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UPPER-ATMOSPHERE ROTATION RATE FROM ANALYSIS OF THE ORBITAL INCLINATION OF EXPLORER 1

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Feb 1958 to mid 1960	1.5 rev/day
Mid 1960 to Dec 1967	1.2 rev/day
Jan 1968 to Mar 1970	1.3 rev/day

Solar activity was very high in 1958-60, low from 1961 to 1967, and high in 1968-70; so the results strongly suggest that the rotation rate depends on solar activity, being greatest when the Sun is most active.

Analysis of the inclination at 14th-order resonance gave values of the lumped 14th-order harmonics in the geopotential $\bar{C}_{14}$ and $\bar{S}_{14}$ as $(6.8 \pm 2.7) \times 10^{-6}$ and $(-3.3 \pm 1.5) \times 10^{-6}$ respectively at an inclination of 33.2°.

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SUMMARY

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CONTENTS

1 INTRODUCTION

Explorer 1, 1958α, was America's first artificial satellite. It consisted of a final-stage rocket with payload attached, and was a cylinder 2.03 m long and 0.15 m diameter, with a mass of 14 kg [1]. It was launched on 1 February 1958 and decayed on 31 March 1970; its orbital period decreased from 114.8 minutes initially to about 88 minutes just before decay. With this large decrease in period, a significant change in the inclination, i, due to atmospheric rotation could be expected, since the change in i is proportional to the change in period.

Explorer 1 was tracked throughout its life by the Baker-Nunn cameras of the Smithsonian Astrophysical Observatory and the published SAO values of inclination[2] have been used previously to evaluate the atmospheric rotation rate[3]. As published orbits were only available until mid 1965, the atmospheric rotation rate could not be evaluated over the whole lifetime. In Ref.3 the analysis was extended to mid 1969 by using the preliminary orbits from the SAO prediction sheets, but in mid 1969 they also ceased. During a recent visit to the SAO, Dr. L. Jacchia kindly made available his unpublished orbits of 1958α at 2-day intervals over six years, from mid 1964 to the end of the satellite's life.

In this Report these orbits are being used, together with the published SAO orbits, to re-evaluate the atmospheric rotation rate during the complete life of the satellite, and also to investigate any changes due to either 14th- or 15th-order resonance. Explorer 1 is unique in being the only satellite of suitably high drag to have experienced the effects of two solar maxima (in 1958 and 1968-9) and the years of low activity between: it therefore offers an opportunity for detecting any variations of the atmospheric rotation rate in the course of the 11-year solar cycle.

2 THE ORBIT

During its 12-year life the orbital inclination of Explorer 1 decreased from 33.24° initially to 33.18° in October 1969, and finally to 33.12° just before decay. The perigee height of the satellite decreased from about 350 km initially to 300 km at the beginning of 1970.

The effects of the changes in density during a solar cycle are readily seen from the variation of period: Fig.1 shows the decrease in anomalistic period. The period decreased rapidly during the years of high solar activity, 1958-60, then much more slowly during the years of low solar activity, 1962-66, and then finally decreased faster again during the solar maximum of 1968-70. A smaller oscillation is also apparent and is due to the day-to-night variation in density.

Explorer 1 exhibited considerable variation in its effective cross-sectional area[4] because it was rotating quite slowly about its axis of maximum moment of inertia. This variability reduces its usefulness for studies of air density, but does not affect the determination of atmospheric rotation because the change in inclination is proportional to the change in period, irrespective of variations in cross-sectional area.

To determine the atmospheric rotation rate, orbital data from the published SAO orbits[2] are used until mid 1964, and, after that, the unpublished orbits provided by Dr. L. Jacchia.

3 UPPER-ATMOSPHERE ROTATION RATE

The upper atmosphere is rotating in the same sense as the Earth: therefore the aerodynamic force acting on a satellite has a component perpendicular to the orbit; this has the effect of reducing the inclination, i, of the orbit to the equator as time goes on. For a high-drag satellite, such as Explorer 1, atmospheric rotation is the most important force perturbing i, and if luni-solar and odd zonal harmonic perturbations are removed, the changes in i give the atmospheric rotation rate, Λ *, in the region near the perigee of the satellite's orbit, averaged over latitudes up to about half the orbital inclination[5].

During the first half of the satellite's life, from launch until MJD 38600, the values of inclination are selected from the published SAO orbits[2] with quoted sd less than 0.005°: they are plotted in Fig.2 after removal of the odd zonal harmonic perturbations, which are of order 0.008° at the beginning of the life. No correction for lunisolar perturbations was made, because these perturbations are of order 0.002° and considerably smaller than the scatter of the values in Fig.2. From MJD 38600 until the end of the satellite's life the values of inclination have had the lunisolar and zonal harmonic perturbations removed using the PROD computer program[6], with the numerical integration at 2-day intervals. The perturbations are of order 0.004°, mainly due to odd zonal harmonics. The resulting values of inclination are plotted as circles in Fig.3, with the final 26 days inset on a larger scale. On this final section the values plotted as crosses are taken from the USAF elements.

The theoretical change in inclination was calculated for various values of Λ, the atmospheric rotation rate, by numerical integration of equation (A.17)

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

of Ref.7, which takes account of atmospheric oblateness. From the beginning of the life to MJD 40260, equation (A.17) was integrated at steps of two cycles in argument of perigee, ω , i.e. at average intervals of about 90 days. Between MJD 40260 and 40567, the interval was reduced to 90° in ω (about 10 days), then after MJD 40567 to 45° (about 4 days), and finally to 22.5° from MJD 40643 to the end of the satellite's life. The smaller interval in ω leads to the wiggles in the curve after MJD 40260, resulting from the $\cos 2\omega$ terms in the theoretical equation.

Previously[3], $\Lambda = 1.4$ over the life of the satellite up to mid 1969 was taken, but with the extended and more accurate data now available, this curve does not provide a satisfactory fit, and it is necessary to split the lifetime into three parts. The $\Lambda = 1.4$ curve is not steep enough in the first few years, too steep in the middle years and slightly too steep in the last two years. During the period of low solar activity, between 1961 and 1967, the decrease in inclination was small, as can be seen from the plotted values in Figs.2 and 3, and after several preliminary trials the best fit between observation and theory was found to be with the theoretical curve for an atmospheric rotation rate of $\Lambda = 1.2$ from mid 1960 to 1967. This curve is carried through from Fig.2 to Fig.3, and is fitted to the points on both graphs.

The observational points from launch to mid 1960 in Fig.2, covering the time of very high solar activity in 1958-9, need a theoretical curve linking with the start of the $\Lambda = 1.2$ curve between mid 1960 and 1967. The curve which best fitted the points was that for $\Lambda = 1.5$.

The observational values of inclination in Fig.3, from 1968 onwards, are well fitted by a single curve with $\Lambda = 1.3$. The values at the end of the satellite's life, from MJD 40650 onwards, given on an enlarged scale in Fig.3, are fitted better by a value of Λ of about 1.5 (broken line), but these values are rather inaccurate so no change was made.

Assessment of the likely errors in these three values of Λ requires a close study of the three sections of the fitted curve in Figs.2 and 3. The first section of the fitted curve, giving $\Lambda = 1.5$ rev/day, could be steeper if more notice was taken of the first group of points, early in 1958, but it is difficult to fit a less steep curve. The likely error can be approximately assessed by estimating how much the curve might possibly be moved up or down at its beginning and end. An increase of 0.004° at the beginning, to 33.2416°, would be within the realm of possibility, but a decrease of more than 0.0015° seems untenable. At the end-point the errors are undoubtedly less and may be taken as 0.001°.

This gives $\Lambda = 1.5^{+0.3}_{-0.15}$. On the second section of the curve, where $\Lambda = 1.2$, the errors can be assessed in the same way. At the beginning the curve is liable to the same error as at the end of the first section, 0.001°, and it seems reasonable to assume the same error at the end of the second section. Thus the decrease in inclination is $0.025^\circ \pm 0.002^\circ$, which gives $\Lambda = 1.2 \pm 0.1$. On the final section the error in Λ has been estimated up to MJD 40600, as after this date the points become inaccurate. At the beginning of this final section the error may be taken as 0.001°, but at the end the curve could be in error by 0.0015° if no account is taken of the later values. Thus the decrease in inclination is $0.033^\circ \pm 0.0025^\circ$, giving $\Lambda = 1.3 \pm 0.1$.

During the life of Explorer 1 the perigee height decreased from 350 km at launch to 300 km at the beginning of 1970. The height at which the atmospheric rotation is being sampled is about $\frac{3}{4}$H above perigee[5], where H is the density scale height at perigee. The appropriate values of H for the levels of solar activity prevalent at the times of the three values of Λ are 62, 46, and 51 km respectively. So the three values of Λ apply at average heights of 400, 380, and 350 km respectively.

The fitting of the theoretical curves to the observational points takes no account of possible changes due to resonance - when the satellite makes an exact number of revolutions per day and the satellite track passes through the same part of the geopotential each day, so that geopotential perturbations may change the inclination appreciably. During its life 1958α passed through 13th-, 14th- and 15th-order resonance and the changes at these resonances are discussed in section 4.

4 OTHER EFFECTS CAUSING CHANGES IN INCLINATION

4.1 13th-order resonance

Explorer 1 passed through 13th-order resonance in January 1960. At this time the period was decreasing rapidly, see Fig.1, due to the high solar activity. The observational data is not accurate enough to determine the change in inclination due to 13th-order resonance, but the satellite passes through 15th-order resonance in 1969 when the slope of the period-versus-time curve is similar; so the change in inclination due to 13th-order resonance would be expected to be of the same order of magnitude as the change at 15th-order resonance. The variation at 15th-order resonance has been calculated, see section 4.3, and could have caused a maximum change in inclination of 0.002°. The theoretical curve for $\Lambda = 1.5$ rev/day in Fig.2 gives a change of 0.024° in inclination, so a change at resonance of 0.002° (if it occurred) could cause a maximum error of about 8% in the value of Λ. As the estimated accuracy of the value of Λ was $1.5^{+0.3}_{-0.15}$ the neglect of any change due to 13th-order resonance will not affect the result.

4.2 14th-order resonance

On 15 November 1967 Explorer 1 passed through exact 14th-order resonance. At this time there are values of inclination available at 2-day intervals from the orbits which Dr. L. Jacchia supplied.

The 14th-order resonant terms in the geopotential may be written[8]

$$\frac{di}{dt} = nG'\left(\frac{R}{a}\right)^{15}\left[\bar{S}_{14}\sin\phi + \bar{C}_{14}\cos\phi\right]$$

$$+ \text{ terms in } \left(\bar{C}_{28}, \bar{S}_{28}\right) \begin{matrix}\cos\\ \sin\end{matrix}\, 2\phi \;, \quad \text{etc.}$$

$$+ \text{ terms in } ke^{|q|} \begin{matrix}\cos\\ \sin\end{matrix}\,(k\phi - q\omega) \qquad (1)$$

where $G' = 0.2146(14 - \cos i)(15\cos i - 1)(1 + \cos i)\sin^{12} i$, and k and q are integers, with k taking the values 1, 2, 3 ... and q the values 0, ±1, ±2, ... The terms with $k = 1$ and $q = 0$ are given explicitly in equation (1). The parameter ϕ in equation (1) is the 'resonance angle' given by

$$\phi = \omega + M + 14(\Omega - \nu) \qquad (2)$$

where ω is the argument of perigee, M the mean anomaly, Ω the right ascension of the node and ν is the sidereal angle. The THROE computer program developed by Gooding[9], now extended to fit a large number of terms in the theoretical expression for di/dt, provides a least-squares fitting of equation (1) to the values of inclination near 14th-order resonance. The zonal harmonic and lunisolar perturbations were removed from the values of inclination and then the THROE computer program was used. The variation in inclination due to an atmospheric rotation rate of 1.3 rev/day was removed within the program, which then fitted the observational points cleared of perturbations. Theoretical curves to fit the values were obtained using THROE with various values of (k,q).

The following sets of values of (k,q) were tried: (1,0); (1,0),(2,0); (1,0),(1,±1); and (1,0),(1,±1),(1,±2). Of these, (1,0),(1,±1) was found to be the best fit. But it was found that including (k,q) = (0,1), i.e. terms in ω, considerably improved the fitting. This implies that there may be some misinterpretation of the definition of the elements, but the fitting of the extra term should dispose of this discrepancy. The values obtained without the (k,q) = (0,1) terms were $10^6\bar{C}_{14} = 10.4 \pm 5.4$ and $10^6\bar{S}_{14} = -4.7 \pm 3.3$; when the (0,1) terms were included, the values became $10^6\bar{C}_{14} = 6.8 \pm 2.7$ and $10^6\bar{S}_{14} = -3.3 \pm 1.5$. The inclusion of the terms in ω improved the fit and the standard deviations by a factor of 2, and the values obtained for $\bar{C}_{14}$ and $\bar{S}_{14}$ are within the sd of the first values.

The fitted curve, giving the values $10^6\bar{C}_{14} = 6.8 \pm 2.7$ and $10^6\bar{S}_{14} = -3.3 \pm 1.5$, is therefore recommended and is plotted with the values of inclination cleared of perturbations in Fig.4. These values will be used in a future determination of individual 14th-order coefficients.

Fig.4 shows that the value of i at the end of resonance is almost the same as the value before resonance. So it happens that there is no appreciable change in inclination for Explorer 1 at 14th-order resonance, and there is no reason to introduce any discontinuity at 14th-order resonance in the curve of Fig.3.

4.3 15th-order resonance

When Explorer 1 experienced 15th-order resonance, on 4 December 1969, it was within four months of decay; the satellite passed through resonance quickly and there were not enough accurate orbits for an analysis of the variation. The expected change in inclination can, however, be calculated using the THROE computer program[9] and the lumped 15th-order harmonics for an orbit of inclination 33.2°, which are known[10] to be $10^6\bar{C}_{15} = 19.0$ and $10^6\bar{S}_{15} = 5.9$. The theoretical curve at 15th-order resonance is plotted in Fig.5: this shows that there is no appreciable change at 15th-order resonance and therefore no need for a discontinuity in the curve in Fig.3 at 15th-order resonance.

4.4 The effect of meridional winds

For an orbit of eccentricity between 0.03 and 0.2, the change Δi in inclination due to an atmosphere rotating at Λ rev/day and having a south-north wind component equivalent to an angular velocity of E rev/day, may be written as[11]

$$\frac{\Delta i}{\Delta T_d} = \frac{1}{3\sqrt{F}}\left[\Lambda \sin i\left\{(1-4e)\cos^2\omega - \frac{1}{z}\cos 2\omega + O\left(e^2, \frac{1}{z^2}\right)\right\}\right.$$
$$\left. - E(1-K)^{\frac{1}{2}}\left\{(1+\tfrac{1}{4}K)\left(1-\frac{1}{2z}\right)\cos\omega - \tfrac{1}{4}K\cos 3\omega + O\left(0.1, \frac{1}{z^2}\right)\right\}\right] \quad (3)$$

where ΔT_d is the change in period, expressed as a fraction of a day, F is a constant factor ($\simeq 0.88$ for Explorer 1), $z = ae/H$ where a is the semi-major axis ($z \simeq 150e$ for Explorer 1), and $K = \sin^2 i/(2 - \sin^2 i) = 0.176$ for Explorer 1.

The effect of meridional winds on Explorer 1 is dominated by the rapidly repeating cycles of the argument of perigee ω. Initially, $\dot{\omega}$ was 6.5 deg/day and it steadily increased to 10 deg/day near the end of the satellite's life, so that a cycle of ω was completed in 55 days at the beginning of the life and 36 days near the end. It is clear from equation (3) that if E has a constant value, the effects of south-north winds will cancel out over each half-cycle of ω from 0 to 180°, because z changes little during the three to four weeks of the half-cycle of ω. Over the whole lifetime of nearly 200 half-cycles, the cancelling-out is even more thorough. The same conclusion applies if E has variable values, provided the variations are not correlated with ω.

The actual variations in meridional winds at heights near 300 km are not yet certainly established, but most recent theoretical studies and experimental measurements indicate that in equinoctial conditions the meridional winds are towards the equator at night, and away from the equator, but much less strongly, by day[12,13]. If so, the value of E suffers a day-to-night variation. The local time at perigee for Explorer 1 completed a 24-hour cycle in about 300 days initially, decreasing to about 150 days near the end of the life (with minor variations dependent on season). So each day-to-night cycle of perigee includes about 11 half-cycles of ω initially, decreasing to about 8 at the end of the life: there will be a strong tendency for the effects of the diurnally-varying meridional winds to cancel over one half-cycle of ω, with any residual effects tending to cancel over the longer day-to-night cycle. Substantial variations in inclination due to meridional winds could arise only if E were a direct function of ω: for example, if $E = 0.1 \cos \omega$, the E term would be permanently negative. At first sight there seems no possibility of any connection between the rotation rate of perigee, determined by Newton's laws and the Earth's oblateness, and E, determined by the outcome of complex upper-atmosphere interactions.

But there *is* a possible connection between E and ω, because perigee oscillates between northern and southern hemispheres, and if the winds were predominantly towards the equator in both hemispheres, E would change sign at the equator and might be proportional to $\sin \omega$ or $\sin \omega / |\sin \omega|$. According to most current dynamic thermospheric models (e.g. Ref.12), the meridional wind averaged over all local times *is* predominantly towards the equator at dates not too far from equinox, and the average magnitude at low latitudes is of order 50 m/s. So, near equinox, instead of taking E constant (a wind blowing right across the equator), it is more appropriate to take $E = -0.1$ for $0 < \omega < 180^\circ$ and $E = +0.1$ for $180^\circ < \omega < 360^\circ$. Strangely enough, this drastic change in E has no effect at all: E is still constant as ω goes from 0 to 180°, and so the effects still cancel. As with constant E, there is only a small oscillatory variation, with period half a cycle of ω, though the sense of the variation is reversed in alternate half-cycles.

There is some doubt about the meridional winds near the equator at solstice, but it is quite likely[12] that the winds blow in the same direction between 30° N and 30° S at the summer and winter solstices. If so, E is constant to a first approximation, and again the effects cancel over a half-cycle of ω.

Though the overall effect is negligible, it is worth calculating the amplitude of the oscillation produced by meridional winds to check the possible significance of short-term effects. In equation (3) the mean value of $E \cos \omega$ from $\omega = 0$ to $\omega = 90^\circ$ is $0.1 \times 2/\pi = 0.064$, if $E = 0.1$. So, if we take $z = 20$, $K = 0.176$, and ignore the small $\cos 3\omega$ term, equation (3) gives the amplitude α of the oscillation in i due to meridional winds as $\alpha = -1.2\Delta T_d$ degrees, where ΔT_d is the change in T_d over the 10 days or so taken by ω to travel from 0 to 90°. For Explorer 1, excluding the final decay phase, the largest rate of decrease of period was about 0.01 minutes per day, attained in 1958 and 1969, and the smallest was 0.0015 min/day in 1964. So the largest $-\Delta T_d$ in any 10 days (except near decay) is 0.1 min, or 0.00007 day, and the smallest 0.00001 day. Thus the oscillation due to consistent (equatorwards or across-equator) meridional winds with $E = \pm 0.1$ has a maximum amplitude of 0.00008° (in 1958 and 1969) and a minimum of 0.00001° (in 1964). Both amplitudes are negligible beside the errors in the values (about 0.003°).

5 CONCLUSIONS

Analysis of the changes in orbital inclination gives accurate average values of Λ, the atmospheric rotation rate in rev/day, from three phases in the satellite's life. These are given in Table 1, together with the heights at which they apply, the average solar flux on 10.7 cm wavelength, and the average wind speeds for a latitude of 20°, where the Earth's rotational speed is 440 m/s.

Table 1

Values of wind speed obtained

Date	Λ rev/day	Height km	Average value of $S_{10.7}$ 10^{-22} W m^{-2} Hz^{-1}	West-to-east wind at 20° latitude m/s
Feb 1958 to mid 1960	$1.5^{+0.3}_{-0.15}$	400	200	350 to 150
Mid 1960 to Dec 1967	1.2 ± 0.1	380	100	130 to 45
Jan 1968 to Mar 1970	1.3 ± 0.1	355	150	180 to 90

These results strongly suggest that the atmospheric rotation rate at heights of 350 to 400 km at latitudes less than 20° depends on solar activity, being greatest when the solar activity is greatest.

Examination of the change in inclination due to 15th-order resonance and meridional winds shows negligible effects. But analysis of the inclination at the time of 14th-order resonance yields values of the lumped 14th-order harmonics as follows: $10^6\bar{C}_{14} = 5.8 \pm 2.7$ and $10^6\bar{S}_{14} = -3.3 \pm 1.5$. When results are available for other inclinations, the values obtained here will be used in determining individual 14th-order coefficients.

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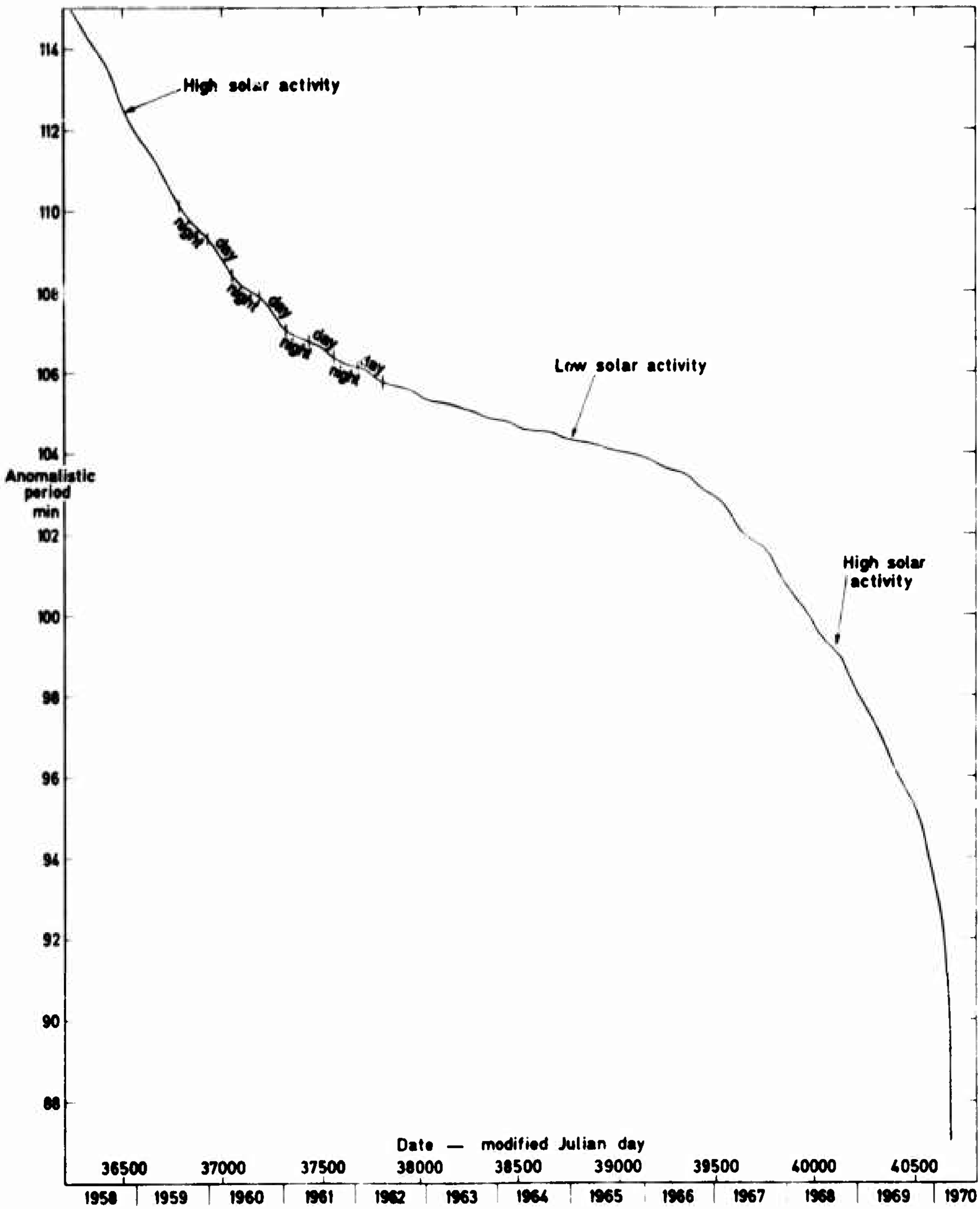

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Fig.1 Orbital period of Explorer 1, 1958α

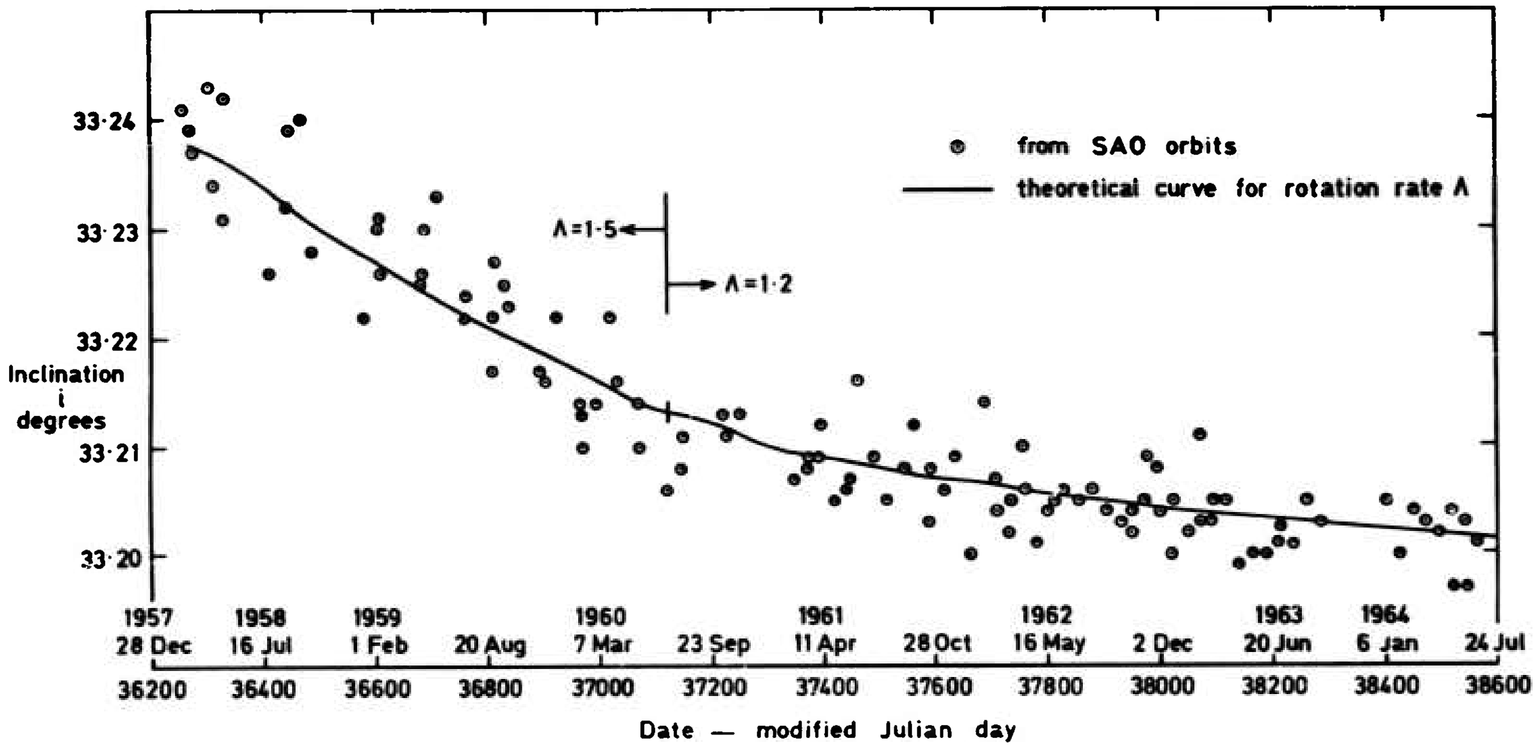

Fig. 2 Orbital inclination of Explorer 1, 1958α, from 1958 to mid 1964, with zonal harmonic perturbations removed

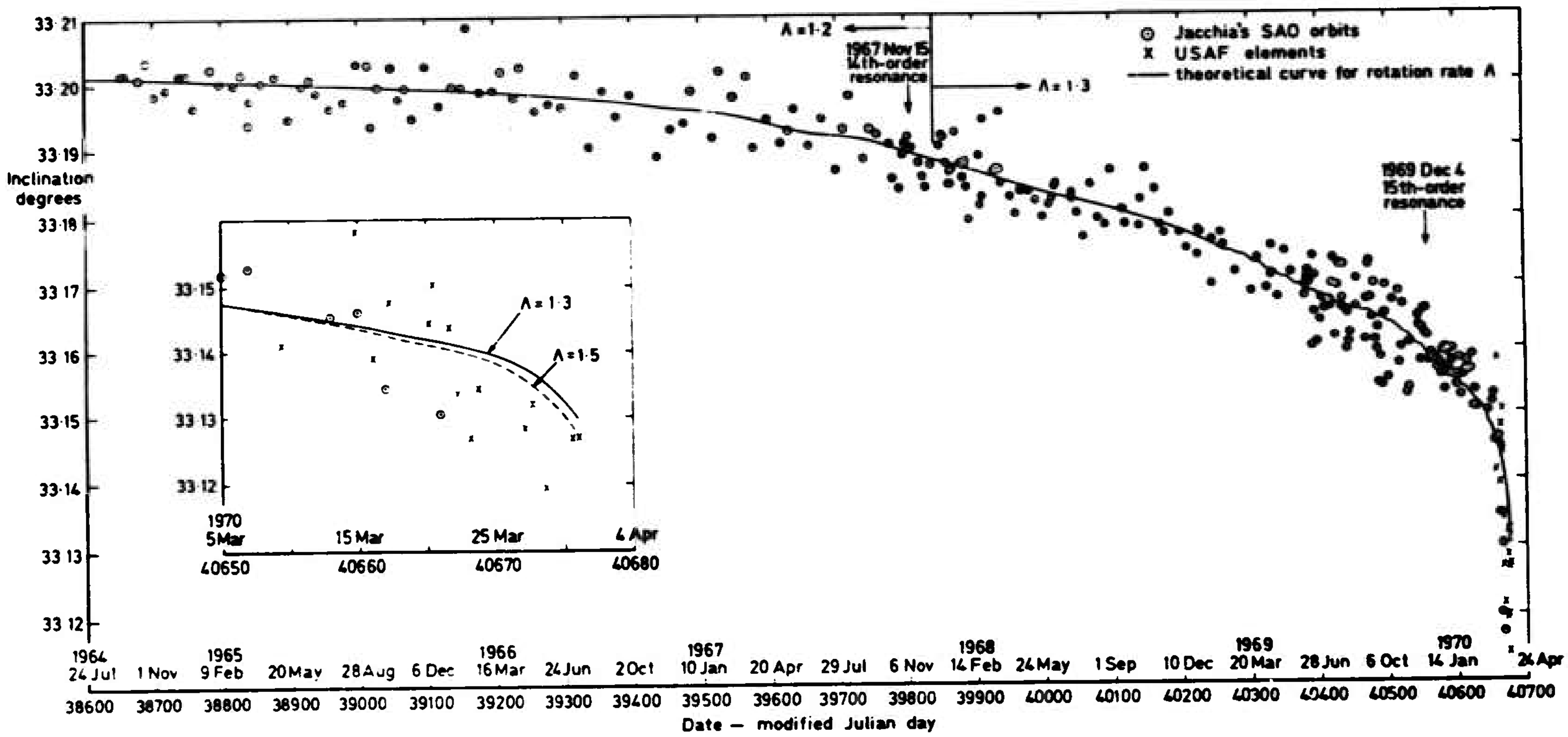

Fig.3 Orbital inclination of Explorer 1, 1958α, from mid 1964 to decay, with zonal harmonic and lunisolar perturbations removed

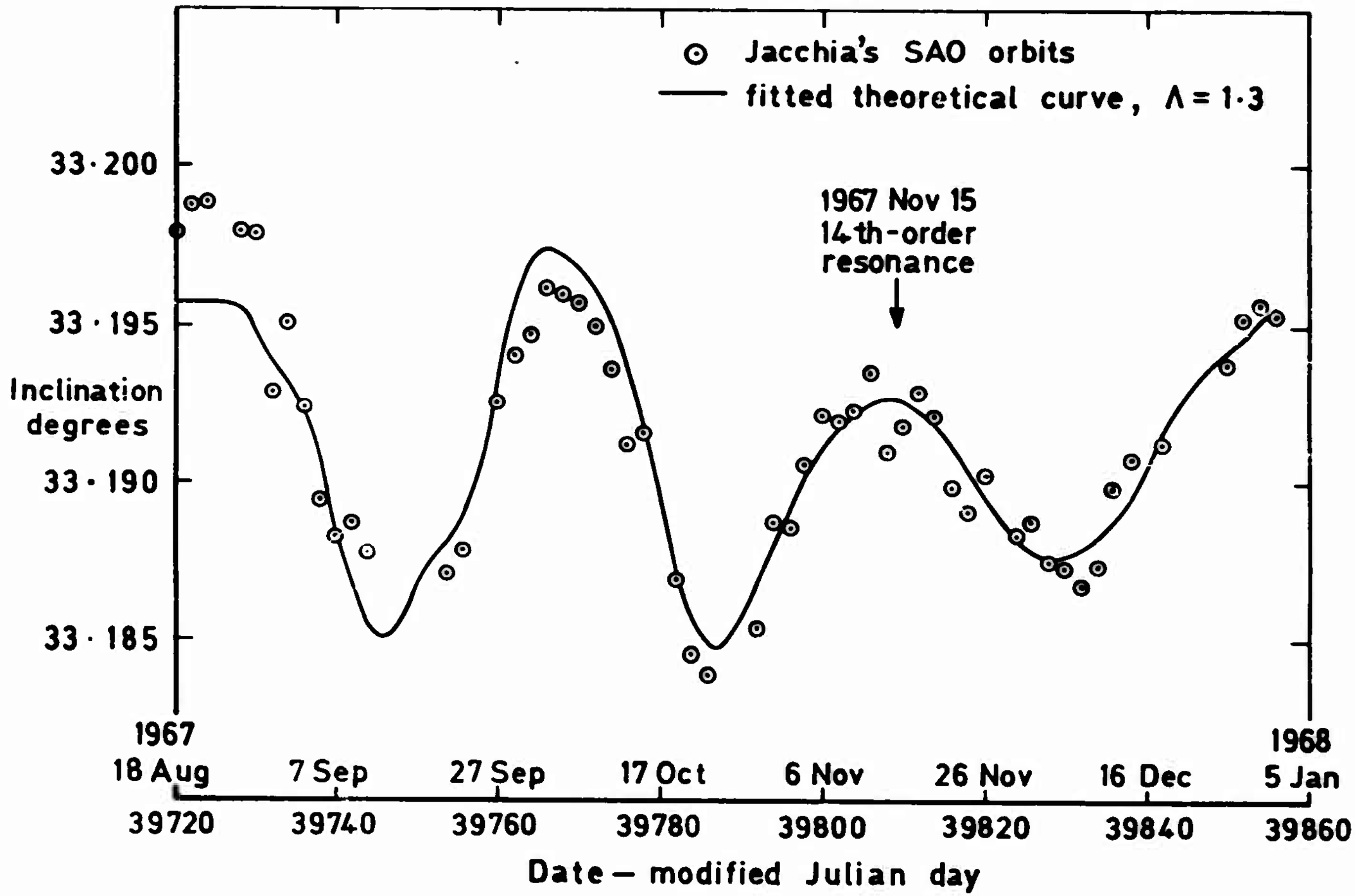

Fig. 4 Values of inclination at 14th-order resonance, with zonal harmonic and lunisolar perturbations removed, and fitted theoretical curve

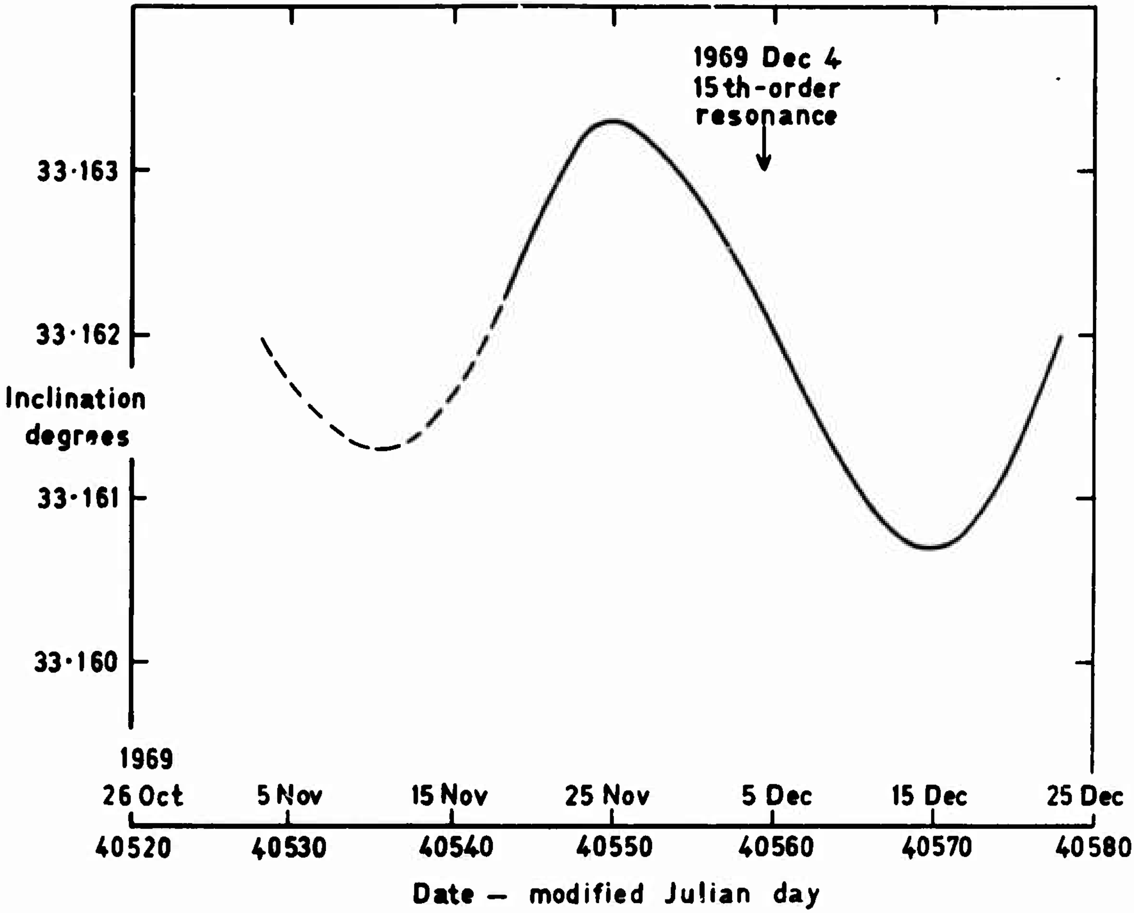

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Fig. 5 Calculated change in inclination at 15th-order resonance