Application of Resonance Technique for Measuring Satellite Magnetic Dipole Moment

by

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Magnetic torques, due to either current loops or residual permanent magnetic moment, constitute a principle source of attitude perturbation on earth satellites. In an effort to control these torques it is necessary to measure and compensate the satellite magnetic dipole moment. This paper presents the theory and application of a resonance technique which is especially designed to measure small dipole moments. In using this technique, the satellite is suspended by torsion wires in a controlled magnetic field. By changing the magnetic field sense 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.

This resonance technique has been successfully employed by the Applied Physics Laboratory in measuring and compensating dipole moments 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 paper discusses the application of resonance testing to several of the larger spacecraft and compares the results of dipole moment trim measurements to their in-flight attitude performance.

Key Words

Spacecraft
Magnetic Testing
Dipole Moment
Resonance Technique

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1. The Johns Hopkins University Applied Physics Laboratory, Silver Spring, Maryland

INTRODUCTION

Magnetic torques form a major disturbance to attitude stabilization of near earth satellites. These torques are due to dipole moments created within the spacecraft by current loops, residual magnetism or permeable materials. In establishing a minimum dipole moment state it is necessary to accurately determine small magnetic moments of typically large spacecraft. Techniques which have been employed to determine magnetic characteristics include field and static torque measurement. Field measurement techniques are often confused by the presence of higher order poles while static torque tests are subject to vibration and atmospheric disturbances.

This paper describes the application of a technique (1), presented in 1965 which is particularly suited to measuring small dipole moments of large spacecraft. 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-zero dipole moments effect no response. The magnitude of the dipole moment present is directly proportional to the rate of change of deflection amplitude.

This technique has been applied by the Applied Physics Laboratory to 12 spacecraft since March 1965. This paper summarizes the theory of this technique and describes its application to several of these spacecraft. It also compares the results of dipole moment trim measurements to in-flight attitude performance.

THEORY

It is assumed that the spacecraft contains a permanent magnetic dipole moment which resolves 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 completely undamped and all aerodynamic effects are minimized by appropriate shrouding.

In order to drive the spacecraft into resonance, a magnetic field is applied in the horizontal plane and reversed periodically at a frequency matching that of the free torsion resonance of the spacecraft. Although almost any periodic function of applied field can be ultilized, the present analysis is based on a square wave generated field as shown in

Fig. 2. This field H(t) has a zero to peak amplitude h and frequency $\omega_n = 2\pi/\tau$ and is generated in such a way that its Fourier series representation consists solely of cosine functions, viz

$$H(t) = \frac{4h}{\pi} \sum_{k=1}^{m} (-1)^{k-1} \frac{\cos (2k-1)}{2k-1} \omega_n t$$

The torque equation for rotation about the torsion wire axis is of the form

$$I \ddot{\theta} + c \dot{\theta} + K\theta = - H(t) \left(M_x \sin \theta + M_y \cos \theta \right) \qquad (1)$$

It is assumed that the rotations are of small amplitude such that the dipole moment component parallel to the applied field produces little torque, while the component normal to H (t) produces a greater torque which reverses its sense as the field is reversed. Assuming no damping, small angular deflections, and $M_x H(t) \ll K$ and substituting for H(t) as given by Eq. (1), the deflection response is given by

$$\theta(t) = \frac{4hM}{\pi I \omega_n^2} \left[\frac{\omega_n t}{2} \sin \omega_n t + \frac{1}{24} (\cos 3\omega_n t - \cos \omega_n t) - \frac{1}{120} (\cos 5\omega_n t - \cos \omega_n t) + \frac{1}{366} (\cos 7\omega_n t - \cos \omega_n t) \ldots \right] + \theta_o \cos \omega_n t + \frac{\theta_1}{\omega_n} \sin \omega_n t \qquad (2)$$

Parameter θ_0 and θ_1 describe initial conditions for displacement and angular velocity respectively.

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

$$\theta(N) = \frac{2hM}{\omega_n^2 I} (N - \tfrac{1}{2} + \rho) \qquad (3)$$

where $\rho = \theta_1 \omega_n I/2hM$

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

$$M = \frac{I\omega_n^2}{2h} \frac{d\,|\theta(N)|}{dN} \qquad (4)$$

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

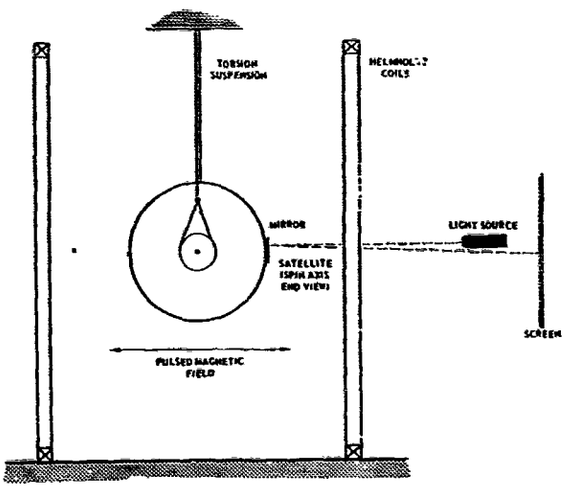


FIG. 1 MEASUREMENT OF SMALL MAGNETIC DIPOLE BY RESONANT PULSING

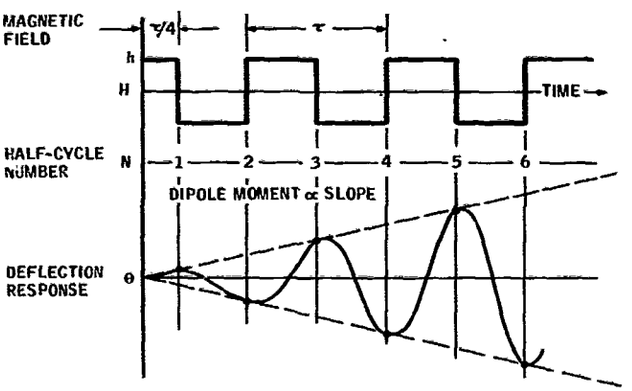


FIG. 2 MAGNETIC FIELD AND DEFLECTION RESPONSE

EXPERIMENTAL TECHNIQUES

This section presents some of the experimental procedures which have enabled pulsed resonance testing to be successfully applied to 500 pound spacecraft. In applying resonance testing to 12 satellites a technique has evolved. The following paragraphs relate the experimental conditions as pertain to spacecraft suspension, shrouding, synchronization of the field frequency, angular determination and establishing near zero initial conditions for rotational position and rate.

Spacecraft Suspension

Typically 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 non-magnetic; the cable length and separation are adjusted to the spacecraft weight and inertia to provide a nominal 30 sec. period of oscillation. The spacecraft symmetry axis is typically suspended horizontally. In this way two components of dipole moment in the horizontal plane are measured, the spacecraft is rotated 90^{o} about its symmetry axis, and the third orthogonal component of dipole moment can be determined.

For payloads with moments of inertia of 3 slug-ft^2 or greater it is necessary to employ the bifilar suspension. For strength and ease of handling non-magnetic stranded cables are used. It was found that if left-lay cable was used for both lengths the bifilar spring constant became non-linear due to unwinding. The spring rate would vary depending on the sense of rotation. It was found that by using a right and left lay cable pair this nonlinear spring characteristic was resolved.

Aerodynamic Torques

Typically 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, I have found it necessary to close all windows and doors, turn off all air-conditioning systems and shield the spacecraft with a dropcloth enclosure about 12 ft. square and 9 to 15 ft. high. Using these precautions angular disturbances can be controlled to within 10 arc sec or about 100 dyne-cm torque. Since dipole moment determination resolves 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 on the order of 20 pole-cm.

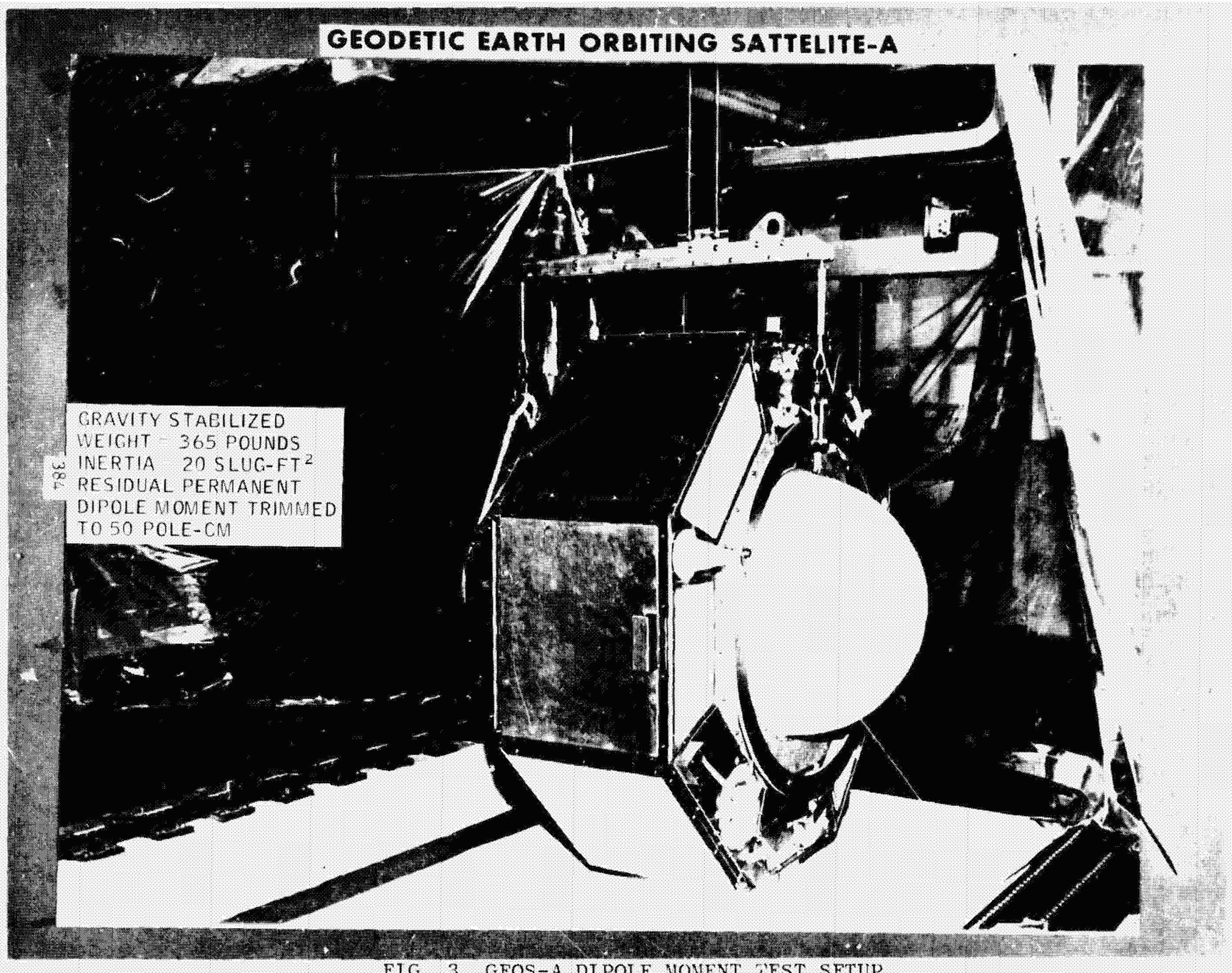


FIG. 3 GEOS-A DIPOLE MOMENT TEST SETUP

Field Synchronization

It is essential that the frequency of the applied magnetic field precisely match the free suspension resonance. By driving with a frequency off, say 10%, the response is 180° out of phase in 5 cycles. I find it necessary to match frequencies better than 1% and do it in the following manner: First the natural period of oscillation of the spacecraft is precisely determined by using a stop-watch 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. In this way higher amplitude non-linearities are discounted. The degree of system damping is observed during this time as the decay is oscillation amplitude. 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 such 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

It was found that in order to obtain the best response for dipole moment determination, initial conditions of zero angle and rate were desirable. Since the suspension provided no damping of oscillations some mechanism was 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 was positioned between two wheels. Each wheel had 6 permanent magnets—poles directed out. Each wheel could be independently driven clockwise by microswitch hand control. By driving the lower wheel an eddy-current reaction force on the vane would rotate the satellite clockwise (looking down); or, by driving the upper wheel, counter-clockwise. By detecting the sense of spacecraft rotation and producing opposing eddy-current torques all motion could be stopped. When the magnet wheels are motionless eddy-current damping on the satellite is negligible.

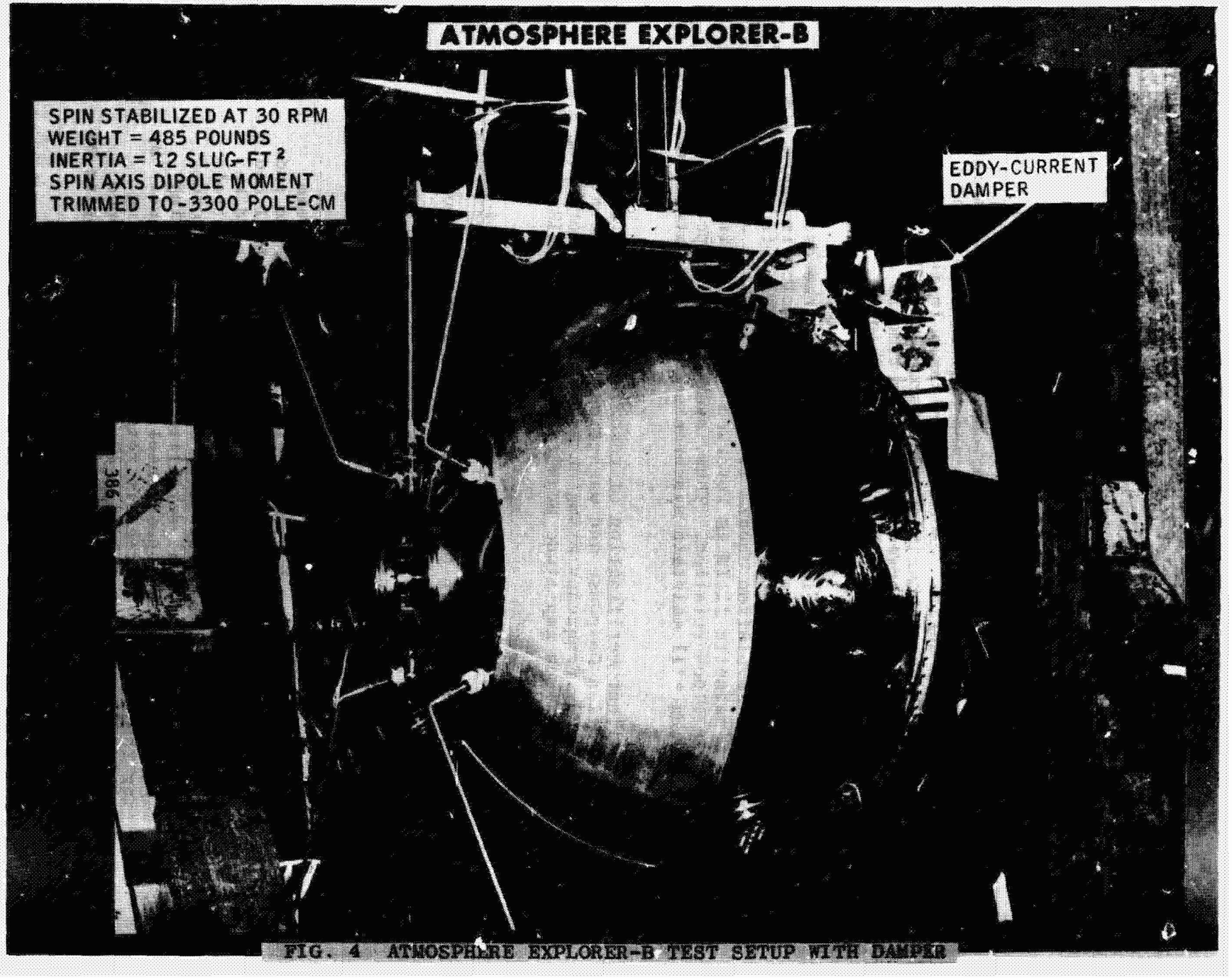


FIG. 4 ATMOSPHERE EXPLORER-B TEST SETUP WITH DAMPER

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-ft^2 an 8 meter optical lever can provide sufficient resolution of angular motion. As an example. let $I = 3$ slug-ft^2 $h = 0.400$ oe $\tau = 30$ sec and $M = 100$ pole-cm. Then from Eq. (4) $d\theta(N)/dN = 9.2$ arc sec/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-ft^2 it becomes necessary to employ 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 2 channel strip chart with the applied magnetic field.

Magnetics Facility

Dipole moment testing has been performed at the Naval Ordnance Laboratories magnetics testing facility — building No. 203. This facility is a 26 ft. square 4-coil system which is capable of nulling Earth's magnetic field and applying up to about 600 millioersted in any direction. The No. 203 facility provides a calibrated magnetic field uniform to .05% over a 4 feet dia spherical volume in the North-South and, vertical directions. The East-West control field volume is somewhat smaller.

When flashing fields for dipole moment testing, Earths field is cancelled by the primary field coil system and the variable field 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 on the order of 0.2%.

ERROR ANALYSIS

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

Errors in Theory

Several assumptions were made in deriving the deflection response from the torque equation. Consider the magnitude of error introduced by these assumptions.

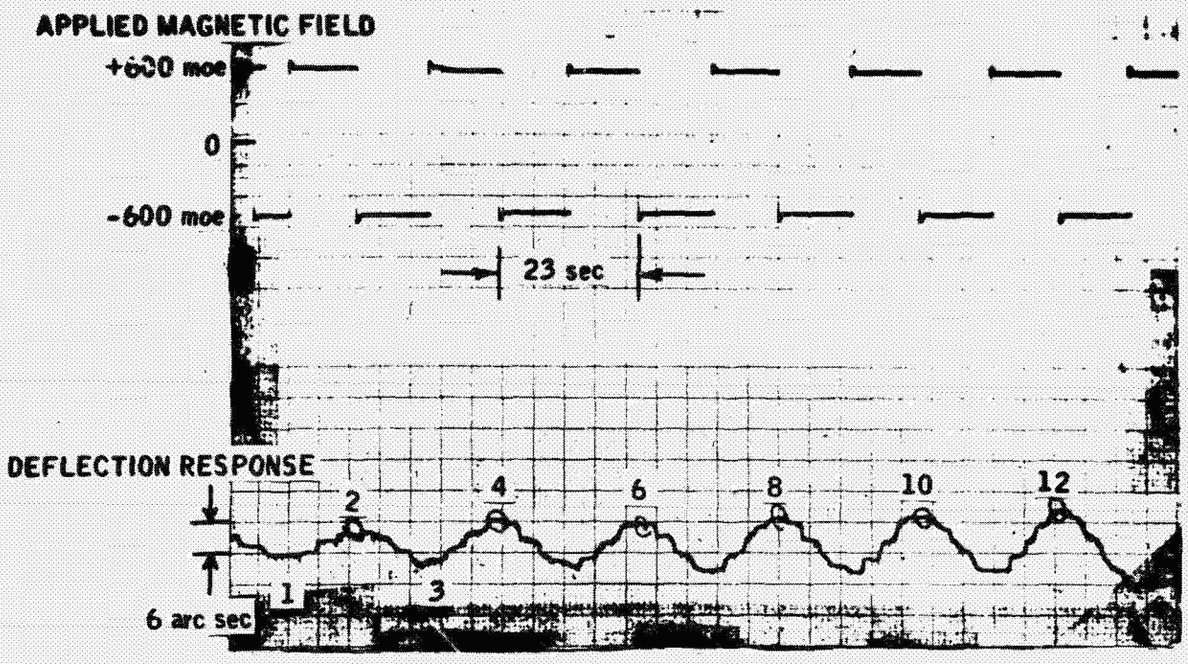


FIG. 5a **DEFLECTION RESPONSE OF DODGE TO 100 POLE-CM MAGNET**

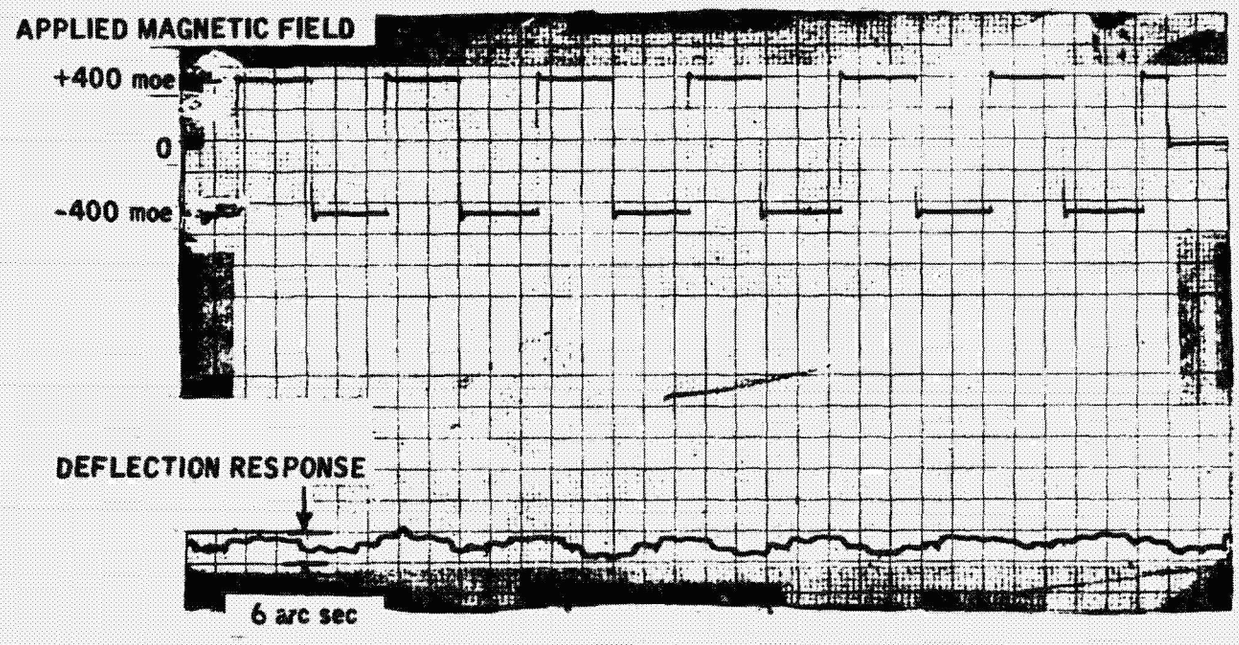


FIG. 5b **DODGE NULL DIPOLE MOMENT DEFLECTION RESPONSE**

1) It was assumed that ϑ remained small so that sin θ = ϑ and cos θ = 1.00. Peak deflections during resonance testing are on the order of 1 arc minute, thus the maximum error introduced by sin ϑ, cos θ assumptions are essentially zero.

2) It was assumed 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 x 10^6 dyne-cm/rad. This anomaly in spring rate effecting a change in resonant period is thus less than 0.2%.

Synchronization Errors

The square wave generated field must be synchronized to the free torsion suspension resonance. By accurately timing the suspension period and synchronizing a clock with a stable frequency source to this period, synchronization errors are reduced to within 0.5%. With this synchronization error it would take 100 cycles before the applied magnetic field would drive 180° out of phase to the mechanical system. Typically dipole moment determination is made within 5 cycles during which time near zero phase shift is encountered.

Consider the error in dipole moment determination due to improper synchronization. It can be shown that since θ(N) is recorded at the instant of field reversal the percent deviation from the true deflection response slope is one half the synchronization error, thus, $\approx$ 0.25%. The error in response slope due to random timing errors in field reversing is also quite small. Since the ϑ(N) positions are near deflection peaks, position rates of change are small. In addition, the response slope is an averaged determination; thus slope error due to small random timing errors is near zero.

Errors in Magnetic Field Strength

When flashing fields a power supply is preset to establish the required field strength and a reversing switch on the field coil used to change the field sense. Coil current is monitored with a DVM and standard resistor in an oil bath. Typical variations in coil current are on 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 precisely 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 more finite dipole moments is proportional to the sine of the alignment error times the transverse axis dipole moment. For equal components of dipole moment this error could be on 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 that due to 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 precisely determining the value of a more finite dipole moment the error might be on the order of 0.89% which is the RSS total of the listed errors.

SPACECRAFT APPLICATION AND ORBITAL RESULTS

Since its inception in 1965, pulsed resonance dipole moment testing has been applied to 12 spacecraft. Most spacecraft 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 select value. This section describes several applications of pulsed resonance testing and compares the results of dipole moment determination to the spacecraft in flight attitude performance.

Direct Measurements Explorer-A

The DME-A spacecraft was built by APL for NASA Goddard for the purpose of 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 which when energized are used to precess the spin axis and maintain its alignment with the orbit normal. (The orbit regresses at the rate of 0.8°/day.) A magnetometer sensor positioned between the chargeable magnets is used to determine their magnetic state. When the chargeable magnets are nulled it is necessary that there be no precession torques, thus a prime spacecraft

requirement called for zero residual dipole moment. In order to establish and confirm this desired magnetic state throughout assembly, minor changes and vibration testing, the spacecraft was taken to NOL a total of 3 times. Figure 6 shows the DME-A spacecraft in its bifilar torsion wire suspension at NOL. The spacecraft weighed 215 pounds and had a moment of inertia of 6 slug-ft^2. The suspension natural period was 22 seconds which provided a dipole moment calibration response of

$$M = 1.36 \times 10^7 \frac{d\,\theta(N)}{dN} \text{ pole-cm}$$

and 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. These test objectives were met using pulsed resonance testing.

In spite of the NOL operations there remained some uncertainty as to the state of magnetic trim. The low gyrostability of DME-A made it quite sensitive to drift produced by spurious dipole moments. A test of the null dipole moment state occurred during the period January 6 through 11, 1966. The magnetometer and null sensor telemetry indicated that the spin axis dipole moment was within 10 to 20 pole-cm of zero. By tracking the spacecraft attitude during this period it was determined that any drift must have been less than one degree. This spin axis stability confirmed the null sensor calibration and indicated that there was no change in magnetic state of the spacecraft throughout shipping, vehicle installation and launch phases.

Geodetic Earth Orbiting Satellite—A

GEOS-A was built by the Applied Physics Laboratory under NASA sponsorship for the general purpose of geodetic study. It was launched on November 6, 1965 into a near earth orbit ranging from 600 to 1230 n mi at 59.4^o inclination. The satellite employed a 2 axis gravity-gradient stabilization system which was designed to have an earth pointing accuracy of 5^o or better in a circular orbit. This degree of alignment with local vertical depended on minimizing magnetic torques. Prelaunch analysis indicated that 5^o gravity 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).

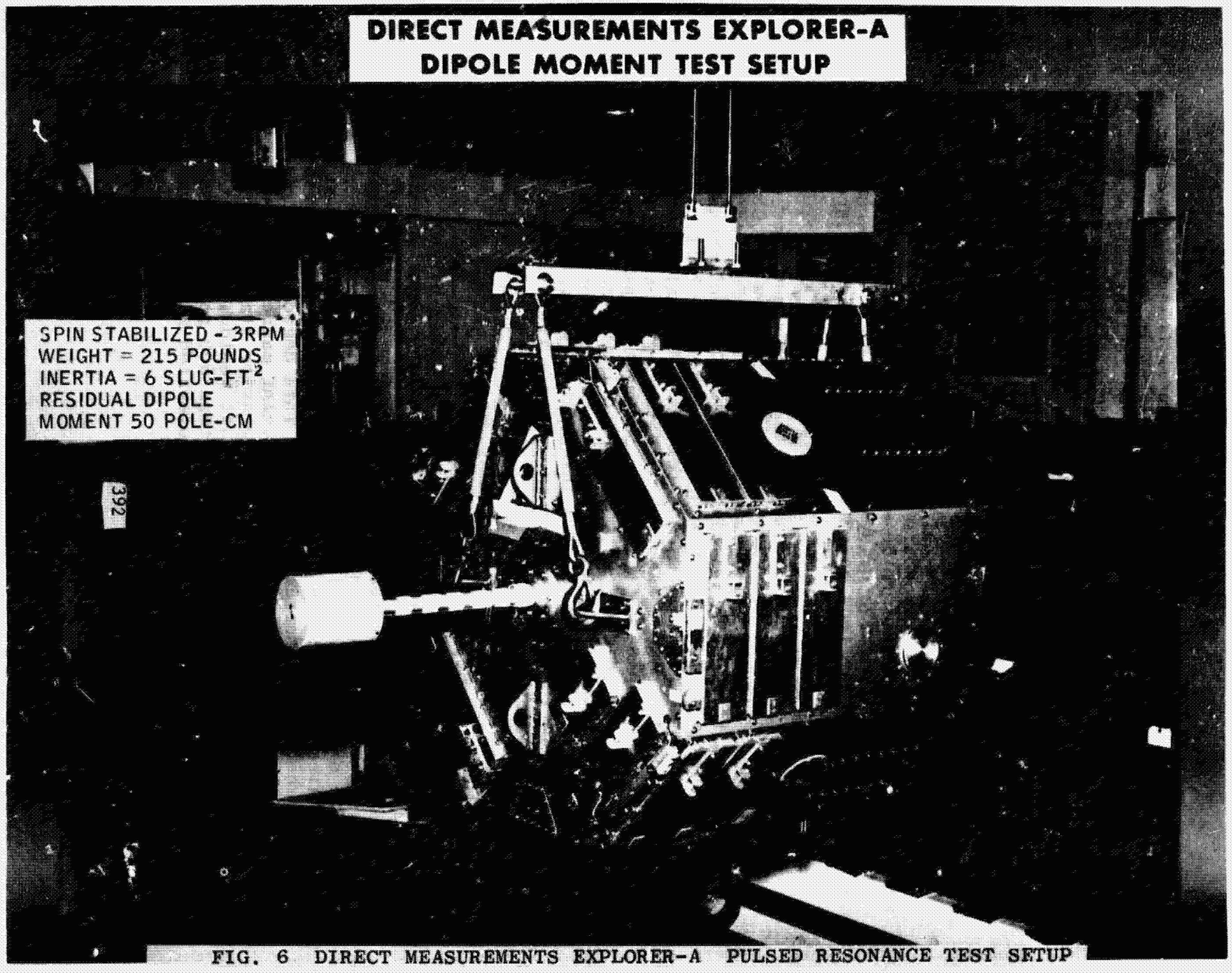


FIG. 6 DIRECT MEASUREMENTS EXPLORER-A PULSED RESONANCE TEST SETUP

The attitude stabilization configuration was a single dumbell formed by a DeHavilland A-18 extendible boom (60 ft 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 would orient along the earth magnetic field. As the satellite librated, eddy-currents induced in a copper sphere which surrounded the magnet but was attached to the boom, would damp satellite motions. In its launch configuration the magnet was located near the spacecraft center and was free to orient in any direction. Since it was impossible to construct a perfectly non-magnetic spacecraft the major problem to be resolved by dipole moment testing was the degree and variation in magnetic perm state that this free magnet would give the spacecraft.

GEOS-A in its non-magnetic torsion suspension at NOL is shown in Fig. 3. The spacecraft weighed 365 pounds, had a maximum moment of inertia of 20 slug-ft^2 and had a bifilar period of 27 seconds. Its symmetry axis (boom axis) was suspended horizontally such 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^o about this axis. The spacecraft was demagnetized prior to dipole moment testing. Components of residual dipole moment following deperm 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 held in its launch position so as to magnetize material (especially battery cases) in its vacinity. The spacecraft components of dipole moment were determined again and this procedure repeated several times. The variation in magnetic state was M_x = ±130, M_y = ±180 and M_z = ±250 pole-cm. These variations in dipole moment strength were acceptable for the 5^o gravity stabilization intended.

Post launch analysis indicated that despite the higher orbital eccentricity steady state pitch errors in the gravity stabilized mode were less than 6^o and roll errors were within 3^o.

Atmosphere Explorer-B

The AE-B satellite was built by the Aeronomy and Meterology Division of Goddard Space Flight Center for the purpose studying the physics of the upper atmosphere. It was launched into a 64^o 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 the Applied Physics Laboratory (3) 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. It was determined that this strength of spin axis dipole moment would precess the spin axis at the same rate as the precession of the orbit normal. Once proper spin axis orientation is achieved, the variable magnet would 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.

The 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-ft^2. 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 gyrostability 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 in fact its spin axis was 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. This attitude performance supports the conclusion that the cancel state spin axis dipole moment was quite close to the NOL established value.

Department of Defense Gravity Experiment

The DODGE satellite is designed to investigate 3 axis gravity-gradient stabilization at near synchronous altitudes. It was launched on July 1, 1967 into a 7^{o} inclination circular orbit at 18,000 n mi altitude. The satellite includes 10 motorized booms which will be extended in various configurations; libration damping is effected by using either an enhanced magnetic damping scheme or a damped gimballed boom. (5) The spacecraft, shown in Fig. 7, is 8 ft long, weighs 500 pounds and has a maximum moment of inertia of 34 slug-ft^2.

DODGE was subject 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 arc seconds. Dipole moment sensitivity on DODGE was on 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 is the deflection response record corresponding to 100 pole-cm in the -Z direction. The deflection response sensitivity to a 100 pole-cm dipole moment is 12 arc seconds peak-to-peak in 5 cycles when using a field of $\pm$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. The applied magnetic field was simultaneously recorded on the two channel Sanborn.

Pulsed resonance testing was extensively employed on DODGE in order to determine the changes in satellite perm state due to the operation of magnetic systems in the spacecraft, as well as determining the strength of current loops when operating various electrical system. Changes in the magnetic perm 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 onto the solar bus to alleviate this problem.

Conclusions

To date, pulsed resonance testing has proven to be an excellent technique for determining small dipole moments of large spacecraft. Measuremert sensitivity has been on the order of 20 to 50 pole-cm for spacecraft weighing up to 500

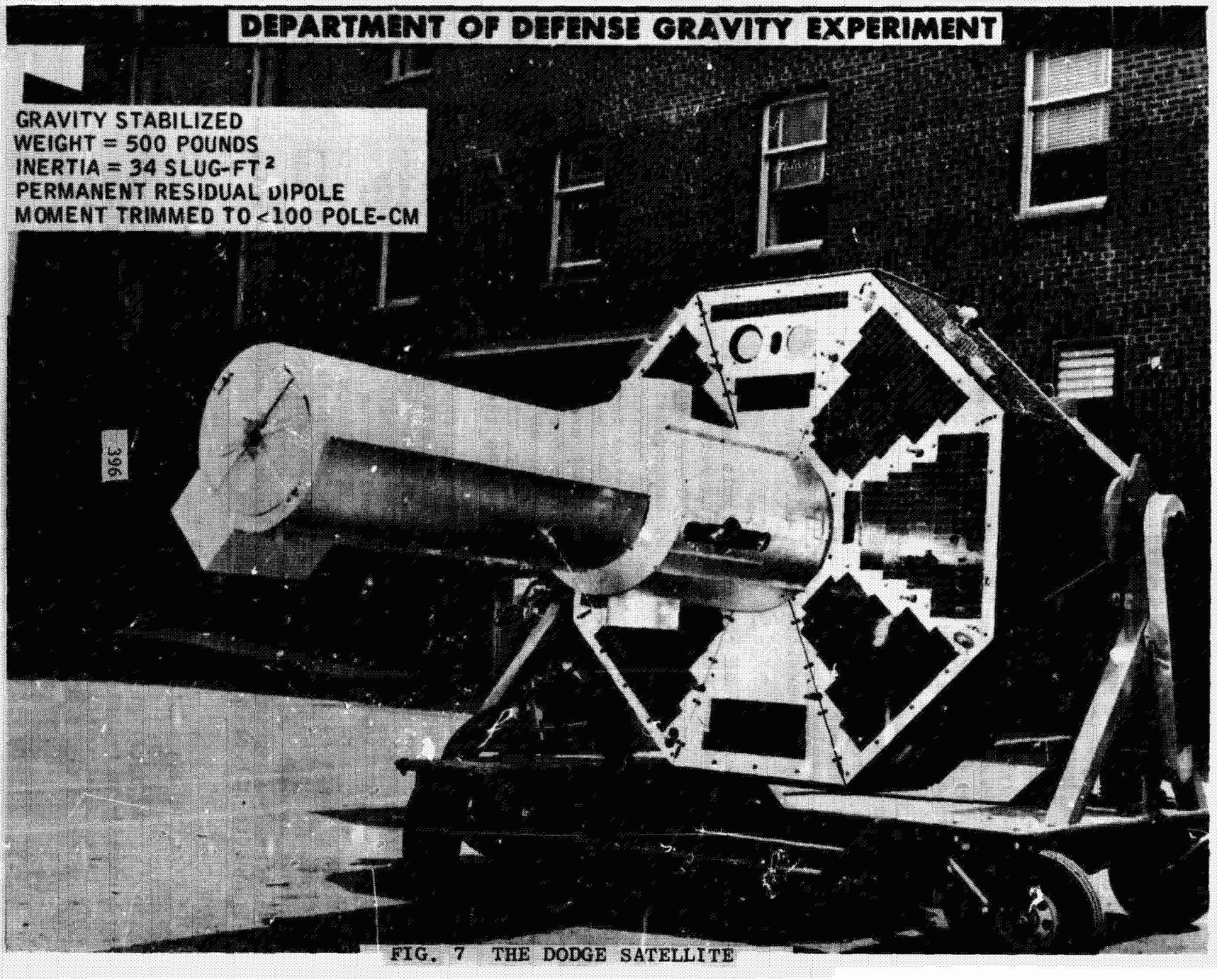


FIG. 7 THE DODGE SATELLITE