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LACE FLIGHT DYNAMICS EXPERIMENT

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ABSTRACT

The Low Power Atmospheric Compensation Experiment (LACE) is scheduled for launch in late 1989 into a 556 km altitude circular orbit of 43^0 inclination. The LACE flight dynamics experiment, described in this report, is an experiment secondary to the primary LACE mission. The purpose of the experiment is to provide on-orbit systems identification of the LACE spacecraft. The structure of the LACE spacecraft is of special interest to the CSI community. It incorporates 3 deployable/retractable booms of maximum length 45.72 m (150 ft) mounted on a rectangular parallelepiped bus of mass 1,200 kg. The zenith directed gravity gradient boom is mounted on the top of the bus; the retroreflector boom is mounted forward and deployed along the velocity vector; the balance boom is mounted and pointed aft. Attitude stabilization is accomplished by means of gravity gradient torques and by a momentum wheel. The LACE flight dynamics experiment is designed to measure modal frequencies, damping ratios, and oscillation amplitudes of the LACE spacecraft, as well as the vibration intensity generated by boom deployments and retractions. It is anticipated that this experiment will provide an opportunity for improvements in the accuracy of computer simulations of flexible structures and multibody dynamics.

DESIGN OF LACE FLIGHT DYNAMICS EXPERIMENT

The Low Power Atmospheric Compensation Experiment (LACE) is scheduled for launch in late 1989 into a 556 km altitude circular orbit of 43^0 inclination, as illustrated in figure 1. The LACE flight dynamics experiment, described in this report, is an experiment secondary to the primary LACE mission. The purpose of the experiment is to provide on-orbit systems identification of the LACE spacecraft. The structural configuration of the LACE spacecraft is indicated in figure 1. Three deployable/retractable booms of maximum length 45.72 m (150 ft) are mounted on a rectangular parallelpiped bus of mass 1,200 kg. The zenith directed gravity gradient boom has a tip mass of 90.7 kg and includes a magnetic damper; the retroreflector boom and balance boom each have a tip mass of 15.9 kg. Attitude stabilization is accomplished by the gravity gradient torques and by a momentum wheel. The flight dynamics experiment hardware consists of 2 germanium corner cubes: one proposed to be on the bus and the other on the balance boom. The FIREPOND laser radar at the MIT Lincoln Laboratory will illuminate the cubes to measure the relative motion of the boom with respect to the bus. Absolute bus rotation rates will be measured by means of the on-board UltraViolet Plume Instrument (UVPI). Measurements will be made of vibration frequencies, damping ratios, and oscillation amplitudes.

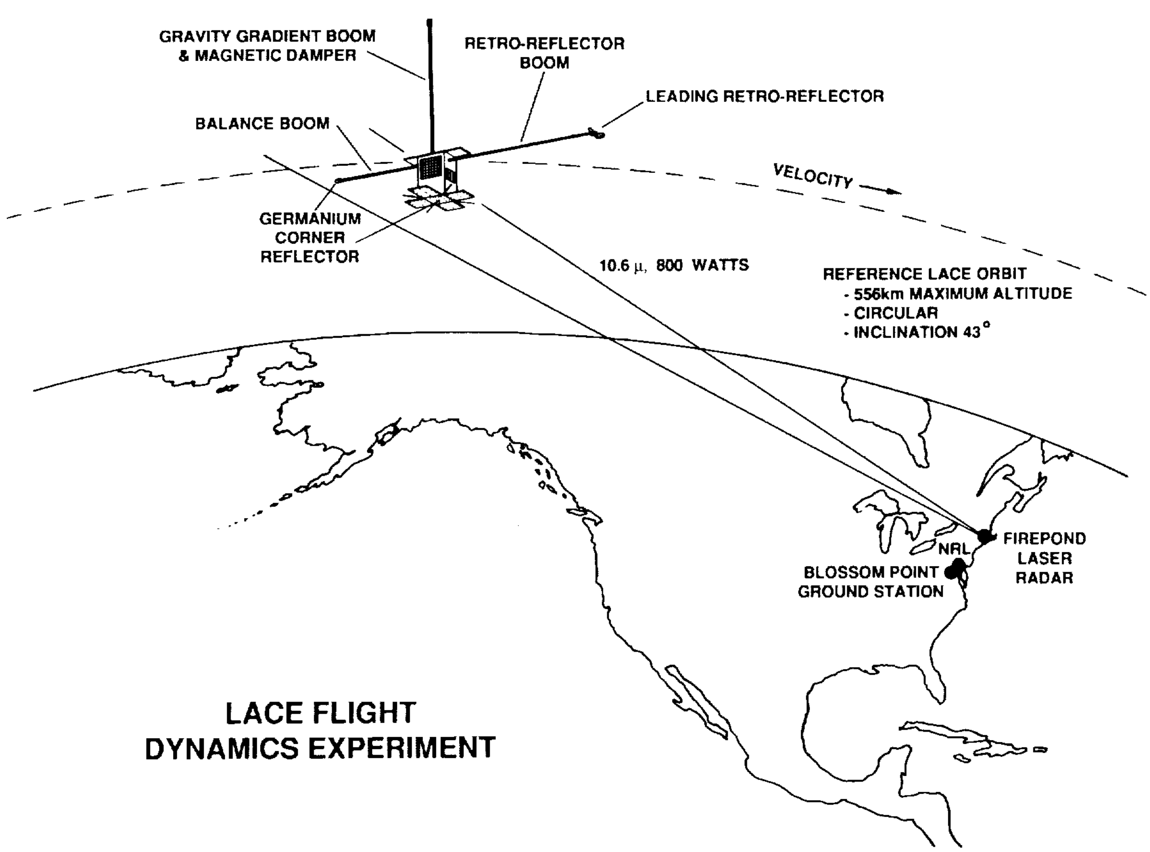

Figure 1

ISSUES ADDRESSED BY THE DYNAMICS EXPERIMENT

Structural modelling, environmental interactions, and boom deployment dynamics are areas where the LACE flight dynamics experiment can provide useful data. At the present time estimates of the vibration frequencies are based on static ground tests of the boom structure. The flexural rigidity value obtained thereby ranges from $1.26 * 10^4$ N-m^2 ($4.4 * 10^6$ lb-in^2) to $1.6 * 10^4$ N-m^2 ($5.5 * 10^6$ lb-in^2), giving an uncertainty in the vibration frequencies of about 20%. Further uncertainties in the vibration frequencies, as well as in the gravity gradient libration frequencies, are generated by twisting from differential day/night heating. The amount of vibration damping is not well known. For example, in the SAFE experiment of 1984* a flexible, deployable "wing" of polymer film was attached to a boom similar to the LACE booms. Damping rates were observed to be nonlinear (reference 1) with most of the damping induced by the attached wing. In the case of LACE, with no boom attachments, the experiment will measure the damping intrinsic to the boom structures.

Furthermore, the flight dynamics experiment will provide a mechanism for evaluating the influence of magnetic torques, gravity-gradient torques, and atmospheric drag on the LACE structure. Also, vibrations generated by boom deployments and retractions such as were observed in the SAFE experiment will be measurable by means of this experiment. (Fig. 2.)

*Lockheed Missiles & Space Company, "Solar Array Flight Experiment: Final Report," LMSC-F087173, National Aeronautics and Space Administration, Marshall Space Flight Center, Alabama, April 1986.

ISSUES ADDRESSED BY THE DYNAMICS EXPERIMENT

Accuracy of mathematical models and computer simulations

- Structural Models

  Damping rates of vibration oscillations: estimates .2 % to .5%

  Oscillation frequencies: uncertainties of 20%

  Thermoelastic changes: day/night changes in frequency
  twisting from differential heating

- Environmental interactions: atmospheric drag
  gravity gradient torques
  magnetic damping

- Oscillations generated by boom deployments/retractions

Figure 2

EXPERIMENTAL HARDWARE

With this experiment, two germanium corner cubes are proposed to be mounted on the spacecraft: one on the bottom of the spacecraft bus, the other at the tip of the balance boom. The corner cubes will serve as targets for the FIREPOND 10.6 micron laser radar at the MIT Lincoln Laboratory. It is anticipated that this experimental setup will provide resolutions of 2 mm/sec relative motion between the bus and the boom tip, and thereby readily resolve the lowest mode of 0.019 Hz. A typical relative motion is expected to be 18 mm/sec, based upon a NASTRAN simulation with an assumed 60 cm amplitude of vibration at the tip of the retro-boom. The FIREPOND laser radar has a 4 millisecond square wave pulse at a frequency of 62.5 Hz and pulse energy of 3.2 joules. It has tracked reflections from similar corner cubes on the LAGEOS spacecraft at ranges of 6000 km to resolve satellite spin motion (reference 2).

The Ultra-Violet Plume Instrument (UVPI), primarily installed for other experiments, will be used to measure the absolute bus rotation rate. It has the capability of resolving angular velocities of $5 * 10^{-5}$ radians/sec ($3 * 10^{-3}$ deg/sec). A typical angular rate is 0.2 deg/sec, based upon the NASTRAN simulation. The resolution capability is therefore almost 2 orders of magnitude better than what is needed. (Fig. 3.)

- **Two corner reflectors: one on bus and one at tip of balance boom**
  - **Targets for FIREPOND 10 microns laser radar (far infrared)**
  - **Germanium composition gives high acceptance angle**
  - **Will measure relative motion between boom tip and bus**
  - **FIREPOND has 2 mm/sec velocity resolution capability**
  - **Lowest vibration mode of spacecraft: 18mm/sec (assume 2 ft vibration amplitude at retro boom tip)**
  - **Factor of 10 better than needed for resolution**
- **Ultra-violet Plume Instrument (UVPI): bus rotation rate**
  - **Resolution capability of $5 * 10^{-5}$ radians/sec ($3 * 10^{-3}$ deg/sec)**
  - **Lowest vibration mode : 0.2 deg/sec**
  - **Factor of 60 better than needed for resolution**

Figure 3

LACE DEPLOYABLE/RETRACTABLE BOOM STRUCTURE

The LACE spacecraft incorporates three deployable/retractable booms, of maximum length 45.72 m (150 ft) and diameter 0.254 m (10 in). Figure 4 shows the basic design. The longerons are of fiberglass composition, are continuous, and are coiled when stowed in the canister. The diagonals and battens are attached to the longerons via the corner fitting assemblies. Basic characteristics of the booms, from static ground tests, are as follows:

weight of motor, cannister and gears:	16.8 kg (37.1 lb)
weight of booms:	13.3 kg (29.5 lb)
bending stiffness, EI:	$1.26 * 10^4$ to $1.58 * 10^4$ N-m^2 (4.4 to $5.5 * 10^6$ lb-in^2)
torsional stiffness, GJ:	631 N-m^2 ($2.2 * 10^5$ lb-in^2)
bending strength:	47.45 N-m (420 in-lb)
torsional strength:	13.6 N-m (120 in-lb)
stiffness of longerons:	$2.3 * 10^4$ N/m^2 ($8 * 10^6$ lb/in^2)
boom deployment/retraction rates (depend upon bus voltage)	6 to 9 cm/sec
deployment/retraction	7.6 cm/turn

BASIC DESIGN

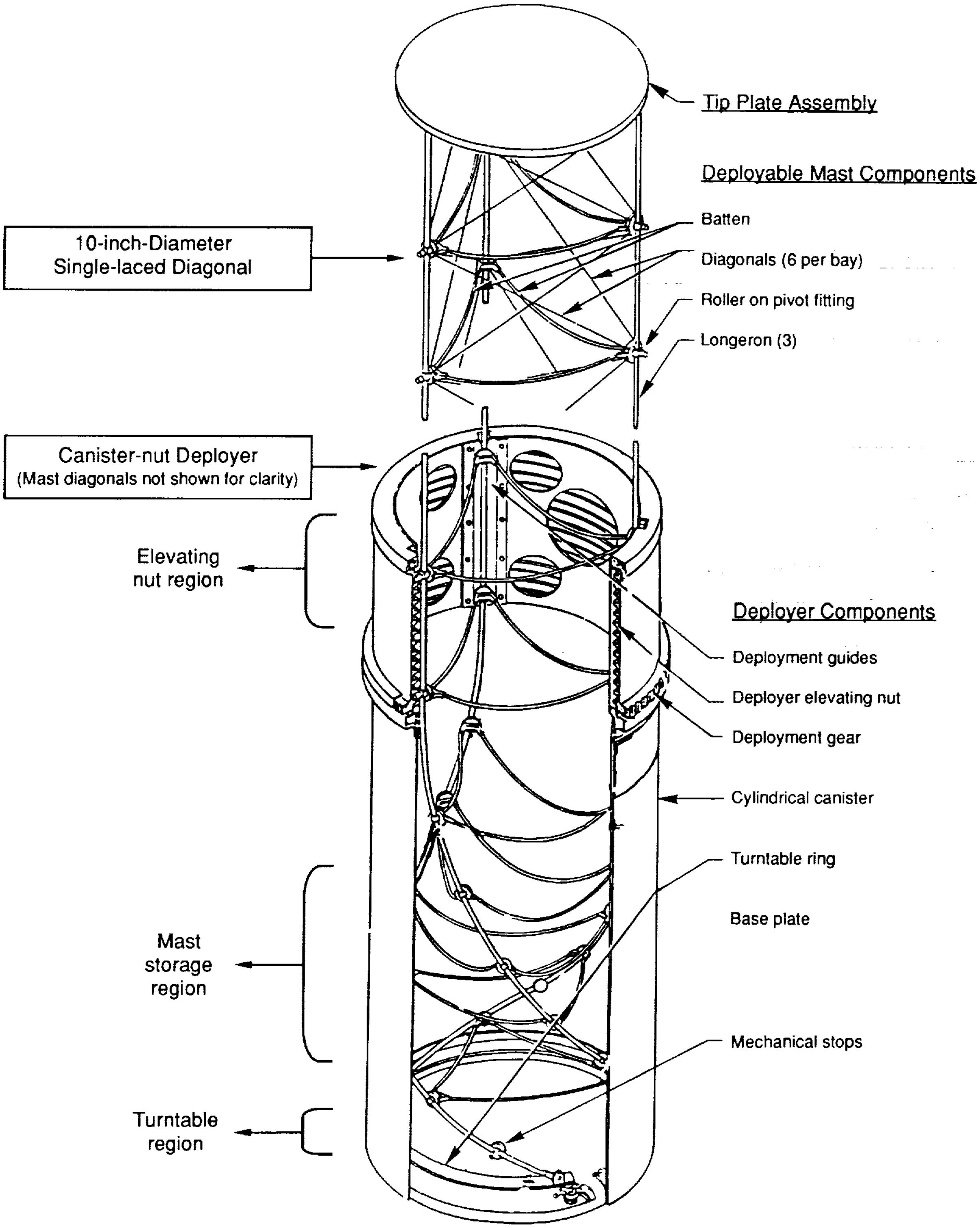

Figure 4

COORDINATE SYSTEM OF LACE ANALYSIS

Figure 5 shows the spacecraft oriented coordinate system used for the structural analysis and environmental modelling of the LACE experiment. The yaw or "z" axis is directed toward the zenith, with the pitch or "x" axis directed toward the negative orbit normal, and the roll or "y" axis is perpendicular to the other two to form a right-handed coordinate system. With LACE in a circular orbit, the roll axis is along the velocity vector.

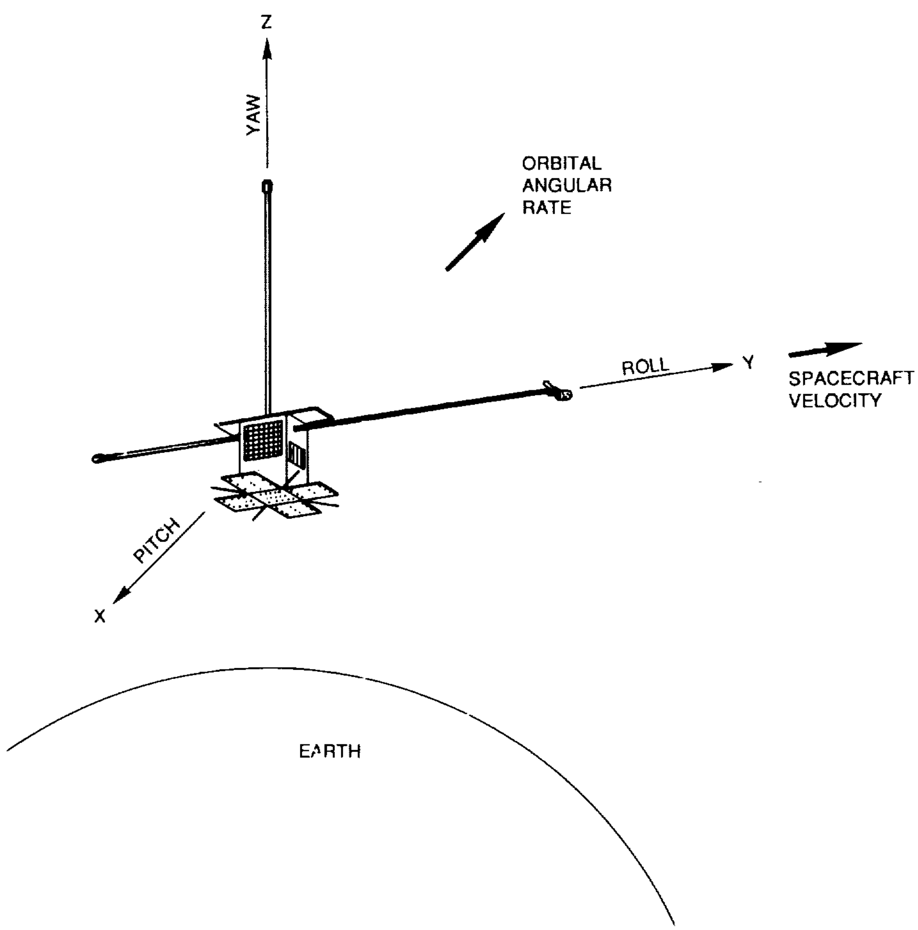

Figure 5

NASTRAN FINITE-ELEMENT ANALYSIS OF LACE SYSTEM

A NASTRAN finite-element analysis has been performed on the LACE system in its nominal operational configuration. This configuration has the gravity gradient boom at 45.72m (150 ft), the retro-boom at 45.72 m (150 ft), and the balance boom at 22.86 m (75 ft). The lowest four modes are shown in figures 6 and 7 with the frequencies and mode shapes from two different perspectives. The spacecraft coordinate system is as shown in figure 5. The first 7 modes are as follows:

mode #	frequency in Hz	mode type
1	.0194	transverse
2	.0473	"
3	.0536	"
4	.1104	"
5	.1808	"
6	.2019	"
7	.2304	torsion

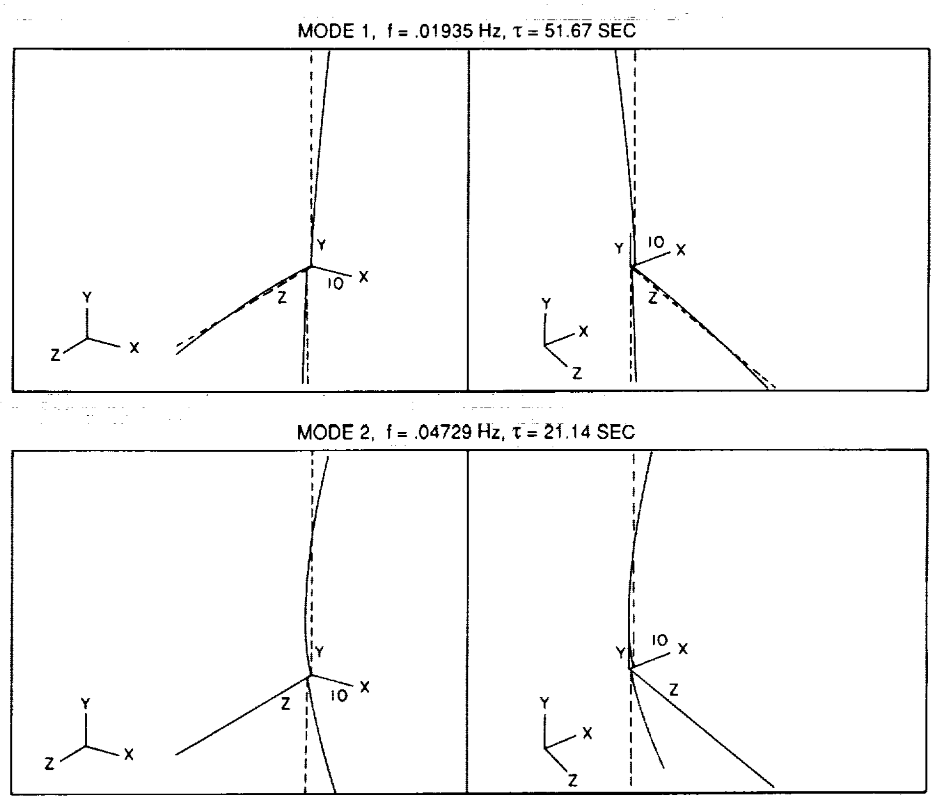

Figure 6

FINITE-ELEMENT MODELLING: LACE BUS MASS PROPERTIES

The finite-element modes were computed using the following weights, inertias and products of inertia about the LACE bus mass center; the boom masts and tip masses are not included. (Fig. 7.)

Weight	1177.68 kg	(2596.33 lb)
I_{xx}	1448.67 kg-m^2	(1068.48 slug-ft^2)
I_{yy}	1426.43 "	(1052.10 ")
I_{zz}	1026.16 "	(756.86 ")
I_{xy}	3.61 "	(2.66 ")
I_{xz}	19.985 "	(14.740 ")
I_{yz}	14.86 "	(10.959 ")

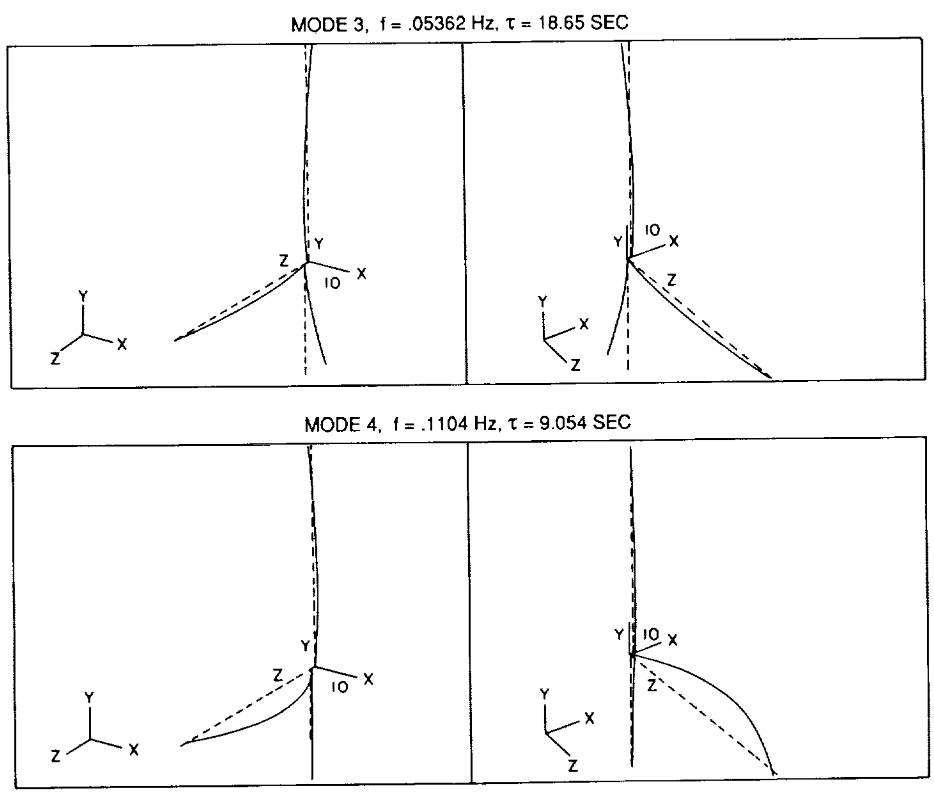

Figure 7

FLEXIBLE SYSTEM DYNAMICS IN THE SPACE ENVIRONMENT

The flexibility of the LACE spacecraft complicates the dynamical interaction of the system with the space environment even though the system modal frequencies, with the lowest mode of .019 Hz, are widely separated from the gravity gradient pitch libration frequency of $2.3 * 10^{-4}$ Hz. One complication, for example, is that elastic deformations from environmental stresses can generate 2nd order changes in the system inertial properties and thereby modify the biases in roll, pitch and yaw that apply to rigid-body spacecraft. Another complication is mode coupling generated by thermoelastic deformations. The environmental stresses include components that are time dependent functions of orbital motion and spacecraft orientation, as well as components that are more steady-state such as atmospheric drag.

The estimation of the magnitude of these effects is part of the LACE flight dynamics experiment. The study is proceeding by means of the DISCOS and TREETOPS simulation programs (reference 3**), using system vibration modal data obtained from a NASTRAN finite-element program. A 3 -D model of the boom structure has been developed with NASTRAN, to estimate the thermoelastic distortions generated by solar heating. (Fig. 8.)

**TREETOPS is a simulation program written by R.P. Singh and R. J. Vandervoort of Dynacs Engineering Co., Inc., Clearwater, Florida, under contract to Marshall Space Flight Center, Huntsville, Alabama.

Systems Dynamics in the Space Environment

- Structural deformations, vibrations, biases

  Gravity-gradient torques: LACE pitch freq ~ $2.3 * 10^{-4}$ Hz

  Atmospheric drag: changes with orbital decay

  Magnetic torques on damper at end of gravity-gradient boom

- Thermoelastic deformations from differential solar heating

  Mode coupling, effects on gravity gradient libration dynamics

NASTRAN modelling DISCOS and TREETOPS simulations

Need to estimate magnitude of effects

Figure 8

EXPERIMENT DESIGN OVERVIEW

The experiment includes the modelling of the LACE system with NASTRAN and the multi-body simulation programs DISCOS and TREETOPS, together with environmental models of the atmospheric drag (reference 4), magnetic damping, and solar heating. An analysis of the on-orbit measurements requires a good estimate of system outputs through numerical simulation. Feedback between the measurements and predicted values enables upgrades of structural parameter estimations and environmental assumptions to improve the computer modelling. (Fig. 9.)

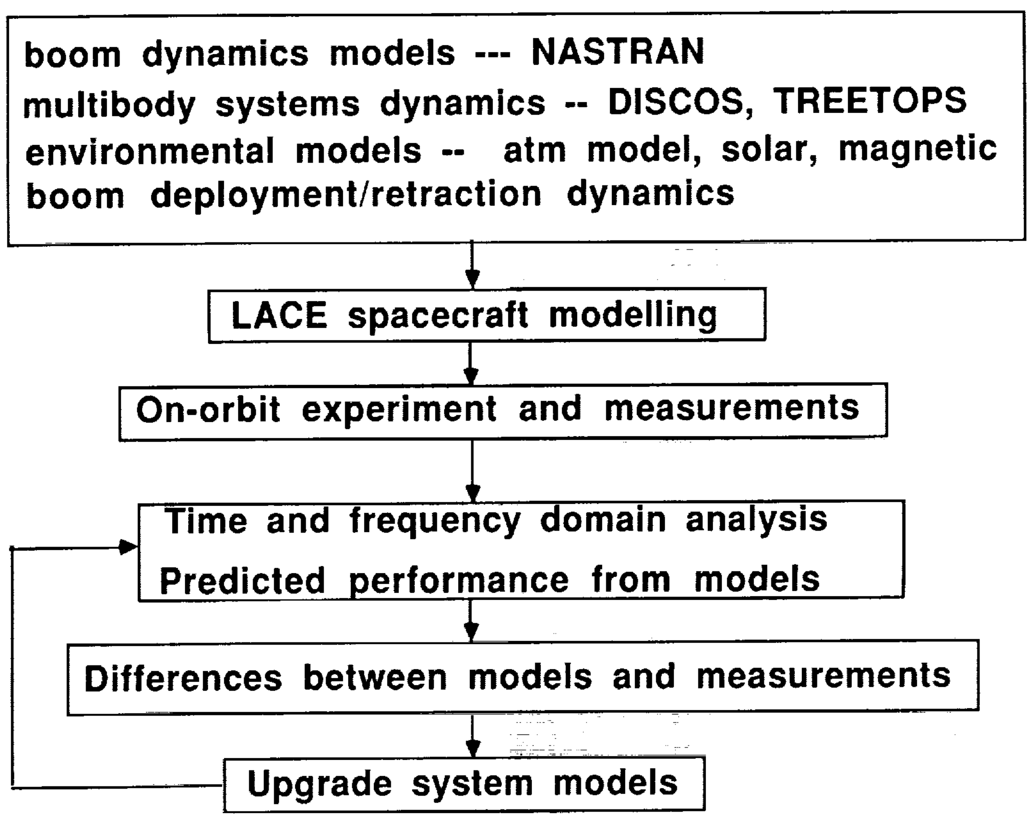

Figure 9

SCHEDULE FOR LACE FLIGHT DYNAMICS EXPERIMENT

Figure 10 shows the schedule for the experiment. Hardware procurement and integration on the LACE spacecraft is proceeding simultaneously with the LACE systems simulation. An analysis of expected sensor information requires inputs from simulation results. The projected launch of the LACE spacecraft is Fall, 1989. It is expected that valuable information will become available early in the LACE mission to allow an initial study of the dynamical behavior of the spacecraft. During the later phases of the 3 year projected lifetime, it is anticipated that the scheduling of boom deployments and retractions, together with a lower orbit and increased atmospheric drag, will allow for a thorough and complete analysis.

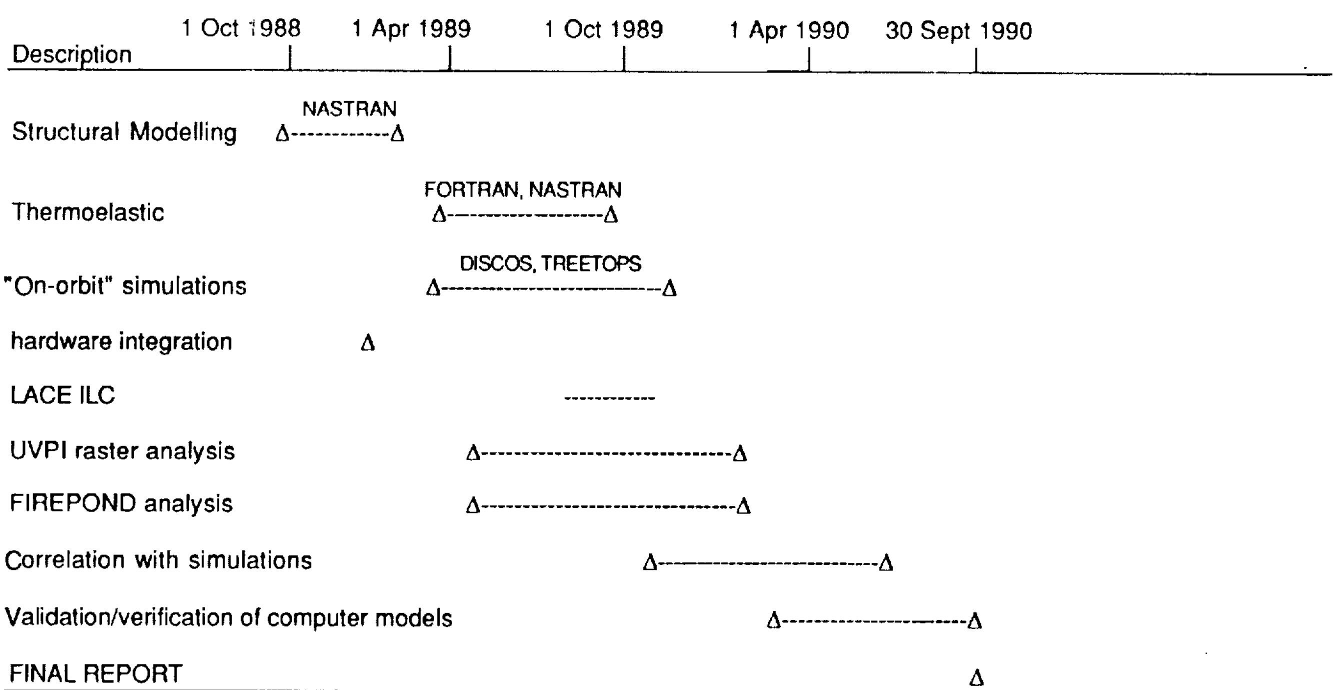

Figure 10

ACKNOWLEDGEMENTS

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