DYNAMICAL IN-ORBIT BEHAVIOR OF THE RADIO ASTRONOMY EXPLORER SATELLITE

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The Radio Astronomy Explorer satellite, or the RAE 1 as it is commonly known, was launched 2½ years ago and is presently in a near-circular Earth orbit at an altitude of almost 6000 m. Aside from its impressive achievements in the field of radio astronomy, the RAE satellite is of interest because it is the first system to deploy successfully a directive antenna array. Another distinctive feature which enhances the interest in its actual in-orbit dynamical behavior is the length of its primary antenna booms, which measure almost 0.5 m tip to tip. These booms are far longer than the appendages of any other spacecraft orbited to date, and for this reason, the RAE satellite is the largest array yet placed in space, in terms of longitudinal dimensions.

From a dynamical point of view, the objective of the RAE mission is the attainment of a stable orbital capture by gravity-gradient forces. This is a method of completely passive three-axis attitude stabilization. The purpose of this stable capture is twofold: to permit modest pointing accuracies by the directive antennas and to achieve small antenna deformations. Such deformations create antenna pattern distortions in the measurement of long-wavelength radio emissions from extraterrestrial sources, and it is for this reason that the antenna boom flexural motions must be minimized. Because of their extreme length, 460 m tip to tip, the RAE booms are, in effect, much more flexible than those of other satellites. The natural bending frequencies of the booms are very low, and the amplitudes of the bending motions have the potential of becoming very large. This introduces problems of stability and dynamics not encountered previously in other satellite missions. Static bending of the booms due to gravity-gradient and inertial forces and boom vibration due to time-varying thermal, solar, and dynamic effects can have a significant influence on RAE spacecraft stabilization. Hence, the success of the radio astronomy experiments depends, in large part, on the dynamical in-orbit behavior of the satellite.

The main sensing apparatus of the RAE spacecraft consists of four flexible antenna booms extending outward from a rigid central hub in a double "Vee" configuration. The spacecraft is stabilized in a nonspin mode about the local vertical. In this way, one "Vee" antenna is continuously directed toward the Earth, while the other antenna scans the celestial sphere. The four main sensing antenna booms each extend 230 m from hub center to tip when fully deployed. A damper mechanism, consisting of a torsion wire suspension with magnetic hysteresis damping and two additional booms, is also included on the spacecraft. The damper attenuates rotational oscillations of the spacecraft hub and the resulting indirect vibration of the primary antennas.

Knowledge of the spacecraft dynamical in-orbit behavior is obtained from several on-board sensors and the associated ground-based processing systems. An on-board attitude determination system, consisting of a solar aspect sensor and a triaxial magnetometer, measures the orientation of the central hub. Four television camera systems enable the lateral displacements of the tips of the main booms from their straight-line locations to be computed. In practice, only one of the four vidicons has provided useful boom tip information in this regard.

The passive attitude control system of the RAE satellite has maintained a well stabilized attitude condition during the more than 2 years that the main antenna booms have been at full lengths. Figure 1 shows typical central hub attitude motions, in this case on a date about 3 months after the final boom deployments and during an extended interval of full sunlight conditions. None that the pitch and roll angles of the central hub usually remain within ±2 deg of the ideal zero-degree equilibrium condition. Deviations as large as ±4 deg occur comparatively rarely. Central hub motions in yaw only occasionally exceed ±4 deg about an equilibrium value of about −13 deg. The nonzero equilibrium value for yaw is due to the fact that the two damper booms are skewed from the plane of the primary double "Vee" antenna. This so-called yaw bias value was anticipated in prelaunch mathematical simulations. The motions of all three attitude angles are well bounded but quite erratic, although a definite correlation in the motions of all three angles exists. (The break in the otherwise continuous curves is caused by operational difficulties in receiving observational data.) Almost all three-axis attitude motions observed since the first few weeks after the final deployments has been similar to that shown in

Figure 1, i.e., small and erratic. It is virtually impossible to distinguish between actual central hub rotations and sensor system noise and inaccuracies.

Figure 2 displays the measured boom tip displacements (from straight-line positions) of the one observable boom on the day after the final deployments. In this figure, "in-plane" refers to tip displacements in the direction parallel to the ideal plane formed by the four main booms when they are straight; "out-of-plane" indicates deflections perpendicular to this plane. The in-plane deflection is much larger because by far the larger component of the gravity-gradient force occurs in this direction. The out-of-plane deflections are further minimized by very low boom cross-section temperature gradients. The oscillatory short-period motions shown in Figure 2 probably are due in large part to the boom deployment operations on the preceding day. Prelaunch computer simulation studies had predicted average static in-plane tip deflections of about 40 m. This value is only slightly greater than the average value displayed by the data in Figure 2, which includes only a fractional portion of a long-period boom motion.

Most boom tip pictures have been taken only over time durations which are too short to permit much useful analysis. The basic purpose in taking these pictures has been to monitor the satellite rather than to obtain data for dynamics investigations. Table 1 summarizes the results of a large number of boom tip pictures taken between January and October of 1969. Three convenient data blocks, labeled "A", "B", and "C", were formed with varying numbers of picture sets in each block, as shown. The mean values in this table should be approximately the average value of the boom tip deflection during each respective time interval shown. The three in-plane mean values are all in reasonably close agreement with the predicted average value of 40 m. During the time interval covered by data block A, the satellite was being eclipsed from the sun for a portion of each orbit. Blocks B and C, however, were taken during full sunlight conditions. The standard deviations include both actual boom tip motion relative to the average displacement and also any time-varying inaccuracies that may be present in the measurements. The resolution of each tip deflection measurement is about 1 m in both the in-plane and the out-of-plane directions. The average out-of-plane tip deflection is difficult to predict from mathematical models since it is very sensitive to central hub yaw angle, boom warpage, boom temperature gradients, and solar pressure. The variation in the orbit-sunline geometry during the later intervals may have produced solar pressure effects responsible for the indicated decrease in the average out-of-plane tip deflection.

In conclusion, the dynamical in-orbit behavior of the RAE satellite demonstrates that the large boom vibrations and major attitude stability problems anticipated prior to launch have not materialized. In the more than 2 years since full deployment of the antenna booms in October 1968, the RAE spacecraft has remained well stabilized in local orientation and has continued to transmit valuable radio astronomy data.

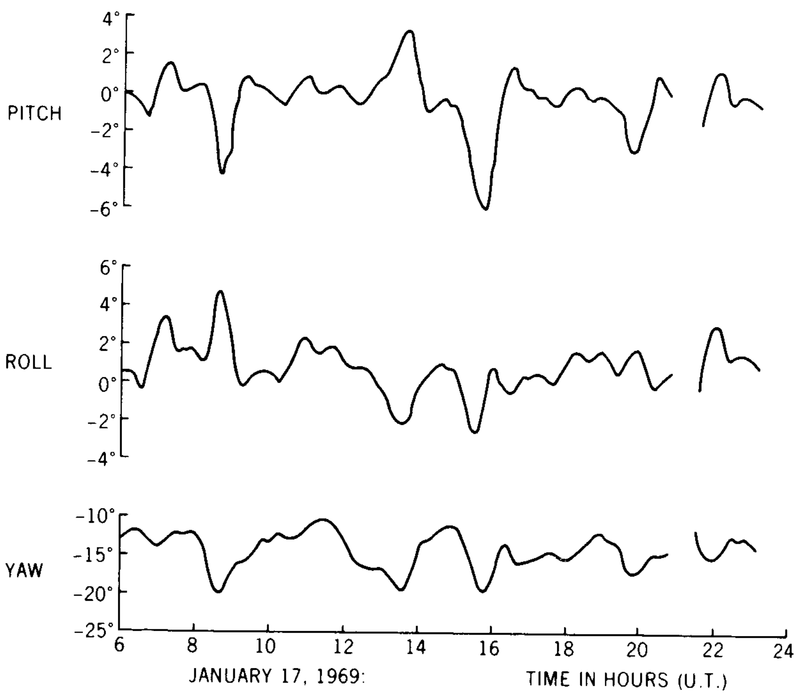

Figure 1—Central hub attitude motions on January 17, 1969.

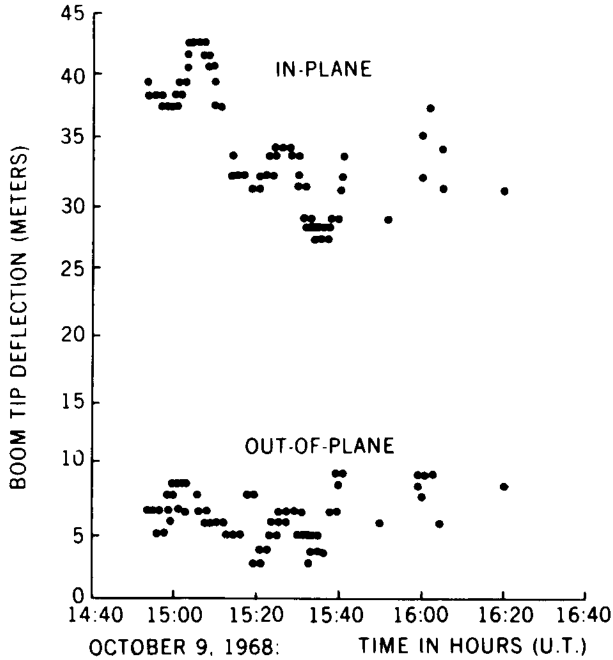

Figure 2—Main boom tip deflections on October 9, 1968.

Table 1—In-orbit tip deflections of upper trailing main boom.

DATA BLOCK	TIME PERIOD COVERED IN DATA BLOCK (1969)	NO. OF PICTURE SETS IN DATA BLOCK	TIP DEFLECTIONS (METERS)			
			IN-PLANE		OUT-OF-PLANE	
			MEAN VALUE	STANDARD DEVIATION σ_i	MEAN VALUE	STANDARD DEVIATION σ_o
A	JAN. 29 TO MARCH 24	15	42	11	4.3	2.2
B	JULY 9 TO SEPT. 6	14	36	7	-0.1	0.7
C	SEPT. 7 TO OCT. 7	27	40	1	-0.2	0.7