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CLOUTIER, Paul Andrew, 1943-
VECTOR MEASUREMENT OF THE MID-LATITUDE Sq
IONOSPHERIC CURRENT SYSTEM.

Rice University, Ph.D., 1967
Geophysics

University Microfilms, Inc., Ann Arbor, Michigan

RICE UNIVERSITY

VECTOR MEASUREMENT
OF THE
MID-LATITUDE Sq IONOSPHERIC
CURRENT SYSTEM

by
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CLOUTIER

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY
IN
SPACE SCIENCE

THESIS DIRECTOR

A handwritten signature in black ink, reading "Robert C. Hoyme". The signature is written in a cursive style with a large, looping "R" and a long, sweeping "H".

Houston, Texas

March, 1967

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I. Introduction

The objective of the research described herein is to present and evaluate the results of two rocket-borne vector magnetometer experiments. These experiments were designed to detect and measure the vector components of the magnetic field due to the ionospheric current layer associated with the solar quiet daily magnetic variation. Direct vector measurements of this current system have not previously been made. The experiments were conducted in November, 1965 and February, 1966.

The observational and theoretical history of the solar quiet daily magnetic variation is presented, and recent theoretical and experimental developments are discussed in detail. The results of the present experiments will be compared to previous rocket-borne experiments and also related to the present state of the theoretical development.

A. Observation and Theoretical Analysis of the Solar Quiet Daily Magnetic Variation.

Non-secular magnetic time variations of the surface geomagnetic field have been observed for nearly 250 years. Chapman and Bartels (1940) credit the discovery of a daily variation of magnetic declination to George Graham (1724), a famous instrument maker who constructed a declinatorium and magnetic observatory. A review of the works of early geomagneticians by C. Hansteen in 1819 contains a reference to a confirmation of Graham's

discovery by Andreas Celsius and Hiorter in 1740, who also discovered that the effect was nearly symmetric with respect to local noon. Canton in 1759 found that the daily oscillation on undisturbed days was more pronounced in summer than in winter.

The foundation of a world-wide network of magnetic observatories in the early nineteenth century (See Chapman and Bartels (1940)) allowed the dependence of the effect on latitude, longitude, local time, and season to be established. This effect, called the solar quiet daily magnetic variation, or Sq, was characterized at middle latitudes by an eastward deviation of the horizontal field component (at the earth's surface) followed by a westward deflection several hours later. The maximum eastward deflection characteristically occurred about four hours before local noon, with the maximum westward deflection occurring about six hours later. More recently, with the invention of highly sensitive vector magnetometers, the vector components of the disturbance have been precisely measured by ground observations.

Comparison of the records obtained from the world-wide network of observatories shows that the effect is global in scope, and that the pattern of variation changes systematically with latitude and local solar time. Schuster (1889, 1908) and Chapman (1919) were among the first to use global observations to obtain a spherical harmonic analysis of the surface magnetic field and the non-secular time variations.

Their work showed that the S_q variation could be divided into two parts, one part produced by sources external to the earth's surface, and the other produced by internal sources. The external sources were found to produce an average of two-thirds of the total variation at the earth's surface. The remainder of the effect could be explained by induced electric currents in the conducting earth. The earth currents are induced by the changing magnetic field of external origin.

Examination of various possibilities for the mechanism producing S_q led Balfour Stewart "by exhaustion of other mechanisms" (See Chapman and Bartels (1940) and Hess (1965)) to conclude in 1882 that the effect must be produced by an electric current flowing in the high atmosphere. He also proposed that convective motions of the air caused by solar heating was responsible. He assumed that the upper atmosphere was a good electrical conductor, so that air motions perpendicular to the earth's magnetic field direction would produce an electric field which could drive the currents.

In the reference frame of the moving air flow, an electric field $E = v \times B$ would be produced, in the same manner than an electric field is induced in an electric generator or dynamo. For this reason, Stewart's theory is referred to as the atmospheric dynamo theory of S_q . To produce the observed magnetic effects, a high conductivity and high air flow (wind) velocities are necessary.

Various mechanisms have been proposed for the source

of the winds. Tidal pressure winds were investigated as a possible source, but it was found that the observed solar semi-diurnal pressure variation at the earth's surface could not be explained by a simple gravitational tide. The observed variations were apparently 100 times larger than predicted by atmospheric tidal amplitudes. This led to a proposal (See Chapman and Bartels (1940) that some amplification process must occur in the gravitational tides. Kelvin, Pekeris, and others suggested that the earth's atmosphere must have a resonance with a period of 12 hours that was responsible for the amplification. Although resonant periods of about 12 hours have been found, these resonances are highly sensitive to variations in the atmospheric temperature and density profiles. It therefore seems unlikely that such resonances could be maintained with the regularity observed in the diurnal pressure variation and Sq.

The difficulties inherent in the mechanism of resonant amplification of gravitational tides led to consideration of solar heating of the atmospheric constituents as the alternate energy source. Small and Butler (1961) found that direct absorption of solar radiation by ozone was the most significant energy source for solar tidal oscillations. They indicate that absorption of solar energy by ozone, and to a lesser extent by water vapor, can account for 80 percent of the observed solar semidiurnal pressure variation on the ground. Although this energy source explains the gross features of the

surface pressure variations, it appears that some form of amplification mechanism is still required to account for the necessary ionospheric wind system. Fejer (1953, 1964) indicates that the amplification factor must be approximately 60, although he stresses that there are considerable gaps in our knowledge of both tidal oscillations at ionospheric heights and their theoretical explanation. Baker and Martyn (1952) had previously shown that ionospheric conductivities required such an amplification mechanism for tidal oscillation amplitudes.

Extensive analyses of the global current system responsible for the observed magnetic field variations have been performed by many investigators. Wasserfall (1953), Hasegawa (1960), Fairfield (1963), Matsushita (1965a), Matsushita and Maeda (1965b) have investigated the dependences of the current structure on local time and latitude. A typical global current pattern is shown in Figure 1. A current of 1,000 amperes flows between adjacent contour lines, with the current circulation being counter-clockwise in the northern hemisphere and clockwise in the southern hemisphere. The intense eastward current structure seen near the equator is referred to as the equatorial electrojet.

Asymmetries in the patterns and seasonal dependences have been examined by Hasegawa (1960), Westcott et. al. (1963), and Winch (1966). The magnetospheric effects of the dynamo electric fields driving the Sq currents have been considered by Maeda (1964) and Dewitt and

FIGURE 1.

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Akasofu (1964).

Although global wind patterns are complicated due to the complex distribution and shape of land masses, an idealized wind pattern may be used to obtain current patterns in rough agreement with those obtained from magnetic variation patterns. (See Hess (1965), page 34). A description of the current pattern is complicated by global polarization electric fields, but the part of the electric field produced directly by the dynamo mechanism depends critically upon the neutral wind profile between 90 and 140 kilometers altitude. Below 90 kilometers, the ion-neutral collision frequency is high enough to cause the ions to move with the wind, but the conductivity is too low to allow significant currents to flow. Above 140 kilometers, the rapid decrease in ion-neutral collisions prevents neutral winds from moving ions across magnetic field lines, so that the dynamo effect does not occur for the ions.

The analyses of the global current circulation indicate that the focal points of the currents in the northern and southern hemispheres follow lines of equal dip angles rather than lines of equal geographic latitude, and that the northern and southern foci are not located on the same geographic meridian. The current intensities show seasonal and day-to-day variations, with the average current intensity being greatest in the summer hemisphere.

As previously stated, a highly conducting upper

atmosphere (ionosphere) is a necessity in the dynamo theory of Sq. A calculation of the currents driven by the dynamo electric field is complicated by an anisotropy in the conductivity of the medium. This anisotropy is caused by the geomagnetic field, and its presence requires the use of a tensor conductivity to describe the medium. It is most convenient to represent the tensor components in terms of the direct (scalar) conductivity σ_0 , the Pederson (reduced) conductivity σ_1 , the Hall (transverse) conductivity σ_2 , and the dip angle I . The derivations and descriptions of these conductivities are given in most elementary plasma physics texts and references.

The high conductivity along magnetic field lines in the ionosphere results in the formation of equipotential surfaces along field lines between hemispheres, since any net electric field along the field lines drive currents which quickly cancel the parallel component of the electric field by polarization. Thus, if the electric field is slowly varying with time, only the electric field components perpendicular to the magnetic field can be maintained. At mid-latitudes, where the magnetic field is mostly vertical, only those tensor conductivity components which result in steady-state horizontal currents are usually considered.

Complete mathematical analysis of the current components has been done by Baker and Martyn (1952) and Fejer (1964), using height-integrated conductivities to

obtain the effective components of conductivity in the horizontal plane. Kamiyami (1966), citing the work of Hirono (1952), obtains quantitative results for the tensor conductivity components as a function of altitude. He gives for the horizontal current components the equations:

$$j_x = \sigma_{xx} E_x + \sigma_{xy} E_y, \quad (1)$$

$$j_y = -\sigma_{xy} E_x + \sigma_{yy} E_y \quad (2)$$

It is convenient to assume that the magnetic declination is zero. We may later adjust the results by rotating the total current vector by the declination angle. Choosing the system of coordinates so that the x-axis points due south, and the y-axis due east, the tensor conductivity components may be written:

$$\sigma_{xx} = \frac{\sigma_0 \sigma_1}{\sigma_0 \sin^2 I + \sigma_1 \cos^2 I} \quad (3)$$

$$\sigma_{xy} = \frac{\sigma_0 \sigma_2 \sin I}{\sigma_0 \sin^2 I + \sigma_1 \cos^2 I} \quad (4)$$

$$\sigma_{yy} = \frac{\sigma_0 \sigma_1 \sin^2 I + (\sigma_1^2 + \sigma_2^2) \cos^2 I}{\sigma_0 \sin^2 I + \sigma_1 \cos^2 I} \quad (5)$$

For the case $I = 0$ (dip equator) these components reduce properly to the forms:

$$\sigma_{xx} = \sigma_0 \quad (6)$$

$$\sigma_{xy} = 0 \quad (7)$$

$$\sigma_{yy} = \sigma_1 + \frac{\sigma_2^2}{\sigma_1} = \sigma_3 \quad (8)$$

where σ_3 is called the Cowling conductivity. The enhancement of σ_{yy} is caused by vertical polarization of the horizontally stratified medium by the (vertical) Hall current. The eastward current is then increased by a second Hall current driven by the polarization electric field. This effect is important in production of the intense eastward electrojet current at low latitudes.

At the dip poles ($I = 90^\circ$), the conductivities reduce as expected to:

$$\sigma_{xx} = \sigma_{yy} = \sigma_1 \quad (9)$$

$$\sigma_{xy} = \sigma_2 \quad (10)$$

Kamiyami (1966), using computed values of σ_0 , σ_1 , and σ_2 as a function of altitude, with a constant electron density of 10^5 cm^{-3} , obtained the conductivity curves shown in Figure 2. These curves were computed for $I = 36^\circ$. Since it will be necessary to obtain the corresponding conductivities for $I = 70^\circ$ (Wallops Island, Virginia), the translation in latitude will now be performed.

In the ionosphere between 90 and 140 kilometers, the direct conductivity σ_0 is much greater than either

FIG. 2

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σ_1 or σ_2 , and σ_2 is greater than σ_1 . (See Hanson (1965), pages 44-46). Under these conditions, if I is not close to either 0° or 90° , the explicit dip angle dependence of the tensor conductivity may be written as:

$$\sigma_{xx} \simeq \sigma_1 \csc^2 I \quad (11)$$

$$\sigma_{xy} \simeq \sigma_2 \csc I \quad (12)$$

$$\sigma_{yy} \simeq \sigma_1 \quad (13)$$

An additional implicit dependence upon I is due to the dependence of σ_1 and σ_2 upon the magnetic field magnitude B_g through the cyclotron frequency. In the ionosphere, this dependence (for constant altitude) may be written:

$$\sigma_1 \propto 1/B^2 \quad (14)$$

$$\sigma_2 \propto 1/B \quad (15)$$

Using the centered dipole approximation, $\tan \lambda = \frac{1}{2} \tan I$, where λ is the latitude, the I dependence of the conductivity components may be expressed as:

$$\sigma_{xx}(I') = \sigma_{xx}(I) \left[\frac{f(I) \sin I}{f(I') \sin I'} \right]^2 \quad (16)$$

$$\sigma_{xy}(I') = \sigma_{xy}(I) \left[\frac{f(I) \sin I}{f(I') \sin I'} \right] \quad (17)$$

$$\sigma_{YY}(I') = \sigma_{YY}(I) \left[\frac{f(I)}{f(I')} \right]^2 \quad (18)$$

where $f(I) = \sqrt{4 - 3 \cos^2(\text{Arctan}(\frac{1}{2} \tan I))}$.

A numerical evaluation of the angular terms in equations (16), (17), and (18) shows that the change from $I = 36^\circ$ to $I' = 70^\circ$ reduces all three conductivities, with σ_{xx} being reduced more than σ_{xy} and σ_{yy} , as would be expected. The results are:

$$\sigma_{xx}(70^\circ) = 0.2 \sigma_{xx}(36^\circ) \quad (19)$$

$$\sigma_{xy}(70^\circ) = 0.4 \sigma_{xy}(36^\circ) \quad (20)$$

$$\sigma_{yy}(70^\circ) = 0.4 \sigma_{yy}(36^\circ) \quad (21)$$

Figures 3 and 4 show the results of Kamiyami's calculation of current components at $I = 36^\circ$ for various orientations of the electric field vector. Analysis of equations (1) and (2) together with (19), (20), and (21) shows that the net effect of the latitude translation is a decrease in all conductivity components to 0.4 of their original values, and an additional reduction by a factor of 2 in the σ_{xx} component. Since Figures 3 and 4 show only relative current values, Figure 4 is unaffected by the latitude change. Only the south component of current produced by a south component of the electric field is changed relative to the other south current components. This alters the curves in Figure 3 to the curves shown in Figure 5. The net current vectors at altitudes of 100, 120, and 140 kilometers for the

1. EAST ELECTRIC FIELD 3. SOUTH ELECTRIC FIELD
 2. SOUTHEAST ELECTRIC FIELD 4. SOUTHWEST ELECTRIC FIELD
 DASHED LINE SHOWS NEGATIVE (NORTH) CURRENT

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1. EAST ELECTRIC FIELD 3. SOUTH ELECTRIC FIELD
2. SOUTHEAST ELECTRIC FIELD 4. SOUTHWEST ELECTRIC FIELD
DASHED LINE SHOWS NEGATIVE (WEST) CURRENT

**LOG₁₀ SOUTH CURRENT COMPONENT
(MODIFIED FOR $I = 70^\circ$)**

1. EAST ELECTRIC FIELD 3. SOUTH ELECTRIC FIELD
2. SOUTHEAST ELECTRIC FIELD 4. SOUTHWEST ELECTRIC FIELD

DASHED LINE SHOWS NEGATIVE (NORTH) CURRENT

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various electric field directions are shown in Figure 6.

It should be remembered that the results of Figures 2, 3, 4, 5, and 6 are independent of an electron density altitude profile, since they were computed for a constant electron density of 10^5 cm^{-3} . As Kamiyami has pointed out, the height profile of current direction and intensity shows a complicated dependence upon the electric field direction. The pertinence of these results will be discussed by comparison with the experimental results in a later section of this thesis.

B. Experimental Investigations of Sq Currents by Rocket-Borne Magnetometers.

Since the pioneering rocket flight of a nuclear free precession magnetometer (scalar) by Maple, Singer, and Bowen (1950) at White Sands, New Mexico in 1948, many attempts have been made to detect and locate the Sq ionospheric current sheet by rocket-borne scalar magnetometers. The intense currents and favorable field orientation at low latitudes result in a large change in total field magnitude due to the Sq current. For this reason, the first experimenters concentrated on measurements of the equatorial electrojet. The White Sands experiment was launched when no current was expected, and none was observed. Singer et. al. (1951) later launched a similar magnetometer near the geomagnetic equator. The experiment was carried by an Aerobee rocket to 106 kilometers altitude, and the magnetometer data indicated that the

CURRENT VECTORS
 FOR
 VARIOUS ALTITUDES

FIG. 6

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rocket entered a current sheet at 93 kilometers. Between 93 kilometers and the vehicle apogee at 106 kilometers a total field change of 400 ± 50 gammas was detected. The slope of the field profile at apogee indicated that the rocket may not have completely penetrated the current sheet, and that the current extended to higher altitudes.

Three flights by Cahill (1959a) near the Pacific Line Islands produced the first details of the structure of the equatorial electrojet. These experiments were rocket-balloon (rockoon) flights that carried proton scalar magnetometers. The results suggested that the electrojet consisted of a double current layer, with a thin intensity maximum near 100 kilometers and a second more diffuse maximum near 125 kilometers.

The first successful measurements of the magnitude of midlatitude Sq currents was obtained by Burrows and Hall (1965). These investigators flew two proton magnetometer experiments from Woomera, South Australia in March, 1964. Both experiments were carried by Skylark sounding rockets that reached 175 kilometers altitude. Both rockets were launched within one-half hour of local noon on different days. The first flight occurred at a time when the horizontal component of the geomagnetic field on the ground was near its mean value, and, as expected, no field discontinuity was observed during the flight. At the time of the second flight the surface variation in H was -35 ± 2 gammas, and the rocket-borne magnetometer showed a deviation of 24 ± 3 gammas between 104 and 115

kilometers altitude on both ascent and descent. Recent experiments by several investigators (Maynard and Cahill (1965a), Maynard et. al (1965b), Maynard et. al. (1965c), Davis et. al. (1965), Davis et. al. (1966)) have furnished information on the structure of the Sq current at various latitudes.

An equatorial measurement at Thumba, India by Maynard et. al. (1965b, 1965c) was obtained by a rocket-borne nuclear free precession scalar magnetometer flown in conjunction with a D. C. Langmuir probe that measured electron density. At the time of launch, a 50 gamma change was measured on the ground, and the flight magnetometer showed a deviation in the total field of 60 gammas between 105 kilometers altitude and apogee at 170 kilometers. The main portion of the current seemed to lie between 105 and 125 kilometers altitude. No thin layers of high electron density of the type associated with Sporadic E were found by the Langmuir probe.

Three experiments employing alkali-vapor scalar magnetometers were flown in June, 1964 from Wallops Island, Virginia by Davis, Stolarik, and Heppner (1965). Double-cell rubidium-vapor magnetometers were carried by Nike-Apache rockets to altitudes near 150 kilometers. One rocket was launched on a magnetically quiet day when no Sq effect was observed on the ground, and no current was observed by the flight magnetometer. Another rocket was launched earlier the same day when the change in H on the ground was -44 gammas. A deviation of 17 gammas was

observed between 105 and 123 kilometers, with the maximum current intensity near 110 kilometers altitude. The third rocket was launched on a magnetically disturbed day when the decrease in the horizontal component due to S_q was estimated to be 35 gammas. The flight data indicated a change of 11 gammas between 105 and 123 kilometers altitude, with maximum current density near 116 kilometers.

Twelve rocket-borne magnetometer experiments were undertaken as part of the N.A.S.A. Mobile Launch Expedition to the coastal waters of Peru in an attempt to obtain a latitudinal cross-section of the equatorial electrojet and low latitude S_q currents. Four-cell rubidium-vapor magnetometers were employed by Davis, Burrows, and Stolarik (1966) in eight of the flights launched between the equator and $14^{\circ}17'$ south of the equator. The data from these flights showed a decrease in current density with horizontal distance from the center of the electrojet. The electrojet was observed to have a lower boundary near 87 kilometers altitude, with maximum current density of 10 amperes per square kilometer. The maximum current intensity was typically located near 107 kilometers altitude. No doubly-structured layers such as were reported by Cahill (1959a) were found. The flight farthest from the latitude of the electrojet center showed a current density profile extending from near 100 kilometers altitude to 140 kilometers, with a broad intensity maximum centered near 116 kilometers altitude.

The remaining four magnetometer experiments of the

Mobile Launch Expedition were performed by Maynard and Cahill (1965a), employing nuclear free precession magnetometers in conjunction with D. C. Langmuir probes. A flight near the center of the electrojet found a deviation of 120 gammas between 95 and 130 kilometers, with the intensity maximum near 108 kilometers altitude. A measurement made to the north of the electrojet showed a diffuse current layer between 93 and 130 kilometers altitude. The total magnetic field change observed was about 45 gammas, and there appeared to be a double-layered current structure with the lower peak at 100 kilometers and the upper peak at 118 kilometers.

C. Motivations for Continued Experimentation.

Because of the small change in total field magnitude associated with mid-latitude Sq currents and the rather complicated altitude dependence of the conductivity components at mid-latitudes, total field measurements are of limited value in describing complexities in the Sq current structure. For this reason, we decided to attempt to measure the vector direction of the magnetic field caused by the Sq current sheet, and thereby to deduce the current direction. A vector measurement permits comparison between theoretical models of ionospheric conductivities, with a direct check of the tensor conductivity components available from such measurements. Extremely accurate instrumentation is required, since the expected total field change is only about 5×10^{-4} of the ambient field magnitude, and the expected angular change in the total

field vector of about $1/4$ degree must be separated from the much larger (10^0) angular change due to vehicle precession. Obviously, the vehicle attitude must be determined to a high degree of precision. An instrument design was selected that met the above requirements and provided the redundancy of total field measurements in the event of failure of the vector system, as will be discussed in the following sections.

Wallops Island, Virginia was chosen as the launch site, since it provided a convenient mid-latitude rocket range with adequate telemetry and radar tracking facilities. Nike-Apache sounding rockets were found to be capable of carrying the 50 pound instrument package to altitudes near 200 kilometers, well above the expected altitude range of Sq currents.

II. Experimental Techniques

A. Design Criteria

In order to obtain meaningful vector information on the magnetic fields due to the solar quiet daily magnetic variation, one measures the vector components in a vehicle-oriented coordinate system, and then translates the results to a ground-based reference system by knowledge of the vehicle attitude. This places severe requirements on both the magnetic sensor and the vehicle aspect sensor, since the expected change in magnetic field intensity as the vehicle penetrates the current sheet is of order 10^{-4} of the ambient field intensity and the change in the direction of the field vector is a fraction of a degree.

In addition, the high spin rate (10 or more rps) of a spin-stabilized vehicle results in rapid changes in the magnitudes of the vector components; the magnetometer must be able to track component changes which may be as much as 100,000 gammas per revolution. The aspect sensor must also respond to the rapid aspect changes caused by spin.

The mechanical structure must be able to withstand the shock and vibration of rocket launch, but must be free of permanent magnetic fields and not contain highly permeable materials. The stray fields due to current loops in the payload electronics should also be controlled through careful planning of current paths, and the use of twisted leads and coaxial cables. Use of fiberglass nose

cones and instrumentation racks, non-magnetic fasteners, nuts, bolts, and connectors, and careful magnetic testing of components allow the mechanical structure requirements to be met.

B. Magnetometer Design

Alkali vapor magnetometer sensors were found to meet the sensitivity and dynamic range requirements mentioned above, but such sensors measure only total field magnitude. They may be converted, however, to vector instruments by the addition of a magnetic bias system. The operation of such sensors depends on an optical pumping techniques which will be briefly described.

A block diagram of a single-cell cesium vapor magnetometer is shown in Figure 7. A small glass sphere containing some cesium metal is mounted within the coil of a circuit tuned to a 1 watt 90 megahertz oscillator. The oscillator excites the cesium to produce an electrodeless discharge of very uniform intensity and wavelength. Light from the cesium lamp is collimated and filtered by a combination of Fresnel lenses and an optical interference filter which passes only the cesium D_1 line at 8943 Å. The light is circularly polarized, passed through a cesium vapor cell and is then focused on a silicon photodetector.

A cesium atom in the vapor cell undergoes an electronic transition from the $^2S_{\frac{1}{2}}$ ground state to the $^2P_{\frac{1}{2}}$ state upon absorption of an incident photon, and the polar-

FIG. 7
SINGLE-CELL CESIUM MAGNETOMETER

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ization of the photon causes a unit increase in the quantum number $\underline{m}$ of the excited electron. The lifetime of the excited state is short, and decay into any of the allowed ground-state sublevels occurs. The absorption of a D_1 photon is repeated and the result of such absorption and re-emission of photons is a shift of the ground-state population towards higher $\underline{m}$ values. Since the $^2P_{\frac{1}{2}}$ state contains no levels higher than $m=4$, transitions out of the $^2S_{\frac{1}{2}}$ ($m=4$) level to a $^2P_{\frac{1}{2}}$ level are forbidden, and the atoms are trapped in this state. There can be no further absorption, and the gas becomes transparent to the incident D_1 photons. The gas is then said to be "pumped" to the $^2S_{\frac{1}{2}}$ ($m=4$) level. In the presence of an ambient magnetic field, the net magnetic moment vector will "precess" about the magnetic field vector and modulate the intensity of the component of transmitted light perpendicular to the pumping component at the classical Larmor precession frequency. If the signal of the photo-cell receiving this light is amplified and fed back as a modulation current of the proper phase (90°) to the cesium lamp excitation coil, the process of light modulation at Larmor frequency will continue automatically, with the frequency changing in proportion to the strength of the ambient field change. For cesium, the constant of proportionality is 3.49854 hertz/gamma; very small fields may be measured by such a device.

The magnetometers and associated electronics employed in these experiments were furnished by Varian Associates, Palo Alto, California. Also furnished by Varian were the bias systems, which will be described separately. In ad-

dition to the magnetometer sensor, the electronics consisted of the lamp oscillator and regulator and gas cell temperature controller.

The lamp oscillator is a class C transistorized oscillator furnishing 90 megahertz at 1 watt, and is shown schematically with the regulator and signal amplifiers in Figure 8. The temperature controller, which maintains a gas cell temperature between 50°C and 55°C , is shown in Figure 9.

Because of the vector sense of polarization of the photons about the optic axis of the sensor, and the vector dependence of the precessional components on the magnetic moment vector, the sensor is not able to operate at all orientations with respect to the ambient magnetic field. For a single cell sensor the region of sensitivity lies between 10° and 80° of the sensor optic axis in one hemisphere and is azimuthally symmetric about the optic axis. A diagram of the sensitive region is shown in Figure 10, where the optic axis is taken as lying in the plane of the paper, and directed downward. The presence of null regions in which an ambient field will not be sensed places a restriction on the orientation of the sensor within the vehicle for a given vehicle launch orientation. The null regions also restrict the bias orientation relative to the vehicle and sensor.

The bias system provided by Varian consisted of a pair of temperature-compensated circular coils surrounding the sensor unit. Current was supplied by a regulated power

FIGURE 8

OVEN TEMPERATURE MONITOR

FIGURE 9

FIG. 10

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supply that maintained a constant bias field at the sensor of approximately 10,000 gammas along the bias coil axis precise to within 1 gamma over a period of an hour or more. The current could be switched on and off in order to alternately impose a bias or remove it. A schematic diagram of the bias electronics is shown in Figure 11.

Photographs of the sensor and coil system, both assembled and disassembled, are shown in Figures 12-14.

C. Analysis of Vector Components

Consider the case of a scalar magnetometer with a single-axis bias fixed with respect to some vehicle coordinate system such that the bias axis lies in the yz -plane and is inclined an angle ϵ from the y -axis, as shown in Figure 15. Assume in this case that the magnetometer sensor has no null regions, and that the ambient field of magnitude B_g is inclined at an angle θ from the z -axis with angular velocity ω . At time $t_0 = 0$, let the vector B_g lie in the yz -plane. Then if B_0 is the bias magnitude, the components of the vector sum of B_g and B_0 as a function of time are:

$$B_x = B_g \sin\theta \sin\omega t \quad (22)$$

$$B_y = B_g \sin\theta \cos\omega t + B_0 \cos\epsilon \quad (23)$$

$$B_z = B_g \cos\theta + B_0 \sin\epsilon \quad (24)$$

BIAS CURRENT SUPPLY

FIGURE 11

FIG. 12

FIG. 13

FIG. 14

FIG. 15

201074

The sensor output as a function of time is then:

$$B_{\tau} = \sqrt{B_x^2 + B_y^2 + B_z^2} = \sqrt{B_g^2 + B_o^2 + 2B_o B_g (\sin \epsilon \cos \theta + \cos \epsilon \sin \theta \cos \omega t)} \quad (25)$$

Making the transformation $\cos \omega t = 1 - 2 \sin^2 \frac{\omega t}{2}$ we obtain

$$B_{\tau} = \sqrt{B_g^2 + B_o^2 + 2B_o B_g (\cos(\theta + \epsilon) - 2 \cos \epsilon \sin \theta \sin^2 \frac{\omega t}{2})} \quad (26)$$

where B_{τ} is the magnitude of the total field (sum of ambient plus bias fields) seen by the sensor. This may be written in the form,

$$B_{\tau} = \sqrt{X} \sqrt{1 - k^2 \sin^2 \frac{\omega t}{2}} \quad (27)$$

where,

$$X = B_g^2 + B_o^2 + 2B_o B_g \cos(\theta + \epsilon) \quad \text{and}$$

$$k^2 = \frac{4B_o B_g \sin \theta \cos \epsilon}{X}$$

In this form B_{τ} may be recognized as an elliptic function of the first kind. In the special case of $\theta = 0$, B_{τ} is a constant. For a bias vector aligned along the x-axis ($\epsilon = 0$), the function reduces to the form:

$$B_{\tau} = \sqrt{B_g^2 + B_o^2 + 2B_o B_g \sin \theta \cos \omega t} \quad (28)$$

For a bias that is switched alternately on and off at some multiple of the apparent rotation period of B_g , the functional value alternates as shown in Figure 16. For known values of B_o , ϵ and ω , recovery of the parameters B_g and θ from the functional values may be effected by one of the methods outlined below:

(a) Direct integration of $B_r(t)$

Since an alkali vapor magnetometer produces as a signal a frequency proportional to the field scalar magnitude, integration of $B_r(t)$ may be accomplished electronically through direct counting of the frequency $f(t) = 3.49854 B_r(t)$ over some time interval. Because of the periodicity of the elliptic function, integration over integral multiples of the rotation period of the vector B_g will yield a result which is more sensitive to changes in the magnitude of B_g than to changes in θ . (This may be easily seen by analogy to a circular function (sine or cosine) for which integration over a complete cycle yields a result completely independent of the amplitude of the rotating component of the vector.) The integral is most sensitive to the value of θ when the interval is one-half cycle or less, centered about a maximum of $f(t)$ ($\omega t = 2\pi n$, where $n = 0, 1, 2, \dots$). By the symmetry of the function about the maximum, integration over the range $\omega t_1 = (2\pi n - \phi_o)$ to $\omega t_2 = (2\pi n + \phi_o)$

FIG. 16 201075

yields twice the value of the integral:

$$E(k, \Phi_0) = \sqrt{X} \int_{\frac{2\pi n}{\omega}}^{\frac{2\pi n + \Phi_0}{\omega}} \sqrt{1 - k^2 \sin^2 \frac{\omega t}{2}} dt \quad (29)$$

which is an incomplete elliptic integral of the first kind. The corresponding equation for frequency count C over the interval t_1 to t_2 is:

$$C_{t_2 - t_1} = 3.49854 (2) E(k, \Phi_0) \quad (30)$$

For a frequency count over some time $(t_4 - t_3)$ with the bias off, we obtain $C'_{t_4 - t_3} = 3.49854 (t_4 - t_3) B_g$. If we solve this equation for B_g , then equation (30) for $C_{t_2 - t_1}$, becomes an equation in θ alone, since all other parameters are known. This equation may be solved numerically for θ on a digital computer, either by series approximation of the elliptic function or by interpolation of tabulated values of $E(k, \Phi_0)$.

(b) Measurement of $B_\tau(t)$ maximum

This is a simplified case of the previous technique in which integration is replaced by exact measurement of the functional value at its maximum value. In this case, B_g is found by the same method as before, but the value of θ is obtained directly from the equation:

$$\sin(\theta + \epsilon) = \frac{B_{\tau(\max)}^2 - (B_g^2 + B_o^2)}{2B_o B_g} \quad (31)$$

which was obtained by setting $\omega t = 0$ in the general expression for B_τ . Electronically, an oscillator may be phase-locked to the frequency $f(t)$ until a maximum is detected, at which point the oscillator is de-coupled and held to the peak frequency by phase-locking the oscillator to itself. Count of the frequency of the oscillator over some period of time then yields $B_{\tau(\max)}$.

For the special case $\epsilon \rightarrow 0$, an alternate method employing only the function $f(t)$ with the bias on is useful. In this method, the minimum and maximum values of $f(t)$ are measured, giving the two relations:

$$B_{\tau(\max)}^2 \simeq B_g^2 + B_o^2 + 2B_o B_g \sin \theta \quad (32)$$

$$B_{\tau(\min)}^2 \simeq B_g^2 + B_o^2 - 2B_o B_g \sin \theta \quad (33)$$

Addition of the two relations gives a result independent of θ , which may be solved for B to yield:

$$B_g = \sqrt{\frac{B_{\tau(\max)}^2 + B_{\tau(\min)}^2}{2} - B_o^2} \quad (34)$$

Substitution of B_g into either the maximum or minimum relations yields the value of θ directly.

(c) Determination of phase with bias on.

In this method, the values of $B_\tau(t)$ at two times t_1 , and $t_2 = t_1 + \frac{\pi}{\omega}$ are compared. At the time when

$B_{\tau}(t_1) = B_{\tau}(t_2)$, $\omega t_1 = \frac{\pi}{2}$ and $\omega t_2 = \frac{3\pi}{2}$, so that:

$$B_{\tau}(t_1) = \sqrt{B_g^2 + B_o^2} = B_{\tau}(t_2) \quad (35)$$

This relation may be solved for B_g , and measurement of either the maximum or minimum value of $B_{\tau}(t)$ may be used to evaluate θ .

The previously derived relations represent physically the case of a coordinate system fixed with respect to a spinning vehicle containing a scalar magnetometer sensor with fixed bias system. The quantities ωt , θ , and B_g fix the vector components of $\vec{B}_g$ in the vehicle coordinate system, and the translation of coordinates from the vehicle system to a ground-based system may be accomplished by determination of vehicle attitude relative to some vector whose coordinates are known in the ground-based system.

For the purpose of analysis, it will be assumed that vehicle attitude relative to this vector will be expressed by an angle σ between the vector and the vehicle spin axis when the vector lies in some plane fixed relative to the vehicle and containing the vehicle spin axis. For the present purpose, let this plane be the vehicle yz-plane, which also contains the bias axis. Assume also that the direction of the geomagnetic field vector $\vec{B}_g$ is known in the ground-based coordinate system, and that any observed change in the vector $\vec{B}_g$ may be referenced to the unperturbed vector direction and magnitude.

Let α_B and β_B denote the zenith angle and north azimuth angle of B_g in geographic coordinates, and α_v , β_v and α_z , β_z represent the corresponding angles for the reference vector $\vec{V}$ and the vehicle spin axis z , respectively. Let ϕ denote the angle of vehicle spin between the time a maximum occurs in the field $B_T(t)$ and the time vector $\vec{V}$ crosses the yz -plane. The relative orientations of the vehicle axis, the reference vector, and the field vector are shown in Figure 17.

The evaluation of the vehicle attitude in the geographic coordinate system, assuming α_B and β_B are known, is straight-forward. Denoting the great circle arc between $\vec{B}_g$ and $\vec{V}$ as ψ , by the spherical law of cosines we obtain:

$$\psi = \text{Arccos}[\cos\alpha_B \cos\alpha_v + \sin\alpha_B \sin\alpha_v \cos(\beta_B - \beta_v)] \quad (36)$$

Let the angle at $\vec{V}$ between $\vec{B}_g$ and the zenith be χ . Then by the spherical law of sines:

$$\chi = \text{Arcsin}[\sin\alpha_B \sin(\beta_B - \beta_v) / \sin\psi] \quad (37)$$

Substitution of ψ and χ into the law of cosines allows solution for Ω , the angle at $\vec{V}$ between the vehicle spin axis and the zenith:

$$\Omega = \text{Arccos}[(\cos\theta - \cos\psi \cos\sigma) / \sin\psi \sin\sigma] - \chi \quad (38)$$

FIG. 17

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The vehicle axis zenith angle may now be obtained:

$$\alpha_z = \text{Arccos}[\cos\alpha_v \cos\sigma + \sin\alpha_v \sin\sigma \cos\Omega]. \quad (39)$$

Likewise, the vehicle axis azimuth angle is:

$$\beta_z = \beta_v - \text{Arccos}[(\cos\sigma - \cos\alpha_z \cos\alpha_v)/\sin\alpha_z \sin\alpha_v]. \quad (40)$$

The angle Φ corresponding to the above azimuth and elevation of the vehicle axis is given by:

$$\Phi = \text{Arccos}[(\cos\psi - \cos\theta \cos\sigma)/\sin\theta \sin\sigma]. \quad (41)$$

For the case of a vehicle outside the atmosphere, the vehicle attitude should be a smoothly varying function of the time (precession and nutation). Any discontinuous change in the apparent vehicle attitude may be interpreted as a change in the direction of $\vec{B}_g$, since the other reference vector $\vec{V}$ is precisely determined. The apparent change must be along a contour of constant σ , so that the change in direction of $\vec{B}_g$ may be separated into a change in θ and a change in Φ .

If the change occurs at some time t_0 , let σ , θ , and Φ denote the measured values at t_0 when the change occurred. The direction of the new field vector $\vec{B}_g$ may be found, and the component changes easily extracted.

Consider the spherical triangles pictured in Figure 18. Let ξ be the great circle arc between the old field vector $\vec{B}_g$ and the new field vector $\vec{B}_g'$, and let η be the angle at the vehicle axis between the zenith and the old field vector. We then obtain:

$$\alpha'_B = \text{Arccos}[\cos\alpha_z \cos\theta' + \sin\alpha_z \sin\theta' \cos(\eta + \Phi - \Phi')], \quad (42)$$

FIG. 18

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and

$$\beta'_B = \beta_B - \text{Arccos}\left[(\cos\xi - \cos\alpha_B \cos\alpha'_B)/\sin\alpha_B \sin\alpha'_B\right], \quad (43)$$

where,

$$\xi = \text{Arccos}\left[\cos\theta\cos\theta' + \sin\theta\sin\theta'\cos(\Phi - \Phi')\right], \quad (44)$$

$$\eta = \text{Arccos}\left[(\cos\alpha_B - \cos\alpha'_B \cos\theta)/\sin\alpha'_B \sin\theta\right]. \quad (45)$$

The changes in the components in a geographic coordinate system are therefore:

$$\Delta B \text{ (EAST)} = B_g \sin\alpha_B \sin\beta_B - B'_g \sin\alpha'_B \sin\beta'_B \quad (46)$$

$$\Delta B \text{ (SOUTH)} = B_g \sin\alpha_B \cos\beta_B - B'_g \sin\alpha'_B \cos\beta'_B \quad (47)$$

$$\Delta B \text{ (VERTICAL)} = B_g \cos\alpha_B - B'_g \cos\alpha'_B \quad (48)$$

For a vehicle which has no angular motion except spin, the elements θ and Φ should be constant in time due to the vehicle motion, so that any change in the field direction will be readily recognized. The more general, realistic motion of the vehicle above the atmosphere is that of combined spin, precession, and nutation. A complete analysis of the dynamics of the vehicle requires introduction of techniques not pertinent to this discussion, but in general the various motions may be described by superposition of cyclic functions. The precession motion may be viewed as periodic motion of the vehicle spin axis in a cone centered about a fixed direction in space, and nutation as a modulation of the coning motion by still another

periodic function. For a well-balanced vehicle, nutation effects are minor, and will not be considered in the following discussion. When precession is significant, extrapolation of the vehicle position depends on the form of the precessional curve expressed in geographic coordinates. This shape is in general rather complicated, as will be seen from the following analysis. Let α_c and β_c respectively represent the zenith angle and north azimuth angles of the center of precession. Let ρ represent the half-angle of the cone, and $\omega_c(t - t_0)$ the phase of the coming motion measured along the cone from the highest point of the cone, as shown in Figure 19.

The zenith angle and north azimuth angle of the vehicle spin axis are given by:

$$\alpha_z = \text{Arccos}[\cos\alpha_c \cos\rho + \sin\alpha_c \sin\rho \cos \omega_c(t - t_0)] \quad (49)$$

$$\beta_z = \beta_c - \text{Arccos}[(\cos\rho - \cos\alpha_c \cos\alpha_z)/\sin\alpha_c \sin\alpha_z] \quad (50)$$

Extrapolation of a precessing vehicle's attitude thus requires fitting a center of precession and precession half-angle to a known portion of the curve of the vehicle's attitude.

A further complication is introduced by the possibility of the reference vector direction being a function of time, or vehicle geographic position, or both. The experiments described herein employed solar

FIG. 19

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aspect sensors, whose operation will be subsequently described. Because of the change in the vehicle's latitude and longitude and the westward movement of the sun during the flight, the sun's geographic attitude vector changes direction (with time) in the ground-based coordinate system. Knowledge of the sun's declination (δ), the equation of time (E), Local Standard Time (LST), and the vehicle latitude and longitude as a function of time allow the sun vector direction to be expressed in the ground-base coordinate system. Let the vehicle's latitude and longitude be represented by λ and L , respectively. Denoting the standard meridian for the time zone by L_s , the hour angle H of the sun in degrees at the vehicle longitude is given by:

$$H = 15(12^h - \text{LST} - E) - (L - L_s) \quad (51)$$

From the diagram given by Figure 20, it may be seen that the solar zenith angle at the vehicle position is:

$$\alpha_v = \text{Arccos}[\sin\lambda\sin\delta + \cos\lambda\cos\delta\cos H] \quad (52)$$

The solar azimuth is given by:

$$\beta_v = \text{Arcsin}[\cos\delta\sin H / \sin\alpha_v] \quad (53)$$

The vehicle position obtained from radar tracking data allows the determination of the solar vector direction at any time in the flight.

The analysis thus far has assumed no restriction on the field of view of either the aspect sensor or the magnetometer sensor. When the actual angular field of

FIG. 20

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view of both are considered, care must be taken to optimize a vehicle trajectory and attitude with respect to the direction of the sun and the field. In some instances, the configuration of the bias coil, magnetometer sensor, and solar aspect sensor within the vehicle must be altered. In addition, severe coning may not be tolerated, so that vehicle dynamics must also be considered. These restrictions will be discussed in a later section.

D. Apparatus Construction, Calibration, and Testing

The flight instrument package consisted of the magnetometer sensor and bias coil, the electronics for the magnetometer and bias systems, logic circuits, the solar aspect sensor and its electronics, the telemetry system, and the battery pack. The components were mounted on a fiberglass rack assembly as shown in Figure 21, and a continuous fiberglass shroud and nose cone protected the instrument package in flight. Photographs in Figures 22 through 24 show the details of the various systems and the assembled instrument package. The functions and designs of the separate systems are as follows:

1. Magnetometer

The operating principles of the sensor and bias system were explained previously. The magnetometers and bias systems were furnished by Varian Associates, Palo Alto, California, and each flight unit weighed approximately 4.8 pounds. The magnetometer electronics were designed to operate over the temperature range 0-55°C

FIG. 21
NIKI I, NIKI II
NIKE-APACHE
FIBERGLASS
HOUSING

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FIG. 22

FIG. 23

FIG. 24

with cesium chosen rather than rubidium because of its greater stability over that temperature range. The frequency response at the signal amplifier stages allowed the field magnitude to vary from 35,000 to 70,000 gammas with no distortion. Recovery time after a change of bias state was less than a millisecond, and no significant switching noise was observed.

2. Solar Aspect Sensor

The solar aspect device was furnished by Goddard Space Flight Center and manufactured by Adcole Corporation, Waltham, Massachusetts. The angle sensor consists of a rectangular slab of quartz having opaque templates on the upper and lower sides. Light passing through a slit in the upper template is screened by a Gray-coded pattern on the bottom template so that each of seven photosensitive strips lying beneath the lower template are or are not illuminated by the sun. The angle of incidence thus determines which photocells are illuminated. The outputs from each cell are amplified and processed electronically for serial digital output to the telemetry system. Illumination is sensed as "one" and absence of illumination is sensed as "zero". The pattern and seven photocells provide 2^7 combinations; 128 one-degree increments are available. The accuracy at a transition between combinations is better than 0.25 degrees, half the angular diameter of the sun. The slit of the angle sensor is usually mounted perpendicular to the spin axis of the vehicle, so that the angle between the normal to the spin

axis and the sun direction is sensed. Readout is automatically triggered by a separate command sensor that operates on the same principle as the angle sensor, when the sun is in the plane normal to the sensor face. The orientations of the two sensors are shown in Figure 25, and the angular field of view for normal positioning of the sensor is shown in Figure 26.

3. Logic and control circuitry

The switching signal for the bias coil was provided by a binary counter monitoring the aspect command sensor. This provided a change of bias state every second revolution of the rocket. The bias switched state at the start of the solar aspect readout. A schematic diagram of the switching logic electronics is shown in Figure 27.

External preflight monitoring of the bias state, magnetometer signal, battery voltage, and magnetometer bias current supply temperature was provided through the umbilical connection. Remote switching of the bias current, transmitter power, and internal-external system power were also provided as well as battery charge capabilities. Redundancy for the power switches was provided by three pressure switches in parallel that closed at 10,000 feet altitude and bypassed the power switches; the altitude switches were provided to turn the system "on" even if the mechanical relays failed at launch. In addition, power diodes provided safeguards against accidental polarity reversals of the battery charger or external power supply. All logic and control

FIG. 25

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FIG. 26

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BIAS SWITCHING LOGICS

FIGURE 27

circuits were designed and built by the Rice University Space Science Facilities.

4. Telemetry System

A five-channel FM-FM telemetry system employing a 2-watt transmitter operating at 231.4 megahertz carrier frequency was used for data transmission. The five input frequencies were combined in a mixer amplifier which provided the input to the transmitter. Four of the frequencies were produced by voltage controlled oscillators (VCO) operating on IRIG subcarrier frequency channels 15, 16, 17, and 18 (30, 40, 52.5, 70 Kiloherztz). These channels monitored the solar aspect shift register output, the battery voltage, the bias current supply temperature, and the bias switch state, respectively. The magnetometer sensor output frequency (180 ± 25 Kiloherztz) was fed directly to the mixer-amplifier; the magnetometer directly frequency-modulated the carrier. The magnetometer signal and the VCO signals were emphasized according to frequency to provide equal amplitudes in the telemetry output. All telemetry components were supplied by the Conic Corporation, San Diego, California.

5. Battery Pack

Internal power for the instrumentation package was supplied by a series-connected string of 19 cells, each of 1.5 ampere-hour capacity. The pack furnished 1 ampere at 28 volts. The cells were of the silver-zinc type, used KOH electrolyte, and were manufactured by Yardney Electric Corporation, New York, New York.

A schematic of the interconnected systems is shown in Figure 28. The entire payload section with fiberglass shroud and antenna section weighed 49.6 pounds.

In order to insure magnetic cleanliness in the instrument package and associated mechanical structure, an attempt was made to utilize non-magnetic materials and components wherever possible. Efforts were made to demagnetize those objects which could not be constructed of non-magnetic materials. Steps were taken to cancel any residual fields at the magnetometer sensor position by proper arrangement or placement of the remaining magnetic components. Because of the lack of a controlled field facility at Rice, a Schonstedt gradiometer consisting of two aligned flux-gate probes was used for measuring the stray fields associated with the various components. The gradiometer is designed to indicate the difference of the fields measured by each probe, and is therefore able to operate with high sensitivity in a large ambient field such as the geomagnetic and laboratory fields. Local gradients in the ambient field may be compensated for by adjustable bias coils located near the probes. If an object is placed at a distance from the probes that is relatively large compared with the object's size, its field will be essentially dipole-like; knowledge of the probe separation allows the total field to be deduced from the gradient. Consider a dipole of moment M placed at a distance d from the nearer probe, which is separated from the other probe by a distance a . Let the dipole

FIGURE 28
PAYLOAD SYSTEMS DIAGRAM

polar axis and the axis of both probes lie on the same line. The field difference between probes will be:

$$\Delta B = 2M \left[\frac{1}{d^3} - \frac{1}{(d + a)^3} \right] \quad (54)$$

The total field at the nearer probe is therefore:

$$B = \frac{2M}{d^3} = \frac{\Delta B}{\left[1 - \left(\frac{d}{d + a} \right)^3 \right]} \quad (55)$$

Since the gradient of the field is steepest along the polar axis, rotation of the object until a gradient maximum is reached assures that the dipole axis lies on the line through the probes' axes. In addition, two measurements at different distances allows one to determine whether the dipole approximation is valid. The accuracy of the gradiometer was $\pm \frac{1}{2}\gamma$, allowing very accurate determination of the residual fields of the various components of the instrument package and mechanical structure, such as nuts and bolts.

A magnetic tape eraser and a color television degaussing coil were used to degauss those components having a residual field. After a component was degaussed, it was subjected to shock and vibration in a high ambient magnetic field and then retested for residual fields. In general, it was found that degaussing provided permanent elimination of stray fields if it was effective in removing the fields initially.

The main sources of permanent magnetic "dirtiness" were the latching relays used to switch from external to internal power and to switch on the transmitter power. Small permanent magnets provided the latching mechanism in these relays, and it was necessary to place these relays as far as possible from the magnetometer and reduce their fields by placing them so that their magnetic fields cancelled vectorially.

Stray magnetic fields due to current loops in the instrument package were kept to a minimum by careful planning of the return current paths and the use of twisted or coaxial leads. Also, the magnetometer sensor was mounted in the far upper portion of the instrument rack and the other payload components were mounted at the lower end of the payload as far as possible from the magnetometer sensor to further reduce stray fields.

Because of the limited range of angles with respect to the field allowable for proper operation of the magnetometer, severe vehicle precession or nutation could not be tolerated. It was therefore decided to leave the instrument package attached to the vehicle second stage (Apache) for added stability. The system was tested and calibrated in facilities of the N.A.S.A. at Goddard Space Flight Center. The combined instrument package and Apache motor were dynamically balanced in the vertical spin-balance facility at Wallops Island, Virginia. The instruments were then subjected to vibration and shock levels established for the Nike-Apache vehicle in the Goddard

facilities. Finally, the combined instrument package and Apache motor were taken to the Goddard Magnetic Test Facility for calibration of the magnetometer and bias system.

Calibration took place in a 20-foot coil facility which maintained complete cancellation of the geomagnetic field over a 3-foot volume through a field-sensing servo system. The three-axis coil system was capable of producing a field vector at any angle and with any magnitude up to 0.6 Gauss so that the vehicle fields at the sensor position could be accurately measured by the flight magnetometer. The calibration procedure was as follows: With the bias off, a field vector B_1 was externally impressed along one of the vehicle-based axes which fell in a sensitive region of the magnetometer field of view. A reading of the total field $B_{\tau 1}$ was made, and then the vector was reduced in magnitude to B_2 with no change in direction. The total field $B_{\tau 2}$ was measured, and a component B_3 along another axis was added, with B_2 still applied in the original direction. The total $B_{\tau 3}$ was measured, and a component B_4 was then added along the remaining axis, with B_2 and B_3 maintained, and the total $B_{\tau 4}$ was measured.

Choosing a coordinate system such that B_1 is along z , B_3 is along y , and B_4 is along x , and denoting the vehicle fields by D_x , D_y , and D_z , the following relations must hold:

$$B_{\tau 1}^2 = D_x^2 + D_y^2 + (D_z + B_1)^2, \quad (56)$$

$$B_{\tau 2}^2 = D_x^2 + D_y^2 + (D_z + B_2)^2, \quad (57)$$

$$B_{\tau 3}^2 = D_x^2 + (D_y + B_3)^2 + (D_z + B_2)^2, \quad (58)$$

$$B_{\tau 4}^2 = (D_x + B_4)^2 + (D_y + B_3)^2 + (D_z + B_2)^2. \quad (59)$$

If the above equations are taken in successive pairs, and one is subtracted from the other, the vehicle fields may be easily found:

$$D_z = \frac{(B_{\tau 2}^2 - B_{\tau 1}^2) - (B_2^2 - B_1^2)}{2 (B_2 - B_1)}, \quad (60)$$

$$D_y = \frac{(B_{\tau 3}^2 - B_{\tau 2}^2) - B_3^2}{2 B_3}, \quad (61)$$

$$D_x = \frac{(B_{\tau 4}^2 - B_{\tau 3}^2) - B_4^2}{2 B_4}. \quad (62)$$

Similarly, the bias coil may be switched on, and another four readings taken, varying the components as before. Typical vehicle fields were ~40 gammas, compared with a bias value of approximately 10,000 gammas. The full results of calibration of both flight units are given in Table 29. The sensor optic axis was mounted along the vehicle spin axis for the first flight, and was inclined 45° from the plane containing the spin axis and the bias axis for the second flight. The criteria for these sensor orientations will be discussed in the next section.

III. Experimental Results

A. Payload Configuration and Launch Angles

Due to the restricted field of view of the magnetometer sensor and of the solar aspect sensor, the azimuth and elevation of rocket launch must be selected such that the vehicle attitude above the atmosphere allows simultaneous sensing of both the magnetic field and the sun at all times. Since the sun's declination varies with time of year, the launch angles of the vehicle vary with time also. Test-range requirements and the necessity of high elevations for the desired altitude impose further constraints on the launch angle. Allowances must also be made for vehicle precession and the change in field direction due to vector addition of the bias field.

The maximum change in direction of the field due to the bias may be easily computed. Denoting the bias by B_o and the ambient field by B_g as before, the maximum angular deviation Δ from the ambient field direction is:

$$\Delta = \text{Arcsin} (B_o/B_g) \quad (63)$$

For the expected ambient field during flight (~53,000 gammas), Δ is approximately 11° .

An analysis of vehicle dynamics based upon the center of gravity and the turning moments of the payload and Apache motor combination gave a maximum coning half-angle of between 3° and 5° for both payloads when the vehicle balance was completed. The maximum angular variation due to vehicle motion (precession of vehicle and spin-modulation by the bias vector) was thus expected

Table 29
MAGNETIC CALIBRATION

NASA 14.242 UE

Bias State	Components (gammas)			
	X	Y	Z	TOTAL
OFF	-124.4	-86.3	29.0	154.1
ON	-9989.0	-493.3	48.8	10001.3

NASA 14.243 UE

Bias State	Components (gammas)			
	X	Y	Z	TOTAL
OFF	-3.9	-21.0	47.6	52.2
ON	10155.6	-336.5	23.1	10161.5

REFERENCE AXES

X : Radial in Solar Aspect Sensor plane
Y : Radial orthogonal to Solar Aspect plane
Z : Vehicle Spin Axis

to be $\pm (11 + 5) = \pm 16$ degrees.

At Wallops Island, Virginia, where both vehicles were launched, the geomagnetic field azimuth is 172.5 degrees (eastward from geographic north) and its elevation is approximately 70 degrees. For launch times between 10:30 and 11:30 a. m. local apparent time, the solar hour angle in degrees is between $22\frac{1}{2}^{\circ}$ and $7\frac{1}{2}^{\circ}$.

The original launch schedule set the launch of the first vehicle (Nike-Apache 14.242UE) in late September 1965, when the solar declination is nearly zero. The desired altitude was in excess of 160 km., requiring an elevation angle at launch of 80° or more. Vehicle analysis indicated a final elevation angle of the vehicle axis after leaving the atmosphere of 68° - 75° . These parameters may be inserted into equations 36 through 41 (refer to Figures 17 and 20) and the angle between the vehicle spin axis and the field direction may be obtained as a function of the vehicle's effective launch azimuth for selected values of the elevation of the vehicle axis. Figure 30 gives the value of the vehicle axis-field angle (θ) as a function of azimuth for elevation angles of 70° and 75° . The azimuth is equal to the angle measured clockwise from the radial line marked "North" and the vehicle axis-field angle is given by the radial scale. Similarly, Figure 31 gives the value of the vehicle axis-sun angle (σ) as a function of azimuth for 70° and 75° elevation at 11:00 a. m. local apparent time. The family of curves shows the dependence of the

FIG. 30

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FIG. 31

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vehicle-sun angle on solar declination, and therefore on time of year. The lightly shaded region and the darkly shaded region interior to it represent those solar vector angles which lie outside the solar aspect sensor's field of view as it is normally mounted in the vehicle. As may be seen, extreme southward azimuths are not allowed in September, since the sun vector lies so close to the vehicle attitude vector that it is outside the field of view of the solar aspect sensor. For an azimuth of 180° (due south), the angle between the payload axis and the sun direction is between 17° and 22° , whereas the solar aspect sensor can only view the sun for angles greater than 28° (up to 152°). The solar aspect sensor was therefore mechanically tilted toward the forward direction of the vehicle axis by 11° ; with this sensor attitude an azimuth of 100° (10° south of east) was required to insure a 16° margin between the sun direction and the edge of the aspect sensor's field of view. The darkly shaded region whose edge is marked by small arrows represents the solar vector attitudes outside the sensor field of view after tilting the sensor. The azimuth of 100° resulted in an angle of approximately 26° between the vehicle spin axis and the field direction. Analysis of various magnetometer sensor configurations (see Figures 26 and 30) indicated that alignment of the sensor optic axis along the vehicle spin axis provided continuous sensing of the field for the expected angular deviations of field direction in the vehicle coordinate

system. Although launch of the first payload was postponed until November, 1965, the only effect of the delay was to improve the solar viewing angle by $15^{\circ} - 20^{\circ}$, and the launch azimuth was held to 100° .

The second flight (Nike-Apache 14.243UE) was planned for the middle of February, 1966, when the solar declination was approximately -10° . Evaluation of the solar angle and field angle for various azimuth angles by use of equations 36 through 41 indicated that an azimuth of 150° (30° east of south) allowed sensing of both the field and the sun with the least stringent limits on vehicle precession. This could be achieved if the magnetometer sensor were mounted so that the optic axis was inclined 45° from the plane containing the vehicle spin axis and the bias axis. (By previous definition, this direction would be 45° from the z-axis of Figure 15, and in the xz-plane.) This azimuth and sensor configuration allowed a $\pm 22^{\circ}$ variation due to vehicle spin and precession, which was 6° greater than the maximum expected. The mean vehicle axis-field angle at this azimuth was expected to be 12° and the vehicle axis-sun angle was expected to be 41° .

The bias axis was oriented as nearly perpendicular as possible to the vehicle spin axis on both flights. The direction of the field along this axis was chosen so that a total field maximum would occur less than 90° in spin phase from the start of solar aspect readout.

B. Flight Conditions

(1) NASA Nike-Apache 14.242UE was launched at 10:37 a. m. Eastern Standard Time on November 24, 1965. Effective azimuth and elevation were 100° and 80° , respectively, with apogee of 169 kilometers occurring at 209.5 seconds after launch. The impact point was 178.2 kilometers downrange at latitude 38.16° N, longitude 72.65° W, and occurred at 412 seconds. The launch position was on Wallops Island, Virginia at latitude $37^{\circ}50'$ N, longitude $75^{\circ}29'$ W. An approximate event table (for both flights) is given in Table 32.

The flight occurred at a time of low solar activity, with no significant disturbances predicted or observed for several days before and after the flight. Geomagnetic activity was low, with the K_p index varying from 1 to 1- over the three-hour period containing the flight time. Ionosonde measurements were made over an hour period covering the flight. Before the flight, ionospheric conditions were rather disturbed, and a sporadic E layer at about 105 kilometers was enhanced during the flight.

Electron-density profiles were computed for the flight time by the Ionospheric Structures group of the Environmental Science Services Administration at Boulder, Colorado. Magnetograms were provided by the Fredricksburg Magnetic Observatory at Corbin, Virginia, which is situated approximately 2° of longitude due west of Wallops Island. The magnetogram for the period of the flight is shown in Figure 33. The observed decrease in H was

Table 32

FLIGHT EVENT TABLE

EVENT	TIME (sec.)	ALTITUDE (km.)	RANGE (km.)	VELOCITY (km./sec.)
Nike Burnout	3.5	1.7	.15	1.0
Apache Ignition	20.0	13.1	1.2	.5
Apache Burnout	26.4	20.2	2.0	1.9
Enters D Region	50.	61.	17.	-
Enters E Region	66.	85.	25.	-
Enters F Region	113.	140.	50.	-
Peak	220.	192.	102.	1.6 (hor)
Enters E Region	323.	140.	152.	-
Enters D Region	371.	85.	176.	-
Leaves D Region	388.	61.	184.	-
Atmospheric Re- entry	404.	31.	192.	-
Impact	430.	0	206.	-

FIG. 33

approximately 17 gammas and the decrease in Z was approximately 4 gammas at Fredericksburg. The total field change was thus approximately 18 gammas. The geomagnetic declination exhibited a decrease during the flight.

(2) NASA Nike-Apache 14.243UE was launched on February 17, 1966 at 11:16 a. m. E.S.T. Effective azimuth and elevation of launch were 152° and 83° , respectively. Apogee altitude was 189.6 kilometers; it occurred at 219.9 seconds after launch. Impact point was 183.5 kilometers downrange at latitude 36.39 N, longitude 74.53 W, and impact occurred at 430 seconds.

Solar activity was again low during the time of this flight, with no observed disturbances. Geomagnetic activity was slightly greater than during the previous flight, with the K_p index varying from 20 to 10 over the three-hour interval covering the flight time. Ionosondes indicated the presence of patchy sporadic E at about 105 kilometers during the flight, and a density-ledge was beginning to form at approximately 150 kilometers between the E and F regions. Magnetic records from Fredericksburg (shown in Figure 34) indicate a decrease of approximately 11 gammas in both H and Z, giving a total field change of about 15 gammas. The declination at the time of the flight was approximately equal to the undisturbed declination.

C. Data Recovery and Evaluation

The flight data were received by the Wallops Island main base telemetry station as well as the telemetry

FIG. 34

sub-station located near the launch position. The transmitted mixed video was received by two 500 kilohertz bandwidth receivers and combined in a diversity combiner which selected the strongest signal. The receiver output was recorded on half-inch magnetic tape at 120 inches per second. A time code and speed-lock signal for the recorder drive system were simultaneously recorded on separate tape tracks. An oscillograph connected to the output of frequency discriminators for each of the telemetry subcarriers was used to visually display the magnetometer signal and the subcarrier signals. The vehicle trajectories were obtained from radar information supplied by the Wallops Island tracking network. Profiles of altitude-range versus time for both flights are shown in Figures 35 and 36. Radar errors were reported to be no greater than several tens of meters at 100 kilometers by Wallops Island personnel.

Instrumental difficulties were encountered on both flights; only portions of each flight provided useable data. Both magnetometers and solar aspect sensors were highly sensitive to radio frequency interference (RFI) produced by the 2-watt transmitter. Extensive shielding of payload components and interconnecting cables as well as careful placement of cables were required to reduce the RFI effects to a tolerable level. However, mechanical failures during rocket launch produced severe degradation of data on both flights. The specific causes of these failures as deduced from telemetered records were as

FIG. 35

NASA 14.242 UE
ALTITUDE VS. TIME

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FIG. 36
NASA 14.243 UE
ALTITUDE VS. TIME

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follows:

(1) Flight 14.242UE (November, 1965)

During Nike thrusting, severe fadeout of the magnetometer signal during certain portions of the vehicle spin period began to occur. At the same time, the solar aspect sensor readout began to give rapidly fluctuating angle values, and readout began to occur at nearly twice the actual vehicle spin rate of 6 revolutions per second. The time interval between aspect readouts corresponded to the maximum data rate possible for the aspect-sensor electronics, indicating that the aspect device was being continually triggered by a perturbation more rapid than 12 sec^{-1} . The periodic magnetometer signal fadeout was observed during the entire flight, but the signal strength of the various telemetered subcarriers (VCO's) was not noticeably affected. Analysis of the magnetic field vector attitude in the vehicle coordinate system indicated that fadeout occurred when the vector sum of the geomagnetic field and the bias field was nearest to the edge of a magnetometer null-region. However, the vector sum should have been no closer than 6° from the edge of the null-region for the vehicle's expected attitude and precession angle. Ground tests conducted before the flights indicated that severe radio frequency interference could effectively shrink the viewing area of the magnetometer sensor by introducing excessive noise when the magnetic field vector was near the edge of the normal null-region. The solar aspect sensor behavior had also been duplicated

in ground tests by the introduction of severe RFI. It was therefore concluded that the likely source of the degradation of data was the introduction of a high level of radio frequency interference due to the telemetry transmitter, probably caused by a mechanical failure during rocket launch which altered the RFI grounding and shielding configuration. Suspected failure points include cable clamps, grounding leads, and antennae cables.

Because of the failure of the sun sensor and the loss of magnetometer signal over significant portions of a spin cycle vector information could not be obtained from the recovered data on the first flight. Since neither the vehicle aspect nor the magnetic vector components in the vehicle coordinate system could be determined over a long enough interval of time to separate the vehicle's actual and apparent motions, only total field magnitude could be recovered from this flight. Data were obtained over the altitude range expected to contain the Sq current sheet location on both ascent and descent. The method of data reduction and the results will be discussed in the next section.

(2) Flight 14.243UE (February, 1966)

Approximately 2 seconds after Nike ignition, the transmitter signal strength was observed to drop sharply. The VCO monitoring battery voltage showed an abrupt drop in battery voltage at the same time. The magnetometer and solar aspect sensor continued to function normally,

with normal bias switching and solar angle readout continuing throughout the flight. The rapid drop in battery voltage in coincidence with the drop in transmitter power was interpreted as an increase in current through the transmitter. This could have been caused either by a change in the transmitter output load or by a short-circuit in one of the transmitter output stages. In the first case, the change of load may have been due to mechanical separation of one of the coaxial cables between the transmitter final output stage and the antenna elements.

The low signal strength of the telemetered data made it possible to obtain meaningful vector data above 120 kilometers altitude on the ascent portion of the trajectory, with no data-recovery possible on the downward portion due to the small signal-to-noise ratio.

D. Data Reduction

The instrumental failures discussed in the preceding section made direct electronic counting of the magnetometer frequency difficult for both flights. The fadeout of the magnetometer signal on the first flight prevented continuous counting of the signal frequency for more than a small fraction of a vehicle spin cycle. The data from the second flight were more amenable to direct electronic analysis, but the relatively high noise level made it impossible to separate the magnetometer signal from the recorded mixed receiver video signal without using a very

narrow bandwidth filter. Introduction of such a filter distorted the sharp transition at a change of bias state so that the phase of vehicle spin between the solar direction and the field direction (θ) could not be accurately determined electronically. In addition, the noise level was sufficient to reduce the resolution of the magnetometer measurements from an expected ± 0.3 gamma to approximately ± 5 gammas. Since a comparable resolution was attainable through visual display by a frequency-calibrated oscillograph connected to a tuneable frequency discriminator, this manual method was used for interpretation of the data from both flights.

The magnetometer signal was filtered by a tuneable band-pass filter, discriminated, and the discriminated output was filtered by a low-frequency tuneable output filter.

For reduction of the data from the first flight, the input filter passband was $\pm 15\%$ of the center frequency of approximately 190 kilohertz, and the output filter was left open. The calibration curve for the oscillograph is shown in Figure 37. Measurements made from the oscillograph of the magnetometer frequency with the bias off produced the curves, corrected for vehicle fields, shown in Figures 38a, b. Using Jensen and Cain coefficients for 1962, the magnetic field profiles along the vehicle trajectory were computed, and are shown by the solid lines in Figures 38a, b. The resolution was poor, being of the order of ± 11 gammas for a measuring accuracy of $1/4$ millimeter on the oscillogram.

A deviation in slope of the measured field magnitude from the Jensen and Cain curve was seen on both ascent and descent. On ascent, the deviation amounted to 17 ± 11 gammas increase in field intensity and appeared to occur over the altitude range 106 to 110 kilometers. Because of the poor resolution of the data, the altitude range may have been somewhat greater. On descent, the deviation was approximately 20 ± 11 gammas, and appeared to extend in altitude from 108 to 111 kilometers.

Because the southward azimuth of the second flight resulted in a smaller angle between the vehicle spin axis and the field line than in the first flight, the total variation in field magnitude (and hence magnetometer frequency) due to bias modulation was relatively smaller. This required an input filter bandwidth of only $\pm 7.5\%$ with a lower center frequency of approximately 186 kilohertz. Since full scale deflection of the oscillograph galvanometer corresponded to the discriminator bandwidth, this resulted in a resolution of measurement of ± 3.5 gammas for a measuring accuracy of $1/4$ millimeter. The calibration curve of the oscillograph for this flight data reduction is shown in Figure 39. Because of the low signal-to-noise ratio, it was necessary to close the output filter to 10 sec^{-1} . The results of alternate methods of data reduction were then compared to obtain the best total field profile.

First, the galvanometer trace of the magnetometer

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frequency in the bias off state was divided into 12 equal time segments, and a measurement was made at the center of each segment to determine the frequency at that point. The set of 12 points was averaged, and the average value assigned to the middle of the interval. Since the vehicle's spin period was approximately 1/6 second, the bias was off about 1/3 second out of every 2/3 second interval. Because of the vehicle's speed at 100 kilometers, the altitude resolution at that altitude was about 2/3 kilometer. The data obtained by this method will be discussed and compared with data obtained by a second method in the next section.

The second method used to obtain the field magnitude was that of phase determination discussed previously. (See Section II-C-(c)). The rate of change of frequency at the elliptic phase values of $\frac{\pi}{2}$, $\frac{3}{2}\pi$ was very close to the maximum rate of change allowed by the output filter, so that noise spectrum distortion at these phase values was extremely small. The precision of this technique was therefore expected to be good even for relatively small signal-to-noise ratios. The main source of error was expected to be rapid variations in the speed of the paper chart drive system. Altitude resolution was comparable to that of the first method. However, since averaging would tend to reduce the effects of rapid fluctuations in field magnitude, the phase determination method would be expected to give a better indication of small-scale variations.

The field profiles obtained by the two methods are shown in Figure 40. The data points obtained by averaging of values with bias off have been corrected for vehicle inherent fields by vectorially subtracting the axial component of the measured vehicle field from the total field vector measured by the magnetometer. The angle between the total field vector and the vehicle axis was obtained from Figure 30, using the nominal final azimuth and elevation of 150° and 75° , respectively. The rotation of the vehicle caused the effect of the radial component of the vehicle field to average to zero over two spin periods. The error bars were obtained by computing the standard deviations for the sets of 12 data points used in the averages, and indicate a $\pm 1\sigma$ deviation.

The error bars on the data points obtained by the phase determination method were determined by the measuring precision alone. Since two independent measurements were required to establish the phase and the frequency value at that phase, the total resolution was taken to be $2(\pm 3.5) = \pm 7$ gammas for a precision of $1/4$ millimeter in each measurement.

The solid line in the same figure shows the calculated field magnitude along the vehicle trajectory from the Jensen and Cain 48-term expansion (1962).

As may be seen from Figure 40, the uncertainty in the field values determined by 12-point averages increased rapidly with increasing altitude. The values also showed a general increase with altitude compared to the values

FIG. 40

NASA 14.234 UE
TOTAL FIELD VS. TIME-ALTITUDE

obtained by the method of phase determination. Both sets of values showed a similar sharp increase between 102 and 109 kilometers. The total deviation estimated from the set of higher resolution data points was 35 ± 7 gammas.

Investigation of the deviation between the data obtained by the two methods produced a possible explanation of the cause, as will be discussed. Statistically, the method of averaging over 12 data points should reduce purely random noise fluctuations and help to recover the original magnetometer signal. However, the noise spectrum affecting the discriminator in this case had been shaped by the input bandpass filter used in the data reduction. This filter was centered at a significantly higher frequency than the magnetometer frequency in the bias off state. The resulting noise spectrum passed into the discriminator with a larger portion of the spectrum containing noise frequencies higher than the magnetometer frequency than below it. The average deflection of the galvanometer would thus be raised. The combined increase in noise level and decrease in magnetometer frequency with increasing altitude would have the effect of increasing the average value with increasing altitude, as was observed. Since the low-pass output filter prevents significant noise distortion of the rapidly changing frequency with bias on, this effect would not be observed in the phase determination method. As would be expected from the foregoing, the values

obtained by the two methods should agree at lower altitudes where the signal-to-noise ratio was better. This was also observed, as shown in Figure 40.

The angle between the vehicle spin axis and the field line (θ) was obtained by measurement of the maximum frequency with the bias on. (See Section II-C-(b)), since the condition that the bias have a small axial component ($\epsilon \rightarrow 0$) was met. (See magnetic calibration results in Figure 29.) The curve of maximum field values with the bias on is shown in Figure 41.

The measured angle between the vehicle axis and the sun between 90 and 125 kilometers is shown in Figure 42. The smooth curve shown in the same figure was obtained by connecting the mid-points of the line segments between adjacent but different solar angle values. The solar aspect device assigns a given angle value when the true solar angle lies within $\pm \frac{1}{2}\%$ of the given value, so that the most accurate determination of solar position is obtained when a change of angle value occurs. The time of the change was taken as the median time between the adjacent but different values, and the median value was assigned to that time. The maximum and minimum values were obtained by fitting a precession curve to the points determined by a change of solar angle. The ratio of time spent above or below the last reported angle value to the period of precession was used to determine the amplitude, and hence the maximum or minimum value. As may be seen, the average precession period was of order 30 seconds, with

average half-amplitude of 5° . Using equations 36 through 40, with equations 51-53, the vehicle's apparent attitude (azimuth and elevation) was obtained as a function of time.

Numeric evaluation of the equations was done through the use of the Rice University IBM 1620 digital computer. The calculations were based on the assumption of a fixed field vector. The values of the vehicle axis-field line angle θ is shown plotted as a function of altitude in Figure 43, and the plot of vehicle attitude is shown in Figure 44. The altitude corresponding to each data point is indicated in the figure. The smooth solid curve drawn in the same figure is the expected shape of the vehicle attitude curve for free precession. It was obtained by solving equations 49 and 50 with the coning center chosen at 76.94° elevation and 140.0° azimuth, and coning half-angle of 5.0° . The arcs designed by values of σ and θ show contours of constant sun angle and field angle, respectively.

The expected variation of the phase of vehicle spin between the sun direction and field direction (Φ) based upon the computed apparent vehicle attitude is shown by the dashed line in Figure 45. This calculation was also based upon the assumption of a fixed (unperturbed) magnetic field vector. The solid line in the same figure shows the curve of measured values of Φ matched to the curve of expected values. Because of the data reduction techniques, the process of obtaining the value of Φ was rather complex,

as will be seen.

The low-pass output filter used in the reduction of the data prevents the galvanometer of the oscillograph from responding as fast as the frequency transition caused by a change of bias state. For the particular configuration of vehicle attitude, solar attitude, and field attitude on this flight, a switch from bias state off to bias state on resulted in a transition to a higher but rapidly decreasing frequency. The slow "rise time" of the galvanometer prevents the galvanometer from ever reaching the deflection corresponding to the frequency value just after the bias transition. Instead, the frequency corresponding to the galvanometer deflection "meets" the decreasing magnetometer frequency at some lower value, and then tracks the magnetometer signal, which is changing at a rate inside the pass-band of the output filter. This is illustrated schematically in Figure 46.

The dashed line in Figure 46 shows the actual curve of the magnetometer frequency, while the solid line shows the resulting galvanometer deflection. After an initial transient at the bias change, the galvanometer deflection becomes linear in time. If this linear rate is measured and the galvanometer deflection is taken to be linear from the point of the bias change, then the time between the bias change and the maximum deflection is:

$$\Delta t = \Delta f / \left. \frac{df}{dt} \right|_0 + \tau \quad (64)$$

FIG. 46

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where:

Δf is the change in frequency from the bias off state to the point of maximum deflection.

$\frac{df}{dt}_0$ is the constant rate of deflection of the

galvanometer with time.

τ is a constant which compensates for the non-linear transient after the change of bias state.

Measurement of the frequency at the point of maximum deflection f_0 allows the phase (ωt_0) of the elliptic frequency function at that point to be found from equation 28, since the values of B_g , B_0 , and θ have been previously determined. Measurement of the frequency difference Δf and of the spin rate ω allows the phase angle Φ to be obtained by the relation:

$$\Phi = \omega(t_0 - \Delta f / \frac{df}{dt}_0) - \omega\tau \quad (65)$$

It may be seen from equation 65 that if the point of maximum deflection occurs after the linear portion of the deflection curve has been reached, then the phase measured by this method will differ from the actual phase by an additive constant. It was found that the above condition was satisfied everywhere in the altitude range 90 to 140 kilometers, so that the curve of measured values of Φ could be matched to the curve of expected values of Φ by subtraction of a constant. The curve shown in Figure 45 was obtained by setting $\omega\tau = 24.5^\circ$.

E. Errors and Approximations

The accuracy of measurement of galvanometer deflection on the oscillogram was taken to be 0.25 millimeter, which corresponded in the case of the second flight to a frequency error of ± 12 hertz (± 3.5 gammas). Since the magnetometer signal frequency was ideally accurate to less than 1 gamma, the resolution of measurement was limited by the resolution of the oscillograph. Assuming that the bias vector components and vehicle field components did not change significantly from the measured values before the flight, the maximum resolution of the angles θ and ϕ may be obtained. By equation 28, the change in θ with respect to a change in the total (measured) field is:

$$\frac{d\theta}{dB_T} = \frac{2B_T}{\sqrt{(2B_O B_g \cos \omega t)^2 - (B_T^2 - B_g^2 - B_O^2)^2}} = \frac{B_T}{B_O B_g \cos \omega t \cos \theta} \quad (66)$$

If the value of B_T used is a maximum, then $\omega t = 0$. Taking as an example the values of B_T , B_g and θ computed for flight time $t = 77$ seconds, which were 55746 gammas, 53204 gammas and 9.11 degrees, respectively, we obtain:

$$\frac{d\theta}{dB_T} \sim 6 \times 10^{-3} \text{ degrees/gamma} \quad (67)$$

For a maximum resolution of ± 3.5 gammas, the angular resolution in the angle θ is therefore about ± 0.02 degrees.

However, in practice a change of only .02 degrees would go virtually unnoticed, since the precession curve must be extended over several degrees to establish a curve of apparent vehicle attitude. As can be seen from Figure 44, a resolution of order 0.1 degree appears more reasonable in practice.

The resolution in the angle ϕ is more difficult to obtain, since several somewhat artificial assumptions were required to determine ϕ . These will now be considered.

The first assumption was that of the existence of a portion of the deflection curve which was linear with time. This assumption included a constant transient time between the change of bias state and the time when the total deflection reached some point on the linear portion of the deflection curve. Since the transient time might be expected to depend on the frequency difference Δf in equation (64), a relative change in ϕ might result in a non-linear change in deflection owing to the change in the transition rate. This would still allow the direction of the change in ϕ to be determined, but could prevent an accurate determination of the magnitude of the change.

Another assumption was that the bias state was changed at precisely the same phase of vehicle spin every second revolution. The maximum angular resolution in ϕ is the same as the maximum precision of the solar aspect command sensor, which is nominally $\pm 0.25^\circ$.

Other sources of error are a possible change of

sensitivity of the magnetometer, change of vehicle fields or bias value, and the use of an average vehicle field vector to compensate for vehicle fields.

Although the magnetometer and bias stabilities could not be determined during the flight, evidence from ground tests and from flight data indicates that their combined stability probably remained within the resolution of the data reduction technique. Tests conducted at the Goddard Magnetic Testing Facility, in a field environment controlled to better than $1/3$ gamma, showed that the magnetometer frequency was repeatable to within ± 1 hertz ($1/3$ gamma) with bias off or on over periods of at least 30 minutes, in spite of many changes in the ambient field magnitude and direction between repeated measurements (see Figure 29). Measurements were made through telemetry at a remote location, and the instrument package was in full flight configuration with empty Apache motor attached.

In addition, a comparison of the measured geomagnetic field magnitudes obtained during flight with bias off and bias on showed agreement to within the data reduction resolution when the signal-to-noise ratio was relatively large. (See Figure 40). This would tend to indicate that both vehicle inherent fields and the bias field remained essentially the same to at least 70 seconds after launch. The deviation between the fields measured with bias off and with bias on at higher altitudes may conceivably be a result of a change in vehicle field or bias field, or both. However, this deviation may be explained as due

to the effects of the filtering system used in data reduction. (See Section III-D). Although the most likely time for a change in magnetometer stability, vehicle field, or bias field would seem to be during launch and powered portions of flight, the possibility of such changes cannot be positively ruled out.

The approximation made of a purely radial bias vector also seems entirely justified, since the inclination of the bias vector from the radial direction (ϵ) was only $8'$ of arc. (See Figure 29). This does not significantly affect the expected resolution in θ .

The correction of the total field magnitude B_g for the vehicle fields with bias off was accomplished by subtracting (algebraically) the component of the axial vehicle field along the direction of $\vec{B}_g$ from the magnitude of B_g . Since the field magnitude (bias off) was obtained by averaging over two revolutions, the contribution of the radial vehicle field averaged to zero over the two revolutions. Absolute errors could be introduced by a change in the axial component of vehicle field at launch, but the effect would be a shift in total field magnitude by a constant amount everywhere. Relative errors between data points could arise by a continual change in vehicle fields, but there is no means at present to determine whether such a change occurred. A large change can be ruled out; the bias-off data show no modulation by a non-axial component of a vehicle field.

IV. Evaluation of Results

Wallops Island, Virginia is situated approximately 8° north of the latitude of the focus of the Sq current system in the northern hemisphere. (See Figure 1) Because of the large horizontal extent of the current sheet, it may be approximated by an infinitely broad current layer at distances from the focus large compared to the altitude of the sheet. Assuming that the electric fields driving the current do not vary rapidly with time, the total current and mean current density of the layer may be easily calculated from the total field magnitude change and the layer thickness. By Maxwell's equations, the line integral of the magnetic field around a closed path is equal to a constant times the current enclosed by the path (Ampere's Law), or:

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 \int_S \vec{J} \cdot \vec{n} da \quad (68)$$

It is convenient to choose the path of integration to be the edges of a rectangular surface whose normal points in the direction of current flow, and whose width is one unit. Let the upper and lower edges of the surface coincide with those of the current sheet, whose thickness is h . Carrying out the integration of equation (68) gives the result:

$$|\vec{B}| = \frac{\mu_0 J}{2} \quad (69)$$

where J is the equivalent surface current density (amperes/

meter). The vector $\vec{B}$ is perpendicular to the current direction and horizontal, being directed in opposite directions above and below the current sheet.

The average current density in the layer is:

$$j_o = J/h \quad (70)$$

For field changes that are small compared to the ambient (geomagnetic) field, the change in total field magnitude is caused primarily by the component of the field change along the horizontal component of the ambient field. Let the angle between the horizontal component of the ambient field and the current direction be δ , and let the ambient field B_g be inclined an angle I from horizontal. The change in total field magnitude between the lower and upper edges of the current sheet is given by:

$$\begin{aligned} \Delta B = & \sqrt{B_g^2 \sin^2 I + (B_g \cos I + \mu_o J \sin \delta)^2} \\ & - \sqrt{B_g^2 \sin^2 I + (B_g \cos I - \mu_o J \sin \delta)^2} \end{aligned} \quad (71)$$

For $B_g \gg \frac{1}{2}\mu_o J$, equation (71) leads to the approximate relation:

$$\Delta B \approx \mu_o J \cos I \sin \delta \quad (72)$$

The S_q effect on the ground may be separated into two parts, the direct contribution of the ionospheric current sheet and the effect due to the induced earth currents. If we assume that a fraction f of the change ΔH in the horizontal component at the ground is due to

the (horizontal) ionospheric current sheet, the expected change in field magnitude due to penetration of the sheet is given by:

$$\Delta B = 2f \Delta H \cos I \sin \delta \quad (73)$$

Shielding effects of the ionosphere may be neglected in this problem, since the magnetic diffusion time between 90 and 120 kilometers, given by $\mu_0 \sigma_3 \ell^2$, is of order 10 seconds.

At the time of the first flight (NASA 14.242UE), the current direction was estimated to be approximately 80° from the horizontal component of the earth's field. (See Figure 1). The effective surface current density for the deviation of 17 ± 11 gammas observed on ascent is 40 ± 25 amperes/kilometer. The change of 20 ± 11 gammas observed on descent corresponds to a surface current density of 47 ± 25 amperes/kilometer. The poor resolution of the data makes it difficult to determine the thickness of the layer, but an estimated thickness of 5 kilometers yields an average current density of 8 ± 5 amperes per square kilometer on ascent, and 9.4 ± 5 amperes per square kilometer on descent. By equation (73), the expected change in total field as the sheet is penetrated is $12f$ gammas for the value $\Delta H = -17$ gammas observed at Fredericksburg. The ascent measurement agrees with the predicted change within experimental accuracy for $f \geq 0.5$, while descent data required $f \geq 0.75$ for compatibility.

The electron density profile calculated from ionograms obtained during the flight is shown in Figure 47. From Figure 2, the conductivity in the altitude range where the current was observed (107 to 112 kilometers?) on this first flight is dominated by the component σ_{xy} , which has a value of approximately 3.5×10^{-4} mho/meter. (Refer to Figures 47, 4, and 5, and equations (19), (20), and (21).) The required electric field is therefore 2.3×10^{-2} volts/meter or 23 ± 14 volts/kilometer. In order for this electric field to be generated solely by a dynamo wind mechanism, the wind velocity would have to be between 434 and 500 meters/second, which is a factor of 3 larger than has been observed.

Another apparent difficulty is seen in the location of the current sheet in altitude. From Figure 1, the expected current direction is slightly south of west. Examination of Figures 4, 5, and 6 shows that such a current direction between 100 and 110 kilometers altitude would indicate a southward electric field. Curve 3 of Figures 4 and 5 and the electron density profile of Figure 47 may be combined to obtain the conductivity profile, and hence the current profile. (Since the conductivity along the field lines is so large, the field lines are equipotentials through the ionosphere.) It may be seen that the expected current profile should be broad and diffuse over the altitude range 100 to 140 kilometers, with a broad intensity maximum near 125 kilometers altitude. The current density at 125 kilometers should be

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roughly 1.5 times the density at 110 kilometers for the observed electron density profile.

A possible explanation of the apparent discrepancies in the position and thickness of the current sheet, assuming that the estimated current thickness of 5 kilometers is accurate, is electron density enhancement by the Sporadic E layer observed near 105 kilometers altitude. This layer was observed to be enhanced at the time of flight by the ground-based ionosondes. The electron density profiles were computed by extrapolation of a theoretical ionospheric model based upon normal ionospheric conditions, and no attempt was made to include possible electron density increases by the observed Sporadic E layer (W.Wright, private communication). The enhancement required by the position and intensity of the observed current layer may be estimated by comparing the conductivity at 125 kilometers altitude (where the current maximum should occur) with the conductivity at 110 kilometers (where the current maximum is observed to occur). From Figure 47, the ambient electron density at 110 kilometers (without Sporadic E) is about 8.6×10^{10} per cubic meter, and at 125 kilometers it is 1.25×10^{11} per cubic meter. Since the experimental error is roughly half of the observed total current, not more than half the observed current is expected to be flowing near 125 kilometers. Assuming a constant electric field over the altitude range 100 to 130 kilometers, the probable enhancement factor must be at least $(1.25/0.86) \cdot (2 \pm 1) \approx 3 \pm 1.5$. Sporadic E layers having electron density

enhancements greater than 10 have been observed (See review article by Schmerling (1966)), so this seems entirely possible. The above estimate is only the lower limit required by the current position, and greater enhancement than this may have occurred. Assuming the actual enhancement factor was between 3 and 6, the required wind velocities lie between 170 meters/second and 73 meters/second. Although wind velocities of 170 meters/second are only rarely observed, 100 meters/second winds are common at mid-latitudes (Macdonald (1963)) in the altitude range 100 to 130 kilometers. The wind velocity becomes less critical if it is assumed that the current layer is actually thicker than 5 kilometers, and that the error in thickness was due to the poor resolution of the data.

The difference in the slope of the measured field and the calculated field on both ascent and descent is attributed to ground anomalies not described by the Jensen and Cain field expansion, although the possibility of changing vehicle fields or magnetometer sensitivity changes may not be completely ruled out, as was previously discussed. Such ground anomalies are known to exist beneath the vehicle flight path. A map of ground anomalies near Wallops Island as given by Davis et. al. (1965) shows that the rocket trajectory crossed a large anomaly on descent. The +300 gamma difference between the measured field and the calculated field observed near 100 kilometers altitude occurred at the time the vehicle was directly

above this +400 gamma surface anomaly. The expected cumulative error in the Jensen and Cain field expansion at the surface (neglecting anomalies) is indicated by Cain (1965) to be less than 30 gammas in 1965.

The second flight (NASA 14.243UE) occurred closer to local noon than the first flight (11:16 a. m.), so that the current direction was expected to be nearly perpendicular to the horizontal component of the earth's field. (See Figure 1.) A total field change of 35 ± 7 gammas was observed between 102 and 109 kilometers altitude on ascent; no data was available on descent because of the instrumental failures previously described. From equation (72), the effective surface current density was 81.9 ± 16.4 amperes per kilometer. For an estimated layer thickness of 7 kilometers, the average current density was 11.7 ± 2.3 amperes/kilometer². The expected change in total field for $\Delta H = -11$ gammas at Fredericksburg was $7.7f$ gammas. The observed change was nearly 5 times greater than this number, even for no ground currents ($f = 1$). This discrepancy will be discussed in the following sections.

The current location and extent are similar to those encountered on the first flight, with a slightly lower and thicker layer measured on the second flight. From Figure 48, the electron density at 105 kilometers altitude was approximately 1.1×10^{11} meter⁻³, giving a conductivity component σ_{xy} of 4.4×10^{-4} mho/meter (See Figure 2). The corresponding electric field was

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26 ± 5 volts/kilometer. The required (but impossible) wind velocities would be approximately 500 meters/sec. Figures 2 and 6 give a current direction almost due west, and an electric field almost due south. The expected current structure should be broad and diffuse between 105 and 135 kilometers. (See Curve 3 in Figures 4 and 5, and Figure 48). The current density maximum should occur near 130 kilometers, with a gradual intensity change below it. Above 120 kilometers, the current direction should turn southward. The observed position and intensity of the current layer, with the observation of Sporadic E near 105 kilometers at the time of this flight, again suggests the possibility that electron density enhancement in a Sporadic E layer is responsible for the apparent discrepancies in wind velocity. Again using the resolution of measurement to place an upper limit on the current flowing above 110 kilometers, we obtain a minimum enhancement factor of 7.5 ± 1.5 . The required wind velocity for such an electron density increase is only about 70 meters/second, which presents no difficulty.

Although no information was available at higher altitudes, the total field curve appeared to regain its original slope after the field discontinuity was passed. Because of the intense current observed and the recovery to the original slope, no other currents are believed to be flowing at higher altitudes.

The vector information obtained from this flight ascent (NASA 14.243UE) shows a definite change in the field vector in approximately the same altitude range in which the total field change was observed. The greatest change is apparent in the behavior of the spin phase angle ϕ (See Figure 45), although it is difficult to evaluate the net amount of the change. The measured values of ϕ deviate from the calculated values by several degrees at several points below 100 kilometers, but the values appear to recover rapidly and approach the calculated curve. However, an extreme transient is seen at 101 kilometers, and the measured values of ϕ fluctuate violently between 101 and 106 kilometers. Above 110 kilometers, the values recover somewhat but continue to show some smaller fluctuations at higher altitude. Because of a rapid decrease in the signal-to-noise ratio above 115 kilometers and the continued fluctuations, it is difficult to determine the net change in ϕ , but it appears that there is an overall decrease from the calculated curve. This would correspond to a decrease in the elevation angle of the field, which would be caused by a westward current component. (See equations (36) through (48)). The extreme fluctuations observed in ϕ are interpreted as evidence of a highly disordered field in the current layer, with localized regions of extremely intense magnetic fields. The scale of these regions is apparently less than the 2/3 kilometer resolution of the magnetometer system. The smaller, less

violent fluctuations observed above and below the current sheet may be due to effects within the main current sheet, rather than to additional currents outside the main sheet. This is borne out by the increasing size of the fluctuations as the main part of the current sheet was approached, suggesting that the vehicle was approaching the sources of the fluctuations.

The curve of apparent vehicle attitude (Figure 44) shows some slight fluctuation of the vehicle axis-field angle (θ) between 101 and 109 kilometers, with apparent recovery above 110 kilometers. Although it is difficult to determine whether the slight offset from the fitted precession curve is a real effect, or merely due to a small error in the choice of precession parameters, it is obvious that no net change larger than 0.1° occurred in the angle θ . If the offset is real it represents a slight westward deflection of the field line corresponding to a south current component of approximately 7 amperes per kilometer. Since it is possible to slightly adjust the precession parameters used for the calculated attitude curve so that these points coincide exactly with the precession curve, this effect is attributed to errors in determining appropriate precession parameters. The most significant vector change thus appears to be a net decrease in the elevation angle of the field line, which would be caused by a westward current component. (See equations (36) through (48)). Because of the difficulty in determining the magnitude of the change in θ , no at-

tempt was made to obtain the magnitude of the westward component of current. The current thus appears to be mainly westward (perhaps with some south component) with net current of approximately 80 amperes/kilometer. The apparent direction and magnitude is in agreement with the values expected from the global current pattern and the tensor conductivities. The Sporadic E electron density enhancement required to lower the current sheet to its observed altitude gave a corresponding electric field magnitude compatible with a wind dynamo mechanism.

A discrepancy still exists, however, between the observed field change and that expected from the Fredericksburg data. Since there was no evidence of instrumental errors or failures, this discrepancy is attributed to a real difference in the current pattern between the vehicle's geographic position and Fredericksburg (a distance of ~200 kilometers). This flight occurred at a time when the focus of the Sq current pattern was close to the Wallops Island meridian, as indicated by the observed change in the vertical component at Fredericksburg. ($\Delta Z \sim \Delta H \sim 11\gamma$). The high current density may be due to a general intensification of the current near the focus, or it may be a localized phenomenon confined to the horizontal extent of the Sporadic E layer. The latter explanation is supported by the linear relation found to exist between ground Sq effects and maximum electron density in the E-region (Fatkullin and Fel'dshteyn (1964)). The effects of localized increases in ionospheric conductivity (electron

density) have been investigated by Ivanov (1963), who has shown that the Sq magnetic field variation would be enhanced in the region of the increase. In this case, the simple horizontal current sheet concept may not apply, since horizontal polarization effects become important. To maintain large currents in the region of high conductivity, additional return current loops must be set up, since the normal conductivity outside the region of high conductivity cannot provide the required currents. The possibility of vertical currents requires introduction of all components of the tensor conductivity, and boundary effects must also be considered. Although detailed analysis of the current patterns and associated magnetic effects depends critically on the assumed boundary conditions and conductivities, it would appear that highly localized differences in magnetic effects are possible in the case of localized conductivity enhancements.

The possibility of a general current density intensification very close to the focus is not ruled out by the results of Davis et. al. (1965). Their flights occurred at a time when the current focus was estimated to be 750 to 1000 miles more distant than at the time of this flight (45 to 60 minutes earlier in local apparent time). However, a local electron density enhancement by Sporadic E appears more reasonable when compared to both experimental and theoretical results.

Maynard and Cahill (1965a) have reported a double-layered structure in the Sq currents observed near Peru, with a lower intensity maximum near 100 kilometers and

the upper maximum near 120 kilometers. A similar structure was reported earlier by Cahill (1959a) in the equatorial electrojet south of Hawaii, with intensity maxima near 100 and 125 kilometers. Cahill suggested that one of these maxima might be due to Sporadic E observed by nearby ground ionosondes. The theoretical work of Matsushita (1962) on the relation of Sporadic E to ionospheric currents suggests that Sporadic E may be formed by the Sq dynamo electric fields at mid-latitudes. In this case, Sporadic E formation would be a normal feature of the Sq current system, with varying degrees of electron density enhancement responsible for the variations in current structure and location reported by this and other investigators. From the foregoing, it appears that the results of these two experiments and most of the previous total field measurements by other investigators are compatible with the theoretically predicted results within observed variability of the ionospheric winds and electron densities.

V. Conclusions and Recommendations

This paper has attempted to present the theoretical and experimental background of investigation of the solar quiet daily magnetic variation, and to compare and relate the experiments herein described to this background. The experiments reported here include the first in situ vector measurement of an ionospheric current sheet, and the current direction obtained from these measurements was

found to be compatible with that predicted by spherical harmonic analysis of global patterns. As was previously discussed, the various current altitude ranges and current structures reported by other investigators, as well as the results obtained by these two experiments, appear to be compatible with calculated ionospheric conductivity profiles. The observed broad, diffuse current layers over altitude ranges of 105 to 135 kilometers and intensity maxima near 125 kilometers are compatible with the tensor conductivity profiles for normal ionospheric electron density profiles. The presence of double-layered current structures, or thin intense low-altitude (100 to 110 kilometers) current sheets appears to be explainable by low-altitude Sporadic E electron density enhancements, since Sporadic E has been reported in conjunction with such effects. A relatively small enhancement (~ 2) at low altitude would cause the double layers to appear, with the upper layer being the normal intensity peak, and the lower layer corresponding to the Sporadic E layer. Larger enhancements would increase the current intensity of the lower layer and decrease the intensity of the upper layer. For very large electron densities (≥ 10 times the normal ambient), the Sq current would be almost entirely confined to a thin, intense low-altitude layer.

The assumptions of Sporadic E electron density increases and the enhancement factor required by the observed position and thickness of the current layers led to wind velocities compatible with observed mid-latitude winds.

It thus appears possible to explain most of the experimentally observed features of the mid-latitude Sq current systems within the framework of observed ionospheric variability.

While this compatibility provides some comfort to the experimenter, the range of ionospheric variability represents a problem to the theoretician by providing too many possible explanations of observed phenomena. That is, knowledge of possible ionospheric conditions does not allow a critical comparison of experiment and theory when the variability of possible conditions is so great. The most critical problem in the investigations of the Sq undertaken to date is the simultaneous and localized determination of ionospheric parameters pertinent to the generation and structure of the current layer, such as ionospheric wind velocities, electron densities (including such occurrences as Sporadic E), and ground-based vector magnetic records very near the experimental site. Although other investigators have attempted to obtain such information (See Section I-B), it has not been practical to obtain the various measurements at the time and position of launch. In most cases, the launch position has been several hundred kilometers from the magnetic observatory furnishing vector field data, or from the nearest ionospheric sounding station. Obviously, ionospheric variations on a small scale (Sporadic E, wind structure, etc.) cannot be accurately accounted for in such cases. The lack of information allows more speculation

than precise calculation of ionospheric conditions.

An additional problem is that of precisely determining the vector components in the vehicle's coordinate system and the vehicle's aspect, so that the measured vector may be fixed with respect to the ground-based coordinate system. It is hoped that future improvements in the accuracy and time resolution of vector magnetometer systems and vector aspect-sensing systems will remove a part of the difficulty in obtaining meaningful vector measurements of ionospheric current systems. However, until the indicated problems of precise determination of pertinent ionospheric parameters are solved, a critical test of theoretical developments cannot be made with the best measurements. Consideration of the difficulties involved in obtaining the necessary description of the complexities of the ionosphere compels one to recall the words of Smiley (1966):

"It may be that the voices of men are only mouse-like squeakings in the tornado of . . . eternity. . ."

Acknowledgments:

It is a pleasure to thank Dr. R. C. Haymes, my research advisor, for his support and advice in this project, and Dr. A. J. Dessler for his pertinent comments and suggestions. Special thanks are extended to Mr. Delbert Oehme of the Rice University Space Science Facilities, who served as electronics design engineer and payload manager, for services above and beyond the call of duty. Thanks are also due for the many services performed by the members of the Rice University Space Science Department. I wish to acknowledge the help of the personnel at Goddard Space Flight Center and Wallops Island Test Range. The cooperation of the staff members of Varian Associates who participated in the design and construction of the magnetometer systems is greatly appreciated. I also wish to thank the personnel of the Fredericksburg Magnetic Observatory and of the Ionospheric Structures Group of E. S. S. A. at Boulder, Colorado for their services. I am indebted to Miss Carmena Cloutier and Mrs. E. C. Dickson for their help in typing this thesis. And finally, I wish to thank my wife Sybil for her help in preparing this thesis, and to acknowledge my daughter Niki, for whom the payloads were named.

This work was supported by NASA Contract No.
NSR-44-006-023.

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