

Magnetic torques, caused by either current loops or residual permanent magnetic moments, constitute a source of attitude perturbation on earth satellites. To control these torques it is necessary to measure and compensate the satellite magnetic dipole moment. This article presents the theory and application of a resonance technique that is especially designed to measure small dipole moments. In this technique, the satellite is suspended by torsion wires in a controlled magnetic field. By changing the magnetic field in synchronism with the natural torsion suspension frequency the satellite is driven into resonance. The rate of change of amplitude is a direct measure of dipole moment.

B. E. Tossman

RESONANCE TECHNIQUE MEASURING SATELLITE MAGNETIC

Unwanted magnetic torques are a major disturbance to attitude stabilization of near earth satellites. These torques are caused by dipole moments created within the spacecraft by current loops, residual magnetism, or permeable materials. To minimize residual dipole moments it is necessary to accurately determine small magnetic moments of large spacecraft. Techniques which have been used to date to determine magnetic characteristics include field and static torque measurement. The field measurement technique computes the magnetic dipole moment from the spacecraft magnetic field. The static torque technique computes dipole moment from the static torque reaction to an applied magnetic field. Field measurement techniques are disturbed by the presence of higher order poles while static torque tests are very sensitive to vibration and atmospheric disturbances.

This article describes the application of a technique,¹ presented in 1965 which is designed to measure small dipole moments of large spacecraft. This method is almost an order of magnitude more sensitive than either field or static torque techniques. The spacecraft is suspended by torsion wires and an applied magnetic field is reversed synchronously with the free torsion resonance. Dipole moments within the satellite cause it to be pulsed into resonance, while higher order moments effect no response. The magnitude of the dipole moment is directly proportional to the rate of change of deflection amplitude.

This resonance technique has been used successfully to measure and compensate dipole moments

¹B. E. Tossman, "A Resonance Technique for Measurement of Satellite Magnetic Dipole Moment," Proceedings of Magnetics Workshop, Jet Propulsion Laboratory Technical Memo No. 33-216, April 1965.

for DIPOLE MOMENT

on 12 satellites. Testing methods have been improved to the extent that dipole moments as small as 50 pole-cm have been detected on satellites weighing up to 500 pounds. This article discusses the application of resonance testing to several of the larger spacecraft and compares the results to their in-flight attitude performance.

Theory

It is assumed that the spacecraft contains a permanent magnetic dipole moment which may be resolved into three orthogonal components, M_x , M_y , M_z , aligned with the spacecraft axes. The spacecraft is suspended by torsion wires according to Fig. 1 such that it is constrained to rotate about a vertical axis. The suspension torsional stiffness K is adjusted to provide a natural period of oscillation τ of about

30 seconds. The motion of the satellite in this suspension is undamped and aerodynamic effects are minimized by appropriate shrouding.

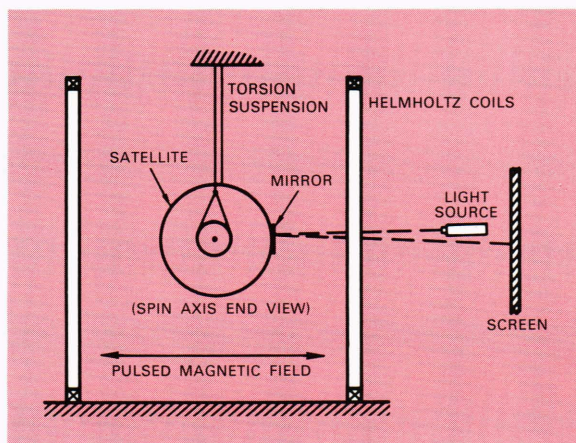


Fig. 1—Measurement of small magnetic dipole by resonant pulsing.

To drive the spacecraft into resonance, a magnetic field (Fig. 2) is applied in the horizontal plane and reversed periodically at a frequency matching that of the free torsional resonance of the spacecraft.

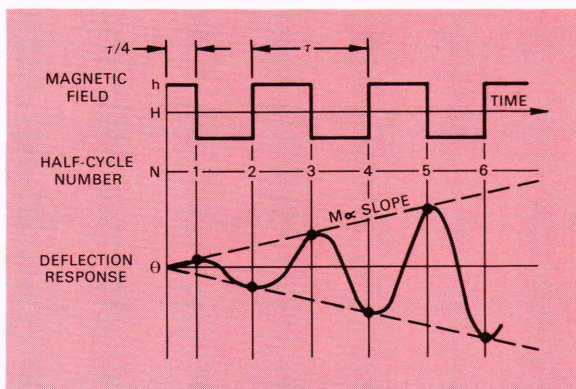


Fig. 2—Magnetic field and deflection response.

The field $H(t)$ is a square wave with amplitude h and frequency $\omega_n = 2\pi/\tau$ which has the Fourier series representation

$$H(t) = \frac{4h}{\pi} (\cos\omega_n t - 1/3 \cos 3\omega_n t + 1/5 \cos 5\omega_n t - \dots)$$

Let the magnetic field be directed along the X axis and the torsion wire along the Z axis. The equation for rotation, θ , about the torsion wire can be written as

$$I\ddot{\theta} + C\dot{\theta} + K\theta = -H(t) (M_x \sin\theta + M_y \cos\theta), \quad (1)$$

where I is the moment of inertia, C is a damping constant, K is the torsional spring constant, and M_x and M_y are the dipole moments along the X and Y axes, respectively. If one assumes that the rotations are of small amplitude so that $\sin \theta \approx \theta$ and $\cos \theta \approx 1$, and that the magnetic restoring torque due to M_x is negligible compared to the spring constant, i.e., $M_x H(t) \ll K$, and furthermore neglects damping, then the deflection response is given by

$$\theta(t) = \frac{4hM_y}{\pi I \omega_n^2} \left[\frac{\omega_n t}{2} \sin \omega_n t + \frac{1}{24} (\cos 3 \omega_n t - \cos \omega_n t) - \frac{1}{120} (\cos 5 \omega_n t - \cos \omega_n t) + \dots \right] + \theta_0 \cos \omega_n t + \frac{\theta_1}{\omega_n} \sin \omega_n t \quad (2)$$

where θ_0 and θ_1 are respectively the initial conditions for angular displacement and angular velocity.

Spacecraft rotation $\theta(t)$ is tracked by means of an optical lever and screen or automatic autocollimator. The position is recorded at the instant of field reversal i.e., for $\omega_n t = (N - \frac{1}{2})\pi$, where N is a positive integer. These positions, defined as $\theta(N)$ although not deflection peaks, define a linear amplitude growth

$$|\theta(N)| = \frac{2hM_y}{\omega_n^2 I} (N - \frac{1}{2} + \rho) \quad (3)$$

$$\text{where } \rho = \theta_1 \omega_n I / 2hM_y$$

Dipole moment magnitude is determined from Eq. (3) by

$$M_y = \frac{I \omega_n^2}{2h} \frac{d|\theta(N)|}{dN} \quad (4)$$

and its polarity determined by the rotation sense during each half cycle.

Experimental Techniques

This section presents some of the experimental procedures that have enabled pulsed resonance testing to be successfully applied to 500-pound spacecraft. The following paragraphs relate the experimental conditions pertaining to spacecraft suspension, shrouding, synchronization of the field frequency, angular determination, and establishing near zero initial conditions for rotational position and rate.

SPACECRAFT SUSPENSION—Larger spacecraft are supported by a pair of long cables and strongback, forming a bifilar suspension as shown in Fig. 3. The complete suspension is nonmagnetic; the cable

GRAVITY STABILIZED
WEIGHT = 365 POUNDS
INERTIA = 20 SLUG-FT²
RESIDUAL PERMANENT DIPOLE
MOMENT TRIMMED TO 50 POLE-CM

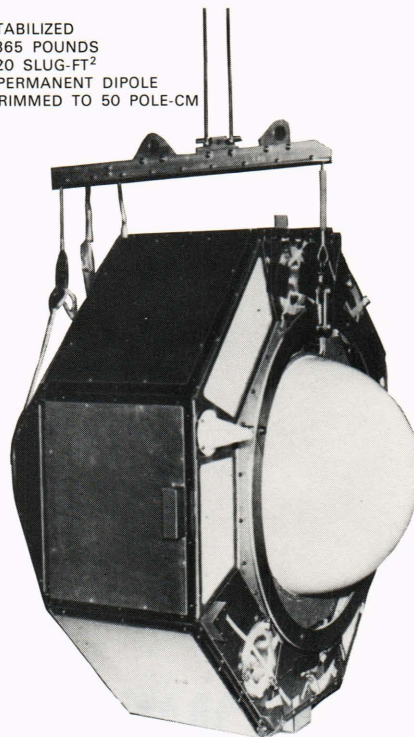


Fig. 3—GEOS-A dipole moment test setup.

length and separation are adjusted to provide a nominal 30-second period of oscillation. The spacecraft is suspended horizontally. In this way two components of dipole moment in the horizontal plane are measured; the spacecraft is rotated 90° about its symmetry axis, and the third orthogonal component of dipole moment can be determined.

For payloads with moments of inertia of 3 slug-ft² or greater it is necessary to use the bifilar suspension. For strength and ease of handling, nonmagnetic stranded cables are used. It was found that if right-lay cable, i.e., cable wound in a clockwise sense, was used for both lengths the bifilar spring constant became nonlinear due to unwinding, and the spring rate would vary depending on the sense of rotation. It was also found that by using a right and left lay cable pair this nonlinear spring characteristic was eliminated.

AERODYNAMIC TORQUES—In the large open space of a magnetics facility, drafts from windows, doors, and people moving can create significant disturbances unless painstakingly controlled. For the more sensitive tests, it is necessary to close all windows and doors, turn off all air-conditioning systems and shield the spacecraft with a dropcloth enclosure about 12 feet square and 9 to 15 feet high. Using these precautions angular disturbances can be con-

trolled to within 10 seconds of arc or about 100 dyne-cm torque. Since dipole moment determination is obtained from a sinusoidal response, it has not been found necessary to protect for radiator convection currents or seal windows and doors. The lower bound on dipole moment determination established by residual aerodynamic effects is currently of the order of 20 pole-cm.

FIELD SYNCHRONIZATION—It is essential that the frequency of the applied magnetic field precisely match the free suspension resonance to better than 1%, and this is done in the following manner. First, the natural period of oscillation of the spacecraft is determined by using a stopwatch or electronic timer and observing many periods of oscillation. The amplitude of oscillation during these timed cycles is no greater than that expected during resonance testing so that higher amplitude nonlinearities are discounted. The degree of system damping is observed during this time. In general the amplitude decay rate is less than 0.2% per cycle.

A clock is synchronized to the period of free oscillation. The clock, driven by a hysteresis synchronous motor is energized by a signal generator whose frequency is adjusted so that one clock revolution equals two natural periods of oscillation. The magnetic field is reversed by manual switching every quarter clock rotation. Thus, over long time periods field reversing will maintain synchronism with the satellite frequency.

An excellent verification of resonant pulsing is obtained if the deflection response and magnetic field can be continuously recorded. Frequency mismatch is noted by an increasing phase shift between amplitude peaks and field reversals.

DAMPER AND INITIAL CONDITION CONTROL—To obtain the best response for dipole moment determination, initial conditions of zero angle and rate are desirable. Since the suspension provides no damping some mechanism is needed to establish rest conditions at the start of each run. To this end an eddy-current damper was developed.

This device, shown in Fig. 4, consists of a thin beam, attached to the strongback with an aluminum vane at the end. The vane is positioned between two wheels. Each wheel has six permanent magnets—poles directed outward. Each wheel can be independently driven clockwise by microswitch hand control. By driving the lower wheel, an eddy-current reaction force on the vane rotates the satellite clockwise. By detecting the sense of spacecraft rotation and producing opposing eddy-current torques all motion can be stopped. When the mag-

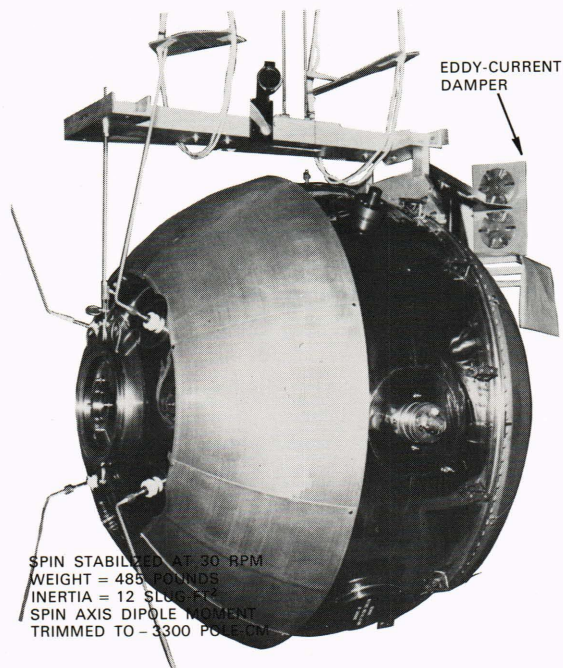


Fig. 4—Atmosphere Explorer-B test setup with damper.

net wheels are motionless eddy-current damping on the satellite is negligible.

MEASUREMENT OF SATELLITE ROTATION—The deflection response is tracked by an optical lever or automatic autocollimator. If the payload moment of inertia is less than 3 slug-ft², an 8-meter optical lever can provide sufficient resolution of angular motion. As an example, let $I = 3$ slug-ft², $h = 0.400$ oe (oersted), $\tau = 30$ seconds, and $M = 100$ pole-cm. Then, from Eq. (4), $d|\theta(N)|/dN = 9.2$ pole seconds of arc/half cycle. The deflection of an 8-meter optical lever in this case would be 1 cm in 14 half cycles. For payloads with moments of inertia greater than 3 slug-ft² it is necessary to use an automatic autocollimator. One excellent feature of the automatic autocollimator is that it allows for permanent recording of the deflection response. Figure 5 is a sample of such a response recorded simultaneously on a 2-channel strip chart with the applied magnetic field.

MAGNETICS FACILITY—Dipole moment testing has been performed at the Naval Ordnance Laboratory's magnetism testing facility, Building No. 203. This facility has a 26-foot-square, 4-coil system which is capable of nulling earth's magnetic field and applying up to about 600 moe (millioersted) in any direction. The No. 203 facility provides a calibrated magnetic field uniform to 0.05% over a 4-foot-diameter spherical volume in the North-South and

vertical directions. The East-West control field volume is somewhat smaller.

When reversing fields for dipole moment testing, the earth's field is cancelled by the primary field coil system and the variable field is generated from a second set of coils. This second coil set is driven by a regulated power supply which is set to generate, say, 400 moe. A switch is used to reverse the current to this set of field coils. Variations in coil current during the pulsing sequence are of the order of 0.2%.

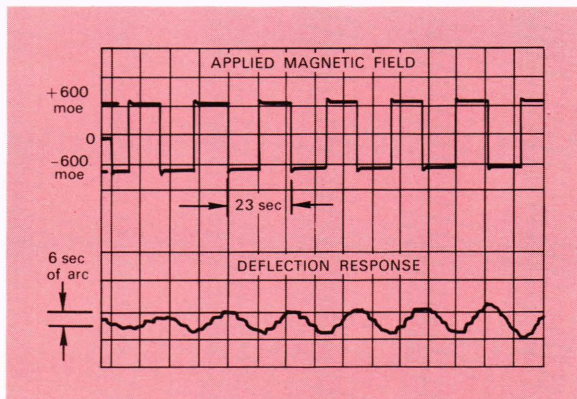


Fig. 5a—Deflection response of DODGE to 100 pole-cm magnet.

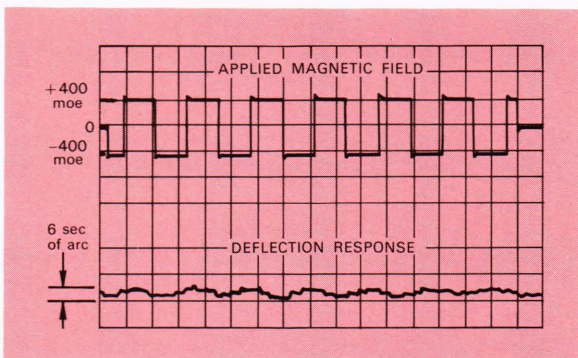


Fig. 5b—DODGE null dipole moment deflection response.

Error Analysis

This section considers sources and magnitudes of error in the determination of dipole moment. These errors result from assumptions made in the analysis of the torque equation, alignment and setup error, and random disturbance torques.

THEORETICAL ASSUMPTIONS—Consider the errors introduced by the assumptions made in deriving the response from the torque equations:

1. That θ remained small so that $\sin \theta = \theta$ and $\cos \theta = 1.00$. Peak deflections during

resonance testing are on the order of 1 minute of arc, so these errors are negligible.

2. That magnetic restoring torques were negligible compared to the bifilar spring constant. For dipole moments as great as 1000 pole-cm and $H = 0.4$ oe, $MH = 400$ dyne-cm/rad as compared to typical $K \approx 2 \times 10^6$ dyne-cm/rad. The effect on spring rate is to change the resonant period by less than 0.2%.

SYNCHRONIZATION ERRORS—It is essential that the frequency of the applied magnetic field precisely match the suspension frequency. This is accomplished by timing the spacecraft period and synchronizing a clock to this period. The clock-driving frequency is adjusted such that one clock revolution equals two resonant periods. The applied magnetic field is reversed by manual switching every quarter of the clock cycle. Over long periods field reversing maintains synchronism with the spacecraft. It is estimated that synchronization errors are within 0.5%. This error would produce less than 10° phase shift in applied field in 5 cycles. In addition, since the response slope is an averaged determination the slope error due to random timing errors is negligible.

ERRORS IN MAGNETIC FIELD STRENGTH—When reversing fields, a power supply is preset to establish the required field strength and a reversing switch on the field coil is used to change the field sense. Coil current is monitored with a digital voltmeter and standard resistor in an oil bath. Typical variations in coil current are of the order of 0.2%. When attempting to achieve a null dipole moment the error in field strength is not a factor since any resonance response indicates the presence of a dipole moment. Field strength error is a factor when using Eq. (4) to determine the magnitude of a magnetic moment.

ALIGNMENT ERRORS—Spacecraft axes are aligned parallel to the field coil axes to within 0.5% by using spirit levels and sighting on coil references. If it is desired to trim all components of spacecraft dipole moment to zero, alignment error is not a factor. The error in precise determination of larger dipole moments is proportional to the sine of the alignment error times the transverse axis dipole moment. For large components of dipole moment this error could be of the order of 0.8%.

It is noted that most errors can be fairly well controlled. If a null dipole moment state is desired, the predominate error sources are aerodynamic effects and sensitivity of the optical sensor. Presently, the smallest dipole moment which can be detected on a 500-pound spacecraft is about 50 pole-cm. In determining a large dipole moment the error might be of

the order of 0.5% which is the root mean square of the listed errors.

Spacecraft Applications and Orbital Results

Pulsed resonance dipole moment testing has been applied to 12 spacecraft. Most missions called for trimming residual moments to zero for which the technique is particularly suited; other missions required setting a component of dipole moment to some specified value. This section describes several applications of pulsed resonance testing and compares predicted results with attitude performance in orbit.

DIRECT MEASUREMENTS EXPLORER-A—The DME-A spacecraft was built by APL for NASA Goddard for sampling and measuring charged particles. It was launched in November 1965 into a near-earth orbit ranging from 500 to 3000 km altitude. The spacecraft was intended to be spin stabilized with its spin axis aligned with the orbit normal.²

The spacecraft contains two chargeable magnets that are used to precess the spin axis and maintain its alignment. (The orbit regresses at the rate of 0.8° /day.) A magnetometer sensor positioned between the magnets is used to determine their magnetic state. When the magnets are nulled it is necessary that there be no magnetic precession torques, thus a prime spacecraft requirement called for zero residual dipole moment. To establish and confirm this desired magnetic state throughout assembly, minor changes, and vibration testing, the spacecraft was taken to the Naval Ordnance Laboratory (NOL) a total of three times. Figure 6 shows the DME-A spacecraft in its bifilar torsion wire suspension at NOL. The spacecraft weighed 215 pounds, had a moment of inertia of 6 slug-ft², and a natural period of 22 seconds. The dipole moment response had a resolution of 20 pole-cm. The purpose of NOL testing was to trim the components of residual dipole moment normal to the spin axis to less than 50 pole-cm and to establish a calibration curve of spin axis dipole moment versus null sensor.

In spite of the NOL operations there remained some uncertainty as to the state of magnetic trim. The low gyrostatic stability of DME-A made it quite sensitive to drift produced by spurious dipole moments. An orbital test of the null dipole moment state occurred during the period January 6 through 11, 1966. The magnetometer and null sensor tele-

metry indicated that the spin axis dipole moment was within 10 to 20 pole-cm of zero, and spacecraft attitude tracking showed that drift was less than one degree over the 5-day period. This spin axis stability confirmed the null dipole moment state and indicated that there was no change in magnetic state of the spacecraft throughout shipping, vehicle installation, and launch phases.

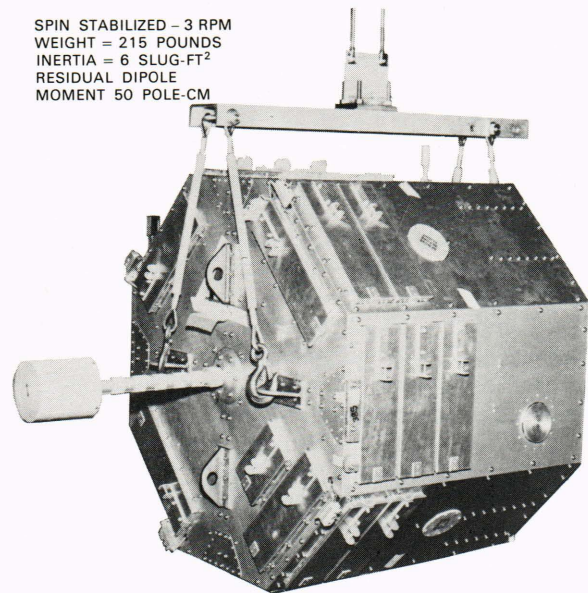


Fig. 6—DME-A pulsed resonance test setup.

GEODETIC EARTH ORBITING SATELLITE-A—GEOS-A was built by APL under NASA sponsorship for geodetic study. It was launched on November 6, 1965, into a near earth orbit ranging from 600 to 1230 n. miles at 59.4° inclination. The satellite uses a 2-axis gravity-gradient stabilization system which was designed to have an earth pointing accuracy of 5° or better in a circular orbit. Prelaunch analysis indicated that 5° stabilization could be achieved only if the spacecraft residual dipole moment along the pitch axis was less than 500 pole-cm. Somewhat greater dipole moment could be tolerated along the yaw axis (boom axis).

The attitude stabilization configuration was a single dumbbell formed by a DeHavilland A-18 extendible boom (60 feet maximum length) and a magnetically anchored eddy-current damper. This damper included as its active element a permanent magnet of 25,000 pole-cm dipole moment strength which orients along the earth's magnetic field. As the satellite librates, eddy-currents induced in a copper sphere which surrounds the magnet but is attached to the boom, damp satellite motions. In its launch configuration the magnet was located near

² F. F. Mobley, et. al., "Performance of the Spin Control System of the DME-A Satellite," Proceedings AIAA/JACC Guidance and Control Conference, Seattle, Wash., August 1966.

the spacecraft center and was free to orient in any direction. Since it was impossible to construct a perfectly nonmagnetic spacecraft the major problem to be resolved by dipole moment testing was the degree and variation in magnetic permeability that this free magnet would give the spacecraft.

GEOS-A in its nonmagnetic torsion suspension at NOL is shown in Fig. 3. The spacecraft weighed 365 pounds, had a maximum moment of inertia of 20 slug-ft² and as suspended had a free oscillation period of 27 seconds. Its symmetry axis (boom axis) was suspended horizontally so that once the two components of dipole moment in the horizontal plane were determined, the third orthogonal component could be measured by rotating the spacecraft 90° about this axis. The spacecraft was demagnetized prior to installation of the damper assembly. Components of residual dipole moment following demagnetization were $M_x = +350$, $M_y = -471$ and $M_z = -183$ pole-cm. These components were nulled to within 50 pole-cm of zero by adding permanent compensating magnets.

The eddy-current damper with its randomly oriented magnet was then installed in its launch position to magnetize materials (primarily the nickel-cadmium batteries) in its vicinity. The damper was removed and the spacecraft components of dipole moment were determined again. This procedure was then repeated several times. The variation in magnetic state was $M_x = \pm 130$, $M_y = \pm 180$, and $M_z = \pm 250$ pole-cm. These variations in dipole moment strength were acceptable for the 5° gravity stabilization intended.

Post-launch analysis indicated that despite an orbital eccentricity that was three times greater than the nominal value, steady state pitch errors in the gravity stabilized mode were less than 6° and roll errors were within 3°.

ATMOSPHERE EXPLORER-B—The AE-B satellite was built by the Aeronomy and Meteorology Division of the Goddard Space Flight Center for studying the physics of the upper atmosphere. It was launched into a 64° inclination orbit ranging from 250 km to 1200 km altitude in August 1966. The satellite is spin stabilized at 30 rpm with its spin axis normal to the orbit plane. Sampling instruments with ports on the equator of the spacecraft see both the forward and wake regions of the free-stream during each cycle and can thus compensate for forward velocity.

The attitude control system was designed and built by APL³ and had the functions of controlling spin axis orientation and maintaining spin rate.

Controlled spin axis precession was achieved by using a chargeable magnet system which consisted of a permanent plus a variable magnet. The magnetic state of the variable magnet was established by capacitor discharge through windings on the magnet. When the variable magnet is charged to full strength in the same sense as the permanent magnet a net dipole moment of 1.8×10^5 pole-cm results which can produce a precession rate of 1.4 deg/min. In the cancel state, i.e., where the variable magnet is fully charged in the opposite sense, a dipole moment of -3300 pole-cm was established, which had been calculated to be the dipole moment required to precess the spin axis at the same rate as the precession of the orbit normal. Once proper spin axis orientation was achieved, the variable magnet was to be pulsed into this cancel state thereby reducing the subsequent number of precession maneuvers. Pulsed resonance testing was used to establish this "cancel" dipole moment state.

AE-B was taken to NOL in December 1965 and February 1966; the test setup at NOL is shown in Fig. 4. The satellite weighed 485 pounds and had a spin axis moment of inertia of 12 slug-ft². Deflection response was determined through the use of an automatic autocollimator. Components of dipole moment normal to the spin axis were measured at $M_x = -9,090$ and $M_y = +2,960$ pole-cm. These components were not compensated since the spin rate and gyro stability of AE-B were high. The variable magnet was then charged into its full cancel state. By adding permanent magnets the net spin axis dipole was trimmed to -2980 ± 50 pole-cm as compared to the desired value of -3300 pole-cm. One of the permanent magnets was later chipped during spacecraft assembly which brought the final spin axis moment even closer to the desired value.

AE-B was launched in August 1966. After several maneuvers the spin axis was aligned with the orbit normal and the spin rate set at 30 rpm. Close watch on the AE-B attitude revealed that its spin axis was in fact drifting at nominally the same rate as the orbit normal.⁴ A minimum of precession maneuvers over the following months were required to maintain the desired alignment, indicating that the cancel state spin-axis dipole moment was quite close to the NOL established value.

DEPARTMENT OF DEFENSE GRAVITY EXPERIMENT—The DODGE satellite was designed to investigate 3-axis gravity-gradient stabilization at near synchronous altitudes. It was launched on July 1, 1967, into a 7° inclination circular orbit at 18,000 n. miles altitude. The satellite includes ten motorized

³F. F. Mobley, "Attitude Control System for the Atmosphere Explorer-B Satellite," AIAA 2nd Annual Meeting, Paper No. 65-432, San Francisco, Calif., July 1965.

⁴R. Werking, "Summary of Definitive Attitude Results for the Satellite Atmosphere Explorer-B," NASA Document X-541-67-374, Goddard Space Flight Center, Greenbelt, Md., August 1967.

booms which may be extended in various configurations; libration damping is effected by using either an enhanced magnetic damping scheme or a damped gimbaled boom.⁵ The spacecraft, shown in Fig. 7, is 8 feet long, weighs 500 pounds, and has a maximum moment of inertia of 34 slug-ft².

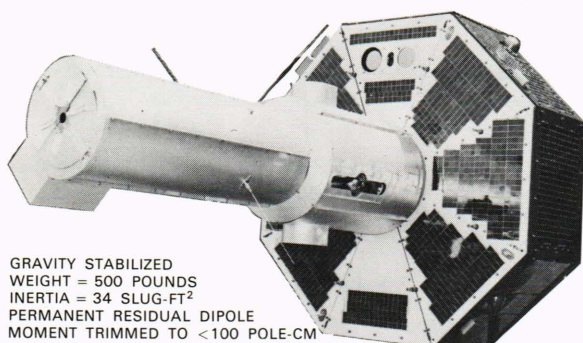


Fig. 7—DODGE Satellite.

DODGE was subjected to magnetics systems testing including pulsed resonance dipole moment measurements at NOL in April 1967. Aerodynamic disturbances were slightly greater on DODGE due to its stack. Additional shrouding was sufficient to reduce angular disturbances to within several seconds of arc. Dipole moment sensitivity on DODGE was of the order of 50 pole-cm.

Components of residual dipole moment in the spacecraft measured at the start of testing were $M_x = +150$, $M_y = -150$, and $M_z = +200$ pole-cm. These components were trimmed to less than 50 pole-cm by the addition of compensating magnets. Figure 5a shows the deflection response record corresponding to 100 pole-cm in the $-Z$ direction. The deflection response sensitivity to a 100 pole-cm di-

pole moment is 12 seconds of arc peak-to-peak in 5 cycles when using a field of ± 600 moe. The deflection response record of a null dipole moment is shown in Fig. 5b. The continuous angular response record was obtained from a Kollmorgan automatic autocollimator.

Pulsed resonance testing was used extensively on DODGE to determine the changes in satellite magnetization caused by the operation of magnetic systems in the spacecraft, as well as the strength of current loops when operating various electrical systems. Changes in the magnetic state were under 50 pole-cm even after exercising the 8.64×10^4 pole-cm electromagnets. Peak variations due to current loops were within 300 pole-cm in battery mode but as high as 1200 pole-cm when operating off the solar array. Compensating current loops were added to the solar bus to alleviate this problem.

Conclusions

To date, pulsed resonance testing has proved to be an excellent technique for determining small dipole moments of large spacecraft. Measurement sensitivity has been of the order of 20 to 50 pole-cm for spacecraft weighing up to 500 pounds. The technique is particularly suited for compensating spacecraft residual permanent dipole moments and confirming the null state. Variations in a null dipole state caused by satellite current loops or changes in magnetization caused by satellite operations are readily detected. Accurate dipole moment determination extends to moments as large as several thousand pole-cm as evidenced by the AE-B attitude performance. Determination of dipole moments in the 10^4 pole-cm range is probably more conveniently accomplished by field measurement techniques. The accuracy and sensitivity of pulsed resonance testing have proved to be quite acceptable for achieving the null magnetic state required by many present near-earth orbiting spacecraft.

⁵ R. E. Fischell, "The DODGE Satellite," Proceedings AIAA/JACC Guidance and Control Conference, Seattle, Wash., August 1966.

ADDRESSES

Principal recent addresses made by APL staff members to groups and organizations outside the Laboratory.

The following three addresses were given at the 14th Annual Meeting of the Society of Nuclear Medicine, Seattle, Wash., June 20-23, 1967:

A. G. Schulz, L. C. Kohlenstein, L. G. Knowles, W. A. Yates, and R. F. Mucci, "Quantitative Assessment of Scanning System Parameters;"

L. C. Kohlenstein, A. G. Schulz, L. G. Knowles, and R. F. Mucci, "The Simulation of Data from Scan Detector Systems;"

A. G. Schulz (APL), F. Rollo (The Johns Hopkins University), and Kurt Fölber (Siemens A.G. WW f. Medizinische

Technik; Erlangen, Germany), "In Vivo Measurement of Absolute Quantities of Radioactivity within an Organ."

F. S. Billig, R. C. Orth, and M. L. Lasky, "Effects of Thermal Compression on the Performance of Estimates of Hypersonic Ramjets," AIAA Third