MICRO-PRECISION CONTROL/STRUCTURE INTERACTION TECHNOLOGY FOR LARGE OPTICAL SPACE SYSTEMS

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INTRODUCTION

The CSI program at JPL is chartered to develop the structures and control technology needed for sub-micron level stabilization of future optical space systems. The extreme dimensional stability required for such systems derives from the need to maintain the alignment and figure of critical optical elements to a small fraction (typically $1/20^{th}$ to $1/50^{th}$) of the wavelength of detected radiation. The wavelength is about 0.5 micron for visible light and 0.1 micron for ultra-violet light. This $\lambda/50$ requirement is common to a broad class of optical systems including filled aperture telescopes (with monolithic or segmented primary mirrors), sparse aperture telescopes, and optical interferometers. The challenge for CSI arises when such systems become large, with spatially distributed optical elements mounted on a lightweight, flexible structure.

In order to better understand the requirements for micro-precision CSI technology, a representative future optical system was identified and developed as an analytical testbed for CSI concepts and approaches. An optical interferometer was selected as a stressing example of the relevant mission class. The system that emerged was termed the Focus Mission Interferometer (FMI).

This paper will describe the multi-layer control architecture used to address the FMI's nanometer level stabilization requirements. In addition the paper will discuss on-going and planned experimental work aimed at demonstrating that multi-layer CSI can work in practice in the relevant performance regime.

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THE VIBRATIONAL STABILITY CHALLENGE

High performance space optical systems typically have total light pathlength stability goals on the order of $\lambda/50$ ($\approx 12nm$ visible, $\approx 2nm$ ultraviolet). Because the total pathlength stability budget must be allocated among several contributors, a reasonable stability goal for any one of the system's optical elements is in the neighborhood of $\lambda/200$ ($\approx 3nm$ visible, $\approx 0.5nm$ ultraviolet). Structural vibrations, even on very quiet spacecraft, are typically larger than the desired "nanometers" goal. (Consider that only four millionths of a "g" vibration level at $10Hz$ is ±100 nanometers of motion.) Analysis of large optical structures indicates that between a few-hundred and a few-thousand nanometers of dynamic motion are caused by noise from even the extremely quiet Hubble Space Telescope reaction control wheels (RCW's) operated at less than 50% of their design spin rate (higher rate gives greater disturbance). Beyond RCW's, other disturbance sources, such as tape recorders, pointing drive mechanisms, control moment gyros, etc, have not yet been evaluated but they are likely to induce vibration levels at least as severe as the HST RCW's.
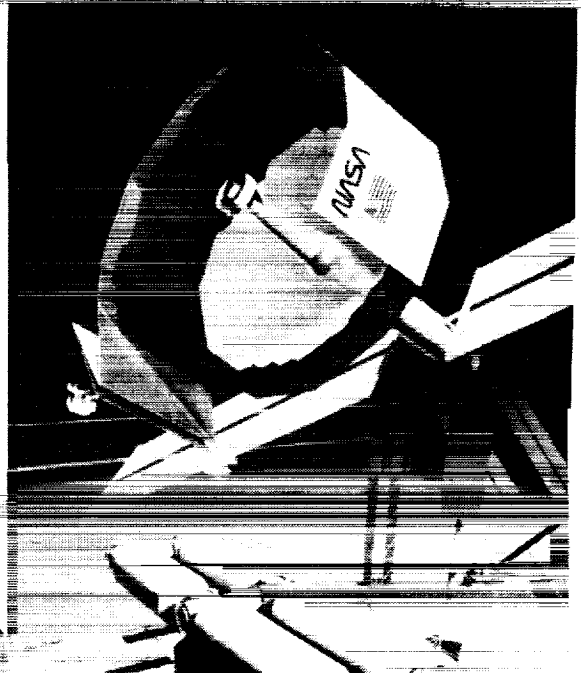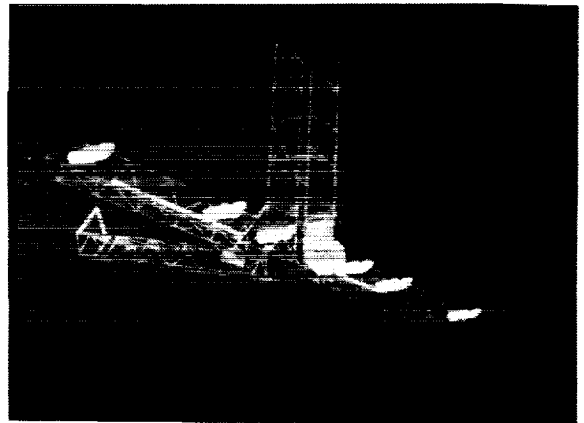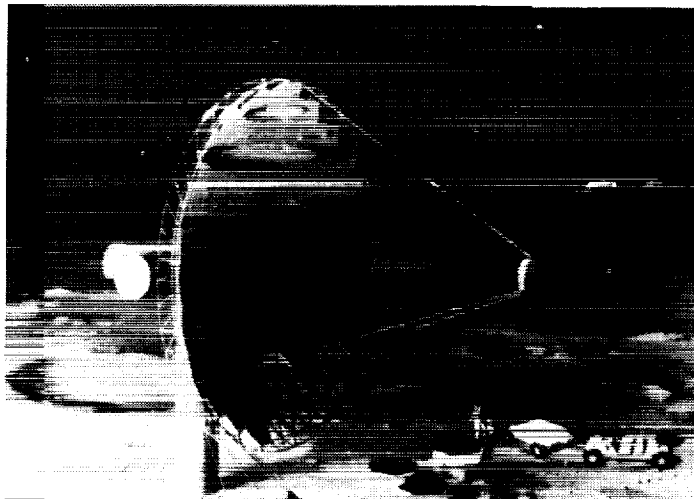
CSI FOCUS MISSION INTERFEROMETER

Future spacebased large optical systems can be divided into two broad categories: interferometers, where spatially distributed "small" collecting apertures are combined to synthesize the performance of a single large aperture; and filled aperture systems, which are essentially large conventional telescopes that typically incorporate segmented primary mirrors due to the difficulty (and inherent weight) of fabricating very large monolithic mirrors. JPL has selected a representative optical interferometer as the target application on which to focus its CSI technology development efforts - hence the name Focus Mission Interferometer (FMI). An optical interferometer can be used for high resolution imaging as well as extremely precise astrometry (astrometry is the mapping of stellar positions in the sky). When used for imaging, the FMI's effective baseline of 24 meters would give it roughly 10 times the resolving power of the Hubble Space Telescope. This translates into a resolution of 5 miliarcseconds.

The optical performance of the FMI relative to its 2.5 nanometer differential pathlength stabilization requirement has been analyzed in some detail and it has been determined that vibration attenuation factors of between 1,000 and 10,000 are necessary to meet the requirement with margin. In order to meet this challenge, CSI has adopted an approach that entails a multi-layer control architecture, with each layer responsible for providing between one and two orders of magnitude attenuation. The three layers are: structural control, disturbance isolation, and active optical control.
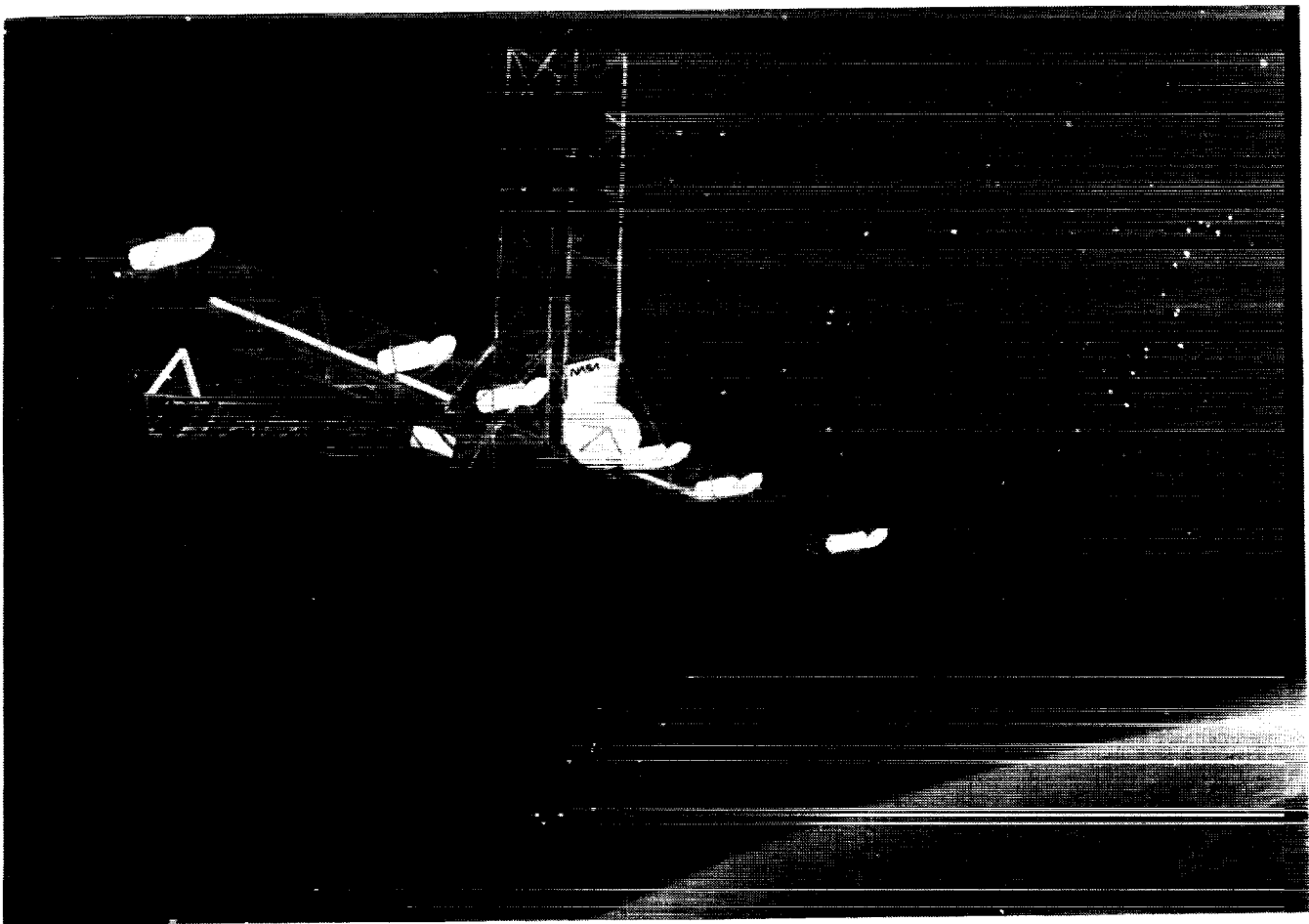
MULTI-LAYER CSI ARCHITECTURE

Rather than use only a single (centralized) control system, we have broken up the problem into autonomous subsystems, each of which has its own task. This autonomy makes the overall system more robust. In addition the first two systems help accomplish other objectives besides optical pathlength control, for example the siderostats need to be coaligned and the metrology tower should be kept quiet.

o THREE LAYERS OF CONTROL:

1. STRUCTURAL CONTROL - ADD DAMPING TO THE MODES. THIS REDUCES THE GENERAL VIBRATION LEVEL AND MAKES THE OPTICAL CONTROLS MORE ROBUST.

2. ISOLATION OF DISTURBANCE SOURCES - ATTACKS THE KNOWN SOURCES OF DISTURBANCES. IN OUR CASE WE SOFTMOUNT THE REACTION WHEELS.

3. OPTICAL CONTROL - CONTROL OF THE OPTICAL ELEMENTS DIRECTLY. THIS ACTUALLY ENCOMPASSES 3 SEPARATE CONTROL SYSTEMS FOR PATH-LENGTH CONTROL (TIMING BELT, VOICE COIL, AND PZT) ON EACH TROL-LEY, AND A POINTING SYSTEM FOR EACH SIDEROSTAT.

STRUCTURAL MODEL

The FMI design [1]* incorporates 25 active struts of the truss to provide for structural vibration suppression. The struts are located symmetrically in the two "arms" of the interferometer as well as in the "tower." Strut locations were chosen via heuristic modal kinetic and strain energy arguments. Each active strut spanning two nodes of the interferometer truss is composed of a passive truss element and an active piezoelectric element in series. The specific stiffness of the active element was designed to be the same as that of the truss elements for complete interchangeability with other elements. Each active element incorporates its own force and precision displacement measurement system.

A NASTRAN finite element model of the FMI structure was built incorporating 527 modes. In former analyses [1,2], reduced order models were built, but in the present work the full model was used. Rather than combining the models for the plant and controllers in state space, which would produce state space models of order around 1300, (double the number of modes plus 25 active element controllers plus pathlength control and isolation) models were combined in the frequency domain. This requires inversions of the order of the number of loops, independent of the state order. Since each block of the model is brought into the frequency domain separately, special knowledge of each block can be used [3].

STRUCTURAL MODEL

o NASTRAN FINITE ELEMENT MODEL
- 297 GRIDS, 465 RODS, 17 BARS, 37 RBE2 ELEMENTS
- 527 MODE DIAGONAL Pro-Matlab MODEL, DAMPING RATIO 0.1%.
- 25 ACTIVE MEMBERS
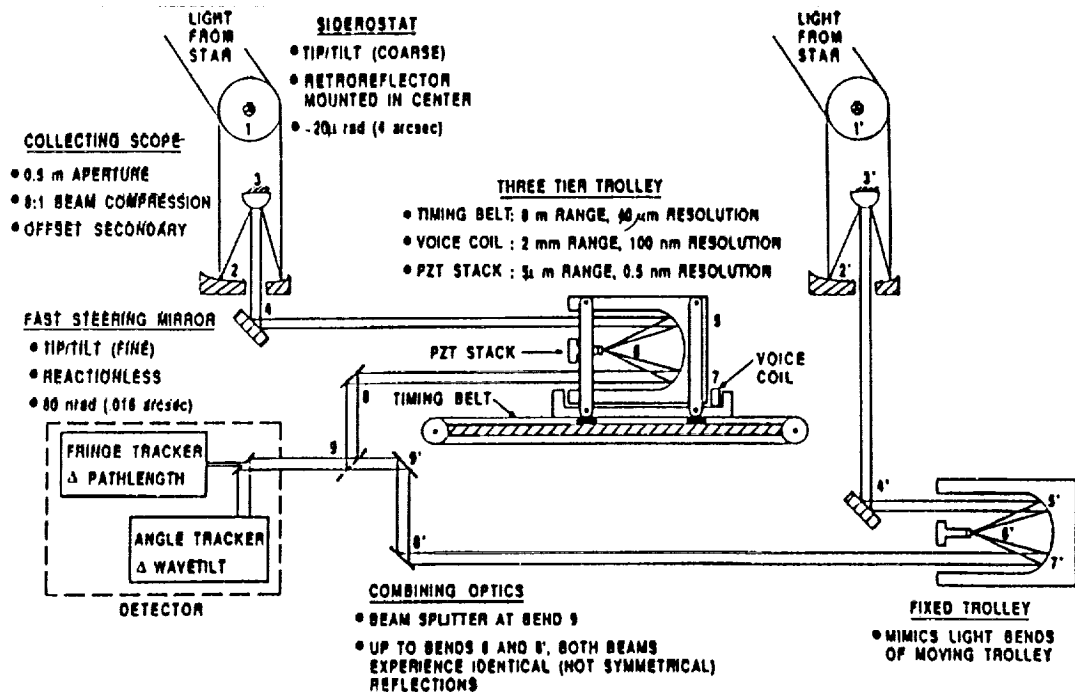- REACTION WHEEL FORCE DISTURBANCE (FOUR WHEELS, SPIN UP FROM 0 TO 3000RPM)

*References 1–8 are cited in text.

OPTICAL MODEL

Each interferometer (a pair of siderostats) takes light from the +Y and -Y arms, compressing the beam, adjusting the pathlength and tilt to compensate for structural vibration, and combines the beams at a focal plane. The optical train consisted of 19 elements, 9 on the +Y half, 9 on the -Y half, and the focal plane. One of the three interferometers of the FMI has been modeled using the Controlled Optics Modeling Package (COMP, based on [4]). One purpose of this tool is to determine the partial derivatives of the optical pathlength to the motion of the individual optical elements. This gives a matrix that transforms structural vibration (six degrees of freedom at each element) into optical pathlength, a component of the C matrix.

OPTICAL MODEL

o OPTICAL MODEL BUILT WITH THE CONTROLLED OPTICS MODELING PACKAGE (COMP)

o COMPLETE INTERFEROMETER, 19 OPTICAL ELEMENTS

o LINEAR CHIEF RAY MODEL OUTPUT TO Pro-Matlab

Optical Layout for Interferometer A

OPTICAL PATHLENGTH CONTROL

For the vibration analysis, the disturbance source used was the imbalance force from 4 Hubble Space Telescope reaction wheels spinning from 0 to 1200 RPM [1,2]. This spin up takes place slowly, for example at the orbital period to counter gravity gradient torques, and hence the disturbance may be applied quasi-statically in the frequency domain. At each wheel speed, the reaction wheel imbalance harmonics are multiplied by the appropriate values from the transfer function and combined using the rms.

To control the optical pathlength directly, a controller similar to that used in [1] is implemented. The primary difference is that while in [1] the bandwidth was limited to 10 Hz due to light levels, current studies [8] indicate that this is overly conservative, and hence a bandwidth of $250Hz$ was used.

OPTICAL PATHLENGTH CONTROL

o OPTICAL PATHLENGTH
 PERFORMANCE

o OPEN VERSUS CLOSED LOOP

Pathlength Error

sws 28-Feb-92   Wheel Speed, Hz
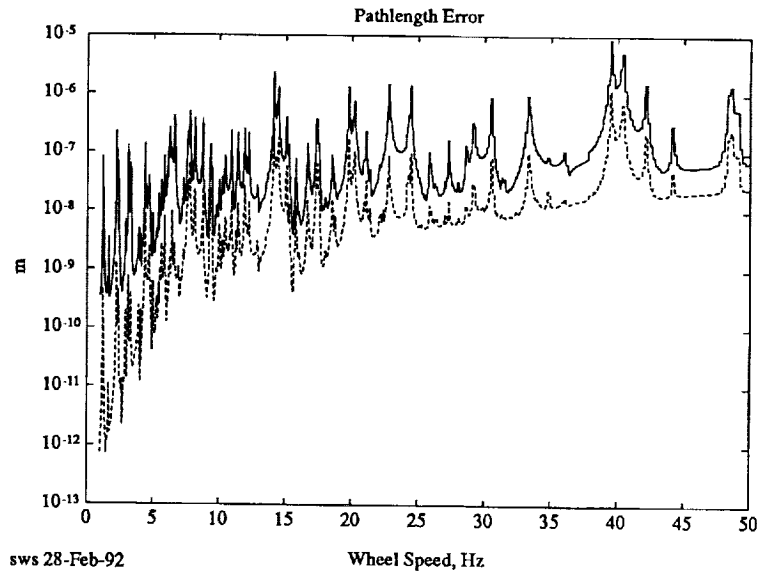
CONTROL	RMS PATHLENGTH ERROR (nm)
None	702
250Hz	94

VIBRATION ISOLATION

Vibration isolation can be carried out at the source of the disturbance - suspending the reaction wheels in the same manner as is done on the Hubble Space Telescope. This is implemented as a simple second order filter with $10Hz$ poles damped by $\zeta = 0.3$ on the disturbance source. Isolation has a large effect on high frequency disturbances, and is therefore very desirable. Of course in practice it is not possible to isolate all disturbances, leaving some (hopefully smaller) disturbances to be handled solely by the other layers.

VIBRATION ISOLATION

o OPTICAL PATHLENGTH
  PERFORMANCE

o NO ISOLATION
o 10 Hz ISOLATION

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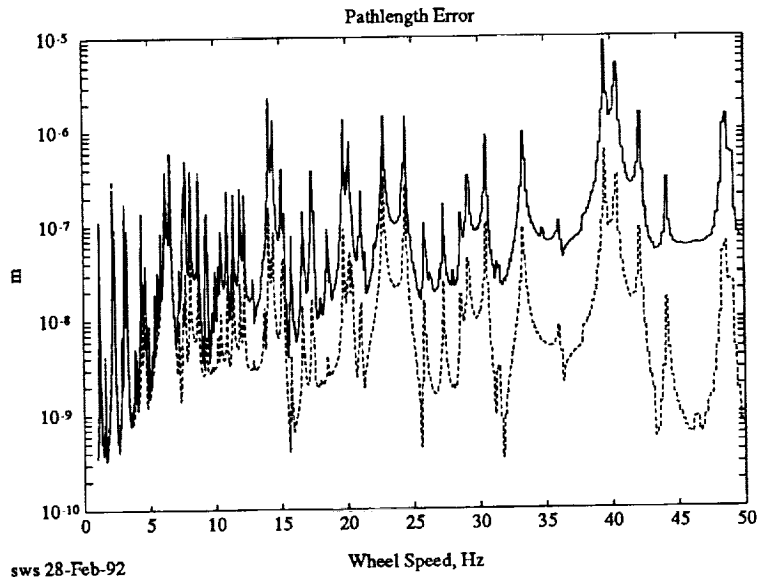
ISOLATION FREQUENCY (Hz)	RMS PATHLENGTH ERROR (nm)
∞	702
10	60

DIAL-A-STRUT CONTROLLER

A robust way of implementing a softening controller is with bridge feedback [5-7, 8] using both force and displacement measurements. At JPL a Dial-a-Strut controller has been developed that has a simple form, can easily be adjusted to work with a wide variety of structures, and is insensitive to plant and control parameter variations.
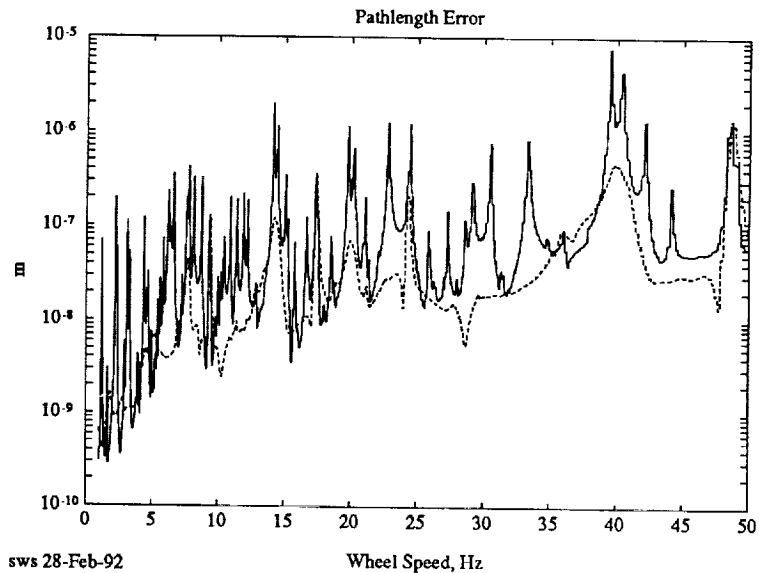
The Dial-a-Strut is designed to control the strut so its impedance (using the force-current analogy so we get $Z = velocity/force$) is determined by the impedance of selected electrical components:

$$Z \rightarrow \frac{1}{\gamma Z_d},$$

$$Z_d(s) = \left(C_1 s + \frac{C_2 s}{1 + RC_2 s}\right)^{-1}.$$

DIAL-A-STRUT CONTROLLER

Pathlength Error

sws 28-Feb-92   Wheel Speed, Hz

o OPTICAL PATHLENGTH
  PERFORMANCE

o OPEN VERSUS CLOSED LOOP

CONTROL	RMS PATHLENGTH ERROR (nm)
None	702
Dial-a-Strut	191

MULTI-LAYERED CONTROL SYSTEM

Combining the various control strategies yields the pathlength control results shown. The plot shows the results with (in order of descending pathlength error) no control, with Dial-a-Strut control (all 25 struts), with Dial-a-Strut and the disturbance isolator, and with all the controllers. The table shows that all the various layers are necessary to get down to the nanometer level. Implementing the high bandwidth pathlength control has not been examined carefully for the FMI, though similar bandwidths have been used on much simpler ground-based structures. The NASTRAN model is not accurate much above $100Hz$. The highest bandwidth loop of the pathlength control moves only a small mirror, and is almost uncoupled from the structural modes. The voice coil loop that moves a trolley is coupled much more closely to the structure and it is likely that structural damping will be essential for that loop to be robust and high performance.

MULTI-LAYERED CONTROL SYSTEM

o OPTICAL PATHLENGTH
   PERFORMANCE

o ADDING SUCCESSIVE LAYERS
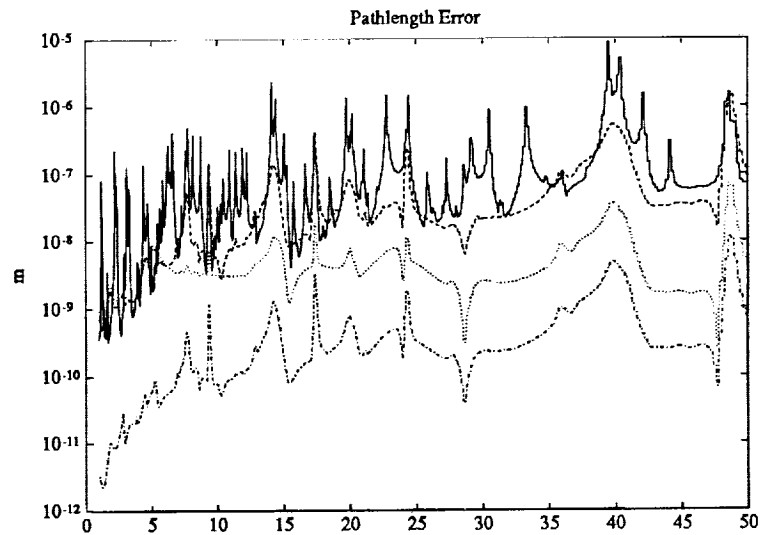
Pathlength Error

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| CONTROL	RMS PATHLENGTH ERROR (nm)
None	702
Dial-a-Strut	191
Dial-a-Strut+ Isolator ($10Hz$)	10
Dial-a-Strut+ Isolator ($10Hz$) + PL Control ($250Hz$)	1.5

CSI PHASE B MULTI-LAYER TESTBED

The Phase B Multi-Layer Testbed incorporates three layers of control which either attenuate or reject the effects of disturbances. They consist of the optical compensation layer, the structural quieting layer, and the disturbance isolation layer. The CSI Phase B Testbed Facility has been built to resemble a portion of an interferometer telescope, including a laser star simulator, a metering truss structure, an optical pathlength delay line, and the associated instrumentation and real time control computers. Preliminary experiments using the optical compensation layer have demonstrated the ability to reduce jitter in the optical pathlength by a factor of 4,000. Preliminary experiments using the structural quieting layer have demonstrated the ability to increase the amount of damping in the metering truss by a factor of 25, reducing the level of jitter in the optical pathlength by a similar factor. A prototype disturbance isolation layer has been tested separately from the Phase B Testbed, and preliminary experiments have demonstrated the potential to reduce the level of disturbance forces transmitted to the structure by at least a factor of 10. Future experiments will operate these three layers in combination, where the attenuation effects are expected to cascade, thereby multiplying together the benefits of each layer to achieve levels of disturbance rejection approaching 10,000.
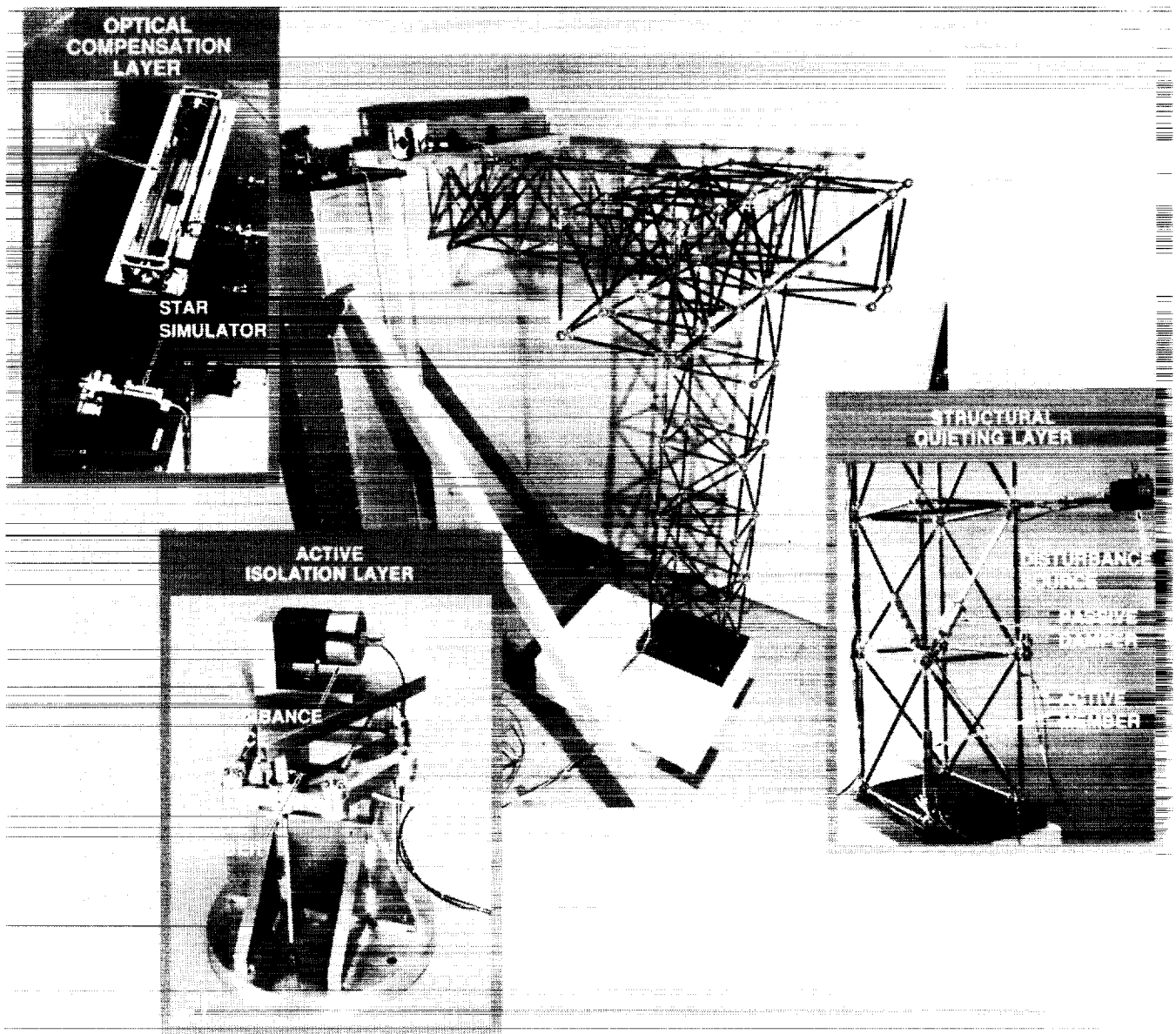
CSI OPTICAL COMPENSATION EXPERIMENT

The optical delay line experiment was designed to capture the interaction between structural flexibility and optical pathlength as it would occur in a space-based optical interferometer such as the Orbiting Stellar Interferometer (OSI). Varying levels of control/structure interaction can be emulated by reconfiguring the testbed optical train. The approach is to conduct experiments with optical trains of increasing complexity, ultimately replicating the characteristics of an interferometer flight instrument system. The current optical delay line control is implemented by translating coarse and fine mirror stages based upon detected variations in the laser (star simulator) pathlength.

Experimental results obtained by closing control loops around the initial optical configuration pictured have demonstrated approximately 12 nanometers RMS laser pathlength stabilization, which represents a factor of 4,000 attenuation from open loop response to the laboratory environment. The challenge is to provide the same level of control when the optical train is reconfigured to couple more structural motion into the laser pathlength which is a situation more representative of a flight system. Meeting this challenge (planned for FY '92) will be a major step toward validating the CSI technology necessary to enable the next generation of precision space optical systems.
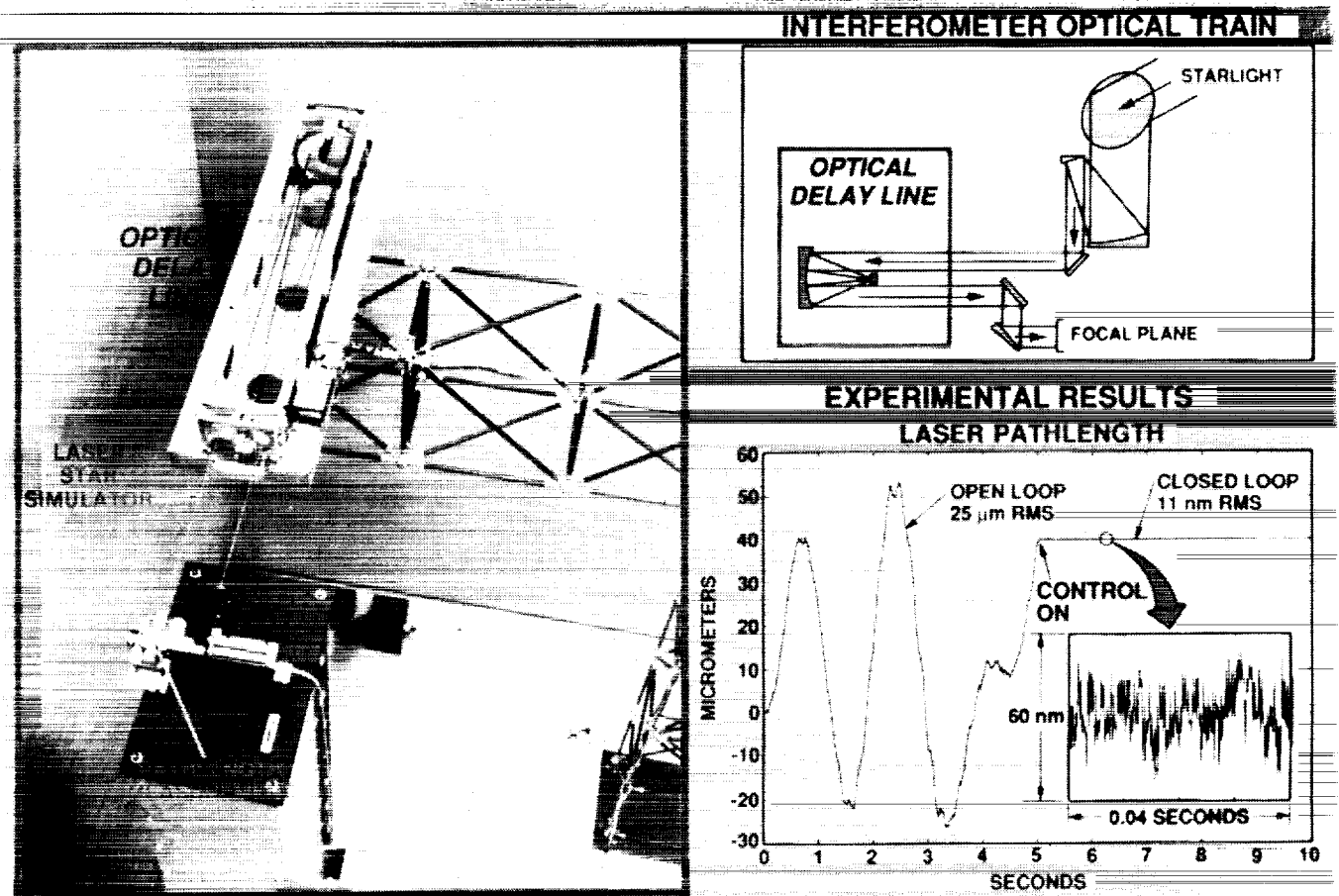
CSI STRUCTURAL QUIETING EXPERIMENTS

The CSI Structural Quieting Layer is specifically designed to reduce the level of vibration in the structure. This is accomplished through a combination of passive damping and active control using active structural members. Passive dampers have the advantages of simplicity of design and of requiring no power for operation. Preliminary experiments with passive dampers have demonstrated the ability to increase the level of damping in the structure by a factor of 25, reducing the degree of vibration in the structure by a similar amount.

Active structural members, which utilize an embedded piezoelectric actuator, have the advantage of being tunable for optimal performance even after the structure has been assembled and/or deployed. The active dial-a-strut control circuit cannot only be tuned to emulate passive dampers, but can also be designed to achieve a more exact impedance match to the structure, providing specific damping performance. For example, the active member can be tuned to specifically damp just the lowest structural mode, as is shown in the figure. Preliminary experiments using the dial-a-strut to emulate a passive damper have achieved results similar to a passive damper and have verified the control circuit design. Future experiments will explore the tunable nature of the active approach to provide the highest levels of performance.

CSI PHASE B STRUCTURAL QUIETING LAYER
TEST RESULTS
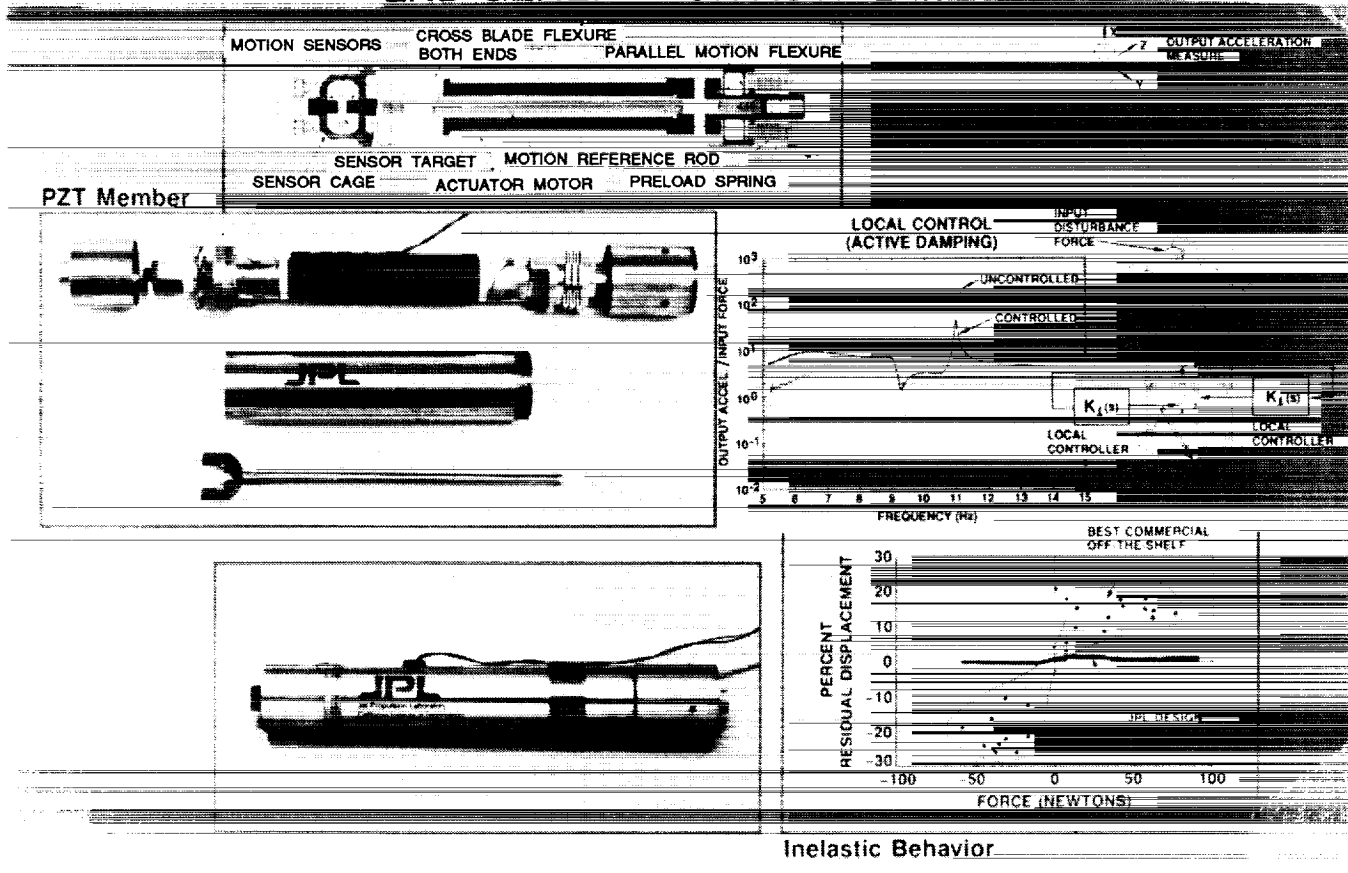
CSI PHASE B MULTI-LAYER TESTBED
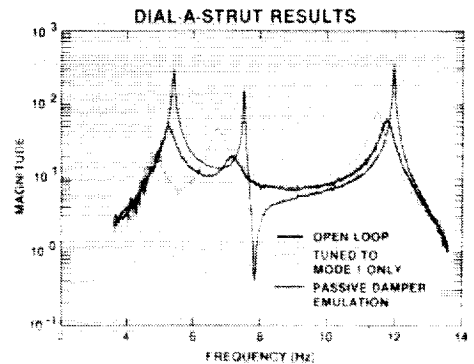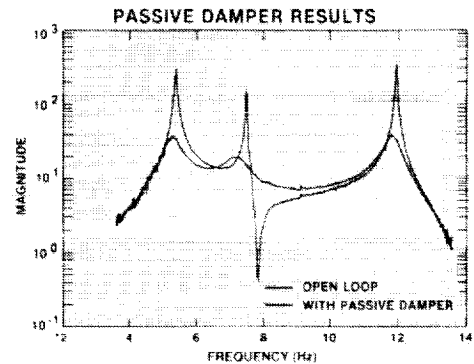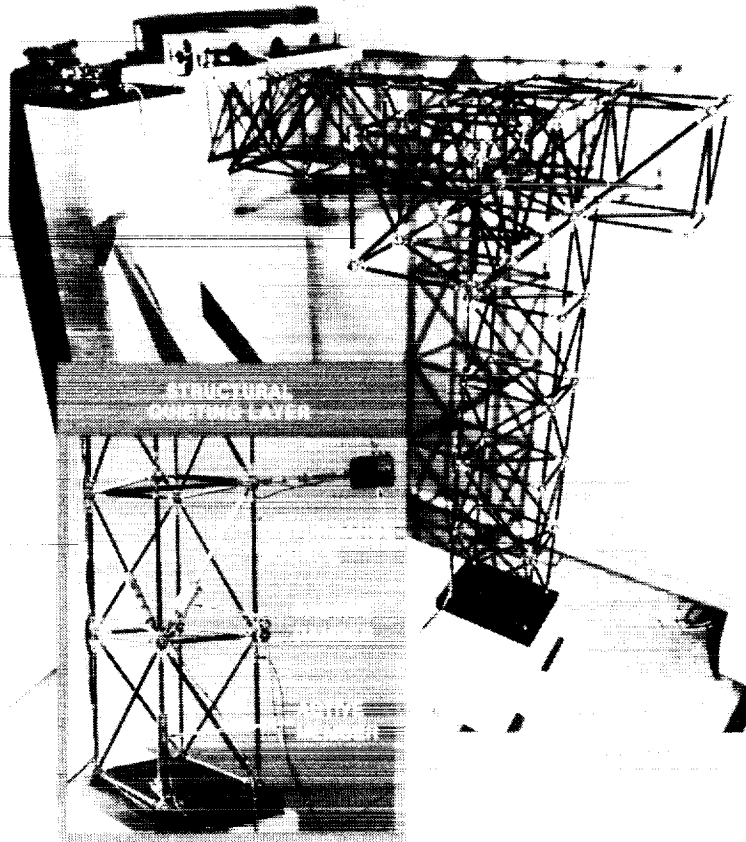
JPL ACTIVE MEMBER TECHNOLOGY

2nd Generation Active Members: JPL testing has established that even the best commercially available piezoelectric actuators exhibit hundreds of nanometers of stiction and nonlinear offset. The JPL 2nd generation Active Member actuator vastly reduces these nonlinear behaviors, and insures the feasibility of precision structural control at the nanometer level. The "Inelastic Behavior" scatter plot shows virtual elimination of nonlinear offsets with the JPL Active Member.
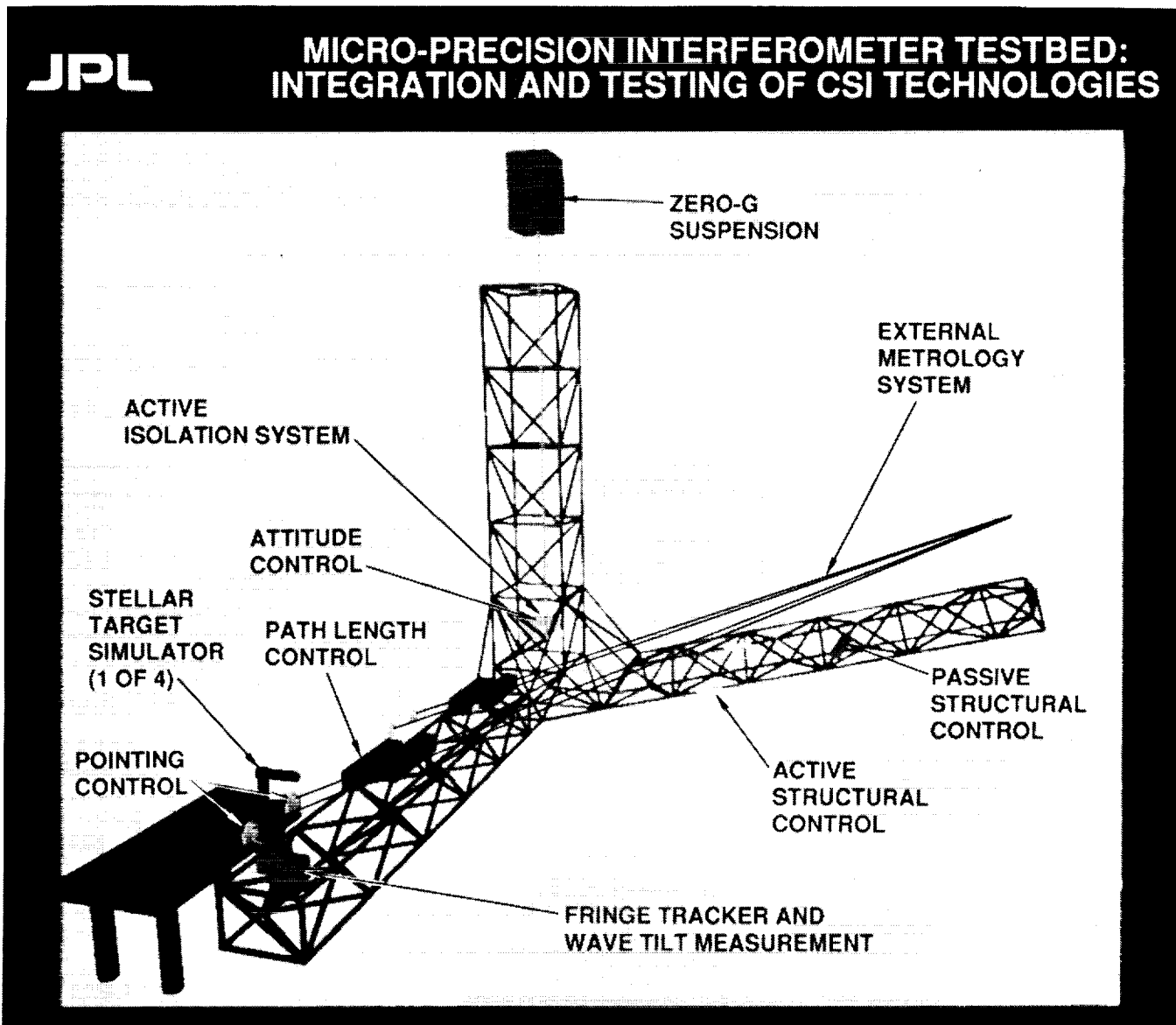
Impedance Based "Dial-A-Strut" Local Control: Structural control performance and robustness are both difficult to achieve on highly resonant structures. JPL has developed robust, impedance-based local controllers which "de-reverberate" the structure, greatly reducing resonant behavior. After the structure is de-reverberated, it becomes possible to design high performance robust global controllers to further stabilize the structure. The "Local Control (Active Damping)" frequency response plot shows successful de-reverberation of the JPL Phase 0 Precision Truss using impedance-based local controllers on two active members. These "Dial-A-Strut" controllers permit independent setting of active member stiffness and damping with the simple adjustment of a dial.

2ND GENERATION ACTIVE MEMBER

Inelastic Behavior

# JPL MICRO-PRECISION INTERFEROMETER (MPI) TESTBED

As a follow-on to the Phase B Multi-Layer Testbed, JPL is in the process of constructing a more ambitious test facility with the goal of conducting system level ground validation tests of micro-precision CSI technology. The new facility, named the Micro-Precision Interferometer (MPI) Testbed, will incorporate the multi-layer architecture but will embody several additional features: attitude control (over small angles), a soft suspension system to simulate free-free boundary conditions, an external metrology system for precise sensing of structure geometry, and high precision pointing control of optical lines-of-sight. The physical scale of the structure will be approximately 7 meters by 7 meters by 7 meters resulting in roughly a one half scale "one-armed" version of the FMI. Perhaps most importantly, the MPI is expected to operate at a level of precision comparable to that of an ultimate interferometer flight system. From a scientific standpoint, the MPI will clearly demonstrate end-to-end operation of a multi-baseline optical interferometer. From an engineering standpoint the MPI represents the ultimate ground-based demonstration that micro-precision CSI technology is ready for application to a broad class of future precision optical space systems.

JPL

MICRO-PRECISION INTERFEROMETER TESTBED: INTEGRATION AND TESTING OF CSI TECHNOLOGIES

- ZERO-G SUSPENSION
- EXTERNAL METROLOGY SYSTEM
- ACTIVE ISOLATION SYSTEM
- ATTITUDE CONTROL
- STELLAR TARGET SIMULATOR (1 OF 4)
- PATH LENGTH CONTROL
- POINTING CONTROL
- PASSIVE STRUCTURAL CONTROL
- ACTIVE STRUCTURAL CONTROL
- FRINGE TRACKER AND WAVE TILT MEASUREMENT

CONCLUSIONS

A large class of future astronomy and astrophysics space missions will entail the development of large optical systems that will be distributed over lightweight, flexible structures. Maintaining the required nanometer level alignment and stability of optical surfaces for such systems will be a challenge of the first order. JPL's CSI Program is developing structures and control technologies to address this challenge, and is conducting both analytic and experimental research toward this end.

This paper has presented an analytical study that demonstrates the feasibility of applying a multi-layer control architecture to a representative large optical space system. The three to four orders of magnitude vibration attenuation predicted in this analysis is currently being buttressed by the results of laboratory tests on the CSI Phase B Multi-Layer Testbed. Future CSI experiments on the Micro-Precision Interferometer Testbed (pictured below undergoing structural assembly) will demonstrate similar levels of vibration attenuation while performing at the relevant nanometer level in an end-to-end fashion on a large scale structure. The MPI Testbed should be completed by the summer of 1993 and ready to begin coarse testing shortly thereafter.
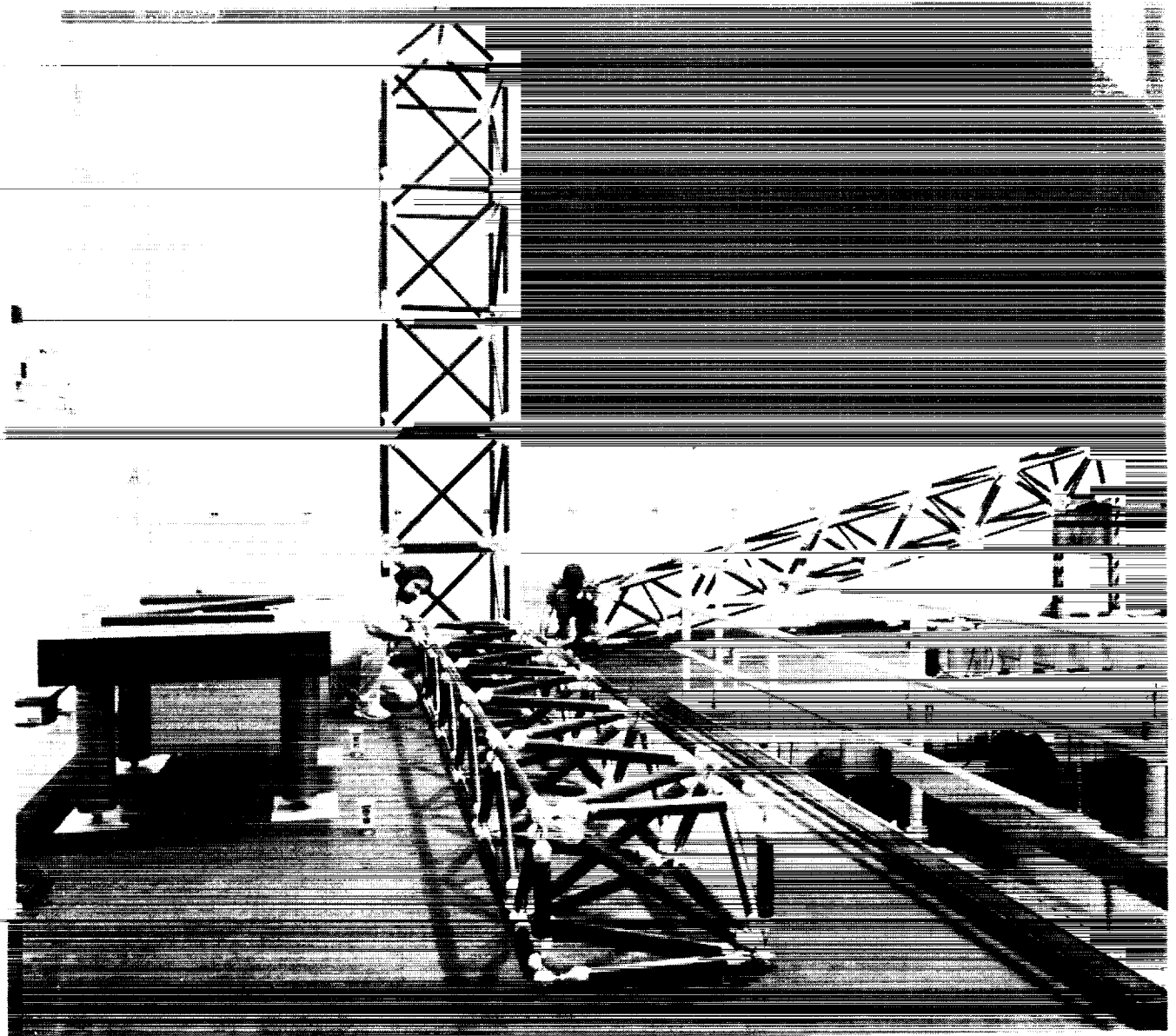
ACKNOWLEDGEMENT

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