GRAVITY-GRADIENT DYNAMICS EXPERIMENTS PERFORMED IN ORBIT UTILIZING THE RADIO ASTRONOMY EXPLORER (RAE-1) SPACECRAFT

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Between December 1970 and December 1971, a series of six dynamics experiments was performed in earth orbit utilizing the RAE-1 spacecraft as an experimental apparatus. This satellite, launched into a near-circular earth orbit at nearly 6000-kilometer altitude on July 4, 1968, measures radio emissions from extraterrestrial sources at frequencies which are obscured from ground-based instruments due to ionospheric interference.

As shown in Figure 1, the spacecraft consists of four highly flexible antenna booms mounted in a double-vee configuration with a rigid cylindrical spacecraft hub at the center. The four main radio frequency sensing antenna booms each extend 230 meters from the hub center, making the RAE-1 spacecraft the largest array in longitudinal dimensions ever placed in space. In addition to monitoring long-wavelength emissions from cosmic sources,

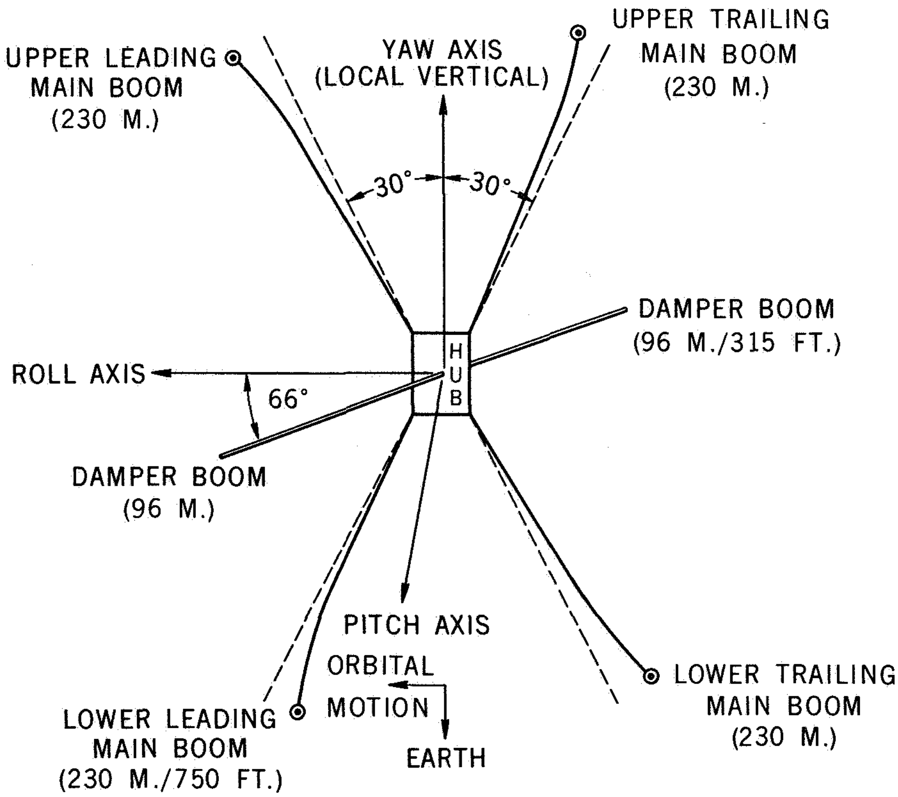

Figure 1. Basic configuration of the RAE-1 satellite.

the vee-antennas serve to stabilize the spacecraft in a nonspin mode about the local vertical axis by the passive three-axis gravity-gradient method. In this way, one vee-antenna is continuously directed toward the earth, while the other antenna scans the celestial sphere under the combined effects of orbital motion and orbital precession in inertial space. Rotational oscillations of the spacecraft hub and the resulting indirect vibration of the primary antennas are attenuated by a magnetic hysteresis damper mechanism consisting of two additional damper booms, each 96 meters from hub center to tip.

In the 26 months following full deployment of the primary antenna booms in October 1968, the RAE-1 satellite remained stabilized by gravity-gradient forces about the roll, pitch, and yaw axes to within a few degrees of local orientation. Altitude stabilization was entirely passive, with the basic control torques provided solely by gravity-gradient and inertial forces. Damping was provided by the magnetic hysteresis libration damper system and by whatever structural damping was present in the primary booms. The well stabilized attitude motions about the three axes were so small and erratic, in fact, that it was often impossible to distinguish between actual oscillations and sensor system noise and inaccuracies.

In light of the numerous difficulties encountered in attitude control of previous flexible gravity-stabilized spacecraft, and in order to advance current understanding of the dynamics of gravity-gradient stabilization, the six in-orbit experiments (as shown in Figure 2) were conducted. These dynamics experiments were developed to test the accuracy of the mathematical model of the RAE dynamics, which was formulated prior to the 1968 launch and used subsequently to predict and describe the spacecraft in-orbit dynamical behavior.

- DAMPER CLAMPING
  - FULL SUNLIGHT CONDITIONS (DEC. 1–7, 1970)
  - PARTIAL SOLAR SHADOWING (JUNE 14–21, 1971)
    19- TO 25-MIN SHADOW PER 225-MIN ORBITAL PERIOD
- SINGLE LOWER LEADING BOOM OPERATIONS
  - PARTIAL RETRACTION TO 165-M LENGTH (JAN. 18, 1971)
    DAMPER ACTIVE THROUGHOUT
  - FULL REDEPLOYMENT TO 230-M LENGTH (JAN. 25, 1971)
    DAMPER CLAMPED FOR 29 HR INITIALLY
- DOUBLE LOWER BOOM OPERATIONS
  - PARTIAL RETRACTION TO 200-M LENGTH (DEC. 7, 1971)
    DAMPER CLAMPED FOR 24 HR INITIALLY
  - FULL REDEPLOYMENT TO 230-M LENGTH (DEC. 15, 1971)
    DAMPER ACTIVE THROUGHOUT

Figure 2. RAE-1 gravity-gradient dynamics experiments.

The RAE-1 spacecraft was, thus, deliberately perturbed in precise and well-calculated fashion so that flight data relating to the spacecraft dynamics under mildly adverse situations could be gathered.

In the first pair of experiments shown in Figure 2, the damper was clamped, or rendered inactive – once for a six-day period when the satellite was in full sunlight, and later again for a similar period when it was experiencing partial solar shadowing during each orbit. These experiments were designed to determine how great a role the damper system had been playing in maintaining the excellent spacecraft attitude stability under steady-state sunlight and time-varying solar pulsing conditions. The second pair of experiments involved creating an asymmetrical spacecraft configuration in order to perturb the satellite away from equillibrium, and observe the resultant transient attitude motions and subsequent damper effectiveness. The lower leading boom was partially retracted some 54 meters to a shortened length of 165 meters with the damper mechanism remaining active. After seven days in this state of mismatched boom lengths, the retracted boom was fully redeployed, but, during this experiment, the damper was kept clamped for the initial 29 hours after deployment. This experiment was intended to investigate the spacecraft's dynamical behavior when initially considerably removed from the steady-state equilibrium condition for the nominal symmetric configuration and when deprived of damper action. In the final pair of experiments, two lower booms were partially retracted simultaneously some 30 meters to 200 meter lengths, and then eight days later, redeployed back to full lengths. In this pair, however, the damper was clamped for a 24-hour interval after the boom retraction operation and, conversely, the damper was allowed to remain in active status upon redeployment. These last two experiments were designed to investigate the spacecraft dynamics under a third distinct configuration, known as a semisymmetric array (two pairs of vee-antennas at unequal length), both with, and without benefit of damper action.

The performance of the entire series of six dynamics experiments was completed successfully over the course of 13 months. No hardware failures aboard the spacecraft, or major operational difficulties were experienced. Figure 3 provides a sample of in-orbit attitude measurements observed and a comparative match with the results of a computer simulation of the flexible-body spacecraft dynamics. These data were recorded during the second dynamics experiment, performed on January 18, 1971, beginning at the time at which a single lower boom was partially retracted and extending for 25 hours thereafter with the damper active throughout. Although the motions in roll remain fairly small in amplitude, it is seen that the retraction excited a very noticeable pitch libration, with an initial amplitude of ±10 degrees, about an average value of -4 degrees. The fact that the equilibrium value is biased negative by 4 degrees, as compared to the pre-experiment zero equilibrium value, is a direct result of the asymmetry caused by the boom retraction. A significant reduction in the pitch motions is observed during the first eight hours or so after retraction; further attenuation in amplitude was slow and irregular. The retraction operation also excited an initial yaw libration of ±14 degrees, centered about an

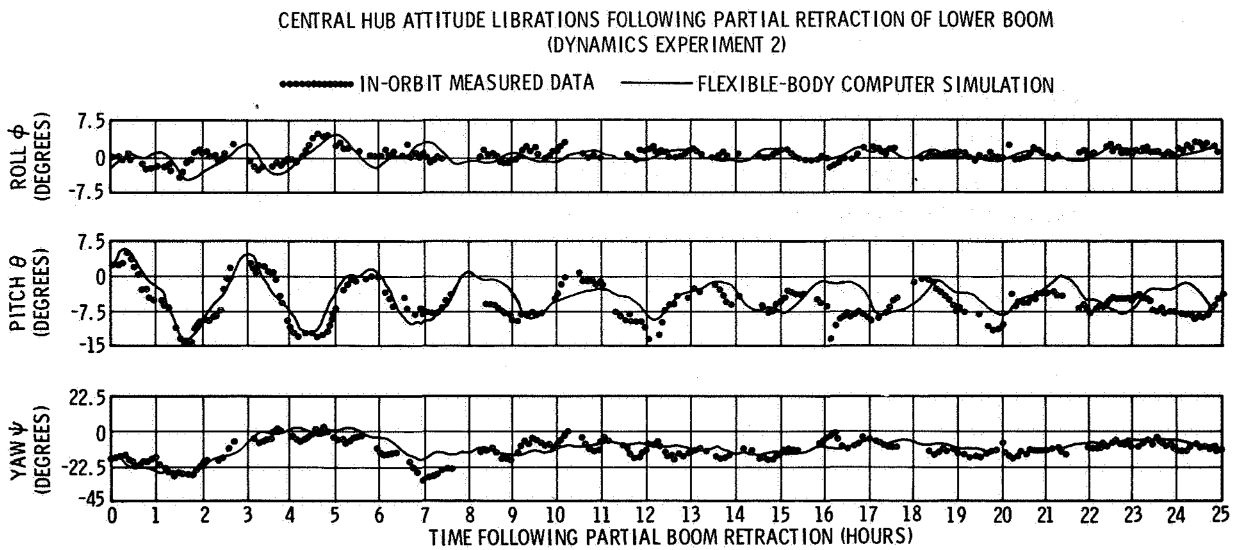

Figure 3. Central hub attitude librations following partial retraction of lower boom.

equilibrium value of −12 degrees (which is approximately the equilibrium value under a symmetric configuration, with the negative bias caused by the fact that the damper booms are skewed at an angle of 66 degrees from the plane of the primary double-vee antennas; see Figure 1). The yaw motions observed immediately after retraction reduced fairly rapidly to ±5 degrees and less. The cause of the pitch libration immediately following the signal boom retraction is the resultant reduction of the spacecraft moment of inertial about the pitch axis. This, according to the principle of conservation of angular momentum, caused the pitch rate, relative to both inertial space and to the rotating local vertical, to increase. The conservative restoring torque due to gravity gradient counteracted the resulting pitch motion, and hence, the spacecraft began to oscillate. The results of the computer simulation of the flexible-body spacecraft dynamics are seen to provide an excellent duplication of the flight data.

The primary results and conclusions of the full series of in-orbit dynamics experiments are displayed in Figure 4. Based upon the excellent correlation that was observed between the in-orbit measurements and the results of the computer simulations throughout the series of experiments, increased confidence in the accuracy of the analytical techniques used to model the RAE dynamical behavior has been generated. The dynamics experiments also provided an opportunity to investigate the in-orbit capabilities of the damper system aboard the RAE-1 spacecraft. The effectiveness of the damper system was significant in reducing large angular attitude disturbances and in alleviating adverse dynamical situations, as was indicated in Figure 2. However, the absence of a substantial increase in attitude oscillations during the two damper clamping experiments verified that external disturbances produce only minor effects on the spacecraft. Therefore, the damper system is only marginally useful in maintaining dynamical stability (at least over time intervals not

- **INCREASED CONFIDENCE IN VALIDITY AND ADEQUACY OF**
  - **COMPUTER SIMULATIONS** } **USED TO MODEL RAE DYNAMICS**
  - **ANALYTICAL TECHNIQUES** }
- **RAE-1 ON-BOARD DAMPER SYSTEM CAPABILITIES IN ORBIT**
  - **SIGNIFICANT FOR REDUCING LARGE-AMPLITUDE ATTITUDE OSCILLATIONS**
  - **ONLY MARGINALLY USEFUL IN MAINTAINING DYNAMICAL STABILITY NEAR EQUILIBRIUM**
  - **MORE EFFECTIVE FOR ASYMMETRIC SPACECRAFT CONFIGURATION**
- **IN-ORBIT OBSERVATION OF PITCH-YAW NONLINEAR COUPLING PHENOMENON THAT HAD BEEN THEORETICALLY PREDICTED**
- **EXTERNAL IN-ORBIT DISTURBANCES ON SPACECRAFT ARE VIRTUALLY NEGLIGIBLE**
- **ON-BOARD MECHANICAL AND ELECTRICAL SYSTEMS PERFORM RELIABLY EVEN AFTER 3½ YEARS IN SPACE ENVIRONMENT**
- **INCREASED CONFIDENCE IN ACHIEVING SUCCESSFUL RAE-B LUNAR MISSION (SPRING 1973)**

Figure 4. Primary results of in-orbit gravity-gradient dynamics experiments.

greatly exceeding one week) after the spacrcraft is brought close to equilibrium conditions. These results, in fact, confirm the design criteria adopted for the damper prior to launch. The surprisingly rapid damping of large pitch and yaw motions, as shown in Figure 3, indicates that the damper is more effective for an asymmetric spacecraft configuration (such as mismatched boom lengths) than for the nominal symmetric configuration, and this result reflects a point of new knowledge about the system.

During the single boom redeployment experiment, when the damper was inactive, a non-linear coupling phenomenon was observed between the pitch and yaw modes of oscillatory motion. During the interval of damper clamping, the pitch motions excited by the redeployment operation remained fairly constant, but the yaw librations increased dramatically and then decreased at about the same rate. Apparently, the RAE-1 is the first satellite known conclusively to have demonstrated this instability in orbit, although such a resonance phenomenon had been predicted previously on theoritical grounds.

Finally, the wholly successful performance of the series of dynamics experiments, without adverse impact to either the spacecraft structure or to its scientific mission, was due largely to the fact that the mechanical and electrical systems aboard the satellite performed satisfactorily and reliably, even after exposure to the hostile space environment for more than three years. In sum, these results will aid the design and planning of the forthcoming RAE-B mission (now scheduled for launch in spring 1973 into lunar orbit with a nearly identical spacecraft to RAE-1) and provide increased confidence in achieving a successful lunar mission.