N90-21064

Zenith Star:
A Structural Control Challenge

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3rd Annual NASA/DOD CSI Conference
San Diego, California
January 29 - February 2, 1989

INTRODUCTION

The Zenith Star experiment (Figure 1) is designed to demonstrate and evaluate the performance of a laser in space to answer critical issues relevant to SDI. This experiment is fully compliant with the restrictive interpretation of the 1972 Anti-ballistic Missile (ABM) Treaty. As such it does not directly perform all of the functions of a defensive system nor to the level required by an operational system. Its results however, do provide a measure of the potential of the operational systems by applying the appropriate scaling from the benchmarks achieved by it in space.

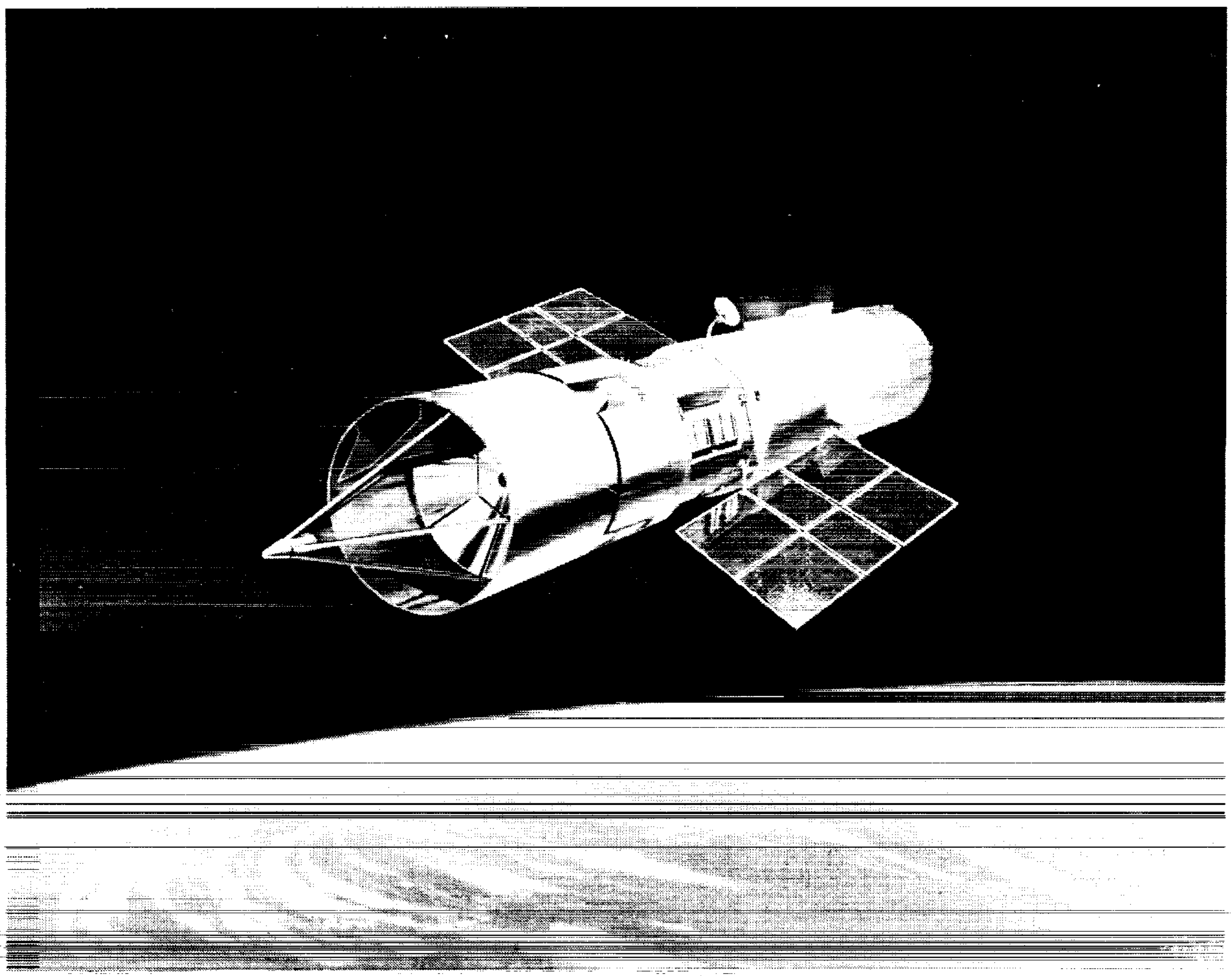

Figure 1: Zenith Star Experiment

The experiment (Figure 2) consists of a series of high power evaluations of beam control and a series of low power evaluations of the tracking and pointing functions of the system.

The high power experiments evaluate the beam control by direct measurement of the far field beam performance with a high power target board. Both space propagation and upper atmospheric effects are measured.

The low power experiments evaluate the tracking and pointing function performance while tracking a booster throughout its boost phase flight. The Agile Control Performance is evaluatd by performing structured characterization and large and small angle repointing of the system against a star field, small test objects (carried on board), and multiple boosters to exercise the system under multiple conditions.

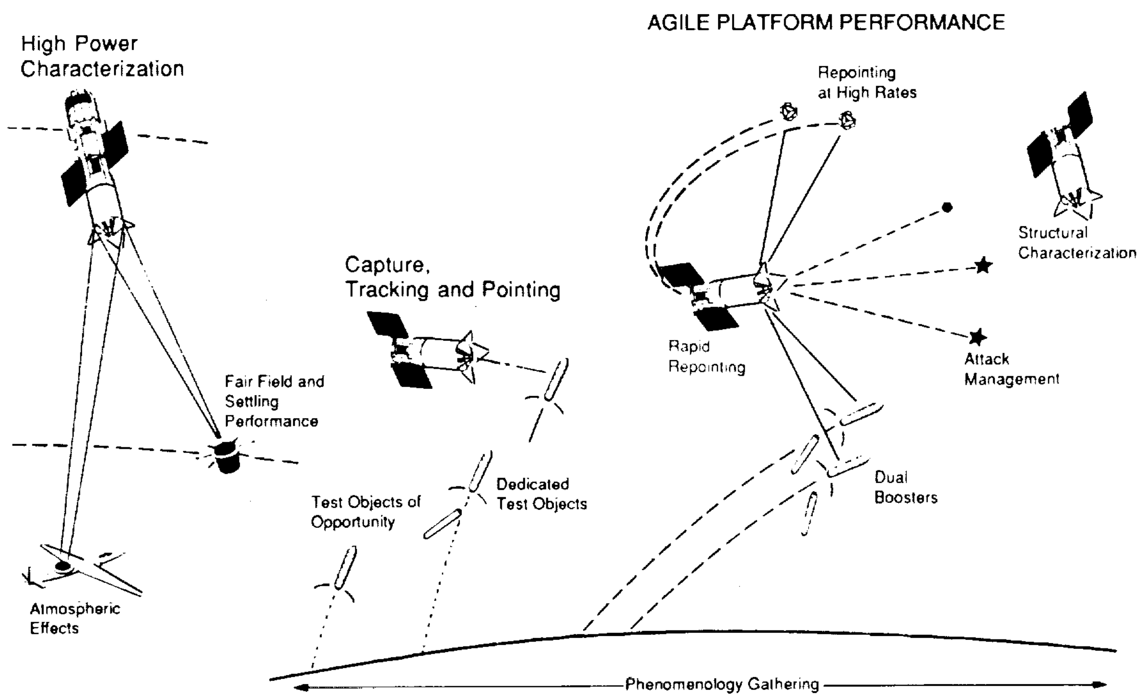

Figure 2: Zenith Star Objectives

ZENITH STAR SPACECRAFT

The basic hardward for the Zenith Star experiment is shown in Figure 3. It consists of a chemical laser of the class of the alpha program, a beam expander that utilizes the segmented LAMP mirror for the primary optical element, an actuator for pointing the beam expander, and an isolator for attenuating the laser noise from the beam expander. The latter two are combined into one subsystem called the actuator/isolator. The laser energy is directed through the aft body to the beam expander by a series of transfer optics and steering mirrors (beam control transfer assembly) on the aft body. A capture track system (consisting of a suite of sensors) is utilized to point the beam expander and optical train for tracking a series of test objects. The remainder of the equipment is a set of standard spacecraft subsystems that allow it to be in orbit as a free flyer that is commanded by ground operations personnel.

The system is delivered into orbit by two Titan IV launch vehicles. The forward spacecraft is launched first and checked out completely. Then the aft spacecraft consisting of the Alpha laser and spacecraft support subsystems is launched into the same orbit as the first, orbit phased, and remotely operated from the ground for rendezvous and docking.

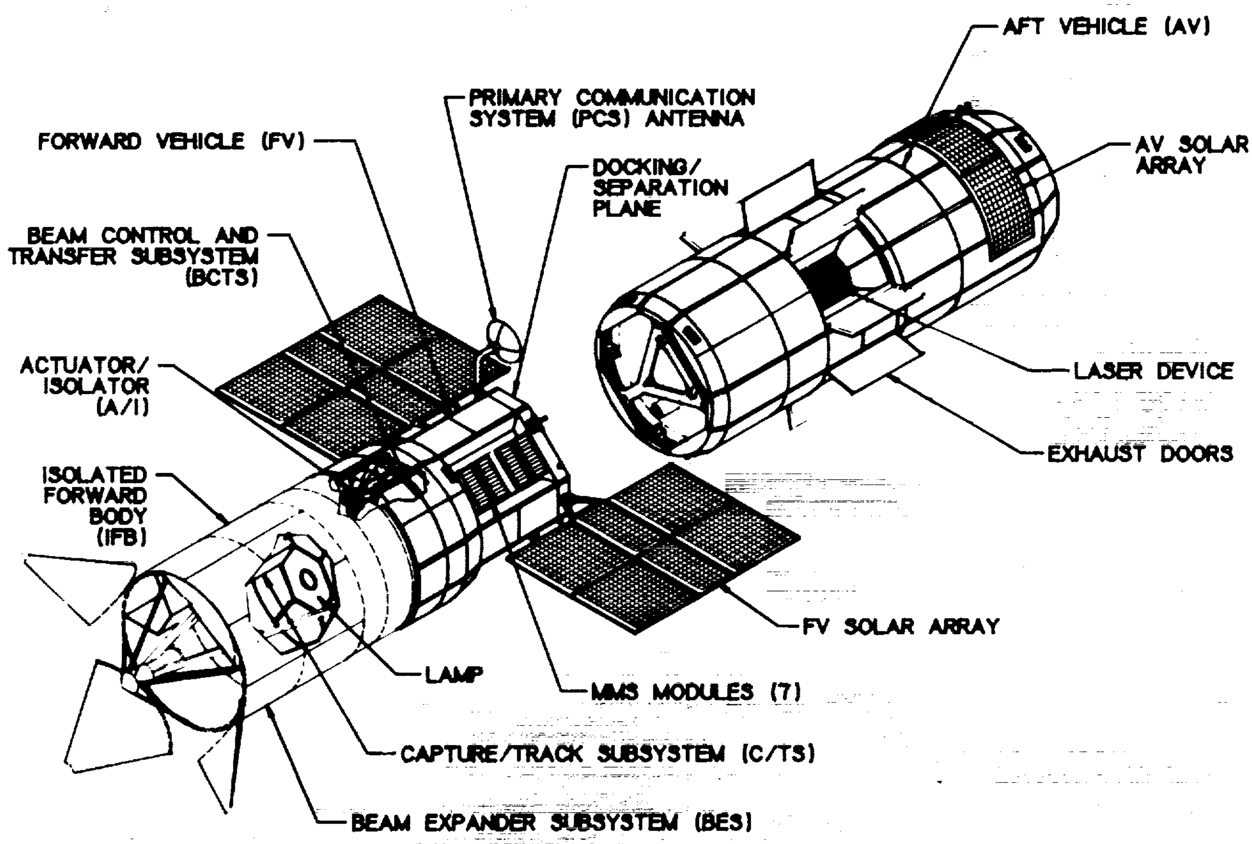

Figure 3: Zenith Star Space Vehicles

CONTROL SYSTEM ARCHITECTURE

The control architecture for the space based laser is derived from a series of stringent tracking and pointing requirements depicted in Figure 4 and the resulting interactive implications lead to a complex hierarchical control architecture. Tight accuracy and jitter requirements combined with the need for rapid repointing of the line-of-sight from one object to another necessitates isolation and suppression of disturbances to the large beam expander. The Zenith Star control system is designed to duplicate this architecture so that the experiment results can be directly related to the SBL performance.

The precision and jitter are analogous to hitting a basketball on the Empire State Building in New York from Pike's Peak in Colorado. It must accomplish this while tracking objects at angular rates more than an order of magnitude higher than the capability of the Hubble Space Telescope. To accomplish this, the line-of-sight must be isolated from disturbances by as much as 100 million to one and yet be able to repoint from one object to another in less than one second so that the system effectiveness can be high.

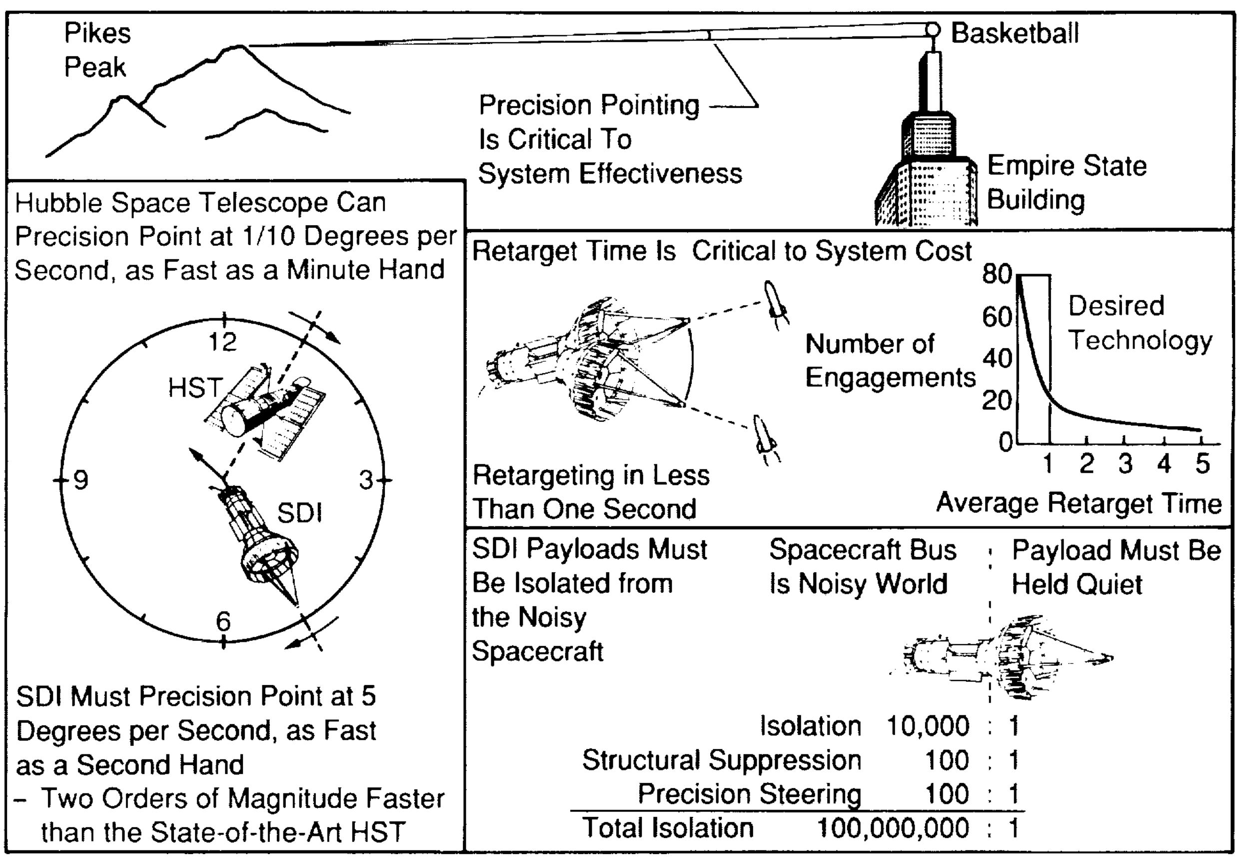

Figure 4: Space Based Laser Control Requirements

While the structure is made as stiff as possible, there is sufficient deformation (Figure 5) of the beam expander structure and optical geometry resulting in line-of-sight disturbances to require isolation of aft body noise from the beam expander. There are other self-induced beam expander disturbances such as fluid flow and rapid repointing that require structural disturbance suppression on the beam expander itself.

Either technique can be readily handled without two body interaction, but when combined an actuator/isolator is required between the bodies. This actuator/isolator must provide six degrees of freedom operation which introduces other control issues, such as translation and beam walk control, that further complicate the controls problem.

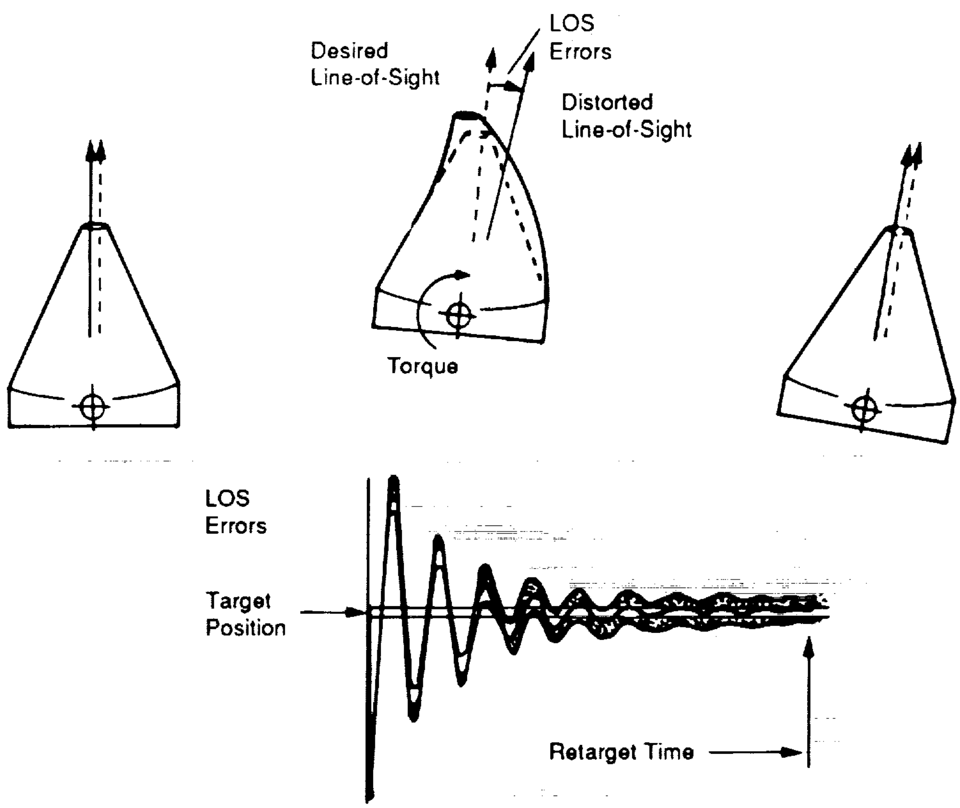

Figure 5 Beam Expander/Optical Distortions

In order to ease the burden of pointing the line-of-sight of the system, a precision pointing set of controllers is introduced to provide beam expander off-axis pointing and stabilization so that the structure control can be relaxed within a small field of view and as shown in Figure 6. So long as the line-of-sight disturbance is within the range of the precision pointing controller authority the beam expander controller requirements are eased. In other words, the settling time is satisfied when the beam expander line-of-sight is within this band.

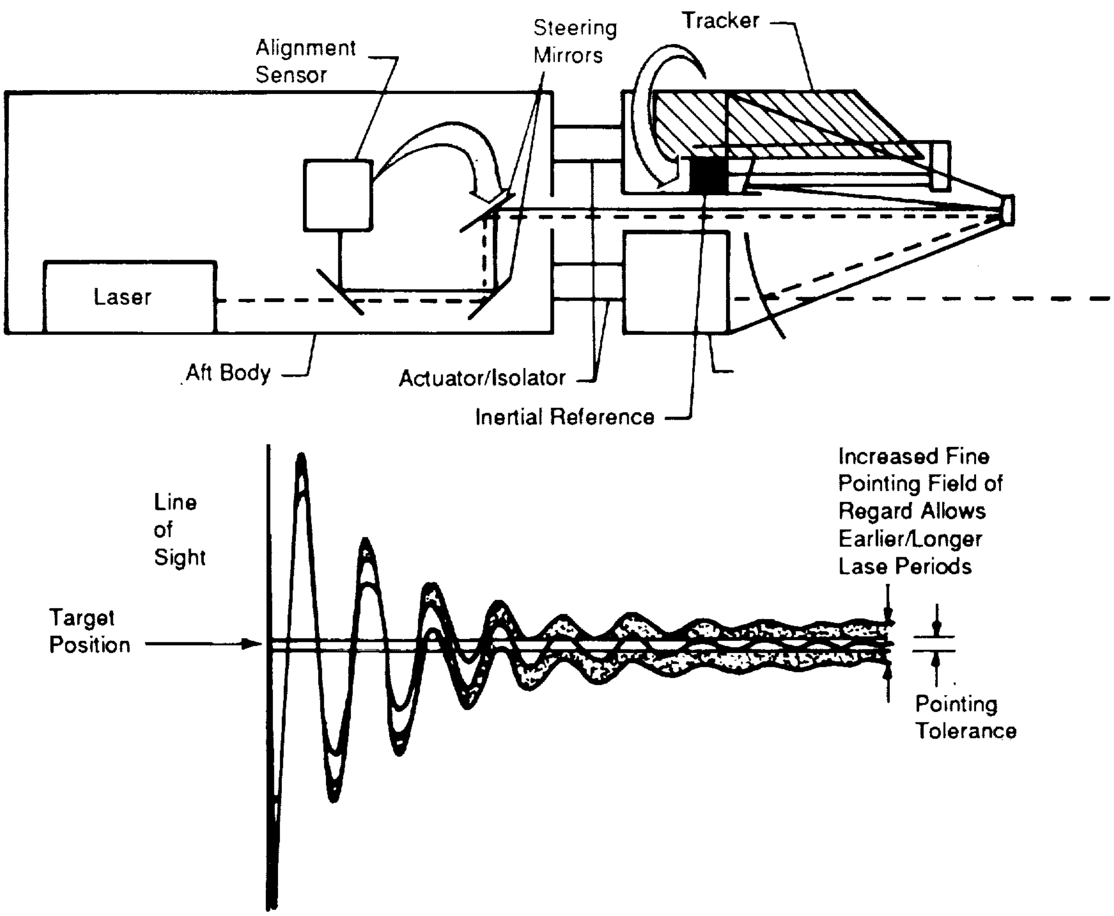

Figure 6 Precision Pointing Control System

VEHICLE CONTROL

The formulation of the control architecture for the beam expander can be described as follows in the next series of figures in Figure 7.

An easy method of isolation (Figure 7a) of the aft body disturbances from the beam expander is to provide a gap between the forward and aft bodies, control the beam expander to point to the test object from on-board sensor data by external torques (such as control moment gyros), and control the aft body to follow this motion by external forces and torques to maintain the desired gap within some tolerance. This is ideal isolation since there is no actuation between the bodies to force alignment of the two bodies, hence there is no transfer of disturbances from one body to the other.

Since each body tends to rotate about its own center of mass there will be large translational displacements (Figure 7b) at the optical interface between the beam expander and aft body. Also since the beam expander disturbances are to be minimized the aft body must be translated as well as rotated by external forces and torques to maintain the proper separation. This is not practical for a highly agile control system because of the large heavy aft body and the fact that the gap must be small, on the order of centimeters. Consequently an actuator between these bodies is required.

This actuator introduces a coupling path from the aft body to the beam expander which then requires an isolator between the bodies (Figure 7c). This actuation and isolation must be combined into one subsystem because of this interaction. This subsystem is called the actuator/isolator and it must minimize this coupling while producing the desired pointing forces and torques. This function is nontrivial even for the baseline magnetic isolator because of nonlinear magnetic forces and eddy currents which must be cancelled.

Self-induced disturbances on the beam expander arising from fluid flow and rapid pointing must be dissipated through damping in the structure, transferred to noncritical structural motion (non-critical modes), or transferred off the beam expander to the aft body (Figure 7d). The incorporation of the actuator/isolator allows this energy to be transferred to the aft body which can then remain isolated. Hence the beam expander line of sight can be stabilized while still tracking objects.

The pointing of the beam expander causes severe disturbances. In order to move the line-of-sight from one object to another (rapid repointing)it is desirable to make maximum use of the available torque from the actuator/isolator. In fact, the optimal repointing for a rigid body is a bang-bang command. This, however, causes severe disturbances to the line-of-sight.

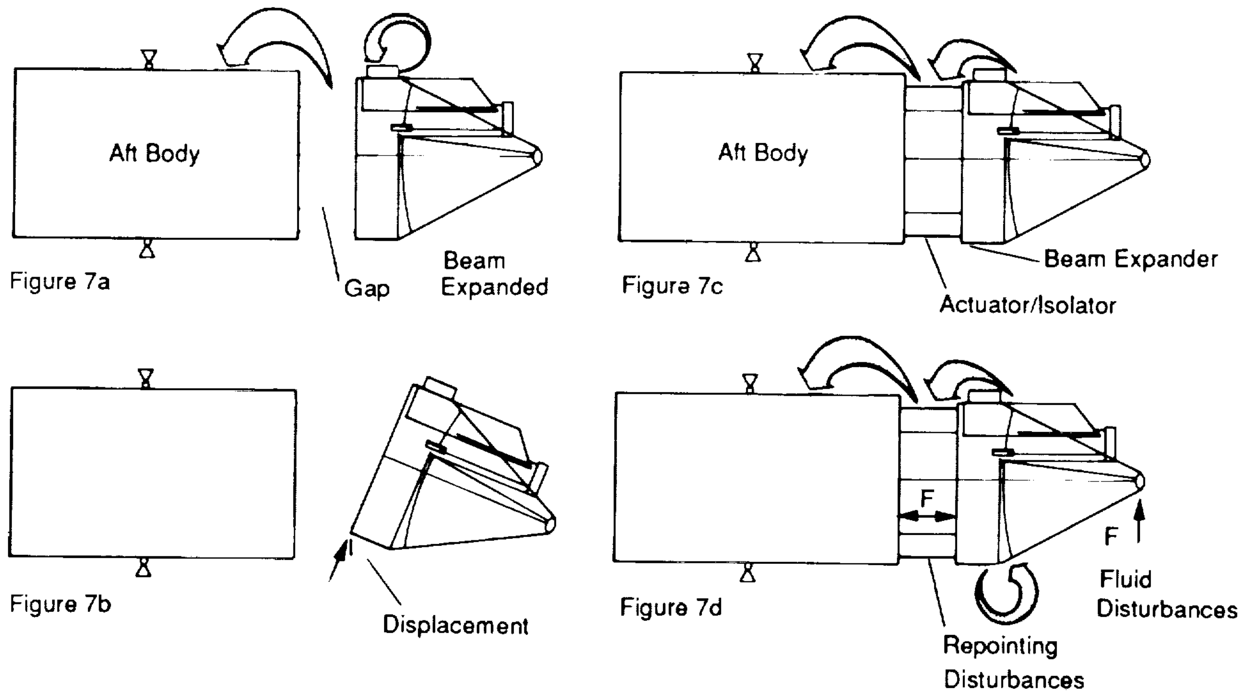

Figure 7 Vehicle Control Architecture Evolution

The severity is dependent on the relationship of the angle to be repointed (frequency of the bang-bang torques) and the structural frequencies. Figure 8 shows the effects of a single structural frequency of 4 Hz and 8 Hz separately as a function of repointing angle. The time to hand over is the time that the line-of-sight error takes to settle to within the field of reguard of the beam expander where the fine off-axis steering takes over. The rigid body response is included since it represents the lower bound of maneuver time for the system.

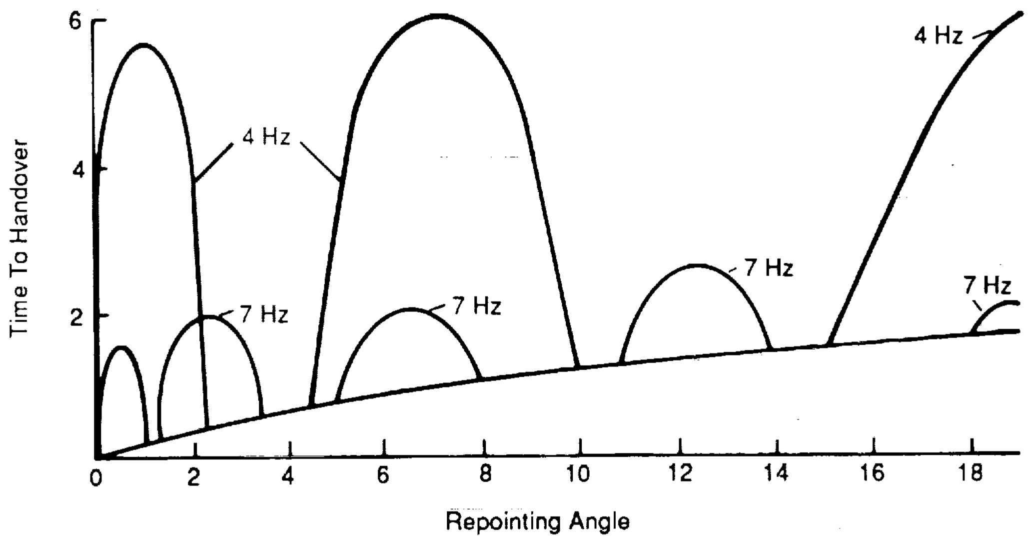

Figure 8 Effects of Structural Frequencies on Repointing Time To Precision Track Handover

When all structural modes are considered the picture is not quite so easily displayed because the relative effects on the line-of-sight are intermixed. An envelope of these effects is indicated in Figure 9 where the lower bound is limited by the rigid body response and the upper bound depends on advanced structural controllability.

The regions of interest for structural control are the torque-limited and rate-limited regions. The algorithm-limited region is the area of responsiveness of the precision off-axis control system for scene interpretation and control.

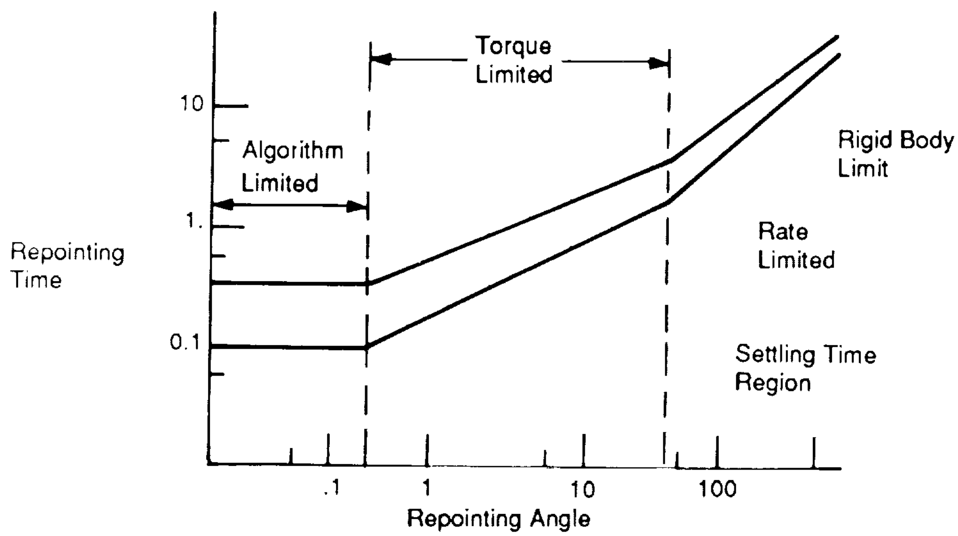

Figure 9 Repointing Characteristics

Figure 10 shows the improvement in repointing time that can be made by a simple modulation. The technique is based on the relationship of the repointing angle and the knowledge of the structural frequencies of the beam expander. By properly commanding or modulating the torque commands, disturbances can be minimized as shown in the figure for one technique called modulated bang-bang control.

This technique concentrates on modal avoidance and cancellation and its effectiveness. There are other techniques that have been investigated by several members of the community that should also be evaluated in space. These include both other modal avoidance, modal suppression, and modal displacement.

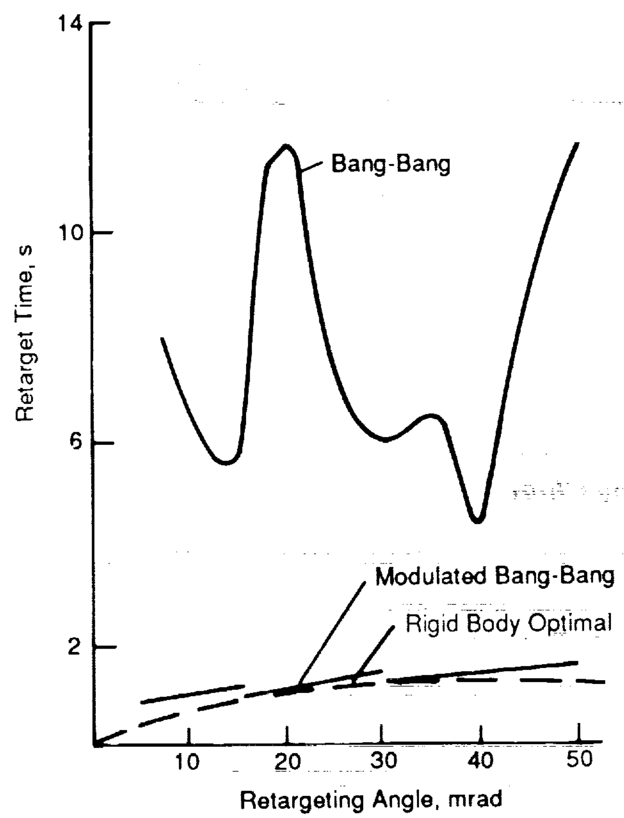

Figure 10 Multiple Mode Controller Characteristics

SUMMARY

The space based laser control tasks are indeed challenging because of the variety of requirements that demand different types of controllers, all competing simultaneously. The architecture derived for the SBL resulted in a hierachical control formulation that demands advanced control techniques. Each portion of the architecture has interaction with the others which demands careful orchestration of the control commands to fulfill the control requirements.

The Zenith Star duplicates the SBL functions and provides performance levels close enough to the SBL performance to provide valid scaling for evaluation of the SBL expectations.

One dominant crucial control function is the beam expander controller. It must place and stabilize the beam expander line-of-sight within a few hundred microradians of the object tracked in a very short time. The accuracies involved require careful control of the structural deformations even with structural resonances on the order of 20 Hz.

There is no precedence for this type of structure control since this is the first opportunity to control a structure of this nature in space. Experiments such as structural identification and modal surveys are also planned for in the experiment objectives. Utilization of other techniques for controlling the structure, such as distributed actuator structural control, are not currently available on Zenith Star but may be available in the future depending in the interest within the community and the risk to the other Zenith Star objectives.

In either case there is ample opportunity for industry participation during the Zenith Star mission operations. This can be accomplished by submitting ideas for structural control techniques to SDIO for consideration. If approved, these experiment ideas will be integrated into the experiment objectives and the implementation incorporated into the mission planning.

Space Based Laser Control Complex & Challenging

- **Stressing Pointing & Tracking**
- **Repointing In Short Time Requires New Control Thinking**
- **Control Large Optical Structures Requires Interactive Control Strategies**

Zenith Star Challenges Rival the SBL Control Difficulties

- **Pointing & Tracking is Severe**
- **Repointing & Structural Control is Scaleable to SBL**
- **Results from Beam Expander Control is First Attempt in Space**

Zenith Star Offers Opportunity

- **Demonstrate & Validate Wide Variety of Structural Control Issues**
- **Industry Wide Participation in Large Structure Experiments in Space**

Figure 11 Summary