X-612-66-305

NASA TM X-55665

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FACILITY FORM 602

N67 18567	
(ACCESSION NUMBER)	(THRU)
22	1
(PAGES)	(CODE)
TMX-55665	31
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

GPO PRICE $ ________

CFSTI PRICE(S) $ ________

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

JULY 1966

GODDARD SPACE FLIGHT CENTER
GREENBELT, MD.

Presented at the Ninth Plenary Meeting of COSPAR - May 13, 1966,
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ABSTRACT

The OGO-2 (1965-81A) satellite was launched October 14, 1965 into an orbit with an inclination of 87.4°, perigee of 414 Km and apogee of 1510 Km. Digital samples of the total magnetic field F were obtained with a rubidium vapor magnetometer at 0.5 second intervals (accuracy $\pm 2\gamma$). Root-mean-square differences between the measured field values and those computed from previously derived spherical harmonic expansions were computed. The best comparison to the data is with the GSFC (9/65) field which showed residuals of 47γ. Computation of fields fit to this limited data sample show RMS deviations of 4.1γ using 143 internal spherical harmonics. The residuals from this field show oscillations near the north pole of a few tens of gammas amplitude and irregular structure elsewhere of the order of a few gammas.

Introduction

Near the close of the IGY Prof. Sydney Chapman (1961) suggested that an essential project for the IQSY period would be the renewed surveying of the geomagnetic field. As a result of this suggestion and independent recognition by other geophysicists of the lack of worldwide magnetic survey data since the accidental destruction by fire of the survey ship "Carnegie" in 1929, there was instituted, as a major goal of the IQSY co-operation, the measurement of the earth's main field on a global basis (Vestine, 1960). Already by the end of the IGY there was renewed activity of airborne magnetic surveying by the U.S. Navy's Project MAGNET, by the Canadians and also by such surface ships as the Russian non-magnetic ship "Zarya". A limited satellite survey was carried out by the Vanguard-3 satellite in 1959 (Cain, et. al., 1962). Further impetus was given the space survey by the exchange of letters between President Kennedy and Chairman Krushchev in 1962 (Frutkin, 1965) to include magnetic surveys by satellite as one of the three areas of peaceful co-operation in outer space between the U.S. and the U.S.S.R. The proposal by Boroson, Cain and Heppner (1962) to incorporate an experiment for magnetic field studies on board the first of the NASA series of polar Orbiting Geophysical Observatories was designated as the U.S. space contribution to the IQSY World Magnetic Survey and the cooperative venture between the U.S. and the U.S.S.R. This experiment is planned on a continuing series of three near-earth polar Orbiting Geophysical Observatories that also include twenty other scientific experiments to investigate the physical phenomena in this region. It is the preliminary analysis of data from this first experiment that is being reported here.

Experimental Objectives

Since the prime initial objective of the magnetic field experiment was the mapping of the main field, it would have been desirable to measure the vector field components. However, an early evaluation of the OGO vehicle motions and available instruments for vector measurement revealed that only an accurate absolute instrument would be suitable to improve the presently available description of the earth's field. Some concern has been expressed as to whether a set of only scalar field measurements is sufficient to uniquely define the potential function from which the earth's vector geomagnetic field may be derived. Although the detailed mathematical proofs of the postulate are yet lacking, we have demonstrated (Cain, et. al., 1965) that at least a combination of scalar and vector measurements can be used to differentially adjust the Gauss coefficients of the potential so as to produce a realistic field. Also, numerical exercises have been carried out with this procedure using synthetic data computed from a potential function of internal origin with the result that the original coefficients were readily retrieved starting only with a set of data generated on one spherical shell.

The ambient magnetic field measured by a satellite contains contributions not only from the core field and possibly the field of surface anomalies, but also contributions from electric currents in the ionosphere, and from the distortions due to trapped plasmas and the magnetospheric boundary. It is the study of all of these phenomena so far as it is possible from a near-earth polar satellite, that extend the experiment objectives beyond that of a simple mapping of the field (Cain, 1966). Indeed, the determination of the main field itself requires a simultaneous investigation of these other influences; and conversely the availability of an accurate main field is a necessary analytic tool to be able to study the time variations.

MAGNETIC FIELD INSTRUMENTATION

The magnetic field instrumentation was carried out under the direction of Dr. James P. Heppner by Mr. W.H. Farthing and W.E. Folz (Heppner, 1963) using a crossed pair of double-cell Rubidium vapor magnetometers (Bloom, 1962) of a design similar to the single Rubidium vapor magnetometer used on OGO-1 but tailored to the higher fields to be encountered by OGO-2.

A sample interval of 0.5 sec was chosen to read out the counts of the Rb^{85} magnetometer. Since the field F is derived from the frequency f by the relation $F = f/4.66737$, (Driscoll, 1964; Balling, 1964) a count of C over a time t (the frequency of the clock measuring t is much greater than that of the magnetometer) leads to a field $F = \frac{1}{t}\left(\frac{C \pm 1}{4.66737}\right)$ or $\approx 2C/4.66737 \pm 0.4\gamma$ for the 0.5 sec sample interval. Exhaustive testing of the effects of any permanent or transient spacecraft field on the sensing unit failed to find any interference at the magnetometer sensor above 1γ. The absolute accuracy of this magnetometer is believed to be within $\pm 2\gamma$ with a precision of $\pm 0.4\gamma$.

OGO-2 OPERATION

The OGO-2 vehicle was launched October 14, 1965 into an orbit with an inclination of 87.4°, equatorial perigee and apogee altitudes of 413 and 1510 km respectively, and a resulting anomalistic period of 104.3 minutes. The magnetic field experiment was one of 20 scientific experiments on board the spacecraft (Ludwig, 1963; Scull and Ludwig, 1962). Although it was planned to maintain an earth orientation of one face of the spacecraft for a period of 6-12 months through the use of a system of reaction wheels and gas jets, it was noted soon after injection that anomalous oscillations in the attitude were causing the spacecraft to use the Argon control gas at a very high rate (Wiggins, 1965). Since the plane of the orbit at launch was in the twilight meridian, the spacecraft was initially in sunlight 100% of the time and could maintain orientation of its solar panels to the sun in a spinning mode without entering the "earth acquiring" mode. It was thus initially possible to return to the spinning mode until the difficulty could be located. During these initial maneuvers the rubidium magnetometer was turned on nearly all of the time and the readings were recorded alternately by a pair of tape recorders on the vehicle. The data on these tapes were "dumped" every orbit or two to a ground station recorder so that the data from the magnetometer and other operating experiments were acquired for over 19 hours per day. On October 22 the orbital plane began to enter the earth's shadow with the result that the spacecraft began to use large amounts of gas to reacquire the sun each time it came out of the earth's shadow. (This problem would not have been encountered under normal operation since the spinning mode was designed to be used only for the first few orbits.) By then it had been concluded that the anomalous gas useage in the normal earth acquisition mode was due to a design error on the infrared horizon sensors which resulted in their mistaking temperature gradients below the horizon for the gradients expected at the horizon. The sensors thus produced erroneous control signals that would cause the spacecraft to frequently tip through large angles from horizontal. Since this behavior could not be corrected it was decided to obtain as much "normal" operation as possible and the spacecraft was again returned to the "earth acquire" mode. The remaining supply of Argon control gas was exhausted by the end of October 23. The solar panels soon could not track the sun and the batteries were drained by October 24 to a point where all experiments were automatically switched off by an "undervoltage" relay.

Surprisingly, on October 29 the batteries were found to be recharged and the spacecraft was returned to operation. It was then learned that even with the lack of control gas some partial operation was possible. A total of some 70 days of magnetic field data has been subsequently acquired during those intervals when the orbital plane was in a nearly full sunlight condition or when the spacecraft motion allowed keeping the solar panels oriented towards the sun. Only a few orbits of data every few days were obtainable for the period in December when the orbit plane was near the noon-midnight configuration. Further deterioration of the spacecraft occurred with the loss of one of its two batteries December 29 and partial malfunctions of the tape recorders. Even so, nearly continuous magnetic field data were obtained for the period from mid-January 1966 through March and it is expected that more data can be acquired in late June when the orbit plane is again fully sunlit.

REDUCTION OF MAGNETIC FIELD DATA

Of the total set of data recorded by the spacecraft, the final processing including final application of time corrections has only recently (May, 1966) been completed for the data acquired during October 14 and 15, 1965. The substance of the analysis reported herein is based on data taken November 9-11, 1965 and subjected to a preliminary processing. A plot of the locations of these data is given in the map of Figure 1. One coincidental feature of this time interval is that the global magnetic activity index K_p is 0, rising to 2 only for the last 9 hours of November 11.

ORBIT DETERMINATION

The reason the above interval was chosen for a preliminary analysis was that it was the only one for which an "interim-definitive" orbit was available. Since there was a heavy use of the gas jets during the period October 14-24, it is assumed that there will be perturbations making the determination of a definitive orbit more difficult.

The November 9-11 orbit was determined for us by Dr. J. Siry and Mr. D. Stewart of Goddard Space Flight Center and based on the available radio tracking observations from the NASA Minitrack and its newer S-band Range and Range-Rate system (Habib, et. al., 1963). The orbital arc of nearly five days November 7 to November 12, 1965, was determined with the residuals to the tracking data as given in Table I.

Table I

Observation Type	Minitrack	Range	Range Rate
No. of observations	209	75	75
standard deviations	0.0006(l,m)	125 m	0.54 m/sec
approximate relative weights in fit	1	50	22

The technique of orbital determination was based on Brouwer's (1959) theory which includes effects of geogravitational zonal harmonics through the fifth. Certain additional effects associated with drag and lunar and solar perturbations were included by means of a numerical integration method. The following values for the zonal gravitational field terms up to J_5 were utilized (all x 10^{-6}): $J_2 = 1082.48$, $J_3 = -2.56$, $J_4 = -1.84$ and $J_5 = -0.06$.

Private discussions with Guier and Newton (1965) and Yionoulis (1965) have brought to light the possibility that the OGO-2 satellite is likely subject to a resonance due to the J_{15}^{14} and J_{14}^{14} terms of the gravitational potential and other effects due to the neglect of the other major non-zonal terms. The resonance possibliity is based on the fact that the ratio of the node-to-node period of the earth rotation (1437 min) is 13.8 times the nodal period of 104.1 minutes. However, without further study it is not clear whether the neglect of the non-zonal terms poses any problem for the final computed orbit in terms of inaccuracies of the computed magnetic field values.

A real danger in this orbital determination is the extreme sparseness of the data. Since apogee for this period was near the southern apex of the orbit, most of the tracking data were concentrated in the low southern latitudes. It would not be unlikely for the actual errors to mushroom to several times those indicated in Table I over unobserved portions of the orbit.

COMPARISON OF DATA WITH FIELD MODELS

The measured values of scalar field F were compared with those computed from previously published models of the earth's core field using the positions given from the above orbit. The root-mean-square residuals from the three fields LME (Leaton, Malin and Evans, 1965), GSFC(4/64) (Cain, et. al., 1965), and GSFC(9/65) (Hendricks and Cain, 1966) are given in the top half of Table 2. As noted previously, (Cain, 1965) it is thought that the LME field does not extrapolate as well in altitude as do the GSFC fields since it ignores the earth's oblateness in its derivation. However, it is known (Cain, 1966) to fit the surface data slightly better than does the GSFC(4/64) field. At the present time it is thus demonstrated that the overall error of the GSFC(9/65) field is the lowest for the current epoch of all models known to us. We have also investigated the distribution of the peak deviations of the GSFC(9/65) field from the data to determine where the largest errors appear and whether there is any systematicity to their occurrence. The result is that the few values where the error is largest, lying in the range 100 to 150γ, occur in the South Pacific, Antarctic and Eastern Russia as predictable by the paucity of data; though the peaks are displaced somewhat from the locations of the predicted maxima (Cain, 1966). Also, the remaining peak errors follow a definite pattern in regard to regions of positive ΔF (computed field too low) and negative ΔF (computed field too high). That is, with the exception of data taken over the Pacific in latitudes from 10 to 35° N, all peaks at low latitude are negative (computed field too large). Correspondingly, the field computed in polar regions tends to be a few tens of gammas too low.

TABLE 2

Root-Mean-Square Residuals to OGO-2 Magnetic Data From Computed Fields (November 9-11, 1965).

Field Model	GSFC(9/65)	GSFC(4/64)	LME
Gauss Coefficients	99	63	80
RMS(γ)	47	80	83

Field Model	OGO-2(5/66)			
Gauss Coefficients	143	120	99	80
RMS(γ)	4.1	4.7	6.3	14.2

We think it most likely that these systematic deviations in ΔF arise from errors in the secular change estimates (the GSFC(9/65) field contained time derivatives <u>only</u> for the first 48 coefficients) and from ignoring systematic Dst (storm-time) effects in all calculations.

PRELIMINARY ANALYSIS OF DATA

Since the ΔF = (F measured - F computed) is still quite large when the field is computed from the GSFC(9/65) coefficients it was decided to follow the technique used for the Vanguard-3 analysis (Cain, et. al., 1962) and make a differential correction of the coefficients using the OGO-2 data alone. Because the data occupy such a small time span, the time derivatives of the coefficients were held fixed. The results of this exercise are given in the lower half of Table 2. Here are shown four field models fit to the data themselves using a varying number of Gaussian coefficients corresponding to truncating the series equally in n and m. Thus for a maximum n = m = 11, the number of parameters is 143. (The number of Gauss coefficients = $(\text{nmax} + 1)^2 - 1)$. One can note that the percentage drop in the RMS residuals halves with each increase of nmax. That is, the improvement from 8 to 9 is 50%, from 9 to 10 is 25%, and from 10 to 11 is 13%. The fact that the RMS error is almost an order of magnitude less for these models than for those in the upper half of the Table is indicative of the future improvement that should be possible in the main field models.

Of course, one should not attempt to use any of these preliminary analyses of the OGO-2 data as a realistic world-wide model of the core field since the data distribution still contains large gaps and the orbit was in a fixed local time vs. latitude orientation during the period of the data acquisition. As seen in Figure 2, all of the mid-latitude data were either at 2-4 am or 2-4 pm and the polar data were at the intervening local times. Further, during this period perigee was near the north pole and apogee near the south pole. Since any quiet daily variation or external field configuration will have systematic components with local time, these will likely be absorbed into the set of internal Gauss coefficients.

A typical curve of the residuals of ΔF verses time for one complete orbit is given in Figure 3. Shown here is the plot of all of the data taken from $9^h\ 45^m$ to $12^h\ 0^m$ U.T. on November 10, 1965. The latitude, longitude (east positive), and altitude (kilometers above geoid) are given each 15 minutes. The precision of $\pm 0.4\,\gamma$ in the digitization accounts for most of the thickness of the curve. However, superposed on this noise level are seen both a fine structure of perhaps $\pm 1\gamma$ amplitude and a fraction of a minute period, irregular sharp discontinuities of 1 to 2γ and a wave structure of up to 15 minutes period and only 5γ amplitude except near perigee. Experience at comparing various of such graphs has shown that the character of the longer period structure changes when a different number of coefficients are used.

However, near perigee there always appear sharp oscillations with peak deviations of a few tens of gamma. Since perigee occurs for these data near the northern apex of the orbit it is not yet clear whether this phenomenon is due to some peculiarity of the temporal field in the night time polar region, some anomalous orbital error, or simply some unknown characteristic of the analysis technique. Since the change in altitude from apogee to perigee is a smooth one, it is difficult to see how the sudden appearance of such a large oscillation could be due to any increase in sensitivity to higher harmonics of the spatial field structure with decreasing altitude.

One of the pertinent features of the geomagnetic field is that the spatial gradients in the horizontal direction are everywhere of the order of $2\gamma/\mathrm{km}$

whereas the vertical gradients vary from about 5γ/km near apogee to 20-30γ/km near perigee. If we assume that the errors in the orbit are roughly spherical, then the oscillations at perigee could arise from altitude errors of only 0.5 to 1 km. Such a postulate could also account for the oscillations of periods of the order of 15 minutes since these are of sufficiently long wavelength that they should be fit by the high order ($n = m = 11$) polynomials used. Of course any temporal changes in the field would have the same result. However, if such changes are temporal, they would likely be a result of the day-to-day variability in the quiet solar daily variation Sq instead of disturbance since the field was very quiet during most of the interval.

Discussions and Conclusions

The preliminary work done to date on the OGO-2 magnetic data lends support to the hope that a complete analysis will result in a description of the main field that has errors at least an order of magnitude less than do present models. These new models will serve as benchmarks for refined studies of the secular variations of the core field and as tools for understanding the nature of the field distortions above the ionosphere. Visual inspection of the present results already indicates possible detection at a few gamma level of such spatially narrow phenomena as crustal magnetic anomalies. The lack of enough tracking data to guarantee a precise position of the satellite at the time of the field measurement is seen to pose a possible problem to the data analysis. Nevertheless, it is expected that at least the initial objectives of the IQSY World

Magnetic Survey can be satisfied with the data from this satellite with hopes that some insights may be achieved in understanding the physical processes determining the temporal changes of the magnetic field above the ionosphere.

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Figure Captions

1. Locations of OGO-2 Magnetic Field Data November 9-11, 1965
2. Local time - Latitude - perigee configuration for the OGO-2 orbit November 9-11, 1965
3. Typical ΔF vs. time plots of OGO-2 data where the computed field is that designated in Table 2 as OGO-2(5/66) with 143 parameters

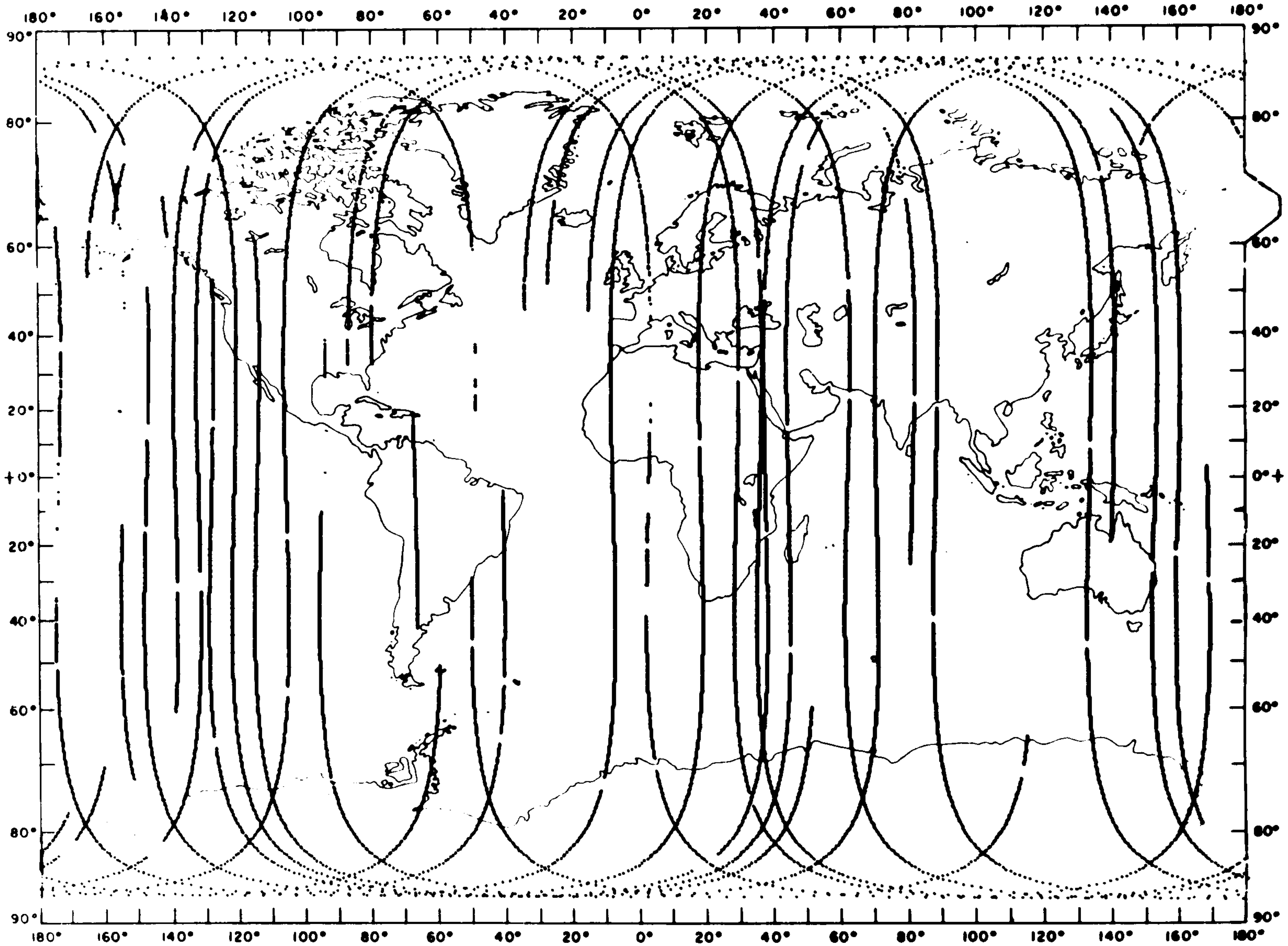

180°
160°
140°
120°
100°
80°
60°
40°
20°
0°
20°
40°
60°
80°
100°
120°
140°
160°
180°
90°
80°
60°
40°
20°
+0°
20°
40°
60°
80°
90°

FIGURE 1.

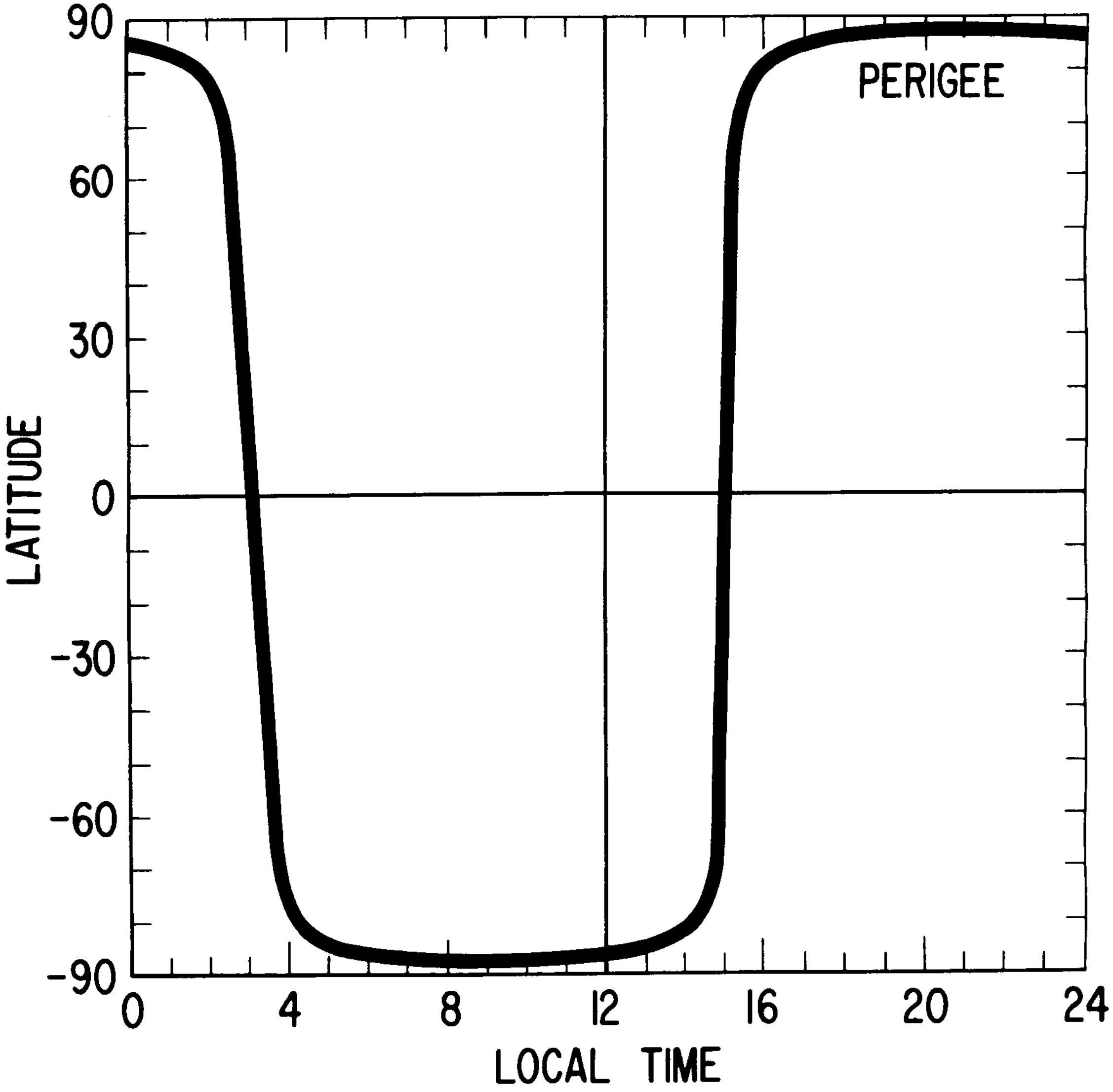
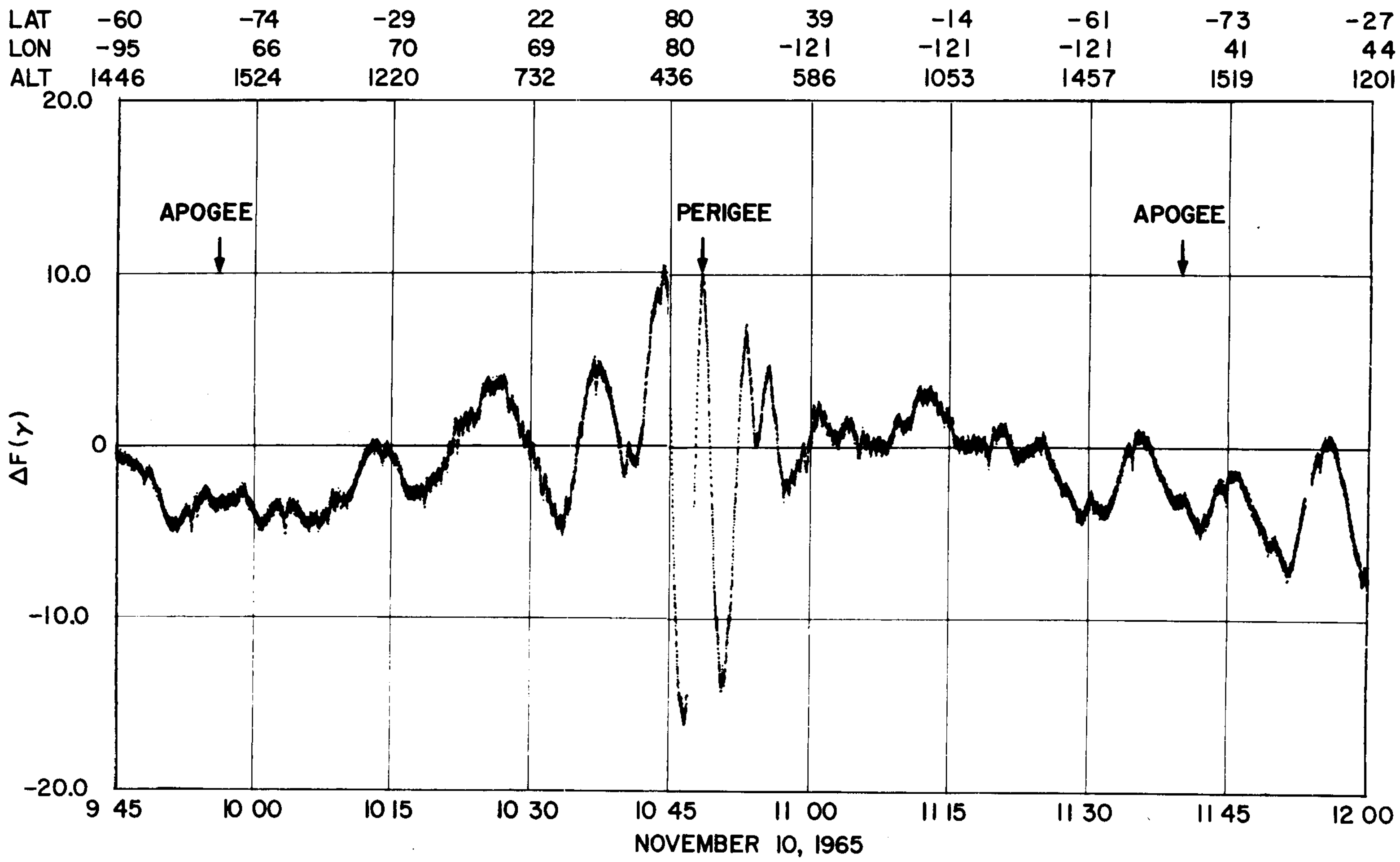


FIGURE 2.


LAT
LON
ALT
-60 -95 1446
-74 66 1524
-29 70 1220
22 69 732
80 80 436
39 -121 586
-14 -121 1053
-61 -121 1457
-73 41 1519
-27 44 1201
20.0
10.0
0
-10.0
-20.0
ΔF(γ)
APOGEE
PERIGEE
APOGEE
9 45
10 00
10 15
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10 45
11 00
11 15
11 30
11 45
12 00
NOVEMBER 10, 1965

FIGURE 3.