TR 82126

TR 82126

ROYAL AIRCRAFT ESTABLISHMENT

*

Technical Report 82126

December 1982

UPPER-ATMOSPHERE ZONAL WINDS FROM SATELLITE ORBIT ANALYSIS

by

D. G. King-Hele
Doreen M. C. Walker

*

Procurement Executive, Ministry of Defence
Farnborough, Hants

UDC 551.510.53 : 551.55 : 525.35/37 : 629.19.077.3

ROYAL AIRCRAFT ESTABLISHMENT

Technical Report 82126

Received for printing 23 December 1982

UPPER-ATMOSPHERE ZONAL WINDS FROM SATELLITE ORBIT ANALYSIS

by

D. G. King-Hele

Doreen M. C. Walker

SUMMARY

We review and interpret the values of upper-atmosphere rotation rate (zonal winds) obtained by analysing satellite orbits determined from observations. The history of the method is outlined, the basic principles are explained, objections to the method are answered, and three examples are given. Existing analyses of the atmospheric rotation rate Λ are critically reviewed, and, after rejecting some and revising others, we are left with 85 values. These are divided according to local time and season, to give the variation of Λ with height in nine situations - namely morning, evening and average local time, for summer, winter and average season. These observational results indicate that the value of Λ (in rev/day), averaged over both local time and season, increases from 1.0 at 125 km to 1.22 at 325 km and then decreases to 1.0 at 430 km and 0.82 at 600 km. The value of Λ is higher in the evening (18-24 h), with a maximum value (near 1.4) corresponding to a west-to-east wind of 150 m/s at heights near 300 km. The value of Λ is lower in the morning (06-12 h), with east-to-west winds of order 50 m/s at heights of 200-400 km. There is also a consistent seasonal variation, the values of Λ being on average 0.15 higher in winter and 0.1 lower in summer than the average seasonal value. No significant variation with solar activity is found, but there is a slight tendency for a greater rotation rate at lower latitudes for heights above 300 km. Unexpectedly, the values for the 1960s are found to be significantly higher than those for the 1970s. Finally, these observational values are compared with the theoretical global model of Fuller-Rowell and Rees: there is complete agreement on the trends, though there are some differences in the mean values.

Departmental Reference: Space 622

LIST OF CONTENTS

LIST OF CONTENTS (concluded)

1 INTRODUCTION

A spherical satellite in orbit about a planet with a non-rotating atmosphere would experience aerodynamic forces only in the direction tangential to its orbit, and these forces would not alter the orientation of its orbital plane. But a satellite in orbit about the Earth is travelling through an atmosphere which may (as a first approximation) be regarded as steadily rotating about the Earth's axis. The drag force on an Earth satellite acts in the direction opposite to its motion relative to the air; so the drag generally has a component perpendicular to the orbital plane. This component of force has the effect of progressively reducing the inclination of the orbit to the equator as the satellite's life proceeds, and the rate of decrease is proportional to the angular velocity of the atmosphere at the satellite height (if the orbit is circular). By determining the orbit accurately and removing any other sources of perturbation, we can measure the rate of decrease of inclination and hence the atmospheric angular velocity Λ. The convenient unit for measuring Λ is revolutions per day, so that $\Lambda = 1$ corresponds to an atmosphere rotating with the Earth; $\Lambda > 1$ implies that the mean wind is from west to east; and $\Lambda < 1$ implies an east-to-west wind. By contrast, the measurement of south-to-north (meridional) winds is usually very difficult, because the effects of meridional winds have a tendency to cancel out and thus produce very little change in inclination.

This method of measuring winds has two virtues and one serious limitation. The first virtue is its comprehensiveness. Analysis of a satellite in a circular orbit over several years gives a value of Λ averaged over these years and over a wide range of latitudes. This value can therefore serve as a basic upper-atmosphere rotation rate on which variations may be superposed. (It would perhaps be better to use this basic value in the equations of motion for a particular height, but most theorists are still wedded to the time-honoured but incorrect value $\Lambda = 1.00$.) Other methods of measuring wind speed are localized geographically, and often also in time, and cannot provide long-term average values. As its second virtue, orbit analysis has the advantage that it measures the wind directly; no substratum of possibly erroneous ionospheric theory intervenes, and the method would still apply even if normal atmospheric processes were completely disrupted. Consequently the results are clear - provided the orbits are accurate enough. Even the very first results[1] from Sputnik 2 have proved to be correct, though much criticized at the time by experts who thought they knew better.

The limitations of the method are the obverse of their first virtue: the results generally have poor resolution in time and position. At best, with a high-drag orbit of eccentricity about 0.1, a resolution of about 1 hour in local time can be achieved, but the change in inclination would still have to build up for at least a week before it could be measured, and during that time the latitude sampled would usually spread over at least 30°. So, although the local time resolution is often quite adequate (for example in studying diurnal variations), there is little hope of measuring day-to-day variations in winds until laser tracking of high-drag satellites can be accomplished[2]. For measurements with fine resolution in time or position, other methods must be used, such as analysis of the motion of vapour trails, the Doppler shift in airglow lines or radar backscatter. These methods are largely ignored here, where the aim is to show how the orbit analysis method fares on its own.

The plan of this Report is as follows. Section 2 briefly describes the progress of the method, from 1958 onwards. Section 3 outlines the principles and gives the basic equations. Section 4 outlines the techniques of analysis, and section 5 answers objections that have been uttered. Section 6 gives three examples of the analyses that have been made. After re-examining all available results, rejecting some and revising others, we are left with 85 values of Λ, presented in tabular form in section 7. In section 8 an attempt is made to present these results graphically and to give some indication of the variation of Λ with height, local time, season, and other parameters. In section 9 the results are compared with those of the theoretical global model of Fuller-Rowell and Rees[3]. Section 10 discusses the opportunities for determining meridional winds from orbit analysis, and section 11 investigates the possibility of evaluating zonal winds from changes in the right ascension of the node.

The following numerical <u>aide-mémoires</u> may be found useful:

(1) For a polar orbit with initial period 100 minutes, the orbital inclination usually decreases by about 0.1°, equivalent to about 12 km, during the lifetime of the satellite.

(2) The accuracy of orbital inclination for high-drag orbits is usually about 0.001° (120 m), or somewhat better.

(3) At a height of 200 km, an atmosphere rotating with the Earth would have a west-to-east velocity of 480 cos ϕ m/s at latitude ϕ, and it is convenient to take a mean latitude such that this velocity becomes 400 m/s

(this implies $\phi = 33.6°$). The west-to-east wind velocity, for a rotation rate Λ , is then $400(\Lambda - 1)$ m/s.

2 HISTORY OF THE METHOD

The first indication that the orbital inclination i of a satellite might suffer measurable changes came when Merson determined the orbit of Sputnik 2 from observations made by kinetheodolites on trials ranges of the Royal Aircraft Establishment. This result was published in the July-August 1958 issue of the Journal of the British Interplanetary Society[4] and the rotation of the atmosphere was mentioned as a possible cause. A detailed diagram of the variation was given in an article published in Nature[5] on 6 September 1958. The inclination decreased from about 65.33° initially to 65.18° at the end of the life.

The theoretical issues were apparently first discussed by Wildhack[6], who indicated the order of magnitude of the change in i , and by Bosanquet[7], who derived a simple expression for the change Δi in inclination (radians) in terms of the change ΔT in orbital period, expressed in non-dimensional form as a fraction of a day,

$$\Delta i = \frac{1}{3} \sin i \cos^2 \omega \, \Delta T , \qquad (1)$$

where ω is the argument of perigee - the angle between the northward equatorial crossing and the perigee, measured round the orbit (see Fig 1).

A fuller theory was developed by Plimmer[8], still on the assumption that the atmosphere rotated with the Earth. Plimmer obtained the following expression, applicable for orbits of eccentricity e less than 0.2:

$$\Delta i = \left(\frac{\sin i}{6}\right) \frac{I_0 - I_2 + (2I_2 - 4eI_1) \cos^2 \omega + O(e^2)}{(1 - T \cos i)\, I_0 + 2eI_1} \, \Delta T , \qquad (2)$$

where the I_n are Bessel functions of the first kind and imaginary argument of order n and argument $z = ae/H$. Here a is the semi major axis and H the density scale height. A somewhat similar equation was derived by Sterne[9] and the effects of atmospheric rotation on right ascension as well as inclination were determined by Cook and Plimmer[10].

If the Bessel functions are replaced by their asymptotic expansions, and the small term $T \cos i$ is ignored, equation (2) reduces to

$$\Delta i = \frac{\Lambda \sin i}{3} \left\{ (1 - 4e) \cos^2\omega - \frac{1}{z} \cos 2\omega + O\left(e^2, \frac{1}{z^2}\right) \right\} \Delta T \quad , \tag{3}$$

where the factor Λ has been introduced to generalize the result to an atmosphere rotating at Λ rev/day. The expansion (3) is most useful when $0.05 < e < 0.2$, because $1/z$ is then usually also less than 0.2: since many of the orbits suitable for determining Λ have eccentricities within this range, equation (3) is often of service.

When applied to Sputnik 2, Plimmer's theory (with $\Lambda = 1$) gave a decrease of 0.12° in inclination, as compared with the observed change of about 0.15° on the RAE orbits: thus $\Lambda \simeq 1.25$ was required. This comparison was published in Nature[1] in January 1959, and it was concluded that the presence of 'a strong wind from west to east' would improve the fit by increasing the slope of the theoretical curve. Fig 2 reproduces the diagram as printed in Nature. Sterne[9] made an independent analysis of the RAE orbits of Sputnik 2, and obtained a rotation rate $\Lambda = 1.18 \quad 0.17$. When RAE orbits of Sputnik 3 rocket were computed early in 1959, the observed decrease was again[11] considerably steeper than that given by equation (2).

No further accurate high-drag orbits became available during 1960; and in 1961, on the basis of the results from these two satellites, an atmospheric rotation rate Λ of 1.25 was suggested[12] for heights near 250 km. This corresponds to a mean west-to-east wind of about 100 m/s.

In 1963 Nigam[13] gave results from Sputnik 3, Explorer 1 and Explorer 3, the values of Λ being 1.19, 1.36 and 1.16 respectively. Several further analyses, including Cosmos 2 ($\Lambda = 1.3$), 1962 $\beta\tau 3$ ($\Lambda = 1.2$) and revisions of Sputnik 2 ($\Lambda = 1.2 \pm 0.2$) and Sputnik 3 rocket ($\Lambda = 1.4 \pm 0.2$), were made in 1964 by King-Hele[14] who gave the mean of all the values then obtained as $\Lambda = 1.46 \pm 0.28$. However, this value was greatly influenced by three very high values with large standard deviations (0.3 or more), and, with hindsight, it would clearly have been better to quote the mean of the more reliable values - the seven given in this paragraph - namely $\Lambda = 1.26 \pm 0.09$. Both these mean values, and the significant fact that all the values of Λ exceeded 1.0, suggested that the mean zonal wind at the relevant heights, 200-350 km, was from west to east with a velocity of order 100 m/s. This conclusion was not in accord with ideas at that time, because most atmospheric models indicated much smaller mean zonal winds.

The theory had been extended to include the effects of atmospheric oblateness by Cook[15] in 1961 and five years later was taken to second order in eccentricity and oblateness by King-Hele and Scott[16], who also analysed the orbits of 13 further satellites, found $\Lambda = 1.27 \pm 0.18$ and concluded that 'Λ increases significantly with height'. After analysing the orbits of 9 more satellites they concluded[17] that '(i) Λ increases with height, and (ii) Λ is greater than average in late afternoon and evening'. In 1969 the theory was extended[18] to take account of the variation of scale height with height. Analysis of the orbits of 11 further satellites by King-Hele, Scott and Walker[19] confirmed the increase of rotation rate with height, from $\Lambda = 1.1 \pm 0.05$ at 200 km to $\Lambda = 1.4 \pm 0.1$ at 350 km.

Meanwhile a theory for the effect of meridional winds had been published[20]: it was concluded that the contribution of meridional winds to Δi would generally be small, but might sometimes need to be taken into account.

Then in 1971 Gooding[21] made an accurate analysis of Ariel 3 over three years and obtained an unexpectedly low value, $\Lambda = 0.7 \pm 0.1$ at a height of 500 km. Taken with two other values at heights above 400 km, this suggested[22] that Λ reached a maximum at heights of 300-350 km and then decreased to about 0.7 at 500 km. The theory was extended to cover the day-to-night variation in density by King-Hele and Walker[23], who also developed a theory for high-eccentricity orbits[24].

New observational determinations of Λ gradually accumulated, including numerous analyses in the 150-500 km region and the important studies of balloon satellites by Slowey[25] and by Blum and Schuchardt[26] at heights between 550 and 700 km. All these results were critically reviewed by King-Hele and Walker[27] and, after a number of rejections, 44 values of Λ were used to produce curves showing the variation of Λ with height, (a) averaged over local time, (b) evening (18-24 hours local time), and (c) morning (04-12 hours local time). This graph, reproduced as Fig 3, serves as the starting point for the present review.

3 BASIC EQUATIONS

3.1 Assumptions

In developing the theory for the change in orbital inclination due to atmospheric rotation, we assume

(a) that the aerodynamic force on the satellite acts in the direction opposite to its motion relative to the air, and

(b) that the rotation is west to east; thus meridional winds are ignored and treated separately.

Objections to these assumptions are discussed in section 5.

The results obtained are independent of variations of density with time, because both Δi and ΔT are affected equally by such variations, and we work with $\Delta i/\Delta T$. Therefore, no assumptions are needed about density variations: the method would still apply even if the atmosphere transformed itself into a vacuum for one week and returned to normal afterwards. The only constricting assumption about the atmosphere is the need to assign an average value of density scale height, H, with an accuracy of about 20%. In practice, the choice of a value for H presents little difficulty.

3.2 The system of forces

Fig 4 shows the force system appropriate to the assumptions stated above, for a satellite S as it crosses the equator, with the Earth assumed to be spherical. The velocity $\underline{v}$ of the satellite relative to the Earth's centre is the vector sum of its velocity $\underline{V}$ relative to the air and the west-to-east velocity $\underline{V}_A$ of the air relative to the Earth's centre. The drag $\underline{D}$ acts in the direction opposite to $\underline{V}$, the velocity relative to the air, and therefore has a component, D_n say, normal to the orbit. From Fig 4 we have

$$\frac{D_n}{D} = \sin\alpha = \frac{V_A}{V}\sin i = \frac{rw}{V}\sin i \,, \tag{4}$$

if w is the angular velocity of the atmosphere (rad/s) and r is the distance from the Earth's centre. Thus the force normal to the orbit is directly proportional to the angular velocity of the atmosphere, and so are the changes in i caused by this force.

If the satellite, instead of being on the equator at the ascending node, is at angular distance u from the node (see Fig 1), equation (4) becomes

$$\frac{D_n}{D} = \frac{rw}{V}\sin i \cos u \,, \tag{5}$$

and on substituting into Lagrange's planetary equations, we find[28] that the rate of change of the orbital inclination i is given by

$$\frac{di}{dt} = -Qw \sin i \cos^2 u \,, \tag{6}$$

where the (positive) quantity Q depends on air density ρ, on the orbital elements, and on the mass and dimensions of the satellite*. Equation (6) shows clearly that $(di/dt) \leqslant 0$ for all values of u (that is, anywhere on the orbit) for an atmosphere rotating in the same sense as the Earth ($w > 0$). Equation (6) also shows that the atmosphere has a maximum effect in altering inclination when the satellite is at the equator ($u = 0°$ and $180°$) and zero effect at maximum latitude ($u = 90°$ or $270°$).

3.3 Circular orbits

If the satellite is moving in a circular orbit about a planet with a spherically symmetrical atmosphere, the quantity Q is independent of latitude, and equation (6) gives the variation of di/dt with latitude, as shown in Fig 5. The effect is of course greatest for a polar orbit, and, for any inclination i, the effect decreases from a maximum value at the equator to zero at latitude i.

For a circular orbit in the Earth's atmosphere, assumed spherically symmetrical, equation (6) can be integrated at once to give

$$\frac{\Delta i}{\Delta t} = -\tfrac{1}{2}Qw \sin i = -\tfrac{1}{2}\Lambda Q w_E \sin i \,, \qquad (7)$$

where w_E is the Earth's angular velocity. The decrease ΔT in period T (expressed non-dimensionally in days) for a circular orbit contracting under the action of air drag can also be expressed in terms of Q by the equation

$$\frac{\Delta T}{\Delta t} = -3Qw_E\sqrt{F} \,, \qquad (8)$$

where $\sqrt{F}$ is a factor close to 1, given by

$$\sqrt{F} = 1 - \frac{V_A}{V} \cos i \qquad (9)$$

in the notation of Fig 3. Dividing (7) by (8), we have

$$\frac{\Delta i}{\Delta T} = \frac{\Lambda \sin i}{6\sqrt{F}} \,, \qquad (10)$$

---

* $Q = (\rho V^2 r^2 S C_D)/(2m\sqrt{pGM})$ where C_D is the drag coefficient based on cross-sectional area S, m is the mass, $p = a(1 - e^2)$ and GM is the gravitational constant for the Earth ($398600\ km^3\ s^{-2}$).

which is the simplest equation expressing the decrease Δi in i accompanying a decrease ΔT in T, for a circular orbit in a spherically symmetrical atmosphere.

Thus the factor Q, which depends on atmospheric density and the size and shape of the satellite, cancels out, leaving equation (10) free of all atmospheric parameters except Λ.

If Δi is expressed in degrees, ΔT in minutes and $\sqrt{F} = 1$, equation (10) gives

$$\Delta i \text{ (deg)} = \{0.0066\ \Lambda \sin i\} \Delta T \text{ (min)} . \qquad (11)$$

Equation (11) is useful in indicating the order of magnitude of the effects: for example, with a polar orbit in an atmosphere rotating at 0.9 rev/day, a 10-minute decrease in orbital period would be accompanied by a 0.06° decrease in inclination.

3.4 Eccentric orbits

If the orbit is appreciably eccentric, nearly all the action of drag occurs quite near perigee. Consequently the decrease in inclination depends crucially on the argument of perigee ω, as shown by equation (3), which is applicable for eccentricities greater than about 0.05 (and should have a factor $\sqrt{F}$ in the denominator if it is to be comparable with equation (10)). When $\omega = 90°$ or $270°$, the first term in equation (3) is zero, so atmospheric rotation has little effect in changing inclination when perigee is near apex, for orbits of eccentricity greater than 0.05. Fig 6 shows how $\Delta i/\Delta T$ varies with ω, as given by equation (3) with the factor $\sqrt{F}$ included: the effect is 7-10 times greater when perigee is near the equator than when perigee is at apex.

The upper atmosphere generally has an ellipticity ε nearly equal to that of the Earth, 0.00335, and this can have an important influence on $\Delta i/\Delta T$. The effects of atmospheric oblateness are usually expressed in terms of the parameter c, where

$$c = \frac{\varepsilon a(1 - e)}{2H} \sin^2 i , \qquad (12)$$

and the theoretical equation for $\Delta i/\Delta T$, expanded as a second-order series in e and c is as follows[28,16,29]:

$$\frac{\Delta i}{\Delta T} = \left(\frac{\Lambda \sin i}{6\sqrt{F}}\right) \frac{\begin{array}{l}\Big[I_0 + I_2(1 + c)\cos 2\omega + \tfrac{1}{2}c(I_0 + I_4 \cos 4\omega) - 2eI_1(1 + \cos 2\omega) \\ \quad + \tfrac{1}{4}c^2(I_0 + \tfrac{3}{2}I_2 \cos 2\omega + I_4 \cos 4\omega + \tfrac{1}{2}I_6 \cos 6\omega) \\ \quad + \tfrac{1}{4}e^2\{3I_0 + I_2 + \tfrac{1}{2}(11I_0 - 2I_2 - I_4)\cos 2\omega\} \\ \quad - ce\{I_1(1 + 2\cos 2\omega) + \tfrac{1}{2}(3I_3 - I_5)\cos 4\omega\}\Big] + O(c^3, e^3, c^2e, ce^2)\end{array}}{\begin{array}{l}\Big[I_0 + cI_2 \cos 2\omega + 2eI_1 + \tfrac{1}{4}c^2(I_0 + I_4 \cos 4\omega) \\ \quad + \tfrac{3}{4}e^2(I_0 + I_2) + 2ceI_3 \cos 2\omega\Big] + O(c^3, e^3, c^2e, ce^2)\end{array}} \quad \ldots\ldots (13)$$

Equation (13) is intended for use when $e < 0.2$ and $c < 0.2$. For near-polar orbits of low perigee, c may exceed 0.2: if so, it may be necessary to use the third-order form of the numerator derived by Boulton and Swinerd[30], with the third-order form of the denominator given in equation (5.10) of Ref 28.

When $e > 0.2$ the high-eccentricity form of equation (13) derived by King-Hele and Walker[24] is appropriate:

$$\frac{\Delta i}{\Delta T} = \frac{\Lambda \sin i\,(1 - e)^{5/2}}{3\sqrt{F}(1 + e)^{3/2}}\left[\cos^2\omega + \frac{(1 + e)^2 - (2 + 2e + e^2)\cos^2\omega}{z(1 - e^2)} + \frac{\varepsilon}{e}(1 + e)\sin^2 i \sin^2 2\omega + O\left(\frac{1}{z^2}, \frac{\varepsilon^2}{e^2}, \frac{\varepsilon}{ez}\right)\right]. \qquad (14)$$

Since $1/z < 0.03$ and $\varepsilon/e < 0.02$ when $e > 0.2$, the neglected terms here are of order 0.001. Atmospheric oblateness has much less effect when the eccentricity is large; this is why only terms of the first order in ε are needed in equation (14).

These results are derived on the assumption that the density scale height H is constant, but in reality H increases with height y in the relevant regions of the upper atmosphere, the value of $\mu = dH/dy$ usually being between 0 and 0.2. The theory developed[18] on the assumption that H varies linearly with height shows that the effects of μ can be accounted for, to the first order, by using a value of H appropriate to a height $\tfrac{3}{4}H$ above perigee. (Strictly, this applies for $z > 1.25$, and a height $0.6zH$ above perigee should be taken for $z < 1.25$; but the error incurred by ignoring this refinement is negligible.) The values of H are normally taken from the COSPAR International Reference Atmosphere 1972 (Ref 31).

3.5 Height at which Λ applies

The atmospheric forces producing the changes in inclination are usually effective over quite a wide range of heights and it is not easy to define logically an 'effective height' y_1 at which Λ applies. The question was discussed by King-Hele and Scott[18], who concluded that y_1 could appropriately be taken as the height at which H is evaluated, as defined in the previous paragraph: that is, y_1 is taken as $\frac{3}{4}H$ above perigee for $z > 1.25$ (corresponding to eccentricities greater than about 0.01), and at height $0.6zH$ above perigee for $z < 1.25$. This rather arbitrary recommendation has recently been re-examined by Boulton and Swinerd[30], who have concluded that it is reasonably satisfactory.

Although y_1 suffers from 'fuzziness', and is in a sense undefinable (except for circular orbits), its imprecision is unlikely to produce significant error. Since $|d\Lambda/dy| < 0.003\ \mathrm{km}^{-1}$, an error of 10 km in y_1 would not lead to an error in Λ of more than 0.03, which is less than any of the standard deviations in the observational values of Λ.

For circular orbits the value of Λ clearly applies at the orbital height, but there is still a problem when the orbital height decreases greatly during the time interval over which Λ is evaluated. To a first approximation, the average of the initial and final heights may be used, but it is often necessary to use a more accurate mean value: see Ref 32.

4 OUTLINE OF THE TECHNIQUE

4.1 Treatment of perturbations

Satellite orbits suffer many perturbations other than those caused by atmospheric rotation, and these other perturbations must be removed if their magnitude is comparable with the standard deviations of the observational values of inclination.

In practice the perturbations due to zonal harmonics in the geopotential and lunisolar gravitational forces are always removed because they are expected to be significant. Perturbations caused by the second-order tesseral harmonic $J_{2,2}$ are also removed.

Resonance with the Earth's gravitational field is another important perturbation, which affects nearly all the satellites used in studies of atmospheric rotation. For example, a satellite with an initial period of 104 minutes will, as it decays, pass through 14th, 15th and 16th-order resonance, when it completes 14, 15 or 16 revolutions while the Earth rotates once relative to its orbital plane. The orbit will also pass through 29:2 resonance (29 revolutions in two days) and 31:2 resonance, though the effects are smaller than for the primary resonances. If the drag is low at the time of a primary resonance, so that the satellite remains near resonance for a year or two, a large change in inclination can occur - the largest yet analysed is for 1971-54A, which suffered a change of 0.10° during its two-year passage through 15th-order resonance[33]. But if the drag is high at the time of the resonance, the change is very much smaller, and with high drag the effects of the secondary resonances are usually negligible.

Perturbations due to solar radiation pressure are removed if the satellite is of low mass/area ratio, as with balloon satellites[34]. The effects of luni-solar precession of the Earth's axis[35] have to be removed for long-lived near-polar orbits. Perturbations due to earth and ocean tides often hover between significance and negligibility, being of order 50 m at most, if the orbit is not near-resonant; but when these perturbations are resonant, as for polar orbits, and the orbit under analysis extends over several years, it is essential to estimate and remove the earth and ocean tidal perturbations, as Moore and Holland[36] showed.

4.2 Treatment of the data

When the relevant perturbations have been removed, the resulting values of inclination are fitted with theoretical curves calculated from equation (13), and the value of Λ which best fits the values is selected. This value may be determined by least squares, but more often fitting by eye is to be preferred, for several reasons. First, least squares is a blunt instrument ill-suited to such a delicate task; in particular, least squares takes too much notice of a value having a very low standard deviation, which the eye can discount as vitiated by bias if it conflicts with a consistent run of values with larger standard deviations. Second, when no such subtleties arise, the values obtained from eye and least squares are found to be very similar. Third, the standard deviation in Λ obtained from a least-squares fit is often too small to be acceptable if the points are numerous, and the suspicion arises that the least-squares fitting has been made merely to achieve a low standard deviation rather than a realistic error estimate. Fourth and most important, it is often necessary to make a commonsense decision on where to break the fitted curves.

When the curves are fitted by eye, we try to make realistic estimates of the errors in inclination, σ_B and σ_E, at the beginning and end of the curve. The error in Λ is then taken as $\Lambda\sqrt{\sigma_B^2 + \sigma_E^2}/(i_B - i_E)$, where i_B and i_E are the values of i at the beginning and end. Sometimes σ_B and σ_E can be estimated confidently, but sometimes it may be necessary to take them equal at a value σ, say, assessed from the rms scatter (excluding freak points) about the curve.

Fitting by eye is not always reliable when the slope of the curve changes greatly between the beginning and end points. For circular orbits this problem can be avoided by plotting i against orbital period T, which should give a straight line if Λ is constant, see equation (10). This straight-line fitting is often preferable, and always provides a useful check on the value of Λ. For examples, see Refs 32 and 37.

5 OBJECTIONS, AND CRITICISMS OF THE METHOD

5.1 Temporal variations in density and satellite cross-sectional area

It is sometimes suggested that error can arise because of variations in drag due to irregular changes with time in either air density or the satellite's effective drag cross-section. As already explained, however, both Δi and ΔT are equally affected, so this objection is a mere phantom of the untutored mind.

5.2 The day-to-night asymmetry in density

This objection is more substantial, because upper-atmosphere density is strongly dependent on local time and there is a 'bulge' of density with its maximum centred at about 14 hours local time. It is possible that an orbit asymmetrically disposed relative to the density bulge might suffer unexpected variations. But the theory developed by King-Hele and Walker[23] shows that there are only some rare resonant orbits for which the day-to-night variation in density produces appreciable long-term changes in $\Delta i/\Delta T$. The dangerous orbits are those which simultaneously satisfy five conditions: perigee height near 500 km; eccentricity near 0.01; inclination of 58°, 76°, 110° or 120°; solar activity low; and special numerical values for the right ascension of the node and the argument of perigee.

This theory has recently been extended by Boulton and Swinerd[30], who obtain results for a satellite in an oblate atmosphere with diurnal density variation. Their work confirms the conclusions above, while carrying the theory to a higher order of accuracy.

5.3 Effect of lift (forces normal to V)

Winged objects flying through normal air tend to generate a lift force perpendicular to their flight direction, and although conditions are very different in free-molecule flow where no vortices arise, satellites with wing-like solar panels can develop appreciable lift. The effect of aerodynamic lift on satellite orbits was studied by Cook[38]. He concluded that for any satellite with "a fairly rapid and uncontrolled spinning motion, the effect of lift is extremely small and can be ignored". However, a satellite which is attitude-stabilized (relative to either Earth or space) may suffer significant orbital perturbations due to the action of the systematic lift force, and such perturbations are likely to be particularly large for a satellite design which incorporates flat plates such as solar panels. More detailed calculations of these effects were made by Fiddes[39] and by Karr, Cleland and DeVries[40].

In view of these conclusions, it has been recognised since 1964 that attitude-stabilized satellites should not be used for determining atmospheric rotation rates. The method has been used only for satellites that are rapidly spinning or tumbling uncontrolled, and also, of course, for spherical satellites.

The possible objection that lift might be affecting the results is therefore not valid. This has been pointed out many times, from 1964 onwards[14], but repetition is still necessary because the accusation has also been repeated many times. Karr[41], in the Introduction to a NASA Contractor's Report in 1976 states: "In Chapter 3, a study is presented which shows that satellite lift effects may be responsible for the observed orbit precession rather than a super rotation of the upper atmosphere". This assertion is false, and the conclusions of Karr's 'Chapter 3' apply only to attitude-stabilized satellites, which are not used in determining atmospheric rotation rates.

As Cook[38] pointed out, the effects of lift could be used creatively to study accommodation coefficients, and this has been attempted by Ching, Hickman and Straus[42] and by Sehnal[43]. However, it has not proved possible to determine accommodation coefficient and Λ simultaneously.

5.4 Meridional winds

The most serious criticism of the method concerns the effect of meridional winds. King-Hele[20] developed a theory for these effects, and the change in inclination due to a steady south-to-north meridional wind, at a speed equivalent to an angular rate of Φ rev/day, was derived for $e < 0.2$ as

$$\frac{\Delta i}{\Delta T} = -\frac{\Phi}{3\sqrt{F}}(1-K)^{\frac{1}{2}}\left\{(1-\tfrac{1}{4}K)\frac{I_1}{I_0}\cos\omega - \tfrac{1}{4}K\frac{I_3}{I_0}\cos 3\omega\right\} + O(\Phi e, 0.1\Phi) \ , \quad (15)$$

where

$$\left.\begin{aligned} K &= \frac{\sin^2 i}{2-\sin^2 i} \\ \text{so that} \qquad (1-K)^{\frac{1}{2}} &= \left(\frac{2}{1+\cos^2 i}\right)^{\frac{1}{2}}\cos i \end{aligned}\right\} . \quad (16)$$

Boulton and Swinerd[30] have extended equation (15) to include the effects of atmospheric oblateness and diurnal variation. Equation (15) shows, as would be expected, that $\Delta i = 0$ for polar orbits and for circular orbits.

If $z > 5$ (e greater than about 0.04) and the inclination is low, equation (15) may be written

$$\frac{\Delta i}{\Delta T} \simeq -\frac{\Phi \cos i}{3\sqrt{F}}\left\{\left(1+\frac{1}{8}\sin^2 i\right)\left(1-\frac{1}{2z}\right)\cos\omega - \frac{1}{8}\left(1-\frac{9}{2z}\right)\sin^2 i\cos 3\omega + O(0.1\sin^4 i)\right\} . \quad (17)$$

Comparison with equation (3) shows that at inclinations of 45° or less, meridional winds are just as effective as zonal winds in changing inclination. However, equation (15) is periodic in ω ; thus, for any long-lived satellite, the effects of a steady meridional wind tend to cancel out (unless i is close to the critical inclination of 63.4°, when the perigee can take several years to complete one rotation).

For high-eccentricity orbits, the change in inclination due to meridional winds is given to a first approximation by

$$\frac{\Delta i}{\Delta T} = -\frac{\Phi\cos i\cos\omega}{3\sqrt{F}(\cos^2 i + \sin^2 i\cos^2\omega)^{\frac{1}{2}}}\frac{(1-e)^{5/2}}{(1+e)^{3/2}} + O(0.02\Phi) \ . \quad (18)$$

See Ref 24 for a more accurate form of equation (18).

The 'steady south-to-north' wind so far assumed is a convenient fiction introduced to make the mathematics tractable. Taken literally, this assumption would appear to imply winds for ever blowing towards an insatiable sink at the north pole, as proposed by Darwin[44] in 1792 and accepted by Coleridge[45]. The assumption is not so silly as it seems at first sight, because most orbits are eccentric and the satellite suffers appreciable drag only near perigee. So it is only the meridional wind in the region of perigee which is being specified, and this can reasonably be assumed constant in direction, as a first approximation. However, the assumption is unrealistic for circular orbits.

The real meridional winds in the atmosphere at heights of 200-500 km are subject to great variations whenever heating occurs in the auroral zones; but in the absence of these frequent events, most atmospheric models indicate that in months not too far from equinox, the winds tend to be away from the equator in the daytime and towards the equator at night (see Ref 3). This is probably the best basic pattern that can be offered as an aid in assigning somewhat more realistic values for Φ. For an eccentric orbit, this pattern suggests that Φ would change sign as perigee crosses the equator if the equator crossing occurred at a local time not too near dawn or dusk. That means that the sign of the main $\Phi \cos \omega$ term in equation (15) when $-90° < \omega < 0$ is opposite to the sign when $0 < \omega < 90°$. So, for a long-lived satellite in an eccentric orbit, the changes in inclination will, if the specified pattern of winds occurs, cancel out as ω increases from -90° to +90°, or from -45° to +45°. The introduction of more realistic winds thus tends to produce the cancellation more quickly than the unrealistic constant wind.

If the eccentric orbit is of short lifetime, however, and ω does not vary greatly, the change in inclination due to meridional winds may exceed that due to zonal winds when the inclination is less than 45°, and needs to be taken into consideration for any inclination less than about 70°. Since an accurate meridional wind speed cannot be assigned, the accuracy of the values of Λ obtained from these orbits may be seriously limited by the lack of knowledge of meridional winds (see Ref 46).

With circular orbits, we have already noted that the (unrealistic) steady south-to-north wind leads to a zero result: the effects of the meridional winds cancel out over one orbit. To study a more realistic situation, we need to go back to the basic equation for the change in inclination due to a meridional wind Φw_E, which is

$$\frac{di}{dt} = Q w_E \Phi \frac{\cos i \cos u}{(1 - \sin^2 i \sin^2 u)^{\frac{1}{2}}} . \tag{19}$$

This is the equivalent of equation (6), but for meridional rather than zonal winds. Equation (19) shows that, on integration over one revolution ($0 < u < 360°$), $\Delta i = 0$ if Φ is constant, in accordance with equation (15). If we take the more realistic picture of winds towards and away from the equator, with Φ changing sign at the equator, the effects of meridional winds tend to cancel out over any shorter range of values of u that is symmetrical about $u = 0$. Thus the introduction of more realistic conditions tends to indicate even smaller meridional wind effects.

It is easy enough, however, to think of special situations where these cancellations do not occur because the satellite experiences different local times north and south of the equator, thus possibly modifying the symmetry.

It seems fair to summarize by saying that meridional winds have a strong tendency to cancel their effects, and rarely contribute much to the decrease of inclination in a long-lived orbit. But situations can arise - in perhaps 5% of orbits likely to be used - when meridional winds have important effects which prevent an accurate determination of the zonal rotation rate. These situations are very likely to occur for orbits of inclination less than 45° in which the argument of perigee has only a limited range of travel (60° or less); but appreciable effects may occur for inclinations up to about 70°.

5.5 Undiscovered or neglected perturbations

It is unlikely that any significant new sources of perturbation to the orbital inclination will be discovered, because all non-aerodynamic sources producing effects of more than a few centimetres have been examined and evaluated in determining the orbit of the Lageos satellite[47], where laser tracking is accurate to about 10 cm and an observed decrease in semi major axis at a rate of 1 mm/day has led to an intensive study of possible causes by Rubincam[48]. By contrast, the orbits used for studies of atmospheric rotation have typical accuracies of 50-100 m, and so perturbations amounting only to centimetres are not significant.

A more likely source of error is a perturbation which is known but wrongly believed to be negligible. This is a danger that orbit analysts must continually bear in mind, and try to avoid. The neglect of resonance perturbations did cause errors in a few of the values of Λ determined during the 1960s, but these have now been corrected; since 1971, any significant resonances have been removed by calculation, or have been used as convenient break-points in determinations of Λ.

To summarize, vigilance is needed over perturbations which seem negligible but may not be. Errors due to lack of vigilance cannot be ruled out, but should be rare.

6 EXAMPLES OF THE ORBIT ANALYSES

Here we give three examples of the determination of Λ from the changes in orbital inclination, each illustrating different types of orbit.

The first and simplest is the analysis of 1972-05B during its last 16 days in orbit by Hiller[49]. Fig 7 shows the values of inclination, with sd, and the chosen theoretical curve, $\Lambda = 1.4$. The values of inclination have been cleared of lunisolar, zonal harmonic and $J_{2,2}$ perturbations, but there is no allowance for tidal effects, precession, or solar radiation pressure, since these effects are all judged to be negligible over such a short time-interval. The 16th-order resonance is also ignored, because the drag is so high. Meridional winds have no effect, as the orbit is polar. Most analyses have unusual features: here the fit is unusually good and the value of Λ, 1.40 ± 0.05, equivalent to a west-to-east wind of 160 ± 20 m/s, is unusually high for a local time of 00-02 hours.

The second example is a satellite of much longer life, 1971-106A, which was initially in an orbit of period 105 minutes, eccentricity 0.11 and inclination 65.7°, and had a lifetime of 40 months. The orbit was determined at 100 epochs from 9000 radar and optical observations by Walker[29], and the changes in inclination were analysed to determine atmospheric rotation rates and resonant coefficients in the geopotential, with divisions at the times of the 14:1, 29:2 and 15:1 resonances, as shown in Fig 8. The resonances, indicated by rectangles in Fig 8, were fully analysed and the fittings within the rectangles were linked with the 'atmospheric' sections, providing a continuous variation. Otherwise the perturbations taken into account were the same as in the first example. The unusual feature of this orbit was the slow movement of perigee, which led to seasonal bias, as shown on the diagram, and suggested that Λ was larger in winter than in summer. Also, the influence of meridional winds was important during the last 15 days of the life.

The third example is 1973-27B, which also had a fairly long lifetime (20 months), but was initially in a circular orbit at a height near 400 km at an inclination of 50° to the equator. Fig 9 shows the decrease in inclination as analysed by King-Hele[37]. The effects of 31:2 resonance were appreciable and the detailed variation at this time is shown. This analysis is unusual because of the numerous accurate orbits during the first half of the life, from Hewitt camera observations, as a result of which a good value of Λ was obtained despite the small decrease in inclination. Also, because the orbit was circular, there is little chance of error due to meridional winds, despite the rather low inclination.

Other examples may be found in the References given in Tables 1 and 2.

7 RESULTS

7.1 Introduction

In our previous review of results from analysis of satellite orbits[27], we utilized 36 RAE results and 8 from other sources. We have now again carefully reviewed these results, accepting most of them, discarding a few, and altering the standard deviations on a few more. We have added new RAE results and new results from other sources, the great majority of these being from the University of Aston. As before, any values of Λ with sd greater than 0.15 are excluded.

The complete list of results, old and new, is given in Tables 1 and 2, with details of the height, inclination, solar activity, local time, season and calendar date for each value of Λ, and a Reference. Since local time and season were not specified in many of the papers, it was often necessary for us to go back to the orbits in question in order to evaluate these parameters.

Table 1 contains 61 RAE values and Table 2 has 24 results from other sources. Thus, we now have 85 results, as compared with 44 previously. The revisions, rejections and new entries are discussed in sections 7.2 to 7.7.

Table 1

The 61 values of Λ from RAE analyses: see section 7.2

Satellite		Λ	Height km	Inclination deg	$S_{10.7}$	Local time hours	Season	Date for which Λ value applies	Reference
1957β, 1958δ1 and 1958δ2		1.23 ± 0.15	210	65	210	Average	Average	1958-60	King-Hele (1964) Ref 14
1958α	Explorer 1	1.5 ± 0.15	400	33	200	Average	Average	1958-60	Walker (1975) Ref 50
		1.2 ± 0.1	380	33	100	Average	Average	1960-67	
		1.3 ± 0.1	355	33	150	Average	Average	1968-70	
1960γ2	Transit 1B	1.3 ± 0.1	360	51	90	Average	Average	1963-67	King-Hele and Walker (1977) Ref 27
1962ο1	Ariel 1	1.1 ± 0.15	420	54	110	Average	Average	1962-69	King-Hele and Walker (1977) Ref 27
		1.1 ± 0.1	400	54	130	Average	Average	1969-73	
1962βτ1 and 1962βτ5		1.3 ± 0.1	250	70	90	Average	Average	1963-66	King-Hele and Scott (1967) Ref 17
1962βτ2	Injun 3	1.3 ± 0.1	260	70	90	Average	Average	1963-67	King-Hele and Walker (1977) Ref 27
		1.2 ± 0.1	255	70	150	Average	Winter	Oct 1967-May 1968	
1962βτ6	Injun 3 rocket	1.1 ± 0.15	270	70	95	Average	Average	1965-67	King-Hele and Walker (1977) Ref 27
		1.2 ± 0.1	265	70	140	Average	Winter	Apr 1967-Jan 1968	
1963-27A		1.05 ± 0.05	390	82	150	Average	Average	May 1968-Oct 1969	King-Hele and Walker (1977) Ref 27
1965-11D	Cosmos 54 rocket	1.1 ± 0.15	305	56	120	Average	Average	Mar 1966-Nov 1967	King-Hele and Walker (1977) Ref 27
		1.0 ± 0.1	290	56	150	Average	Summer	Jan-Nov 1968	
		1.1 ± 0.1	280	56	160	Average	Average	Dec 1968-Jun 1969	
		1.05 ± 0.1	245	56	150	Morning	Winter	Aug 1969-Dec 1969	
1965-11A,B&C and 1965-20A,B&C		1.15 ± 0.1	280	56	120	Average	Average	1965-68	King-Hele, Scott and Walker (1970) Ref 19
1966-51C	ORS 2	1.25 ± 0.1	210	90	110	18-21	Average	Jul 1966-Sep 1966	King-Hele (1977) Ref 51
		0.80 ± 0.06	210	90	120	02-12	Average	Oct 1966-Jan 1967	
1966-118A		0.86 ± 0.1	410	75	150	Average	Average	May 1968-Apr 1969	King-Hele and Walker (1977) Ref 27
1967-42A	Ariel 3	0.77 ± 0.05	530	80	150	Average	Average	May 1967-Aug 1969	Gooding (1971) Ref 21
1968-59A	OV1-15	1.2 ± 0.1	170	90	150	18-21	Average	Aug-Oct 1968	King-Hele and Walker (1977) Ref 27
		1.1 ± 0.1	165	90	150	Average	Average	Oct-Nov 1968	
1968-86A		0.94 ± 0.12	440	75	160	Average	Average	Nov 1969-Jan 1971	Hiller (1972) Ref 52
1968-103A	Proton 4	1.10 ± 0.05	260	52	160	Average	Average	Mar-Jul 1969	Hiller and King-Hele (1977) Ref 53

Table 1 (continued)

Satellite		Λ	Height km	Inclination deg	$S_{10.7}$	Local time hours	Season	Date for which Λ value applies	Reference
1969-20B	Cosmos 268 rocket	0.8 ± 0.1 1.3 ± 0.15	250 245	48 48	150 140	04-14 19-03	Average Average	Apr-Jul 1969 Aug-Oct 1969	King-Hele and Winterbottom (1972) Ref 54
1969-94B	Cosmos 307 rocket	1.0 ± 0.15 1.3 ± 0.1	240 235	48 48	160 160	05-13 20-03	Average Average	Nov 1969-Mar 1970 Mar-May 1970	King-Hele and Walker (1977) Ref 27
1969-108A	Cosmos 316	1.05 ± 0.05	160	49	160	Average	Average	Jan-Jun 1970	King-Hele (1972) Ref 55
1970-43B	Cosmos 347 rocket	1.3 ± 0.1	230	48	160	18-01	Average	Oct 1970-Jan 1971	Hiller (1974) Ref 56
1970-65D	Cosmos 359 rocket	1.04 ± 0.05	220	51	120	Average	Average	Dec 1970-Sep 1971	Walker (1974) Ref 57
1970-97B	Cosmos 378 rocket	0.75 ± 0.05 1.0 ± 0.1	250 230	74 74	120 120	06-14 Average	Average Average	Jun 1971-May 1972 Jun 1972-Sep 1972	Hiller (1975) Ref 58
1971-18B	China 2 rocket	1.15 ± 0.05 1.05 ± 0.05 1.10 ± 0.05 1.05 ± 0.05 1.6 ± 0.1	315 310 295 270 195	70 70 70 70 70	120 95 90 75 70	Average Average Average Average 19-23	Average Summer Average Summer Winter	Apr 1971-Aug 1972 Dec 1972-Dec 1973 Apr 1974-Dec 1974 Apr 1975-Jan 1976 Feb 1976	Hiller (1979) Ref 59
1971-106A	Cosmos 462	1.1 ± 0.05 0.9 ± 0.05 1.0 ± 0.05 1.0 ± 0.03 1.1 ± 0.1	253 250 239 218 199	66 66 66 66 66	130 95 85 80 70	Average Average Average Average Average	Winter Summer Average Average Average	Jan-Sep 1972 Jan-Sep 1973 Jan-Jul 1974 Oct 1974-Mar 1975 21 Mar-4 Apr 1975	Walker (1979) Ref 29
1971-109A	Ariel 4	0.81 ± 0.04	520	83	110	Average	Average	Dec 1971-Oct 1973	King-Hele and Walker (1977) Ref 27
1972-05B	Heos 2 2nd stage	1.40 ± 0.05	240	90	160	00-02	Average	Sep 1978	Hiller (1981) Ref 49
1972-23A	Cosmos 482	0.90 ± 0.05 1.05 ± 0.10	200 180	52 52	190 210	08 Average	Average Average	21 Apr-2 May 1981 2 May-5 May 1981	King-Hele (1982) Ref 60
1973-27A	Skylab 1	1.10 ± 0.07	210-220	50	190	Average	Average	28 Jun-11 Jul 1979	Walker (1982) Ref 32

Table 1 (concluded)

Satellite		Λ	Height km	Inclination deg	$S_{10.7}$	Local time hours	Season	Date for which Λ value applies	Reference
1973-27B	Skylab 1 rocket	1.04 ± 0.05 1.34 ± 0.09 1.06 ± 0.06	380 305 200	50 50 50	90 90 80	Average Average Average	Average Average Average	Jun 1973-Jul 1974 Oct 1974-Dec 1974 28 Dec 1974-11 Jan 1975	King-Hele (1980) Ref 37
1973-101A	Explorer 51 (AE-C)	1.3 ± 0.1	165	68	90	17-22	Winter	21 Dec 1973-18 Jan 1974	Walker (1978b) Ref 61
1976-87B	China 6 rocket	1.0 ± 0.1 0.8 ± 0.1 0.8 ± 0.1	230 215 200	69 69 69	80 100 120	Average Average Average	Average Summer Summer	Oct 1976-May 1977 28 Nov 1977-16 Jan 1978 20 Jan-4 Feb 1978	Hiller (1980) Ref 62
1978-50B	Cosmos 1009 rocket	1.0 ± 0.07 0.8 ± 0.07	160 150	65 65	140 140	Average Average	Summer Summer	23-28 May 1978 29 May-4 Jun 1978	Hiller and King-Hele (1981) Ref 63
1980-43A	NOAA-B	1.1 ± 0.1 1.15 ± 0.06	300 225	92 92	210 215	Average Evening	Average Average	Oct 1980-Feb 1981 2 Apr 1981-3 May 1981	Winterbottom and King-Hele (1982) Ref 64

7.2 RAE results

The new results are from 11 satellites: 1968-103A, 1971-18B, 1971-106A, 1972-05B, 1972-23A, 1973-27A, 1973-27B, 1973-101A, 1976-87B, 1978-50B and 1980-43A. For most of these satellites, the value of Λ in Table 1 is straight from the Reference given there. However, only the first of the three values from 1973-101A was used, because the others were not considered accurate enough, and for the last value from 1976-87B, the sd has been increased to 0.1. It should be noted that the results for 1972-05B, 1972-23A and 1973-27A are for the last two weeks of the life, and other values of Λ for the first two of these satellites earlier in their lives appear in Table 2. For 1968-103A the average value of Λ was taken in preference to the separate 'morning' and 'evening' values, which are questionable because the orbit is so nearly circular.

Two results in our previous review have been discarded. The first was for 1971-37B, for which the more accurate value obtained by Brookes[65], given in Table 2, was preferred. The second was for 1972-04A ($\Lambda = 1.1 \pm 0.1$), where examination of the data led us to conclude that the standard deviation should be considerably greater than 0.1. In the hope of providing a replacement, the orbit of 1972-04B was calculated from US Navy and visual observations[66] but the value of Λ obtained was not of adequate accuracy.

The results for Sputnik 2, Sputnik 3 and Sputnik 3 rocket, were also re-examined, but we could not improve on the values already obtained[14], namely $\Lambda = 1.2 \pm 0.2$, 1.1 ± 0.2 and 1.4 ± 0.2. Since these had too large a standard deviation to qualify, and were all for a height close to 210 km in 1958-60, we combined them to give one value, $\Lambda = 1.23 \pm 0.15$.

7.3 Results from the University of Aston

In Table 2 there are ten values of Λ from orbit analyses made at the University of Aston on five satellites: 1962ol; 1964-76A; 1971-37B; 1972-05B over the whole of its life; and 1972-23A between 1975 and 1977. The values are taken unchanged from the original papers, except for the first value from 1962ol, where we considered the sd was too low and increased it from 0.075 to 0.13. For 1971-37B, only the value after resonance was used; for 1972-23A the average value was chosen in preference to the less accurate values over shorter time intervals.

Table 2

The 24 further values of Λ : see sections 7.3 to 7.7

Satellite		Λ	Height km	Inclination deg	$S_{10.7}$	Local time hours	Season	Date for which Λ value applies	Reference
1961δ1	Explorer 9	1.41 ± 0.14	355	39	80	20-22	Average	Aug 1963-Apr 1964	Slowey (1975) Ref 25
1962ο1	Ariel 1	0.9 ± 0.13	375	54	85	Average	Average	Aug 1973-Sep 1975	Holland and Moore (1981) Ref 67
		1.25 ± 0.13	340	54	80	Evening	Average	Sep 1975-Mar 1976	
		0.75 ± 0.06	270	54	70	Morning	Summer	Mar 1976-May 1976	
1963-30D	Dash 2	0.79 ± 0.11	360	85	140	06-08	Average	Jan-Mar 1971	Slowey (1975) Ref 25
1964-04A	Echo 2	0.78 ± 0.07	675	81	160	06-08	Average	Feb-Jun 1969	Slowey (1975) Ref 25
1964-76A	Explorer 24	0.72 ± 0.14	580	81	130	11	Average	Jan 1965-Aug 1968	Blum and Schuchardt (1976) Ref 26
		1.08 ± 0.14	580	81	130	22	Average	Jan 1965-Aug 1968	
		0.90 ± 0.09	580	81	130	Average	Average	Jan 1965-Aug 1968	
1964-76A	Explorer 24	1.17 ± 0.09	520	81	150	18	Winter	Jun, Aug & Oct 1968	Swinerd (1981) Ref 34
		0.84 ± 0.05	525	81	140	06	Average	Jul & Sep 1968	
1967-50A		0.94 ± 0.08	166	91	200	Average	Summer	25-29 May 1967	Forbes (1975) Ref 68
1967-103A		1.04 ± 0.06	138	112	140	Average	Average	31 Oct-3 Nov 1967	Forbes (1975) Ref 68
1968-18A		1.00 ± 0.04	151	100	130	Average	Average	14-20 Mar 1968	Forbes (1975) Ref 68
1968-31A		1.03 ± 0.10	147	111	120	Average	Average	18-21 Apr 1968	Forbes (1975) Ref 68
1968-47A		1.17 ± 0.10	138	111	140	Average	Summer	12-15 Jun 1968	Forbes (1975) Ref 68
1970-57A	Intercosmos 3	1.2 ± 0.1	222	48	150	Evening	Average	Aug-Dec 1970	Sehnal (1975) Ref 69
1971-37B	Cosmos 408 rocket	1.25 ± 0.05	215	81	110	16-23	Average	Aug-Sep 1971	Brookes (1978) Ref 65
1972-05B	Heos 2 2nd stage	1.0 ± 0.05	350	90	95	Average	Average	Mar 1972-Sep 1975	Moore and Holland (1982) Ref 36
		1.1 ± 0.05	330	90	100	Average	Average	Feb 1977-May 1978	
		0.95 ± 0.10	300	90	130	Morning	Average	Jun 1978-Sep 1978	
1972-23A	Cosmos 482	1.1 ± 0.1	210	52	80	Average	Average	Aug 1975-Oct 1977	Moore (1981) Ref 70
1973-82A	Intercosmos 10	1.20 ± 0.16	286	74	75	Average	Average	May 1975-May 1976	Sehnal and Klokočnik (1979) Ref 71
1974-70A	ANS 1	1.20 ± 0.16	317	98	80	Average	Average	Jun-Nov 1975	Wakker, Klokočnik, Kostelecky and Sehnal (1981) Ref 72

7.4 The results of Blum and Schuchardt (Ref 26)

When we made our previous review, this paper had not been published and we used the results from a pre-print. We now give the results from the published paper: there are some small differences.

7.5 The results of Slowey (Ref 25)

These are used again, without alteration.

7.6 The results of Sehnal, Klokočnik and Wakker

Sehnal[69] analysed the decrease of inclination of Intercosmos satellites and obtained values of Λ with nominal accuracy better than 0.15 for Intercosmos 3, 5 and 9. (The values were 1.20 ± 0.05, 1.25 ± 0.05 and 1.10 ± 0.05 respectively.) However, Klokočnik[73] showed that these three satellites suffered appreciable perturbations at the time of 15th-order resonance, and the effect of meridional winds also needs to be considered, since the inclination is low (48°) and the variation in local time at perigee is rather slow. It is very difficult to assess the likely influence of these effects in relation to the scatter of the original data, but our judgment was that we should only include the result from Intercosmos 3 (1970-57A), with the sd doubled to allow for the effects mentioned. During the time interval when the curve descends steeply, the local time proceeds from 23 hours to 18 hours, so the value of Λ applies for the evening. For the other two Intercosmos satellites it seemed that detailed calculations of the resonance and meridional wind effects would be needed before the values could be substantiated.

Sehnal and Klokočnik[71] analysed the variations of inclination of Intercosmos 10 between its resonances, but only one of their four values had sd less than 0.2. This is the interval between 29:2 and 15:1 resonance, where they find $\Lambda = 1.2 \pm 0.16$. Since the inclination is 74°, meridional wind effects are likely to be small. Although we have set an upper limit of 0.15 on the sd of Λ, we decided it would be unfair to exclude this value, so it appears in Table 2.

Wakker et al[72] have made a detailed analysis of the variation of inclination of the Astronomical Netherlands Satellite 1974-70A, and obtained a value of $\Lambda = 1.20 \pm 0.16$ over the time interval preceding 15:1 resonance, from June to November 1975. The inclination is 98° and meridional wind effects should be negligible, so we accept this value.

7.7 Revision of the results of Forbes

Forbes[68] gave graphs showing the variation of inclination for six USAF satellites with perigee heights in the region 130-150 km. The values of inclination, extending over time intervals of 3-6 days, appear to be of excellent accuracy (about 0.0003°) and they define the value of di/dt with an accuracy of 5-10%. Unfortunately, however, the values of Λ deduced by Forbes range between 0.36 and 2.6 (if one subsidiary value, $\Lambda = 3.8$, is omitted), and very few are near 1.0. Since the original values of i appear to be so good, we decided to reanalyse them, using the full equation (13) for di/dt. The results obtained for the six satellites are listed in Table 3 below.

Table 3

Values of Λ from USAF satellites

Satellite	Height y_1 (km)	Forbes's Λ	Our revised Λ
1967-50A	166	2.4	0.94 ± 0.08
1967-64A	161	0.90	2.7
1967-103A	138	1.9	1.04 ± 0.06
1968-18A	151	0.36	1.00 ± 0.04
1968-31A	147	0.85	1.03 ± 0.10
1968-47A	138	2.6	1.17 ± 0.10

The revisions are of three kinds. First, Forbes's equation (1) requires a factor of 2 on the right-hand side, thus reducing all his values of Λ by a factor of 2. Second, the values of dT/dt in his Table 1 for the second, fourth and fifth satellites in our Table 3, appear to differ from the values measured off the graphs by factors of 7.4, 6.1 and 2.6 respectively. With these two corrections, the six values in the 'Forbes's Λ' column of our Table 3 become 1.2, 3.3, 0.95, 1.10, 1.11 and 1.3 respectively.

The third revision is needed because satellites with such low perigees are very sensitive to the effects of atmospheric oblateness, with the oblateness parameter c in equation (13) taking values of order 0.5 because the scale height is so small (15-20 km). The equation used by Forbes does not include the effect of oblateness, and this leads to further revisions of order 20%.

The revised values of Λ in the last column of Table 3 were calculated by reading off values of di/dt and dT/dt from the graphs given by Forbes, and using the full theoretical equation (13). The terms in c^3, not recorded in equation (13) but derived by Boulton and Swinerd[30], were also evaluated to assess the error incurred by their neglect. For all the satellites, the errors were less than 1%.

The standard deviations of the values of Λ given in Table 3 depend primarily on the accuracy of di/dt, since it is believed that the theoretical equation (3) is accurate to about 1%, unless there are variations in the atmospheric oblateness associated with geomagnetic storms. The accuracy of di/dt has been assessed in the usual way (see section 4.2) from the graphs given by Forbes. We discard the anomalous value for 1967-64A.

The local time at perigee for the six satellites in Table 3 is between 11 and 13 hours, but all the satellites are in orbits of low eccentricity and remain at heights below y_1 over a wide range of local time, typically from 08 to 16 hours. Thus, it is appropriate to record the values of Λ in Table 3 as nearer 'average' than 'morning'. Furthermore, the morning/evening distinction probably does not apply at heights below 160 km, where the day-to-night variation in density is scarcely perceptible. So the values in Table 3 are treated as 'average' in local time. Since perigee is at high northern latitudes, however, nearly all the drag occurs in the northern hemisphere, so seasonal bias is applicable (see Table 2).

These five new values of Λ are very useful, since there are few other values at such low altitudes. In our previous review we accepted two of Forbes's original values: these have now been discarded.

8 VARIATIONS OF Λ WITH HEIGHT, LOCAL TIME AND SEASON

8.1 Definitions

Each value of Λ in Tables 1 and 2 is accompanied by the appropriate values for height, orbital inclination, solar activity, local time (LT) and season, in the hope of detecting variations linked with some or all of these parameters. It soon became apparent that variations with inclination and solar activity would not be easy to detect, so we decided to concentrate on height, local time and season.

As in our previous review[27], we define three regimes of local time - morning, evening and average. 'Morning' applies when the local time at perigee, and in the region near perigee where drag is important, is predominantly (> 75%) between local times of 06 h and 12 h. 'Evening' applies when the local time is predominantly between 18 h and 24 h. 'Average' covers all the remaining situations, namely:

(1) Local time predominantly 0-6 h;

(2) Local time predominantly 12-18 h;

(3) Local time covering several 6-hour intervals (often several 24-hour cycles) and not appreciably biased;

(4) Near-circular orbits, with eccentricity usually less than 0.006.

Unfortunately, the satellites do not place themselves neatly into the required categories, and it was sometimes difficult to choose the appropriate one. So although we have done our best to assign each value of Λ to the correct category of local time, there is scope for argument and alternative judgments. Only one choice violated the criteria: we decided to allow 'evening' to continue for an hour or two beyond midnight in September 1978, to accommodate the value from 1972-05B in Table 1.

Similarly, we define three seasonal categories - summer, winter and average. 'Summer' applies when the local seasonal situation of perigee is predominantly within 1½ months of the summer solstice. 'Winter' applies similarly for the winter solstice. 'Average' covers the remaining situations, namely:

(1) Date predominantly between 6 February and 6 May;

(2) Date predominantly between 6 August and 6 November;

(3) Date covering several seasons, with no marked bias;

(4) Near-circular orbits.

Values for equinox would of course appear in our 'average' category, but the term 'average' is preferable to 'equinox' as so many of the results are obtained from analysis of orbits over several years.

The categories so far defined offer the possibility of producing curves of the variation of Λ with height for a maximum of nine sets of conditions, and these are discussed in the next three sections.

Although we present the results in the form of curves of Λ versus height throughout, for consistency, it should be remembered that if the local time is 'evening' or 'morning', it is more logical to look on the results not as 'a rotation rate Λ' but as 'a west-to-east wind of $400(\Lambda - 1)$ m/s' (if the effective latitude is 30-40°).

8.2 Variation with local time: average season

Fig 10 shows all the 67 values in Tables 1 and 2 that are seasonally average. Evening values are denoted by upward-pointing triangles, morning values by downward-pointing triangles and average-LT values by circles.

The average-LT values in Fig 10 are rather widely spread, as would be expected from the wide spectrum of conditions lumped together as 'average', but the curve drawn through them seems to provide a reasonable mean: this will be called the 'average/average' curve, that is, average in local time and average in season. The curve is made to decrease to near 1.0 at 120 km and is arbitrarily assumed to have zero slope at 700 km.

All the 'evening' points in Fig 10 are above the average/average curve, and all the 'morning' points are below. The morning and evening curves are drawn as parallel as possible to the average/average curve and we assume that the distinction between morning and evening ceases to operate at heights below about 120 km, so that the curves merge there. The morning and evening points conform quite well to the curves drawn: obviously, however, many more points are required, and the increase shown in the morning curve near 300 km may prove to be unjustified.

8.3 Average local time: variation with season

In Fig 11, the 45 'average/average' points are reproduced from Fig 10, together with the 13 values from Tables 1 and 2 that are seasonally biased but average in local time.

Nine of the ten summer values in Fig 11 are below the average/average curve, and a curve has been drawn through them well below the average/average. Unfortunately, there are only three winter values and a curve through them would be unacceptably close to the average/average curve. So the average/winter curve has been raised to a level slightly above the three points. The reason for this seeming discrepancy will become apparent later (section 8.8).

8.4 Non-average local time and non-average season

Figs 10 and 11 give five distinct curves, and these are reproduced as unbroken lines in Fig 12, without the 80 points on which they are based. Also plotted are the remaining five points. Three of these are evening/winter and they show consistently high values of Λ , through which a broken curve has been drawn.

The single morning/summer point is the lowest of all the 85 values of Λ , and a tentative morning/summer curve has been sketched in.

A morning/winter curve has been drawn through the one morning/winter value. This, taken with the evening/winter curve, again suggests that the average/winter curve of Fig 11 should be appreciably above the average/average curve.

The last of the nine possible curves is evening/summer, and in the absence of any points this has been sketched so as to be consistent as an extrapolation of both the evening/winter and evening/average curves, and the average/summer and morning/summer curves.

8.5 Discussion

Although several of the curves in Fig 12 are tentative and unproven, the pattern that emerges is consistent and can be stated simply, as follows:

> At a height of 300 km, the average/average rotation rate is about 1.2 rev/day. In the evening Λ is about 0.2 higher, in the morning 0.3 lower. There is also a seasonal variation, the values being on average 0.15 higher in winter and 0.1 lower in summer. At heights above and below 300 km, the average/average rotation rate decreases to about 1.1 at heights of about 400 and 230 km, while the changes dependent on local time and season vary only slightly in this height-band.

The curves for morning and evening in Fig 12 represent the average conditions between 06 and 12 h, or between 18 and 24 h, and not the extremes. Similarly for summer and winter.

Fig 12 should be of value as a guide to the general dynamical behaviour of the upper atmosphere, and also in providing suitable values of Λ for use in orbit analysis, for example when analysing resonances with the gravitational field.

8.6 The effect of solar activity

The 45 average/average values of Λ in Tables 1 and 2 are plotted against the solar 10.7-cm radiation values in Fig 13. No trend is discernible: any variation with solar activity is swamped by variability from other sources.

This conclusion, though inescapable, is rather surprising because the air pressure at 300 km varies between day and night by a factor of 3.8 when $S_{10.7} = 75$ and by a factor of 2.2 when $S_{10.7} = 180$, from CIRA 1972, so that different wind strengths might be expected.

Another effect that could be linked with solar activity is discussed in section 8.8.

8.7 The effect of latitude

The 45 average/average values of Λ are plotted against orbital inclination i in Fig 14. These atmospheric rotation rates can be regarded as applying over latitudes up to about two-thirds of the inclination, so any strong variation of zonal wind with latitude should lead to a clear variation of Λ with inclination. In fact, the trend in Fig 14 is too feeble to inspire any confidence: there is a slight tendency for Λ to decrease as i increases - especially if the values for $i > 90°$ are plotted at inclination $(180° - i)$ - but this tendency can be destroyed by omitting a few points, such as those at 33° inclination, or those at heights above 500 km.

Since the simple plotting against inclination is unrevealing, the values have been divided into two groups, with inclinations less than and greater than 60°, and have been plotted against height in Fig 15. At heights up to 250 km, the two groups seem to be quite jumbled, but above 300 km the open circles ($i < 60°$) have distinctly higher values than the black circles ($i > 60°$), and tentative curves have been drawn to indicate this difference. This graph is quite similar to that produced in our previous review[27], because there are only a few extra points at heights above 400 km. So there is some justification for thinking that the west-to-east winds are stronger at low latitudes than at higher latitudes, for heights above 300 km. However, this conclusion is not certain, and more evidence is required.

8.8 An unexpected effect

So far, we have been exploring the effects of geophysically plausible influences - local time, season, solar activity and latitude. However, there is another effect, geophysically unlikely, that has forced itself upon us uninvited, namely, a general decrease in Λ between the 1960s and the 1970s. This is illustrated in Fig 16, where the 45 average/average values are replotted as open circles for the 1960s or black circles for the 1970s. The date refers to the time when the atmosphere was sampled, of course, not the date of computation of the results, and 'the 1960s' in fact covers the years 1958-1969, while 'the 1970s' covers 1970-1981. As it happens, these periods are nearly from maximum to maximum of solar cycles.

In Fig 16 the average/average curve of Fig 10 is replotted and separate curves for the 1960s and 1970s have been drawn. From these curves it appears that Λ was on average about 0.1 higher in the 1960s than in the 1970s, at heights of 200-500 km.

This is a strange result, for which we can offer no good explanation. It may be relevant that the amplitude of the semi-annual variation in density changed markedly between the 1960s and the early 1970s[74] but it is difficult to see why this should be linked with the winds. It is even more difficult to credit the idea that the upper atmosphere was 'spun up' at the 1958 solar maximum, which was the highest ever, and has been 'running down' ever since. A second possibility, just as difficult to defend, is that conditions at solar maximum somehow 'set the tone' for the next ten years. If so, higher values of Λ will occur in the years 1982-1992: all the values of Λ at present available are for dates before the high maximum of October 1981. A third possibility is a link with the so-called 'decade fluctuations' in length of day[75]: there was a change in the behaviour of the Earth's rotation rate between the 1960s and the 1970s, but any effect would be very indirect, because the upper atmosphere makes only a trivial contribution to the total atmospheric angular momentum.

9 COMPARISONS WITH THE GLOBAL MODEL OF FULLER-ROWELL AND REES

All the graphs so far presented have been based on the observational evidence, subject to the assumptions that $\Lambda \to 1.0$ at $y = 120$ km and that $d\Lambda/dy \to 0$ at $y = 700$ km. T.J. Fuller-Rowell and D. Rees have kindly provided an extensive print-out of the results from their three-dimensional time-dependent global model of the thermosphere[3], and we have plotted these results in a format similar to ours, for comparison. These curves were not drawn until after ours had been decided upon; and our graphs have not been altered retrospectively in any way. So the two sets of results are independent, and ideal for comparison, one being observational and the other a theoretical model.

Fuller-Rowell and Rees provide a harmonic analysis of their results to give a prevailing wind component and the amplitude and phase of a diurnal component (together with semi-diurnal, ter-diurnal and quar-diurnal modes, which are usually small at heights above 180 km). The diurnal component has its west-to-east maximum value in the late evening (usually near 21 h) in nearly all the relevant situations, thus fitting in with our evening maximum of Λ. The print-out gives results for 18 latitudes, and we have selected the results for 30° latitude, which is the best estimate for the mean latitude of our results. Thus, their 'prevailing wind', divided by 400 m/s, gives a value of $(\Lambda - 1)$, for comparison with our diurnally averaged value of Λ ; and the sum of their prevailing wind and diurnal amplitude, divided similarly, gives a measure of the evening value of $(\Lambda - 1)$. Subtracting the diurnal amplitude from the prevailing wind gives a value of $(\Lambda - 1)$ for the morning.

Fuller-Rowell and Rees provided us with results for equinox, summer and winter, for two levels of solar activity, corresponding to values of the $S_{10.7}$ index of 75 and 165. We chose the latter as standard, chiefly because the results extend to a greater height (380 km, rather than 300 km for $S_{10.7} = 75$). The Volland Model 1 electric field, corresponding to geomagnetically quiet conditions, was taken.

Fig 17 shows the values of Λ from the model of Fuller-Rowell and Rees, with our corresponding values on the right. Nearly all the trends are in agreement: the diurnal (morning/evening) variation has an amplitude of about 0.2 at heights above 200 km, and in the same sense; the summer-winter variation has nearly the same amplitude in both diagrams, about 0.1, the values being higher in winter than summer; also the effects increase greatly with height between 120 and 200 km, and then become fairly constant.

The mean values of Λ and the amplitude of the diurnal oscillation for 250 km (the only height where we have complete results) are given in Table 4.

Table 4

Comparison of our values of Λ with those of Fuller-Rowell and Rees, for 250 km height

	Average season		Summer		Winter	
	Average Λ	Diurnal amplitude	Average Λ	Diurnal amplitude	Average Λ	Diurnal amplitude
Our values	1.13	0.25	0.94	0.22	1.20	0.26
Fuller-Rowell and Rees[3]	1.04	0.18	0.95	0.23	1.12	0.20

For our values the 'diurnal amplitude' is taken as half the difference between evening and morning.

There is excellent agreement on the summer values, but we have a larger diurnal variation in winter and in average (equinox) conditions; also we have higher winter and seasonally-averaged values of Λ, the mean difference being 0.085, or 35 m/s. However, it could be argued that a difference of 35 m/s is within the likely limits of error. Certainly it could not be claimed that the results from satellite orbit analysis have an accuracy better than 20 m/s, because of the inevitably varied conditions in which they are derived: for example, the average difference between the values for the 1960s and 1970s is nearly 40 m/s.

The other obvious difference between the results, apparent in Fig 17, is that the values of Λ from the model tend to become constant as height increases above 350 km, whereas our values decrease at these heights.

Although we have made detailed comparisons only with the model of Fuller-Rowell and Rees, this does not imply either dismissal of or disagreement with other models. For example, a recent detailed study of atmospheric tides by Forbes[76] gives a solar diurnal tide of amplitude about 100 m/s, having maximum west-to-east value at 20-21 h local time, at heights above 200 km at equinox, corresponding to a 'diurnal amplitude' of 0.25 in Table 4, in agreement with our values. Also the computations of Roble, Dickinson and Ridley[77] indicate that, at a height of 250 km, the diurnally-averaged Λ is about 0.15 higher (60 m/s) in winter than in summer, in fair agreement with Table 4. Similar seasonal variations are found in Doppler measurements of airglow lines (eg Burnside et al[78]).

10 MERIDIONAL WINDS

We have already seen how evaluations of zonal winds from the changes in orbital inclination can sometimes be hampered and limited in accuracy by the effects of meridional winds (section 5.4). The problem is much worse when attempting to determine meridional winds, because the zonal winds usually cause larger perturbations, which cannot be removed with sufficient accuracy.

However, there are circumstances when meridional winds could be accurately determined. One possibility is an orbit at an inclination less than 15°, which would be little affected by zonal winds. Unfortunately there have so far been few accurate orbits available for high-drag satellites at inclinations lower than 30°, though it might be feasible to analyse the orbits of the satellites 1970-17A, 1970-107A or 1970-109A.

It is also sometimes possible to determine meridional winds by analysing an orbit of very high drag and high eccentricity having ω near 90° or 270°.

If $e > 0.2$ and $\cos\omega$ is small, the change in i due to atmospheric rotation is of order $\frac{1}{3}\Lambda \sin i \cos^2\omega\,(1 - e)^{\frac{5}{2}}(1 + e)^{-\frac{3}{2}}$ by equation (14), while that due to meridional winds is of order $\frac{1}{3}\Phi \cos\omega(1 - e)^{\frac{5}{2}}(1 + e)^{-\frac{3}{2}}$ by equation (18). Thus if $\cos\omega \simeq 0.1$, the perturbation due to zonal winds will be negligible while that due to meridional winds may be measurable. In practice, ω will stay near 90° or 270° only if the orbital inclination is near 63°, and the only satellite to which this method has been successfully applied is 1970-114F, inclination 65°, which decayed very rapidly, having an eccentricity of 0.3 and an apogee height of 7000 km only 20 days before decay. In those last 20 days, ω remained between 260° and 263°, and the perigee height decreased from 112 to 107 km. Analysis of the inclination and right ascension of the node[79] gave consistent values for meridional winds, namely 150 ± 30 m/s south to north at a height of 110 km at latitude 63-65° south and 07-09 h local time on geomagnetically disturbed days (22 February - 3 March 1973). This type of orbit can only be analysed successfully, however, if the drag is very high, so there is little hope of results at heights above about 150 km.

11 PERTURBATIONS IN RIGHT ASCENSION

The aerodynamic forces created by atmospheric rotation cause perturbations not only in the orbital inclination but also in other orbital elements, notably the right ascension of the node Ω (defined in Fig 1). The change $\Delta\Omega$ in right ascension may be expressed[28] as

$$\Delta\Omega = \frac{\Lambda \sin 2\omega}{6\sqrt{F}}\left(\frac{I_2}{I_0}\right)\left\{1 - 2e\left(\frac{I_1}{I_2} + \frac{I_1}{I_0}\right) + c\left(\frac{I_4}{I_2} - \frac{I_2}{I_0}\right)\cos 2\omega + O(c^2, e^2)\right\}\Delta T \quad . \qquad \ldots\ldots (20)$$

(See equation (2) for definitions.) Since I_2/I_0 is less than 0.1 for $z < 1$ and tends to zero for circular orbits, there is little hope of determining Λ from changes in right ascension unless the orbit is eccentric enough to ensure that z is greater than about 2. Even then the perturbation nearly cancels out over each half cycle of ω, so the best hope of analysing the changes in right ascension is with an orbit where $\sin 2\omega$ remains large - for instance, if ω increases from 30° to 60° during the analysis.

The change in Ω due to the Earth's gravitational field amounts to several degrees per day except for near-polar orbits, and if this gravitational effect is to be removed with adequate accuracy, near-polar orbits are to be preferred. Since ω decreases at about 4 deg/day for near-polar orbits, a 30°

change in ω occurs in about seven days. So a very high-drag orbit is required if a large enough change in orbital period is to be built up in seven days.

In summary, a very high-drag, highly-eccentric and preferably near-polar orbit with $|\sin 2\omega| > 0.5$ would offer a good opportunity for determining Λ from changes in right ascension. Unfortunately, no such satellite has yet materialized.

The most promising of the orbits already analysed might seem to be that of 1972-05B, for which the inclination was 89.7° and accurate orbits[49] are available for the last 14 days. Also the numerical value of $\sin 2\omega$ happens to be favourable, being greater than 0.7 during the last eight days. Unfortunately, however, e was less than 0.005 at this time, so that $z < 0.8$ and $I_2/I_0 < 0.07$, giving a total perturbation in Ω of less than 0.0004°, which is slightly less than the sd of the values.

A better example is 1980-43A, where analysis of the values of Ω in the last seven days of the life[64] reveals a variation which is consistent with that given by equation (20) with $\Lambda = 1.15$ (the value obtained from analysis of i). The total variation is 0.0028° and the average sd of the values is about 0.0006°.

Another example is 1972-23A, in its last 15 days[60], where the total change in Ω is about 0.006° and the average sd of the values is 0.0006°. The inclination is 51.9°, so the removal of the very large gravitational perturbation (up to 66°) may have created some errors. But the results are good enough to provide a confirmation of the values of Λ obtained from analysis of the inclination.

12 CONCLUSIONS

We have reviewed all existing results on values of atmospheric rotation rate Λ obtained from orbit analysis and, after rejecting some and revising others, we have a total of 85 values. These have been used in an attempt to establish the variation of Λ with height and the dependence of this variation on local time and season. The dependence is brought out by classifying the values as morning, evening or average local time, and as summer, winter or average season. This leads to nine curves of variation of Λ with height, given in Fig 12, though some of the curves are quite fragmentary through lack of data.

The results (Fig 10) indicate that the average/average rotation rate increases from 1.0 rev/day at 125 km height to 1.22 at 325 km, and then falls to 1.0 at 430 km and 0.82 at 600 km. Fig 12 shows that the rotation rate is about 0.2 higher than average in the evening (18-24 h) and about 0.3 lower than average in the morning (06-12 h); and is higher than average in winter and lower in summer, though generally the seasonal variation is smaller than the morning-evening. Thus there are west-to-east winds in the evening at all seasons, but most strongly in winter when the speeds can exceed 200 m/s at heights near 300 km. The morning winds are generally from east to west but not as strong as those in the evening.

Rather surprisingly, no significant variation with solar activity has been found (Fig 13), and variations with latitude were rather feeble, with an indication of a greater rotation rate at lower latitude for heights above 300 km Fig 15). Unexpectedly, the values for the 1960s (actually 1958-1969) were found to be appreciably higher than those for the 1970s (actually 1970-1981), as shown in Fig 16; no convincing explanation can be given.

When these results, based purely on observational material, are compared with the theoretical global model of Fuller-Rowell and Rees[3] there is excellent agreement on the trends, though with some differences in the mean values: see Fig 17. The model and the observational results both give higher values of Λ in the evening than in the morning, and higher values in winter than in summer, and the magnitudes of the variations show satisfactory agreement. The variations with height are also fairly similar, although the model shows the values becoming constant above 300 km, rather than decreasing. The average values of Λ for the three seasons and the amplitudes of the morning-evening variation are compared in Table 4 for a height of 250 km. Our average/average value of Λ is higher than that of the model - it is 1.13 rather than 1.04 - but the sd of both values might be estimated as about 0.05, so the difference is only just significant.

In summary, the observational results have yielded consistent but incomplete curves for the variation of atmospheric rotation rate with height between 125 and 700 km, showing dependence on local time and season; and these results agree well, on the whole, with the picture emerging from the model of Fuller-Rowell and Rees.

Acknowledgments

We thank the authors whose orbit analyses have contributed to this Review. We are also grateful to T.J. Fuller-Rowell and D. Rees for making available a detailed printout of their thermospheric model.

REFERENCES

No.	Author	Title, etc
1	R.H. Merson D.G. King-Hele R.N.A. Plimmer	Changes in the inclination of satellite orbits to the equator. Nature, 183, 239-240 (1959)
2	D.G. King-Hele	Upper-atmosphere studies by ranging to satellites. Phil. Trans. Roy. Soc., A284, 555-563 (1977) RAE Technical Memorandum Space 234 (1976)
3	T.J. Fuller-Rowell D. Rees	A three-dimensional time-dependent global model of the thermosphere. J. Atmos. Sci., 37, 2545-2567 (1980)
4	D.G. King-Hele R.H. Merson	Satellite orbits in theory and practice. J. Brit. Interplan. Soc., 16, 446-471 (1958)
5	R.H. Merson D.G. King-Hele	Use of artificial satellites to explore the Earth's gravitational field: results from Sputnik 2. Nature, 182, 640-641 (1958)
6	W.A. Wildhack	Effect of transverse atmospheric drag on satellite orbits. Science, 128, 309-310 (1958)
7	C.H. Bosanquet	Change of inclination of a satellite orbit. Nature, 182, 1533 (1958)
8	R.N.A. Plimmer	The effect of the Earth's atmospheric rotation on the orbital inclination of a near Earth satellite. RAE Technical Note GW 504 (1959)
9	T.E. Sterne	Effect of the rotation of a planetary atmosphere upon the orbit of a close satellite. ARS Journal, 29, 777-782 (1959)
10	G.E. Cook R.N.A. Plimmer	The effect of atmospheric rotation on the orbital plane of a near Earth satellite. Proc. Roy. Soc., A258, 516-528 (1960)
11	D.G. King-Hele	Analysis of the orbits of the Russian satellites. Proc. Roy., Soc., A253, 529-538 (1959)

REFERENCES (continued)

No.	Author	Title, etc
12	D.G. King-Hele	Properties of the atmosphere revealed by satellite orbits. Progress in the Astronautical Sciences, I, pp 1-49 (1962)
13	R.C. Nigam	On the secular decrease in the inclination of artificial satellites. AIAA Journ., 1, 1454-5 (1963)
14	D.G. King-Hele	The rotational speed of the upper atmosphere determined from changes in satellite orbits. Planet. Space Sci., 12, 835-853 (1964) RAE Technical Note Space 59 (1964)
15	G.E. Cook	Effect of an oblate, rotating atmosphere on the orientation of a satellite orbit. Proc. Roy., Soc., A261, 246-258 (1961) RAE Technical Note GW 550 (1960)
16	D.G. King-Hele D.W. Scott	A revaluation of the rotational speed of the upper atmosphere. Planet. Space Sci., 14, 1339-1365 (1966) RAE Technical Report 66189 (1966)
17	D.G. King-Hele D.W. Scott	Further determinations of upper-atmosphere rotational speed from analysis of satellite orbits. Planet. Space Sci., 15, 1913-1931 (1967) RAE Technical Report 67179 (1967)
18	D.G. King Hele D.W. Scott	The effect of atmospheric rotation on a satellite orbit, when scale height varies with height. Planet. Space Sci., 17, 217-232 (1969) RAE Technical Report 68066 (1968)
19	D.G. King-Hele D.W. Scott D.M.C. Walker	Upper-atmosphere rotational speed and its variation with height. Planet. Space Sci., 18, 1433-1445 (1970) RAE Technical Report 69263 (1969)

REFERENCES (continued)

No.	Author	Title, etc
20	D.G. King-Hele	The effect of a meridional wind on a satellite orbit. Proc. Roy. Soc., A294, 261-272 (1966) RAE Technical Report 66010 (1966)
21	R.H. Gooding	Lumped fifteenth-order harmonics in the geopotential. Nature Phys. Sci., 231, 168-9 (1971) [See also RAE Technical Report 71068 (1971)]
22	D.G. King-Hele	Decrease in upper-atmosphere rotation rate at heights above 350 km. Nature, 233, 325-326 (1971)
23	D.G. King-Hele D.M.C. Walker	The change in satellite orbital inclination caused by a rotating atmosphere with day-to-night density variation. Celestial Mechanics, 5, 41-54 (1972) RAE Technical Report 70208 (1970)
24	D.G. King-Hele D.M.C. Walker	The effect of atmospheric winds on satellite orbits of high eccentricity. Proc. Roy. Soc., A350, 281-298 (1976) RAE Technical Report 75150 (1975)
25	J.W. Slowey	Systematic winds at heights between 350 and 675 km from analysis of the orbits of four balloon satellites. Planet. Space Sci., 23, 879-886 (1975)
26	P.W. Blum K.G.H. Schuchardt	Exospheric zonal winds between 540 and 620 km from the orbit of Explorer 24. Planet. Space Sci., 24, 529-539 (1976)
27	D.G. King-Hele D.M.C. Walker	Upper-atmosphere zonal winds: variation with height and local time. Planet. Space Sci., 25, 313-336 (1977) RAE Technical Report 76055 (1976)

REFERENCES (continued)

No.	Author	Title, etc
28	D.G. King-Hele	*Theory of satellite orbits in an atmosphere.* Butterworths, London (1964)
29	D.M.C. Walker	Cosmos 462 (1971-106A): orbit determination and analysis. Phil. Trans. Roy. Soc., A292, 473-512 (1979) RAE Technical Report 78089 (1978)
30	W.J. Boulton G.G. Swinerd	The change in satellite orbital inclination due to a rotating oblate atmosphere with diurnal variation. Proc. Roy. Soc. (in press)
31	-	CIRA 1972 (COSPAR International Reference Atmosphere 1972) Akademie-Verlag, Berlin (1972)
32	D.M.C. Walker	The last 14 days of Skylab 1: orbit determination and analysis. RAE Technical Report 82067 (1982)
33	D.G. King-Hele	Lumped harmonics of 15th and 30th order in the geopotential, from the resonant orbit of the satellite 1971-54A. Proc. Roy. Soc., A375, 327-350 (1981) RAE Technical Report 80088 (1980)
34	G.G. Swinerd	Determination of zonal wind speeds at heights near 530 km from the orbit of Explorer 24 (1964-76A). Planet. Space Sci., 29, 349-358 (1981)
35	R.H. Gooding	The evolution of the PROP6 orbit determination program, and related topics. RAE Technical Report 74164 (1974)
36	P. Moore D. Holland	Analysis of the orbital inclination of Heos 2 second-stage rocket 1972-05B. J. Brit. Interplan. Soc., 35, 368-379 (1982)

REFERENCES (continued)

No.	Author	Title, etc
37	D.G. King-Hele	Skylab 1 rocket, 1973-27B: orbit determination and analysis. Phil. Trans. Roy. Soc., A296, 597-637 (1980) RAE Technical Report 79044 (1979)
38	G.E. Cook	The effect of aerodynamic lift on satellite orbits. Planet. Space Sci., 12, 1009-1020 (1964) RAE Technical Note Space 58 (1964)
39	S.P. Fiddes	Motion of an artificial Earth satellite subject to aerodynamic forces. MSc. thesis, Imperial College, London (1975)
40	G.R. Karr J.G. Cleland L.L. DeVries	Aerodynamic lift effect on satellite orbits. AIAA Paper 75-12 (1975)
41	G.R. Karr	Environmental dynamics at orbital altitudes. NASA Contractor's Report CR-2765, NASA; Washington DC (1976)
42	B.K. Ching D.R. Hickman J.M. Straus	Effects of atmospheric winds and aerodynamic lift on the inclination of the orbit of the S3-1 satellite. J. Geophys. Res., 82, 1474-1480 (1977)
43	L. Sehnal	Determination of satellite drag coefficient from the orbital analysis of the ANS satellite (1974-70A). Bull. Astron. Inst. Czech., 33, 244-249 (1982)
44	E. Darwin	The Botanic Garden Part 1, Canto IV, lines 321-336 Johnson, London (1792)
45	S.T. Coleridge	Letter to Lord Liverpool (28 July 1817) Collected Letters, Vol IV, p 760, Oxford Univ. Pr., (1959)
46	J.M. Straus B.K. Ching	Effects of meridional winds on the interpretation of satellite inclination data. Nature, 252, 672-674 (1974)

REFERENCES (continued)

No.	Author	Title, etc
47	D.E. Smith P. Dunn	Long term evolution of the Lageos orbit. Geophys. Res. Lett., 7, 437-440 (1980)
48	D.P. Rubincam	On the secular decrease in semimajor axis of Lageos's orbit. Celestial Mechanics, 26, 361-382 (1982)
49	H. Hiller	The orbit of 1972-05B in its final phase, with geophysical inferences. Planet. Space Sci., 29, 579-588 (1981) RAE Technical Report 80119 (1980)
50	D.M.C. Walker	Upper-atmosphere rotation rate from analysis of the orbital inclination of Explorer 1. Planet. Space Sci., 23, 1573-1579 (1975) RAE Technical Report 75066 (1975)
51	D.G. King-Hele	Analysis of the orbit of 1966-51C. Planet. Space Sci., 25, 343-352 (1977) RAE Technical Report 76109 (1976)
52	H. Hiller	The orbit of the satellite 1968-86A RAE Technical Report 72147 (1972)
53	H. Hiller D.G. King-Hele	The orbit of Proton 4 redetermined, with geophysical implications. Planet. Space Sci., 25, 511-520 (1977) RAE Technical Report 76143 (1976)
54	D.G. King-Hele A.N. Winterbottom	Analysis of the orbit of Cosmos 268 rocket (1969-20B) Planet. Space Sci., 20, 2153-2163 (1972) RAE Technical Report 71202 (1971)
55	D.G. King-Hele	Analysis of the orbit of Cosmos 316 (1969-108A) Proc. Roy. Soc., A330, 467-494 (1972) RAE Technical Report 72062 (1972)

REFERENCES (continued)

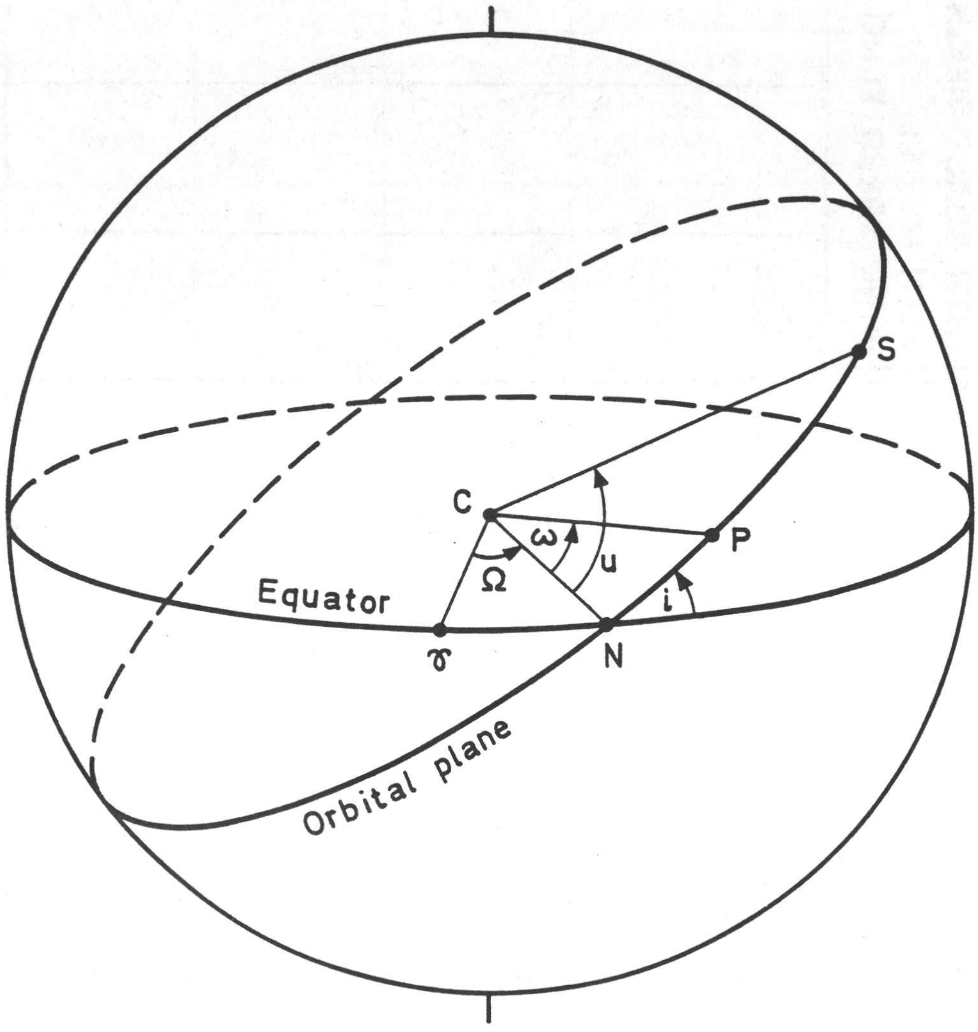
No.	Author	Title, etc
56	H. Hiller	Upper-atmosphere rotation rate, from analysis of the orbit of 1970-43B. Planet. Space Sci., 22, 1565-1569 (1974) RAE Technical Report 73118 (1973)
57	D.M.C. Walker	Analysis of the orbit of 1970-65D, Cosmos 359 rocket. Planet. Space Sci., 22, 391-402 (1974) RAE Technical Report 73110 (1973)
58	H. Hiller	Analysis of the orbit of 1970-97B (Cosmos 378 rocket). Planet. Space Sci., 23, 1369-1376 (1975) RAE Technical Report 74161 (1974)
59	H. Hiller	Determination and geophysical interpretation of the orbit of China 2 rocket (1971-18B). Planet. Space Sci., 27, 1247-1267 (1979) RAE Technical Report 78107 (1978)
60	D.G. King-Hele	Analysis of the orbit of Cosmos 482 in its last 15 days. RAE Technical Report (to be issued)
61	D.M.C. Walker	Upper-atmosphere winds from the orbit of 1973-101A. J. Brit. Interplan. Soc., 31, 197-199 (1978) RAE Technical Memorandum Space 254 (1977)
62	H. Hiller	Upper-atmosphere rotation rate determined from the orbit of China 6 rocket (1976-87B). Planet. Space Sci., 28, 549-558 (1980) RAE Technical Report 79115 (1979)
63	H. Hiller D.G. King-Hele	Features of the upper atmosphere revealed by analysis of the orbit of Cosmos 1009 rocket, 1978-50B. Planet. Space Sci., 29, 35-45 (1981) RAE Technical Report 80052 (1980)
64	A.N. Winterbottom D.G. King-Hele	Upper-atmosphere features revealed by the orbit of 1980-43A. RAE Technical Report 83002 (1983)

REFERENCES (continued)

No.	Author	Title, etc
65	C.J. Brookes	Upper-atmosphere winds from the orbit of 1971-37B, Cosmos 408 rocket. J. Brit. Interplan. Soc., 31, 176-180 (1978)
66	D.M.C. Walker	Ten orbit determinations for Cosmos 472 rocket. RAE Technical Memorandum Space 314 (1982)
67	D. Holland P. Moore	Geophysical inferences from the final thousand days of the orbit of Ariel 1. Planet. Space Sci., 29, 989-998 (1981)
68	J.M. Forbes	Wind estimates near 150 km from the variation in inclination of low-perigee satellite orbits. Planet. Space Sci., 23, 726-731 (1975)
69	L. Sehnal	Rotational speed of the upper atmosphere determined from orbital inclinations of Interkosmos satellites. Bull. Astron. Inst. Czech., 26, 300-306 (1975)
70	P. Moore	Upper-atmosphere zonal winds determined from orbital analysis of Cosmos 482, 1972-23A. Planet. Space Sci., 29, 495-504 (1981)
71	L. Sehnal J. Klokočnik	Analysis of the inclination variations of Interkosmos 10. Bull. Astron. Inst. Czech., 30, 205-214 (1979)
72	K.F. Wakker J. Klokočnik J. Kostelecky L. Sehnal	Analysis of inclination variations of the first Netherlands satellite. Bull. Astron. Inst. Czech., 32, 168-178 (1981)
73	J. Klokočnik	Resonant coefficients of the Earth's gravity field derived from the inclination of Interkosmos satellites. Bull. Astron. Inst. Czech., 26, 293-300 (1975)
74	D.M.C. Walker	Variations in air density from January 1972 to April 1975 at heights near 200 km. Planet. Space Sci., 26, 291-309 (1978) RAE Technical Report 77078 (1977)

REFERENCES (concluded)

No.	Author	Title, etc
75	K. Lambeck	The Earth's variable rotation, Ch 5. Cambridge University Press, Cambridge (1980)
76	J.M. Forbes	Atmospheric tides 1. Model description and results for the solar diurnal component. J. Geophys. Res., 87, 5222-5240 (1982)
77	R.G. Roble R.E. Dickinson E.C. Ridley	Seasonal and solar cycle variations of the zonal mean circulation in the thermosphere. J. Geophys. Res., 82, 5493-5504 (1977)
78	R.G. Burnside F.A. Herrero J.W. Meriwether J.C.G. Walker	Optical observations of thermospheric dynamics at Arecibo. J. Geophys. Res., 86, 5532-5540 (1981)
79	D.G. King-Hele	Analysis of the orbit of 1970-114F in its last 20 days. Planet. Space Sci., 24, 1-16 (1976) RAE Technical Report 75088 (1975)



C Earth's centre

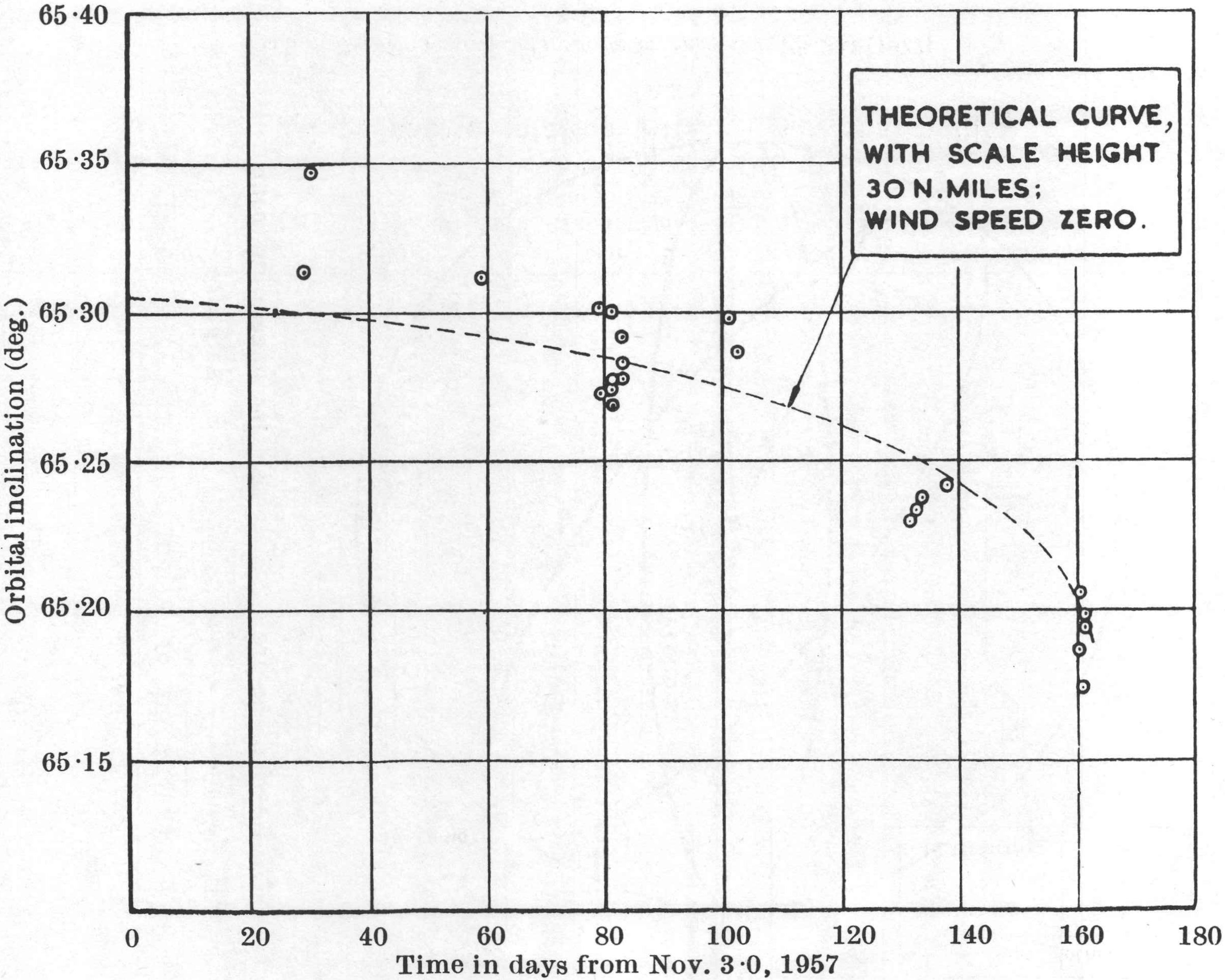
P perigee

♈ first point of Aries

N ascending node

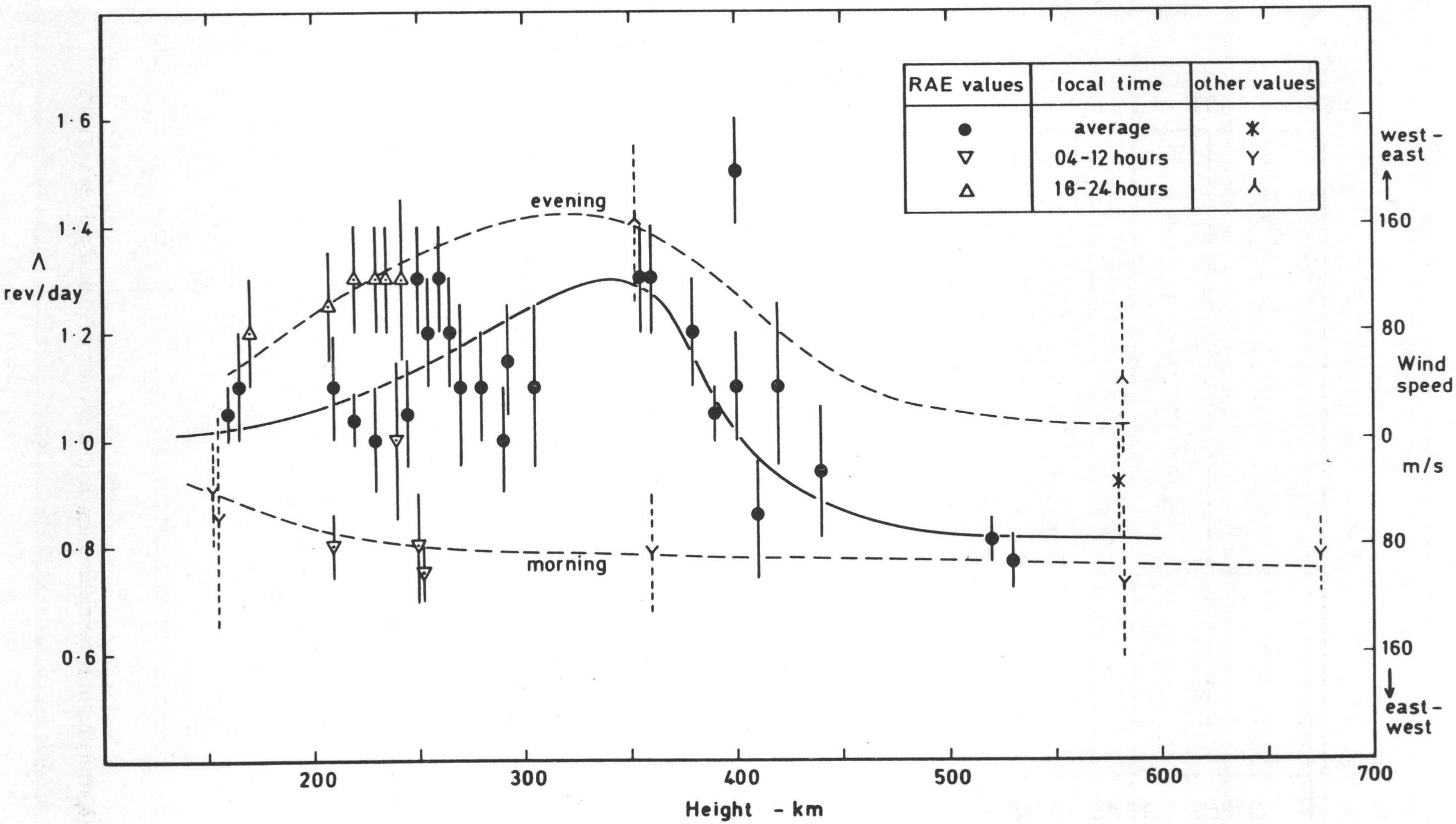
S satellite

Fig 1 Diagram defining orbital elements i, u, ω and Ω relative to unit sphere



Mean orbital inclination of *Sputnik* 2 (1957β)

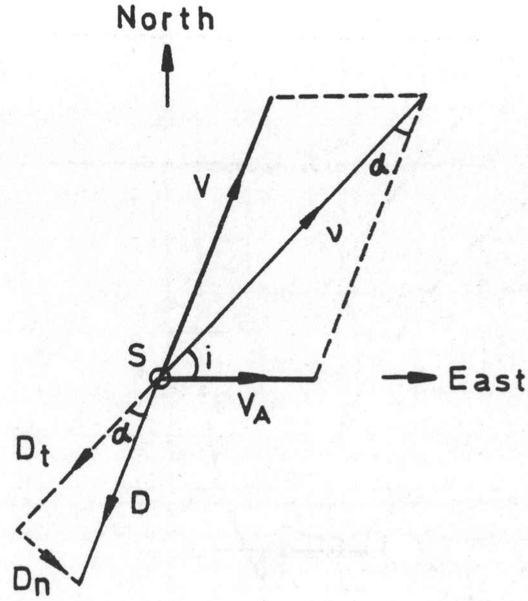
Fig 2 Diagram reproduced from *Nature*, 183, 240 (24 January 1959)



Atmospheric rotation rate, Λ, versus height

Fig 3 Diagram reproduced from *Planet. Space Sci.*, 25, 331 (1977)

Fig 3



ν = Velocity relative to Earth's centre

V = Velocity relative to air

D = Drag

D_t, D_n = Tangential and normal components of D

Fig 4 Kinematics of spherical satellite S in a circular orbit as it crosses the equator

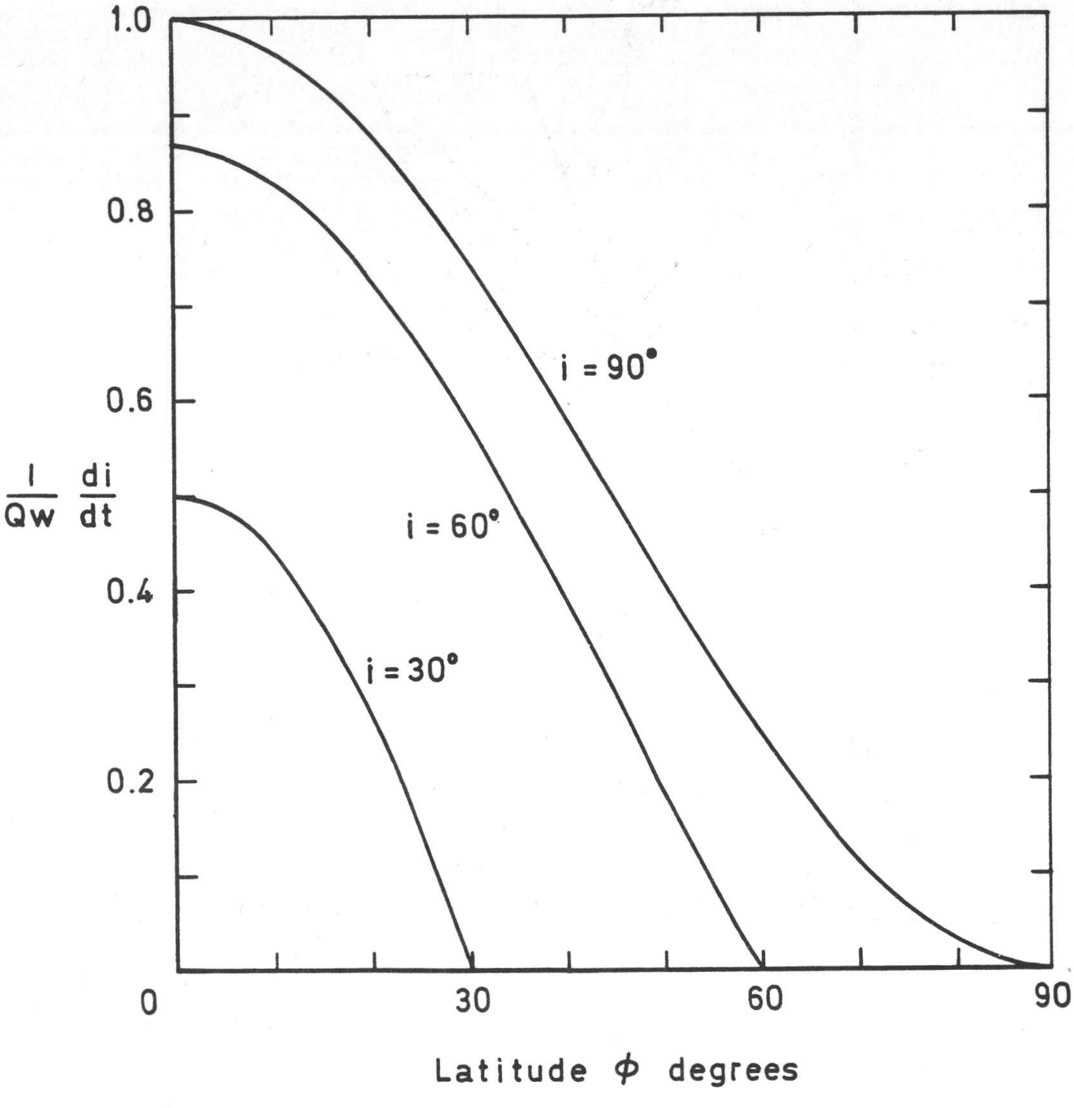


Fig 5 Rate of change of inclination for satellite in circular orbit: effect of inclination i and latitude ϕ

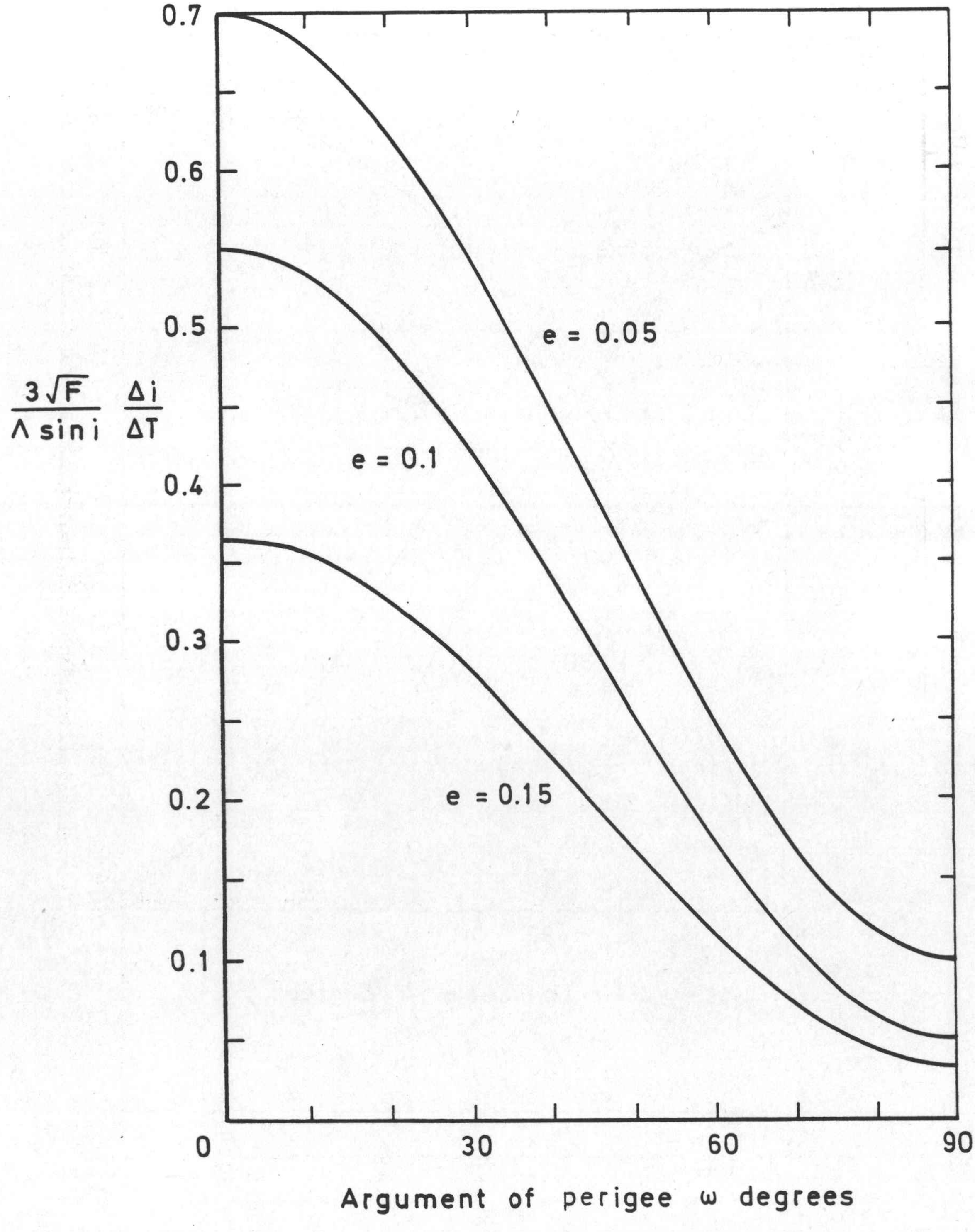


Fig 6 Variation of $\Delta i/\Delta T$ with ω for eccentric orbits, as given by equation (3)

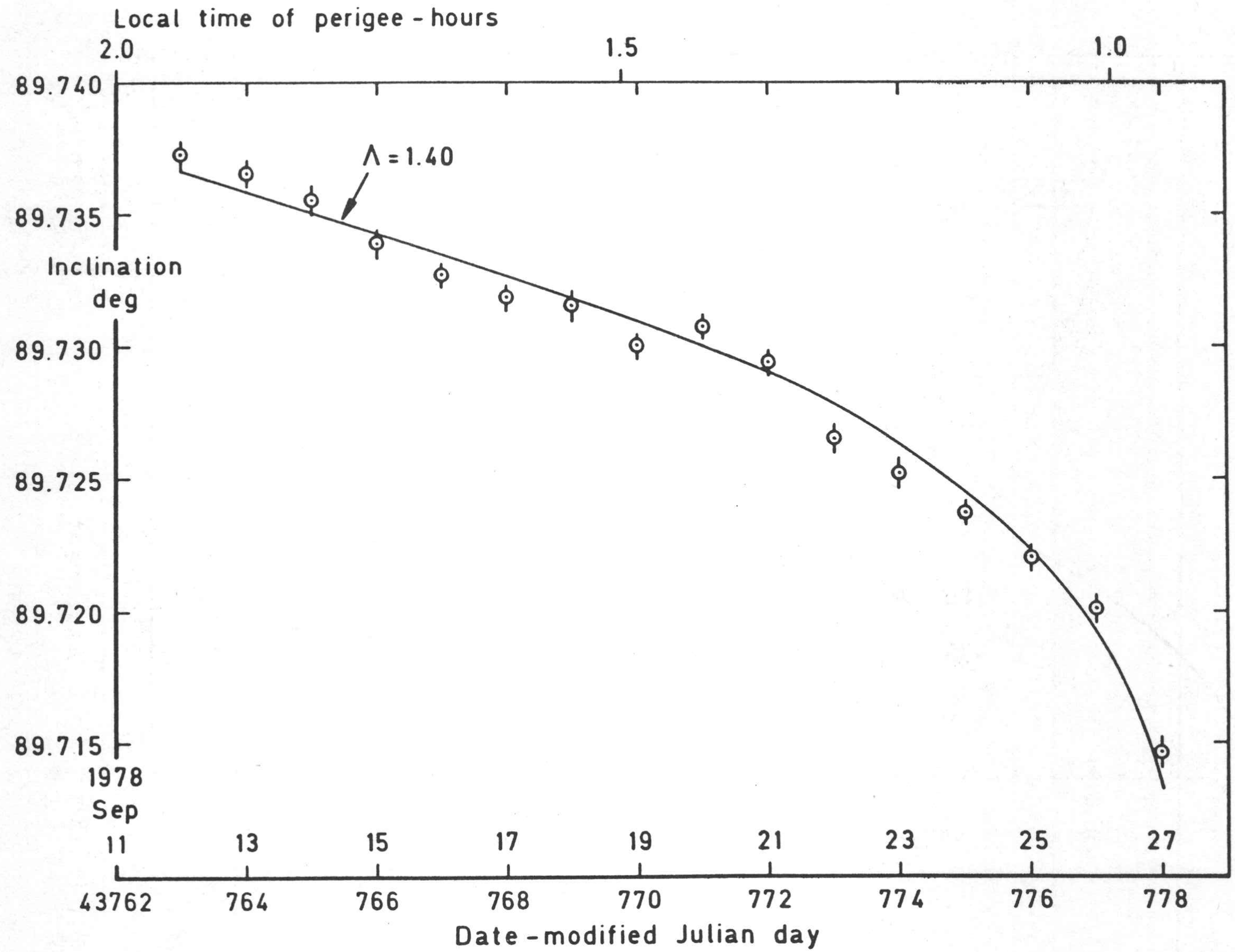


Fig 7 **1972-05B: values of inclination cleared of lunisolar, zonal harmonic and $J_{2,2}$ perturbations**

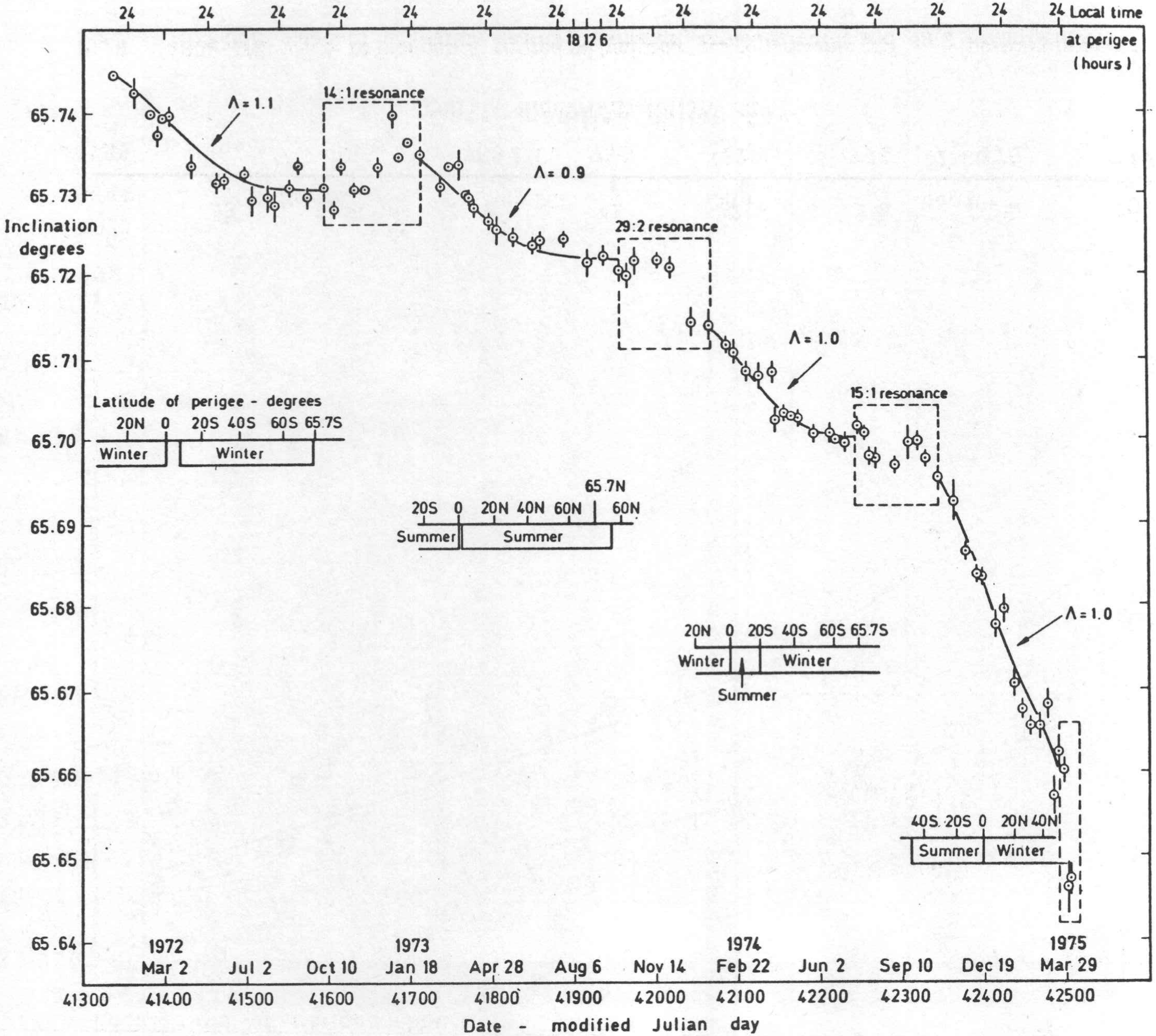


Fig 8 1971-106A: values of inclination cleared of lunisolar, zonal harmonic and $J_{2,2}$ perturbations

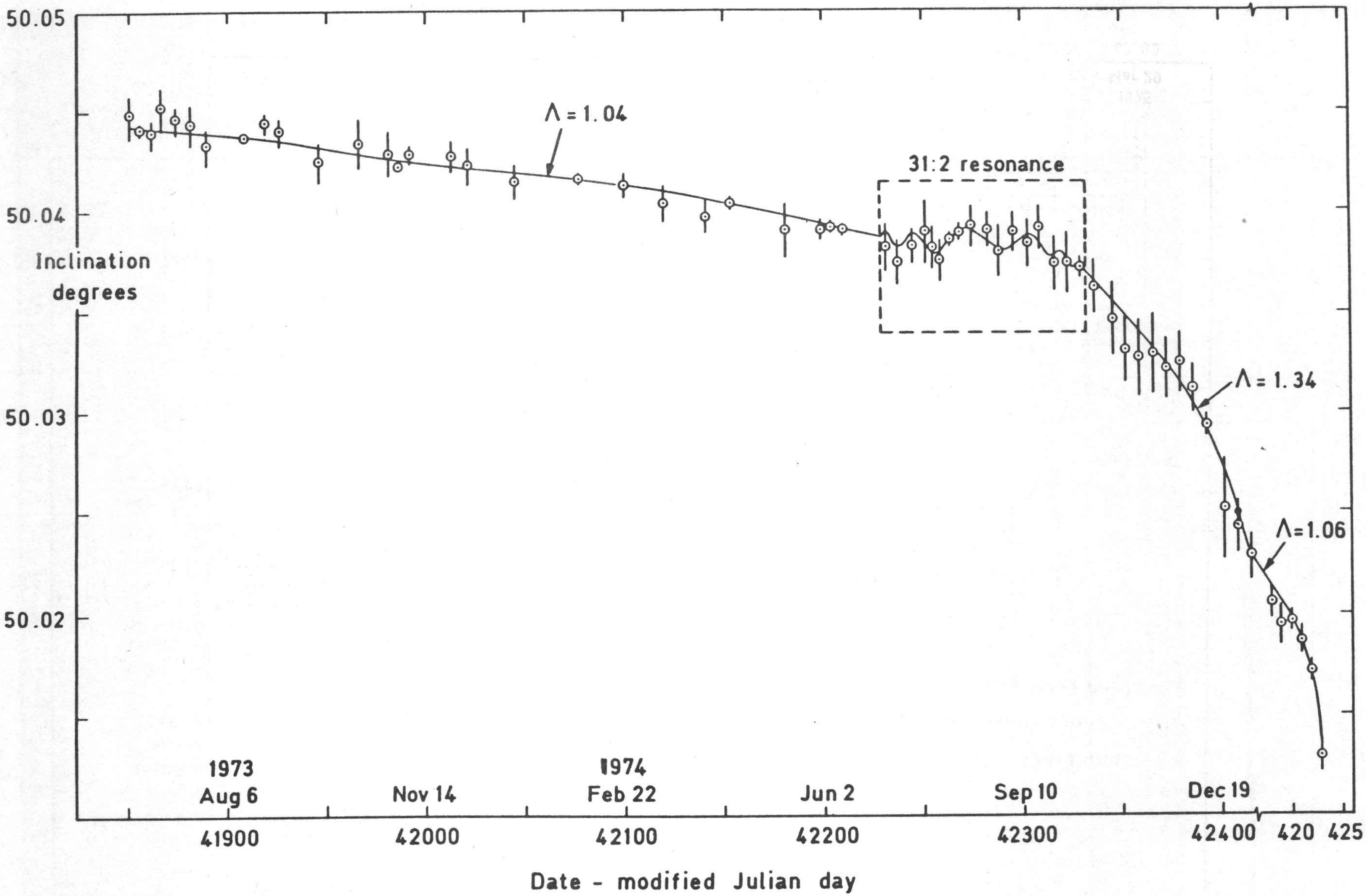


Fig 9 1973-27B: values of inclination cleared of lunisolar, zonal harmonic and $J_{2,2}$ perturbations

Fig 9

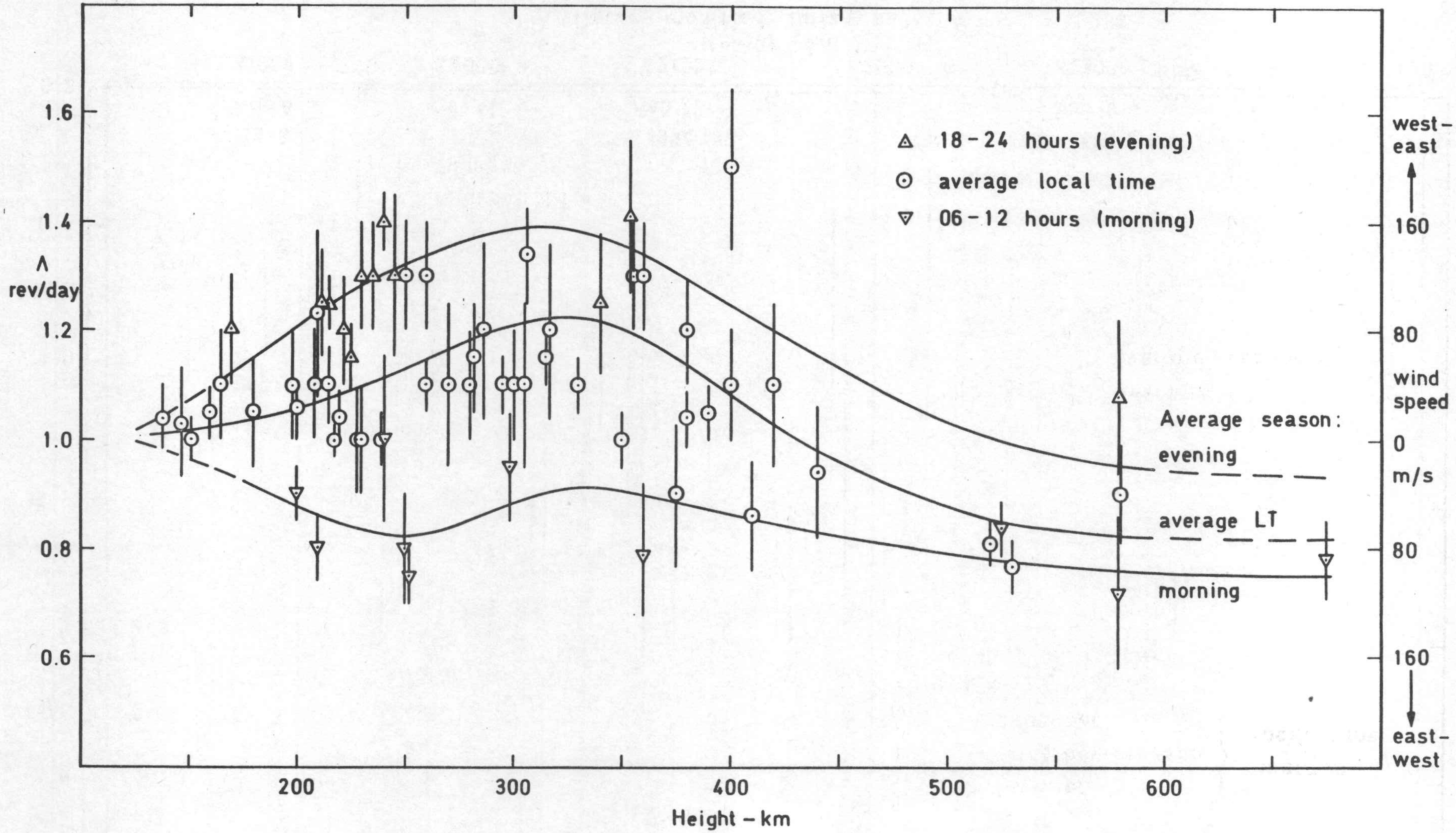


Fig 10 Variation of Λ with height and local time: average season

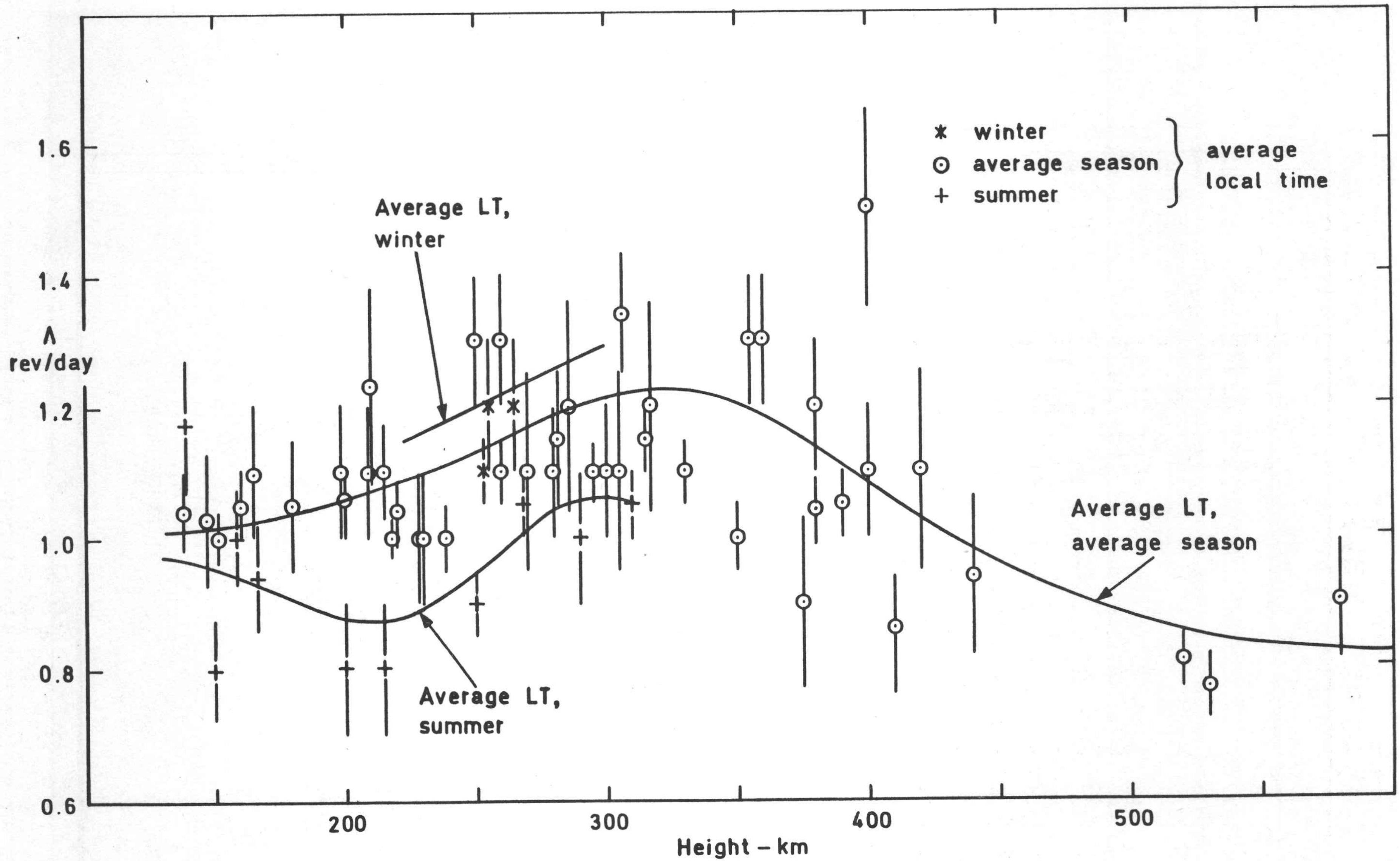


Fig 11 Variation of Λ with height and season: average local time

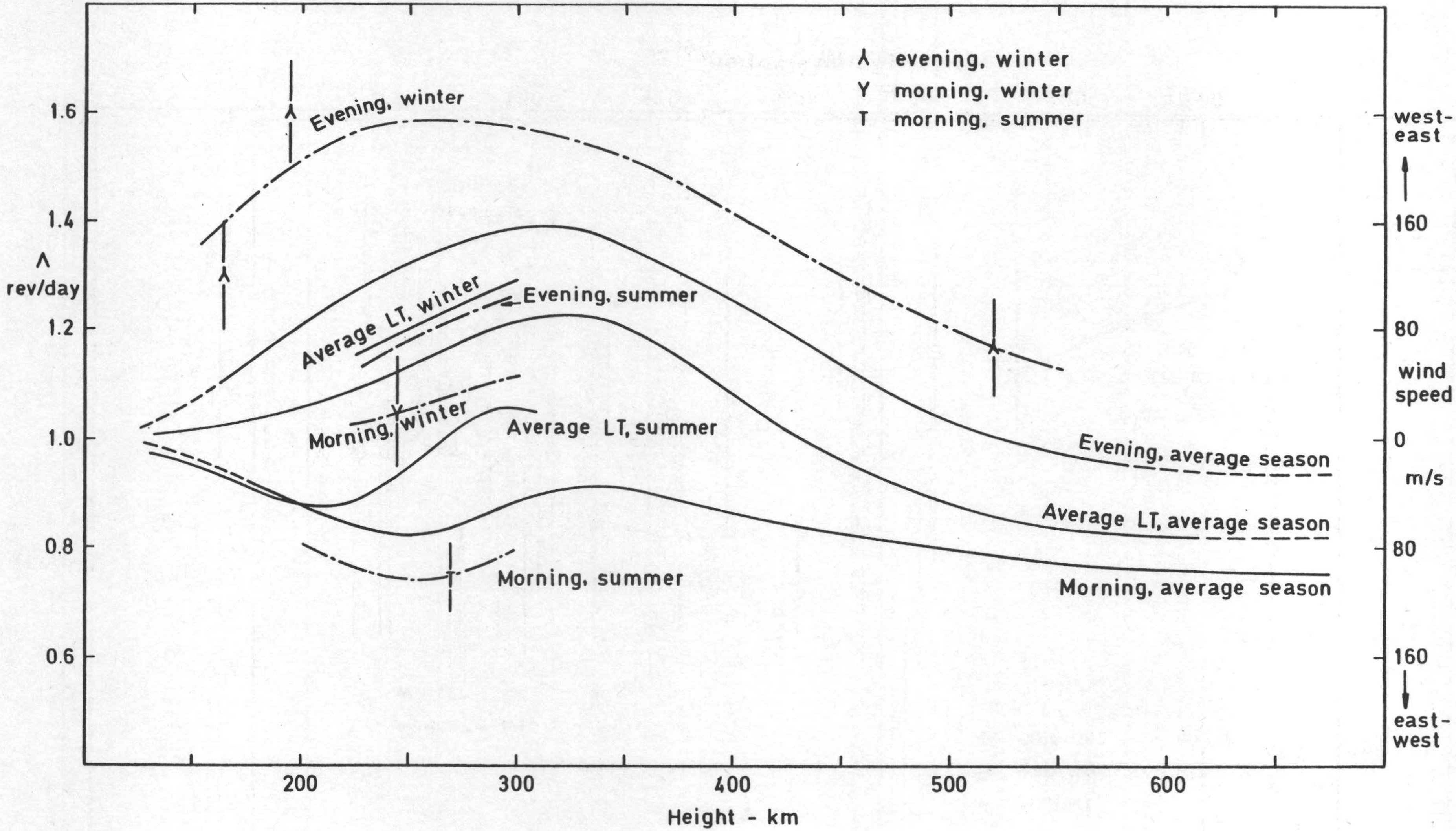


Fig 12 Variation of Λ with height, local time and season

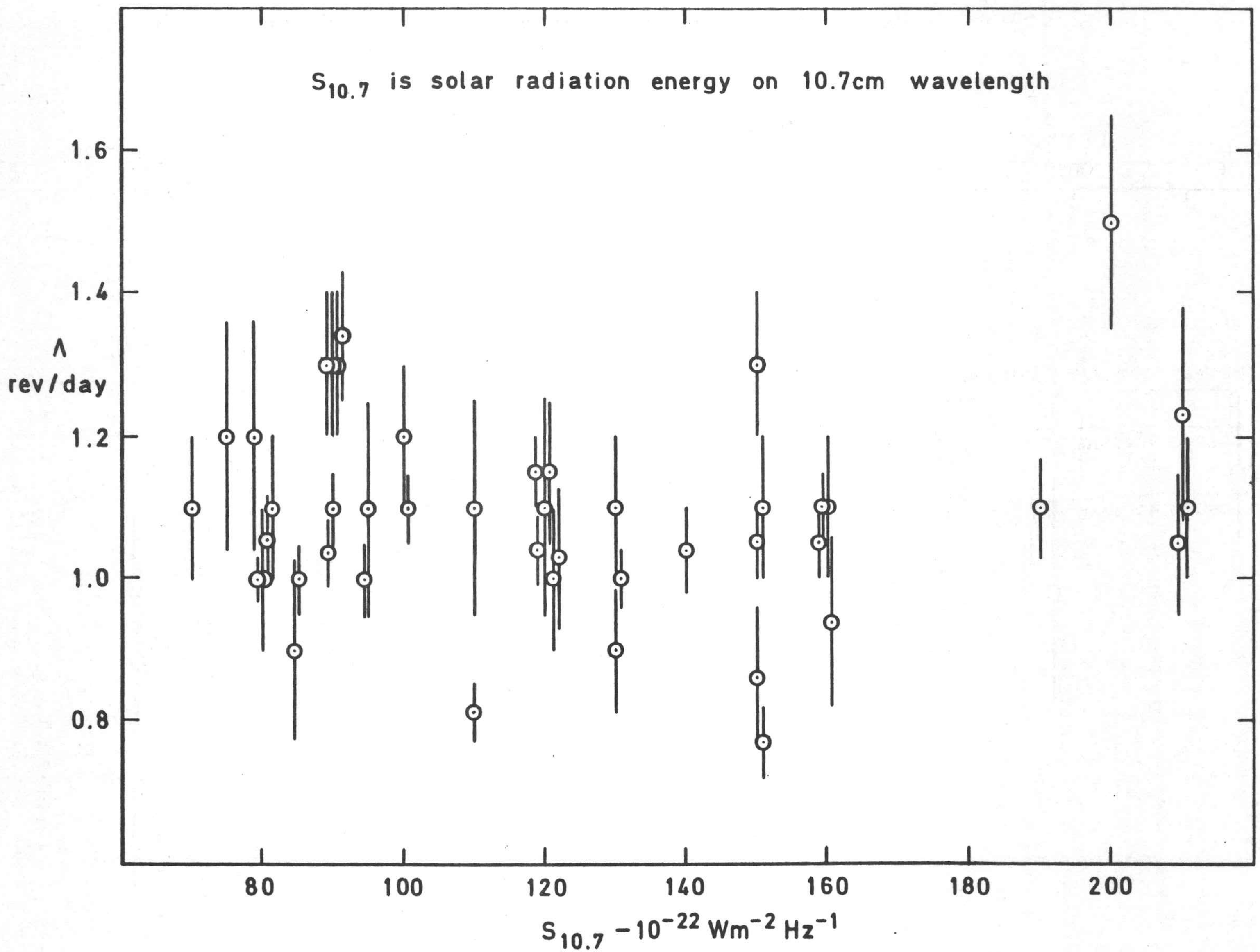


Fig 13 Variation of Λ with solar activity: average local time and season

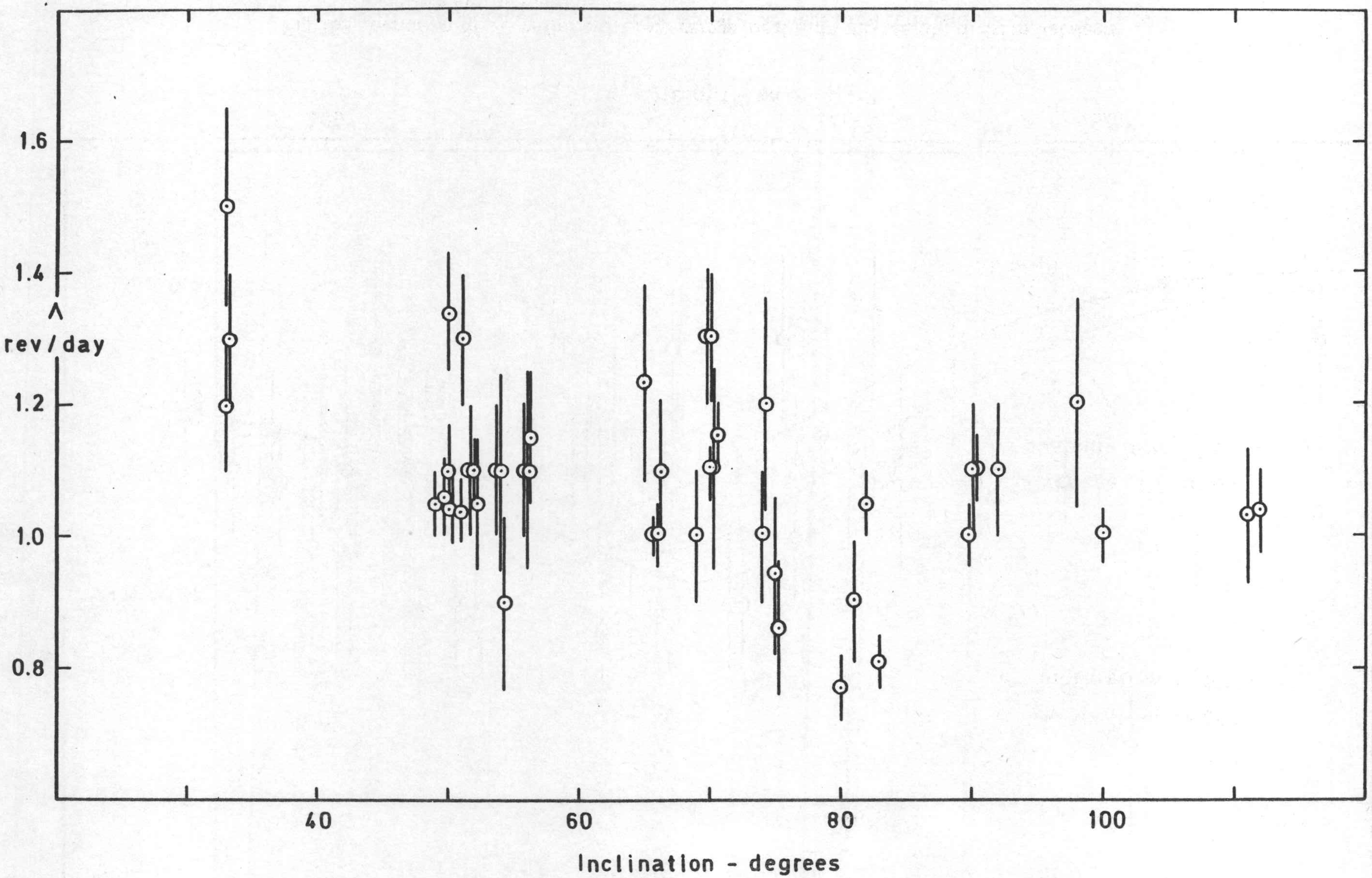


Fig 14 Variation of Λ with orbital inclination: average local time and season

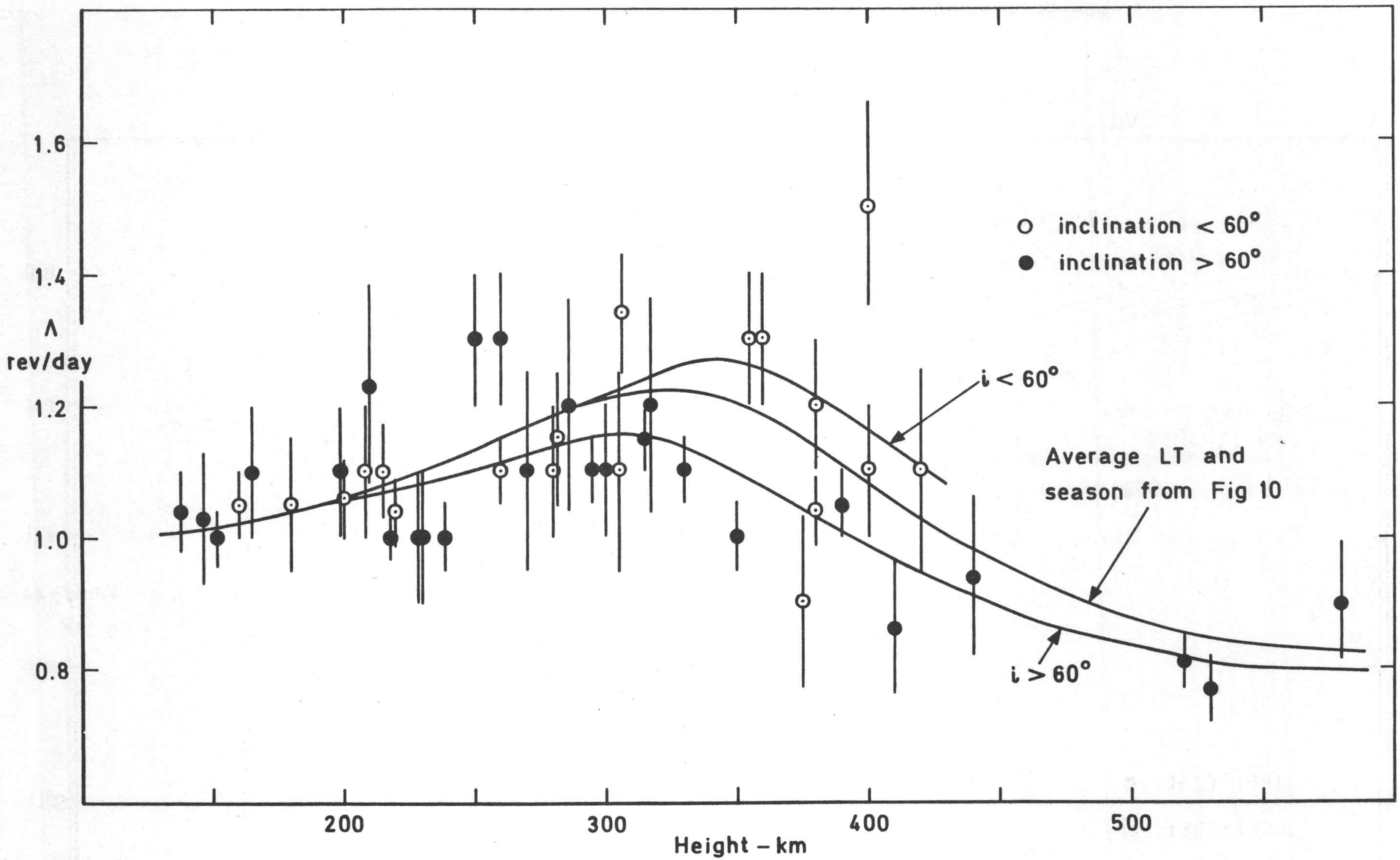


Fig 15 Variation of Λ with height for average local time and season: division between high and low inclination

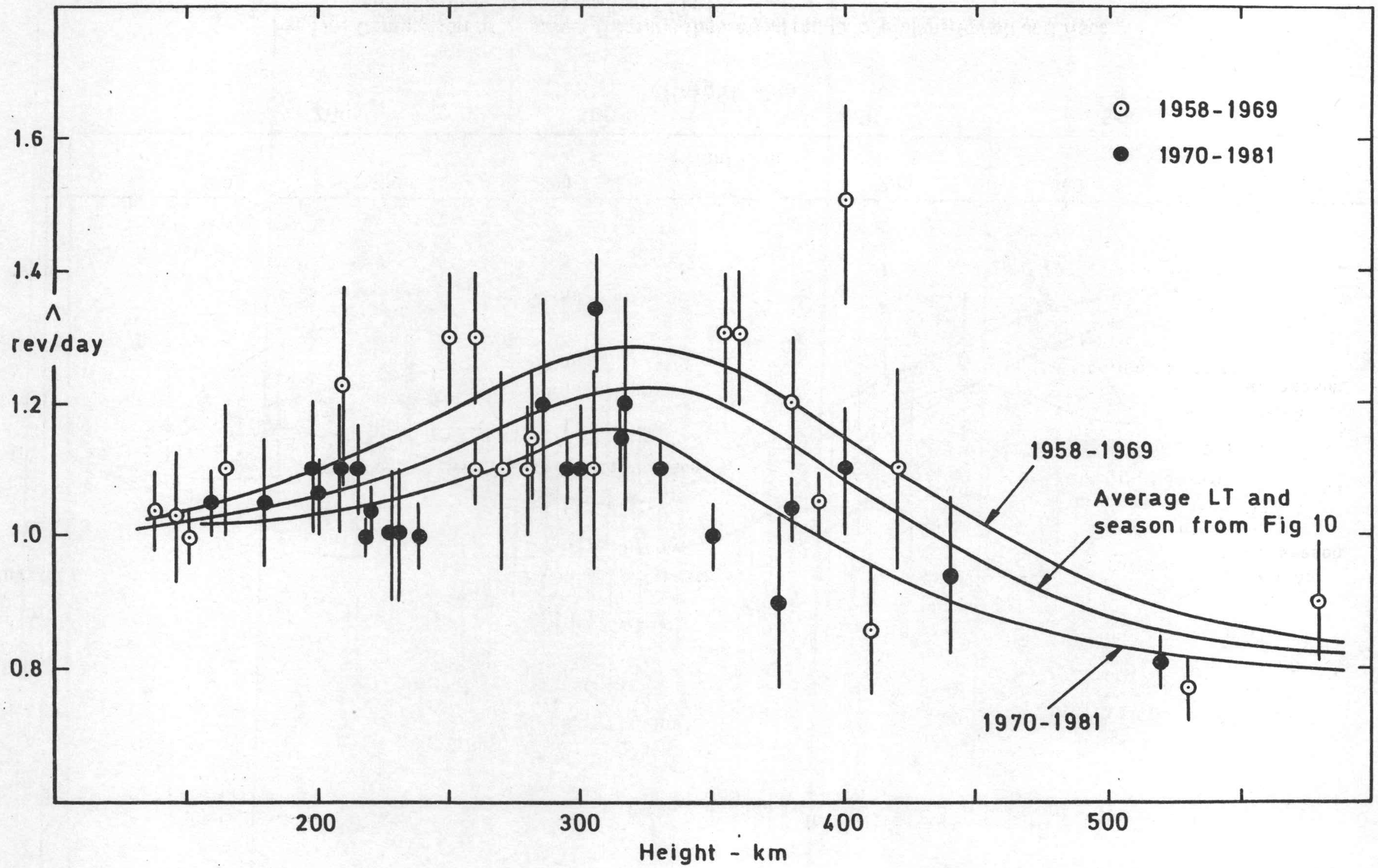


Fig 16 Variation of Λ with height for average local time and season: division between 1960s and 1970s

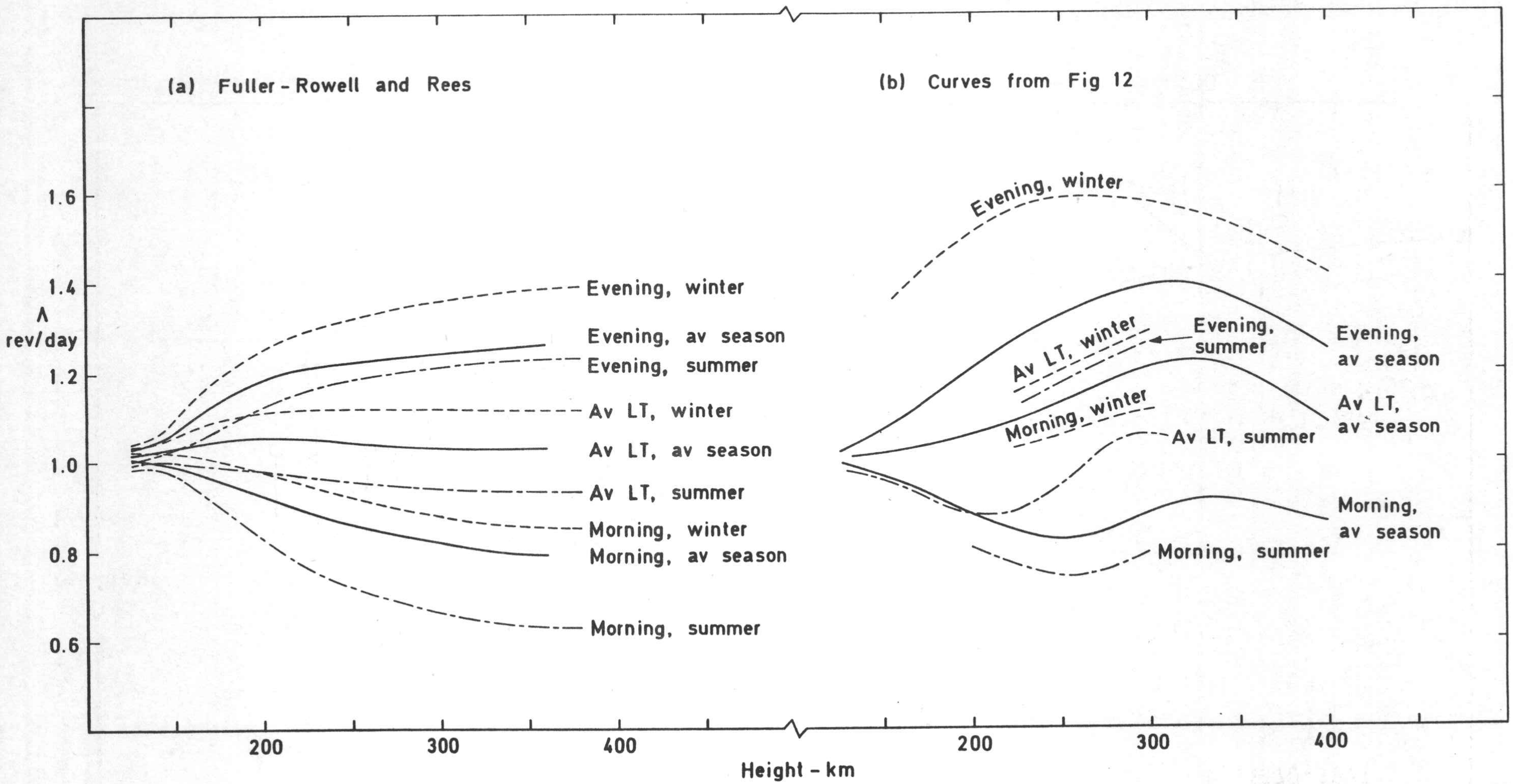


Fig 17 Comparison of Λ-curves from the theoretical model of Fuller-Rowell and Rees with the observational results of Fig 12

REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNCLASSIFIED

As far as possible this page should contain only unclassified information. If it is necessary to enter classified information, the box above must be marked to indicate the classification, e.g. Restricted, Confidential or Secret.

1. DRIC Reference (to be added by DRIC)	2. Originator's Reference	3. Agency Reference	4. Report Security Classification/Marking
	RAE TR 82126	N/A	UNCLASSIFIED

5. DRIC Code for Originator	6. Originator (Corporate Author) Name and Location
7673000W	Royal Aircraft Establishment, Farnborough, Hants, UK
5a. Sponsoring Agency's Code	**6a. Sponsoring Agency (Contract Authority) Name and Location**
N/A	N/A

7. Title Upper-atmosphere zonal winds from satellite orbit analysis

7a. (For Translations) Title in Foreign Language

7b. (For Conference Papers) Title, Place and Date of Conference

8. Author 1. Surname, Initials	9a. Author 2	9b. Authors 3, 4	10. Date	Pages	Refs.
King-Hele, D.G.	Walker, Doreen M.C.		December 1982	65	79
11. Contract Number	**12. Period**	**13. Project**	**14. Other Reference Nos.**		
N/A	N/A		Space 622		

15. Distribution statement
(a) Controlled by –
(b) Special limitations (if any) –

16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Winds. Upper atmosphere. Satellite orbits. Orbit analysis.

17. Abstract

We review and interpret the values of upper-atmosphere rotation rate (zonal winds) obtained by analysing satellite orbits determined from observations. The history of the method is briefly discussed, the basic principles are explained, objections to the method are answered, and three examples are given. Existing analyses of the atmospheric rotation rate Λ are critically reviewed, and, after rejecting some and revising others, we are left with 85 values. These are divided according to local time and season to give the variation of Λ with height in nine situations - namely morning, evening and average local time, for summer, winter and average season. These observational results indicate that the value of Λ (in rev/day), averaged over both local time and season, increases from 1.0 at 125 km to 1.22 at 325 km and then decreases to 1.0 at 430 km and 0.82 at 600 km. The value of Λ is higher in the evening (18-24 h), with a maximum value (near 1.4) corresponding to a west-to-east wind of 150 m/s at heights near 300 km. The value of Λ is lower in the morning (06-12 h), with east-to-west winds of order 50 m/s at heights of 200-400 km. There is also a consistent seasonal variation, the values of Λ being on average 0.15 higher in winter and 0.1 lower in summer than the average seasonal value.

F5910/1

RAE Form A143