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TIME, FREQUENCY, AND POLAR MOTION LABORATORY
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QUARTERLY REPORTS Nos. 1 AND 2.

To: NASA, Office of Scientific & Technical Information (Code US)

From: Wm. Markowitz, Principal Investigator

Subject: Report on Time, Frequency, and Polar Motion

Ref.(a): Research Grant NGR 50-001-010

Encl: (1) Preprint, "Sudden Changes in Rotational Acceleration of the Earth and Secular Motion of the Pole," by Wm. Markowitz.

1. The subject grant runs from 1 January to 31 December 1969, but was not approved until 28 March 1969. The first two quarterly reports follow.

Quarterly Report No. 1, 1 January to 31 March 1969.

1. Studies were begun on the rotation of the earth and the polar motion.

Quarterly Report No. 2, 1 April to 31 June 1969.

2. Rotation and Polar Motion. Analysis of the Washington and Richmond PZT observations of UT minus atomic time shows that sudden changes in rotational acceleration occur but not in speed.

CASE FILE
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Analysis of the International Latitude Service observations shows that the mean pole continues to move secularly. The above results were presented at a NATO Advanced Study Institute, held at the University of Western Ontario, London, Ontario, 23 to 27 June 1969. See encl. (1).

3. NASA Timing Discussions. Opportunity was provided at the NATO meeting to confer with the NASA technical representative, Dr. Martin Swetnick, and other NASA personnel on timing problems of NASA. Arrangements were made to visit the Wallops Island tracking station and to attend the NASA/MIT summer institute.

4. Synchronization. VLF and Omega were used to maintain synchronization to 10µs, through use of the Marquette quartz clock, when the atomic clock failed. Chart readings of the transmissions enabled corrections to be applied to relate the clock to the Naval Observatory master clock to ± 1µs. After a power failure had stopped the quartz clock and power was returned, Loran-C was used to recover synchronization, visually, to 0.1µs.

5. Time Allocations. See Appendix I.

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copies to: Mr. Jerome Rosenberg, NASA
Dr. Martin Swetnick, NASA

APPENDIX I.

TIME ALLOCATIONS OF PRINCIPAL INVESTIGATOR

Marquette University has contracts with both ONR and NASA concerning Time, Frequency, and Polar Motion. The work carried out under the ONR contract for the Naval Observatory concerns principally time and frequency determination and dissemination; that for NASA concerns principally earth sciences, including geodesy. Studies carried out by the Principal Investigator have applications to both contracts. The table lists the working hours allocated to each project for the interval 1 April to 30 June 1969.

		ONR	NASA
1.	Monitoring and synchronization.	60	30
2.	Rotation of the earth and polar motion.	80	160
3.	Meeting (London, Ontario).	15	30
	Totals	155	220

375

SUDDEN CHANGES IN ROTATIONAL ACCELERATION OF THE EARTH AND SECULAR MOTION OF THE POLE*

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ABSTRACT

Introduction of the atomic clock in 1955 has made possible the detailed determination of irregular variations in speed of rotation in the 1 to 10 year range. Sudden changes do not occur in speed but do in acceleration, about every 4 years. The motion of the mean pole consists of a progressive component of 10cm/yr plus a 24-yr oscillation. A deviation for 1966.0 is noted. No correlation is found between earthquakes and changes in rotational speed or acceleration, or in polar motion.

1. Introduction. The study of the rotation of the earth, considered as a geophysical phenomenon, proceeds along two lines, observational and theoretical. Analysis of the observations provides a mathematical description of the rotation of the earth. This provides constraints which theories should fit.

By using ephemeris time (ET) based on the orbital motion of the moon for comparison with universal time (UT), dating back several thousand years, it has been possible to determine the secular retardation and the gross features of the irregular variation, that is, those in the range from one to several decades. Quartz crystal clocks were brought to a sufficiently high state of development by 1950 to enable the seasonal variations, yearly and semi-yearly, to be determined accurately.

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*Presented at the NATO Advanced Study Institute, "Earthquake Displacement Fields and the Rotation of the Earth," 22 to 29 June 1969, London, Ontario.

An interesting problem was how changes in speed of rotation of the earth occur, in particular, whether sudden changes occur. The moon is too coarse a reference time standard to settle this question, and quartz clocks cannot be used because their frequencies change with time. The development of the cesium-beam atomic clock in 1955 permitted solution of the problem.

The precision of determining UT has increased in the last few decades, through introduction of the photographic zenith tube (PZT) and the astrolabe.

The studies reported here are based on the comparison of UT, determined with the two PZT's of the U.S. Naval Observatory, at Washington, D.C., and Richmond, Florida, with atomic time, A.1[1]. The system A.1 is based on the frequency 9 192 631 770 cycles/sec (of ET) for cesium. This value was obtained in a joint experiment which utilized the cesium clock and the dual-rate moon camera [2].

The two PZT's are separated about 1500 km, so that local refraction anomalies are independent. The PZT's are similarly affected, however, by changes in speed of rotation of the earth. The use of two PZT's not only provides increased accuracy but enables observational error to be separated from changes in speed.

It was assumed formerly that the speed of rotation of the earth remained constant for a number of years, changed abruptly to a new value, and then remained constant for a number of years. Such changes would be described by a step function. In 1952, however, D. Brouwer, in a classic paper [3], made the hypothesis that sudden changes in speed do not occur but that sudden changes in acceleration occur instead. Brouwer represented $\Delta T=ET-UT$ by arcs of parabolas. With the moon as a reference, it was impossible to either verify or disprove this hypothesis. The atomic clock permitted verification.

Data of geophysical interest also come from observations of the polar motion. The International Latitude Service (ILS) stations provide the fundamental polar motion. The position of the mean pole is obtained from 6-year means, which are essentially free of the 12 and 14-month terms.

2. Rotation of the Earth. In comparing theory with observation it is essential that one understands just what quantities are obtained from the observations. When using the moon the observed quantity is $\Delta T=ET-UT$. With the atomic clock it is $H=UT1-A.1$. A derived quantity

K=UT2-A.1, is obtained through the relation UT2=UT1+ΔSV, where ΔSV is a correction for seasonal variation. The adopted BIH formula is

$$\Delta SV = 25.1\text{ms} \sin(2\pi t - 0.499) - 9.2\text{ms} \sin(4\pi t - 0.862),$$

where t is the fraction of the year.

Time. The heavy line in figure 1 shows the mean monthly values of H, for Washington and Richmond combined, from 1955.45 to 1961.0. The variations in speed of rotation of the earth are given by the variations in H. The irregular and 12-month variations are clearly seen. A 6-month variation is evidenced from the asymmetry of the annual variation. To study the irregular variation it is advantageous to use K, given by the light line. K can be represented by two parabolic arcs which are tangent just before 1958.0.

Figure 2 shows the mean value of K for each quarter of a year from 1955.62 to 1969.38. No smoothing was used. The observations are well represented by 4 parabolas, which are discussed later.

Speed. Let g be the length of the day in seconds of atomic time. Then $\sigma = -dg/g$ is the deviation from nominal in speed of rotation, expressed as a fraction. If dg=1 millisecond then $\sigma = 116 \times 10^{-10}$. Figure 3 shows the mean values of σ for each quarter of a year, obtained from the formula $\sigma = +\Delta K/(91.3 \times 86{,}400)$, where ΔK is the change in K, in seconds, for the quarter. The speed of rotation of the earth is well represented by segments of straight lines.

Sudden changes in speed of rotation, equivalent to a step change in g of 1 to 3ms, or 116 to 348×10^{-10} in σ, have been announced at various times. No such sudden changes are shown by the atomic clock.

Figure 4(a) shows the speed of rotation from 1820.5 to 1969.5. The values up to 1950.5 are those given by Brouwer in Table VIIIa of ref. [3]. The values from 1955.5 to 1969.5 obtained here. A constant acceleration is assumed from 1950.5 to 1955.5. The connection between ET and A.1 is based on moon camera observations from 1955.5 to 1958.5 [1,4].

Acceleration. Let $\alpha = d\sigma/dt$ be the rotational acceleration. Values of the secular retardation derived by several authors indicate a change in g of about 1.4ms per century, or $\alpha=-1.6\times10^{-10}$/yr. This slope is shown in figure 4(a). The magnitude of the irregular excursions in σ shows why it is so difficult to determine α and to decide whether it has changed during the past few thousand years. Figure 4(b) shows the step changes in α, derived from the data of 4(a).

A significant fact revealed with the atomic clock is that the changes in α occur about every 4 years instead of about every 10 years, as found by Brouwer. This difference, of course, is due to the reduction in observational error. The probable error of an annual mean of ΔT in [3] is 260 milliseconds, whereas the observational probable error of an annual mean of K obtained from two PZT's and the atomic clock is only 1.2 milliseconds. Indeed, it is remarkable that Brouwer was able to determine sudden changes in α with the moon. That he was able to do so at all demonstrates his deep insight into the problem of the rotation of the earth.

3. Solutions and probable errors. Table 1 gives the coefficients of the parabolas, $K_i=a+bt+ct^2$, which were fitted to the observed K, and α. The parabolas have a common tangent at the points of contact so that only 9 of the 12 coefficients are independent. Four straight lines would have required 8 independent constants, only 1 less.

Table 2 gives the quarterly residuals, $R=K(\text{obs.})-K_i(\text{comp})$, and yearly means. The last column gives the mean yearly observational difference, S=K(Washington)-K(Richmond), which is independent of changes in speed of rotation.

Table 3 gives probable errors based on the observed R and S, except for the first entry in (a) which was obtained previously [5]. Other values in line (a) were obtained from the observed S for the intervals indicated. Line (b) was computed from the entry above and to the left in (a) by dividing the square root of the number in parentheses. The systematic error is $(c)=[(a)^2-(b)^2]^{1/2}$. This is less than 1 ms for the quarterly mean of one PZT. Line (d) gives the observational error for the mean of two PZT's.

Line (e) gives the probable errors of R. Correcting for (d) we obtain the quarterly and yearly deviations in time, expressed as probable errors, V. The values of V are significantly larger than those in (d). Hence, two PZT's plus an atomic clock produce a sufficiently low noise level so that quarterly variations in speed of rotation can be determined.

In terms of the basically observed H=UT2-A.1, we have

$$R=(\text{UT1-A.1}) - [a+bt+ct^2-\Delta SV],$$

where a,b, and c are fixed for several years and ΔSV has fixed coefficients. It is remarkable that the variations in timekeeping of the earth can be represented by an analytical formula to within about 5 milliseconds for an annual mean.

4. Variations in acceleration, speed, and time. Recent values of α are given in table 1. Values of σ at the turning points in acceleration and at the observational ends are as follows:

	σ
(1955.5)	-53×10^{-10}
1957.81	-170
1961.84	-122
1965.93	-227
(1969.5)	-280

Variations in speed of rotation are classified as (A) secular, due chiefly to tidal friction, (B) irregular, due to coupling of mantle and core or to changes in moment of inertia, and (C) seasonal, due chiefly to winds. Table 4 lists maximum effects for (B) and (C) and, for (A), the cumulative effects in speed and time during the past 2000 years.

Accelerating torques are proportional to α. What is surprising is the large torque due to winds, about 8 times that of the irregular variation and 40 times that of the lunar tidal couple.

5. Discussion of rotation. Accelerations are produced by torques whose sources are internal or external to the earth. The numerous possible sources are discussed by W. Munk and G.J.F. MacDonald [9]. The internal possibilities fall into two classes, a torque produced by coupling of mantle to core or a progressive change in moment of inertia. What has to be explained is what are the specific sources of the irregular variation and why the variation continues so uniformly for intervals of about 4 years and then changes abruptly.

The PZT and atomic clock enable variations in speed of rotation in the range of 3 months or longer to be determined. Small variations, R, have been found, but we cannot say what part of R is due to variations in the winds and what part is due to changes within the earth. The use of radio telescopes as interferometers or of corner reflectors on the moon may enable variations shorter than 3 months to be determined. It is not immediately apparent, however, that we shall be able to relate such variations with specific causes. Nevertheless, such variations would be of great interest if found.

Two large earthquakes occurred in the interval covered in figure 5, at 1963.78, Kurile Islands, and at 1964.24, Alaska. No changes in acceleration or speed of rotation is noted for these times.

6. Motion of mean pole. The fundamental determination of the position of the pole of rotation is derived by the International Polar Motion Service (IPMS) from observation of the 5 stations of the International Latitude Service (ILS). Checks by the method of control latitudes [6,7] show that the ILS polar motion is independent of errors in star positions, proper motions, or of micrometer scale values, or changes in the observing lists.

A 6-year mean gives the position of the mean pole, as the 12 and 14-month terms are effectively removed. The motion of the ILS mean pole was found in 1960 to consist of a progressive component of about $0''.0035$/yr, or 10cm/yr, along the meridian 65°W and a librational component (oscillation) of 24-year period along the meridian 122°W [8]. Figure 6 shows the position of the mean pole, based on 6-year normal points, up to 1966.0. The last point was kindly furnished by Dr. S. Yumi.

The 24-year term is empirical; we do not know whether it will continue. Indeed, the position for 1966.0 deviates from the pattern previously found. However, between 1932 and 1938 the motion also did not follow the usual pattern. We must wait a number of years to see whether the 24-year motion continues.

7. Earthquakes and the rotation of the earth. The possibility of correlating earthquakes and the polar motion has been a subject of many studies since this motion was discovered. Recently, L. Mansinha and D. E. Smylie attempted to correlate earthquakes with changes in the motion of the pole and sudden changes in the position of the mean pole [10,11]. They find good correlation between 13 major earthquakes, of magnitude greater than 7.75, which occurred between 1957 and 1964 and the BIH polar motion, but not the ILS polar motion. They state "No significant relation between changes in the ILS-IPMS pole path and earthquakes is found." This circumstance makes the findings doubtful.

In 1955 the International Astronomical Union directed the BIH to furnish corrections $\Delta\lambda$ for timekeeping based on the ILS coordinates of the pole [12]. These could not be obtained with sufficient speed and the BIH began determining the polar motion from about 9 independent stations. The addition of new stations each year necessarily introduced discontinuities, despite attempts to maintain homogeneity. In contrast, there has been no change in the ILS stations since 1931.

The BIH methods of calculation, described by B. Guinot and Martine Feissel in the BIH Annual Report for 1968 (1969), were reorganized from 1965 through 1968. The BIH polar motion is fairly homogeneous now but was not in the early years, 1957 to 1964.

Changes in speed or acceleration of the earth shows no correlation with earthquakes. Nor is any correlation apparent in the Annual Reports of the IPMS, published since 1962. Hence, it does not appear that a correlation between earthquakes and the rotation of the earth has yet been established. Whether this can be done through the newly proposed methods of determining the polar motion with increased accuracy remains to be seen.

ACKNOWLEDEMENTS

I thank Dr. R. G. Hall, with whom I began these studies at the U.S. Naval Observatory some years ago, for helpful discussions and for providing recent results. Also, I am indebted to Dr. G.M.R. Winkler, Director of the Time Service Division, and Mr. Don R. Monger, Director of the Richmond station, for discussions.

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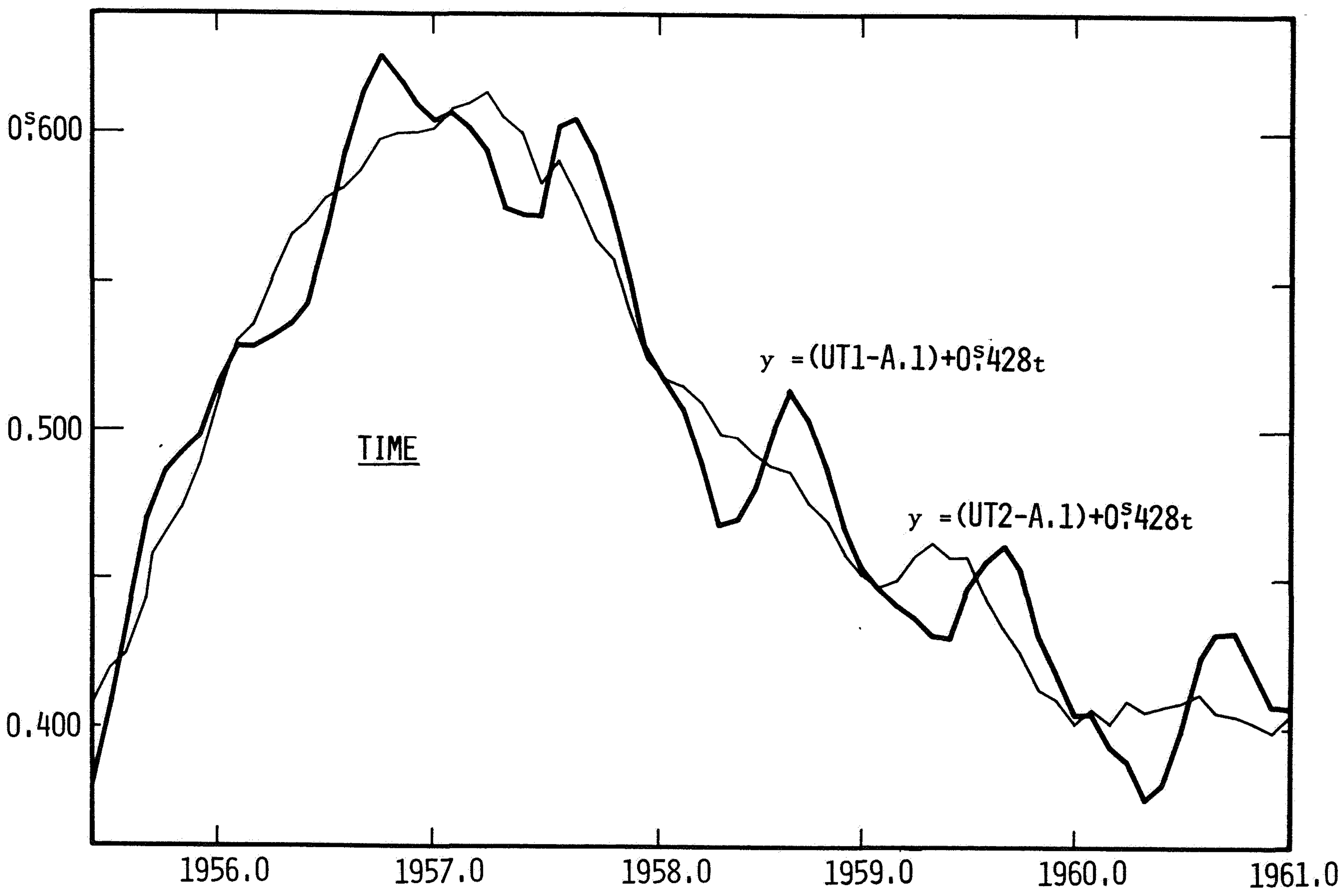

Fig. 1. Monthly means of (UT1-A.1) and (UT2-A.1), plus a linear term, for Washington and Richmond; 1955.45 to 1961.0.

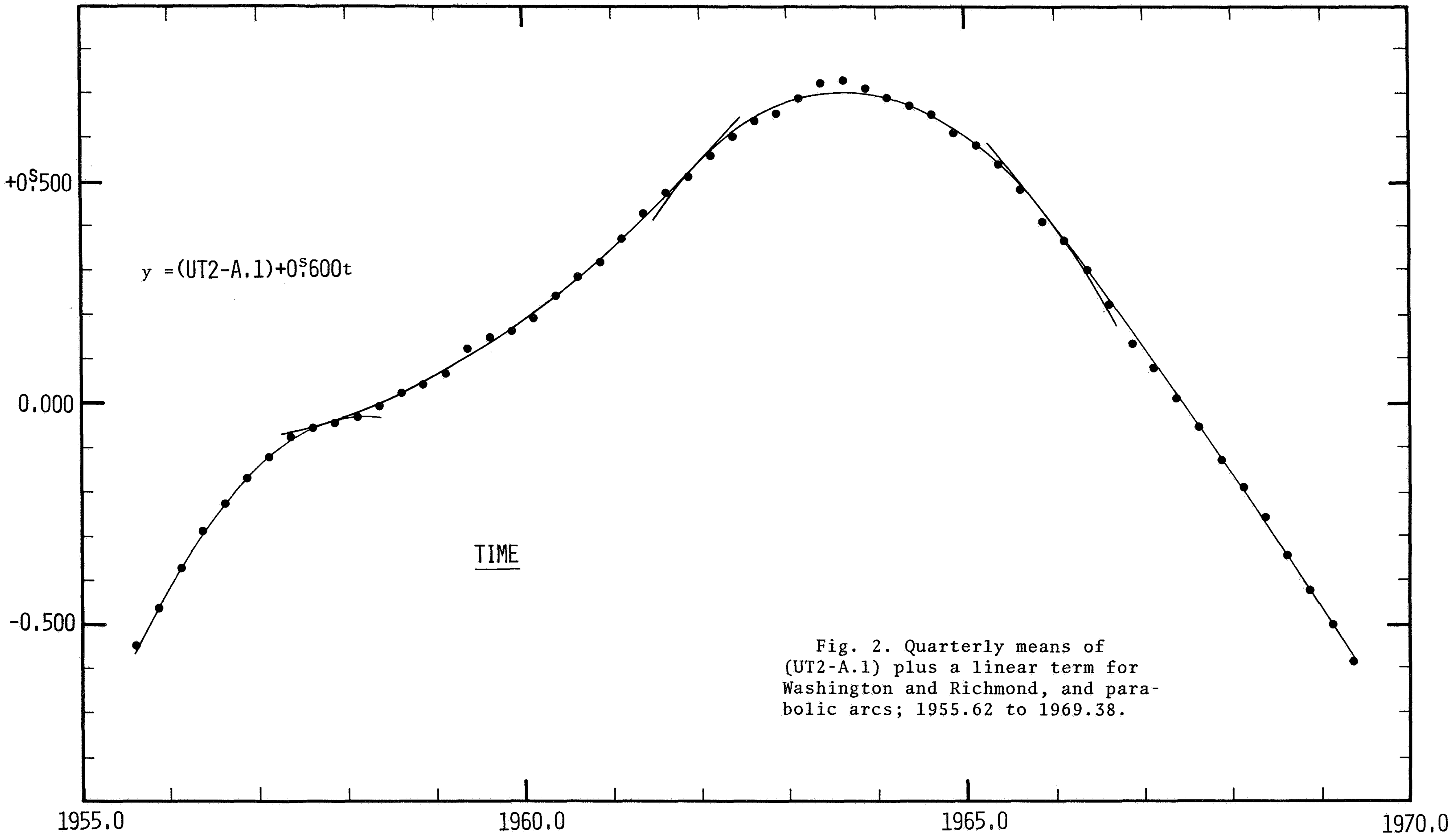

Fig. 2. Quarterly means of (UT2-A.1) plus a linear term for Washington and Richmond, and parabolic arcs; 1955.62 to 1969.38.

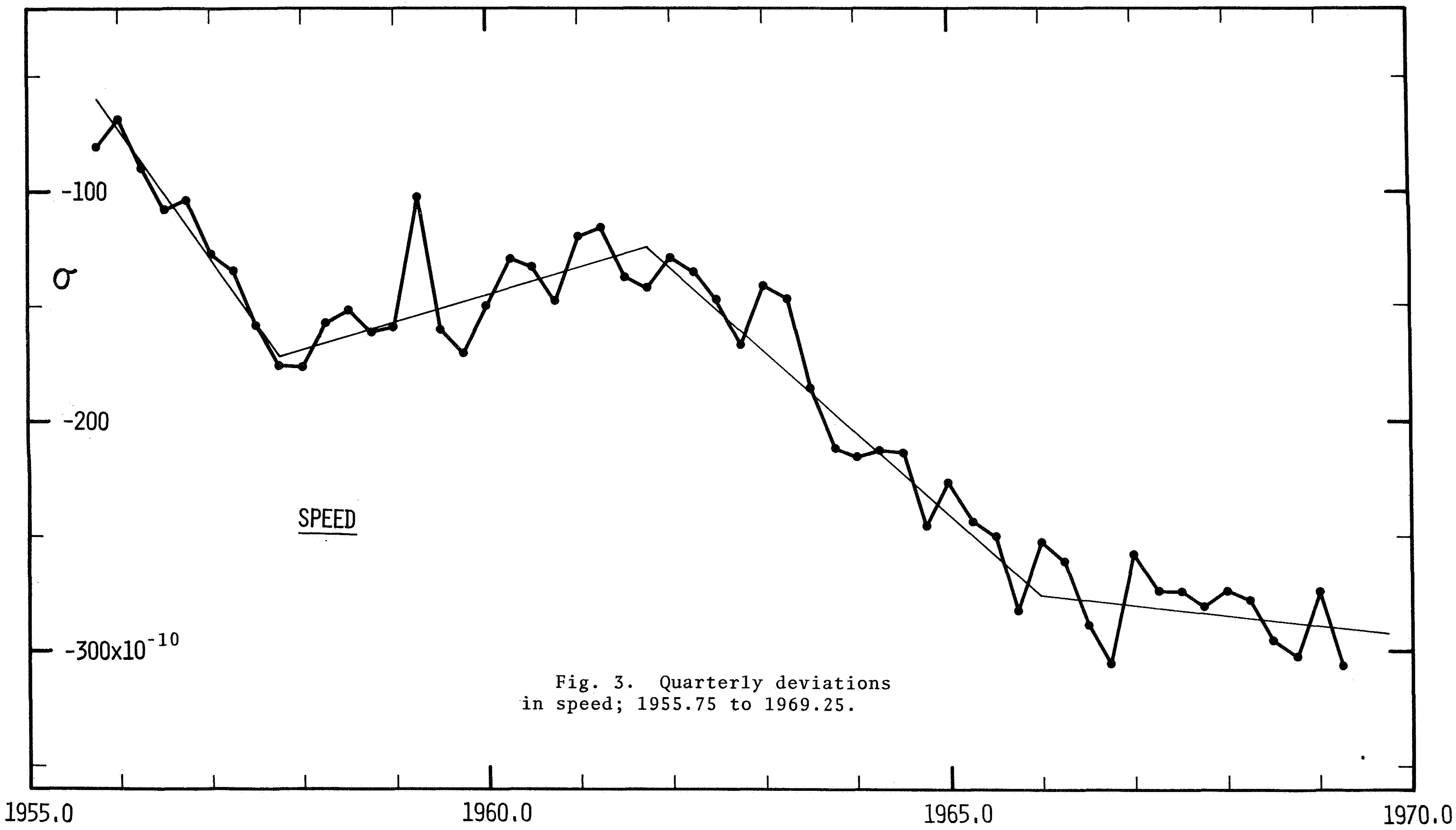

Fig. 3. Quarterly deviations in speed; 1955.75 to 1969.25.

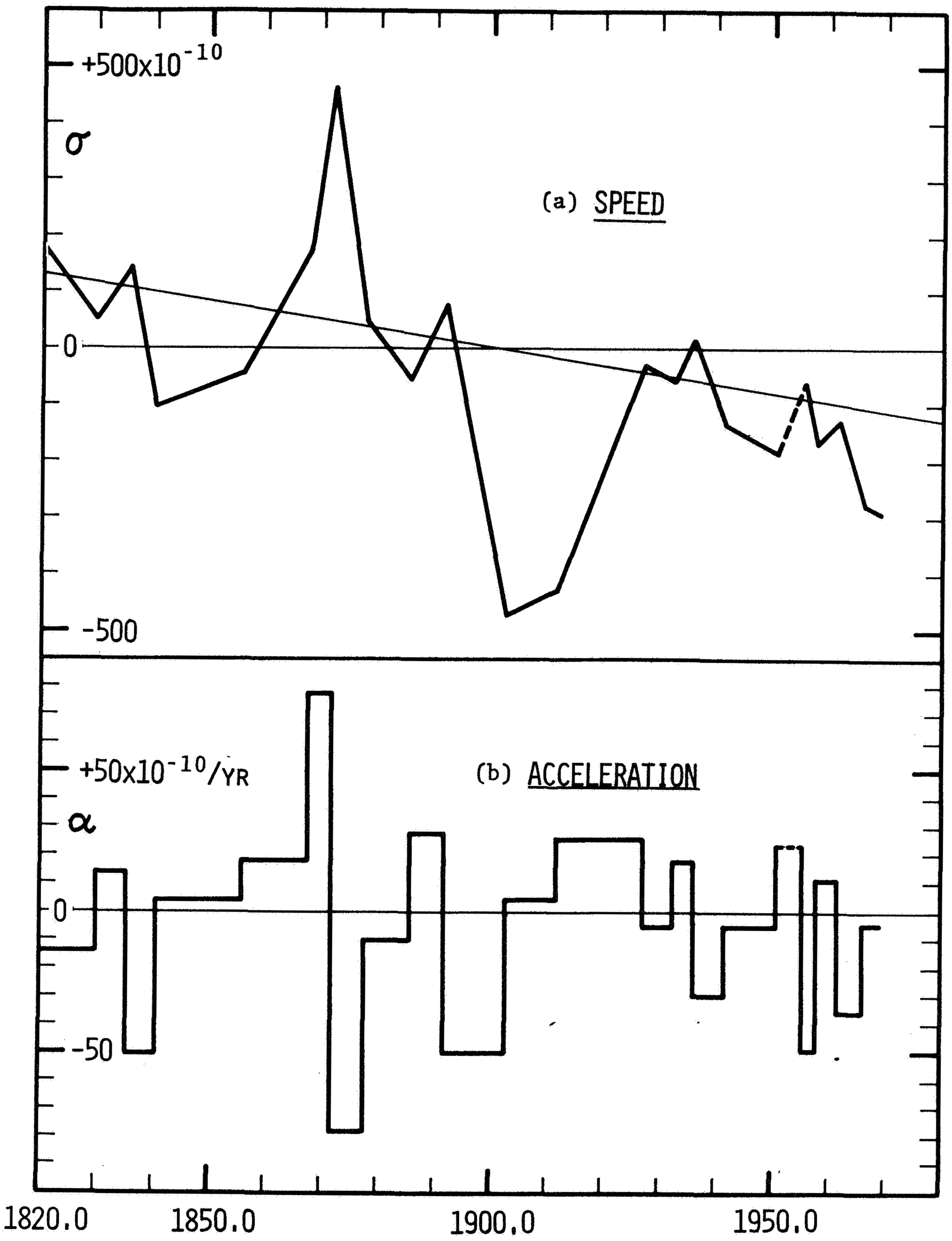

Fig. 4. (a) Deviations in speed of rotation, and (b) acceleration; 1820 to 1969.

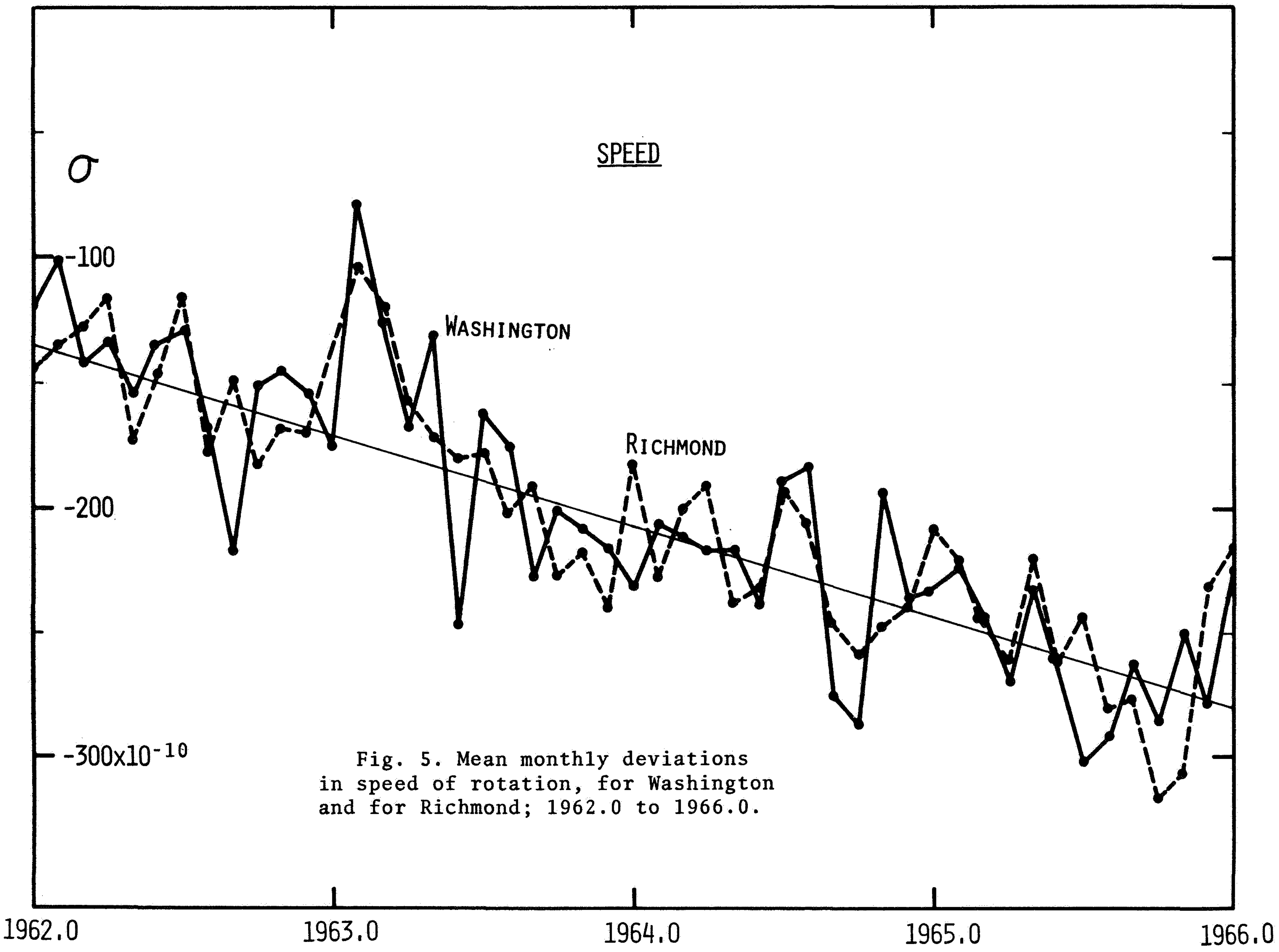

Fig. 5. Mean monthly deviations in speed of rotation, for Washington and for Richmond; 1962.0 to 1966.0.

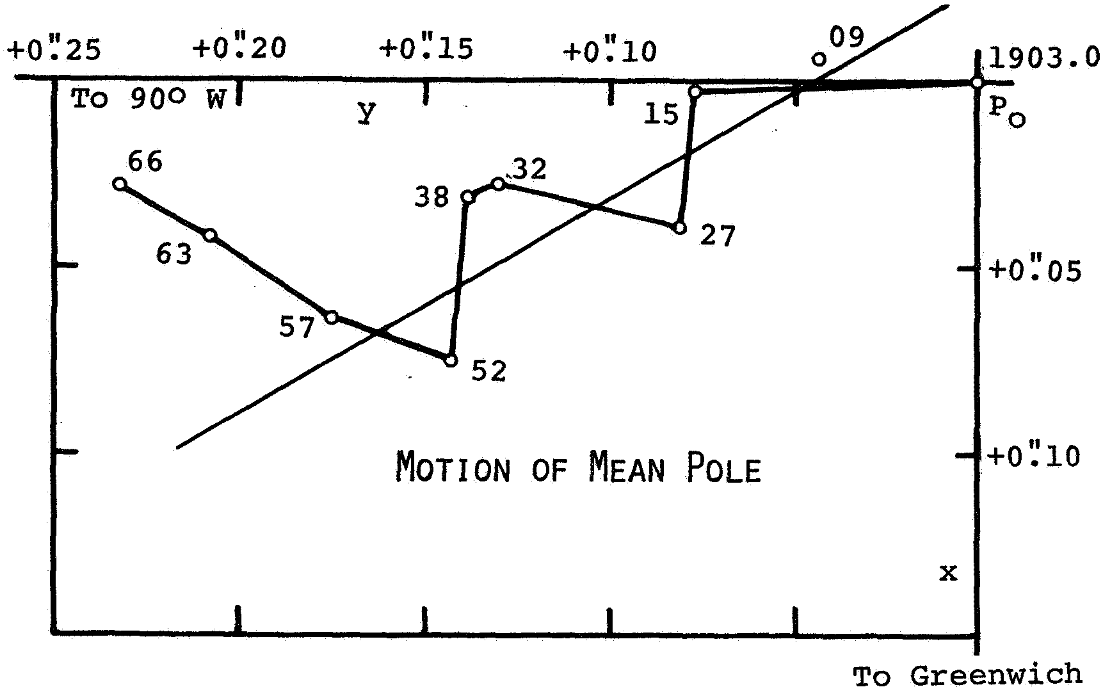

Fig. 6. Motion of mean pole, ILS; 1903.0 to 1966.0. Each point is a 6-year mean.

Table I. Coefficients of parabolas; Unit = 1 second, t is in years from 1960.0.

	a	b	c	α
K_1	-1.487	-0.888	-0.0800	-51 x 10^{-10}/yr
K_2	-1.014	-0.457	+0.0184	+12
K_3	-1.265	-0.178	-0.0576	-32
K_4	+0.480	-0.766	-0.0080	- 5

Table 2. Residuals, R, based on the mean for Washington plus Richmond, and S, the difference; unit=1 millisecond.

	R					S
	.125	.375	.625	.875	yr	yr
1955			+ 9	- 7		
56	+ 2	+ 2	- 3	- 2	0	-6
57	0	+ 6	+ 2	- 6	0	-2
58	-16	- 9	- 2	- 5	- 8	-2
59	- 7	+24	+15	- 4	+ 7	0
60	-11	- 1	+ 3	- 6	- 4	-5
61	+ 5	+15	+ 8	- 9	+ 5	-5
62	- 9	- 8	- 9	-16	-10	+6
63	+ 3	+25	+22	+ 8	+14	+3
64	- 1	- 3	+ 1	-11	- 4	0
65	- 1	+ 3	- 1	-13	- 3	0
66	0	+ 9	- 1	-25	- 4	-2
67	- 9	- 5	+ 1	+ 1	- 3	+1
68	+ 9	+15	+ 8	- 5	+ 7	-2
69	+ 7	- 6				

Table 3. Observational errors and time variations; unit = 1 millisecond.

	1 night	1 mo(16)	1 qtr(3)	1 yr(4)
(a) 1 PZT, external	5	3.8	3.0	1.7
(b) 1 PZT, internal		1.2	2.2	1.5
(c) Systematic error		3.6	2.0	0.8
(d) Obs. error, 2 PZT's		2.7	2.1	1.2
(e) P.E. of R			7.1	4.8
(f) Time variation, V			6.8	4.7

Table 4. Variations in acceleration, speed, and time.

	Secular	Irregular	Seasonal
α	$-1.6\text{x}10^{-10}$/yr	$\pm 80\text{x}10^{-10}$/yr	$\pm 650\text{x}10^{-10}$/yr
σ	($-3\text{x}10^{-7}$)	$\pm 500\text{x}10^{-10}$	$\pm$ $70\text{x}10^{-10}$
Time	(-10,000s)	± 30s	± 0.03s