THE ATTITUDE CONTROL and DETERMINATION SYSTEMS of the SAS-A SATELLITE

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A high-speed wheel inside the satellite provides the basic attitude stabilization for SAS-A. Wobbling of the spin axis is removed by an ultra-sensitive nutation damper which uses a copper vane pendulum on a taut-band suspension to dissipate energy by eddy-currents. The spin axis can be oriented anywhere in space as required for the X-ray experiment by a magnetic control system operated by commands from the ground station at Quito, Ecuador. Magnetic torquing is also used to maintain the satellite spin rate at 1/12 revolution per minute. These systems are outgrowths of APL developments for previous satellites, chosen for simplicity and maximum expectation of satisfactory performance in orbit. The in-orbit performance has been essentially flawless.

Introduction

THE ATTITUDE CONTROL SYSTEM is used to orient SAS-A so that the X-ray detectors can scan the regions of the celestial sphere in an orderly and efficient manner to detect and measure new X-ray sources. The two X-ray collimators are mounted perpendicular to the satellite spin (Z) axis. As the satellite rotates slowly about its Z axis, the detectors scan a 5-degree-wide great circle path in the celestial sphere. The experiment plan calls for scanning a particular great circle for about one day, then maneuvering the spin axis to a new heading in space to scan a new great circle the next day. This continues until the entire celestial sphere has been scanned. This plan is flexible to permit intensive data collection in a specific region if new or especially interesting X-ray sources are found.

The attitude control system provides the spin axis stabilization required to collect data for long periods from one great circle path and the ability to maneuver the spin axis to a new orientation. The spin rate control system is used to keep the spin rate within 10% of the desired rate of 1/12 rpm.

The wide field of view of the X-ray detectors (5 degrees) means that the orientation accuracy need be only a few degrees in order to sample any desired point in the celestial sphere. This modest control objective can be achieved with a simple and reliable open-loop system, using commands from the ground. This is very appealing since the weight and power limitations on the SAS-A satellite do not permit an elaborate closed-loop control system.

In addition to detecting and analyzing new X-ray sources, the experimenter is interested in correlating X-ray sources with known visible stars, or sources of radio emission, if possible. This requires after-the-fact attitude determination to 1 minute of arc accuracy. This precise attitude determination is done with data from two scanning star sensors provided by AS&E. APL's responsibility in attitude determination is to provide a rough estimate to a few degrees accuracy. AS&E then uses this information as a starting point in determining the precise attitude.

One of the fundamental objectives of the SAS satellite series is to do significant astronomical research with a relatively modest financial investment. Keeping the satellite small and lightweight would permit launching with the relatively low cost Scout rocket. Consistent with this philosophy, the approach to the design of the attitude control system for SAS-A was to meet modest control objectives with simple and well-proven systems. At first the idea of using a spin-stabilized satellite was considered, but the experimenter desired the very slow spin rate of 1/12 rpm, too slow to develop enough angular momentum to stabilize the satellite adequately. We had used spin stabilization on the DME-A satellite (launched in 1965) with a rotation rate of 3 rpm and knew that drift due to external torques was a problem even then. We decided to get the necessary angular momentum for stabilization by incorporating a flywheel rotating at a high rate inside the satellite. There was some apprehension at this decision because of known problems with bearing lubrication under the vacuum conditions of space, but our experience with a flywheel in the DODGE satellite led us to believe that this problem could be solved.

Nutation damping is essential for a spin-stabilized or wheel-stabilized satellite. A "nutation damper" is a device that eliminates wobble motions of the satellite and keeps the spin vector aligned with the desired axis in the satellite. Typically it is a purely mechanical device that is free to respond to nutation and dissipate energy by friction, viscous fluid damping, or eddy-current damping. We had used a passive damper in the DME-A satellite with success, but not operating at the slow spin rate of SAS-A. We recognized that the nutation damper for SAS-A would require the absolute minimum of threshold sensitivity and hysteresis.

With a momentum wheel and a nutation damper we have the necessary elements for holding a given orientation in space for some time and eliminating wobble, but a scheme to achieve the desired orientation and spin rate is also necessary.

The classic approach to this problem at APL has been to do it with magnets. The earth's magnetic field can be used to produce torque on the satellite. Magnetic torques are generally much weaker than torques from jet thrustors or reaction wheels used in other satellites, but the magnetic torque system is less complicated and more reliable than jet thrustors. We had used magnetic torquers for control of the AE-B satellite and the DME-A satellite. The spin rate control system using X- and Y-axis electromagnets employed on these two satellites was an original concept developed and first used by APL.[1] We chose to do this with coils instead of electromagnets on SAS-A but the concept is the same.

[1] F. F. Mobley, J. W. Teener, R. D. Brown, B. E. Tossman, "Performance of the Spin Control System of the DME-A Satellite," AIAA Guidance and Control Conference, Aug. 15, 1966.

Orienting the Z axis in space is accomplished by magnetic torquing using a Z axis coil. Upon ground command the Z coil is energized with a fixed and known electric current. This produces a magnetic dipole that reacts with the earth's field to produce a predictable torque to precess (or move) the spin axis in a known direction in space. At the proper time the coil is turned off and precession stops. These "attitude maneuvers" are planned in advance by computer analysis on the ground, and commands to turn the coil on and off at the proper times are sent to the satellite. After a maneuver, there is a small residual wobble of the spin axis which is damped out by the nutation damper.

"Drift" of the spin axis in space is the name given to undesirable shifting of the spin axis owing to the accumulated effects of disturbance torques acting on the satellite. The principal causes of these torques are gravity-gradient effects, aerodynamic forces, and spurious magnetic torques on currents and magnets in the satellite. Our objective has been to keep the accumulated drift to less than 5 degrees/day. Gravity-gradient torques can be eliminated by making the three principal moments of inertia of the satellite equal. But this would prevent operation in a back-up mode with the wheel off (in case of wheel failure) because the satellite would have no "preferred" axis of rotation and would be unstable. It is necessary that the Z axis inertia, I_z, be at least 5 to 10% greater than I_x and I_y to retain a feasible back-up mode. An inertia margin of 10% would lead to drift rates of 5 degrees/day from gravity-gradient torques alone. This leaves no margin for magnetic and aerodynamic induced drift. A scheme for in-orbit compensation of drift appeared desirable.

In-orbit compensation of drift effects is achieved with a magnetic trim system. Three small Alnico V magnets are arranged in a mutually perpendicular fashion. They are wound with coils and can be pulsed by capacitor discharge to be magnetized to full strength in positive or negative sense or to intermediate values. The Z-axis trim magnet has a full strength of 1000 pole-cm. The X and Y trim magnets have full strengths of 200 pole-cm. The Z magnet is used to compensate for gravity-gradient drift by establishing a magnetic torque to oppose the gravity torque. The X and Y magnets compensate for internal spurious magnetic dipoles that could modulate satellite spin rate.

The attitude detection system provided by APL uses a three-axis vector magnetometer to measure the components of the local magnetic field of the earth as seen by the satellite. These data are telemetered to the ground. In addition, the angle between the Z axis and the sun-line is measured with a digital solar attitude detector and telemetered. By computer analysis of these data the satellite orientation can be determined to an accuracy of 1 to 3 degrees.

This briefly summarizes the elements of the attitude control and detection system, their concepts, and their purposes. A more detailed description of these elements follows.

The Momentum Wheel

The objective in the development of the momentum wheel for SAS-A has been to achieve the desired angular momentum in a device of minimum weight and power consumption, with tolerable size, and with high expectation of satisfactory operation in orbit for at least one year. In the SAS-A context it might be said that we were seeking a device weighing a few pounds, running on a few watts, and small enough to fit within a 22-inch-diameter satellite without taking an unreasonable amount of the available space. Our final design is 10 inches in diameter by 4.5 inches high, weighs 7.5 pounds, and draws 1.35 watts. A photograph of a disassembled wheel is shown in Fig. 1. It is completely self-contained, including a 100 Hz square wave inverter powering an AC hysteresis-synchronous motor that drives an epoglas flywheel at 2000 rpm. It contains a mechanical caging system consisting of a small DC motor driving three beveled pins that engage a groove in the flywheel rim to hold it firmly during the heavy vibration and acceleration of the rocket launch. This prevents damage to the two ball bearings that support the flywheel.

A critical problem for mechanical devices in space has been that of lubrication of bearings. If ordinary ball bearings with oil lubricant are exposed to the vacuum conditions of space, the lubricant gradually vaporizes leaving bare metal-to-metal contact, or a gummy residue. In either case the bearing torques go up and the system comes to a premature halt.

The solution to this problem, which we have chosen after studying and testing alternatives, is to use a dry lubricant for the ball bearings. A familiar dry lubricant is graphite. Graphite has the peculiar characteristic of losing its lubrication capability under vacuum conditions. An acceptable substitute for space applications is molybdenum disulphide (MoS_2). Ball bearings typically consist of an inner and an outer race, the balls, and an element called the retainer—a toroidal-shaped piece with holes for the balls, which is placed between the inner and outer races to keep the balls spaced properly and prevent them from bumping and damaging each other. The retainer for our ball bearings is impregnated with 2% MoS_2. As the bearings run, the MoS_2 is dragged out of the retainer by the balls and deposited on the the inner and outer races. Thus the balls roll on a thin film of MoS_2. We had used bearings of this type in space applications previously, but not in continuous operation. Therefore we expected to encounter new problems, and we were not disappointed.

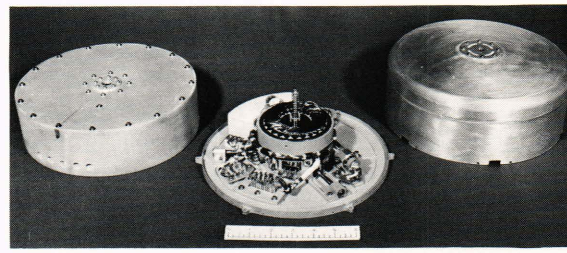

Fig. 1—Momentum wheel (disassembled); wheel, motor and caging mechanism, and cover.

Wheel development began in 1968. We knew that proof of life-time capability of one year was highly desirable so we made haste to develop an acceptable design and get a unit into a life test well in advance of the scheduled satellite launch.

History of Wheel Development

In the search for a suitable wheel for SAS we evaluated a commercially available wheel made for the Nimbus satellite. It was an hermetically-sealed assembly using ball bearings with conventional oil lubrication, running at 1200 rpm, drawing 7.5 watts, and weighing 8.8 pounds. This wheel used an induction motor, and much of the power was consumed in overcoming air drag inside the sealed container. We felt that we could do the job for less power and weight.

With our first APL-designed wheel we developed a mechanical configuration which put as much weight as possible into the flywheel, and proved our design of the DC to AC electronic inverter powering an induction motor. We also developed a device for measuring the wheel speed very accurately, using a light source and a detector mounted on the assembly base, and a small metal finger attached to the flywheel. During each wheel revolution the finger cuts the light beam once. This produces an electrical pulse; the time between pulses is measured very accurately using an atomic clock standard and recorded for analysis of wheel speed stability. We used dry lubricant bearings in this first model.

One consideration of major importance in the wheel design was to obtain very good wheel speed stability. The experimenter relies on steady satellite rotation between star detections to interpolate accurate positions for X-ray sources. Any wheel speed variations would be reflected immediately in satellite speed variations as predicted by Newton's law of the conservation of angular momentum. For our second wheel model we selected a special hysteresis-synchronous motor developed for this application by H. C. Roters, Inc. This type of motor has the advantage over the more common induction motor in that it will run at synchronous speed and does not "slip" relative to the rotating magnetic field. Thus its speed is governed by the frequency of the AC inverter. This we control to 1 part in 10^6, so we should expect very good speed stability.

The situation is not quite as rosy as this implies. The hysteresis-synchronous motor tends to "hunt", i.e., the speed has a tendency to oscillate about the synchronous speed. The period of these oscillations is about 5 seconds and the amplitudes are generally quite small. Figure 2 shows a histogram made from data taken on the wheel in orbit in the latter part of December 1970. Most of the measured wheel speeds cluster around 2000 rpm, with occasional deviations up to 0.08 rpm. The worst case we observed in 10 orbits of data was 0.14 rpm. This variation would cause an attitude error of only 0.03 minute of arc, 10 times less than our design limit of 0.3 minute of arc. The hysteresis-synchronous wheel seems to have been a good choice for this application.

With the second wheel, we experimented with oil lubricated bearings using the proprietary Vac-Kote process of Ball Brothers Research Corp. This lubrication scheme was used in the OSO

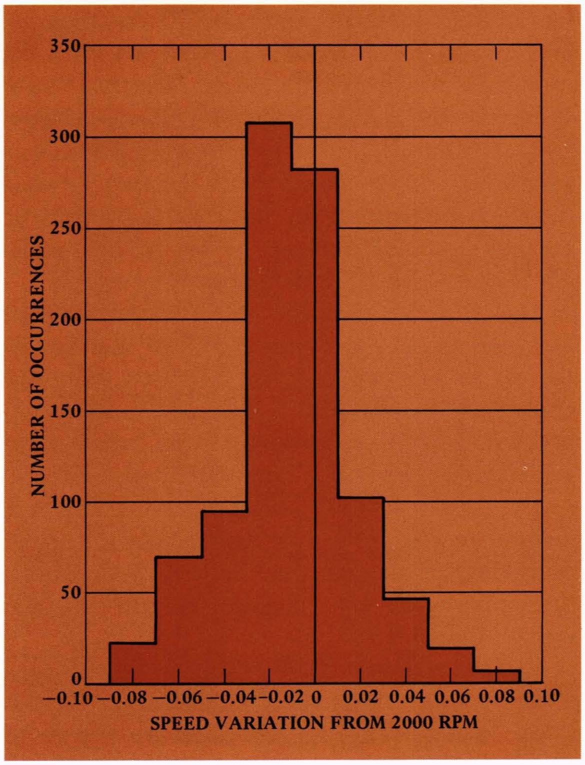

Fig. 2—Histogram of wheel speed variation in orbit.

satellites and had proven lifetime capability under vacuum conditions. However, we found that at a moderately low temperature such as 55°F the viscosity of the lubricant increased to the point where the motor could no longer keep the wheel up to speed.

Our measurements of power consumption of the hysteresis-synchronous motor showed that satisfactory performance could be obtained with less than 2 watts dissipation.

A unique problem was encountered in our initial wheel design. The rim of the first two wheel models was aluminum. As it rotates in the earth's magnetic field, electrical eddy-currents would be induced in the rim. These would produce a retarding torque on the flywheel. This torque would cause a spin rate loss of 6% per day, too much to tolerate. To eliminate this problem, the rim material was changed from aluminum to epoglas, a nonconductor. Tests with this rim showed no torque associated with magnetic field strength.

A third wheel was designed using the experience gained from our first two units, and including all essential features of a possible flight unit. This unit was put through the full gamut of vibration and thermal vacuum testing. It was then put into a special vacuum chamber for extended life testing. Life testing continued for 308 days. Wheel speed was measured each week and was consistently within acceptable limits. Bearing torque was measured occasionally. The bearing torque dropped dramatically in the first few weeks as the lubricant film built up on the bearing races. Thereafter it was low but somewhat erratic.

The wheel development effort was not without its surprises. In the eighth month of the life test the wheel was stopped and removed from the chamber to permit repairs on the vacuum chamber. Upon being set up again in the chamber the wheel would not start. The wheel was removed, disassembled, carefully checked for defects but none were found. It was then reassembled and reinstalled in the vacuum chamber. This time it started without any difficulty and the life test was continued.

It was not until a similar problem was encountered with the flight momentum wheel that the source of our problem was discovered. Late in the satellite qualification testing the entire satellite was given its vibration test. After the tests all satellite subsystems were operated to confirm that they had survived the test without damage. The momentum wheel was uncaged, then power turned on to start it. It did not start. Measurements of the amount of torque required to start rotation showed several in.-oz were required. This was well above the motor capability of 0.7 in.-oz. Once rotated, however, the wheel would then start and run satisfactorily although it sounded more noisy than usual.

Some problem in the bearings was suspected. The wheel was removed, disassembled and the bearings removed and disassembled. A thick film ($\sim$ 0.001 inch) of MoS_2 was found deposited in the raceways as expected. However there were gaps in the film at each place where a ball was in contact with the raceway. Apparently, during the vibration when the wheel was caged the balls had broken through the lubricant film. Then to get started they had to roll up on top of the film. This took more torque than the motor could produce.

A series of subsequent tests showed that this problem could be minimized by carefully controlling the film buildup by limiting the wheel running time before launch. Keeping the film very thin can prevent excessive starting torque. The problem with the life test unit was probably caused by one of the balls making depressions in the film and producing excessive starting torque.

Since encountering these problems with high starting torque, we have designed a special starting motor system to provide much more starting torque. It uses a small DC motor engaged with the rim during the uncaging process. This motor starts the rim rotating as the caging pins are being retracted. Then the AC motor takes over, and at the end of uncaging the DC motor is fully disengaged, and turned off electrically. A wheel with this feature was made for SAS-A but not used. The wheel for SAS-B will use this feature.

Nutation Damper

For the experimenter to locate X-ray sources to an accuracy of 1 minute of arc, it is essential that the satellite rotate about its Z axis and *only* the Z axis. This amounts to requiring that the lateral angular velocity rates be damped to zero. A "nutation damper" does this by dissipating the energy associated with these rates.

Anything that can move in the satellite and dissipate energy can conceivably be used as a nutation damper. A toroid filled with a fluid, a ball rolling in a tube, spring-mass-dashpot concepts, etc., have been used. For the DME-A satellite we used a copper ball in a curved tube with permanent magnets. As the ball rolled in the tube it rolled through the magnetic field of the magnets, electrical eddy-currents were induced in the ball, and the energy of nutation was dissipated as heat.

We felt that the DME-A scheme would not work for SAS-A because the nutations are much weaker and therefore the ball would not roll in the tube, but simply stop at the smallest grain of dust or irregularity in the tube.

To get the ultimate in sensitivity we use a delicate hair-wire torsion suspension for a heavy pendulum. Since, in orbit the pendulum is weightless, the hair-wire does not support the weight of the pendulum, and therefore can be extremely fine. The wire is a nickel-platinum alloy 0.0016 in. thick by 0.016 in. wide and about 2 in. long. This type of suspension is called a "taut-band" suspension, and is popular in high-quality electrical meter movements.

Figure 3 shows the pendulum assembly. It consists of a heavy copper vane, two arms which are joined at one point and attached to the center of the taut-band, and a special coded mask used to measure the pendulum position.

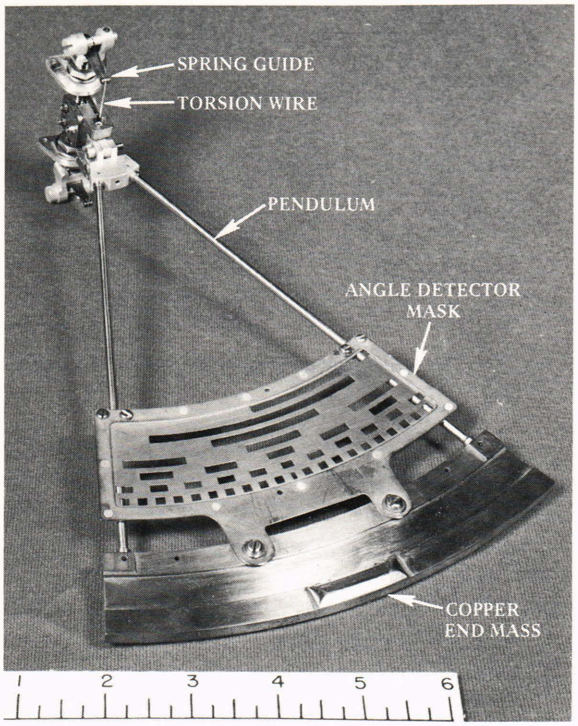

Fig. 3—Nutation damper pendulum.

As the satellite nutates, the copper vane swings back and forth through magnetic fields produced by permanent magnets. Eddy-currents are induced in the copper vane. The energy of nutation is dissipated as heat in the vane. This is a very simple concept—one may wonder at the complexity of the final design shown in Fig. 4. The reasons for the complexity are that, in addition to the basic concept, the damper also:

1. Has a caging motor and associated mechanism to grasp the copper vane and support it during the vibration and acceleration of the rocket launch.

2. Has an angle detector system consisting of an optical mask with a coded hole pattern, seven light sources, and seven light detectors to detect the position of the vane to ±½ degree accuracy, and an electronics module to operate the sources and detectors. This feature is not essential to the damper function but provides confirmation of proper operation in orbit.

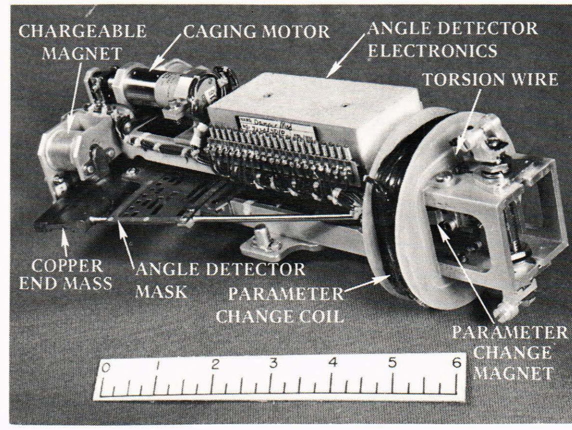

Fig. 4—Nutation damper.

3. Can have its damping constant and spring constant changed in orbit by command.

The reason for the last feature is as follows. The damper must function after injection into orbit when the satellite spin rate is 5 rpm. It must continue to function effectively as the spin rate is reduced to 1/12 rpm, the nominal operating condition. It must also be effective in case of a momentum wheel failure, necessitating spinning the satellite at 1/4 rpm to get some gyro-stability. Satisfactory operation over these widely different conditions cannot be achieved by a nutation damper with fixed damping and spring constant. Hence the provision for variability of these two parameters.

The effectiveness of this type of damper has been analyzed theoretically. The results are expressed in Fig. 5 where the time constant of the

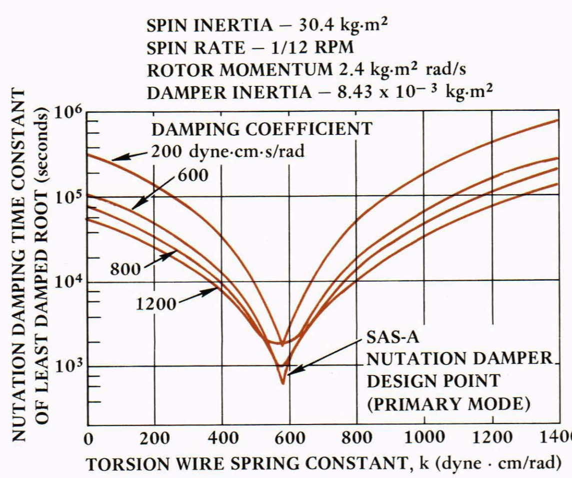

Fig. 5—Theoretical results of nutation damper performance with various design parameters.

least damped mode of nutation is plotted versus the spring constant for various values of damping constant. The best damping is associated with the smallest time constant. These curves show a definite "tuning" characteristic; the taut-band must be chosen to give the spring constant near the peak damping. And, for that spring constant, a damping constant of approximately 600 dyne-cm/(rad/sec) is optimum. This theory predicts time constants of about 12 minutes.

We were not very successful in matching the tuning of the SAS-A damper to the satellite. The specific spring constant for optimum tuning depends on the satellite moment of inertia. The taut-band was purchased and adjusted for our best estimate of satellite moment of inertia at that time, but the final value was significantly different from the estimate. For this reason the adjusted theoretical time constant for SAS-A is 40 minutes instead of the predicted 12 minutes. Nevertheless this is quite adequate to meet the SAS-A requirements.

Figure 6 shows computer predictions of the nutation damping. The damper angle swings nearly ± 2 degrees initially but damps to near zero in 100 minutes. The satellite nutation angle is started arbitrarily at 0.08 degree and damps to less than 0.01 degree in 100 minutes. The simulation is believed to be a valid model of SAS-A as we know it.

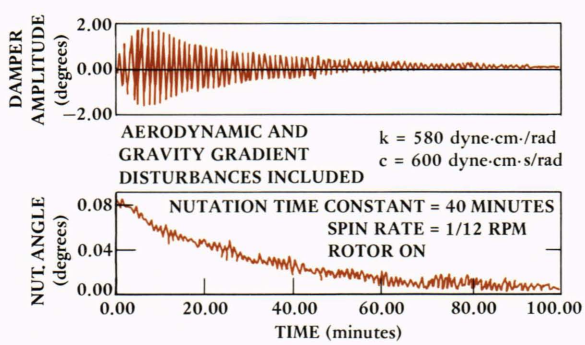

Fig. 6—Computer predictions of nutation damping of SAS-A.

For good damping when the satellite is rotating in the range of 1 to 5 rpm (during the immediate post launch phase), we need much stronger damping than the optimum value for the normal operating mode. To get more damping we increase the magnetic flux in the damper magnets. Figure 7 shows how this is done. The copper vane swings between two pole faces with magnetic flux lines going from one pole to the other. The magnetization of the pole pieces is achieved by two permanent magnets, one of which can be changed by discharging a large electric current into a winding around the magnet. This is called a "chargeable" magnet. When polarized so as to add to the field of the other permanent magnet, we get large flux in the gap and strong damping. When the chargeable magnet is oppositely polarized, the flux in the gap is very weak, and the damping is at the optimum value for the normal operating mode. Thus by pulsing the chargeable magnet we can adjust the damping constant in orbit.

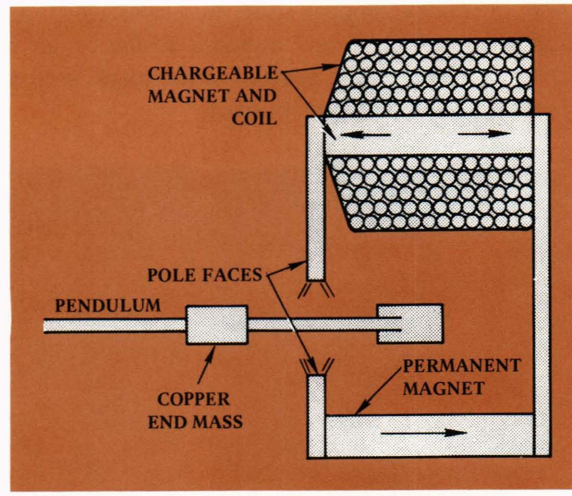

Fig. 7—The chargeable magnet system of the nutation damper.

For good damping in the wheel-off mode (used in case of wheel failure) we need a much weaker spring constant. The problem is how to do this without great mechanical complexity. If the spring is too stiff how could it be made weaker? Cut it mechanically? That is rather irreversible. The technique we have used here is to mount a small permanent magnet on the pendulum assembly (the reader may get the impression that we do everything with magnets), and energize a large solenoid (see Fig. 4) to produce a field of 30 gauss on the magnet but opposite to the magnet polarization. Therefore the magnet is in an unstable orientation and effectively produces a negative spring constant. The magnet and field are adjusted to just the right value to almost overcome the taut-band, but not quite. The result is a spring constant reduction by a factor of 20.

The addition of the angle detector may seem to be an unnecessary luxury. If the damper works, what does it matter what the angles are? And if it doesn't work, knowing the angles will be small consolation. As a general rule there are always some surprises in satellite operation in orbit. A great deal of importance for future missions is attached to explaining what is happening with a current satellite. The results from the angle detector have been used extensively in post-launch analysis to attempt to explain the damping performance. We are very grateful now that it was included in the design. Further details of the nutation damper have been given.[2]

Magnetic Torquing System

This system consists of three main parts: (a) the Z coil system used for maneuvering the spin axis in space, (b) the spin-despin system used to control the satellite spin rate, and (c) the trim magnet system used to provide bias torques to compensate for drift and to cancel unwanted magnetic dipoles.

Z-Coil System—The simplest concept of a Z coil system would consist of a DC power source, an on/off switch, a reversing switch, and the Z coil itself. Such a system would have the following disadvantages:

1. It could only be operated when the satellite is in view of the command station at Quito, Ecuador.

2. The current in the Z coil (and therefore the magnetic dipole) would be somewhat unpredictable because of variations in supply voltage and coil resistance. Supply voltage varies some ±20%, and coil resistance varies ±20% due to temperature effects on the coil. The net uncertainty would be ±40%. Maneuver prediction with this system would be very crude.

To overcome the first disadvantage, we designed a "programmer" that can be loaded with a 24-bit program by ground command. This program is then stepped through at the rate of 2.5 minutes per bit. The state of the last bit in the program determines whether the Z coil is on or off. Thus the Z coil can be programmed to turn on and off automatically at any time in a 60 minute interval with 2.5 minute resolution. The predictability of the on/off timing is accurate to a fraction of a second since the timing of the program is derived from the satellite crystal oscillator with stability better than one part in 10^6.

To deal with the second problem we use a "constant current source" to supply the current to the Z coil. The current in the coil is sensed by the voltage drop in a 0.1 ohm stable resistor in series with the coil. This is fed back to an operational amplifier and compared with a stable reference voltage. The output of the operational amplifier drives three cascaded transistors which control the Z coil current. The result is current stability of ±1%, and therefore good predictability of maneuvering.

The system is sketched in Fig. 8. It draws about 15 watts to produce a dipole of 5×10^4 pole-cm. The maximum maneuver rate is about 2 degrees/minute.

Figure 9 shows a computer result of predicted

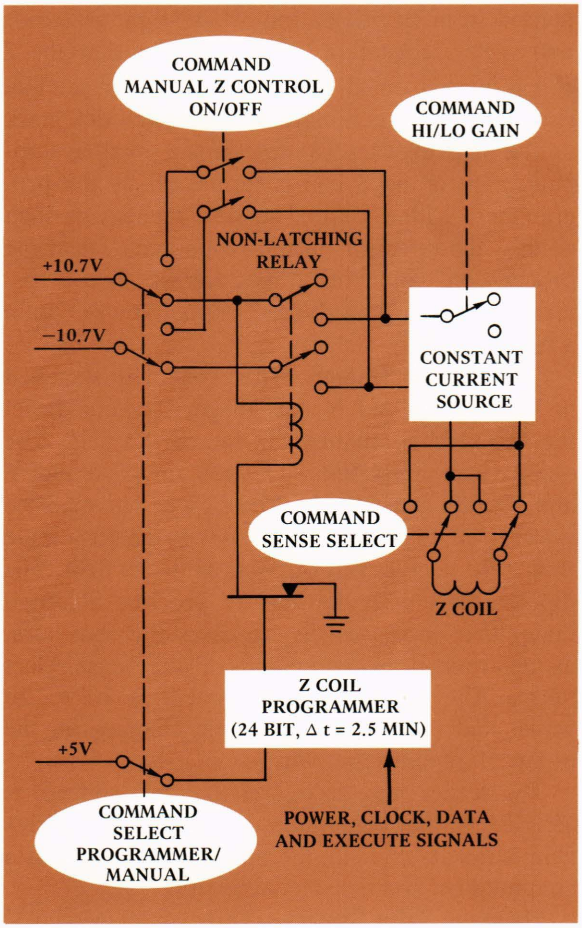

Fig. 8—Spin axis orientation system.

[2] B. E. Tossman, "Variable Parameter Nutation Damper for SAS-A," AIAA Paper No. 70-972, Aug. 1970.

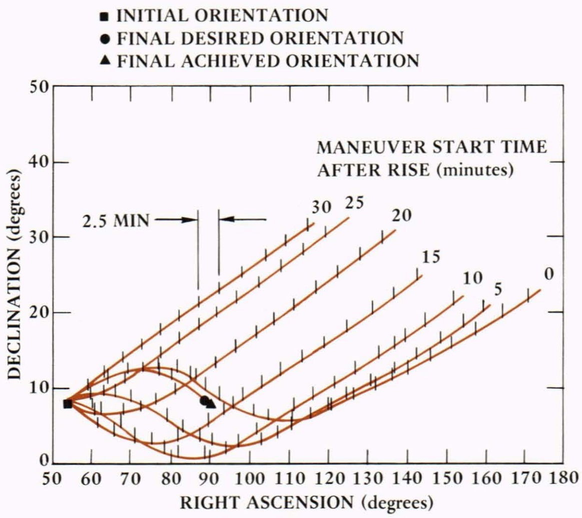

Fig. 9—Typical spin axis orientation maneuvers.

spin axis maneuvers using the Z coil. The angles, right ascension and declination, define a spin axis direction in space. All these maneuvers are started from an orientation of 54° right ascension and +8° declination. They differ in that the Z coil is turned on at different times after satellite rise at the Quito command station. Each tick mark on the maneuver tracks represents a possible stopping point if the Z coil is turned off by the programmer. With a map of possible maneuvers such as this, the operator on the ground can select the proper "on" and "off" times for the Z coil system to reach a final desired orientation to within a few degrees.

Spin-Despin System—This system is sketched in Fig. 10. X and Y axis magnetometers detect the X and Y components of the earth's field. The outputs are amplified and used to drive the Y and X coils respectively. The sign of one of these is reversed. The result is a net magnetic dipole that is 90 degrees out of phase with the field. The dipole reacts with the field to produce a torque that either increases or decreases the spin rate, as determined by command of the sense-select relays. The power for this system is 10 to 20 watts, and it produces spin rate changes on the order of several rpm/day.

The reader may recognize that this concept is identical to that of the DC motor where the earth's field is the stator field, the magnetometer acts as a commutator, and the satellite is the rotor.

Magnetic Trim System—Three small Alnico V magnets are aligned with the satellite X, Y, and Z axes respectively. Upon command a capacitor bank is charged, then discharged into a copper wire winding around one of the three magnets. This pulse of current magnetizes the magnet. Sending a number of such pulses will magnetize the magnet to full strength. Reversing the sense of the current pulse and sending another series of pulses magnetizes the magnet to full strength but opposite polarity.

The strength of the magnet is measured by small Hall effect detectors glued to the ends of the magnets. The outputs of these detectors are telemetered to the ground station to confirm the magnet strength. The Z magnet can be commanded to any value between ±1000 pole-cm, and the X and Y magnets can be commanded in the range ±200 pole-cm.

The entire trim magnet system consisting of magnets, Hall detectors, and associated electronics and relays weighs about 1.5 pounds and draws no steady power.

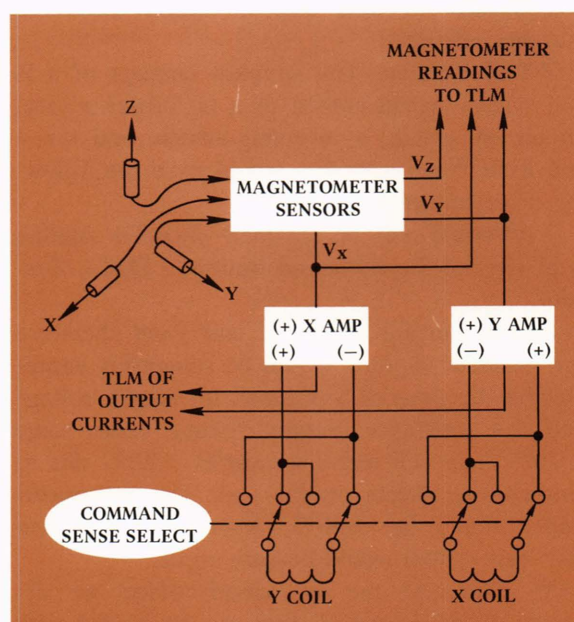

Fig. 10—Spin rate control system.

Attitude Determination System

The very precise attitude determination of SAS-A, to one minute of arc accuracy, is done by the experimenter, AS&E, using data from the two star sensors provided by AS&E. Each sensor uses a 3-inch-diameter lens to focus star images on an N-shaped slit pattern. When the star image crosses a slit the light passes through to a photomultiplier tube where it is amplified and the signal is telemetered (or stored on the tape recorder). As a star crosses the N-shaped slit from side to side it produces three pulses. The time between the first and last pulse depends on the spin rate; the position of the middle pulse depends on the elevation of the star.

The telemetry data are analyzed to find the pulse triplets produced by stars, then the stars must be identified by a computer search of the star catalog. This search is expedited by knowing the approximate spin axis orientation in space.

This approximate attitude determination is provided by APL. A three-axis vector magnetometer is used to sense the orientation of the magnetic field relative to the satellite. A sun sensor measures the angle between the spin axis and the sun. Since we know the magnetic field orientation and the sun relative to the star background, we can analyze the satellite data to find the satellite orientation relative to the stars. The accuracy of this system depends on the magnetometer accuracy, alignment of the magnetometers, telemetry accuracy, and the accuracy of our knowledge of the magnetic field and sun-line orientation in space. The net accuracy is believed to range from 1 to 3 degrees. This is quite adequate for maneuver planning and initializing the star sensor analysis.

This technique of attitude determination with magnetometer and sun sensor data has been a fixture of APL satellite technology since 1962. It was used in the ANNA and GEOS series, the TRANSIT satellites, DME-A, DODGE, and others. For SAS-A we have continued to use this scheme but with more modern and sophisticated equipment. The magnetometer was developed for SAS-A by the Schonstedt Instrument Co. It was designed for minimum weight and power consumption consistent with high reliability and high accuracy. The sensors can tolerate a temperature range from —150° to +150°F, and the electronics from —10° to +120°F. Over this environment its accuracy is ±1 percent of full scale (±3.5 millioersteds*). It weighs about 1.5 pounds and consumes only 0.6 watt.

SAS-A uses a type of sun sensor new to APL. The detector head is shown in Fig. 11. It was developed by Adcole Inc., and has been used on many other satellite programs. It is called a digital sun sensor because the sun angle is determined by two arrays of eight small silicon solar cells mounted behind perforated masks; at different sun angles different cells are either illuminated or dark, and an eight-bit "word" is produced which tells the sun angle to an accuracy of ±0.75 degree. We designed special low-power lightweight electronics to collect the data from the sensor and hold them for eventual sampling by the telemetry system.

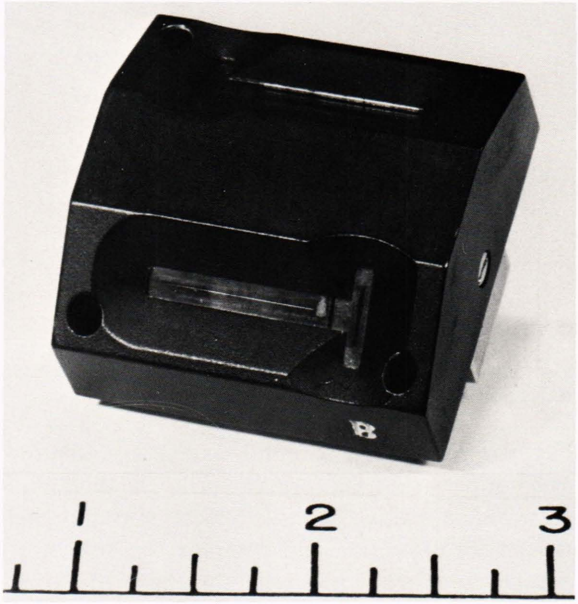

Fig. 11—Digital solar attitude detector.

A block diagram of the digital sun sensor system is shown in Fig. 12. One set of eight angle bits detects the sun when it crosses the field-of-view of the "command" detector in the upper hemisphere (i.e., sun angles in the range 0 to 90 degrees). A second identical set detects sun crossings in the lower hemisphere (90 to 180 degrees). The command detector has a narrow field of view only 2 degrees wide. As the satellite rotates, the sun eventually crosses the command detector. At that instant the angle detectors are read and the eight-bit angle word is stored for telemetry.

Previous APL sun sensing has relied on analog sun sensors consisting of small solar cells whose output varies as the cosine of the sun angle. This type of detector is affected by glare from the earth,

* The earth's magnetic field in the SAS-A orbit is about 300 millioersteds.

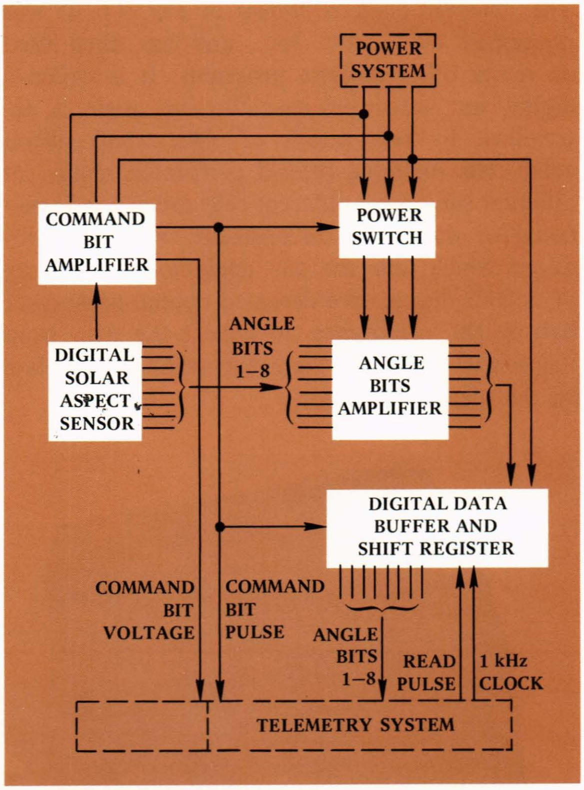

Fig. 12—Block diagram of the digital solar attitude detection system.

changes in solar cell output due to space radiation, and temperature effects on the cell. The digital detector is insensitive to these effects, and, although it is more expensive and complex, we believe its greater consistency and reliability justified its use.

Performance in Orbit

SAS-A was launched on December 12, 1970, from the San Marco launch range off the east coast of Kenya. During the first pass over the command station at Quito, Ecuador, the wheel and the nutation damper were uncaged (i.e., the mechanical restraints were removed). The wheel started to rotate immediately and reached synchronous speed in 5 minutes. It has continued to function flawlessly since that time.

The nutation damper oscillated back and forth as expected and damped satellite nutations effectively.

The spin-despin system was used intermittently over the next few days to remove the initial spin rate of 5 rpm. Using the spin-despin system caused some overheating of the satellite interior because of power dissipation in the amplifier transistors. The power dissipation was anticipated but the internal temperatures were higher than expected.

As the satellite spin rate neared 1 rpm, the nutation damper magnets were commanded to the low damping level for optimum damping at low spin rates.

Some spin axis maneuvers were accomplished to orient the satellite relative to the sun to minimize internal temperatures.

After about 5 to 6 days the desired spin rate of 1/12 rpm was reached, and the spin axis was maneuvered to the desired orientation to begin data collection.

Since that time spin axis maneuvers have been accomplished on the average of several times per day. The spin-despin system is used infrequently to adjust the spin rate near 1/12 rpm. Recently the experimenter has asked for spin rates on the order of 1/100 rpm for specific tests on a number of occasions. This has been accomplished very easily with the spin rate control system.

The momentum wheel continues to function properly. Analysis of wheel speed variations in orbit shows a root mean square variation of only 0.0025%. This is about 10 times better than our test results prior to launch, probably due to the weightless condition of wheel operation in orbit.

In late December 1970, AS&E reported higher nutation angles (±0.5 degree) than expected. This was a result of their analysis of star sensor data. We then commanded the damper magnets to a slightly higher flux level. AS&E reported nutation angles reduced to ±0.15 degree. More recent analysis of their data indicates that the nutations may be appreciably lower than this. However, we are observing nutation damping time constants on the order of two hours as compared to our expectations of 40 minutes. Nevertheless, the system is meeting its requirements in an acceptable fashion.

The sun sensor and magnetometer system for attitude determination is functioning very well. Occasional double checks of these results using star data show accuracies on the order of 1 degree.

Some slight drifting of the spin axis has occasionally been observed, but it has not been a problem and no attempt to compensate for it by using the magnetic trim system has been made. The spin axis stability is substantially better than our design objective of 5 degrees/day.