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ANOMALOUS ATTITUDE MOTION OF THE POLAR BEAR SATELLITE

After an initial three-month period of nominal performance, the Polar BEAR satellite underwent large attitude excursions that finally resulted in its tumbling and restabilizing upside down. This article describes the attitude motion leading up to the anomaly and the subsequent reinversion effort.

INTRODUCTION

The Polar BEAR satellite was launched successfully from Vandenberg Air Force Base, Calif., in November 1986. A Scout launch vehicle placed Polar BEAR into a circular, polar orbit at an altitude of 1000 km. The satellite's four instruments are designed to yield data on RF communications, auroral displays, and magnetic fields in the earth's polar region.

The Polar BEAR attitude control system is required to maintain an earth-pointing orientation for the on-board instruments. For nominal operation, Polar BEAR is stabilized rotationally to within ±10° about any of three orthogonal axes. An 18.3-m gravity-gradient boom and a constant-speed momentum wheel, together with magnetic hysteresis rods and a boom-mounted eddy-current damper, make up Polar BEAR's passive attitude control system.

Until mid-February 1987, the Polar BEAR mission proceeded as designed, and its attitude performance was nominal. However, as the satellite entered its first period of full sunlight, APL was notified of unexpectedly large attitude oscillations. The attitude motion continued to diverge from the desired operational range until Polar BEAR finally "flipped over" and was orbiting upside down.

ATTITUDE HISTORY AND PERFORMANCE

A gravity-gradient-stabilized satellite has one axis (usually the z axis) always pointed earthward. Such a spacecraft is designed to take advantage of the fact that the earth's gravitational field tends to stabilize a triaxial body (i.e., one with unequal principal moments of inertia). Its principal axis of minimum inertia is aligned with the local vertical (an imaginary line from the earth's mass center to the satellite's mass center), and its principal axis of maximum inertia is aligned with the normal-to-the-orbit plane.[1-3]

Many spacecraft built by APL have used extendable booms to achieve a favorable moment-of-inertia distribution, that is, an inertia ellipsoid where the smallest principal moment of inertia is at least an order of magnitude less than the others. The Polar BEAR satellite includes a constant-speed rotor with its spin axis aligned with the spacecraft's y (pitch) axis. The addition of the wheel enhances the overall stabilization by adding gyroscopic stiffness and stability to the alignment of the y axis.[4]

Satellite attitude refers to the rotational orientation of the axes relative to some reference triad of Cartesian axes. For a gravity-gradient-stabilized spacecraft, the reference system is called the local vertical system, which consists of the outbound local vertical, the normal-to-the-orbit plane, and the vector that completes the right-hand set.

The orientation (or attitude) of Polar BEAR relative to the local vertical system is defined by three Euler rotation angles, where pitch is "nose" down (positive) or up (negative), roll is "left wing" up (positive) or down (negative), and yaw is nose left (positive) or right (negative). Each attitude angle is shown in terms of spacecraft motion in Fig. 1.

A summary of Polar BEAR's attitude performance during 1987, up to the inversion (i.e., upside-down capture), is shown in Fig. 2. The time-history plot shows that the attitude dynamics before entering the 100% sun

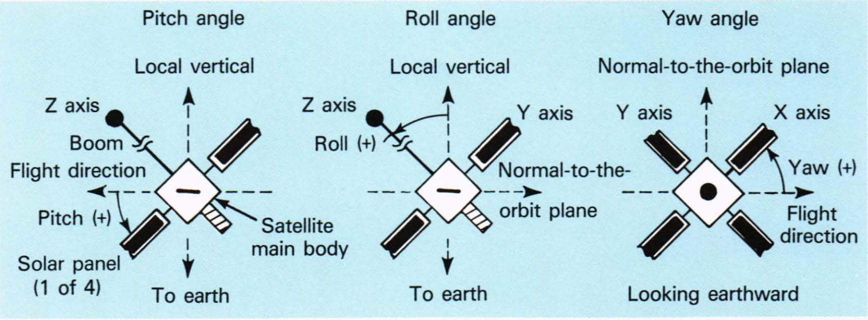

Figure 1—Satellite attitude angles.

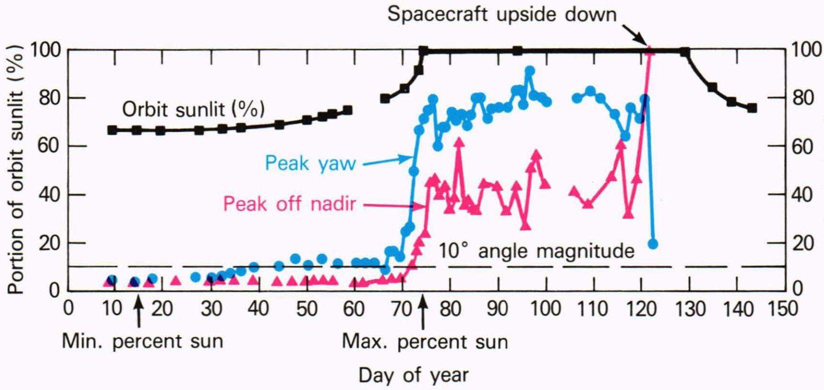

Figure 2—Polar BEAR attitude performance in 1987.

orbits was significantly better than (and substantially different from) the attitude dynamics after entering the 100% sun orbits.

The gravity-gradient stabilization of Polar BEAR was initiated on November 16, 1986 (day 320). Until March 11, 1987 (day 70), attitude stabilization was characterized by the satellite "flying" with the nose down (approximately 2 to 3° positive pitch bias), the left wing down (approximately 1° negative roll bias), and the nose turning left (positive yaw) and right (negative yaw) no more than 12°. The yaw angle showed an average growth of 0.3°/day, which was acceptable up to day 40, when the peak yaw consistently exceeded the 10° performance specification.

Figure 3 shows the attitude dynamics typically observed after gravity-gradient stabilization was initiated. The roll and yaw oscillations, which are phased in quadrature, have approximately a 7-min period. This motion, which appeared after the satellite entered eclipsed orbits, could be the response of the spacecraft to the thermal "twanging" of its boom as it enters and exits the shadowed portions of the orbit. Boom oscillations are seen in the processed magnetometer telemetry shown in Fig. 4.

Near day 70, large-angle dynamics appeared, followed by a significant degradation in attitude stabilization. Within five days, the peak yaw angle increased more than 50°, the peak pitch angle increased more than 30°, and the peak roll angle increased more than 10°. Figure 5 shows the attitude dynamics on April 6, 1987 (day 96).

By day 123 (May 3, 1987), the peak yaw angle had exceeded 90° consistently, and the peak pitch angle had exceeded 90° during three out of five consecutive observations. Shortly thereafter, spacecraft upside-down capture was confirmed.

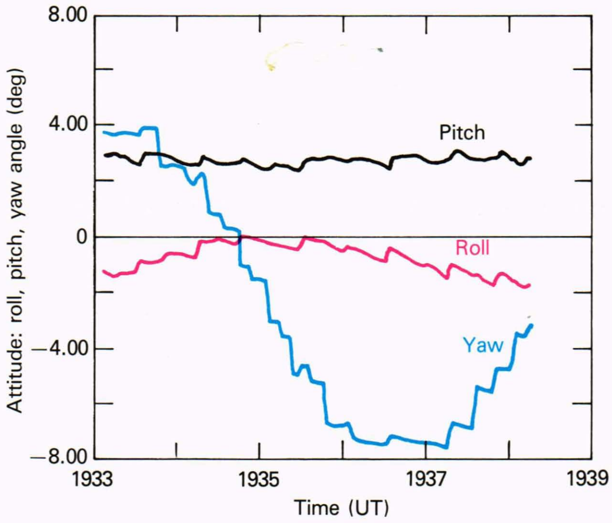

Figure 3—Polar BEAR attitude dynamics (day 339, 1986).

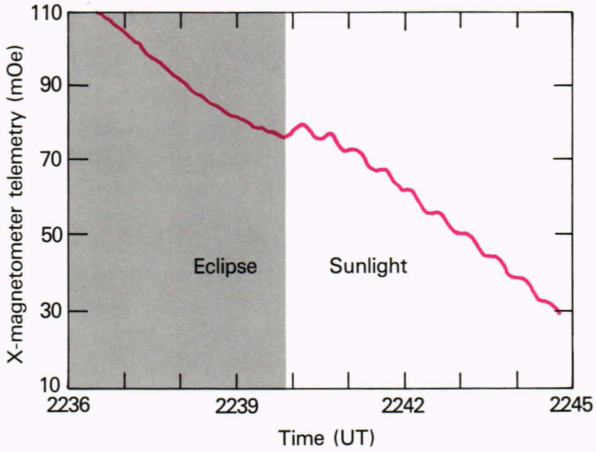

Figure 4—Evidence of Polar BEAR boom oscillation caused by thermal twang (day 44, 1987).

POLAR BEAR REINVERSION

Maneuver Planning

After Polar BEAR turned over and was flying upside down (with the instruments pointing away from the earth), a plan to reinvert the satellite using the momentum wheel was formulated.[5] The maneuver entailed turning the wheel off during the first of a cluster of passes visible from the APL ground station. The wheel would be allowed to spin down until the spacecraft was visible during the following pass at APL and then would be turned on again. During wheel spin-down, a small, positive (nose-down) pitch torque is applied to the spacecraft as a result of bearing drag on the wheel. The torque by

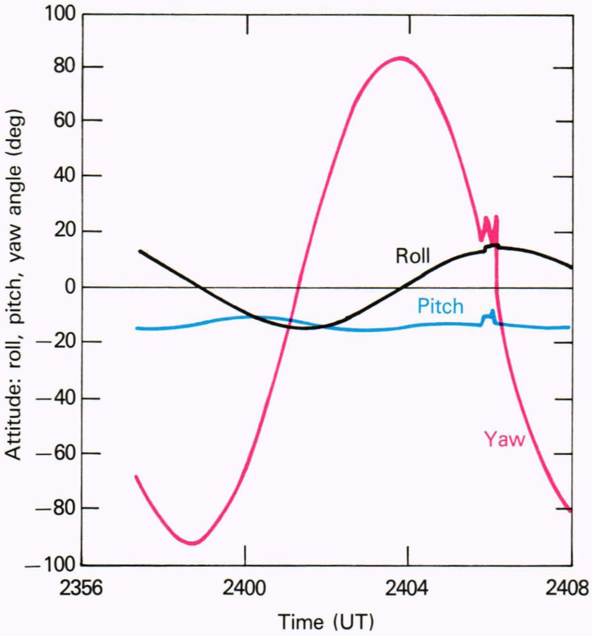

Figure 5—Polar BEAR large-angle attitude dynamics (day 96, 1987).

itself is too small to overcome the gravity-gradient torque and invert the satellite.

After spinning down for one orbit, the momentum wheel is commanded back on. Wheel spin-up to synchronous speed (2049 rpm) occurs rapidly, with the wheel taking approximately 4.5 min to reach synchronous speed from zero. The wheel spin-up reaction torque on the spacecraft is strong enough to overcome the gravity-gradient-restoring torques and cause the satellite to tumble "backward" (negative pitch rate). Passive damping of pitch tumble using the magnetically anchored eddy-current damper decreases the tumbling motion until the gravity-gradient torques once again capture the satellite in a vertically stabilized mode. Because the gravity gradient does not discriminate between right side up and upside down, any individual sequence of wheel off/on commands as described above has an equal probability of achieving the right-side-up or upside-down orientation.

The rigid-body attitude dynamics of a gravity-gradient-stabilized spacecraft with a constant-speed momentum wheel like Polar BEAR has three libration modes: pitch, high-frequency roll/yaw, and low-frequency roll/yaw. For small-angle motion, the pitch mode (62-min period) is decoupled from the two roll/yaw modes. The high-frequency roll/yaw mode (6.1-min period) can be thought of as the motion of the satellite's wheel axis about the system's total angular momentum vector in a cone, while the low-frequency roll/yaw motion (78-min period) corresponds to a slow precession of the total angular momentum vector resulting from gravity-gradient torques. Consequently, although pitch can be thought of as a one-dimensional rotation, any activity that involves changing the wheel angular momentum will also have an influence on the roll and yaw motions that are coupled through wheel dynamics. In any wheel maneuver considered, it was important that the wheel not be allowed to come to a complete stop, which would result in the loss of yaw stabilization.

Inversion Maneuvers

Before inverting Polar BEAR by turning the wheel off, allowing it to run down for an orbit, and then spinning it back up, a short calibration maneuver was executed. The maneuver consisted of turning the wheel off during a real-time pass, leaving it off for a few minutes, and then commanding it back on in order to provide a warning of anomalous wheel spin-down times. The maneuver was performed on May 18, 1987, with no discernible change in the attitude angles; wheel deceleration was acceptable. Consequently, plans to perform attitude inversion were prepared.

The first attempt to invert Polar BEAR was scheduled for the afternoon cluster of passes at APL on May 20, 1987. During the first pass of the cluster, the wheel-off command was sent and, 96 min later, when the next pass occurred, the wheel was turned on again. Because there were only two passes at APL during the cluster, the success or failure of the inversion attempt could not be determined until the following cluster 11 h later. By then, Polar BEAR had stopped tumbling and had recaptured its upside-down orientation. The resulting peak libration angle was about 30°, with under 10° of roll and 30° of yaw.

With the failure of the first inversion attempt, a second inversion maneuver was scheduled for the afternoon cluster of passes on May 21. During the maneuver, the wheel was allowed to spin down for 112 min before being turned on again. However, the second attempt was also unsuccessful, since Polar BEAR once again stabilized upside down. The residual peak pitch libration was increased to 45°.

A third (and what proved to be a successful) inversion maneuver was scheduled for the afternoon of May 22. At 1846 UT (2:46 PM EDT), during the first pass of the afternoon cluster, the wheel was commanded off and allowed to spin down. During the following pass, at 2026 UT, the wheel was commanded on again. The wheel spin-down time for the attempt was 100 min.

Figure 6 shows the real-time attitude motion for the inversion attempt of May 22, along with the results of a rigid-body attitude simulation of the maneuver. The simulation has been used to fill in gaps in attitude data between real-time passes when the satellite is not visible from the ground station. It models the major attitude systems and disturbances, including the wheel spin-down and spin-up events. Initial conditions for the simulation are obtained from the real-time attitude data after a pass and are used to propagate the attitude forward to the following pass.

The simulated inversion data (the black curve in Fig. 6) shows that during the wheel spin-down, Polar BEAR began to tumble. For each of the two previous inversion attempts, the gravity-gradient torques were strong enough to prevent the satellite from tumbling during wheel spin-down. In this case, however, there was enough residual

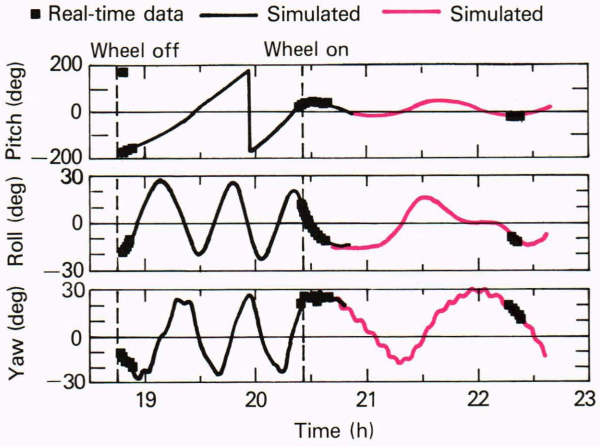

Figure 6—Polar BEAR attitude motion during the successful reinversion maneuver on May 22, 1987. The momentum wheel was turned off during the first pass and back on during the second pass. The third pass of the cluster confirmed the successful reinversion.

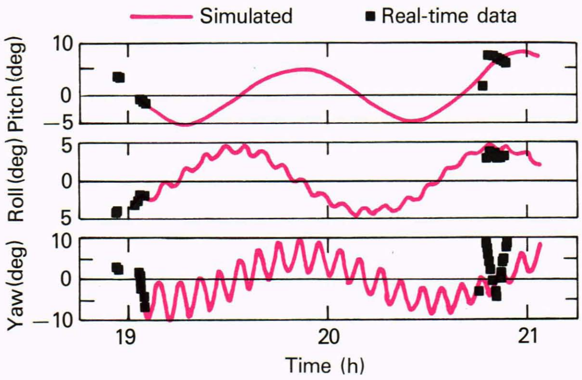

Figure 7—Polar BEAR attitude motion on May 26, 1987, four days after reinversion. Attitude motion had damped to within mission specifications of ±10° about all three axes.

libration before the start of the maneuver that—with the pitch rate and wheel-pitch torque acting in the same direction—the "kick" provided by the wheel spin-down torque was sufficient to tumble the satellite. After performing 1.5 revolutions between passes, Polar BEAR reappeared right side up with a positive pitch rate. When the wheel-on command was sent, the large, negative pitch torque on the satellite generated by the wheel spin-up was sufficient to stop the tumble and capture the satellite in the desired orientation, as seen about midway during the time span shown in Fig. 6.

The confirmation of Polar BEAR's right-side-up capture came 90 min after the wheel-on command was sent, since the afternoon cluster of May 22 had three passes visible from the APL ground station. Figure 6 also shows the real and simulated attitude motion for the second and third passes of the cluster. The second simulated attitude set (colored curve) was initialized from data taken during the second pass of the cluster. The peak pitch libration that was left after the successful inversion was about 45°; roll and yaw were both under 30°.

With the successful inversion of Polar BEAR, active attitude control of the satellite was discontinued, and preparations were made to return the satellite to operational status. Within four days after the inversion maneuver, the Polar BEAR attitude motion had settled to within mission specifications of ±10° for the pitch, roll, and yaw angles, as shown in Fig. 7. APL continued to monitor the attitude until operational control was returned to the Naval Astronautics Group on May 29, 1987.

ANOMALY INVESTIGATIONS

The causes of Polar BEAR's anomalous attitude motion as it entered its first period of full sunlight are still unknown. Current investigations into the anomaly are focusing on the thermal dynamics of the satellite's gravity-gradient boom. The boom is made of 51-μm-thick silver-plated beryllium copper formed into an interlocked tube 1.27 cm in diameter. Solar radiation produces thermal gradients in the boom material, inducing deformation of the deployed boom element. The deformation is approximately 1 m at the end of the 18.3-m boom for normal solar incidence.

As the satellite's gravity-gradient boom deforms, the spacecraft's mass properties change. Associated with each new boom deformation state is a new spacecraft axis of minimum moment of inertia. Gravity-gradient torques continuously attempt to align the principal axis of minimum moment of inertia with the local vertical. Also, as the spacecraft attitude changes, the solar input on the boom changes, resulting in a different thermal equilibrium position. If the thermal boom deflection were acting in phase with the attitude motion, it could potentially resonate with the attitude motion, increase the attitude errors, and perhaps lead to an inversion. Simulations that model boom-bending dynamics have not been able to predict satellite inversion.

The solar-induced bending of gravity-gradient booms has been known to cause anomalous attitude motion for some time. In general, the motion has been attributed to unexpected, undamped oscillations of torsionally weak, open section booms.[6-8] "Zippering" the gravity-gradient tape booms, as was done for Polar BEAR's boom, substantially increases torsional stiffness, and thermal flutter generally disappears. Thermal boom vibrations as a satellite enters and leaves the earth's shadow still exist (see Fig. 4) but do not cause spacecraft attitude instabilities.

Zippering was supposed to eliminate thermally induced attitude instabilities. However, the Naval Research Laboratory (NRL) has flown momentum-wheel-augmented gravity-gradient-stabilized satellites with eddy-current dampers that also have experienced unexpected behavior. The NRL satellites have similar dynamical configurations, but a few have become inverted when entering full-sun orbits. In two incidents, the anomaly occurred only once. NRL's investigations were inconclusive, but they believe that the motion may be caused by some subtle properties of the gravity-gradient booms that cannot be currently quantified.

Investigations into Polar BEAR's attitude anomaly are continuing in efforts to gain a better understanding of the dynamics involved. Efforts are focusing on possible boom–sun interactions that could convert solar energy into destabilizing mechanical motion. As Polar BEAR enters its next period of 100% sun in early September, the attitude motion will be closely monitored to determine if the May inversion was an isolated incident or a recurring problem.

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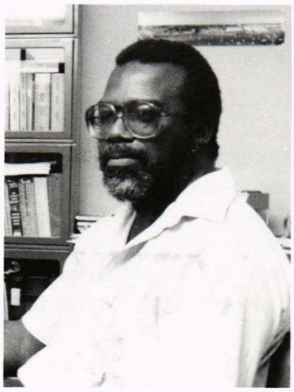

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