FREDERICK F. MOBLEY

MAGSAT PERFORMANCE HIGHLIGHTS

This article describes the commands given to the spacecraft during the first week after launch to prepare for collection of scientific data. It also discusses the performance of systems and instruments during the data-gathering phase.

POST-LAUNCH ACTIVITY OCTOBER 30 — NOVEMBER 3, 1979

Attitude Control

It was critically important for Magsat to obtain the proper attitude relative to the sun very soon after launch. Most satellites are designed to generate adequate electrical power regardless of their solar orientation; in such cases the post-launch attitude control adjustments can proceed gradually. However, Magsat had many electrical load requirements that could not be dispensed with, and the solar array could not meet those loads except when the B axis of the satellite was within 60° of the sun (see Glossary, Fig. A). At the moment of satellite release in orbit, this angle (β) would be near 90°, and the solar array output would be zero. Therefore, an immediate attitude control maneuver was required to move the B axis toward the sun before the battery became dangerously discharged.

Figure 1 shows the attitude control maneuvers that were programmed to occur in the first two orbits of Magsat. These maneuvers were accomplished by commanding a B-axis coil to be energized with a current of 0.9 A, producing a magnetic dipole parallel to the satellite B axis. This dipole interacted with the earth's magnetic field and produced a torque on the satellite. Since the satellite had substantial angular momentum (due to an internal wheel spinning at 1500 rpm as well as to the rotation of the satellite itself) and the torque is applied perpendicular to the momentum vector, the effect is to shift slowly the *direction* of the momentum vector in space.

To move the vector in a desired direction requires knowledge of the magnetic field strength and direction at the satellite position and the proper choice of command timing to take advantage of the field direction. This led to a particular command sequence and timing; the result is the predicted track of the B axis shown in Fig. 1. The commands for these maneuvers consisted of a series of B-coil commands, e.g., + SENSE, COIL ON, OFF, − SENSE, ON, OFF, etc., each at a particular time.

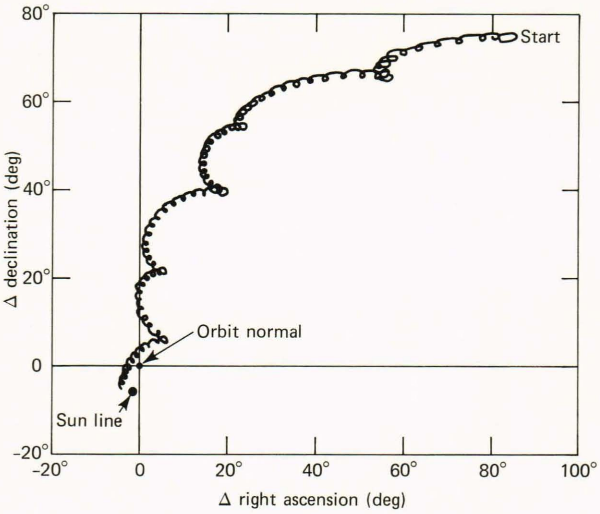

Fig. 1—Predicted track of + B-axis maneuver in initial orbits of Magsat. Initial spin rate: 0.67 rpm.

The Magsat command system could accommodate 82 stored commands in each of its two redundant systems. Almost all of this capability was used to carry out the following commands in the first orbit:

1. Turn off a tape recorder a few minutes after injection into orbit to save power;
2. Fire pyrotechnics to release two of the five mounting points for the optical bench and to release the mechanical retention of the boom links (but not the magnetometer platform — that would come later);
3. Turn the Doppler transmitter on for the benefit of a receiving station in Winkfield, England;
4. Turn the B coil on and off at the right times and with the correct polarity in order to maneuver the B axis toward the sun; and
5. Extend the aerotrim boom to balance aerodynamic yaw torques.

Figure 1 shows the predicted track of the + B axis with an assumed satellite spin rate of 0.67 rpm. Figure 2 compares the predicted variation of the angle β versus time with the actual result in orbit. Since the actual spin rate was 1.22 rpm, the angular momentum was greater than expected and the B axis failed to reach the sun line. Nevertheless, the final angle of 20° was more than adequate to provide the power requirements of the satellite.

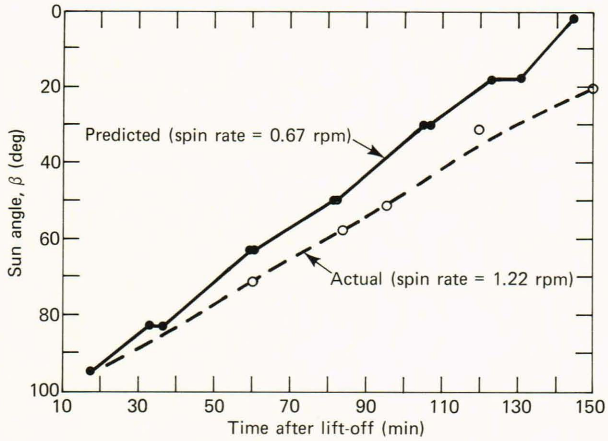

Fig. 2—Sun angle versus time for initial attitude maneuver of Magsat. A B-axis coil is turned on to interact with the earth's magnetic field to precess the satellite spin axis toward the sun in a programmed maneuver. The predicted motion was not fully achieved because the satellite spin rate was higher than expected. The solar array generated 135 W at the final orientation.

Two additional manually controlled magnetic maneuvers were carried out in the next 48 hours to bring the B axis within 5° of the sun line.

The magnetic spin/despin system was used to reduce the spin rate from 1.22 to 0.05 rpm in the first day. This system used X- and Y-axis coils that were energized proportionally to Y and X magnetometers, respectively, making the satellite behave like the armature of a DC electric motor and changing its spin rate slowly.

On October 31, 1979, the scalar and precision vector magnetometers were turned on to help absorb some of the excess solar-array power (even though the magnetometer boom was not yet extended and the data would be useless for scientific purposes). Very little drift in B-axis attitude was observed during this time period. The aerotrim boom had been extended to 4.63 m as part of the initial stored command sequence. Even though this was shorter than the planned length of 5.30 m, the yaw aerodynamic torques were well trimmed.

Until this time the attitude of the satellite was not under any form of continuous active control. The momentum wheel was running at a constant speed of 1500 rpm, and the associated angular momentum provided a form of "gyro" stability. Now the orientation of the satellite allowed the IR scanner to see the earth, and closed-loop pitch control was possible. At 1644 UT (Universal Time) on October 31, the attitude control was changed by command from the constant wheel-speed mode into the active pitch-control mode. In the latter mode the pitch angle of the satellite is detected by the IR scanner and if the pitch angle differs from the desired value, the wheel speed is increased or decreased to produce a reaction torque on the satellite in pitch, driving the pitch angle to the desired value. At 1730 UT on November 1, the automatic system for active roll-and yaw-angle control was activated. Full control of pitch, roll, and yaw angles was maintained thereafter.

Boom Extension and ATS Capture

Late on November 1, 1979, the magnetometer boom was deployed by command. Figure 3 shows the observed extension process versus time. The entire extension took 20 minutes, and was followed immediately by a further extension of the aerotrim boom to 6.99 m.

At this point the "moment of truth" came for one of the most challenging engineering tasks of the Magsat program. The pitch/yaw head of the attitude transfer system (ATS) sent a narrow beam of collimated light from the satellite to a small mirror (9 by 9 cm) mounted at the end of the boom, 6 m away. The mirror reflected the light back into the lens of the sending unit in order to measure the mirror angles of pitch and yaw. The ATS measures the mirror angles accurately over a range of ±3 arc-min (0.01667°) and is able to detect a signal out to ±6 arc-min (but cannot measure the angle accurately). Beyond that angle there is no signal. The critical question was, would the boom position and angle be correct for an ATS signal to be received? We had simulated the zero-gravity condition of space in a flow-tank test setup, but the pitch and yaw angles had to be simulated separately. Were our ground calibrations correct? Had some last minute changes disturbed our final alignments? Had the vibration of launch changed some critical angle? We were relieved and happy to discover after the boom extension that ATS signals in pitch,

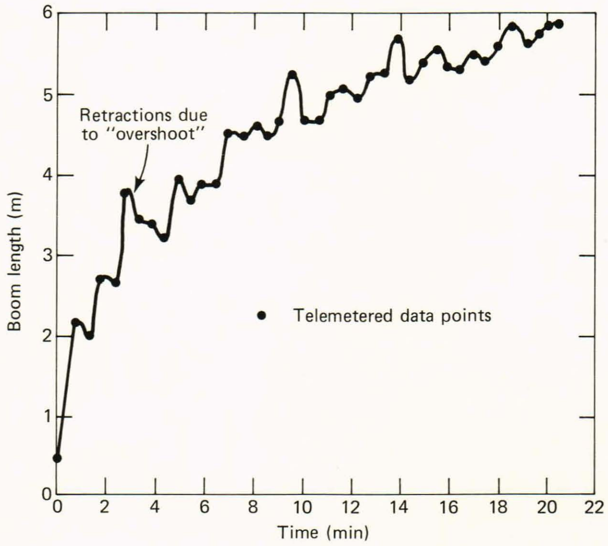

Fig. 3—Magnetometer boom extension on November 1, 1979. The boom is extended by a screw drive at the base of the boom. Static friction is overcome and the boom extends rapidly, overshoots, and partially retracts – then the process repeats. This accounts for the irregular extension process.

yaw, and roll were immediately received! On November 2 the three-axis gimbals at the base of the boom were commanded to adjust the boom angles to bring all three ATS outputs into the linear range of the system. Subsequent boom deflections due to temperature changes are discussed on p. 203. It is important to note that the ATS signals were in their nominal range continuously, a credit to the design of the boom.

Star Camera Operation

With attitude control fully established and the magnetometer boom extended, the star cameras were turned on during the morning of November 2 and functioned normally. Figure 4 shows typical outputs of a star camera. The position of a star in the field of view of the camera is recorded in terms of its X′ and Y′ coordinates. While tracking a star, the Y′ voltage stays relatively constant and the X′ voltage increases steadily, which is expected because the satellite rotates slowly about its B axis. At a rate of ≈4°/min, a star would seem to move across the field of the star camera in ≈2 min because the star camera field of view is 8 by 8°. However, the star camera was programmed to break lock on a star after a shorter time (e.g., 30 s). The camera then began a raster scan to find another star and to track it for 30 s. Occasionally a star passed out of the field of view before the 30 s had elapsed; in such cases the camera started searching again.

Thermal Problems

During the first few days in orbit, the internal temperatures of the base module rose about 10°C higher than predicted. This caused concern because the tape recorder lifetime could be shortened at elevated temperature and the battery as well as the IR detector could be damaged by high temperatures. The temperature of the IR detector stabilized at 43°C, about 3°C higher than the recommended maximum operating temperature. Battery temperature was reduced by operating the battery in a mode in which it was not charged from the solar cells but was used to supply power during peak demand. The battery was recharged about once every 5 days. The tape recorder temperature reached 38°C after a period of continuous recording. This temperature was higher than desired but was tolerable for the short mission lifetime of Magsat. No satisfactory explanation for the higher temperatures has been found.

SUBSEQUENT PERFORMANCE

By November 3, 1979, the satellite was fully operational and collection of scientific data began. In the normal operating mode, tape recorder data playbacks were scheduled four times per day. Each playback proceeded at a data rate of 320,000 bits/s for telemetering to the ground data that were accumulated at ≈2000 bits/s during the previous 6 to 7 hours. Before a playback was initiated the second tape recorder was started so that no scientific data were missed during the playback itself. Doppler transmitters were on continuously and Doppler data at 162 and 324 MHz were received by the worldwide Tranet stations of the Defense Mapping Agency. These data were forwarded to APL where the definitive satellite position versus time was produced by B. Holland. Position accuracy of better than 70 m root mean square was achieved in spite of the high drag condition of the Magsat orbit.

Observation of attitude drift indicated that we had overcompensated for yaw aerodynamic torque with an aerotrim boom length of 6.99 m. A series of retractions brought the boom back to 4.48 m where a very good trim condition was established. Figure 5 shows the drift track of the satellite B axis from November 22 to December 3. The B axis drifts in a small clockwise circle about 1.5° in

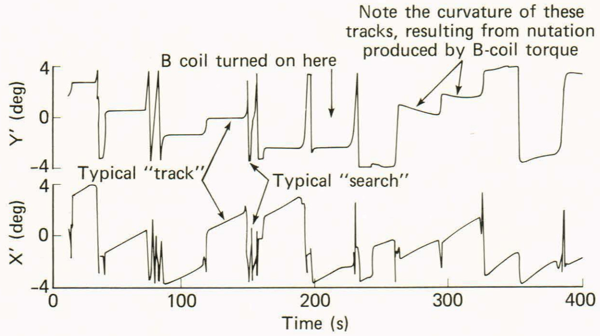

Fig. 4—Typical X′ and Y′ coordinates from star camera No. 2 versus time (Day 311, 1835 UT), showing "tracking" of stars and the effect of nutation produced by the B-coil torque with the earth's magnetic field.

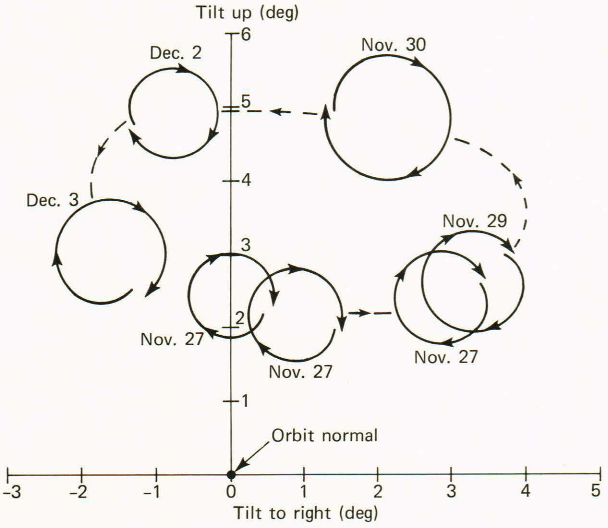

Fig. 5—Drift of B axis in space. The direction of the B axis drifts in a small circle during each orbit, and the center of this circle drifts in a larger elliptical path.

diameter in each orbit. The circle gradually drifted about in a large counterclockwise elliptical path whose center was displaced about 4° above the orbit normal. We believe this apparent tendency to circle about an orientation offset from the orbit normal was due to the rotation of the earth's atmosphere — a predicted effect. However, subsequent drift tracks have not been as simple and the cause is uncertain. It is important to note that hardly any magnetic torquing was necessary to maintain the satellite attitude except when the satellite came into lower altitudes and encountered higher aerodynamic forces.

Orbit Decay

Figure 6 shows the actual decay of the apogee and perigee of the Magsat orbit versus time as compared with an initial prediction made shortly after launch. Magsat remained in orbit longer than predicted, allowing more data collection when the magnetic field was quiet. However, there was a disadvantage because the low altitude data were delayed, to the extent that eclipsing of the satellite by the earth in April 1980 had deleterious effects on power, so that duty cycling of subsystems was necessary.

Vector and Scalar Magnetometers

The scalar magnetometer data were noisy from the start, probably because of lamp instability problems similar to those encountered before launch. However, the 20 to 40% of the data points that were valid have been used to make final adjustments in the calibration of the vector magnetometer to achieve a correlation of 1.2 nT rms in the total field as measured by the two instruments. (More detail on these devices may be found in the Farthing and Acuna articles in this issue.)

Star Camera Operation

Loss of star camera data for time periods of 30 to 40 minutes was observed beginning in early November. It occurred only in the southern hemisphere and is believed to be caused by sunlight falling directly on the sides of the sunshades and penetrating the black plastic skin of the sunshade. As expected, this phenomenon shifted from the southern to the northern hemisphere in March and April as the sun moved north.

FINAL EVENTS

On April 12, 1980, eclipsing of Magsat by the earth began, as predicted. The loss of solar array power during the eclipse meant that the satellite systems were entirely dependent on the stored energy in the nickel-cadmium battery. The battery voltage dropped much more rapidly than we expected during the eclipse. After the data were analyzed it became apparent that the battery capacity had dropped to about 12% of its nominal capacity of 8 ampere-hours. This loss in capacity has been ascribed to the "memory" effect associated with shallow discharging of nickel-cadmium batteries (which occurred prior to the eclipsing period) and also to simultaneous exposure to elevated temperatures.

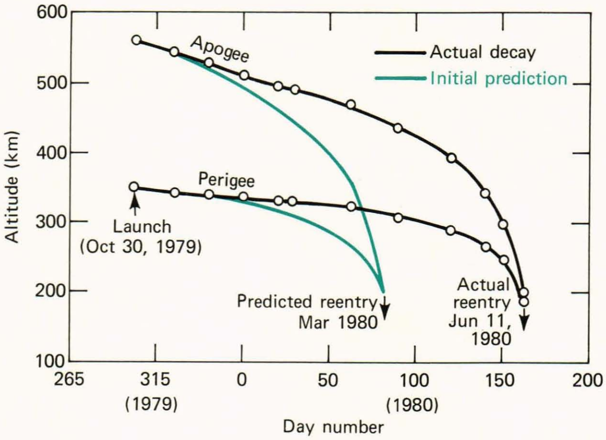

Fig. 6—Magsat orbit decay. The decay was slower than predicted because the density of the atmosphere was less than expected. The satellite reentered on June 11, 1980.

The reduced battery capacity caused operational problems. During each orbit various subsystems were commanded OFF prior to eclipse and ON after eclipse. In spite of this effort, a low battery voltage condition occurred on April 17. The battery voltage dipped below 13.2 V and the satellite automatically went into a self-protective mode, which included turning off the gyro. The attitude control system responded by going automatically into another pitch control mode that does not require gyro input. Several hours later, the satellite was restored to normal operation by commands from the ground. A similar event occurred in May.

In early June, the satellite altitude decayed to ≈240 km and eclipse times of 35 minutes were experienced. It was necessary to turn off the scalar magnetometer, the star cameras, and the ATS to save power. The vector magnetometer data were acquired until a few hours before reentry. Since the star cameras were off, the vector data cannot be used to determine the field direction. However, the three components will be combined to form the magnitude of the field, and those data will be analyzed for evidence of geomagnetic anomalies.

Reentry of the satellite occurred at 0720 UT on June 11, 1980, in the Atlantic Ocean. The satellite probably vaporized from the heat of aerodynamic friction. However, the momentum wheel (made of tungsten) may have survived. Some mariners of future civilizations may be puzzled at the strange "anchors" we used.