ROYAL AIRCRAFT ESTABLISHMENT

Technical Report 71171

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SUMMARY

The rotation of the upper atmosphere subjects a satellite to an aerodynamic force normal to the orbit, which has the effect of slightly reducing the inclination of the orbit to the equator. The average rotational speed of the upper atmosphere at heights a little above that of perigee can be evaluated from the observed changes in orbital inclination. Since the change in inclination is small (less than 0.1^{o}), the values generally have to be averaged over several months, and they can also be regarded as applying over latitudes up to about half the inclination, the effects being strongest at the equator.

Recent results reviewed in this Report confirm the previous finding that the upper atmosphere at heights of 200 to 350 km rotates on average faster than the Earth, and that the average rate of rotation increases with height from about 1.1 rev/day at 200 km to nearly 1.4 rev/day at 350 km. However, it appears that the rotation rate decreases above 350 km, to about 1.0 rev/day at 420 km and 0.7 rev/day at 500 km. In addition, new studies at heights of 120 to 230 km indicate wide variations in the rotation rate over short time intervals.

A preliminary version of this Report was presented at the COSPAR meeting in Seattle in June 1971.

Departmental Reference: Space 376

CONTENTS

1 INTRODUCTION

The rotation of the upper atmosphere subjects a satellite to an aerodynamic force normal to the orbit, and this force continuously but very slowly reduces the inclination of the orbit to the equator. The inclination can decrease by as much as 0.1° for a satellite in an orbit of low perigee and high inclination, with an initial orbital period greater than 100 minutes. By measuring the observed decrease in inclination, we can determine the average rotational speed of the upper atmosphere at heights a little above that of perigee. Since the change of inclination per month is usually very small, the values of rotational speed so far obtained have usually been averaged over several months; this generally means that the local time at perigee is an average over at least 6 hours. The values can also usually be regarded as being averaged in latitude over latitudes up to about half the inclination, the effects being strongest at the equator. So far, most results have been confined to the height range 170 to 380 km, where the influence of air drag is strongest; and the errors (sd) have been about 3% at best and 10% at worst.

Results from 27 orbits were available in 1969, and were reviewed at the meeting of COSPAR in Prague[1]. These results showed that the upper atmosphere at heights between 200 and 360 km was on average rotating faster than the Earth, and the speed increased with height from about 1.1 rev/day at 200 km to about 1.4 rev/day at 350 km. This would correspond to average west-to-east winds at 30° latitude increasing from 40 m/s at 200 km to 160 m/s at 350 km height. Since 1969 great improvements have been made in the accuracy of orbit determination of high-drag satellites, largely as a result of a campaign of observations of low-perigee satellites by the Hewitt cameras at Malvern and Edinburgh, and the 200-mm camera at Meudon. The first results from these more accurate orbits are now becoming available and are reviewed in this Report.

2 RESULTS FROM INDIVIDUAL SATELLITES

2.1 Explorer 1, 1958α

A good example of the use of the method is shown in Fig.1, which gives the observational values of orbital inclination for Explorer 1, as determined by the Smithsonian Astrophysical Observatory[2] over 11½ years from its launch in 1958 to the end of 1969. The inclination decreased from 33.24° initially to 33.17° at the end of 1969. Fig.1 also shows the theoretical curve for an atmospheric rotational speed 1.4 times that of the Earth (Λ = 1.4)*. The agreement between theory and observation is excellent, allowing for errors of about 0.005° in the observational values, and shows[3] that, at latitudes up to about 20°, the upper atmosphere at heights near 370 km was rotating on average at 1.4 ± 0.1 rev/day over the complete cycle of solar activity between 1958 and 1969.

2.2 1968-59A

The satellite 1968-59A was launched in June 1968 into a polar orbit with an initial perigee height of 160 km and an initial period of 104.8 minutes: it offered the first good opportunity for evaluating the atmospheric rotational speed below 200 km. The orbit of the satellite was determined at RAE from Baker-Nunn, visual and radar observations[4], and Fig.2 shows the 9 RAE observational values of inclination, with standard deviations, together with values from USAF Spacetrack and US Navy orbital elements, all after correction for luni-solar and other relevant perturbations. The theoretical curve fitted is divided into two parts, with Λ = 1.20 ± 0.07 up to MJD 40150, applicable for a height of 175 km, and Λ = 1.1 ± 0.1 after MJD 40150, applicable for a height of 150 km.

The orbit of this satellite has also been determined, quite independently and from different observations, at the Aerospace Corporation. By fitting these data, Mrs. Ching[5] obtained Λ = 1.32 with nominal standard deviation of 0.05. However, other statistical tests applied by Mrs. Ching suggested that a realistic standard deviation would be somewhat larger, and it is probably fair to quote Λ = 1.32 ± 0.1 at a height of 175 km as a value comparable to the Λ = 1.20 ± 0.07 from the results in Fig.2. So the difference between the two independent determinations is not significant.

2.3 Cosmos 307 rocket, 1969-94B

Cosmos 307 rocket entered orbit on 24 October 1969 and decayed on 20 July 1970. The initial perigee height was 210 km, the inclination 48.4°, and the initial period 108.8 minutes. So the object was very suitable for studies of atmospheric rotational speed, and was intensively observed by the British optical tracking network, including the Hewitt cameras, by the camera

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*Λ is defined as the ratio of atmospheric angular velocity to the Earth's angular velocity; or, in other words, the atmospheric rotation rate in revolutions per day.

at Meudon, and also by radar. From the observations the orbit has been determined by Hiller[6] at 25 epochs, and the values of inclination obtained are plotted in Fig.3, with standard deviations, after correction for luni-solar, odd zonal harmonic, and tesseral harmonic perturbations. Six of the standard deviations are too small to show, being less than 0.0004°. The solid line in Fig.3 is the theoretical curve for $\Lambda = 1.06$, which gives the best fit over the complete lifetime. The standard deviation of this mean value of Λ is estimated as 0.04, and the height at which it applies is about 230 km.

This is the most accurate set of values of inclination yet produced for a high-drag satellite with an initial period of more than 100 minutes, and some of the observational points seem to differ significantly from the values given by the theoretical curve: in particular, there is a run of 10 values below the curve between 1 March and 1 June 1970. To fit all these points satisfactorily requires at least 3 different values of Λ during the 3 months. The broken and dotted curves in Fig.3 show the values given by taking $\Lambda = 1.2$ between MJD 40653 and 40696, $\Lambda = 1.8$ between MJD 40696 and 40723, and $\Lambda = 0.5$ from MJD 40723 to 40747. The fit is of course much better, but the numerical values of Λ may be unreliable, because a different choice of values might be made if one of the orbits was in error.

At first sight the value $\Lambda = 1.8$ may seem rather outrageous, since it implies west-to-east winds of order 300 m/s at low latitudes, while $\Lambda = 0.5$ implies east-to-west winds of order 200 m/s. It seems possible, however, that upper-atmosphere rotation may sometimes depart greatly from normality: Rees[7] has measured local east-to-west neutral air winds of up to 500 m/s in the auroral region at times of geomagnetic disturbance (corresponding to an even more outrageous local value, $\Lambda = -2$); and Feess[8] reports even higher neutral wind speeds, of order 1000 m/s. It may be relevant that a geomagnetic storm, with $A_p = 149$, occurred at MJD 40653, at the beginning of the section with $\Lambda = 1.2$ in Fig.3, and another, with $A_p = 90$, at MJD 40697, at the beginning of the $\Lambda = 1.8$ section.

Even though the values of Λ for the broken and dotted curves in Fig.3 are probably inaccurate, the rotation is presumably most rapid, i.e. west-to-east winds are strongest, at the time when $\Lambda = 1.8$; and the scale at the top of Fig.3 indicates that if local time is the most important controlling factor, west-to-east winds are strongest between 21 h and 24 h local time, in conformity with theoretical studies[9,10] and observational results from the orbit of 1966-51C and rocket firings[11-13].

2.4 Cosmos 316, 1969-108A

Cosmos 316 was launched on 23 December 1969 into an orbit with initial perigee height 150 km, inclination 49.5° and initial period 102.8 minutes. The satellite was very massive, and despite its low initial perigee remained in orbit until 28 August 1970. Because of its obvious interest for studies of upper-atmosphere density and rotational speed, Cosmos 316 was intensively observed, and its orbit is now being determined[14] at RAE from visual, radar and photographic observations, including observations from the Hewitt camera at Malvern. Computations are now complete on the last 11 orbit determinations, between 3 July and 28 August 1970, and the resulting values of inclination, with standard deviations, are shown in Fig.4 after correction for luni-solar, zonal harmonic, and tesseral harmonic perturbations. The curve at the top of Fig.4 shows the perigee height, which ranges between 147 and 119 km, and the local time and latitude at perigee are marked on this curve. In Fig.4 the theoretical curve for $\Lambda = 1.2$ is drawn as a broken line. Although 1.2 may be approximately the correct average value, it is clear that the points cannot be properly fitted if Λ is kept constant. The curve has therefore been split into 3 parts with $\Lambda = 1.0$, 1.8 and 0.6, shown by the 3 unbroken curves in Fig.4. The values of inclination are now fitted to within one standard deviation, though it should be remembered that the numerical value of Λ may not be reliable, because the observational values of i are not adequate either in number or accuracy to define Λ at all precisely over such short time intervals. However, there seems little doubt that Λ is exceptionally large between 24 July and 31 July, when the local time at perigee was about 15 h, perigee height was 140 km, and perigee latitude was between 0 and 20°S. It would be rash to guess whether date, height, local time or latitude was the most important controlling factor; a clearer picture may emerge when the orbit determinations are completed.

2.5 Ariel 3, 1967-42A

In a careful analysis of the changes in orbital inclination of Ariel 3 during its first two years in orbit, Gooding[15] has determined lumped fifteenth-order tesseral harmonics in the gravitational field, and as a by-product has obtained a value of 0.7 ± 0.1 rev/day for the average atmospheric rotational speed at a height of 500 km in the time interval between May 1967 and August 1969.

At first sight this result seems out of line with the previous indications that Λ increased from 1.1 at 200 km to 1.4 at 350 km. But there were no previous reliable results above 370 km, so it appears that Λ reaches a maximum and then decreases.

Subsequently[16] Gooding has obtained a value $\Lambda = 1.00$ from Ariel 3 at an average height of about 390 km for the time between August 1969 and its decay in December 1970. Although the nominal sd of this value is 0.05, it is derived from only two orbit determinations near decay and, since these could suffer from a bias error, it seems wise to increase the 'sd' to 0.1 in comparing with other values of Λ. (The value from Explorer 1, for example, must be given greater weight because it is based on such a mass of data.)

2.6 1963-27A

Like Ariel 3, the satellite 1963-27A was in a near-circular, near-polar orbit. Fig.5 shows US Navy values of inclination, between May 1968 and October 1969, plotted against orbital period T. For a circular orbit the variation of i with T should be almost linear, and for this satellite theory[17] gives $di/dT \simeq 0.0073\Lambda$ deg/min. The straight line fitted in Fig.5 gives $di/dT = 0.0086$ deg/min, whence $\Lambda = 1.17$, at a mean height near 390 km, with sd estimated as 0.1.

2.7 1968-86A

This satellite was also in a near-circular orbit at a high inclination 75°. The orbit is soon to be determined from observations at RAE, but a preliminary estimate of Λ has already been made by plotting i against T using US Navy elements between August 1969 and the satellite's decay in March 1971, and fitting a straight line, as for 1963-27A. The value of Λ obtained is 1.04, with estimated sd 0.1, at a mean height of 410 km.

3 DISCUSSION AND CONCLUSIONS

3.1 Mean values of Λ

The 29 most accurate mean values of Λ so far obtained, including the new values at heights above 380 km, are plotted against height in Fig.6. For Cosmos 316 a preliminary value of $\Lambda = 1.0 \pm 0.1$ over the whole lifetime[14] at a height of 155 km is given; the values for 1968-59A are those from Fig.2, rather than that of Ref.5.

The two broken lines in Fig.6 show the trend of the values: the line on the left indicates that the mean rotational speed of the upper atmosphere increases with height, from about 1.1 rev/day at 200 km height to about 1.4 rev/day at 350 km. The line on the right, however, indicates that the mean rotation rate decreases from about 1.1 rev/day at 400 km to about 0.7 rev/day at 500 km. It is possible that the two lines should be redrawn as a single curve with a maximum near 350 km; and it may be significant that this is quite near the height of maximum electron concentration at night in the F-layer of the ionosphere, as would be expected if the rotation rate is governed by electrodynamic forces, as suggested by Allan[18] and Rishbeth[19].

However, it should also be noted that the satellites giving results above 380 km were all in near-polar orbits, whereas the two satellites giving the highest values of Λ (1958α and 1960γ2) were in orbits nearer the equator and would have been more affected by any strong 'super-rotation' of the atmosphere at low latitudes. At heights below 350 km there is no divergence between results from near-polar orbits and orbits nearer the equator. So it may possibly be better for the line on the right of Fig.6 to be faired into the line on the left at a height of about 300 km, leaving the values from 1958α and 1960γ2 'out on a limb'. Further results should settle this question.

The decrease in the mean atmospheric rotation rate at heights between 400 and 500 km is not surprising. Pressure gradients and electrodynamic forces should be less important in the exosphere at heights of 500 to 1000 km, where the neutral molecules, which are still numerically dominant, tend to pursue independent ballistic paths. Rapid rotation would imply that molecules in direct orbits travel considerably faster, on average, than those in retrograde orbits: but the faster molecules are more likely to escape, and this escape of the 'high-velocity tail' should reduce the rotation rate in the exosphere, perhaps to much less than 1 rev/day.

3.2 Variations in Λ

The other main conclusions concern the degree of detail revealed by the new orbital studies. It is clear from Figs.3 and 4 that the more accurate orbits of low-perigee satellites now being determined, particularly when Hewitt camera observations are available, are not adequately fitted by choosing a single mean value of Λ. The fitted curve must be split into several sections, with di[illegible]ing values of Λ. The parameters controlling the variations in the rotation rate cannot yet be certainly identified; but local time is likely to be an important factor, and, if so, the results indicate a rapid rotation rate, i.e. strong west-to-east winds, between 20 h and 24 h local time.

The new results also strongly suggest that the upper-atmosphere rotation rate may sometimes depart greatly from normality. In both Fig.3 and Fig.4, values of Λ near 1.8 are sometimes required in fitting the observational points, and although the accuracy of these numerical values is questionable, the indication of strong departures from the average is probably valid, especially in view of recent measurements of very strong local winds[7,8].

Future results should clarify the dependence of Λ on local time, latitude, and any other influential parameters.

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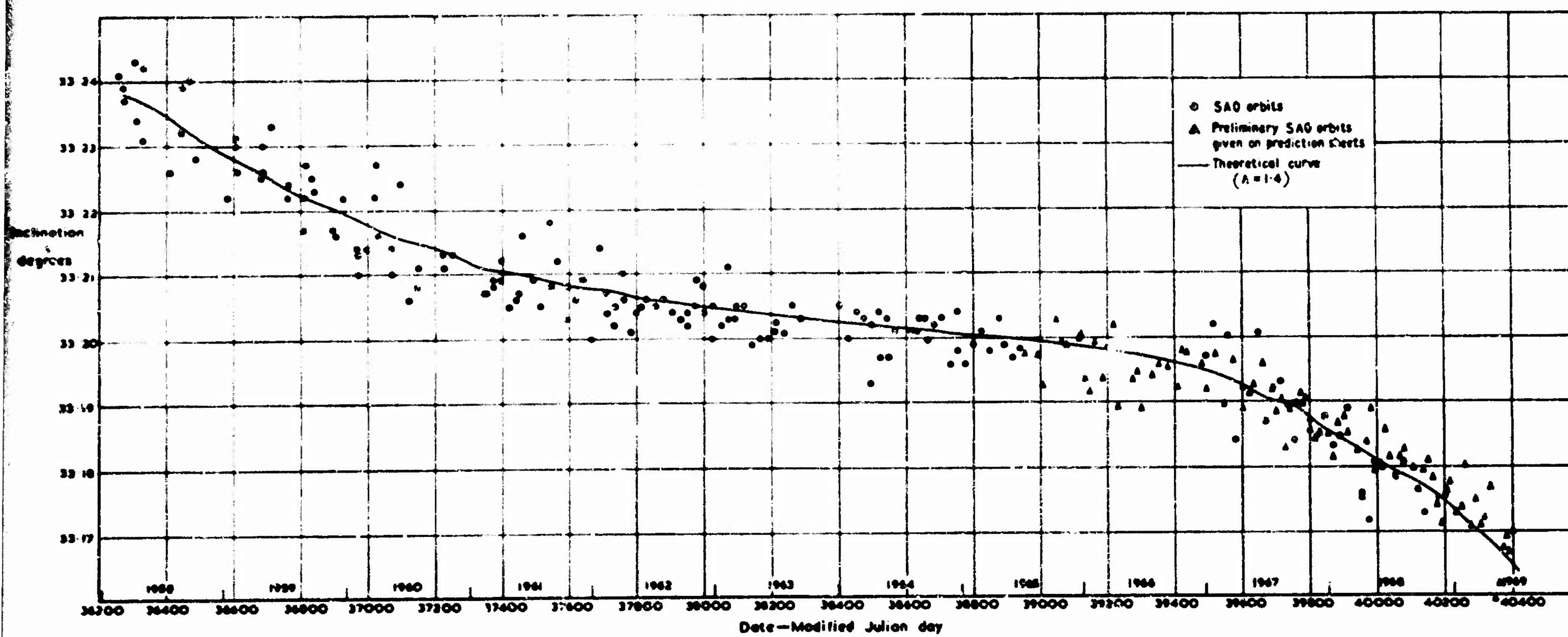

Fig.1 Orbital inclination of Explorer I (1958 α), from 1958 to 1969

Fig. 2

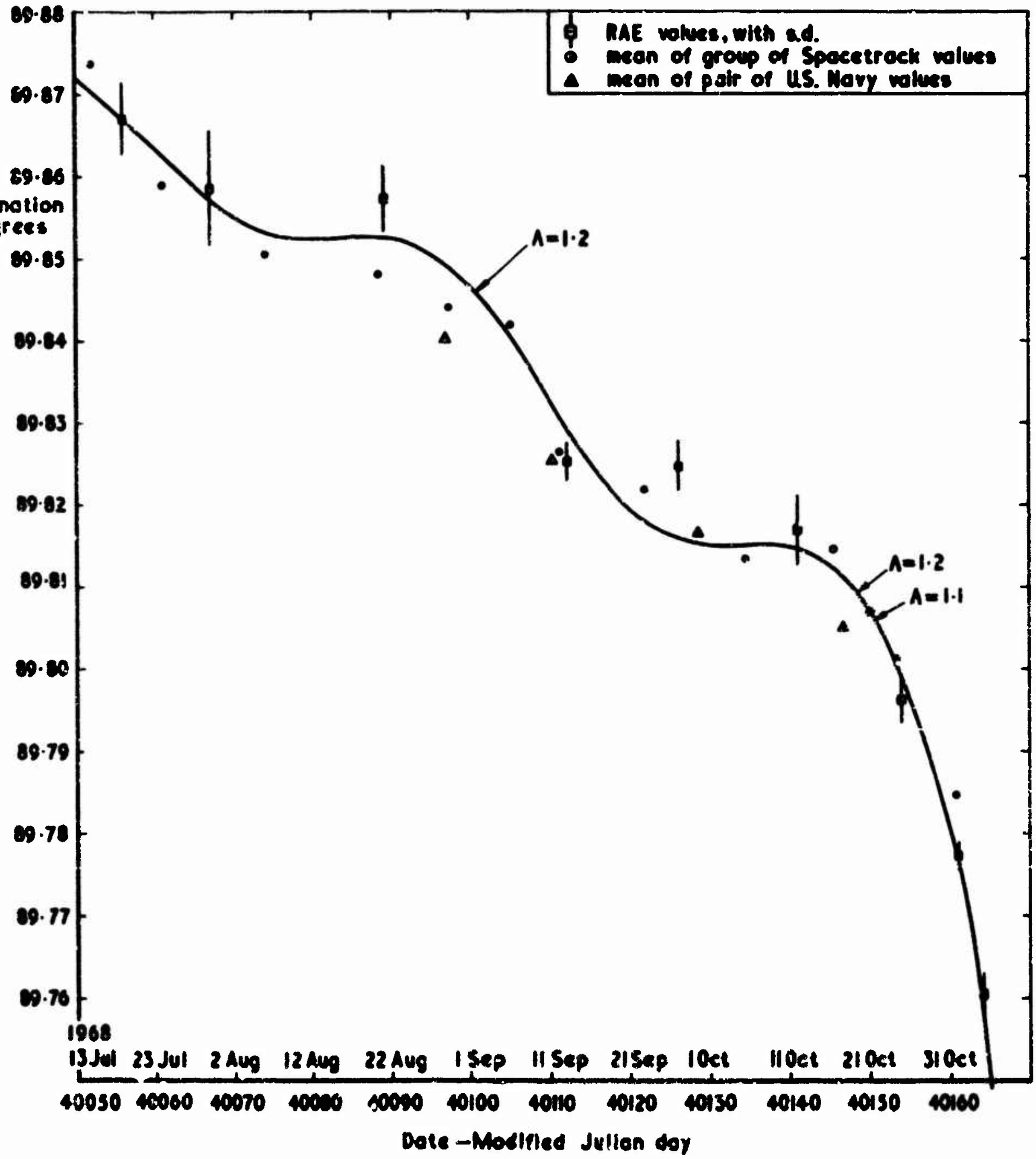

Fig. 2 Values of inclination for 1968-59A, corrected for luni-solar perturbations, with theoretical curve for Λ = 1·2/1·1

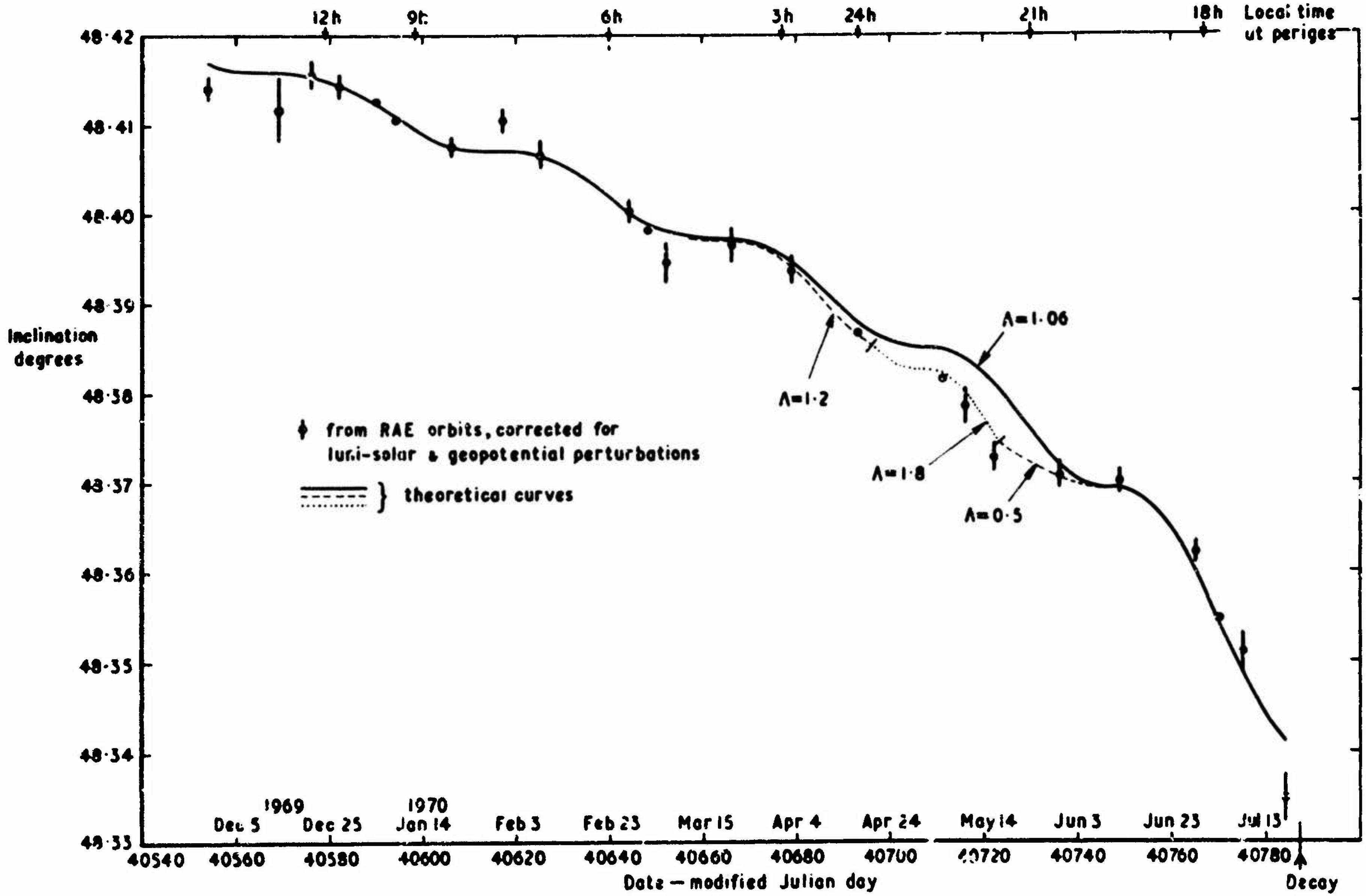

Fig.3 Change in inclination of Cosmos 307 rocket, 1969-94B

Fig.4

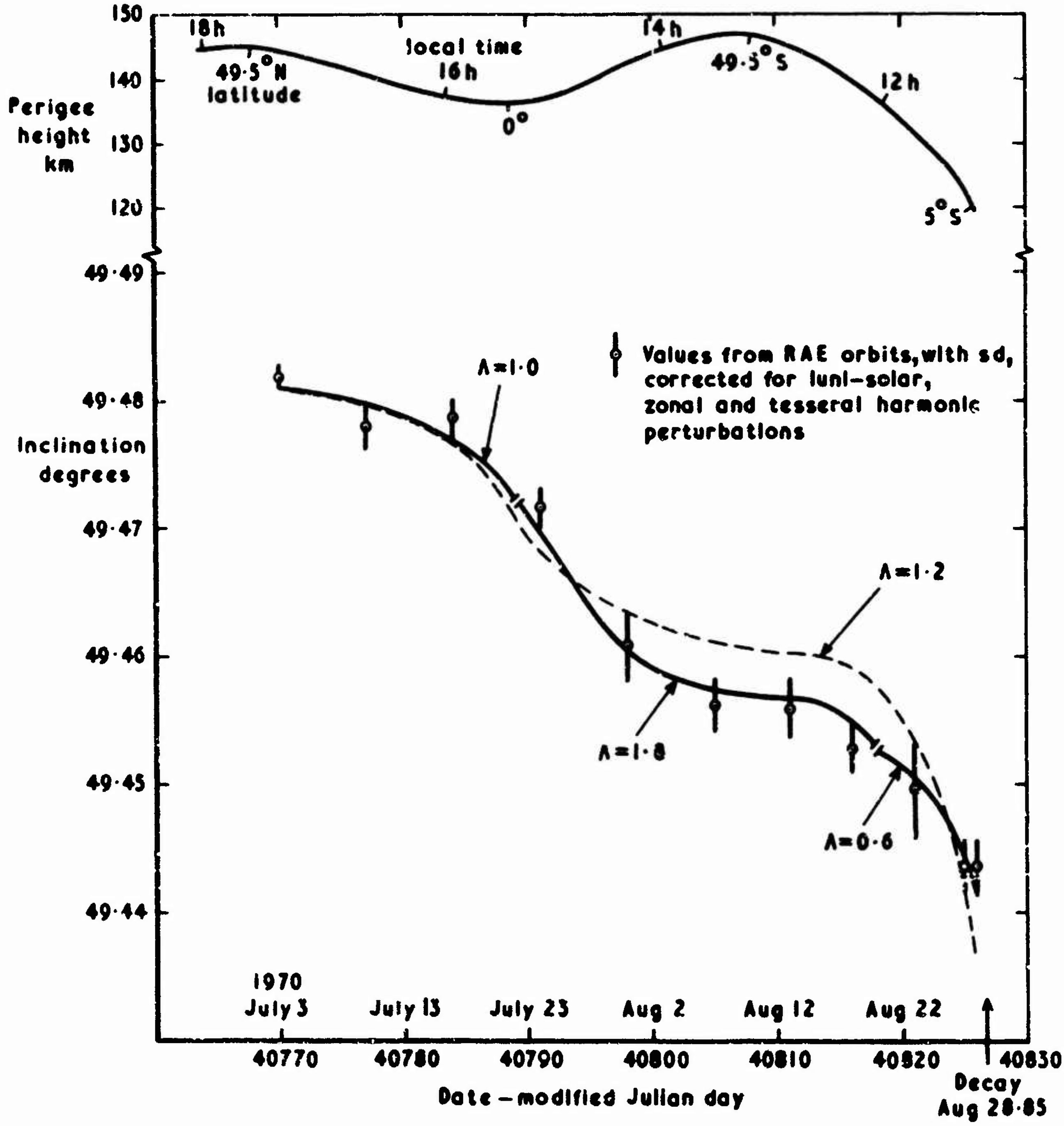

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Fig.4 Values of inclination for 1969–108A, with theoretical curves

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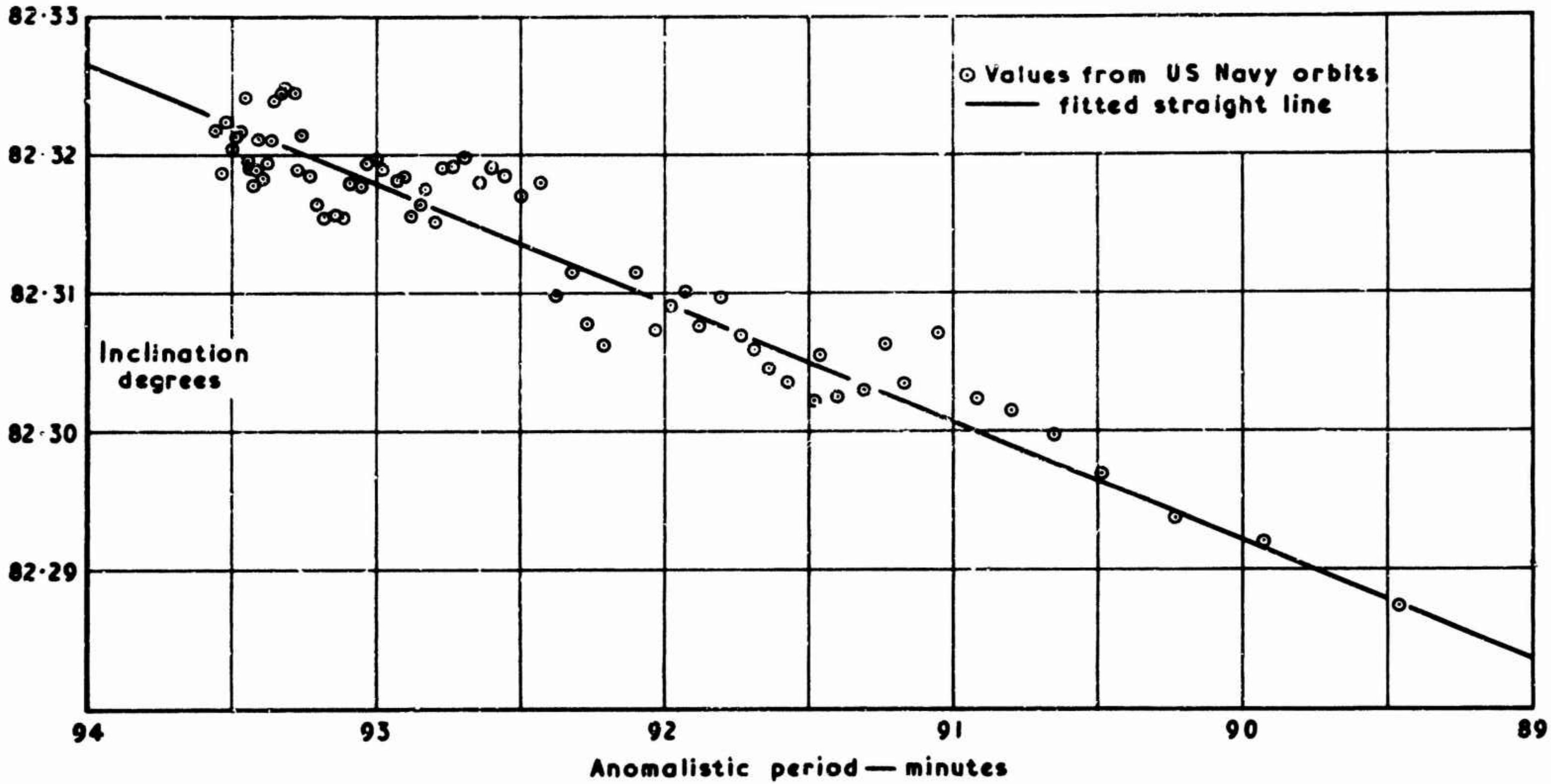

Fig. 5 Variation of inclination with orbital period for 1963-27A between May 1968 and October 1969

Fig. 5

Fig.6

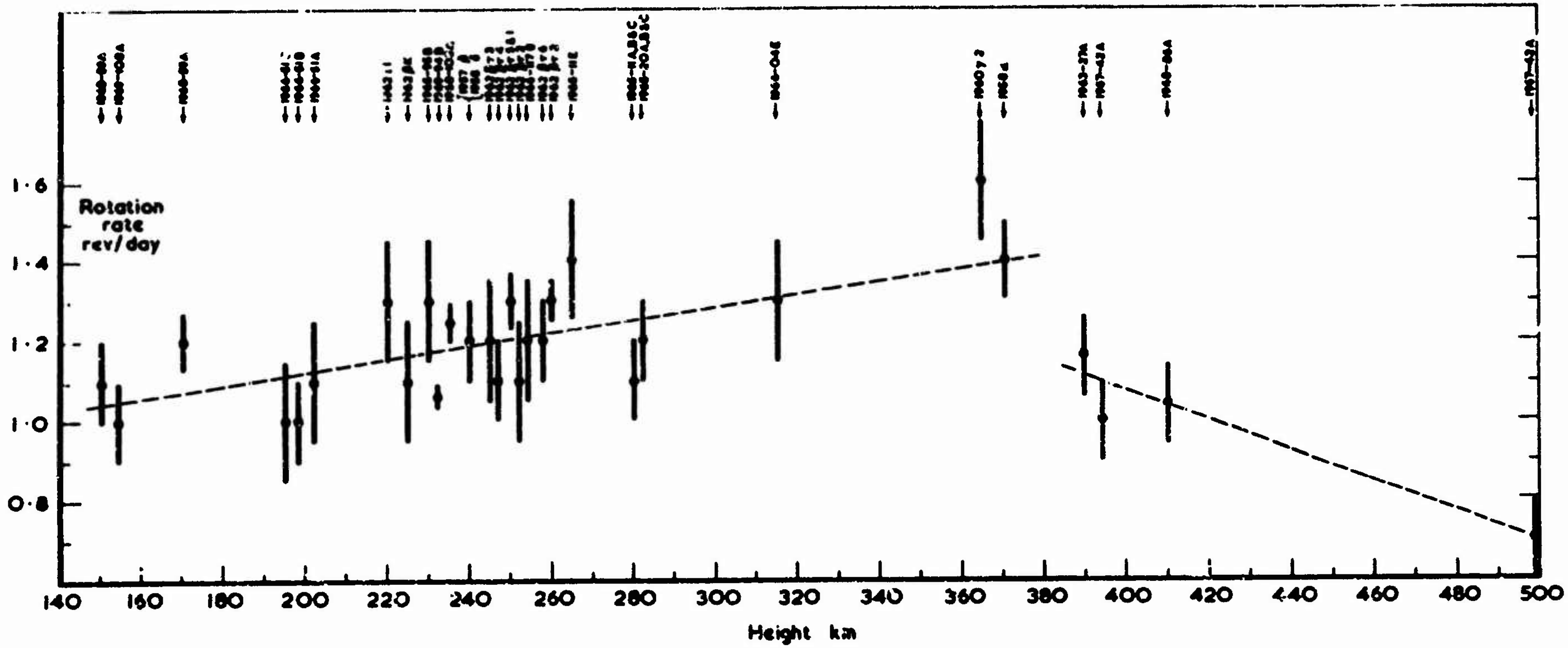

Fig.6 Mean upper-atmosphere rotation rate, derived from analysis of 32 satellite orbits