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CSI FLIGHT EXPERIMENT PROJECTS OF THE NAVAL RESEARCH LABORATORY

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ABSTRACT

The Naval Research Laboratory (NRL) is involved in an active program of CSI flight experiments. The first CSI flight experiment of the Naval Research Laboratory, the Low Power Atmospheric Compensation Experiment (LACE) dynamics experiment, has successfully measured vibrations of an orbiting satellite with a ground-based laser radar. The observations, made on January 7, 8 and 10, 1991, represent the first ever measurements of this type. In the tests, a narrowband heterodyne CO_2 laser radar, operating at a wavelength of 10.6 microns, detected vibration induced differential-Doppler signatures of the LACE satellite. Power spectral densities of forced oscillations and modal frequencies and damping rates of free-damped vibrations were obtained and compared with finite element structural models of the LACE system. Another manifested flight experiment is the Advanced Controls Technology Experiment (ACTEX) designed to demonstrate active and passive damping with piezo-electric (PZT) sensors and actuators. This experiment was developed under the management of the Air Force Phillips Laboratory with integration of the experiment at NRL. It is to ride as a secondary, or "piggyback," experiment on a future Navy satellite.

LACE SATELLITE: DESIGN AND FLIGHT HARDWARE OF DYNAMICS EXPERIMENT

The first of the CSI flight experiments of the Naval Research Laboratory (NRL) is the Low Power Atmospheric Compensation Experiment (LACE) dynamics experiment. The experiment was a low-cost "piggyback" opportunity, secondary to the primary LACE mission. Its design was initiated at meetings held at NRL in May and June of 1988. Costs were kept low, and rapid integration of the experiment into the satellite design was made possible because the LACE satellite was built and launched by NRL, i.e., design and integration of the experiment took place at the same facility. The LACE satellite was launched on February 14, 1990 into a 540 km altitude circular orbit of 43^0 inclination. The structural configuration of the LACE spacecraft is illustrated in Figure 1. Three deployable/retractable booms of maximum length 45.72 m (150 ft) are mounted on a rectangular parallelepiped bus of mass 1,200 kg. The zenith directed gravity gradient boom has a magnetic damper at its tip; the forward or retro-boom is deployed along the velocity vector; the balance boom is mounted and deployed counter to the velocity. The tip end of the retro-boom carries a reflector plate on which an array of glass corner cubes is mounted. The glass corner cubes are intended to reflect visible light for the primary LACE mission. Attitude stabilization to within about 1^0 libration amplitude is accomplished by the gravity gradient torques and by a constant speed momentum wheel. Constant rate boom deployment/retraction maneuvers are remotely controlled through a ground based telemetry link.

The dynamics experiment flight hardware consists of three germanium corner reflectors, as shown in Figure 1. One of the reflectors is included in the array of corner cubes mounted on the end of the retro-reflector boom; one is on the bottom of the bus, and the third one is on the end of the balance boom. The germanium has an index of refraction of 4.0 for light of wavelengths between 1.8 microns and 15 microns. With this very high index of refraction, light striking the reflector surface at angles of 20^0 or greater will be reflected. Therefore, a ground-based light source will see a return signal even for the satellite at a low elevation angle.

LACE Spacecraft

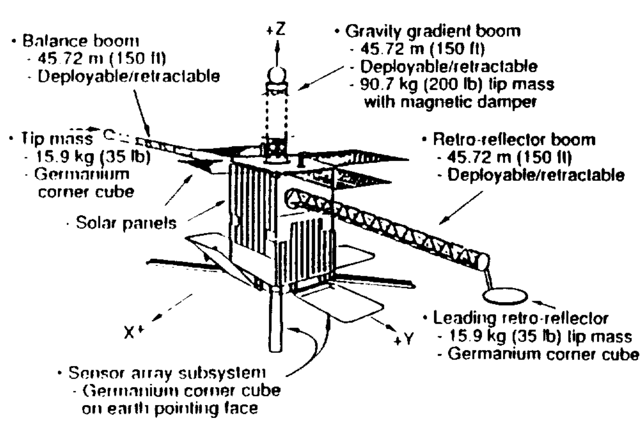

FIGURE 1: Design of the LACE satellite showing placement of germanium corner reflectors.

The laser illuminations are made with the MIT Lincoln Laboratory's Firepond laser radar located in Westford, MA as shown in Figure 2. The Firepond radar used for the illuminations is a narrowband, CO_2 laser radar operating at 10.6 microns. The aperture of the laser telescope is 1.2192 m (48 in), giving a nominal diffraction limited footprint of about 5 m at a range of 550 km (minimum target range). A 0.6096 m (24 in) telescope, boresighted with the CO_2 telescope, can track in visible light either passively by reflected sunlight or actively with a 25 watt, 514.5 nm Argon-ion laser. Acquisition and tracking are assisted by the Millstone L-band radar located nearby. The Millstone radar also supplies target frequency information for range-rate (Doppler) acquisition. Observations are made with the sun 10^0 to 30^0 below the horizon, either before sunrise or after sunset. In this "terminator mode," the site is in darkness but the satellite is still in sunlight. The CO_2 illuminations are limited by NORAD to windows unique to each pass, and by a safety requirement that the elevation angle must be 30^0 or more.

With the Firepond apparatus, vibration measurements were made on January 7, 8 and 10, 1991 (denoted hereafter in this report as days 91007, 91008 and 91010). The targeting of LACE was accomplished with active tracking by means of the Argon-ion laser targeted on the retroreflector array of glass corner cubes at the tip of the lead boom.

Before and during the targeting, vibrations of the LACE satellite structure were excited by retraction of the lead boom from 24.38 m (80 ft) to 4.572 m (15 ft). The reflector on the lead boom tip and the reflector on the bus were simultaneously illuminated, after the boom length decreased to 9.144 m (30 ft), to provide differential Doppler measurements of the relative motion between the end of the boom and the spacecraft body. Simultaneous observations could only be made for a boom length of 9.144 m (30 ft) or less because of the narrow width of the laser beam. The relative motion includes boom vibration as well as the rigid-body satellite motion and the boom retraction motion.

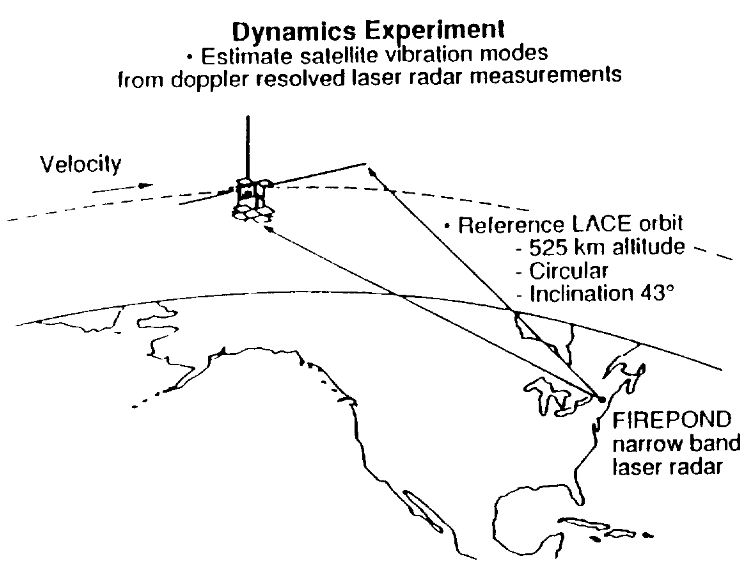

FIGURE 2: On-orbit targeting of LACE with the Firepond narrowband laser radar.

OBJECTIVES OF THE DYNAMICS EXPERIMENT

With the dynamics experiment, the primary design goal was to perform on-orbit system identification, i.e. to measure modal frequencies and damping ratios of the satellite structure as stated in Figure 3. The large size of the LACE structure precluded ground tests of the dynamics of the deployed structure or tests of boom deployment dynamics prior to launch. The damping ratios, measured by the experiment, provide a useful assessment of the amount of vibration damping intrinsic to the type of deployable/retractable truss structures used in LACE. Such structures are used in a number of space applications, i.e., the Voyager magnetometer booms and in the Galileo spacecraft. The on-orbit system identification provides a mechanism to validate finite element structural models of the satellite system; to refine and improve them, and to measure the level of vibration induced by boom deployments/retractions.

- Unique opportunity to measure effects of disturbances on spacecraft flexure; give boom vibration knowledge during LACE spacecraft operations.

- Goal is to perform on-orbit system identification: vibration frequencies, damping and amplitude ratios.

- Assess flexible structural modelling accuracies:

    deployment/retraction vibrations
    finite element models (FEM): NASTRAN
    dynamics simulation models: DISCOS, treetops
    deployment dynamics: DART

- Facilitate control of jitter and rapid slews in future spacecraft.

FIGURE 3.

KEY POINTS OF THE DYNAMICS EXPERIMENT

Figure 4 states the significant events of the dynamics experiment. The LACE satellite was launched on February 14, 1990. As previously mentioned, observations of vibrations of the LACE satellite were made on January 7, 8 and 10, 1991 (denoted in this report as days 91007, 91008 and 91010). In the observations, the Firepond narrowband laser radar telescope, boresighted with the visible light radar, observed differential Doppler reflections from the germanium corner reflectors on the lead boom and body of the spacecraft after the boom length reached 9.144 m (30 ft) or less. The laser Doppler measurement window of day 91007 observed about 38 seconds of forced dynamics motion of the lead boom while the boom was being retracted. The window of day 91008 contained about 68 seconds of retraction data and 25 seconds of free-decay data after retraction was stopped. Day 91010 data contained about 45 seconds of useful free-decay data after retraction was stopped.

- LACE spacecraft launched February 14, 1990
  altitude at launch 540 km, circular, 43^{o} inclination
- LACE satellite built and launched by Naval Research Lab.
- Dynamics experiment is a low-cost "piggyback" experiment.
- Germanium corner cubes (3) serve as targets for Firepond
  laser radar of MIT Lincoln Laboratory, Westford, Mass.
- Corner cubes installed on LACE on December 22, 1989.
- Laser Doppler data collected on January 7, 8 and 10, 1991.
- Observed forced vibration and free-damped oscillations.

FIGURE 4:

COMPENSATION FOR RIGID BODY MOTION AND BOOM RETRACTION

In addition to the vibrational motion, the Doppler data includes the rigid body motion of the spacecraft as well as the boom retraction speed of about .076 m/sec (.25 ft/sec). Since the spacecraft is gravity-gradient stabilized it rotates once per orbit in inertia space at a uniform rate. However, from the ground, its aspect angle changes at a variable rate with time; the rate appears to be a maximum when the spacecraft is at its maximum elevation angle, as illustrated in Figure 5. These aspect angle changes and aspect angle rate changes have several effects on the observed Doppler shifted laser return:

1. The rigid body motion and boom retraction speed will bias the vibration motion. It will be shown that the boom retraction speed is several times larger than the vibration speed.

2. The frequency separation between the apparent rigid body motion and the lowest vibrational mode of 0.019 Hz is small. Therefore the observability of this mode is affected.

3. The observed damping factors of the detected modes will be biased by an amount that depends upon the position of the satellite in the sky. The calculated damping factors will be smaller for observations with the satellite ascending to its maximum elevation angle, than for observations with the satellite descending.

The effects of this apparent motion are treated by calculating the apparent rigid body motion during the observation period using the spacecraft orbital rate, range, the boom lengths and boom retraction rate. The bias produced by the rigid body motion is subtracted from the observed motion. The change in observed damping with aspect angle is corrected by dividing the damping factor by the cosine of the angle between the LOS vector and the pitch plane.

Figure 5 appears on the following page.

ROTATION OF EARTH-POINTING SATELLITE AS OBSERVED BY A GROUND STATION

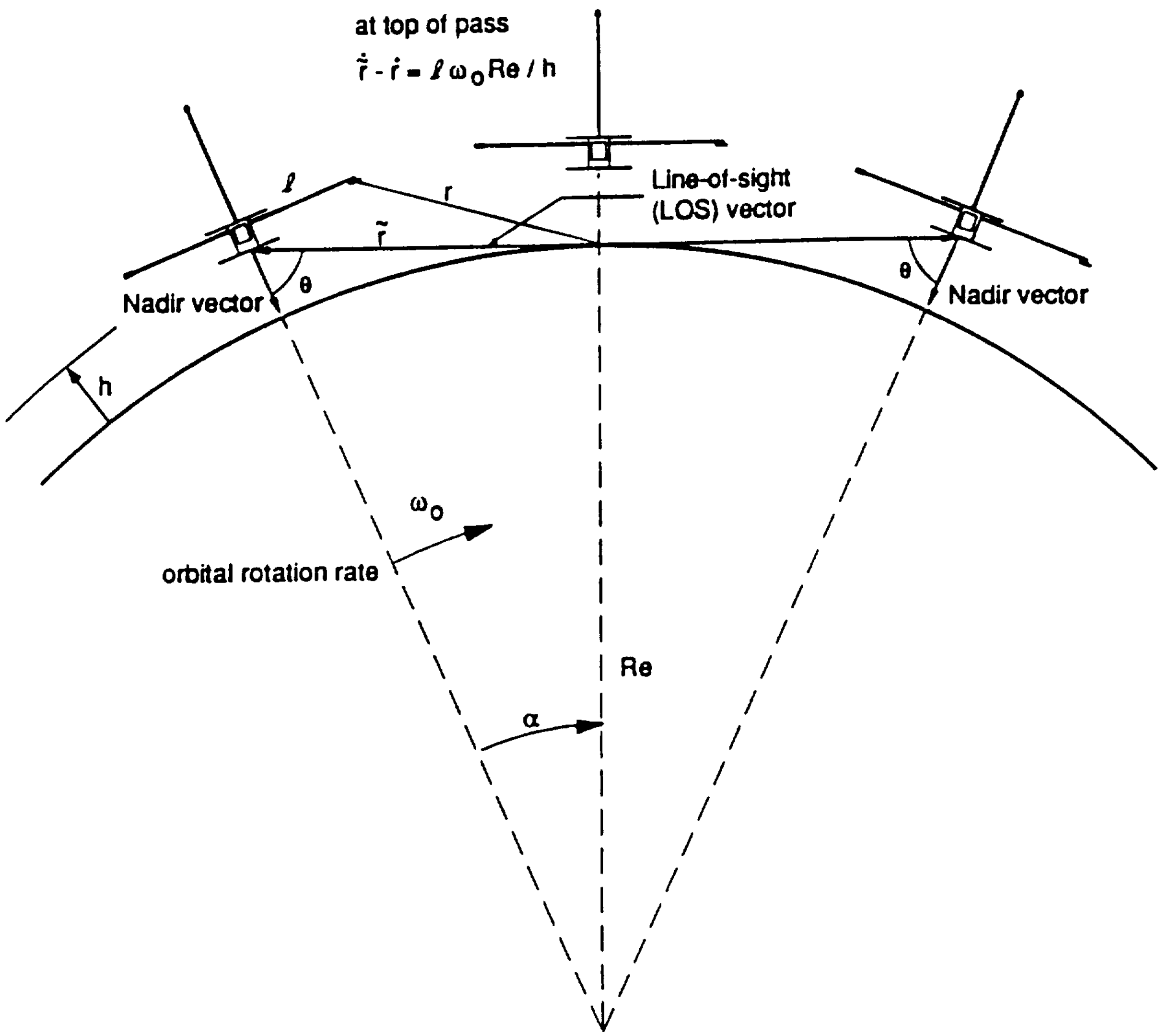

FIGURE 5: Rotation of LACE as observed from a ground site.

OBSERVED STRUCTURAL VIBRATIONS

Figure 6 shows observed data from day 91008. The figure shows forced vibration data to about 67 seconds, followed by about 28 seconds of free-decay vibration data, on which is superimposed a simulation of the rigid-body motion and boom retraction rate. The simulation comes fairly close to the median of the observed vibration data: orbital uncertainties and uncertainties in the boom retraction rate could account for the slight discrepancy between the real and computed central body motion. It can be seen that the amplitude of the forced vibration is about 20 mm/sec. The boom retraction rate is about 75 mm/sec. Figure 7 shows a power spectral density plot obtained by Hamming weighting the data of the entire temporal window and computing the power spectrum. The nominal resolution of the resultant spectrum is 0.01 Hz. The result indicates the presence of multiple vibration frequencies. Values of observed vibration frequencies are listed as follows: 0.12 Hz, 0.28 Hz, 0.51 Hz, 1.03 Hz, 1.25 Hz, 1.29 Hz, 1.31 Hz, 1.41 Hz, 1.45 Hz, 1.55 Hz, and 2.46 Hz. The accuracy of these measurements has not been determined due to the limited number of observations.

The time-frequency analysis of the forced oscillation data from day 91008 is presented in Figure 8. Represented in this way, the data clearly indicate that modes in the 0.28 Hz regime and in the higher 1.25 Hz - 2.46 Hz regime increase in frequency as the boom retracts. The figure also indicates the relative stability of the 1.03 Hz frequency, a frequency close to the driving frequency of the boom deployment mechanism.

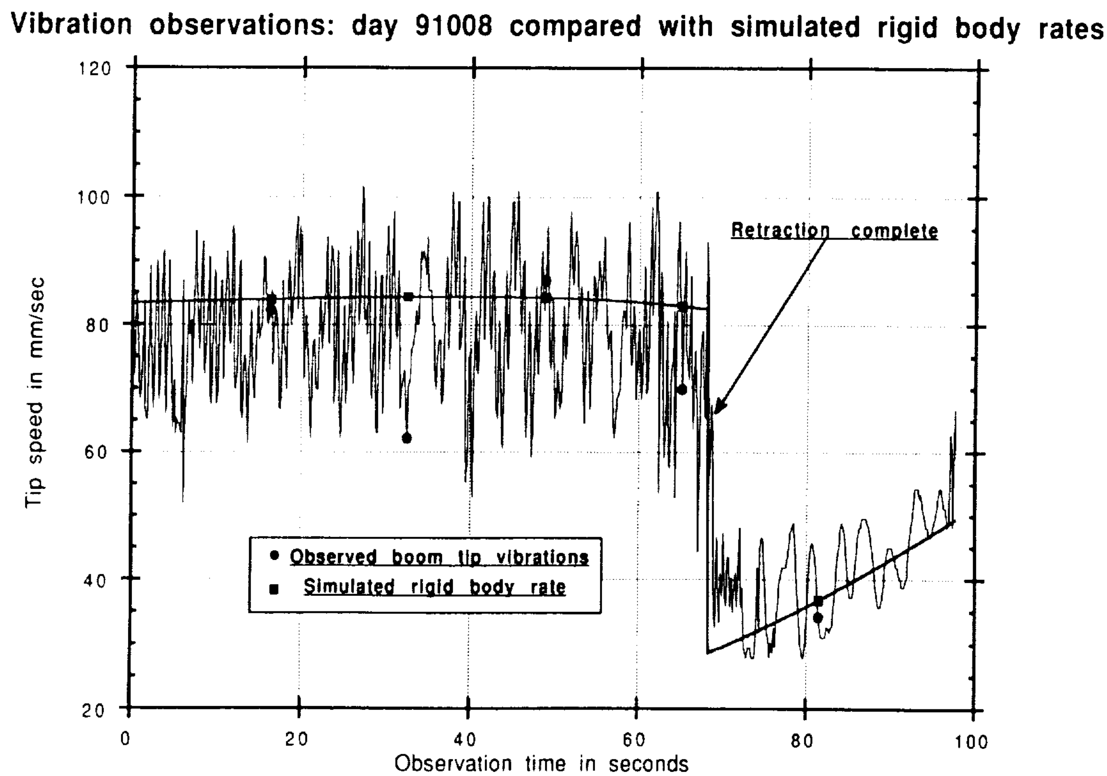

FIGURE 6: Observed vibration of LACE on day 91008.

Figures 7 and 8 appear on the following pages.

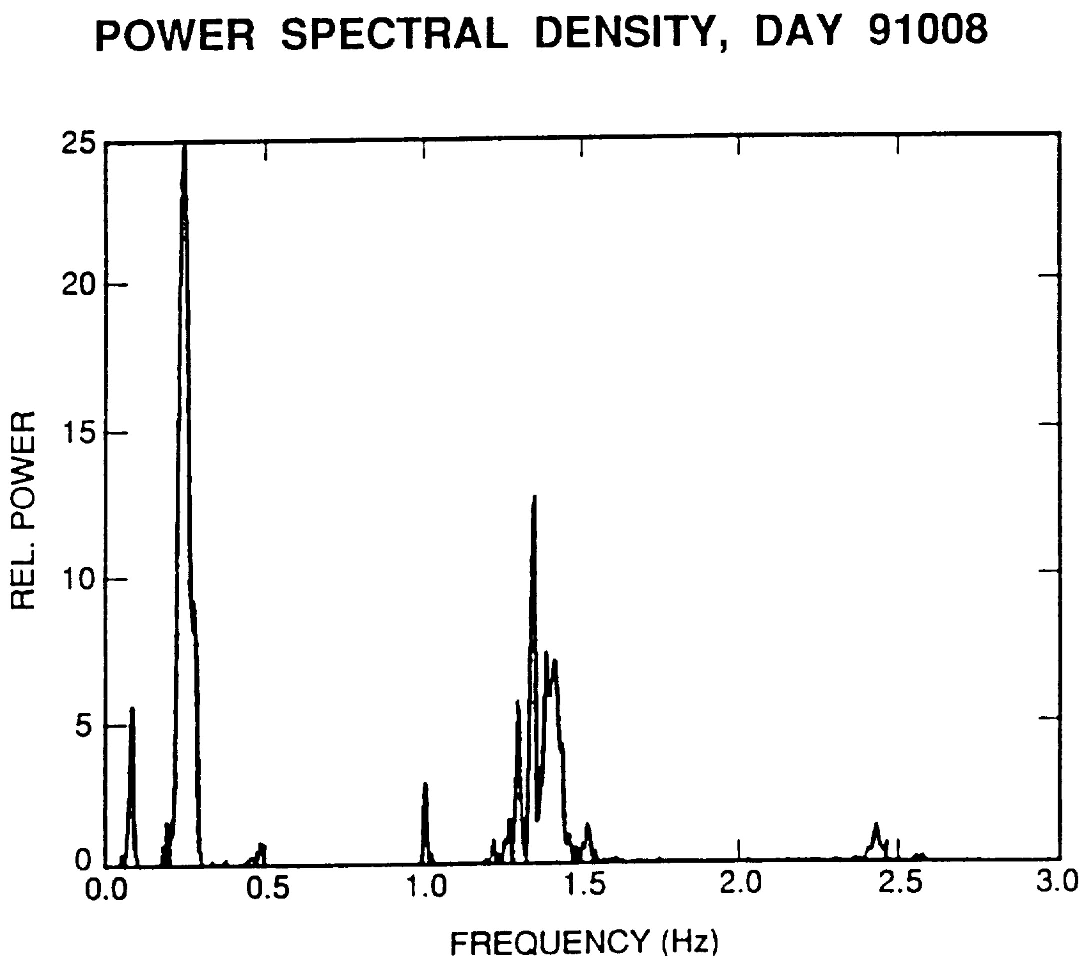

FIGURE 7: Power spectral density plot of vibrations observed during boom retraction.

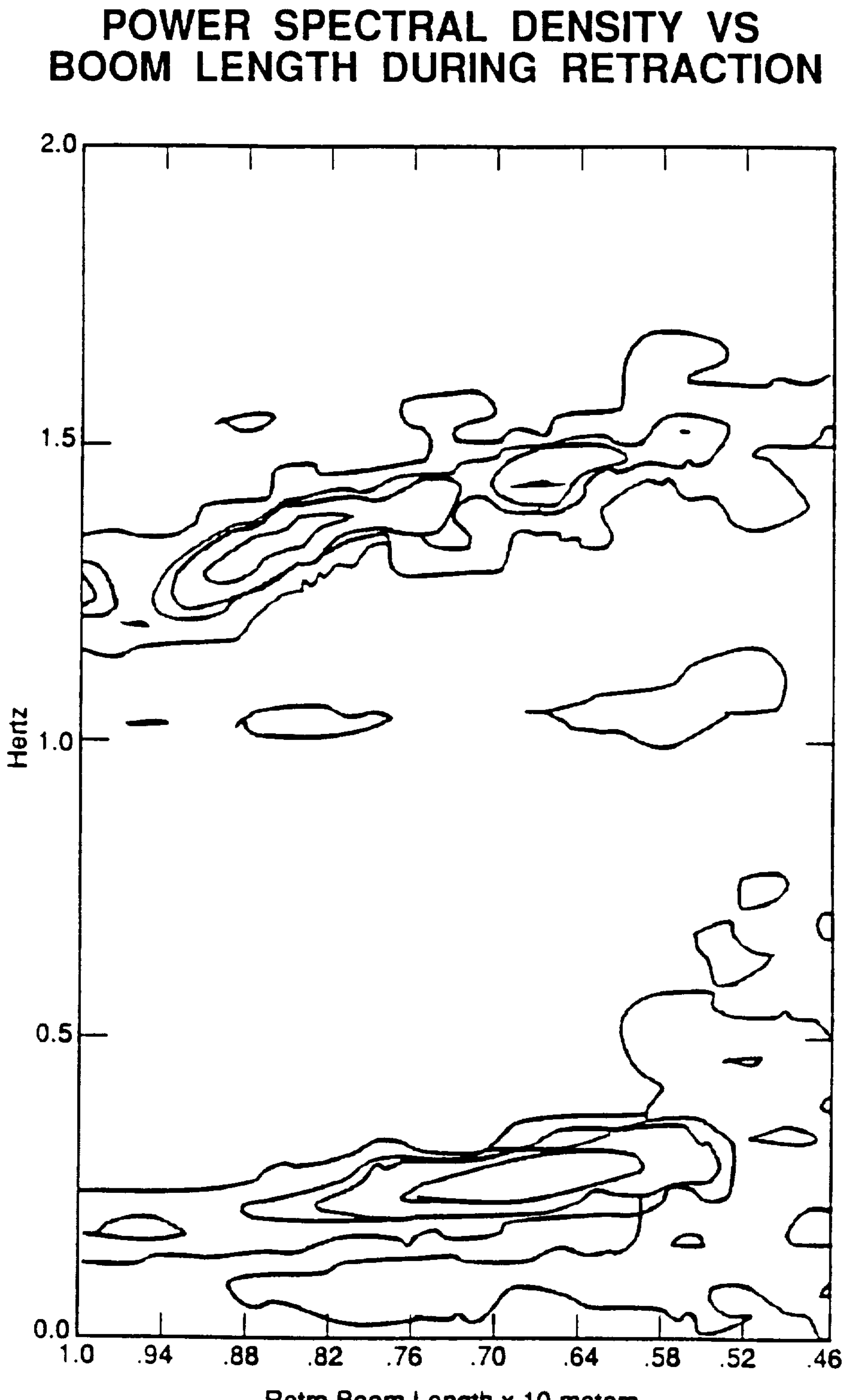

FIGURE 8: Forced oscillation frequencies versus boom length during retraction.

COMPARISON BETWEEN FEM MODES AND OBSERVED MODES

The eigensystem realization algorithm[1] (ERA) was used to calculate values of the observed modal frequencies and damping factors. Table 1 shows a comparison between the ERA derived modes (order = 8) and modes computed with a finite element (FEM) structural model. The finite element model used was a "stick" model in which the booms were modelled as simple beams rather than as trusses. Table 1 also shows the boom tip modal displacements obtained from the FEM model. The displacements are normalized so that the maximum displacment is 1.0. The observable modes are those with substantial modal displacement, Δz, perpendicular to the boom axis and coplanar with the line-of-sight vector and a vector along the boom axis. The lowest ERA derived mode of .019 Hz does agree quite well with the lowest FEM calculated mode. However, the day 91010 observation period was about 45 seconds, i.e., it was close to the 53 second period of that mode. Therefore, the agreement in frequency between the observed and calculated mode may be coincidental. The other observed modal frequencies of 0.124 Hz, 0.335 Hz and 0.547 Hz agree within 10% of the modal frequencies for the more highly observable modes. Another interesting feature of the comparison is the presence of the FEM mode at 0.646 Hz, which should have been observed, but was not. The close spacing between the FEM mode of 0.577 Hz and the mode at 0.646 Hz might have produced a nonlinear modal coupling that resulted in a combination mode at a frequency different from either, at 0.547 Hz. A more detailed modelling scheme with the booms modelled as full trusses might produce a closer agreement with the observations.

TABLE 1: Comparison of ERA-identified modal frequences with FEM modes.

Comparison of observed with modes computed from FE modelling (stick model)

$EI = 1.55 * 10^4$ N - m^2 $GJ = 5.74 * 10^2$ N - m^2

Obs freq	FEM freq	tip modal displacements Δz	tip modal displacements Δx
*0.019 Hz	0.019 Hz	.010	--
	0.110 Hz	.001	.05
	0.112 Hz	.002	.09
•0.124 Hz	0.125 Hz	.09	.004
	0.258 Hz	.009	--
	0.297 Hz	--	.08
•0.335 Hz	0.316 Hz	.10	.006
	0.320 Hz	.02	.02
•0.547 Hz	0.577 Hz	.14	.124
	0.646 Hz	.127	.135
	0.819 Hz	.004	--

•Denotes modes observed.* Not positively identified

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OBSERVED MODAL DAMPING

An important result of the dynamics experiment is a measurement of the modal damping of the LACE satellite as shown in Table 2. The damping shown in Table 2 was also obtained with the ERA algorithm. The damping of the .547 Hz mode seems quite high and is an indication that the mode may have anomalous characteristics, i.e. it may be a combination of modes and not a simple mode. However, the computed damping of the other modes at 0.019 Hz, 0.124 Hz and 0.335 Hz is comparable to the values of 1.4% to 2.7% measured for the Voyager magnetometer boom by the Marshall Space Flight Center, Huntsville, Ala.[2] and values of 1.2% to 3.5% measured at the Canadian Communications Research Centre, Ottawa, Canada[3] for an astromast of design similar to the LACE booms.

A flight experiment that can be compared with the LACE dynamics experiment is the Solar Array Flight Experiment [4]. In that experiment a boom similar to the LACE booms was deployed with a solar blanket and attached tension wires for an 18 hour period on board the space shuttle. The vibration damping of modes out of the plane of the solar blanket can be compared with our results. These out-of-plane modes had damping factors of 3% to 6% depending on day/night. This damping was higher than ours, possibly because of the tension wires[5].

TABLE 2: ERA-identified damping of the observed modes.

System vibrations: ERA compared to FEM model

frequency	% damping	FEM simulation
0.019 Hz	1.8	1st mode: 0.019 Hz
0.124 Hz	2.3	4th mode: 0.125 Hz
0.335 Hz	2.1	7th mode: 0.316 Hz
0.547 Hz	10.4	9th mode: 0.577 Hz

CONCLUSIONS FROM LACE DYNAMICS EXPERIMENT

The dynamics experiment performed on the low power atmospheric compensation experiment satellite has established the feasibility of ground-based laser measurements of vibrations, slews and deployments in orbiting satellites. The technique can be applied to health monitoring of large structures such as the space station. The experiment has demonstrated that velocity resolutions of 1.8 mm/sec are attainable with the current narrowband Firepond apparatus of the MIT Lincoln Laboratory.

ADVANCED CONTROLS TECHNOLOGY EXPERIMENT (ACTEX)

The ACTEX experiment, illustrated in Figure 9, is a secondary payload, manifested to fly on a future Navy spacecraft. The experiment is being built at the present time and will be exposed to space on the outside of the flight deck. Of course the electronics, comprised of a computer and solid state data recorder, are below deck for shielding and thermal control. The experiment includes three graphite-epoxy struts with embedded piezo-electric (PZT) sensors and actuators. Two of the struts are wrapped with mylar thermal insulation blankets, while the other strut is painted. One of the stuts has an extra set of PZT actuators to excite vibrations of the system.Thermistors are placed on the struts for temperature measurements. Both the top plate and mounting bracket contain three-axis accelerometers, with a heater on the top plate. The tripod is about 0.6 m (24 in) in length and weighs about 8.2 kg (18 lbs).

The experiment is intended to demonstrate that the technology of embedded PZT's is mature enough to be used on space based payloads. It is also intended to demonstrate the application of PZT's for passive and active vibration control in a large space structure. Different control algorithms, based on changing gains, filter cutoffs or sensor averages, can be telemetered to the experiment computer. The dynamic change mechanism (DCM) is attached to one of the struts. It contains a nitinol wire with attached electrodes. Passing a current through the wire pulls the strut snugly against the top plate, thereby increasing the strut stiffness. The purpose is to test the capability of modifying the control laws to damp out vibrations in the presence of on-orbit structural changes. An additional goal of the experiment is to evaluate the effect of radiation, thermal cycling and atomic oxygen erosion on the experiment performance over a three year lifetime.

Figure 9 appears on the following page.

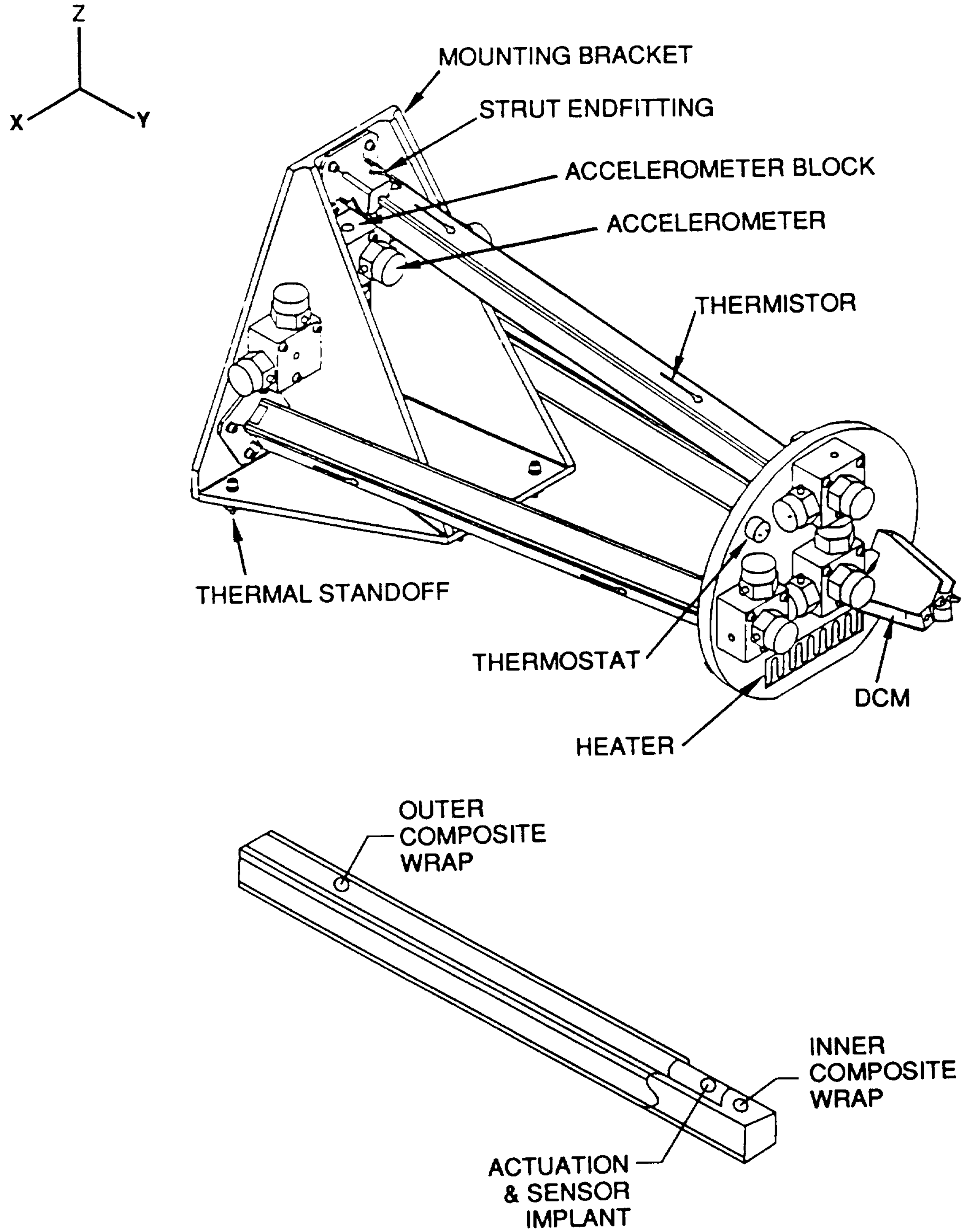

FIGURE 9: Design of the ACTEX experiment.

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