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GREENBELT, MARYLAND

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UK-4 PROTOTYPE SPACECRAFT

MAGNETIC TESTS

W. E. Pruett

Test and Evaluation Division
Systems Reliability Directorate

April 1972

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

UK-4 PROTOTYPE SPACECRAFT

MAGNETIC TESTS

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PROJECT STATUS

This is the final report on magnetic testing of the UK-4 Prototype Spacecraft. Magnetic testing of the UK-4 flight model was completed in the month of October 1971 and will be discussed in a later report.

AUTHORIZATION

Test and Evaluation Charge No. 325-870-41-25-02

UK-4 PROTOTYPE SPACECRAFT MAGNETIC TESTS

W. E. Pruett
Test and Evaluation Division

SUMMARY

The UK-4 prototype spacecraft was tested in the GSFC Spacecraft Magnetic Test Facility. The tests were conducted during the period June 7 through 10, 1971.

The results of measurements made during the tests are tabulated below.

Magnetic State	Resulting Dipole Moment in Milliampere-Meters Squared		
	M_z	M_{xy}	M_t
As Received	986 Dn	1,918	2,157
Post 1.5 Millitesla Vertical Exposure	3,404 Dn	1,925	3,911
Post 2 Millitesla Low Frequency Deperm	1,064 Dn	1,346	1,716
Post Vertical Compensation	<250	1,032	1,062
Torquing Coils Energized* at 16 V, Fwd-Dn	66,213 Dn	1,415	16,228
Induced	M_x	M_y	M_z
30 Microtesla (30K Gamma) N	1,223 N	<250	<250
30 Microtesla (30K Gamma) E	<250	1,370 E	<250
30 Microtesla (30K Gamma) Dn	<250	<250	1,362 Dn

*Proper torque directions of both spin-up and spin-down modes were confirmed.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (continued)

TABLES

UK-4 PROTOTYPE SPACECRAFT MAGNETIC TESTS

INTRODUCTION

A magnetic torquing system will be used for attitude control of the UK-4 spacecraft. It will be used for initial orientation of the spacecraft spin axis after insertion into orbit and for subsequent maintenance of the desired attitude to within a cone of 5 degrees semi-angle about Earth's polar axis. The coil axis is parallel to the spin axis to provide maximum useful torque when the local field vector is normal to the spin axis. The coil will be operated on command from the ground. The design goal for the spin axis moment is a nominal value of 90,000 milliampere-meters squared at 16.0 volts.

Objectives of the tests were:

- To determine the permanent, induced and stray magnetic moments of the spacecraft and to assess its magnetic stability.
- To evaluate the magnetorquer coil system:

  To determine the dipole moment produced by energizing the magnetorquer coil.

  To measure the reduction in magnetorquer dipole moment due to a modification of the coil configuration.

  To assess the effect of mechanical resonance on the dipole moment of the magnetorquer coil.

  To measure the despin torque due to eddy current and magnetic hysteresis.

- To deperm, compensate, and make other adjustments necessary to achieve satisfactory magnetic characteristics for the spacecraft.

TEST DESCRIPTION

Set-up

The UK-4 prototype spacecraft was tested in the GSFC Spacecraft Magnetic Test Facility, which uses a 12.8 meter (42 foot) diameter Braunbek coil system to produce a controlled magnetic field of high uniformity over a large central volume. Appendix A describes the facility.

The UK-4 prototype spacecraft was mounted on the Mark VI torquemeter on top of a ten-degree tilt plate. The torquemeter, shown in Figure 1, was immobilized during the acquisition of magnetic data and was activated for the torque measuring portion of the test. This assemblage was mounted on the turntable dolly with an intermediate spacer to bring the center of the main body of the spacecraft to the height of the array of magnetometers and was positioned at the center of the 12.8 meter (42 foot) coil system with the +X axis of the spacecraft oriented to the north, its +Y axis directed east, and its +Z axis directed upwards. The set-up is shown in Figure 2.

Magnetic measurements were made at locations 1.829 meters (6 feet), 2.438 meters (8 feet), 3.048 meters (10 feet) and 3.658 meters (12 feet) north of the coil system center at an elevation of 1.505 meters (59.25 inches) above the floor level (probe locations are depicted in Figure 3). The signals from the probes were hard wired to the Operations and Instrumentation Building for monitoring. The signals were displayed as meter indications and as analog tracers on brush recorders. They were also recorded in digital coding on magnetic tape (MADAS). The meter reading and analog traces were used for real-time "quick look" monitoring. The MADAS data were processed by digital computer programmed to perform a near field analysis of dipole moment.

In order to make torque measurements it was only necessary to activate the torquemeter while using the same assemblage as in magnetic tests. With the spacecraft at the center of the coil system, the floor rugs and plastic curtains were installed to minimize spurious torques produced by stray air currents. When the spacecraft was tilted, a counter-balance was used, consisting of a 12.25 kilogram (27 pound) mass at 45.7 cm (18 inches) lever arm. The instrumentation consisted of the basic torquemeter electronics, electronic filter and two 2-channel Sanborn recorders with synchronized time marks. A block diagram is shown in Figure 4.

Procedure

Magnetic tests consisted of the following:

- Measurement of initial permanent dipole moment.
- 1.5 millitesla (15 gauss) exposure and subsequent dipole measurement.
- Deperm from 2.5 millitesla (25 gauss) maximum and subsequent dipole moment measurement.
- Vertical compensation and subsequent dipole moment measurement.

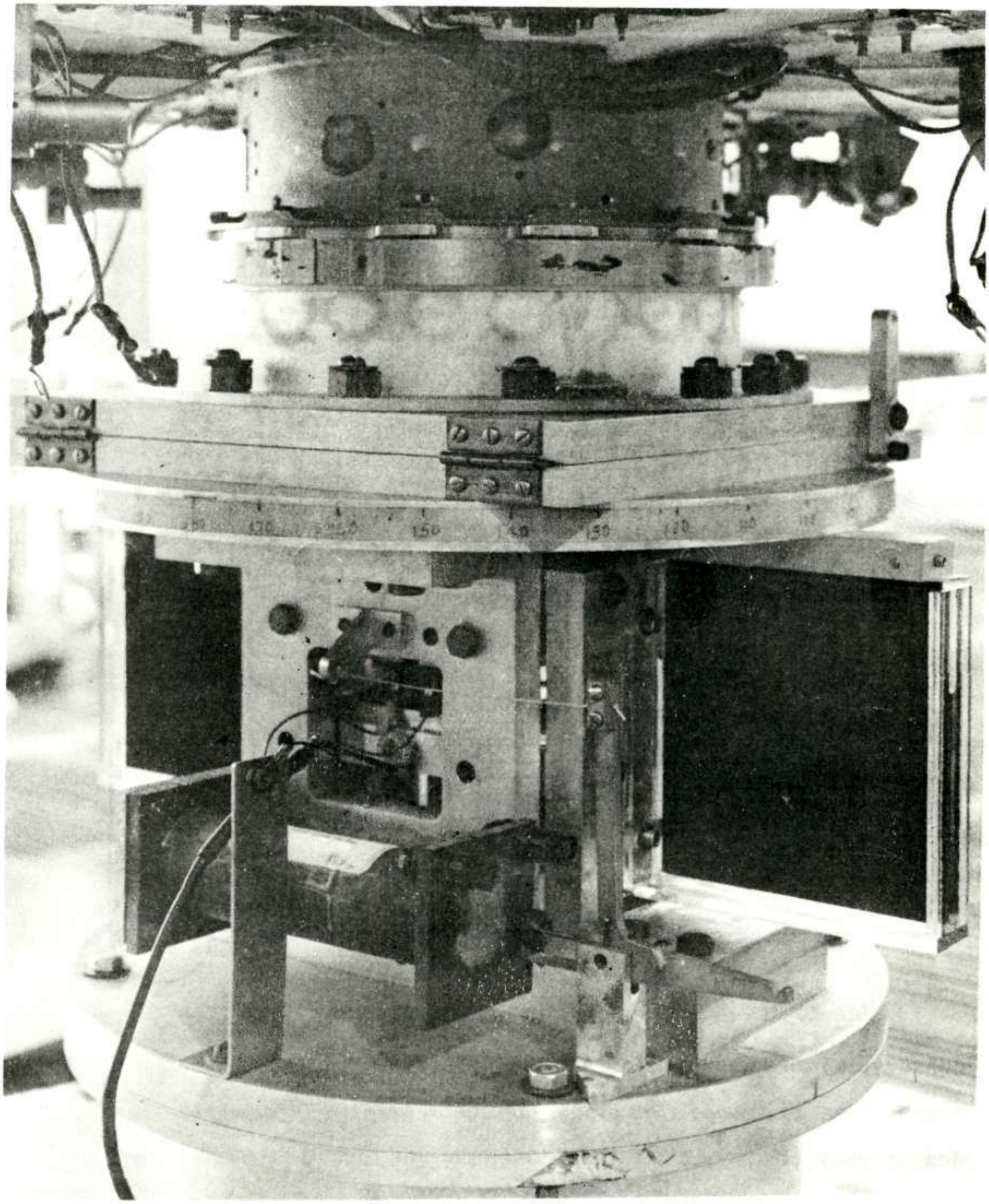


Figure 1. Mark VI Torquemeter

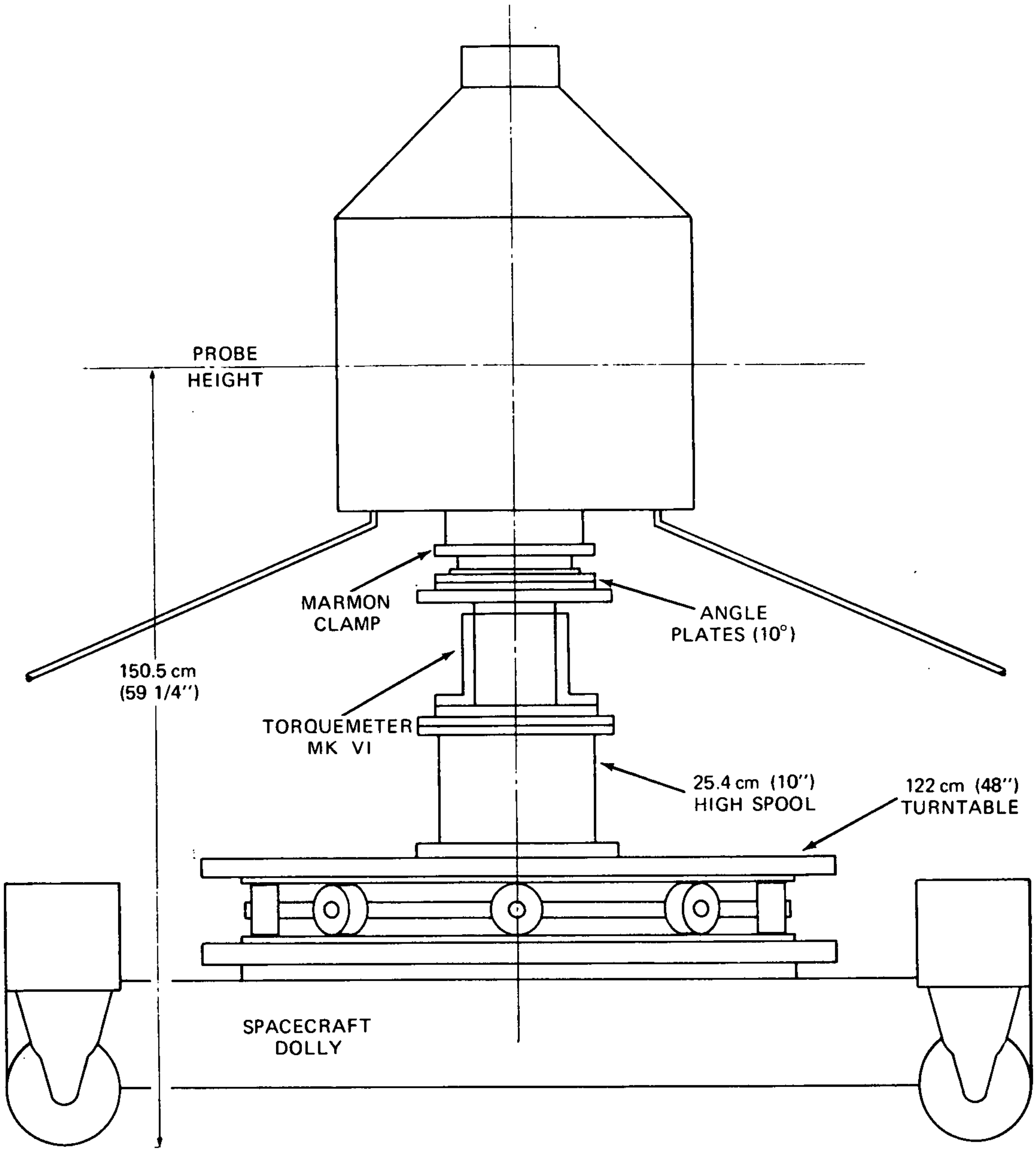


Figure 2. UK-4 Prototype Mounting for Spacecraft Tests

- Measurement of induced dipole moments.
- Measurement of stray fields dipole moments.
- Measurement of torquer coil dipole moment and torque.
- Mechanical resonance tests.
- Eddy current and hysteresis torque.

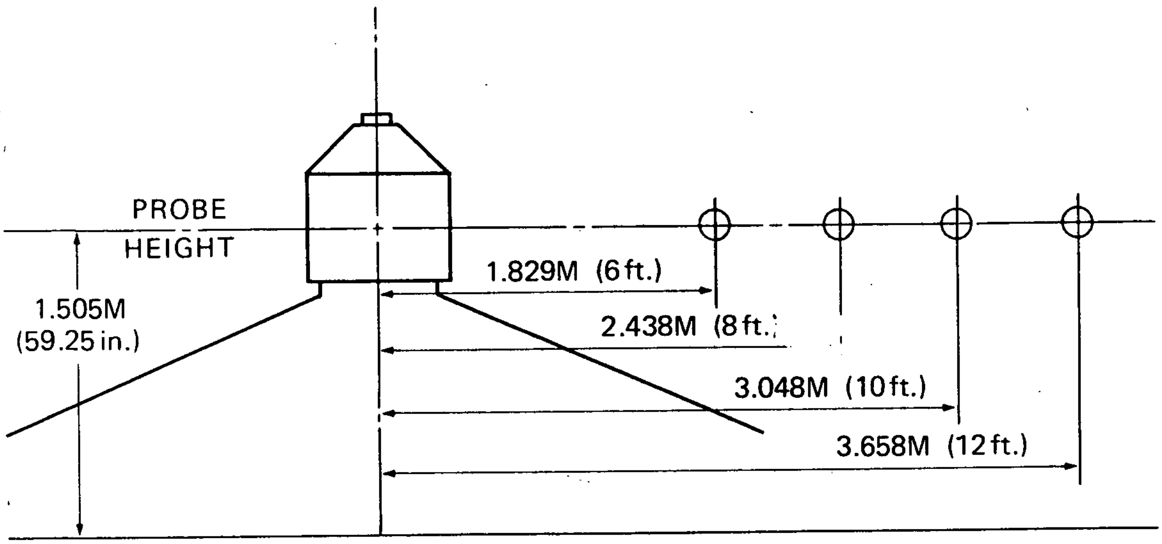


Figure 3. UK-4 Prototype Spacecraft and Probe Locations

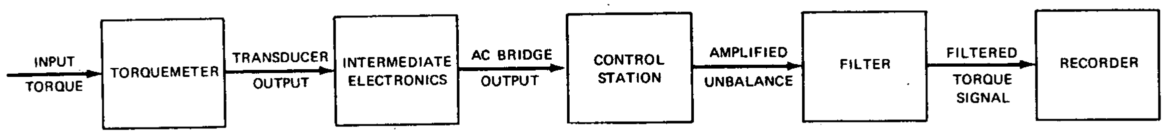


Figure 4. Block Diagram of Torque Measuring System

Appendix B contains details of the procedures followed in performing these tests, as well as the computational techniques used.

TEST RESULTS

Magnetic Moment

The magnetic moment record for the spacecraft appears in Table I. Although the post deperm magnetic moment was less than the moment in the initial state, the vertical component was greater than the 1000 mA-m^2 nominal called for in Reference 2. It was therefore necessary to introduce compensation in order to reduce the vertical component to its final value of 250 mA-m^2. The change in moment due to drawing current from the solar cells while stimulated by a bank of sun guns was negligible.

The change in the spacecraft permanent moment due to operation of the magnetorquer coil was negligible.

Table I

Magnetic Moments

Moment Magnitude (Milliampere-Meters Squared)			
	M_z	M_{xy}	M_t
Initial Perm	986 Dn	1,918	2,157
Post 1.5 Millitesla (15 Gauss) Vertical Exposure	3,404 Dn	1,925	3,911
Post Deperm, 2 Millitesla Low Frequency	1,064 Dn	1,346	1,716
Post Vertical Compensation	<250	1,032	1,062
Torque Coil Moment at 16 Volts Fwd	66,213 Dn	1,415	66,228
Induced	M_x	M_y	M_z
30 Microtesla (30K Gamma) North	1,223 N	<250	<250
30 Microtesla (30K Gamma) East	<250	1,370 E	<250
30 Microtesla (30K Gamma) Down	<250	<250	1,362 Dn

NOTE: Orientation of the horizontal moment component was approximately 30° cw from +X direction in each case.

The change in moment due to energizing the various experiments was negligible.

Torque Measurement

The results of the torquemeter dipole measurements are shown in Table II. The spin axis moment of 66,213 milliampere-meters squared at 16 volts is lower than the nominal value of 90,000, but is reasonably close to the value of 70,000 at 16.5 volts, which appears in the Design Review Memorandum of W. Maddox, dated April 30, 1971.

Since the coil configuration is influenced by gravity and the lack of centrifugal forces, the values obtained for all three components should be considered somewhat flexible.

Table II

Torquemeter Test Results

Spacecraft State	Quantity	Dipole Moment in mA-m^2				
		M_x	M_y	M_z	M_t	Coil Voltage
Post Comp	Perm	8,035	681E	483 Up	1,158	
Coil on Forward	Coil Moment	1,135S	845W	66,213 Dn	66,228	16
Coil on Rev.	Coil Moment	—	—	66,213 Up		16
Coil on Folded	Coil Moment	—	—	62,380 Up		16
Coil on Rotating Field	Coil Moment	—	—	74,892		—

No measureable eddy current or hysteresis torques were noted during this aspect of the test. Based on the sensitivity of the torque recording, such torque, if present, was less than 30 x 10^{-7} newton-meters (30 dyne-cms).

Folding in of a portion of the magnetorquer coil produced a reduction in spin axis moment of about 6% - presumably equal to the decrease in projected area.

The magnitude of moment produced by the magnetorquer coil was the same for both forward and reverse commands.

CONCLUSIONS

Magnetic field measurements taken in the vicinity of the folded booms indicate the maximum field due to the magnetorquer coil to be no more than 50 microtesla (0.5 gauss). When combined with the field due to the permanent magnetization, a maximum of 90 microtesla (0.9 gauss) was present. Since normal earth's field is 70 microtesla (0.7 gauss), the additional exposure is negligible.

When the facility field was rotated with the magnetorquer coil energized, a sinusoidal torque was produced at the frequency of rotation. Furthermore, the phase of this torque with respect to the rotating field was the same as when the torquemeter solenoid was energized (actually 180° out of phase). This leads to the conclusion that the observed torque is entirely consistent with a coil moment which is constant in magnitude and direction. It thus appears that no spurious torques are produced due to mechanical oscillation, if any, of the unsupported elements of the coil.

PROBLEMS

During the testing period, the relative humidity fluctuated around the 60% mark. This is the maximum allowable figure for operation of the Iowa experiment. It is expected that the flight spacecraft will be tested in October, at which time the humidity is generally lower.

At the start of the magnetorquer coil testing it was not realized that the coil voltage would show a considerable variation and this quantity was not at first correlated with the moment data. This should be corrected during the flight model tests.

The present tilt plate hinge was designed for a lighter load than the UK-4 and is only marginally adequate. This should be replaced with a more robust hinge when the flight model is tested.

ACKNOWLEDGMENT

The magnetic testing of this spacecraft and the acquisition of all data presented were accomplished as a team effort by the personnel of the Magnetic Test Section. Acknowledgment is also made of the excellent cooperation of the personnel of British Aircraft Corporation, Ltd., the UK-4 project personnel and by D. M. Shipley, the T&E flight project support manager.

REFERENCES

1. Design Review on Magnetic Torquing System, prepared by British Aircraft Corporation, Ltd., dated 3 April 1971.

2. Magnetic Moment Tests on the Prototype UK-4 Spacecraft, prepared by British Aircraft Corporation, Ltd., dated 20 April 1971.

3. GSFC Report X-325-69-350 by W. L. Eichhorn, dated August 1969, entitled "New Method for Determination of the Magnetic Dipole Moment of a Spacecraft from Near Field Data."

4. GSFC Report G-1020, by J. C. Boyle, entitled "The Mark VI Torquemeter, An Instrument for Measuring Magnetic Torques on Spacecraft," dated

APPENDIX A

DESCRIPTION OF MAGNETIC TEST FACILITY

The Spacecraft Magnetic Test Facility at Goddard Space Flight Center produces a controlled magnetic environment for magnetic tests of spacecraft or spacecraft components. The 12.8 meter (42 foot) diameter three-axis coil system permits establishment of zero field, or of a field of any desired magnitude and direction with a maximum of 60,000 nanoteslas (gammas) per component. Current-regulated power supplies provide stability of ±1 nanotesla (gamma) over a 24-hour period, and the coil geometry provides uniformity of field within 0.6 nanotesla (gamma) over a spherical volume of 2-meters (6.6 feet) diameter. Three earth-field magnetometers and associated control systems provide automatic compensation for the daily variation of the earth's field. Figure A-1 illustrates the total magnetic field reconnaisance survey of the magnetic test site.

Besides generating static magnetic fields, the coil currents are programmable to produce a resultant vector that will rotate about any desired axis through the center of the coil system at a maximum rate of 100 radians per second. The magnitude of the rotating vector has a maximum limit of 60,000 nanoteslas (gammas).

The facility also includes a 2,268 kilogram (5000 pound) capacity overhead hoist, a 907 kilogram (2000 pound) capacity hydroset for gentle handling of delicate spacecraft, a track system and dolly for transporting the spacecraft from the truck lock to the center of the coil system, and a turntable at the coil center powered to rotate the spacecraft through 360 degrees while it is centered in the coil.

An angle encoder on the turntable permits synchronization of angular-position and magnetic measurements. A gimbal is available that can rotate the spacecraft about a horizontal axis.

A portable 2.7 meter (9 foot) diameter Helmholtz coil pair generates fields up to 2.5 milliteslas (25 gauss) for perming and deperming the spacecraft along one axis. Also avialable is a 1.5 meter (5 foot) diameter coil for applying such fields along a second axis of the smaller spacecraft.

A series of highly sensitive torquemeters are available, permitting direct measurement of torques resulting from the interaction between the magnetic moment of the spacecraft under test and the field produced by the coil system itself. The torquemeter used in testing the UK-4 prototype is designated as Mark VI and is described in reference 4.4.

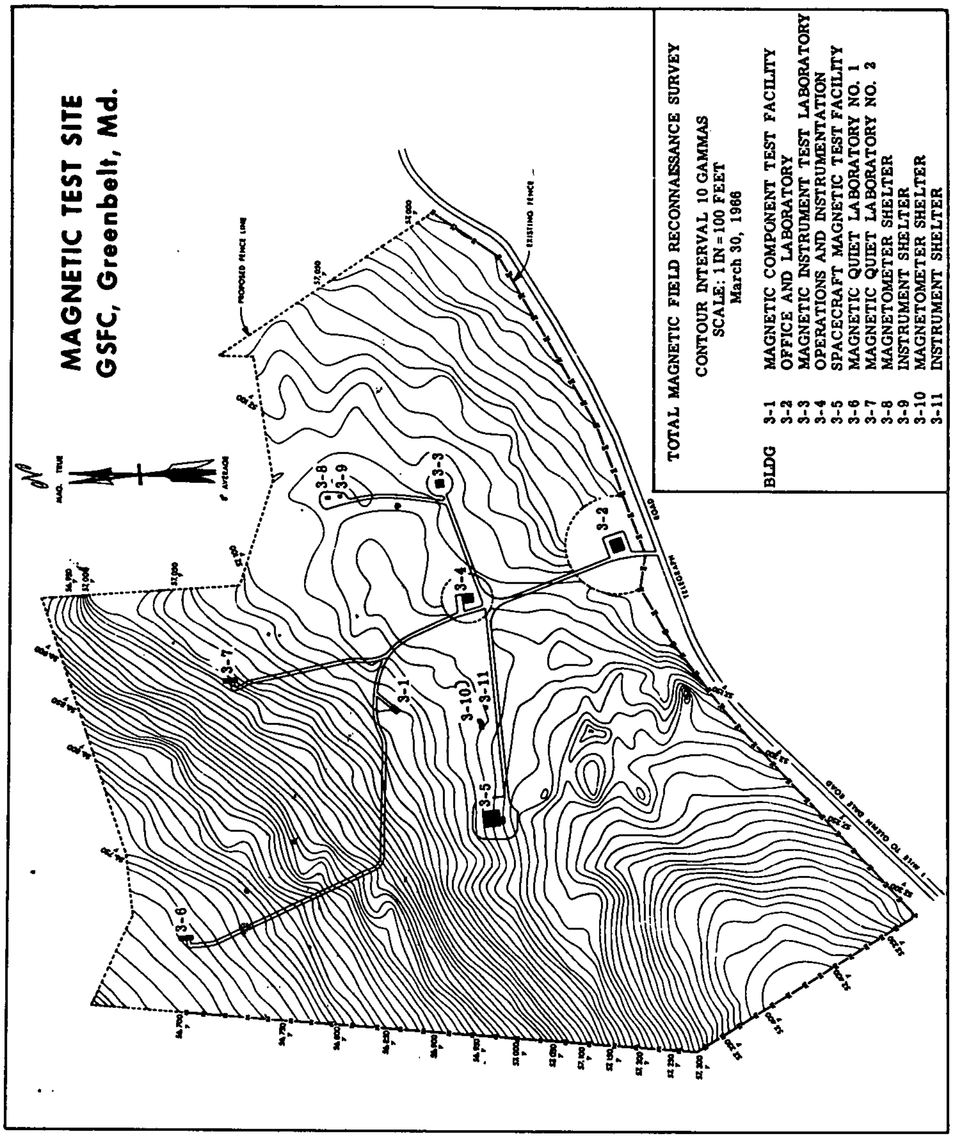


Figure A-1. Total Magnetic Field Reconnaisance Survey of Magnetic Test Site

The equipment also includes four triaxial fluxgate magnetometers that can be used simultaneously to provide meter display, stripchart records, and digital printout records. The positions of the magnetometer probes can be varied to suit the particular needs of the spacecraft or subsystem under test.

Figure A-2 is a photograph of the recording instrumentation for the magnetic tests, and Figure A-3 is a photograph of the UK-4 spacecraft in the magnetic test facility.

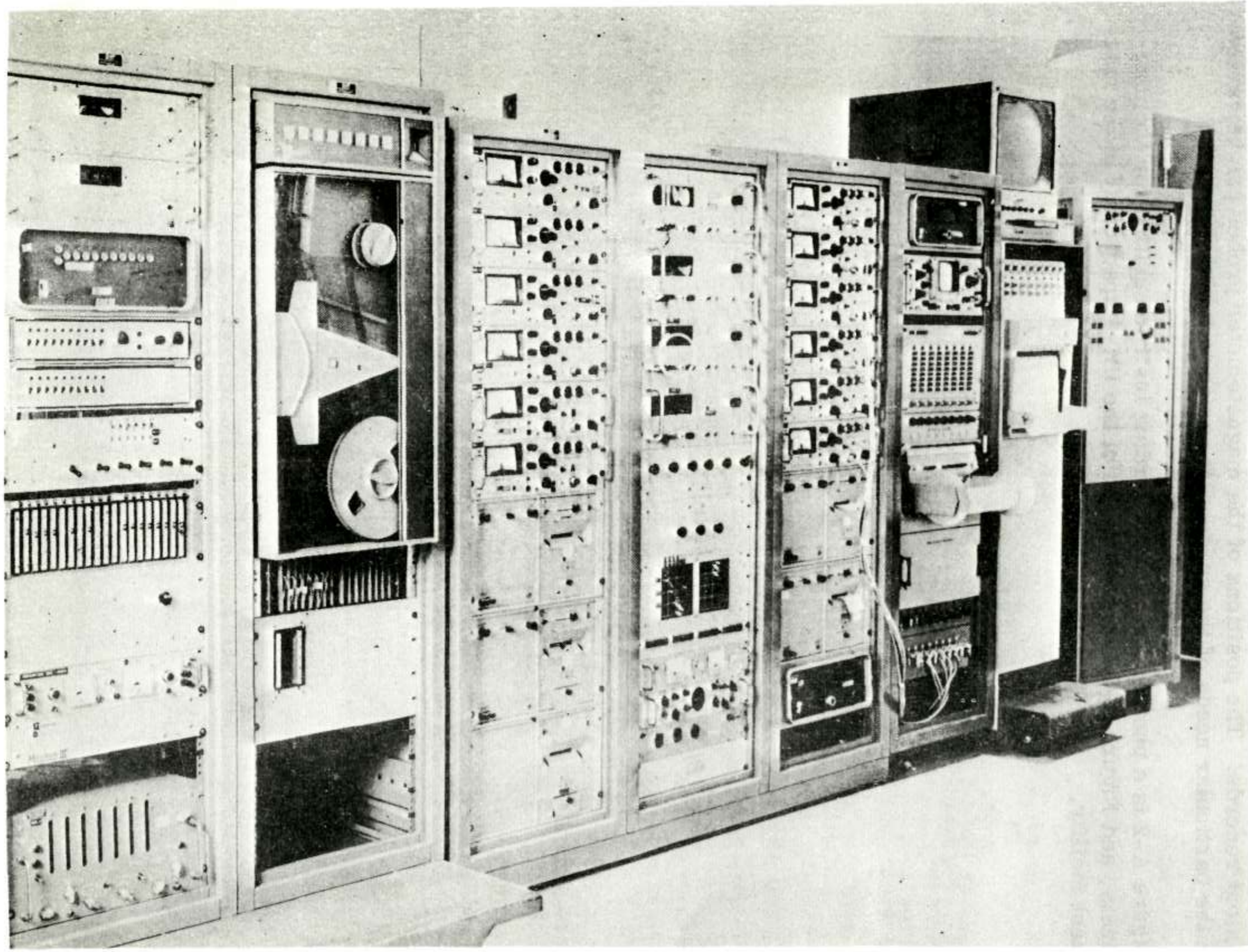


Figure A-2. Recording Instrumentation for Magnetic Tests

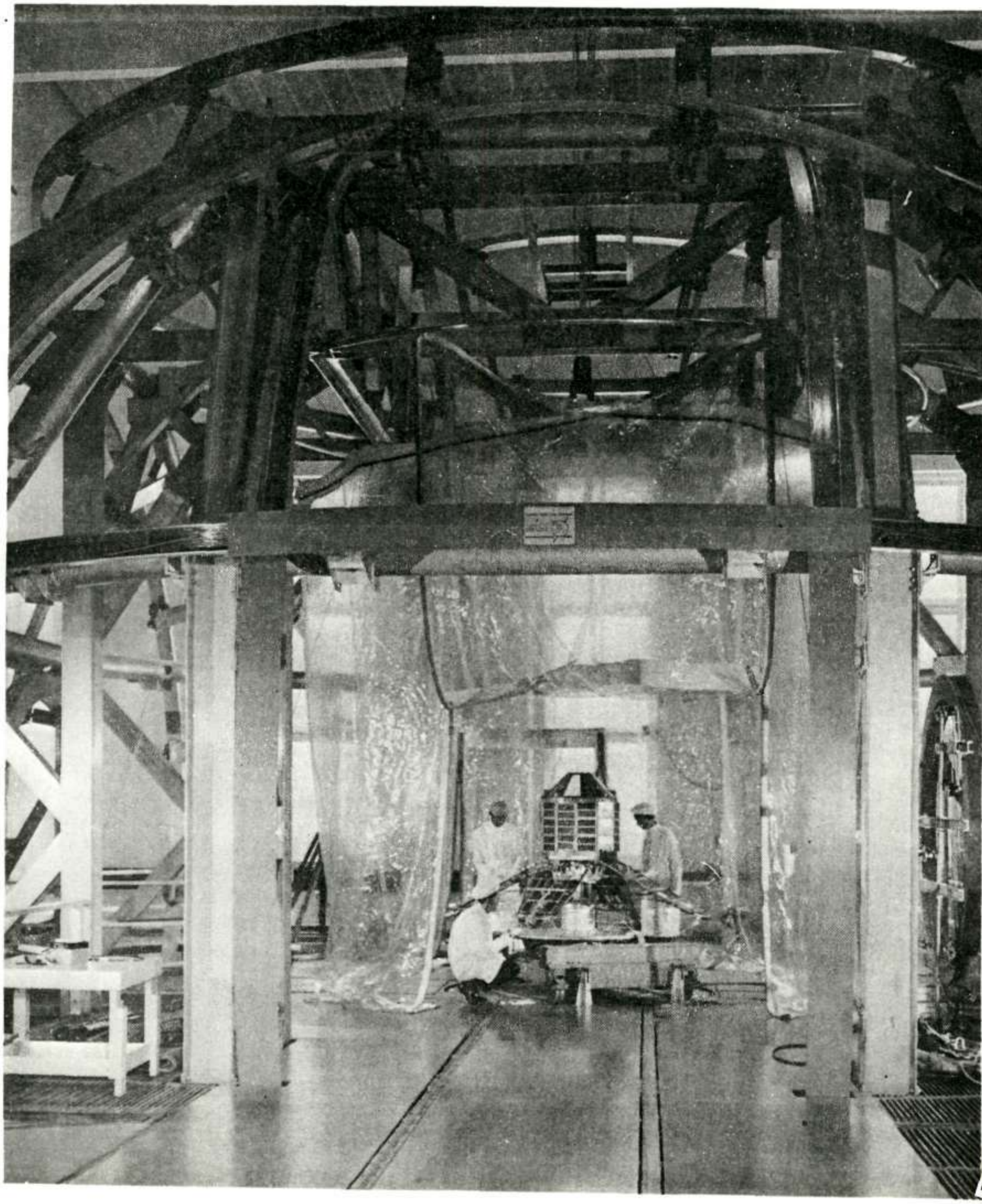


Figure A-3. UK-4 Prototype Spacecraft in the Spacecraft Magnetic Test Facility

APPENDIX B

TEST PROCEDURES

DIPOLE DETERMINATION

With the spacecraft in the truck lock, zero field is established at the center of the coil using the station Schoenstedt magnetometer. All four Forster Hoover probes are then adjusted to read zero. The spacecraft is then rolled in on the dolly and rotated clockwise (as seen from above) through a complete revolution about a vertical axis.

The magnetic field data obtained from the procedure just described allows calculation of the dipole moment components on the assumption that near field effects can be disregarded and that the measured field is due to a theoretical dipole. The total moment of the XY plane may be calculated from the peak-to-peak Forster Hoover readings as follows:

$$M_{xy} = \frac{(H_x)_{p-p}\ r^3}{4}$$

$$M_{xy} = \frac{(H_y)_{p-p}\ r^3}{2}$$

The vertical component of dipole moment may be calculated by subtracting the H_z with spacecraft out of the coil from the average H_z obtained during rotation of the spacecraft in the center of the coil. The expression used is

$$M_z = \left[(H_z)_{in} - (H_z)_{out} \right] r^3$$

When significant distortion appears in the probe signatures during rotation, near field analysis will produce more accurate results. The mathematics of this approach, which are quite complex, will not be described here. Reference 3 contains a description of the process. The magnetometer data are recorded in digital form on magnetic tape (MADAS system), and calculations are performed by digital computer, using a GSFC program written for this purpose.

Vertical exposure consisted of dc-energizing the pair of 2.7 meter (9 foot) diameter deperming coils within which the spacecraft was centered. The current was adjusted to produce a field level of 1.5 milliteslas.

Deperming was accomplished by slowly alternating the flux produced by the 2.7 meter (9 foot) diameter coils in the form of dc pulses. Current to the coils was programmed to produce pulses alternating in polarity with a period of approximately 12 seconds and gradually reducing from 2.5 milliteslas (25 gauss) to zero amplitude in a period of 5 minutes.

TORQUEMETER TESTS

Calibration

The torquemeter was mechanically calibrated using a small bellcrank and accurately known weight. The meter was also magnetically calibrated using the north-south and east-west torquemeter solenoids. When these solenoids were energized with a given current, they produced a known dipole moment. This moment, when interacted with an applied facility field, produced a known calibrating torque.

Permanent Dipole Moments

The X and Y components of the permanent dipole moment were measured with the spacecraft in the untilted position. A nulling technique was used, in which the X or Y component was countered by producing an equal and opposite dipole moment with the corresponding torquemeter solenoid. For example, to determine the X component of dipole moment, a field of 60,000 nanoteslas was oscillated at 1.9 radians per second in an east-west direction. This was the torsional resonance of the assembly, thus a dynamic augmentation of the signal resulted. The north-south (X axis) solenoid was energized and the current varied until the torque record showed a minimum. The X dipole moment component was then calculated as:

$$M_X = CI$$

where

M_X = X dipole moment component

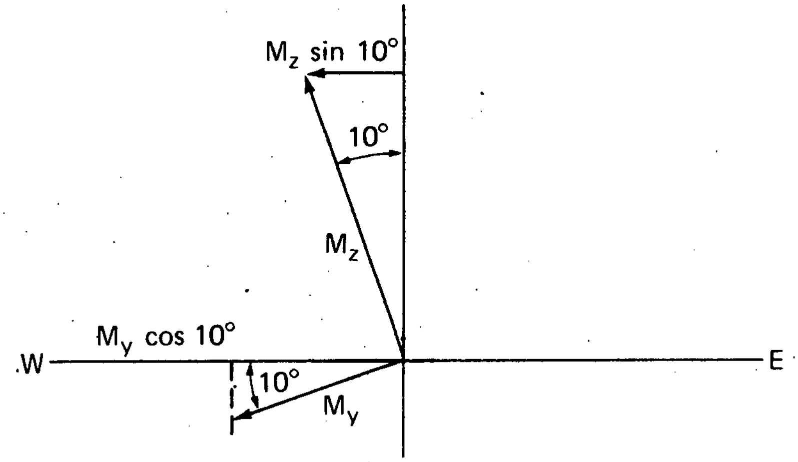
C = Solenoid coil constant

I = Solenoid current

The sense of the moment is opposite to that produced by the nulling current.

Determination of the Z component of permanent dipole moment required tilting of the spacecraft through a ten-degree angle.

The hinge of the tilt plate was parallel to the X (north-south) axis as follows:



Tilting of the spacecraft reduces the horizontal component of M_y to M_y cos 10° and produces a horizontal component of $M_z = M_z \sin 10°$. The resultant east-west moment ($M_{e\text{-}w}$) is nulled out in the same way that the X and Y components were nulled before tilting the spacecraft. Assuming west positive, we have

$$M = M_y \cos 10° + M_z \sin 10°$$

so that

$$M_z \sin 10° = M - M_y \cos 10°$$

According to measurements taken

$$M = -0.250 \times 2349 = -587.25 \text{ milliampere-meters squared}$$
$$(-587.25 \text{ gauss - cms}^3)$$

$$M_y = -681 \text{ milliampere-meters squared}$$

so that

$$M_z \sin 10° = -587.25 + 681 \times 0.9848$$

$$= -587.25 + 670.6488$$

$$= +83.3988 \text{ milliampere-meters squared}$$

$$M_z = \frac{83.3988}{0.17365} \text{ Up}$$

M_z = 480.27 milliampere-meters squared, upwards

Magnetorquer Coil Moments

The X and Y components of the coil moment were measured at zero tilt in the same manner as the permanent moment components; that is, by using the nulling technique. The coil moment components were obtained by taking the difference between the values obtained with the coil energized and with the coil off, with due regard to the algebraic sign. The values obtained were

M_x = 1135 milliampere-meters squared, south

M_y = 845 milliampere-meters squared, west

M_{xy} = 1415 milliampere-meters squared

The Z component of magnetorquer coil moment was measured with the spacecraft tilted ten degrees. A static field was applied in order to ensure that no dynamic effects were present on the coil. A north directed field was first applied, a zero obtained, then the magnetorquer coils was commanded on and the resulting static torque signal recorded. Taking into account the ten-degree tilt, the Z component of magnetorquer coil was calculated from the expression:

$$M = (M_c)_y \cos 10° + (M_c)_z \sin 10°$$

where

$(M_c)_y$ = Y component of magnetorquer coil moment

$(M_c)_z$ = Z component of magnetorquer coil moment

Commanding the coil on forward in a north directed field produced a torque of 6400 dyne-centimeters clockwise. M, therefore, was equal to

$$M = \frac{L}{B} = \frac{6400}{0.6} = 10,666 \text{ mA-m}^2$$

$$M = -10,666 \text{ mA-m}^2$$

Solving the moment equation we have

$$-10{,}666 = 845 \times 0.9848 + (M_c)_z \sin 10°$$

$$(M_c)_z \sin 10° = -10{,}666 - 832$$

$$= -11{,}498 = \text{east}$$

$$(M_c)_z = \frac{11{,}498}{0.17365} = 66{,}213 \times 10^{-7} \text{ mA-m}^2$$

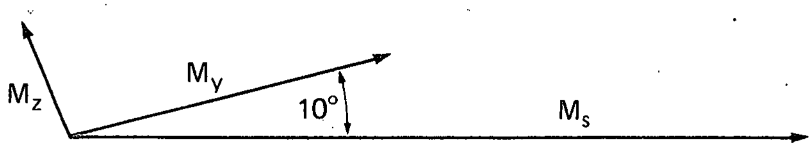
(66,2130 dyne-cms) Down at 16 volts

Mechanical Resonance Tests

The natural frequency of the torque coil segments in transverse bending was estimated to be 2 Hz or 12.6 rad/sec. This was determined by impulsing the coil and observing the frequency of the ensuing vibration. With the spacecraft tilted at ten degrees and the coil energized, a field of 30,000 nanoteslas was rotated at 12.6 radians per second in order to excite this resonance by magnetic forces. Direct observation of the coil as well as observation through a transit telescope produced negative results. No oscillation was visible.

The rotating field interacting with the magnetorquer coil produced an oscillating torque. In order to evaluate this torque, a dynamic calibration was made using the east-west torquemeter solenoid. In doing this, the field was rotated at 12.6 radians/second; first with both magnetorquer coil and torquemeter solenoid off and then with the torquemeter solenoid energized to 2 amperes to produce an easterly directed moment of 2819 mAm^2. The difference in amplitude of the torque record was ascribed to the moment of the solenoid, thus producing a dynamic calibration. The torquemeter solenoid was then turned off and the magnetorquer coil turned on and the corresponding amplitude of torque recorded. The phase relation between torque record and the rotating field vector was obtained by simultaneously recording torque and the north-south component of field.

The dynamic torquemeter moment was calculated as follows: With ten-degree tilt, torquemeter solenoid on and magnetorquer coil off, we have a moment picture as follows:



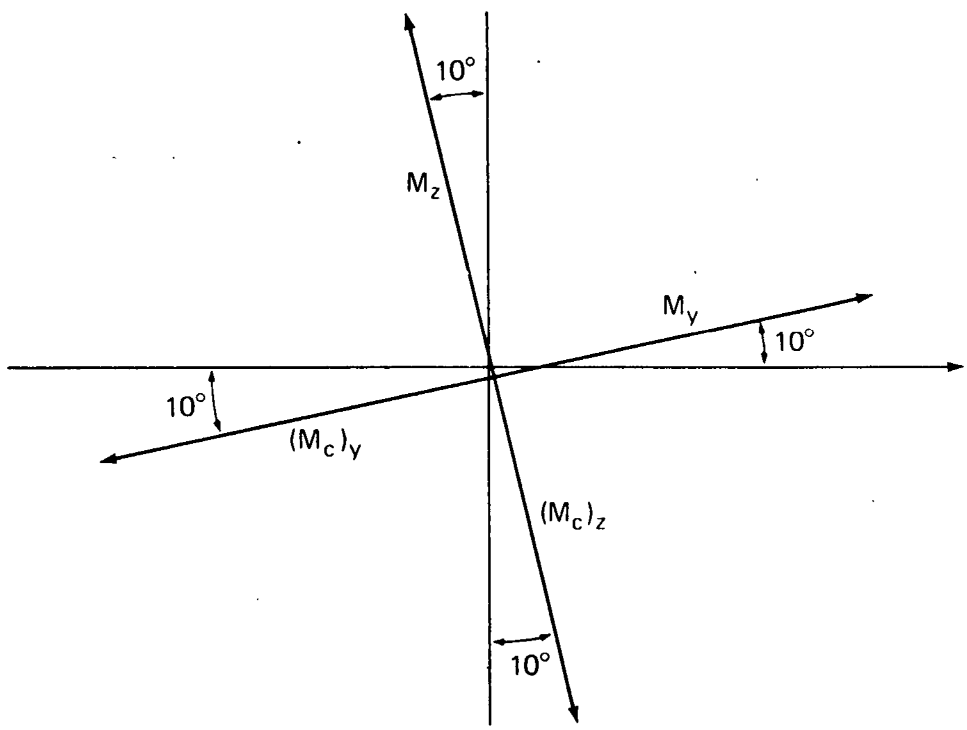
In the east-west direction

$$M = M_s + M_y \cos 10° - M_z \sin 10°$$

Dividing this moment by the peak-to-peak deflection D_1 when rotating 30,000 nanoteslas at 12.6 rad/sec we have

$$\text{Calibration Factor} = \frac{M_1}{D_1} = \frac{M_s + M_y \cos 10° - M_z \sin 10°}{D_1}$$

If we now turn the solenoid off and energize the magnetorquer coil, we have the following picture:



$$M_2 = M_y \cos 10° + (M_c)_z \sin 10° - M_z \sin 10° - (M_c)_y \cos 10°$$

If D_2 is the peak-to-peak deflection with the magnetorquer on, we have

$$M_2 = D_2 \times \frac{M_1}{D_1}$$

from which

$$(M_c)_z = \frac{\frac{D_2 M_1}{D_1} + (M_c)_y \cos 10° + M_z \sin 10° - M_y \cos 10°}{\sin 10°}$$

Eddy Current and Hysteresis Torque

In making these measurements, a field of 30,000 nanoteslas was rotated in the horizontal plane at a rate of 10.5 radians per second with the spacecraft shut down. No observable torque deflection occurred.

APPENDIX C

CHRONOLOGY OF EVENTS

Monday, 7 June 1971

UK-4 spacecraft mounted on turntable at the Magnetic Test Site and solar paddle installed.

Measured initial perm moment "as received."

Performed vertical axis exposure.

Measured post vertical exposure magnetic moment.

Tuesday, 8 June 1971

Performed vertical axis deperm.

Measured post vertical deperm magnetic moment.

Performed horizontal axis deperm.

Measured post horizontal deperm magnetic moment.

Performed second horizontal axis deperm.

Measured post second horizontal deperm dipole moment.

Installed compensation magnets.

Measured post compensation magnetic moment.

Measured induced dipole moment.

Measured stray field dipole moment.

Wednesday, 9 June 1971

Performed solar simulation.

Measured eddy current and hysteresis effects.

Thursday, 10 June 1971

Performed torque test of attitude control system.