Suspension Preliminary Design Review

June 6, 1996

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AGENDA

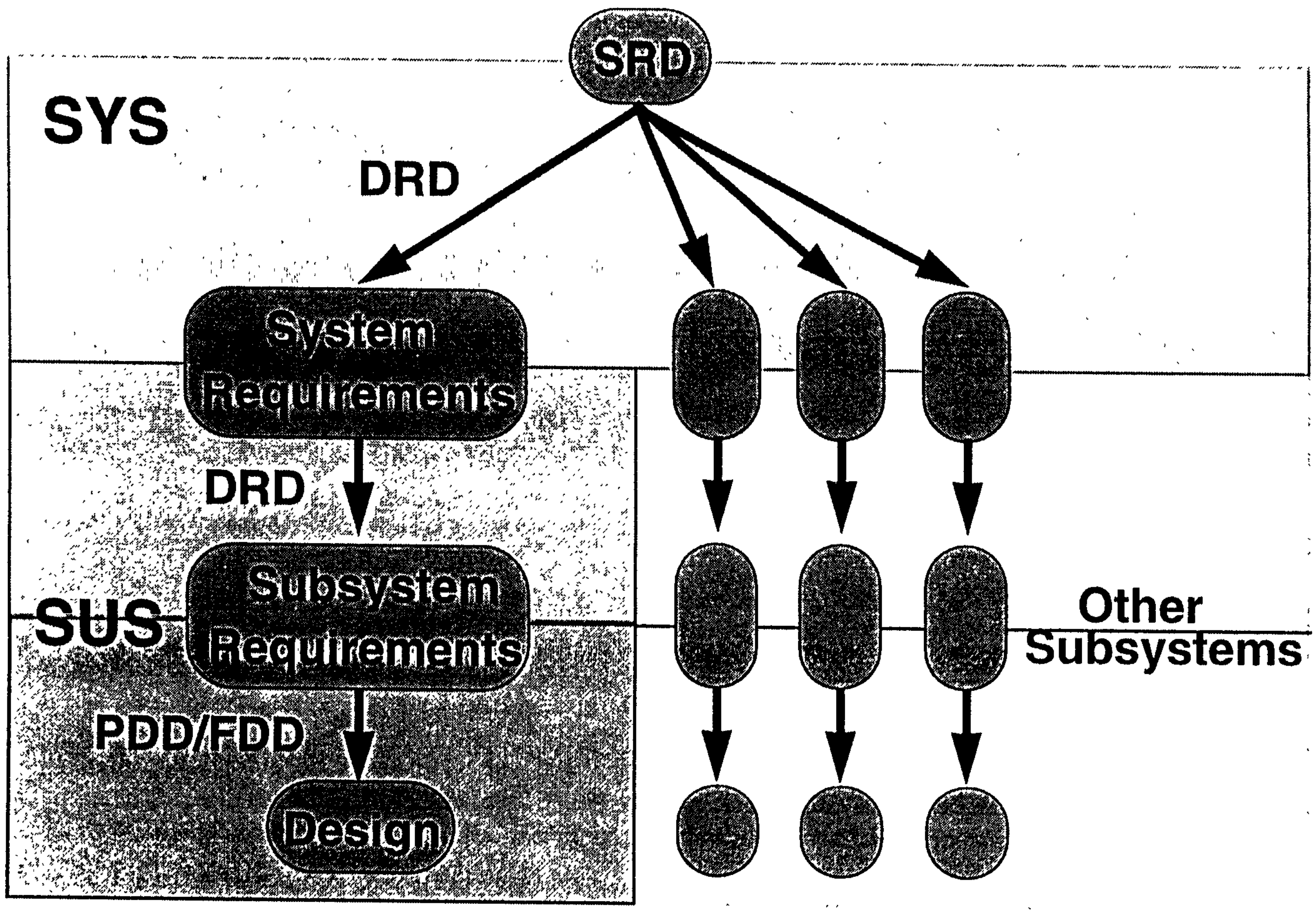
0. Major Changes since DRR

- SUS task re-defined to deal with assembly and installation of large optics suspension.
- Derivation of requirements clarified.
- Actuator range expanded to deal with the noisier Louisiana site.
- Incorporated Braginsky's suggestions to some extent: welding and annealing instead of bolting.

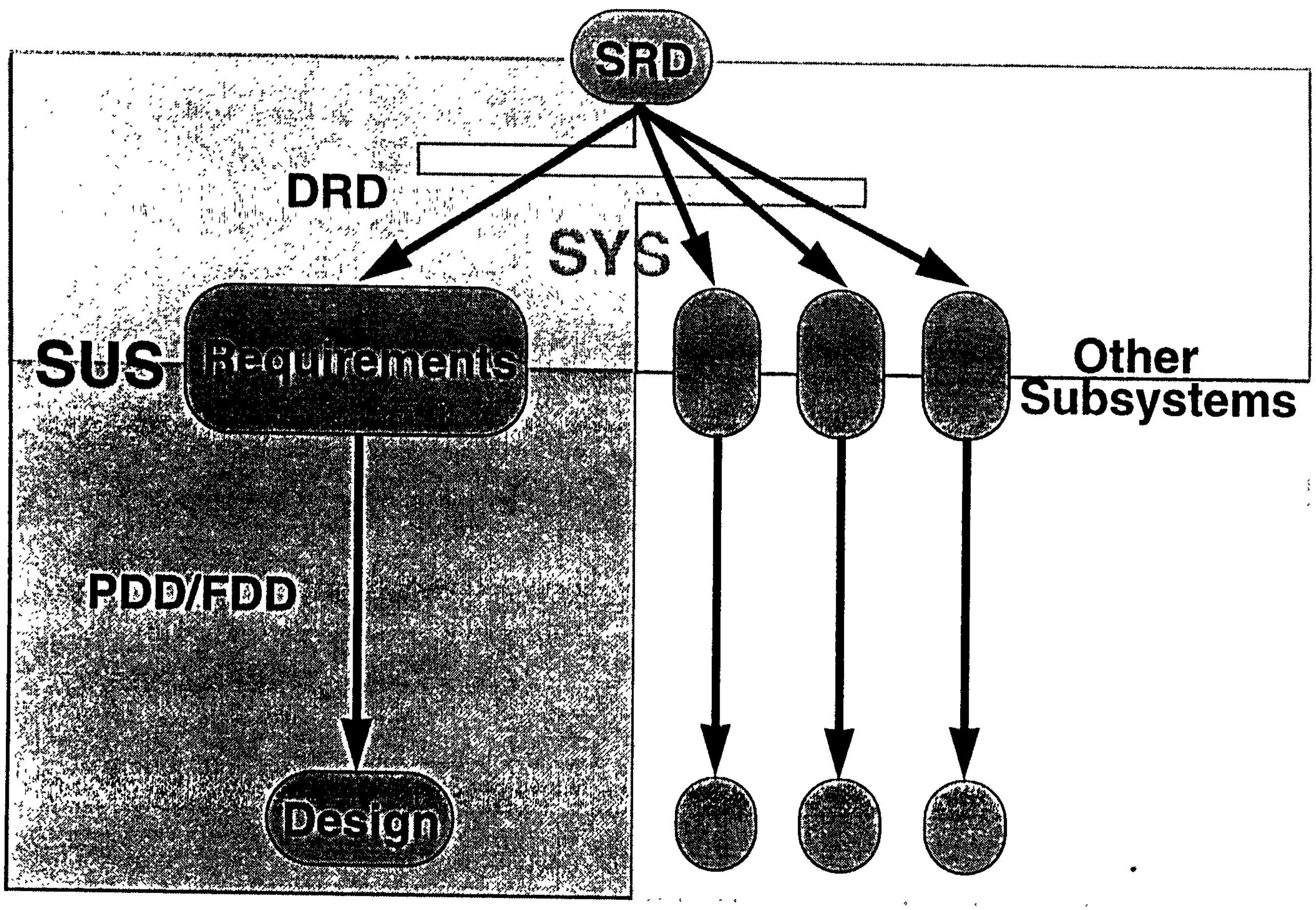
1. Requirements

- Flowdown
- Each item
  - ››(Top) level Requirements
  - ››Derivation
  - ››Required value

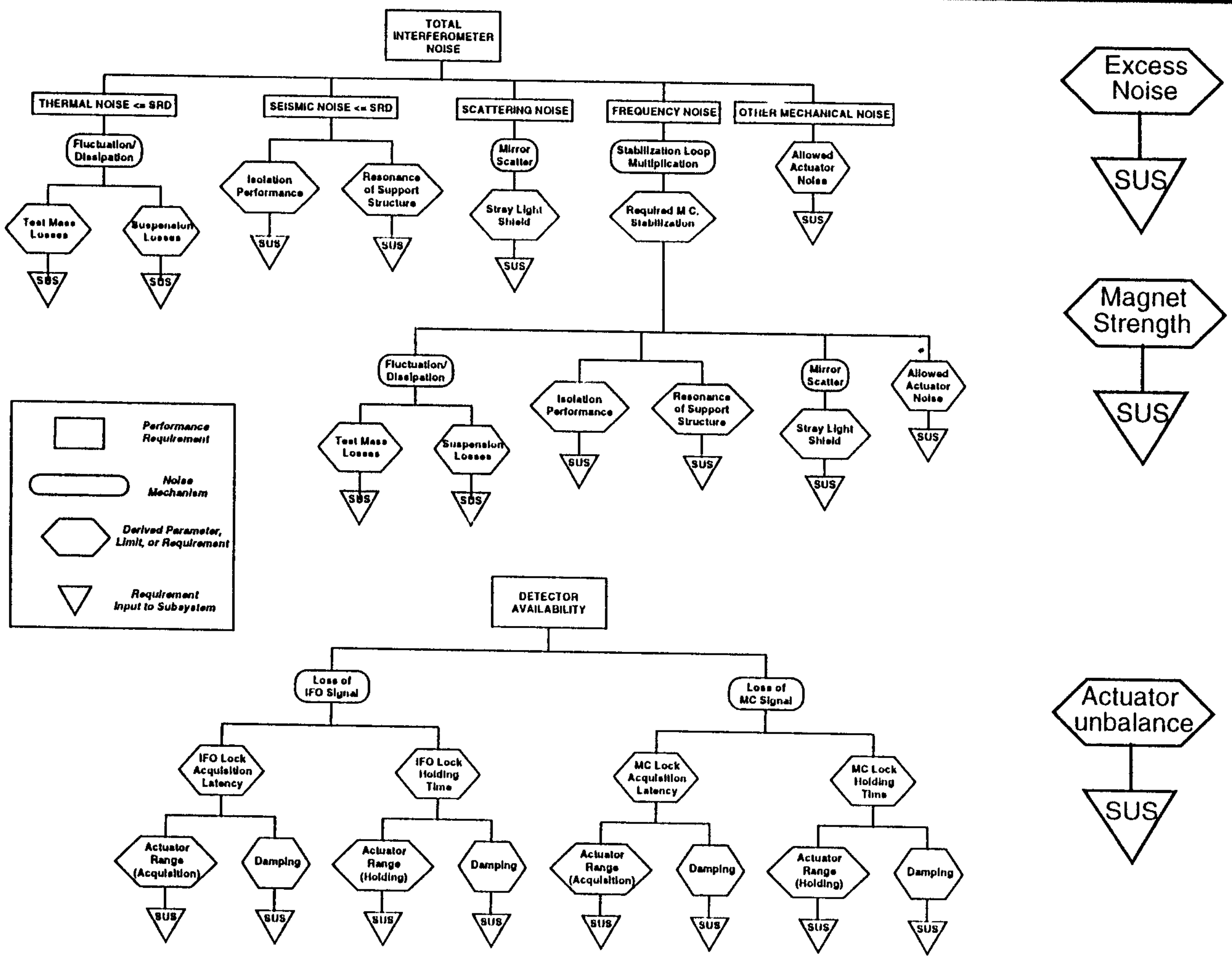
Requirement Flowdown to Design (Final)



Requirement Flowdown to Design (Present)



Requirement Flowdown

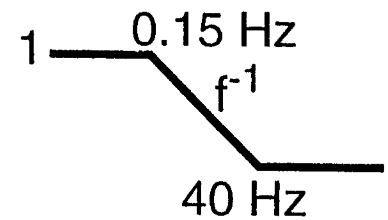
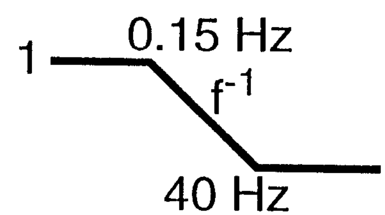


Range of Actuator (Top Level Requirements & Derivation)

- Top level requirements
  - ››Continuous operation of the LSC system
  - ››Smooth acquisition of the LSC system
  - ››Proper initial alignment
  - ››Continuous operation of the ASC system
- Derivation
  - ››Cover micro-seismic peak (2 μm)
  - ››Assume plausible frequency dependence of the driver --- noise at 40 Hz
  - ››Impose stack transfer function on SEI (See SEI DRD)
  - ››Assume designed pitch/yaw frequency for orientation range

Range of Actuator (Requirements)

Table 1: Requirements of the suspension actuator range.

Mode		*DC Peak-to-Peak Motion*	*Weighting Function*
Displacement	Operation	80 mm_{pp}	
	Acquisition	80 mm_{pp}	
Orientation		2 $mrad_{pp}$	

Quality of Damping

- Top level requirements
  - ››Stable operation of the LSC system
  - ››Smooth acquisition of the LSC system
  - ››Negligible up-conversion noise of the spurious interferometer
- Derivation
  - ››Best we can do --- Sensor noise at 40 Hz, phase delay around a few Hz
  - ››Impose stack transfer function on SEI
- Requirement
  - ››The residual Q must be less than 3.

Unbalance of Actuator

- Top level requirements
  - ››Smooth transition of the LSC system from acquisition to operation mode
- Derivation & requirements (TBD)
  - ››Depending on ASC baseline
  - ››Without optical lever < ~1%

Noise Criteria

- LOS1/LOS2
  - ›› δx_{TM} < SRD (Seismic Noise, Thermal Noise)
  - ›› δx_{TM} < 10% of SRD (Other Noise)
    - —SRD: LIGO displacement sensitivity defined in SRD
- SOS
  - ›› $\Sigma\ \delta x_{MC}$ < FN
    - —FN: Required MC displacement noise (IOO - LSC)

Transfer Function of Suspension (Top Level Requirements & Derivation)

- Top level requirements
  - ››Seismic noise must meet SRD
- Derivation
  - ››Either T_{hh} or T_{vv} is dominant.
  - ››Impose 10% of them on others
  - ››Impose stack isolation requirement on SEI (See SEI DRD)

Transfer Function of Suspension (Detailed Derivation I)

- T_{hh}
  - $\delta x_{OP,h} \times T_{hh} <$ SRD (LOS1/LOS2)
    - $\delta x_{OP,h}$: Horizontal motion of optics platform
  - $\delta x_{OP,h} \times T_{hh} <$ 10% of FN (SOS)
- T_{hp}
  - $d \times T_{hp} <$ 10% of T_{hh}
    - d: Beam spot offset, d = 1 mm (LOS1/LOS2), d = 3 mm (SOS)

Transfer Function of Suspension (Detailed Derivation II)

- T_{vv}
  - $\delta x_{OP,v}$ x T_{vv} x (3×10^{-4}) < SRD (LOS1/LOS2)
    - $\delta x_{OP,v}$: Vertical motion of optics platform
  - $\delta x_{OP,v}$ x T_{vv} x (3×10^{-4}) < 10% of FN (SOS)
- T_{vh}
  - T_{vh} < 10% of (3×10^{-4}) x T_{vv}
- T_{vp}
  - d x T_{vp} < 10% of (3×10^{-4}) x T_{vv}
    - d: Beam spot offset, d = 1 mm (LOS1/LOS2), d = 3 mm (SOS)

Transfer Function of Suspension (Requirements)

Table 2: Requirements of the transfer function of the suspension system.

Transfer Function (*To* →, *From* ↓)	*Horizontal (m)*	*Vertical (m)*	*Pitch (rad)*
Horizontal (m)	$< \left(\frac{f_p}{f}\right)^2$ m/m $f_p = 0.74$ Hz (LOS1/2), 1.0 Hz (SOS)	Trivial	$< \alpha \times \left(\frac{f_p}{f}\right)^2$ rad/m $\alpha = 100$ (LOS1/2), 30 (SOS)
Vertical (m)	$< 3\times10^{-5} \times \left(\frac{f_v}{f}\right)^2$ m/m	$< \left(\frac{f_v}{f}\right)^2$ m/m $f_v = 13$ Hz (LOS1/2), 16 Hz (SOS)	$< b \times \left(\frac{f_v}{f}\right)^2$ rad/m $\beta = 3 \times 10^{-2}$ (LOS1/2), 1×10^{-2} (SOS)

Resonance of Suspension Support Structure

- Top level requirements
  - ››Seismic noise must meet 10% of SRD above 40 Hz
- Derivation
  - ››Best we can obtain with practical design
  - ››Impose stack isolation requirement on SEI

Table 3: Requirements for resonances of the suspension support structure.

Mode	*LOS1/LOS2*	*SOS*
Resonance Frequency	> 160 Hz	> 150 Hz
Q	< 300	< 300

Mechanical Loss (Top Level Requirements & Type)

- Top level requirements
  - ››Thermal noise must meet SRD (LOS1)
  - ››Thermal noise must meet FN (SOS)
- Type of Mechanical Loss
  - ››structural loss of the suspension pendulum, pitch/yaw, and vertical mode
  - ››structural loss of the mass internal mode due to the suspension attachments
    - —Question: Are they really structural loss?
  - ››Eddy current loss of the suspension pendulum mode due to interaction between the suspension attachments and the external components.

Mechanical Loss (Allocation)

Table 4: Allocation of mechanical loss of the suspension system.

Loss Type		*Allocation (in amplitude)*	
Damping Mechanism	*Mode*	*LOS1*	*SOS*
Structural (Loss: frequency independent)	Internal Mirror	< SRD	< 70% of FN
	Pendulum	< 10% of SRD	< 20% of FN
	Pitch/Yaw	< 10% of SRD	< 20% of FN / < 10% of FN
	Vertical	< 10% of SRD	< 10% of FN
Eddy Current (Loss: linear to frequency)	Pendulum	< 20% of SRD	< 70% of FN

Mechanical Loss (Derivation)

- Internal Mechanical Loss
  - ››Method used in Gillespie & Raab's paper
  - ››Adjusted to 1.06 μm
- Pendulum, Pitch/Yaw, Vertical, and Viscous Loss
  - ››General Equation:

$$\tilde{x}^2(f) = \frac{4k_BT}{M} \cdot \frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2 - \omega^2)^2 - \omega_0^4\varphi^2(f)]}$$

  - ››Misalignment of 3×10^{-4} (LOS1/LOS2 & SOS)
  - ››Beam spot offset of 1 mm (LOS1/LOS2) and 3 mm (SOS)
  - ››Half breaking strength load

Mechanical Loss (Requirements)

Table 5: Requirements of mechanical loss of the suspension system.

Loss Type		*Loss*	
Damping Mechanism	*Mode*	*LOS1*	*SOS*
Structural (Loss: frequency independent)	Internal Mirror	$< 4\times10^{-7}$	$< 1\times10^{-5}$
	Pendulum	$< 7\times10^{-6}$	$< 5\times10^{-6}$
	Pitch/Yaw	$< 5\times10^{-4}$ / $< 8\times10^{-4}$	$< 3\times10^{-4}$ / $< 9\times10^{-5}$
	Vertical	$< 3\times10^{-3}$	$< 7\times10^{-2}$
Eddy Current (Loss: linear to frequency)	Pendulum	$< 8\times10^{-7}$ at 100 Hz $< 6\times10^{-9}$ at 0.74 Hz	$< 6 \times 10^{-5}$ at 100 Hz $< 6 \times 10^{-7}$ at 1 Hz

Control Noise
(Top Level Requirements & Derivation)

- Top level requirements and derivation
  - ›› LOS1/LOS2: 10% of SRD
  - ›› SOS: 10% of FN

Control Noise (Requirements)

Table 6: Requirements of the control noise per mass.

Mode	*Control Noise*	
	LOS1/LOS2	*SOS*
Displacement	$< 5 \times 10^{-20} \times \left(\frac{40\text{Hz}}{f}\right)^2 \text{m}/\sqrt{\text{Hz}}$	$< 2 \times 10^{-19} \times \left(\frac{100\text{Hz}}{f}\right)^2 \text{m}/\sqrt{\text{Hz}}$ (f < 100 Hz) $< 2 \times 10^{-19} \times \left(\frac{100\text{Hz}}{f}\right)^{0.5} \text{m}/\sqrt{\text{Hz}}$ (f > 100 Hz)
Pitch/Yaw	$< 2 \times 10^{-17} \times \left(\frac{40\text{Hz}}{f}\right)^2 \text{rad}/\sqrt{\text{Hz}}$	$< 6 \times 10^{-17} \times \left(\frac{100\text{Hz}}{f}\right)^2 \text{rad}/\sqrt{\text{Hz}}$ (f < 100 Hz) $< 6 \times 10^{-17} \times \left(\frac{100\text{Hz}}{f}\right)^{0.5} \text{rad}/\sqrt{\text{Hz}}$ (f > 100 Hz)

Other Noise Sources

- Stray light shield
  - ››TBD
- Excess noise
  - ››TBD
- Noise from external AC magnetic field
  - ››TBD

Size Constraints (Optics)

Table 7: Size and optical clear aperture of suspended components.

Physical Quantity	*LOS1*	*LOS2*	*SOS*
Diameter of Suspended Component	25 cm	25 cm / 28cm **TBD**	7.62 cm
Thickness of Suspended Component	10 cm	4 cm / 6cm **TBD**	2.54 cm
Weight of Suspended Component	10.7kg	4.3 kg / 8.1 kg **TBD**	0.25 kg
Required Optical Clear Aperture	24 cm (Fore) 19 cm (Back)	11 cm **TBD**	2 cm
Wedge Angle of Suspended Component	Maximum 3° Vertical **TBD**	Maximum 3° Vertical **TBD**	**TBD**

Size Constraints (Beam Height)

Table 8: Beam height for chambers.

Physical Quantity	*BSC Chamber*		*HAM Chamber*
	Test Mass	*Beamsplitter*	
Beam Height	**TBD**	**TBD**	**TBD**

2. Preliminary Mechanical Design

- Introduction
- Design overview
- Detailed description of each component
- Fixtures
- Installation

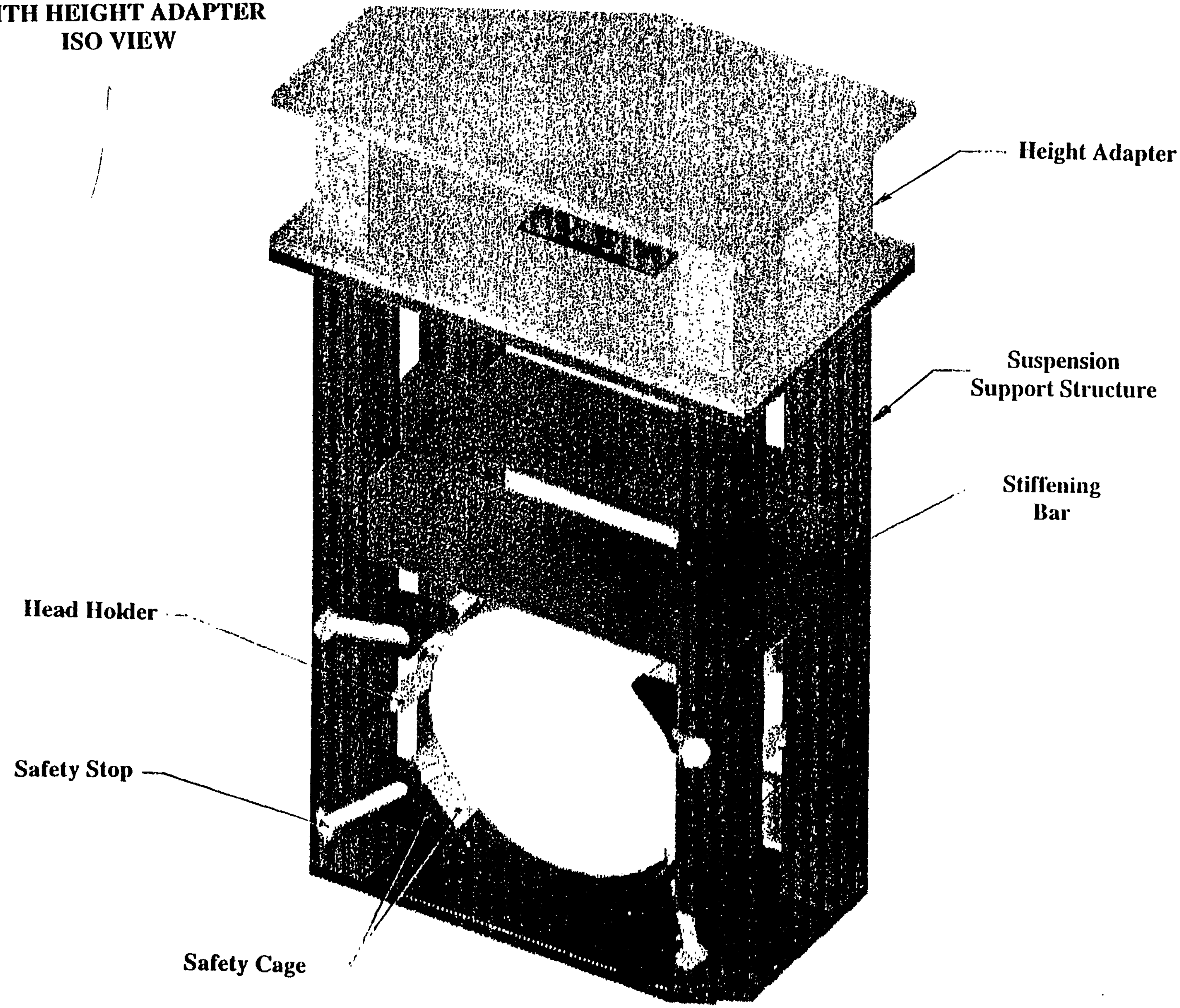
Design Philosophy

- Meet Requirements
- Reliability
- Simplicity
- Tractability
- Safety
- As little excess noise as possible

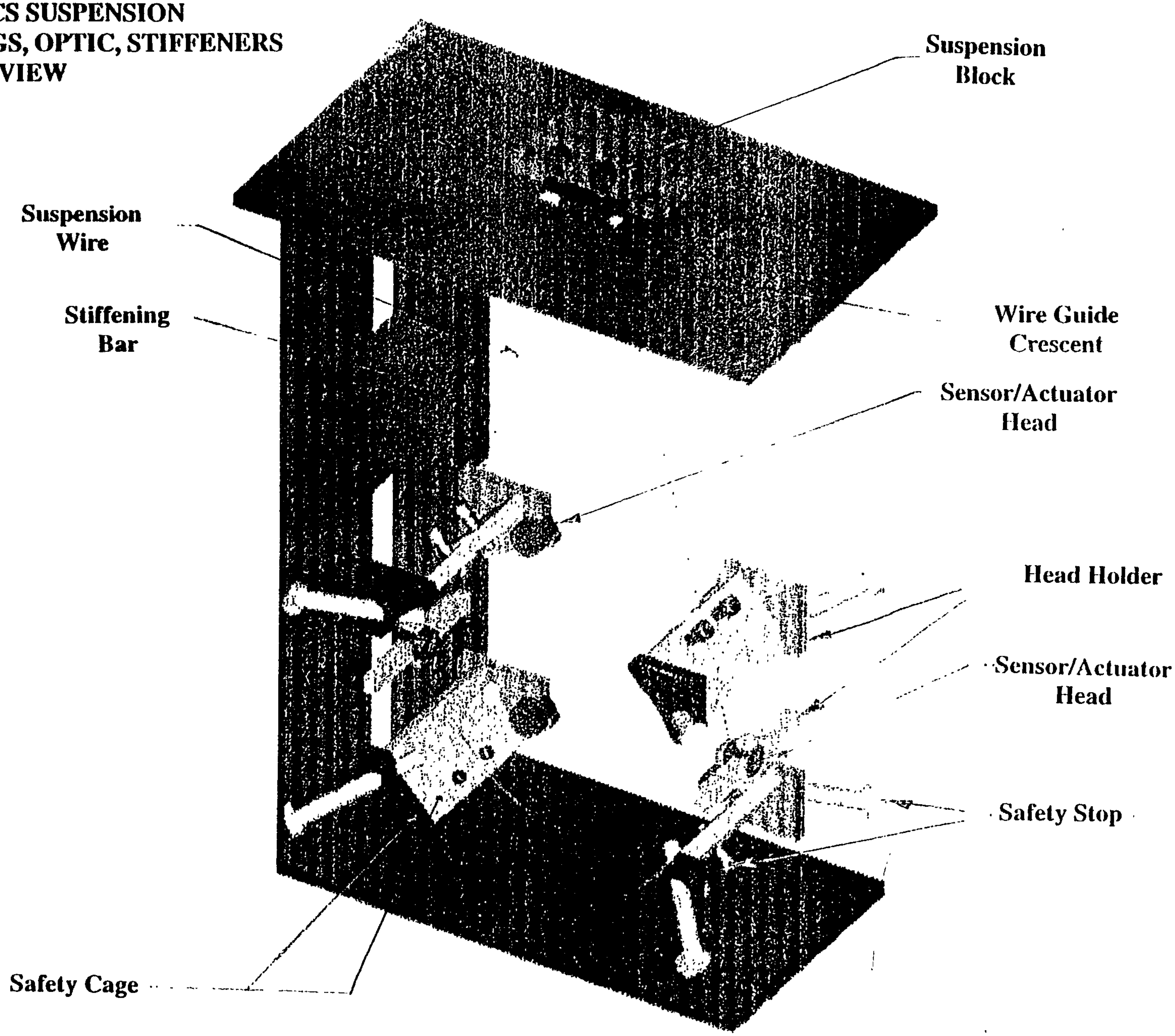
Design Type

- Design for LOS1 and SOS
  - Assumed wedge angle: 3° vertical thick side up (LOS1)
0° (SOS)
- LOS2: Similar to LOS1 except size TBD

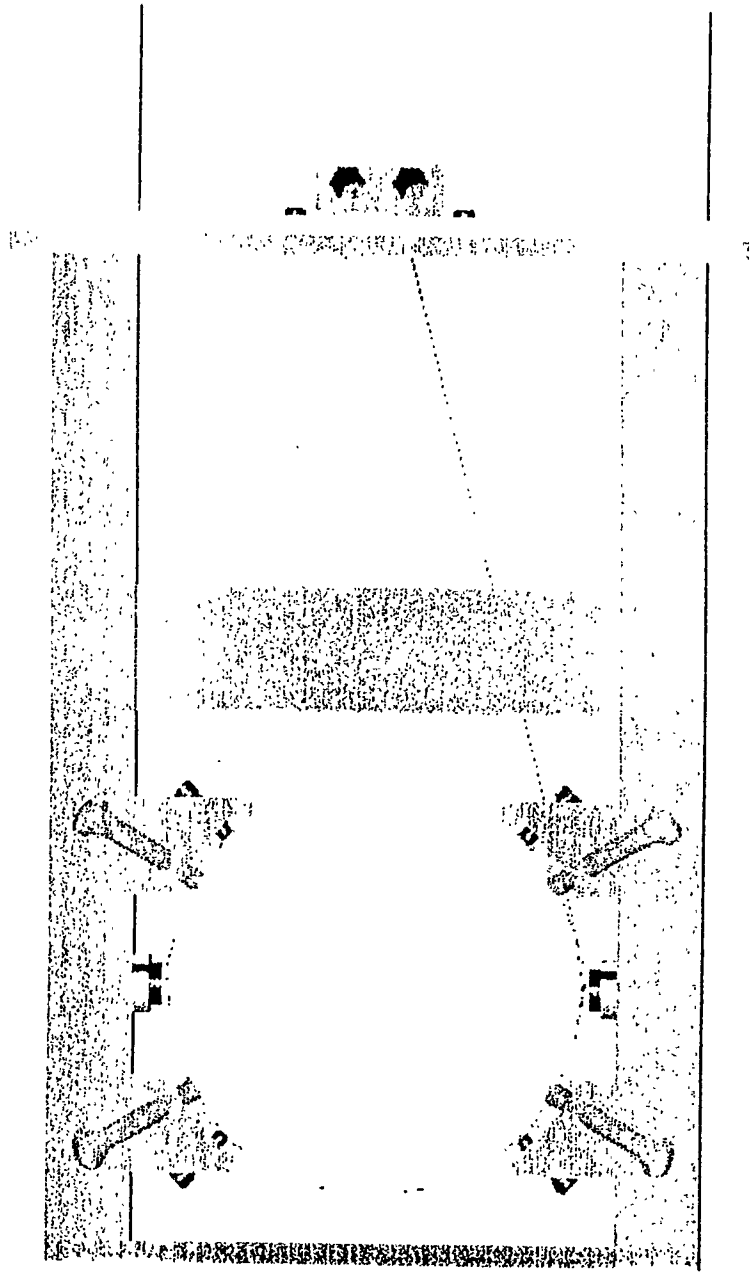
LARGE OPTIC SUSPENSION WITH HEIGHT ADAPTER ISO VIEW



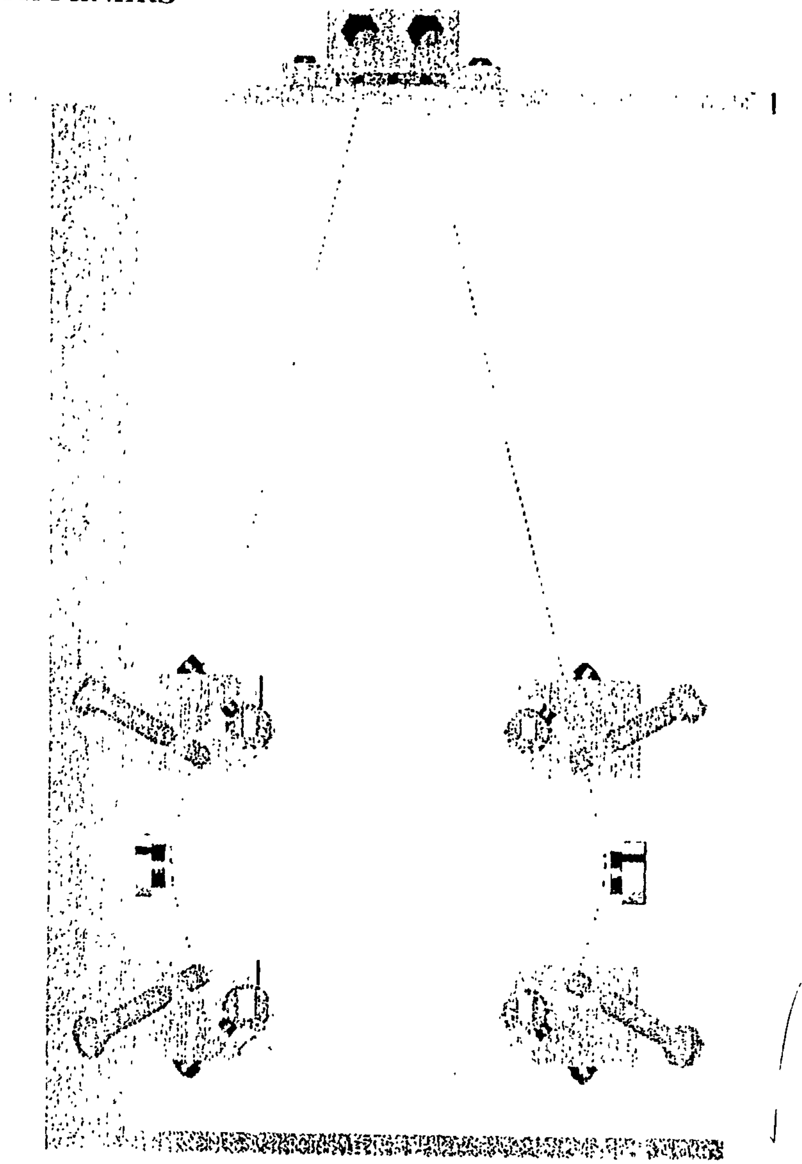
LARGE OPTICS SUSPENSION
WITHOUT RIGHT LEGS, OPTIC, STIFFENERS
ISO VIEW



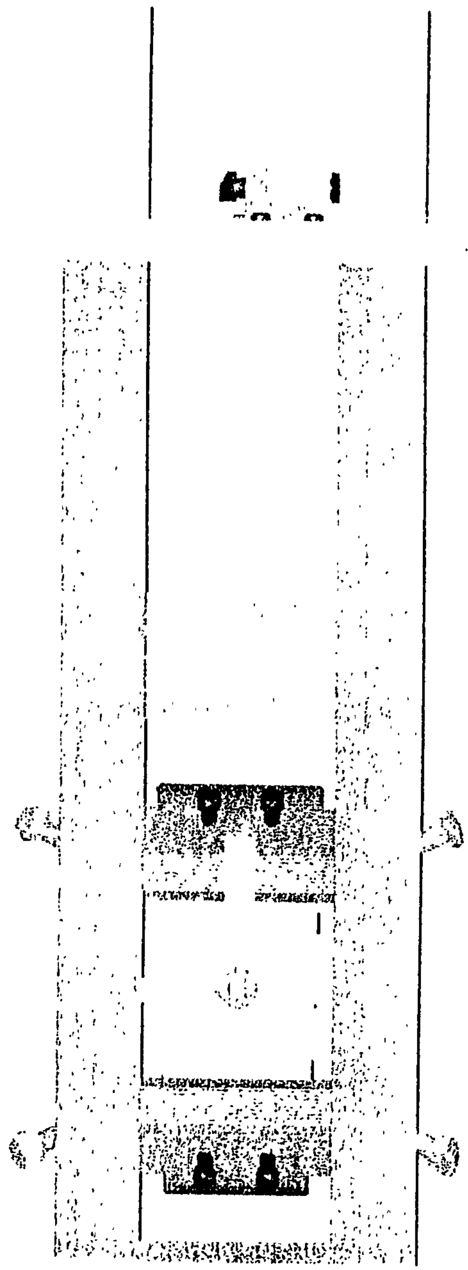
LARGE OPTIC SUSPENSION WITH HEIGHT ADAPTER FRONT VIEW



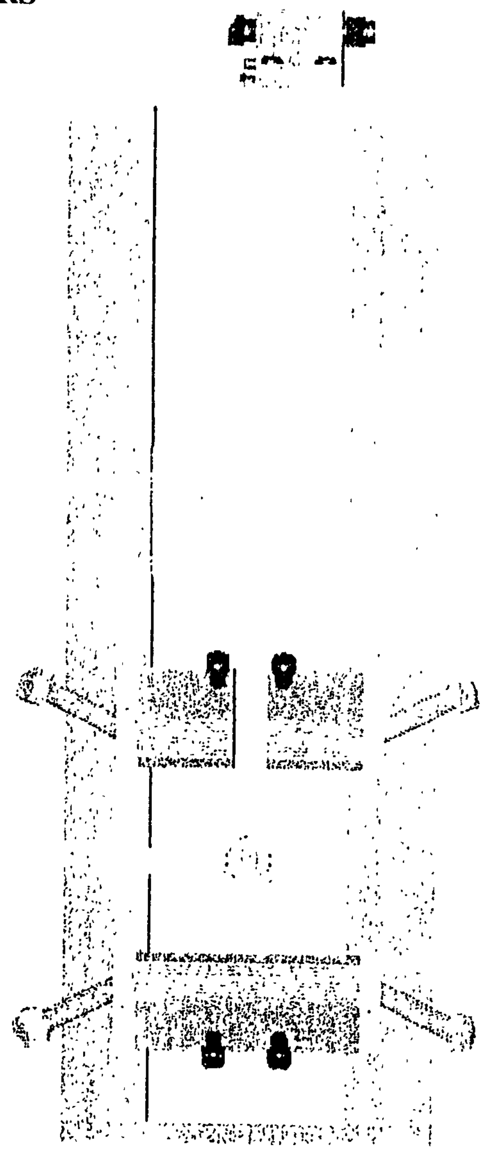
LARGE OPTICS SUSPENSION
WITHOUT RIGHT LEGS, OPTIC, STIFFENERS
FRONT VIEW



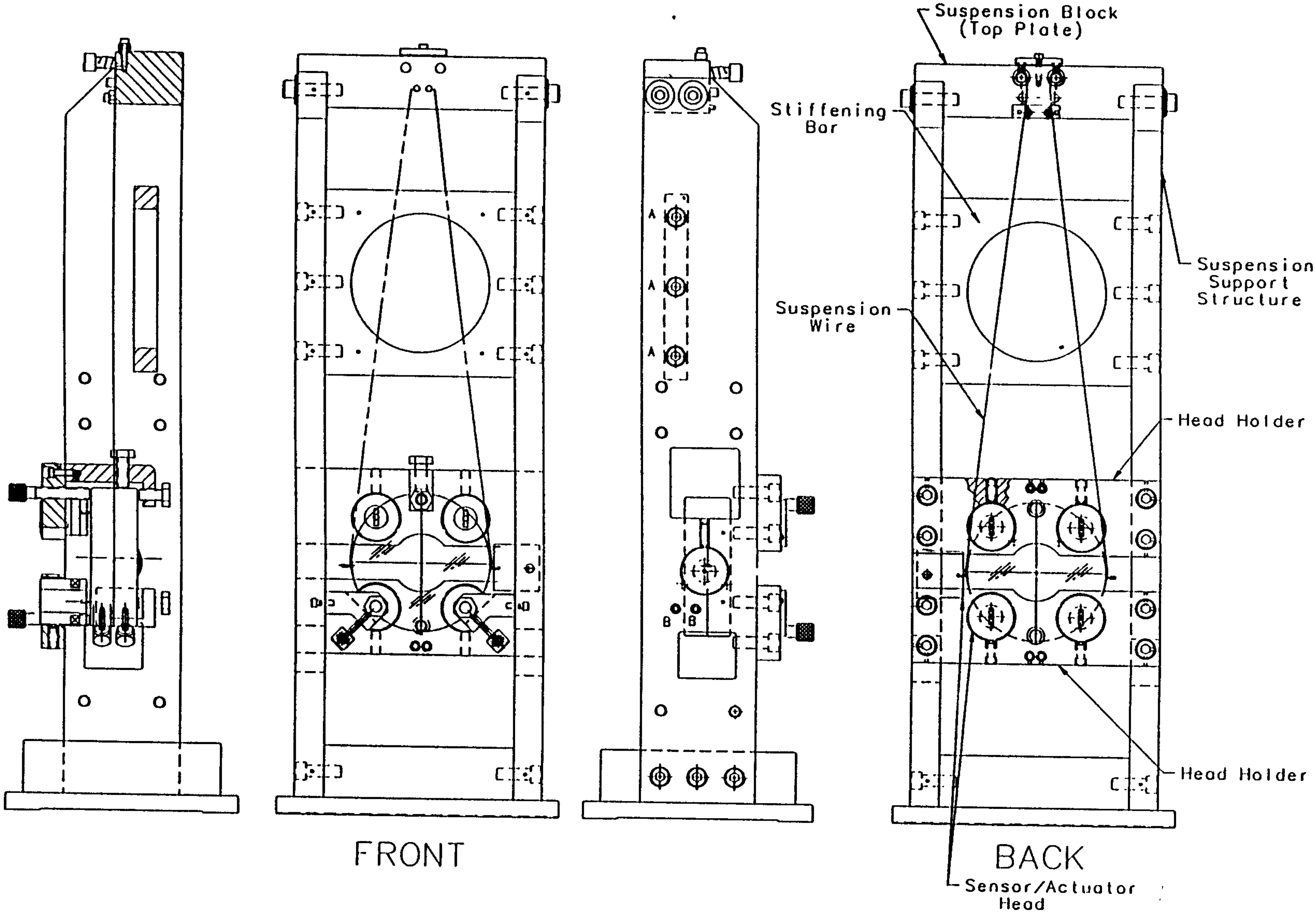
LARGE OPTIC SUSPENSION WITH HEIGHT ADAPTER SIDE VIEW



LARGE OPTICS SUSPENSION
WITHOUT RIGHT LEGS, OPTIC, STIFFENERS
SIDE VIEW



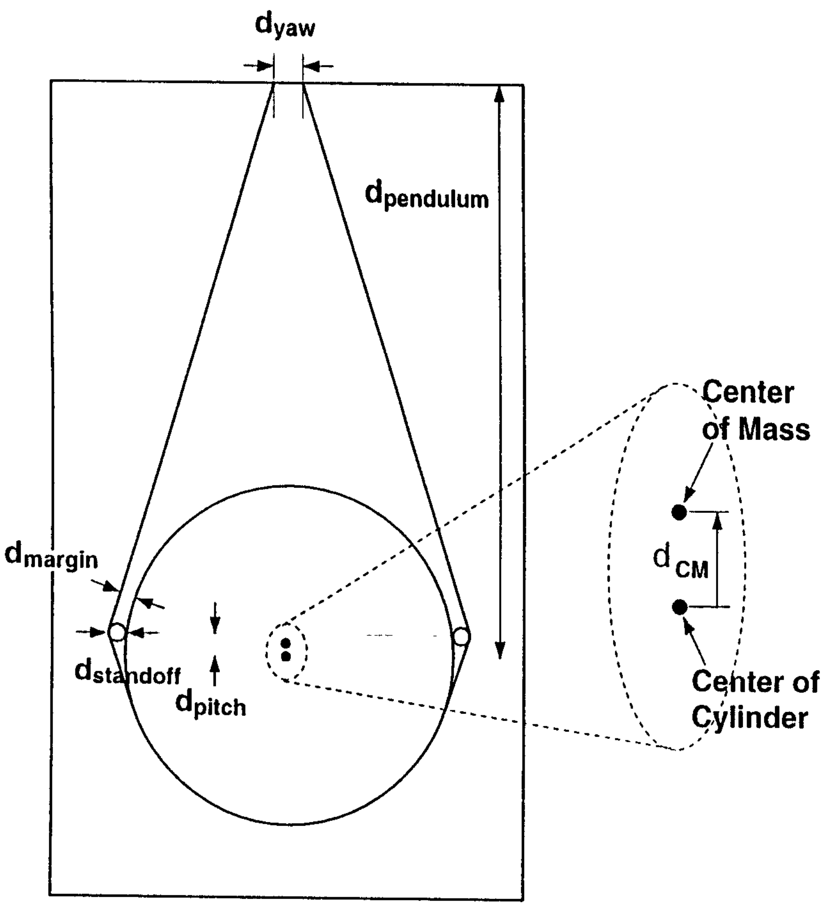
SMALL OPTIC SUSPENSION



DESIGN OVERVIEW

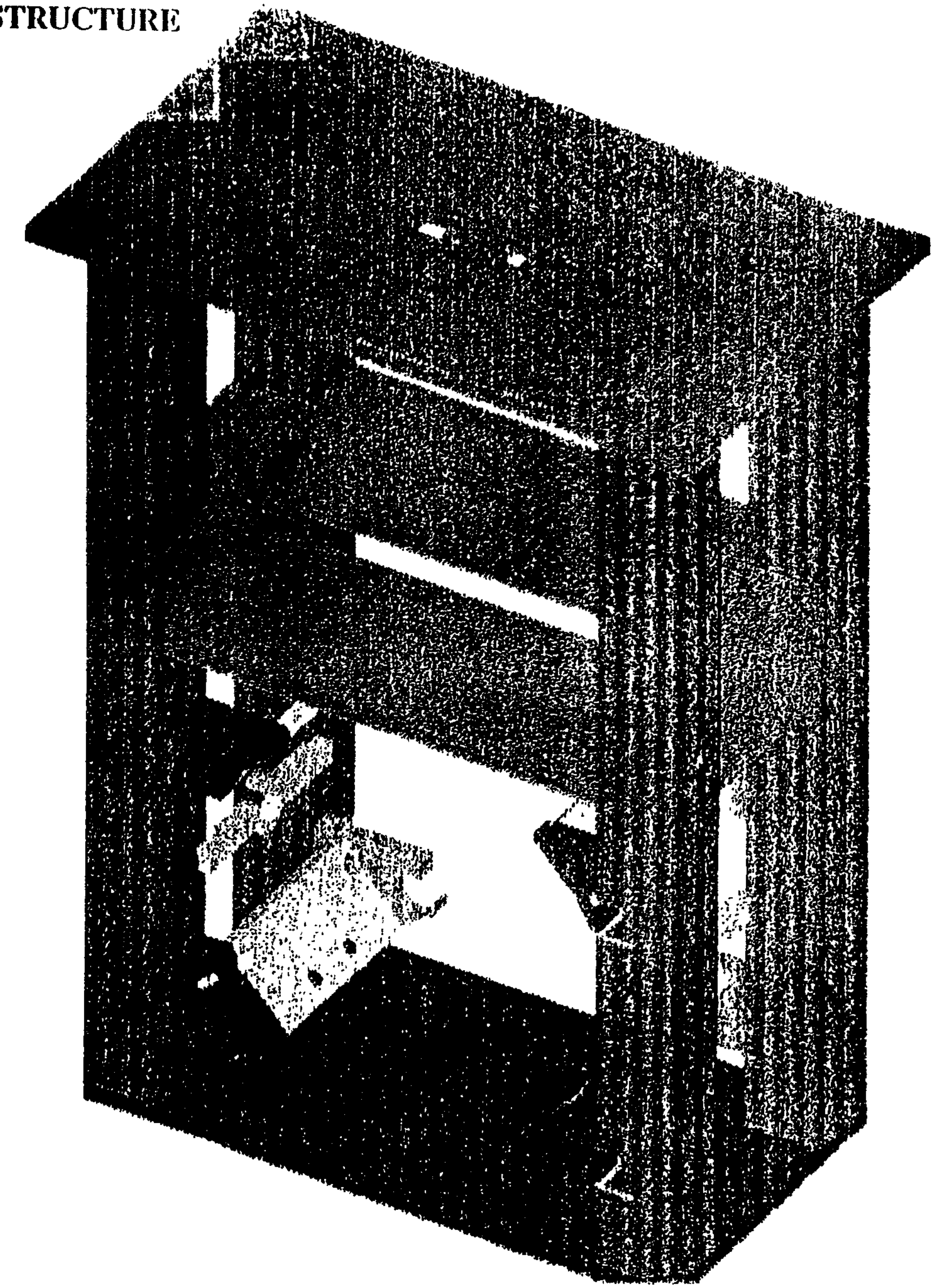
- The suspension assembly is held together by a suspension support structure.
- The optical component is suspended by a single loop of wire from a suspension block (and a wire guide crescent for LOS1) with wire stand-offs and guide rods between the suspension wire and the component.
- The optical component is damped and actuated by sensor/actuator heads and magnet/standoff assemblies.
- The optical component is protected during operation or held during transfer by a safety cage and safety stops.
- The suspension support structure is strengthened by stiffening bars to increase its resonance frequencies.

SUSPENSION CONFIGURATION

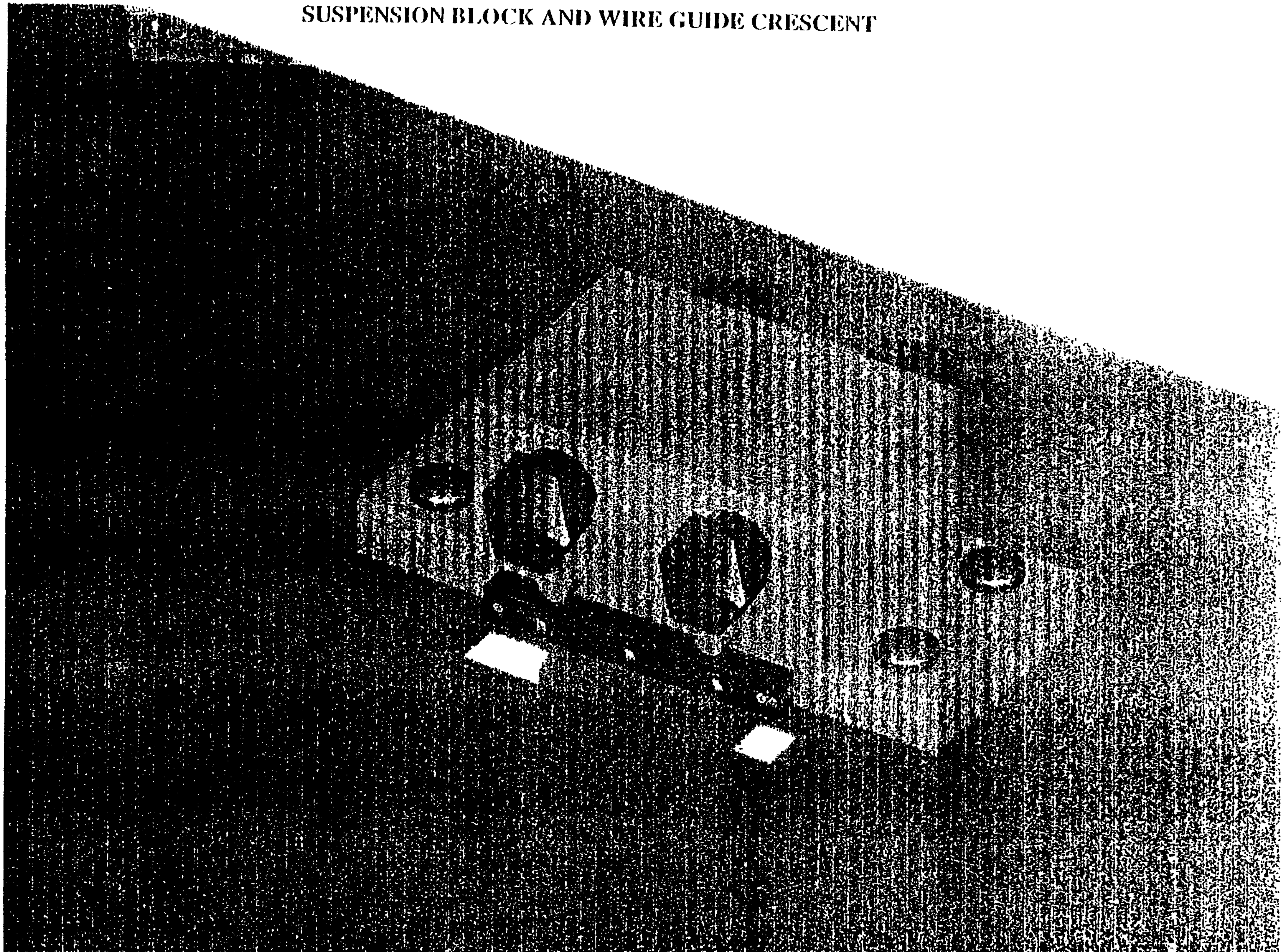


Physical Quantity	*Specification*	
	LOS 1 (TM)	*SOS (MC mirror)*
Pendulum Frequency	0.74 Hz	1.0 Hz
Pitch Frequency	0.6 Hz	0.85 Hz
Yaw Frequency	0.5 Hz	0.75 Hz
$d_{pendulum}$	45 cm	24.8 cm
d_{CM}	2.0 mm	0 mm
d_{pitch}	8.9 mm	0.9 mm
d_{yaw}	33.5 mm	15.7 mm
$d_{standoff}$	2.8 mmD	1.0 mmD
d_{margin}	1.1 mm	0.8 mm

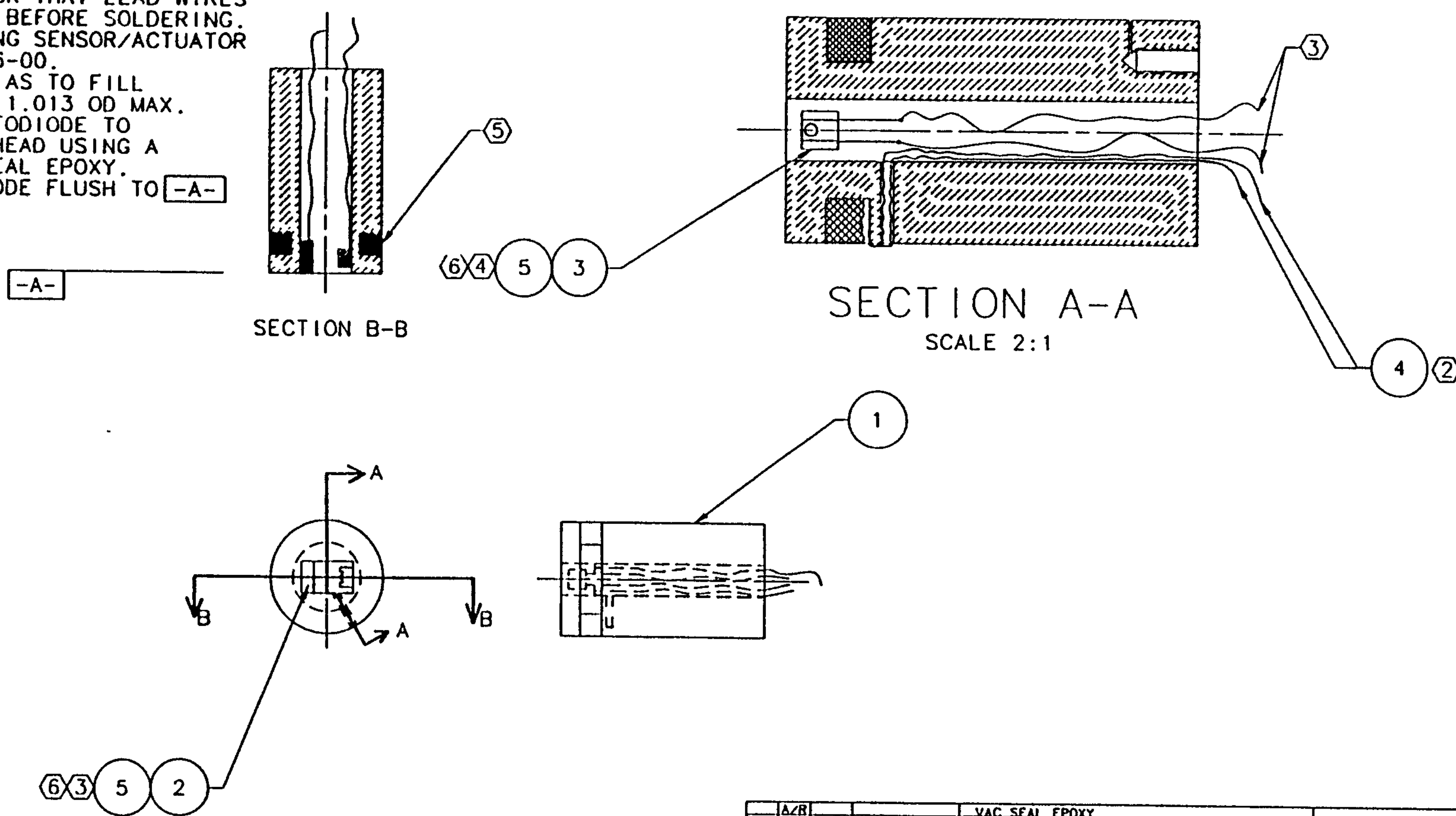
SUSPENSION SUPPORT STRUCTURE



SUSPENSION BLOCK AND WIRE GUIDE CRESCENT



NOTES, UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES.
2. LABEL BEGINNING AND END OF COIL.
3. SOLDER WIRES TO LED AND PHOTODIODE LEAD WIRES. CHECK THAT LEAD WIRES ARE NON-MAGNETIC BEFORE SOLDERING.
4. POSITION LED USING SENSOR/ACTUATOR TOOL, P/N D950126-00.
5. WIND MAGNET WIRE AS TO FILL VOLUME AS SHOWN, 1.013 OD MAX.
6. BOND LED AND PHOTODIODE TO SENSOR ACTUATOR HEAD USING A MINIMUM OF VAC SEAL EPOXY. POSITION PHOTODIODE FLUSH TO -A-



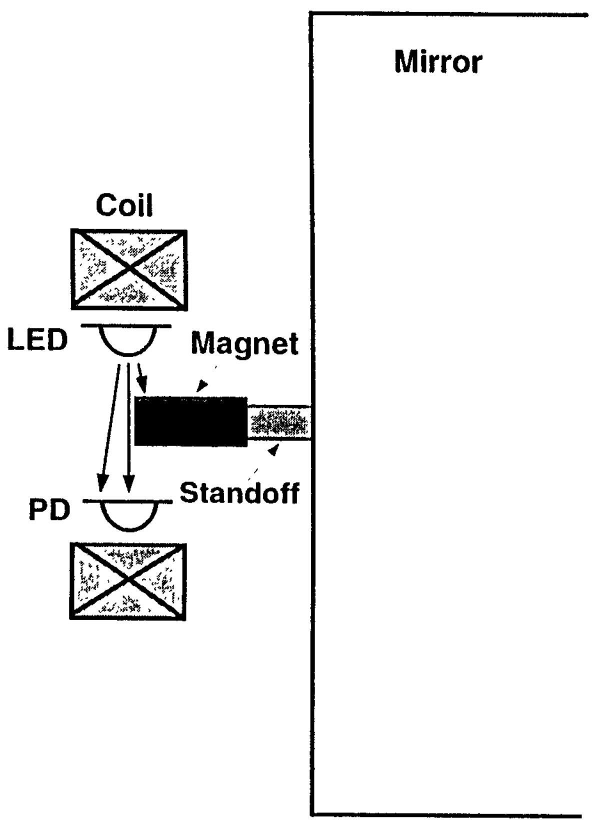
NOT TO SCALE

QTY REQD	FSCM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO
A/R			VAC SEAL EPOXY		5
A/R		EY-5456-1	WIRE, MWS INDUSTRIES P/N		4
1		TLN107A	LED, TOSHIBA P/N		3
1		TPS703A	PHOTODIODE, TOSHIBA P/N		2
1		D960012	SENSOR/ACTUATOR HEAD		1

PARTS LIST

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN IN (mm) TOLERANCES ARE: FRACTIONS DECIMALS N/A DO NOT SCALE DRAWING	APPROVALS: DRAWN J. Hazel; CHECKED	DATE 1/96	LIGO CALIFORNIA INSTITUTE OF TECHNOLOGY MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MATERIAL N/A			TITLE SENSOR/ACTUATOR HEAD ASSEMBLY
FINISH N/A			SIZE B · DWG NO. D960011 · REV 00
SCALE NONE	FILENAME ~janeen/D960011.asc		SHEET 1 OF 1

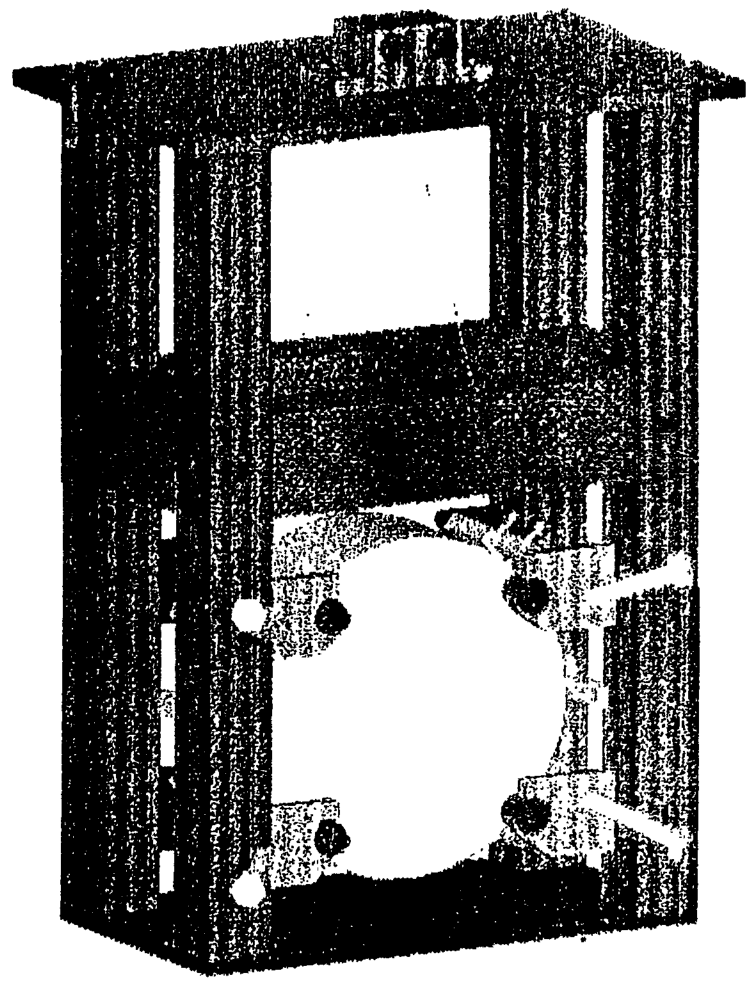
MAGNET/STANDOFF ASSEMBLY

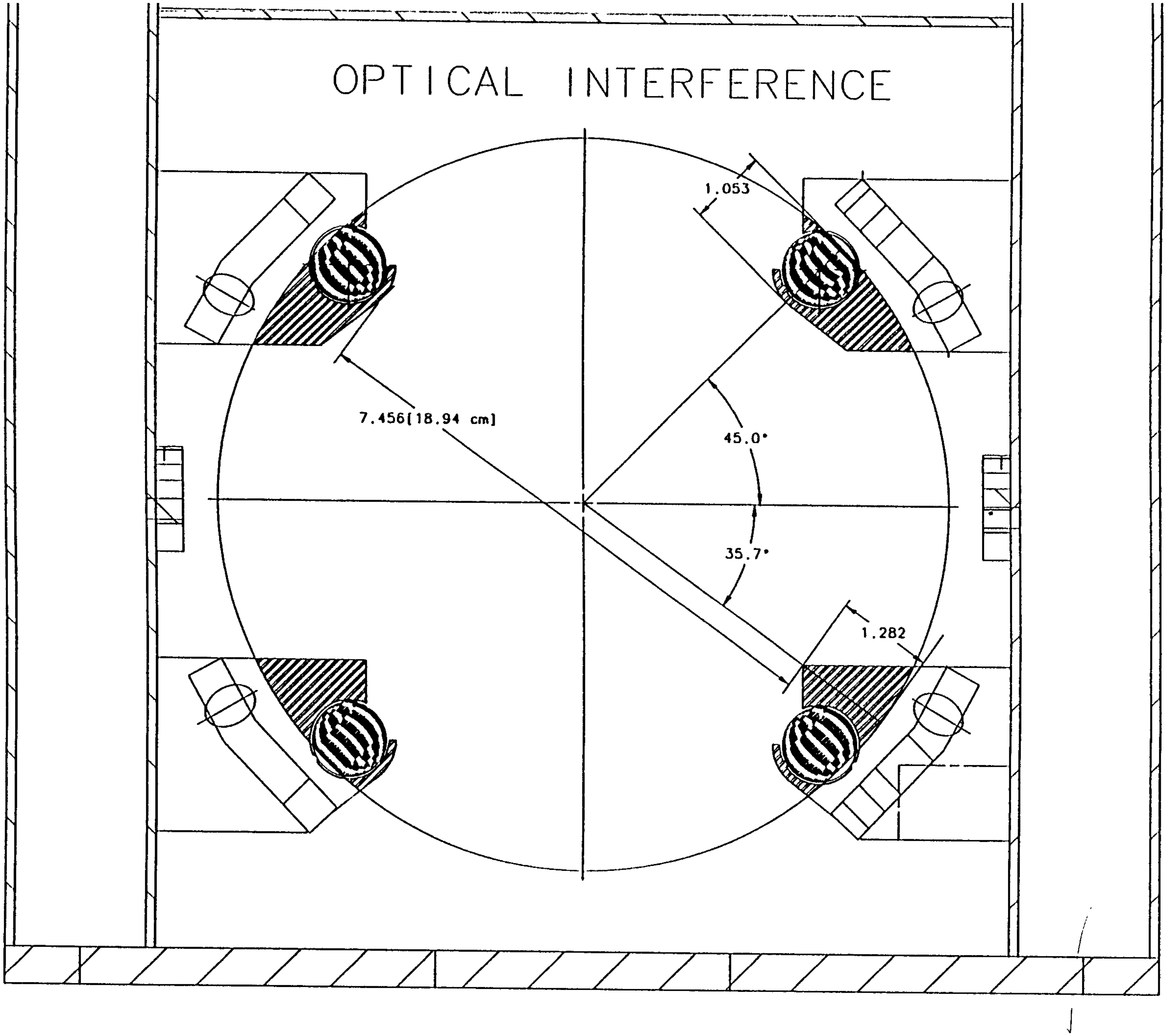


- Magnet
  - Material: Nd:Fe:B (NEO-35, Curie temp 337 degrees C)
  - Dimensions: 1.9 mmD x 3.2 mmL [0.075"D x 0.125"L]
- Standoff
  - Material: aluminum
  - Dimensions: 1.0 mmD x 2.0 mmL [0.04"D x 0.08"L] except for side standoff on LOS1: 1.0 mmD x 3.2 mmL [0.04"D x 0.13"L]

LARGE OPTIC SUSPENSION

BACK VIEW



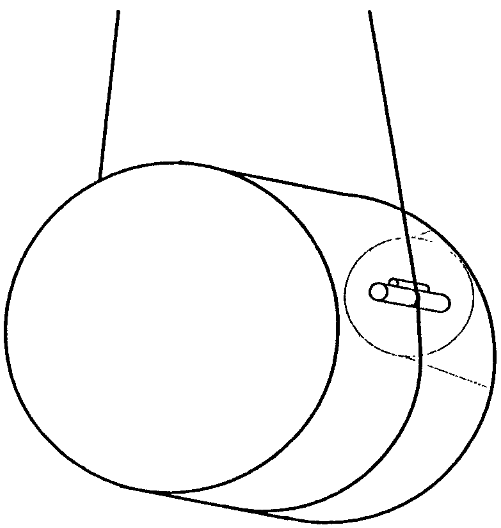


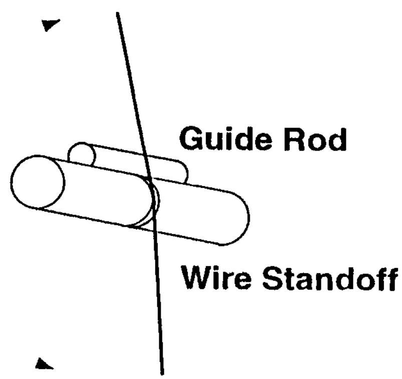
OPTICAL INTERFERENCE
1.053
7.456[18.94 cm]
45.0°
35.7°
1.282

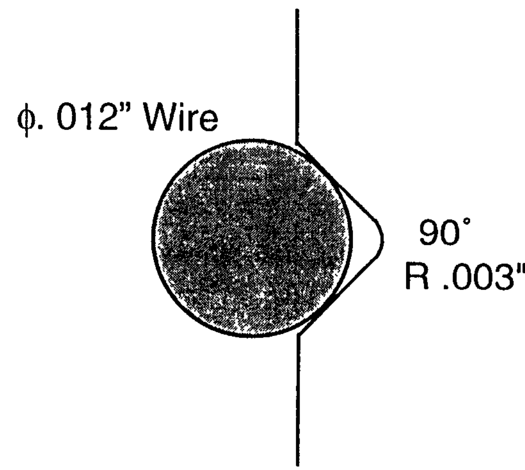
SUSPENSION FIBER

- Type: Steel music wire
- Density: 7.8 g/cm^3
- Diameter: 0.044 mm for SOS
  0.31 mm for LOS1
- Ultimate Tensile Strength: 0.5 kg for SOS
  21.4 kg for LOS1
- Yield Strength: 75% of Ultimate Tensile Strength
- Violin Mode Frequency: 660 Hz for SOS
  340 Hz for LOS1
- Vertical Frequency: 16 Hz for SOS
  13 Hz for LOS1

WIRE STANDOFF AND GUIDE ROD





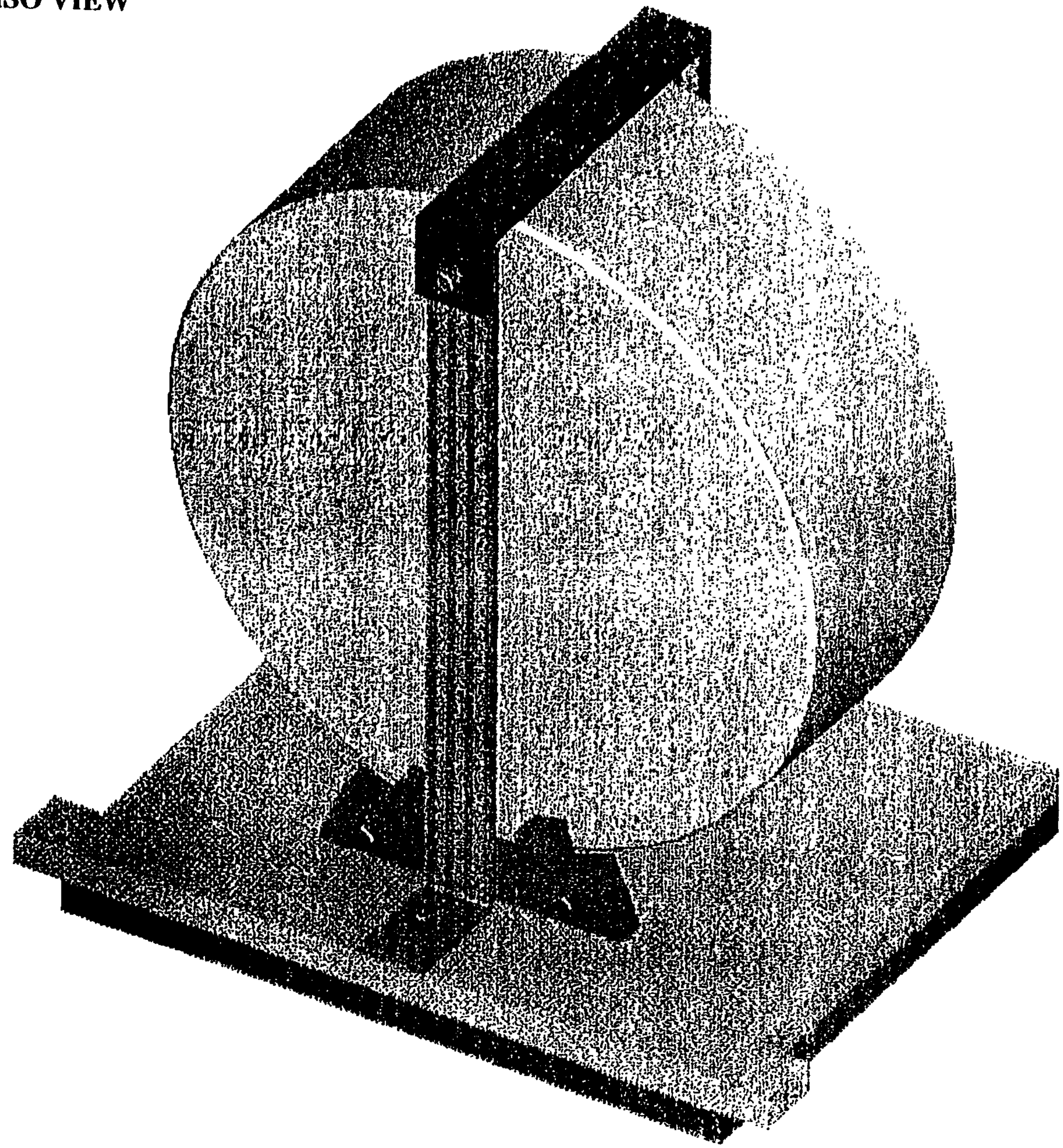


SAFETY CAGE AND SAFETY STOPS (VIEWGRAPH 29 AND 30)

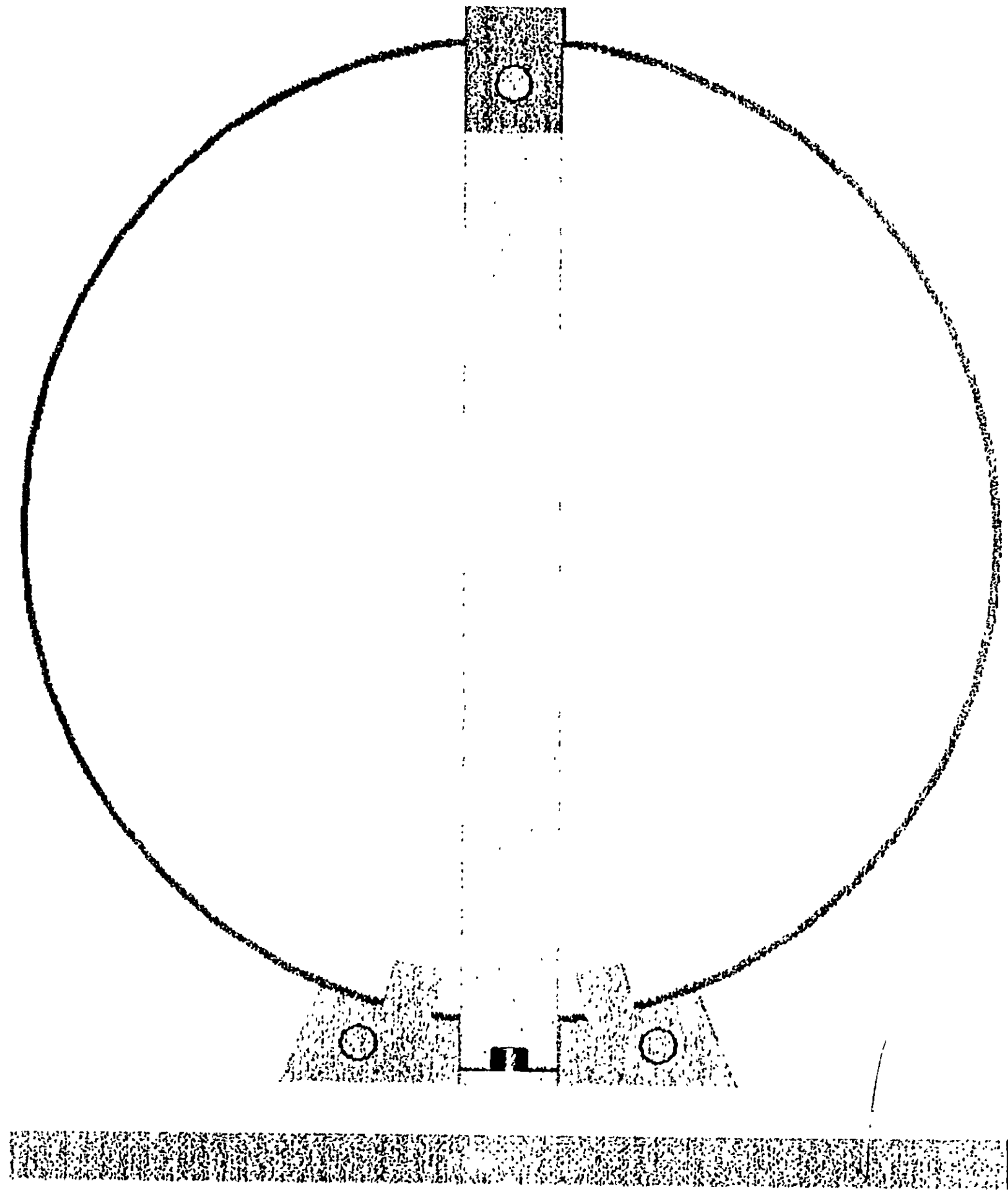
Excess Noise Treatment (per V. Braginsky Concept)

- Bolts eliminated from LOS1 suspension support structure
  - »Structure to be welded and annealed.
- Bolts or clamps needed to attach height adapter to suspension structure and to optics platform.
  - »Cone-anticone method: NOT adopted because of concerns with wobbling, adjustments and excess cost.
  - »Alternative: suspending LOS1 suspension assembly from optics platform using cone-anticone connection at the lower end and bolts at upper end.
- Wire positioned by wire guide crescent
  - »Cone-anticone method: NOT adopted because of above concerns.
  - »Alternative: remove suspension block and clamp and attach wire to itself or to the wire guide crescent using adhesive or solder.
- Conventional wire standoff
  - »Parallel line contact but wire is close to plastic deformation
  - »Alternative: redesign wire standoff and/or wire to provide area contact.

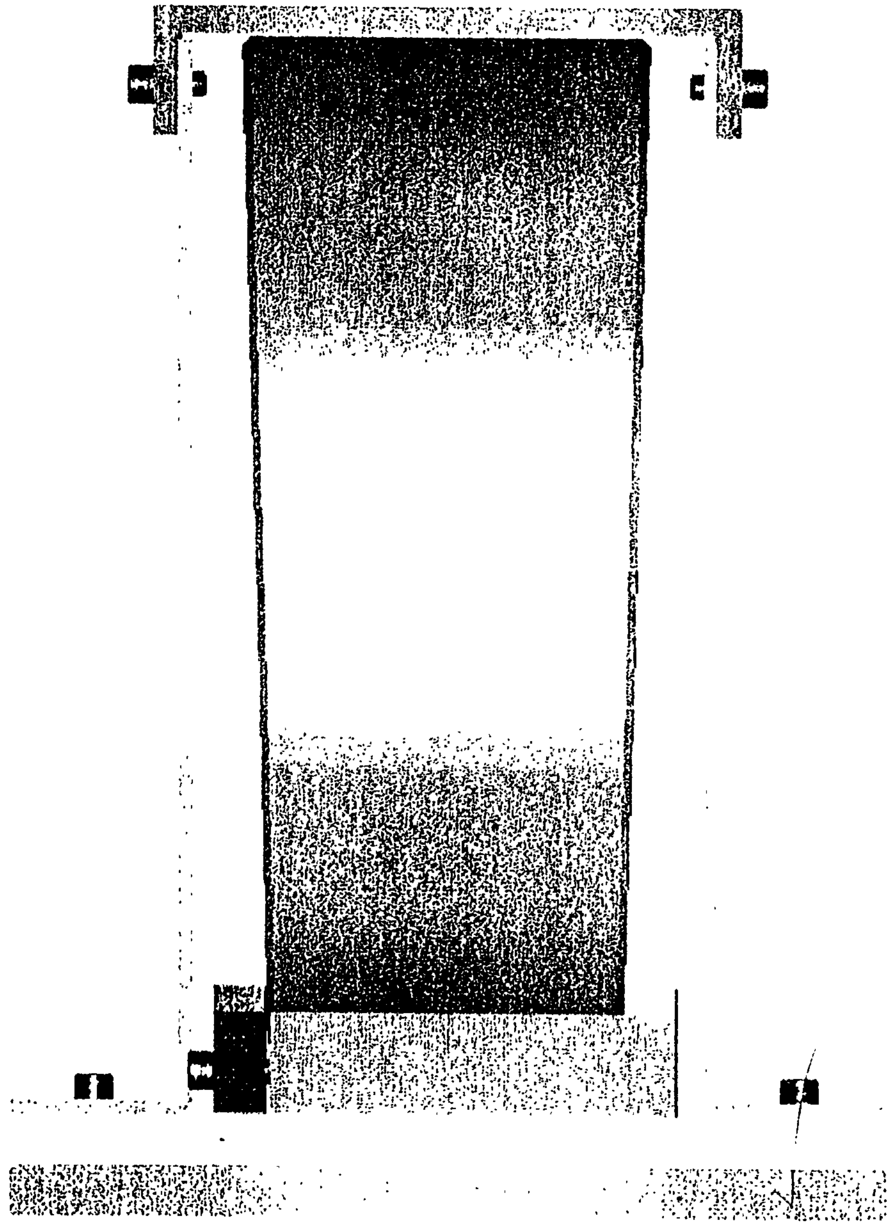
WIRE AND OPTICS FIXTURE
ISO VIEW



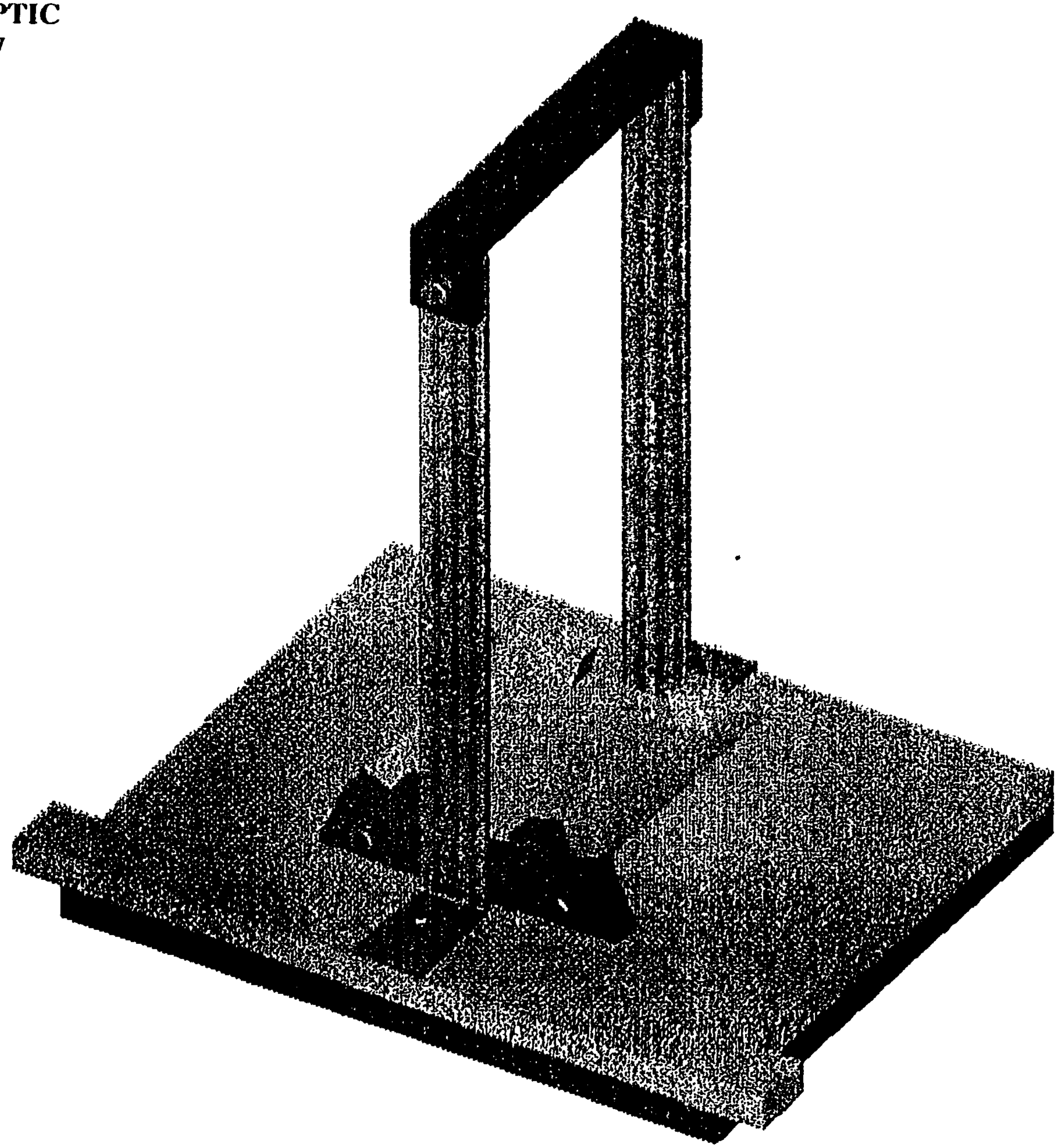
WIRE AND OPTICS FIXTURE
FRONT VIEW

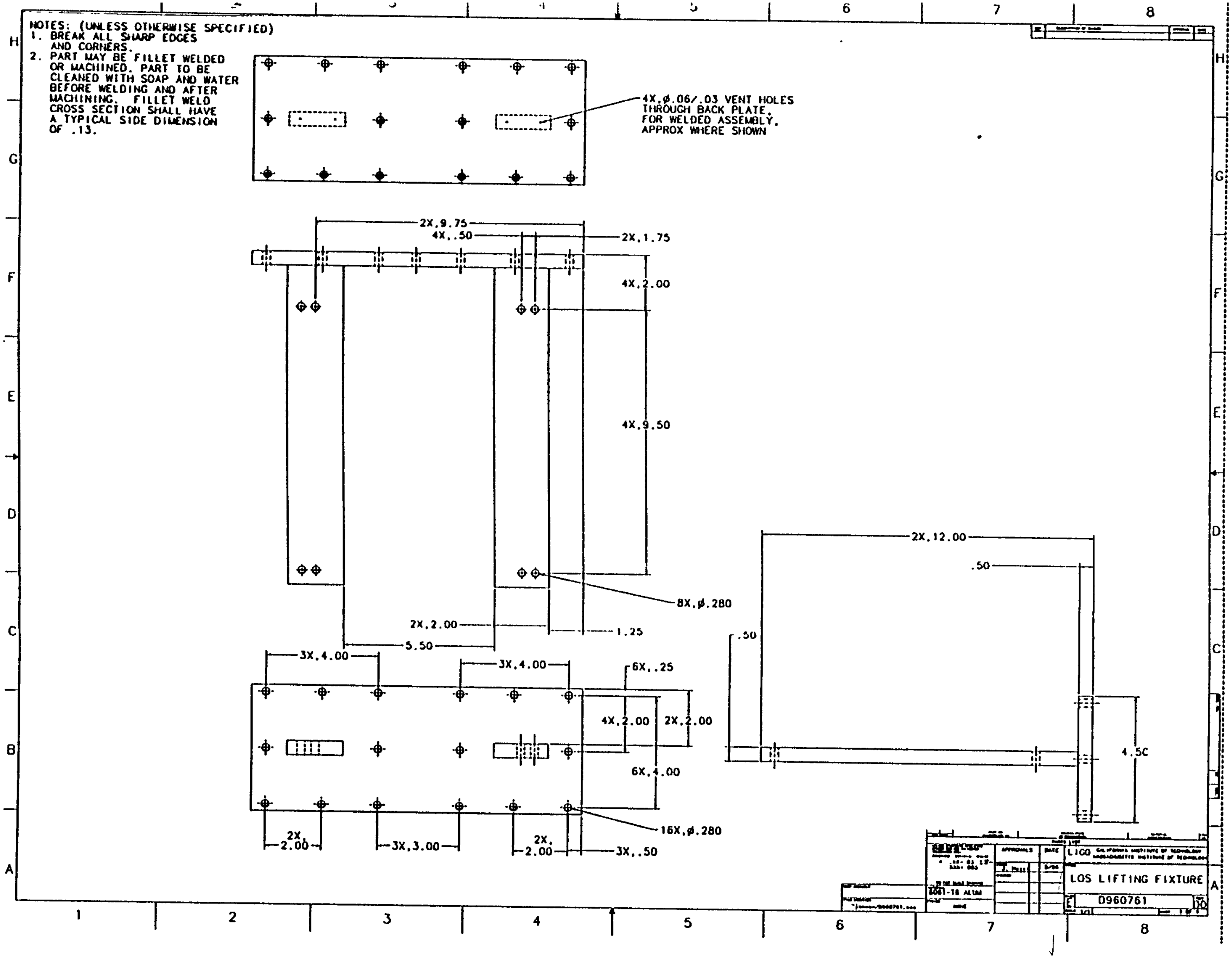


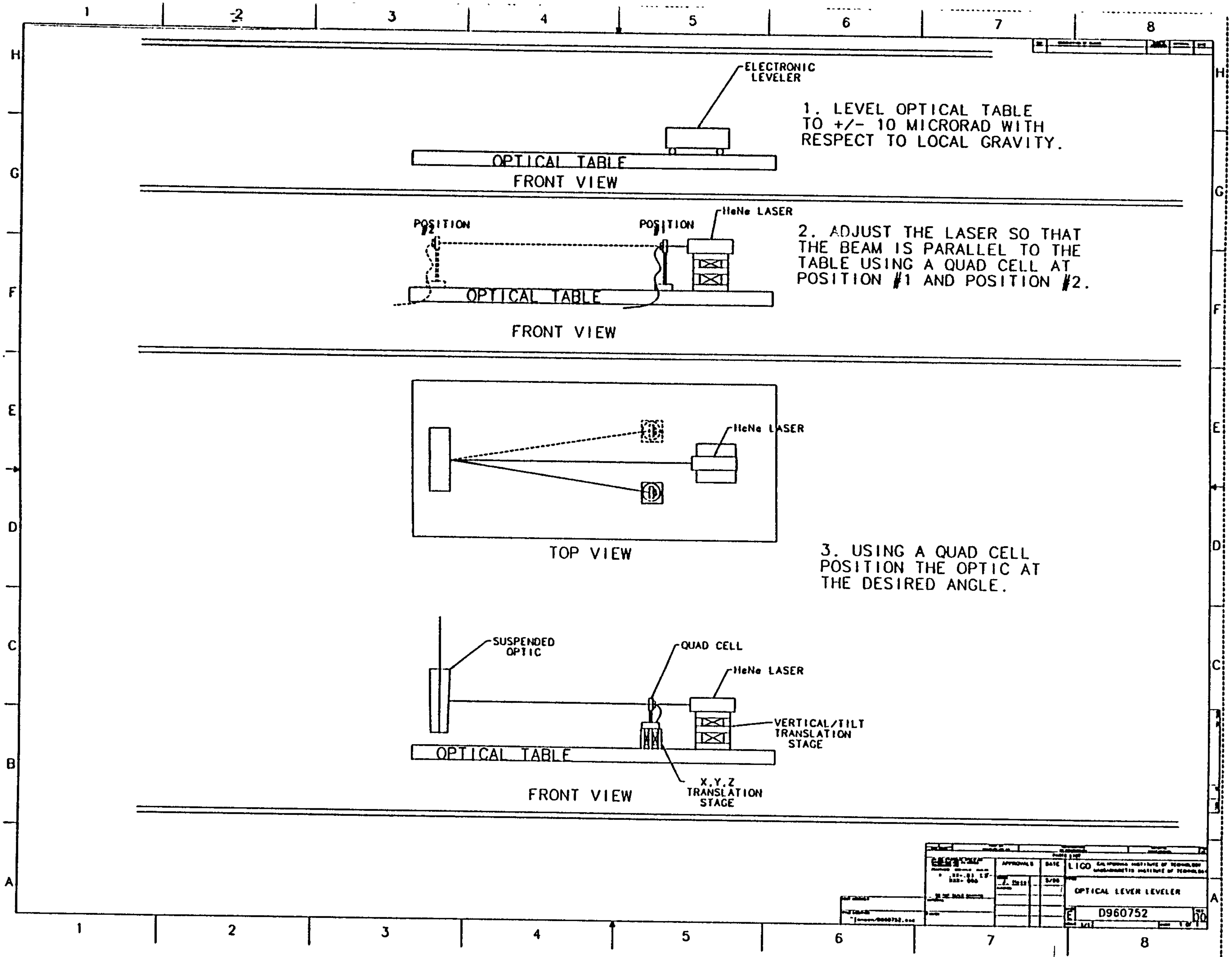
WIRE AND OPTICS FIXTURE
SIDE VIEW



WIRE AND OPTICS FIXTURE
WITHOUT OPTIC
ISO VIEW




NOTES: (UNLESS OTHERWISE SPECIFIED)
1. BREAK ALL SHARP EDGES AND CORNERS.
2. PART MAY BE FILLET WELDED OR MACHINED. PART TO BE CLEANED WITH SOAP AND WATER BEFORE WELDING AND AFTER MACHINING. FILLET WELD CROSS SECTION SHALL HAVE A TYPICAL SIDE DIMENSION OF .13.
4X,ø.06/.03 VENT HOLES THROUGH BACK PLATE, FOR WELDED ASSEMBLY, APPROX WHERE SHOWN
2X,9.75
4X,.50
2X,1.75
4X,2.00
4X,9.50
8X,ø.280
2X,2.00
1.25
5.50
3X,4.00
3X,4.00
6X,.25
4X,2.00
2X,2.00
6X,4.00
16X,ø.280
2X, 2.00
3X,3.00
2X, 2.00
3X,.50
2X,12.00
.50
.50
4.50
6061-T6 ALUM
LIGO
LOS LIFTING FIXTURE
D960761


ELECTRONIC LEVELER
1. LEVEL OPTICAL TABLE TO +/- 10 MICRORAD WITH RESPECT TO LOCAL GRAVITY.
OPTICAL TABLE
FRONT VIEW
POSITION #2
POSITION #1
HeNe LASER
2. ADJUST THE LASER SO THAT THE BEAM IS PARALLEL TO THE TABLE USING A QUAD CELL AT POSITION #1 AND POSITION #2.
OPTICAL TABLE
FRONT VIEW
HeNe LASER
TOP VIEW
3. USING A QUAD CELL POSITION THE OPTIC AT THE DESIRED ANGLE.
SUSPENDED OPTIC
QUAD CELL
HeNe LASER
VERTICAL/TILT TRANSLATION STAGE
OPTICAL TABLE
X,Y,Z TRANSLATION STAGE
FRONT VIEW
LIGO
OPTICAL LEVER LEVELER
D960752

CHANGES TO LOS1 FOR LOS2

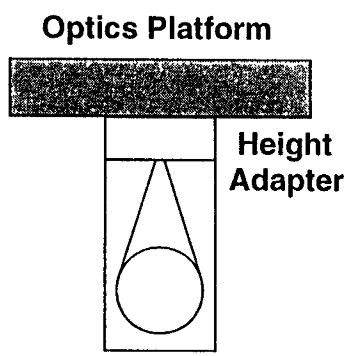
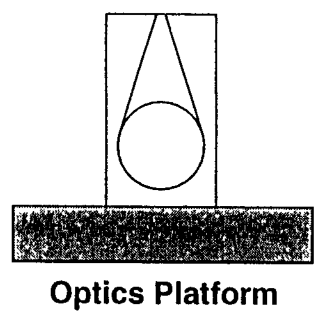
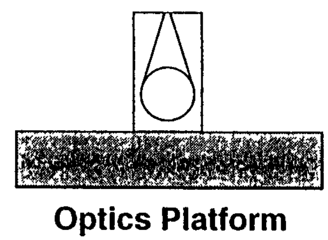
- Change Top Assembly Drawing
  - ›› New part number
- Change Structure Assembly Drawing
  - ›› New part number
  - ›› New bracket part numbers
  - ›› Define new welding positions for brackets
  - ›› Add new welding brackets
- Change LOS Bracket, Safety Stop, Top, Back
  - ›› New Part Number
  - ›› Reduce Length

LOS1 TO LOS2, CONT.

- Change LOS Bracket, Safety Stop, Top Front
  - New Part Number
  - Reduce Length
- Change LOS Bracket, Safety Stop, Bottom
  - New Part Number
  - Reduce Length
- Design New Welding Brackets
- Change LOS Leg
  - Define new position for chamfer stop cutouts

INSTALLATION TYPE

Table 9: Suspension assembly installation type.

Suspension Type	LOS 1/LOS 2	LOS 1	SOS
Chamber Type	BSC	HAM	HAM
Installation			

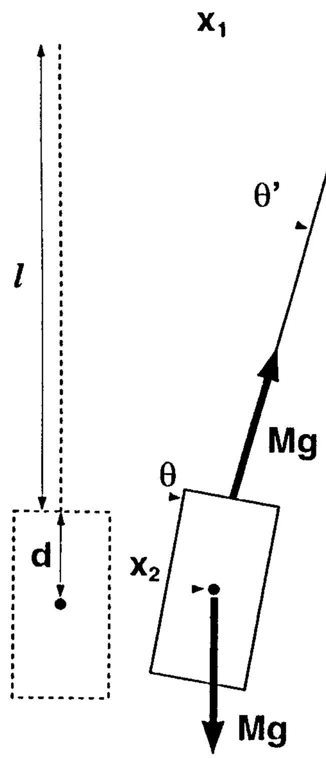
3. Mechanical System Design Match to Requirements

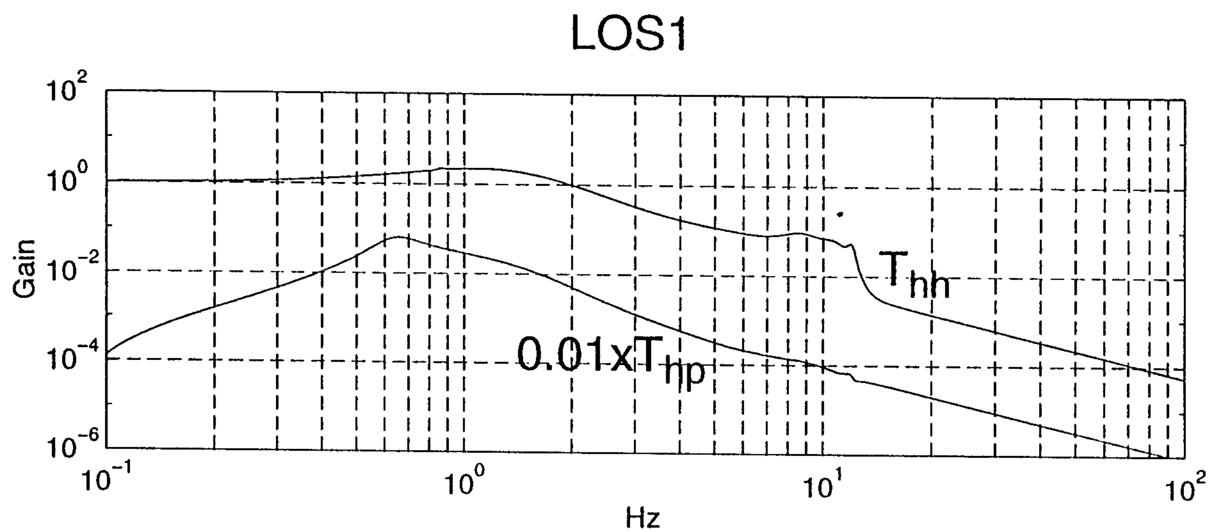
- Transfer function of suspension
- Resonance of suspension support structure
- Mechanical loss

Transfer Function (T_{hh} and T_{vv})

- T_{hh}
  - ››Pendulum frequency: 0.74 Hz (LOS1), 1.0 Hz (SOS)
  - ››Meets $T_{hh} < (f_p/f)^2$
- T_{vv}
  - ››Vertical frequency: 13 Hz (LOS1), 16 Hz (SOS)
  - ››Meets $T_{vv} < (f_v/f)^2$

Transfer Function (T_{hp})



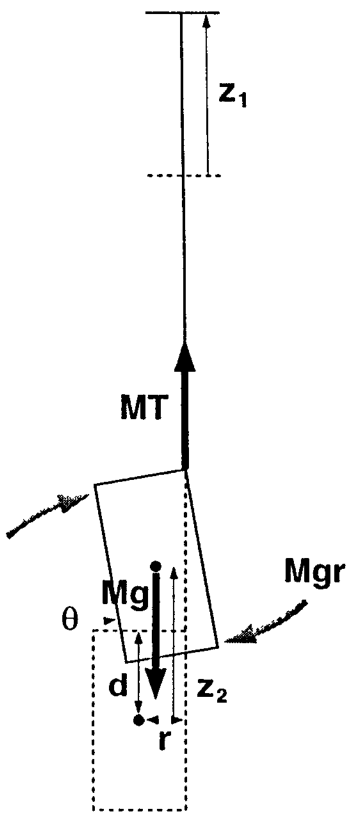


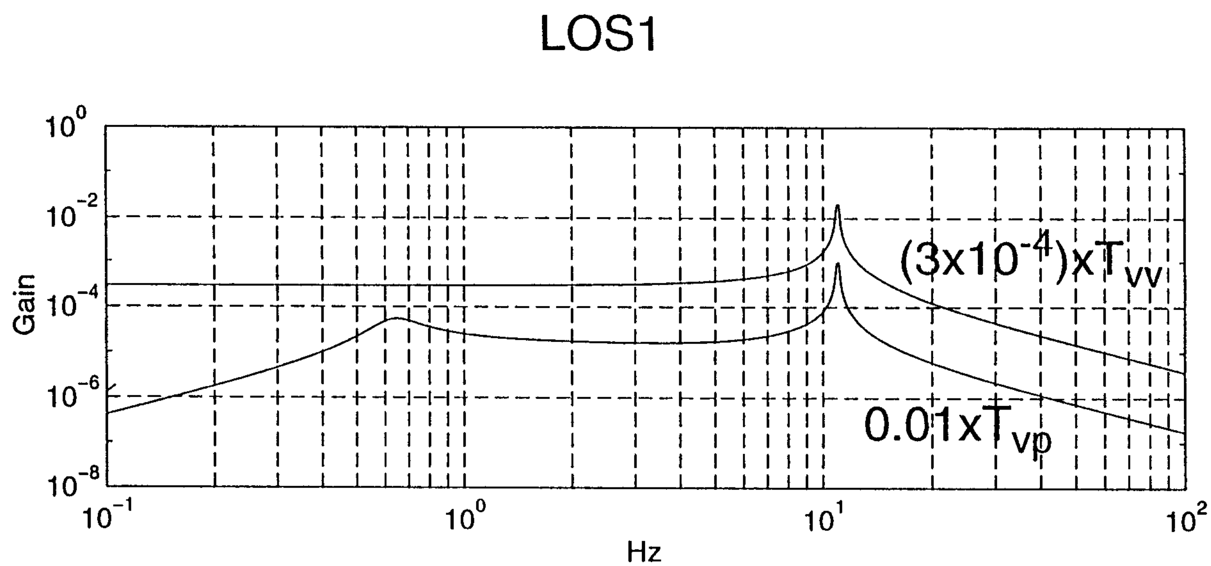
Req: $0.01 x T_{hp} < (f_p/f)^2$

Transfer Function (T_{vh})

- DC force variation due to vertical motion of coil
  - ››Negligible
- Probably meets $T_{vh} < 3x10^{-5} x (f_v/f)^2$

Transfer Function (T_{vp})





Req: $0.01xT_{vp} < (3x10^{-4}) \ x \ (f_v/f)^2$

Resonance of Suspension Support Structure

- FEM analysis -> 190 Hz (LOS1)
  Req: > 160 Hz
- Measurement -> 160 Hz (SOS)
  Req: > 150 Hz
- Q: To be measured

Mechanical Loss Estimate

- *M*easurement
  - ››40m TM
  - ››Pathfinder
  - ››Eddy current
- *S*caling
  - ››Pendulum to violin: 1 to 2
  - ››Pendulum loss: $d^2 \cdot M^{-0.5} \cdot L^{-1}$
  - ››Pitch to pendulum: $d_{pendulum}$ to $2(d_{pitch} - d_{CM})$
  - ››Vertical loss: constant

Mechanical Loss (LOS1)

Table 10: Estimates of mechanical loss of the LOS1 suspension.

Mode	*Derivation*	*Estimates*	*Requirements*	*Allocation %SRD*
Internal	$\mathcal{M}$ (Subst. + Wire Standoff) $\mathcal{M}$ (40m TM + Magnet) -> $\mathcal{S}$	3.7×10^{-7}	$< 4\times10^{-7}$	100%
Pendulum	$\mathcal{M}$ (Violin) -> $\mathcal{S}$	6.3×10^{-6}	$< 7\times10^{-6}$	10%
Pitch	Pendulum -> $\mathcal{S}$	2.1×10^{-4}	$< 5\times10^{-4}$	10%
Yaw	Pendulum -> $\mathcal{S}$	small	$< 8\times10^{-4}$	10%
Vertical	$\mathcal{M}$ (40m TM) -> $\mathcal{S}$	2.5×10^{-4}	$< 3\times10^{-3}$	10%
Eddy Current Pendulum	$\mathcal{M}$ (10 g Mass + Mag. + Al) -> $\mathcal{S}$	5×10^{-9} ? at 0.74 Hz	$< 6\times10^{-9}$ at 0.74 Hz	20%

Mechanical Loss (SOS)

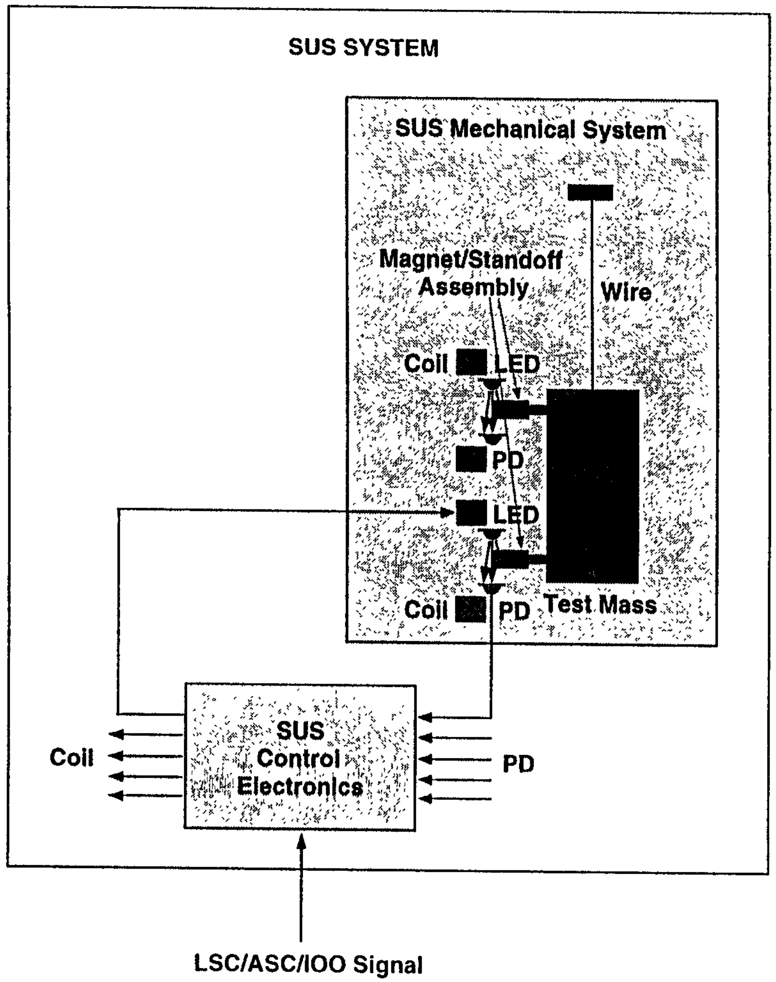
Table 11: Estimates of mechanical loss of the SOS suspension.

Mode	*Derivation*	*Estimates*	*Requirements*	*Allocation %FN*
Internal	$\mathcal{M}$(40m TM + Magnet) -> $\mathcal{S}$	8.1×10^{-6}	$< 1\times10^{-5}$	70%
Pendulum	LOS1 Pendulum -> $\mathcal{S}$	1.5×10^{-6}	$< 5\times10^{-6}$	20%
Pitch	Pendulum -> $\mathcal{S}$	2.1×10^{-4}	$< 3\times10^{-4}$	20%
Yaw	Pendulum -> $\mathcal{S}$	small	$< 9\times10^{-5}$	10%
Vertical	$\mathcal{M}$(40m TM) -> $\mathcal{S}$	2.5×10^{-4}	$< 7\times10^{-2}$	10%
Eddy Current Pendulum	$\mathcal{M}$(10 g Mass + Mag. + Al) -> $\mathcal{S}$	5.9×10^{-7} at 1 Hz	$< 6\times10^{-7}$ at 1 Hz	70%

4. Sample Control Design (Mainly for LOS1)

- Framework
- Mode of operation
- Electronics configuration
- Output driver
- Control system
- Cross-coupling

Framework

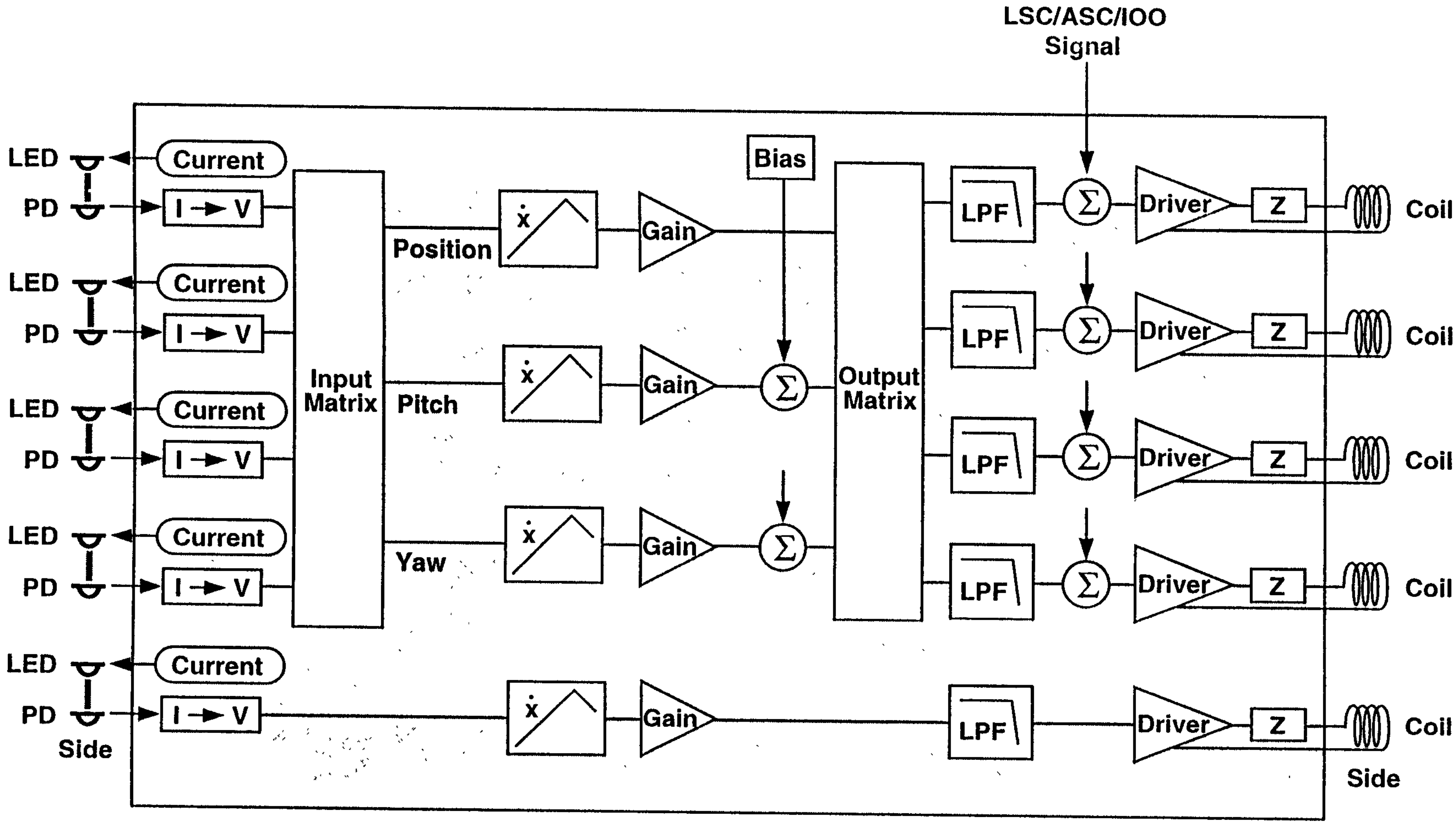


SUS SYSTEM
SUS Mechanical System
Magnet/Standoff
Assembly
Wire
Coil
LED
PD
LED
Coil
PD
Test Mass
SUS
Control
Electronics
Coil
PD
LSC/ASC/IOO Signal

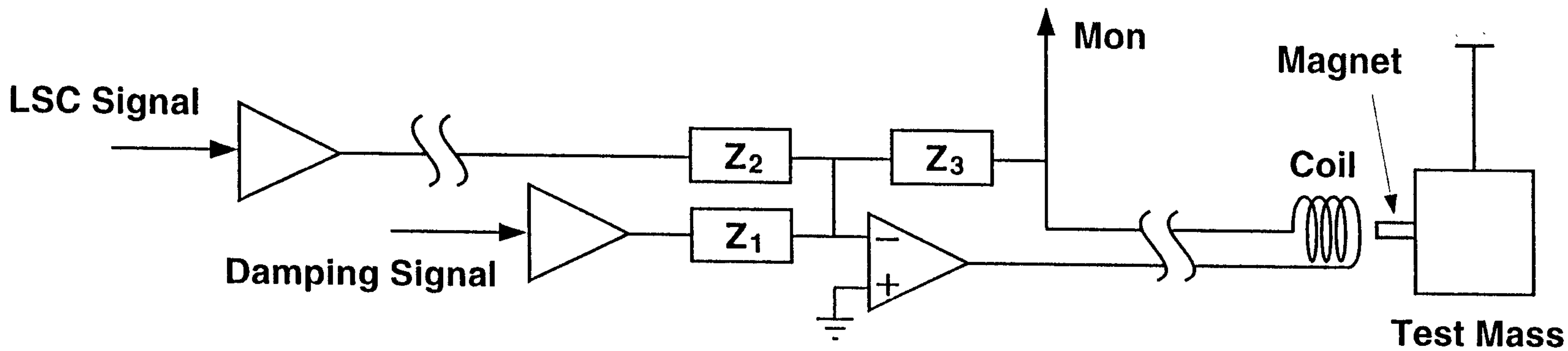
Mode of Operation

- Normal mode
- Undamped mode
  - ››for TM in operation mode
  - ››for side for test
- High gain mode
  - ››To prevent a large motion of the optics from external disturbances

Sample Electronics Configuration

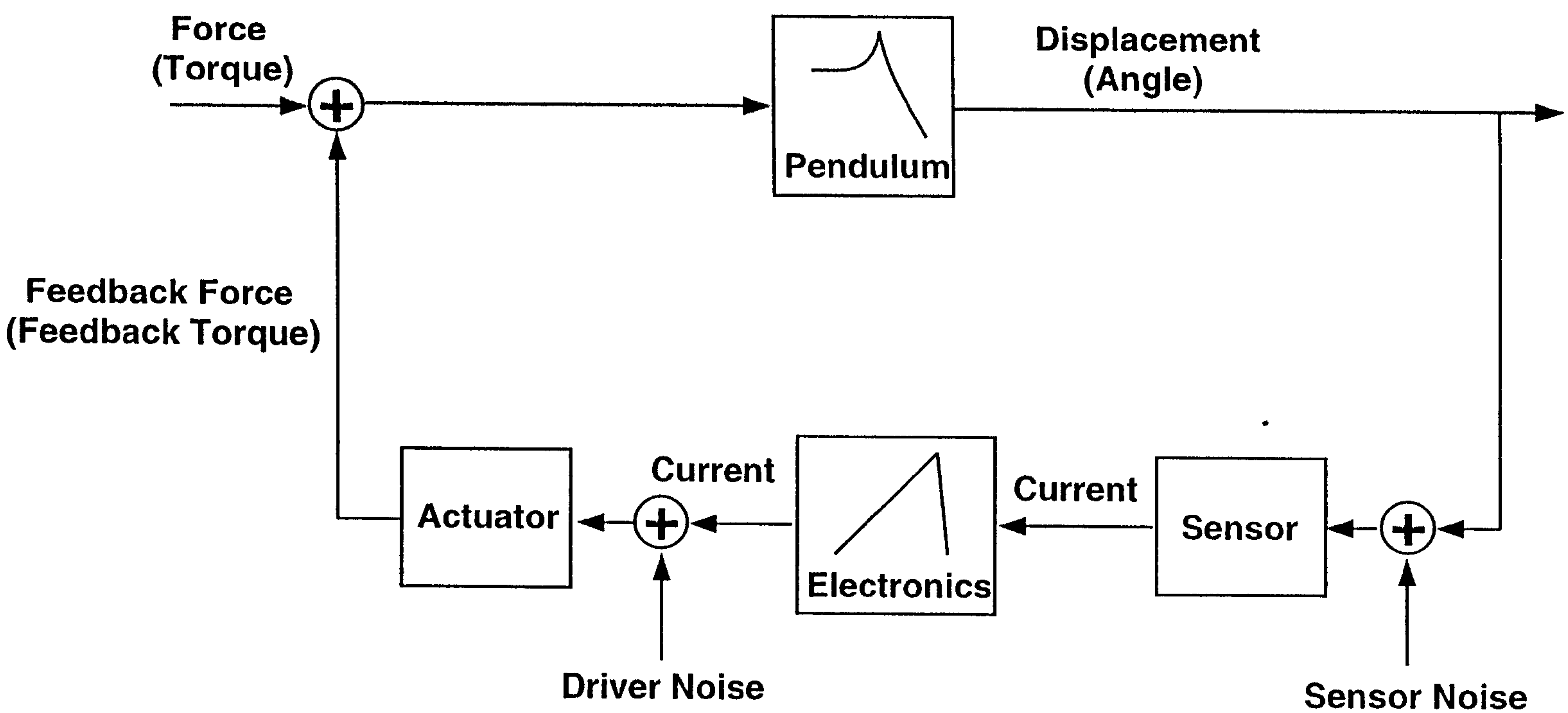


Sample Output Driver



- No pick-up current in the coil.
- No dragging the mass by vibrating coil
- No pick-up voltage in monitor signal
- Suppressed noise produced before Z_3
- Large dynamic range
- Smooth switching between acquisition and operation mode

Sample Control System



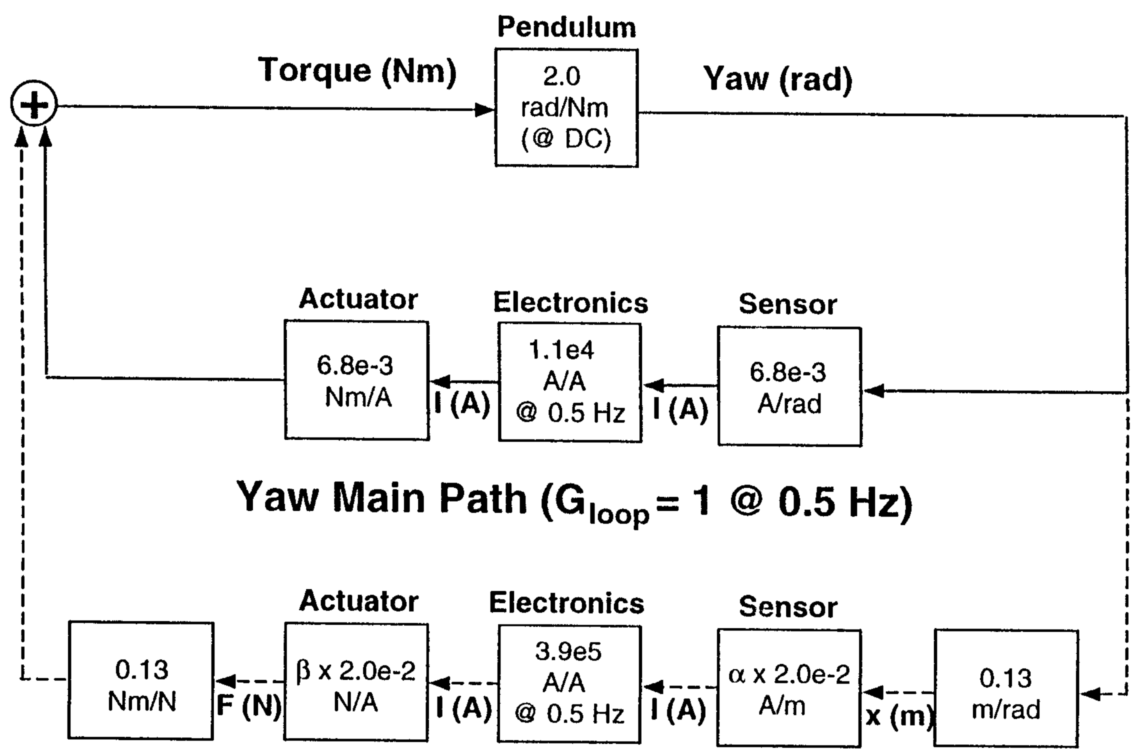
Sample Control Parameters

- Sensor: $2x10^{-2}$ A/m each, Actuator: $2x10^{-2}$ N/A each
- Pendulum (@ DC) x Sensor x Electronics (@ f_0) x Actuator = 1

Table 12: Sample control parameters for each degree of freedom for LOS1.

Degree of Freedom	*Resonance Frequency f_0(Hz)*	*Pendulum (m/N or rad/Nm) @ DC*	*Sensor (A/m or A/rad)*	*Electronic (A/A) @ f_0 Hz*	*Actuator (N/A or Nm/A)*
Position	0.74	4.3×10^{-3}	8.0×10^{-2}	3.6×10^{4}	8.0×10^{-2}
Side	0.74	4.3×10^{-3}	2.0×10^{-2}	5.8×10^{5}	2.0×10^{-2}
Pitch	0.60	1.4	6.8×10^{-3}	1.5×10^{4}	6.8×10^{-3}
Yaw	0.50	2.0	6.8×10^{-3}	1.1×10^{4}	6.8×10^{-3}

Cross-coupling



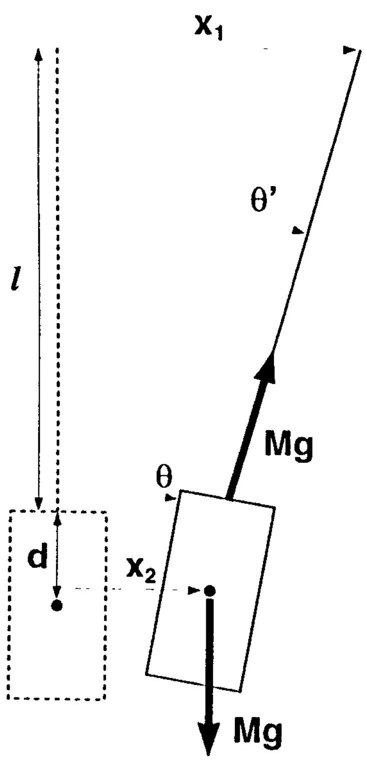
Spurious Path via Side ($G_{loop} = 5.3\alpha\beta$)

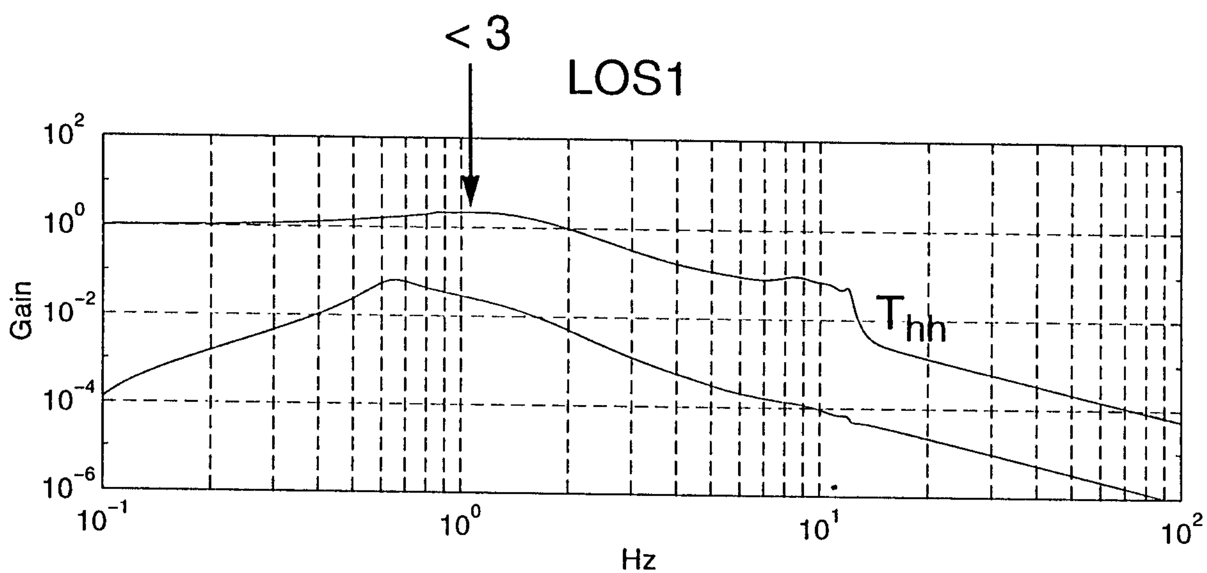
- $5.3 \times \alpha \times \beta << 1$

5. Control System Design Match to Requirements

- Damping
- Sensor Noise
- Driver Noise
- Range

Damping





Damping force: $-k\,(\dot{x}_2 - \dot{x}_1)$

LPF: Chebyshev (1dB) 10 pole @ 12 Hz

Sensor Noise

- Displacement Noise = Sensor Noise x Loop Gain (at 40 Hz) x Coupling

Table 13: Sensor noise for each degree of freedom.

Degree of Freedom	*Sensor Noise*[a] *(m/rHz or rad/rHz)*	*Loop Gain*[b] *@ 40 Hz*	*Coupling*	*Displacement Noise @ 40 Hz (m/rHz)*
Position	1.0×10^{-10}	7.0×10^{-10}	1	7.0×10^{-20}
Side	2.0×10^{-10}	7.0×10^{-10}	< 0.1	$< 1.4 \times 10^{-20}$
Pitch	1.2×10^{-9}	5.7×10^{-10}	1 mm	6.8×10^{-22}
Yaw	1.2×10^{-9}	4.7×10^{-10}	1 mm	5.6×10^{-22}

a. Average effective sensor noise per channel.
b. LPF: Chebyshev (1dB) 10 pole @ 12 Hz

Driver Noise

- Displacement Noise (@ 40 Hz) =
  Driver Noise (@ 40 Hz) x Actuator x Pendulum (@ 40 Hz) x Coupling

Table 14: Driver noise and the resultant displacement noise for each degree of freedom.

Degree of Freedom	*Driver Noise[a] @ 40 Hz (A/rHz)*	*Actuator (N/A or Nm/A)*	*Pendulum @ 40 Hz (m/N or rad/Nm)*	*Coupling*	*Displacement Noise @ 40 Hz (m/rHz)*
Position	1×10^{-12}	8.0×10^{-2}	1.5×10^{-6}	1	1.2×10^{-19}
Side	2×10^{-12}	2.0×10^{-2}	1.5×10^{-6}	0.1	6.0×10^{-21}
Pitch	1×10^{-12}	6.8×10^{-3}	3.2×10^{-4}	1 mm	2.2×10^{-21}
Yaw	1×10^{-12}	6.8×10^{-3}	3.2×10^{-4}	1 mm	2.2×10^{-21}

a. Average effective driver current noise per channel.

Range of Actuator

- Range = Driver Maximum Current (@ DC) x Actuator x Pendulum (@DC)

Table 15: Range of actuator for each degree of freedom.

Degree of Freedom	*Driver Max. Current @ DC (A_{pp})*	*Actuator (N/A or Nm/A)*	*Pendulum @ DC (m/N or rad/Nm)*	*Range @ DC (m_{pp} or rad_{pp})*
Position	0.25	8.0×10^{-2}	4.3×10^{-3}	8.6×10^{-5}
Side	0.25	2.0×10^{-2}	4.3×10^{-3}	2.2×10^{-5}
Pitch	0.25	6.8×10^{-3}	1.4	2.4×10^{-3}
Yaw	0.25	6.8×10^{-3}	2.0	3.4×10^{-3}

6. Suspension Test Plan

- Fixturing Tests
- Construction/Alignment/Fit Checks
- Installation Tests
- Frequency/Q Measurements on Suspended Optics
- Suspension Structure Mode Measurements
- Sensor/Actuator Head Tests
- Demonstration of Local Damping
- Transfer Function Tests

Fixturing Tests

- Construct fixtures for gluing magnet assemblies and guide rods
- Construct Al models of Test Mass and Mode-leaner Mirror
- Install models with wedge angles properly oriented
- Glue attachments to models
- Evaluate
    - ››ease of assembly
    - ››accuracy of alignment
    - ››quality of glue joints

Construction/Alignment/Fit Checks

- Construct Test-Mass and Mode-Cleaner-Mirror suspension structures.
- Level optical table for alignment tests
- Suspend and coarse align each model optic by tapping on the wire standoffs.
- Verify that magnet assemblies align properly with the sensor/actuator heads.
- Perform a fine optical alignment
  - ››Use a PZT buzzer to adjust the position of the wire standoffs
  - ››measure alignment using the alignment fixture.

Construction/Alignment/Fit Checks (continued)

- Adjust alignment to absolute level within tolerance.
- Following alignment, standoffs will be glued in place.
- Demonstrate that components can be dismounted and remounted into proper optical alignment.
- Verify that the correct value for d_{pitch} was obtained after gluing. The frequency shall be 0.60 +/- 0.05 Hz.
- Verify that f_{yaw} equals 0.50 +/- 0.05 Hz and $f_{pendulum}$ equals 0.743 +/- 0.002 Hz.

Installation Tests

- Following the fine alignment of each model optic, the optic will be locked in its safety cage.
- A removable lifting fixture will be attached to the suspension structure and the structure will be transported away from the optical table and then returned to its original position.
- The optic will then be unlocked and checked for optical alignment to within the required tolerances.

Frequency/Q Measurements on Suspended Optics

- The suspension development facility will be used to measure the frequencies and Q's of a suspended TM and a suspended MCM.
- Substrate internal-mode Q's for lowest five axisymmetric modes shall be measured after gluing on all attachments and compared to requirements.
- The violin-mode will be excited and frequencies and Q's will be measured with the substrate hanging in its appropriate suspension support structure. Violin-mode Q's for the lowest three harmonics of both suspension wires shall be measured and compared to requirements.

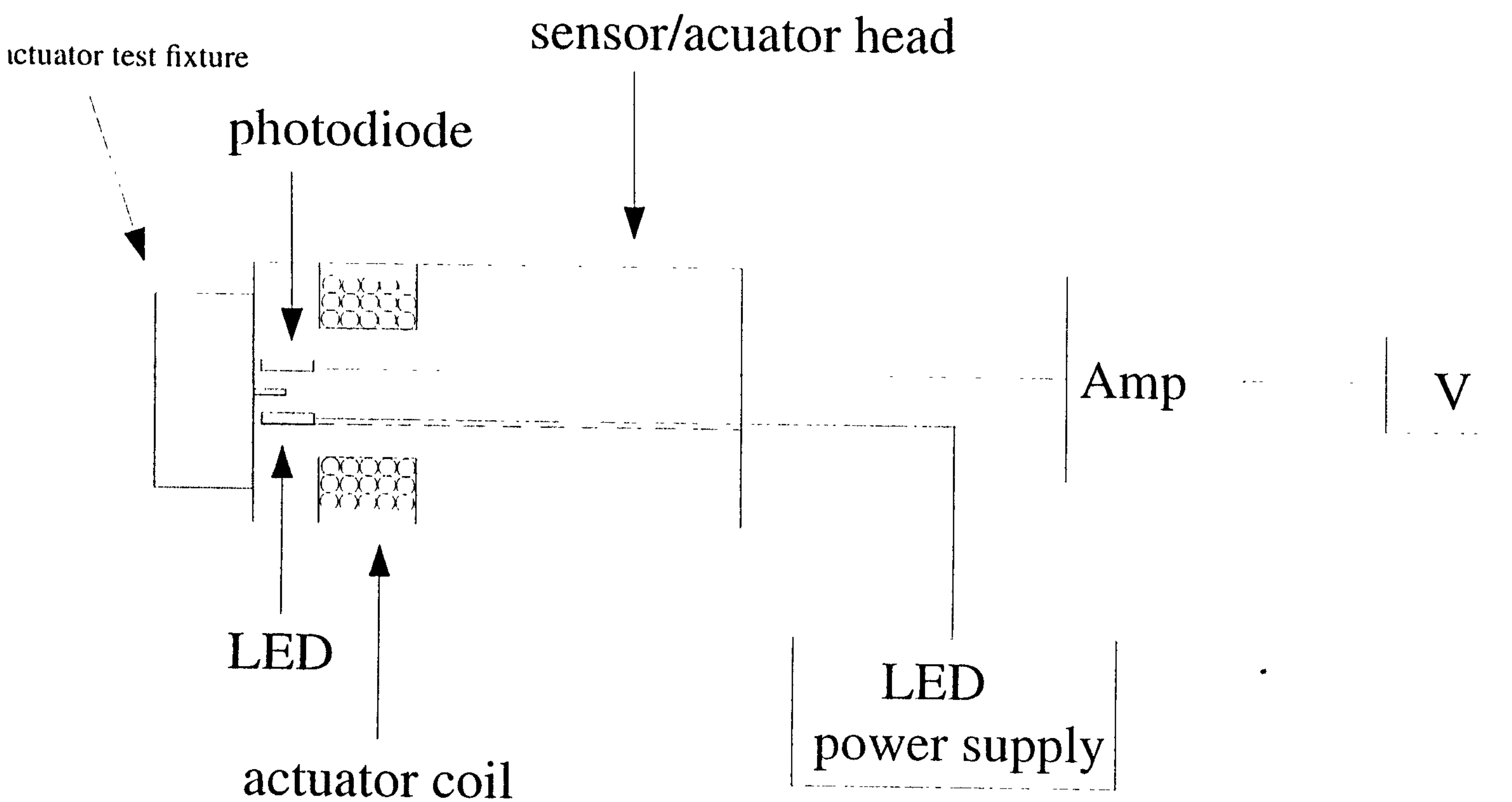
Suspension Structure Mode Measurements

- Measurements of the mechanical resonances of the suspension structures will be made to compare with the FEA modeling.
- LOS and SOS structures will be bolted to the top of an optical table. LOS structure will also be tested, bolted upside down to an optical table. Model optics will be suspended.
- Structural resonances will be excited by tapping on the structure at various spots. The mode frequencies and Q's will be read out using an accelerometer.
- Verify that there are no modes below the gravest mode specified in the design requirements.

Sensor/Actuator Head Tests

- All coils should measure within +/- 5% of the nominal resistance and inductance values.
- The sensor will be tested for operation and alignment of the LED/photodiode pair. A test fixture will be placed against a sensor/actuator head. The fixture will protrude far enough into the head to block half of the LED/photodiode pair. The photodiode output voltage will be measured. It shall be 50% +/- 10% of the maximum output voltage prior to insertion of the test fixture.
- One actuator coil will be tested in vacuum to establish its current handling capacity.

Sensor-Head Test Fixture



Local-Damping and Transfer-Function Tests

- Local-Damping Tests
  - ››Demonstrate critical damping under local control
    - — use servo electronics for the beam splitter for the Mark II interferometer.
    - —use Aluminum models in place of optical components.
  - ›› LOS1 suspension and SOS suspension will be tested.
- Transfer-Function Tests
  - ››Measured for LOS 1 suspension and SOS suspension.
  - ›› The response of the system will be measured at DC and AC
    - —show that the specified forces and torques can be applied and no mechanical/ electrical interactions affect the stability of the feedback loop.

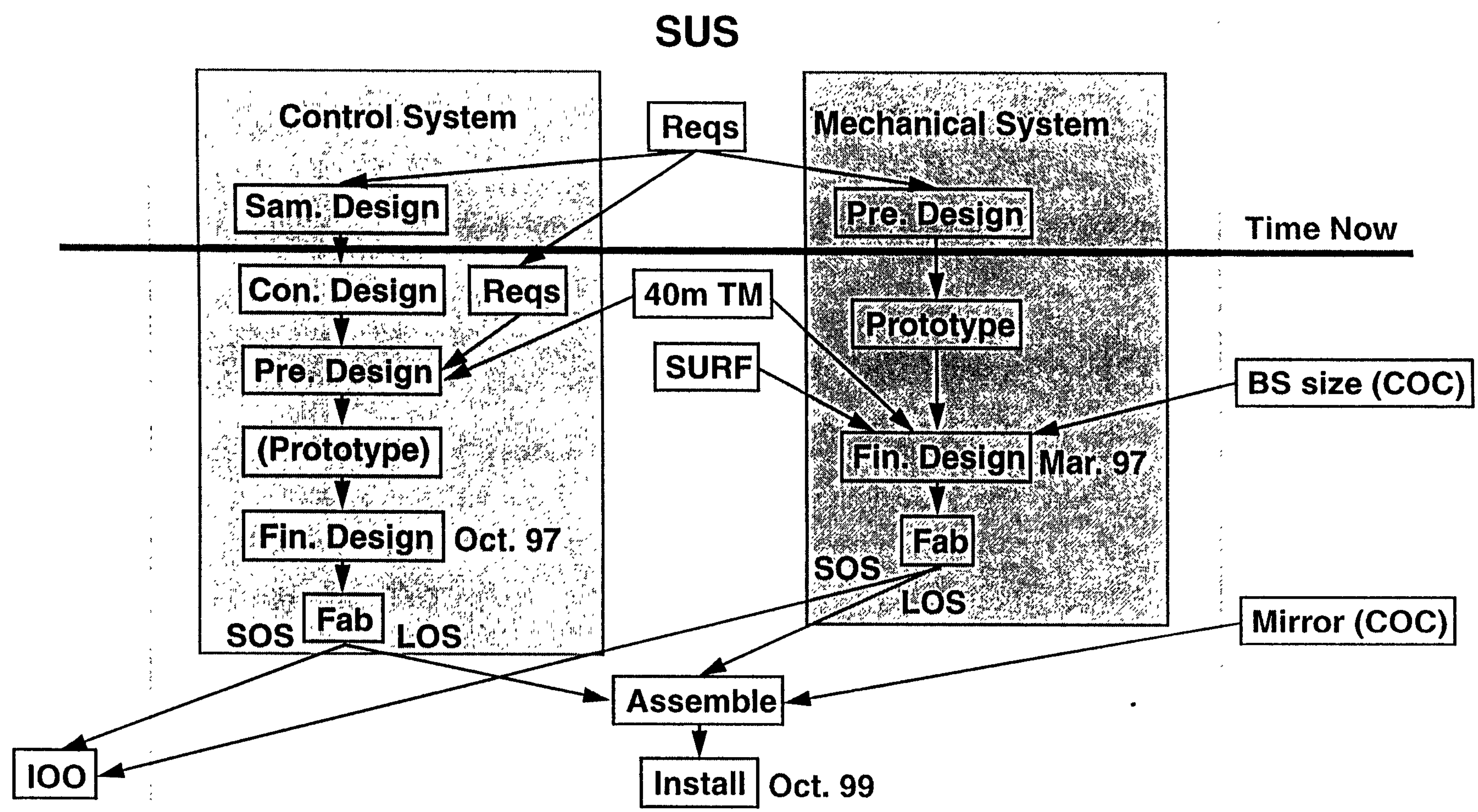
Components and Instruments for Testing

Test	Components to be acquired	Existing Instrument
Fixtures for Gluing Attachments	Aluminum model optics (TM, BS, MCM). Sizes are **TBD**. Gluing fixtures	N/A
Construction and Alignment/Fit Checks	Optical alignment components - Hg level. Suspension assembles. PZT Buzzer.	He-Ne Laser
Installation Tests	lifting mechanism	Optical tables in S. Annex Building
Frequency and Q Measurements	PZT actuator	Suspension Development Facility, accelerometer, HP 3962
Mode Measurements of the Suspension Structure	N/A	Accelerometer, HP 3962, optical tables in S. Annex Building
Sensor/Actuator Head Tests	Sensor test fixture	N/A
Demonstration of Local Damping	Servo Electronics for Mark II (minor modification necessary)	N/A
Transfer Function Tests	N/A	HP 3962
Feedback from R&D	N/A	Mark II

7. Future Plan

- Schedule
- Resources
- 40m Suspension
- SURF
- Critical Design Issue

Overall Flow



Resources

- Task Leader: S. Kawamura
- Scientist: F. Raab
- Mechanical Design: J. Hazel and D. Coyne
- Control System: J. Heefner and CDS people
- SURF Student: J. Dawid
- ?: ?

Short-term Schedule (Original Date ... To Be Reviewed)

- LOS1 prototype Fab/Test: to Sep. 11, 96
  - Review: Sep. 12, 96
- SOS prototype Test: to Aug. 29, 96
  - Review: Aug. 30, 96
- LOS1/LOS2 final design: to Oct. 22,96
- SOS final design: to Oct. 10, 96
  - Review: Oct. 23, 96

40m Suspension Schedule

- Test mass suspension
  - ››Installation of the first set: to Jul. 21, 96
  - ››Characterization: to Aug. 21, 96
  - ››Installation of the remaining sets: ?
- BS & RM suspension
  - ››Test (= SOS prototype test): to Aug. 29, 96
  - ››Installation of BS: Dec. 9, 96
  - ››Installation of RM: Apr. 11, 97

SURF

- Wire material - Q (Summer 96')
  - ››Molybdenum, Tantalum, Titanium, Aluminum, Tungsten, Niobium, etc.
  - ››Replace the steel wire with better one.

Critical Design Issue

- Range & driver noise
  - ››Gyrator, high voltage, etc.
  - ››Heating of the coil
- Eddy current loss
  - ››Use longer sensor/actuator heads and repositioned head holders for LOS1.
  - ››Increase size of support structure to accommodate longer sensor/actuator heads for SOS for final design.