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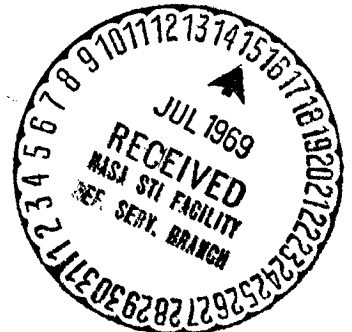
NASA
SPACE VEHICLE
DESIGN CRITERIA
(GUIDANCE AND CONTROL)

SPACECRAFT
MAGNETIC TORQUES



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MARCH 1969



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. This document, Spacecraft Magnetic Torques, is one such monograph. A list of all monographs in this series prior to this one can be found on the last page of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that the criteria sections of these documents, revised as experience may indicate to be desirable, eventually will become uniformly applied to the design of NASA space vehicles.

This monograph was prepared under the cognizance of the Electronics Research Center by S. Schalkowsky and M. Harris of Exotech, Inc. An advisory committee, consisting of the following engineers and scientists, assisted in the effort.

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Comments concerning the technical content of these monographs will be welcomed by the National Aeronautics and Space Administration, Office of Advanced Research and Technology (Code RVA), Washington, D.C. 20546.

March 1969

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Spacecraft Magnetic Torques

1. INTRODUCTION

All torques that tend to disturb the attitude of a spacecraft must be considered in the design of spacecraft attitude control systems. One of these torques, the magnetic torque resulting from the interaction between the magnetic properties of the spacecraft and the ambient magnetic field, is the subject of this monograph.

Determination of the magnetic torque requires knowledge of the strength and direction of the ambient magnetic field, the magnetic dipole moment of the spacecraft, and the orientation of this dipole relative to the local magnetic field vector.

Current loops and materials subject to permanent or induced magnetism are the primary sources of magnetic torques, but eddy current and hysteresis effects can be appreciable when the spacecraft or portions thereof rotate rapidly in the magnetic field.

Magnetic disturbance torque is one of the factors that must be considered in the determination of spacecraft attitude motion, control actuator sizing, expendable fuel requirements, and spin decay. Minimization of magnetic disturbance torques is particularly important when the available torques for control are small, e.g., gravity stabilization, or when small disturbances acting over a long period of time may introduce significant effects, such as precession of the spin axis of spin-stabilized spacecraft. Magnetic disturbance torque will not be a significant problem in spacecraft attitude control system design if the ambient field is negligibly small or if the spacecraft is designed to be magnetically "clean" for reasons other than control consideration, e.g., when sensitive magnetometers are present.

The models for the ambient magnetic field used in this document have been extracted from NASA SP-8017, Magnetic Fields—Earth and Extraterrestrial (ref. 1). This environment document contains detailed information that will be useful in special situations when the attitude control system performance is sensitive to small variations in the magnetic field.

There are three design considerations associated with magnetic disturbance torques: (1) assessment of the magnitude of the torque; (2) determination of an acceptable magnitude; and (3) control over the spacecraft magnetic characteristics during design and development to assure achievement of an acceptably low magnetic disturbance torque. This document deals only with items (1) and (3). Determination of acceptable magnetic torque levels is

primarily a systems decision and requires consideration of attitude control system design, mission requirements, and other sources of disturbance torques (solar radiation, aerodynamic interactions, gravity effects, man and equipment motion, fuel sloshing, etc.).

Because the evaluation of torque is often independent of the use to which the results are applied, much of the material contained herein can also be used for purposes other than the assessment of magnetic disturbance torques, e.g., spacecraft attitude determination with respect to the Earth's magnetic field or active magnetic control system design. However, only magnetic disturbance torques are treated explicitly in this monograph.

2. STATE OF THE ART

2.1 Flight Experience

The effect of a magnetic disturbance torque was observed on Vanguard I. This satellite was despun by the interaction of the Earth's magnetic field with eddy currents generated in the satellite's rotating outer shell (ref. 2). As a result of this magnetic disturbance torque, the spin rate was reduced from an initial value of 2.7 revolutions per second (rps) at launch to less than 0.2 rps 2 years later.

Another type of magnetic disturbance torque was observed on the Tiros I (ref. 3). In this instance a substantial magnetic dipole moment in the satellite, interacting with the Earth's magnetic field, caused the spin axis to precess and resulted in unpredicted changes in orientations of the meteorological cameras relative to the Earth.

Both of the effects described in the preceding paragraphs have more recently also been applied for useful purposes. For example, the Transit IB and Transit 2A satellites were deliberately and rapidly despun employing, in principle, the same type of magnetic torque that decreased the rotation rate of Vanguard I (ref. 4). Transit IB also utilized a permanent magnetic dipole to stabilize the satellite's symmetry axis along the local direction of the Earth's magnetic field (ref. 5). Similarly, by the use of ground-controlled variations of the magnetic moment of more recent Tiros satellites, accurate control of the orientation of meteorological cameras was achieved (ref. 6).

For satellites stabilized by gravitational torques and when it is desired to accurately control the spin-axis orientation of a spin-stabilized satellite, it has been found necessary either to minimize or to cancel essentially all of the spacecraft magnetic dipole moment that would otherwise disturb satellite orientation. The technique of precisely canceling the extraneous magnetic dipole moments of spin-stabilized satellites is illustrated by the recent Direct Measurements Explorer A and the Atmosphere Explorer B satellites (ref. 7).

2.2 Spacecraft Magnetic Properties

The need to attain magnetic cleanliness in spacecraft that incorporate a field measurement experiment has produced a considerable body of knowledge applicable to the assessment and minimization of spacecraft dipole moments. A number of detailed magnetic cleanliness programs have been evolved and implemented. Parts and material selection criteria, test procedures, design considerations, and project management procedures have been developed. The collection of papers in reference 8 provides a survey of key problems associated with the maintenance of exacting control over spacecraft magnetic properties. References 9 through 13 deal specifically with the magnetic cleanliness requirements associated with the in-flight measurement of magnetic fields; the low dipole moment attained as a consequence is a fringe benefit.

While magnetic disturbance torque is reduced by lowering the dipole moment of the spacecraft, magnetic cleanliness for instrumentation is primarily achieved by reducing the field at a particular location on the spacecraft. The absolute value of the field needs to be determined and the stability of the field is of great importance because it should not absorb a significant portion of the dynamic range of the instrumentation. This absolute value can often be deduced from proper data reduction. In the case of the Ness experiment on Pioneer (ref. 14), aids to the data-reduction process were built into the instrumentation.

Procedures for magnetic properties control associated directly with the reduction of magnetic disturbance torques in a long-life, spin-stabilized spacecraft (Medium Altitude Communication Satellite (MACS) program) are given in references 15 and 16.

2.3 Compensation and Test Methods

Today, most major magnetic test facilities are capable of both diagnostic measurements and curative procedures (ref. 8). Among the latter techniques are "deperming," i.e., removal of residual magnetization of major components and entire spacecraft, and compensation, wherein small permanent magnets are affixed to the spacecraft to minimize the dipole moment or the field at some specified location. The development of techniques for determining the torque acting on a spacecraft that is exposed to a known, uniform field provides an accurate means for assessing the dipole moment. By means of compensating magnets, achievement of residual moments in the range of 0.050 to 0.10 ampere-meter² (A-m²) (50 to 100 pole-cm) is possible in small, magnetically clean spacecraft in the laboratory. The lower limit attainable by compensation is restricted more by the instability or variability of the components that contribute to the total moment than by the resolution of the test equipment. Also in the transportation, prelaunch, and launch phases the spacecraft may be exposed to relatively high fields, and, unless specific precautions are

taken after deperming and compensation, magnetic characteristics of the spacecraft in orbit may be significantly different from those measured in the laboratory.

Separation of the "induced" from the "permanent" moment can be accomplished at a number of magnetic test facilities. However, measurement of the energy losses associated with hysteresis and eddy current effects requires test facilities and techniques that are not, as yet, in widespread use; hence few data are available on the subject. Induced magnetism is the major factor that has, in the past, prevented accurate calculation of the spacecraft dipole moment from the measured dipole moments of all the major assemblies.

2.4 Magnetic Field

Knowledge of the magnetic field varies with the different regions of extraterrestrial space (ref. 1). Knowledge of the Earth's field at low and medium altitudes is adequate for virtually all attitude control purposes. However, at synchronous altitudes and beyond, an accurate magnetic field model and its temporal variations are still being determined (refs. 17, 18, 19, and 20).

The interplanetary field, originating from the Sun and its solar wind, may be viewed as extending beyond about 10 Earth radii (i.e., beyond the magnetopause). Its magnitude has been measured to be between 2 and 40 nT (2 and 40 gammas) at approximately 1 astronomical unit from the Sun. The field can assume any direction from time to time and has been described as a spiral. Both magnitude and direction are dependent on solar activity. Beyond about 10 Earth radii in the midnight sector (the Earth's magnetic tail), field magnitudes fall within the same limits; but the direction is quite nearly sunward in the northern, and antisolar in the southern, hemisphere.

2.5 Summary

The state of knowledge of magnetic disturbance torques is generally adequate for the formulation of suitable design criteria. This knowledge is based both on theory and flight experience. The theory of magnetism and related phenomena (refs. 21 and 22) has, of course, been available for many years and its presentation is continually refined to meet the needs of new applications. Both data and theory on the magnetic field in interplanetary space and in the outer extremities of the magnetosphere are as yet incomplete.

3. CRITERIA

Disturbance torques arising from the interaction of spacecraft magnetic characteristics with the ambient magnetic field shall be considered in the design of attitude control systems. It shall be demonstrated that such magnetic torques acting in combination with all other disturbance torques do not degrade the performance of the attitude control system.

Where it is determined that magnetic disturbance torques are an important factor in the attitude control system design, the spacecraft dipole moment shall be controlled or minimized during spacecraft design, development, fabrication, and test.

3.1 Sources of Magnetic Disturbance Torques

Sources of magnetic disturbance torques to be considered should include but should not be limited to:

- Permanent magnetism in the spacecraft
- Spacecraft generated current loops
- Magnetism induced by external fields
- Currents induced by external fields

Additional torques, such as those resulting from the presence of assemblies that rotate relative to each other (e.g., rapidly spinning parts or movable solar panels) should also be considered.

3.2 Ambient Magnetic Field

For missions conducted within the Earth's magnetosphere (approximately 10 Earth radii from the geocenter), the magnetic field should be described by: (1) a steady-state, nominal analytical model that defines magnitude and direction as a function of location; with corrections for (2) distortion in the field caused by influences from outside the magnetosphere (effects of solar plasma) not accounted for by the nominal model; and (3) time dependent disturbances that alter and are superimposed on the model.

For missions conducted outside the Earth's magnetosphere, a value of 40 nT (40 gammas) in an arbitrary direction is a suitable upper-bound characterization of the interplanetary magnetic field at approximately 1 AU. The magnetic field decreases with increasing distance from the Sun.

3.3 Control of Magnetic Dipole Moment

Magnetic dipole moment control procedures, whether formally instituted or issued as design guides, should be initiated early in the program. The designer should consider classifying the spacecraft in accordance with table I to facilitate control.

Where control of the dipole moment is critical to the minimization of magnetic disturbance torques, the specified dipole moment should be validated by measurement of the entire spacecraft assembly.

Table I.—Criteria for Magnetic Properties Control

	Class I	Class II	Class III
Design	Formal specification on magnetic properties control; approved materials and parts lists; cancellation of moments by preferred mounting arrangements and control of current loops.	Advisory specifications and guidelines for material and parts selection. Avoidance of "soft" magnetic materials or current loops and awareness of good design practices.	Nominal control over current loops; guidelines for avoidance of "soft" magnetic materials.
Quality control	Complete magnetic inspection of parts and testing of subassemblies.	Inspection or test of suspect parts.	Test of subassemblies that are potentially major sources of dipole moment.
Test and compensation	Deperming either at subassembly or spacecraft level; test of final spacecraft assembly and compensation if required.	Deperming and compensation frequently used.	Test and compensation optional.

Note.—Class I—Magnetic torques dominant when compared with other torques.

II—Magnetic torques comparable to other torques.

III—Magnetic torques insignificant when compared with other torques.

4. RECOMMENDED PRACTICES

Assessment of the magnetic disturbance torque should be accomplished in the early design phase of spacecraft development. When the magnetic disturbance torque is dominant or comparable in magnitude to other torques, greater accuracy in the estimation and continuing control over the spacecraft magnetic properties will be required.

Section 4.1 recommends procedures for the estimation of magnetic disturbance torque based on the spacecraft equivalent dipole moment and the ambient field in the regions of space traversed. Section 4.2 recommends procedures for the minimization of dipole moment via control of spacecraft magnetic properties.

4.1 Magnetic Disturbance Torque Determination

The instantaneous magnetic disturbance torque T_m is the vector cross-product of the spacecraft effective dipole moment M and the local magnetic induction or flux density B ; viz,

$$T_m = M \times B \quad (4-1)$$

where

M is in ampere-meter² (A-m²);

B is in webers per meter² (Wb/m²) or tesla (T); and

T_m is in newton-meters (N-m)

Sections 4.1.1 and 4.1.2 give procedures recommended for the determination of B and M , respectively.

Table II gives the scope of the magnetic disturbance torque assessment for spinning and nonspinning spacecraft and identifies significant torque sources.

Table II.—*Scope of Magnetic Disturbance Torque Assessment*

Source	Permanent magnetism	Spacecraft-generated current loops	Magnetism induced by external field	Currents induced by external field
Nonspinning spacecraft		Major source of torque $T = M \times B$ (secs. 4.1.1 and 4.1.2).	Causes M to vary depending on intensity of external field, shape and characteristics of material (sec. 4.2).	No significant effect
Spinning spacecraft (or spinning portions of spacecraft)		Component of torque normal to spin axis has zero average value; consider only component of dipole moment along spin axis (sec. 4.1.3).	As above and also causing spin decay due to non-reversible process of magnetizing ferromagnetic material (i.e., magnetic hysteresis) (sec. 4.1.3.)	Causes spin decay and precession (i.e., alters spin-axis dipole moment) (sec. 4.1.3).

4.1.1 Magnetic Field Characterization

4.1.1.1 Steady State Models

The following analytical models for the undistorted steady-state magnetic field, listed in order of increasing accuracy and complexity, are appropriate for the estimation of magnetic torques:

- (1) Spin-axis, centered dipole
- (2) Tilted, centered dipole
- (3) Quadrupole model
- (4) Spherical harmonic expansion

The various steady-state field models differ in the accuracy with which magnetic field magnitude and direction can be obtained. However, increased accuracy is obtained at the expense of computational complexity and, as a practical matter, the use of anything more complex than a centered, tilted dipole model cannot be entertained unless a digital computer facility is available.

Computer programs that provide numerical solutions of the field equations are available at NASA centers as well as most of the major aerospace contractors. Generally, these programs allow for variation in the number of coefficients used, and thus are applicable when limitations in the storage capacity of a particular machine or other considerations make utilization of all the harmonic coefficients inadvisable.

The simple, less accurate models, (1) and (2), may be used:

- (a) For conceptual or preliminary design studies
- (b) When the magnitude of spacecraft dipole moment M is an estimated value.
- (c) When long term effects are of primary importance, i.e., average torque or torque impulse over several orbits, days, or longer.
- (d) When the orbit radius (distance from the geocenter) is greater than 3 Earth radii.

The more complex, more accurate models, (3) and (4), should be used when the spacecraft dipole moment is accurately known and the instantaneous attitude behavior of the spacecraft must be analyzed in detail.

Figure 1 shows the maximum deviation of the tilted dipole and quadrupole models from the field represented by the spherical harmonic expansion (ref. 23). The figure shows both magnitude and angular errors as a function of distance from the geocenter. Thus, at 3 Earth radii, the substitution of the tilted dipole model for the spherical harmonic expansion will introduce an error of no more than 10 percent in the magnitude and no more than 6° in the direction for the field calculated at any point in the orbit.

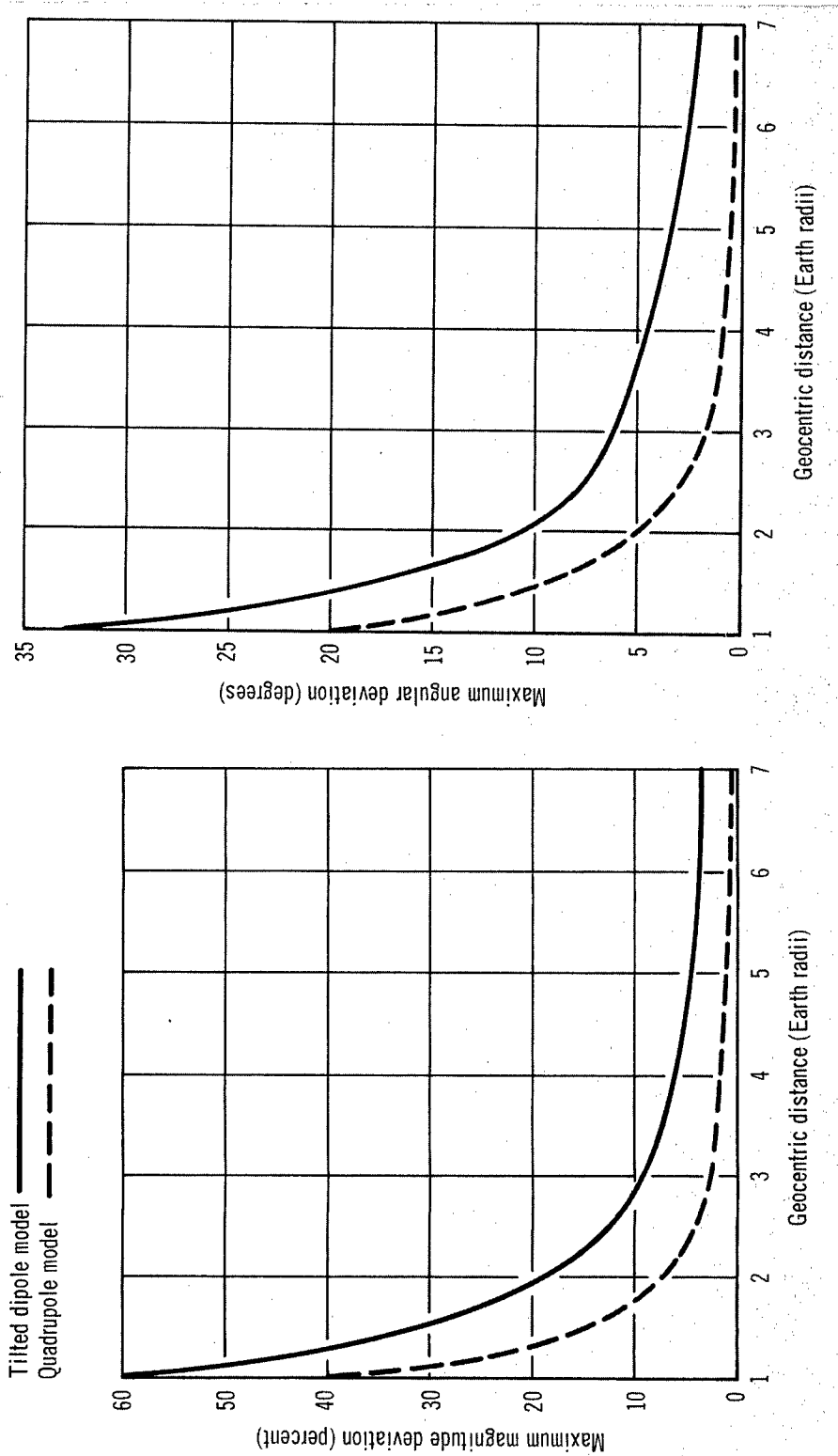


Figure 1.—Maximum deviations for approximate models.

The effects of temporal variations should be included in the analysis:

- (1) When the orbital altitude is near synchronous or beyond, or
- (2) When the instantaneous attitude behavior of the spacecraft must be analyzed in detail.

For the size of spacecraft now in use, the magnetic field can be considered to be uniform throughout the volume of space occupied by the spacecraft, i.e., torques caused by field gradients need not be considered.

Table III gives information for the application of the tilted, centered dipole model and the spin-axis, centered dipole model.

4.1.1.2 Disturbing Effects

Secular variations.—The Earth's magnetic field undergoes small, but continuous, time variations as a result of change in the internal sources of the Earth's field (ref. 24). Where an accuracy of field representation in the order of 0.1 percent is required, the coefficients of the spherical harmonic expansion should be updated, using the time derivatives of the spherical harmonic coefficients (ref. 1).

Field distortions—uncertainties in Earth's far field.—For geocentric distances of less than 5 Earth radii, the magnetic field is accurately calculated from a spherical harmonic expansion. Beyond 5 Earth radii, there is progressively less correspondence between the measured and the theoretically calculated field. The designer should, therefore, separately evaluate these effects when high altitude (near synchronous orbit) missions are analyzed. An increase in field magnitude, particularly in the equatorial plane along the noon meridian, of at least 25 percent should be considered as well as angular deviations of up to 20° at latitudes away from the Equator.

Temporal variations.—In addition to the secular variations, disturbances of comparatively short duration are frequently encountered in the Earth's field. Two types of disturbances are to be noted:

- (1) Geomagnetic storms:

A geomagnetic storm is typified at or near the Earth's surface by (1) an initial increase of about 50 nT (50 gamma), (2) a subsequent decrease which can be as large as 400 nT in a few hours, (3) a rapid recovery to a nearly prestorm level, and (4) final recovery over a period of several days.

Table III. — Spin Axis and Tilted Dipole Models

Dipole model	Spin axis	Tilted
Number of terms in harmonic expansion (ref. 1)	$k = 1$	$k = 3$
Tilt angle from Earth's spin axis	$\theta_0 = 0^\circ$	$\theta_0 = 11.44^\circ$
Direction of tilt (longitude)	$\lambda_0 = 0^\circ$	$\lambda_0 = 290.24^\circ$
Displacement from geocenter	0	0
Analytical representation values for harmonic coefficients in $n\Gamma$ (gamma) (Epoch 1965.0) (ref. 1, table 3.2-1):		
g_1^0	$= \left(\frac{R_e}{R}\right)^3 g_1^0 \sin \theta$	$B_X = \left(\frac{R_e}{R}\right) (g_1^0 \sin \theta + g_1^1 \cos \theta \cos \lambda + h_1^1 \cos \theta \sin \lambda)$
g_1^1	$= 0$	$B_Y = -\left(\frac{R_e}{R}\right)^3 (g_1^1 \sin \lambda - h_1^1 \cos \theta)$
h_1^1	$= 0$	$B_Z = 2 \left(\frac{R_e}{R}\right)^3 (g_1^0 \cos \theta + g_1^1 \sin \theta \cos \lambda + h_1^1 \sin \theta \sin \lambda)$
Annual change in $n\Gamma/\text{yr}$ (gamma/yr):		
g_1^0	$= 14.03$	
g_1^1	$= 8.76$	
h_1^1	$= 3.71$	

Note. — B_X , B_Y , and B_Z are the components of \mathbf{B} in the B coordinate frame (see app. A, fig. A-2).

The frequency of occurrence of geomagnetic storms and their magnitude in near-Earth orbits is indicated in figure 2 (ref. 25). These data derive from measurements at high northern latitudes and at an altitude of 1100 kilometers; they are typical of disturbances for satellites in near-Earth orbit.

(2) Sudden impulse disturbance:

The disturbance shown in figure 3 is typical of disturbances frequently observed and associated with fluctuations in the intensity of the solar wind (ref. 26). They are of relatively short duration, i.e., less than 1 hour, and, although an increase of about 18 nT (18 gamma) is shown in figure 3, reductions of comparable magnitudes are also observed.

During periods of high solar activity, the magnetic field at synchronous altitudes can undergo large fluctuations in magnitude and direction (ref. 20).

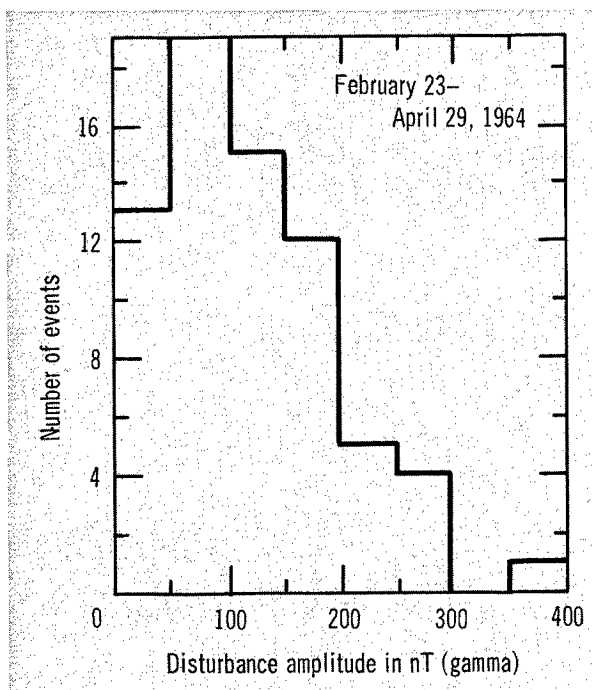


Figure 2.—Amplitude distribution of magnetic storms in the auroral region at 1100-kilometer altitude (ref. 25).

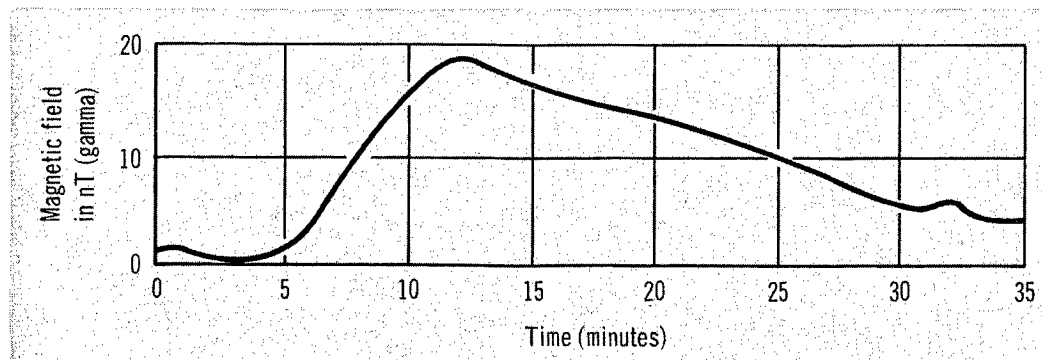


Figure 3.—A sudden impulse-type magnetic disturbance.

4.1.2 Determination of Spacecraft Dipole Moment

Depending on the phase of the spacecraft development program, any one of the following situations may exist:

- (A) The spacecraft dipole moment is known from measurements made on the flight hardware.
- (B) The spacecraft dipole moment is estimated on the basis of measurements made on similar equipment.
- (C) Little similarity with previous spacecraft exists and the estimate of dipole moment must be based on other known parameters of the spacecraft such as mass, mission requirements, and on-board equipment.

These situations are listed in the order of increasing uncertainty regarding the value of M . Generally, the dipole moment will be measured at some point in the program. For situations (B) and (C), only when the analysis has shown the magnetic disturbance torque to have negligible effect on control system performance will it be possible to consider the elimination of direct measurements.

When situation (C) occurs and the designer must establish an initial estimate for the spacecraft dipole moment, it is recommended that the estimate be based on the factors given in table IV. The factors are, of course, related to the stringency of the magnetic properties control program and increase as the control is relaxed. (See table I, sec. 3, for classification of magnetic properties control.)

For spinning spacecraft, the estimated value of M obtained from table IV is the component along the spin axis. For nonspinning spacecraft, the dipole orientation must either be determined from available information regarding equipment location or assumed to be in the worst case orientation, i.e., the direction that imposes the maximum torque burden on the system.

The numerical factors shown in table IV for class III require that sources of usually large dipole moment be avoided or individually compensated and that the use of materials subject to induced magnetism be minimized (sec. 4.2). Without these precautions, the dipole moment per unit mass may be a factor of 10 or more greater than the nominal value shown in the table.

The estimate of the spacecraft dipole moment obtained from table IV may be improved through a comparison of the planned spacecraft with past or current spacecraft for which magnetic properties have been established.

Table IV.—*Factors for Estimating Spacecraft Dipole Moment (M).*

Category of magnetic properties control (see table I)	Estimate of dipole moment per unit mass for nonspinning spacecraft		Estimate of dipole moment per unit mass for spinning spacecraft	
	A-m ² /kg	(pole-cm/lb)	A-m ² /kg	(pole-cm/lb)
Class I	1X10 ⁻³	(0.45)	0.4X10 ⁻³	(0.18)
Class II	3.5X10 ⁻³	(1.6)	1.4X10 ⁻³	(0.63)
Class III	10X10 ⁻³ and higher	(4.5)	4X10 ⁻³ and higher	(1.8)

When the initial analysis indicates that the magnetic torques dominate or are comparable to other major torque sources, a continuing effort must be made to improve the estimate of the dipole moment, culminating in a test of the assembled spacecraft and compensation, if required.

However, even when compensation is employed to reduce the measured dipole moment to a very low value, the design must make allowance for the fact that exposure to levels of magnetic induction of up to 2.5×10^{-3} T (25 gauss) (and more on rare occasions) may be expected during the transportation, prelaunch, and launch phases. As an example of some observed variations, table V gives data for the Tiros and ESSA series of satellites.

A test that measures the magnetic stability of the spacecraft dipole moment is the "perm-deperm" sequence. Generally, the dipole moment is measured (by one of the methods described in app. B) in the "as received" condition. The spacecraft is then exposed to a magnetic flux density of, say, 2.5×10^{-3} T (25 gauss) and the measurement repeated. Finally, the spacecraft is "depermed" (see sec. 4.2.1.5) and the final measurements and compensation, if used, completed.

4.1.3 Magnetic Disturbance Torque Estimates

4.1.3.1 Instantaneous Torque Values

Where mission requirements indicate that a complete analysis of the attitude behavior of a spacecraft is needed, instantaneous torque values must be computed. This may be done by taking the vector cross product of the spacecraft effective dipole moment and the local magnetic flux density (magnetic induction), each expressed in terms of a common reference

Table V.—*Change in Spacecraft Dipole Moment*

Spacecraft	Spin-axis dipole moment measured prior to transportation to launch site		Spin-axis dipole moment in orbit (computed from motion of spin axis)	
	A-m ²	(pole-cm)	A-m ²	(pole-cm)
Tiros II	+0.1	(+100)	+0.9	(+900)
Tiros III	+0.34	(+340)	-.45	(-450)
Tiros V	-.40	(-400)	-.56	(-560)
Tiros IX	+0.08	(+80)	-.02	(-20)
ESSA II	+0.01	(+10)	+0.10	(+100)
ESSA III	.00		+0.10	(+100)
ESSA IV	+0.03	(+30)	+0.35	(+350)
ESSA V	(a)	(a)	+0.05	(+50)
ESSA VI	+0.17	(+170)	-.15	(-150)

Note.—Specified spin axis dipole moment for all spacecraft listed is 0.1 A-m² (100 pole-cm).

(a) Information is not available.

frame. Computer simulations using instantaneous values of all torques, vehicle attitude, and control torques are recommended for the complete analysis.

4.1.3.2 Maximum Magnetic Disturbance Torque

The magnitude of the maximum torque acting on the spacecraft or the magnitudes of the maximum torque components along specific axes (i.e., the control axes) prove to be useful for sizing the control system maximum torque and evaluating system performance when the detailed time history of the magnetic disturbance torque is not of great significance to the designer. An approximation of the maximum magnetic disturbance torque acting on the spacecraft can be obtained by estimating the maximum spacecraft dipole moment and

assuming it to be normal to the magnetic flux density vector, \mathbf{B} at perigee.¹ The magnitude of \mathbf{B} at the magnetic equator (designated B_e) is given in figure 4. The figure is based on a tilted centered dipole model.

The magnitude of \mathbf{B} for any other magnetic latitude can be determined from

$$|\mathbf{B}| = aB_e \quad (4-2)$$

where a is a function of magnetic latitude and is given in figure 5. Figure 6 can be used to convert from geocentric to magnetic latitudes and longitudes.

A similar procedure can be used to establish an upper bound on the torque components. In this case, the magnetic dipole moment must be resolved into components along the axes of the spacecraft (see app. A, fig. A-4). Designating these axes as x , y , and z and the corresponding equivalent dipole moments as M_x , M_y , and M_z , then the torque component in one axis, say x , is

$$T_x = B_z M_y - B_y M_z \quad (4-3)$$

where B_y and B_z represent the magnitude of the field components along axes y and z , respectively. Similar equations for the torque in the other two axes are obtained by cyclic permutation of the subscripts.

If the designer has a priori information regarding the satellite orientation relative to the magnetic field, these equations can be used to determine a bound on the torque components. In the more general case, the upper bound is established by assuming a worst-case orientation at the point where the field is maximum. Thus, if $M_x > M_y > M_z$,

$$\begin{aligned} |T_x|_{\max} &\approx |\mathbf{B}|_{\max} M_y \\ |T_y|_{\max} &\approx |\mathbf{B}|_{\max} M_x \\ |T_z|_{\max} &\approx |\mathbf{B}|_{\max} M_x \end{aligned} \quad (4-4)$$

whereas if $M_x \approx M_y \approx M_z$, the upper bound is

$$|T|_{\max} = \sqrt{2} |\mathbf{B}|_{\max} M_x \quad (4-5)$$

¹For circular orbits or orbits where the eccentricity is near zero, the field strength will be maximum when the subsatellite point reaches the highest latitude.

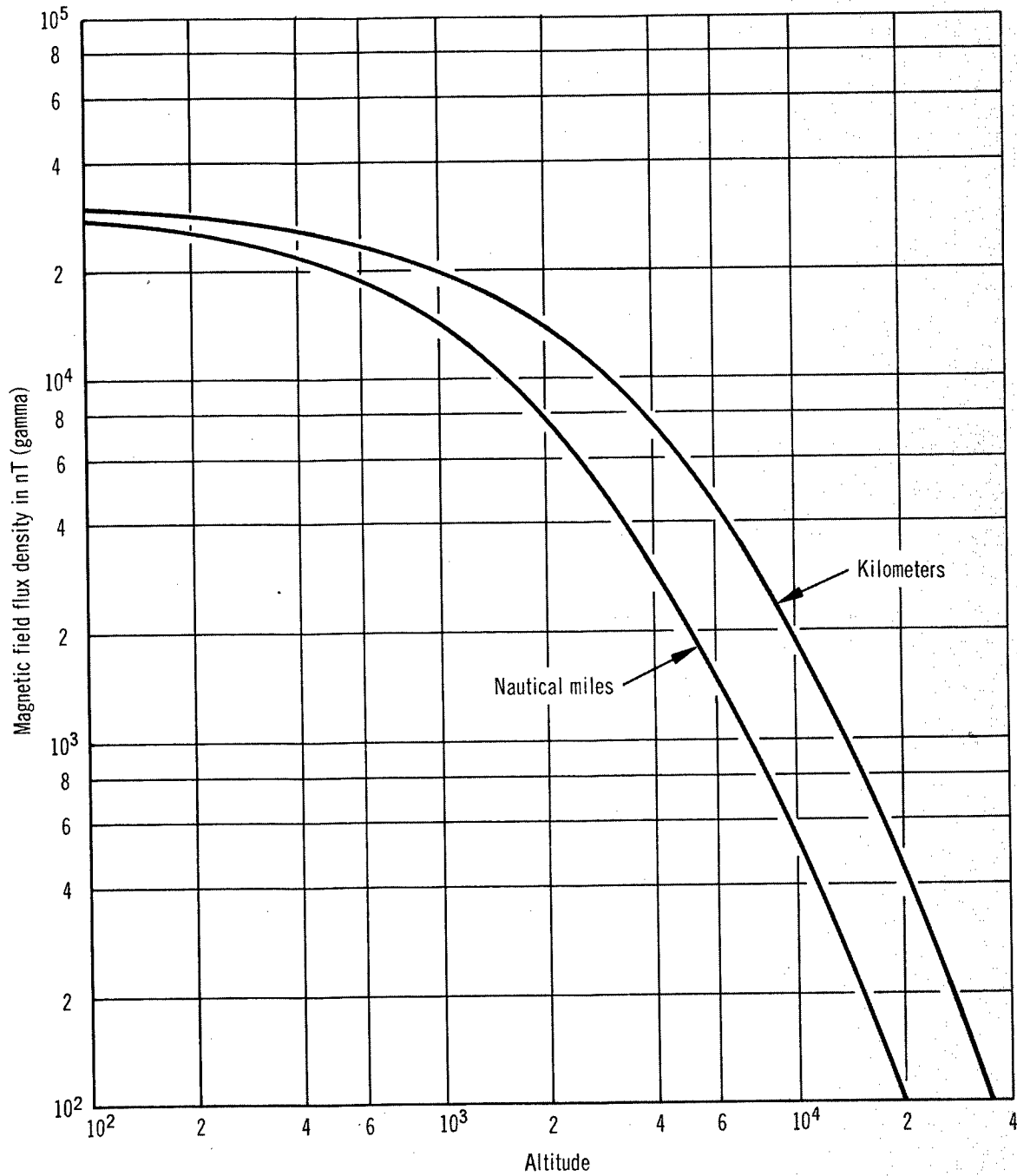


Figure 4.—Earth's magnetic field intensity at the magnetic equator for $M_e = 1 \times 10^{17}$ Wb-m (8×10^{25} pole-cm)

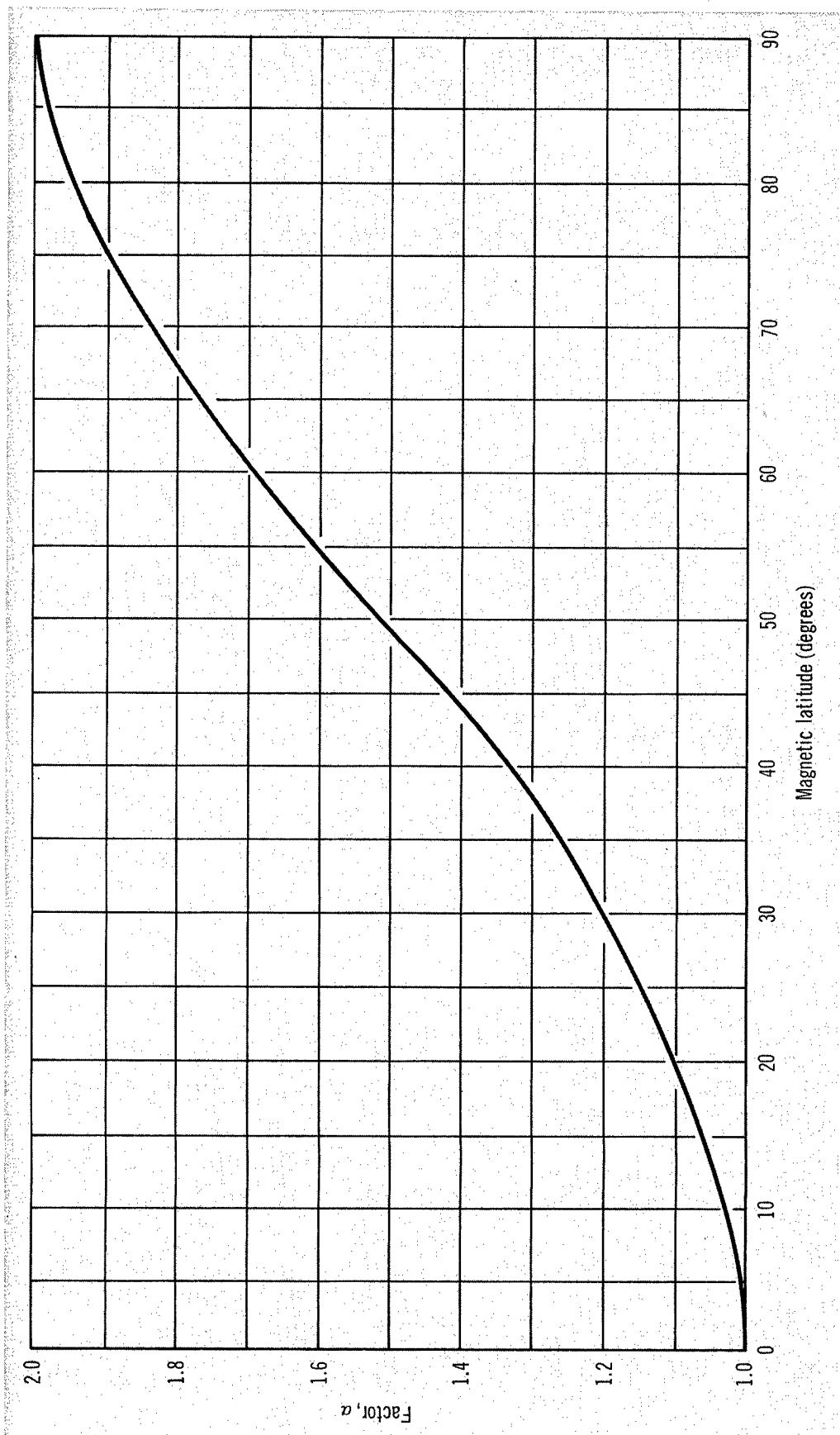


Figure 5.—Multiplication factor for magnetic intensity as a function of magnetic latitude.

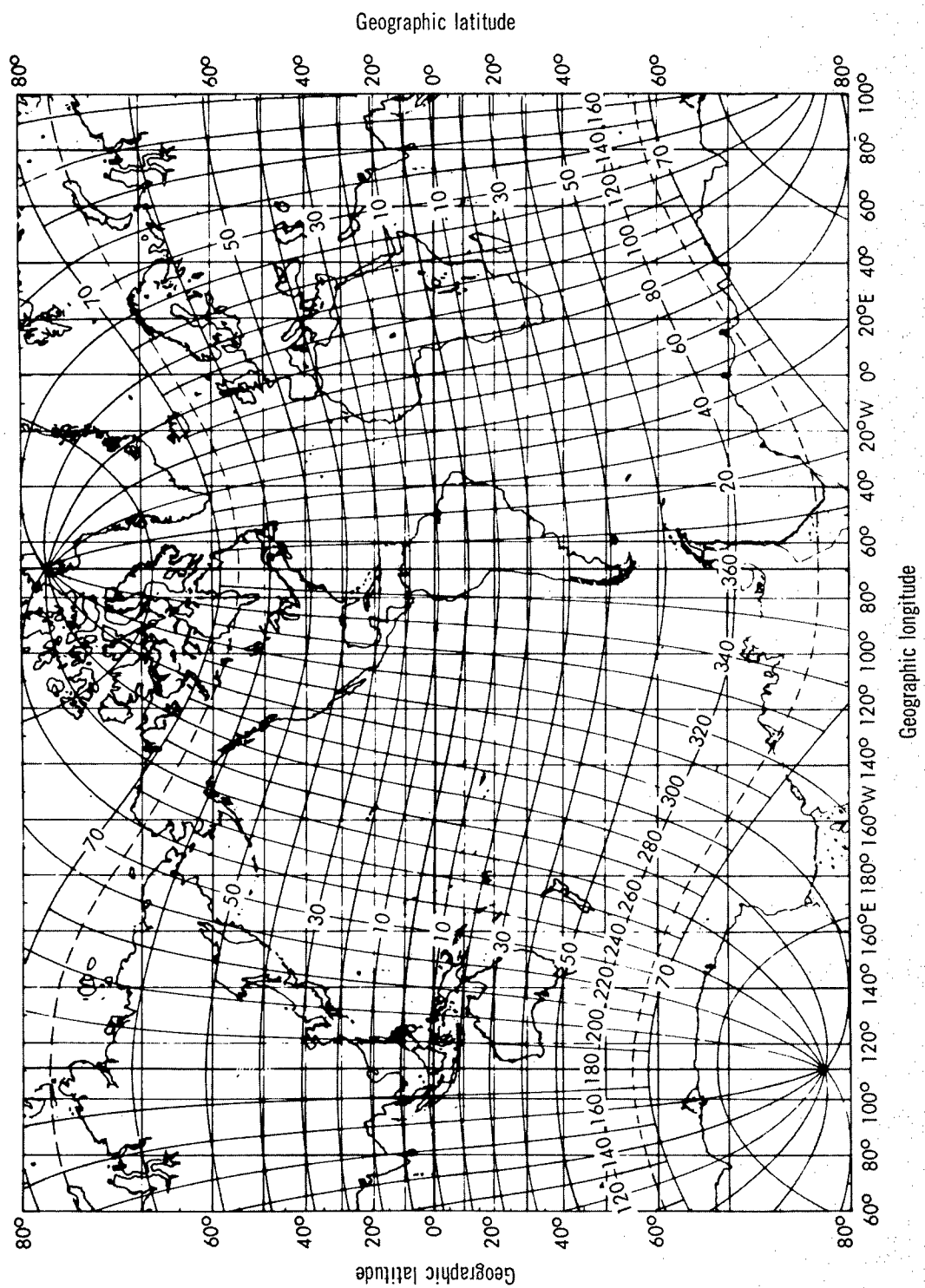


Figure 6. Comparison of geographical and geomagnetic coordinate system. (Curved lines are geomagnetic coordinates superposed on a geographic Mercator projection.)

4.1.3.3 Average Magnetic Disturbance Torque

Where applicable, averaging techniques (ref. 27) can be used to simplify the assessment of the magnetic torque by reducing the number of variables under consideration. In general, the method of employing the techniques, as well as the determination of which parameters can be averaged out of the problem, is specific to the mission, and no universal practice can be recommended. However, certain special situations that occur frequently have been studied extensively and in these cases, procedures are available (refs. 28, 29, 30, 31, and 32).

Average absolute value of disturbance torque.—When the attitude control system incorporates only control jets for control of spacecraft orientation, the average of the absolute value of torque is the appropriate measure of expendable propellant requirements.

Average and cyclical disturbance torques.—When the attitude control system incorporates momentum conserving devices (control moment gyros or momentum storage wheels) and control jets for control of spacecraft orientation, the average value of the disturbance torque is the appropriate measure of expendable propellant requirements and the torque impulse over one-half cycle about the average will be needed to size the momentum storage device.

4.1.3.4 Additional Considerations

Induced magnetism, eddy currents, the motion of conductors in the ambient field, and magnetic disturbances associated with moving parts are not readily translated into contributions to the effective dipole moment M . Each of these effects is a function of spacecraft attitude relative to the magnetic field, spacecraft motion, as well as the instantaneous magnitude of the flux density and is best assessed directly in terms of magnetic disturbance torques and superimposed on the torques resulting from the effective spacecraft dipole moment M .

Additional sources of magnetic disturbance torque that may derive from design characteristics of the spacecraft should be included in the assessment. In particular, attention should be given to effects resulting from the presence of assemblies that rotate relative to each other, e.g., rapidly spinning parts or movable solar panels. (For example, a solar array that completely covers a spinning section can produce a space-fixed dipole moment that does not coincide with the spin axis. Solar commutation of panel-to-bus wiring could then occur, if array interconnection is by panels that are configured around the spin axis. This will produce the effects of a stationary current loop and become a source of magnetic disturbance torque.)

All of the various sources of spacecraft magnetic disturbance torques should be accounted for either in terms of their contribution to the "effective spacecraft dipole moment" M or directly in terms of torque magnitude.

The effective spacecraft dipole moment is the vector sum of individual dipole moments, each of which can be viewed as being rigidly fixed to the spacecraft structure. As a minimum, the effective dipole moment M should include dipoles caused by permanent magnetism and electric current loops in which the current is independent of the local magnetic field. (In most instances, these two effects account for the major part of magnetic disturbance torques.) For purposes of test verification the effective dipole moment M can be viewed as that dipole moment that most closely approximates the distant field produced by the spacecraft when the spacecraft is situated in an otherwise field-free region.

4.1.4 Special Considerations Affecting Spinning Spacecraft

4.1.4.1 Precession Torques on Spinning Spacecraft

For rapidly spinning satellites (i.e., where the orbital period is very much greater than the spin period) only the spin-axis component of the satellite's dipole moment will produce a torque that does not have a zero average value over a spin period. This torque (which is orthogonal to both the spin-axis and the magnetic-field vector) tends to cause precession of the spin axis.

When the satellite attitude with respect to an inertial reference frame varies infinitesimally throughout an orbit (i.e., a spin-stabilized, a stellar, or solar-oriented satellite), the average torque over an orbit is often important. Because M is fixed, the problem becomes that of determining an average value for B . For this computation, the tilted-dipole model for the Earth's magnetic field can be employed. When a longer time average is desired, i.e., a day or longer, the simple spin-axis dipole model is adequate (ref. 6).

4.1.4.2 Despin Torques on Spinning Spacecraft

When the orientation of the spacecraft or a portion of the spacecraft moves with respect to the magnetic field vector, torques caused by induced currents (eddy currents) and the irreversible magnetization of permeable materials (hysteresis effects) must be considered. In general, an accurate assessment of these torques is extremely difficult and simplifying assumptions regarding the shape of the spinning section, its magnetic characteristics, and the nature of the interaction with the ambient field are required to approximate the magnitude of these effects.

In most practical situations, the rotating or moving sections in which eddy currents flow will consist of structural material that has a permeability very nearly equal to that of free space. While eddy currents are also generated in rotating permeable material, the resulting torques are usually negligible compared to torques resulting from magnetization of the material. The following equations for the estimation of eddy current torques on simple geometric figures are based on the assumption that the permeability of the material is equal to that of free space and that the magnetic field caused by the induced currents is so small compared to the ambient field that the field remains uniform. For rotating objects with very high angular velocity (reaction wheels, for example), the latter assumption may be invalid and the equations below will overestimate the despin torque.

4.1.4.3 Eddy Current Effects (Refs. 4, 33, 34, 35)

$$\text{Total torque} \quad T_e = k_e (\boldsymbol{\omega} \times \mathbf{B}) \times \mathbf{B} \quad \text{N-m} \quad (4-6)$$

$$\text{Despin component of torque} \quad T_{se} = -k_e (B_{\perp})^2 \omega_s \quad \text{N-m} \quad (4-7)$$

$$\text{Precession component of torque} \quad T_{\perp e} = k_e \omega_s B_s B_{\perp} \quad \text{N-m} \quad (4-8)$$

$$\text{Spin acceleration caused by eddy current} \quad \frac{\Delta \omega_s}{\Delta t} = \frac{-k_e (B_{\perp})^2 \omega_s}{I_s} \quad \frac{\text{rad}}{\text{sec}^2} \quad (4-9)$$

where

$$\frac{\Delta \omega_s}{\Delta t} = \text{change in spin rate in rad/sec}^2$$

$$\mathbf{B} = \text{ambient magnetic flux density in tesla or weber/meter}^2$$

$$B_{\perp} = \text{component of } B \text{ orthogonal to spin axis in tesla}$$

$$B_s = \text{component of } B \text{ parallel to spin axis in tesla}$$

$$\boldsymbol{\omega} = \text{spacecraft angular velocity vector}$$

$$\omega_s = \text{spin angular velocity in rad/sec}$$

$$I_s = \text{spacecraft spin-axis moment of inertia in kilogram/meter}^2$$

$$k_e = \text{a constant which depends on the geometry and conductivity of the rotating object}$$

(1) For a thin spherical shell of radius r , thickness d , and conductivity σ

$$k_e = \frac{2\pi}{3} r^4 \sigma d \quad (4-10)$$

(2) For a circular loop, located in a plane through the spin axis, with radius r , cross-sectional area S , and conductivity σ

$$k_e = \frac{\pi}{4} \sigma r^3 S \quad (4-11)$$

- (3) For a thin-walled cylinder, with length L , radius r , thickness τ , and conductivity σ

$$k_e = \pi \sigma r^3 L \tau \left(1 - \frac{2\tau}{L} \tanh \frac{L}{2\tau} \right) \quad (4-12)$$

- (4) For a thin-walled cylinder spinning about a transverse axis through the geometrical center, the average torque is one-half of that produced by rotation around the cylinder axis (ref. 34).

4.1.4.4 Hysteresis Damping (Refs. 4 and 22)

When a permeable material is rotated in a magnetic field, energy is dissipated because of the motion of the magnetic domains. The energy loss over any complete period of rotation is constant and is given by

$$\Delta E_h = V \left(\oint H dB_i \right) \quad \text{joules/cycle} \quad (4-13)$$

where

V = volume of the rod in meters³
 $(\oint H dB_i)$ = area of hysteresis loop. Here H is the intensity of the external field in amperes/meter, and B_i is the induced magnetic flux in the magnetic material

Because the energy loss per cycle is independent of spin rate, the spin rate will decrease linearly with time and can actually go to zero (with respect to the ambient field) in a finite length of time.

On Transit 1B this hysteresis effect was used to despin the satellite. Eight rods of AEM 4750, each 31 inches long and 0.25 inch in diameter, were mounted orthogonal to the spin axis. The spin rate decreased from 2.8 to 2.6 rps in 6 days representing an energy loss of approximately 10^{-4} joules/cycle or an average despin torque of 3.2×10^{-5} N-m.

4.2 Control and Minimization of Magnetic Disturbance

When it is necessary to insure that the magnetic disturbance torques do not exceed a specified value, procedures must be established to control the spacecraft dipole moment and other magnetic torque sources, such as current loops and permeable materials. This section presents recommended practices for minimizing magnetic disturbance torques and describes test procedures used to verify that the specified torques are not exceeded.

4.2.1 Minimization of Spacecraft Dipole Moment

When a maximum value for the spacecraft dipole moment is specified, it is essential that a control procedure be initiated at the start of the program and continued throughout design and development. Experience with past spacecraft development programs has shown that the institution of controls midway in the program (to "clean up" a magnetically "dirty" spacecraft) is costly and generally ineffective. In particular, basic precautions for the avoidance of current loops and unnecessary magnetic materials must be incorporated in the design phase.

4.2.1.1 Materials

Avoidance of magnetic materials is more difficult than a casual consideration would indicate because many of the "nonmagnetic" alloys are misnamed. A list of acceptable materials such as that given in references 10 and 15 is necessary. Aluminum, magnesium, titanium, and beryllium are acceptable materials, as are copper and some (but not all) brasses and bronzes, although weight considerations may prevent their use. Electroplated materials must be examined carefully because nickel is often used in the process.

Stainless steel is particularly difficult because even "nonmagnetic" stainless steel (e.g., alloy 304) becomes magnetic when machined. This is a processing effect.

The "misnomer effect" and "mysterious substitution" (ref. 36) are further illustrations of the ways in which unexpected magnetic properties can appear in "nonmagnetic" materials. Thus, sintered tungsten cannot be trusted to be pure tungsten, 18-carat gold may contain iron, etc. "Mysterious substitution" is an example of the seldom documented but frequently observed case of a batch of "nonmagnetic" screws containing three or four that are very definitely magnetic. Unless care is exercised, significant dipole moments can be caused by such items as nuts, bolts, screws, threaded inserts, washers, rivets, etc.

Close control over materials must include: (1) knowledge of the materials; (2) knowledge of the suppliers; (3) documentation of approved materials and sources; and (4) inspection. In addition, preference is to be given to magnetically "hard" over magnetically "soft" materials, and long and narrow shapes are to be avoided. Here a "hard" magnetic material means a material in which the magnetic moment is essentially unchanged by small changes in the field around it, whereas, conversely, the magnetic state of a "soft" material is predominantly determined by the ambient field. Generally, "hard" magnetic materials are also physically hard (i.e., a high Brinell hardness number) and conversely for magnetically soft materials. Alnico V and cobalt steel are magnetically hard, while Mu-metal and mild steel are examples of soft magnetic materials.

4.2.1.2 Components

In some functional spacecraft components, use of magnetic materials is unavoidable. Typical items that generally produce substantial dipole moments are traveling-wave tubes, tape recorders, latching relays, batteries, motors, gyros, coaxial switches, circulators, photo-multiplier tubes, and solenoid valves. The best practice is to perform a routine check (with a magnetometer or compass) on suspicious components and, preferably, on all components.

Components having a large dipole moment should be paired to produce cancellation, or if this is not feasible, they should be individually compensated. It must be recognized that because of temporal instabilities of the dipole moment of equipment or the compensating magnets, complete cancellation is not practical.

Shielding, i.e., enclosing the offending component in a container of highly permeable material, can create problems in the functioning of the shielded component (ref. 37). Shielding should, therefore, be avoided as a means of reducing the dipole moment of a component containing functional magnets. If essential, a shield can be used to reduce the external effects of dipole moment variations caused by moving magnetic parts. A preferred practice, if functionally feasible, is to mount a compensating magnet on the moving part.

Small components used in large quantities lead to significant dipole moments (ref. 11). Thus, many electronic components, such as transistors and capacitors, have nickel cases and nickel-plated leads; metal-to-glass seals are usually Kovar (a magnetic material); connectors contain mostly nonmagnetic material, but occasionally magnetic lock washers and compression washers find their way into the assembly; and shielding on coaxial cables will often be magnetic. Wire should, in general, be checked because nickel plating of conductors is frequent.

4.2.1.3 Current Loops

Current flowing in the solar array can be a major contributor to the spacecraft dipole moment unless proper wiring is included in the design. The recommended technique is to route current return wires directly behind the solar cells (backwiring). This minimizes loop area, and the technique is effective when portions of the array will be switched on and off (ref. 13). Twisting of leads in wiring harnesses is also recommended. However, there is a compromise between reliability and minimization of dipole moment that must be considered, because twisting of the wires may lead to insulation failure.

Ground currents are often neglected as a potential source of current loops. Unless care is exercised in grounding, particularly through the use of single-point grounding, a current loop of substantial area may exist. Batteries, regardless of the material used for the case of

the electrodes, will have a dipole moment caused by current flow. To avoid this, batteries should be used in pairs so as to produce dipole moment cancellation or, if an odd number is essential, a loop of wire in series with the battery can be used to cancel the moment.

4.2.1.4 Processing and Handling

The more stringent magnetic properties control programs should include specifications to cover handling and processing procedures. The aim of such procedures is the avoidance of such sources of contamination as metal particles being picked up in storage or mixing of nonmagnetic potting compounds or the embedding of magnetic particles during machining of nonmagnetic materials. Also, attention must be given to the tools and handling techniques used, particularly when the assemblies in process have been depermed and magnetization must be avoided.

4.2.1.5 Deperming

Deperming of parts and assemblies is recommended for all programs having magnetic control. In addition, for Class I magnetic control programs, special precautions and procedures are essential in handling and installing depermed assemblies.

Deperming of the spacecraft will reduce the dipole moment if it is initially quite large (greater than 1.0 A-m^2 (1000 pole-cm)). The effectiveness of deperming the spacecraft depends on the magnetic hardness of the assembly and subsequent exposure to magnetic fields. Where possible, deperming in the Earth's ambient field should be avoided.

4.2.2 Minimization of Spin Decay

Hysteresis and eddy current losses in spinning spacecraft can normally be reduced to negligible levels through the observation of good design practices.

Hysteresis effects are appreciable only in soft magnetic materials having long, rodlike shapes $\left(\frac{\text{length}}{\text{diameter}} \gg 1\right)$. When such characteristics are unavoidable, the component should be aligned with its axis parallel to the spin axis. Note, however, that this conflicts with the practice of attempting to align assemblies with their dipole moment orthogonal to the spin axis so as to minimize the spin-axis component of spacecraft dipole moment.

Eddy current losses are significant only on rapidly spinning spacecraft and the effect diminishes very quickly with increasing geocentric distance (i.e., as $1/R^6$). Conducting paths that enclose appreciable area in a plane through and including the spin axis should be avoided. These paths occur primarily in the structure and skin of the spacecraft, hence the insertion of insulating material may require trade-off consideration between spin decay and structural integrity. Figure 7 shows the eddy currents in a thin rotating shell. The ideal solution would be to laminate the shell into thin rings. A practical compromise (similar to the technique used on the Tiros satellites) is vertical insulation as shown in figure 7. However, if the assembly consists of several sections where the separation plane is normal to the spin axis, insulation should be applied at these separation planes.

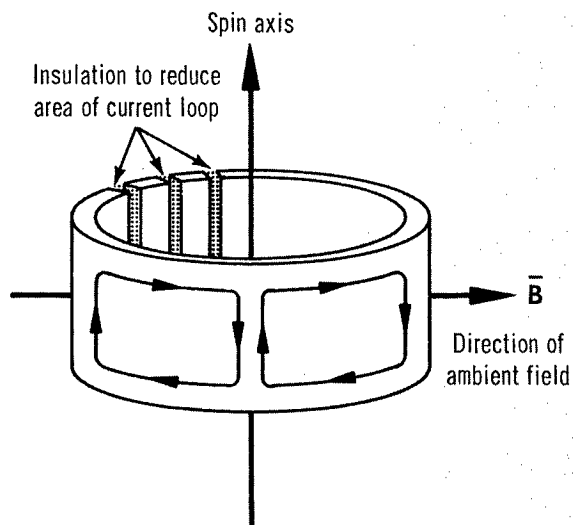


Figure 7.—Illustration of induced current loops.

Measurement and separation of hysteresis and eddy current losses can be accomplished in test facilities capable of producing a rotating magnetic field (see app. B and ref. 41). However at present, these techniques are not in widespread use, and published test data are not readily available.

4.2.3 Dipole Measurement and Compensation

4.2.3.1 Components and Subassemblies

Testing at this level is to be viewed as a quality control measure and should be confined to measurement with a magnetometer. An exception to this is the determination of the dipole moment of an assembly for cancellation purposes either by pairing or compensation. A measurement technique appropriate for this purpose is described in section 4.2.3.3. When compensating, the permanent magnet should be located as close as possible to the assembly or component being compensated.

4.2.3.2 Dipole Measurement

Tests that can be performed on a spacecraft depend to a large extent on the available facilities. (See app. B.) When possible, a measurement of the dipole moment should be obtained in the deployed, or orbital configuration with all systems activated.

4.2.3.3 Measurement Techniques

Measurements of magnetic properties are based either on torque measurement or magnetic field plots. For the assessment of disturbance torques, methods based on torque measurement are preferable. The techniques described in appendix B are representative of those most widely used in determining dipole moment.

4.2.4 Compensation

Compensation consists of affixing to the spacecraft a permanent magnet whose dipole moment is equal and opposite to that of the spacecraft. The use of three orthogonal components of the dipole moment is an equivalent procedure.

Generally, the spacecraft dipole moment is determined using one of the test methods described in appendix B. Compensation magnets are then added and the measurement repeated. Because the addition of the permanent magnets will cause a change in induced effects, the dipole moment after addition of the compensating magnets will rarely correspond to the difference between the initially measured moment and the compensating moment. Further, the value achieved will normally depend on the location of the compensating magnets. When the initial dipole moment is 1 A-m² (1000 pole-cm) or greater, compensation is best accomplished in several stages, using small trim magnets for the final stage.

Appendix A

COORDINATE FRAMES AND NOMENCLATURE

In the assessment of magnetic torques several different reference frames are employed. Additionally, the nomenclature for the various magnetic-field quantities often differ from that used in the literature of geomagnetism. The purpose of this appendix is to define the reference frames used in the text and relate the nomenclature to terms used elsewhere. Where possible, the standard coordinate systems defined in reference 38 are used.

The five reference axes are illustrated and described in figures A-1 through A-4 as follows:

Figure	Reference frame	Base vectors
A-1	Geocentric inertial frame	X_I, Y_I, Z_I
A-2	Earth fixed frame	X_E, Y_E, Z_E
A-2	Polar coordinate frame	X_B, Y_B, Z_B
A-3	Orbital (or local vertical) frame	X_F, Y_F, Z_F
A-4	Vehicle (or principal body axes) frame	X_S, Y_S, Z_S

Figure A-5 and table A-1 relate the nomenclature and coordinate system encountered in the literature of geomagnetism to the nomenclature and coordinate system used in this document.

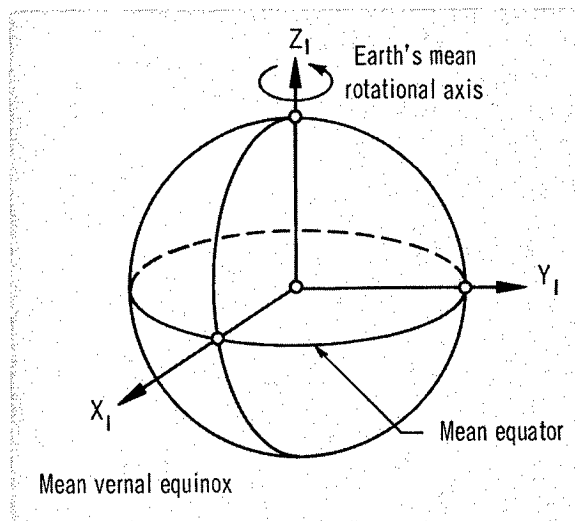


Figure A-1.—Geocentric inertial reference frame (I-frame).

Type: Nonrotating, Earth referenced.

Origin: The center of the Earth.

Orientation and labeling:

The Z_I -axis is directed along the Earth's mean rotational axis, positive north.

The X_I -axis is directed toward the mean vernal equinox.

The Y_I -axis completes a standard right-handed system.

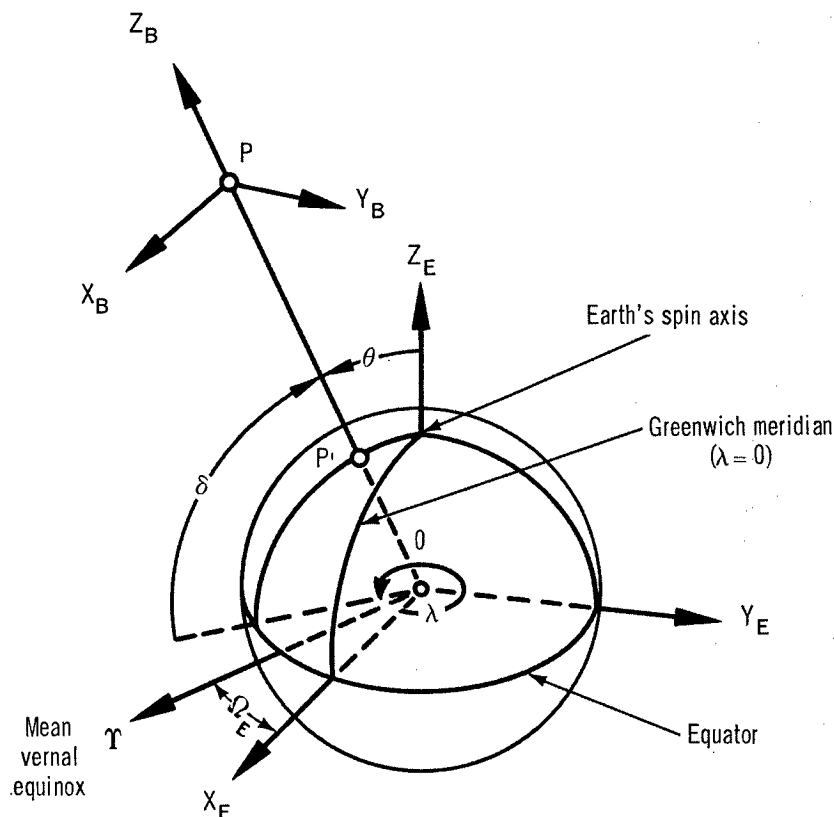


Figure A-2.—Earth fixed frame (E-frame) and polar coordinate frame (B-frame).

E-frame

Type: Rotating, Earth referenced.

Origin: The center of the Earth.

The Z_E -axis is directed along the Earth's mean rotational axis, positive north.

The X_E -axis is positively directed through the Earth's Equator at the meridian of Greenwich.

The Y_E -axis completes a standard right-handed system.

B-frame

Type: Rotating, Earth referenced.

Origin: Space point P.

The Z_B -axis is directed along the radius connecting point P to the Earth's center positive outward.

The X_B -axis is directed along the local meridian toward increasing θ .

The Y_B -axis completes a standard right-handed system.

- | | | |
|------------|---|--|
| P' | = | the point on the Earth's surface on the line joining O and P |
| R | = | distance from Earth's center to P |
| R_e | = | distance from Earth's center to P' = mean Earth radius = 6371.2 kilometers |
| Ω_E | = | the right ascension of the Greenwich meridian measure positive eastward |
| λ | = | geocentric longitude, measured positive eastward from the Greenwich meridian to the meridian containing P' |
| δ | = | geocentric latitude (declination measured positive north from the Earth's mean equator) |
| θ | = | geocentric colatitude = $90^\circ - \delta$ |

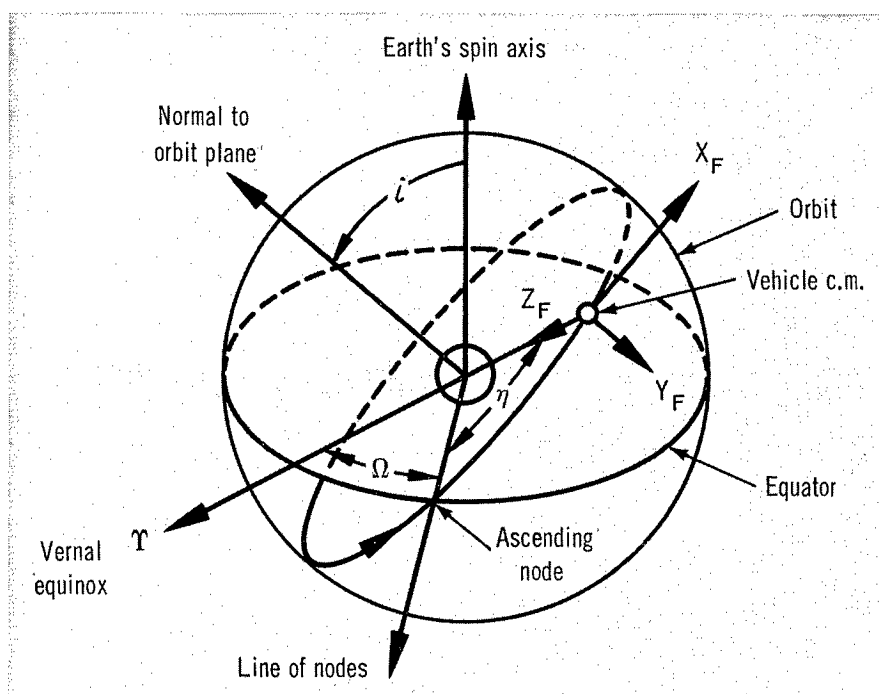


Figure A-3.—Orbital reference frame (F-frame).

Type: Rotating, Earth referenced.
 Origin: Vehicle center of mass.

The Z_F -axis is along a line joining the Earth's center and the vehicle's center of mass, positive toward the Earth.

The X_F -axis is in the orbital plane normal to Z_F and positive in the sense of forward motion along the orbit.

The Y_F -axis completes a standard right-handed system.

Ω = the angle in the equatorial plane between the vernal equinox and the ascending node

i = the orbital inclination = the angle between the equatorial plane and the orbital plane = the angle between the Earth's spin axis and the normal to the orbital plane.

η = an angle locating the vehicle in orbit measured from the ascending node.

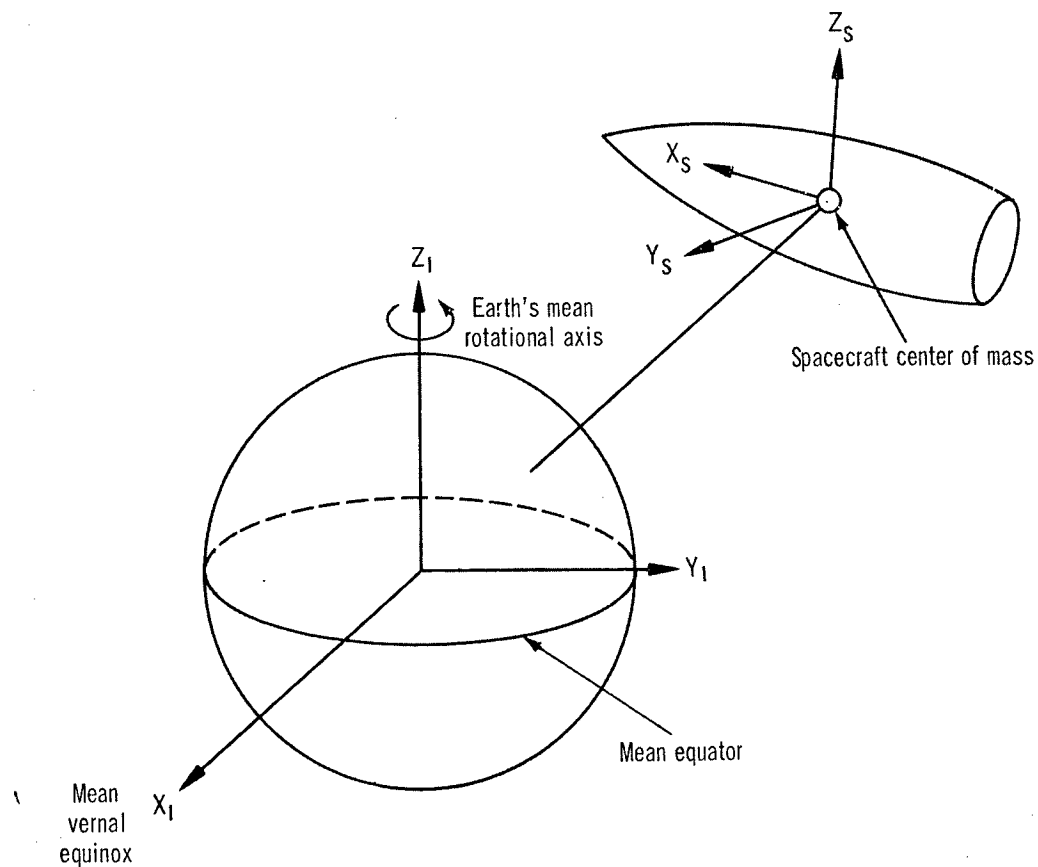


Figure A-4.—Spacecraft (principal body axes) frame (S-frame).

Type: Rotating, vehicle referenced.

Origin: Vehicle center of mass.

The X_S -axis is along the vehicle longitudinal axis of symmetry.

The Y_S -axis is a principal axis of inertia.

The Z_S -axis is a principal axis of inertia orthogonal to the X_S and Y_S plane.

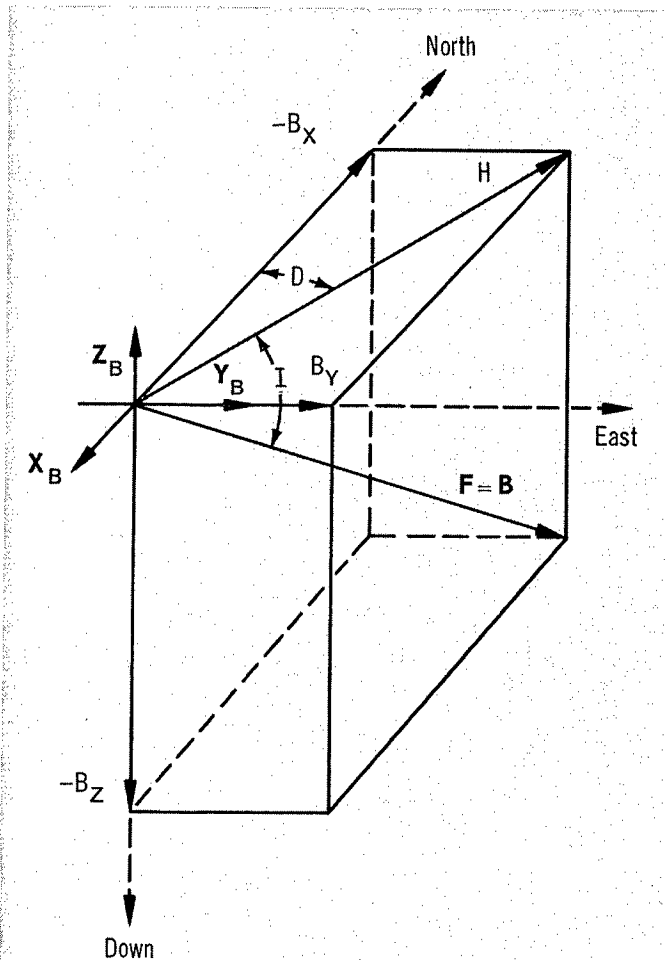


Figure A-5.—Geometry and nomenclature of the magnetic field elements.

- $-B_X$ = North magnetic field component; i.e., the projection of \mathbf{B} onto a north-south line.
 B_Y = East magnetic field component, i.e., projection of \mathbf{B} onto a line in the eastward direction.
 $-B_Z$ = Vertical downward magnetic field component; i.e., the projection of \mathbf{B} onto a radial line from the Earth's center.
 H = $[(-B_X)^2 + B_Y^2]^{1/2}$
 = Horizontal component of Earth's magnetic field; i.e., the projection of \mathbf{B} onto a plane perpendicular to a radial line from the Earth's center. (Not to be confused with symbol for magnetic field intensity.)
 I = $\tan^{-1}(-B_Z/H) = \tan^{-1}[-B_Z/(B_X^2 + B_Y^2)^{1/2}]$
 = magnetic inclination (dip angle); i.e., the angle between the vector \mathbf{B} and horizontal component H .
 D = $\tan^{-1}(B_Y/-B_X)$
 Magnetic declination; i.e., the angle between H and the north magnetic field component.

Table A-1.—Comparison of the Nomenclature Used in Geomagnetic Literature With That Used Herein

Geomagnetic nomenclature	Monograph equivalent
F	B
D	D
I	I
X	$-B_X$
Y	B_Y
Z	$-B_Z$

Note.— $-B_X$, B_Y , and B_Z are the components of \mathbf{B} on the vectors X_B , Y_B , and Z_B , respectively.

Appendix B

TECHNIQUES FOR MEASUREMENT OF SPACECRAFT MAGNETIC PROPERTIES

Ambient Field Mapping

In this technique the effective dipole moment is obtained by measuring the change in the ambient field caused by the presence of the equipment to be measured. The spacecraft is rotated in a (nonmagnetic) fixture and magnetometer measurements are made as a function of angle of rotation (fig. B-1). The resolution of the magnetometer will determine how far away it can be placed, which should be as far as possible. When small dipole moments are to be measured, requiring close placement of the magnetometer, the measurement may be affected by changes in the distance from the magnetometer to local dipole sources as the spacecraft is rotated. This may be partially offset by the use of two magnetometers on opposite sides, equidistant from the center of rotation.

Generally, the magnetometer is a single-axis device and the data obtained will thus give the radial component of the magnetic field at a number of selected locations on a spherical surface. Using integral equations (ref. 39) three orthogonal components of the spacecraft dipole moment can be calculated.

This method is subject to the following limitations: (1) temporal variations in the Earth's field cause measurement noise; (2) moments are induced by the Earth's field, and these are time and position dependent; and (3) data reduction is time consuming unless machine computation is available.

The measurement resolution of the field-mapping technique is in the range of 2 to 5 percent of the dipole moment measured.

Mapping in a Field-Free Region

Field-free regions are produced by shielded magnetic enclosures or by coil arrangements that cancel the ambient field. The latter is the most commonly used system and, when coupled with instrumentation that measures the Earth's field and adjusts the coil currents accordingly, compensation for temporal variations in the Earth's field is also obtained.

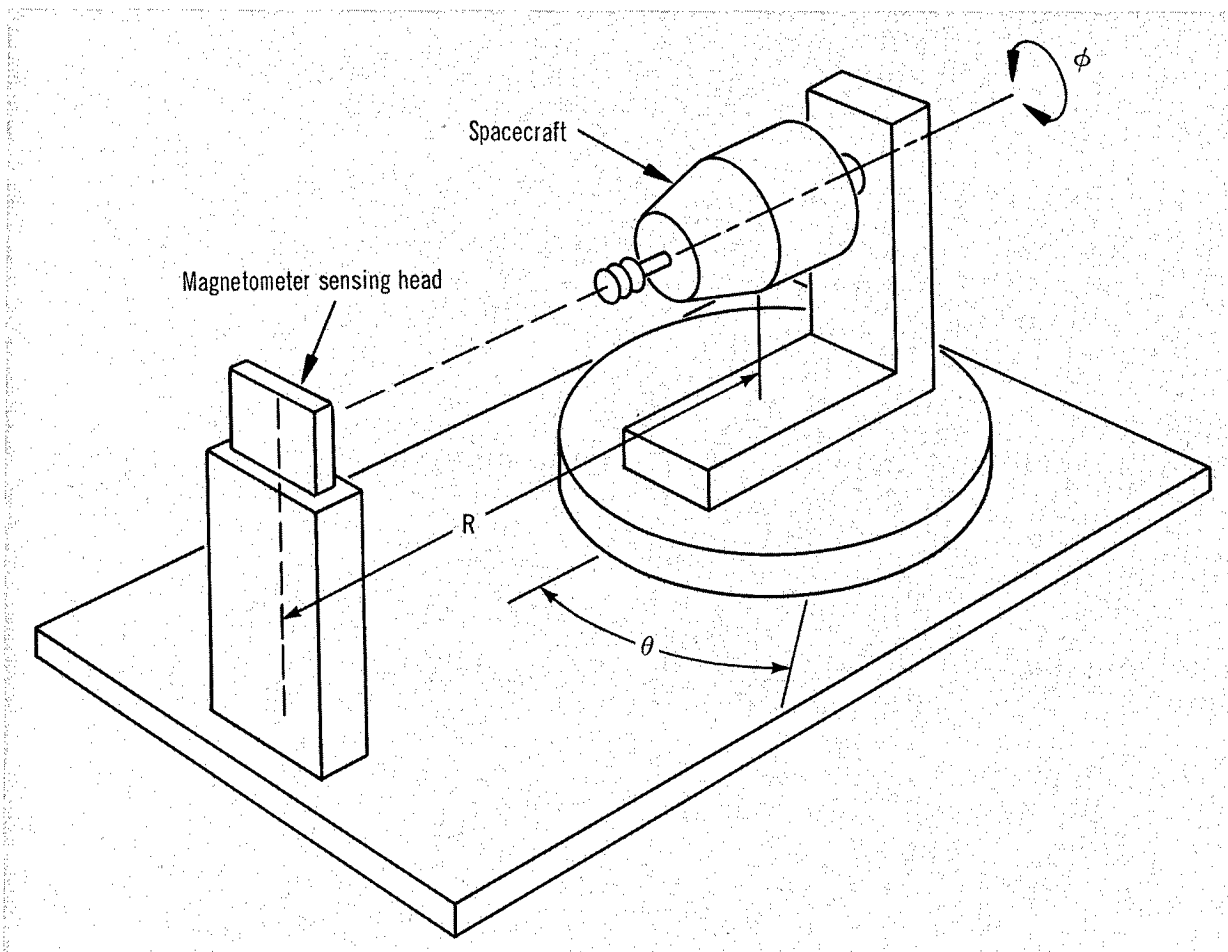


Figure B-1.—Fixture for magnetic field measurements (from ref. 39).

The major problem associated with this technique is that to produce a large field-free volume is difficult and expensive. Thus, relatively few facilities have the capability of making measurements of this nature on a large spacecraft. The method can be employed, however, to measure the dipole moment of small spacecraft and assemblies of the larger spacecraft.

The data are obtained in the manner described above and the same limitation regarding data reduction applies. However, when it is known that the assembly is characterized almost entirely by its dipole moment (i.e., higher order moments are small in comparison), the technique described in reference 40 and outlined below provides a means for rapidly measuring the direction and magnitude of M .

To measure the dipole moment, the assembly is placed on a table capable of rotation around two orthogonal axes (pitch and yaw) and the magnetometer located at a distance in the plane orthogonal to the yaw axis with its sensitive axis aimed at the assembly. Figure B-2 illustrates a gimbal system used for such measurements. With the pitch position at zero, a rotation is made around the yaw axis until the peak reading on the measurement is obtained. Then with the yaw axis locked, a rotation is made around the pitch pivot until a peak is found. The dipole axis is located in azimuth and elevation and the magnitude of M is obtained from

$$|M| = \frac{Br^3}{2} \times 10^7 \quad \text{ampere-meter}^2 \quad (\text{B-1})$$

where r is the distance from the magnetometer to the center of rotation in meters and B is the maximum flux density obtained from the magnetometer reading in tesla. If r is measured in centimeters and B in gauss, the factor 10^7 does not appear in the equation and $|M|$ is obtained in pole-cm. When using this technique, the distance r should be sufficiently large to insure that the field caused by the higher order multipoles is negligible compared to the dipole field.

With this technique, the orientation of M can be determined to within 1° and the magnitude measured with a resolution of 1 to 2 percent.

Direct Torque Measurements, Coilless Systems

If the spacecraft is suspended or placed on a platform floating in a fluid, the horizontal component of the Earth's field and the dipole moment in the horizontal plane (for the particular mounting position) will cause a torque about the suspension. If the local field is accurately known and if the (generally small) torque can be measured, then the component of M in the horizontal plane can be determined. Reorienting the spacecraft so that the axis that was initially vertical now lies in the horizontal plane and repeating the measurement allows the magnitude and direction of M to be determined.

The accuracy is limited by (1) the precision of measuring the average value of the horizontal component of the Earth's field, and (2) difficulties associated with the measurement of an extremely small torque.

In the coilless technique, measurement resolution is 0.030 to 0.050 A-m² (30 to 50 pole-cm).

Direct Torque Measurement, Controlled Field

This test method is used at the Goddard Space Flight Center Magnetic Test Facility; it is described in detail in reference 41.

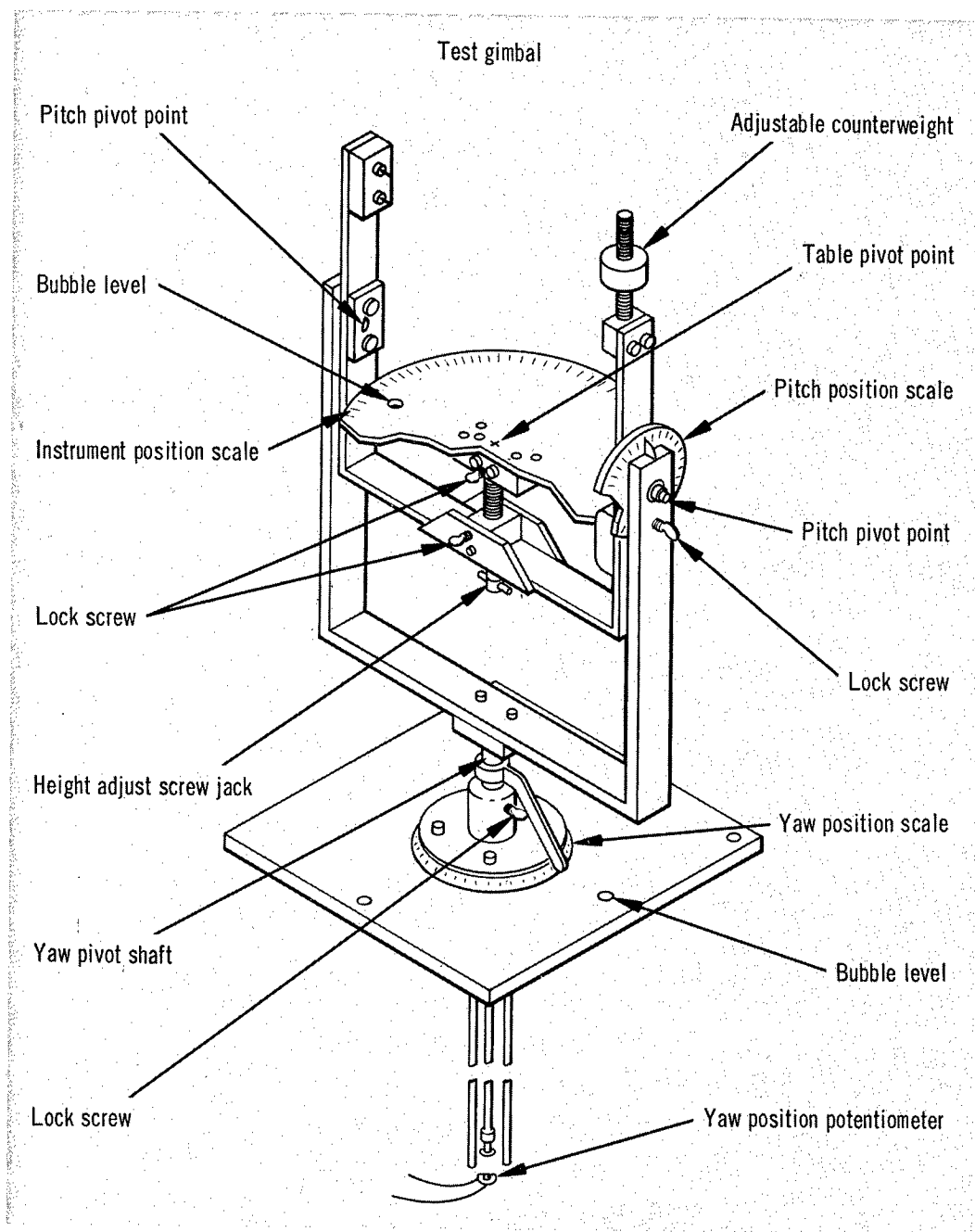


Figure B-2.—Gimbal system for magnetic mapping in a field region (from ref. 40).

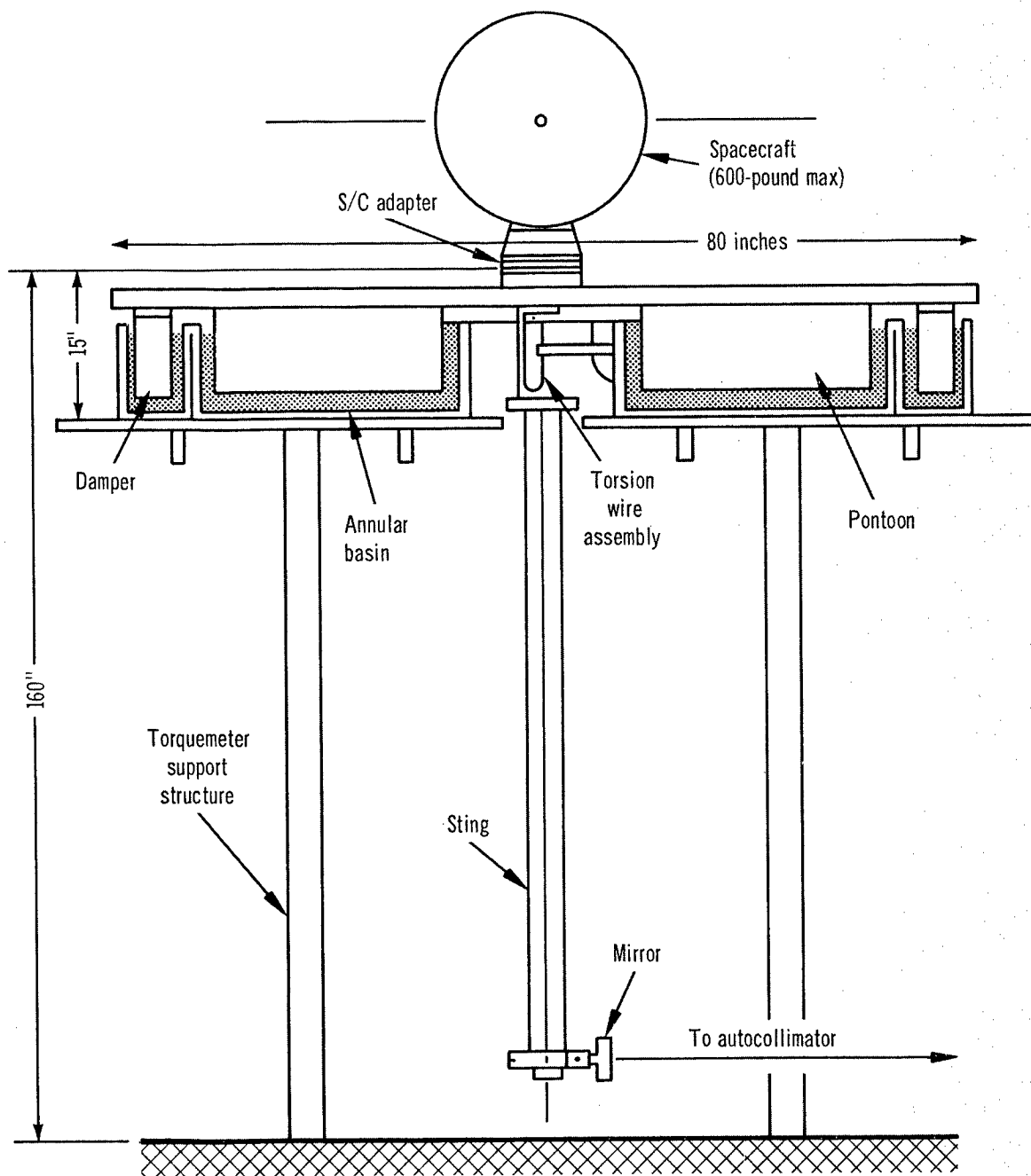


Figure B-3.—The Goddard Space Flight Center magnetic torquemeter apparatus (from ref. 41).

The platform and details of the suspension are shown in figure B-3. The fluid in the annular basin is water. The entire apparatus is located within a spherical coil system in a region where the magnetic field direction and magnitude can be carefully controlled. By observing the deflection of the floated portion of the apparatus in the presence of a magnetic field, it is possible to make a direct measurement of the torque produced by a component of the spacecraft dipole moment. Explicitly, if the satellite x -axis is aligned along the direction of the angle measuring autocollimator line of sight (which coincides with the equilibrium position of the torsion wire restraint) and if a magnetic field is then applied along the y -axis, the component of the magnetic dipole moment in the x -direction will cause the platform to rotate through an angle θ which is measured by the autocollimator. M_x is obtained from:

$$M_x = \frac{k_t \theta}{B_y} \quad \text{A-m}^2 \quad (\text{B-2})$$

where

- k_t = torsion wire spring constant in N-m/radian
- θ = measured angular deflection from the rest position in radians
- B_y = magnetic flux density in the y -direction in tesla

The field is then rotated 90° in the horizontal plane and the effective satellite dipole in the y -direction, M_y , determined.

To measure the z -component, the spacecraft is rotated 90° about an axis in the x - y plane.

Factors that contribute errors in the measurement are: (1) air currents in the vicinity of the test apparatus; (2) currents and surface tension in the flotation fluid; and (3) vibration affecting the autocollimator readout mirror.

Table B-1 gives typical measurements using the test technique and indicates the accuracy attained.

There are presently available at Goddard Space Flight Center three instruments for the direct measurement of magnetic torques. The capacities of these instruments are 100, 600, and 5000 pounds.

Pulse Resonance Technique

The pulse resonance technique is described in reference 42. It is similar to the method described in the previous section except that the entire weight of the spacecraft is supported by a multifilar suspension. Figure B-4 shows a diagram of this apparatus.

Table B-1.—Accuracy of Direct Torque Measurement in a Controlled Field (Ref. 41).

Test no.	Actual dipole strength, (A-m ²)	Measured dipole strength (A-m ²)	Percent error
1	1.130	1.152	1.91
2	2.055	1.998	2.85
3	2.835	2.736	3.62
4	5.321	5.453	2.42
5	118.500	113.800	4.13

To circumvent the loss of accuracy caused by the stiffer torsion suspension, the spacecraft and torsion wire are excited at their resonant frequency. This frequency is measured by observing the torsional oscillations of the suspended spacecraft over many periods of oscillation.

To determine the satellite's magnetic dipole moment in the x -direction, M_x , the satellite is suspended with the z -axis vertical and a square-wave magnetic field is pulsed along the y -axis at the resonance frequency. The shape of the applied wave and the resulting satellite motion are shown in figure B-5. The slope of the line which envelops the increasing angular oscillations is proportional to the magnitude of M_x . Explicitly, M_x is determined from

$$M_x = \frac{I_z \omega_0^2 m}{2B_m} \text{ A-m}^2 \quad (\text{B-3})$$

where

- I_z = satellite moment of inertia about the z (vertical) axis in kg-m²
- ω_0 = resonant angular frequency in rad/sec
- m = slope of the envelope of the oscillation peak amplitudes in radians/cycle (dimensionless)
- B_m = peak flux density in tesla

M_y and M_z are determined in a similar manner.

The effects of air currents can be reduced by enclosing the spacecraft and torsion wire within a plastic air-motion shield.

Sources of error in the measurement arise from: (1) variations in the average field during the measurement; and (2) deviation between the applied square wave and the true period of oscillation.

Under carefully controlled conditions (air currents, etc.) a resolution of 0.025 to 0.050 A-m² (25 to 50 pole-cm) in measuring components of M can be obtained.

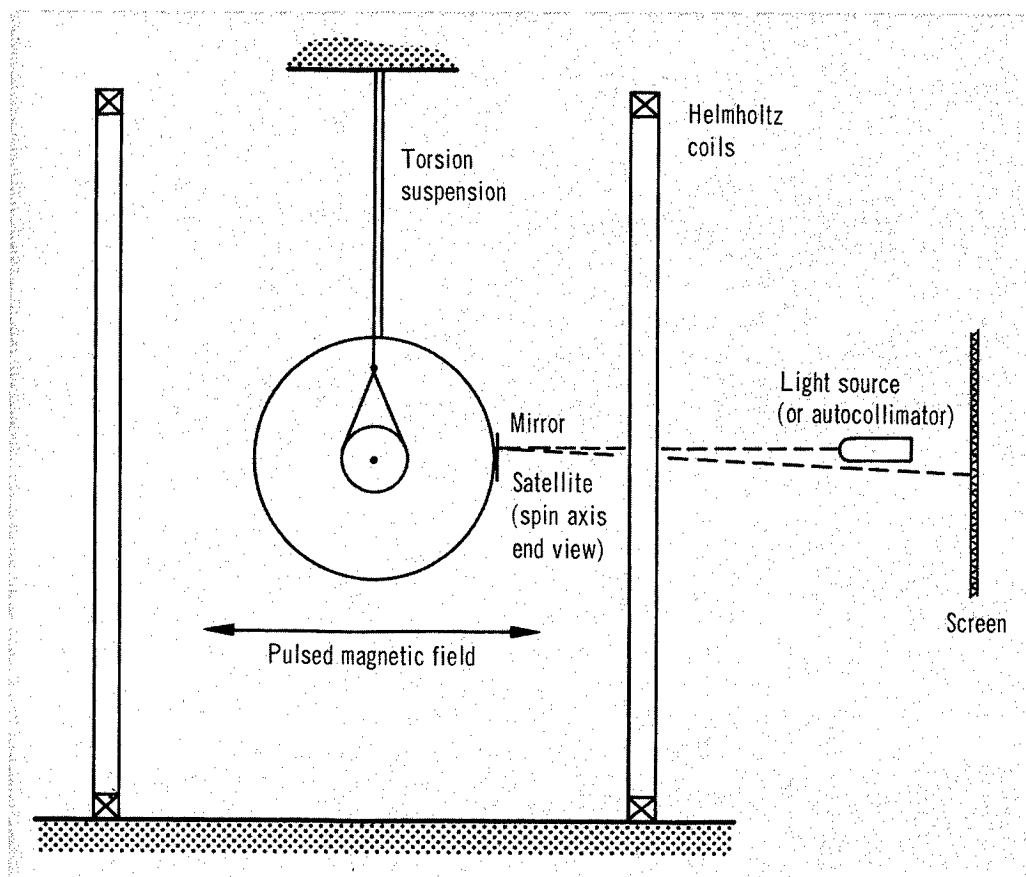


Figure B-4.—Measurement of small magnetic dipole by resonant pulsing (from ref. 42).

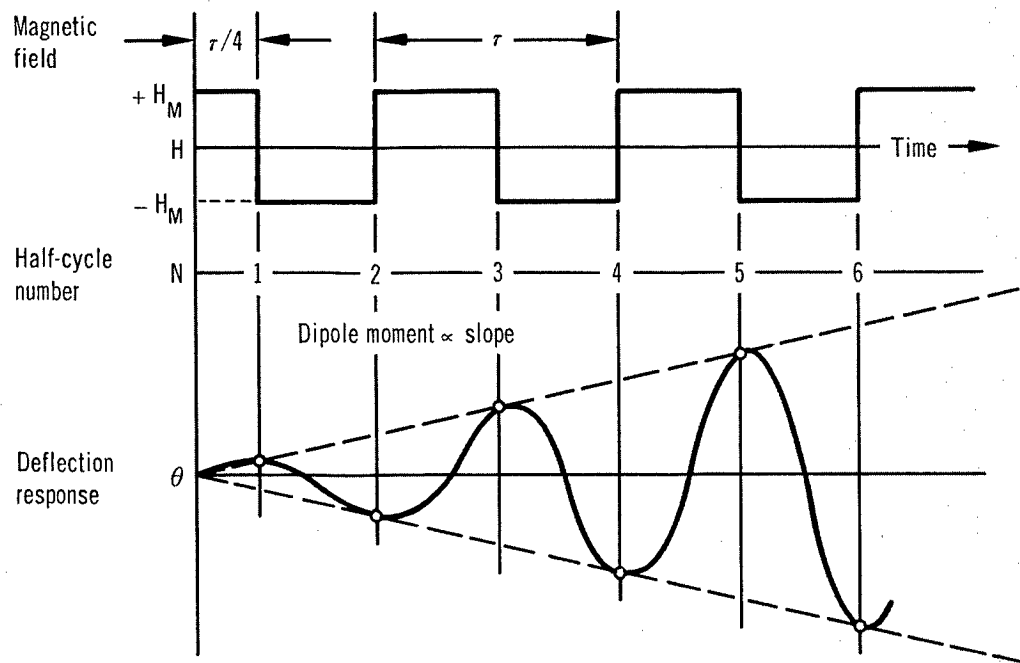


Figure B-5.—Magnetic field and deflection response (from ref. 42).

Appendix C

SYMBOLS

B	magnetic flux density vector
B_e	magnetic of B at the magnetic equator
B_i	field for particular model
B_{ref}	reference field
B_s	component of B parallel to spacecraft spin axis
B_X, B_Y, B_Z	components of B in the B-frame (i.e., on the X_B, Y_B, Z_B base vectors)
B_{\perp}	component of B perpendicular to spin axis of spacecraft
ΔE_h	energy loss over a complete period of rotation caused by hysteresis
I_s	spacecraft spin-axis moment of inertia
k_e	constant that depends on the geometry and conductivity of the rotating object
M	magnetic dipole moment of spacecraft
M_e	Earth's magnetic dipole moment
M_s	spin-axis component of spacecraft dipole moment
M_X, M_Y, M_Z	components of M along the control axis of the spacecraft
R	radius vector from geocenter to a point in space
R_e	mean radius of Earth
T_e	total torque caused by eddy current
T_m	vector magnetic torque acting on spacecraft
T_s	despin component of torque caused by eddy current
T_X, T_Y, T_Z	components of torque along axes of spacecraft
T_{\perp}	precession component of torque caused by eddy current
a	a function of magnetic latitude (fig. 5)
ω	spacecraft angular velocity vector
ω_s	spin angular velocity
$\Delta\omega_s/\Delta t$	change in spin rate per unit time

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