech	Advanced interferometers
P. Saulson	Syracuse Univ	Thermal noise

- **Data Analysis:**

C. Cutler	Penn State	A. Oppenheim	MIT
S. Finn	Northwestern	B. S. Sathyaprakash	IUCAA India
E. Flanagan	Univ of Chicago	B. Schutz	Cardiff Wales
K. Kokatos	Greece	J. Shuttleworth	Cardiff Wales
A. Krolak	Warsaw	J. Sussman	MIT
		K. Thorne	Caltech

- **Theory:**

Consortium on Binary Inspiral Waveforms

T. Apostolatos	Jena Germany	M. Sasaki	Kyoto Japan
L. Blanchet	Paris France	G. Schafer	Jena Germany
C. Cutler	Penn State	K. Thorne	Caltech
T. Damour	Paris France	C. Will	Washington Univ
B. R. Iyer	Raman Inst India	A. Wiseman	Caltech
L. Kidder	Northwestern		

Numerical Relativity Grand Challenge Alliance

J. Browne	Univ Texas Austin	E. Seidel	NCSA Univ Ill
C. Evans	Univ N. Carolina	S. Shapiro	Cornell
S. Finn	Northwestern	L. Smarr	NCSA Univ Ill
G. Fox	Syracuse Univ	S. Teukolsky	Cornell
P. Laguna	Penn State	K. Thorne	Caltech
R. Matzner	Univ Texas Austin	J. Winicour	Univ of Pittsburgh
F. Saied	NCSA Univ Ill	J. York	Univ N. Carolina
P. Saylor	NCSA Univ Ill		

Independent programs on final stage of NS/NS coalescence

W. Benz	Arizona	K. Oohara	Kyoto Japan
J. Centrella	Drexel	T. Piran	Harvard
M. Davies	Caltech	F. Rasio	MIT
D. Lai	Caltech	S. Shapiro	Cornell
T. Nakamura	Kyoto Japan	M. Shibata	Osaka Japan
		F. Thielemann	Harvard

GRAVITATIONAL BURST DETECTION STRATEGY

- **Operation of interferometers at widely separated locations**

Coincidence measurements: $R_{12} = \tau_w R_1 R_2$

$$\tau_w = \tau_p + 2D/c$$

$D >$ environmental noise correlation length

- **Operation of an environmental and instrument monitoring system**

Reduce R_1 and R_2.

seismic noise	acoustic noise
magnetic fields	radio frequency interference
cosmic ray showers	electrical power transients
residual gas column density	instrument housekeeping

- **Operation of a half length interferometer at one site**

Gravitational wave signal proportionality to length as a discriminant.

Triple coincidence detection with some correlation due to common vacuum system and location.

$$R_{123} = (\tau_p + 2D/c)\tau_p R_1 R_2 R_3$$

correlations increase accidental triple coincidence by

$$\Delta R_{123} = R_{c1} R_2 (\tau_p + 2D/c)$$

To Stan

Interferometer Cost Overview

F. J. Raab

September 21, 1994

Major Detector Subcategories

WBS No. 1.2 — Detector		Subtotal Estimate	Contingency		Total
WBS Number	Item	$K	%	$K	$K
1.2.1	IFO Design/Fabrication	29,098	33.37	9,710	38,808
1.2.2	Control/Data System	11,456	24.28	2,782	14,238
1.2.3	Physics Monitoring	3,093	5.00	155	3,248
1.2.4	Support Equipment	1,446	5.00	72	1,518

- Interferometer (IFO) consists of seismic isolation, optical components, etc
- Control/Data System is the electronic and computing hardware that makes interferometer components work together and collects data
- Physics Monitoring System collects data on the physical environment of the interferometer for signal verification and certain diagnostics
- Support Equipment is the instrumentation and test equipment used to work on the detector.

Major Interferometer Subcategories

WBS No. 1.2.1 — Interferometer Design/Fabrication		Subtotal Estimate	Contingency		Total
WBS Number	Item	$K	%	$K	$K
1.2.1.1	IFO Design/Non-recurring Items/System Engineering	7,446	34.33	2,556	10,002
1.2.1.2	IFO Fabrication — WA Site	14,706	32.98	4,851	19,557
1.2.1.3	IFO Fabrication — LA Site	6,946	33.15	2,303	9,249

- Each interferometer is of comparable cost (WA has 2) and the total of design, systems engineering and other non-recurring costs is comparable to a single interferometer
- Further breakdown for the interferometer has a high degree of parallelism, corresponding to the major interferometer subsystems
- Interferometer subsystems were chosen to optimize definition of hardware interfaces and responsibilities
- Interferometer Level 4 Categories

Breakdown for Fabrication of One Interferometer

WBS No. 1.2.1.2.1 — WA 4km Interferometer Fabrication		Subtotal Estimate	Contingency		Total
WBS Number	Item	$K	%	$K	$K
1.2.1.2.1.1	Seismic Isolation	2,490	20.29	505	2,995
1.2.1.2.1.2	Prestabilized Laser	292	16.00	47	338
1.2.1.2.1.3	Input/Output Optics	1,288	34.00	438	1,726
1.2.1.2.1.4	Core Optics Components	1,184	50.00	592	1,776
1.2.1.2.1.5	Core Optics Support	614	50.00	307	922
1.2.1.2.1.6	Alignment Sensing/Control	1,024	28.00	287	1,311
1.2.1.2.1.7	Length Sensing/Control	131	52.00	68	199
WBS No. 1.2.1.2.1 Subtotals		7,023	31.95	2,244	9,267

- Breakdown for each interferometer is similar at level 6
- Breakdown for WBS No. 1.2.1.1, Design/Non-recurring Items/Systems Engineering, runs parallel at level 5

Breakdown for Interferometer Design/Non-recurring Items/Systems Engineering

WBS No. 1.2.1.1 — IFOs Design/Non-recurring Items/Systems Eng.		Subtotal Estimate	Contingency		Total
WBS Number	Item	$K	%	$K	$K
1.2.1.1.1	Seismic Isolation	916	29.36	269	1,185
1.2.1.1.2	Prestabilized Laser	212	25.00	53	265
1.2.1.1.3	Input/Output Optics	429	31.00	133	561
1.2.1.1.4	Core Optics Components	1,756	43.00	755	2,510
1.2.1.1.5	Core Optics Support	215	39.01	84	298
1.2.1.1.6	Alignment Sensing/Control	1,177	35.00	412	1,589
1.2.1.1.7	Length Sensing/Control	258	39.00	101	358
1.2.1.1.8	Suspension Design	503	31.00	156	659
1.2.1.1.9	IFO Systems & Integration Eng.	1,982	30.00	594	2,576
WBS No. 1.2.1.1 Subtotals		7,446	34.33	2,556	10,002

How Costs Were Generated

- Define subsystems, exercising care to arrive at clean interfaces
- Assign knowledgeable people to each subsystem, who will likely be involved in the actual design and fabrication of the subsystem
- Break down subsystem into component parts and subassemblies
- Develop costs for design phase:
  - Assess complexity of subassemblies, maturity of design and/or experience with similar systems, to estimate manpower for design
  - Assess whether prototype testing or separate first-article production is warranted (generate estimates for manpower and materials when appropriate)
  - Estimate any other non-recurring costs associated with this subsystem that are not directly assignable to a particular interferometer
  - Estimate manpower for documentation and subsystem reviews
- Develop costs for fabrication phase:
  - manpower for component procurement
  - manpower for in-house fabrication, assembly and testing
  - cost of purchased components and subassemblies
- Estimate costs for contracts and travel which support design or fabrication activities
- Estimate contingency

Example: Generate Manpower Estimate for Design of a Mechanical Subassembly

- Assume enabling R&D is completed
- Identify how many drawings are needed for fabrication
- Estimate the level of complexity of the drawings
- Determine whether the design can be supported by simple design rules or if finite-element or other modeling is required
- Estimate manpower required to produce drawings
- Estimate how much scientific or technician support is needed for this phase
- Determine whether there will be a prototyping phase and what level of scientific, engineering and technician support will be required

Example: Generate Materials Estimate for Subassembly

- For standard components, use catalog prices, vendor quotations or data from previous purchases
- For non-standard components, develop engineering estimates based on
  - — level of complexity in component
  - — level of difficulty in achieving specification
  - — number and type of operations in fabrication
  - — appropriate scaling rules (especially where size, weight, etc. are expected to dominate costs)
- Estimate costs of fabrication tooling and other special hardware required for production
- Estimate costs of cleaning, vacuum preparation/certification, crating, etc.

Considerations Used to Determine Contingency

- Assessment of maturity of design
  - maturity of R&D
  - status of conceptual design
  - comparable experience with detailed design
  - comparable experience with fabrication
- Assessment of difficulty in achieving specification
- Assessment of degree of interaction of various specifications
- Assessment of risk of production delays, price increases, etc.

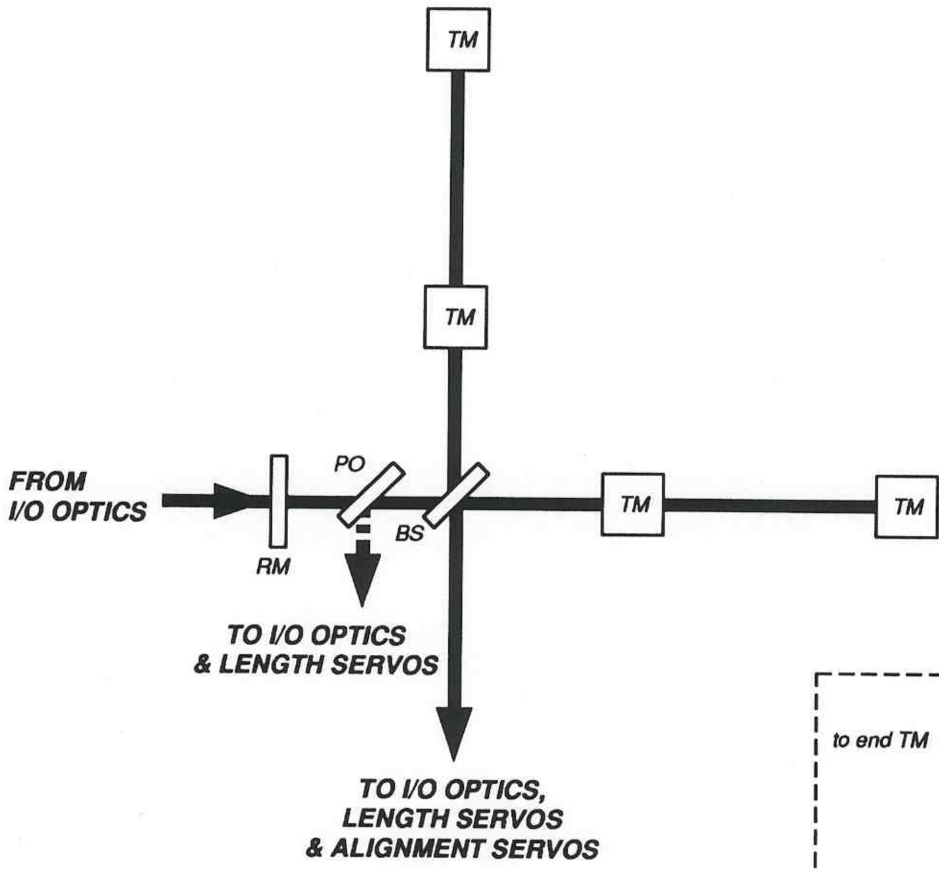
Core Optics Components

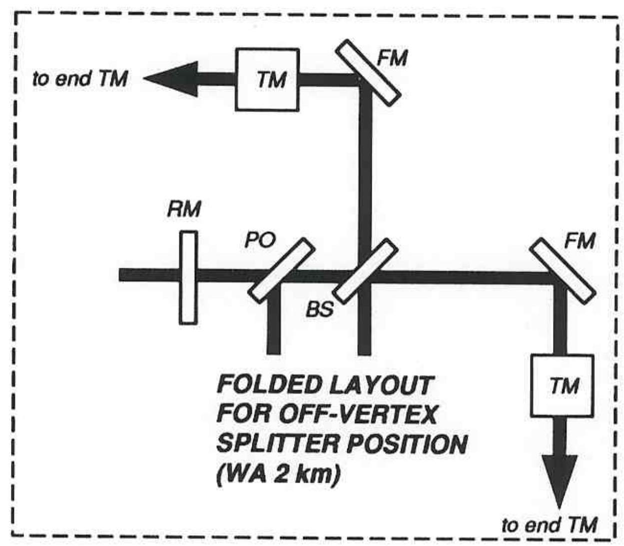
R. Savage
(D. Jungwirth)

September 21, 1994

Cost Overview – Core Optics Components

WBS Number	Item	Cost ($k)	Contingency		Total Cost ($k)
			(%)	($k)	
1.2.1.1.4	Design/NR Costs/SE	1,755.7	43	754.9	2,510.6
1.2.1.2.1.4	WA 4km	1,184.0	50	592.1	1,776.1
1.2.1.2.2.4	WA 2km	1,592.7	50	796.4	2,389.1
1.2.1.3.1.4	LA 4km	1,184.0	50	592.1	1,776.1
TOTAL		**5,716.4**		**2,735.5**	**8,451.9**





CORE OPTICS
mez 7/12/94
rev'd 8/9/94

Parts Count – Core Optics Components

Description	Sub-strate	WA 4km	WA 2km	LA 4km	Spares	Total
Recycling Mirror - 4km	S1	1	0	1	2	4
Recycling Mirror - 2km	S1	0	1	0	2	3
Pickoff	S2	1	1	1	2	5
Beamsplitter	S3	1	1	1	2	5
Input Test Mass - 4km	S1	2	0	2	2	6
Input Test Mass - 2km	S1	0	2	0	2	4
End Test Mass - 4km	S1	2	0	2	2	6
End Test Mass - 2km	S1	0	2	0	2	4
Fold Mirror - 2km	S1	0	2	0	2	4
TOTAL		**7**	**9**	**7**	**18**	**41***

- Spares policy – maintain an inventory of two spares of each **type** of optic. Once the first spare is required, begin fabrication of a replacement spare.

* Eight substrate spares will be procured to cover losses during fabrication.

Fabrication Spares – Core Optics Components

Substrate Type	Number Required	Fabrication Spares	Total
S1	31	4	35
S2	5	2	7
S3	5	2	7
TOTAL	**41**	**8**	**49**

Performance Specifications – Core Optics Components

- Initial LIGO detector performance goals drive optics performance specifications.
- Extensive modeling effort – Fast Fourier transform interferometer simulator.
- Analysis of Hughes Danbury Optical Systems (HDOS) AXAF project calibration flat.
- Performance specifications in draft form – not yet reviewed internally.
- Polishing, coating, and metrology requests for quotations in draft form.

CORE OPTICS

Components: WBS 1.2.1.1.4, 1.2.1.2.1.4, 1.2.1.2.2.4, 1.2.1.3.1.4
Support: WBS 1.2.1.1.5, 1.2.1.2.1.5, 1.2.1.2.2.5, 1.2.1.3.1.5

Large aperture optical elements, including test masses, beam splitters, recycling mirrors

		Subtotal Estimate ($K)	Contingency Allocation (%)	Contingency Allocation ($K)	Total Cost ($K)
Design:		1,971	43	839	2,808
Fab:	WA 4 km	1,798	50	899	2,698
	WA 2 km	2,325	50	1,162	3,487
	LA 4 km	1,798	56	970	2,769
		7,892		3,870	11,762

1. CORE OPTICS COMPONENTS

The challenge: To combine "Large Optics" technology (e.g., astron. telescopes, 5000 ppm) with "Small Optics" (e.g., laser gyro, 10 ppm) "supermirror" technology.

typically: 25 cm diam.
10 cm thick

7 to 9 suspended Core Optics/IFO

Requirement:

Substrate: OAA fused silica
homogeneity: $< 5 \times 10^{-7}$ entire aperture

Surface specs:

figure errors:

$< \lambda/600$ rms over central 8 cm
$< \lambda/400$ rms over central 20 cm

scatter:

< 100 ppm over *all* spatial frequencies

absorption:

1 ppm differential between mirrors
< 5 ppm overall (4 kw circulating power)

metrology specs:

state of the art (AXAF)
$\lambda/500$ absolute calibration over 20 cm diam.

mechanical Q's:

$\gtrsim 2 \times 10^6$

2. CORE OPTICS SUPPORT

Suspensions

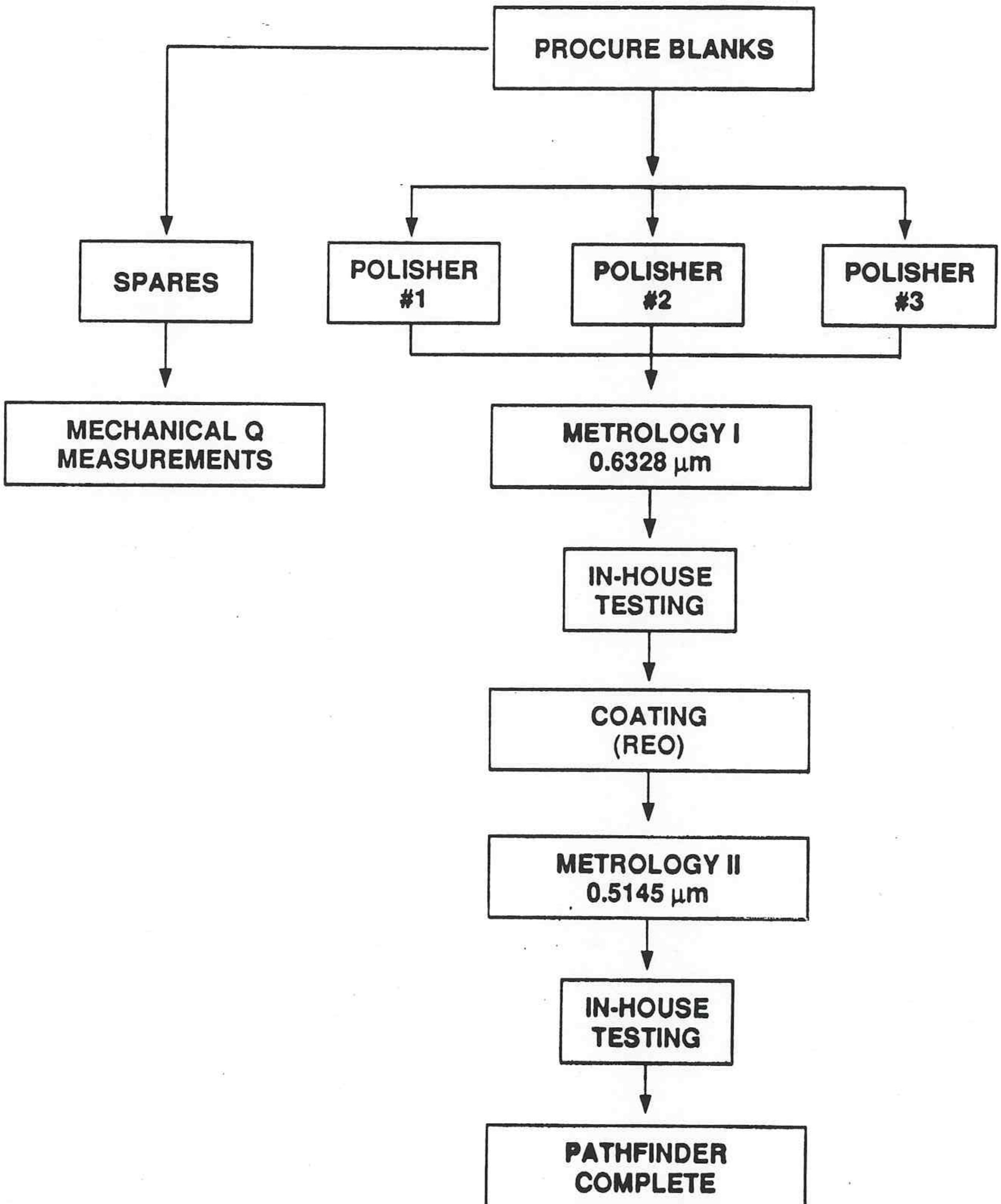
Beam Blocks

Baffles

Status: R&D complete

Next: "Pathfinder" task
"Suspension" task

PATHFINDER PROCESS



LIGO

MATERIALS - CORE OPTICS COMPONENTS

Tasks	Number	Spares	Total	Unit Cost	Total Cost	WA 4Km (30%) Number Needed	WA 4Km (30%) Total Cost	WA 2Km (40%) Number Needed	WA 2Km (40%) Total Cost	LA 4Km (30%) Number Needed	LA 4Km (30%) Total Cost
Fused Silica Blanks	23	26	49	18	882	14.5	261	20	360	14.5	261
Polishing	23	22	45	40	1800	13.5	540	18	720	13.5	540
Coating (Surfaces)	46	36	82	3	246	24.5	73.5	33	99	24.5	73.5
Metrology (Surfaces)	46	44	90	1.5	135	27	40.5	36	54	27	40.5
Shipping Containers	41		41	1.5	61.5	12.25	18.375	16.5	24.75	12.25	18.375
Shipping Costs	82		82	0.05	4.1	24.6	1.23	32.8	1.64	24.6	1.23
In-House Measuremer					0		0		0		0
Analysis					0		0		0		0
Fabrication Task					0		0		0		0
Oversight					0		0		0		0
			TOTAL		**3128.6**		**934.605**		**1259.39**		**934.61**

Cost Summary – Core Optics Components

WBS Number	Item		Cost ($k)	Contingency (%)	Contingency ($k)	Sub Totals ($k)	Totals ($k)
1.2.1.1.4	Design	Manpower	1,018.9	43	438.1	1,457.0	2,510.6
		Materials	736.8		316.8	1,053.6	
1.2.1.2.1.4	WA 4km	Manpower	249.4	50	124.7	374.1	1,776.1
		Materials	934.6		467.3	1,401.9	
1.2.1.2.2.4	WA 2km	Manpower	333.3	50	166.7	500.0	2,389.1
		Materials	1,259.4		629.7	1,889.1	
1.2.1.3.1.4	LA 4km	Manpower	249.4	50	124.7	374.1	1.776.1
		Materials	934.6		467.3	1,401.9	
Sub Totals		Manpower	1,851.0	49	854.2	2,705.2	
		Materials	3,865.4		1,881.1	5,746.5	
TOTALS			**5,716.4**	**49**	**2,735.5**		**8,451.9**

LIGO Control and Data System

15 September 94

LIGO CDS team

(R. Bork, J. Chapsky,

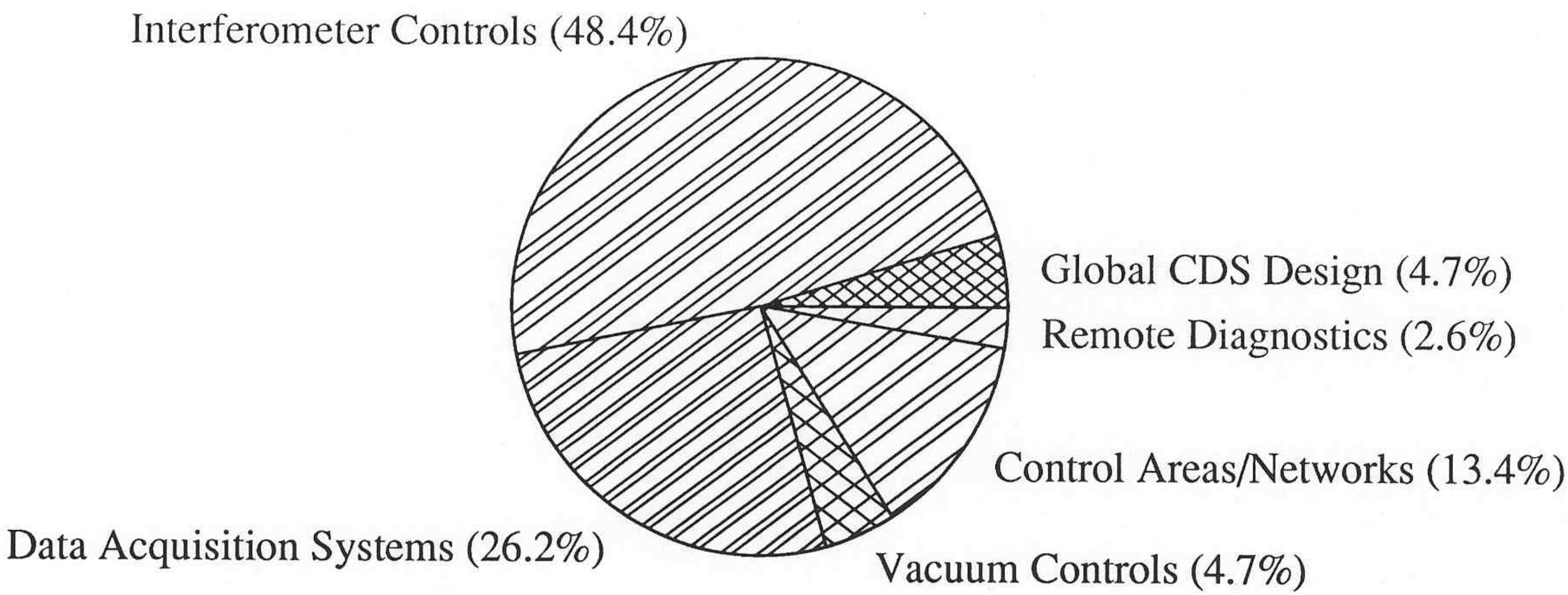
J. Heefner, V. Schmidt)

The LIGO Control and Data System (CDS)

- Scope
- CDS Functional Structure
- Interferometer Controls
- Data Acquisition Systems
- Vacuum Control and Monitoring
- CDS System Aspects
- Remote Diagnostics
- CDS Design Approach

CDS cost distribution by system

Total cost 14,238 k$



WBS title	estimate k$	contingency %	contingency k$	total k$	% of total CDS
Global CDS Design	545	24.0%	131	675	4.7%
Interferometer Controls	5,241	31.6%	1,657	6,897	48.4%
Data Acquisition Systems	3,172	17.5%	556	3,726	26.2%
Vacuum Controls	561	18.5%	104	666	4.7%
Control Areas / Networks	1,617	17.8%	287	1,903	13.4%
Remote Diagnostics	322	15.2%	49	370	2.6%
CDS	*11,456*	*24.3%*	*2,782*	*14,238*	

Table X CDS cost distribution by system

Scope of CDS

- remote plant operation from a central control room at each facility
- interferometer controls
- acquisition of interferometer data
- acquisition of physics monitoring data
- data handling and archiving
- remote diagnostic function

CDS Functional Structure

- CDS is organized in functional systems
- Each functional system is as far as possible autonomous
- CDS functional system structure matches LIGO functional structure
- CDS WBS structure matches functional structure

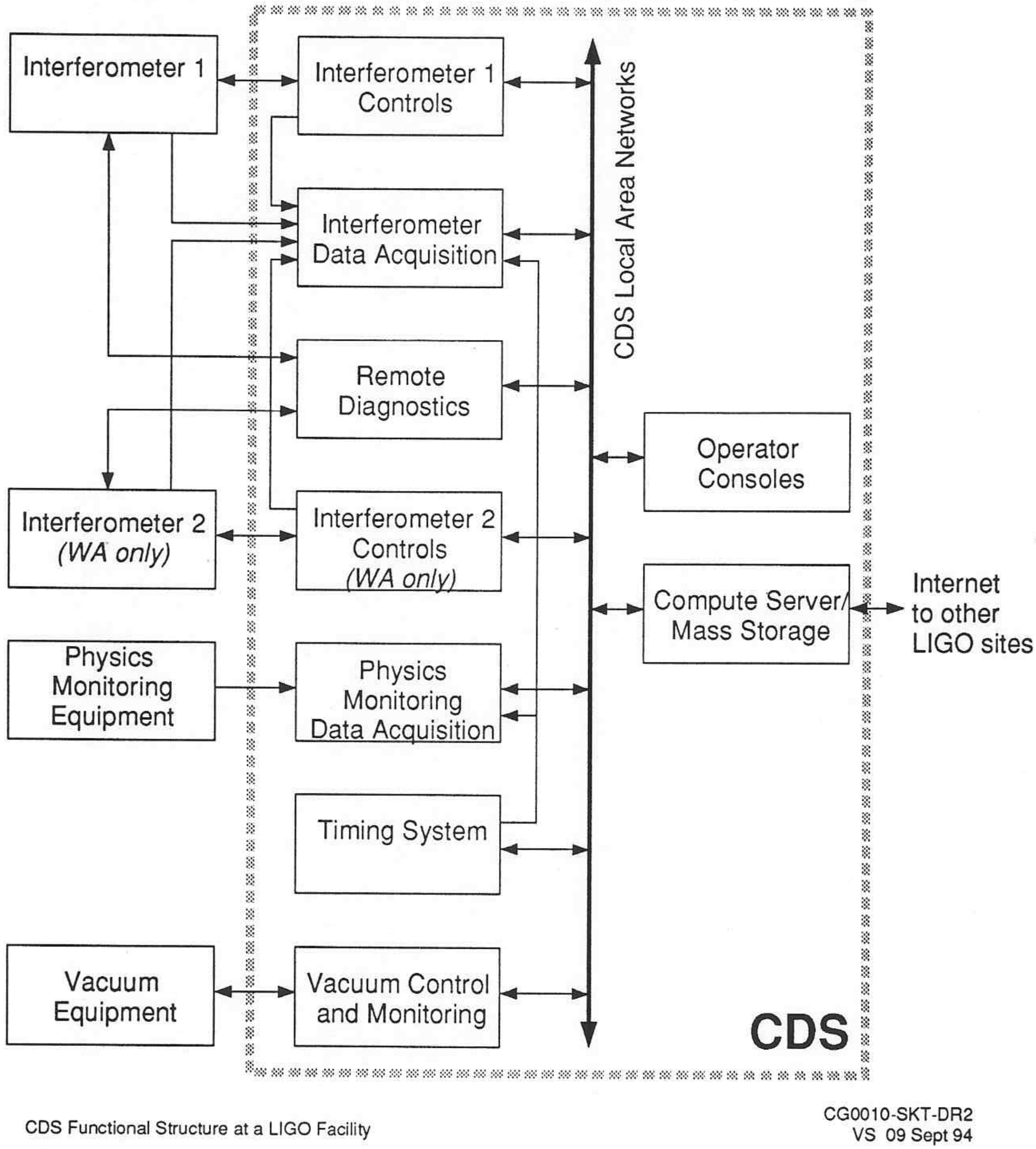


Figure 1: CDS Functional Structure

Cost

WBS	WBS title	estimate k$	contingency %	contingency k$	total k$
1.2.2.1.9	**CDS Global Design** *(includes k$ 124 for test rigs for VME equipment and 114 k$ for travel)*	545	24.0%	131	**675**
	% of total CDS				***4.7%***

Interferometer Controls

Scope

LIGO interferometers will be equipped with a large number of servo loops for:

- frequency control
- intensity stabilizing
- attitude control
- positioning control

Implementation

- Servo loops are implemented as analogue feedback loops.
- Servo loop electronics will be implemented on semi custom VME modules.
- Each module consists of two half boards:
  - a standard backplane interface with a set of components for binary and analogue input/output
  - a purpose-built board with the specific servo loop components
- data acquisition channels are independent from control and monitoring channels
- The servo loops are remotely monitored and controlled from the LIGO control rooms. This includes the execution of "high-level", slow servo loops.
- EPICS software tools are used for operation

Interferometer Controls – Cost

WBS	WBS title	estimate k$	contingency %	contingency k$	total k$
1.2.2.1.1	Interferometer Controls Design	2083	28%	583	2666
1.2.2.2.1	WA 4km Interferometer Controls	1095	34%	372	1467
1.2.2.2.2	WA 2km Interferometer Controls	961	34%	327	1287
1.2.2.3.1	LA 4km Interferometer Controls	1102	34%	375	1477
	Total Interferometer Controls	*5241*	*31.6%*	*1657*	***6897***
	% of total CDS				***48.4%***

Data Acquisition Systems

Scope

Data have to be acquired from

- the interferometers
- the physics monitoring instruments
- some facility monitoring signals

signal class	sampling rate	site	number of channels	data rate (MBytes/s)
"fast" interferometer data	20 kHz	WA	260	10.400
		LA	130	5.200
"slow" interferometer data	2 Hz ... 2 kHz	WA	2500	1.000
		LA	1250	0.500
"fast" physics monitoring data	2.5 kHz	WA	263	1.315
		LA	162	0.810
"slow" physics monitoring data	0.1 ... 25Hz	WA	82	0.001
		LA	61	0.001
total Data Acquisition Systems		**WA**	**3105**	**12.7**
		LA	**1603**	**6.5**

Table 1 Data Acquisition Rates

(Data Acquisition Systems) Implementation

- Both data acquisition systems use identical software and hardware components
- Both systems share the GPS (General Positioning System) based precision timing (microsecond range precision between sites)
- VME as front-end standard
- Both systems share the communication systems, the compute servers, and data archiving tape units
- on-site 19 mm tape storage

Data Acquisition Systems – Cost

WBS	WBS title	estimate k$	contingency %	contingency k$	total k$
1.2.2.1.3	Interferometer Data Acquisition Design	689	18%	124	813
1.2.2.2.3	WA Interferometer Data Acquisition	920	20%	184	1104
1.2.2.3.3	LA Interferometer Data Acquisition	488	20%	98	586
1.2.2.1.4	Physics Monitoring Data Acquisition Design	156	12%	19	174
1.2.2.2.4	WA Physics Monitoring Data Acquisition	325	14%	46	371
1.2.2.3.4	LA Physics Monitoring Data Acquisition	330	14%	46	376
1.2.2.1.7	Timing System Design	129	14%	18	147
1.2.2.2.7	WATiming System	84	15%	13	97
1.2.2.3.7	LA Timing System	51	15%	8	58
	Total Data Acquisition Systems	3172	17.5%	556	***3726***
	% of total CDS				***26.2%***

Vacuum Control and Monitoring

Scope

The Vacuum CDS provides all components for the integrated operation of the LIGO vacuum systems. This includes

- issuing of commands and command sequences
- status monitoring
- alarm handling
- trend recording
- graphical user interface

Implementation

- Programmable Logic Controller (PLC) solution
- 2000 I/O points, 10 PLCs (WA + LA)
- software development will be made independent from the PLC manufacturer by using third party software which is suitable for different PLC makes
- The user interface (consoles) is based on the EPICS GUI tools
- a name server is needed between the PLC front-end equipment which uses an addressing scheme based on the location of the signals (physical addressing) and the EPICS console software which uses a name-based addressing scheme.

Cost

WBS	WBS title	estimate k$	contingency %	k$	total k$
1.2.2.1.5	Vacuum Controls Design	206	16%	33	239
1.2.2.2.5	WA Vacuum Controls	211	20%	42	254
1.2.2.3.5	LA Vacuum Controls	144	20%	29	173
	Total Vacuum Controls	*561*	*18.5%*	*104*	***666***
	% of total CDS				***4.7%***

CDS System aspects

CDS Software and Hardware Standards

- UNIX as operating system for User consoles and compute servers
- EPICS (*) software tools for control and monitoring front-end
- VxWorks as operating system on the front-end computers (I/O controllers)
- front-end electronics: VME
- front-end controllers: Motorola 68000 based VME controllers
- all servoloop amplifier modules use identical back half board
- all data acquisition channels use the same VME ADC module

(*) EPICS – "Experimental Physics and Industrial Control System"

- provides tools for
  - distributed database
  - interactive, graphical operator interface
  - data logging
  - alarm handling
  - sequential control
- EPICS is jointly developed and maintained by several major accelerator labs (Los Alamos, Argonne, CEBAF, LBL)
- It is in use at some twenty large physics installations and (optical) telescopes worldwide.

CDS Communication and Computers

Two communication networks:

- Ethernet
  - for control and monitoring components
  - for all user consoles
  - mixed fibre-optic and copper implementation
- Fiber Channel
  - for data acquisition components
  - all fibre-optic implementation
  - fast: 255 Mbit/s per connection

Computers:

- user consoles: UNIX workstations (SPARCstations)
- central compute servers: UNIX systems (SPARCcenter)
- mass storage: RAID plus 19mm cartridge tape

Cost

WBS	WBS title	estimate k$	contingency %	k$	total k$
1.2.2.1.6	Control Area and Networking Systems Design	224	16%	36	259
1.2.2.2.6	WA Control Area and Networking Systems	793	18%	143	936
1.2.2.3.6	LA Control Area and Networking Systems	600	18%	108	708
	Total Control Area and Networking Systems	*1617*	*17.8%*	*287*	***1903***
	% of total CDS				***13.4%***

Remote Diagnostics

Scope

To provide remotely operated diagnostics for the interferometers for

- characterization
- improvement
- trouble shooting

Features

- injection of arbitrary shape test signals at selectable test points in the system
- remote oscilloscope function (up to 70 MHz) at selectable test points
- possibility to observe reaction of the instrument to controlled disturbances
- works in conjunction with the normal data acquisition system

Cost

WBS	WBS title	estimate k$	contingency %	contingency k$	total k$
1.2.2.1.8	Remote Diagnostics Design	113	18%	20	133
1.2.2.2.8	WA Remote Diagnostics	139	14%	19	158
1.2.2.3.8	LA Remote Diagnostics	70	14%	10	79
	Total Remote Diagnostics	*322*	*15.2%*	*49*	***370***
	% of total CDS				***2.6%***

CDS Design Approach

Technology

- use existing industry standards
  - VME for front-end electronics
  - UNIX operating system for all back-end computers and workstations
  - VxWorks real time operating system in all front-end computers
  - GPS-based timing system
- use existing technology wherever possible
  - computers and communication (sw and hw) are catalogue items
  - all VME system components are catalogue items
  - off-the-shelf system software (EPICS) for control and monitoring tasks
  - industrial type control and monitoring equipment for Vacuum controls
- standardization of components
  - one type of ADC module (purpose built) for all data acquisition channels
  - one type of VME local controller
  - SPARC computers and workstations
  - all servoloop VME modules have the same "back" half board as interface to the VME bus
- avoid in-house developments

Open Issues

- no major open issues

Major risks

- interferometer control loops (technical/cost/schedule risk mainly due to possible requirement changes during interferometer development)
- data acquisition and archiving software are new developments and subject to the normal schedule/cost risk of new software developments
- data acquisition rate
  - a modest increase in data or channel rate (up to about 25%) could possibly be absorbed without cost effect and with only minor performance degradation
  - a moderate increase (less then three-fold increase in data rate) would cause a roughly proportional increase in cost
  - a more than three-fold increase in data acquisition rate (approaching 32 MBytes at one facility) would cause an additional jump in cost:
    - it would require a different technical solution for the fast communication network
    - it would require a different technical solution for the data storage

R&D: Cost Summary

S. Whitcomb

R&D Costs

Scope

- Lab Operations: All Laboratory Expenses for Maintenance and Operation not Identified with Specific Deliverable Item
  - Laboratory Supplies (solvents, small electronic components, cables, cleanroom supplies, vacuum supplies, etc)
  - Equipment Maintenance (maintenance contracts for major pieces of equipment, repairs to electronics, preventative maintenance for vacuum equipment)
  - Small Equipment (tools, multimeters, minor machining expenses for general laboratory fixtures, general purpose laboratory software)
  - General Purpose Laboratory Equipment (oscilloscopes, power supplies and filters, vacuum equipment)
- R&D Tasks
  - R&D Tasks to Support Design of Initial LIGO Interferometers
  - R&D Tasks to Develop Techniques for Subsequent Advanced Interferometers

Lab Operations

Cost Estimate

	Estimate		Contingency		Total
Labor	$2,085k	36.3%			
Material	3,655	63.7%			
Total	$5,740k		$675k	11.8%	$6,416k

Basis of Estimate	Estimate	Percentage
Actual Costs	$1,289k	19.3%
1994 (Nearly Actual)	893	13.9%
Engineering Estimate	4,284	66.8%

Estimating Method

- Use 1991–93 Actuals to Calculate Average Cost per Person Working in Lab for Lab Supplies, General Equipment, Etc.
- Project Costs By Scaling to Number of Staff (Scientists, Engineers, Graduate Students) Planned for R&D and Detector Development

Lab Operations

Contingency

- Cost Estimating Plan Contingency Assignment Method Not Applicable
- Have Assigned 15% Contingency to All Future Lab Operations Expenses
- Risks:
  - Possible Increase of Staff Over Projection
  - Possible Higher Usage of Lab Supplies During Detector Fabrication Phase

R&D Tasks

Cost Estimate

	Estimate		Contingency		Total
Labor	$13,359k	78.8%			
Material	3,388	20.0%			
Subcontract	200	1.2%			
Total	$16,947k	100.0%	$3,435k	20.3%	$20,383k

Basis of Estimate	Estimate	Percentage
Actual Costs	$5,497k	27.0%
1994 (Nearly Actual)	4,161	20.4%
Vendor Quote	650	3.2%
Engineering Estimate	$10,075k	49.4%

Estimating Method

- Scheduled R&D Tasks Leading to Initial Interferometers
  - Determine Scope and Duration of Task
  - Breakdown of Materials by Experienced, Involved Scientists
  - Estimate of Labor by Consensus of Senior Scientists
- After Initial Interferometer design Freeze
  - Select a Set of Representative R&D Tasks Leading toward Advanced Interferometers
  - Estimates Complexity Relative to Similar Past Efforts and Scale accordingly

R&D Tasks

Contingency

- Cost Estimating Plan Contingency Assignment Method Not Applicable
- Have Assigned 30% Contingency to All Future R&D Tasks
- Risk Issues:
  - In General, R&D Tasks Intrinsically Have High Technical and Schedule Risk
  - Initial Interferometer R&D Tasks Are Aimed at Integrating Existing Technologies Rather than Developing New Technologies
    - Relatively Lower Risk
  - Advanced Interferometer R&D Has High Risk, But Limited Impact on Other Parts of Project
- Effectiveness of Contingency Limited for R&D Tasks
  - Ability to Add Qualified Personnel to Cope with Problem Areas Limited
    - Technicians: Relatively Easy
    - Engineers: Possible in Most Areas
    - Scientists: More Difficult in Some Areas
  - Equipment Expenditures Can Sometimes Resolve Unforeseen Problems

Recombination and Recycling			
Key Dates (FY95)			
•Completion of recombination installation and characterization			Apr 1995
•Review of experimental plan for recycling			Aug 1995
•Completion of recycling installation and characterization			Jul 1996
Budget	**FY94**	**FY95**	**FY96**
Material	$47,500	$142,500	–
Labor			
Scientist	–	12 m/m	6 m/m
Engineer	–	6	3
Grad Student	–	12	6
Technician	–	6	6

- Materials:
  - Vacuum system modifications
  - New suspended optic and controls
  - New servo electronics
  - New modulators
- Basis: Detailed parts list

Phase Noise Demonstration

Key Dates (FY95)			
•Initial operation with asymmetry readout			Feb 1995
•Installation of mode cleaner complete			Sept 1995
•Completion of high power performance characterization			May 1996

Budget	FY94	FY95	FY96
Material	$350,000	$150,000	nil
Labor			
Scientist	–	24 m/m	12 m/m
Engineer [a]	–	2	
Graduate Student	–	24	12
Technician[b]	–	6	3

[a]Cost of contract engineer included under materials

[b]Cost of contract technician included under materials

- Materials:
  - pre-stabilized laser
  - optic suspensions and isolation stacks
  - vacuum system modifications
- Basis: detailed parts list and SOW

LIGO

R&D Tasks

Task Management

- Tasks Identified and Responsible Scientist Assigned
- Statement of Work (Including Scope, Schedule, Budget and Milestones) Negotiated with Project Management
- Regular Reporting on Progress
    - Contributions to Project Weekly Report (Circulated by e-mail to All Project Staff)
    - More Detailed Reports by Responsible Scientist to R&D Group Leaders, either Through Regular Meetings and/or Periodic Written Reports
    - Monthly Budget Update
- Focus on Early Problem Identification and Resolution