A magnetic torqueing system has been developed at APL for controlling satellite spin rate and spin (Z) axis orientation. The spin rate control system consists of two vector magnetometers whose outputs are amplified and properly phased to provide a constant-amplitude magnetic dipole moment perpendicular to the projection of the earth's magnetic field in the satellite X–Y plane. This torque can be used to increase or decrease the satellite spin rate. Spin axis orientation is obtained by commanding on a magnetic dipole moment in the Z–direction. When activated, this magnetic moment causes the satellite to precess to a desired orientation, at which time the dipole moment is restored to zero.

SPIN CONTROL for Earth Satellites

R. E. Fischell

One of the simplest and most reliable attitude control systems for earth satellites consists of fixing the position of one satellite axis by means of gyroscopic torques resulting from spin about that axis. Among the satellites that have been stabilized in this manner are Vanguard,[1] several Explorers,[2] all Tiros satellites,[3] Alouette,[4] and Syncom.[5] The earliest experiments merely allowed the satellites to spin because it was more convenient than despinning them; nor was any attempt made to orient the spin axis after separation from the launch vehicle. However, as space technology developed, two significant improvements became essential for spin-controlled satellites: (1) control of spin rate; and (2) control of spin axis orientation.

Control of Spin Rate

A satellite spinning in the earth's magnetic field will lose its angular kinetic energy from induced eddy currents in electrical conducting materials and from eddy currents and hysteresis loss in magnetic materials. For example, the Vanguard satellite (1958 β2) decreased in spin rate from 2.7 rps to 0.55 rps in a period of one year.[6] For this satellite the principal loss of spin rate was caused by eddy currents in its aluminum shell. Mostly by magnetic hysteresis

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[1] R. H. Wilson, Jr., "Rotational Decay of Satellite 1960 η2 Due to the Magnetic Field of the Earth," *Proc. XII Intern, Astronaut. Congr.*, Academic Press, New York, 1963, 368-379.

[2] G. Colombo, "The Motion of Satellite 1958-ε Around Its Center of Mass," Smithsonian Astrophysical Observatory, Special Report No. 70, July 18, 1961.

[3] W. R. Bandeen and W. P. Manger, "Angular Motion of the Spin Axis of the Tiros I Meteorological Satellite Due to Magnetic and Gravitational Torques," *J. Geophys. Res.*, **65**, Sept. 1960, 2992-2995.

[4] J. E. Jackson, "Swept Frequency Topside Sounder S–27," NASA Payload Description N–90005, Mar. 1, 1961.

[5] D. D. Williams, "Dynamical Analysis and Design of the Synchronous Communications Satellite," Hughes Aircraft Co., Tech. Memo 649, May 1960.

[6] R. H. Wilson, Jr., "Magnetic Damping of Rotation of the Vanguard I Satellite," *Science,* **131**, Feb. 5, 1960, 355-357.

loss, the satellite 1960-η1 despun from 0.785 rps to less than 0.002 rps in a period of 24 days.[7]

For spin attitude control to be useful, some means is usually necessary to prevent the decay of spin rate. Probably the first system used for this purpose was the three pairs of spin-up rockets mounted on the outside cylindrical surface of the Tiros I satellite.

A different system for controlling the spin rate of an earth satellite has been designed at the Applied Physics Laboratory for inclusion on two different satellites for the National Aeronautics and Space Administration, Goddard Space Flight Center. These are the Atmosphere Explorer satellite, designated AE-B, and the Direct Measurements Explorer satellite, DME-A. Each uses a magnetic spin-rate control system as indicated in the block diagram in Fig. 1. In this system, vector magnetometers are used to sense the magnetic field along the X- and Y-axes of the satellite. The Z-axis will always be taken as the spin axis of the satellite. The output of the X-magnetometer is amplified and fed into a winding of an electromagnet along the satellite's Y-axis. In a similar manner the Y-magnetometer output is amplified, but in this case inverted in sign, and fed into a winding of an electromagnet in the X-direction. If H_{xy} is the projection of the earth's magnetic field in the satellite's X-Y plane, this system of magnetometers and electromagnets will create a magnetic dipole, M_s, in the satellite that is always perpendicular to H_{xy}. The torque then acting on the satellite about its Z-axis is given by

$$\tau_z = M_s H_{xy} \text{ (dyne-cm)}, \quad (1)$$

where M_s is satellite dipole moment (pole cm), and H_{xy} is projection in the earth's magnetic field in the satellite's X-Y plane (oersted). Depending on which way the satellite is rotating, it will cause the satellite either to increase or to decrease its spin rate. If despin results when spin-up is desired, reversing the polarity of the output of both the X and Y amplifiers will accomplish this objective. For either spin-up or despin, the time rate of change of spin rate will be given by

$$\frac{d\omega_z}{dt} = \tau_z/I_z = M_s\ H_{xy}/I_z \text{ (rad/sec}^2\text{)} \ , \quad (2)$$

where I_z is the spin moment of inertia (gm-cm^2), and ω_z is satellite spin rate (rad/sec).

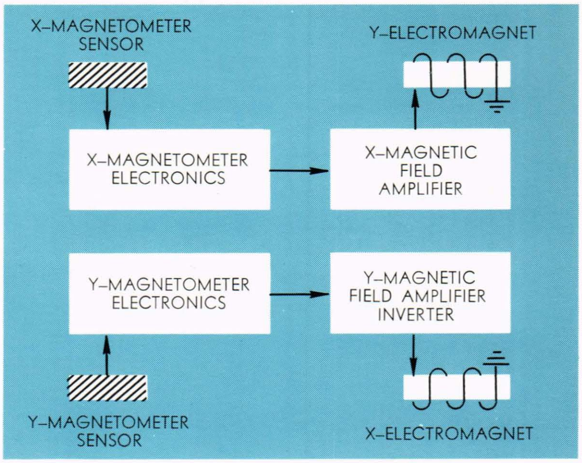

Fig. 1—Block diagram of the spin-control system.

When the spin system is in operation there is also a torque acting on the satellite that tends to make it precess. This torque is given by

$$\vec{\tau} = \vec{M}_s \times \vec{H} \text{ (dyne-cm)} \ , \quad (3)$$

where $\vec{H}$ is the total magnetic field vector (oersted). If the satellite is spinning rapidly, and if the product $\vec{M}_s \times \vec{H}$ is reasonably small, the induced precession can be kept negligibly small.

If it is desired to keep a constant spin rate, the satellite electronics can include a device to measure the spin rate (by counting zero crossings of one magnetometer) and to compare this rate to that generated from some accurate timing device such as a tuning fork. The power to the spin-up electronics can be turned on if the rate is too low and kept off when the spin rate exceeds some specified value.

It is desirable to provide the satellite with a centrifugal switch for high spin-rate cutoff. This avoids the possibility of the satellite destroying itself from centrifugal force if it is inadvertently left in the spin-up mode. The DME-A spacecraft currently being designed at APL for the NASA incorporates a centrifugal switch that turns off spin-control power if the satellite ω_z exceeds 25 rpm.

Both the AE-B and DME-A satellites require that the satellite spin axis be orthogonal to the orbital plane. Since both these spacecraft are to be placed in near-polar orbits the earth's magnetic field always has a large component in the satellite's X-Y plane. Both these satellites

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[7] R. E. Fischell, "Magnetic Damping of the Angular Motions of Earth Satellites," *ARS J.*, **31**, Sept. 1961, 1210-1217.

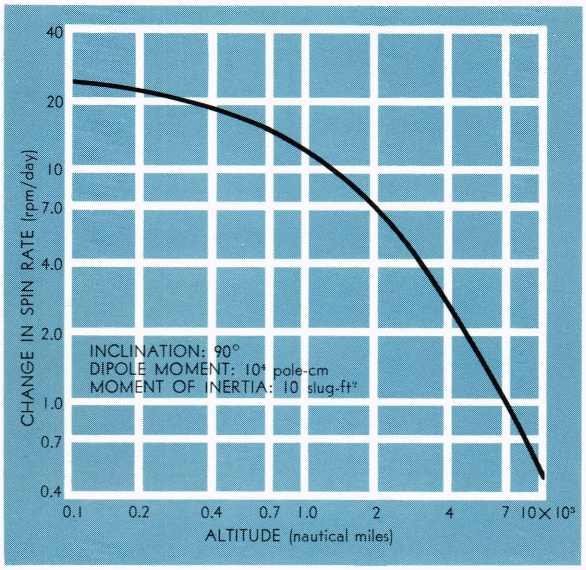

Fig. 2—Daily change of the spin rate as a function of altitude for polar-orbiting satellites.

have been designed to provide a spin dipole moment, $M_s = 10^4$ pole-cm. At an average altitude of 1000 n. miles, the DME-A spacecraft provides the capability of approximately 15 rpm/day change in spin rate.

The DME-A spin control system weighs 3.8 lb. This includes those parts of the command system that are used to operate the spin-rate control system. A three-axis magnetometer that is also used for attitude detection is included in the total of 3.8 lb.

The DME-A spin-control system dissipates 2.0 watts while in operation. To maintain the satellite at the desired spin rate, the spin energy must be increased by the same amount that is removed by eddy current losses in the satellite's structure and by hysteresis losses in the electromagnets and other magnetic materials in the satellite. Since this is very little energy, it will be possible to operate the satellite spin-up system on a duty cycle of less than 0.1%. The average energy dissipation of less than 0.002 watt is completely negligible for this mission.

Since the intensity of the earth's magnetic field decreases inversely as the cube of the distance from the center of the dipole, the intensity at very high altitudes is drastically reduced. Therefore, the capability for spin-up also decreases sharply at higher altitudes. Figure 2 shows the capability for obtaining a change in spin rate as a function of orbital altitude. This curve is for polar-orbiting satellites with $M_s = 10^4$ pole-cm, $I_z = 10$ slug-ft^2, and with the spin axis oriented perpendicular to the orbital plane.

Compared to using rockets or cold-gas jets for maintaining the spin rate of the satellite, the magnetic system described above has the advantage because there is no dissipation of materials and, as a result, there is essentially an unlimited operational capability. Also, the absence of moving parts provides improved reliability, especially for extended lifetimes in orbit. Actually, either the X- or the Y-magnetometer, with its associated amplifier and electromagnet, will provide the desired spin-rate control, but at half the capability of change in spin rate per day. In this respect the magnetic system provides additional reliability by redundancy. The magnetic system also has the advantage of being able to spin-up or despin the satellite at any time to any desired rotation rate with almost infinitesimal resolution.

Control of Spin-Axis Orientation

Many earth satellites such as Tiros, Syncom, AE-B, and DME-A require that the spin axis be oriented in some prescribed direction. Tiros was oriented to produce the best meteorological observations; Syncom was oriented perpendicular to its orbital plane to obtain good radio signal strength at the earth's surface. Both AE-B and DME-A are to be oriented with their spin axes perpendicular to their orbital planes so that particle detectors will first be oriented along the satellite's trajectory and then rotated around in its wake. This provides an ideal condition for studying particles that are moving slowly relative to the satellite.

To provide spin-axis orientation, the Tiros II and later satellites used a dipole moment generated by electric current flowing in a large coil in the X-Y plane of the satellite.[8] This produced a dipole moment, M_z, which resulted in a comparatively slow precession of the spin axis of the satellite. Generally, the dipole moment remained on for several orbits, as required to achieve the desired orientation of the television cameras.

The Syncom satellite used pairs of cold-gas jets to cause the satellite to have its spin axis oriented perpendicular to the orbital plane.[5]

The AE-B and DME-A satellites being developed at APL use a system of chargeable

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[8] E. A. Goldberg, "TIROS Preflight Testing and Postlaunch Evaluation," *J. Spacecraft and Rockets,* **1**, July-Aug. 1964, 374-380.

magnets along the Z-axis of the satellite to produce a magnetic dipole moment that results in precession of the satellite's spin axis so that it can be oriented perpendicular to the orbital plane. Figure 3 illustrates a type of chargeable magnet system that was used for orienting satellites 1963-38B and 1963-49B magnetically and will be used for orienting the spin axis of the AE-B spacecraft. A source of voltage causes a condenser to be charged and then, by radio command, discharged through an electrical winding wrapped around a permanent magnet material. When the polarity switch is in the "add" position a dipole moment equal to $+M/2$ is produced in the chargeable magnet. If the polarity switch is reversed and the condenser is charged and then discharged through the windings, a dipole moment $-M/2$ is produced. If the satellite also contains a permanent dipole moment of magnitude $+M/2$ in the Z-direction, the satellite can readily obtain two magnetic states, $M_z = +M$ and $M_z = 0$. The state $M_z = +M$ may be used to precess the satellite's spin axis; the state $M_z = 0$ is used when no further Z-axis reorientation is desired.

The rate of precession of the satellite spin axis is given by

$$\frac{d\phi}{dt} = \frac{\tau_{xy}}{I_z\,\omega_z}\ (\text{rad/sec})\ , \qquad (4)$$

where τ_{xy} is the component of magnetic torque perpendicular to the Z-axis. For the case of precession control by the interaction of the earth's magnetic field with a magnetic dipole in the satellite along the Z-axis, τ_{xy} is given by

$$\tau_{xy} = M_z\,H \sin\theta\ (\text{dyne-cm})\ , \qquad (5)$$

where M_z is the satellite magnetic dipole moment along the spin axis (Z-direction), in pole-cm, H is the magnitude of the earth's magnetic field at the satellite's position in orbit (oersted), and θ is the angle between the vectors $\vec{M}_z$ and $\vec{H}$. Then, substituting Eq. (5) in Eq. (4) gives the rate at which the satellite's spin axis can be moved by precession, namely

$$\frac{d\phi}{dt} = \frac{M_z\,H \sin\theta}{I_z\,\omega_z}\ (\text{rad/sec})\ . \qquad (6)$$

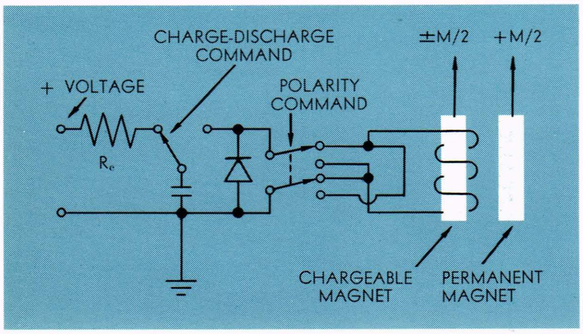

Fig. 3—Chargeable magnet system used in satellites 1963-38B and 1963-49B.

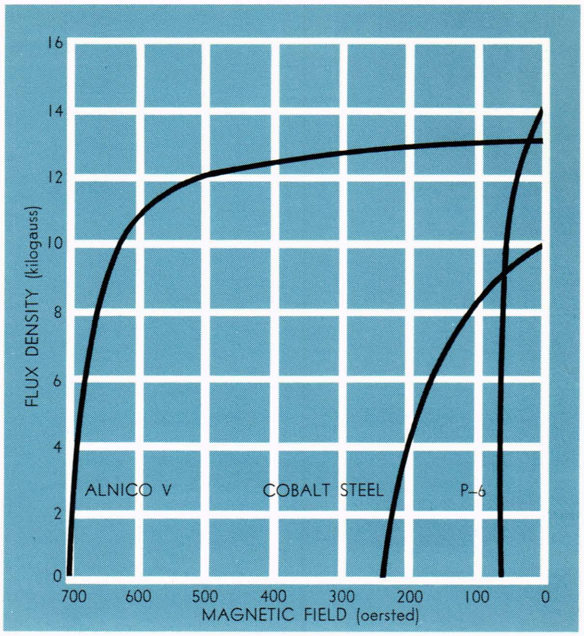

Fig. 4—Demagnetization curves for Alnico V, cobalt-steel, and P-6 alloy.

Design of Spin-Axis Orientation Magnets

The selection of materials for the chargeable magnets is based on obtaining a high value for the residual magnetization without requiring too large a value for the energy stored in the condenser. Figure 4 shows the demagnetization curve for three permanent magnetic materials that were considered for this application. Alnico V* has a high remanence and a high coercive force so that it retains a large magnetic dipole moment even for comparatively low length-to-diameter (l/d) ratios. However, the extremely high coercive force makes it difficult to magnetize with a reasonable weight of condensers. The permanent magnet material, 40% cobalt steel, requires considerably less condenser energy but

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* Registered trademark of the General Electric Company.

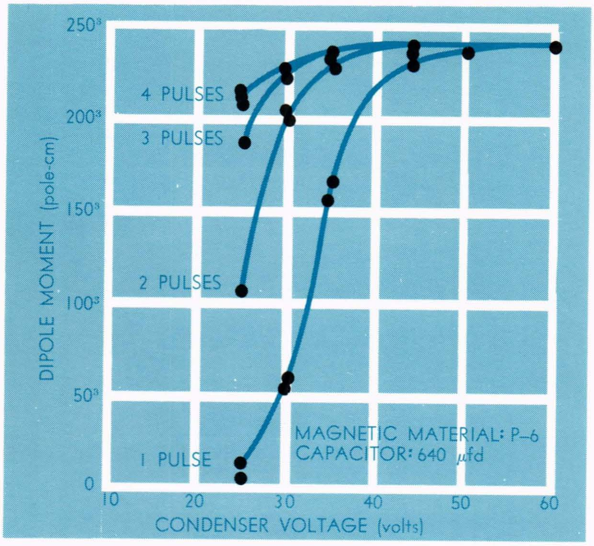

Fig. 5—Characteristics of a P-6 alloy magnet.

has a comparatively low flux density. The material that provided the best system performance was manufactured by the General Electric Company and is termed alloy P–6. This material combines a moderate coercive force with a high flux density. When used with l/d ratios greater than 40, it provides a system for obtaining a large dipole moment for comparatively little weight.

The dipole moment for these magnets can be enhanced for the same system weight by repeating the charging and discharging cycle of the condenser several times. Figure 5 shows the characteristics for a P–6 magnet that saturated at a dipole moment of approximately 2.5×10^4 pole-cm. For this magnet $l/d = 41$, and the total weight of windings plus P–6 core was 1.5 lb. As can be seen from Fig. 5, increasing the condenser voltage or increasing the number of pulse discharges resulted in a greater magnetization of the core material. However, the magnetization always leveled off at its saturation value for this material at a particular l/d ratio.

This system for obtaining a permanent magnetic dipole in a satellite was used successfully for more than 100 operations over a period of nearly one year in the satellites 1963-38B and 1963-49B. For producing a magnetic dipole moment, this system has an advantage over a coil carrying current (such as used on Tiros) because it requires no steady-state power. When large dipole moments are required or when it is not convenient to have a large coil diameter, chargeable magnets can provide a tremendous weight savings as compared to a coil carrying current. A magnetic system has the advantage over a gas jet for exerting torque because it does not expend material or have moving parts; it thereby provides a potentially longer operating life with a greater reliability.

Application of Magnetic Torque for Satellite Spin-Axis Orientation

Figure 6 shows a block diagram for a magnetic torque spin-axis control system similar to that being used for the DME–A satellite. Instead of using a chargeable and a permanent magnet, this system uses a single chargeable magnet that can be magnetized to any desired level, i.e., $-M \leq M_z \leq +M$. The values of $-M$ and $+M$ are obtained as described above. Intermediate values are obtained by charging the condenser for only a short period of time before discharging it. For example, the state $M_z = 0$ can be obtained by first charging the satellite to the state $M_z = +M$, then commanding the polarity switch to the negative state, then charging the condenser through a large resistor for a short time (typically 6 sec for the DME–A magnet), and finally discharging the condenser through the windings of the chargeable magnet. If a state greater than $M_z = 0$ is desired, the condenser can be charged for less than the time required to achieve zero magnetization; if a magnetic dipole more negative than zero is desired, the charging time is lengthened accordingly. Thus, all magnetization states between $+M$ and $-M$ are readily achievable.

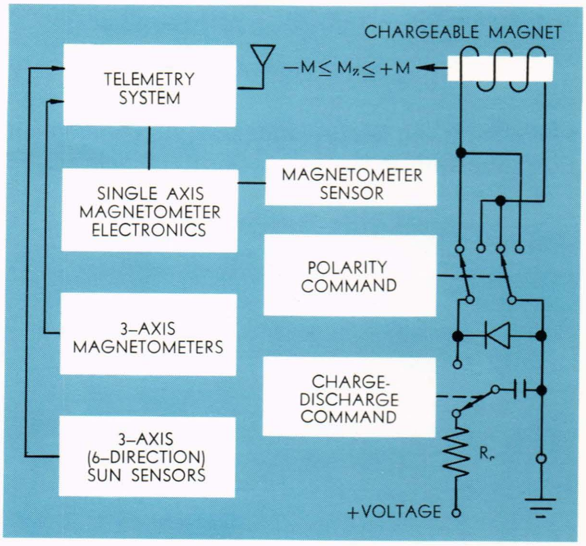

Fig. 6—Block diagram of a magnetic-torque spin-axis control system.

Figure 6 also shows a separate magnetometer mounted near the chargeable magnet as a measuring device for determining the magnet's dipole moment. It illustrates, in addition, the type of attitude detection system that will be used in the DME–A spacecraft to determine its orientation. Attitude detection is a requirement for any spin-axis orientation system since one has to know the satellite's attitude in order to cause it to precess to the desired orientation.

The DME–A system uses a six-direction sun-sensing system and a three-axis magnetometer to determine the attitude of the satellite's spin axis. For magnetic spin-axis control one must also have a reasonably good knowledge of the satellite's orbit, and one must have a moderately accurate idea of the magnitude and direction of the earth's magnetic field at the position of the satellite.

For spin-axis orientation control it is necessary to provide the satellite with a nutation damper so that motion other than that about the Z-axis will be damped out. Of course it is also necessary that the satellite spin moment of inertia, I_z, be somewhat larger than the other principal moments of inertia, I_x and I_y, so that the satellite will stabilize with its spin about the Z-axis. The DME–A satellite uses a nutation damper consisting of two circular aluminum tubes, each containing a copper ball that is free to roll inside the tube. These tubes are mounted as far away as possible from the satellite's center of mass. The center of curvature of the tubes is located 2 in. from the satellite's Z-axis. When the satellite has either $\omega_x \neq 0$ or $\omega_y \neq 0$, the ball in each tube will roll back and forth from its equilibrium (center) position. When there is nutation motion, several permanent magnets surrounding the tube cause eddy currents to be generated in the moving copper ball, thereby dissipating the nutation energy of the satellite. The magnets around each of the two tubes are so arranged that they have a zero net dipole moment in order that they will not perturb the desired spin-axis orientation.

As can be ascertained from Eq. (6), the rate at which the spin axis can be precessed is determined by the strength of the dipole moment in the satellite, the satellite's spin rate and moment of inertia, and the intensity of the earth's magnetic field at the satellite's position. For the DME–A spacecraft, $I_z = 5$ slug-ft^2, $\omega_z = 3$ rpm, $M_z = \pm 10^5$ pole-cm, and at 1000-n. miles altitude near the north magnetic pole a precession rate of approximately $\pm 5°/\text{min}$ can be achieved.

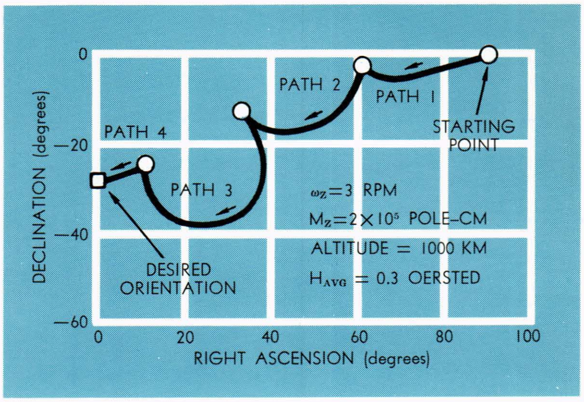

Fig. 7—Spin-axis attitude maneuver for typical spacecraft.

Messrs. F. F. Mobley and W. E. Allen of the Applied Physics Laboratory have programmed the IBM 7094 computer to determine the best path for moving the spin axis of a satellite to its desired orientation. A typical maneuver accomplished by this programming is illustrated in Fig. 7. The objective of this maneuver was to move the satellite spin axis from a right ascension of +90° and a declination of 0° to a right ascension of 0° and a declination of −25°. Imposed upon this maneuver was the stipulation that all magnet turn-on and turn-off commands would be sent when the satellite was in view of the Applied Physics Laboratory. As can be seen in Fig. 7, this required four separate attitude-control commands.

Conclusion

A magnetic spin-up and spin-down system can be provided to maintain a satellite's spin rate at any desired level, and it can be done without dissipation of materials and without the use of moving parts. Precession of the spin axis of a satellite to a desired orientation can be achieved by means of a chargeable permanent magnet. Such a system can provide a large magnetic dipole moment with essentially no dissipation of electrical power. It is quite possible to use a digital computer to determine when to turn the dipole moment on and off to cause the spin axis to precess to a desired orientation.

The author wishes to acknowledge the invaluable assistance of Messrs. F. F. Mobley and R. D. Brown for data on chargeable magnets and for providing information on the spin-axis orientation. Mr. B. E. Tossman is chiefly responsible for the design of the nutation damper described herein.