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PROJECT VANGUARD MAGNETIC-FIELD INSTRUMENTATION AND MEASUREMENTS

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by

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SUMMARY

The Vanguard III Satellite, 1959 Eta, placed in orbit on September 18, 1959, contained a proton precessional magnetometer for magnetic-field studies of exceptional accuracy. Throughout the 85 days of battery life, the instrumentation functioned according to plan. Measurements of the absolute total field were obtained in the meridian belts of Minitrack stations at altitudes 510 to 3750 kilometers and at latitudes ± 33.4 degrees. Surface magnetic observatories were operated at eight of the Minitrack stations to furnish correlative information.

This paper reviews briefly the instrumentation employed in these experiments, and the data collection and reduction procedures. Emphasis is given to results from a preliminary analysis. Specifically, this analysis bears on the accuracy of computed fields, the stability of the earth's field in space, the Capetown anomaly, and magnetic-storm effects.

CONTENTS

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PROJECT VANGUARD MAGNETIC-FIELD INSTRUMENTATION AND MEASUREMENTS*

INTRODUCTION

The IGY satellite Vanguard III (1959 Eta), which was placed in orbit on September 18, 1959, contained a proton precessional magnetometer designed to obtain geomagnetic-field measurements of exceptional accuracy. From the firing of the vehicle to the ultimate exhaustion of the satellite batteries, the entire operation proceeded as planned.

Accurate measurements were obtained at all altitudes (510 to 3750 kilometers) and latitudes (± 33.4 degrees) within the meridian belts covered by Minitrack stations. Relative to the Van Allen radiation belts this means that measurements were taken below the inner belt, in the inner belt, in the slot between the two belts, and close to the lower edge of the outer belt over regions near longitudes 78° W and 137° E.

Prior to flight it was estimated that the batteries would last for about 3 months and that 50 magnetic-field measurements per day could be taken by ground command over that period. In actual performance the separate battery packs for the command receiver and the tracking transmitter were exhausted after 85 days, and operation ceased.

During the 85 days about 4300 successful responses to ground commands were recorded by the Minitrack stations. From tape playbacks it is estimated that 80 to 90 percent of these responses will have signal-to-noise ratios adequate to yield the proton precession frequency with an accuracy equivalent to field errors of less than 1 gamma (1 gamma = 10^{-5} gauss). Errors in the remaining 10 to 20 percent will probably be between 1 and 5 gammas.

Magnetic observatories were operated at eight Minitrack stations throughout the flight, and at Fort Myer, Florida for part of the flight. These provided a ground reference on the behavior of the magnetic field, to assist in interpreting field variations.

The satellite and its instrumentation and the ground-station magnetometers are briefly described herein. The last section of this paper outlines some preliminary results compiled in a period of several days following computer runs, giving space coordinates and a reference field. As there was not time to consider many special features, only the obvious features are considered in this report. This analysis uses less than 10 percent of the data.

*Originally presented at the First International Space Symposium sponsored by the Committee on Space Research (COSPAR), Nice, France, January 1960.

THE SATELLITE

The Vanguard III satellite has often been referred to as the "Magne-Ray" satellite. The name represents the fact that it is a combination of two previous Vanguard satellites — an X-Ray and meteoritic satellite and a magnetic-field satellite.

The payload portion of the satellite is shown assembled in Figure 1a and disassembled in Figure 1b. The lower three-fourths of the 20-inch sphere was coated magnesium and the top one-fourth and the 26-inch extension holding the magnetometer sensing head were made of fiberglass. The payload, weighing 51 pounds, was purposely left attached to the last stage of the launching rocket (which also weighed about 50 pounds) in order to produce a long tumble period, and thus to avoid corrections to the proton precession frequency that would be required in the case of rapid rotation about an axis perpendicular to the magnetometer coil axis.

Specially built Yardney Silvercels with nonmagnetic lugs were used for instrumentation power (Figure 1b, lower left). These were located in a pressurized can with a relief valve to avoid excess pressure. Electronics for the X-ray experiment, micrometeorite experiments, temperature measurements, telemetry encoding, and the 108.00-Mc transmitter (Figure 1b, upper left) were located in a central cylinder set into the battery can. The magnetometer electronics, command receiver, and 108.00-Mc transmitter (Figure 1b, lower right) were located in a short cylinder at the top of the internal instrumentation package.

Surface coatings on the metal sphere, and the fiberglass' absorptivity-to-emissivity ratio of unity, provided an excellent thermal design. The extremes of internal temperature were about 6°C and 30°C.

THE SATELLITE MAGNETOMETER

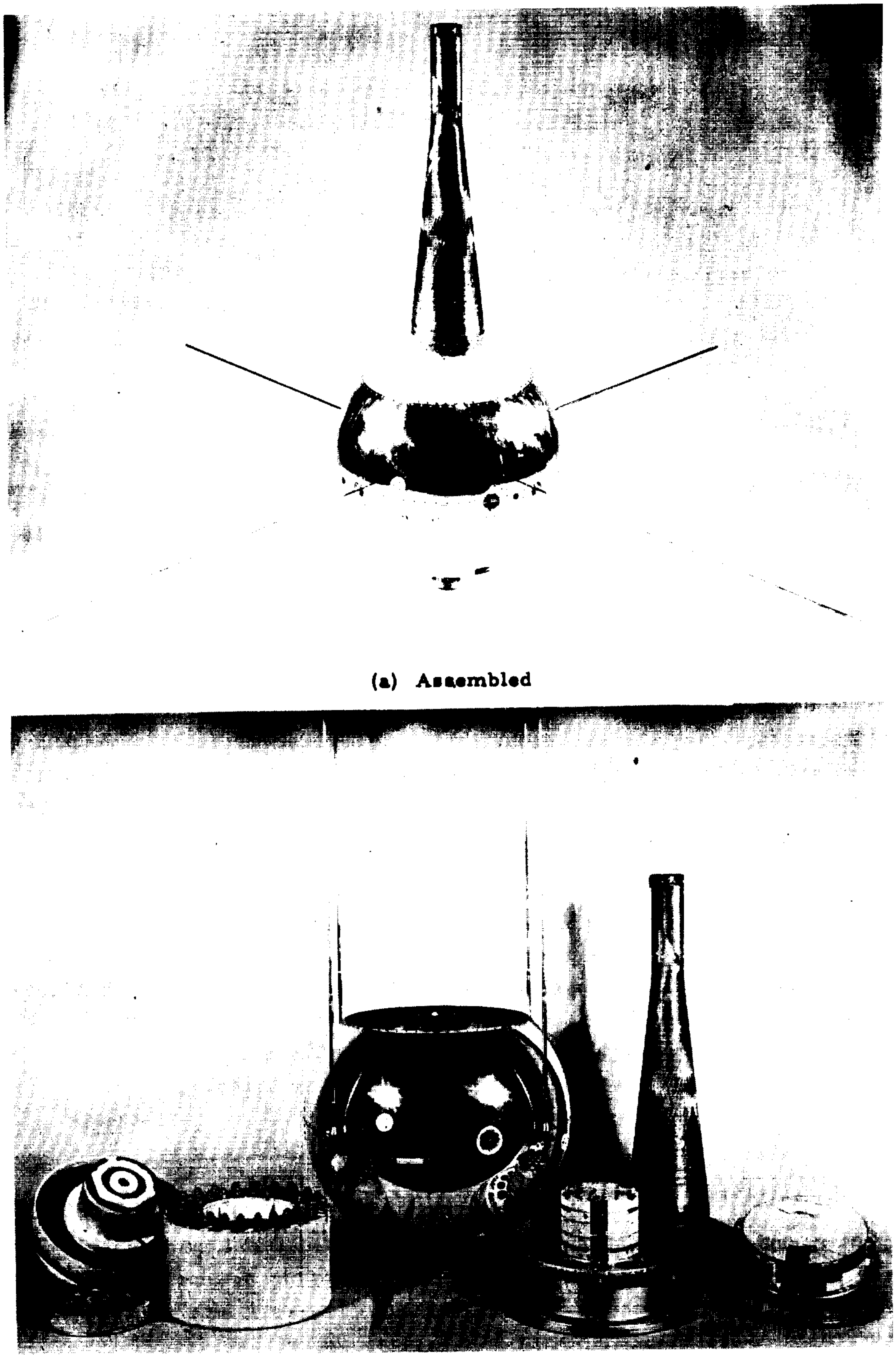
The principles of proton precessional magnetometers are well known (Reference 1). The absolute total scalar intensity of the magnetic field is measured independently of orientation by measuring the proton precession frequency

$$f = 4257.6 \times F, \tag{1}$$

where F is the field intensity in gauss and the constant 4257.6 comes from the gyromagnetic ratio of the proton.

For the satellite experiment a completely transistorized magnetometer was designed by Dolan Mansir of Varian Associates, Palo Alto, California; this work was sponsored by the Naval Research Laboratory. The satellite unit is shown in Figure 2. (This model differs from a unit previously described in Reference 2.)

The operation in the satellite proceeded as follows: A command signal from the ground was received by a tuned receiver in the satellite; a relay closure at the output of



(a) Assembled

(b) Disassembled

Figure 1 - The Vanguard III (1959 Eta) satellite payload

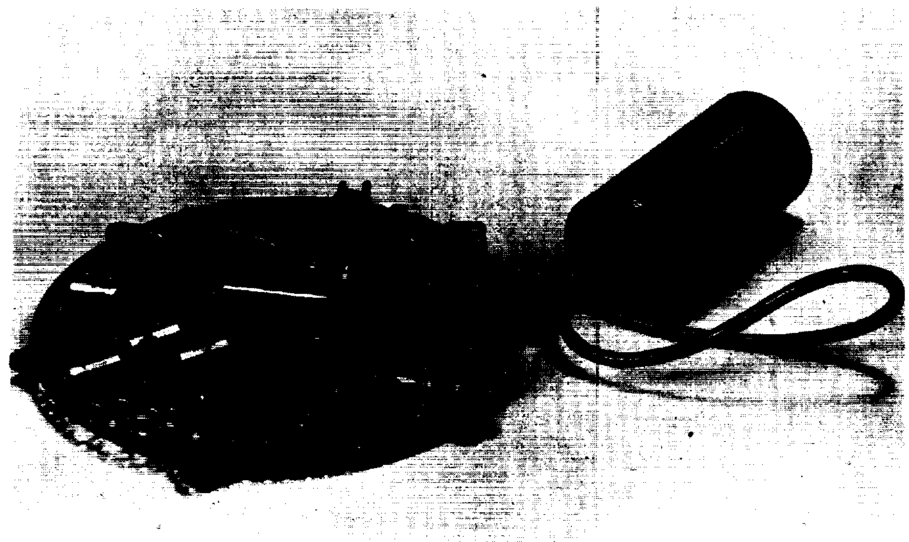


Figure 2 - Satellite proton magnetometer with an accuracy of 1 part in 100,000

the receiver then actuated a multivibrator programming circuit in the magnetometer. The magnetometer programmer then performed the following functions: (1) turned off the modulation to the 108.00-Mc transmitter; (2) turned on the 108.03-Mc transmitter; (3) turned on the magnetometer amplifier; (4) connected the sensing-head coil to the battery pack for about 2 seconds, during which the protons were put in phase coherence by the polarizing field; (4) switched the coil wires to the amplifier following the polarization period; and (5) after about 4 seconds, switched off the 108.03-Mc transmitter and magnetometer circuits and switched on the modulation to the 108.00-Mc transmitter. Thus, one precession signal about 2 seconds in length was produced by each ground command.

To cover the field range (0.57 gauss for tests on the ground to 0.07 gauss near apogee over South America) and to compensate for the linear amplitude dependence on field intensity, the magnetometer was designed to have broad frequency response with increased gain toward the low frequencies. As a result of this design and the quality of the 80-mw 108.03-Mc transmitter (designed and built by M. G. Dennis and C. A. Gorday) the absolute accuracy of the readings is essentially independent of field intensity.

THE GROUND-STATION MAGNETOMETERS

The ground-station magnetometers located at Minitrack stations give the total scalar field F, the declination angle D, and the inclination angle I by measuring F, ΔD, and ΔI, since the fixed position of the magnetometer relative to geographical coordinates is known. These quantities determine the vector field.

The technique and accuracies achieved are fully described elsewhere (Reference 3). In brief, a reversal of bias fields in two directions approximately perpendicular to the field vector is used to obtain ΔD and ΔI from a proton magnetometer. The total field F is obtained directly. The accuracies achieved are generally equal to or greater than the accuracies from conventional observatories.

The data from the present nine stations and the previous stations in Havana, Cuba and Georgia, U.S.A. are currently being machine processed and are not used in this preliminary analysis.

DATA REDUCTION

The magnetic tapes returned from Minitrack stations contain the telemetered signal, coded Greenwich Mean Time (GMT), and a 100-Kc standard frequency. The proton precession signal is usually of smaller amplitude than the noise, as a result of broadband operation both in the satellite and in the ground receivers. Simple prediction charts enable the operator to locate the approximate frequency for setting filters. An unfiltered and a filtered signal are illustrated in Figure 3. When the correct frequency is found, a filter with a passband of 20 cps is used to give a high signal-to-noise ratio. A number of runs are made on each signal to assure the correctness of the frequency and to average out the inherent ± 1 count in the 100-Kc counter. The precession frequency is always determined by counting the period for a preset number of precession cycles, employing the tape-recorded 100-Kc standard. When the signal is counted for 1 second, the accuracy is usually ± 1 part in 10^5; for 0.5 seconds, ± 2 parts in 10^5, etc. The signals are usually counted with this accuracy for periods between 0.4 and 1.5 seconds. Errors from this count are generally ± 0.5 gamma or less.

To evaluate the total error in each measurement, field distortion due to currents and iron in the satellite and errors caused by the tumble frequency must be considered. From preflight tests the field distortion error is believed to be 1 gamma or less. The tumble frequency that adds or subtracts from the proton precession frequency (Reference 1) is about 0.09 cps. This gives an average error of 2 gammas, which is correctable; but this correction was applied to the present analysis.

Greenwich Mean Time is recorded to ± 0.01 second for each measurement by adding one-half the period of counting to the time of the trigger pulse at the start of the count. The usefulness of this accuracy becomes apparent when gradient determinations are made.

METHOD OF PRELIMINARY ANALYSIS

Of the magnetic-field values reduced from 10 percent of the telemetry recordings, only those occurring in selected latitude-longitude zones are used here. An additional restriction in the present analysis is that data from the ground magnetometers are being entered on punched cards and are not readily available for reference now. Because of these restrictions it has been necessary to deviate from the normal method of analysis to arrive at these preliminary results.

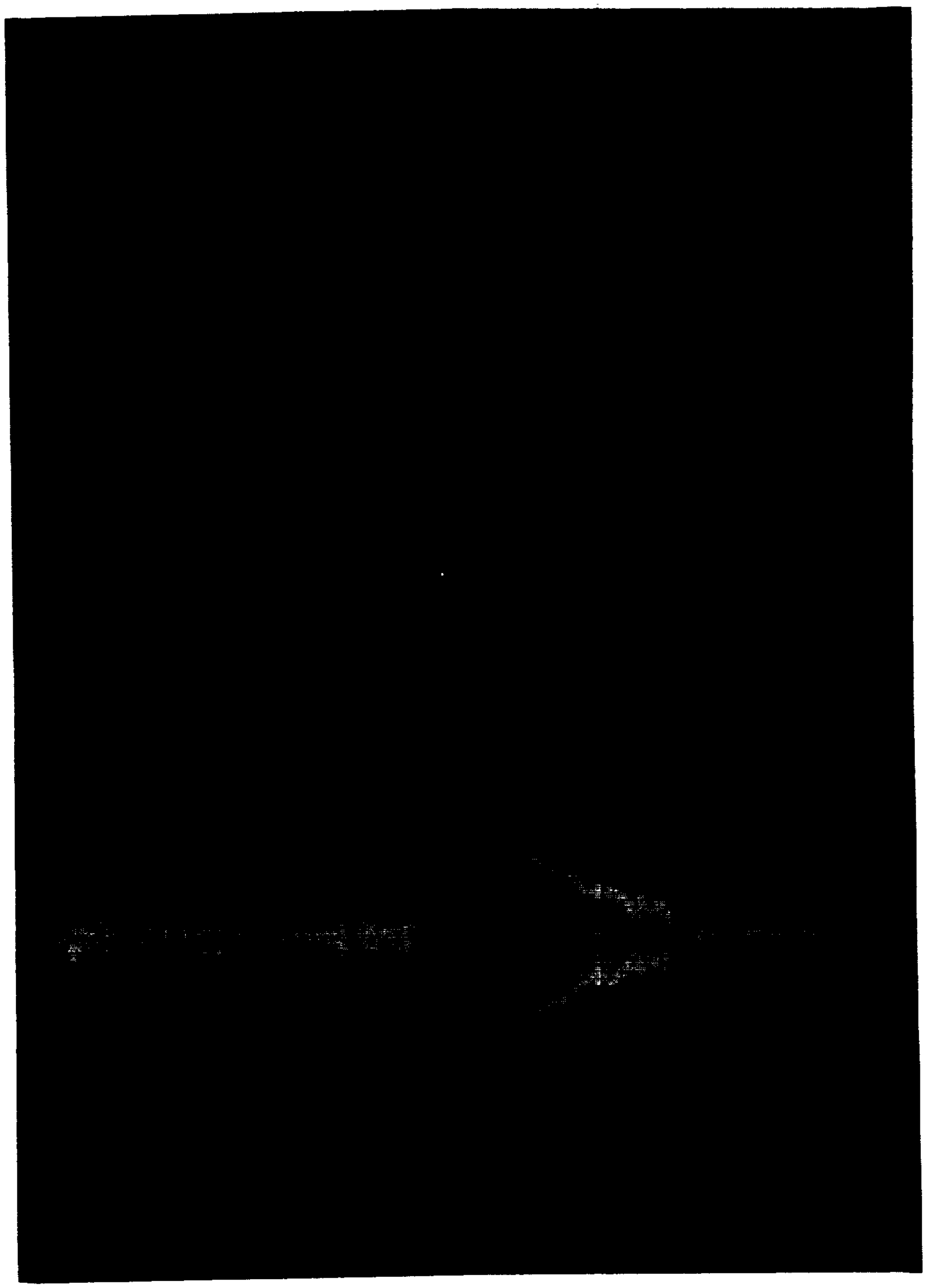


Figure 3 - Telemetered signals: unfiltered (top) and filtered (bottom)

The first essential for an analysis is an accurate reference field. Normally, the reference field would be generated from satellite readings taken during periods of magnetically quiet conditions, as indicated by the ground station. The readings, of course, have to be selected for consistency to avoid the possibility of disturbances at altitude that are not indicated on the ground.

For the present analysis it was decided to use a reference field computed by spherical harmonic analysis. Vestine and Sibley of the Rand Corporation and Jensen and Whitaker of the Special Weapons Center, Kirtland Air Force Base, generously provided their computer programs. The program of Vestine and Sibley uses the coefficients of Finch and Leaton (Reference 4) through order $m = 6$ and degree $n = 6$. The program of Jensen and Whitaker utilizes coefficients through $m = 17$, $n = 24$ (unpublished) which were derived from U. S. Naval Hydrographic Charts for 1955. Comparison with the satellite points showed that the field derived by Jensen and Whitaker fitted the measured field best in most of the regions where measurements are available. The exceptions are over South Africa, where the $m = 6$, $n = 6$ field fitted better, and in regions near Australia, where it is difficult to make a choice. To illustrate these results, the Special Weapons Center (SWC) computed field is used in the following section.

PRELIMINARY RESULTS

ACCURACY OF COMPUTED FIELDS

In Figure 4 the difference between the measured field and the SWC computed field is plotted as a function of altitude for selected zones of latitude and longitude. If for the present the scatter of points is neglected, the following can be concluded by referring these differences to the magnitude of the field (also using differences for regions not illustrated).

(1) The percentage error in the SWC computed field is roughly constant as a function of altitude and is about equal to the percentage error in the charts from which the coefficients are derived, that is, approximately ± 1 percent.

(2) Errors in the SWC computed field in regions over the south part of North America and to the southeast and southwest of North America are less than 1 percent.

(3) Errors in the SWC computed field over South America are very close to 1 percent.

(4) Errors in the SWC computed field over Australia and the south tip of Africa are in general slightly more than 1 percent.

(5) The sign (plus or minus) of the errors in the SWC computed field is in general the same as the sign of the errors in a dipole field. This would indicate that the dipole term is given too much weight in the analysis.

Statements (2) through (5) do not apply when the Finch and Leaton coefficients are used, for two reasons: First, as was stated previously, the errors in most of these regions are slightly greater; and second, the errors have the opposite sign over Australia and southern United States.

When the fact that the errors in the SWC computed field are systematic over large regions (except South Africa) is considered, it appears that corrections to the low-order terms based on the satellite measurements would lead to an excellent computed field.

DATA SCATTER RELATED TO ORBIT DETERMINATION AND STABILITY OF THE MAGNETIC FIELD

The scatter of data points in Figure 4 tends to misrepresent the accuracy of the measurements and the stability of the magnetic field. There are three obvious reasons for the scatter, and a fourth reason with some practical implications:

(1) The differences as a function of altitude are shown for large zones in latitude and longitude; thus, the gradient of errors in the reference field can contribute to the scatter in this representation.

(2) To fit the computer program for obtaining space coordinates for each measurement, the time of a measurement was rounded off to the nearest ± 0.01 second. Thus, between any two measurements the space position error can be as large as 5 to 8 kilometers. This of course gives an unreal comparison of measured and computed field, as the latter is correctly located. Most of the nonsystematic scatter is undoubtedly of this origin. This is apparent from a comparison of scatter at low altitudes, where the field gradients and satellite velocities are large, with the scatter at high altitudes, where the gradients and satellite velocities are considerably reduced.

(3) The data plotted have not been examined for diurnal and small disturbance effects in the magnetic field. It is doubtful that these contribute much scatter in comparison with reason (No. 2) (see the following discussion). In fact, it may not be possible to study these with confidence until time accuracy is inserted into the orbit computations. The difficulty of studying diurnal and small disturbance effects with an inaccurate orbit was discussed at length in an earlier paper (Reference 5).

The fourth factor, like (2), arises from the methods and accuracies of orbit computation. The present Minitrack computing technique is such that a transition takes place at weekly intervals. The magnitude of the transition is approximately equal to the orbital errors. In Figures 4a, b, d, and e, the effects of the transitions on the magnetic-field data are noted. The numbers to the right of the plots designate the "orbit week". Two features should be noted: First, the magnitude of the apparent field discontinuity caused by the transition is approximately 40 gammas; and second, within each week there is a definite pattern. This is most evident in Figure 4a, where each week produces a curve which is convex to the right.

These features present important implications. The fact that a weekly pattern related to errors in space position is evident, despite (2) above, implies that the magnetic field is exceptionally stable at these altitudes when magnetic storms are absent. This implied stability and the magnitude of the transition effect suggest that errors in orbit determination could be significantly reduced by including absolute magnetometers in future satellites. Relative to the present Minitrack computation technique, the error reduction would be at least a factor of 10. However, this would only be a consistency check between satellites until a reference field is established with field measurements from a satellite of geodetic quality. The magnetic field would be especially useful in studies of orbit perturbations with short periods, because it gives values at discrete points to whatever density is desired.

THE CAPETOWN ANOMALY

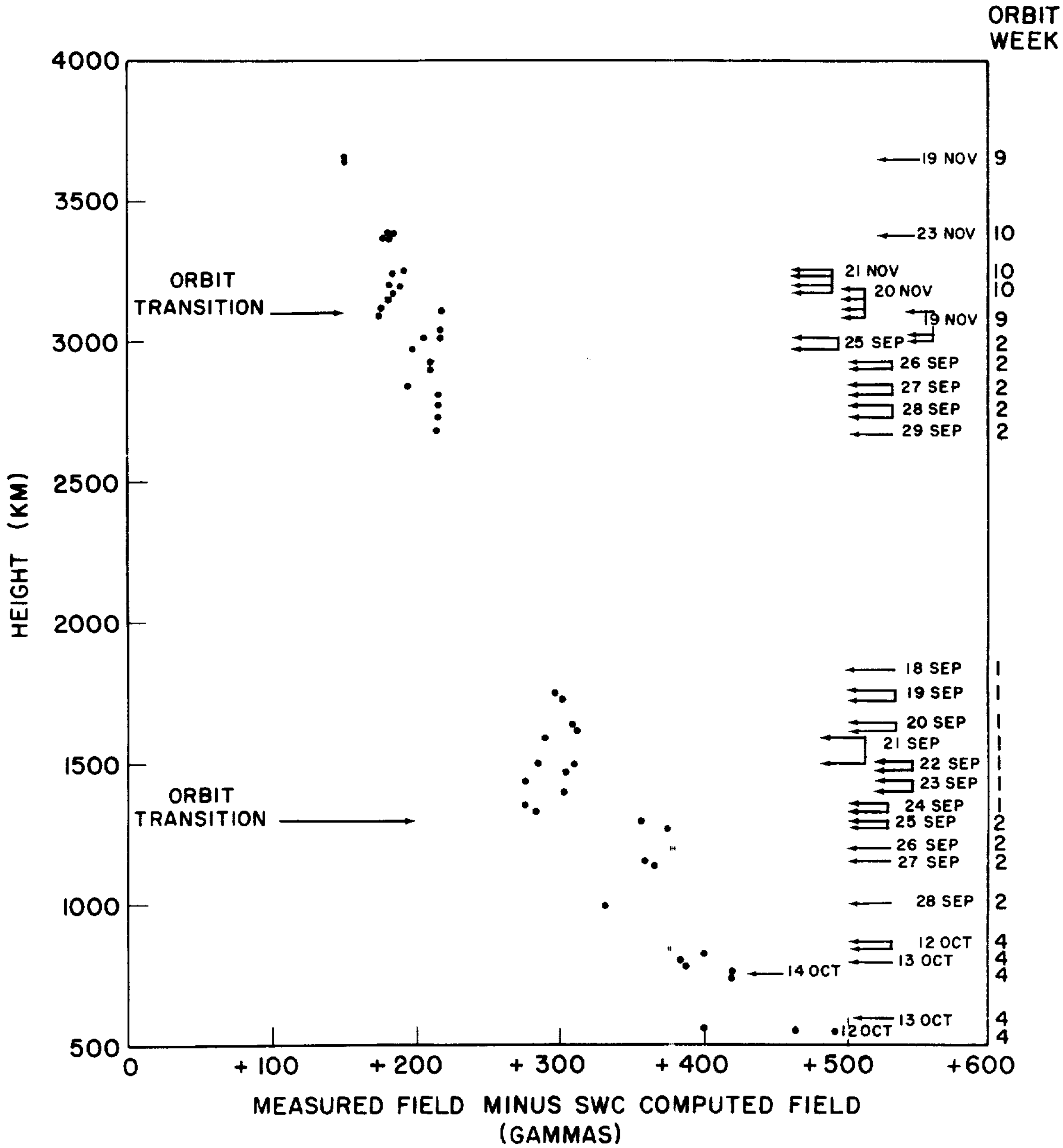
The decrease in radiation intensity between the inner and outer Van Allen belts has been attributed by Dessler (Reference 6) to a low mirror altitude for trapped particles over the southern tip of Africa. The negative magnetic anomaly in that region on the earth's surface is conspicuous on total intensity maps.

To check whether or not the negative anomaly was still significant at altitude, a command and recording station was established at the Johannesburg Minitrack station. Fortunately the station went into operation two weeks before the satellite batteries were exhausted, and a number of records were obtained. Several of these have been played back and the measurements have been referred to the computed fields, with the results shown in Table 1. The first point, at 10°S latitude, is an isolated point; the other three are taken from multiple ground commands.

Two features are apparent: First, the anomaly is a much sharper feature at altitude from the measured values than it is from the computed values. Second, the actual field at altitudes up to at least 3740 kilometers over the anomaly has less intensity at a given altitude than the computed field. Thus, the mirror altitude for particles of a given energy will be slightly lower than is predicted from the computed fields. The use of more of the measurements should make it possible to estimate the depth and strength of the source of the anomaly within the earth.

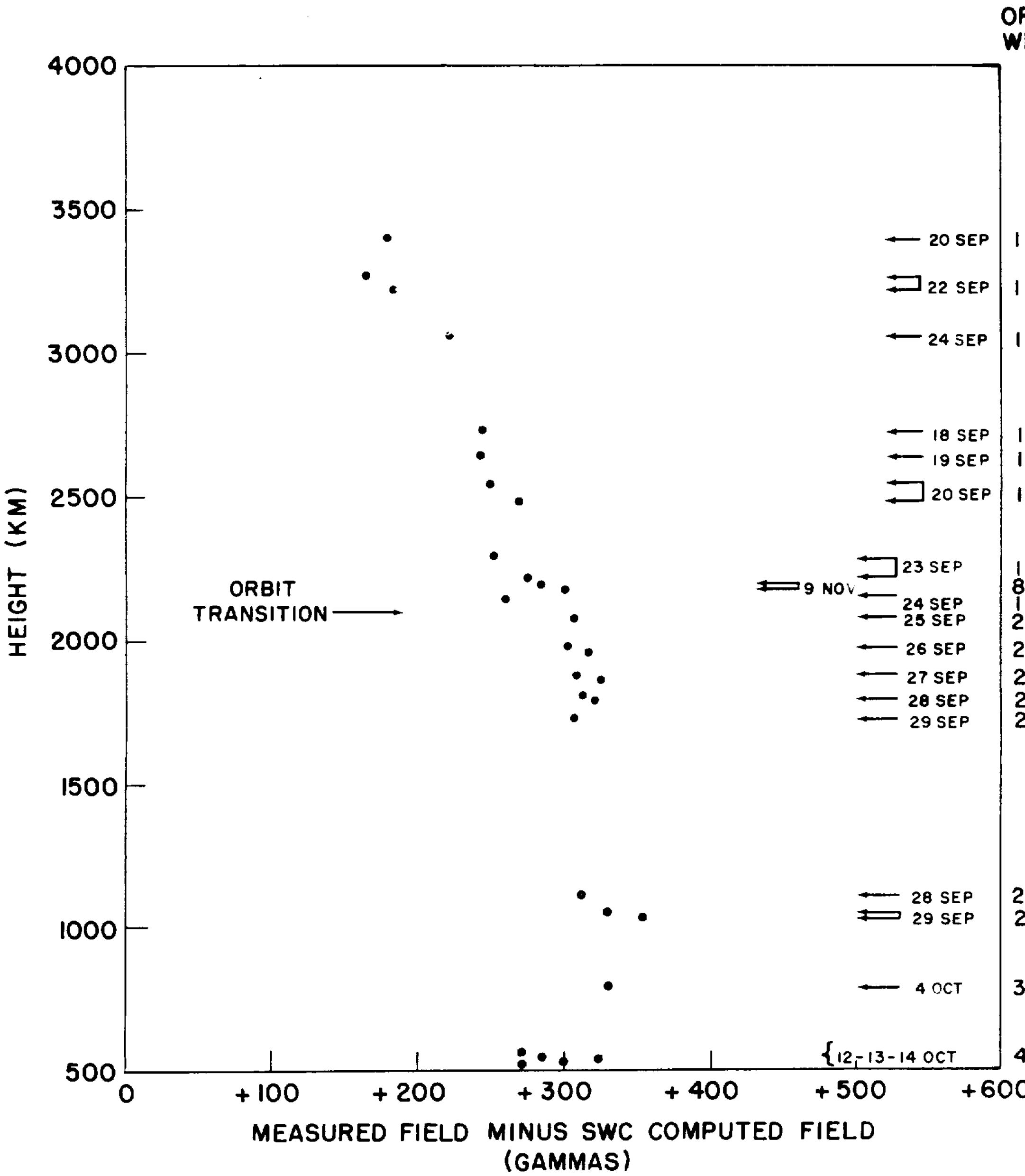
MAGNETIC-STORM EFFECTS

During the satellite's life, five magnetic storms with intensities ranging from moderate to weak occurred. Through chance some of the measurements reduced fall into these intervals, but the lack of ground magnetometer data at this writing further restricts the degree of study. For a rough picture, Figures 4c, d, and e give some special points which can be referred to the U.S.C. & G.S. Observatories at Fredericksburg, Tucson, and San Juan. In Table 2 the simultaneous disturbance values are listed for the horizontal and



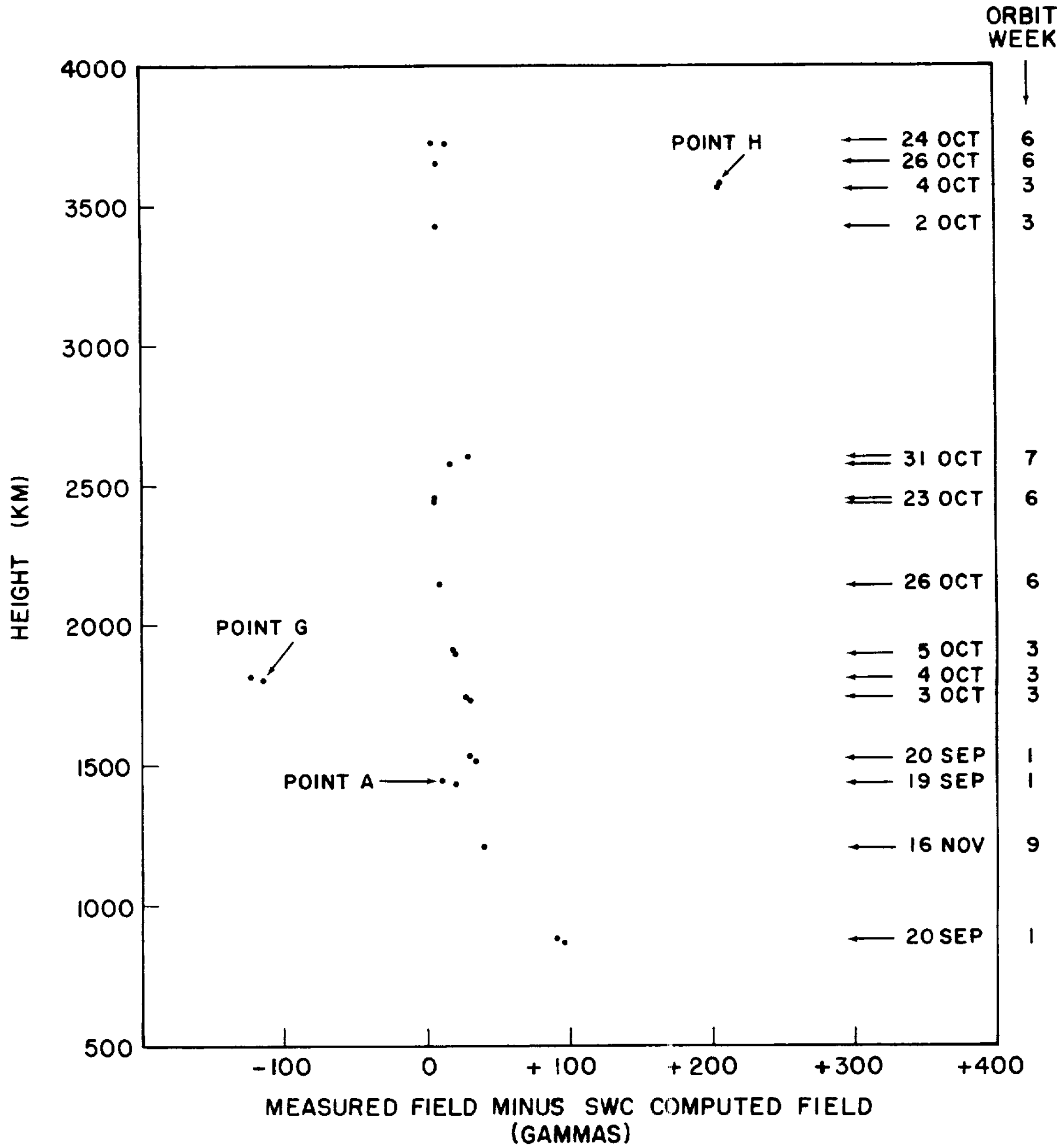
(a) Longitude, 134°E to 140°E; latitude, 24°S to 30°S

Figure 4 - Comparison of measured anc SWC computed fields



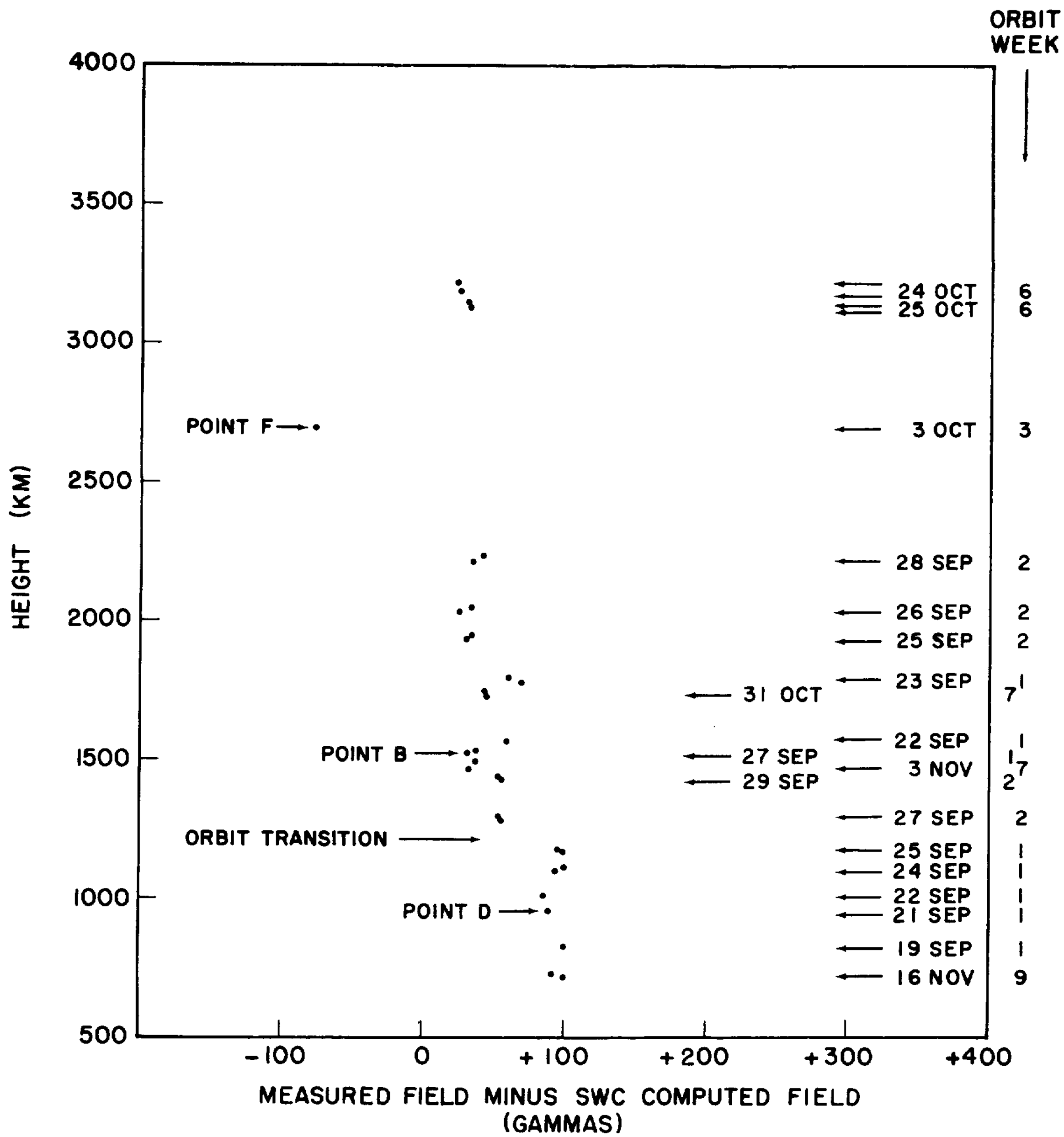
(b) Longitude, 134°E to 140°E; latitude, 30°S to 33.5°S

Figure 4 - Continued



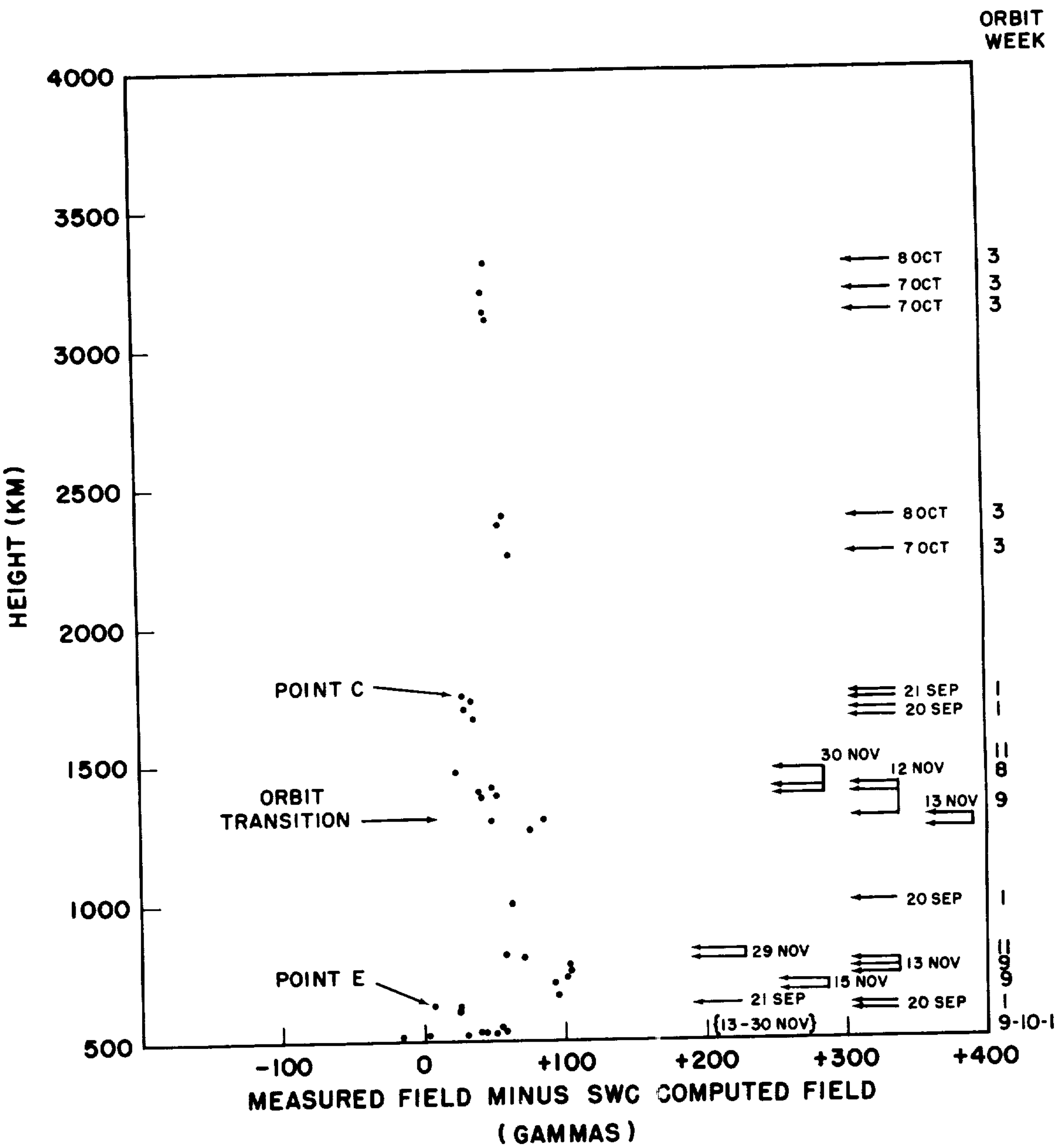
(c) Longitude, 74°W to 80°W; latitude, 26°N to 30°N

Figure 4 - Continued



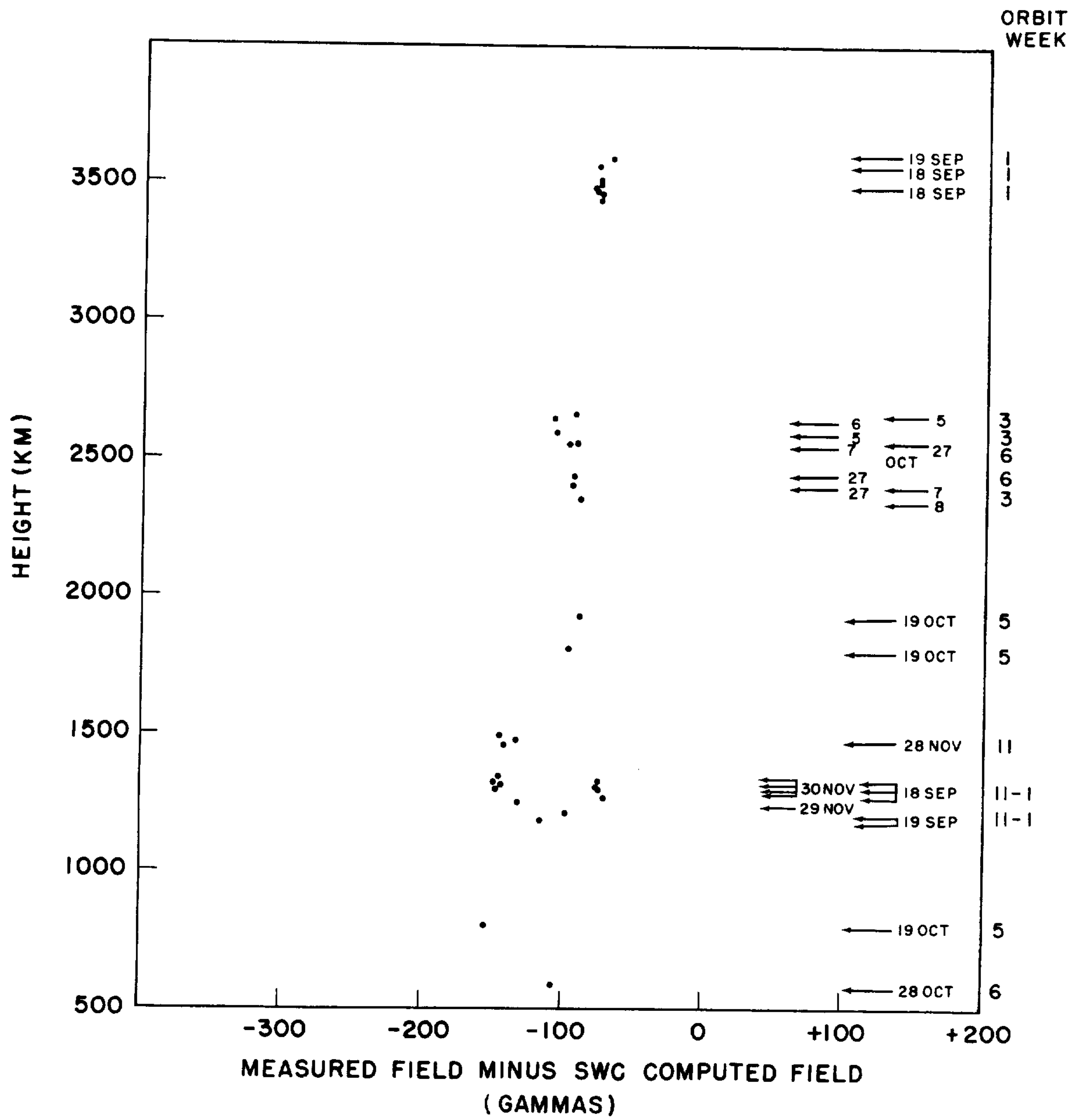
(d) Longitude, 74°W to 80°W; latitude, 30°N to 33.5°N

Figure 4 - Continued



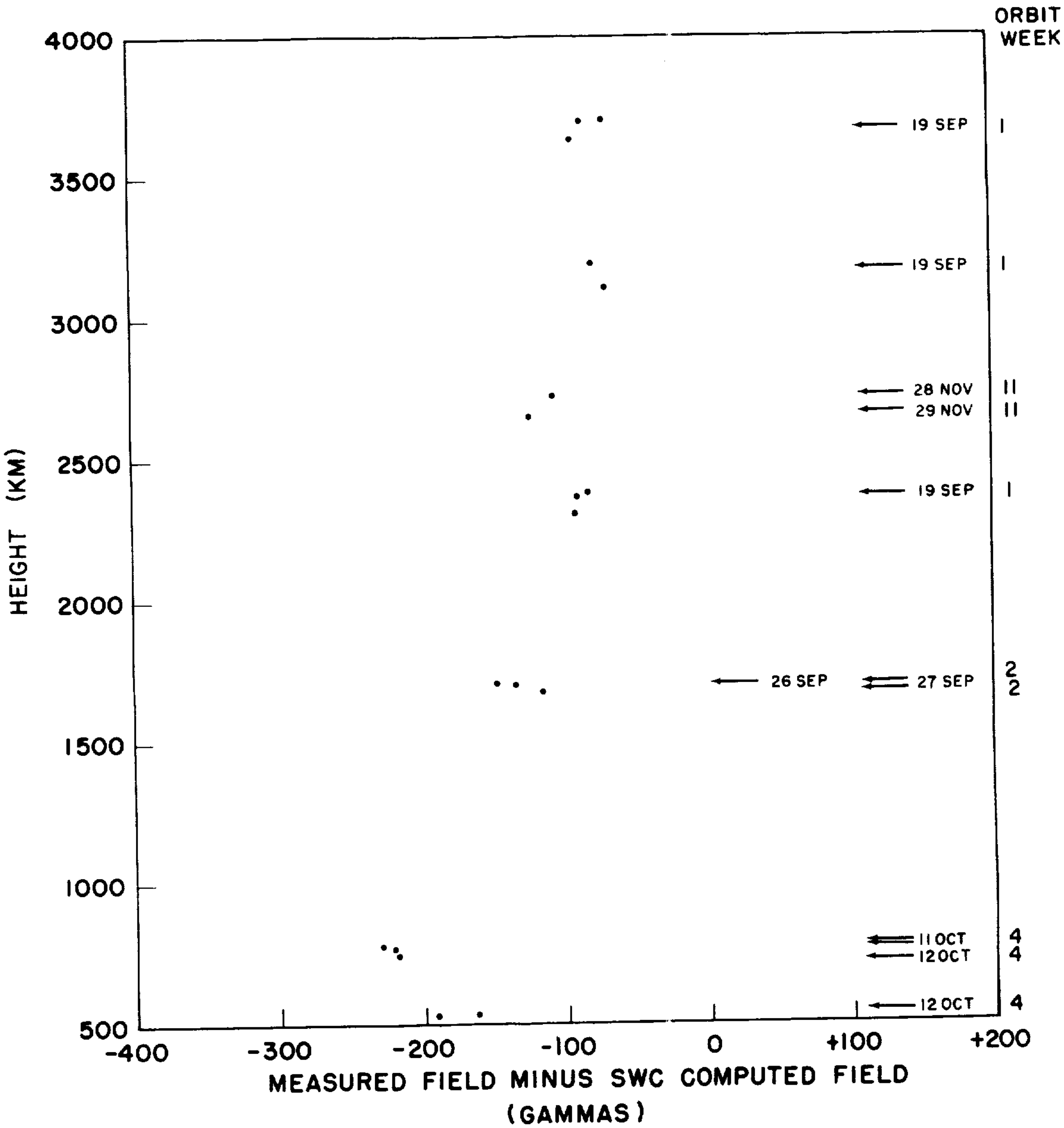
(e) Longitude, 114°W to 120°W; latitude, 26°N to 33.5°N

Figure 4 - Continued



(f) Longitude, 74°W to 82°W; latitude, 5°S to 20°S

Figure 4 - Continued



(g) Longitude, 66-74°W; latitude, 25°S-33.5°S

Figure 4 - Continued

Table 1
Measurements of Capetown anomaly

Location			Measured value minus computed value	
Longitude (°E)	Latitude (°S)	Height (km)	SWC (gammas)	Finch and Leaton (gammas)
26	10	2990	+ 40	+ 138
29	13	1790	- 214	- 41
28	27	3740	- 188	- 80
28	29	2750	- 290	- 119

vertical components with errors believed to be ± 10 gammas from a rough determination of the mean undisturbed value for the particular time of day. The letters "ND" used for the vertical component at Tucson and San Juan indicate that the disturbance was less than the errors in the selection of quiet-hour values.

The points given fall in three groups, 19 September, 20-21 September, and 3-4 October, which must be considered separately. The disturbance on the 19th may or may not be considered a storm.

On September 19 there was a 4-hour period in which the H component was depressed. The satellite reading was taken during the first hour near the time of maximum deviation. A horizontal disturbance at the satellite of magnitude equal to that on the ground would account approximately for the satellite disturbance. In a simple picture this would place an electric-current source at a greater height than the satellite. The value does not rule out the possibility of some contribution from below the satellite.

September 20-21 was a period of very irregular storm effects. Satellite readings are presented in Table 2. The first, third (Point C), and sixth (Point E) readings may be interpreted quite simply, in terms of a current source at greater altitude giving a horizontal disturbance, by calculating $\Delta H \cos I$ using ΔH from the nearest observatory and the inclination angle I appropriate to the satellite location. A simple calculation also works for the second reading (Point B) if a small fraction of the $+\Delta Z$ observed at Fredricksburg is considered. However, this cannot be considered with confidence in the absence of an explanation for the magnitude of ΔZ. The fourth (Point D) and fifth readings cannot be simply interpreted because of possible errors and the smallness of the disturbances at the closest observatories.

The storm on October 3-4 had a very mild beginning and increased in intensity gradually over a period of a half-day. Measurements F and G were taken several hours before maximum intensity was reached. Measurement H was taken late in the storm. When

Table 2

Satellite readings of magnetic-field disturbance

Figure No.	Point	Date	Time (GMT)	Long. (°W)	Lat. (°N)	Satellite height (km)	Disturbance at satellite; total field (gammas)	Disturbance at observatories (all values ± 10γ)					
								38° N 77° W Fred., Va.		32° N 111° W Tucson		18° N 66° W San Juan	
								ΔH	ΔZ	ΔH	ΔZ	ΔH	ΔZ
4c	A	19 Sept.	00:42	79	29.3	1435	-15 to -25	-55	+30	-63	ND	-60	ND
Not shown	--	20 Sept.	22:02	77	17.2	2517	-35 to -50	-55	+60	-63	ND	-67	ND
4d	B	21 Sept.	00:25	77	30.8	1530	-20 to -30	-90	+60	-83		-73	
4e	C	21 Sept.	02:32	117	28.8	1735	0 to -20	-25	+20	-33		-50	
4d	D	21 Sept.	02:43	79	33.3	954	approx. 0	-33	-17	-50		-43	
Not shown	--	21 Sept.	05:05	62	18.0	514	approx. 0	-33	-23	-15		-33	
4e	E	21 Sept.	07:10	117	27.8	629	-20 to -50	-57	-65	-83		-30	
4d	F	03 Oct.	22:25	77	33.4	2695	-100 to -120	-46	+67	-95	ND	-95	ND
4c	G	04 Oct.	00:47	76	28.2	1807	-130 to -155	-105	+55	-90		-110	
4c	H	04 Oct.	19:50	79	27.6	3562	+200	-25	+20	-60		-57	

points F and G are considered, the magnitude of the disturbance at the satellite is considerably greater than that obtained by vector addition of the ground disturbance values. Again with a simple picture, an obvious interpretation is that an electric "ring" current, bounded by field lines so that it extends to lower altitude with increasing latitude, is located at an altitude not greatly in excess of the satellite altitude at the satellite latitude. Furthermore, between the time of measurement F and the time of measurement G the ring current would have to move closer to the earth (i.e., to lower altitude and latitude) to explain the values tabulated. Three hours after measurement G, the disturbance changed character completely, and the horizontal disturbance at all three stations returned to approximately zero within 20 to 30 minutes. When this occurred, ΔZ at Fredricksburg went negative rapidly and large declination changes occurred. At Tucson the vertical component was not greatly disturbed, but the declination was disturbed. At San Juan neither the vertical component nor the declination were appreciably disturbed. After this outstanding event the horizontal component at all stations again went negative, and a period of slowly varying disturbance followed. Point H, measured 16 hours after the change in character, differs from all other values in the table. To get the +200-gamma disturbance at the satellite, it must be assured that the satellite at 3560 kilometers was slightly above, and close to the maximum of, a current belt causing the negative disturbance on the ground.

A plausible explanation for the disturbance values and the sequence of events on October 3-4 is that a ring-current shell was located in the inner part of the outer radiation belt at the time of Point F and that it moved closer to the inner edge between points F and G. It is then postulated that 3 hours after point G the current-producing particles moved abruptly into the gap between the radiation belts and were then absorbed through a lowering of their mirror altitudes. If east-west particle drift is assumed and additional satellite measurements lend support to this explanation, a check of time differences between this event's occurrence at stations around the world should provide a check on whether or not absorption took place at only one longitude. Point H definitely supports the idea that current shells can exist at the inner edge of the outer belt at least for short times. The Explorer VI observations (Reference 7) of an intense radiation belt at the inner edge of the outer belt lends additional credence to these ideas.

CONCLUSIONS

From the analysis of a small fraction of the total number of measurements, the following statements can be made:

1. A comparison of computed fields (synthesized by using spherical harmonics) with the measured field in the space regions covered by 1959 Eta shows that, in general, the computed fields have accuracies comparable with those of magnetic charts for the earth's surface (i.e., approximately 1 percent).

2. In the absence of magnetic storms, fields in the regions covered by 1959 Eta appear to be exceptionally stable. In the future it should be possible to use absolute magnetometers in satellites to improve the accuracy of radio determination of satellite positions at selected times. This also implies that the magnetic field can be useful in the navigation of powered space vehicles.

3. The negative magnetic anomaly over South Africa is found to be a sharper and more negative feature than that shown by computed spherical harmonic fields. This finding tends to support the idea that the mirror altitude for reflection of trapped particles is especially low in this region.

4. The magnetic-field disturbances observed by the satellite during magnetic storms are, with some exceptions, negative when they are negative on the earth's surface. This indicates that the main portion of an electric current producing a storm at low latitudes is located at some distance above the inner radiation belt. In the case of one magnetic storm the readings indicate that a current shell exists in the inner part of the outer radiation belt during the main phase of the storm and moves closer to the earth as the storm progresses. It is postulated that a sudden change in the character of this storm is a result of the current shell moving into the gap between the inner and outer radiation belts. A measurement taken a number of hours after this event at a point near the inner edge of the outer belt indicates that a current shell was then present slightly below the inner edge of the outer radiation belt. Analysis of additional readings should prove or disprove this explanation. The general picture from the preliminary analysis is that electric-current shells occur at different distances from the earth for different storms and that the distance may vary with time during a given storm.

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