KEVIN J. HEFFERNAN, GLEN H. FOUNTAIN, BARRY E. TOSSMAN,
AND FREDERICK F. MOBLEY

THE MAGSAT ATTITUDE CONTROL SYSTEM

An account is presented of techniques used for orienting Magsat in the desired three-axis controlled attitude in space. The pitch angle was sensed by an infrared horizon scanner and controlled by reaction torques from an internal reaction wheel. Roll angle was also sensed by the infrared scanner and controlled by torquing the satellite with a magnetic coil that interacted with the earth's magnetic field. A small on-board computer assessed the roll error and computed the proper strength of the magnetic coil in order to correct the error, accounting for the actual magnetic field strength and internal angular momentum. No direct measurement or control of yaw was necessary.

INTRODUCTION

The first two Small Astronomy Satellites, SAS-1 and SAS-2, are good examples of previous APL attitude control systems. A constant speed momentum wheel provided open-loop gyro stabilization of the Z axis in space (see Glossary, Fig. A and Ref. 1). X- and Y-axis coils were used to interact with the earth's magnetic field to control the satellite spin rate. A Z-axis coil was used to precess the Z axis to the desired orientation in space. Nutation damping was accomplished using a mechanical device to dissipate nutation energy in the form of heat. Only the Z-axis orientation was controlled, and that only by command from the ground.

The third Small Astronomy Satellite, SAS-3, had a somewhat more sophisticated attitude control system (ACS). An internal gyro system was used to sense the satellite spin rate, and closed-loop control of spin rate was achieved by modulation of the wheel speed to provide the necessary torque. The wheel also incorporated an IR earth horizon scanner for closed-loop pitch angle control of the satellite. While this was not the desired flight mode for SAS-3, we did have the opportunity to demonstrate its proper operation several times during the four years of SAS-3 life. This form of control became the primary operating mode for Magsat.

In Magsat, the satellite was three-axis controlled to follow the local vertical axis system as the satellite moved in orbit. The axis system makes one complete rotation about the pitch axis during each orbit. The angles describing the satellite attitude are called pitch, roll, and yaw, where pitch refers to nose-up or -down (B axis), roll is rotation about the flight path axis (A axis), and yaw is rotation about the local vertical axis (C axis).

The momentum wheel had its axis of rotation aligned with the satellite pitch axis. The angular momentum of the wheel, spinning at approximately 1500 rpm, provided a form of weak gyro stabilization to keep the roll and yaw angles from changing rapidly. However, the wheel momentum did not force the roll and yaw angles to return to zero. The IR earth horizon scanner provided a pitch error signal, and closed-loop control in pitch was achieved by modulation of the wheel speed. A pitch-axis gyro system provided a measure of pitch rate and was used to enhance the damping of the pitch control system. In time the accumulated effects of external pitch disturbance torques caused the wheel speed to drift away from 1500 rpm. When the deviation reached a specified threshold, a magnetic torquing system was turned on to restore the wheel speed to 1500 rpm.

The IR scanner also sensed the roll angle of the satellite. This information was used at four specific points in the satellite orbit to decide whether corrective action was necessary. If the roll angle exceeded a specified threshold (which could be set by command in the range from 0 to 16°), the B-axis magnetic coil was turned on with the correct polarity and strength to precess the roll error to zero. This calculation was done by a new electronic system called the attitude signal processor (ASP). It was a small on-board computer system using the RCA 1802 microprocessor. The ASP was the "brains" of the ACS — it sampled the roll angle and computed the necessary B-coil strength based on the sampled strength of the X and Y magnetic field components and the internal angular momentum as indicated by the wheel speed. In addition, it decided when to initiate momentum dumping, selected the proper polarity, and shut off momentum dumping when the wheel speed reached 1500 rpm.

No direct measurement or control of yaw was made, nor were they necessary. By controlling roll at four points 90° apart in the orbit, the yaw angle was automatically controlled. We relied on the fact that yaw would not change by more than 1 or 2° in the 23 minutes during which the satellite moved from one roll sample point to the next. This depended on an adequate ratio of internal angular momentum to external torque. Being able to ignore yaw permitted a very important simplification in system design. Yaw is difficult to observe directly in a satellite; an inertial reference platform with three-axis gimbals and gyros would be required, with a substantial increase in complexity and cost, and a loss in reliability.

SYSTEM REQUIREMENTS

Four requirements played a major role in determining the design of the attitude control system. These were:

1. Stabilize pitch, roll, and yaw to ±5° to orient the star cameras, sun sensor, and solar panels properly;
2. Minimize angular rates and short-term motion (jitter) to avoid boom bending and to ease the analysis of the star camera data;
3. Minimize the demand on the ground station operators for rapid attitude control; and
4. Minimize the amount of magnetic torquing activity because the associated magnetic fields would degrade the fields at the primary scientific data sensors.

SYSTEM DESIGN

A block diagram of the ACS is shown in Fig. 1. Some of these elements are in common with the SAS-3 design described in Ref. 2, namely, the IR scanner wheel, the redundant gyro system, the B-axis coil used for orientation of the B axis, the X and Y coils and X and Y magnetometer and electronics that make up the magnetic spin/despin system, and the passive nutation damper. The ASP and the yaw aerodynamics trim boom are new features for Magsat.

The control of pitch and the control of roll and yaw use quite different and independent schemes. Both schemes are managed and operated by the ASP.

Pitch Control

Maintaining pitch control of the spacecraft is vital to the success of the mission. Loss of control for more than one orbit could prove disastrous; the motion of the spacecraft could cause the B axis to move away from the sun line far enough to reduce the power-generating capability below that required by the critical loads. As a result, five pitch-control modes were designed into the system to be used during different phases of the mission or in failure situations.

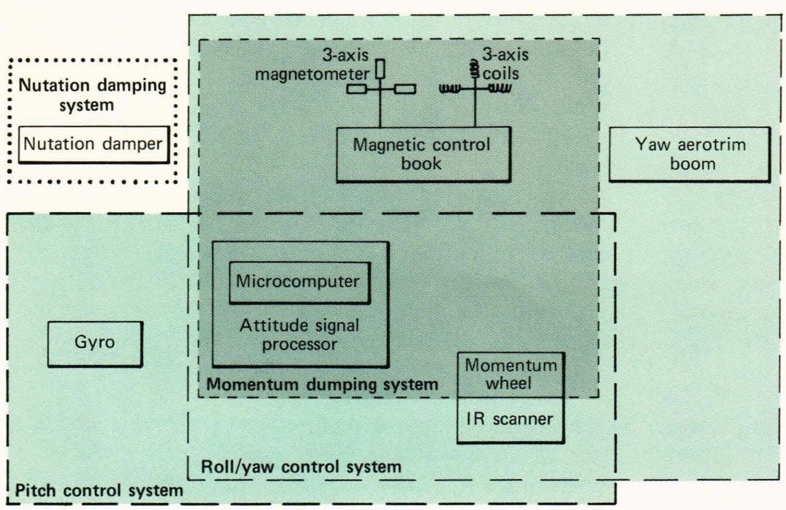
The ASP monitored a number of points as a check on the system's ability to make correct control decisions and, upon detecting a malfunction, switched to a safe mode. A microprocessor bypass mode was provided in the event of a microprocessor failure.

Figure 2 is a block diagram of the Magsat pitch control system. There were five modes, four of which were closed loop. Relay position numbers in the diagram correspond to the mode numbers.

Mode 1: IR Scanner Pitch-Bias Mode with Gyro Damping — This was the primary mode of the mission. The IR scanner provided pitch angle feedback, and a gyro simultaneously provided pitch rate feedback for damping purposes. The error in pitch angle was reduced to zero by accelerating or decelerating the momentum wheel. The equilibrium pitch angle could be offset from zero by a command from the ground. This "pitch bias" could be commanded to any angle in the range of −10 to +10°. We correctly anticipated that this feature would be useful in seeking a pitch angle that had minimum pitch disturbance torque.

Mode 1 was designed with high damping and minimum bandwidth to provide a slow but smooth pitch response and thereby minimize the pitch jitter motion. The system bandwidth was approximately 0.01 Hz.

Great care was taken in the design to eliminate



Attitude signal processor (ASP): Provides automatic signal processing and control capability for various attitude control systems via a 5 kilobyte microcomputer and associated circuitry.
Momentum wheel: Provides angular momentum for spin axis stabilization and a torquing capability used to control pitch rate and/or angle.
Infrared scanner (within the reaction wheel): detects infrared radiation above the earth and converts this information to signals proportional to spacecraft pitch and roll angles.
Gyro: Provides a signal proportional to pitch rate.
Orthogonal magnetic coils (3), 3-axis vector magnetometer, magnetic control book: Provide magnetic torquing capability for aligning spacecraft spin axis, controlling pitch rates and dumping reaction wheel momentum.
Nutation damper: Dissipates nutational energy via mechanical damping of a torsion wire pendulum.
Yaw aerotrim boom: Reduces frequency of roll/yaw control maneuvers by providing in-flight balancing of yaw aerodynamic torques.

Fig. 1—Block diagram of the Magsat attitude control system.

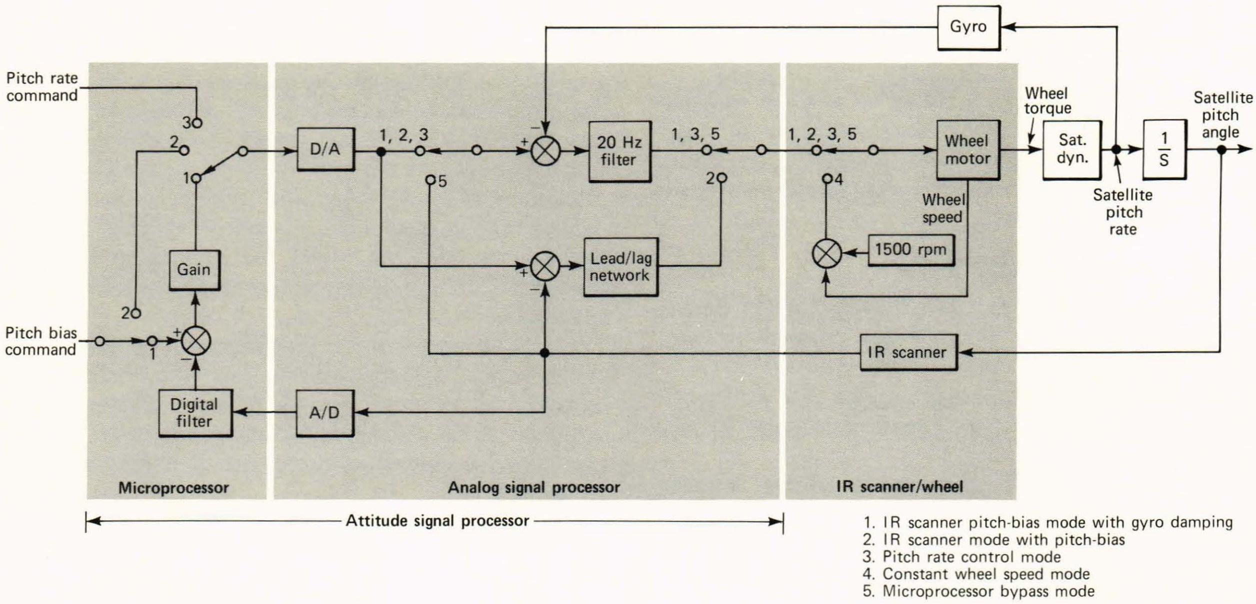


Fig. 2—Block diagram of the Magsat pitch control system.

any internal noise effects on system operation. The pitch voltage, which was noisy due to a differentiating network in the IR scanner, was digitally filtered at 0.02 Hz in the microprocessor. Gyro noise was measured and found to be negligible.

This mode was initiated approximately 24 hours following pitch capture and was intended to continue for the lifetime of the mission.

Mode 2: IR Scanner Mode with Pitch Bias — This was a pitch angle control mode, again with a commandable pitch bias capability to ±10°. However, the gyro was not required for this mode; it was a backup mode in case of gyro failure.

Mode 3: Pitch Rate Control Mode — In this mode the pitch rate was controlled, rather than the pitch angle. The gyro signal was used as a measure of the actual pitch rate, which was compared with the desired rate (as loaded by command). This mode was intended as a backup mode in case of an IR scanner failure or a roll angle so excessive that the IR scanner did not see the earth. The desired rate was set at 1 revolution per orbit.

Mode 4: Constant Wheel Speed Mode — In this mode the wheel speed was held fixed at 1500 rpm and no control of pitch angle or rate was attempted. The system was operating in this mode during launch and during the initial attitude maneuvers before closed-loop control was established.

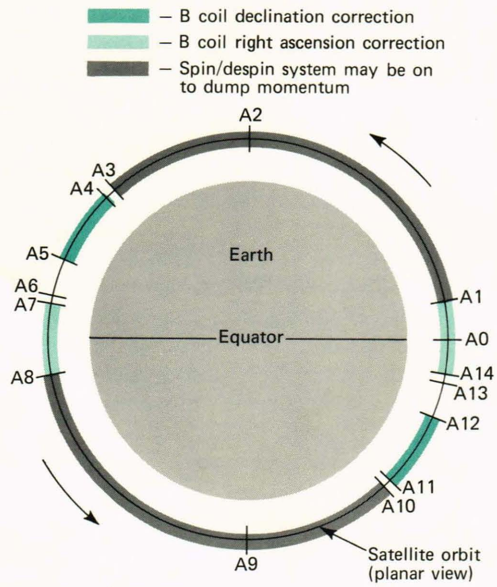
Mode 5: Microprocessor Bypass Mode — As in the primary mode, both pitch angle and rate feedback information were provided. However, unlike Mode 1, this mode had no microprocessor interface and therefore no pitch bias capability or 0.02 Hz filtering of the pitch signal. This loop would have been used only in the event of a microprocessor failure and, due to loop gains, would have resulted in a steady state pitch angle of −0.7°. All microprocessor control and signal processing functions would have been disabled in this mode. This was the only pitch control mode that was not used during the lifetime of the mission.

Momentum Dumping

Momentum dumping was required to keep the wheel speed in the range where it was capable of producing reaction torque (1100 to 1900 rpm). Wheel speed changes were the result of external disturbance torques acting on the satellite. There were two techniques available to achieve momentum dumping, pitch angle bias and magnetic spin/despin torquing. The pitch angle bias was used to allow aerodynamic, gravity-gradient, and other disturbance torques to offset one another, the accumulated effect being to minimize the overall external pitch torques. The bias angle was determined from analysis by the satellite operators, and a command was sent to the satellite to implement the bias.

The magnetic spin/despin system was used automatically under the control of the attitude signal processor. If the wheel speed deviated from 1500 rpm by more than a predetermined amount, say 200 rpm, the ASP selected the proper polarity and turned on the magnetic spin/despin system. When the wheel speed reached 1500 rpm, the ASP turned off the magnetic torquing.

In order not to interfere with roll/yaw control, this could only be done at specific times in the orbit. Figure 3 shows the orbit track about the earth and the assigned points for various allowed activities by the ASP. Only at points A1 and A8 could



Orbit location	Action
A0	Orbit ascending node
A1, A8	B coil turned OFF after right ascension correction; wheel speed sampled, spin/despin system turned ON if desired and necessary
A2, A9	Roll angle sample for declination correction
A3, A6, A10, A13	Spin/despin system turned OFF to sample magnetometers
A4, A11	B coil turned ON for declination correction if desired and necessary
A5, A12	B coil turned OFF after declination correction
A7, A14	Roll angle sampled and B coil turned ON if desired and necessary for right ascension correction

Fig. 3—Orbit locations of roll/yaw control and momentum dumping events.

momentum dumping be initiated. Momentum dumping had to be completed by A3 or A10, respectively, or it would have been terminated in preparation for possible roll control maneuvers.

The magnetic spin/despin system worked in the following manner: Voltages proportional to the X and Y components of the earth's magnetic field were amplified and used to drive the Y and X coils, respectively. One of the signals was inverted. This produced a net magnetic dipole that led or lagged the earth's field by 90°. The result was a torque about the satellite spin axis, the sense of the torque being determined by the ASP.

Roll/Yaw Control

The roll/yaw control system was designed to maintain nominal alignment of the B axis with the orbit normal. The automatic roll/yaw control mode took advantage of the system's ability to detect both declination and right ascension errors from the roll output of the IR scanner and corrected these errors by using an application of a B-axis magnetic dipole at appropriate places in the orbit.

For example, at equatorial crossings the roll angle provided a measure of the error in right ascension between the B axis and the orbit normal. The earth's magnetic field is oriented north in this region. With knowledge of the roll error, magnetic field strength, and wheel speed, the B coil could be energized at a specific strength and for a specific length of time to precess the B axis in right ascension to correct the error almost exactly. By energizing the B coil for an integral number of nutation periods (150 seconds each), residual nutational motion of the spacecraft was minimized. Two nutation periods were used. This action was initiated at points A7 and A14 (Fig. 3) if the roll angle exceeded a specified threshold value. The torquing was terminated at A8 and A1, respectively.

In a similar manner, spacecraft roll angle at the orbit poles is a measure of the declination error of the B axis from the orbit normal. Energizing the B coil when the earth's magnetic field is nearly parallel to the earth's equatorial plane would precess the B axis in declination and correct the observed error. Figure 3 shows the orbit locations at which the roll angle was sampled (A2 and A9) and the B coil was energized (A4 and A11) if the roll angle exceeded the threshold.

In the interest of minimizing B-coil activity, a threshold on roll error was chosen below which no B-coil activity would occur. This threshold was normally set by command between 1 and 3°.

Computer analysis of the attitude dynamics showed that a significant yaw aerodynamic torque existed because the center of mass of the satellite was offset from the center of frontal area. This yaw torque would have continually perturbed the satellite, requiring frequent control activity. We therefore decided to balance the frontal area by installing a yaw aerodynamic trim boom. It was a motorized boom made up of a silver plated beryllium-copper tube 1.2 cm in diameter that could be extended to any length up to 12 m. Our analysis showed that about 5 m of extension would be required to balance the yaw torques. This boom protruded from the base of the satellite.

Nutation Damping

The primary means of reducing satellite nutational motion during the attitude acquisition phase was the nutation damper. It consisted of a damped pendulum pivoting on a torsion wire. The pendulum's arm swung in a plane normal to the intended spin axis and oscillated when the spacecraft nutated. Damping in the pendulum movement dissipated kinetic energy until all nutation ceased.

The predominant nutation damping mechanism for the mission phase used product-of-inertia coupling between nutational motions and the pitch control loop. Damping in the pitch loop simultaneously damped nutations via the passive coupling. Loop gains and phase shifts were analyzed to assure stability. The nutation period was approximately 150 seconds, and the damping time constant was 40 minutes.

ATTITUDE SIGNAL PROCESSOR

The attitude signal processor (ASP) coordinated and controlled the activity in the attitude control system. It used the RCA 1802 microprocessor with 4096 bytes[3] of programmable read-only memory (PROM) and 1024 bytes of random-access memory (RAM). The 1802 microprocessor employed a four-level, individually maskable, priority-interrupt scheme. The highest priority interrupt used a direct memory access to enter commands to the ASP directly into the RAM. The computer was synchronized to the telemetry clock by an interrupt generated every half second.

A command of 256 bits was required to initiate the ASP activity. This message contained such information as the orbital period, the time when the satellite would cross the equator north bound, the desired pitch mode, the pitch bias angle, the roll threshold, the desired pitch rate, etc. These data were stored in the RAM and used by the computer as it proceeded through its routine, which was stored in the PROM.

One of the most important features of the microcomputer was its diagnostic capability. The microcomputer performed a "checksum" every half second to verify that its embedded software had remained static. Also it checked for certain "faults" in the IR scanner and the gyro system; if any were detected, appropriate action was taken to change the pitch mode. Discrepancies in the command word were also detected and, depending upon the error, the command was either rejected or corrected. Flags were generated for each fault both in a 128-byte telemetry output and in a special 4-bit status word provided as a warning system for the ground operators.

In the event of a momentary loss of the 5 V power supply, the destruction of each copy of the resident ASP command, or a program sequencing anomaly, the ASP would automatically restart, initializing both the foreground and background portions of the firmware and placing the attitude control system in a safe mode. If the microprocessor had failed completely, a relay driven by the command system would have placed the attitude control system in a microprocessor-bypass pitch control mode and would have disabled all microcomputer control and signal processing capability.

The Magsat ACS was the first microcomputer-based ACS built at APL and quite possibly the first satellite microcomputer that was programmed in a high-level language (MICRO-FORTH). The 1802 microprocessor was chosen for the application because of its low power consumption, its compatibility with other systems on board, and its availability in a high reliability version. The ASP weighed 0.86 kg and consumed 0.95 W of power.

PERFORMANCE IN ORBIT

Initial satellite activity following launch included the yo-yo despin, pitch-axis alignment with the orbit normal, satellite despin using the spin/despin system, and acquisition of closed-loop pitch control. Details of the initial attitude maneuvers are given in the "Magsat Performance Highlights" article in this issue.

The satellite was commanded into the primary pitch control mode on November 1, 1979, and remained almost exclusively in that mode until June 10, 1980, the day before reentry. Attitude transfer system outputs indicated a peak-to-peak pitch oscillation of 1.5 arc-s at 0.6 Hz, well within the design specification.

Momentum dumping operations occurred periodically during the first week of the mission. Pitch angle bias was used very successfully to minimize magnetic momentum dumping for the majority of the mission. However, toward the end of satellite life, magnetic momentum dumping became quite frequent as the aerodynamic disturbance torques increased.

The yaw aerotrim boom was deployed to 4.63 m before the initial satellite maneuvers and subsequently was extended to 6.99 m after the magne-

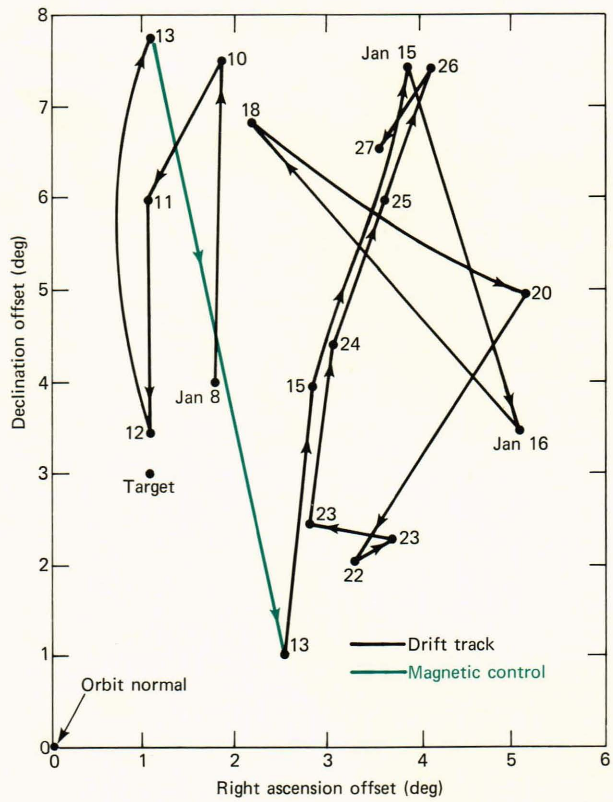


Fig. 4—Magsat attitude activity from January 8 to 27, 1980, showing drift of the +B axis in space. The roll angle had to exceed a threshold of ≈5° (with respect to target position) to initiate roll/yaw control activity. Lack of activity was due to the aerodynamic balancing effect of the yaw trim boom at the skewed target position.

tometer boom extension. Careful observation of the B-axis drift led to the decision to retract the boom to 4.88 m, which resulted in a minimum of B-coil magnetic torquing. Figure 4 shows the B-axis drift over a 17 day period in January 1980, during which only one roll/yaw control maneuver was required.

Nutational motion was reduced from 10 to 0.5° in 12 hours by the mechanical damper prior to magnetometer boom extension and was held to approximately 0.07° peak-to-peak by inertial coupling damping.

The entire ACS performed flawlessly in meeting each of its requirements. It oriented the satellite for optimum power generation and provided minimum aerodynamic torque needed to reduce magnetic torquing operations. In addition, it provided the stable platform needed for arc-second-quality attitude determination solutions and high-resolution magnetic field measurements.

REFERENCES and NOTES

[1]The B axis of Magsat is the same as the Z axis of SAS. The A and C axes are perpendicular to B. The X and Y axes are also perpendicular to B but are rotated 45° from the A and C axes.

[2]F. F. Mobley, P. Konigsberg, and G. H. Fountain, "The SAS-3 Attitude Control System," *APL Tech. Dig.* **14**, No. 3, pp. 16-23 (1975).

[3]A byte is an 8-bit word of data.

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