LIGO-T000147-00-D

Date: Thu, 25 May 2000 15:36:49 -0700
From: Dennis Coyne <coyne@ligo.caltech.edu>
X-Mailer: Mozilla 4.7 [en] (Win98; I)
X-Accept-Language: en
To: Fred Asiri <fba@ligo.caltech.edu>
Subject: LIGO-II Proposal Input for SEI

Attached is a draft proposal outline from Gary Sanders.

Also attached is:

1) my stab at a schedule & assignments for the SUS as an example -- we need to make one for the SEI subsystem.

2) an example WBS dictionary -- this needs to be fleshed out for SEI

Additional information is available at:

1) The LIGO-II site:
http://www.ligo.caltech.edu/~ligo2/

2) The WBS file is at

\\Pictor\p3win\Data\wbs_v6.xls

For Unix, the \ are /

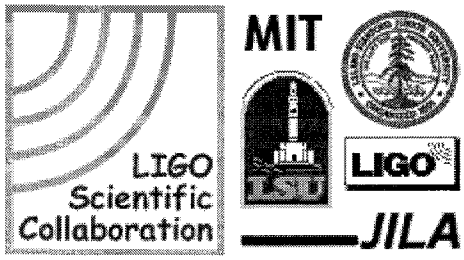
3) The SEI documents you alreafy have I think.

Dennis

proposal_outline_v1.PDF (#1)

wbs_dictionary_v1.PDF (#2)

proposal_v1_SUS.gif (#1)



A Proposed LIGO-II Seismic Isolation System by LSC members at Stanford, JILA, MIT, and LSU.

Some computer renderings and recent photos of our designs and prototype tests.

Documents requested by Technical Advisory Group:

Please note that most of these were made with Acrobat version 4, so cannot be read with version 3 readers. The Acrobat reader version 4 is now available for most all platforms at the Adobe site.

1. A Prototype Test Program Plan. Current version: 1.0, Feb 14, 2000. (LIGO-T000015-00) (#3)
2. Simulation Plan. Current version: 1.0.1, Feb 14, 2000. (LIGO-T000016-01)) (#3)
3. Baseline LIGO-II Implementation Design Description. (LIGO-T000024-00-U) (#5)

Additional Documents:

- 4/27/2000 Brief report of the latest single-stage prototype performance at Stanford. (#6)
- Slides presented at the March 2000 LSC Meeting, presenting the reference design.
- The most recent (I hope!) LIGO-II Seismic Isolation Design Requirements Document. (#4)
- Scanned spec sheets of a key low-noise seismometer in our design, the Streckeisen STS-2. (#7)
- The RSI paper from the JILA Group, describing their two-stage, 12-DOF active seismic isolation platform
- An interesting paper from the Univ. of Washington, describing a 6-DOF active isolation system.
- A huge file with complete transparencies from the Glasgow meeting, at which we tried to set interface requirements between the Seismic isolation and Suspension systems.
- "How to Construct a Mechanical Model of a Mass-Spring System," by Wensheng Hua.
- "LIGO-II Suspension: Reference Designs," by the Univ. of Glasgow GEO group, 31-Jan-00.
- "Quiet Hydraulics for Ultraprecision Actuation," by S. Peirce, H. Tran, M. Wiedemann ,and D. DeBra, (1994).

Server and web pages maintained by Joe Giaime

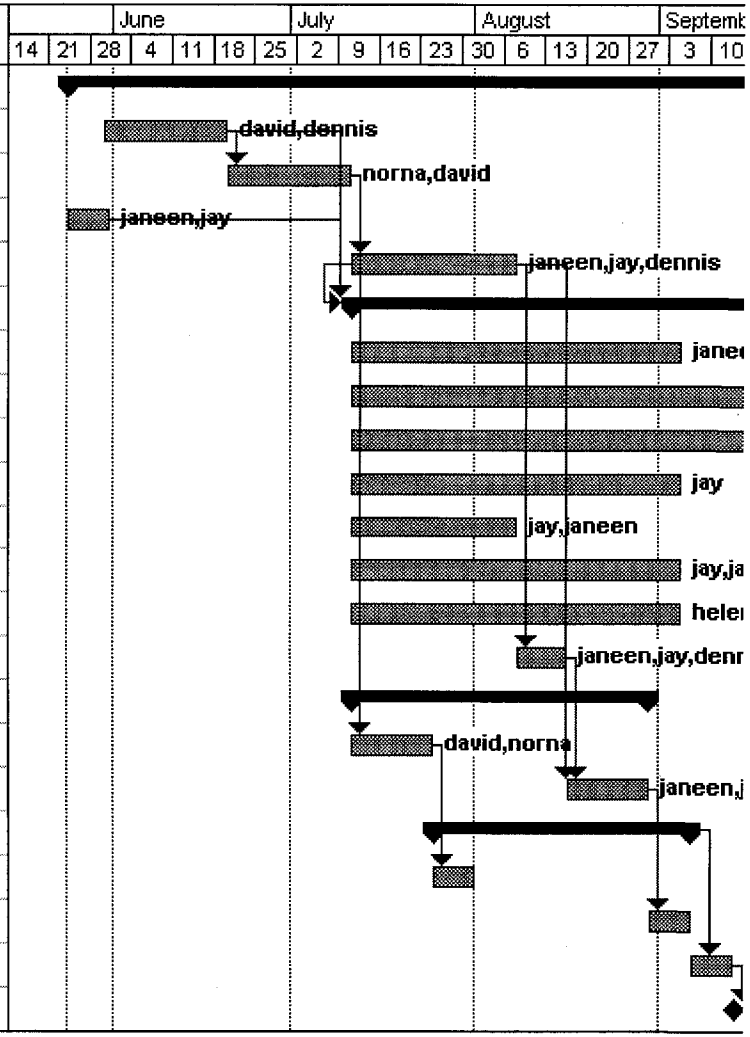
BATCH START

STAPLE OR DIVIDER

LIGO II Construction Proposal Outline					
Chapter	*Description*	*Lead Author*	*Lead Estimator*	*Reference Documents Included on CD-ROM*	*Lead Author*
1	Executive Summary	**Sanders**		1999 LSC White Paper	
				1999 Conceptual Project Book	
2	Astrophysics Motivation and Scientific Goals	**Lazzarini**, Thorne, Prince			
	Estimate of Sensitivity Needed for Each Type of Astrophysics Source	, Finn			
	Description of LIGO II Science Requirements From This Estimate				
3	Reference Design Baseline Definition	**Sanders**, Shoemaker		LIGO II System Design Requirements Document	Fritschel
	Narrative Description of LIGO II Reference Design			Any noise calculation memos	Fritschel, Strain, Finn
	LIGO II Reference Design Parameters and Comparison With LIGO I			Braginsky and Thorne papers on noise	Braginsky, Thorne
	Reference Design Sensitivity Goal and Noise Estimates				
	Reference Design Tradeoff Analysis				
	Reference Design Options				
4	Program Plan	**Sanders**		Draft LIGO II Project Management Plan	Sanders
	LIGO Laboratory Role and Responsibilities			LIGO Annual Report (most recent ?)	Lindquist
	LIGO Scientific Collaboration Role and Responsibilities			LIGO Quarterly Report (most recent)	Lindquist
	GEO Collaboration LIGO II	Hough et al		LIGO II Proposal for LIGO Operations (2002-2007)	Lindquist
	ACIGA Collaboration in LIGO II	McClelland			
	Method of Accomplishment				
5	LIGO II Detector Research and Development Overview				
	Organization of Research in Progress	**Sanders**			
	Interferometer Configuration Research Plan	**Strain**		SWG Web Site	
	Lasers and Optics Research Plan	**Gustafson**		Lasers & Optics Web Site	
	Suspension and Isolation Research Plan	**Shoemaker**		STAIC Web Site	
6	Work Breakdown Structure	**Sanders**		LIGO II WBS Dictionary	Sanders, Coyne
	Level 3 WBS Dictionary (LIGO.4.**XX**)				
7	Facility Modifications	**Sanders**, Asiri	**Asiri**		
	Overview			Site Drawings ?	
	Requirements				
	Reference Design Description				
	Research and Development				
	Work Plan and Subsystem Schedule				
8	Seismic Isolation	**Shoemaker**	**Asiri, Bork**, Mason	Design Requirements Document	
	Overview			Conceptual Design Document	
	Requirements			Evaluation Criteria Document	
	Reference Design Description			Isolation Approach Decision Memo	
	Research and Development			Publications from R&D	
	Work Plan and Subsystem Schedule				
9	Suspension	**Shoemaker,GEO**	Coyne, **Heefner**	Design Requirements Document	
	Overview		**, Romie**	Conceptual Design Document	
	Requirements			Publications from R&D	
	Reference Design Description				
	Research and Development				
	Work Plan and Subsystem Schedule				
10	Prestabilized Laser	**Camp, Savage**	**King,**	180 W Laser Specification	
	Overview		Gustafson, **Abbott,**	PSL Design Requirements Document	Savage
	Requirements			Conceptual Design Document	
	Reference Design Description				
	Research and Development				
	Work Plan and Subsystem Schedule				
11	Input Optics	**Camp**, Reitze	**Reitze,Ouimette**	DRD	Reitze
	Overview			CDD	Reitze
	Requirements				
	Reference Design Description				
	Research and Development				
	Work Plan and Subsystem Schedule				
12	Core Optics Components	**Camp**, Gustafson	**Billingsley**	DRD	Billingsley, Kells
	Overview		**Billingsley**	CDD	Billingsley, Kells
	Requirements				
	Reference Design Description				
	Research and Development				
	Work Plan and Subsystem Schedule				
13	Support Optics (repeated for:				
	Stray Light Control (SLC)	Smith	Smith	DRD and CDD documents	Smith
	Active Optics Compensation (AOC)	Zucker	Zucker	Compensation Results	Zucker
	Output Mode Cleaner Design	ACIGA			
	PO Mirror Assembly and Telescope Design	Smith	Smith		
	Initial Alignment System (IAS)	K. Mason	K. Mason		
	Overview				
	Requirements				
	Reference Design Description				
	Research and Development				
	Work Plan and Subsystem Schedule				
14	*Interferometer Sensing and Control*	Coyne, Zucker,Fritschel	Coyne, Zucker	DRD	Coyne, Zucker
	Overview		, Ouimette	CDD	*Coyne, Zucker*
	Requirements			Results of RSE experiments	Mason
	Reference Design Description				
	Research and Development				
	Work Plan and Subsystem Schedule				
15	Data Acquisition, Networking and Supervisory Control, Diagnostics	Lazzarini, Bork, (Fritsch	Lazzarini, Bork		

	Overview				
	Requirements				
	Reference Design Description				
	Research and Development				
	Work Plan and Subsystem Schedule				
16	Support Equipment	Asiri, Coyne	Asiri		
	Overview				
	Requirements				
	Work Plan and Subsystem Schedule				
17	Computing and Data Analysis	Lazzarini	Lazzarini		
	Overview				
	Requirements				
	Reference Design Description				
	Research and Development				
	Work Plan and Subsystem Schedule				
18	Installation	Coyne	Coyne		
	Overview				
	Requirements				
	Reference Design Description				
	Work Plan and Installation Schedule				
19	Project Management	Sanders	Lindquist	Draft Project Management Plan for LIGO II	Sanders
	Overview				
	Management				
	Project Controls				
	QA Services				
	Systems Engineering			System DRD	
	Documentation				
	Administration				
	General Computing				
20	LIGO II Schedule	Sanders	Sanders, Coyne	some big schedule file from Primavera ?	Frey
	Schedule Planning Assumptions				
	Methodology				
	The LIGO II Design Process				LIGO I Design Process
	Top Level Milestones				
	Relationship to LIGO Laboratory Operations and LIGO I Schedule				
	Schedule Options and Phasing Options				
21	LIGO II Cost Estimate	Sanders	Sanders, Lindquist	LIGO II Cost Estimating Plan	Sanders, Lindquist
	Cost Estimate Methodology			LIGO II Cost Estimating Tool Document	Kratochwill, Frey
	Cost Estimate Summary				
	Cost Drivers				
	Risk Areas and Contingency				
	Funding Profile				
	MRE Construction Request				
	MRE R&D Request				
22	Responsibilities/Resources/Staffing	Sanders	Sanders	MOU's and Attachments	Petrac
	Staffing Estimate and Assumptions				
	Managing Non-Laboratory Participation				
	GEO Participation	Hough			
	ACIGA Participation	McClelland			

ID	Task Name	Duration	Start	Finish	Predecessors	Resource Names
23	**Suspensions**	**94 days**	**5/24/00**	**10/2/00**		
24	Design Requirements	3 wks	5/30/00	6/19/00		david,dennis
25	Conceptual Design	3 wks	6/20/00	7/10/00	24	norna,david
26	WBS Dictionary	5 days	5/24/00	5/30/00		janeen,jay
27	Development Plan	4 wks	7/11/00	8/7/00	25	janeen,jay,dennis
28	**Cost Estimate**	**60 days**	**7/11/00**	**10/2/00**	**24,27SS,26**	
29	structure	8 wks	7/11/00	9/4/00		janeen
30	assy fixtures	12 wks	7/11/00	10/2/00		janeen
31	install fixtures	12 wks	7/11/00	10/2/00		janeen
32	control elect & SW	8 wks	7/11/00	9/4/00		jay
33	sensors	4 wks	7/11/00	8/7/00		jay,janeen
34	actuators	8 wks	7/11/00	9/4/00		jay,janeen
35	ribbons/fibers	8 wks	7/11/00	9/4/00		helena
36	Schedule	1.33 wks	8/8/00	8/16/00	27	janeen,jay,dennis
37	**Proposal Chapter**	**36.67 days**	**7/11/00**	**8/30/00**		
38	req & design	2 wks	7/11/00	7/24/00	25	david,norna
39	plan	2 wks	8/16/00	8/30/00	27,36	janeen,jay
40	**Review**	**31.67 days**	**7/25/00**	**9/6/00**		
41	req & design	1 wk	7/25/00	7/31/00	38	
42	plan, schedule, cost	1 wk	8/30/00	9/6/00	39	
43	revise proposal input	1 wk	9/6/00	9/13/00	40	
44	completed	0 days	9/13/00	9/13/00	43	



To: Fred Asiri <fba@ligo.caltech.edu>
Subject: [Fwd: deliverables outline]

Fred,
Here is the outline of a development plan for the SEI from Joe for a
starting point.

DennisReceived: from 131.215.125.1.ligo.caltech.edu (ligo [131.215.125.1])
by ligo.caltech.edu (8.9.3/8.9.3) with ESMTP id NAA00350;
Tue, 23 May 2000 13:50:32 -0700 (PDT)
Received: from lsuligo.phys.lsu.edu (IDENT:root@lsuligo.phys.lsu.edu [130.39.176.72])
by 131.215.125.1.ligo.caltech.edu (8.9.3/8.9.3) with ESMTP id NAA11592;
Tue, 23 May 2000 13:52:22 -0700 (PDT)
Received: from [130.39.245.132] (joseph.ligo-la.caltech.edu [130.39.245.132])
by lsuligo.phys.lsu.edu (8.9.3/8.8.7) with ESMTP id PAA09416;
Tue, 23 May 2000 15:51:35 -0500
Mime-Version: 1.0
X-Sender: giaime@lsuligo.phys.lsu.edu (Unverified)
Message-Id: <v04220800b5509f28c770@[130.39.245.132]>
Date: Tue, 23 May 2000 15:51:19 -0500
To: Dennis Coyne <coyne@ligo.caltech.edu>,
"Gary H. Sanders" <sanders@ligo.caltech.edu>
From: "Joseph A. Giaime" <giaime@lsuligo.phys.lsu.edu>
Subject: deliverables outline
Content-Type: multipart/mixed; boundary="============_-
1253007411==_============"
X-Mozilla-Status2: 00000000

Dennis & Gary,

Enclosed is that rough and tentative schedule I was referring to during our phone call today.

I haven't had time to "typeset" it, so the columns might not line up for you...

-Joe

deliverables.txt

Joseph A. Giaime, Assistant Prof.
Department of Physics and Astronomy, Louisiana State University
Baton Rouge LA 70803 USA email: giaime@phys.lsu.edu
tel. at LSU: 225 388-5794, Fax. 225 388-5855
at LIGO: 225 686-3169

Activity	Participants	Deliverable	Milestones
Conceptual Design	All	Rough Design	2Q00: Conceptual design
Prototype Design	All	Detailed frame design	3Q00: ready for bidders
		Detailed pod design	3Q00: ready for bidders
		Sensors & Actuators	3Q00: fully defined
		Dynamic model	3Q00: done
		Thermal model	3Q00: done
		Electronics & control	3Q00: specified
Prototype Construction	JILA,SU	Mechanical fab	4Q00: fab done
		Sensor & Actuators	4Q00: ready to install
		Electronics & control	4Q00: ready for test
Prototype supervisory & control sys Tests	SU,JILA,LSU	(Tests at ETF)	2Q01: test results
UHV tests	MIT, ??	Pathfinder for frame production	3Q00: method chosen
		Vac tests of UHV pod	4Q00: construction done
		Wiring design	4Q00: complete
		Installation tooling	4Q00: preliminary design
LASTI tests	MIT, All	Complete Design and bids out	2Q01: Design complete and reviewed
		Production	3Q01: Contracts let

Installation 1Q02: Installed in LASTI!

BATCH START

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LIGO-II Work Breakdown Structure (WBS) Dictionary

1 General Comments:

All research, development, design, construction, assembly and of the LIGO-II instrument are covered under this WBS structure, organized by subsystems.
The design is separated into three sequential phases:

- Requirements/Conceptual Design Phase (CD): The conceptual design and requirements task encompasses the development of a documented set of requirements (Design Requirements Document) in conjunction with the systems engineering group and the development of a documented conceptual design (Conceptual Design Document) which is responsive to the requirements. A project review of the design (Conceptual Design Review, CDR) is held at the end of this phase.
- Preliminary Design Phase (PD): The preliminary design task encompasses the development of a documented set of refined requirements (Design Requirements Document) in conjunction with the systems engineering group and the development of a documented preliminary design (Preliminary Design Document) which is responsive to the requirements. A project review of the design (Preliminary Design Review, PDR) is held at the end of this phase.
- Final Desgn Phase (FD): The final design task encompasses the development of a set of documentation which is sufficient to build the subsystem including an overall detailed design description (Final Design Document) which is responsive to the requirements. A project review of the design (Final Design Review, FDR) is held at the end of this phase. The final design documentation includes reports of supporting simulations, analyses, tests, as well as drawings, fabrication specifications, procurement plans, and assembly and installation procedures.

0 LIGO

Root WBS denotes the overall LIGO project.

0.4 LIGO-II Construction

All research, development, design, construction, assembly and of the LIGO-II instrument are covered under this WBS structure, organized by subsystems.
The installation of the LIGO-II instrument is also part of this WBS, but is handled as a separate WBS element, not prt of the subsystem WBS elements.

0.4.1Facility

All facility modifications and upgrades to support the LIGO-II instrument are included under this WBS element.

0.4.2Seismic Isolation (SEI)

The seismic isolation subsystem (SEI) is the integrated electromechanical, structural and electronic system used to provide an isolated support for the sensitive in-vacuum components. The isolation includes in-band vibration isolation, micro-seismic peak reduction (total rms position and velocity reduction) and tidal motion compensation. The SEI subsystem also provides for at least 4 degree of freedom DC positioning (side-to-side, fore-and-aft, vertical and yaw) over a range sufficient for initial alignment and drift compensation.
The SEI system applies to both the BSC and HAM chamber installations.
The SEI system also includes:
The electrical wiring to connect the active payloads (suspensions and sensors) to electronics outside the vacuum system, including the vacuum-tight feedthrough connections.
All seals associated with structural support through the vacuum envelop (including flexible bellows if required).
The payload elements supported and isolated by the SEI subsystem include the in-chamber component of the suspension subsystems, in-vacuum interferometer sensing and control (ISC) sensors (if required), input optics components (e.g. Faraday Isolators and fixed mount relay optics) and ancillary optical components (pick-off mirrors, beam reducing telescopes, baffles and beam dumps of the Support Optics Subsystem (SOS)).

0.4.2.1 Subsystem Management

All tasks associated with management of the SEI subsystem are covered in this WBS element, including management oversight of the R&D, design and fabrication phases of the effort. The management function entails monitoring and reporting costs and progress against the development plan, assessment and minimization of development risk by allocation and coordination of resources and appropriate planning.

0.4.2.2 SEI R&D

0.4.2.2.1 Seismic Isolation R&D - Caltech (SEI)

0.4.2.2.2 Stochastic Noise R&D - MIT (STO)

0.4.2.2.3 Seismic Isolation R&D – Stanford

0.4.2.2.4 Seismic Isolation R&D – JILA

0.4.2.2.5 Seismic Isolation R&D – LSU

0.4.2.3 SEI Design

0.4.2.3.1 SEI Conceptual Design/Requirements

0.4.2.3.2 SEI Preliminary Design

0.4.2.3.2.1 Sensor Design

0.4.2.3.2.2 Actuator Design

0.4.2.3.2.3 Electronics Design

0.4.2.3.2.4 SEI/HAM Design

0.4.2.3.2.4.1 System Design/Simulation

0.4.2.3.2.4.2 Mechanical Design

0.4.2.3.2.4.3 Assembly Procedure & Tooling Design

0.4.2.3.2.4.4 Installation Procedure & Tooling Design

0.4.2.3.2.4.5 Prototype Fabrication

0.4.2.3.2.4.6 Prototype Testing

0.4.2.3.2.5 SEI/BSC Design

0.4.2.3.2.5.1 System Design/Simulation

0.4.2.3.2.5.2 Mechanical Design

0.4.2.3.2.5.3 Assembly Procedure & Tooling Design

0.4.2.3.2.5.4 Installation Procedure & Tooling Design

0.4.2.3.2.5.5 Prototype Fabrication

0.4.2.3.2.5.6 Prototype Testing

0.4.2.3.3 SEI Final Design

0.4.2.3.3.1 Sensor Design

0.4.2.3.3.2 Actuator Design

0.4.2.3.3.3 Electronics Design

0.4.2.3.3.4 SEI/HAM Design

0.4.2.3.3.4.1 System Design/Simulation

0.4.2.3.3.4.2 Mechanical Design

0.4.2.3.3.4.3 Assembly Procedure & Tooling Design

0.4.2.3.3.4.4 Installation Procedure & Tooling Design

0.4.2.3.3.4.5 Prototype Fabrication

0.4.2.3.3.4.6 Prototype Testing

0.4.2.3.3.5 SEI/BSC Design

0.4.2.3.3.5.1 System Design/Simulation

0.4.2.3.3.5.2 Mechanical Design

0.4.2.3.3.5.3 Assembly Procedure & Tooling Design

0.4.2.3.3.5.4 Installation Procedure & Tooling Design

0.4.2.3.3.5.5 Prototype Fabrication

0.4.2.3.3.5.6 Prototype Testing

0.4.2.4 SEI Fabrication

0.4.2.4.1 Mechanical Fabrication

0.4.2.4.2 Electronics Fabrication

0.4.2.4.3 Software Coding

0.4.2.4.4 First Article Testing

0.4.2.4.5 Assembly

0.4.3Suspension (SUS)

All suspended optics assemblies for the interferometer are covered under this WBS element, including input optics (mode cleaner, mode matching telescope optics and relay optics), output optics (mode cleaner and relay optics) and core optics (Fabry-Perot cavity optics, power and signal recycling cavity optics). Other optics or electro-optics which may need to be suspended are part of the associated subsystem and are not part of this WBS element (e.g. a suspended reference cavity for the PSL subsystem is not part of this WBS element). There are a few different suspension designs required to meet performance requirements, space constraints and variation in the dimensions/geometry of the optics. Commonality of the design elements and components is a goal within the suspension effort.
This is a summary level WBS element only; no costs are allocated to this WBS element.

0.4.3.1 Subsystem Management

Technical management of the subsystem is covered in this WBS element. This is a level of effort task (the level may vary according to the development phase).

0.4.3.2 Suspension R&D

All research & development across the entire LIGO Science Collaboration (LSC) related to suspensions for LIGO-II are reported to, and coordinated by, the Suspension subsystem leader.
This is a summary level WBS element only; no costs are allocated to this WBS element.

0.4.3.2.1 Suspension R&D - Caltech Fiber/Optics Components

TBW

0.4.3.2.2 Suspension R&D – TNI

TBW

0.4.3.2.3 Suspension R&D – GEO

TBW

0.4.3.2.4 Suspension R&D – Stanford

TBW

0.4.3.2.5 Suspension R&D – Syracuse

TBW

0.4.3.3 Suspension Design

All suspension design activities are covered under the following WBS elements.
This is a summary level WBS element only; no costs are allocated to this WBS element.

0.4.3.3.1 Conceptual Design/Requirements

All suspension design work and costs associated with the Conceptual Design Phase are allocated to this WBS element. The principal deliverables from this element are the Design Requirements Document and the Conceptual Design Document. This WBS element is completed when a successful Design Requirements Review (DRR) has been held and the Preliminary Design Phase is initiated.

0.4.3.3.2 Preliminary Design

All suspension design work and costs associated with the Preliminary Design Phase are allocated to this WBS element. The principal deliverables from this element are the revised Design Requirements Document (if required), the Preliminary Design Document a prototype(s) and associated prototype test results. This WBS element is completed when a successful Preliminary Design Review (PDR) has been held and the Final Design Phase is initiated.
Activities and associated costs, which cannot be allocated to the elements below this level, may be defined at this level, such as: preparation of the design review documentation and conducting the design review.

0.4.3.3.2.1 Ribbon/Fiber Process Design

The engineering and process design for the reliable fabrication of silica fibers or ribbons needed in the suspension are covered in this WBS element. The principal deliverables of this WBS element are a preliminary process specification, preliminary ribbon or fiber prototypes and associated testing of their strength, uniformity and suitability for the suspension system.

0.4.3.3.2.2 Optic/Ribbon Attachment Design

Move this WBS element to the Core Optics Component (COC) structure.

0.4.3.3.2.3 Sensor Design

The design activities for the local damping sensors of the suspensions are allocated to this WBS element. The principal deliverables of this WBS element are a preliminary design description including physical drawings and electronic circuit schematics of the read-out/interface, a tested prototype and test report.

0.4.3.3.2.4 Actuation Design

The design activities for the suspension actuators are allocated to this WBS element. The actuators include both magnetic voice coil actuators and electrostatic actuators. (The photon actuator is not part of this WBS element.) The principal deliverables of this WBS element are a preliminary design description including physical drawings and electronic schematics of the drive/interface circuit, a tested prototype and test report.

0.4.3.3.2.5 BSC Suspension Design

The suspensions for optics housed in the BSC chambers (attached to an interface with the SEI subsystem at their tops) are covered under this WBS element.
This is a summary level WBS element only; no costs are allocated to this WBS element.

0.4.3.3.2.5.1 System Design/Simulation

Overall design trade-offs and simulations of the integrated control and system dynamics of the BSC suspension preliminary design are covered in this WBS element. The deliverable from this element is a documented simulation model and a report on comparisons of the simulation of the performance of the preliminary design against requirements and against prototype testing.

0.4.3.3.2.5.2 Mechanical Design

All activities associated with the preliminary mechanical design of the BSC suspension are covered in this WBS element (except or those associated with other preliminary design phase elements such as the sensor design, actuator design and the assembly and installation tooling design). This relates principally to the design of the structure(s) used to interface to the SEI system, suspend the multiple pendulum, mount the sensors and actuators and cage or 'safe' the suspended masses. The principal deliverables of this WBS element are a preliminary design description including physical drawings and schematics, a tested prototype and test report.

0.4.3.3.2.5.3 Control System Hardware & Software Design

All activities associated with the preliminary control system design of the BSC suspension are covered in this WBS element. The principal deliverables of this WBS element are a preliminary design description including a system block diagram, a control block diagram, a hardware layout drawing, a software development plan, electronic circuit schematics of any required custom control and interface electronics, a tested prototype and test report.

0.4.3.3.2.5.4 Assembly Procedure & Tooling Design

All activities associated with the design and definition of a procedure for the physical assembly and test of the BSC suspension are covered in this WBS element. The principal deliverables of this WBS element are a preliminary assembly specification, drawings of assembly tools and fixtures, prototype assembly tools and fixtures and a report on an assembly trial.

0.4.3.3.2.5.5 Installation Procedure & Tooling Design

All activities associated with the design and definition of a procedure for the physical installation and in-situ test of the BSC suspension are covered in this WBS element. The principal deliverables of this WBS element are a preliminary installation specification, drawings of installation tools and fixtures.

0.4.3.3.2.5.6 Prototype Fabrication

Activities and costs associated with the fabrication of integrated BSC suspension prototypes are covered in this WBS element. Prototype fabrication of components (e.g. sensors, actuators, etc.) are covered under other WBS elements; This WBS element is strictly for the development of two complete integrated BSC suspensions that are tested stand-alone. One prototype is to be used in air principally for assembly and installation testing. The other prototype is to be used in a vacuum chamber for use in control system testing. The deliverables for this WBS element are two complete BSC prototype

suspensions, one set of assembly tools and a susupension test stand including limited data acquisition capability to support testing.

0.4.3.3.2.5.7 Prototype Testing

Activities and costs associated with the testing of integrated BSC suspension prototypes are covered in this WBS element. Prototype testing of components (e.g. sensors, actuators, etc.) are covered under other WBS elements; This WBS element is strictly for the testing of the two complete integrated BSC suspensions (from 0.4.3.3.2.5.6). A test report on the assembly, installation, fit, function and (to the extent possible) performance of the suspensions is a deliverable of this WBS element

0.4.3.3.2.6 HAM Suspension Design

0.4.3.3.2.6.1 System Design/Simulation

0.4.3.3.2.6.2 Mechanical Design

0.4.3.3.2.6.3 Control System Hardware & Software Design

0.4.3.3.2.6.4 Assembly Procedure & Tooling Design

0.4.3.3.2.6.5 Installation Procedure & Tooling Design

0.4.3.3.2.6.6 Prototype Fabrication

0.4.3.3.2.6.7 Prototype Testing

0.4.3.3.3 Final Design

0.4.3.3.3.1 Ribbon Process Design

0.4.3.3.3.2 Optic/Ribbon Attachment Design

0.4.3.3.3.3 Sensor Design

0.4.3.3.3.4 Actuation Design

0.4.3.3.3.5 BSC Suspension Design

0.4.3.3.3.5.1 System Design/Simulation

0.4.3.3.3.5.2 Mechanical Design

0.4.3.3.3.5.3 Control System Hardware & Software Design

0.4.3.3.3.5.4 Assembly/Installation Design

0.4.3.3.3.5.5 Prototype Fabrication

Activities and costs associated with the fabrication of integrated BSC suspension prototypes are covered in this WBS element. Prototype fabrication of components (e.g. sensors, actuators, etc.) are covered under other WBS elements; This WBS element is strictly for the development of complete integrated BSC suspensions that are tested in the LASTI system at MIT. Two complete BSC prototype suspensions including one set of assembly and installation tools and fixtures are deliverables of this WBS element.

0.4.3.3.3.5.6 Prototype Testing

Activities and costs associated with the testing of integrated BSC suspension prototypes are covered in this WBS element. Prototype testing of components (e.g. sensors, actuators, etc.) are covered under other WBS elements; This WBS element is strictly for the testing of complete integrated BSC suspensions that are tested in the LASTI system at

MIT. A test report on the assembly, installation, fit, function and (to the extent possible) performance of the suspensions is a deliverable of this WBS element. While labor and infrastructure support will be provided by the LASTI system, all labor for the assembly, installation and test of the suspension prototypes should be allocated to this WBS element.

0.4.3.3.3.6 HAM Suspension Design

0.4.3.3.3.6.1 System Design/Simulation

0.4.3.3.3.6.2 Mechanical Design

0.4.3.3.3.6.3 Control System Hardware & Software Design

0.4.3.3.3.6.4 Assembly/Installation Design

0.4.3.3.3.6.5 Prototype Fabrication

0.4.3.3.3.6.6 Prototype Testing

0.4.3.4 Fabrication (LOS & SOS)

0.4.3.4.1 Fused Silica Mass Fabrication

0.4.3.4.1.1 Fused Silica Blanks

0.4.3.4.1.2 Fused Silica Polishing

0.4.3.4.2 Tooling Fabrication

0.4.3.4.2.1 Assembly Tooling Fabrication

0.4.3.4.2.2 Installation Tooling Fabrication

0.4.3.4.3 BSC Suspension Fabrication

0.4.3.4.3.1 Mechanical Fabrication

0.4.3.4.3.2 Electronics Fabrication

0.4.3.4.3.3 Software Coding

0.4.3.4.3.4 First Article Testing

0.4.3.4.4 HAM Suspension Fabrication

0.4.3.4.4.1 Mechanical Fabrication

0.4.3.4.4.2 Electronics Fabrication

0.4.3.4.4.3 Software Coding

0.4.3.4.4.4 First Article Testing

0.4.3.4.5 Production Assembly & Test

0.4.3.4.5.1 SUS/BSC Test Stands

0.4.3.4.5.2 SUS/HAM Test Stands

0.4.3.4.5.3 BSC Suspension Controllers

0.4.3.4.5.4 HAM Suspension Controllers

0.4.3.4.5.5 BSC Suspensions

0.4.3.4.5.6 HAM Suspensions

BATCH START

STAPLE
OR
DIVIDER

The experimental program in support of stiff-suspension active seismic isolation for LIGO-II

B. Lantz R. Stebbins C. Hardham J. Giaime
for the stiff active seismic isolation team in the LSC.

February 14, 2000. Version 1.0

1 Introduction

This document is provided in response to a request for documentation made by the ad-hoc "Technical Advisory Group," convened by the LSC and the LIGO Laboratory to technically evaluate various proposed seismic isolation (SEI) conceptual designs for LIGO-II. Specifically, this report responds to the Feb. 4, 2000 email request for "A Prototype Test Program Plan." As requested, this report will only cover the elements of our experimental program that will likely lead to results usable to the committee by April, 2000.

We have identified some aspects of our design's performance that we believe are crutial to meeting the requirements[1]; these represent risk to our approach if not well understood. Some understanding can be gained through modeling; our modeling program is described in a companion document, "Computer modeling and simulation in support of stiff-suspension active seismic isolation for LIGO-II," by Lantz, et. al. Here we describe the things best understood through expermental tests, and our polans to carry out these tests.

1.1 Brief overview of stiff active conceptual design

Since this document preceeds the requested "Baseline LIGO-II Implementation Design Description," a brief description of the elements of our cononceptual design is needed to establish a vocabulary for further discussion.

LIGO-II's test mass suspension system is being developed by the GEO group at the University of Glasgow[2]. The interface between it and SEI as well as the performance requirements on SEI are set out in [1]. A well-defined interface has been chosen in order to allow independant testing of the two detector components, and to facilitate their separate parallel development efforts in different continents.

The BSC geometry requires SEI to support its payload from above and the HAM geometry requires payload support from below. This will require two different versions of our SEI design. However, every effort is being made to confine the differences to the physical

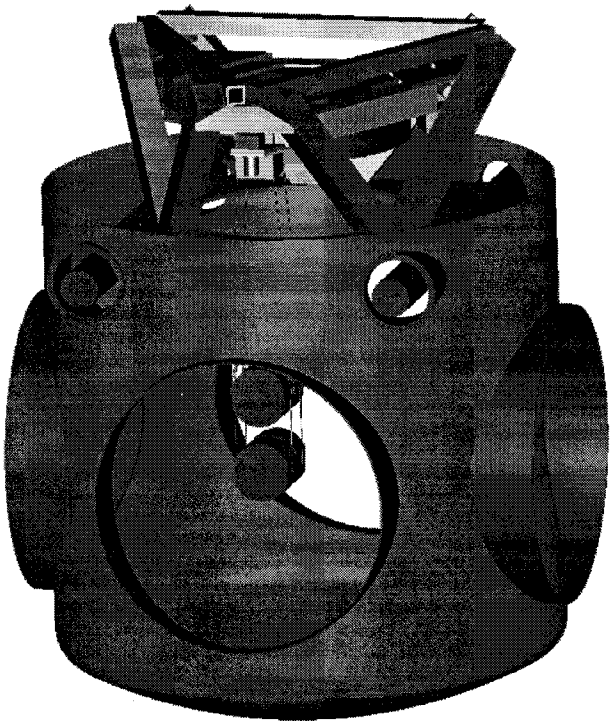

Figure 1: Drawing of the proposed design (here rendered in the BSC configuration.) A single-layer active seismic isolation platform supports the quadruple pendulum test mass suspension.

mounting structures that connect to the optics table and to the support tubes (which enter the vacuum system.) For this reason, we expect that the performance of the two systems will be similar, and the implementation challenges will be similar, so in this document we will not generally differentiate between the two versions.

Our overall design consists of a hydraulic actuator external to the vacuum system and a two-stage active siesmic isolation platform inside the vacuum.

1.1.1 External hydraulic actuator

The physical SEI/SUS interface consists of an optics table from which the SUS will be hung (for optics in BSC chambers), or on which the SUS cage will rest (for optics in HAM chambers). SEI is responsible for this optics table. For periodic manual alignment, SEI must be able to adjust the table's position and angle to allow the full range of the bellows (± 5 mm).

At frequencies below the measurement band of LIGO, there are large amplitude disturbances which can easily be attenuated outside the vacuum chamber. These are the micro-seismic peak at 0.17 Hz, diurnal tidal changes and thermal / seasonal drifts that

approach zero frequency (DC). For these disturbances, an actuator is needed that is capable of maintaining large ($\approx$ .5 mm) DC offsets. Zero frequency pointing is typically addressed mechanically, but in this case, attenuating the microseismic peak requires low noise performance that is difficult to attain with hard-mount (gear driven, contact) mechanical systems. The solution currently under investigation is the use of quiet hydraulics, shown in Fig. 2.

The design specifications of the quiet hydraulic actuator are: ± 1.0 mm of throw, 2 Hz upper unity gain frequency, and working fluid pressure of 75 psi. (The rare adjustments > 1.0 mm are accomplished with screw ajustments in series with the bellows mounting.) The large throw of the actuator is easily sufficient to compensate for tidal and microseismic motion at the LIGO sites, and we expect that the ISC designers will choose to apply that

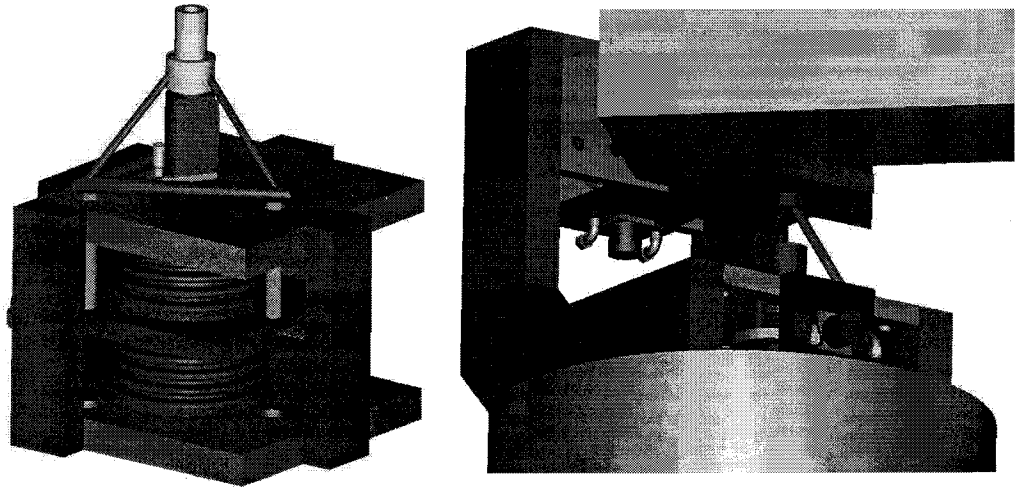

Figure 2: At left is a 1-DOF quiet hydraulic actuator. The gray blocks and red pillars form the reaction frame and are fixed in place. The two red bellows are pumped differentially to move the center purple actuation plate. The yellow bolt at the top attaches to the payload, and the actuation plate is attached to the payload by the rod assembly. An optical sensor (red and magenta) is placed between the yellow actuation point and the frame to allow low frequency servo stabilization. At right, two are shown in the 2-DOF configuration as would be employed in LIGO-II.

global signal here. The pump power requirements remain modest by virtue of the relatively low upper unity gain point at 2 Hz. While the bandwidth of the system could be increased with a more powerful source, isolation at higher frequencies is better addressed inside the vacuum chamber.

1.1.2 Two-stage active siesmic isolation platform

The in-vacuum system, shown in the BSC configuration in Figure 1 is a cascaded two-stage active isolation platform. The stages are suspended through stiff blade springs and short

pendulum links, giving natural frequencies in the 2 - 4 Hz range. The inner plaform stage is built around a 1.5 m diameter optics table (BSC) or a larger rectangular table (HAM). For each suspended optic, the SUS is mounted on this flat table, and may be positioned and oriented as desired.

Global control signals for both optic position and angle may be distributed to each of the three components, large slow motions to the hydraulic outer system and progressively faster and smaller ones to the inner layers, ultimately to the test mass.

Local damping and noise-reduction control signals are generated for each DOF in the in-vacuum active platform by a combination of short- and long-period seismometers and position These sensors will need to be encapsulated in small chambers filled with trace gas, complete with electrical feedthroughs. The actuators are electromagnetic non-contacting forcers. These apply forces between adjacent stages. Both the SEI and SUS systems benefit from all DOFs being exposed to active damping in that they can recover well from accidental excitation.

The SEI component of the BSC scheme very much resembles the pre-prototype built and tested at JILA over the past decade The JILA development effort was directed towards a much more ambitious goal (to detect GWs at 1 Hz), so our scheme can benefit from the JILA experience and 3-D modelling effort without the need for the ultra-high-performance seismometers that were part of JILA's development work. Instead, we can use commercial, off-the-shelf seismometers, greatly simplifying the scheme and reducing risk. The choice of stiffer suspension also promises better thermal drift performance. The prototype tests should show if these changes from the JILA demonstration help.

2 Experimental Activities

Several experimental tests and simulation tasks are desirable in order to gain confidence that we can meet the requirements. These will be highlighted as the prototype tests are described.

2.1 Quiet hydraulics test

To demonstrate quiet hydraulics in alignment and low-frequency isolation, we have designed an actuator and test fixture which are currently under construction. The test fixture is designed to support two actuators in a condition that is similar to the final implementation in LIGO II. In this environment, we will characterize the noise, servo behavior, and dynamic range of the actuators. This testing will begin in March and continue for the following three months. We will characterize the noise performance by April.

The test fixture (Figure 3) is designed to test the actuator in a manner that is representative of the final application supporting one corner of a LIGO in-vacuum SEI. Two actuators are arranged orthogonally about a 300 kg. mass. Each actuator is collocated with a long-period seismometer and a position sensor. Two additional seismometers are placed on the ground next to the suspended mass for feed-forward control and to relative sensor

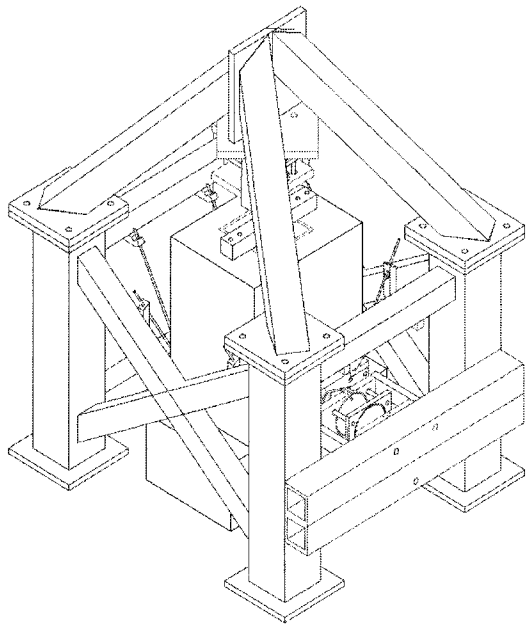

Figure 3: Design for the hydraulic actuator test fixture. The blue block in the center is the 300kg test mass, which is supported by eight large off-load springs (in magenta). The steel frame (gray) holds the off-load springs and two hydraulic actuators, one on the side and one on the top. The seismometers are imbedded in special holders within the blue test mass.

correction. The large support frame and suspended mass enable us to apply significant forces and measure any resulting noise.

2.2 Two-stage prototype

The principal goal of the Two-stage prototype is to demonstrate the performance and robustness of a two-stage active isolation system, similar in design and construction to the analogous active stages of the reference design proposed to meet the LIGO-II seismic isolation requirements. A drawing is shown in Figure 4. The prototype has been designed to fit in the Nu-Vac vacuum chamber at MIT (in the same high bay as LASTI). That chamber includes a heavy aluminum table which stands on legs penetrating the vacuum vessel through belows to the floor. The table is being modified for attachment of the external support structure. The structural members shown have been designed and FE modeled using 3D CAD software, and are currently in production by JILA and its contractors. We expect to keep a current version of the production status on our web site.

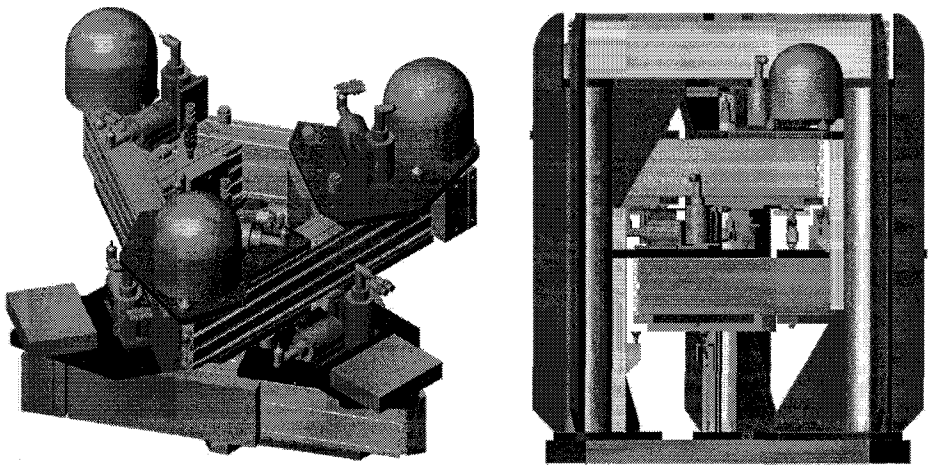

Figure 4: Drawing of the two-layer active seismic isolation platform under construction at JILA and to be installed in a vacuum system at MIT. The width of the platform stages is approximately 1 m.

2.2.1 Vibration attentuation test

The performance demonstration is intended to show a ground-to-payload vibration transfer function equal to that required of the two active stages in the reference design. In particular, demonstrating adequate performance in the 0.1-1 Hz range is a key goal. This will be an isolation transfer function measured with the ambient input noise at MIT, and therefore will not necessarily demonstrate the system noise performance required at a LIGO site. However, this latter performance may be demonstrated if time and conditions permit, either with feed-forward techniques or during quiet times.

Broadly defined, "similar in design and construction to the active stages of the reference design" means that the portion of the dynamic model describing the two active stages in the reference design can be used to model the rapid prototype with minimal change in parameters. In short, the Two-stage prototype will validate the control system dynamics model of the reference design, the sensors, the forcers, the control topology and the control laws. The prototype will also validate some mechanical design choices (e.g., triangular platforms, instrument pods), mechanical components (e.g., springs, flexures) and procedures (e.g., assembly, alignment, operation). This similarity is further defined in Two Stage Prototype Concept below.

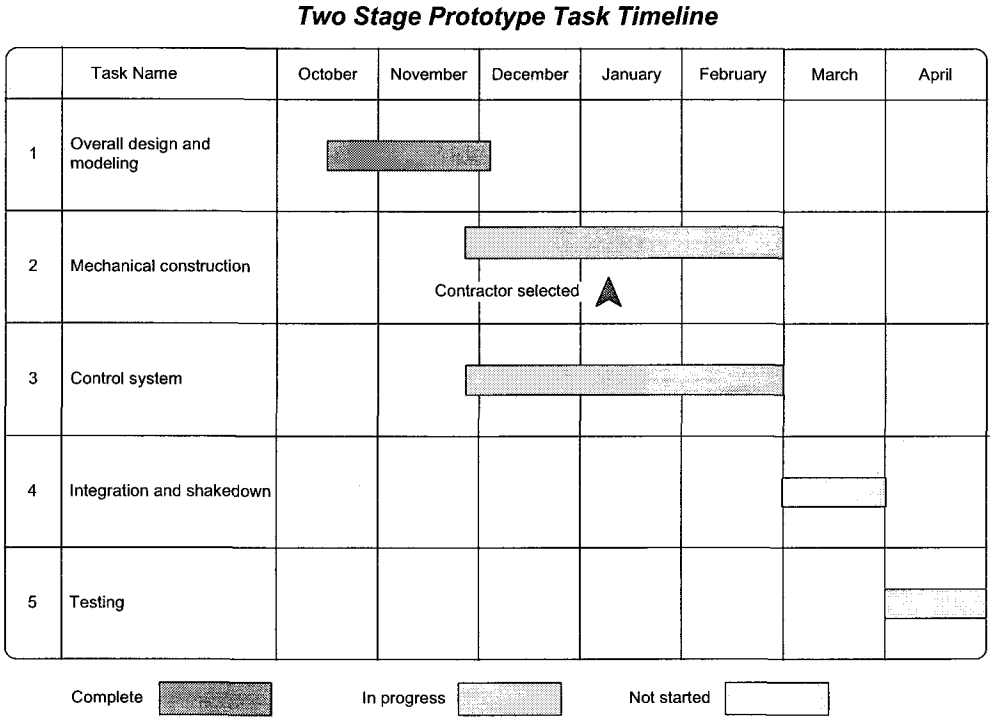

Figure 5: Task timeline for the two-layer active prototype.

2.2.2 Robustness test

The robust operation of two cascaded stages is also a goal, and is to be demonstrated by operation at the required isolation performance level for a substantial period at a high level of availability. Many feel that this sort of robustness can only be convincingly shown in a physical demonstration and not by use of computer models.

This prototype demonstration will also show how dispersed members of our team can marshal the resources and exercise the project management to design, fabricate, integrate and shake down an isolation system appropriate to LIGO-II. The prototype will also familiarize us with fabricators and materials and component suppliers.

The Two Stage Prototype will demonstrate the performance required by the LIGO II with similar, but not identical components. For this reason, it has some features, such as control system components and topology, which closely mimic our reference design for a LIGO II SEI and others, such as the structural foundation, which do not. We have tried to mimic the LIGO II situation wherever critical to demonstrating our system's performance. So, for example, we have not attempted to meet the vacuum requirements or mimic the payload dynamics for lack of time and definition, respectively. We don't expect the former present a problem, and the latter is being tested at Stanford. We expect other tests may follow

to address the vacuum and other interface requirements, leading eventually to a full-scale prototype test at LASTI.

The most important feature of this prototype is that the two active stages will have all of the control system elements (i.e., sensors, actuators, controllers) in the two active stages of the reference design, in the same topology. Control signals originating outside the two active stages in the reference design (e.g., global length control, stage #0, payload signals) will not be present, except possibly by simulation.

2.2.3 Plans and schedule

The top level tasks in our Work Breakdown Structure follow. Some of these have been completed. The top-level schedule is shown in Figure 5.

- Task 1, Overall design and modeling
  - Define goals and concept
  - Identify subsystems: number of platforms, control loops, sensors
  - Specify major performance parameters: uncoupled frequencies, isolation per stage, sensor noise, rms motion
  - Specify structural and control requirements: scale, structural resonances, gain per stage, sensor and actuator requirements
  - Set Two Stage Prototype orporate operational requirements: fabrication, assembly, alignment, vacuum preparation, installation, adjustment
  - Model performance
  - Model "error effects"
- Task 2, Mechanical construction
  - Identify and initiate procurements which are clear or require long lead time Convert conceptual design to engineering design
  - Identify and select contractor
  - Begin vacuum system preparations
  - Contractor fabricates major structural components: space frame/cylinder, stages Inhouse shop fabricates small components: brackets, pods, vacuum enclosures for sensors
  - Test assembly for fit
  - Ship from JILA to test site (MIT)
- Task 3, Control system
  - Identify and initiate procurements which are clear or require long lead time: forcers, sensors, digital controller

  - Specify electrical connections for vacuum system
  - Fabricate feedthroughs for vacuum system
  - Refine control design: detailed block diagram, compensation, acquisition, Setup controller, make operational, make tests with sensors and forcers
  - Generate and test operating code

- Task 4, Integration and shakedown
  - Conduct early test of vacuum enclosure for sensors and actuators
  - Ship parts to test site
  - Prepare for vacuum
  - Assemble outside of vacuum
  - Install in vacuum system
  - Complete assembly/integration

- Task 5, Testing
  - Define test battery
  - Prepare a schedule
  - Perform defined tests
  - Analyze and report results

2.3 Single-active-stage with triple pendulum prototype

The Stanford SEI prototype is a stiff, single layer active platform controlled in six degrees of freedom with a pair of triple pendulums suspended from it. The goals of the prototype are:

- Demonstrate 6 degree-of-freedom (DOF) performance of a stiff active platform with a) collocated sensors and actuators and b) modern Multi-Input Multi-Output (MIMO) control design.
- Demonstrate sensor blending of relative displacement sensors and inertial sensors.
- Validate the computer code used to model the reference design for LIGO II.
- Demonstrate performance improvement from feed-forward control.
- Demonstrate reliable performance of a system with both an active platform and multi-element pendulums.
- Develop reallocation techniques to offload control authority from pendulum actuators to platform actuators.

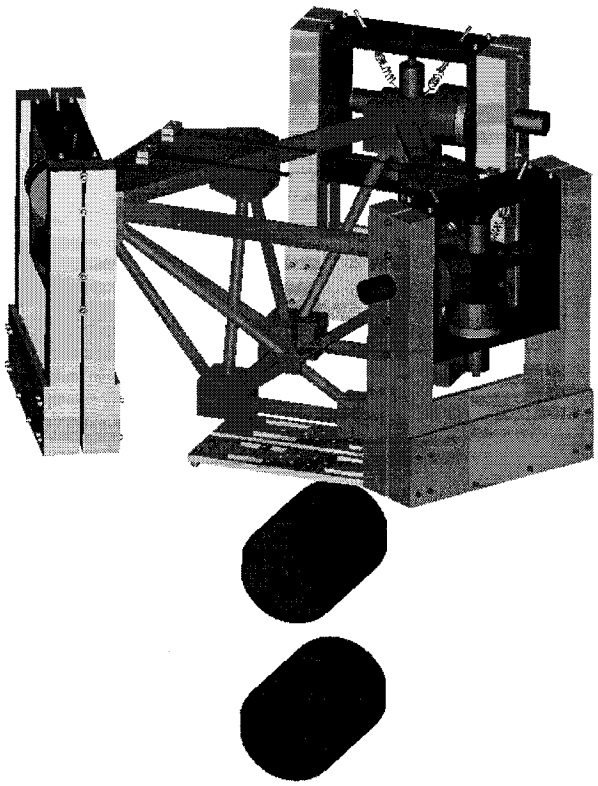

Figure 6: Drawing of the Stanford Active Platform and pendulums Prototype. A single-layer active seismic isolation platform supports two triple pendulums of a design based closely on the GEO triple pendulum.

- Implement watchdog schemes for oversight of the control system operation modes.

These goals are listed in approximate chronological order. We plan to work on the first five points before April, and points 6 and 7 after April. A computer rendering of the fully assembled prototype is shown in figure 6.

2.3.1 Collocated sensors/actuators and modern MIMO control design

The active platform was designed to exploit several lessons we have learned about control. These can be illustrated by examination of the three isolation pods at the corners of the active platform.

Each pod contains two sets of sensors and actuators, one horizontal and one vertical, so the three pods control all six degrees of freedom of the platform. The sensors and actuators are said to be collocated because the motion of the actuated point is directly measured by the sensor. We can see in figure CCC that the sensors and actuators are aligned and there are no intermediate dynamics in the block of metal which connects them (in the frequency

Figure 7: Corwin Hardham and the single layer active platform. The aluminum space frame in the center of the structure is isolated and controlled. Each of the three corners are controlled in 2 DOF by an isolation pod, giving full 6 DOF control of the structure.

range of interest). By collocating the sensors and actuators, we planned to greatly simplify the control problem, because reasonable isolation should be possible with 6 independent single input, single output (SISO) loops. MIMO control can then be used to increase the system's tolerance to drift and misalignment, improving robustness. In the tests we have run so far on the three vertical channels, this is the case. By comparing the SISO and MIMO performance, we are also gaining insight about the relative importance of design details for the reference design.

In the next several weeks we will demonstrate MIMO performance on all 6 degrees of freedom for the single layer active platform, and compare that result with the SISO performance.

The MIMO development is significantly accelerated by the real-time development system we are using for the Stanford prototype (and for the stiff double active stage prototype). The servo control is implemented with a dSpace real-time computer. The dSpace interface allows servo controllers to be developed in Simulink with the modern control tools of Matlab. These controllers can be immediately applied to the experiment (by selecting the "build" option in Simulink). THis tight integration between modeling software and test hardware is expected to allow a fairly short compensation design process.

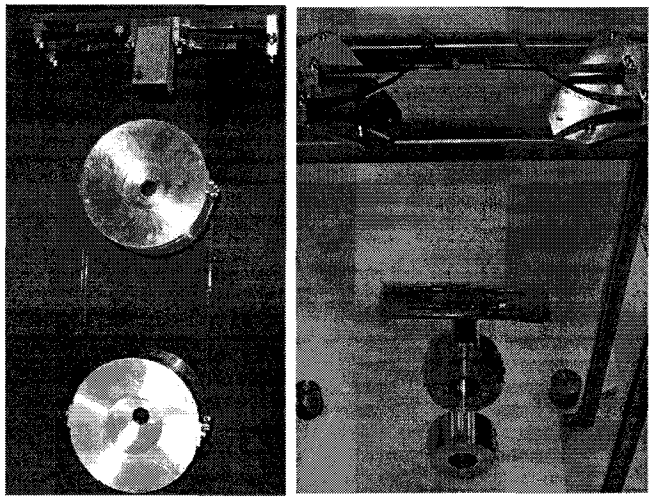

Figure 8: Triple pendulum being balanced in test fixture. The design is closely based on drawings from GEO 600, and the blade springs were made by the JILA instrument shop.

2.3.2 Validation of the LIGO-II reference design computer code

One of the most important results of the MIMO performance demonstration will come from tuning the modeling program. Our goal is to use this physics based model of the system to accurately predict the behavior of the controlled prototype. If the prototype works as the model predicts, we will improve our confidence in our model and in our ability to design controllers using our model. We can already reproduce the vertical plant dynamics with the model reasonably well, and we will soon be using the model to design MIMO controllers.

2.3.3 Demonstration of blending of displacement with inertial sensors

The sensor blending in our prototype is running successfully. Sensor blending is important because active platforms all rely both on inertial sensors and on relative displacement sensors to the previous stages. Inertial instruments can not work at zero frequency. However, by using non-inertial (i.e. relative) sensors at low frequency, we can gain many advantages, including:

- Eliminate the low frequency cross-over in the isolation loops, improving stability.
- Improve performance of the isolation system by requiring that inertial sensors only provide useful information in their sensitive frequency band. This is a direct result of eliminating the low frequency crossover.
- Provide alignment information.

At Stanford, we have been combining sensor outputs for some time, using a technique called complementary filtering (see, for example, reference [4]). Using this method the po-

sition sensor and seismometer are combined to create a "super-sensor" that provides useful information at both high and low frequency.

The single layer active platform uses 4.5 Hz geophones as inertial sensors, and optical sensors as the relative displacement sensors. These sensors can be seen in Figure 7. Figure 9 demonstrates an implementation of complementary filtering. In this figure, the geophone seismometer, shown in green, is significantly attenuated below 4.5 Hz because of the nature of that inertial sensor, but some loop shaping is performed between 1 and 5 Hz to achieve the necessary phase margins between the sensors. Low-frequency information is obtained from the relative position sensor (in red). Although the relative sensor provides many benefits, feedback based on information from the position sensor causes the platform to follow

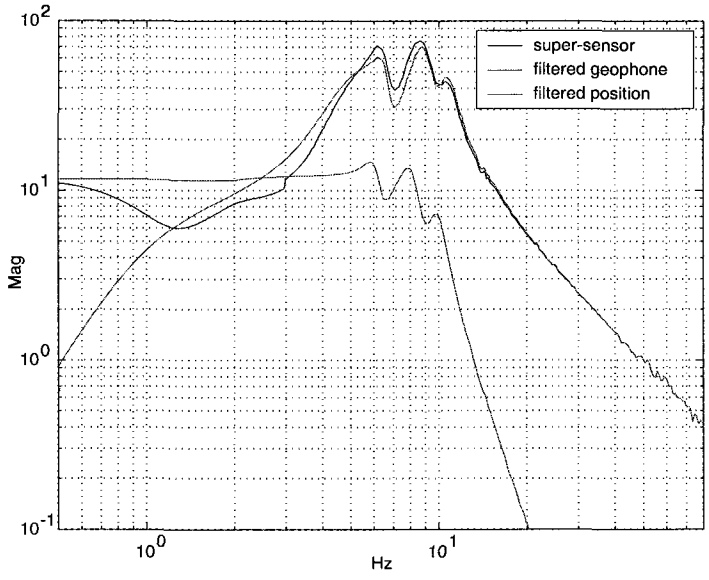

Figure 9: Transfer function from the coil drive to the filtered sensor output. This illustrates the complementary filtering used to combine the geophone signal and the relative position signal.

ground motion, which bypasses the isolation. Therefore, a low pass filter is applied to the position sensor information at low frequency (as low as possible) prior to its combination with seismometer data. The final combination (blue) represents the super-sensor which is used for feedback control.

2.3.4 Demonstration of performance improvement from feed-forward control

We will be implementing feed-forward control and sensor correction on the vertical motion of the single layer platform. Sensor correction is a technique that (in our case) "corrects" a signal from a relative displacement sensor to account for the motion of the stage's motion.

Feed-forward is a technique that removes noise from the system by applying a force calculated to null the transmission of the source noise, based on measurements of that noise and knowledge of how it propagates through the system.

A signal from a high quality geophone will be used to correct the optical displacement sensors, and improve the performance of the system between .7 Hz and 10 Hz. These are the frequencies for which the S-13 sensor we have available is very well suited. The reference design will have an operating mode available that will incorporate both feed-forward and feedback to help improve the isolation, especially during periods of exceptional environmental noise. Since feed-forward corrections improve performance but do not generally impact stability, we believe that the best use of our resources is to implement only a single degree of freedom. This will give us experience with feed-forward in our isolation system, and help our model validation with only minimal hardware. Further studies of feed-forward control and sensor correction will be pursued after April as we try to get the maximum performance from the prototype.

2.3.5 Demonstration of reliable performance of a system with both an active platform and multi-element pendulums

In LIGO II, the isolation platform should provide a quiet, robust platform on which to mount the optics pendulum. One of the advantages of a stiff, active platform is that it will not interact badly with the local control servos of the multiple pendulums which it is designed to support. We are building a pair of triple pendulums, seen in figure EEE, based on the GEO 600 design. The pendulums will hang from the single active stage so that we can investigate two issues: first, what are the requirements for maintaining robust performance of both the active stage isolation servos and the multiple pendulum local damping servos in the presence of interactions, and second, how can we optimize the reallocation of control authority between the pendulum and the active platform to maintain interferometer lock while making best use of the dynamic range, bandwidth, and noise performance of the set of available actuators.

We plan to study the control interaction question before April. we believe this is a very import question to address, and that it will demonstrate a clear advantage of the stiff team approach.

We will also add the triple pendulums to the model and try to predict the performance of that complicated system. We believe that if we can accurately predict the transfer functions of a triple pendulum suspended from a single stiff platform, we will have a good enough grasp of the fundamental issues that we can make reasonable statements about the control of the reference design.

2.3.6 Development of control reallocation techniques

The ability to easily offload control authority from the actuators in the multiple pendulums to the larger actuators in the active platform is a benefit of the stiff active approach. This

control reallocation can easily be tested and developed with the Stanford isolation prototype. However, we have decided to pursue this research during the summer.

2.3.7 Implementation of watchdog schemes for oversight of SEI operation modes

The LIGO control system and the prototype systems run on real time control hardware. This will allow us to monitor the servo performance and change operation modes in response to various events. We will certainly want different control modes for lock acquisition, standard data collection , and system performance tests. Safety modes would be useful in the event of external power loss or large seismic events. The ability to safely and easily change the operation mode of the system provide various safe modes is an advantage of a system with good control performance. We will be investigating various watchdog schemes later in the year .

References

[1] D. Shoemaker, D. Coyne, "LIGO-II Seismic Isolation Design Requirements Document." 11/4/1999. LIGO E990303-02-D

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[3] Richman, S.J.; Giaime, J.A.; Newell, D.B.; Stebbins, R.T.; Bender, P.L.; Faller, J.E.; "Multi-stage active vibration isolation system," Review of Scientific Instruments, **69:6**, 2531. (June '98)

[4] Hong Sang Bae, "Active Vibration Isolation and Alignment Issues for LIGO," Masters Thesis, Department of Mechanical Engineering, Stanford University, August 1999.

Computer Modeling and Simulation in Support of the Stiff-Suspension Active Seismic Isolation for LIGO II.

Brian Lantz, Wensheng Hua, Sam Richman, Jonathan How, and the Stiff Team

Feb 14, 2000, Version 1.0.1, LIGO-T000016-01

We have developed a very general and versatile approach to model and predict the behavior of complex isolation systems that are being designed for LIGO II. The code is currently being validated against the Stanford prototype, it has already been validated against the GEO 600 code for their triple pendulum, and we will also be validating it with the Stiff Double-Active Stage prototype now under construction. As we test the code against the prototypes, we will gain confidence in its predictions about control and performance. Before April, this code will be used to model the performance of the entire suspension and isolation system we are proposing for LIGO II.

1. Description of the modeling tools

The model consists of three fundamental parts: a model constructor, routines for determining the static equilibrium positions and linearizing the equations of motion around those equilibrium points, and a Simulink interface for evaluating the performance of the isolation system. The system is written completely in Matlab, which has an excellent set of tools for conducting system identification and controller design. The code models the isolation system as a set of springs, masses, sensors, and actuators, then creates a linearized model of that system around the equilibrium condition. Control laws can then be added and the performance of the design is evaluated.

1.1 Modeling Techniques and the Numerical Perturbation Method

All of the various mechanical systems are treated as mass-spring mechanical systems in the same way. For example, the GEO triple pendulum is made of three stages. Each stage has certain mass and moments of inertia. These stages are connected to each other by some springs. The springs could be extensible wires or blade springs. There are sensors monitoring the motions of the stages and actuators applying forces and torques to the stages. Another example is the double stage active isolation system which comprises two serial active platforms from which two (or three) quadruple pendulums are suspended. This is a much more complicated system, but it is still a system made of mass stages, springs, sensors and actuators.

In the model, each mass stage is allowed to translate and rotate in three dimensions. Hence, each stage has six degrees of freedom. Thus, the total number of degrees of freedom of a system is six times the number of stages.

The dynamic model of the system is based on a numerical perturbation technique. Because all the stages in the isolation system work only in small ranges around the equilibrium positions, we assume that the reaction forces and torques are linear to the changes of positions of the stages. To set up the dynamic model of the system, we need to know the reaction forces and torques on the stages due to the motions of those stages in all degrees of freedom. We define the stiffness matrix of a system as the matrix which maps the small changes of positions of the stages onto the reaction forces and torques on those stages. Such reaction forces and torques come from both the deformations of the springs and the changes in the directions of the static force on the springs in the system (e.g. small changes to the position of a pendulum mass change the direction of the static forces applied to it, which results in linear restoring forces). A detailed description of the technique can be found in a document by Wensheng Hua, *How to Construct a Mechanical Model of a Mass-Spring System*, available on the stiff team website.

The stiffness matrices are obtained by linearizing the mass-spring systems around their equilibrium positions. However, this information is not precisely known for the real system, but we can calculate the equilibrium positions of the stage given the physical parameters of the stages and springs. This problem is solved using iteration. The steps are as follows:

1) First, we assume that the stages are at the design position and calculate the net static force and torque on each stage. If the net force and torque on each stage is zero, then the current position is the equilibrium position, and we are done.
2) If we are not in equilibrium, then we linearize the system around the current position and calculate the stiffness matrix.
3) We use this stiffness matrix to calculate the new positions the stages move to so that the reaction force and torque balance the net static force and torque on the stages.
4) In the new position, we recalculate the net forces and torques. If the net force and torque on each stage is zero, then the current position is the equilibrium position, and we are done, otherwise, we go back to step 2.

The iterations are continued until the stages are at their equilibrium positions. Once we have reached static equilibrium, we calculate the final stiffness matrix. This iteration method is equivalent to Newton's method for solving nonlinear equations, and it converges quickly (usually in 3 to 5 iterations).

Once we have the stiffness matrix, we can easily construct a model that represents all of the mechanical dynamics of the system (called the mechanical model). For convenience, the mechanical model is written in a state space form. The states are the positions and velocities of all the stages in all degrees of freedom. The inputs of this model are the ground motions and the actuator forces and torques on every degree of freedom of the system. The outputs of this model are the position of the stages and force on the ground. The ground motion is left as an input and the force on ground as an output. This step provides a convenient way to link our model to a dynamic model of the ground (or a mechanical model of another system) which could be added later.

Next, we make the sensor model and actuator model. The inputs of the sensor model are the positions of the stages. The outputs are the electrical outputs of the sensors. For each sensor, we project the motions of the stages into the sensitive direction of that sensor. We then calculate the output of that sensor based on the sensor's transfer function. The whole sensor model is a collection of all the different sensors in the system, although the modeling tools allow them to be arranged in arbitrary groups in the control simulations.

We follow similar steps in the construct the actuator model. The inputs of the actuator model are the electrical inputs to the actuators. The outputs are the force and torque on the stages.

1.2 Model Connections and Queries

Now we construct the whole model of the isolation and alignment system by connecting the actuator model, the mechanical model, and the sensor model using Simulink.

Once the model of the physical system is assembled, we design the control laws, construct the control model, and close the loop of the whole system. Figure 1 shows the model of the GEO triple pendulum, adapted from the geo_example.m code distributed by Ken Strain, Calum Torrie, et. al. The Simulink interface simplifies the interaction between the blocks in the model, so

the user can open and close loops, add sensor banks, change control laws, etc. with a minimum of difficulty.

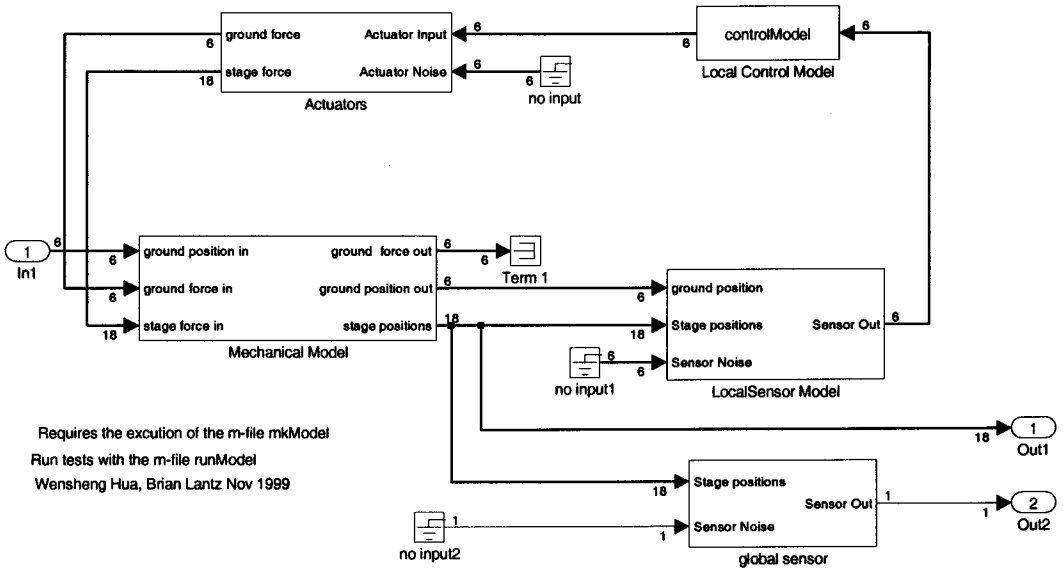


Figure 1. Simulink diagram of the GEO triple model. The parameters match the geo_example.m code distributed by GEO 600.

1.3 The Model Constructor

In the LIGO II isolation system research, we need to model many different systems, such as the GEO pendulums, the various experimental prototypes, and at least two different LIGO II suspension systems (for the BSCs and for the HAMs). These different systems have different kinds of mechanical arrangements, springs, sensors, actuators, and control laws. In order to model these systems effectively, we designed uniform data structures for all the different systems. There are five data structures: stages, springs, actuators, sensors and control laws. These data structures contain all the physical and geometrical parameters of the system. Examples of these data structures can be found in the appendix. These data structures are used as the interface between the system designer and the computer code which constructs the state space model of the system. The designer can easily change the parameters in these data structures and study the performance impacts on the system.

2. Description of the model validation

We are currently engaged in several efforts to validate the performance of the model. The objective is to confirm that the model can be used to accurately predict the performance of our various prototype systems, since this will greatly increase the confidence in our ability to accurately predict the performance of the reference design.

2.1 GEO Triple Pendulum.

We have developed a model of GEO triple pendulum using our model constructor code. We did this in order to compare it with another model of the same system written by GEO. These two models were made independently of each other using different mathematical algorithms. The GEO model has already been experimentally verified. We compared the two systems' stiffness matrices term by term, and the result shows that these two models are exactly the same. These two models produce same transfer functions as well. Figure 2 shows the closed loop transfer function of the GEO triple pendulum from horizontal ground motion to global sensor output.

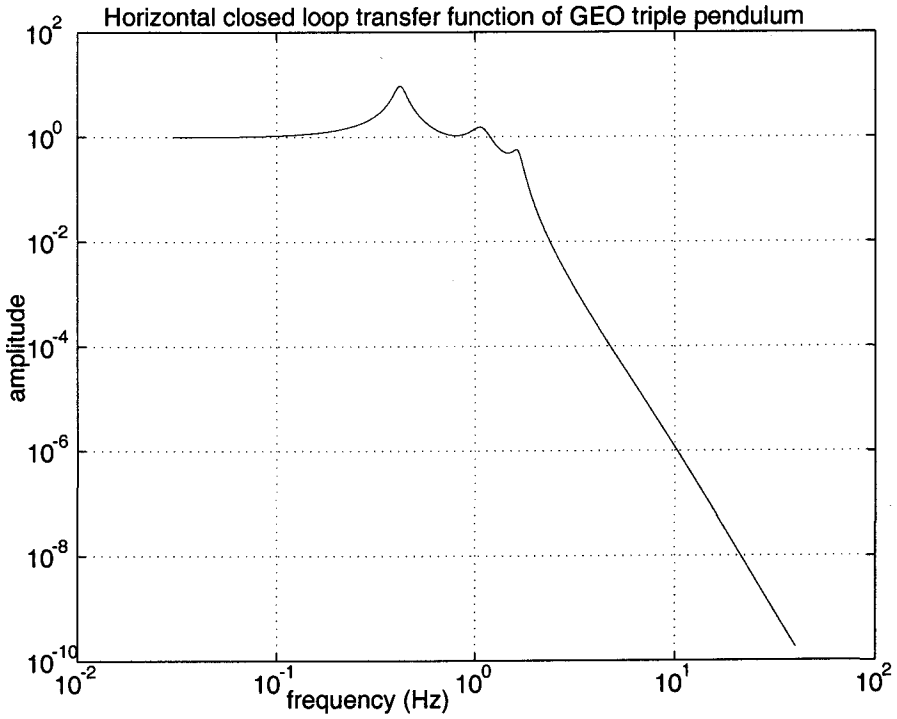


Figure 2. Transfer function from horizontal ground motion to horizontal test mass motion of the GEO triple pendulum as described in the geo_example.m code distribution. This transfer function was generated with the new modeling tools.

2.2 GEO Quadruple Pendulum.

We are constructing a model of the GEO quad pendulum. The GEO group is working on the same model at the same time using their own mathematical algorithms. We are in the process of comparing the models by exchanging the state space matrices and examining them for differences.

2.3 Stanford Prototype

In order to further test our model construction code against a real isolation experiment, we made a model of the single layer active platform built at Stanford. Because it is difficult to measure some of the physical parameters of the system, such as the center of the mass and moment of inertia tensor, we have had to adjust those uncertain physical parameters in the model to fit the transfer function of the model to the experimental results.

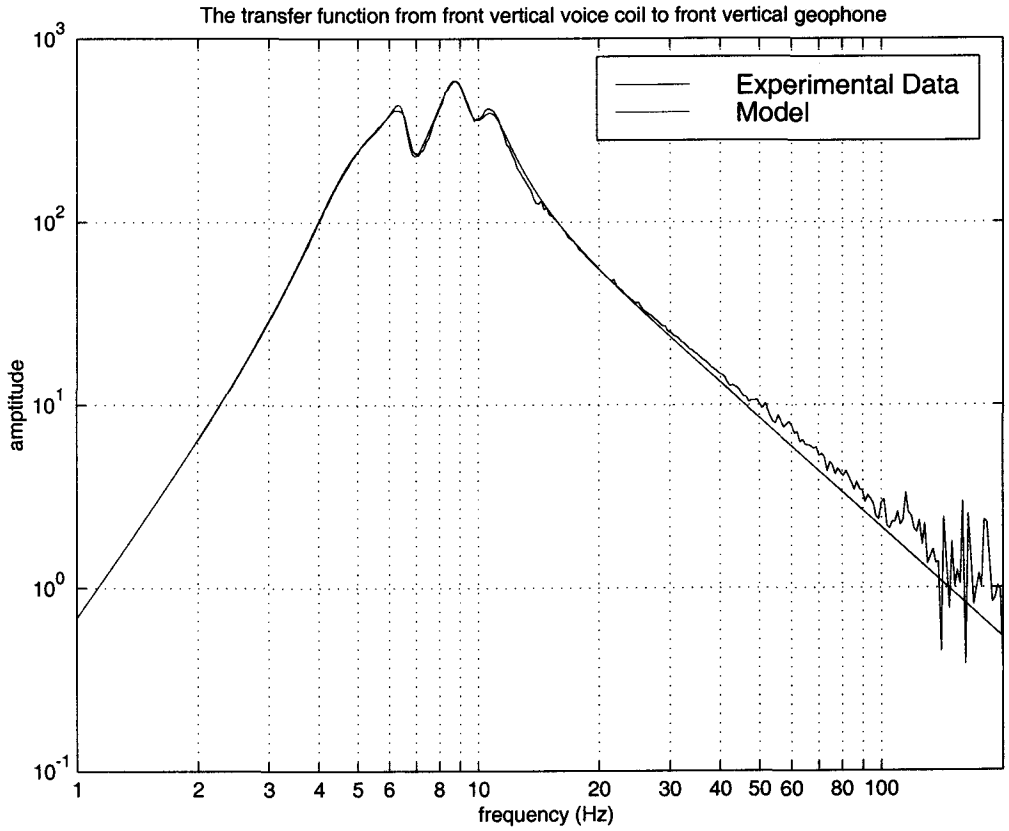


Figure 3. Transfer function of the Stanford single layer active platform and the model, after the model has been tuned.

The red line in Figure 3 shows the transfer function from the front vertical voice coil input to front vertical geophone output according to the model. The blue line shows the same transfer function obtained from the actual system. This transfer function shows a very good match up to about 100Hz. Some of the cross-coupling transfer function fits are not as good as the one in figure 3. These errors in the cross-coupling reflect the sensitivity of the system to slight imperfections in the mechanical system. We will continue to tune the physical parameters of the model to match the measured data as well as possible, and then design the controllers to be robust to any errors in the cross-coupling.

The model validation will continue in the following ways:

1) We will measure all of the necessary transfer functions for the system and form measurement models by fitting a state space system these transfer functions (Liu and Miller '94, Liu et. al. '94). This model will provide very accurate estimates of the modal parameters of the prototype structure, which can be used to further update the physical parameters.
2) These identified models will also be used to design more single-input/single-output (SISO) and multiple-input/multiple-output (MIMO) controllers for the isolation platform. These controllers will be evaluated on the actual testbed and the physical model to determine how accurately we can predict the closed-loop performance.
3) The physical model will also be used to design SISO/MIMO controllers to establish its accuracy as a *control design model*.

The goal is to use this physical model of the system to accurately predict the behavior of the controlled prototype. Close agreement in the close-loop behavior and the ultimate limits in the obtainable performance will greatly improve the confidence of the modeling approach and our ability to develop good control design models using this approach.

When this sequence is complete, we will add the triple pendula to the model to predict the performance of complete Stanford prototype. This model will then be used to evaluate the various control designs and predict the overall performance. The combined model will then be compared with the measured response (e.g. testmass motion and/or forced transfer functions) of the actual system.

2.4 Stiff Double-Active Stage

Preliminary modeling of the two-stage stiff prototype isolation system was done using an adaptation of the model of the JILA technology demonstrator (Richman et. al. '98). This is a state-space representation constructed in Matlab that models the dynamics of the two stages and their respective seismometers. The state-space equations were derived from a Lagrangian of the mechanical system. A controller was developed using single input-single output (SISO) feedback from the seismometers to nearby forcers. This model was used to guide the initial mechanical design of the prototype. The natural suspension frequencies were chosen such that a total isolation factor of 1000 at 10 Hz could be achieved with a 70 Hz bandwidth for the two stage system. The noise from the commercial seismometers used in the prototype was introduced into the model and it was verified that this would not compromise the vibration-limited performance.

We are currently developing another model of the stiff prototype using the numerical perturbation tools and model constructor described in this document. The mechanical model comprises three rigid bodies: the ground and two isolation stages, all with six degrees of freedom. These three are connected in series via idealized blade springs with wires. The outputs of the seismometers and position sensors will be modeled as frequency-dependent combinations of the states of the stages. There is also be a facility for sensor and actuator noise inputs. This model should better represent the stiff prototype than did the preliminary model. Notably, it will include the blending of the low- and high-frequency sensors, and the relative position sensing between the two isolation stages.

The schedule for development of the constructor model of the prototype is slightly advanced with respect to the work on the prototype itself. By February 18 there will be a mechanical model and idealized actuator model in place. This will let us compute transfer functions from actuators and ground motion to motion of the stages. By February 25 we will incorporate transfer function descriptions of the low- and high-frequency seismometers. This will allow for a comparison of driven transfer functions, which will be the first measurements performed with the prototype.

By March 3 we will model a feedback system based on local loops, where the signals from a single position sensor/geophone pair are combined and sent to a single co-located forcer. The algorithm for blending of signals will be based

on previous work done at Stanford (H. S. Bae, '99). The next step will be to construct the model of a feedback system in which a low-frequency seismometer is also blended into the signal from a position sensor/geophone pair for the upper stage loops.

By March 10 we will add sensor noise into the model to make a prediction of the performance limit of the two-stage prototype. Based on results of the preliminary model, it is not expected that sensor noise will preclude the target isolation factor of 1000 at 10 Hz. At that point, further work on the model will be driven by experimental results from the prototype. Possibilities for future work include modeling MIMO feedback, and feed-forward from the low-frequency sensors on the upper stage to actuators on the lower stage.

3. Models of the Reference Design

The goal of the modeling effort is to provide tools for designing and understanding the control and performance of prototypes, so that we can use these tools to establish a reference design for LIGO II. By April, we will have a reference design of all the double active stages and quadruple pendula for the BSC and the HAM. The model will include:

1) Dynamics of the system for all degrees of freedom. This is automatic for this modeling system.
2) The isolation control loops for the double active stage.
3) The pendulum dynamics of the quadruple pendulum with its local damping, and the impact of those dynamics on the performance of the system.
4) Couplings of the ground noise, sensor noise, and actuator noise into the motion of the test mass to show that we meet the noise requirements.
5) Global position feedback and calculations of the rms position of the test mass. We are currently examining the global model distributed by Ken Strain so that we can leverage off of those results.
6) Calculations to show that all states of the system are observable and controllable.

Conclusions

We have developed a powerful tool for analyzing isolation systems. The numerical perturbation technique allows any assembly of masses and springs to be converted into a linear state space model. The model constructor allows

simple modification of the physical structure of the system, and allows simple positioning of sensors and actuators on the system. Since this is done with Matlab, we have a powerful set of modern control tools available for the development of the control systems. By assembling the pieces with Simulink, we have a convenient way of organizing the model connections to simplify the development process.

We have tested the code against the GEO triple results, and it matches perfectly. We are currently testing the code against the experimental prototypes, to further validate the code and gain insight about the control design. This gives us confidence that the simulations of the reference design will be reasonably accurate.

References

Hong Sang Bae, *Active Vibration Isolation and Alignment Issues for LIGO*, Masters Thesis, Department of Mechanical Engineering, Stanford University, August 1999.

Liu, K. and D. W. Miller, ``Structural System Identification: A Study of Different Algorithms,'' *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, Scottsdale, AZ, 1994, pp. 702--714.

Liu, K., R. Jacques, and D. Miller, ``Frequency Domain Structural System Identification by Observability Range Space Extraction,'' *Proceedings of the American Control Conference*, Baltimore, MD, 1994, pp. 107--111.

S. J. Richman, J. A. Giaime, D. B. Newell, R. T. Stebbins, P. L. Bender, and J. E. Faller, *Rev. Sci. Instrum.* **69**, 2531 (1998).

Wensheng Hua, *How to Construct a Mechanical Model of a Mass-Spring System*, this document is available at the stiff team website.

Appendix – Examples of data files used by the model constructor

Mechanical Model: stages

Here is the model constructor for a single stage of a isolation system, many of the parameters are defined elsewhere.

```
% stage.m holds the data structure of stage.


StgSGrd=1;

StgStck=2;


%physical Parameters

stage(StgStck).name='StgStck';

stage(StgStck).center=[0 0 -frameMcz]';

stage(StgStck).axis=eye(3);

stage(StgStck).mass=fmass;
stage(StgStck).Ix=fIx;
stage(StgStck).Iy=fIy;
stage(StgStck).Iz=fIz;
stage(StgStck).inerAxis=Rt;
%derived parameters
stage(StgStck).forceInputAddr=2;
stage(StgStck).posiOutputAddr=2;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Mechanical Model: springs

This is an excerpt of the file used to define the springs of the single layer active platform.

```
% spring.m is the data structure of spring.

SprSGrdStak_1=1;
SprSGrdStak_2=2;
SprSGrdStak_3=3;
SprSGrdStak_4=4;
SprSGrdStak_5=5;
SprSGrdStak_6=6;

% data inform parameters:
```

```
spring(SprSGrdStak_1).name='SprSGrdStak_1';
% geometry parameters:
spring(SprSGrdStak_1).uStageNum=StgSGrd;      % The stage number of the upper stage.
spring(SprSGrdStak_1).uPosition=[fNXOffset -fSprUy -SprUz]'; % The contacting point of
    the spring on the upper stage in the upper stages local coodinate.
spring(SprSGrdStak_1).uDirc=cookUnit([0 0 -1]',[0 1 0]');
spring(SprSGrdStak_1).lStageNum=StgStck; %The stage number of the lower stage.
spring(SprSGrdStak_1).lPosition=[fNXOffset -fSprLy -SprLz]'; % The contacting point of
    the spring on the lower stage in the lower stages local coodinate.
spring(SprSGrdStak_1).lDirc=cookUnit([0 0 1]', [0 1 0]');
% physical parameters:
spring(SprSGrdStak_1).type=STypeWire;  % The type of the spring enable the model to use
    different type of springs.
spring(SprSGrdStak_1).elastic=[sprK sprIniL 0 0]; % some elastic constance, the first one
    is the zero-force spri
%constant the other constance can be used for non-linear springs.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Sensors

Here is the code which defines the first two local sensors of the GEO 600 local control.

```
%GeoTripleLocalSensors.m

% sensor.m The data structure of sensor.

SenPen1PGrdH=1;
SenPen1PGrdT=2;
SenPen1PGrdV=3;
SenPen1PGrdY=4;
SenPen1PGrdP=5;
SenPen1PGrdR=6;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sensor(SenPen1PGrdH).name='SenPen1PGrdH';
% geometry parameters:
sensor(SenPen1PGrdH).mainStageNum=StgPen1;    % The stage number of the main stage, the
    stage that holds the sensor.
sensor(SenPen1PGrdH).mainPosition=[0 0 0]'; % The sensor's position on the main stage in
    the main stage's local coordinate.
sensor(SenPen1PGrdH).mainBaseDirc=[1 0 0;0 0 1]'; % The sensor's sensitive direction in
    the main stage's local coordinate.
sensor(SenPen1PGrdH).refStageNum=StgPGrd; %The stage number of the sensor's reference
    stage.
sensor(SenPen1PGrdH).refPositionA=[0 0 0]'; % The reference points of the sensor on the
    reference stage in the reference stages local coodinate.
sensor(SenPen1PGrdH).refBaseDirc=[-1 0 0;0 0 1]'; % The sensor's sensitive direction in
    the main stage's local coordinate.

% physical parameters:
```

```
sensor(SenPen1PGrdH).type=SenType.IdealRelate;  % The type of the sensor enable the model
    to use different type of sensors.
sensor(SenPen1PGrdH).gain=[1 0 0 0 0 0]; % The gain the sensor
sensor(SenPen1PGrdH).transFunc=tf([1],[1]); % The transfer function of the sensor

%derived parameters:
% Note: All the dumy settings here will only be used for date struture,but not for real
    calculation.
sensor(SenPen1PGrdH).geoFunc=zeros(1,12);
% The sensor's transfer function from the stages' position to the senser output.
% .sensFunc is multi-input-single-output.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

sensor(SenPen1PGrdT).name='SenPen1PGrdT';
%geometry parameters:
sensor(SenPen1PGrdT).mainStageNum=StgPen1;
sensor(SenPen1PGrdT).mainPosition=[0 0 0]';
sensor(SenPen1PGrdT).mainBaseDirc=[1 0 0;0 0 1]';
sensor(SenPen1PGrdT).refStageNum=StgPGrd;
sensor(SenPen1PGrdT).refPositionA=[0 0 0]';
sensor(SenPen1PGrdT).refBaseDirc=[-1 0 0;0 0 1]';
% physical parameters:
sensor(SenPen1PGrdT).type=SenType.IdealRelate;
sensor(SenPen1PGrdT).gain=[0 1 0 0 0 0];
sensor(SenPen1PGrdT).transFunc=tf([1],[1]);
%derived parameters:
sensor(SenPen1PGrdT).geoFunc=zeros(1,12);
```

Actuators

Here is example code to define two actuators. It references several variables which are defined elsewhere.

```
% actuator.m this is the data structure defining the actuators.
ActSGrdStckH1=1;
ActSGrdStckH2=2;
ActSGrdStckH3=3;
ActSGrdStckV1=4;
ActSGrdStckV2=5;
ActSGrdStckV3=6;

actuator(ActSGrdStckH1).name='ActSGrdStckH1';
% geometry parameters:
actuator(ActSGrdStckH1).mainStageNum=Stg.Stck;       % The stage number of the main stage,
    the stage that holds the actuator.
actuator(ActSGrdStckH1).mainPosition=[fNXOffset -fHGeoVoiceBy -hGeoVoicez]'; % The
    actuator's position on the main stage in the main stage's local coordinate.
actuator(ActSGrdStckH1).mainBaseDirc=cookUnit([fNXOffset -fHVoiceTy -hGeoVoicez]'-
    [fNXOffset -fHGeoVoiceBy -hGeoVoicez]' ,[0 0 1]'); % The actuator's Active direction
    in the main stage's local coordinate.
actuator(ActSGrdStckH1).refStageNum=Stg.SGrd; %The stage number of the actuator's
    reference stage.
```

```
actuator(ActSGrdStckH1).refPosition=actuator(ActSGrdStckH1).mainPosition+stage(actuator(A
    ctSGrdStckH1).mainStageNum).center; % The reference points of the actuator on the
    reference stage in the reference stages local coodinate.
actuator(ActSGrdStckH1).refBaseDirc=actuator(ActSGrdStckH1).mainBaseDirc; % The
    actuator's Active direction in the main stage's local coordinate.


% physical parameters:
actuator(ActSGrdStckH1).type=ActType.Voice;  % The type of the actuator enables the model
    to use different type of actuators.
actuator(ActSGrdStckH1).gain=[1 0 0 0 0 0]'; % The gain the actuator
actuator(ActSGrdStckH1).damping=dampLamda; % The damping of the actuator
actuator(ActSGrdStckH1).transFunc=voiceTrans; % The transfer function of the actuator

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
actuator(ActSGrdStckH2).name='ActSGrdStckH2';
% geometry parameters:
actuator(ActSGrdStckH2).mainStageNum=Stg.Stck;
actuator(ActSGrdStckH2).mainPosition=[-osHVoiceBx +osHVoiceBy -hGeoVoicez]';
actuator(ActSGrdStckH2).mainBaseDirc=cookUnit([-osHVoiceTx +osHVoiceTy -hGeoVoicez]'-[-
    osHVoiceBx +osHVoiceBy -hGeoVoicez]' ,[0 0 1]');
actuator(ActSGrdStckH2).refStageNum=Stg.SGrd;
actuator(ActSGrdStckH2).refPosition=actuator(ActSGrdStckH2).mainPosition+stage(actuator(A
    ctSGrdStckH2).mainStageNum).center;
actuator(ActSGrdStckH2).refBaseDirc=actuator(ActSGrdStckH2).mainBaseDirc;
% physical parameters:
actuator(ActSGrdStckH2).type=ActType.Voice;
actuator(ActSGrdStckH2).gain=[1 0 0 0 0 0]';
actuator(ActSGrdStckH2).damping=dampLamda;
actuator(ActSGrdStckH2).transFunc=voiceTrans;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

BATCH START

STAPLE
OR
DIVIDER

Laser Interferometer Gravitational Wave Observatory

- LIGO -

LIGO Science Collaboration

LIGO-II Seismic Isolation Design Requirements Document

D. Shoemaker, D. Coyne; LIGO-E990303-021-D

Distribution of this draft:

Isolation Working Group, LIGO Science Collaboration

1 Introduction

This is a rough draft of the Requirements and Interface Specification for the LIGO II Seismic system. Its primary value is in the qualitative description of the requirements and the interfaces, and it should help seismic isolation designers approach the problem with a full view of the kinds of requirements and interfaces known to be important. In many places numerical values are missing, arrived at by extrapolation from LIGO I, or sketched from back-of-the-envelope calculations. The authors invite comments and questions.

1.1 Purpose

The requirements for the LIGO-II seismic isolation system are defined.

1.2 Scope

Isolation of the LIGO-II optics from ambient vibration is accomplished with a Seismic Isolation Subsystem and a Suspension Subsystem. The scope of this document is limited to the requirements of the seismic isolation subsystem. This includes the requirements for interfacing to the suspension subsystem.

1.3 Definitions

1.4 Relevant Documents

The following documents are relevant:

- LIGO II Strawman Design (Shoemaker, Strain, Gustafson, strawman9jul99.pdf)
- GEO Triple-Pendulum Design Description (Isolation, control and design aspects of the adaptation of a GEO suspension to LIGO (Ken Strain, geopendr.pdf; Control and isolation aspects of the last 3 stages of a suspension designed to perform well at 10 Hz (Ken Strain, mtenhz.pdf)
- Specification Guidance for Seismic Component Cleaning, Baking, and Shipping Preparation (LIGO-L970061-00-D)

- The Effect of Microseismic Noise on a LIGO Interferometer, LIGO-T960187-01-D
- LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022-D)
- LIGO Seismic Cleaning Specification (L970061-01-D)
- LIGO Naming Convention (E950111-A-E)

2 General description

The seismic isolation system must fulfill the following general requirements:

- Provide vibration isolated support for the payload(s)
- Provide a mechanical and functional interface for the suspension
- Provide adequate space and flexibility for mounting of components (suspensions and auxiliary optics) and adequate space for access to components.
- Provide actuation suitable to maintain the total motion of the test mass or optics component within a requirements for lock acquisition and normal operation, in conjunction with suspension actuators.

1.12.1 General Constraints

- LIGO interferometers have strict vacuum-compatibility requirements which constrain the material choices to those materials compatible with LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022-00-D). Wherever possible, material choices should be conservative with regard to vacuum compatibility. In particular polymers and elastomeric materials should not be exposed in the LIGO-II SEI system, with the exception of Kapton and PEEK for cabling.
- All LIGO-II SEI systems must fit within the LIGO vacuum chambers as presently built.
- The SEI piers around the chambers should be left in-place. The present SEI support tubes may be re-used or replaced.
- The suspension subsystem used for sensitive optics/test-masses is a modification of the GEO triple-pendulum system. The allowable range in interface parameters or definition is defined in the requirements section.

1.22.2 Assumptions and Dependencies

The following assumptions have been made:

1. The SEI payload (including all suspended or fixed-mount optics and auxiliary components) for both HAM and BSC chambers is assumed to be a maximum of 600 kg per chamber. This does not include any common structure used to bridge payloads (such as an optics table) to a single SEI suspension or attachment point, nor does it include any counter-weights which may be required to balance the payload for the seismic isolation system.
2. The SEI net payload will always be balanced through the addition of counterweights. The counterweights are in addition to the payload weight cited above.

3. The optical beam height is 10 cm below the BT centerline, 10cm below the BSC aperture centerline and at the same elevation as the HAM aperture. The optical beam height may be displaced within the nominal 1 m LIGO aperture by agreement with the LIGO-II system coordinator for compelling reasons. [Note: The optical beam is in general inclined to the local horizontal by as much as ± 620 microrad. The magnitude of the slope varies with each building at each of the observatories.]
4. The optical beam is nominally 200 mm left or right (depending upon which interferometer and which arm) of the physical beamtube center. The optical beam lateral position may be displaced by agreement with the LIGO-II system coordinator for compelling reasons.

3 Requirements

2.1 Vacuum Chambers

Seismic isolation systems are required for both types of LIGO vacuum chambers: the HAM and the BSC. However, the size and performance of the SEI systems implemented in a chamber are dependent upon the payload and its isolation requirements. The SEI system does not need to have a common design for all implementation instances. However, interchangeability of parts is desired and the number of unique instances of seismic installations should be minimized.

~~1.3~~2.3 Payloads

The fundamental payloads for the seismic isolation system consists of the following optical components:

- Test Masses (TMs) or Core Optics Components (COC) of the Fabry-Perot cavities: Inside Test Masses (ITM), End Test Masses (ETM), Folding Mirrors (FM)
- Core Optics Components (COC) of the Power or Signal Recycling Cavities (RM, BS, SRM, FM)
- Mode Cleaner (MC) optics
- Ancillary Optics (pick-off mirrors, pick-off telescopes, ETM telescopes, etc.)

These payloads in general have different isolation performance requirements. The most stringent requirements are for the test masses (ITM, ETM) which are supported by a (modified) GEO suspension.

In addition to these optical components there is a need for provision for cabling for power and signal wiring to be supported by the isolation system.

The payloads within a single chamber can either be supported all by a single seismic isolation system (for example by providing a common optics table), or by multiple SEI units within the same chamber.

The basic parameters of the payloads are listed in the following Table.

Table 1: Payload Characteristics; a given isolation system carries multiples of these payloads

Optics Payload	Chamber Type	Suspension Type	Weight	Inertia	Size
ITM, ETM, BS Suspensions	BSC	GEO Triple	~200 kg	TBD	~0.5m x 0.5m x 1.5m
RM, SRM	HAM	GEO Triple	~100 kg	TBD	0.5m x 0.5m x 1.0m
MC Suspensions	HAM	GEO Triple	~100 kg	TBD	0.5m x 0.5m x 1.0m
Ancillary Optics: PO Mirror PO Telescope ETM Telescope	HAMBSC	None	 11 kg 56 kg 24 kg	TBD	 0.2m x 0.3m x 0.3m 1.5m x 0.4m x 0.3m 0.7m x 0.2m x 0.2m

2.4 Suspension Interface Definitions & Requirements

The suspension will be a modified version of the GEO multiple-stage pendulum. Our present best approximation to the interface is as follows:

- The seismic system must provide a mechanical interface with a static initial alignment of <100 microrad and a stainless steel or aluminum mounting surface of at least 0.5m x 0.5m per suspension.
- The top stage of the suspension system reacts against the seismic system. This requires a minimum stiffness in 6 degrees of freedom for alignment and isolation; The minimum stiffness (in torque) required in each DOF is 3e-4 rad/N-m at zero frequency TBR.
- If the interface stiffness is to be less than defined above, then the current suspension design approach must be redesigned to allow the reduced stiffness. In addition a means of performing fine alignment either by the seismic system or by the suspension must be provided. This redesign of the suspension is the responsibility of the suspension group.

- ~~If the interface stiffness is to be less than defined above, then the top stage of the suspension must be redesigned to allow the reduced stiffness and to provide a means of performing fine alignment. This redesign of the suspension must be provided with the seismic isolation design.~~

- ~~It~~ It is required that ~~the performance of~~ the integrated system (with the GEO pendulum concept as is, or modified if needed) must be shown to meet isolation ~~performance~~ and control-band performance requirements (see section 2.5 and 2.6~~3.5~~), and to require minimal test mass actuation, ~~with~~ via a fully 3D model including the suspension system, using the model in geo_example.tar.gz or with an alternative 3D suspension model.

1.42.5 Payload Geometry/Spacing

1.4.12.5.1 BSC Chamber

The minimum separation (spacing) of optics payload suspension points in a common vacuum chamber is 250 mm. The maximum separation (spacing) of optics payload suspension points in a common vacuum chamber is 1100 mm. The spacing and relative position between particular optics payloads is not arbitrary, but dictated to the SEI subsystem on the basis of system considerations. The SEI system should accommodate arbitrary placement of the optics payloads within the minimum and maximum separation distances and within a bounding radius of 0.6 m from the chamber center (in plan view); balancing masses may be used to maintain a uniform load presented to the SEI system. Ability to vary the placement of the optics as part of the commissioning of the interferometer is a requirement. Compensating masses may be used to maintain balance.

The maximum number of optics payloads in a common vacuum chamber is 3 for a BSC chamber (of which 2 may be GEO triple pendulums).

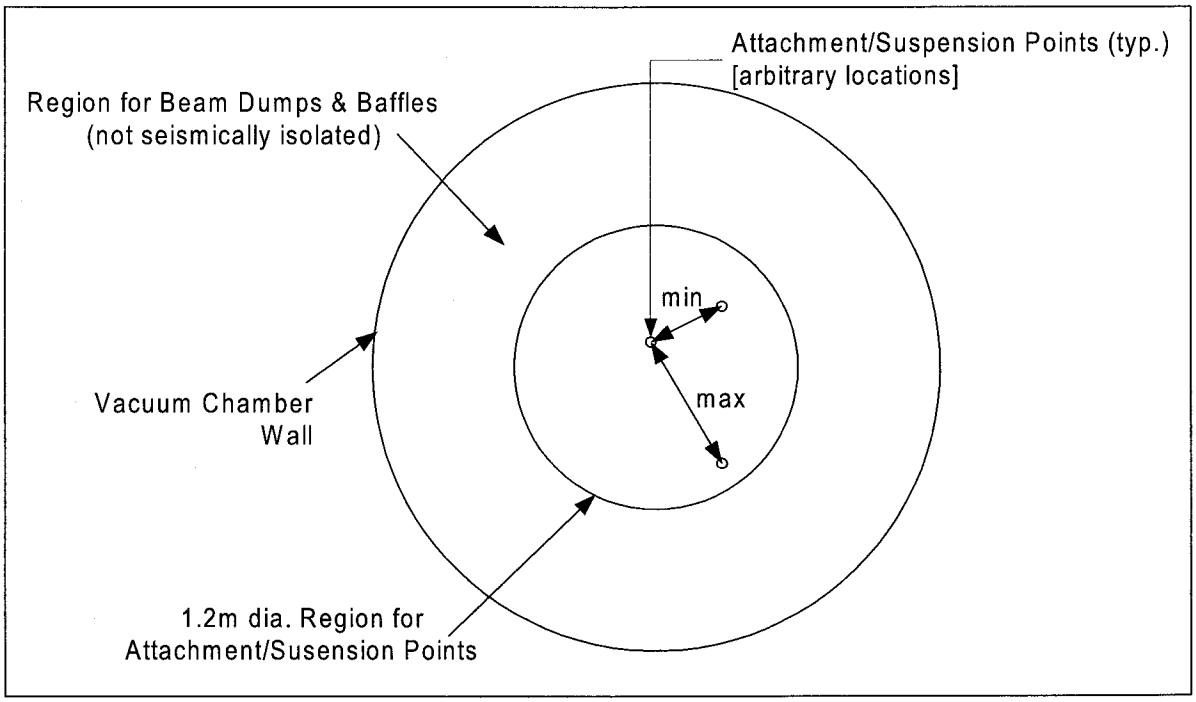


Figure 1: Payload Geometry/Spacing in the BSC chambers

1.1.22.5.2 HAM Chamber

The optical components within the HAM chambers may be located anywhere within a 1.9 m (longitudinal direction) x 1.7 m (transverse to the beam axis) area, centered on the chamber. The minimum separation between suspended components is ~0.25 m. The maximum number of suspended optics payloads in a common vacuum chamber is 6 for a HAM, plus numerous fixed mount relay optics. Due to the numerous optics, particularly for the first HAM chamber in the Input Optics (IO) section of the interferometer, an optics table is required as the interface between the

seismic isolation system and these optics and suspensions payloads; The optics table is the responsibility of the seismic isolation subsystem. The stiffness, mass, resonant frequencies and Qs of the optics structure must be designed to meet all requirements of the seismic isolation subsystem.

1.52.6 Isolation Performance

We distinguish two functional modes: Interferometer Acquisition and Interferometer Operational. In Acquisition mode, the interferometer is not yet providing closed-loop feedback signals to the combined suspension-isolation system, and the isolation system must provide a quiet platform with low enough mirror velocities to allow successful acquisition of the interferometer control system. In Operational mode, the interferometer provides signals in length and alignment to each test mass/suspension.

In addition, there is a startup time for the isolation and suspension system which must be addressed.

2.1.1 Isolation system startup

TBD. The isolation system must go from off (complete power down) to Interferometer Acquisition Mode in no more than 30 minutes TBR. The isolation system must go from loss-of-lock to to Interferometer Acquisition Mode in no more than 1 minute TBR.

2.1.2 Interferometer Acquisition Mode

The maximum (3 sigma) velocity of the suspension optic during the acquisition mode must be less than ? m/s (TBR).

2.1.3 Interferometer Operational Mode

The performance of the seismic isolation system is characterized by the displacement spectrum at the optics table (the surface to which the suspension is attached) for a standard excitation (see Natural Environment below). While the optics table spectrum is the most complete and ultimately useful description, the other more compact measures below should be quoted:

- the frequency at which the displacement noise due to the seismic isolation system equals the given reference ~~displacement~~ noise spectral density
- the rms motion (integrated from 0.01 Hz) when operated closed-loop with the reference suspension transfer function and controller (Ken Strain, Geo Pendulum Matlab Model, geo_example.tar.gz)
- the rms velocity (integrated from 0.01 Hz) operated closed loop

Our present best approximation to the isolation requirements is as follows, all cells TBR. Requirements depend upon the payload, as indicated in the following Table. Empty cells are TBD. The requirements are given at the test mass and include the suspension transfer function, and may assume a closed-loop controller (e.g., the Matlab model above) with no more than 200 Hz upper unity gain frequency.

Table 2: Isolation Operational Performance Requirements

Optics Payload, (Chamber type)	Optic Axis (X-direction)				Y & Z directions		Pitch, Yaw
	Freq. (Hz)	Noise (m/√Hz)	*Motion* (m rms)	Velocity (m/s)	Noise (m/√Hz)	*Motion* (m rms)	*Motion* (rad rms)
ITM, ETM, BS, FM (BSC)	10	10^{-19}	10^{-14}	10^{-9}	10^{-16}	10^{-11}	10^{-96}
RM, SRM (HAM)	10	10^{-17}	10^{-13}	10^{-8}	10^{-14}	10^{-10}	10^{-96}
MC (HAM)	10	$3x10^{-18}$	10^{-12}	10^{-7}	$3x10^{-15}$	10^{-9}	10^{-96}
Ancillary Optics (HAM, BSC)	10						

1.62.7 Actuation requirements

The isolation system will be part of a hierarchical control system for effecting length and angular actuation. A complete requirement must follow a complete interferometer control design. However, anticipated actuation requirements for the seismic isolation system will be fulfilled if the requirements for stand-alone rms performance given in the table above are met. The objective is to re-allocate as much authority as possible away from the test mass actuators, and reductions in force and in bandwidth are desired. The actuation range and bandwidths will be used to reduce low-frequency noise input, due to sources such as the following:

- Microseismic peak: motion in the vicinity of 0.16 Hz due to ocean waves, amplitudes varying but of the order of 10^-5 m rms (see *The Effect of Microseismic Noise on a LIGO Interferometer*, LIGO-T960187-01-D)
- Earth tides: The interferometer arm lengths vary over 6 and 12 hour periods due to earth tides. The differential displacement between two arms is approximately 10^{-4} m pp. The SEI system must include an actuator capable of this rate and dynamic range. (See LIGO-T970059-01-D for details).
- Meteorological changes: the SEI system must allow compensation for longer time period baseline changes (1 week, TBD) due to rain, temperature changes, freezing, etc. Amplitude and time scale TBD.

1.72.8 Coarse Alignment Requirements

A capability for coarse alignment is required for initial installation alignment and, if needed, to compensate for long term drift or seasonal temperature changes. The existing LIGO-I coarse actuation system may be used (stepper-controlled lead screws), or another means of alignment provided. The range requirement of ±5 mm is specified to maintain centering on optics. If the coarse actuation system is outside the vacuum envelope, the restoring forces from the bellows between the support tubes and the vacuum equipment must be managed (~200 lbf). Motions must be made with small accelerations to protect the suspensions and optics.

1.82.9 Internal Resonances

The resonant frequencies and Q's of resonances in the SEI system (either solid-body modes or modes internal to a body) shall be such that the rms displacement and velocity, seismic noise transmission, and thermal noise fluctuation of the optical platform do not exceed the requirements. If an optics platform is used to support the payload(s), then it is considered part of the SEI.

All rigid body modes must be damped (either actively and/or passively) so that any unforeseen cross coupling can not cause unacceptable motion in the modes which are significant for interferometer length control.

The seismic isolation system shall return to the quiescent state from impulsive excitation from minor earthquakes, coarse actuation, power up, etc. within 300 seconds TBR.

1.92.10 Non-Gaussian Noise Limits

Noise due to non-Gaussian processes shall not be excessive; numerical evaluation TBD. Possible sources which should be considered and documented are noise due to mechanical sources (drift, deformation, motion during operational actuation, etc.), or electronic noise sources (popcorn noise, saturation, pickup, digitization etc.).

1.102.11 Drift and Thermal Expansion

Uncompensated drift or positional changes due to temperature changes in the environment, or mechanical creep, shall not exceed a maximum of 0.1 mm vertical, 0.1 mm horizontal, and 100 microrad (for the optics table) in any 30 day period. (The LVEA is regulated to +/- 2 C.)

1.112.12 Motion during power up or power down

The entire SEI system is required to remain in the same absolute position ((+/- 100 microns, TBD; max velocity at suspension point, 10 microns/sec TBD) while being powered on or during voluntary or accidental shut down. May be achieved with a short-term standby power system.

1.122.13 Requirements on In-Vacuo Power & Signal Transmission

Means for the transmission of power and signals from control electronics outside the vacuum chambers to the suspension systems (for monitoring and control) must be provided by the SEI system. Either in-vacuo cabling or wireless power & signal transmission capability must be provided. Roughly 70 channels or conductors are needed per triple suspension.

Cabling that joins equipment mounted to the optics platform to surfaces that have less vibration isolation must satisfy the following:

- Cabling shall be firmly clamped to each successive stage of the seismic isolation to prevent this cabling from conducting vibration around the isolation system.
- In the case of multi-conductor cables, each wire must be firmly fixed in place so that ~~its~~ each wire's effective ~~mass~~ mechanical impedance at the clamped area is comparable to the ~~mass~~ impedance of the stage to which it is clamped.
- The stiffness and mass of the cable must be such that it does not compromise the SEI performance requirements.

- Free lengths of cable must be placed so that they cannot possibly touch other surfaces except where they are clamped.
- Cabling must not "crackle" when vibrated under operating conditions. This may be ensured either by choice of material or by the method in which the material is mounted.
- Cabling and any electronics must satisfy the requirements for vacuum compatibility listed in LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022-00-D)

1.132.14 Natural Environment

1.13.12.14.1 Ground Noise

Vibration of the floor in the LVEA and VEA's is estimated based on seismic measurements at the sites prior to erection of the buildings and support equipment. A composite ground-noise spectrum was compiled to serve as the basis for deriving the requirements on transmission of vibration for the seismic isolation. This composite curve was obtained by concatenating the Livingston noise at frequencies below 4 Hz with the LIGO Standard Spectrum above 4 Hz. The composite curve is shown in Figure 2.

Data on the microseismic peak is available LIGO-T960187-01-D. Performance analyses related to suppression of the microseismic peak should use this reference for the disturbance environment. For $0.001<f<0.1$ Hz, assume $x=3 \times 10^{-7}$ $(f/0.1\ \text{Hz})^{-0.5}$ $m/\sqrt{Hz}$).

The ground noise is assumed to be isotropic, i.e., the same for translation along three orthogonal axes. There are no data available for tilts; to be provided ASAP.

In addition to the above ambient ground vibration spectrum, there is at times a broad resonance at about 5 Hz (and harmonics) at the Livingston Observatory which is due to turbulence in oil pipe lines which cross the site, and related low frequency (<1 Hz) seismic power. The A collection of spectraum for this disturbance is shown in Figure TBD3 (from Mark Coles); improved statistics and low-frequency measurements to be available. The isolation requirements should must be met in the presence of this noise source as well.

Figure 2: Ground noise spectrum assumed for SEI design.

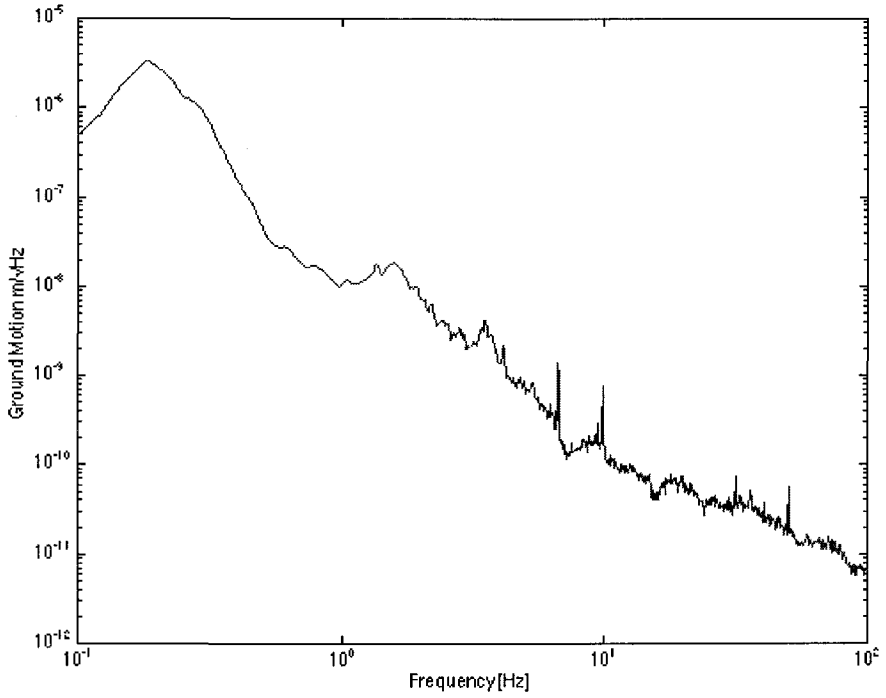
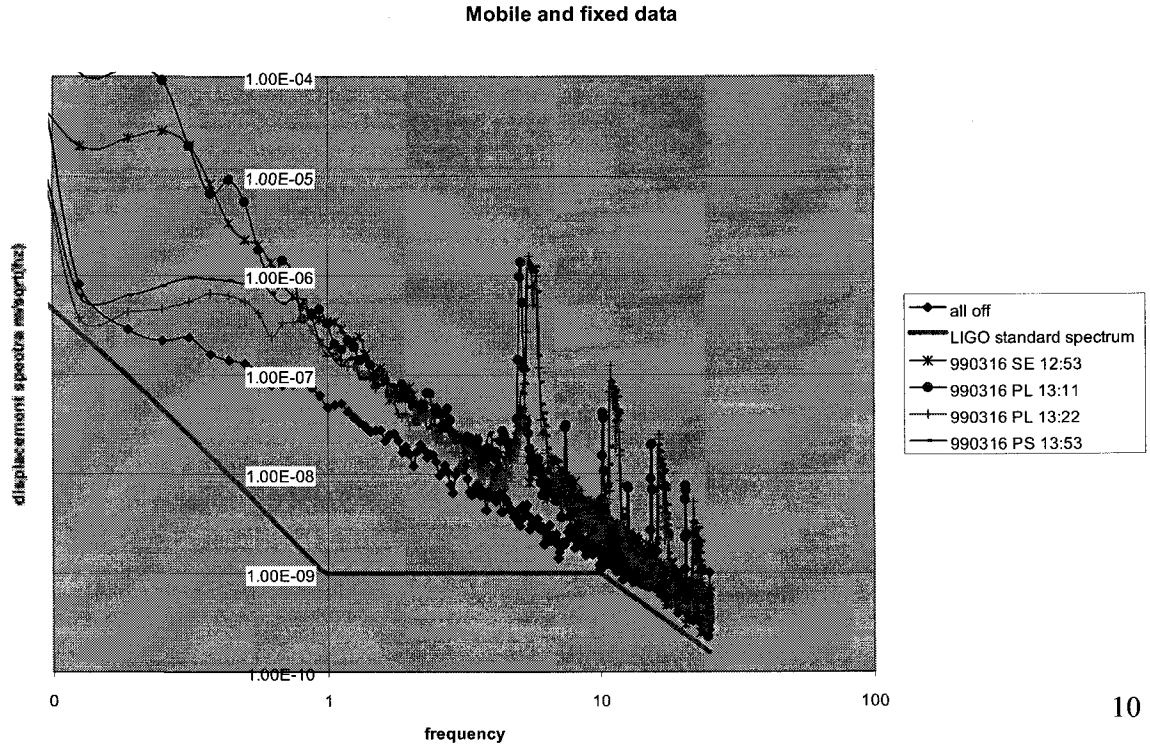


Figure 3: preliminary 'exceptional' ground noise spectrum at LLO



APPENDIX

The information in the appendix is important for a complete design of the seismic isolation system, but is considered secondary for top-level design questions.

1.142.15 Seismic Disturbance

Restraint against seismically induced large motion of the stacks is required.

The SEI shall be designed to resist the static equivalent lateral forces defined in the Uniform Building Code (UBC), 1994 edition, for a seismic zone factor Z = 0.15 (i.e. zone 2B, Hanford) and a structure importance factor I = 1. The support structure shall resist the seismic loads without damage. The seismic stack shall sustain the base shear motion of the support structure without collapse or release of any of the stack layers. At a minimum, failure of the actuators under these loads should not cause failure of the bellows or cause the seismic stack to "drop"; ideally the actuators would survive these loads with no damage.

As an alternative to this static equivalent load, an acceleration design spectrum for use in dynamic analysis could be used.

~~Interpretation of the requirement: If there is no damping or plastic deformation to absorb the seismic loading (Rw = 1), and the SEI first frequency is between 2.5 Hz and 10 Hz (i.e. at the peak), then the base shear,~~

~~Vb = (Z I C/Rw) W = (0.15 (1) 2.75/1) W = 0.4 W~~

~~or the SEI must sustain a 0.4 g lateral load. If, as in the case of the Corner Station building, Rw = 6, then, then SEI must sustain a 0.1 g lateral load.~~

1.152.16 Induced Environment

1.15.12.16.1 Electromagnetic Radiation

Electrical equipment associated with stack actuators shall meet the EMI and EMC requirements of VDE 0871 Class A or equivalent. The SEI system shall also comply with the LIGO EMI Control Plan and Procedures (LIGO-E960036).

1.1.22.16.2 Acoustic

SEI equipment shall be designed to produce the lowest levels of acoustic noise as possible and practical. As a minimum, SEI equipment shall not produce acoustic noise levels greater than specified in Derivation of CDS Rack Acoustic Noise Specifications, LIGO-T960083.

1.1.32.16.3 Mechanical Vibration

Mechanical vibration from SEI actuators on a chamber shall not increase the vibration amplitude of the facility floor within 1 m of any other vacuum chambers and equipment tables by more than 1 dB at any frequency between 0.1 Hz and 10 kHz. Limited narrowband exemptions may be permitted subject to LIGO review and approval.

1.162.17 Reliability

Mean Time Between Failures (MTBF) and Availability requirements are TBD. The system must be designed for a 20-year lifetime.

1.172.18 Maintainability

The Mean Time To Repair (MTTR) is TBD.

1.182.19 Physical Characteristics

The seismic isolation components must be installed inside the LIGO vacuum chambers. This requires that all components of the seismic isolation be handled by the craneage available in the part of the LVEA or VEA where the chamber is located (limited to 5 ton capacity and a 26 ft. 6 in. hook height), or that an independent means of lifting, moving and fine-positioning of the component must be made available. Provisions for attaching lifting and positioning equipment must be provided. These provisions must accommodate the high-vacuum compatibility of the cleaned, seismic-isolation components, including fitting within the portable clean room facilities provided as part of the Vacuum Equipment. Optical platforms (where required) shall have a matrix of 1/4-20 threaded holes, with 5.08 cm center spacing (maximum). Optical platform surfaces to which optical components are mounted shall have overall (edge to edge) flatness of ±0.102 mm (0.004 inch) and over any 0.26 m^2 region, ±0.051 mm (0.002 inch).

1.192.20 Transportability

All items shall be transportable by commercial carrier without degradation in performance. As necessary, provisions shall be made for measuring and controlling environmental conditions (temperature and accelerations) during transport and handling. Special shipping containers, shipping and handling mechanical restraints, and shock isolation shall be utilized to prevent damage and maintain cleanliness. All containers shall be movable by forklift. All items over 100 lbs. which must be moved into place within LIGO buildings shall have appropriate lifting eyes and mechanical strength to be lifted by cranes.

1.202.21 Design and Construction

1.20.1.12.21.1.1 Finishes

- Metal components shall have quality finishes on all surfaces, suitable for vacuum finishes. All corners shall be rounded to TBD radius.
- All materials shall have non-shedding surfaces.
- Aluminum components used in the vacuum shall not have anodized surfaces.
- Optical table surface roughness shall be within 32 micro-inch.

1.1.1.22.21.1.2 Materials

A list of currently approved materials for use inside the LIGO vacuum envelope can be found in LIGO Vacuum Compatible Materials List (LIGO-E960022). All fabricated metal components

exposed to vacuum shall be made from stainless steel, copper, or aluminum. Other metals are subject to LIGO approval. Prebaked viton (or fluorel) may be used subject to LIGO approval. All materials used inside the vacuum chamber must comply with LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022-00-D).

The only lubricating films permitted within the vacuum are dry platings of vacuum compatible materials such as silver and gold.

1.1.1.32.21.1.3 Processes

1.20.1.3.12.21.1.3.1 Welding

Before welding the surfaces should be cleaned (but baking is not necessary at this stage) according to the UHV cleaning procedure(s). All welding exposed to vacuum shall be done by the tungsten-arc-inert-gas (TIG) process. Welding techniques for components operated in vacuum shall deviate from the ASME Code in accordance with the best ultra high vacuum practice to eliminate any "virtual leaks" in welds; i. e. all vacuum welds shall be continuous wherever possible to eliminate trapped volumes. All weld procedures for components operated in vacuum shall include steps to avoid contamination of the heat affected zone with air, hydrogen or water, by use of an inert purge gas that floods all sides of heated portions.

The welds should not be subsequently ground (in order to avoid embedding particles from the grinding wheel).

1.1.1.1.22.21.1.3.2 Cleaning

All materials used inside the vacuum chambers must be cleaned in accordance with Specification Guidance for Seismic Component Cleaning, Baking, and Shipping Preparation (LIGO-L970061-00-D). To facilitate final cleaning procedures, parts should be cleaned after any processes that result in visible contamination from dust, sand or hydrocarbon films.

Materials shall be joined in such a way as to facilitate cleaning and vacuum preparation procedures; i. e. internal volumes shall be provided with adequate openings to allow for wetting, agitation and draining of cleaning fluids and for subsequent drying.

1.1.1.42.21.1.4 Component Naming

All components shall be identified using the LIGO Naming Convention (LIGO-E950111-A-E). This shall include identification (part or drawing number, revision number, serial number) physically stamped on all components, in all drawings and in all related documentation.

1.212.22 Workmanship

TBD

1.222.23 Interchangeability

All HAM-SEI components shall be interchangeable between Ham chambers and all BSC-SEI components shall be interchangeable between BSC chambers. Interchangeable cabling clamps shall be used to attach in-vacuo cabling to the mass elements, down structures and optical platforms.

~~1.23~~2.24 Safety

This item shall meet all applicable NSF and other Federal safety regulations, plus those applicable State, Local and LIGO safety requirements. A hazard/risk analysis shall be conducted in accordance with guidelines set forth in the LIGO Project System Safety Management Plan LIGO-M950046-F, section 3.3.2.

~~1.24~~2.25 Human Engineering

Seismically isolated platforms or points must accommodate addition, removal and adjustment of equipment with a minimum of force or torque applied to the platforms. This requires that adequate space be provided surrounding the optics platform for an individual to move into proper position for the work intended. Equipment mounted to the optics platform should be provided with fasteners that can accommodate these force/torque requirements.

~~1.25~~2.26 Assembly and Maintenance

Assembly fixtures and installation/replacement procedures shall be developed in conjunction with the SEI hardware design. These shall include (but not be limited to) fixtures and procedures for:

- SEI component insertion and assembly into the vacuum chambers without load support from the chambers
- assembly of the in vacuo components in a clean room (class 100) environment
- initial alignment of the SEI components
- installation/removal/replacement of the bellows
- installation/removal/replacement of the actuator components
- installation/removal/replacement of the SEI stage elements

~~1.26~~2.27 Documentation

~~1.26.1~~2.27.1 Specifications

TBD

~~1.1.2~~2.27.2 Design Documents

- LIGO SEI System Preliminary Design Document (including supporting technical design and analysis documentation)
- LIGO SEI System Final Design Document (including supporting technical design and analysis documentation)
- LIGO SEI Prototype/Test Plans
- LIGO SEI Installation and Commissioning Plans and Procedures

1.1.32.27.3 Engineering Drawings and Associated Lists

A complete set of drawings suitable for fabrication must be provided along with Bill of Material (BOM) and drawing tree lists. The drawings must comply with LIGO standard formats and must be provided in electronic format. All documents shall use the LIGO drawing numbering system, be drawn using LIGO Drawing Preparation Standards, etc.

1.1.42.27.4 Procedures

Procedures shall be provided for, at minimum,

- Initial installation and setup of SEI equipment
- Normal operation of SEI equipment
- Normal and/or preventative maintenance
- Installation of new equipment onto SEI platforms
- Troubleshooting guide for any anticipated potential malfunctions

1.1.52.27.5 Manuals

Procedures listed in section 3.4.4.1 and applicable as-built documentation shall be collected into an Operator's Manual for the HAM-SEI and BSC SEI subsystems.

1.1.62.27.6 Documentation Numbering

All documents shall be numbered and identified in accordance with the LIGO documentation control numbering system LIGO document TBD

1.1.72.27.7 Test Plans and Procedures

All test plans and procedures shall be developed in accordance with the LIGO Test Plan Guidelines, LIGO document TBD.

12 Quality Assurance Provisions

This section includes all of the examinations and tests to be performed in order to ascertain the product, material or process to be developed or offered for acceptance conforms to the requirements in section 3. *Note: This section is largely TBD until the design is at the Preliminary Design Level.*

4.1. General

4.1.1. Responsibility for Tests

TBD

4.1.2. Special Tests

4.1.2.1 Engineering Tests

- actuator prototype/test

- drift tests of stage (average drift rates and statistical variations)
- tests for "crackle" noise in cabling and stages
- non-gaussian noise measurement
- outgassing/optical qualification of polymer materials (if required)
- modal survey: verification that resonant frequencies and Q's of the system are within derived limits or acceptable ranges
- performance measurement of full-scale isolation parameters, including characterization of linearity of response
- design checks (form, fit and function)

4.1.2.2 Reliability Testing

Reliability evaluation/development tests shall be conducted on items with limited reliability history that will have a significant impact upon the operational availability of the system. This includes:

- TBD

4.1.3. Configuration Management

Configuration control of specifications and designs shall be in accordance with the LIGO Detector Implementation Plan and the LIGO Configuration Management Plan

4.2. Quality conformance inspections

Design and performance requirements identified in this specification and referenced specifications shall be verified by inspection, analysis, demonstration, similarity, test or a combination thereof per the Verification Matrix. *(Note: The verification matrix is TBD.)* Verification method selection shall be specified by individual specifications, and documented by appropriate test and evaluation plans and procedures. Verification of compliance to the requirements of this and subsequent specifications may be accomplished by the following methods or combination of methods:

4.2.1. Inspections

Inspection shall be used to determine conformity with requirements that are neither functional nor qualitative; for example, identification marks.

4.2.2. Analysis

Analysis may be used for determination of qualitative and quantitative properties and performance of an item by study, calculation and modeling.

4.2.3. Demonstration

Demonstration may be used for determination of qualitative properties and performance of an item and is accomplished by observation. Verification of an item by this method would be accomplished by using the item for the designated design purpose and would require no special test for final proof of performance.

4.2.4. Similarity

Similarity analysis may be used in lieu of tests when a determination can be made that an item is similar or identical in design to another item that has been previously certified to equivalent or more stringent criteria. Qualification by similarity is subject to Detector management approval.

4.2.5. Test

Test may be used for the determination of quantitative properties and performance of an item by technical means, such as, the use of external resources, such as voltmeters, recorders, and any test equipment necessary for measuring performance. Test equipment used shall be calibrated to the manufacture's specifications and shall have a calibration sticker showing the current calibration status.

23 Preparation for Delivery

Packaging and marking of equipment for delivery shall be in accordance with the Packaging and Marking procedures specified herein.

5.1. Preparation

- Vacuum preparation procedures as outlined in LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022-00-D) shall be followed for all components intended for use in vacuum. After wrapping vacuum parts as specified in this document, an additional, protective outer wrapping and provisions for lifting shall be provided.
- Electronic components shall be wrapped according to standard procedures for such parts.

5.2. Packaging

Procedures for packaging shall ensure cleaning, drying, and preservation methods adequate to prevent deterioration, appropriate protective wrapping, adequate package cushioning, and proper containers. Proper protection shall be provided for shipping loads and environmental stress during transportation, hauling and storage. The shipping crates used for large items should use for guidance military specification MIL-C-104B, Crates, Wood; Lumber and Plywood Sheathed, Nailed and Bolted. Passive shock witness gauges should accompany the crates during all transits.

For all components which are intended for exposure in the vacuum system, the shipping preparation shall include double bagging with Ameristat 1.5TM plastic film (heat sealed seams as practical, with the exception of the inner bag, or tied off, or taped with care taken to insure that the tape does not touch the cleaned part). Purge the bag with dry nitrogen before sealing.

5.3. Marking

Appropriate identification of the product, both on packages and shipping containers; all markings necessary for delivery and for storage, if applicable; all markings required by regulations, statutes, and common carriers; and all markings necessary for safety and safe delivery shall be provided.

Identification of the material shall be maintained through all manufacturing processes. Each component shall be uniquely identified. The identification shall enable the complete history of each component to be maintained (in association with Documentation "travelers"). A record for each component shall indicate all weld repairs and fabrication abnormalities.

For components and parts which are exposed to the vacuum environment, marking the finished materials with marking fluids, die stamps and/or electro-etching is not permitted. A vibratory tool

with a minimum tip radius of 0.005" is acceptable for marking on surfaces which are not hidden from view. Engraving and stamping are also permitted.

BATCH START

STAPLE
OR
DIVIDER

SEI requirements for LIGO-II part 1, noise.

It was not widely appreciated until recently that the displacement noise requirement on the HAM SEI, which must fit into fairly tight quarters, is more stringent than that for the BSC.

BSC test mass:

- At 10 Hz we require $x(f) \leq 1 \times 10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$.
- "long" SUS transmits 2×10^{-8}.
- so, SEI requirement on suspension mount point is $x(10\ \mathrm{Hz}) \leq 5 \times 10^{-12}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$.

HAM MC mirror:

- At 10 Hz we require $x(f) \leq 3 \times 10^{-18}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$.
- "short" SUS transmits 1×10^{-5}.
- so, SEI requirement on suspension mount point is $x(10\ \mathrm{Hz}) \leq 3 \times 10^{-13}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$.

SEI Requirements part 2, alignment.

Control of RMS displacement: K. Strain has shown that RMS test mass displacement requirements (1×10^{-14} m) can be met with 200 Hz BW feedback to quadruple pendulum alone, requiring 1×10^{-8} N RMS force to test mass. SEI should significantly relax these requirements.

Control of RMS velocity: Test mass velocity requirement is 1×10^{-9} m/s, with global control loops on. Requirement for loops-off pending design of ISC lock acquisition scheme.

Control of RMS angle: Angle control requirement is 1×10^{-9}, with ≈ 2 Hz BW ASC loops on.

Functional Breakdown

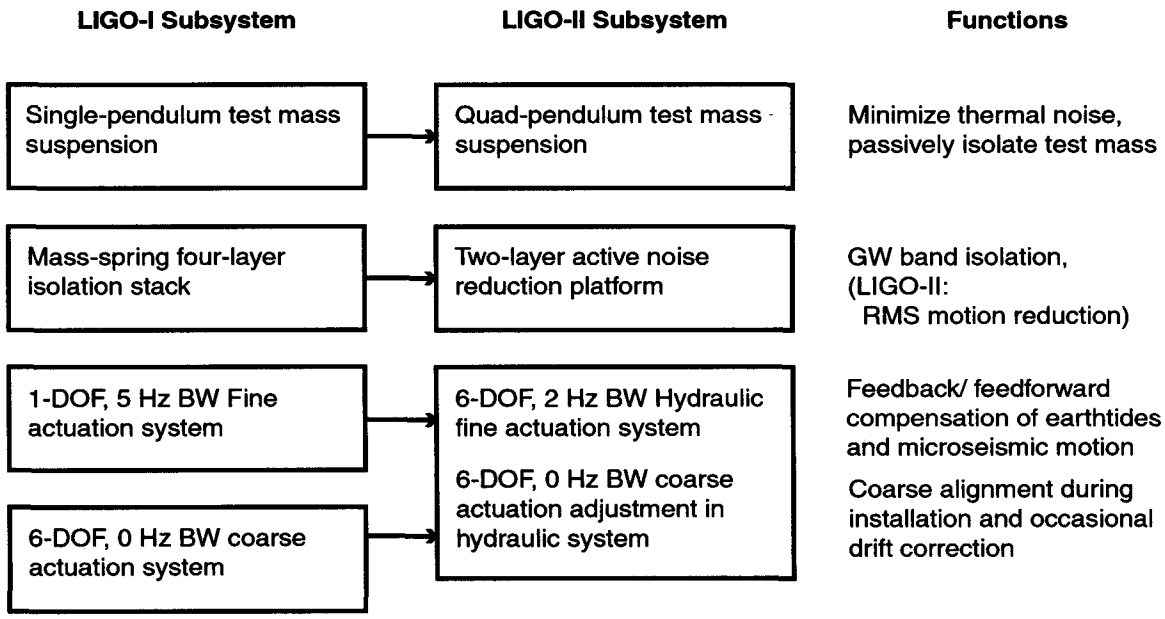


Figure 1: Seismic isolation functions in LIGO-I and LIGO-II. (The pendulum suspension, though not part of SEI, is shown because it contributes significant seismic isolation.)

Active Seismic Isolation

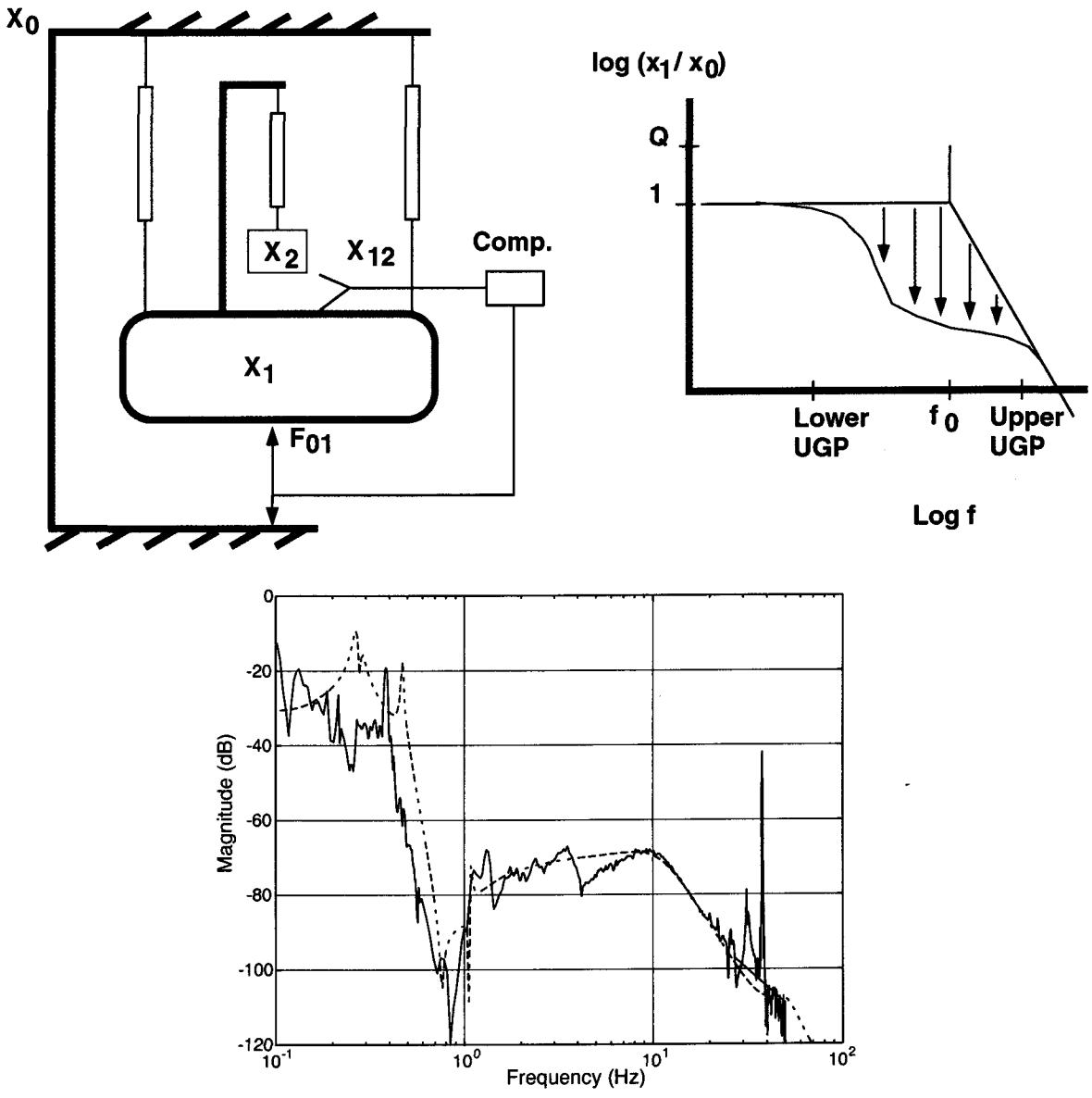


Figure 2: Active seismic isolation, with 1994 JILA results showing 70 dB of isolation.

BSC Two-stage active platform:

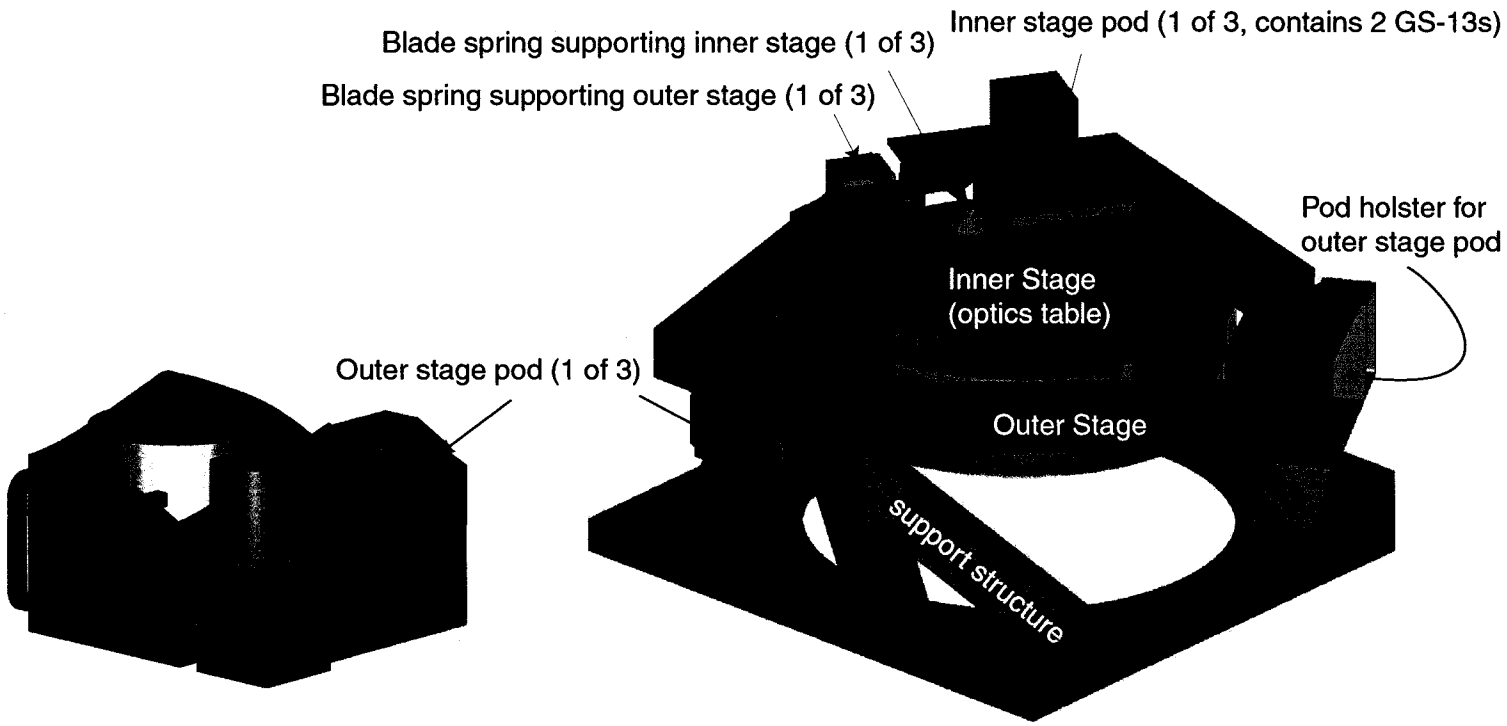


Figure 3: BSC version of the two-stage active platform.

HAM Two-stage active platform:

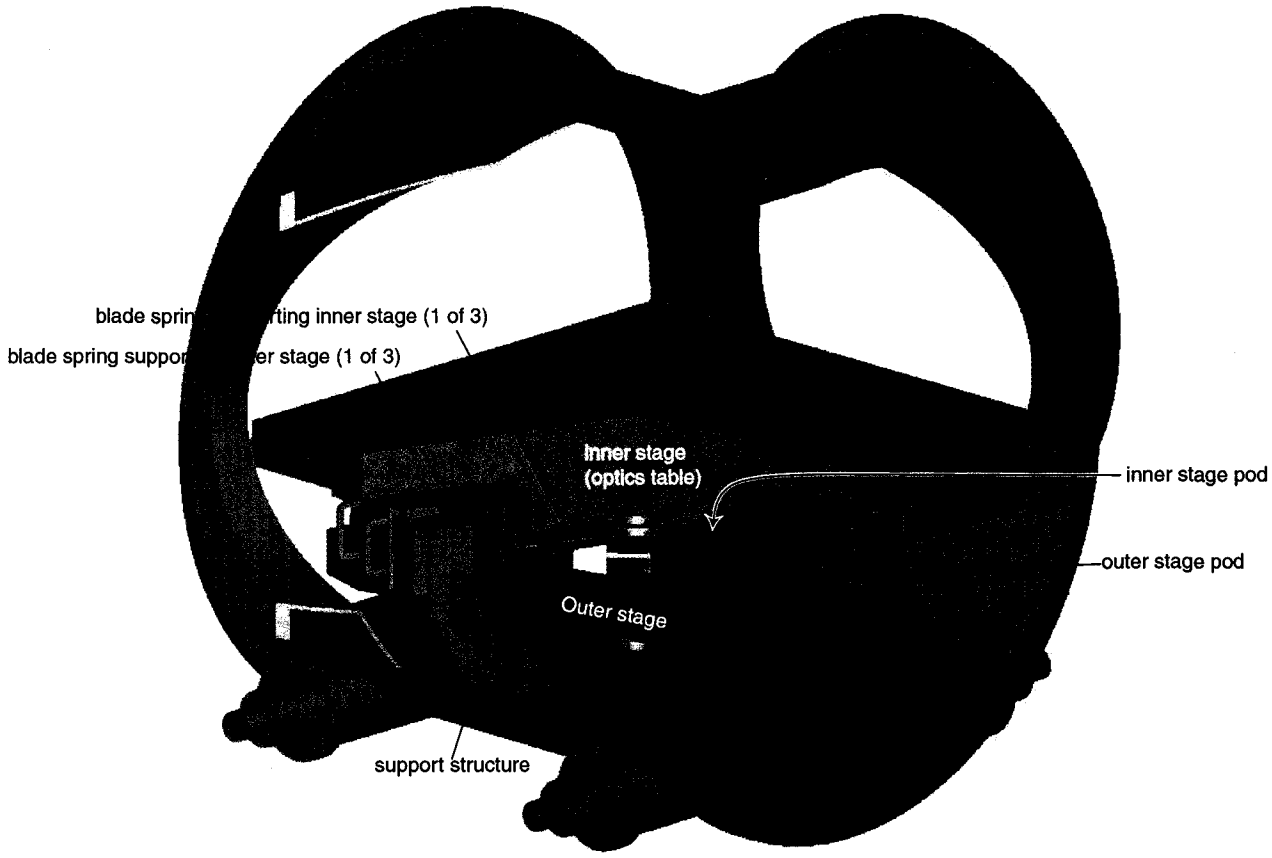


Figure 4: Rendering of the HAM design. Note that the instrumentation pods are positioned so that they are removable through the large HAM doors. The inner stage optics table (blue) is the same size as the table in LIGO-I, and in the same position.

The Quiet Hydraulic Actuator.

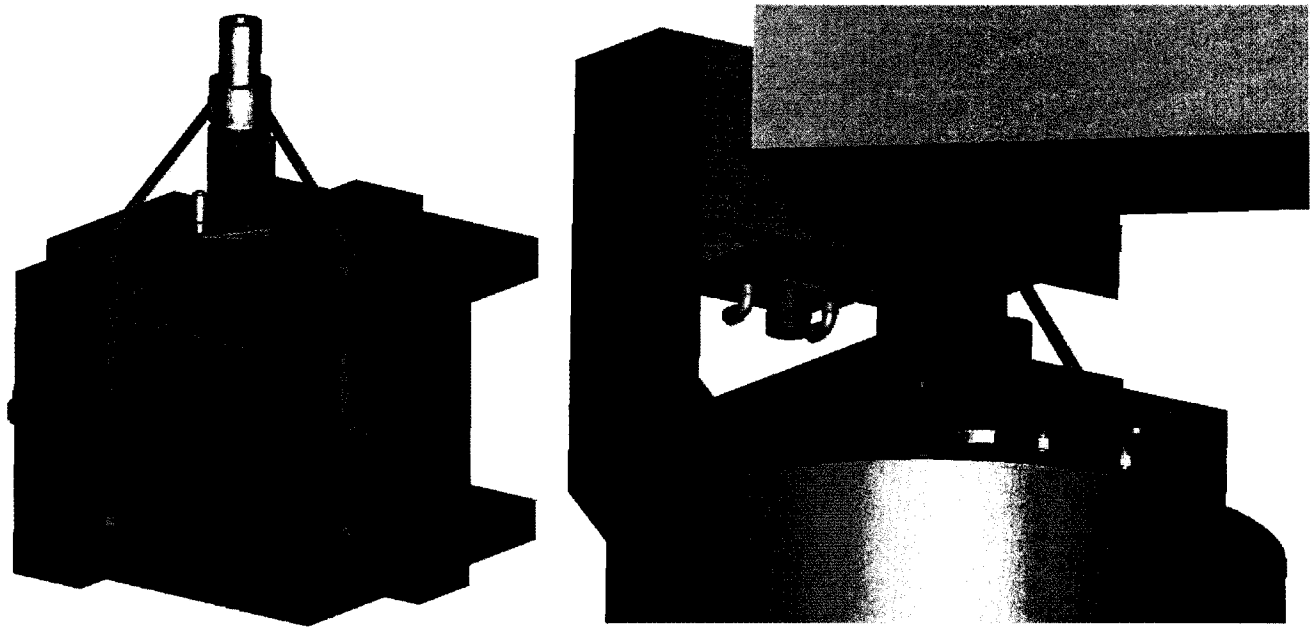


Figure 5: Hydraulic actuator will provide ± 1 mm, 2 Hz BW continuous actuation in 6 DOF. Each bellows assembly acts in 1 DOF; two DOF at each corner. Viscous fluid and remote pump assure quiet operation. Threaded connections to bellows assy will allow coarse actuation to 5 mm.

Differential bellows:

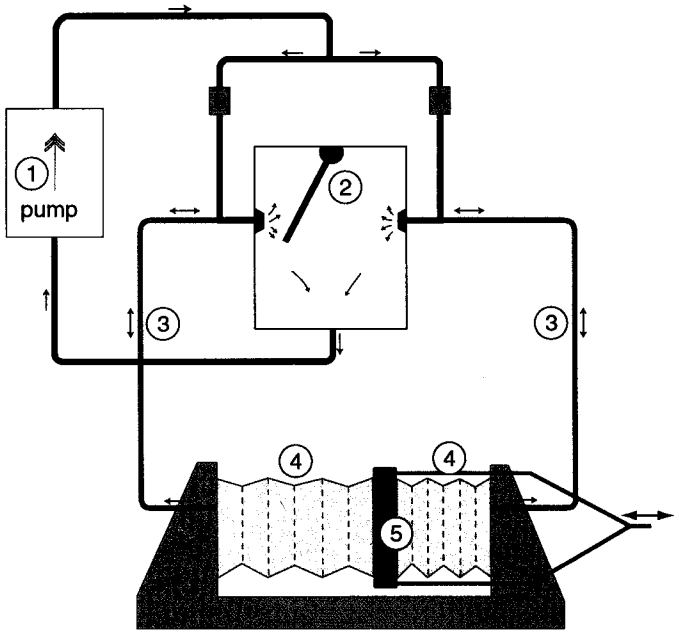


Figure 6: The control valve creates a pressure differential on the bellows. The middle plate is attached with flexures to both the base and the payload, only constraining motion in 1 DOF.

Performance

	units	optics table	BSC test mass	HAM test mass
$x(f)$ at 10 Hz	$\mathrm{m}/\sqrt{\mathrm{Hz}}$	2×10^{-13}	1.0×10^{-20} $[1 \times 10^{-19}]$	2×10^{-18} $[3 \times 10^{-18}]$
RMS displacement	m	6×10^{-7} (1×10^{-8})	4×10^{-17} $[1 \times 10^{-14}]$	
RMS velocity	m/s	3×10^{-7} (3×10^{-9})	4×10^{-17} $[1 \times 10^{-9}]$	

- System noises without (with) hydraulic stage and feedforward.
- RMS integrated down to 0.01 Hz, with the global loops.
- 5×10^{-12} N RMS global control force needed at test mass actuator.
- [requirements] are shown bracketed in red.

Stiff active SEI design advantages:

- Same compact core design used in both HAM and BSC. Only mechanical interfacing specialized for the tank geometry.
- The stiff support of the optics table mounting surface allows easy installation of the optics payload.
- Conventional wires and ribbon cables can be used to carry signals.
- Full active instrumentation allows dynamically-selectable operating modes, and continuous state monitoring.
- Stiff suspension springs can be operated at conservative low stress levels.

BSC Design:

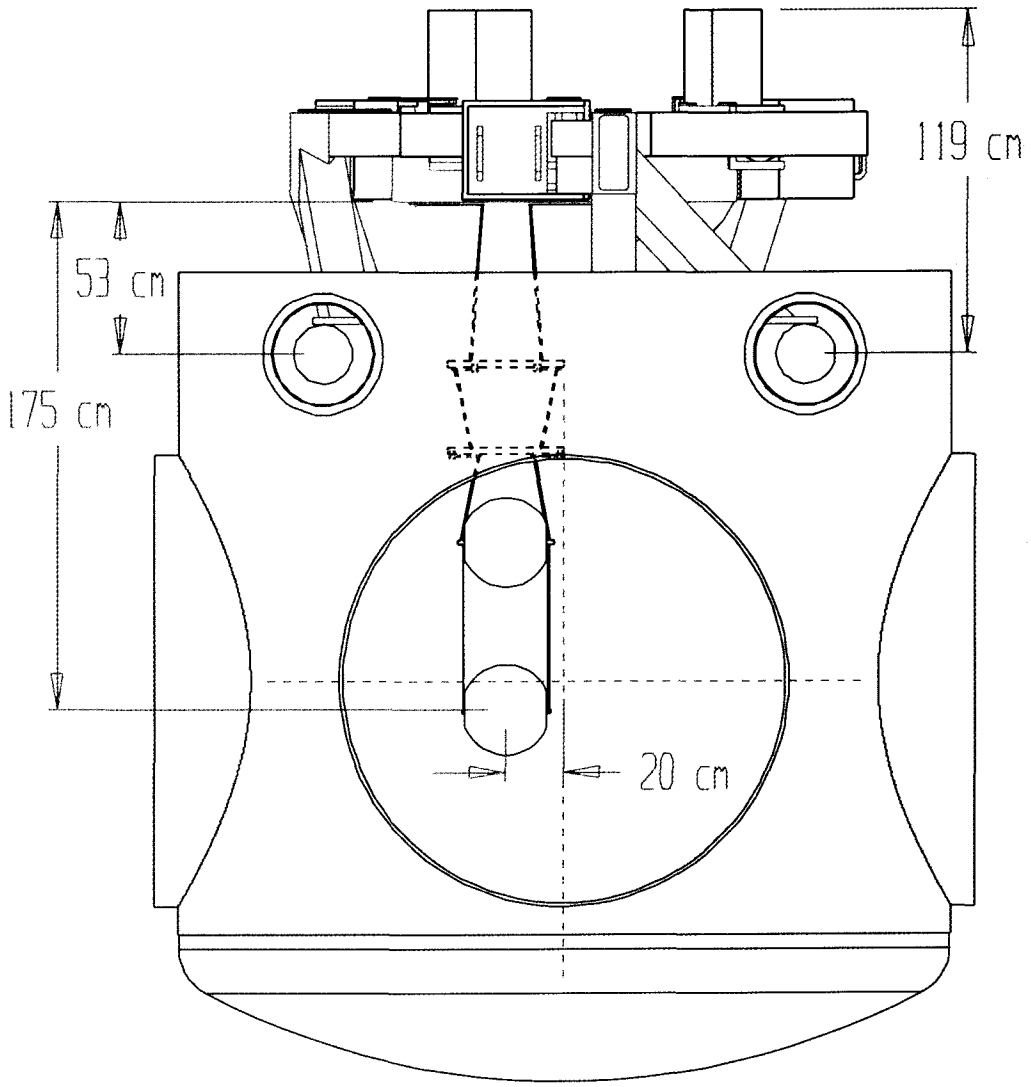


Figure 7: Elevation drawing of the baseline BSC chamber design, with GEO quadruple pendulum shown to scale.

HAM Design:

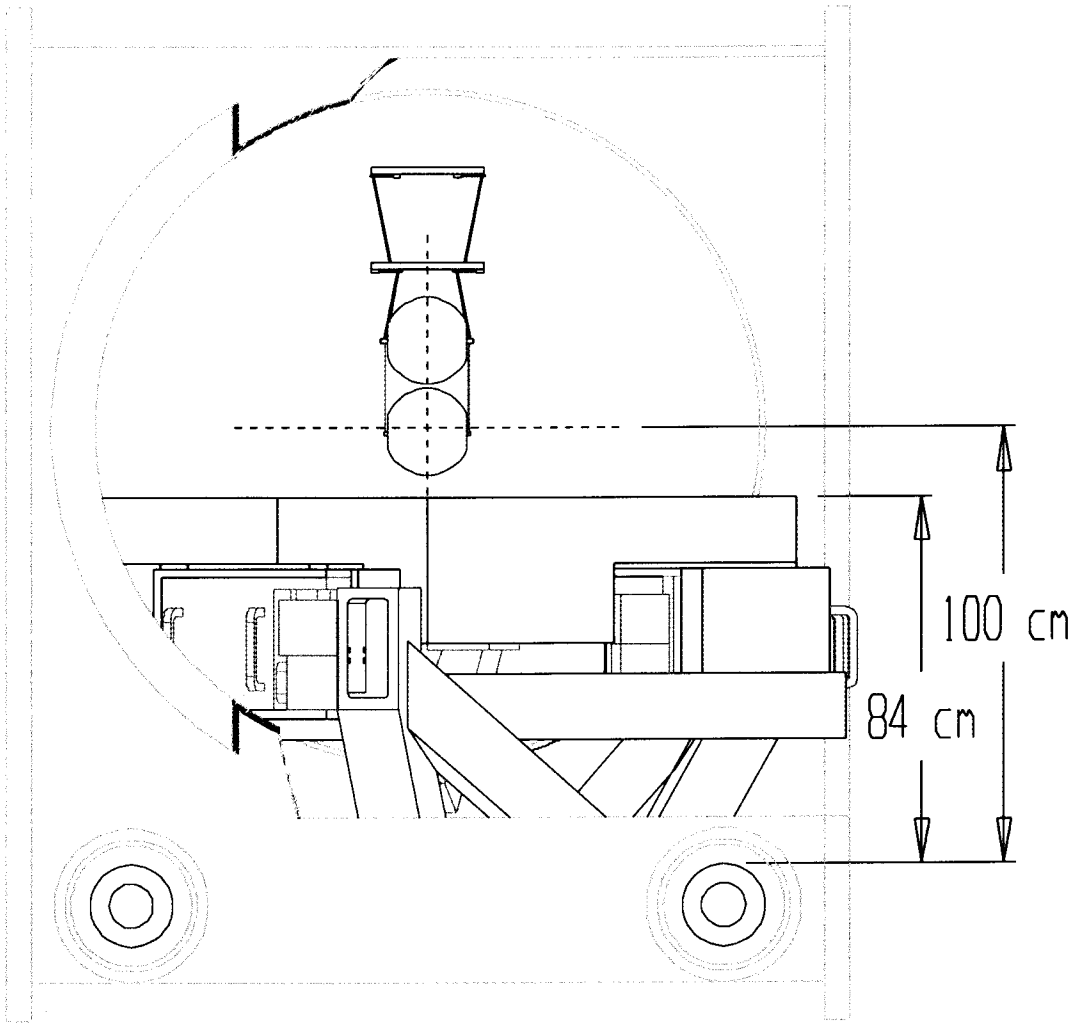


Figure 8: Elevation (cut-away) drawing of the baseline HAM chamber design. The dashed lines indicate beam center for a typical suspension position. The external hydraulic actuators are not shown here.

Sensor Noise:

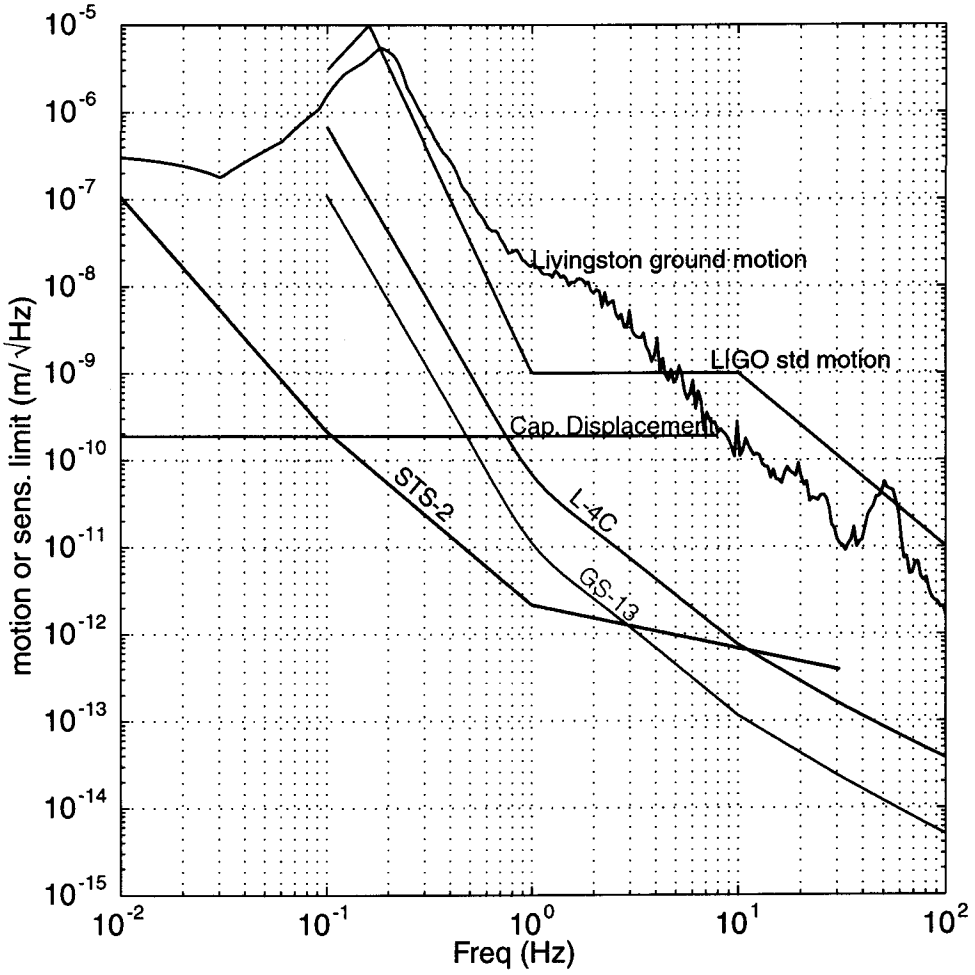


Figure 9: Displacement noise in various sensors used in the two-stage active isolation platform, compared with the LIGO standard ground noise and the measured noise at LLO.

Broadband Seismometer:

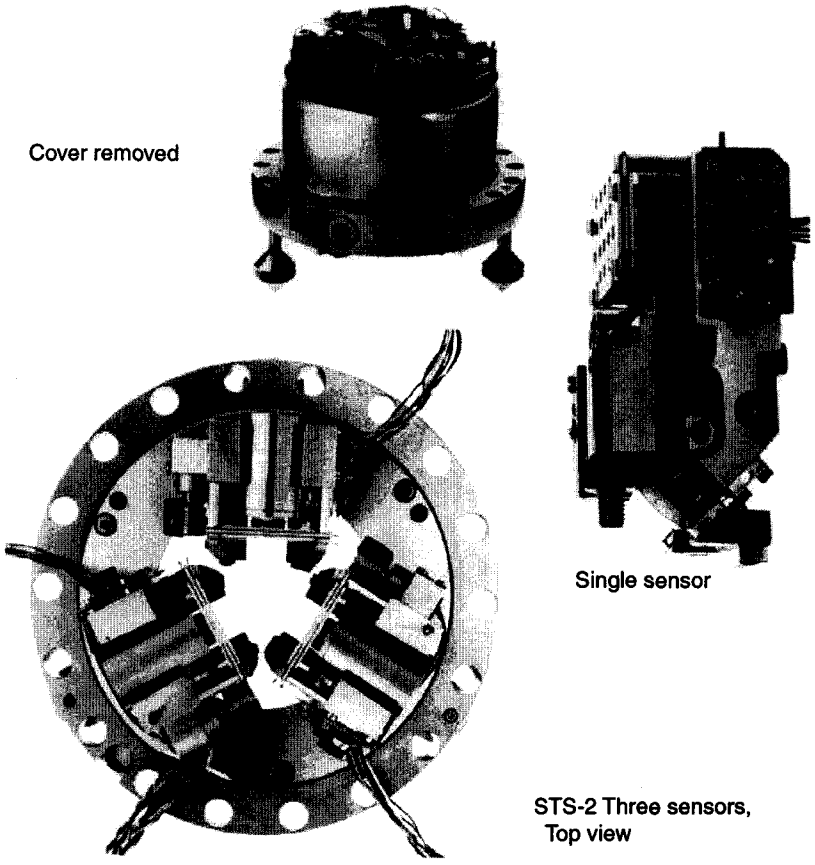


Figure 10: A broadband long-period vibration sensor usable from tens of millihertz to tens of hertz. Each STS-2 seismometer, manufactured by Streckeisen AG, measures vibration in three degrees of freedom. A vacuum-tight domed cover is included but not illustrated here.

Dynamic Model:

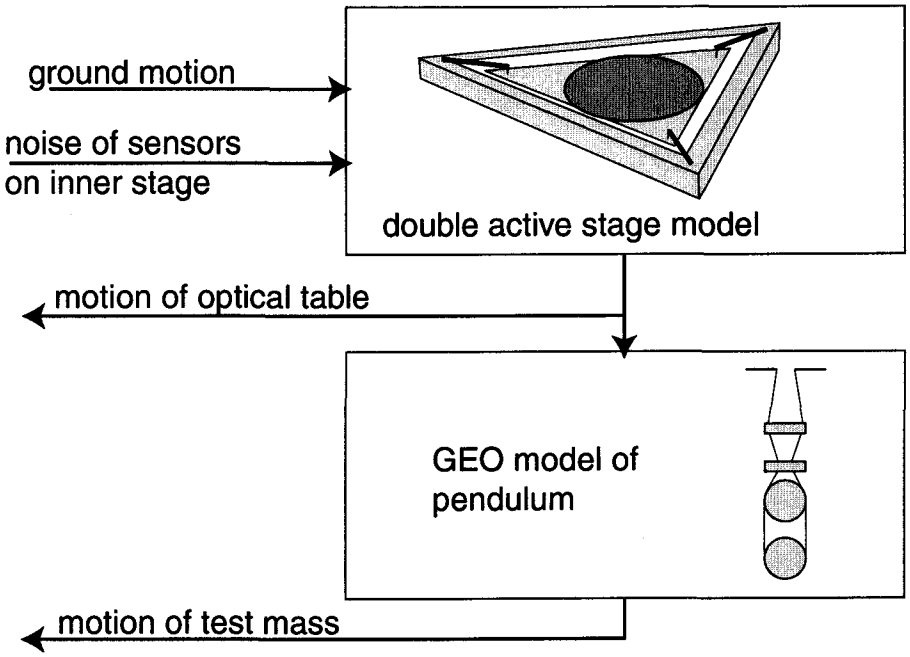


Figure 11: The Model results were generated in a two step process. First, the motion of the optical table was simulated using sensor noise and ground motion. The motion of the optical table was then used as an input to the GEO pendulum model to compute test mass motion.

Test mass noise: two-stage platform and quad pendulum

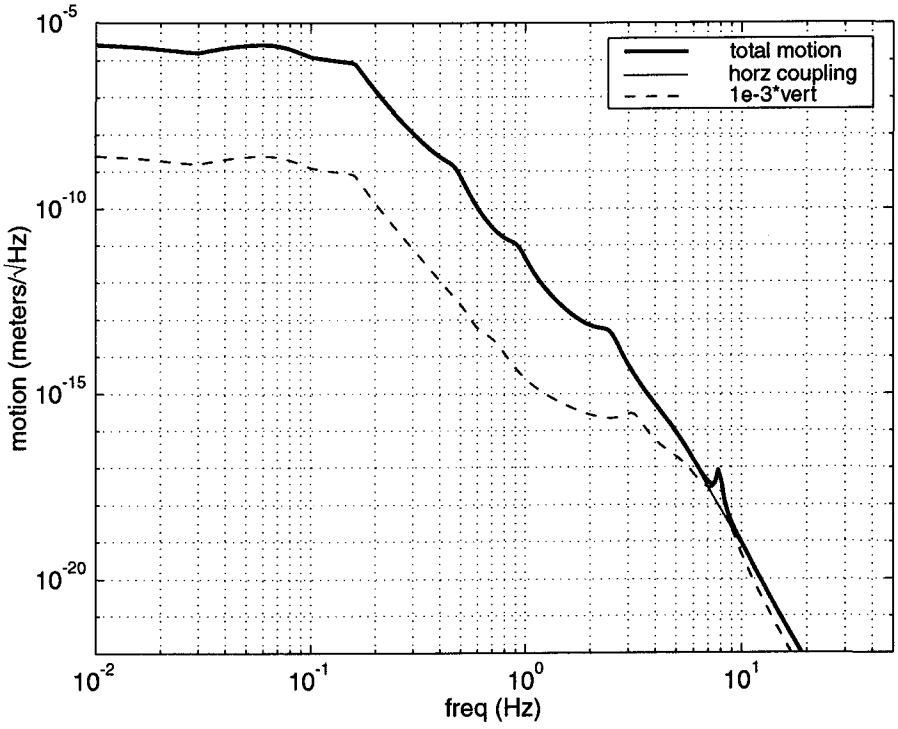


Figure 12: Motion the test mass (ITM and ETM), assuming local pendulum damping loops are on; this meets the requirement. Noise is lower with damping loops off, and still lower when feedforward stages are used.

Optics table noise performance:

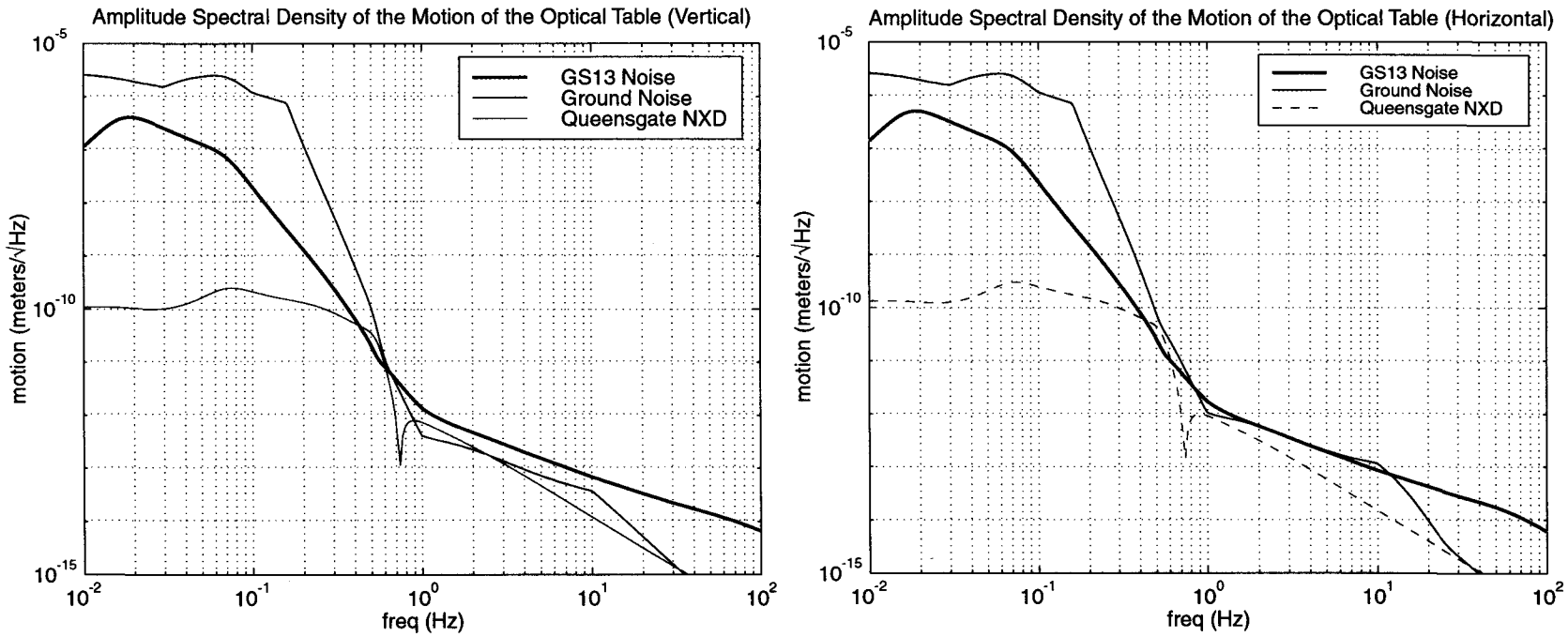


Figure 13: Performance of the two-stage active platform, without feedforward. Here we plot the contributions to the noise level at the SEI optics table, the suspension system mounting point.

Model construction:

1. a set of test inputs and outputs.
2. a mechanical model of the two stage system.
3. a set of sensors which are distributed on the outer stage.
4. filters which blend the outer stage sensors into six super-sensors.
5. a set of sensors which are distributed on the inner stage
6. filters which blend the inner stage sensors into six super-sensors.
7. a set of actuators between the outer stage and the ground.
8. a set of actuators between the inner stage and the outer stage.
9. a set of 12 SISO control laws which connect the 12 actuators with the 12 super-sensors.

Simulink Model Diagram:

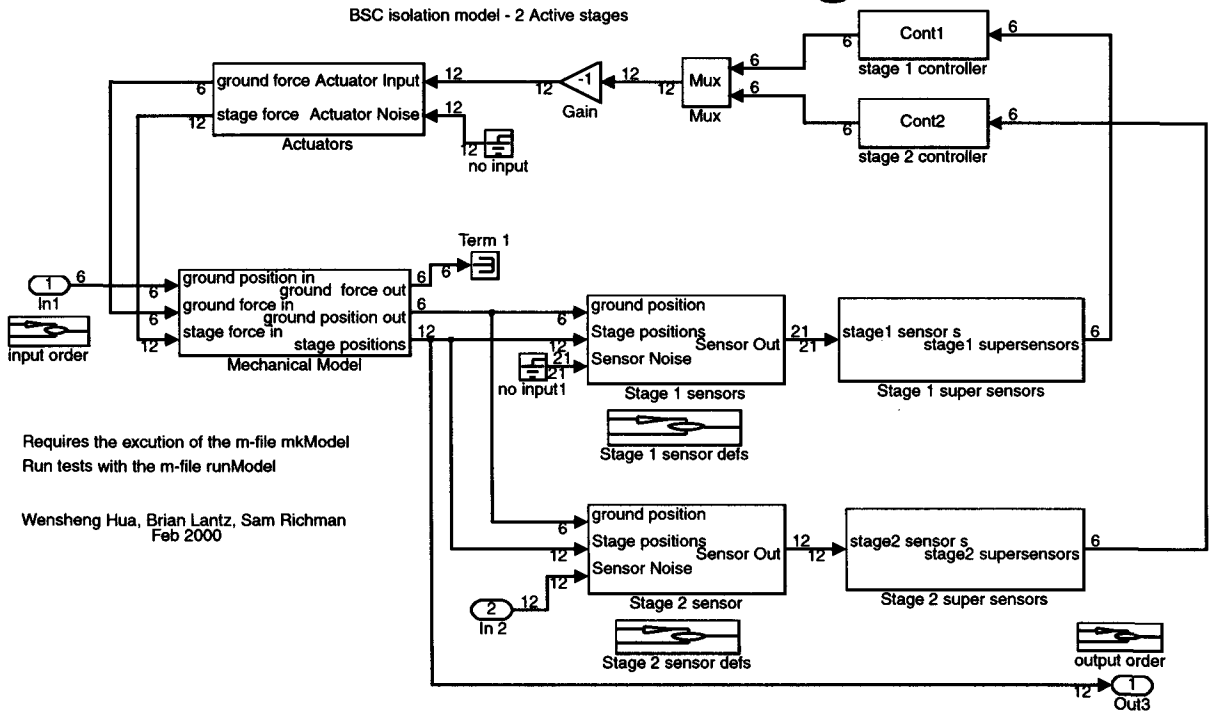


Figure 14: Model used to calculate the dynamics and servo compensation in the reference design two-stage active platform and to cross-compile the controller using the dSpace DSP hardware.

Sensor Blending:

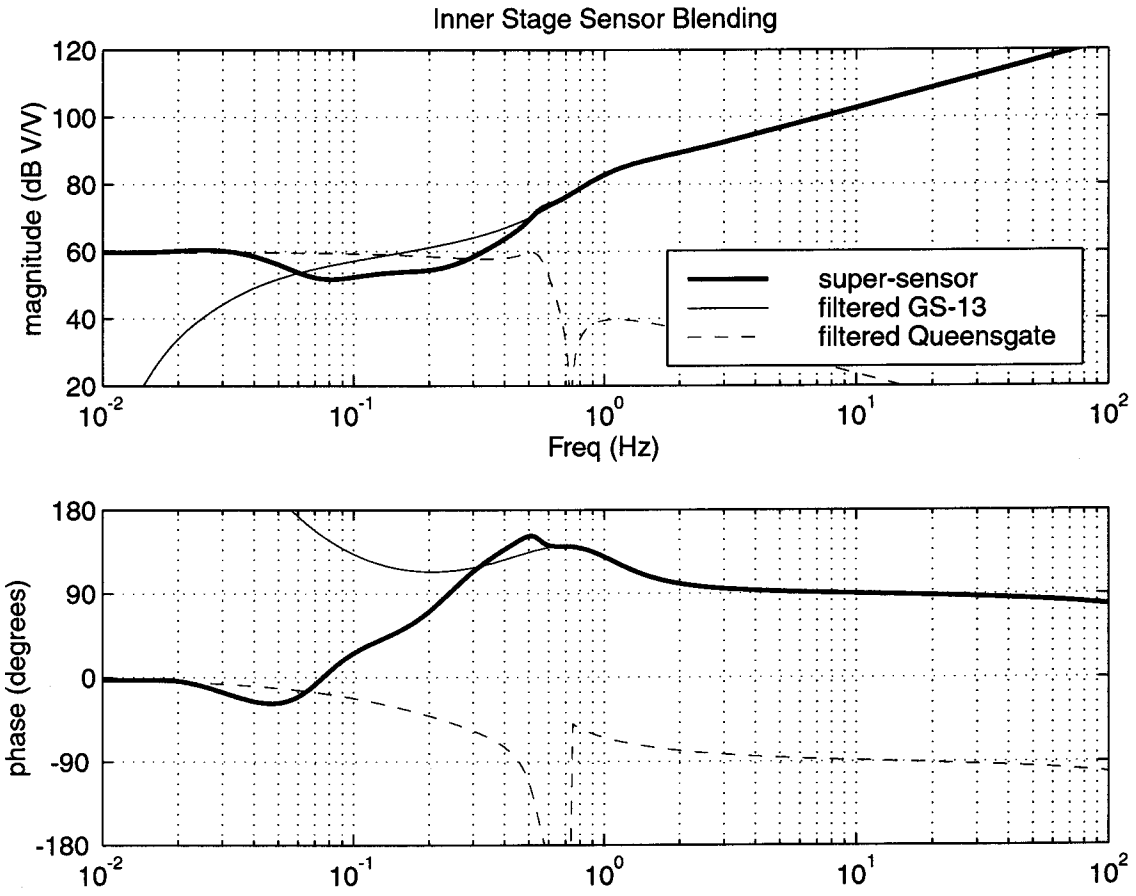


Figure 15: Aggressive filtering of the sensors occurs once the sensor is no longer the dominant signal source of the loop. This is done to improve the performance of the systems. Once the sensors have been combined, they can be thought of as a single, broadband sensor which we call a "super-sensor."

Compensation Example:

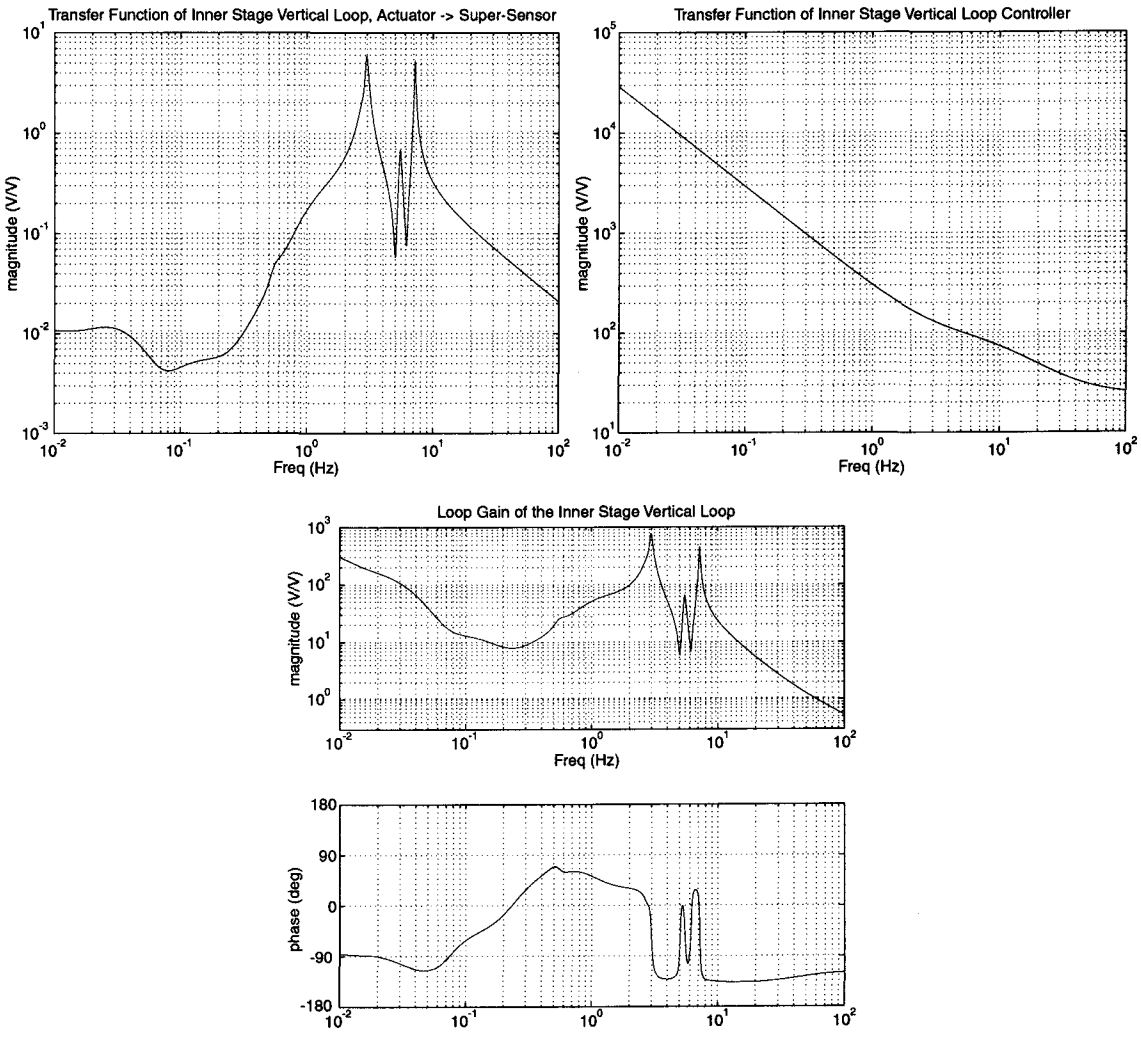


Figure 16: *upper left:* Transfer function from inner stage vertical actuator #1 to its collocated super-sensor. *upper right:* A simple system based on an integrator was chosen as the control law. *lower:* Complete open-loop transfer function.

Stanford active platform with pendulum:

Experiment is underway at Stanford's Engineering Test Facility.

Goals:

- Demonstrate 6 DOF active platform with collocated sensors and actuators and modern MIMO techniques.
- Demonstrate sensor blending.
- Validate computer model used to design LIGO system.
- Demonstrate feedforward.
- Demonstrate reliable operation with active platform and multiple pendulum working together, with control reallocation.
- Develop watchdog schemes.

Stanford active platform with pendulum:

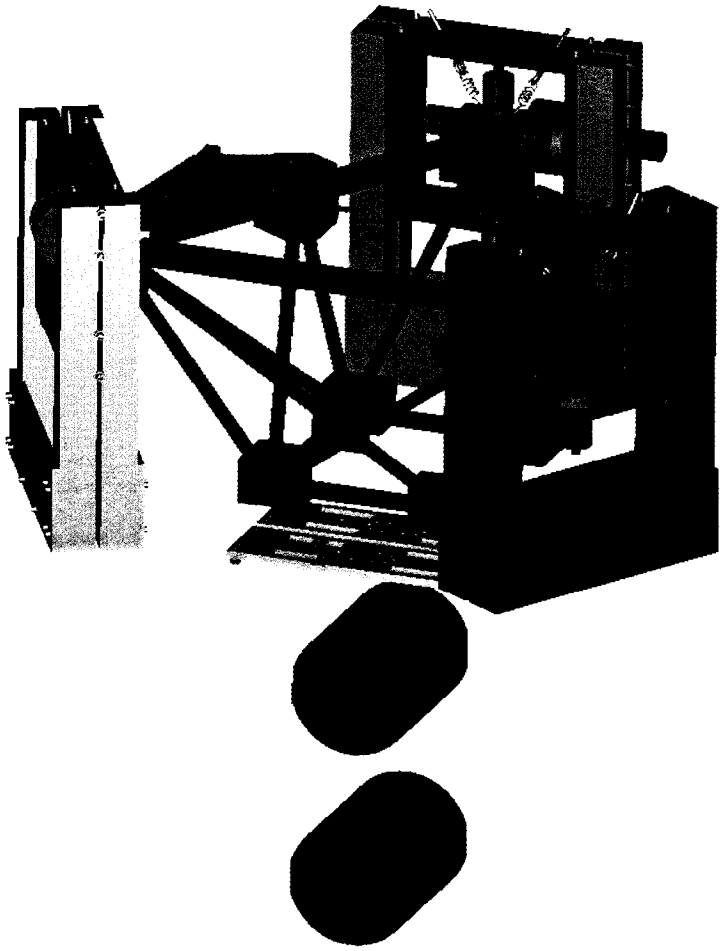


Figure 17: Drawing of the Stanford Active Platform and pendulums Prototype. A single-layer active seismic isolation platform supports two triple pendulums of a design based closely on the GEO triple pendulum.

Stanford lab work:

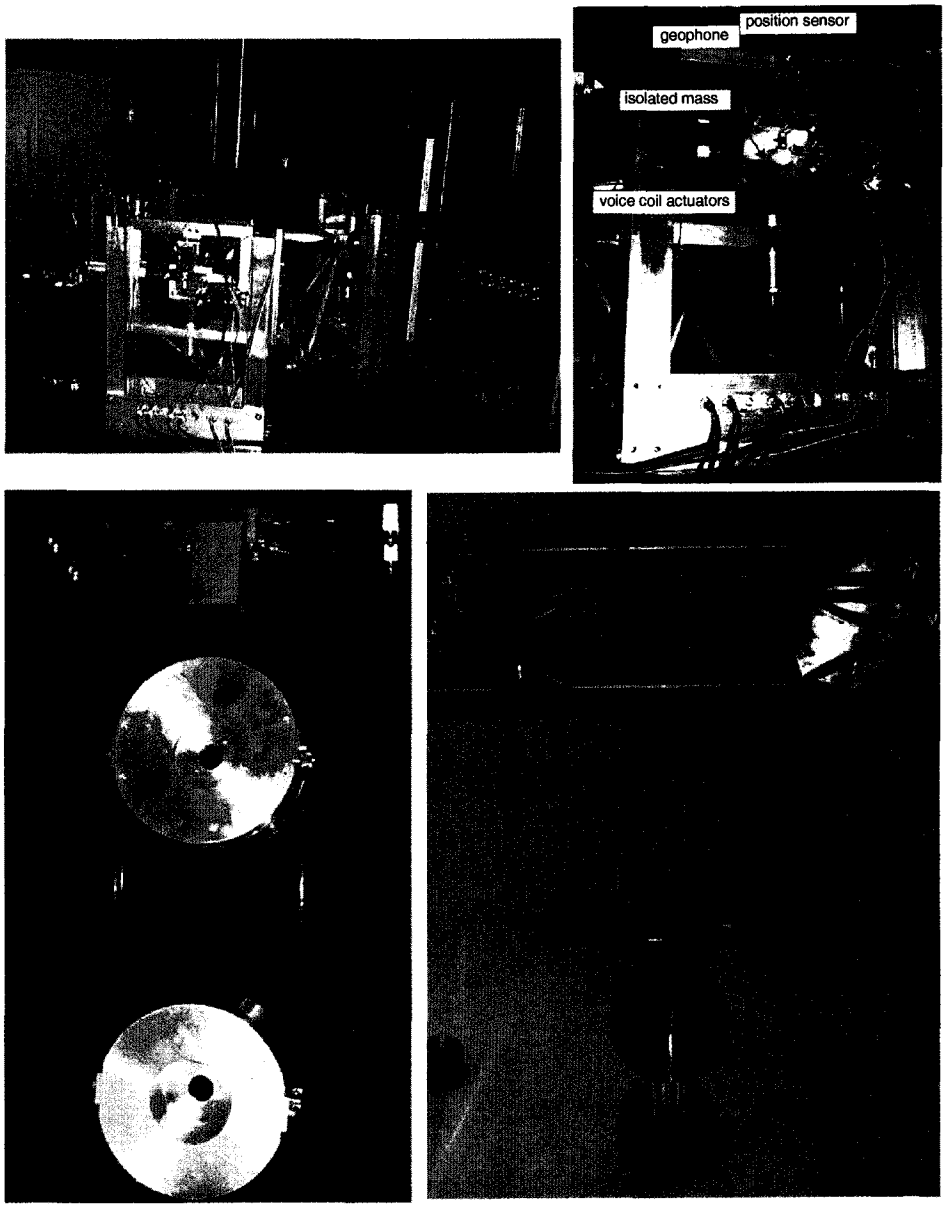


Figure 18: Active platform and triple pendulum.

Two-stage active platform:

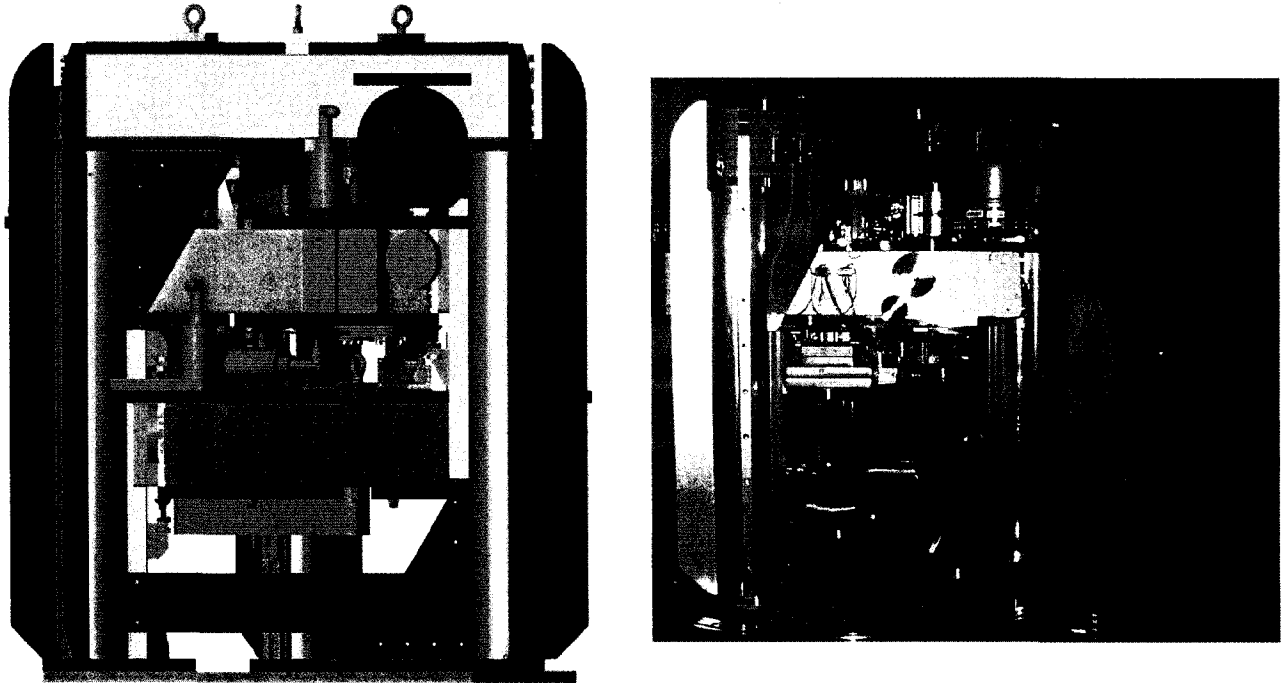


Figure 19: Rendering and installation. 3D mechanical model used to make parts and produce mass and moment inputs for compensation design.

Two-layer active platform test:

- Designed, constructed, paid for, and tested by dispersed group of researchers - scientists at JILA, MIT, Stanford and LSU; detailed engineering at HPD.
- Rapid progress - Project start 15 Oct., conceptual design done 8 Dec., vendor start 15 Jan., delivery to MIT 8 Mar., commissioning at MIT 14 Mar.
- Rapid assembly and alignment offline - First time experience: boxes delivered Wednesday 8 March at noon, assembled by Sunday 12 March, aligned by Monday 13 March, placed in vacuum Tuesday 14 March, first loop closure by the end of Tuesday 14 March.
- Parasitic resonances controlled - coupled body modes 2-9 Hz, first internal resonances above 100 Hz (modes of the external structure predicted by FEA), next resonance above 230 Hz.
- Robust - mechanically very stable, no measurable change (less than 0.003" in stage separation) under locking/unlocking and lifting into vacuum tank (puts 800 kg load on sides of upper support triangle).

First two-stage results:

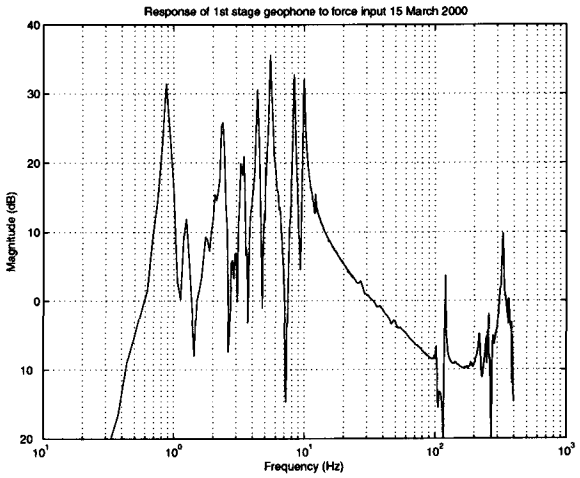


Figure 20: Magnitude of the vertical open loop uncompensated TF (forcer to geophone)

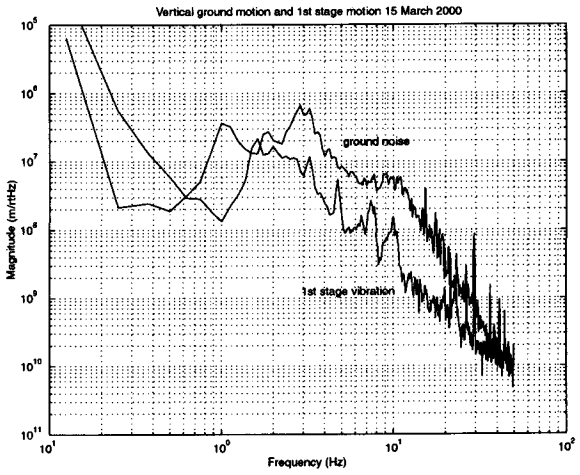


Figure 21: Vertical seismic isolation of single stage on first day after assembly. (3 DOF's closed.)

Preliminary Results of the Stanford Active Platform

Brian Lantz, Wensheng Hua, Corwin Hardham, and the Stiff Team.

April 26, 2000

This is a short document to convey some of the results of the single stage active platform at Stanford University. The Stiff team has been using this platform to research a number of active control issues, and we thought it might be helpful to the TAG team if we would share some early results.

The goal of these tests was to demonstrate sensor blending and confirm the dynamic model when the experimental system is running with performance similar to each stage of the reference design at 10 Hz. We have measured the transmission of the single stage system and compared that to the model predictions.

These measurements were taken when the platform was isolated in all six degrees of freedom, using a controller with six SISO "super-sensor" loops. Each super-sensor is constructed by adding the filtered response of the 4.5 Hz geophone and the differential optical sensor. The blending frequency is set to 2 Hz; the optical sensor dominates below the blend frequency, and the geophone dominates above the blend frequency.

The vertical transmission of the platform is shown in figure 1. The vertical transmission of the system is the vertical motion of the active platform divided by the vertical motion of the ground. The motion of the platform is measured using a "witness seismometer," a Mark Products L-4C 1 Hz geophone mounted near the center of the platform. This sensor is not used in the servo loops. The ground motion is measured with a Geotech S-13 1 Hz geophone, aligned in the same direction as the witness seismometer, and sitting at the base of the active platform. A calibration of the relative sensitivity of the sensors is done by securely locking the platform in place, and measuring the relative response of the two instruments to ground motion.

Figure 1 shows the transmission function of the platform as measured by the seismometers and as calculated by the dynamic model, when the servos are on and when the servos are off. The parameters of the dynamic model were adjusted to fit the measured data when the servos are off, then used to predict the transmission when the servos are on. The coherence of the measurement is good at low frequencies, but becomes poor above 30Hz.

The two features of particular interest are the shape of the transmission from 3 to 10 Hz, and the level of transmission at 10 Hz. The performance limit below 10 Hz is set by the coupling of the optical sensor into the loop. The coupling of the optical sensors to the loop is still measurable at 9 Hz because this prototype only uses 4.5 Hz geophones as inertial sensors, and stable performance sets limits as to how fast the relative gain of the sensors can be changed near the blending

frequency. However, we were able to measure about 30 dB of isolation at 10 Hz, as predicted by the model. Above 10 Hz, the performance is limited by the overall loop gain.

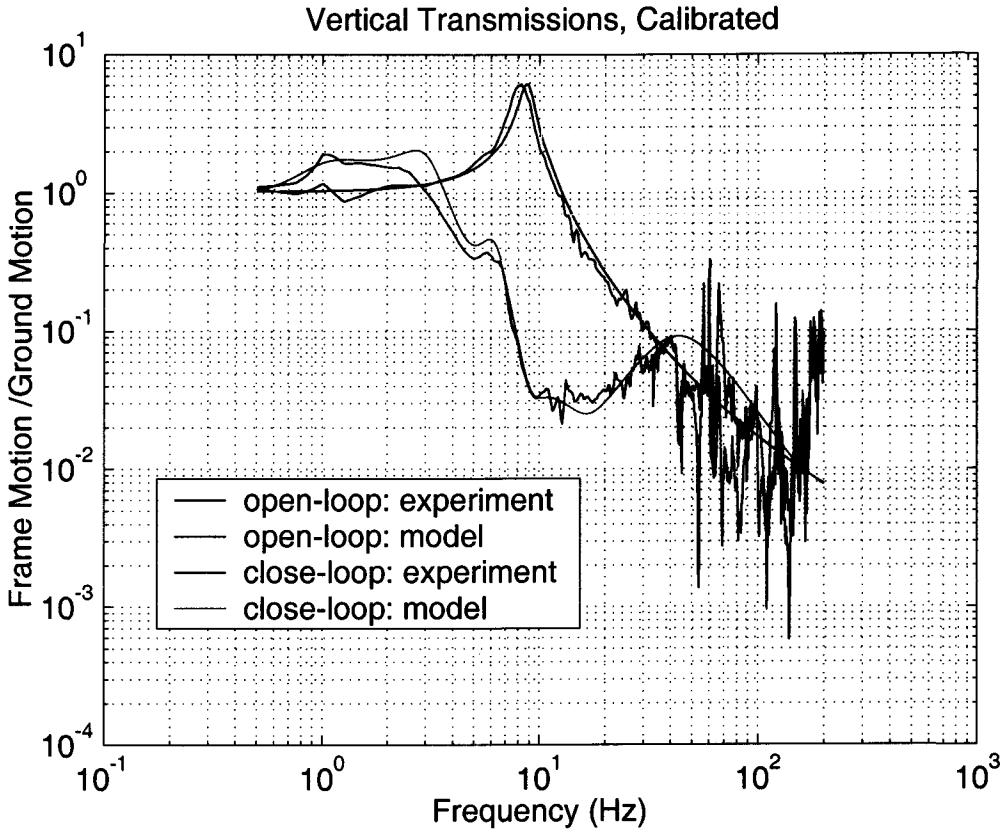


Figure 1: Transmission of the platform, with and without servo correction

The horizontal data is very similar to the vertical data shown in figure 1. The measurement becomes quite noisy about 30Hz, where the coherence of the witness seismometers becomes small. We believe this is due to acoustic coupling, which is why we plan to move the experiment into the vacuum chamber of the ETF.

The dynamic model does a good job of predicting the performance of the system. The actual performance exceeds the model at low frequency, which seems to be due to a difference between the modeled and actual sensor performance below its resonant frequency. Figure 2 shows the measured and predicted change in transmission which results from turning on the servo loops. This plot shows the change in system dynamics, and is an indication of good model performance. It is also insensitive to the relative calibrations of the witness seismometers, so long as they have good signal to noise performance.

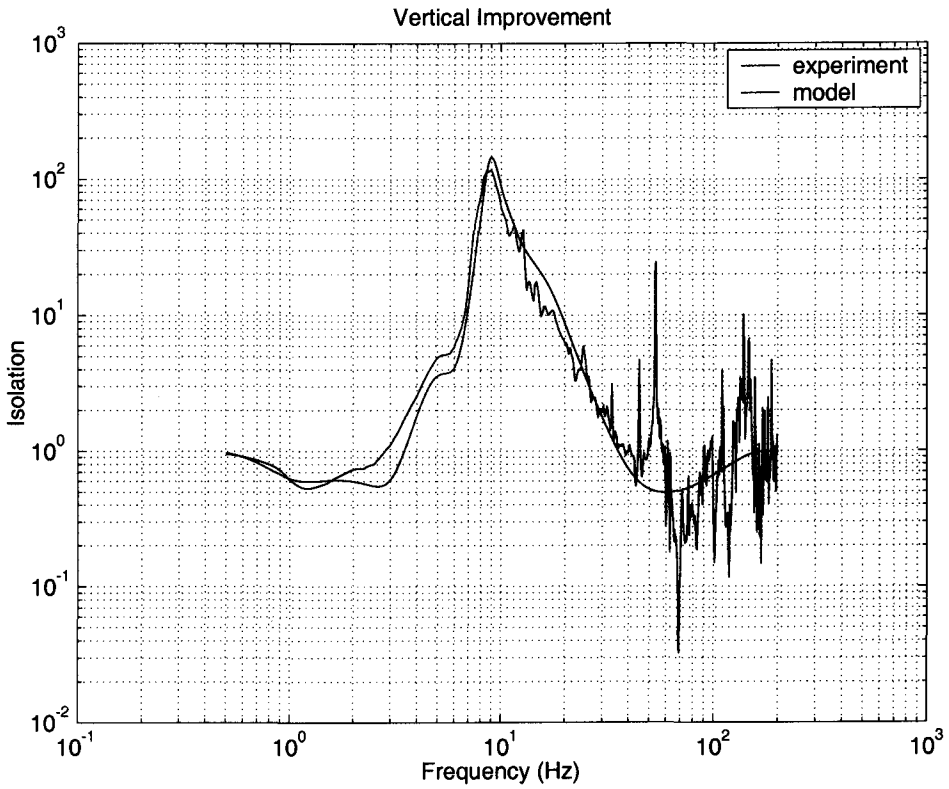


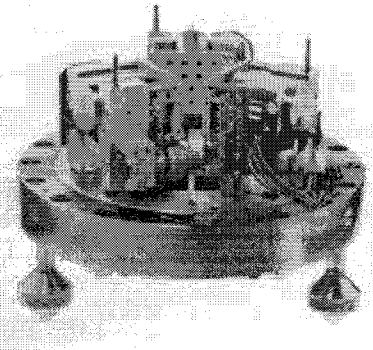
Figure 2. Improvement in the vertical isolation

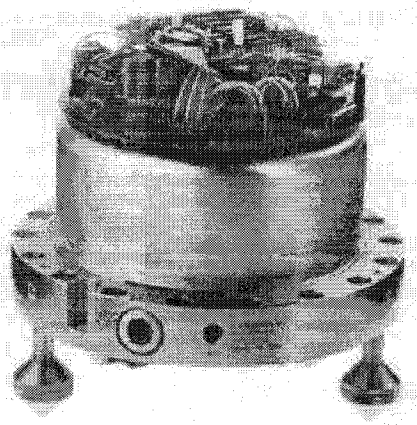
Although this data is preliminary, it is encouraging for several reasons. First, the model is working correctly, and predicts the performance well. Second, since we can predict the performance of the system, we seem to understand the factors which are limiting the performance. The two limiting factors are the overall loop gain, and the speed at which we can roll off the gain of the relative displacement (optical) sensor. This is encouraging, because the reference design uses similar overall loop gains and is designed to have similar limits at and above 10 Hz. Second, the reference design has better inertial sensors, which means we can set the blend frequency below 2 Hz, thus making it easier to roll off the gain of the relative sensors. These results do not change the predictions of the reference design, which are based on these two limits, and the limits set by sensor noise.

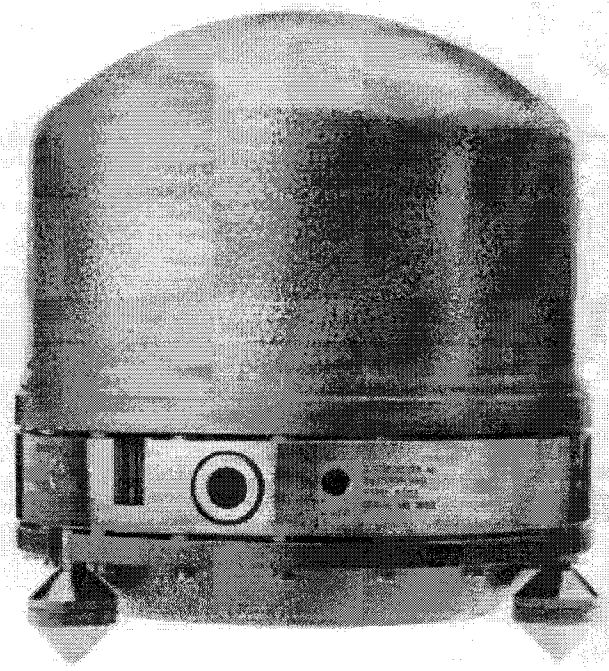
BATCH START

STAPLE OR DIVIDER

STS-2 PORTABLE VERY-BROAD-BAND TRIAXIAL SEISMOMETER







G. STRECKEISEN AG *MESSGERÄTE*
Dättlikonerstrasse 5 CH-8422 Pfungen Switzerland

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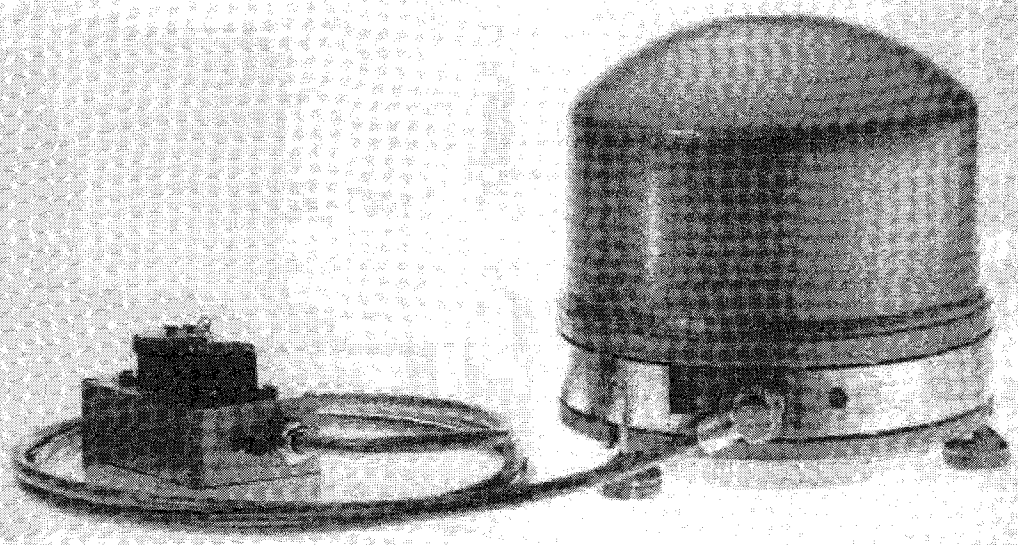


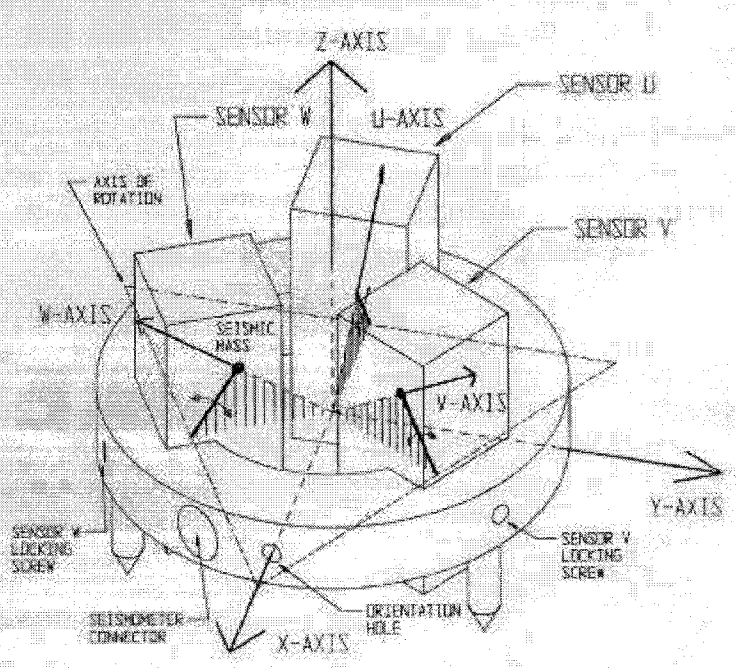
STS-2 SEISMOMETER COMPLETE WITH "HOST-BOX"

INTRODUCTION

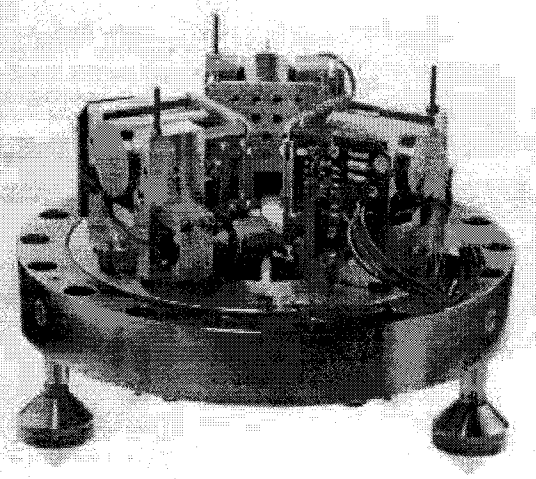
The Streckeisen STS-2 seismometers are sensitive, remotely-controlled, wide-bandwidth seismic sensors. Their high dynamic range and stable transfer characteristics make them ideal for a wide range of applications. The second-generation STS-2 complements the high-performance STS-1 seismometers that have been produced since 1976.

The STS-2 is designed for quick and simple installation, wider temperature range operation, and secure transport, while resolving minimum earth noise levels over the frequency range equivalent to and exceeding traditional long- and short-period instruments. Special shielding is normally not required to resolve levels 10 - 30 times below the limit of World-Wide Standard Seismographs.

The STS-2 uses 3 identical obliquely-oriented mechanical sensors, rather than the traditional separate orthogonal vertical and horizontal sensors. In addition to benefits in standardization of manufacturing, the tri-axial design guarantees that horizontal and vertical components are matched as closely as possible. Standard vertical and horizontal outputs are derived electrically rather than mechanically. To the user, the seismic output signals appear to be those of a conventional three-component seismometer.



STS-2 AXES



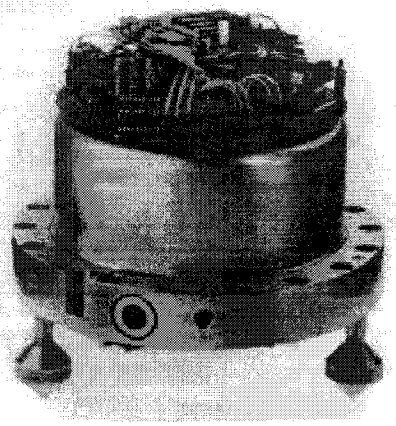
STS-2 INNER SHIELD REMOVED

PHYSICAL

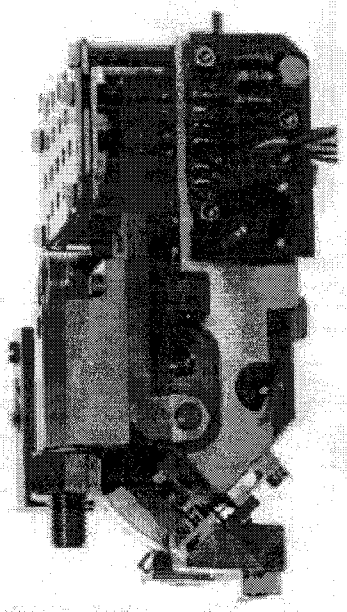
Three sensors with electronics and power conditioning are mounted in a cylindrical package. The electrical access to the STS-2 is provided by a single 18-line connector. Three threaded mounting feet allow levelling of the seismometer package. A screw to actuate the transit lock of each sensor is accessible along the edge of the base ring. The top and bottom of the STS-2 have aluminum covers that are gasketed to the base plate.

The STS-2 is vacuum-tight. The construction is further designed to minimize the distortion of the package by barometric pressure changes by insulating the top and bottom covers from the massive base plate, in a way similar to the insulation of a seismograph pier from its surrounding building. The top and bottom covers are secured to the base plate with compliant O-rings, allowing the covers to compress without stressing the entire package. The sealed construction and massive metal base plate provide thermal insulation and inertia.

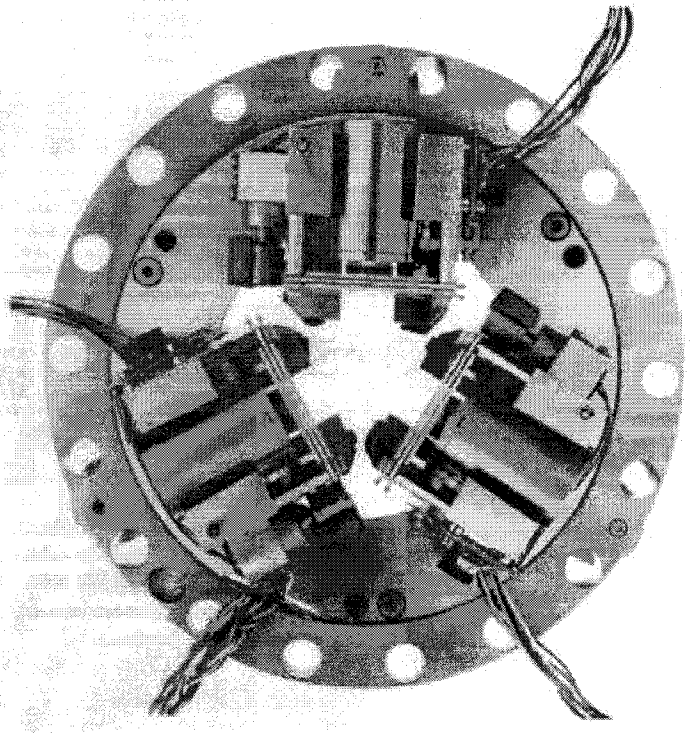
Since the complete package is factory-calibrated, it is necessary to orient and level only a single package in the field.



STS-2 COVER REMOVED



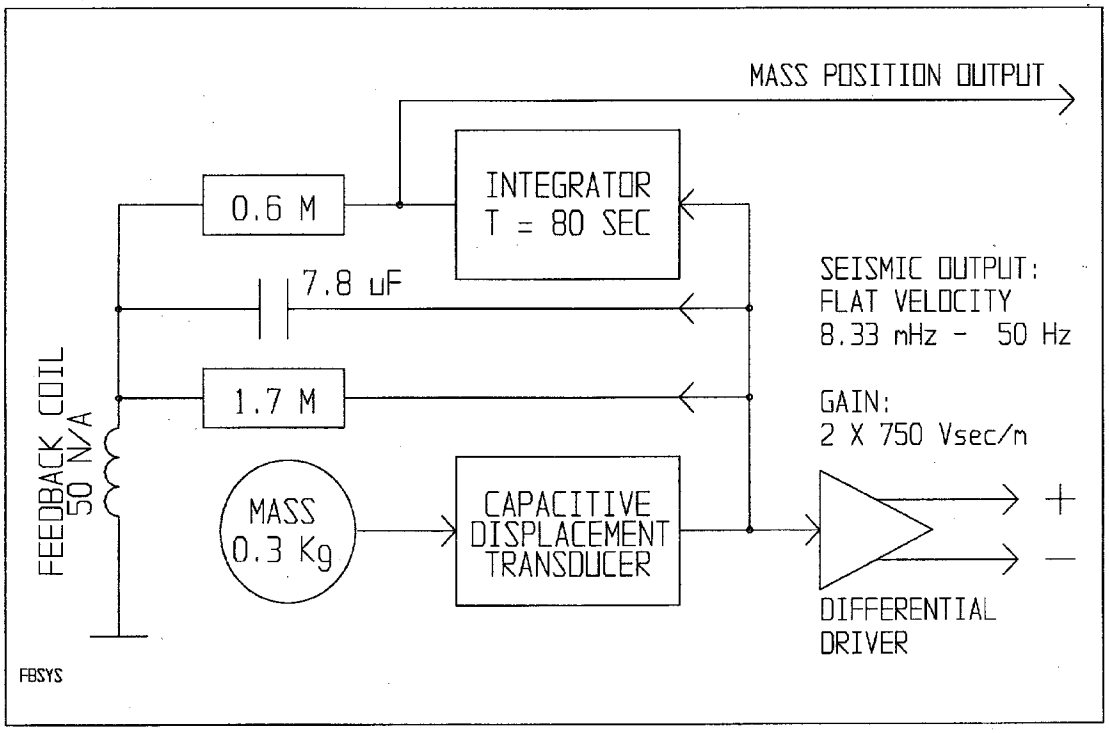
STS-2 SINGLE SENSOR



STS-2 THREE SENSORS IN FRAME, TOP VIEW

ORIENTATION

The orthogonal output signals are factory-adjusted using a standardized 3-dimensional shake table. So they represent motions in the geometrical X, Y, and Z axis of the seismometer with an accuracy of 1 % (0.6°) at a period of 6 sec. Physical orientation of the STS-2 by the user requires the adjustment of only two parameters: the verticality and azimuth of the package. Each STS-2 package is equipped with an integral bubble level for vertical orientation. To facilitate horizontal orientation, a rod is supplied with each instrument that represents the X axis when fitted into the accordingly labelled hole in the edge of the base ring.



STS-2 FEEDBACK SYSTEM

STS-2 FEEDBACK SYSTEM

Electronic force feedback permits a near infinite variety of seismometer responses. Feedback systems can be derived to optimize individual parameters such as saturation level, sensitivity, bandwidth, or frequency response. The feedback system for the STS-2 is chosen to be a compromise suitable for most general applications.

The STS-2 feedback system is basically identical to that of the STS-1/VBB (Wielandt and Steim, Annales Geophysicae, 1986) although the feedback is stronger at short periods improving linearity and extending the high-frequency flat-velocity response. The low-frequency - 3 dB corner of the initial version of the STS-2 is set at 120 sec.

No filters, which limit dynamic range, are used to derive the velocity-proportional output; the STS-2 feedback system delivers velocity directly from the feedback loop.

THE SEISMOMETER'S RESPONSE TO GROUND MOTION

FREQUENCIES BELOW 1 HZ

At low frequencies the STS-2 seismometer may simply be considered as a long-period, velocity-transducer, three-component seismometer with a free period of 120 sec, damping 0.707 of critical, and generator constant 2 x 750 Vsec/m. These parameters are factory-adjusted to within 1 % (generator constant at a period of 6 sec).

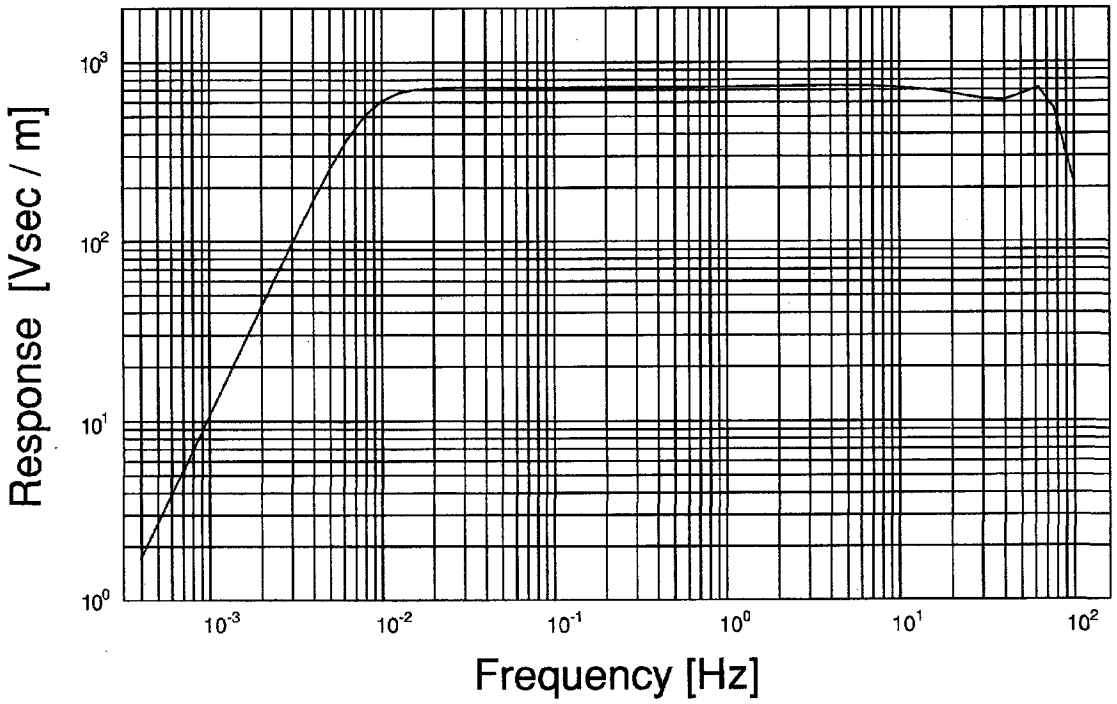
FREQUENCIES BETWEEN 1 AND 10 HZ

Between 1 and 10 Hz, the velocity response of the STS-2 is flat within ± 0.15 dB (about ± 1.5 % in amplitude). The group delay time in this frequency range is nearly constant, about 4 ± 1 msec.

FREQUENCIES ABOVE 10 HZ

The flat velocity response of the STS-2 extends somewhat beyond 50 Hz. However, the overall response at high frequencies depends not only on the seismometer but also on its coupling to the ground. While coupling may influence the amplitude and the phase of the transfer function noticeably, its influence on the signal delay time is small. The group delay time observed on a shake table is a nearly constant 3 ± 1 msec at frequencies between 10 and 50 Hz. The amplitude response may be expected to be constant within ± 1.5 dB (15 % in amplitude).

STS-2 VELOCITY RESPONSE



THE OPERATING RANGE COMPARED WITH THE SEISMOLOGIST'S REQUIREMENTS

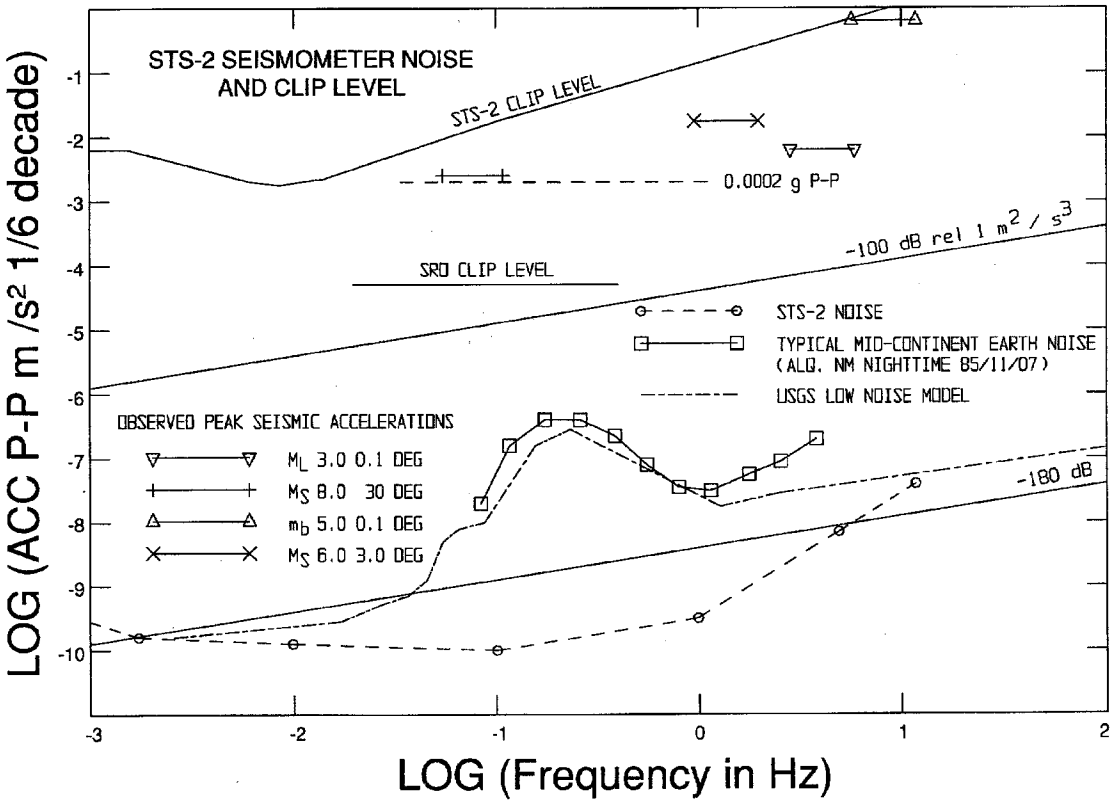
The figure below shows the clip level and typical noise of the STS-2 compared with the USGS Low-Noise-Model (LNM) and the required minimum clip level for high-gain seismometers. Also shown are "typical" intermediate-period earth noise and peak signal levels from regional and teleseismic events spanning 5 orders of magnitude and epicentral distances from 0.1° to 30°.

The figure represents noise and signals on a common scale so that overall operating range can be shown. RMS noise is converted with 99% confidence to equivalent peak-to-peak values by multiplying the RMS values by 6. Peak-to-peak signal levels are derived from 1-octave filtered broad-band accelerograms derived from VBB recordings made by Quanterra / Streckeisen systems. Some estimate of dynamic range as a function of frequency can be read directly from the figure.

The STS-2 electronic self-noise is below the equivalent level of the USGS Low-Noise-Model (LNM of Peterson and Tilgner, USGS OF Report) from > 10 Hz to 200 sec provided that the instrument is additionally protected against air pressure variations by means of a pressure jacket (see chapter "SUGGESTIONS FOR OPERATION").

The flat-velocity STS-2 also covers the critical frequency-amplitude range from 10 sec to 10 Hz with a high acceleration-equivalent saturation level, up to > 0.1 g at 10 Hz. The high saturation level of the STS-2 allows capturing on-scale even moderately large local and regional events.

Because typical short-period earth noise levels (represented in the figure by a wind-free nighttime sample taken at Albuquerque, NM) often substantially exceed the LNM levels, the STS-2 has been optimized for high dynamic range rather than substantially lower self-noise at frequencies beyond 10 Hz. High-frequency resolution is controlled principally by the displacement transducer resolution. The standard STS-2 is more than 1 order of magnitude better than the STS-1, whose short-period resolution has not proven limiting in world-wide deployment for general-purpose earthquake recording.



INPUT AND OUTPUT

The STS-2 comes supplied with a 3-meter interface cable that is terminated at the sensor end in a seismometer connector and at the other end in a "host-box" with two waterproof connectors. Power, control, output signals, and calibration signals are accessible at the "host-box". The "host-box" also contains a DC/DC converter, input protection circuits, and other signal distribution.

POWER INPUT

The "host-box" contains an isolating, regulated DC/DC converter. Primary power is applied through a overvoltage and false-polarity protection network consisting of a thermal current limiter and a voltage limiter. Primary DC operating voltage is 10 - 30 VDC. Power consumption is 1.8 W.

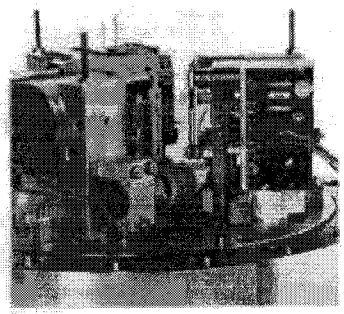
CONTROL INPUTS

Logic-level inputs are provided on the STS-2 "host-box" to control 4 functions: monitor-signal selection (POSITION or raw sensor outputs), initialization of mass recentering, selection of low-frequency corner period, and connection or disconnection of calibration lines.

The STS-2 can automatically recenter the boom position. The autozero cycle requires about 30 sec. To reduce installation and mass centering or recentering time, the STS-2 has the ability on command to change its low-frequency corner period from 120 sec to 1 sec and vice-versa without destabilizing the equilibrium state of the electronic feedback system. The autozero command automatically initiates switching to 1 sec corner period and returning to 120 sec after the autozero cycle has finished.

CALIBRATION CURRENT INPUTS

The STS-2 provides separate inputs to the calibration coils to allow individual excitation of the three sensors.



STS-2 THREE SENSORS IN FRAME, SIDE VIEW

OUTPUT SIGNALS

The raw electrical output of each of the STS-2's obliquely-mounted sensors contains both vertical and horizontal components of motion. These raw sensor signals are electrically summed within the STS-2's electronics to provide standard vertical and horizontal output signals (electrically realized coordinate transformation: U, V, W into X, Y, Z). Cross-coupling between components is suppressed electrically during manufacturing, rather than by mecanical adjustments. The output stage of the feedback electronics for each component provides a high-level (40V p-p,max) differential output signal, suitable for direct connection to a high-resolution A/D converter, such as the Quanterra Q52K-1 (20 Hz sampling) or Q52K-80 (80 Hz sampling).

Three auxiliary output lines are used to monitor either the mechanical balance or the raw broad-band output signals of the individual sensors. The broad-band output signals are selected by applying an external logic control signal.

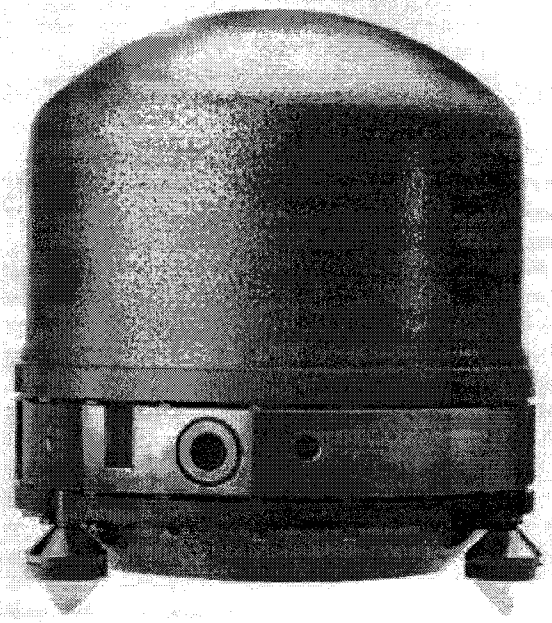
SUGGESTIONS FOR OPERATION

A double styrofoam box is recommended for isolation against rapid temperature changes and air currents; it will substantially improve the long-period noise level. Satisfactory results may also be obtained with a single box. We have found that in a typical seismic vault with still air and relatively constant temperature, an STS-2 covered by a single box without special sealing can resolve minimum earth noise to about 50 sec period. Operating under these conditions, the STS-2 will produce long-period, narrow-band records (with a peak magnification at 25-35 sec) that are virtually identical to those from a properly installed set of STS-1 seismometers.

For recording with substantial gain at very long periods, the STS-2 requires some additional protection from air pressure fluctuations. We recommend in this case to provide a simple pressure jacket which needs not be air-proof for more than a few hours. Evacuation is not required and not recommended.

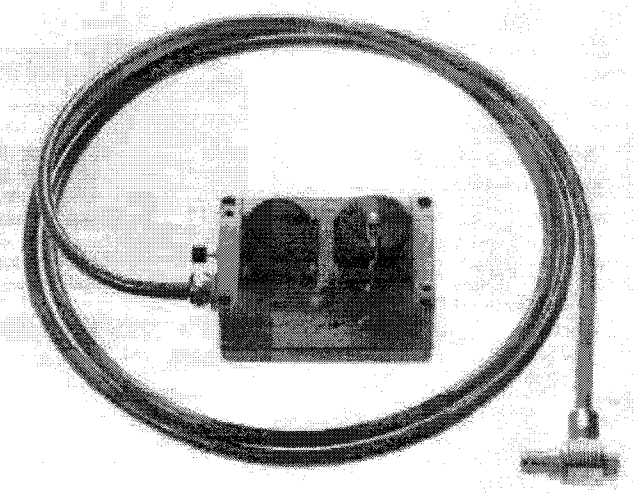
Styrofoam box and pressure jacket are not part of the STS-2 shipment. They must be evaluated, constructed and installed by the user. Detailed information for customers who are interessed in the pressure jacket which we have applied in our test equipment is available on request.

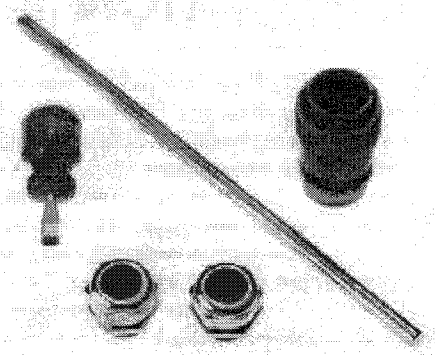
COMPONENTS DELIVERED



TRIAXIAL SEISMOMETER STS-2

"HOST-BOX"
with a 3-meter interface cable terminated
in a seismometer connector





ACCESSORIES

Rod for horizontal orientation of the STS-2
Screwdriver
Connector for "host-box" with 2 cable-glands

SPECIFICATIONS

General

Principle of operation	Force Balance
Mechanical sensors	3 identical inertial pendula in a cube-corner geometry. The mechanical free period is virtually infinite.
Seismic output signals	2 horizontal (X, Y) and vertical (Z) Broad-band velocity response
Size	Cylindrical package 235 mm diameter, 260 mm high
Weight, complete with "host-box"	13 kg
Environmental protection	Vacuum-tight, low-stress construction

Electro-mechanical

Generator constant	2 x 750 Vsec / m
Response	Ground velocity between corners 8.33 mHz (120 sec) and >50 Hz. See chapter "THE SEISMOMETER'S RESPONSE TO GROUND MOTION" for details.
Seismic signal output	± 20 V differential range, 100 Ω serial resistance per line
Auxiliary outputs	± 10 V single-ended, 100 Ω serial
Electronic self-noise	typically below USGS low-noise model between 8.33 mHz and 10 Hz
Clip level	± 13 mm / sec ground velocity equivalent to the following accelerations: g peak-peak at Hz 0.17 10 0.017 1 0.0017 0.1 0.00055 0.03
Dynamic range	see figure "STS-2 SEISMOMETER NOISE AND CLIP LEVEL"
Parasitic resonances	vertical: > 140 Hz horizontal: > 80 Hz
Power	< 1.8 W at 10 - 30 V DC, galvanically isolated
Control inputs	"high": 3 - 30 V, 0.5 mA; "low": < 0.5 V; optically isolated
Calibration inputs	Calibration coils 30 Ω each, approx. 0.002 g / mA (oblique), maximal current 50 mA each
Temperature range	± 10° C without mass recentering
Mass centering	automatic on external command

G. STRECKEISEN AG *MESSGERÄTE*

Dättlikonerstrasse 5
CH-8422 Pfungen
Switzerland

Phone 052 / 31 21 61
Fax 052 / 31 27 10

For U.S. and CANADA please contact:

QUANTERRA, INC
VBB SEISMOLOGICAL INSTRUMENTATION

325 Ayer Road, Suite 16
Harvard, MA 01451 USA

Phone (508) 772-4774
Fax (508) 772-4645

BATCH START

STAPLE OR DIVIDER

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
– LIGO –

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Document Type	**DCC Number**	**Date**
Technical Note	**LIGO- xxxxxx**	**12th of April 2000**

Replies to TAG questions

Alessandro Bertolini, Giancarlo Cella, Riccardo DeSalvo, Szabolcs Marka, Kenji Numata, Virginio Sannibale, Akiteru Takamori

Distribution of this draft:
LIGO

This is an internal working note
of the LIGO Project.

California Institute of Technology
LIGO Laboratory - MS 18-34
Pasadena CA 91125
Phone (626) 395-212
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Laboratory - MS 16NW-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

www: http://www.ligo.caltech.edu/

1) HAM fit: The soft design for the HAM (revised somewhat from what was presented at the LSC meeting; see the sketches in the revised design description) restricts access for installation and adjustment of internal components. Layouts with LIGO-1 components indicate that by 'stretching' the design to the limits of what will fit in the HAM chamber, the LIGO-1 telescopes and the triple pendulum may fit, but it is a tight fit and one which appears to restrict the mode cleaner cavity length beyond the obvious constraint of chamber separation.

The SAS group designed, to the best of its knowledge, the HAM table supports to house the same optics presently in use, all impedimenta have been pushed out of the beam pipe envelope, the only obstructions still present on the table profile are given by the IP legs. If these legs were to represent a problem, they can easily be pushed another 15 cm further out, in the HAM covers and completely clear the present HAM table foot-print. Unless LIGO II has different small optics requirements, what fits in LIGO I will also fit into the LIGO II HAM SAS tables.

The final sentence is especially incomprehensible, because there is no impedimenta whatsoever along the beam direction.

Given that none of the dimensional parameters of the HAM design have been calculated (i.e. the design is based on judgement only), to be dimensionally tight at this early stage seems ill advised.

The design is based on existing SAS components and the present HAM table geometries so it is expected to be adequate.

It is true that the proposed design is mainly based on judgement; it is worth noting though that we already have substantial experience in controlled suspended platforms. Virginio Sannibale already made and operated the control system of the Virgo injection bench at Annecy. This bench was suspended from the earliest version of Virgo top table, provided by Riccardo DeSalvo, and was controlled in six degrees of freedom.

The alternative "backup plan" referred to (commercial active isolators adapted for vacuum use) is undeveloped. Filling in our experience with commercial isolators (Barry STACIS, now marketed by TMC, and negotiations with IDE on similar products) suggests that

a) to interface satisfactorily with arbitrary customer loads (one size fits all) they usually have severely compromised performance,

b) they employ much noisier inertial sensors (only resonant RMS is generally considered an issue), and

c) they do not tolerate working against reactive or resonant "ground" loads (i.e., will not work on structural steel platforms or in cascade).

These above objections are, in our opinion, may apply to other firms and to different technologies, but do not seem to apply in our case:

a) *this is not the case of Minus-K technologies six degree of freedom attenuation units, they deliver a good 60 dB single stage attenuation according to both their and our own measurements.*

b) *there are no sensors in Minus-K units because they are completely passive. For controls, we would use our own, very sensitive, well understood and thoroughly tested sensors and actuators. These sensors are specifically developed for insensitivity to transversal excitations. They are also passive in vacuum.*

c) *passive attenuators happily perform over platforms (provided some attention is paid not to get resonance interferences) and in cascade because they do not apply any active forces. Our chains are precisely conceived to work in cascade modes and Minus-K is quite comfortable in cascading their systems if more than one stage is necessary. Low frequency inertial damping feed back systems operating over low K springs happily perform over structural platforms because in their frequency range the structures are rigid.*

Note that we already are operating three Minus-K platforms and we are perfectly comfortable with their performance.

It is unclear whether the Minus-K option proposed addresses these features, but in view of the primary market, isolation of semiconductor wafer stepping machines, it's unlikely they will serve right off the shelf. How viable are the Minus-K isolators?

We agree that Minus-K isolators need to be upgraded with our zero creep technique and need to be made UHV compatible. To satisfy the first point we expect to implement Maraging elastic components in their units in collaboration with Minus-K under a SBIR type contract framework (actually we are already consulting with them to upgrade their

product line). For what concerns the UHV compatibility, Minus-K have already Know-How in the production of internal units for scanning probe microscopes (STM) and will work in close collaboration with us to satisfy the slightly different LIGO requirements.

How likely is it that this would end up being a sole-source procurement with Minus-K Inc. (e.g. are other designs of this nature possible without patent infringement)?

As Minus-K will finalise the development of the proposed isolators with us, we will be development partners. Even in case of (unlikely) relationship breakdown, I would like to remind that we will be building the attenuators for our own, non profit, use. If Minus-K for whatever reason will not build them for us or will make unreasonable prices, we will be able to build them ourselves without patent problems.

2) Internal mode damping: The "soft" team asserts that only three sets of sensors and actuators on the first stage are adequate to damp all internal modes of the structure.

In reality there are four sets of sensors and actuators, including the vertical axis ones on F0; the two tilt modes of the filters naturally couple with the horizontal movements thus showing clearly in the horizontal sensors. All the chain body modes react against F0 where all action is located and can be damped.

This contradicts our understanding of the Glasgow results (Husman, Strain et al) regarding indirect damping of suspension normal modes. They showed that there is indeed a restricted class of systems in which effective cooling of modes is possible from a partly decoupled upper stage, but a much bigger class in which attempting to do this (esp. with finite SNR sensors) in fact cools some modes at the expense of greatly increasing the RMS of others. At best a point of diminishing returns is reached, at worst, outright instability.

We do not expect any of this. Even pushing the feed back to the point of "freezing" the support point of the rest of the chain, new resonances are observed, corresponding to a shorter passive chain. These resonances are excites by a reduced seismic activity level corresponding to the low floor of the attenuated seismic noise after the first ULF passive stage.

With the large number of potentially "hidden" degrees of freedom in the proposed soft design we are concerned that sensors and actuators will need to be added to at least one and perhaps two more stages.

We do not expect to do any of this; SAS will need no additional active stage. The "hidden" modes are expected to be under control naturally, and if it was the case the Eddy current damping would add suspenders on belt.

This would largely negate the proposed advantage of controls simplicity and in-vacuum reliability, and may expose the soft design to issues of sensor SNR comparable to those of the stiff design. Alternatively the rigid body modes can be made observable by designing in cross-coupling intentionally.

Undoubtedly it could be done, but likely to be unnecessary.

What is the VIRGO relevant experience on damping the rigid body modes of the SAS chain? What calculations or measurements have been performed to support the magnetic damper design element between the F0 and F1 filters? There is clearly a trade off between shorting across the filters (a magnetic brake) and providing sufficient modal damping. Will there be results from the prototype soon which will directly measure the damping of all of the SAS chain modes?

The SAS group will do the measurements as soon as the IP will be available; it is presently busy with the controls developments. The measurements will allow the definition of the damping tradeoffs, which may include the replacement of the broad-band copper plates that will be used initially with LRC coils tuned to specific frequencies. This will allow the recovery of much of the 1/f factor lost with a fully Eddy current brake scenario and possibly lead to the reduction of one filter from the chain. The best trade-off may be to eliminate the Eddy dampers altogether.

3) RMS displacement & velocity: The VIRGO experience to date (~ micron of excess motion, reported by Brillet) may indicate that the projection of 10 nm RMS is not obtainable.

We readily agree that the 10 nm residual motion may be unattainable but the less than 1000 nm achieved by Virgo is already a good result. It must be noted that this result was

only an upper limit obtained with a measurement from a ground based CCD camera in Pisa where the seismic activity is, by more than one order of magnitude, larger than in any of the LIGO sites. Our development target is to improve by a factor of ten over the Virgo inertial damping performance with better accelerometers and actuators. It is not unreasonable to expect that, combining these two advances, we may achieve a single factor of ten improvement from 1000 to 100 nm.

For TAG members: See page 5 and Appendix 3 of the attached revised design description report which explains the reasons that VIRGO has had problems and how the LIGO-2 SAS will improve upon the VIRGO design in this regard.

4) Thermal sensitivity in the Young's modulus of the GAS springs: The temperature coefficient of yield stress (should be like Young's modulus, assuming constant yield strain) seems to be something like 0.1% per degree C for maraging steel (check this?).
It is 0.04% per degree C

For a stage with 10-second period the effective height (l as in sqrt(g/l)) is 30 m, so the equilibrium height of one stage would change about 3 cm per degree.
It makes no sense to drive all the filters this low in frequency (only for F0 there are reasons to go very low in frequency) because the height limited horizontal pendulum frequency is much faster. Two to three second period GASFs are perfectly fine to more than match the horizontal frequencies. At these higher frequencies GASFs are 25 to 9 times less temperature sensitive than in the example above. The result is substantially less than a millimetre per degree vertical sensitivity, just as measured in our prototypes.

Admittedly a forcer on the top stage can counteract this with a force correction (.1% of the stage load per degree, so ~ a full Newton for 100 kg), but without putting forcers on all stages, it seems the cumulative effect becomes intractable within the ~ few mm GAS dynamic range. Is this correct, or have we misinterpreted the design?
Correct but with the wrong parameters.

5) Material stress and non-Gaussian noise: The (presumably) high working stress in the GAS springs and their attachment fixtures raises the issue of non-Gaussian noise generation from strain release events. What is the working stress and the yield stress?

The working stress is about at 60% of the yield stress (yield stress 180 Kg/mm^2 stress test 100 to 120 to be compared with the Virgo parameters of 80 to 100 Kg/mm^2). This is well inside the measured no-micro-creep limits of low temperature precipitated Maraging .
The data presented at the LSC meeting on Q vs. loading seemed to indicate that a regime of anelasticity is not far from the operating point; is our interpretation correct? Some further explanation on the data presented by Szabi Marka would be helpful.
Szabi showed that data to prove that the GASF design is far from the point where micro creep begins. We have extensive measurements that shows that the chosen working point is deeply inside the safe zone. The stress grows very rapidly when the working point is raised because the blade's nose is forced to make a sharp bend thus concentrating the stress on it instead of the uniform curvature along the entire length engineered around the blade's working point. More measurements are scheduled on components and entire filters during the summer. It may be of interest noting that the baking at 85° C of one of our GASFs did not change its working point. If the filter had been close to the creep point it would have shown.

6) Angular stability: There does not appear to be an explicit system or arrangement of restoring forces for vertical torques. How is angular (yaw) motion limited (e.g., by additional constraints or actuators)?
SAS is passive below F0, note though that the yaw mode is completely different and independent from the longitudinal modes. It is treated with a completely different PID filter on the IP. In particular it is possible to introduce in this direction a strong viscous damping on F0 without affecting at all the performance of the chain. The monolithic suspension wires are extremely effective and stable passive attenuators.

7) Installation, alignment & maintenance: From the same considerations regarding thermal sensitivity above, it appears that each GAS stage has to be balanced to something like 0.01% or even 0.001% of its final load to reach the proper equilibrium. The process for converging each to its appropriate final balance (given that each affects all others) looks

extremely laborious and fragile. Dressing wiring and installing and aligning the suspension would need significant jigs and tooling (e.g., fine-control "caging" limiters to freeze stages being worked on).

Installing two systems in the same vacuum envelope (or even two suspensions on a common system) would appear to be a very difficult. Has VIRGO or the soft team, clever solutions to these perceived problems in installation?

The earthquake motion limiters are expected to double up as assembly and transport latches, no problem in assembly, wire dressing (if any), etc.. Virgo has cabled up already a few similar towers without encountering any special problems.

We have no clever solutions to tune up our system, we are used to it and it comes very naturally. To give an example the tuning of a filter working point after some change of a payload is made consists in just measuring how much load change is required by means of a dynamometer or a ruler and change the ballast load accordingly (1 to 2 Kg per filter payload is allotted for this purpose; Virgo has a much more cumbersome system of tuning screws to change the payload). This operation is done in a few minutes per filter starting from the bottom up. An entire chain is tuned to its optimal working point in less than an hour. About fragility, we had filters standing in the synchrotron with everybody touching them continuously for months without ever having any problem.

We do not expect any particular problem in installing multiple units in a tower, filters hook and unhook in a manner of minutes. Except for emergency repair we expect to do most of this work in the assembly halls before baking.

BATCH START

STAPLE
OR
DIVIDER

budget for hydraulic actuator			
		number needed	
estimate of materials for 1 actuator	800		
2 bellows	400		
est of machining time	1500		
est of welding	750		
flapper valve & drive	2500		
flow restrictors	425		
displacement sensor and readout	500		
misc o-rings and bolts, plugs	250		
total per actuator	**7125**	216	1539000
pump	2000		
manifold (parts and machining)	400		
filter	400		
control valve	1300		
pressure sensor	1000		
readout and control electronics	2000		
misc plumbing	300		
total per pump	**7400**	8	59200
plumbing	**?**		?
LIGO needs 8 actuators per tank, 9 tanks per interferometer, 3 interferometers			
LIGO needs 1 pump per building, with 8 buildings			

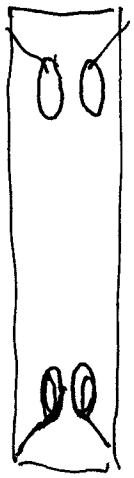
* 5 BSC / interferometers

* 4 HAM / interferometers

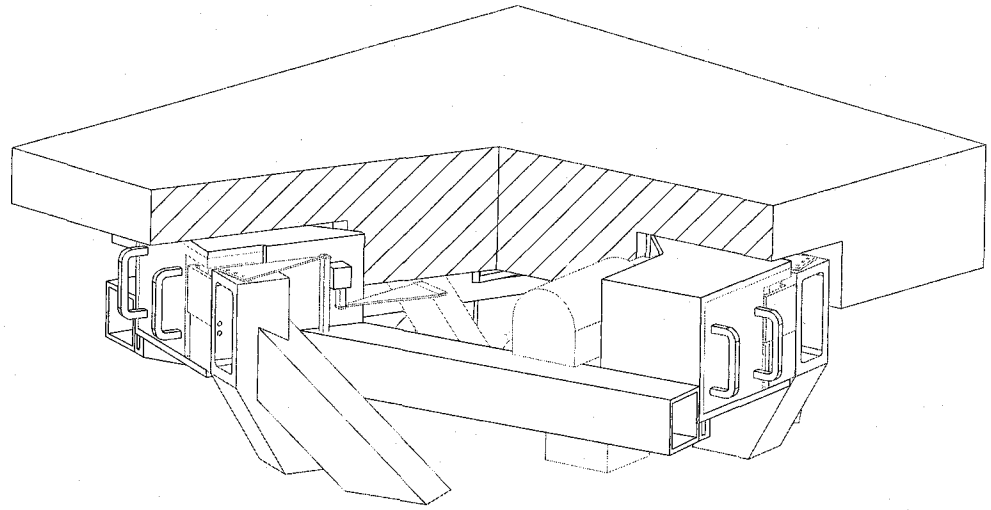
* All out of Vac. are Al or Carbon steel.

Parts for the BSC tank

Piers	in place
attachment fixturing for fine (hydraulic) and course (motorized screw) actuators	4
hydraulic actuators	8
course actuators	8
cross beam weldment and support tubes	in place
bellows	in place
support table	1
platform support structures **(BSC_1)**	3
blades supporting outer stage	3
task flexures supporting outer stage	3
outer stage structure **(BSC_2)** (also called the first active stage)	1
outer stage pod **(BSC_4)**	3
instruments in outer stage pod - see attached	
blades supporting inner stage	3
task flexures supporting inner stage	3
inner active stage **(BSC_3)** (also called the optical table)	1
inner stage pod **(BSC_5)**	3
instruments in inner stage pod - see attached	



REVISIONS			
REV	DESCRIPTION	DATE	APPROVED



	PART DESCRIPTION: HAM DESIGN		TOLERANCES LINEAR: x.xxx +/- .005 x.xx +/- .01 x.x +/- .1 ANGULAR: +/- 1 DEG ALL DIMENSIONS INCHES NOT TO SCALE
	ASSEMBLY TITLE: HAM DESIGN	PART NO.: 0	
	MATERIAL / PROCESS: VARIOUS		
DRAWN BY: CORWIN HARDHAM	PARTS AND MATL REQ'D: 1 PER TANK	4-25-00	