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ATTITUDE CONTROL OF THE LACE SATELLITE: A GRAVITY GRADIENT STABILIZED SPACECRAFT

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ABSTRACT

The Low-power Atmospheric Compensation Experiment (LACE) satellite was launched in February 1990 by the Naval Research Laboratory. The spacecraft's pitch and roll are maintained with a gravity gradient boom and a magnetic damper. There are two other booms with much smaller tip masses, one in the velocity direction (lead boom) of variable length and the other in the opposite direction (balance boom) also of variable length. In addition, the system uses a momentum wheel with its axis perpendicular to the plane of the orbit to control yaw and keep these booms in the orbital plane.

The primary LACE experiment requires that the lead boom be moved to lengths varying from 4.6 m to 45.7 m. This and other onboard experiments require that the spacecraft attitude remain within tight constraints while operating. The problem confronting the satellite operators was to move the lead boom without inducing a net spacecraft attitude disturbance. A description of a method used to change the length of the lead boom while minimizing the disturbance to the attitude of the spacecraft is given. Deadbeating to dampen pitch oscillations has also been accomplished by maneuvering either the lead or balance boom and will be discussed.

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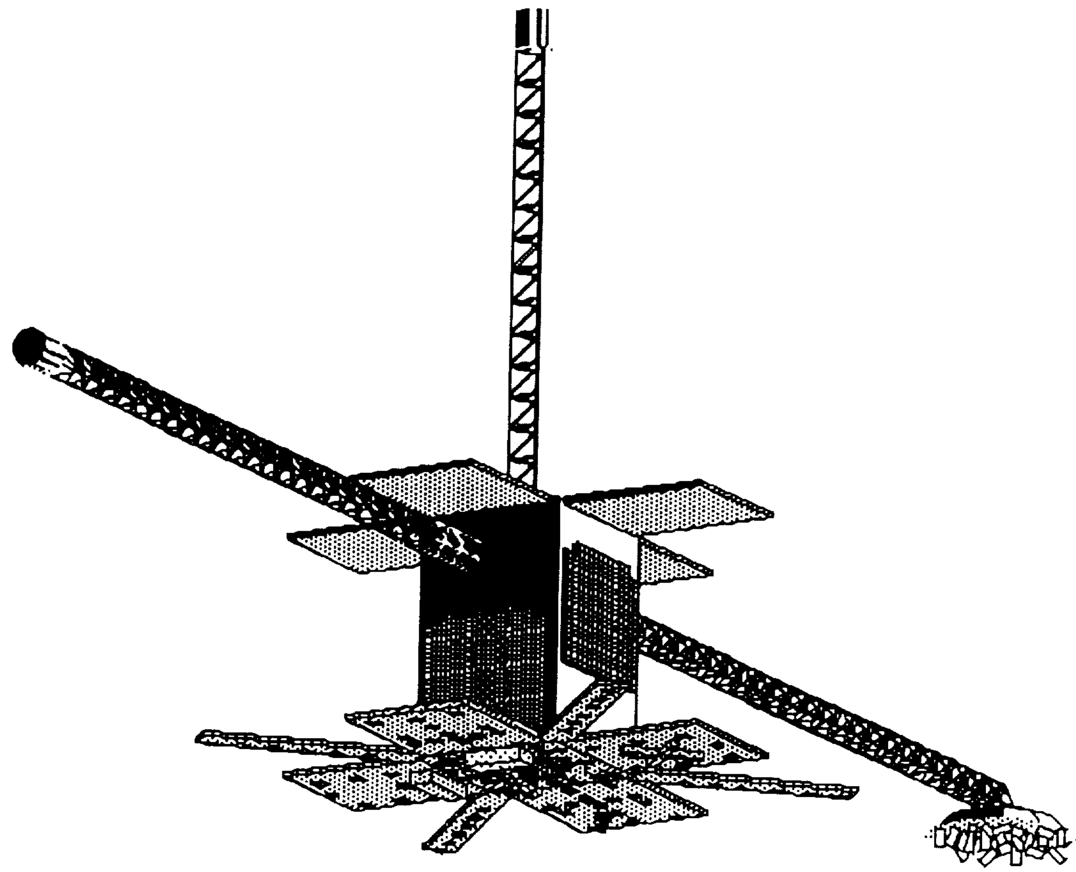

Figure 1. Drawing of the LACE satellite.

LACE SATELLITE DESCRIPTION

The Low-power Atmospheric Compensation Experiment (LACE) satellite was designed and built by the Naval Research Laboratory (NRL) in Washington, DC. The satellite was launched on 14 February 1990 into a circular orbit with an altitude of 541 km and a 43° inclination. The spacecraft weighs 1440 kg and the body of the spacecraft is basically box shaped, 1.2 m by 1.2 m and 2.4 m high. Figure 1 is a drawing of the LACE satellite. The LACE satellite has no orbit adjustment capability. Attitude is controlled with gravity gradient stabilization provided by a retractable boom emerging from the top of the spacecraft with a 91 kg tip mass containing a magnetic damper. There are two additional retractable booms with tip masses each of 12.7 kg; one in the velocity direction of variable length up to 45.7 m (lead boom), and the other in the anti-velocity direction, also variable to 45.7 m (balance boom). The system uses a momentum wheel with its axis perpendicular to the plane of the orbit to keep these booms in the orbital plane. Spacecraft attitude is determined using the output from change in the frequency, amplitude, or phase of any of the attitude components. A very large change was performed to demonstrate the effectiveness of this method. Figure 4 shows the pitch as a function of time for a change in lead boom from 4.6 to 43.3 m and balance boom from 45.7 to 16.5 m. The pitch bias changed by 1° with no significant change in pitch amplitude. In addition, the pitch frequency is not altered during these moves. For completeness, the plots for roll and yaw for the same event are shown in Figure 5 and Figure 6. It was also noted that the step size of 1.5 meters was conservative and one experiment indicated that larger steps could have been used without disturbing the amplitudes of the attitude components.

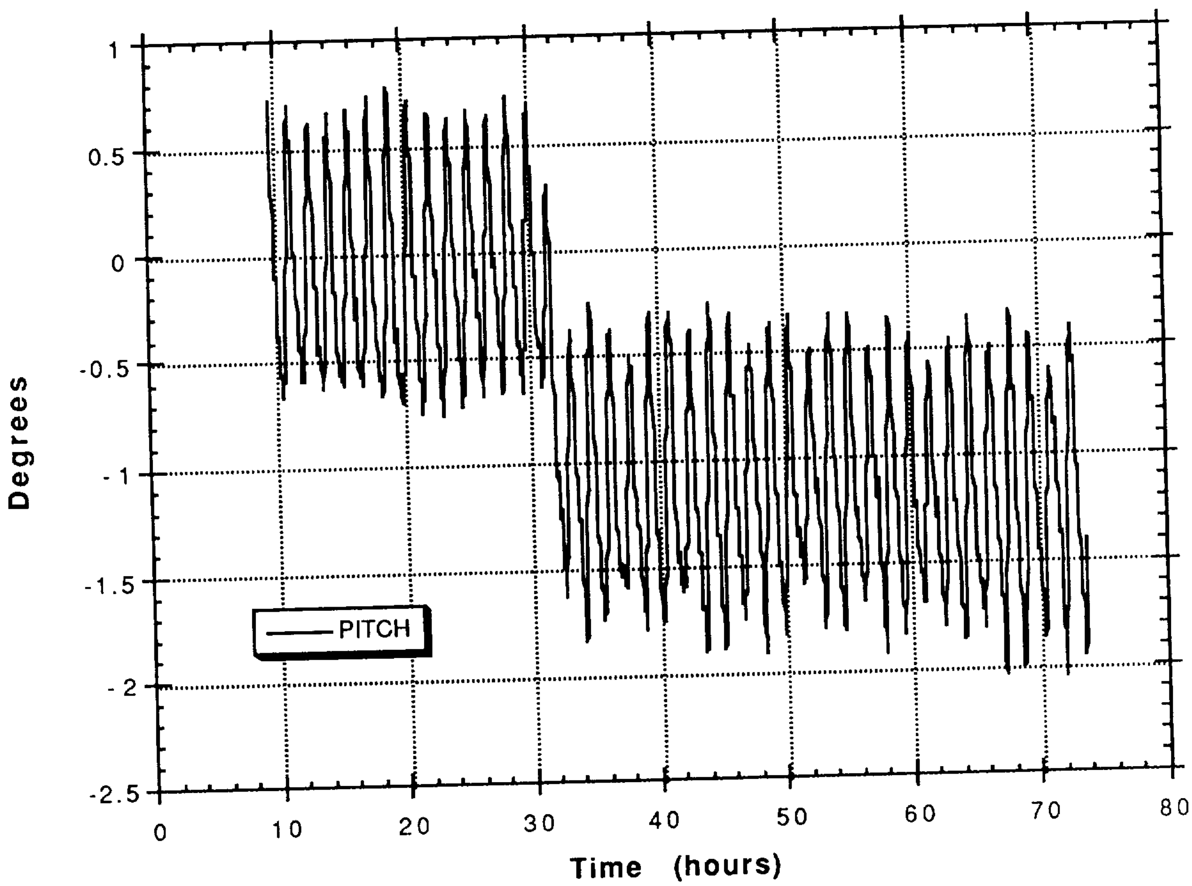

Figure 4. Pitch variations during boom movements.

three sets of sensors: a conical Earth scanner, a set of three magnetometers, and five sun sensors.

NRL operates three ground stations to communicate with and control the LACE spacecraft and its experiments. The LACE spacecraft was designed to support its experiments for 30 months.

ONBOARD EXPERIMENTS

The satellite's primary purpose is to provide an orbiting instrumented target board capable of measuring the effects of active compensation of a ground based laser beam propagated through the atmosphere. This target board consists of an array of sensors on the bottom of the spacecraft. A panel of corner cube reflectors on the end of the lead boom provides a preliminary laser target. The position of the lead boom is fixed for the duration of the pass by the particular requirements of the experiment, but the length varies from one experiment to another.

A second experiment aboard the LACE satellite is the Ultraviolet Plume Instrument (UVPI). This is an ultraviolet imaging system with a maximum field of view of 2.0° x 2.6°. This camera views through the Earth facing side of the LACE spacecraft and is pointed using a precision gimbaled mirror pointing system. Knowledge of the spacecraft attitude to better than ±1° is needed in each axis for UVPI observations. Moving booms for the primary experiment could disturb the spacecraft attitude by inducing unacceptably large oscillations in the pitch direction. Although the large pitch oscillations would damp out in several days, these movements would make attitude predictions for the secondary UVPI experiment pointing functions very difficult since the attitude motion would consist of both transient and steady state oscillations. A method of moving the lead and trailing booms was developed which would not cause a net disturbance to the spacecraft attitude.

MOTION OF LACE

The angular momentum of the spacecraft is dominated by the once per orbit rotation about the pitch axis as the spacecraft keeps one side facing Earth. Added to this once per orbit rotation are perturbations caused by the magnetic damper, by the orbit eccentricity of 0.02, and by aerodynamic forces. These perturbations result in a driven oscillation of the spacecraft's roll, pitch, and yaw about their equilibrium values. The natural oscillation rates of this system are dependent on the moment of inertia (MOI) about each axis. The calculated MOIs of the spacecraft give a natural period of oscillation about the roll, pitch, and yaw axes of 56 minutes, 71 minutes, and 60 minutes respectively. In the steady state condition the natural oscillations are completely damped, but the driven oscillations about the equilibrium attitude remain. This results in oscillations in roll, pitch, and yaw with dominate periods which are orbital (approximately 95 minutes) and half orbital. As with any gravity gradient spacecraft with a momentum wheel in the orbit plane, the roll and yaw are coupled to each other and the pitch is independent of the two. Figure 2 shows typical roll, pitch, and yaw values over two orbits. Note that only the forced oscillations are present. The widely varying yaw values around 2.6, 4.3, and 5.9 hours are associated with the periods when the spacecraft is in darkness. Only the magnetometers, with accuracies of $\pm 1°$, are used for yaw angle determination during this time when the sun sensors are not available.

DAMPING OF LACE

The spacecraft is equipped with an attitude damper consisting of a collection of magnets imbedded in a sphere of oil, located at the tip of the gravity gradient boom. As the spacecraft oscillates, the magnets attempt to align themselves to the Earth's magnetic field. This forced motion in a viscous fluid removes unwanted energy from the the attitude system. Although very effective in removing unwanted natural oscillations in the attitude system, the magnetic damper requires considerable time to remove even a moderate disturbance. Figure 3 shows the natural decay of the spacecraft's pitch motion after an induced disturbance. The time required to damp the oscillations to one half their initial amplitude is about 88.8 hours. This is an unacceptably long time for pitch disturbances caused by moving the boom to return to the steady state oscillations in the pitch axis.

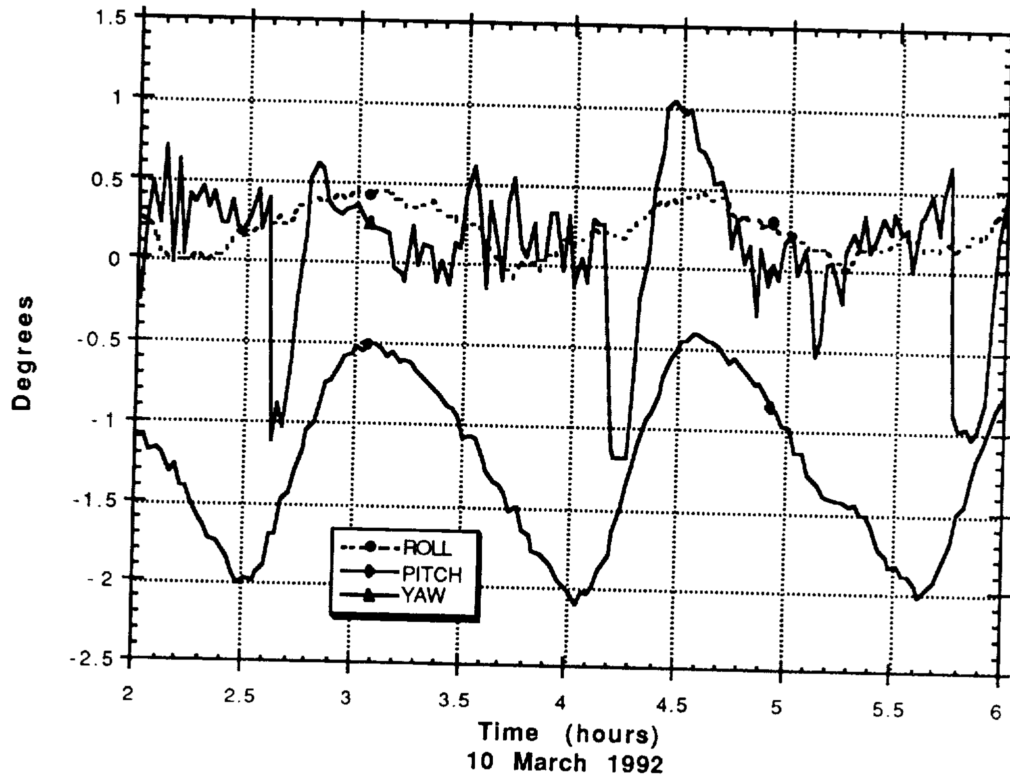

Figure 2. Typical LACE attitude values.

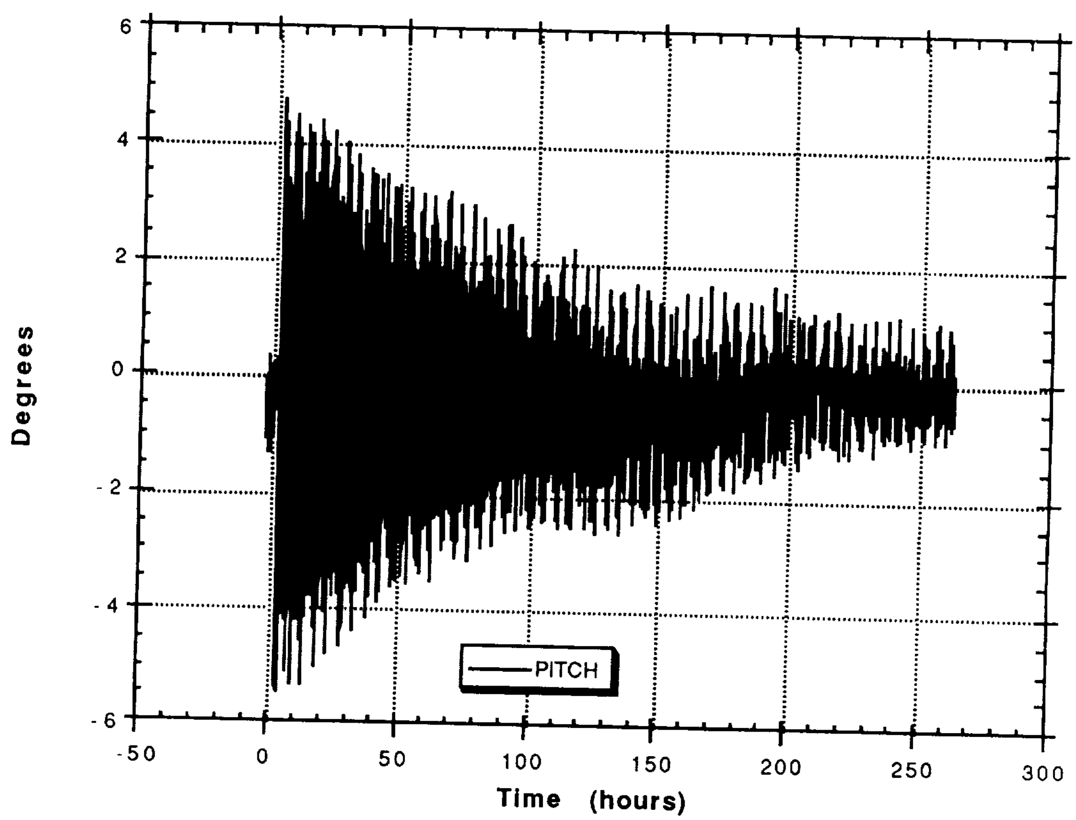

Figure 3. Effect of magnetic damper on LACE pitch value.

DISCUSSION OF ATTITUDE CONTROL DURING BOOM MOVEMENTS

During pre-launch operations planning, a computer program was used to simulate the spacecraft's dynamics. This program simulated naturally occurring forces on the spacecraft such as gravity, aerodynamics, the magnetic damper, and solar pressure. In particular, this program also simulated the effects of the movements in all three spacecraft booms.

It was noted that changing the boom lengths in one step caused changes in pitch amplitude even though the MOI about the pitch axis was the same before and after the move. The difference in MOI due to the uncertainty in the final boom positions and the variation in the MOI during the movement is less than 0.1% of the total and is, therefore, negligible.

The subsequently disturbed pitch motion varied with the magnitude of the change in boom length and the time in the phase cycle of the movement. Therefore, moving booms in one large step was not an acceptable solution to the attitude control requirement. It was also noted that a change in pitch bias (the equilibrium position about which the pitch oscillations occur) is associated with the change in boom positions and is a factor in the change in pitch amplitude. That is, if initially there is no pitch oscillation and the booms are moved in one step with constant MOI, the resulting pitch amplitude will equal the incurred pitch bias change. Simulations showed that changing the boom lengths slowly (making the moves over a time comparable to the pitch period) did not cause changes in the amplitudes of any of the attitude components. Since the speed of movement of the booms is fixed at about 9.1 cm/sec, the slow movement can be approximated by making the moves in small steps. In performing these changes in boom positions, the pitch bias changes and the change can be calculated and included in attitude predictions. Roll and yaw remain unchanged during these moves. A simple calculation of the change in position of the center of mass of the spacecraft yields very good information about the change in the pitch bias.

SPACECRAFT DATA WITH BOOM MOVEMENTS

In normal operation on the LACE satellite the changes required in the position of the lead boom were usually less than 5 meters with an average of 2.5 meters. These movements have been made about 65 times and as often as once per day. The lead boom is usually positioned between 27 to 38 meters, but four special experiments required the lead boom to be at 4.6 meters. Performing these changes using steps of 1.5 meters spread over 95 minutes results in no

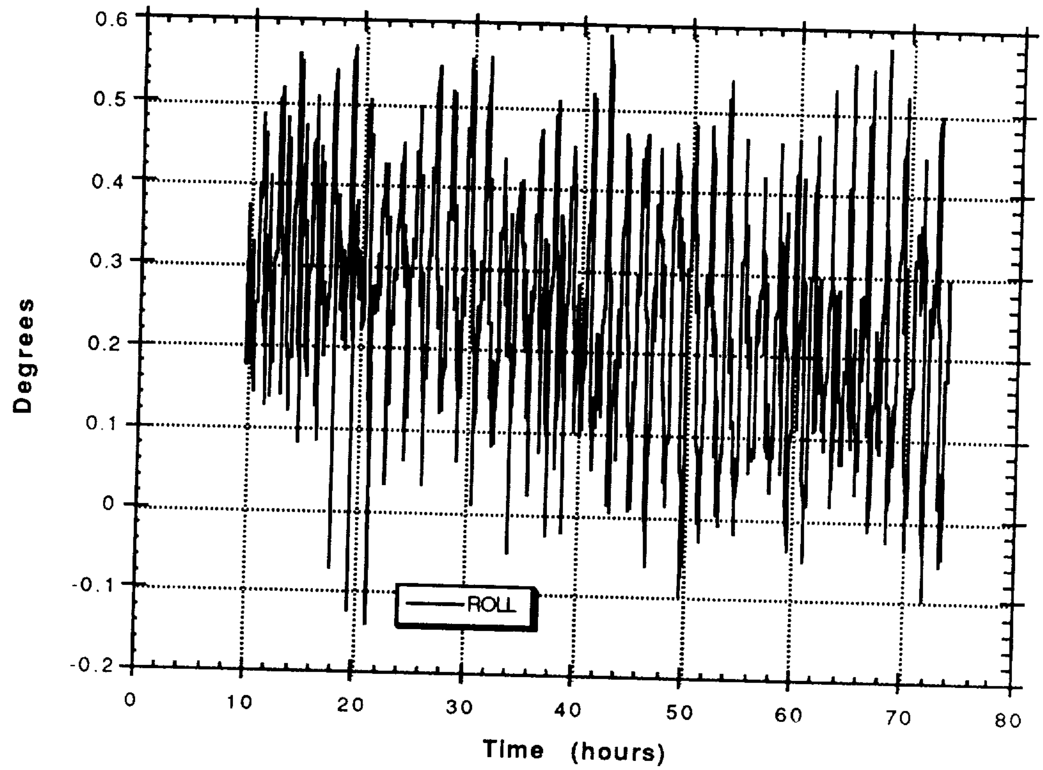

Figure 5. Roll variations during boom movements.

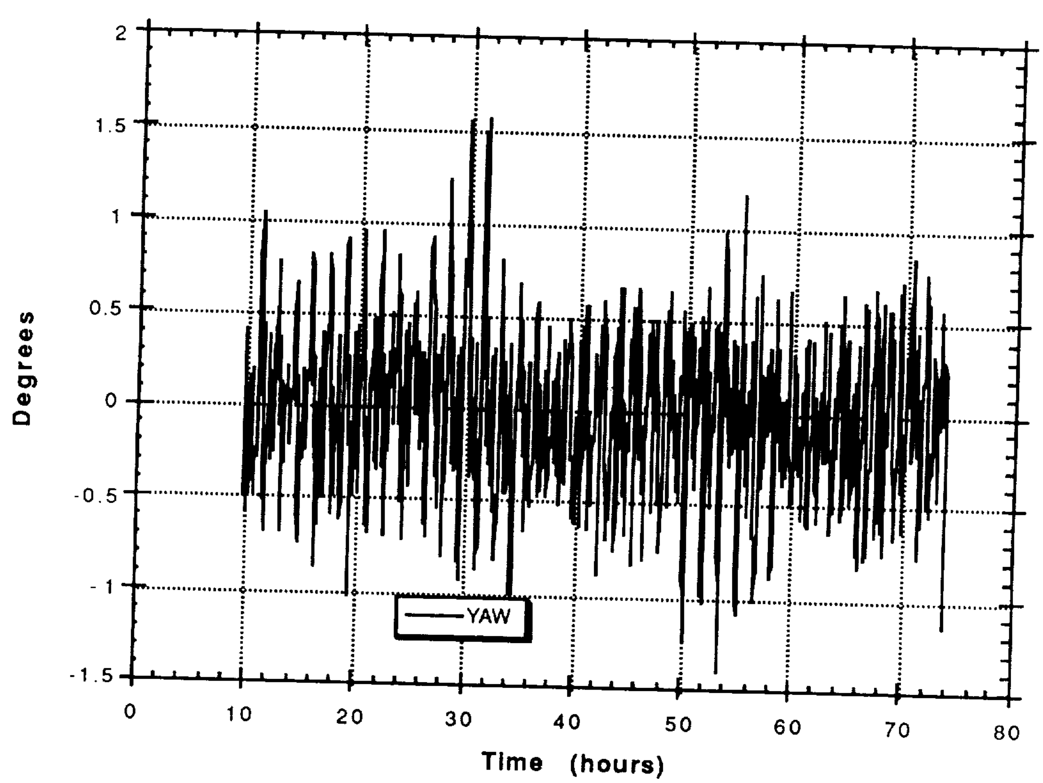

Figure 6. Yaw variations during boom movements.

DISCUSSION OF ATTITUDE CONTROL USING DEADBEATING

Although attitude control using step movements was done by computer simulations prior to launch, it was desired to have a backup solution to the problem. Deadbeating was explored for this purpose. Deadbeating is a method of decreasing the amplitude of pitch motion by moving one boom out at maximum pitch angular velocity and then moving the same boom in to its original position at minimum pitch angular velocity. The orbital angular velocity must be included in the determination of the pitch angular velocity since it is the dominant term in the pitch angular velocity. Because of this, deadbeating has its greatest effect on the pitch motion. The order of these boom moves for deadbeating can be reversed. The magnitude of the boom movement depends on the MOI about the pitch axis and the amplitude of pitch oscillation to be damped. Deadbeating is described in Wertz[1] for a dumbbell and the equation given there can be modified to apply to the LACE configuration by replacing the angular pitch frequency of the dumbbell by that of LACE. Deadbeating maneuvers can be done with any one of the three booms.

SPACECRAFT DATA WITH DEADBEATING

Since boom movements with the small step method caused no disturbance in attitude, the backup deadbeating method used in prelaunch simulations was not required. However, in order to further study the dynamics of large space structures, deadbeating maneuvers were preformed. Testing with simulators, the phasing of the boom movements could be done precisely. This was not possible on the spacecraft since the decision on the timing of the movements had to to predicted in advance of the movements. Several attempts were needed to achieve the proper phasing. Best results were obtained when one movement of the booms was executed, results of the move examined and, based on these results, the timing of the second move was calculated for completion of the deadbeating operation.

Figure 7 shows the change in pitch as a result of this type of deadbeating. Since the configuration of the boom is the same before and after the deadbeating, there is no change in pitch bias. Figures 8, 9 and 10 are blowups of Figure 7 to show the boom movements. Figures 11 and 12 show roll and yaw. Yaw shows little or no effect while there is some change in roll associated with the boom movements. In order to increase the pitch amplitude prior to deadbeating, the principles of deadbeating were used but the phasing of the boom movements were selected to increase the amplitude. This was another application of the deadbeating idea.

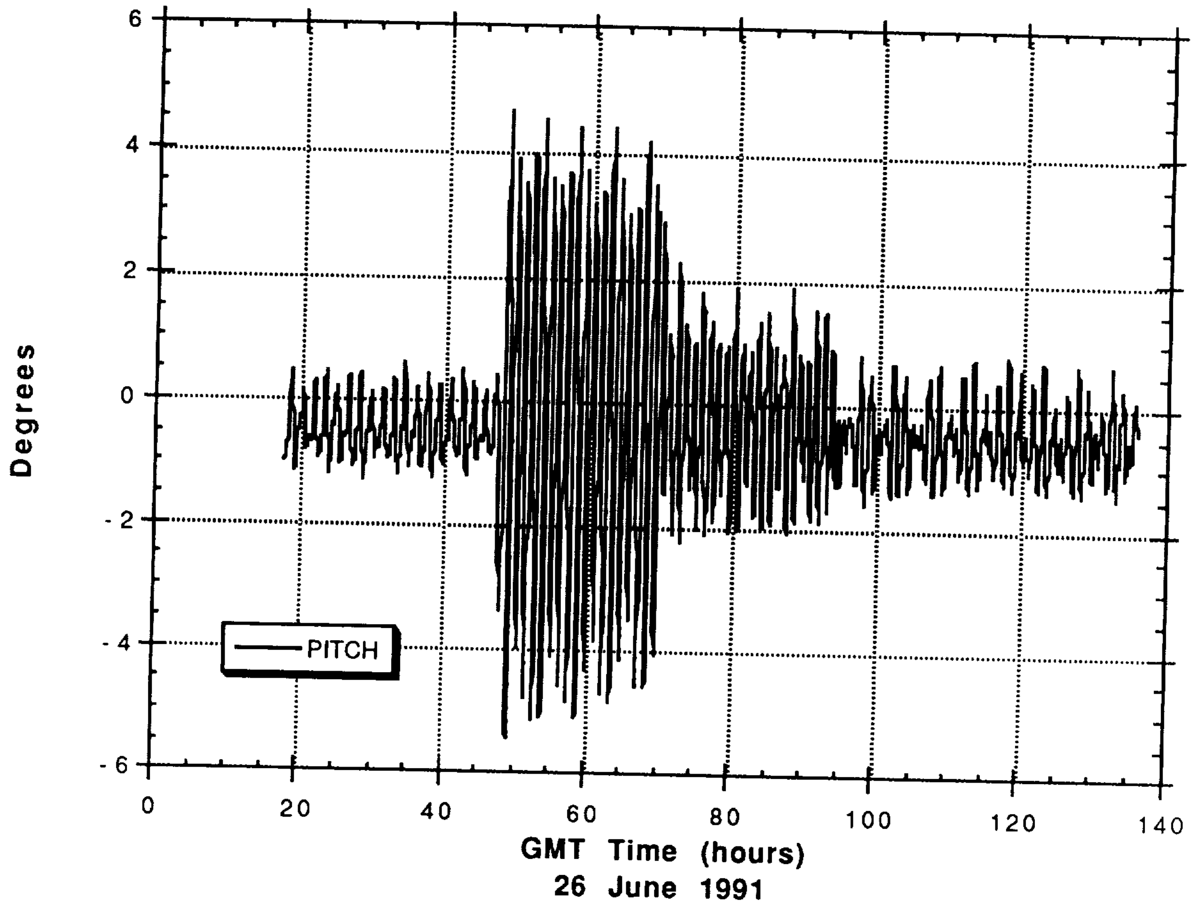

Figure 7. Pitch variations during deadbeating experiment.

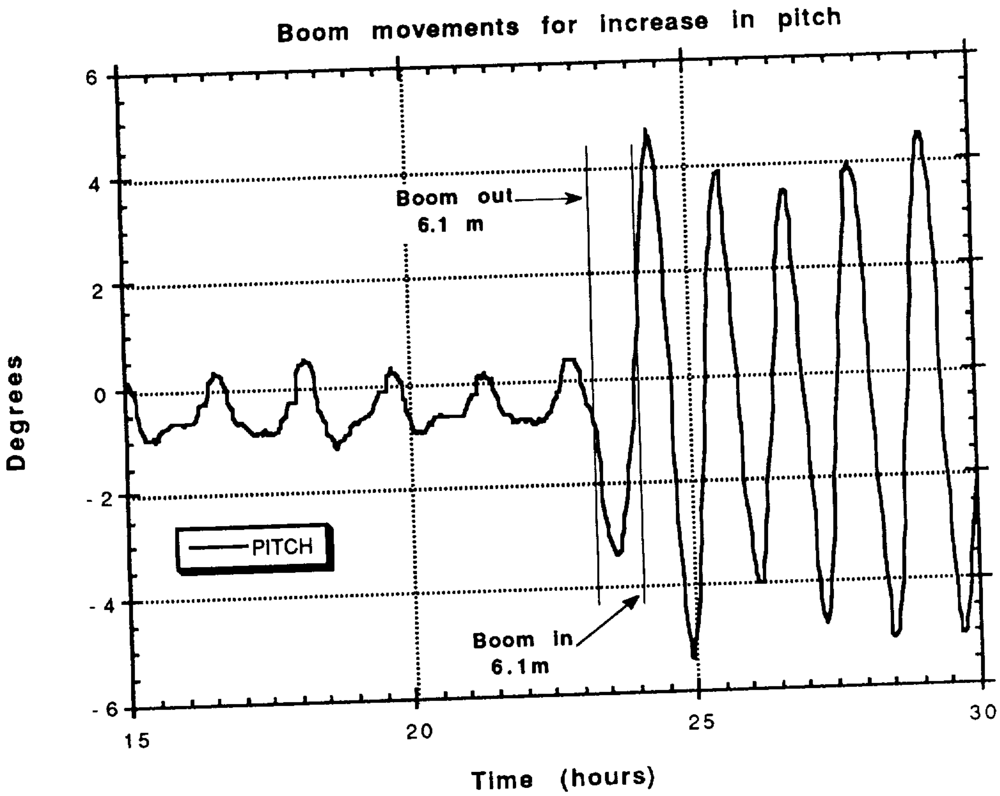

Figure 8. Expansion of figure 7 showing initial disturbance.

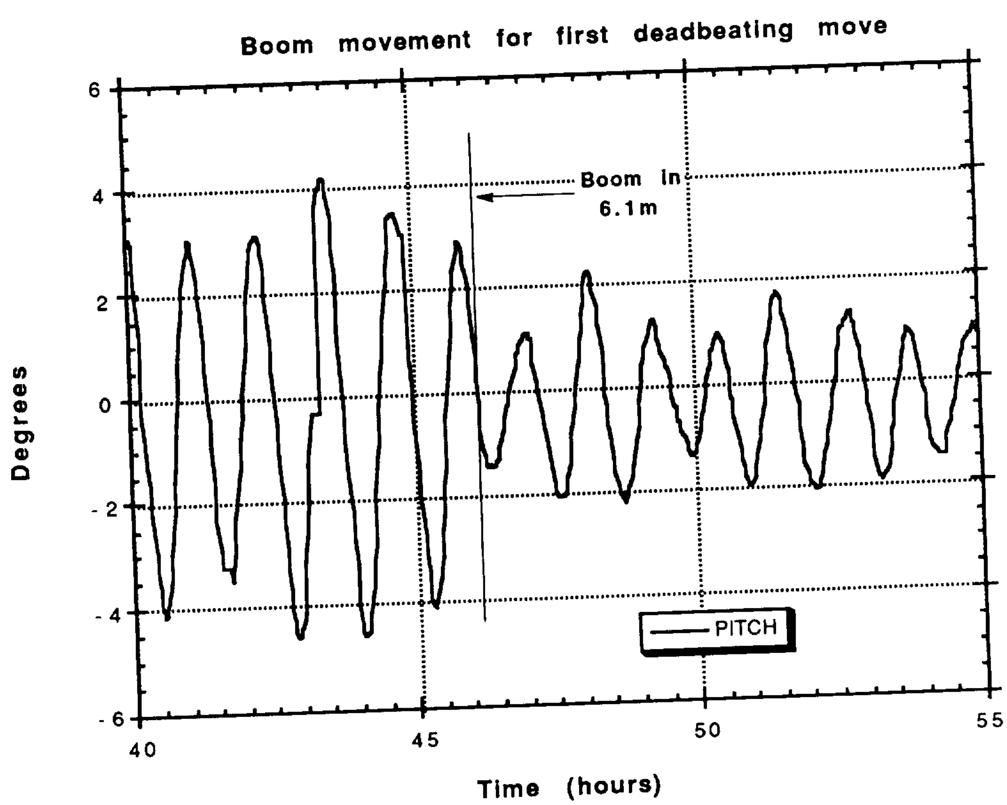

Figure 9. Expansion of figure 7 showing first step of deadbeating.

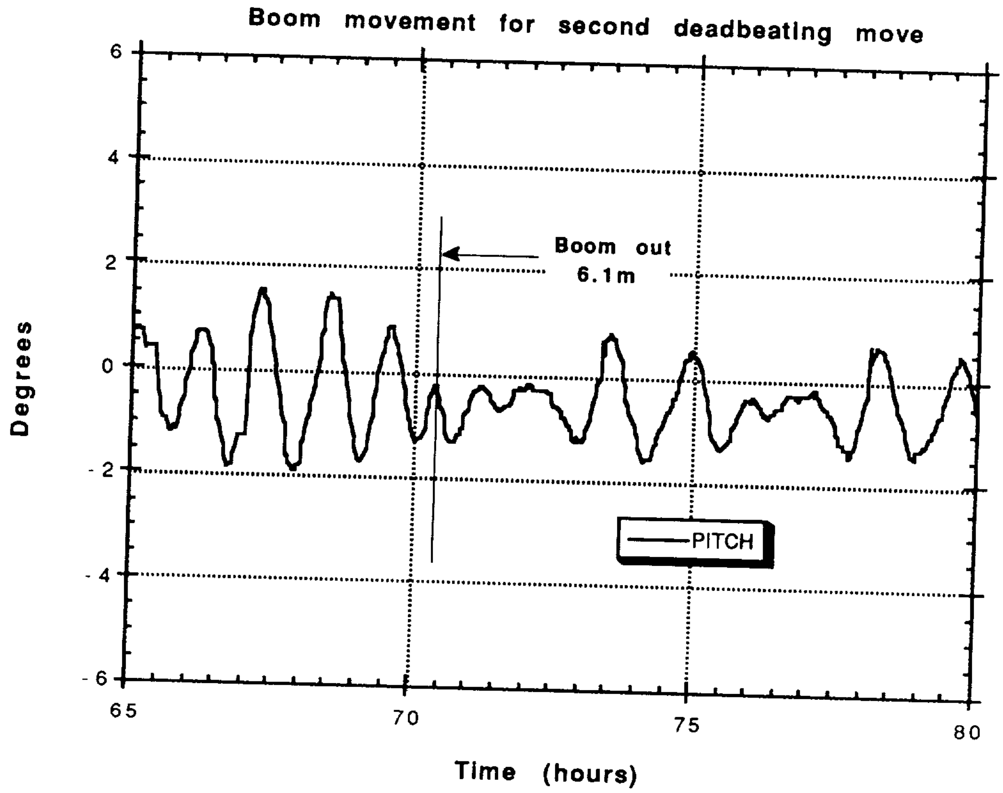

Figure 10. Expansion of figure 7 showing second step of deadbeating.

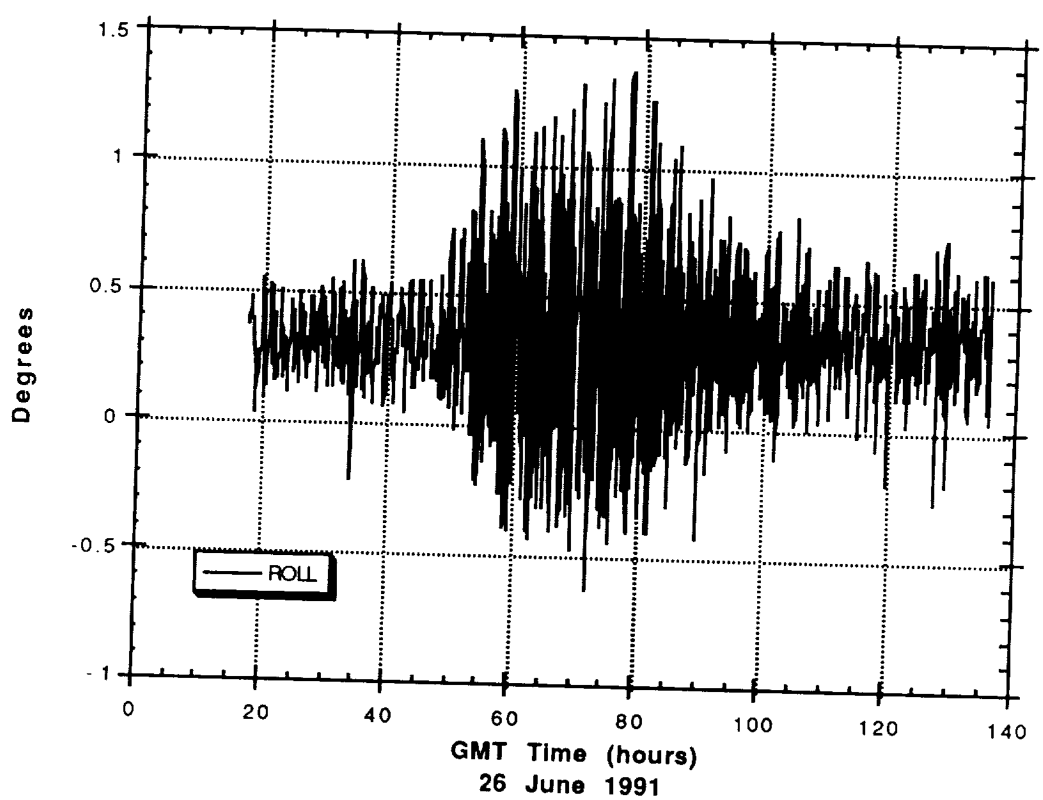

Figure 11. Roll variations during deadbeating experiment.

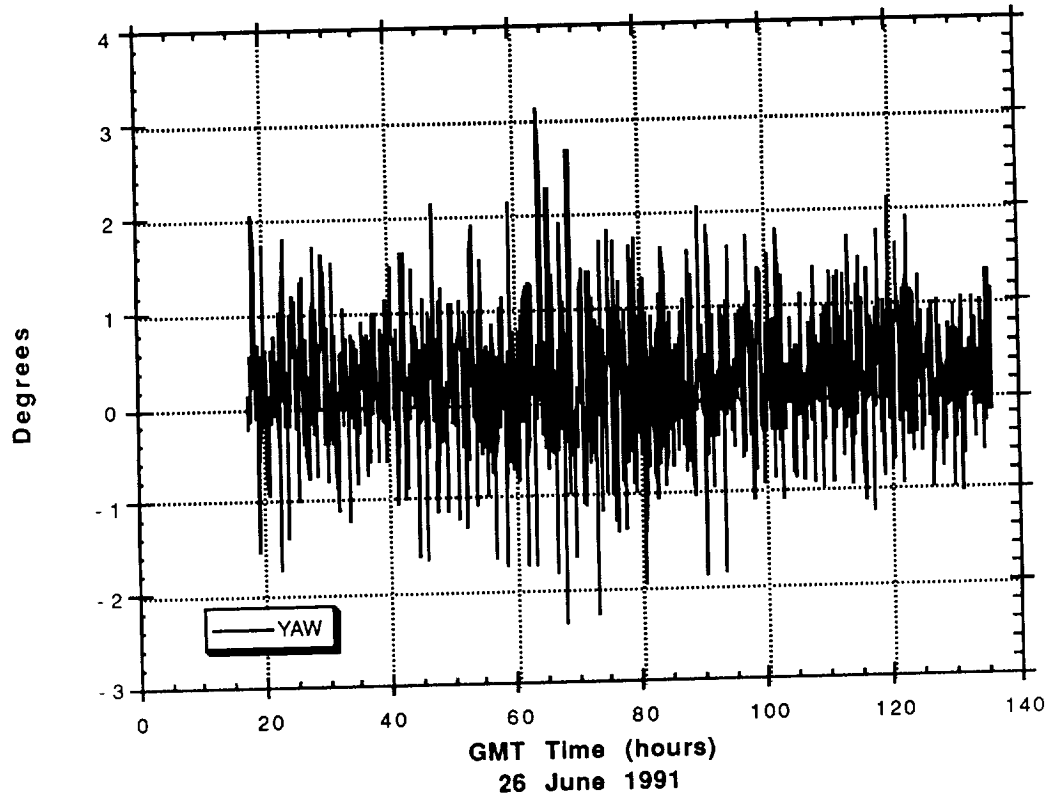

Figure 12. Yaw variations during deadbeating experiment.

CONCLUSIONS

Positioning of the lead boom as required by laser experiments has been satisfied without changing the restrictions demanded by the imaging experiments on the spacecraft. Movement of the booms was repeated many times as required by the experiments without affecting the overall attitude of the spacecraft. The change in pitch bias was expected and predictable.

Deadbeating the pitch oscillations was demonstrated using the lead or balance boom.

ACKNOWLEDGEMENTS

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