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(NASA-CR-192684) THE MIT SERC INTERFEROMETER TESTBED (MIT) 42 p

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The MIT SERC Interferometer Testbed

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Why Build a CST Testbed?

- experimental focus for graduate student theses
- demonstration of progress by experimental evaluation
- testbed provides versatile platform for investigation of CST approaches
- SERC scientific mission orientation provides driver and focus for technology development

SERC Scientific Mission Orientation

- provides challenging goals to focus research
- civil space relevance
- attracts talented students
- fosters interaction with the scientific community
- enables new scientific exploration

Outline

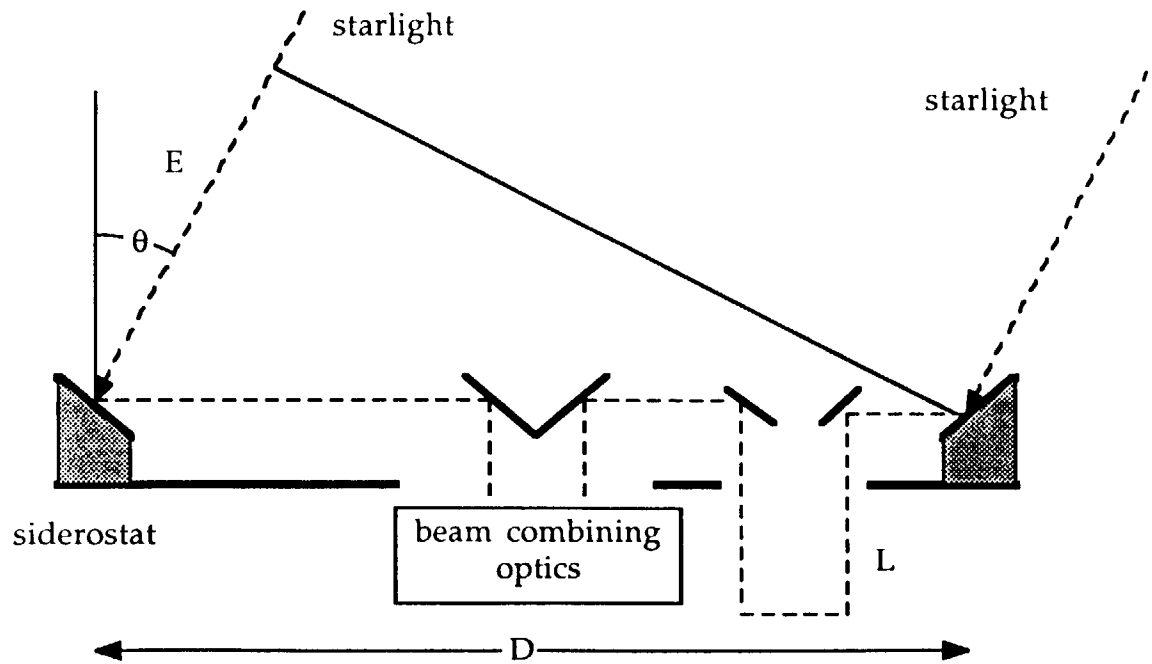
1) Science Motivation for Testbed
2) Research Motivation
3) Testbed Hardware and Optics
4) Results of Nanostrain Damping Measurements
5) Control Experiments Planned

A Testbed Based on a Space-Based Optical Interferometer

- CST
  - SERC Scientific Mission Orientation
    - Candidate Missions
      - robotics
      - reflectors
      - masking
      - platforms
      - materials proc.
      - Optical Interferometry
        - Optical Interferometer Testbed Design Project

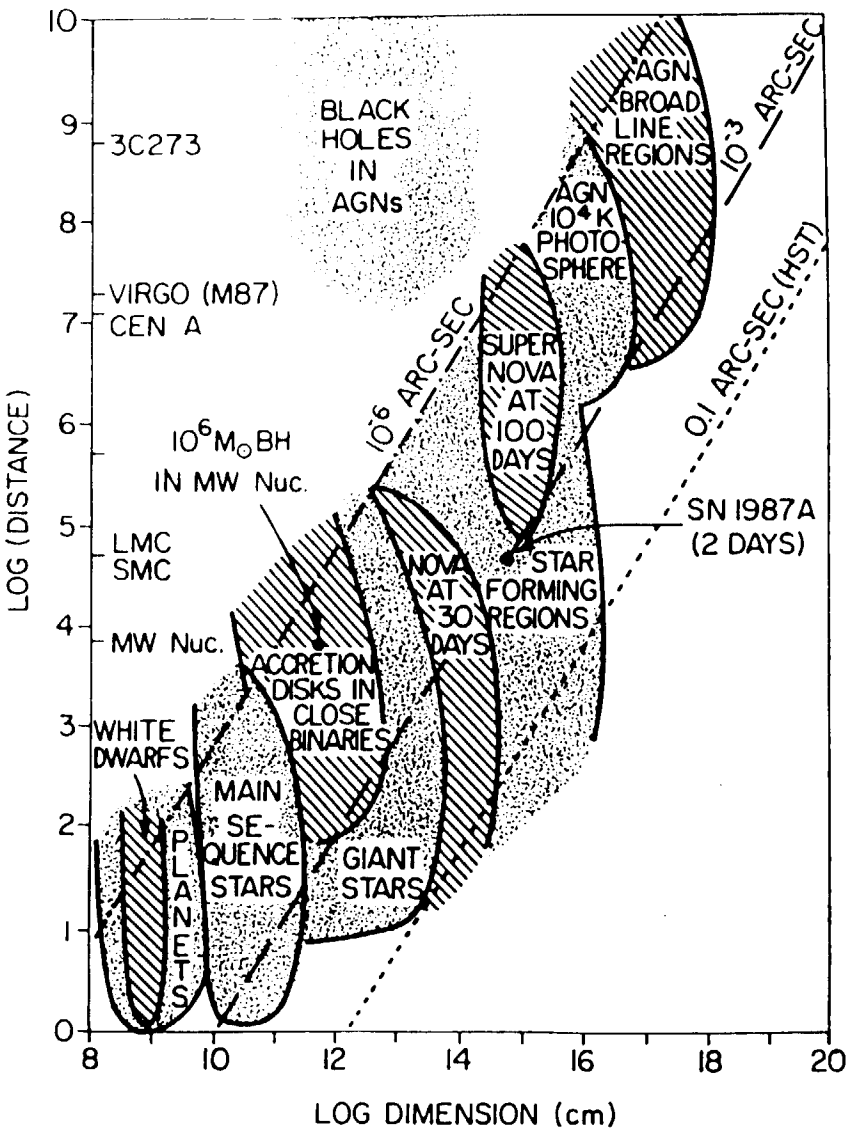
A Stellar Interferometer

- provides increased angular resolution due to greater baseline; used for imaging or astrometric applications



- beam combining optics measure the intensity of the central peak of the interference pattern of the two science beams
- optical delay line L added to compensate for path length difference

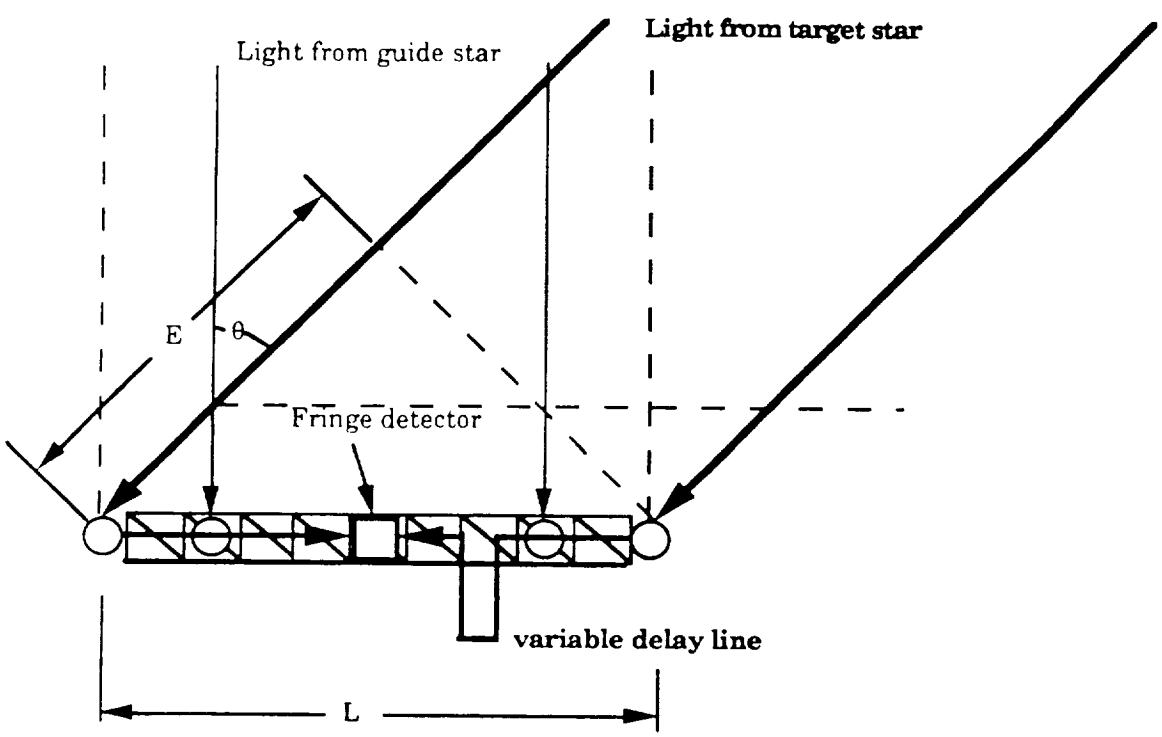
Angular Resolution Required to Study Astrophysical Phenomena



- ground-based telescopes limited to ~ 1 arc-sec by atmosphere
- for unfilled apertures, angular resolution $\alpha \sim 0.1\ \lambda/D$, where D is interferometer baseline
- for $\lambda = 0.55\ \mu m$, baseline D=50 m provides 10^{-3} arc-sec of resolution

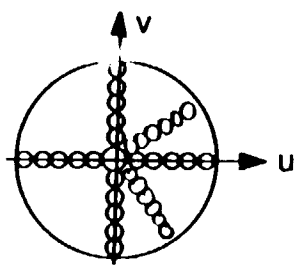
A Space-Based Interferometer

- used for astrometry:
  - measure baseline and delay lines using metrology system
- used for imaging
  - measure intensity (mag) and phase (via delay line distance) of central fringe of interference pattern
  - vary baseline and rotate siderostats about LOS to target star by rigid body motion
  - reconstruct image from 2-D spatial IFT of the measured intensity

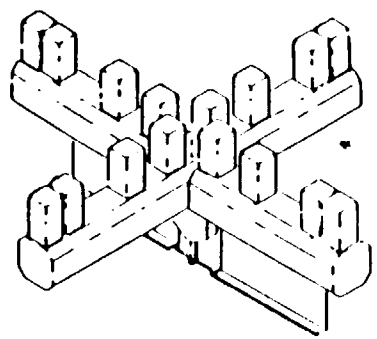


Current Proposals for Space Interferometry

- COSMIC

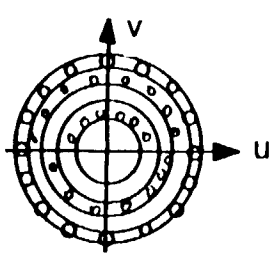


FOURIER PLANE COVERAGE

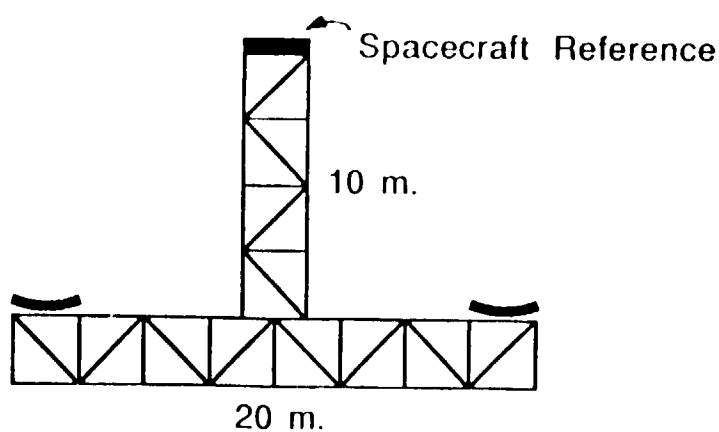


- 36 m MAX ARRAY BASELINE (4 MODULE)
- EACH MODULE:
  - 16 m LENGTH
  - 4 x 1.8m PARALLEL-POINTING TELESCOPES
- U-V PLANE COVERAGE:
  - FIXED BASELINE
  - ROTATE ARRAY ABOUT LINE OF SIGHT TO SWEE PLANE

- JPL - FMI



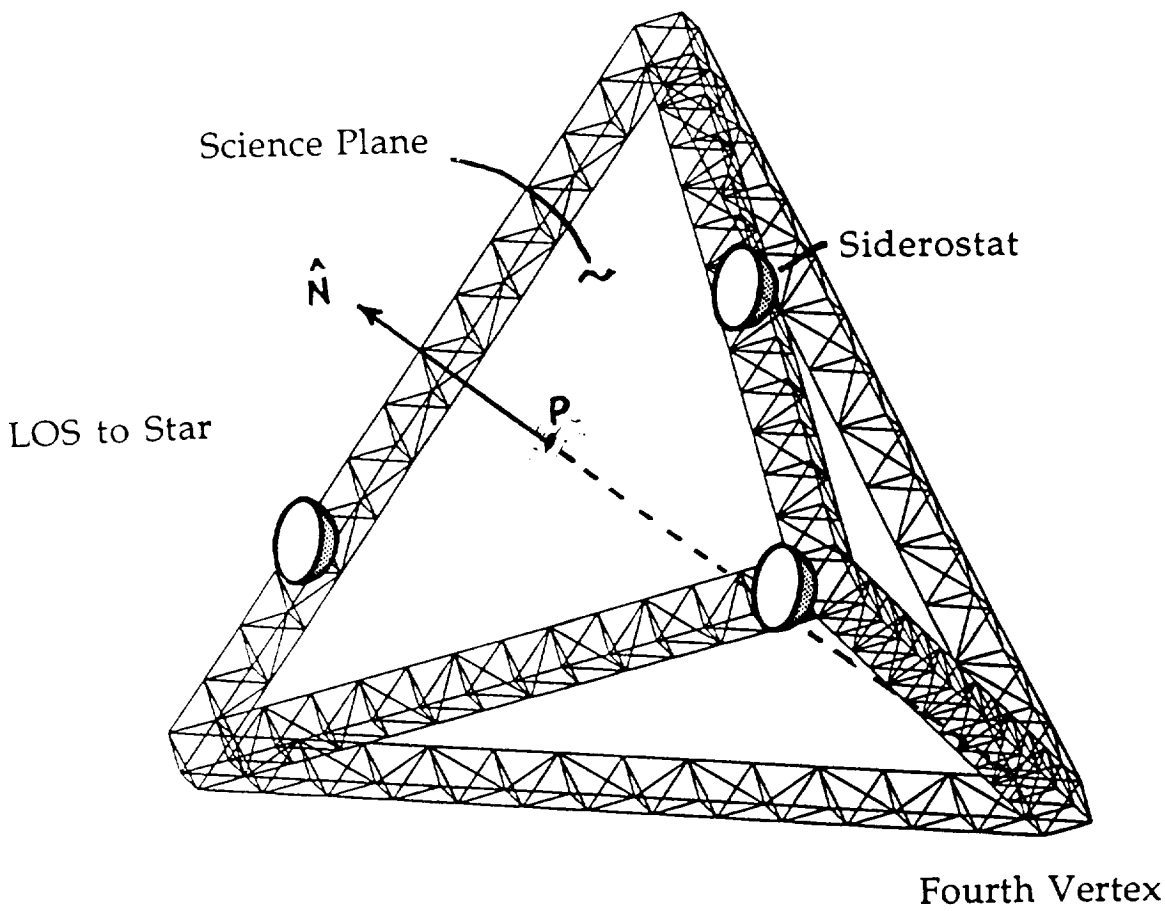
FOURIER PLANE COVERAGE



- METROLOGY SYSTEM UTILIZE 40 LASER BEAMS TO CALIBRATE STRUCTURAL ERR
- U-V PLANE COVERAGE:
  - TILT S/C WRT LINE OF SIGHT TO VARY BASELINE
  - ROTATE S/C ABOUT L.O.S. TO SWEEP ARC IN PLANE

Model Mission for SERC Interferometer Testbed

- 50 meter baseline provides 10-3 arc-sec resolution at $\lambda = .5\ \mu m$
- 1 meter diameter siderostats
- to observe 10th magnitude star for 5 sec requires pathlength stability of 80 nm rms for $f > 0.25$ Hz
- actual testbed: baseline of 3 meters; also target 80 nm rms pathlength stability



CST Issues for Interferometer Mission Focus

Actual Space-Based Interferometer

- beam tilt monitoring
- baseline monitoring and control (rigid body, flexible) to 80 nm rms in presence of space disturbances

SERC Testbed

- reduced problem to capture essential CST issues without over-complication of the testbed
- minimum representative problem involves measurement and control of six path lengths (serves as performance metric) that would be necessary for interferometer metrology system (ignore rigid body and science path)
- control six internal path lengths to 80 nm rms for "high" frequencies ($f > 0.25$ Hz) in presence of scaled space disturbances

Research Motivation for Testbed

- SERC has a Controlled Structures Technology (CST) focus
- experimental verification and demonstration of CST progress is important -- "trial by fire" for new ideas
- a variety of research activities, typically forming the basis of graduate student theses, are addressing the following issues:

Passive damping and dynamics:

- how much damping is necessary for robust control design?
- what is correct mix of passive and active control?
- structural dynamics modelling and testing at the nanostrain level (structural damping, joint damping)
- structural tailoring for control

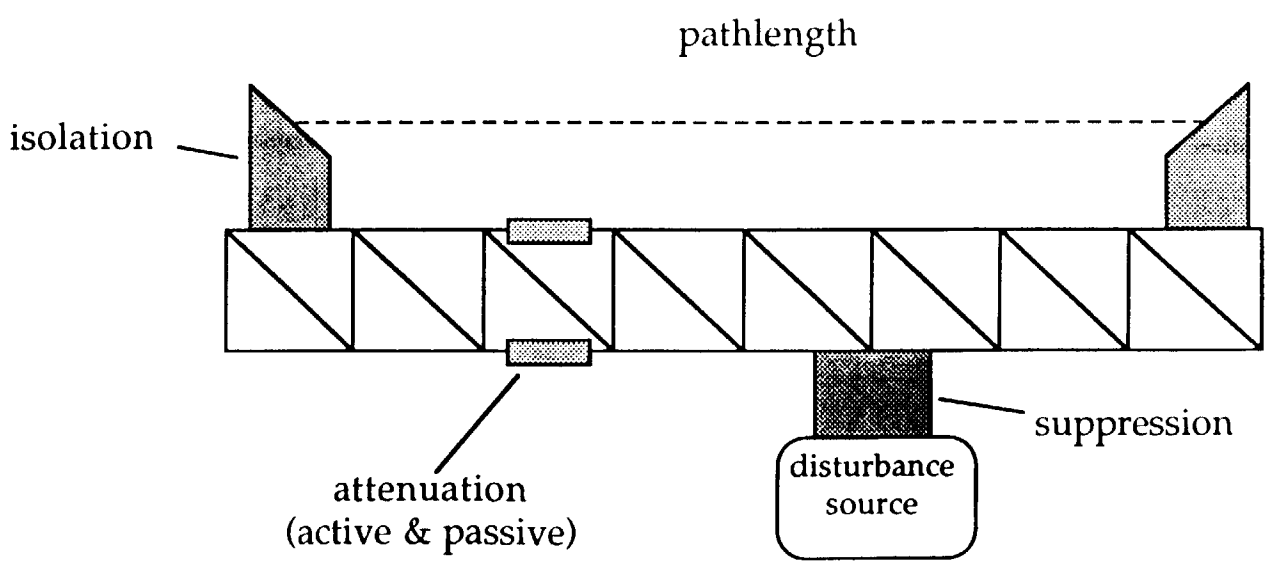
Research Motivation (cont.)

Robust Control Design

- MIMO issues in large space structure control
- active member control
- robust control design in presence of unmodelled, unstructured structural uncertainty ("ignoring the plant dynamics")
- robust LQR design for parametrically uncertain systems
- a probabilistic approach for control design of parametrically uncertain systems
- control of power flow in structures (local control) employing Statistical Energy Analysis and $\mathcal{H}$ -infinity optimization
- vibration isolation - narrowband and broadband - in presence of unmodelled structural uncertainty

CST Applied to Pathlength Control

- use correct mix of control strategies to control performance metric of internal pathlength
  - passive vs active
  - local vs global control



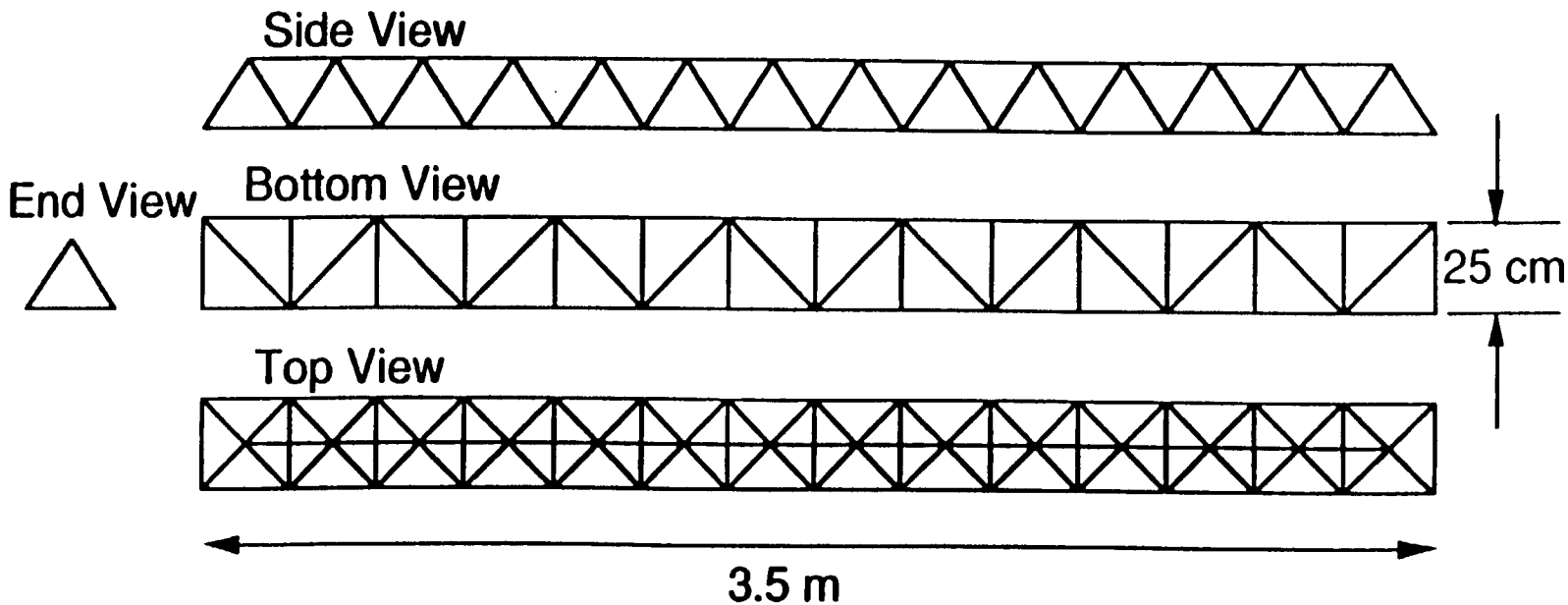
Truss Design

- Tetrahedron
  - 2-D plane for siderostats
  - 3-D stiffness, out of plane reference point
  - Ixx=Iyy=Izz, no gravity gradient torques
- Truss lacing
  - Statically determinant
  - Connects easily at vertex
  - Two bending directions have different EIs
- Joint Design
  - 18 hole geometry, Plenty of attach points
  - Start small, add mass to tune
  - Don't want joint dominated dynamics
- Strut Design
  - Removable, easy to construct
  - Glue question
  - Failure safety margin, total weight

Truss Design

Length of One Leg: 3.5 m
Number of Bays: 14
Strut Dim.: 3/8" x .058"

Global 1st Bending: 31 Hz
Local 1st Bending: 370 Hz
Dry Weight: 60 lb



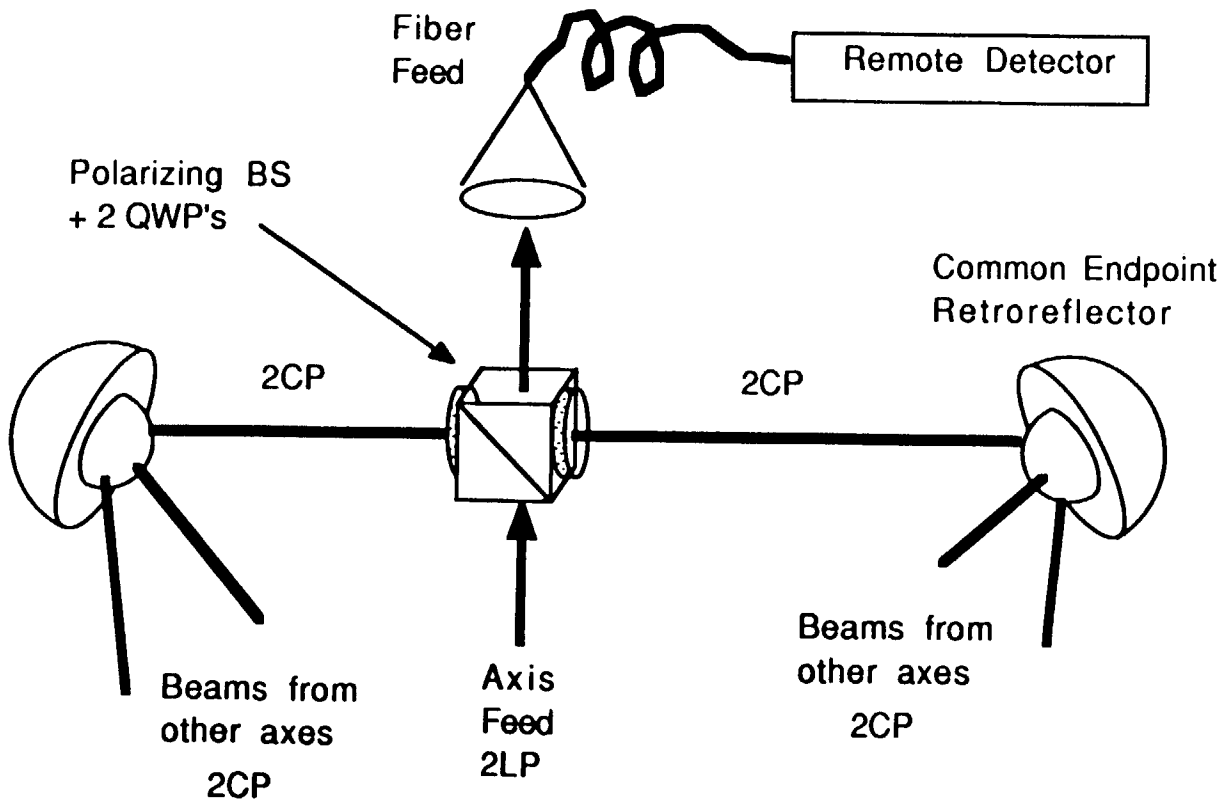
Mass loading to get 1st Global of 20 Hz:
TotalWeight: 100 lbs.

Safety Factor before Tens. Faiure of Strut (Loaded Truss): 45

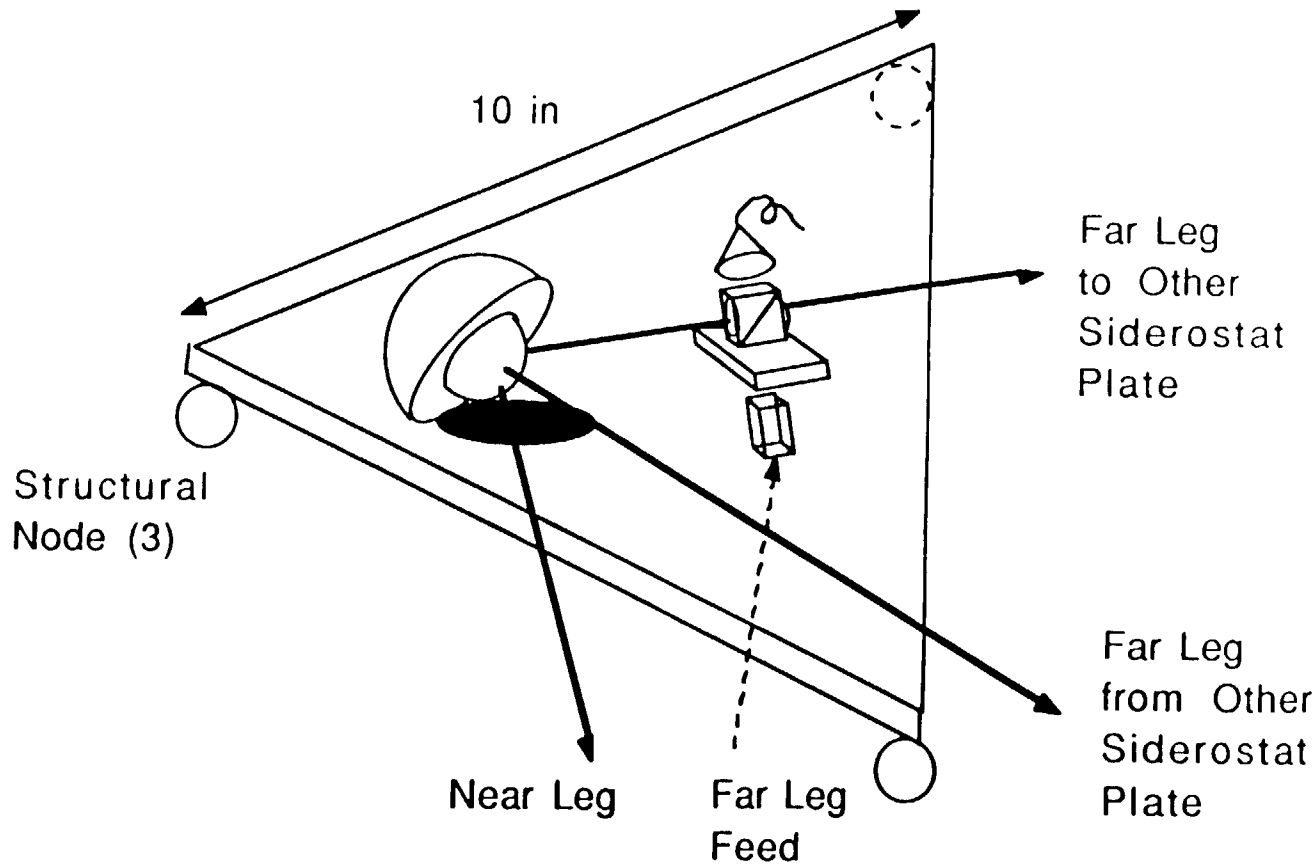
Optical Metrology

- unique feature of testbed is multi-axis laser metrology
- at 3 mock siderostat locations are precision 3 axis active mirror mounts holding common endpoint retroreflectors (cat's eyes)
- Fourth vertex holds laser and other optics
- use commercially available 670 μW laser from Hewlett-Packard
- VME based fringe counting provides seamless link to real time controller
- optical components provide laser interferometry measurements for baseline metrology -- 6 path lengths define position of mock siderostats wrt fourth reference point

One Axis of Metrology System

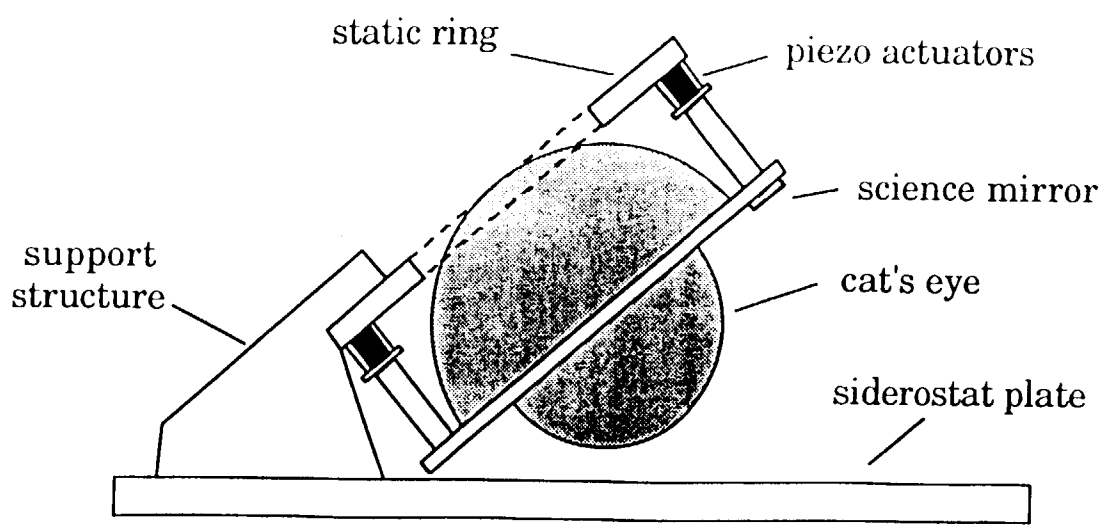


Siderostat Plate Layout

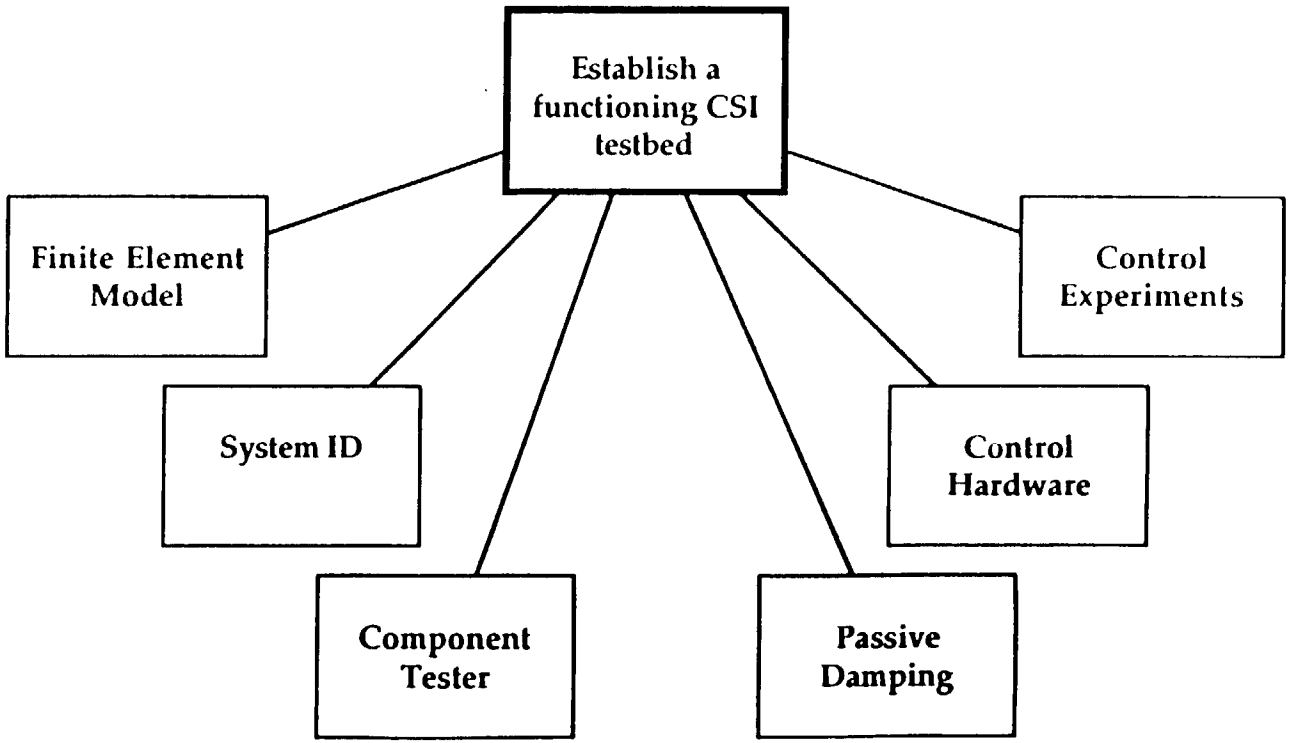


3-Axis Active Mirror Mount

- 3 piezoelectric or electrostrive actuators provide +/- 3.75 μm control in 3 directions
- mass of moving platform varied to represent scaled siderostat mass
- later incorporate mass reactuation



Summer 1990 Goals and Projects



Testbed Instrumentation

Sensors

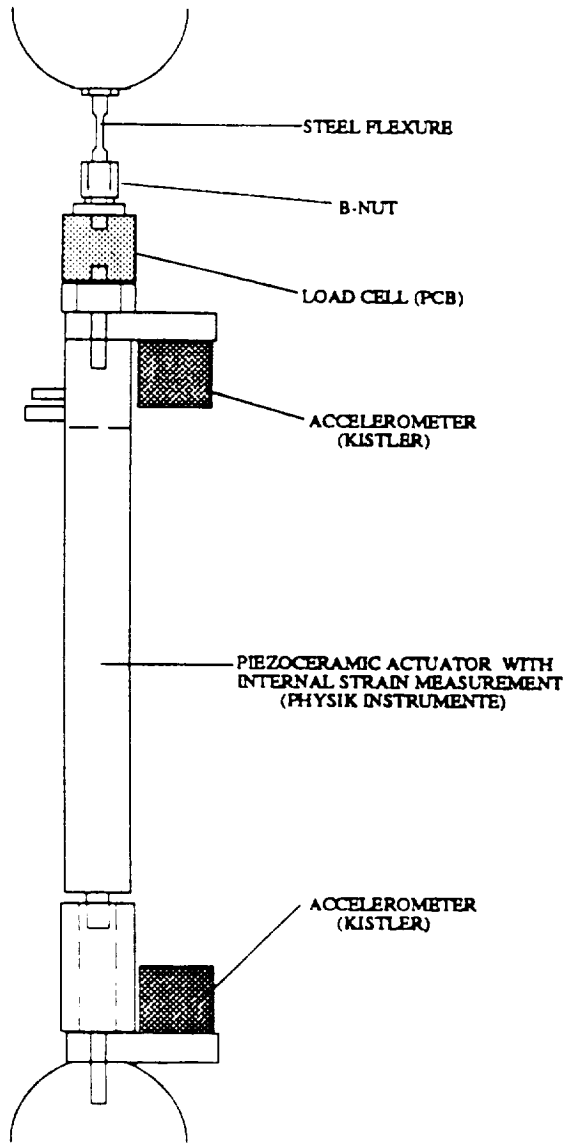
- 32 Kistler accelerometers (1V/g) for system id
- piezoelectric crystal strain gages ($10^{-10}\varepsilon$ resolution)
- Three Sunstrand triax accel mounts (1V/milli-g) to be mounted at mock siderostat locations
- 6 axis laser metrology

Actuators

- 3 piezoelectric active struts (Physik Instrumente) with collocated load cell, accels, and strain gage
- 3 three-axis active mirror mounts (custom built)
- piezoelectric strut for passive shunting
- external shaker for system id

Active Strut Configuration

- stiffness selected to match the local impedance of truss structure (~ 8 N/μm)
- +/- 30 μm of stroke



Real Time Control Hardware

- VME based digital control hardware
  - 68030 processor
  - CSPI vector processor
- Capability:
  - 16 inputs
  - 10 outputs
  - 32 states at 1000 Hz; scales by (ns + ni) * (ns + no)
- Direct link to six HP laser measurement boards
- Control design in MATLAB on Sun SparcStation

- Analog: circuits for displacement and velocity feedback to active struts

Disturbance Actuation

- require pathlength control to 80 nm rms ($f > 0.25$ Hz) for nominal mission
- ambient lab disturbances: approx 40 nm rms in pathlength
- resolution of HP laser metrology: approx 17 nm rms

- apply scaled space-based disturbances (assume linear response of structure with amplitude) and control to 80 nm rms
- use actuators to simulate a specified amplitude and frequency spectrum in pathlength measurements using:
  - rotary proof mass actuators (PMA)
  - piezo struts mounted in structure
  - linear PMA's or external shaker

Testbed Model Development

Models

- continuum beam model
- full scale FE model (228 nodes)
- modal model based on system identification (external shaker; later active struts)

Dynamics of Testbed

- sets of bending modes in 31-50 Hz range; second set of modes in 100-120 Hz range
- with added mass of optics, 50 modes below 200 Hz
- symmetry results in repeated eigenvalues and clumping of modes
- low damping and repeated eigenvalues pose challenges for system identification

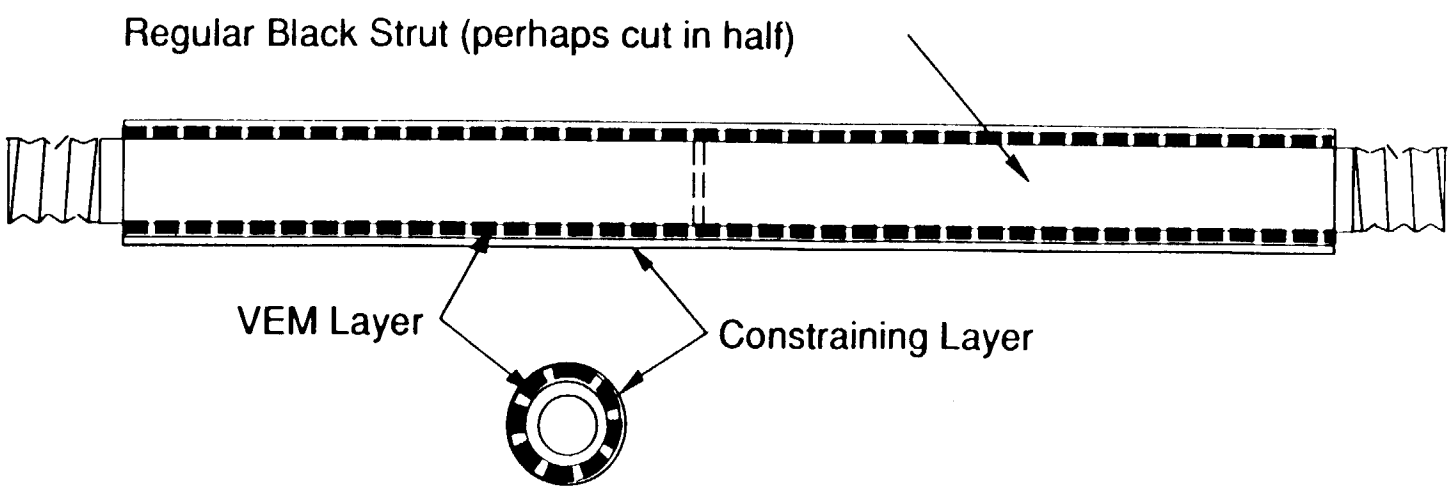
Passive Damping

- consider and incorporate passive damping to greatest extent possible
- less glamorous than active control, but it can only be beneficial for system identification, robust control design, and in reducing controller effort
- naked truss has < 0.1 % damping in most global modes
- damping options:
  - constrained-layer viscoelastic struts
  - shunted piezoelectric struts
  - viscous dashpot
  - proof mass
- problems:
  - difficult to add significant damping due to large number of struts
  - viscoelastics are temperature and frequency dependent
  - other options involve expensive hardware

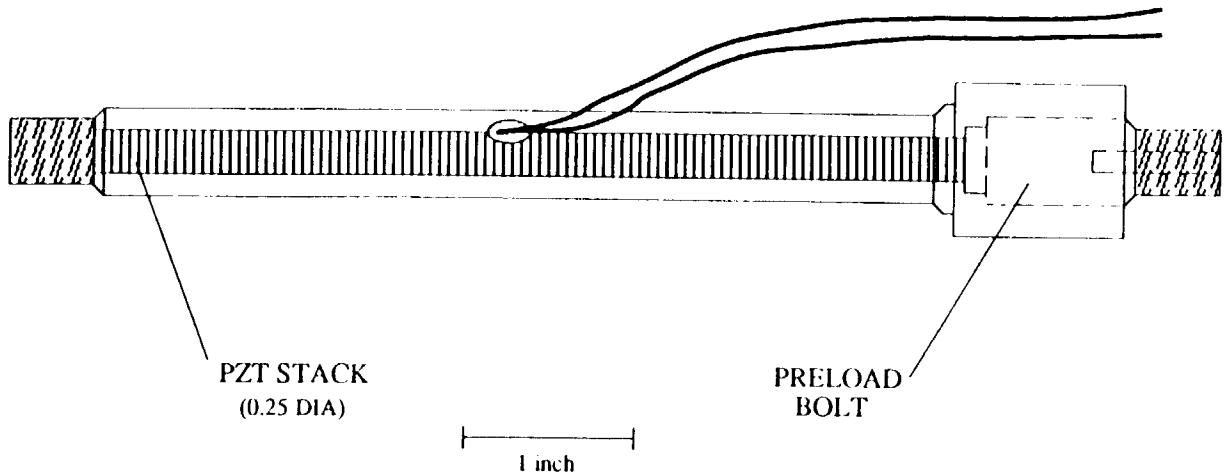
VEM Strut (Passive Damping)

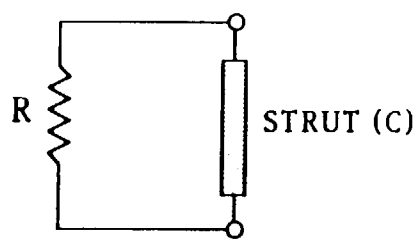
- Whole strut: strut keeps same stiffness
  VEM is not in load path

- Cut Strut: more damping benifits, because...
  strut is de-stiffened
  VEM in load path

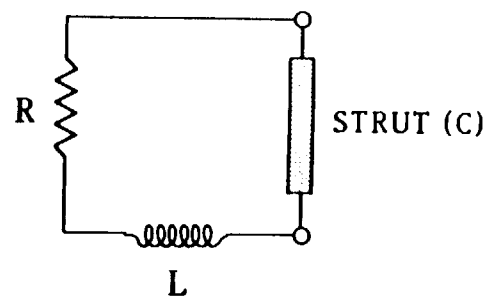


Shunted Piezoelectric Damping





Resistive Shunting



Resonant Shunting

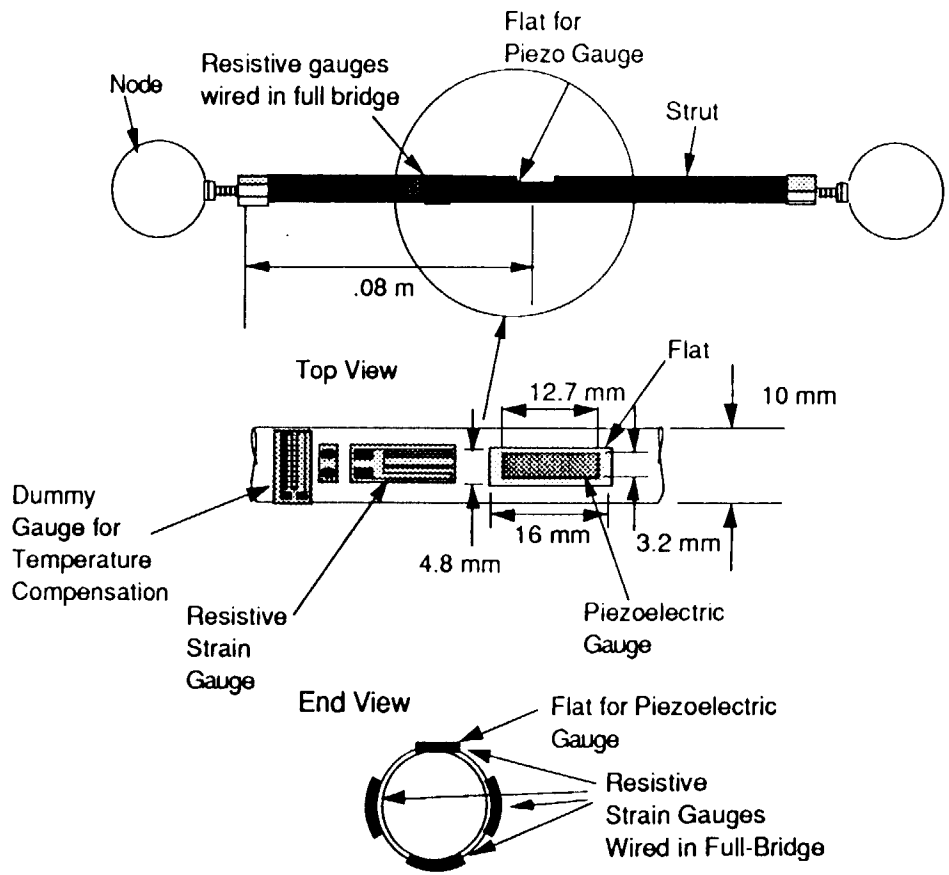
Characterization of Damping at Nanostrain Levels

- Most structural dynamic tests conducted in 10 - 1000 microstrain range
- Typical missions for interferometer-class structures require nanostrain-level operating range
- Uncertainty in aerospace community regarding assumptions of linearity and damping mechanisms at nanostrain levels
- Approach:

  Test rectangular bar and cylindrical specimens of typical spacecraft materials to determine changes in material damping

  - Rectangular 6061-T6 aluminum bars
  - Rectangular $[0]_{24}$ AS4/3501-6 Gr/Ep bars
  - Rectangular $[\pm 15]_{6s}$ AS4/3501-6 Gr/Ep bars
  - 6061-T6 aluminum tubes
  - $[\pm 15]_{3s}$ AS4/3501-6 Gr/Ep tubes
  - Interferometer Testbed

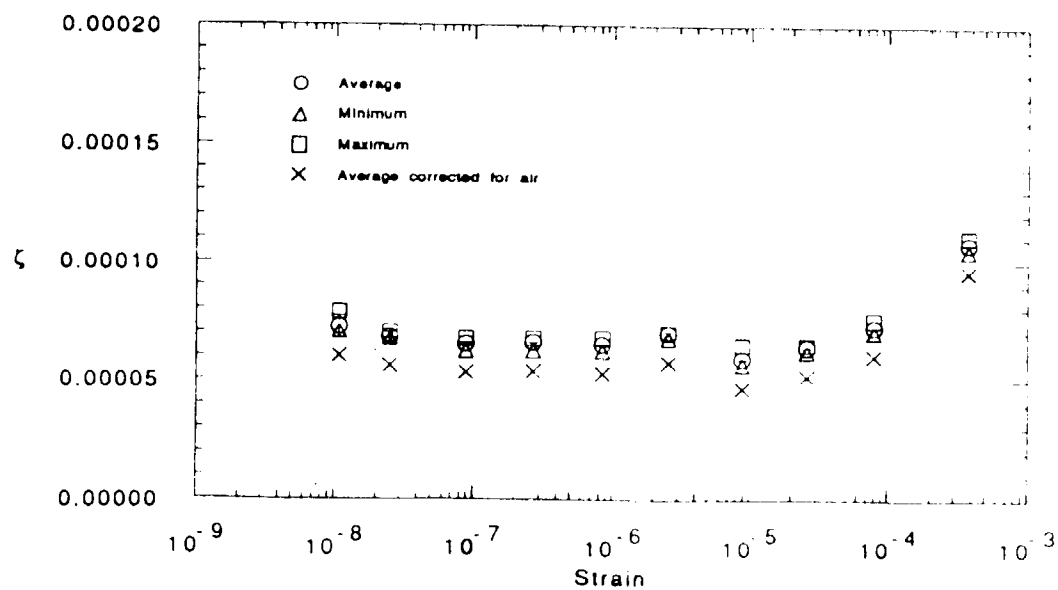
Instrumentation of Testbed



- Instrument one strut using same procedure as for tubes

Damping vs Strain in Aluminum Specimen

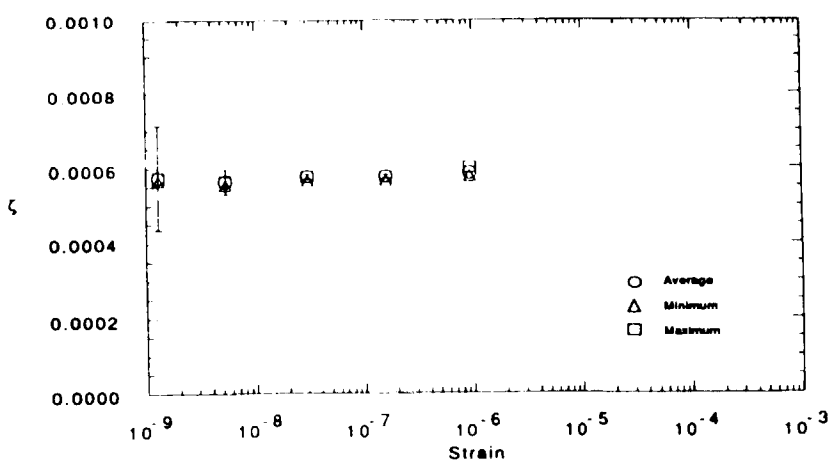
- 0.9m aluminum tube in air
- first mode, 185.1 Hz



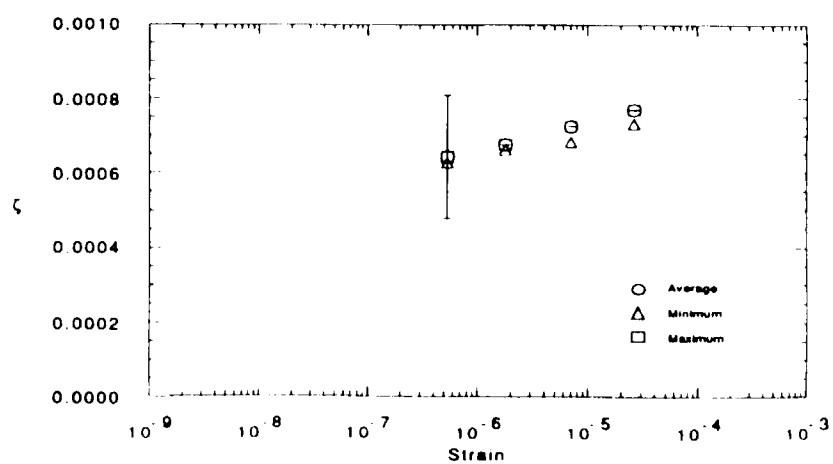
Damping vs Strain in Interferometer Testbed

- mode in first clump of 12 global modes (44.1 Hz)

Small Strain Range
(piezo bimorph actuator)



Large Strain Range
(proof mass actuator)



Results and Conclusions

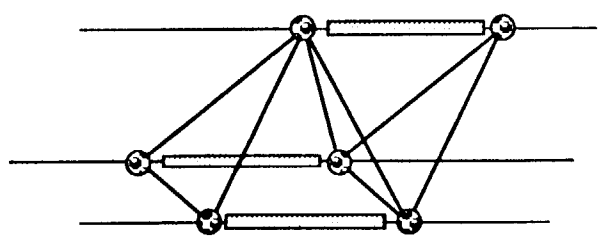
- Material and Structural damping independent of strain up to 10 $\mu\varepsilon$
  - Limit can be predicted with Zener model for aluminum bars and matrix and shear models for Gr/Ep bars
- Damping dependent on strain above 10 $\mu\varepsilon$
  - Dependence due to hysteretic motion of dislocations
- Structural damping dominated by joints

ACHIEVING CONTROL OF GLOBAL MODES

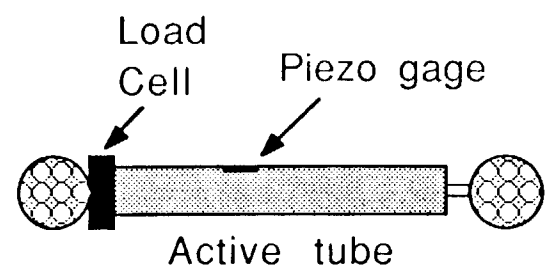
- Optical truss will provide 6 inputs.
  - The change in length of each leg at "each" instant in time.

- Active bays will be used to control the changes in path length.

ACTIVE BAY



ACTIVE STRUT



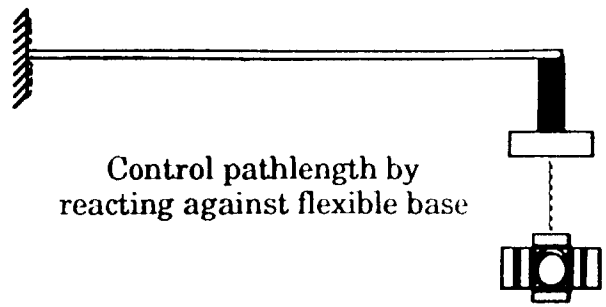
  - 3 strut configuration provides axial and 2 axis bending actuation.
  - The 6 laser inputs and an active bay for each leg should allow for independent control of each leg.
  - For 18 total struts, we could apply 18 distinct signals and have additional DOF to play with.

Positioning of a Mirror Mounted on a Flexible Base

Step One

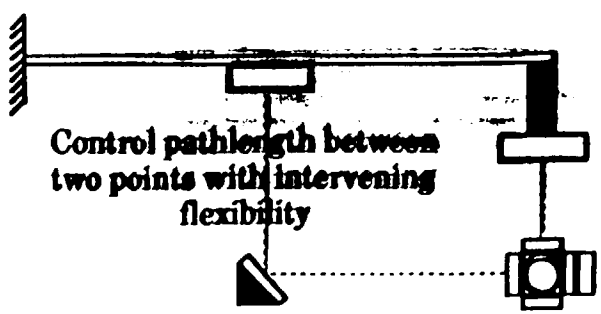
Control pathlength by reacting against rigid base

Step Two



Control pathlength by reacting against flexible base

Step Three



Control pathlength between two points with intervening flexibility

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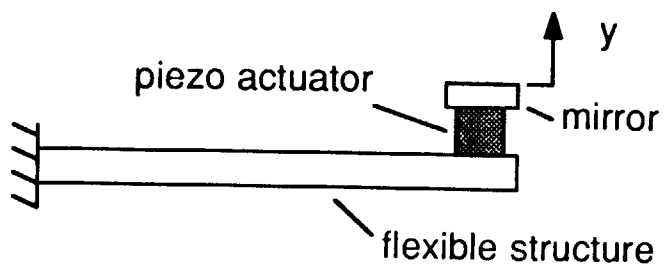
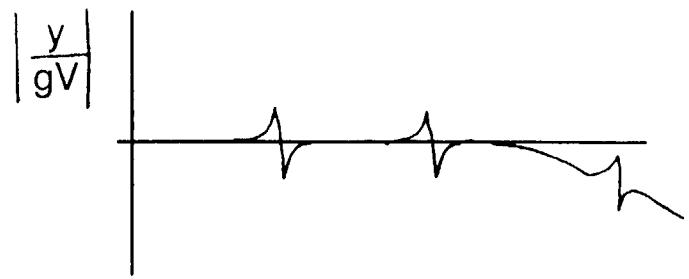
Results

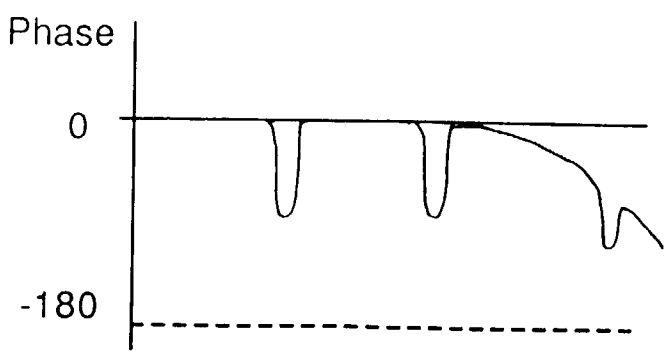
	Motion (rms) (0-20,000 Hz)	Attenuation	Motion (peak) (0-20,000 Hz)
Fixed Block			
Uncontrolled	17 nm		16 nm
Controlled	0.77 nm	-27 dB	5 nm @ piezo mode
Collocated			
Uncontrolled	77 nm		250 nm @ 1st mode
Controlled	3.1 nm	-26.8dB	11 nm @ piezo mode
Non-Collocated (x=0.5)			
Uncontrolled	45nm		190 nm @ 1st mode
Controlled	3.9 nm	-21.2 dB	10 nm @ piezo mode

Gain and Phase Margin Results



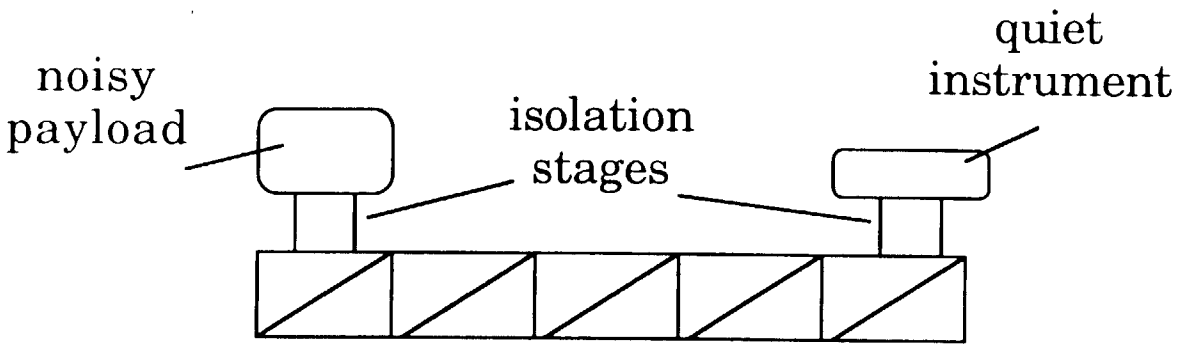


$$\text{gain} = \left\{ 1 + \left(\frac{m_m}{2\,\zeta_i\, m_i} \right)^2 \right\}^{1/2}$$



$$\phi = \frac{1}{2}\,\frac{m_m}{\zeta_i\, m_i}$$

Use Results for Structural Modifications



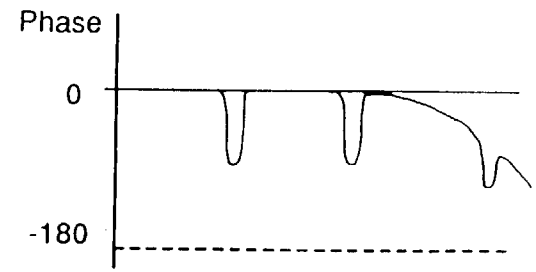
$$R_i = \frac{1}{2}\frac{m_m}{\zeta_i m_i}$$

- passive springs -- "soft enough"
- passive damping of global modes
- reactuation of mass
- local modification of mode shapes

Question: How does this analysis relate to the structural parameters of the interferometer testbed?

SISO Analysis Applied to Testbed FE Model

naked truss damping:	.06 %	(measured)
instrumented truss:	.6 %	(estimated)
damped truss:	6 %	(estimated)
moving mirror mass:	1.5 kg	



Mode # 1		Phase	
	X	Y	Z
ζ = .0006	163	84	167
ζ = .006	68	10	84
ζ = .06	7.8	1	10
m = .15, ζ = .006	7.8	1	10
m = .15, ζ = .06	.8	.1	1

Future Work on Isolation in Presense of Unmodelled Structural Flexibility

Extend analysis of Sievers/Garcia from SISO to

- MIMO collocated (multiaxis mirror mount)
- MIMO noncollocated (three mirrors)

Investigate isolation system design philosophy

Hardware implementation on testbed

Make Ri parameter "spherical" by appropriate local structural modifications

Apply to successive closure of independent control loops:

preserve $R_i = \frac{1}{2}\frac{m_m}{\zeta_i m_i}$ at previously closed loops

Relate analysis to a disturbance source where mass reactuation is utilized for vibration isolation

Continuing and Future Work on Interferometer Testbed

- integration of optics with structure
- system identification
- component identification of passive struts
- close SISO loops with active members
- active MIMO path length control with active mirrors
- achieve functional testbed by October