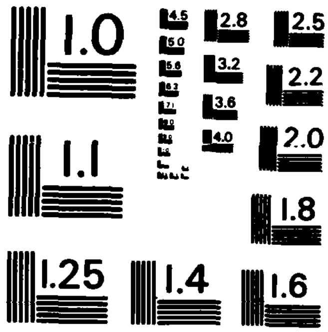

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ORBIT DETERMINATION AND ANALYSIS FOR 1970-97B AT 14TH-ORDER RESONANCE

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SUMMARY

The orbit of the satellite 1970-97B, the rocket of Cosmos 378, at inclination 74°, has been determined at 18 epochs between April and August 1971, when the effects of 14th-order resonance with the Earth's gravitational field were appreciable. The orbits were determined with the PROP 6 program from Hewitt camera, kinetheodolite, US Navy and visual observations, and an average accuracy of 90 m in perigee distance was achieved, despite the low perigee height (near 230 km) and the consequent high drag.

The orbits, together with 13 previously evaluated, have been analysed to reveal the effects of the 14th-order resonance and to evaluate six lumped geopotential harmonics of order 14. Because the orbit passed through resonance rapidly, the values are not as accurate as those from slow resonances; but they are more accurate than any others available for an inclination near 74°, and have proved their worth in a recent determination of individual 14th-order coefficients.

Departmental Reference: Space 646

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1 INTRODUCTION

Cosmos 378 rocket[1], designated 1970-97B, was launched on 1970 November 17 into an orbit inclined at 74.0° to the equator, with perigee and apogee heights of 233 and 1730 km respectively, and an orbital period of 105 min. It decayed on 1972 September 30 after 683 days in orbit.

The orbit has previously been determined between 1971 February and decay by Hiller[2]. The satellite experienced 14th-order resonance in 1971 June, and Hiller analysed the subsequent orbits to obtain values for atmospheric rotation rate and density scale height. In this Report we analyse the inclination and eccentricity of the orbits that are affected by 14th-order resonance.

In evaluating individual geopotential coefficients of order 14 from satellite resonances, it is essential to have values of lumped harmonics from satellites at a wide variety of inclinations, and previously there have been no accurate values of lumped harmonics available for inclinations between 70° and 81°. So it was decided that analysis of 1970-97B (inclination 74°) would be worth trying, even though it was obvious from the start that the values obtained would not be particularly accurate, because of the very rapid decay rate resulting from the low perigee.

A total of 18 new orbits has been determined from observations with the PROP 6 program[3], for dates between 1971 April 3 and August 17. These replace the 10 orbits determined by Hiller[2] during this time interval; all the observations he used, and others, are included in the new determinations. These 18 orbits are supplemented by 13 orbits determined by Hiller (with the same computer program) for dates before April 3 and after August 17. Thus the analysis of the 14th-order resonance utilizes 31 orbits, for dates between 1971 February 21 and September 19. The variations in both inclination and eccentricity are analysed, but the inclination proves to be the more satisfactory of the two.

2 THE 18 NEW ORBITS

Observations of 1970-97B were available from a wide variety of sources: 993 observations were used in determining the new orbits, 58% being from the US Navy Navspasur system, 33% from volunteer visual observers, 3% from the Hewitt cameras at Malvern and Edinburgh, 5% from the theodolite at Jokioinen, Finland, and 1% from the kinetheodolite at the South African Astronomical Observatory. Of these observations, those from the Hewitt cameras were by far the most accurate, but the last two groups were also most valuable in providing a wide spread in latitude to improve the reliability of the orbits. Residuals of the observations were very similar to those of Hiller[2] and are not given again.

The 18 new sets of orbital elements are listed in Table 1, with their standard deviations. The raw values of inclination are plotted in Fig 1. The main perturbation in inclination for a high-drag satellite is usually a decrease due to the effects of atmospheric rotation; but from Fig 1 it appears that the resonance probably causes a considerable increase in inclination, which exceeds the decrease due to atmospheric rotation.

The accuracy of the 18 orbits may be assessed from the average standard deviations of orbital elements. The eccentricity has an average sd of 0.000012, which is equivalent to a distance of 90 m radially. The average across-track error is given approximately by the average of the standard deviations in inclination and right ascension, which is 0.0013°, equivalent to 160 m. For an orbit of such high drag and high inclination these are excellent accuracies.

The values of perigee distance $a(1 - e)$ for the 18 new orbits and the 13 orbits of Hiller are plotted in Fig 2. The standard deviations are smaller than the radius of the circles. *Prima facie*, the values look reliable and the curve joining them is free of ugly discontinuities in slope. However, there is one peculiarity. The main oscillation is attributable to the odd zonal harmonics in the geopotential, but the expected amplitude of this oscillation[4] is 6.5 km, whereas the decrease from the first peak to the minimum is nearly 18 km, instead of the expected 13 km. This gives forewarning of likely problems in interpreting variations in eccentricity, because neither resonance nor air drag would be expected to alter the perigee distance by as much as 5 km. (The shifting of the minimum away from the $\omega = 90^{\circ}$ point could well be due to resonance effects, however.)

3 ANALYSIS OF INCLINATION

3.1 Removal of perturbations

To obtain values of lumped 14th-order harmonics, the values of inclination are fitted with the aid of the THROE computer program[5], after removing the effects of various other perturbations. These are:

(a) the lunisolar gravitational perturbations;

(b) perturbations due to zonal harmonics in the geopotential;

(c) the $J_{2,2}$ perturbation incorporated in PROP;

(d) perturbations due to atmospheric rotation;

(e) the effect of the precession of the Earth's axis, and

(f) the effect of any lumped harmonics of order 14 not included in the THROE model.

Other perturbations, such as solar radiation pressure and tidal effects, are treated as negligible.

The perturbations (a) and (b) above have been calculated by running the PROD computer program[6] with one-day integration intervals, and the $J_{2,2}$ perturbations are available with the PROP output. These perturbations are fairly large, reaching 0.0023° for (a) plus (b), and 0.0017° for (c). The values of inclination from the 31 orbits after removal of these three perturbations are shown in Fig 3.

The perturbations (d) and (e) are removed within THROE. The existence of the perturbation (f) depends on the model adopted for the THROE computer run, which is discussed below.

3.2 The terms to be included in the resonance model

The perturbations of inclination caused by 14th-order harmonics in the geopotential express themselves through terms of the form

$$\frac{\cos}{\sin}(\gamma\Phi - q\omega) \quad , \tag{1}$$

where ω is the argument of perigee, and Φ is the resonance angle, given by

$$\Phi = M + \omega + 14(\Omega - \nu) \quad , \tag{2}$$

M being the mean anomaly, Ω the right ascension of the node and ν the sidereal angle. The parameters γ and q are integers, and explicit formulae for the magnitude of the perturbations due to the most important pairs of values of (γ,q) have been given previously[7,8] and will not be repeated here. These formulae depend on the lumped harmonics, and the magnitudes of these may be very roughly assessed by assuming[9] that the individual coefficient of degree ℓ and order m is of magnitude $10^{-5}/\ell^2$. The relative magnitudes of the main (γ,q) terms for 1970-97B, calculated on this basis, are given in Table 2.

Table 2

Orders of magnitude of the perturbations in inclination for 1970-97B, for various (γ,q)

q \ γ	1	2	3
0	25	2	-
1	18	3	-
-1	16	2	-
2	6	-	-
-2	3	-	-

Here the main terms are likely to be those with $(\gamma,q) = (1,0)$, $(1,1)$ and $(1,-1)$, but because of the high eccentricity of 1970-97B ($e \simeq 0.1$), the $q = 2$ terms, which are of order e^2, are unusually large and cannot be ignored. However, we cannot expect to determine five pairs of lumped harmonics with only 31 orbits to analyse. So the THROE fitting is made with the three main terms already specified, leaving the $(\gamma,q) = (1,2)$ and $(1,-2)$ terms to be estimated separately and removed. Fortunately the removal of these terms could be achieved with good accuracy, because (a) their effect was quite small, the total change in inclination never being more than 0.0005°, and (b) the values for the lumped harmonics to go with these terms were fairly well known beforehand[10], and were then refined by the use of the most recent solution for 14th-order harmonics[11].

So THROE was run with $(\gamma,q) = (1,0)$, $(1,1)$ and $(1,-1)$ terms. The value of the atmospheric rotation rate Λ within THROE, used to remove the perturbation (d), was set at 0.9 rev/day in accordance with the results of Ref 12. Here the relevant values of the parameters controlling Λ were as follows: perigee height near 230 km; local time averaged over three complete cycles[2]; and quite a strong seasonal bias towards summer. So the value of Λ is given by the curve labelled 'average local time, summer' in Fig 12 of Ref 12; whence $\Lambda = 0.9$. The density scale height H at a height $\frac{1}{2}H$ above perigee also has to be specified and was taken as 37 km in accordance with the *COSPAR International Reference Atmosphere 1972*[13] for the appropriate level of solar activity, which gives an exospheric temperature of 900 K.

Although Λ varies between day and night, the constant value taken here should not cause any errors greater than the observational errors of i, because there are three day-to-night cycles. The total decrease in i due to atmospheric rotation is 0.0120°, that is an average of 0.0020° for half a day-to-night cycle. Thus if Λ is in error by 20% over a half cycle, the error introduced would be 0.0004°, to be cancelled by an opposite error in the next half cycle, if the mean value has been correctly chosen.

3.3 The fitting of the variation of inclination with THROE

The 31 values of inclination, after taking account of perturbations as already specified, were fitted with the aid of the THROE computer program with $(\gamma,q) = (1,0)$, $(1,1)$ and $(1,-1)$. The variations of the resonance angle Φ, and of $\dot{\Phi}$, are shown in Fig 4.

The fitting was quite satisfactory. In the initial run the measure of fit ε was 1.57 and after relaxation of the accuracies of 10 points, the value of ε was reduced to 0.77 and the following values for the six lumped harmonic coefficients were obtained:

$$10^9\bar{C}_{14}^{0,1} = -32 \pm 24\,, \qquad 10^9\bar{S}_{14}^{0,1} = -20 \pm 33\,, \tag{3}$$

$$\left.\begin{aligned} 10^9\bar{C}_{14}^{1,0} &= -67 \pm 53\,, & 10^9\bar{S}_{14}^{1,0} &= 12 \pm 50 \\ 10^9\bar{C}_{14}^{-1,2} &= -77 \pm 53\,, & 10^9\bar{S}_{14}^{-1,2} &= -67 \pm 40 \end{aligned}\right\} \,. \tag{4}$$

These lumped harmonics are linear sums of individual 14th-order harmonic coefficients; explicit expressions are given in section 3.4.

The fitting of the curve to the points is shown in Fig 5. In most respects the fitting is good. First, there is a clear increase, of 0.010°, between the early values and those after resonance: this is eight times the average standard deviation of the values, so there is a well-defined change in inclination at resonance, which should be well determined. Second, the first six values are consistent with a constant value of inclination, and so are the last eleven; this suggests that the perturbations have been removed successfully, and in particular that the right value of Λ has been used. Third, although 10 values were relaxed in accuracy, most of the relaxations might be called 'cosmetic', only three of the values (at MJD 41085, 41093 and 41141) being more than twice their original standard deviations distant from the curve. When the character of the fitting became clear, several of the orbits were re-run, to see whether omission of some observations, or relaxation of their accuracy, would lead to values of inclination which were of smaller standard deviation and also closer to the curve*. The values given in Table 1 record the final results of this process. It was found that the point at

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* For the rationale of this procedure, see Ref 14.

MJD 41085 strongly influenced the results when used with its original standard deviation, and in view of its 'nonconformity', we decided to nullify its effect by increasing the standard deviation by a factor of 10.

Although the change in inclination - almost exactly 0.01° - is quite accurately defined by the fitted curve, our attempt to evaluate six lumped coefficients from such sparse data is obviously liable to be over-ambitious - there are only 13 points in the region where the main resonant variation occurs. So it is not surprising that several of the values (3) and (4) are numerically indeterminate. Unfortunately none of the pairs of values is negligible: but since the values of the $(\gamma,q) = (1,0)$ coefficients are quite well known[10,11], we calculated that effect, corrected the values of inclination accordingly, and then made another THROE fitting with $(\gamma,q) = (1,1)$ and $(1,-1)$ only. The $(\gamma,q) = (1,0)$ terms (with $10^9\bar{C}_{14}^{0,1} = -6.5$, and $10^9\bar{S}_{14}^{0,1} = -15.7$) produce an increase in inclination of 0.0021°, which is 20% of the total increase in Fig 5, and so the fitting with $(\gamma,q) = (1,1)$ and $(1,-1)$, shown in Fig 6, has an increase 20% smaller than in Fig 5. But Fig 6 is otherwise similar to Fig 5, thus suggesting that the fitting is quite stable.

The values for the lumped harmonics obtained from the THROE fitting of Fig 6 are:

$$\left.\begin{array}{ll} 10^9\bar{C}_{14}^{1,0} = -49 \pm 48, & 10^9\bar{S}_{14}^{1,0} = 22 \pm 44 \\ 10^9\bar{C}_{14}^{-1,2} = -97 \pm 48, & 10^9\bar{S}_{14}^{-1,2} = -70 \pm 29 \end{array}\right\}, \qquad (5)$$

with $\varepsilon = 0.76$. Although the standard deviations are slightly lower in equations (5) than in equations (4), the earlier solution seems better in principle, because the removal of the important $(\gamma,q) = (1,0)$ terms is rather drastic surgery. The significant feature is the complete consistency between the sets of values (4) and (5). This indicates that the fitting of six coefficients, although a dangerous procedure, was safely accomplished. We therefore opt for the solution given in equations (3) and (4).

3.4 The equations for the lumped harmonics

The six lumped harmonic coefficients appearing in equations (3) and (4) are linear sums of individual 14th-order coefficients, $\bar{C}_{\ell,14}$ and $\bar{S}_{\ell,14}$, and are given by the following equations, in which the numerical values are obtained with the aid of the PROF computer program:

$$\bar{C}_{14}^{0,1} = \bar{C}_{15,14} + 0.472\bar{C}_{17,14} + 0.057\bar{C}_{19,14} - 0.152\bar{C}_{21,14} - 0.198\bar{C}_{23,14} - 0.152\bar{C}_{25,14}, \qquad \ldots\ldots (6)$$

$$\bar{C}_{14}^{1,0} = \bar{C}_{14,14} - 0.830\bar{C}_{16,14} - 0.813\bar{C}_{18,14} - 0.343\bar{C}_{20,14} + 0.083\bar{C}_{22,14} + 0.298\bar{C}_{24,14} + 0.308\bar{C}_{26,14} + 0.199\bar{C}_{28,14}, \qquad \ldots\ldots (7)$$

$$\bar{C}_{14}^{-1,2} = \bar{C}_{14,14} + 0.182\bar{C}_{16,14} - 0.209\bar{C}_{18,14} - 0.369\bar{C}_{20,14} - 0.358\bar{C}_{22,14} - 0.246\bar{C}_{24,14} \quad \ldots\ldots (8)$$

The equations for the S-coefficients are obtained on replacing C by S throughout. The right-hand sides of equations (6) to (8) are terminated when the expected contribution of $\bar{C}_{\ell,14}$, which is assumed to be of order $10^{-5}/\ell^2$, falls to less than 5% of the main term (and remains below 5% for higher-degree terms).

Equations (6) to (8), with the numerical values for the lumped harmonics from equations (3) and (4), have been used in the recent solution for individual harmonic coefficients of 14th order[11]. For five of the six lumped harmonics the new values for the individual coefficients fit the lumped harmonics to within 1.1 standard deviations. (The exception was $\bar{S}_{14}^{-1,2}$, where the residual was 1.4 standard deviations.) We may therefore conclude that the standard deviations in equations (3) and (4) give every indication of being realistic.

The accuracy in geoid height implied by the standard deviations in equations (3) and (4) may be roughly assessed by multiplying by the Earth radius, 6378 km and dividing by the root sum of squares of the numerical coefficients in each of equations (6) to (8). On this basis the average accuracy in geoid height implied by the three sets of lumped harmonics in equations (3) and (4) is 15 cm for $(\bar{C},\bar{S})_{14}^{0,1}$, 20 cm for $(\bar{C},\bar{S})_{14}^{1,0}$ and 25 cm for $(\bar{C},\bar{S})_{14}^{-1,2}$. These accuracies are not nearly so good as for the slower resonances, such as that of 1970-47B[8], but are still useful in providing constraints for inclination 74°.

4 ANALYSIS OF ECCENTRICITY

The eccentricity decreases from 0.095 at MJD 41003 to 0.079 at MJD 41213, mainly as a result of the effect of air drag, and there seems little hope of removing this huge perturbation, equivalent to 115 km, with sufficient accuracy to analyse the resonant variation in eccentricity, which is unlikely to exceed 1 km. This expectation was confirmed by trial runs: when the raw values of e were used and corrected for air drag within THROE, several attempts all led to values of ϵ near 30.

So a different approach was adopted. The perturbations Δe in e due to odd zonal harmonics and lunisolar perturbations were calculated by PROD at 1-day intervals, and the resulting values of $a\Delta e$ were added to the perigee distance $a(1 - e)$ to give values of perigee distance adjusted for the effects of zonal harmonics and lunisolar perturbations. The values of this adjusted perigee distance, Q, are plotted in Fig 7 and should show the variations due to air drag and resonance.

The effect of air drag is to produce a slow decrease in $\dot{Q}$, given by equation (6) of Ref 14, which may here be written with sufficient accuracy as

$$\frac{dQ}{dt} = -\frac{H\dot{M}_1}{3M_1 e}\left\{\frac{1-e}{1+e} + O(0.04)\right\}, \qquad (9)$$

where H is the density scale height. For 1970-97B the average value of $\dot{M}_1$ between MJD 41003 and 41213 is 0.65 deg/day^2, so that, on taking $e = 0.088$ and $M_1 = 5100$ deg/day, we obtain the mean dQ/dt from (9) as

$$\left(\frac{dQ}{dt}\right)_{mean} \simeq -0.00040\,H \quad day^{-1} . \tag{10}$$

The density scale height has to be evaluated at a height 1.5H above perigee, and from *CIRA 1972* [13], this gives $H \simeq 45$ km for 1970-97B (with exospheric temperature 900 K). Thus Q should decrease at approximately 18 m/day, giving a decrease of 3.8 km over the 210 days of the analysis. The actual decrease is about 5 km, which is not very different, but the form of the variation in Fig 7 is most peculiar, with a very rapid decrease at about 60 m/day for the first 60 days, up to MJD 41060. followed by a much slower decrease at about 14 m/day up to MJD 41160, and then an even slower decrease for the final 50 days.

The steep slope in the first 60 days, if caused by air drag alone, would indicate a scale height of about 150 km, which is not credible. So the rapid decrease is puzzling, and the possibility of propellants escaping from the rocket during its first months in orbit cannot be ruled out. The first six points in Fig 7 have therefore been ignored.

Fortunately, the decrease in perigee distance over the main resonance period (MJD 41060-41160) has a reasonable slope, and we removed the effects of air drag by assuming that drag caused a linear decrease in Q , as shown by the unbroken line drawn in Fig 7. If $(\Delta r_p)_{at}$ denotes the decrease in perigee distance, relative to the value at MJD 41061, as given by this line, we may define a revised perigee distance $[a(1-e)]_{rev}$ given by

$$[a(1-e)]_{rev} = Q + (\Delta r_p)_{at} , \tag{11}$$

and this quantity would reflect the variation in perigee distance produced by resonance and smaller perturbations, if the atmospheric perturbation assumed was correct. We then obtain revised values of e , namely

$$e_{rev} = 1 - \frac{1}{\bar{a}}[a(1-e)]_{rev} , \tag{12}$$

where $\bar{a}$ is taken as 7235 km. These values of e_{rev} were then fitted by THROE, with drag suppressed, and with $(\gamma,q) = (1,1)$ and $(1,-1)$, which are[8] by far the most important (γ,q) terms producing variation in e .

The first THROE run fitted quite well, apart from the last five points; so these were dropped. Of the remaining 20 values, two had large residuals and were relaxed, one by a factor of 2 and the other by a factor of 4. The following values of the lumped harmonic coefficients were then obtained, the value of ε being 1.40:

$$\left.\begin{array}{ll} 10^9\bar{C}_{14}^{1,0} = -52 \pm 40 , & 10^9\bar{S}_{14}^{1,0} = -49 \pm 53 \\ 10^9\bar{C}_{14}^{-1,2} = -53 \pm 40 , & 10^9\bar{S}_{14}^{-1,2} = 19 \pm 29 \end{array}\right\} . \tag{13}$$

The fitting of the curve to the points is shown in Fig 8. When the calculation was repeated with the decrease due to air drag represented by the broken line in Fig 7, there was a substantial increase in ε , to 1.59, and in the standard deviations. A solution with lower ε and standard deviations would no doubt be obtained by using a line of lower slope in Fig 7; but this scarcely seems justified, since the unbroken line corresponds to a scale height of 26 km, which is already at the lower limit of credibility.

Because of the interaction between air drag and the resonance, and the difficulty of making a logical choice for the slope of the line in Fig 7, we feel that the values (13) are not so reliable as the values (4), even though three of them have slightly lower standard deviations than the values (4). However, it will be noticed that the C-values in (4) and (13), are consistent to within half the sum of their standard deviations, while the S-values only differ by 0.6 and 1.2 times the sum of their standard deviations. This suggests that the values (13) may be more reliable than expected. Also, three of the four values (13) are within one standard deviation of the values of the four lumped coefficients given by the recent solution for individual harmonics[11] - namely -31 and +31 for $10^9(\bar{C},\bar{S})_{14}^{1,0}$ and -40 and -9 for $10^9(\bar{C},\bar{S})_{14}^{-1,2}$. This again suggests that the values (13) are reliable, despite the rather devious methods required for their derivation.

Although the values (4) have already been used in the recent determination[11] of individual 14th-order harmonics, because the results (13) were not then available, it would probably be more appropriate in any future determination to adopt a weighted mean of (4) and (13), with the smaller of the two standard deviations. This 'compromise solution' is

$$\left.\begin{aligned} 10^9\bar{C}_{14}^{1,0} &= -58 \pm 40 , \quad & 10^9\bar{S}_{14}^{1,0} &= -18 \pm 50 \\ 10^9\bar{C}_{14}^{-1,2} &= -63 \pm 40 , \quad & 10^9\bar{S}_{14}^{-1,2} &= -17 \pm 29 \end{aligned}\right\} . \tag{14}$$

These values are all within 1 standard deviation of the values given by the recent solution for individual coefficients[11]. Their average standard deviations correspond to accuracies in geoid height of 17 cm for $(\bar{C},\bar{S})_{14}^{1,0}$ and 18 cm for $(\bar{C},\bar{S})_{14}^{-1,2}$.

5 CONCLUSIONS

The orbit of 1970-97B has been determined from observations for 31 epochs during 210 days in 1971 when the satellite was close to 14th-order resonance. These 31 orbits comprise 13 previously determined by Hiller[2] and 18 new ones. Some Hewitt camera and kinetheodolite observations were available and the orbital accuracy achieved - about 90 m radial and 160 m cross-track - was good, in view of the very low perigee height (230 km).

Because of the high drag, the orbit passed through 14th-order resonance rapidly, and appreciable resonance effects lasted only for about 100 days, covering 13 of the 31 orbits. As the orbit is quite eccentric ($e \simeq 0.09$), six lumped harmonic coefficients prove to be of importance and have to be evaluated. With so many coefficients in a fitting of (effectively) 13 points, the values obtained are bound to be rather inaccurate. However, consistent values were derived from analysis of both inclination and eccentricity, and there is every sign that these values, as given in equations (3) and (14), are reliable, although far less accurate than those obtained from slower resonances. The orbital inclination of 1970-97B was 74°, and the lumped harmonics provide useful constraints for this inclination, near which no other such accurate results are available. The values have been successfully used in the recent determination[11] of individual coefficients of order 14.

Table 1

ORBITAL PARAMETERS FOR COSMOS 378 ROCKET AT THE 18 NEW EPOCHS, WITH STANDARD DEVIATIONS

	MJD	Date	a	e	i	Ω	ω	M_0	M_1	M_2	M_3	M_4	M_5	ε	N	D	a(1 - e)
1.	41044	1971 Apr 3	7280.696 2	0.09251 1	74.0010 12	103.969 1	218.654 8	18.434 10	5032.139 2	0.3565 11	0.0072 3	0.00235 15	-	0.60	95	6.0	6607.16
2.	41061*	Apr 20	7264.983 1	0.09122 2	73.9997 9	73.992 1	184.789 7	16.410 6	5048.478 1	0.4653 5	0.0012 2	0.00144 6	-0.00009 2	0.64	72	7.1	6602.27
3.	41072	May 1	7256.149 1	0.09045 1	73.9996 11	54.478 2	162.790 8	164.273 7	5057.703 2	0.3293 9	0.0073 6	0.00140 10	-0.00070 6	0.61	64	5.9	6599.83
4.	41085*	May 14	7247.219 1	0.08968 2	74.0048 16	31.338 2	136.856 10	94.295 9	5067.057 1	0.3825 3	0.0091 2	-	-	0.63	53	5.0	6597.29
5.	41093	May 22	7240.985 2	0.08908 1	74.0036 17	17.048 1	120.839 13	337.634 12	5073.604 2	0.3305 5	-0.0053 3	-	-	0.55	33	5.0	6595.96
6.	41099	May 28	7237.399 2	0.08872 1	73.9995 14	6.310 1	108.828 12	190.618 11	5077.376 2	0.2903 10	-0.0009 4	0.00148 20	-	0.53	36	5.0	6595.30
7.	41107	Jun 5	7232.067 1	0.08812 1	74.0000 13	351.965 1	92.774 9	150.906 8	5082.994 1	0.3470 5	-0.0088 3	-	-	0.55	47	5.7	6594.78
8.	41113	Jun 11	7228.465 1	0.08773 1	74.0028 14	341.184 1	80.776 7	60.289 8	5086.796 1	0.3019 7	-0.0021 3	-	-	0.61	54	5.6	6594.31
9.	41121	Jun 19	7223.998 1	0.08712 1	74.0045 21	326.788 2	64.681 10	93.355 8	5091.516 1	0.2721 7	-0.0073 4	-	-	0.59	44	5.3	6594.64
10.	41127	Jun 25	7221.025 3	0.08660 2	74.0084 23	315.980 2	52.570 14	51.640 13	5094.661 3	0.3137 32	0.0320 21	0.00200 79	-0.00288 35	0.64	29	4.9	6595.68
11.	41135	Jul 3	7216.065 2	0.08581 1	74.0048 19	301.532 1	36.358 11	150.034 10	5099.916 2	0.3185 6	-0.0037 5	-	-	0.58	30	4.5	6596.85
12.	41141*	Jul 9	7212.669 1	0.08524 1	74.0106 13	290.674 1	24.213 8	160.401 7	5103.520 1	0.2925 4	-0.0041 3	-	-	0.55	45	4.7	6597.86
13.	41148*	Jul 16	7208.966 1	0.08464 1	74.0084 7	277.994 1	9.880 6	258.566 5	5107.454 1	0.3017 2	-0.0029 5	-0.00030 3	0.00028 4	0.61	71	6.0	6598.80
14.	41155*	Jul 23	7204.434 2	0.08381 1	74.0067 10	265.286 2	355.604 7	26.309 6	5112.275 2	0.4312 9	-0.0279 10	-0.00429 9	0.00240 8	0.73	62	6.0	6600.63
15.	41161*	Jul 29	7200.147 1	0.08308 2	74.0053 10	254.369 2	343.252 4	113.466 3	5116.843 1	0.3903 27	-0.0020 4	0.00192 60	-	0.54	70	4.0	6601.96
16.	41166	Aug 3	7196.215 1	0.08242 2	74.0021 11	245.254 1	332.950 8	148.110 8	5121.038 1	0.4085 3	-0.0036 2	-	-	0.55	69	6.5	6603.10
17.	41173	Aug 10	7191.229 1	0.08165 1	74.0001 11	232.465 1	318.455 8	14.367 9	5126.366 1	0.3755 11	-0.0023 2	-0.00050 9	-	0.48	58	6.5	6604.07
18.	41180	Aug 17	7186.931 <1	0.08091 1	73.9981 15	219.651 1	303.851 10	275.933 11	5130.967 <1	0.3007 4	-	-	-	0.49	61	6.0	6605.44

Key:

* = orbits with Hewitt camera observations
MJD = modified Julian day
a = semi major axis (km)
e = eccentricity
i = inclination (deg)
Ω = right ascension of ascending node (deg)
ω = argument of perigee (deg)

M_0 = mean anomaly at epoch (deg)
M_1 = mean motion n (deg/day)
M_2-M_5 = later coefficients in the polynomial for M
ε = measure of fit
N = number of observations used
D = time covered by the observations (days)

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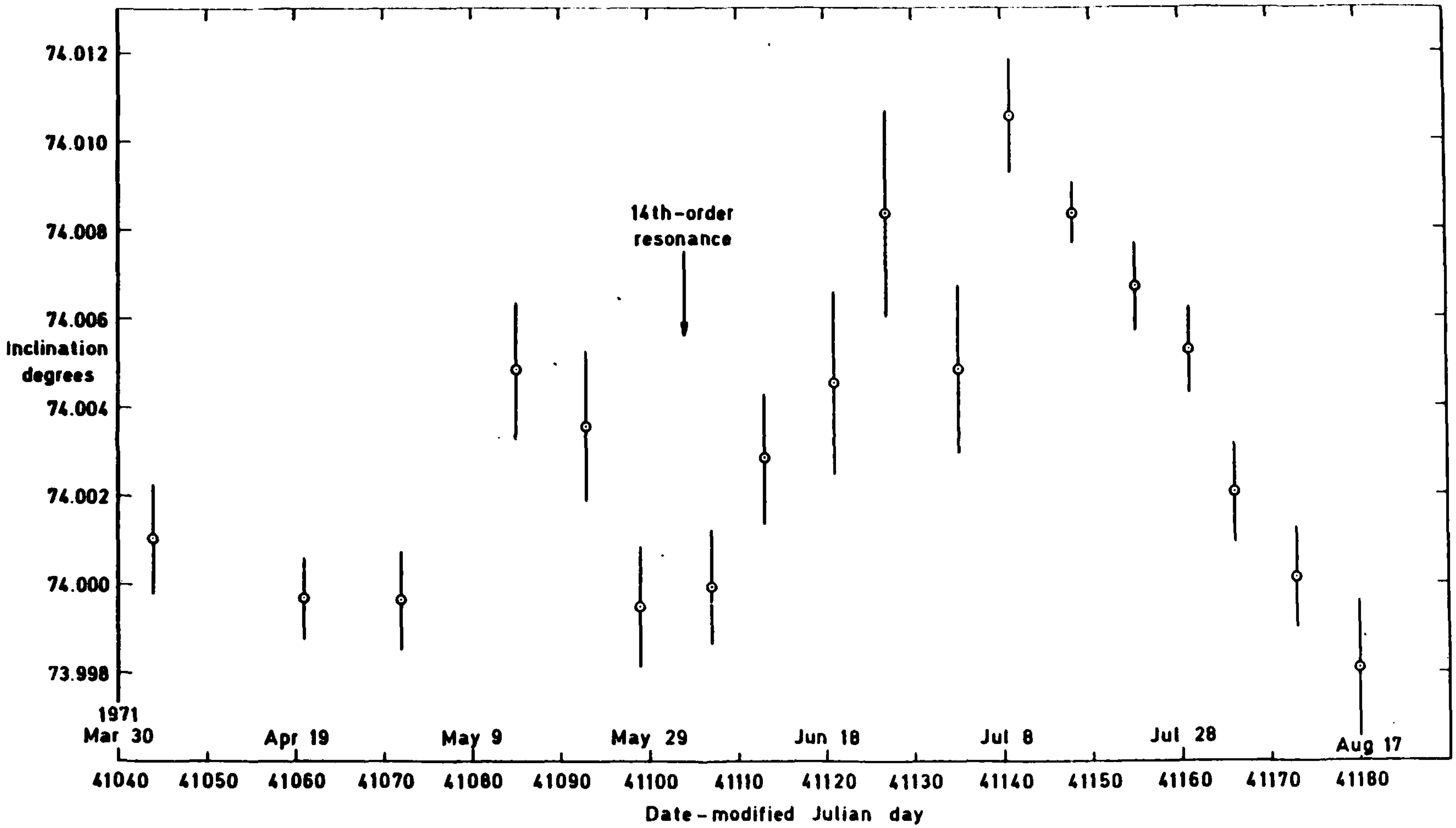

Fig 1 Values of inclination from Table 1

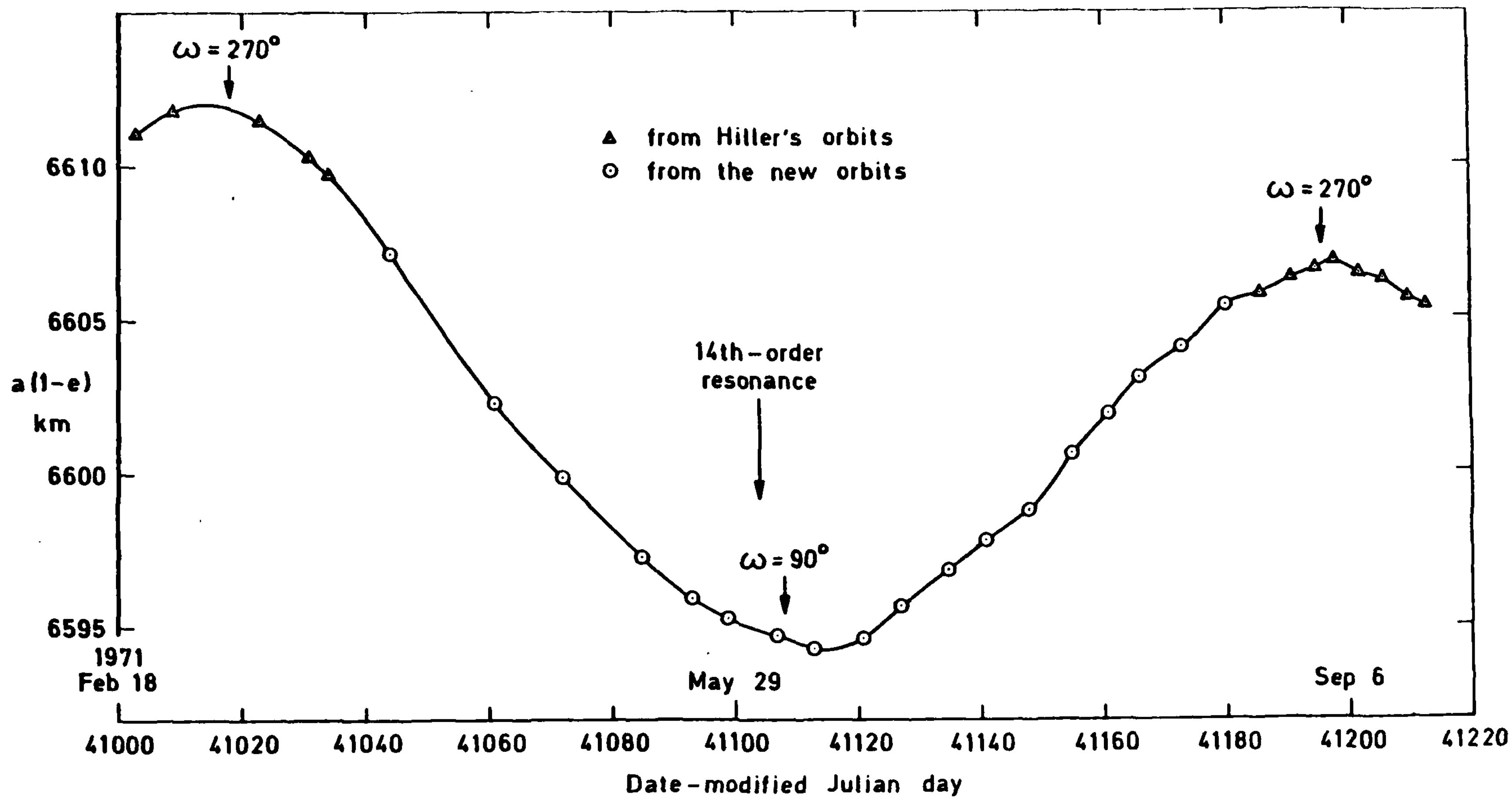

Fig 2 Values of perigee distance, a(1-e)

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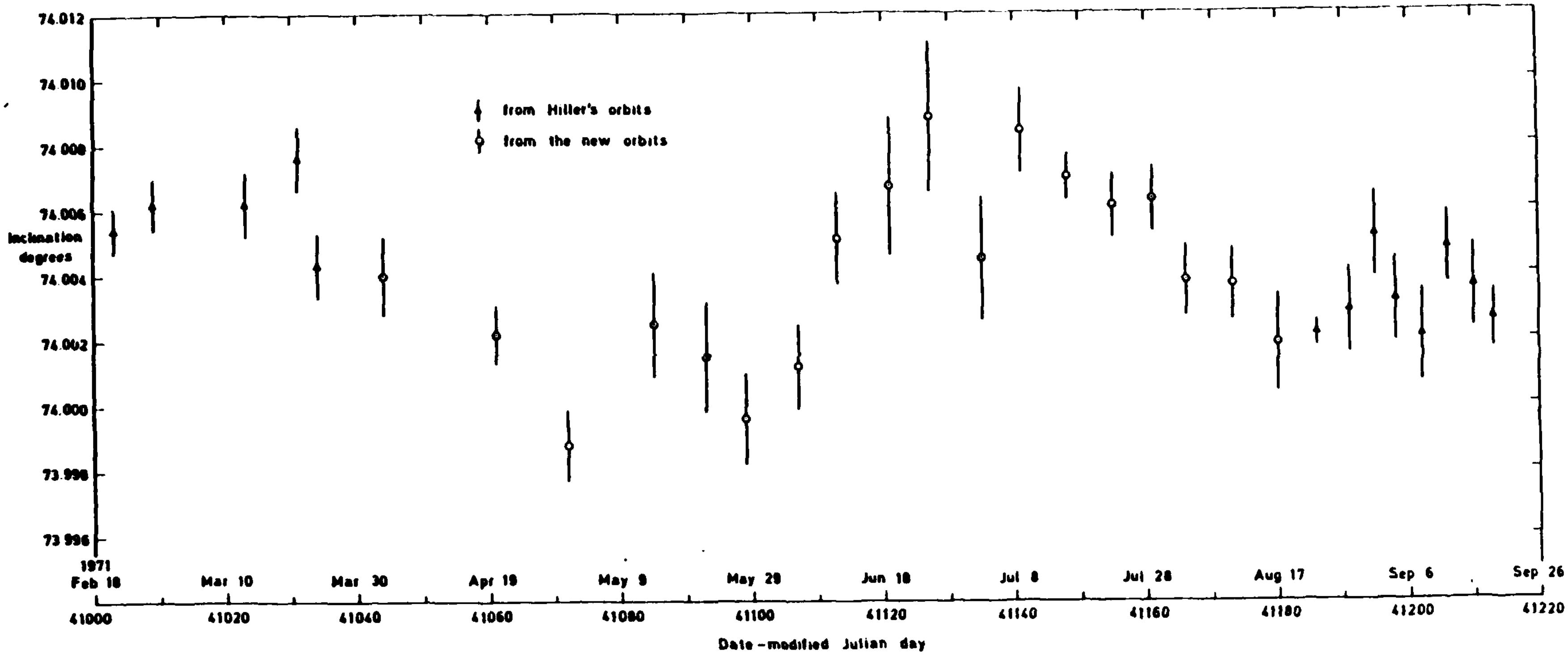

Fig 3 Values of inclination after removal of lunisolar, zonal harmonic and $J_{2,2}$ perturbations

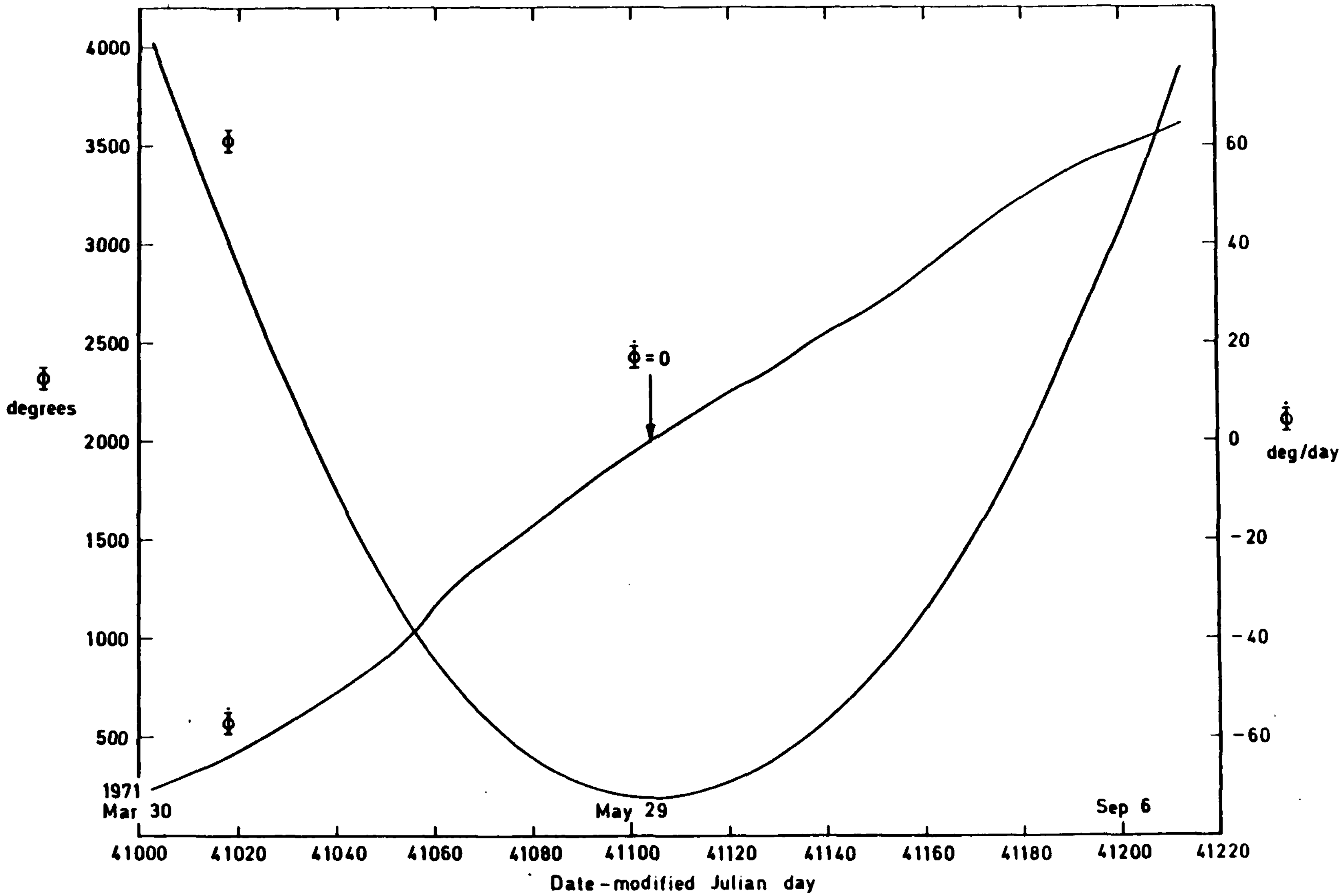

Fig 4 Variation of Φ and $\dot{\Phi}$ near 14th-order resonance

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Fig 5

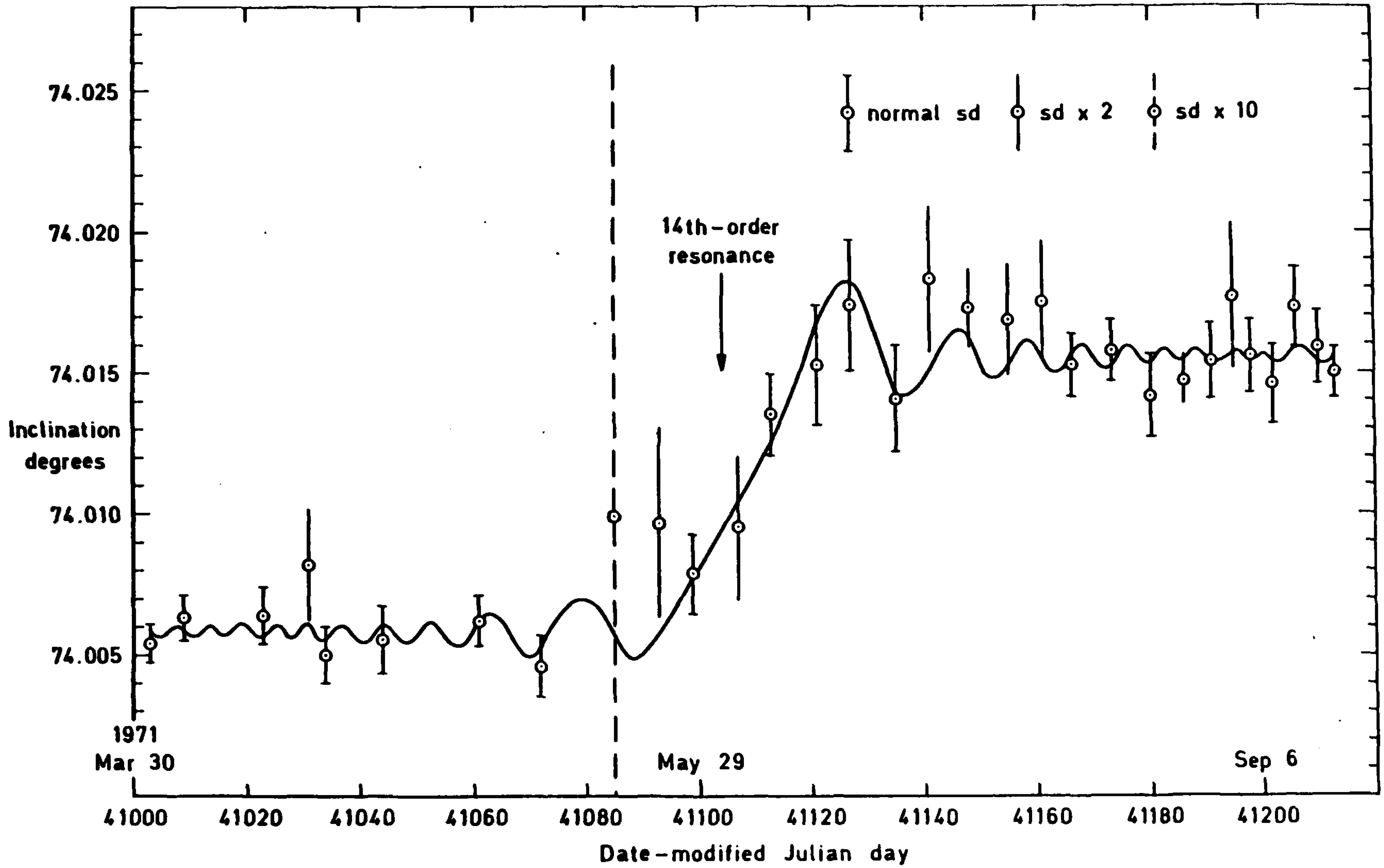

Fig 5 Values of inclination, after removal of perturbations, fitted by THROE with (γ, q) = (1,0)(1,1) and (1,−1)

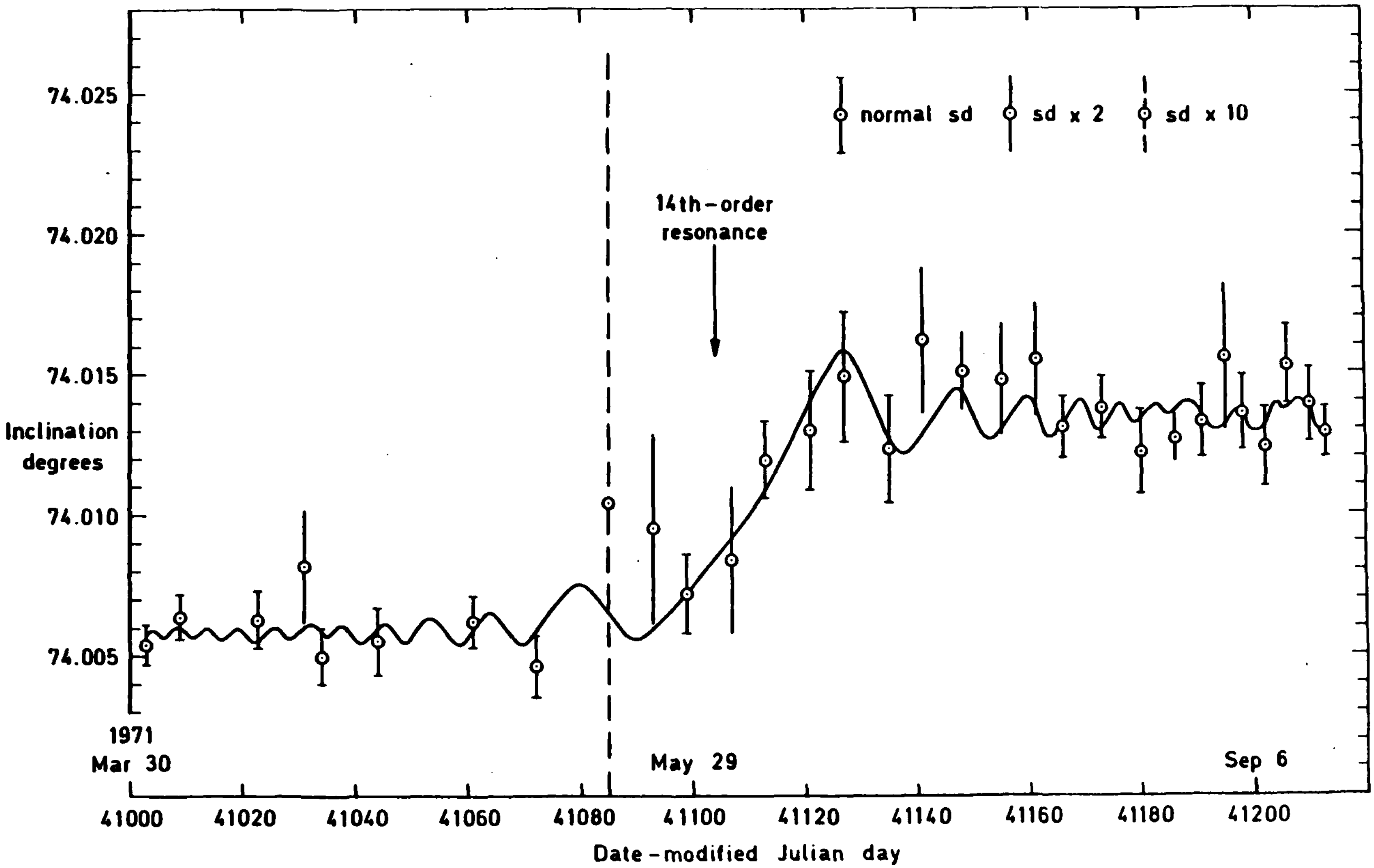

Fig 6 Values of inclination after removal of perturbations and $(\gamma,q) = (1,0)$ terms, fitted by THROE with $(\gamma,q) = (1,1)$ and $(1,-1)$

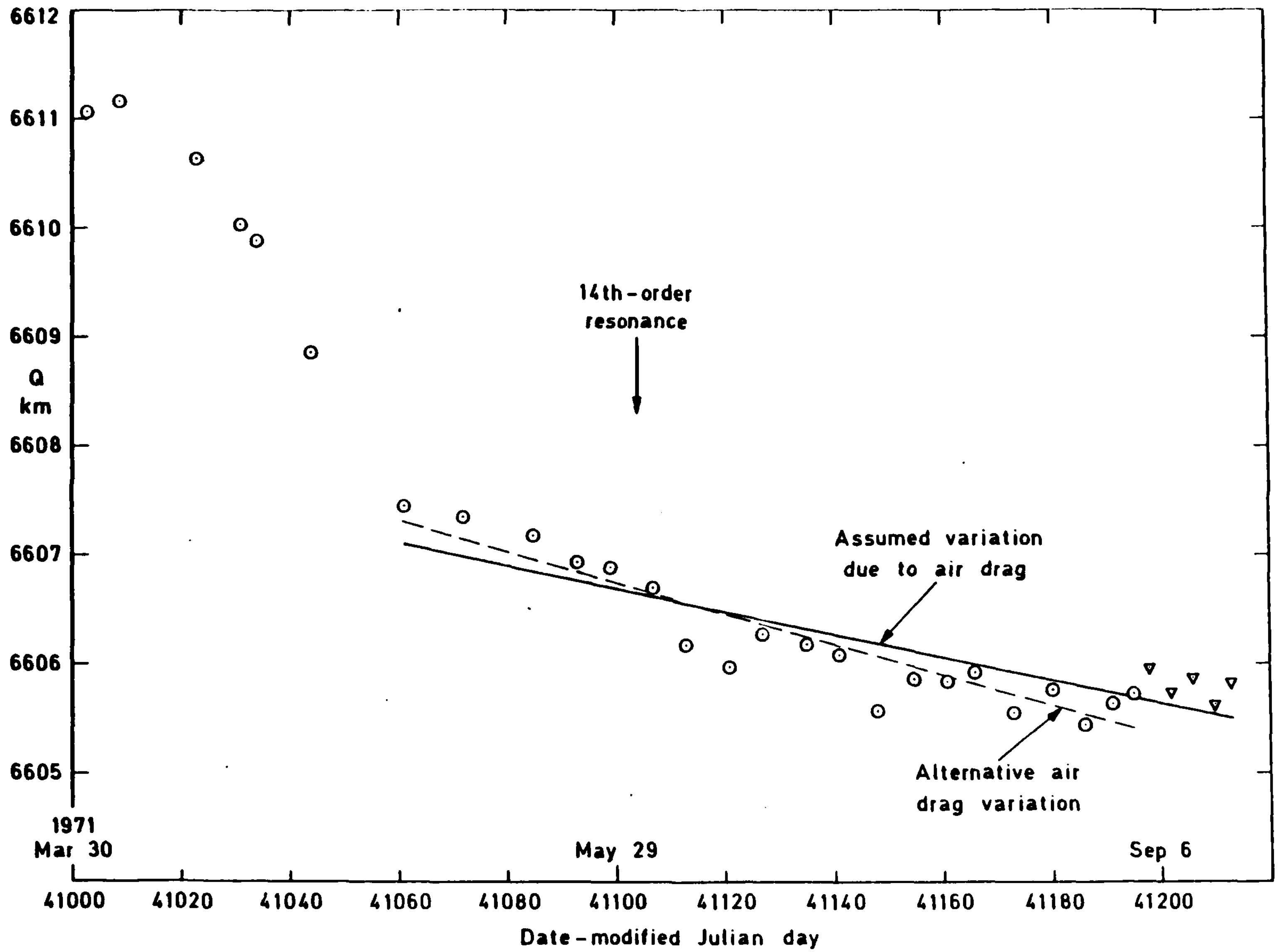

Fig 7 Perigee distance Q after removal of the effects of zonal harmonics and lunisolar perturbations

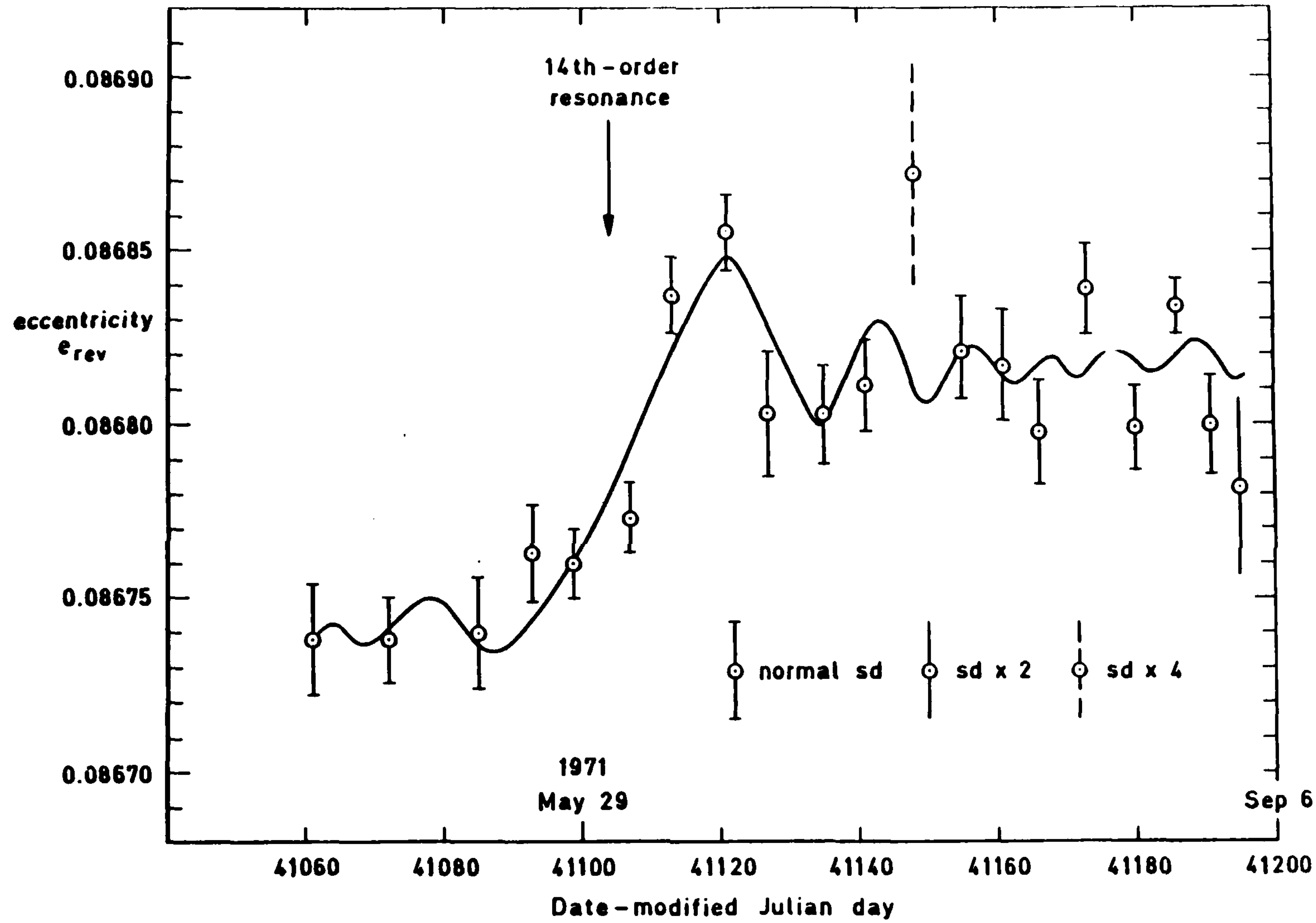

Fig 8 The central 20 values of e_{rev}, fitted by THROE with $(\gamma, q) = (1,1)$ and $(1,-1)$

REPORT DOCUMENTATION PAGE

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17. Abstract

The orbit of the satellite 1970-97B, the rocket of Cosmos 378, at inclination 74°, has been determined at 18 epochs between April and August 1971, when the effects of 14th-order resonance with the Earth's gravitational field were appreciable. The orbits were determined with the PROP 6 program from Hewitt camera, kinetheodolite, US Navy and visual observations, and an average accuracy of 90 m in perigee distance was achieved, despite the low perigee height (near 230 km) and the consequent high drag.

The orbits, together with 13 previously evaluated, have been analysed to reveal the effects of the 14th-order resonance and to evaluate six lumped geopotential harmonics of order 14. Because the orbit passed through resonance rapidly, the values are not as accurate as those from slow resonances; but they are more accurate than any others available for an inclination near 74°, and have proved their worth in a recent determination of individual 14th-order coefficients.

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