

AN INNOVATIVE APPROACH FOR VALIDATION OF LARGE SPACE STRUCTURE CONTROLS-STRUCTURES INTERACTION TECHNOLOGIES (CSI-SAT)

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In-space flight experiments are required to validate dynamic response and control characteristics of ground experiments and their models in order to support future DoD/NASA Large Precision Space Structures missions. This paper, based on an ongoing Small Business Innovation Research(SBIR) Program with the Air Force Astronautics Laboratory, will describe an innovative approach for space flight experiments to demonstrate and validate Control-Structures Interaction(CSI) technologies and methodologies based on emerging Small Satellite Initiatives. The current trends in DoD/NASA missions, the existing CSI ground experiments and the planned space experiments are presented. A concept is identified for a Control-Structures Interaction satellite(CSI-SAT) and compatible launching platform necessary for performing affordable on-orbit testing of CSI technologies which can not be accommodated in ground tests. Selected technologies and technology suites (integrated at subsystem level) for space testing are identified.

INTRODUCTION

As the size and performance requirements of future DoD and NASA spacecraft and payloads increase, so does the dynamic interaction between the associated control systems and the structural behavior of these systems. These interactions between a structure and control system will become increasingly difficult to predict analytically for the class of Large Precision Space Structures (LSS) envisioned for future missions due to the size and complexity of the dynamic models and the associated effects of model uncertainty. The inability to adequately ground test such structures due to gravitational, seismic

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and atmospheric effects further complicates the critical task of designing the spacecraft structure and control systems. Figure 1 shows the typical evolution to verify analytical "structures/dynamics/controls" models and their performance for both ground and space experiments in order to support future spacecraft designs. Since the early 1970's, the challenges posed by CSI

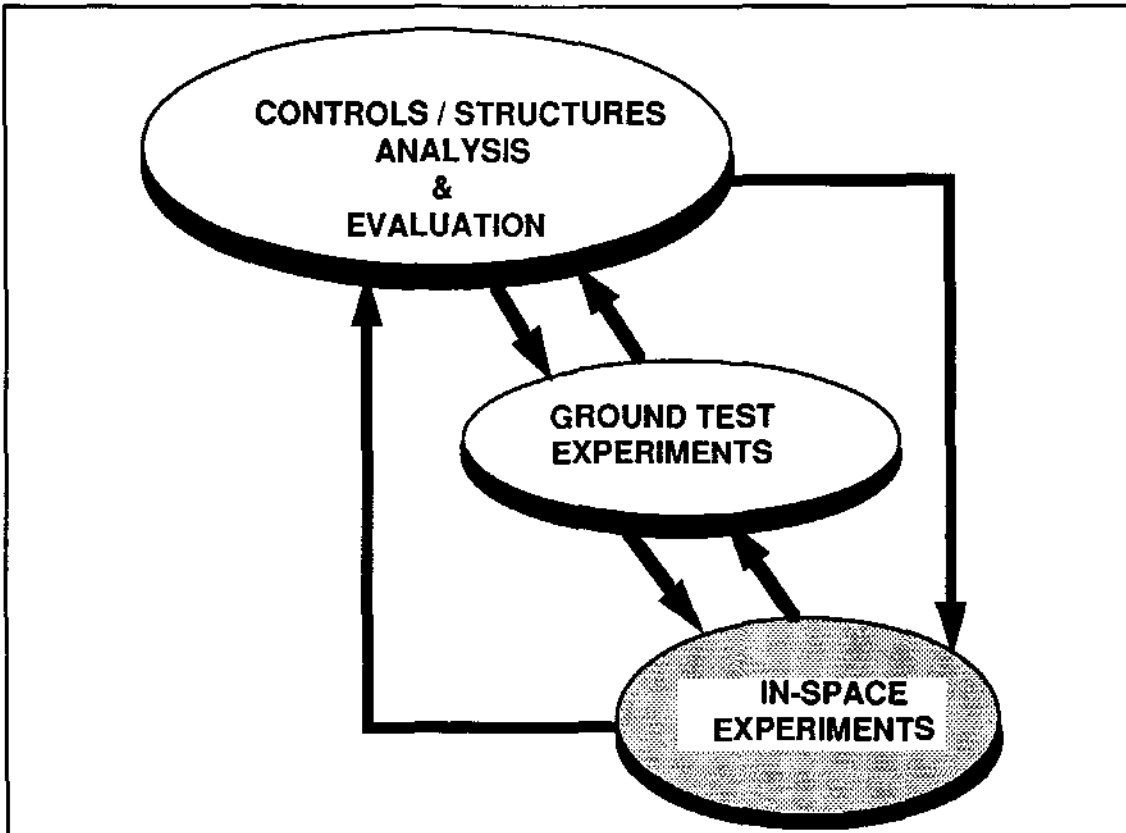


Figure 1. CSI Technology / Methodology Development

have generated numerous theoretical investigations throughout the research community as well as motivated development of experimental ground test articles:¹

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|---|-------|
| (1) Active Control of Space Structures (ACOSS) | DARPA |
| (2) Vibration Control of Space Structures (VCOSS) | AFWAL |
| (3) Passive and Active control of Space Structures (PACOSS) | AFWAL |
| (4) Advanced Control Experiment for Structures (ACES) | MSFC |

Taking the next step to space has been more challenging. NASA initiated a number of programs which were intended to address the CSI issues

¹ Strunce, R., Motyka, P., Schely, B., et. al., An Investigation of Enabling Technologies for Large Precision Space Structures, AFRPL-TR-82-074, Volumes I, II & III, September 1982.

in space. However, these space experiments were expensive (>\$100M) and with a long development time (4-5 years). The Strategic Defense Initiative Organization (SDIO) has several potential missions that would require CSI technology; however, the development of an independent CSI space experiment which is not associated with a planned weapon system is considered too costly. As a result, there are no CSI space experiments planned for the near term.

Consider the current structural control interaction problem that the Hubble Telescope (see Figure 2) is experiencing as a result of thermal distortions of the solar array boom. These dynamic interactions degrade Hubble's performance beyond the original specifications even though the solar array boom is only a relatively small appendage. This points to the development of a better understanding of the structural models and their associated behavior which can only be demonstrated in space. The Small Satellite Initiatives provide a unique opportunity to revisit the possibility of demonstrating CSI technologies in space at an affordable cost and schedule. Otherwise, future DoD and NASA missions are at risk.

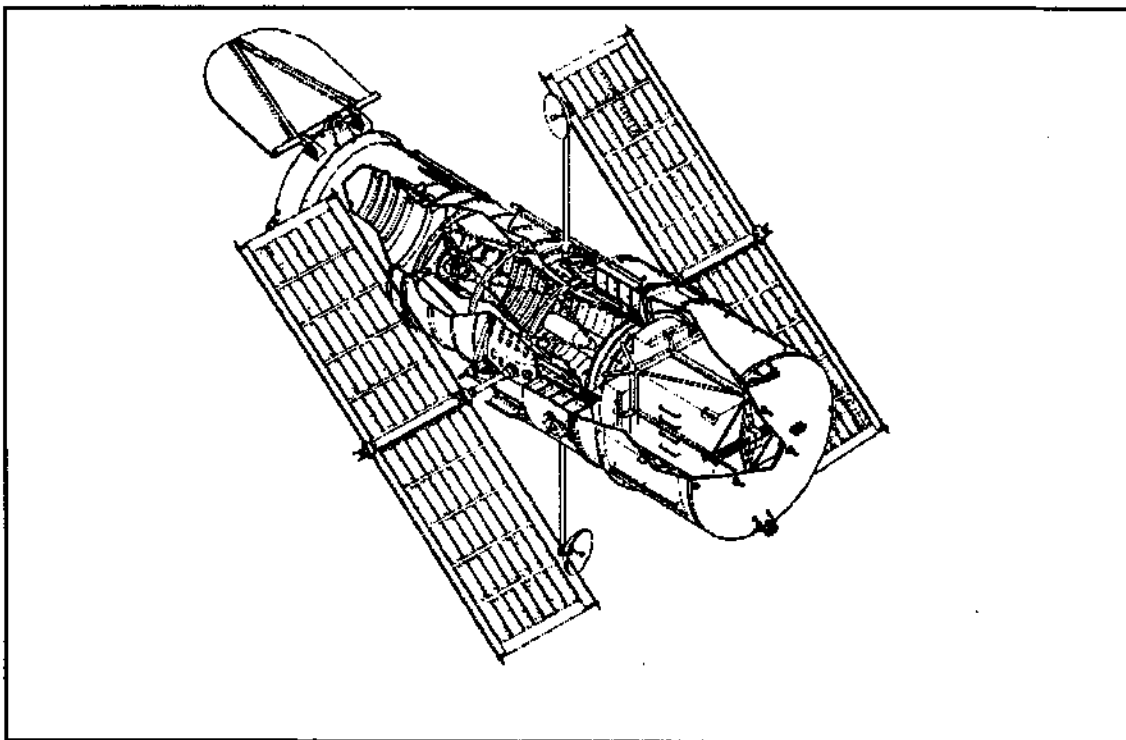


Figure 2 Hubble Telescope

MISSION TRENDS

The future missions for NASA vary according to current scientific and/or public interest while the DoD missions are a function of perceived military threats. The following descriptions of future missions for these organizations are representative of those which will require CSI technology.

NASA Focus Missions

All of the missions listed in Figure 3 were judged to be of significant importance to NASA's future plans for space science and exploration. Likewise all the missions were seen as benefiting from CSI technology development.² The categories were defined as (1) Precision Optical Interferometers such as Coherent Optical System of Modular Imaging Collectors(COSMIC), Optical Space Interferometer(OSI), Precision Optical Interferometry in Space(POINTS); (2) Large Segmented Reflectors such as Large Deployable Reflector(LDR), Advanced Space Telescope(AST); (3) Multiple Payload Platforms such as Earth Observing System(EOS), Space Station Freedom(SSF); (4) Large Telescopes with Monolithic Primaries such as

FLIGHT EXPERIMENT	SIZE	OPERATING WAVELENGTH	POSITIONAL ACCURACY	ANGULAR ACCURACY	DISTURBANCE ENVIRONMENT
INTERFEROMETERS	10-30 m baseline	0.1-1.5 microns (UV to IR)	⁻⁹ 10 m	10 milli-arcsec	LEO
SEGMENTED REFLECTORS	20 m across	0.5-30 microns	⁻⁸ 10 m	.001-.05 arcsec	LEO
MULTI-PAYLOAD PLATFORMS	9-150 m	not applicable	⁻³ 10 m	3-5 arcsec	LEO
MMP PAYLOADS	8-21.3 m by 1.5-2.5 m	0.4-0.9 microns (visible)	⁻⁶ 10 m	.01-.5 arcsec	LEO
LARGE ANTENNAS	5-200 m diameter	8.3-200 mm (K,X,C,S bands)	⁻⁴ 10 m	14-430 arcsec	LEO
LARGE MANIPULATOR ARMS	10-50 m	not applicable	⁻³ 10 m	not applicable	LEO

LEO: drag, thermal stresses, gravity gradient, internal

Figure 3 NASA Mission Characteristics Matrix

Astrometric Telescope Facility(ATF), Circumstellar Imaging Telescope(CIT); (5) Large Space Antennas such as Mobile Satellite System(MSS); (6) Flexible space

² Laskin, Robert A., A Spaceborne Optical Interferometer: The JPL CSI Mission Focus, Third NASA/DoD CSI Technology Conference, San Diego, Ca., Jan 29 - Feb 2 1989.

Manipulators for use on space platforms. A pictorial representation of these NASA future systems is presented in figure 4.

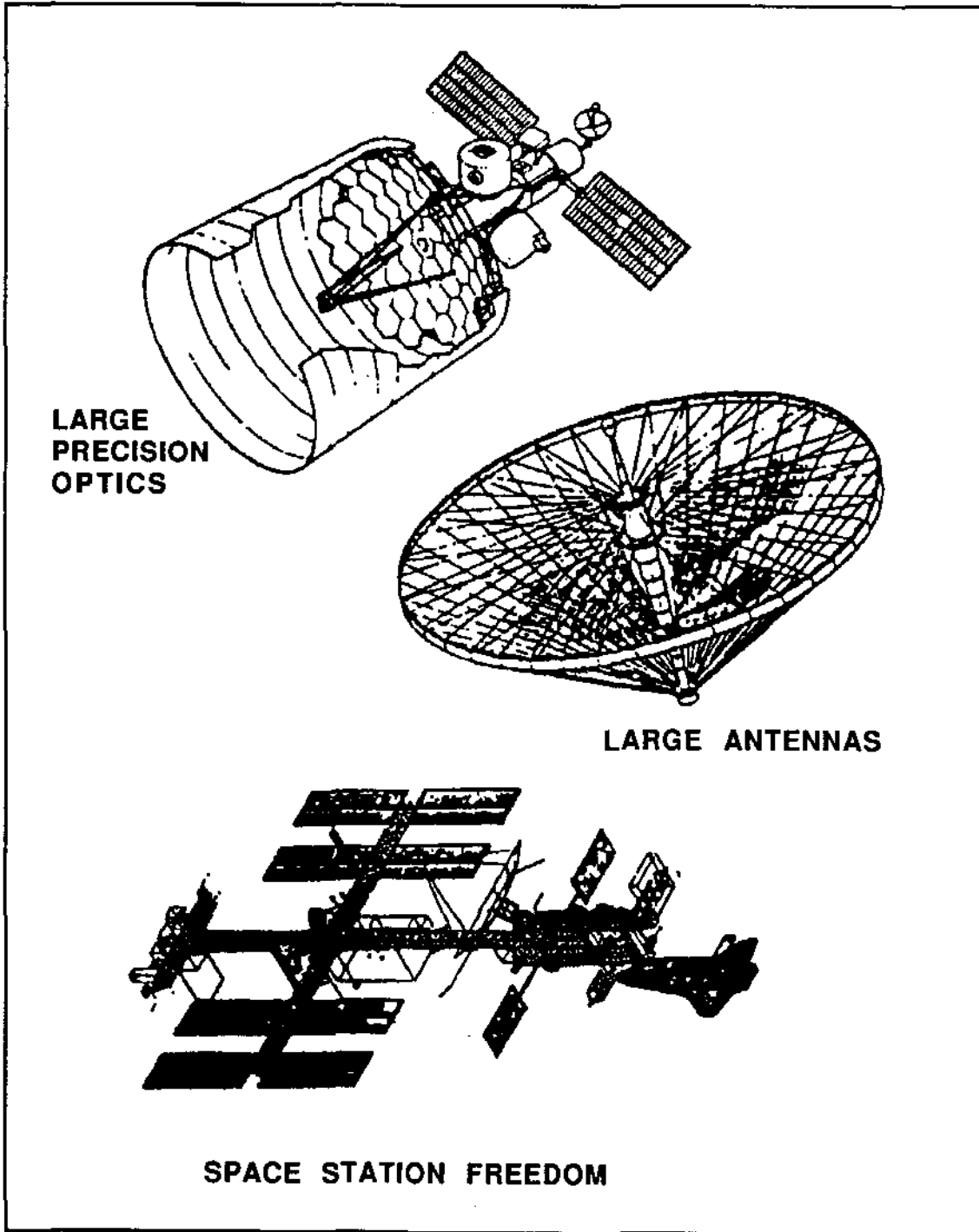


Figure 4 Future NASA Missions

DoD SDI Relevant Missions

The SDI Directed Energy weapons such as the Space Based Laser(SBL) and the Neutral Particle Beam (NPB) are the primary drivers for CSI technology. Examples are shown in figure 5 below.

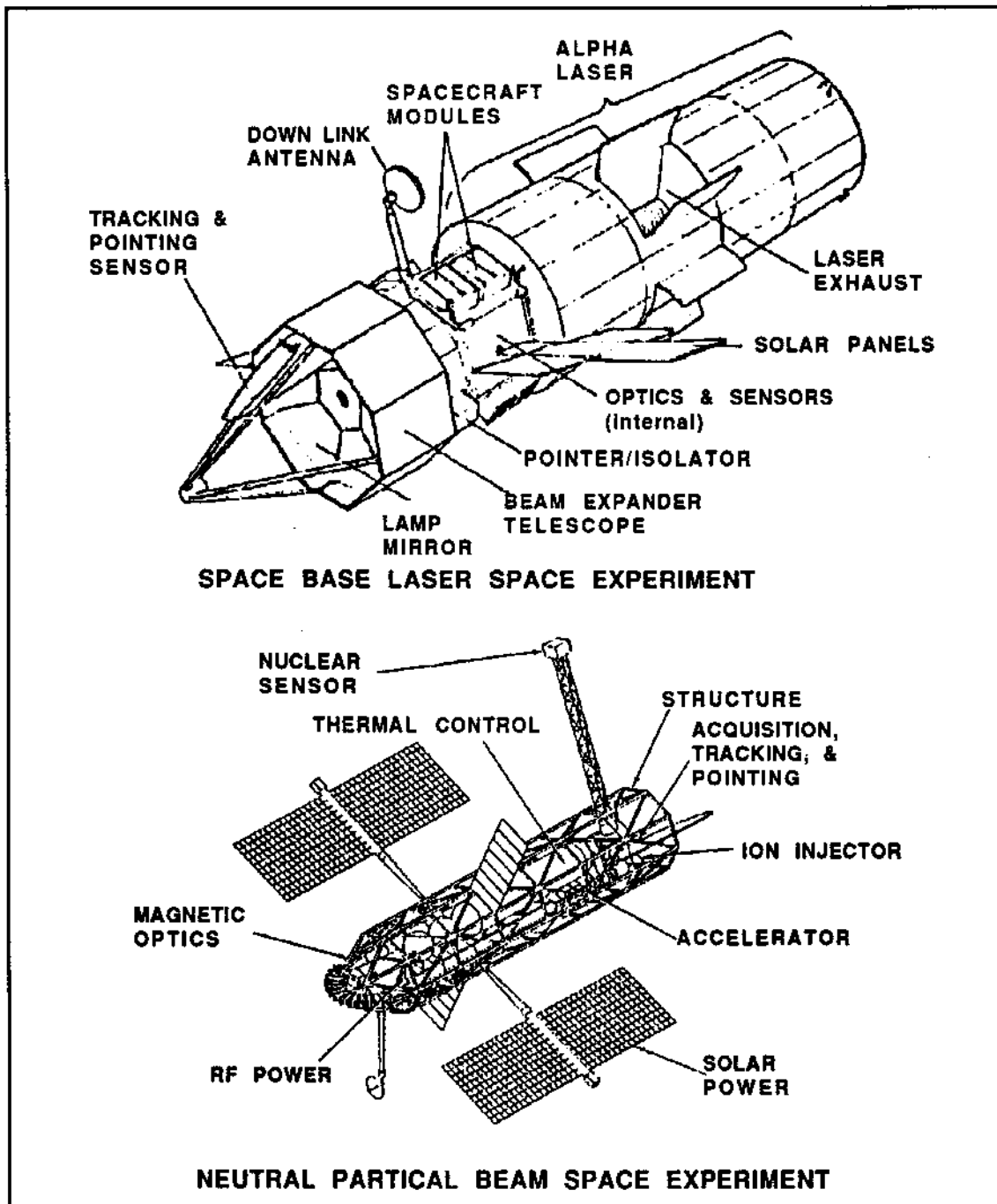


Figure 5 Space Based Laser and Neutral Particle Beam Platforms

CSI SPACE EXPERIMENT OBJECTIVES

Since the early 1970's, the CSI community has addressed analytical modeling and model reduction, structural concepts, system identification, passive/active damping, control system design and synthesis methodology, sensor and actuator development, and ground testing. However, the On-Orbit aspects have not been addressed such as: (1) Determination of the degree to which theory and ground tests can predict open and closed loop performance of large, flexible deployable structures in space; (2) Evaluation of system identification and state estimation algorithms in the space environment; (3) Analysis of deployment dynamics and structural damping in space; (4) Ground and flight demonstration of Multiple Input/Multiple Output (MIMO) control laws and robustness of such control laws to model uncertainties and perturbations; (5) Demonstration of pointing and tracking control of a LSS using linear Bi-directional thrusters acting over a long flexible moment arm; (6) Evaluation of the operational use of unobtrusive sensor technology for measuring low-frequency, low-amplitude motions of LSS.; (7) Demonstration of real-time MIMO control law reconfiguration and fine tuning in orbit.

CSI GROUND TESTING

Recently³, both DoD and NASA have emphasized development of specific CSI ground test facilities to support their respective future directions in large space systems.

NASA CSI Ground Experiments

The current NASA test facilities are motivated by Space Station, Large Deployable Reflector, and a class of large antennas. Although the pointing accuracy and control requirements for these NASA missions can be stressing, the on-board disturbances are benign compared to those of some DoD systems such as Space Based Lasers (SBL). Therefore, the NASA facilities address precision pointing and CSI control over a limited dynamic range. The major ground test issue for these facilities is that the zero-gravity simulation techniques require complex suspensions which limit the CSI dynamics and hinder investigation of structural deployment. These tests are further complicated because gravity effects the true structural dynamics especially joint dominated behavior and restricts sensor/actuator type and location. In addition, tests are conducted in air because vacuum & thermal environments are costly as well as limited to relatively small chambers. The major NASA test facilities are:

³ Sparks, Jr., Dean W., Horner, Garnett C., Juang, Jer-Nan, Klose, Gerhard, A Survey of Experiments and Experimental facilities for Active Control of Flexible Structures, Third NASA/DoD CSI Technology Conference, San Diego, Ca., Jan 29 - Feb 2 1989.

- | | |
|--|----------|
| (1) Flexible Structures Control Laboratory(FSCL) | JPL/AFAL |
| (2) Large Component Test Laboratory(LCTL) | LaRC |
| (3) LSS Ground Test Facility(LSS-GTF) | MSFC |
| (4) JPL's Test Bed Facility | JPL |

JPL's FSCL test article (shown in figure 6) is an 18.5 foot diameter antenna like structure consisting of 12 ribs emanating from a central rigid hub with a 12 foot long antenna feed boom and tip mass. Each of the ribs is supported at two locations by zero-stiffness "levitators" in order to prevent excessive sag due to gravity. A levitator consists of a counterweight hanging over a low friction pulley. The test article is suspended from the center hub with the feed boom hanging vertically down. JPL's Test Bed Facility consists of a modified Astromast, a Precision Truss, and a Free-Free Truss. MSFC's LSS-GTF contains the gimballed Astromast used in ACES and the LaRC's LCTL currently houses the Space Station Truss model.

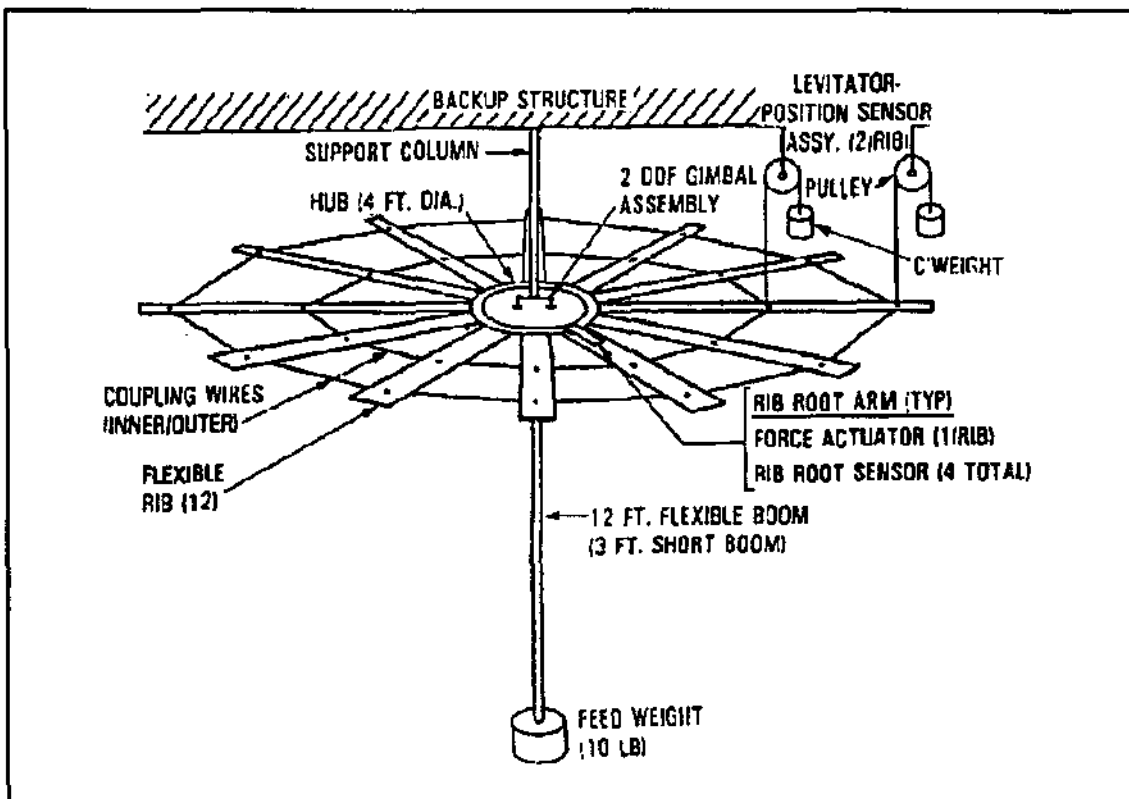


Figure 6 JPL's FSCL Test Article

DoD SDI CSI Ground Experiments

In comparison, the Air Force facilities are intended to investigate CSI technology and its interaction with acquisition, tracking and pointing, beam control, rapid retargeting, isolation and fire-control for a large precision optical structure that is representative of SBLs. These facilities are also constrained by the previously mentioned gravitational, seismic, and atmospheric effects but are further complicated by the limited degrees of freedom available for large motions of the test article, usually restricted to rotations about a fixed point. The major DoD CSI testing facilities are:

- | | |
|--|------|
| (1) Advanced Space Structure Technology Research Experiments(ASTREX) | AFAL |
| (2) Space Integrated Controls Experiment(SPICE) | AFWL |
| (3) Rapid Retargeting Precision Pointing Facility(R2P2) | SDC |

The Air Force Weapons Laboratory's (AFWL) SPICE facility (figure 7) is intended to investigate CSI technology on a large precision optical structure that is representative of SBLs. SPICE will be subjected to large order laser-like disturbances but will still be restricted to the same ground test issues as the

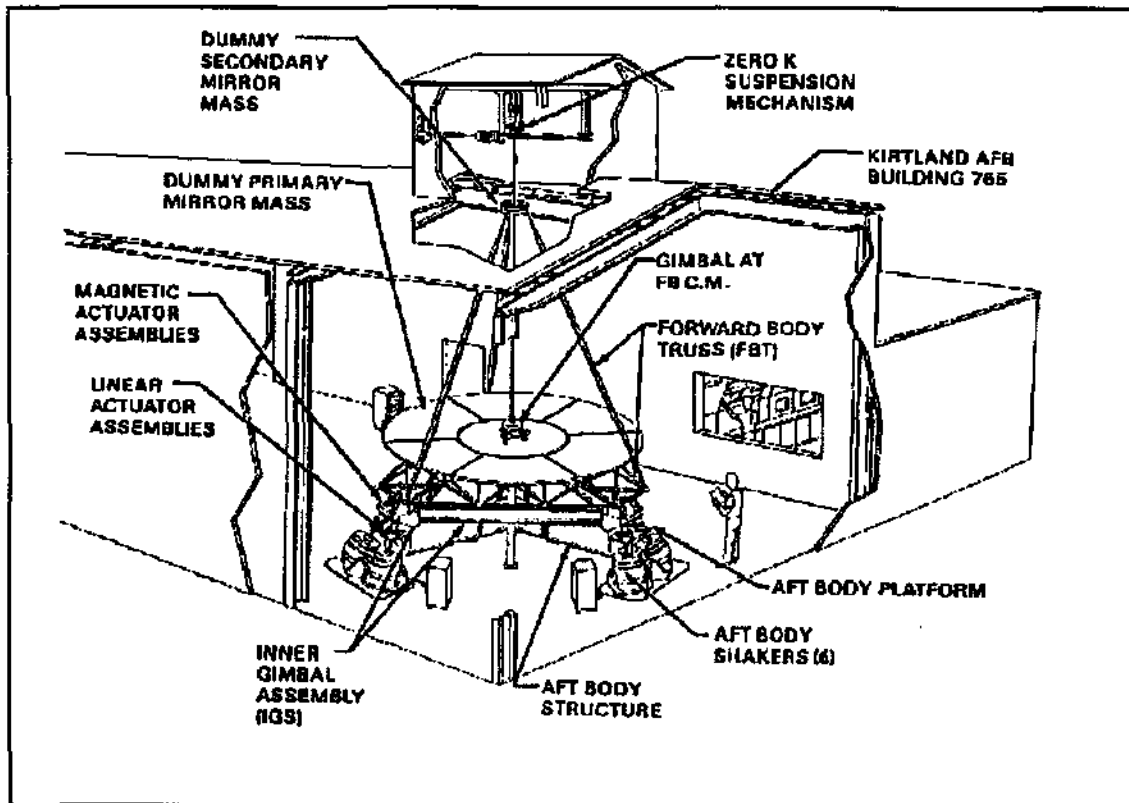


Figure 7 AFWL'S SPICE Facility

NASA facilities. The Army Strategic Defense Center's R2P2 facility located at Martin Marietta in Denver Colorado was designed to investigate rapid retargeting and pointing of SBL's at the accuracy and precision specifications anticipated for these weapon systems. The test article floats on an 18 foot diameter air bearing like ring and simulates structural vibration by tuned pendulums.

AFAL's ASTREX facility will look at slewing a large SBL structure mounted on a 15 foot high air bearing pedestal(see figure 8). This test article will be limited to three degrees of freedom and will investigate large angle retargeting with reduced overall system performance. Again these facilities must contend with limited dynamic range in addition to the previously mentioned gravitational, seismic, and atmospheric effects.

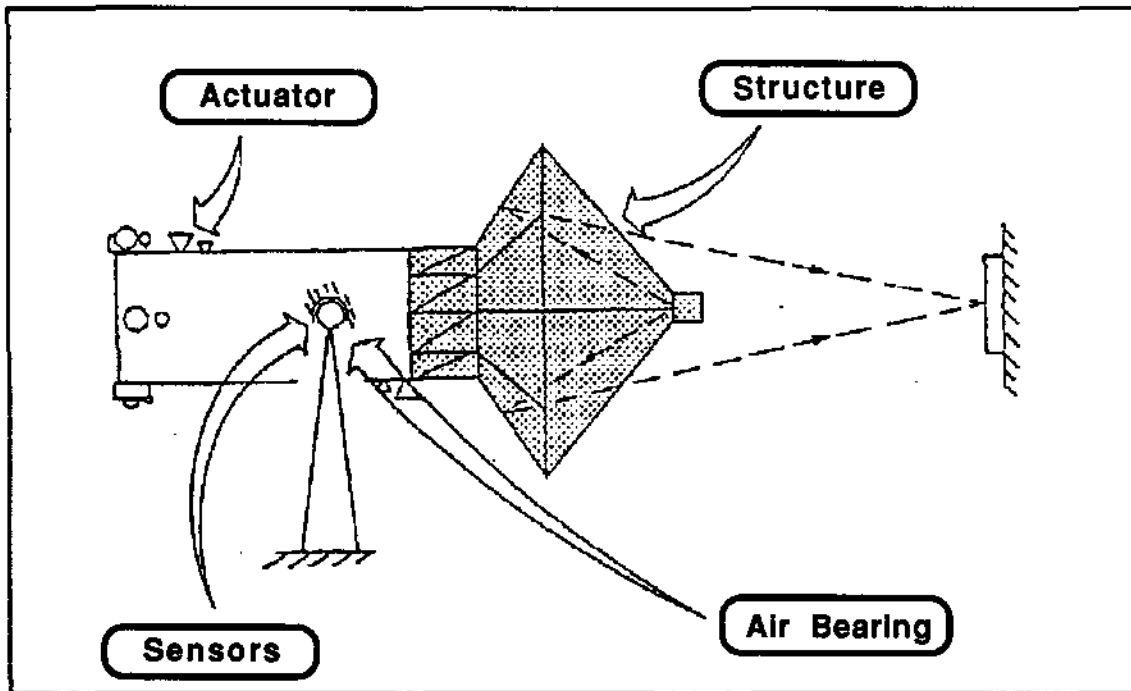


Figure 8 AFAL's ASTREX Test Article Concept

PROBLEMS & ISSUES WITH CSI SPACE EXPERIMENTS

NASA initiated a number of Space Shuttle flight programs for conducting CSI experiments in space. These Shuttle based space flight experiments were initially viewed as having a potential for economically conducting experiments in space. However, Shuttle based flight experiments introduced new issues that affect cost and schedule. For example, taking the nominal cost of \$100M per experiment over five days (assume 8 hours each day) of on-orbit testing yields a cost of \$2.5M/hour of data collected. In addition, the short flight duration constrains the analysis to post flight with no opportunity to re-test if any anomalies are discovered. To date, the initiatives to conduct in-

space experiments have been shuttle base, have large associated costs in excess of \$100M , take 5-8 years to develop and yield limited scientific return for the investment.

CSI Space Flight Experiments

The previously described ground test limitations motivated NASA to initiate a number of studies to develop CSI flight experiments such as: (1) The Antenna Flight Experiment (AFX) was investigated by NASA LaRC as a Shuttle based experiment as well as a free flyer. This experiment was canceled when cost exceeded \$200M; (2) Control Of Flexible Structures (COFS) was initiated by NASA LaRC as a shuttle based experiment with a risk reduction ground test but was canceled because the cost grew greater than \$100M; (3) Controls, Astrophysics and Structures Experiment in Space (CASES), see figure 9, is being advocated by MSFC as both a scientific and controls-structures interaction shuttle based experiment to fly early 1997 at an estimated cost of \$100.M or more.

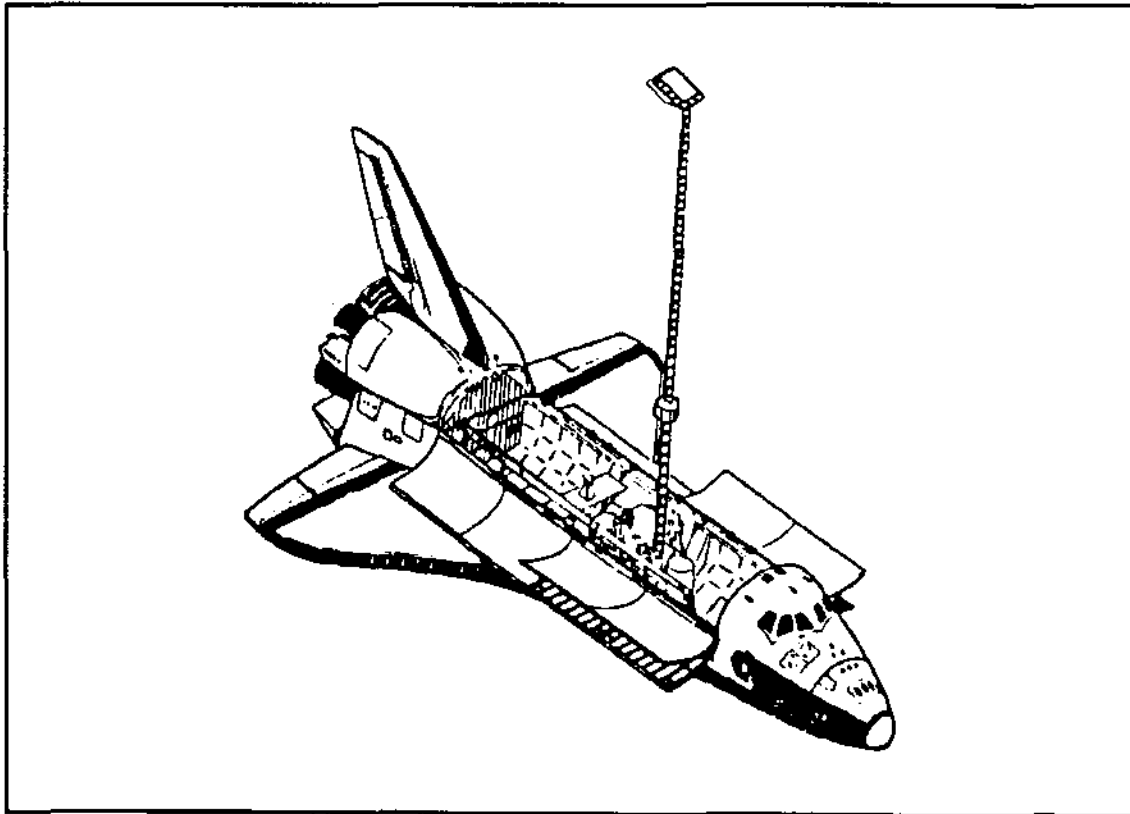


Figure 9 CASES Shuttle Flight Experiment

Why Does CSI Have A Problem?

In-space flight experiments are required to validate dynamic response and control characteristics of ground experiments and their models in order to support future DoD / NASA missions. The shaded area in figure 2 represents the lack of in-space testing to validate CSI technology. Why does a CSI space flight experiment have problems? The scientific(astrophysics) space community does not support a CSI space experiment as a primary mission because it does not directly contain the science of interest; therefore, if CSI is to be considered at all, it has always been as a secondary mission. Up until now, a CSI experiment has always been a secondary mission which is viewed as a risk to the primary mission. When the system trades are conducted, the primary mission has priority with regard to size, weight, and power which translates into minimal(if any) instrumentation, computers, or storage allocated to the CSI experiment. In order to insure the primary mission success, CSI experiments are limited to ultra-conservative testing and only on a non-interference bases with the primary mission. The net result is a limited scientific return and usually leads to the eventual elimination of the experiment.

CSI-SAT APPROACH

A new and innovated approach to conducting CSI experiments in space is to develop the concept around a "Light or Small Satellite" configuration. Currently the DARPA and Air Force light satellite approaches are aimed at an affordable access to space where low cost here means less than \$20M for the satellite and launch with a fast paced 2 year schedule. There are an number of spacecraft builders such as Defense Systems Inc, Fairchild and AeroAstro which are developing designs for small spacecraft. Therefore, the approach is to define the CSI experiment to utilize existing deployable structures (trusses & booms), constrain it to a small satellite bus and limit the performance requirement to those obtainable with the existing hardware. The advantages of this innovative CSI flight experimental approach is that it would be dedicated CSI flight experiment with approximately a one year life time. With the appropriate design , numerous guest investigators could develop system identification and control algorithms to be uplinked to the CSI-SAT for testing and evaluation. This approach is potentially 5 to 10 times lower in cost than previously proposed methods.

Launching Platforms

The launch vehicle is anticipated to be "PEGASUS" which can carry 600 to 1000 pounds of payload into a 250 to 400 km circular orbit. Ground operations facilities currently being used for SDIO mission operations of the Relay Mirror Experiment(RME) and the Laser Atmospheric Compensation Experiment(LACE) are adequate to support a CSI-SAT experiment. These government funded(SDIO) facilities should be available for the CSI-SAT

mission operations. The CSI-SAT approach provides a significant cost savings over previously envisioned CSI space flight experiments.

Small Satellite Concept

The purpose of the CSI-SAT configuration shown in figure 10 would be to resolve the CSI technical issues in space. Selected technologies for space testing would be advanced structural materials or composite structures for damping or protection; space power innovations in solar power, batteries or nuclear power; advanced electronics, micro-chips, special purpose processors, computers; embedded sensor, actuators, and processors for smart structures. Technology suites could demonstrate integrated subsystem and system level CSI technologies in the areas of attitude control, autonomous guidance and navigation, and computer architectures will be identified.

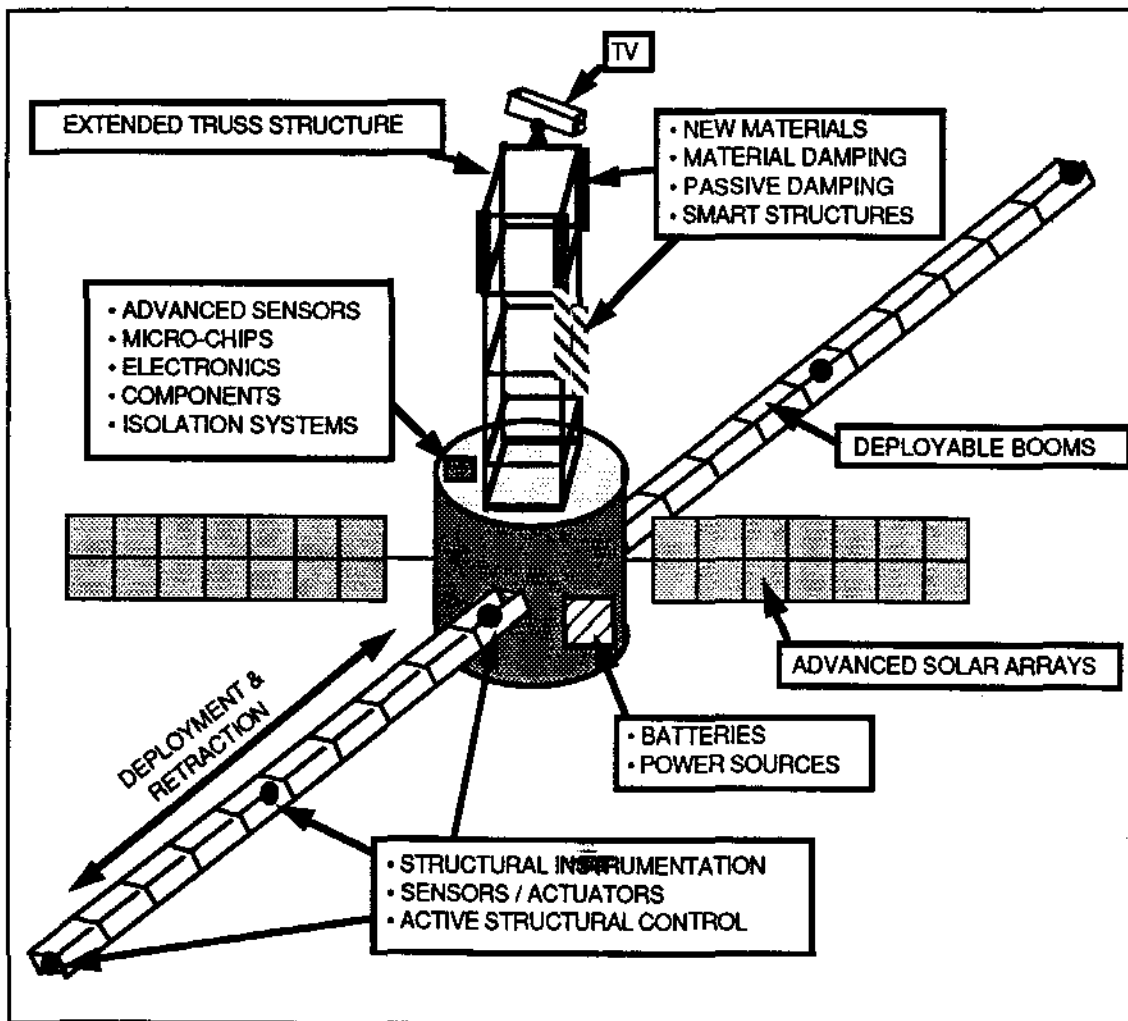


Figure 10 CSI-SAT Configuration

Major emphasis would be with respect to CSI systems depicted in figure 10 below that can not be validated on ground experiments such as integrated structural modeling verification and validation, multibody flexible structural dynamics, deployment dynamics, control system design verification and system identification. CSI-SAT can be constructed such that an exact ground test article could be compared with the actual flight hardware. This will enable the verification of ground tests with on-orbit tests. The CSI-SAT SBIR is addressing (1) the CSI technical issues that could be resolved with small satellite technology; (2) alternative small satellite platforms and their respective launch system; (3) an experiment concept for a CSI payload configuration and (4) an implementation plan for executing the program.

CONCLUSIONS

The advantages of this CSI-SAT flight experiment approach are that (1) it would be a dedicated CSI flight experiment with approximately a one year life time; (2) with the appropriate concept design , numerous guest investigators could flight test innovative materials or components as well as uplink experimental system identification and control algorithms for evaluation; (3) provide a reconfigurable platform for flight testing new CSI technologies/methodologies before applying them to operational systems; (4) this approach is potentially 5 to 10 times lower in cost than previously proposed methods.

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