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THE SEMI-ANNUAL VARIATION IN THE HETEROSPHERE: A REAPPRAISAL[1]

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Past attempts to represent the semi-annual density variation in the heterosphere as a consequence of temperature variation have run into difficulties in two height regions: below 200 km and above 1000 km. The main argument in favor of the temperature variations was the dependence of their amplitude on the solar cycle; it can be shown, however, that this dependence is spurious, being caused by the variation of the density change $d\rho/dT$ with the temperature T. An analysis of the semi-annual density variations at different height levels fails to show a dependence on the amplitude with the sunspot cycle. All difficulties are removed if we assume that the semi-annual density variation is not a direct consequence of temperature variations.

My 1965 static models of the heterosphere [Jacchia, 1965, hereafter referred to as J65] contained empirical equations to represent the different types of density variation that are encountered in that region. In all these equations the exospheric temperature was related to parameters known from ground-based observations, such as the decimetric solar flux, the planetary geomagnetic index, local solar time, latitude, etc. On the whole these equations were rather successful in accounting for the observed variations and were widely used by researchers trying to intercompare observations made at different times, places, and heights.

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While it seemed quite logical to use temperature variations as the basis for the diurnal density variations and of those that accompany solar and geomagnetic activity, it was less evident that the same should be done for the semi-annual variation, whose nature was largely unknown. It seemed to work, however, at least in the region between 250 and 600 km, which at that time was covered by satellite-drag data. Difficulties, however, soon became apparent. Cook and Scott [1966] and Cook [1967, 1969a] found that near sunspot minimum the amplitude of the semi-annual density variation at 1100 km derived from the drag of the Echo 2 and the Calsphere satellites was much larger than that predicted on the basis of the J65 formula. At that height, according to the models, in 1964-1965 any temperature variation would have resulted in extremely small density variations, because of the near-balance of the helium variations in phase with the temperature and the hydrogen variations in antiphase. At the time when the variation should have been not larger than 6%, the observed variations reached a factor of 2. After 1966, when solar activity rose toward its maximum, the discrepancy became smaller and almost disappeared.

Another discrepancy became evident for heights below 200 km, with the launching of longer-lived satellites with low perigee heights. Also here, at heights of 150 to 200 km, the observed variation was larger than that predicted by J65 [King-Hele and Hingston, 1967, 1968; King-Hele, 1967; King-Hele and Walker, 1970]. Initially we attributed this discrepancy to the fact that in the J65 models constant boundary conditions were assumed at 120 km, where fairly large density variations with temperature actually occur: the reasoning was that, approaching 120 km, the computed density variations should have proved too small. My more recent models, however [Jacchia, 1970, 1971], in which the constant boundary conditions were moved to 90 km, proved also inadequate to represent the observed semi-annual density variation in the 150- to 180-km region. Cook [1969b] actually found that the semi-annual variation, still in phase with that in the thermosphere and exosphere, can be discerned even at 90 km, which is a near-isopycnic level at which all other density variations nearly vanish [Groves, 1970]. The range in density found by Cook at 90 km amounts to about 30%, but a reanalysis of his data by this writer, eliminating high-latitude measurements, which are affected by annual (seasonal) variations, reduces the range to 15%, which is still a respectable amount.

Decreasing the amount of hydrogen in the atmosphere would increase the computed amplitudes at 1100 km, but then the computed total density is too low at sunspot minimum. Besides, hydrogen densities from Balmer α observations [Tinsley, 1970] would indicate a larger, not a smaller, hydrogen concentration. Also, any tampering with the hydrogen concentration in the models would not cure the discrepancies observed at heights below 200 km.

An obvious way out of all these difficulties is to assume that the semi-annual density variations are not caused by temperature variations. The main reason for clinging to a model based on temperature variations was the apparent dependence of the amplitude of the diurnal variation on solar activity. As it turns out, however, this is really a built-in variation, because at any given height in the heterosphere the change of density with temperature $d\rho/dT$ is strongly dependent on the temperature T itself. Therefore, even a density variation with constant amplitude throughout the solar cycle, if interpreted as a thermal variation, would yield a temperature amplitude dependent on the phase of the solar cycle. Reanalyzing the density variations obtained from the orbital drag of six satellites in the interval 1958-1970 we find that this is precisely the case.

The semi-annual density variation is characterized by the following maxima and minima:

1. A secondary minimum in mid-January.
2. A secondary maximum in early April.
3. A primary minimum in late July.
4. A primary maximum in late October.

Figure 1 shows the semi-annual density variation derived from the drag of the Explorer 32 satellite; it was obtained by suppressing all other known variations by means of the empirical equations of the 1971 models [Jacchia, 1971] and taking 10-day means of the residuals.

In Figure 2 we have plotted, for six satellites with perigee heights between 250 and 1100 km, the difference in the logarithm of the density between two successive extremes of the density curve: 1-2 denotes the increase in density between the minimum marked 1 (January) and the maximum marked 2 (April); 2-3 denotes the decrease in density between 2 and 3 (April maximum and July minimum), etc. The differences were read off a smooth curve drawn through points representing 10-day means of observed densities in which all other density variations (diurnal, solar activity, etc.) had been suppressed using the equations of the J71 model. The quantity $\overline{z}$ given for each satellite is the effective height to which the data refer — i.e., the weighted mean of the heights along the satellite orbit, in which the drag is taken as the weight; for satellites of moderate eccentricity, $\overline{z}$ lies about half a density-scale height above the perigee height.

An inspection of Figures 1 and 2 shows that:

a) The alternation of primary and secondary minima and maxima is a quite regular feature;

b) The amplitude undergoes irregular variations from year to year that can be recognized in the plots for nearly all satellites (such as the increase in amplitude from 1965-1966 to 1967-1968 and the subsequent decrease in 1969);

c) There is no clear-cut indication of a dependence of the amplitude on the solar cycle.

Averages for each satellite of the data plotted in Figure 2 are presented in Table 1. From the differences between successive extremes we have computed average ordinates for the individual maxima and minima, normalizing the maximum amplitude A (the difference between extremes 3 and 4, i.e., the primary minimum in July and the primary maximum in October) to unity. These data, with the mean values from all satellites together and the average dates of the extremes, are given in Table 2. A smooth curve with the dates and normalized ordinates given at the bottom of Table 2 is shown in Figure 3. Both the relative ordinates and the dates of the maxima and minima are very similar to those found in a previous analysis based on temperatures [Jacchia et al., 1969].

In Figure 4 we have plotted the mean amplitude A against the height $\overline{z}$. To the data in the last column of Table 2 we have added two points:

1) $\overline{z} = 90$ km , $A = 0.06$;

2) $\overline{z} = 185$ km , $A = 0.11$.

The first comes from the reanalysis of Cook's [1969b] data that we mentioned earlier, and the second from the paper by King-Hele and Walker [1970] on satellite 1967-31A. In the latter case we reduced the original value 0.12 observed in 1968-1969 to 0.11 to allow for the larger amplitude of the semi-annual variation during that time interval. Although it might have been expected that A might depend on the density ρ rather than on height, we find that the relation between A and ρ is poorer than that between A and z. Up to 700 to 800 km the amplitude A generally increases as ρ decreases. Since at sunspot minimum ρ is considerably smaller than at sunspot maximum, we should observe an increase in A when solar activity is lower, if there is a unique relation between A and ρ. A look at Fig. 2 shows that this does not happen: in 1963-1965 A was, if anything, a little smaller than the average.

In Figure 4 we have drawn a smooth curve through the plotted points. Calling the relation represented by this curve A = f(z) and calling f(t) the curve of Figure 3, we can represent the semi-annual variation as

$$\Delta \log_{10} \rho_{\text{semi-annual}} = f(z)\, f(t) \quad .$$

Analytical expressions for f(z) and f(t) have been derived and are given below:

$$f(z) = (5.876 \times 10^{-7}\, z^{2.331} + 0.06328) \exp(-2.868 \times 10^{-3}\, z) \qquad (z \text{ in km})$$

$$f(t) = 0.02835 + 0.3817 \left[1 + 0.4671 \sin(2\pi\tau + 4.137)\right] \sin(4\pi\tau + 4.259)$$

where

$$\tau = \Phi + 0.09544 \left\{ \left[\frac{1}{2} + \frac{1}{2} \sin(2\pi\Phi + 6.035)\right]^{1.650} - \frac{1}{2} \right\}$$

Φ is the phase of the semi-annual variation, i.e., approximately, the number of days elapsed since January 1, divided by the duration of the tropical year in days. A more rigorous expression, better suited for computer purposes, is

$$\Phi = (t - 36204)/365.2422$$

where t is time expressed in Modified Julian Days (MJD = Julian Day minus 2 400 000.5). MJD 36204 corresponds to January 1, 1958.

The absolute term (0.02835) in the expression for f(t) has the purpose of making $\int f(t)\, dt = 0$ over one cycle of the variation.

Of the several hypotheses that have been put forward to explain the semi-annual density variation perhaps the most appealing was the one based on the change of shape of the magnetosphere with the change of inclination of the earth's magnetic dipole with respect to the direction of the solar wind during the year — a modernized version of the original explanations of Bartels [1928] and McIntosh [1959] to explain the semi-annual variation of the geomagnetic indexes [for more details, see the review by Jacchia, 1964]. This model would have also been able to explain the 12- and 24-hour density oscillations observed by Jacobs [1967] in the drag of low-perigee Air Force satellites and later confirmed by the analysis of the motion of other satellites in the same series. The original interpretation of Jacobs, that the variation was caused by a thermal density bulge above the geomagnetic poles cannot be supported, because no increase in density is observed in the drag of other satellites in polar orbit when their perigees cross high-latitude regions [Jacchia, 1968]: to explain the observed effect the density bulge should be extremely pronounced and could not have escaped detection. McIntosh [1959] correctly pointed out that an interaction between a solar corpuscular stream and the geomagnetic field would cause both a semi-annual and a semi-diurnal variation in the latter. It would seem, therefore, that an explanation of the semi-annual density variation based on this interaction could account for the oscillations observed by Jacobs. The dissociation of the semi-annual density variation from the solar cycle, as shown in this paper, would tend to make such an explanation less likely, but perhaps not all is lost. It is true that the intensity of the solar wind changes with the solar cycle, but maybe such a change is only weakly reflected in a differential effect such as the change in shape of the magnetosphere in the course of the year.

The purpose of this paper is to show that the semi-annual variation can be represented as a pure density variation whose amplitude is a function of height. Obviously some temperature variation must accompany any density variation, but in this case the temperature variation is clearly small and cannot be evaluated until a truly dynamic model of the semi-annual variation is devised.

REFERENCES

Bartels, J., Handbuch der Experimentalphysik, 25, 161, 1928.

Cole, A. E., Suggestion of a second isopycnic level at 80 to 90 km over Churchill, Canada, J. Geophys. Res., 66, 2773, 1961.

Cook, G. E., The large semi-annual variation in exospheric density: A possible explanation, Planet. Space. Sci., 15, 627, 1967.

Cook, G. E., The semi-annual variation in the upper atmosphere: A review, Ann. Geophys., 25, 451, 1969a.

Cook, G. E., Semi-annual variation in density at a height of 90 km, Nature, 222, 969, 1969b.

Cook, G. E., and D. W. Scott, Exospheric densities near solar minimum derived from the orbit of Echo 2, Planet. Space. Sci., 14, 1149, 1966.

Groves, G. V., Seasonal and latitudinal models of atmospheric temperature, pressure, and density, 25 to 110 km, Air Force Survey in Geophys., 218 (AFCRL-70-0261), 1970.

Jacchia, L. G., Static diffusion models of the upper atmosphere with empirical temperature profiles, Smithsonian Contrib. Astrophys., 8, 215, 1965.

Jacchia, L. G., Recent results in the atmospheric region above 200 km and comparisons with CIRA 1965, in Space Research VIII, edited by A. P. Mitra, L. G. Jacchia, and W. S. Newman, North-Holland, Amsterdam, 800-810, 1968.

Jacchia, L. G., New static models of the thermosphere and exosphere with empirical temperature profiles, Smithsonian Astrophys. Obs. Spec. Rept., 313, 87 pp., 1970.

Jacchia, L. G., Revised models of the heterosphere with analytical temperature profiles, in preparation, 1971.

Jacchia, L. G., J. W. Slowey, and I. G. Campbell, A study of the semi-annual density variation in the upper atmosphere from 1958 to 1966, based on satellite drag analysis, Planet. Space Sci., 17, 49, 1969.

Jacobs, R. L., Atmospheric density derived from the drag of eleven low altitude satellites, J. Geophys. Res., 72, 1571, 1967.

King-Hele, D. G., Upper atmosphere density in 1966-67: the dominance of a semi-annual variation at heights near 200 km, Nature, 216, 880, 1967.

King-Hele, D. G., and J. Hingston, Air density at heights near 190 km in 1966-67, from the orbit of Secor 6, Planet. Space. Sci., 16, 675, 1968.

King-Hele, D. G., and J. Hingston, Variations in air density at heights near 150 km from the orbit of the satellite 1966-101F, Planet. Space. Sci., 15, 1883, 1967.

King-Hele, D. G., and D. M. C. Walker, Air density at heights near 180 km in 1968 and 1969, from the orbit of 1967-31A, Royal Aircraft Establishment, Tech. Rep. 70084, 1970.

McIntosh, D. H., On the annual variation of magnetic disturbance, Phil. Trans. Roy. Soc. London, A251, 525, 1959.

Tinsley, B. A., Variations of Balmer-α emission and related hydrogen distributions, in Space Research X, edited by T. M. Donahue, P. A. Smith, and L. Thomas, North-Holland Publishing Co., Amsterdam, 582-601, 1970.

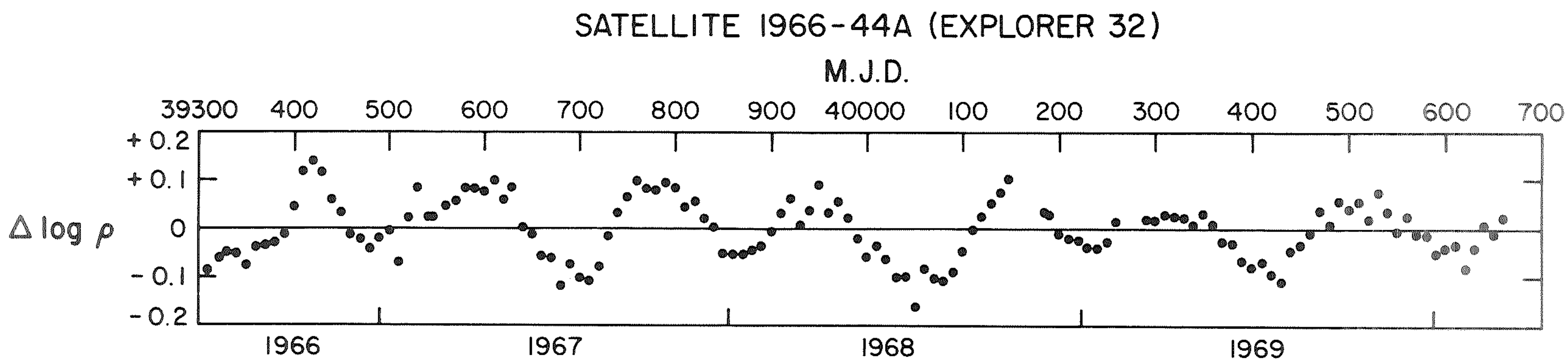

Fig. 1. The semi-annual density variation as derived from the drag of the Explorer 32 satellite.

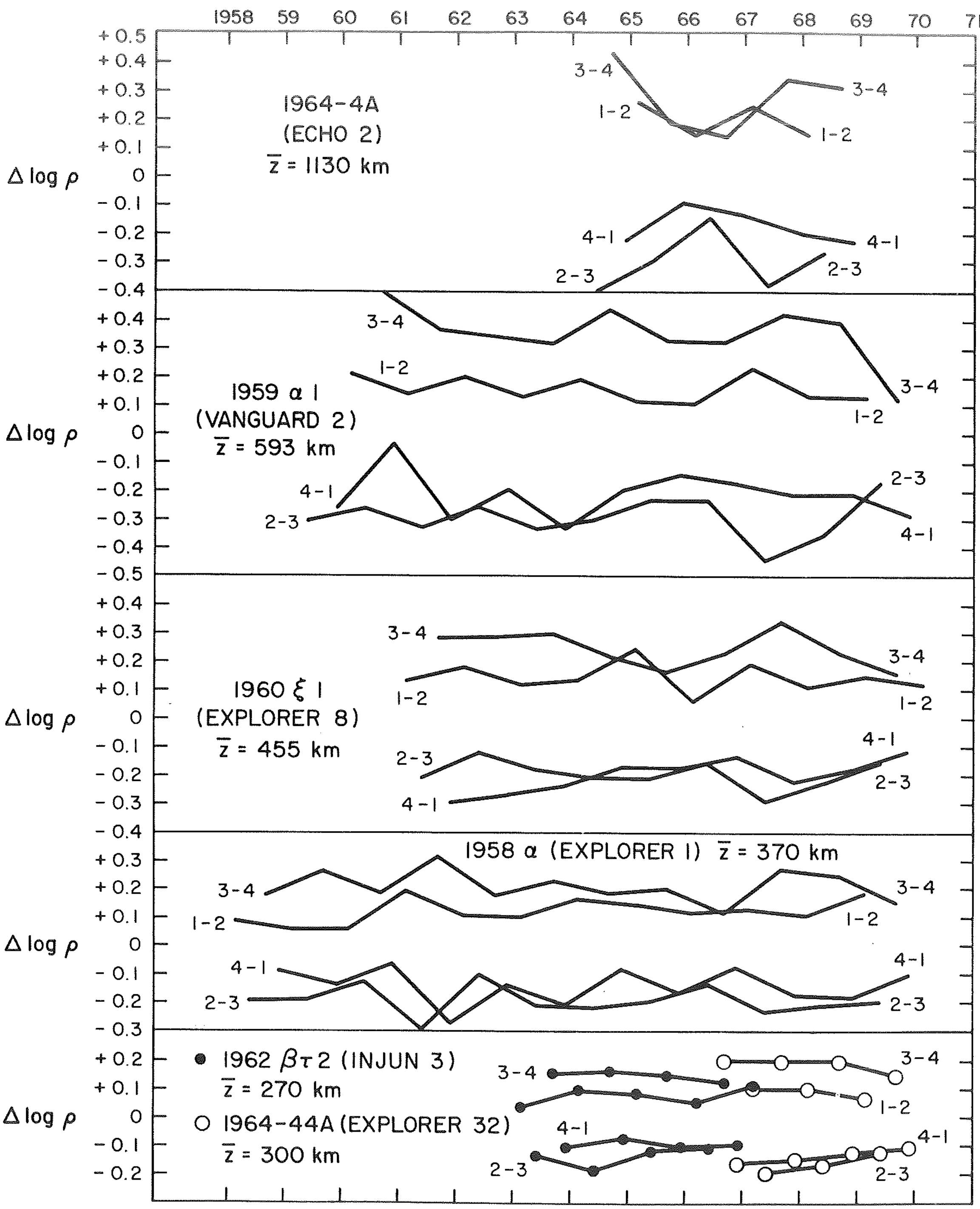

Fig. 2. Differences in $\log_{10} \rho$ between successive extremes (maxima or minima) of the semi-annual variation, from drag data of six satellites.

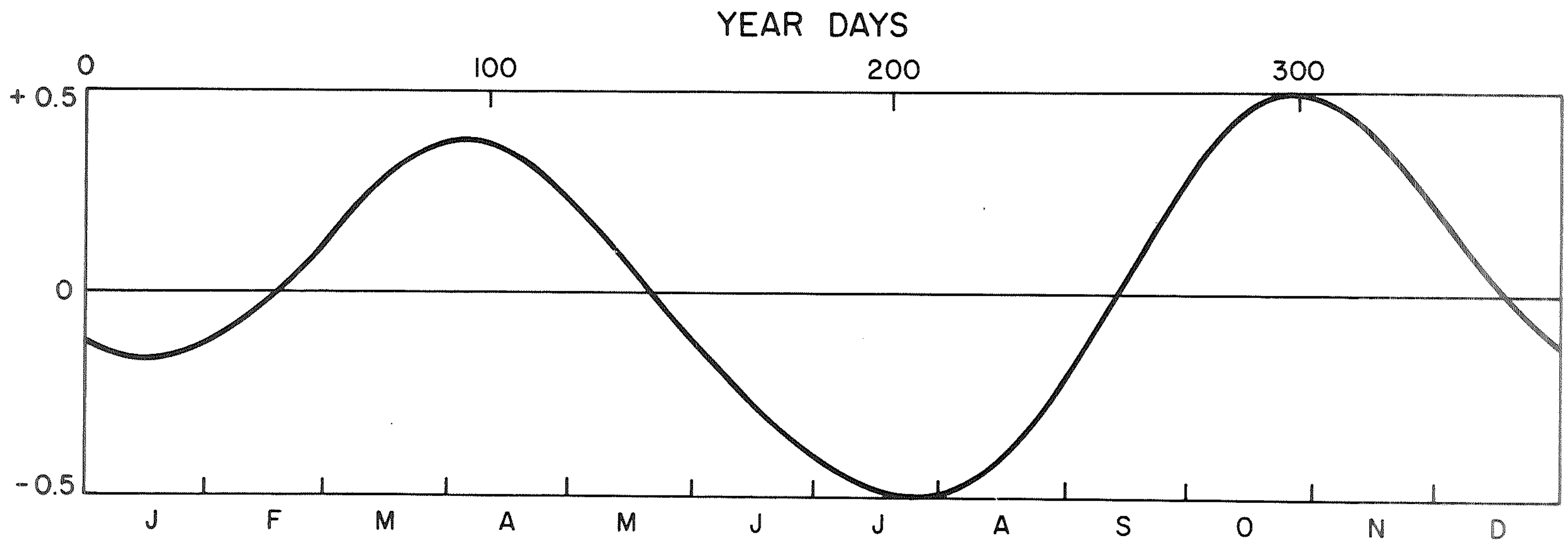

Fig. 3. Normalized average curve of the semi-annual density variation.

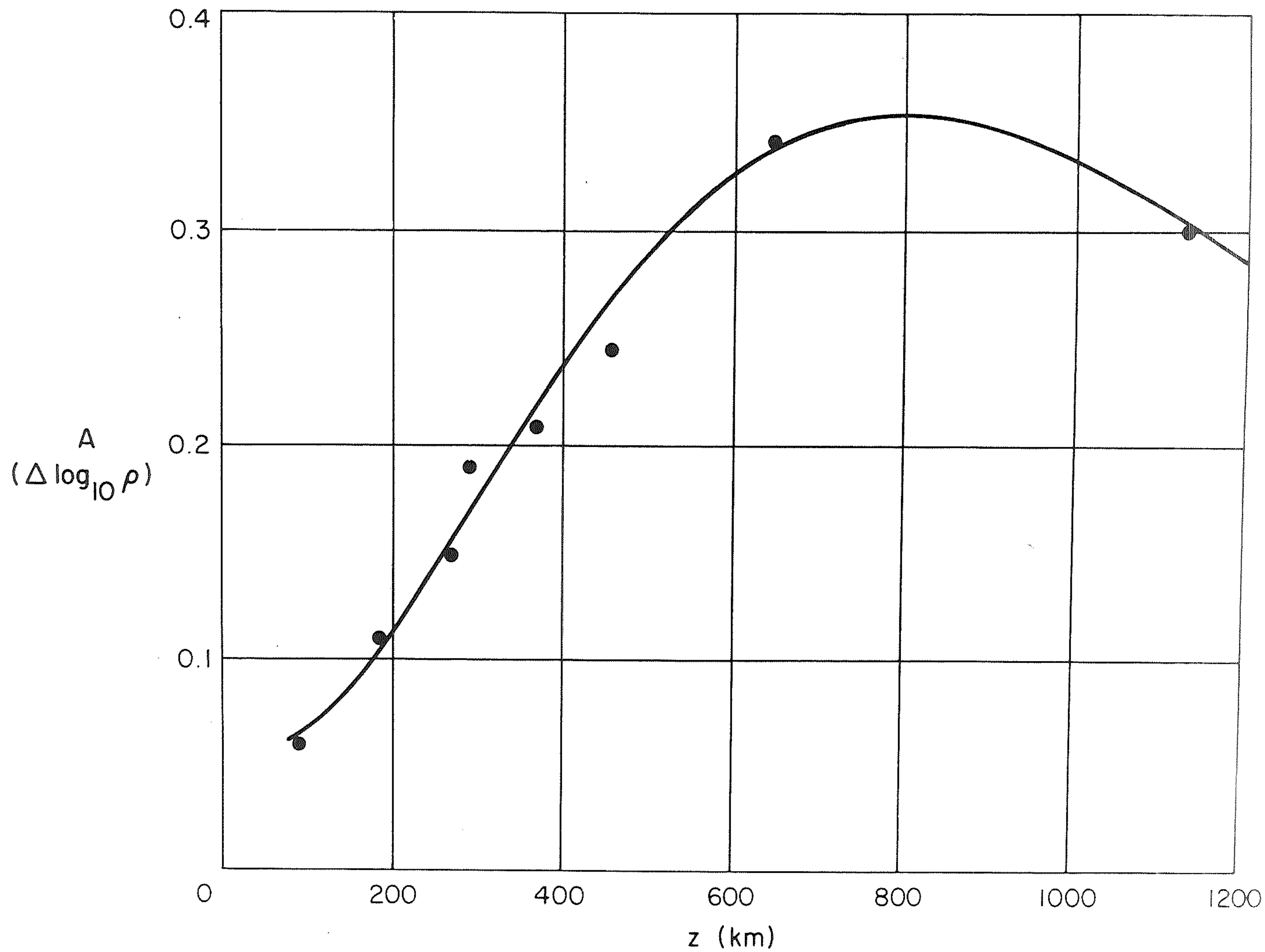

Fig. 4. Variation with height of $A = \Delta_3^4 \log_{10} \rho$, the rise in log ρ between the primary minimum in July and the primary maximum in October.

TABLE 1. Average differences in log ρ between successive extremes of the semi-annual oscillation.

Satellite	$\overline{z}$ (km)	$\Delta \log_{10} \rho$ 1-2	2-3	3-4	4-1
1962 $\beta\tau 2$	270	+0.077	-0.133	+0.149	-0.093
1964-44A	292	+0.096	-0.156	+0.190	-0.130
1958 α	370	+0.122	-0.190	+0.209	-0.141
1960 $\xi 1$	455	+0.147	-0.193	+0.245	-0.199
1959 $\alpha 1$	595	+0.164	-0.292	+0.341	-0.213
1964-4A	1130	+0.196	-0.300	+0.281	-0.177

TABLE 2. Normalized average ordinates of the extremes in the semi-annual density oscillation and mean value A of the July-to-October range A.

Satellite	$\bar{z}$ (km)	1	2	3	4	n (years)	A ($\Delta \log_{10} \rho$)
1962 $\beta\tau 2$	270	-0.12	+0.39	-0.50	+0.50	4	0.149
1964-44A	292	-0.18	+0.32	-0.50	+0.50	3	0.186
1958 α	370	-0.18	+0.41	-0.50	+0.50	12	0.208
1960 $\xi 1$	455	-0.31	+0.29	-0.50	+0.50	9	0.242
1959 $\alpha 1$	595	-0.12	+0.36	-0.50	+0.50	11	0.340
1964-4A	1130	-0.13	+0.57	-0.50	+0.50	5	0.283
Weighted mean		-0.18	+0.38	-0.50	+0.50		
Mean date		Jan. 18	Apr. 5	July 27	Oct. 25		