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ON THE DETERMINATION OF UNIVERSAL TIME AND THE USE OF U. S. NAVAL OBSERVATORY TIME SERVICE BULLETINS NOTICES AND ANNOUNCEMENTS

W. E. FIZELL

MAY 1970

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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CONTENTS

ILLUSTRATIONS

TABLES

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W. E. Fizell

PREFACE

The major part of this report was prepared while the author was a cooperative student from Drexel Institute of Technology working part time in the Timing Systems Section, Space Data Control Branch, during 1967. Upon graduation in 1968 he entered government service as a full time employee and was given the task of summarizing his work in a report as he explored the problems and procedures in the determination of universal time. For this reason, this report gives the general information on time and time determination. The extensive collection of data in time corrections, time variations, coordinated universal time (UT) off-sets, etc., covering the years from 1956 to present is obtained through accumulation through the years as they were issued by the U.S. Naval Observatory in the forms of bulletins, notices, and announcements.

Whenever there were missing data, they were obtained again from U.S. Naval Observatory or through other published or private reports. While it is recognized that all the data contained in this report may be available in different timing laboratories, it is not known, however, that they have been documented in a single report nor have the data been plotted for the length of time as it is done in this report with exception of perhaps the timekeeping agencies such as U.S. Naval Observatory and the National Bureau of Standards.

It is hoped that this report will be of value to those who may not have available all the data contained in this report and also to those who wish to gain preliminary insight and understanding of time and time determination.

A. R. Chi
Head, Timing Systems Section
June 10, 1970

ON THE DETERMINATION OF UNIVERSAL TIME AND THE USE OF U.S. NAVAL OBSERVATORY TIME SERVICE BULLETINS NOTICES AND ANNOUNCEMENTS

I. INTRODUCTION

There are several time scales in current usage which are of prime concern to the time user. For the education and edification of the time user, both NASA employees and others, explanations of the meaning and derivation of atomic and universal time are given here.

In accomplishing this task, use will be made of the U.S. Naval Observatory weekly bulletins which contain values of the three universal time scales, UT0, UT1, and UT2, and the A.1 atomic scale measured with respect to coordinated universal time (UTC), a compromise between atomic and universal time. The values contained in the bulletins are presented in graphical and tabular form to give the reader concrete examples of the meaning of the time scales.

Since it is beyond the scope of this report to expend the time and space necessary to give a complete derivation of the time scales, the explanations are brief but concise; however, references are liberally given for the reader who is interested in a deeper interpretation.

II. TIME SCALES

Basically, two types of time scales shall be considered here: universal time scales, based on the rotation of the earth about its axes; and an atomic time scale, based on the energy difference between two hyperfine states of unperturbed Cesium 133 atoms. As far as is known, this energy difference does not change with time. Therefore a time scale based on this energy difference is uniform. Since the earth's speed of rotation changes with time, universal time scales are not uniform. Bearing these facts in mind, consider some of the time scales.

A. ATOMIC TIME SCALE

A joint program was undertaken between the National Physical Laboratory, Teddington, England and the U.S. Naval Observatory, Washington, D.C., in June 1955 to determine the frequency of Cesium in terms of a second of Ephemeris time. The frequency obtained was 9 192 631 770 ± 20 cycles per second of Ephemeris time during the interval June 1955 to March 1958.[1]

The uniform second interval provided by an atomic frequency source employing the Cesium frequency can be used to generate a system of time if epoch is furnished, since an atomic frequency source does not contain epoch; it merely provides interval. An example of such a system of atomic time is the A.1 time scale maintained by the U.S. Naval Observatory. A.1 time has a rate determined by the second as defined by the CIPM.* The epoch of A.1 time is defined such that at $0^h 0^m 0^s$ UT2 on 1 January 1958 the value of A.1 was $0^h 0^m 0^s$.[3]

1. A.1 System

Originally the A.1 time scale was based on the average of frequencies generated by cesium standards at nine laboratories (Table 1). Although it was the average which was entitled "A.1 time," it was not at all uncommon for an individual laboratory to refer to the time scale generated by its oscillator as A.1 time. Since the inception of the A.1 system, the laboratories contributing to the average have been reduced so that presently A.1 time is based on the mean of a bank of cesium standards kept at the U.S. Naval Observatory.

2. A.3 Time Scale

The A.3 time scale was established by the BIH† in 1958. A.3 consists of the average of phase measurements of radio standard radio frequency emissions in

*In 1967 the 13th General Conference of Weights and Measures defined the second as follows: "The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium atom 133."[2]

† See Bureau International de L'Heure Annual Report for 1968 by Bernard Guinot and Martine Feissel Paris, 1969.

the VLF and LF bands by many laboratories. The origin of A.3 is such that A.3 and UT2 coincided approximately on January 1, 1958. This atomic time scale is maintained by BIH.

B. UNIVERSAL TIME

The universal time is based on the rotational period of the earth about its axis which is subject to the laws of celestial mechanics. Many texts treat the forces governing the rotation of the earth, one of which is Fundamental Constants of Astronomy by Kulikov.[4] Following Kulikov's presentation, the earth's rotational speed is dependent on the moments of inertia about the principal axes. As the axis of rotation changes, the weight given to each moment of inertia changes. Additionally, since the earth is not a rigid body, mass shifts will make the principal moments of inertia variable in time. Corrections for these factors produce the time scales UT0, UT1 and UT2, which will now be discussed.

1. UT0

UT0 is determined from the rate of the apparent diurnal motion of the sun relative to the meridian of Greenwich.

a. Measurement of UT0. The universal time as measured by each observatory without corrections is UT0. One method of observing UT0 utilizes the photographic zenith tube, a telescope mounted in a fixed vertical position, allowing stars to be photographed as they cross the meridian near the zenith. The time of transit is recorded by a clock. The measurement of the position of the star images on the photograph provides data to determine the clock reading at the time the star crosses the meridian. The position of the star is known and the mean solar time at which it was on the meridian may be computed.[5]

This determination assumes the earth is a perfectly rigid body rotating about a unique axis at all times. It therefore does not account for variation of axis and mass shifts. UT0 indicates the rotation of the earth assuming that all conditions are constant.

2. UT1

UT1 is UT0 with correction made for variation of the position of the pole.

a. Polar Variation. The polar position is not fixed and, as discussed earlier, this causes a variation in the UT0 time scale. The actual instantaneous position of the pole is calculated from measurements made by the International Polar Motion Service, formerly the International Latitude Service.

The International Polar Motion Service consists of five stations (Figure 1), each located within a few arcseconds of the 39°08' parallel. These observatories observe latitude utilizing the Horrebow-Talcott method which uses the zenith telescope.[6] Since the observatories are on the same latitude, they are able to use the same star program, eliminating small uncertainties in stellar position from the determination of latitude. Small shifts in each observatory's measurement of a particular star's position may be coordinated to allow a calculation of the observatory's shift in latitude. From the latitude shifts of the five observatories the shift in polar position can be determined.

In Figure 2, the position of the pole with respect to the mean pole of 1900-1905 has been plotted for the period 1956 to 1969.[7] The individual periods of polar motion are shown in Figures 2a through 2k. Upon careful scrutiny of the plots, one can observe a 14-month period. This is the result that was first explained by Newcomb in 1892.[8] In contrast with Euler's theoretical prediction, his explanation takes into account the non-rigidity of the earth.

b. Measurement of UT1. A shift in polar position affects both latitude and longitude. The equations for the corrections in latitude and longitude, respectively, are:

$$\Phi = \Phi_{obs} - x \cos \lambda + y \sin \lambda \qquad (1)$$

$$\Lambda = \Lambda_{obs} - (x \sin \lambda + y \cos \lambda) \tan \phi + y \tan \phi_{Gr} \qquad (2)$$

[10]

where

Φ = astronomical latitude of the observer referred to the mean pole of 1900-1905.

Λ = astronomical longitude of the observer referred to the mean pole of 1900-1905.

Φ_{obs} = astronomical latitude referred to the instantaneous pole.

Λ_{obs} = astronomical longitude referred to the instantaneous pole.

ϕ = geodetic latitude.

λ = geodetic longitude.

$+x$ = pole correction along the Greenwich meridian.

$+y$ = pole correction along the meridian +90° W.

ϕ_{Gr} = the geodetic Greenwich latitude.

(For a description of the astronomical and geodetic coordinates, see the Appendix. A glance at Figure 3 will illustrate the different latitudes for the reader.)

Equation (2) gives the correction for longitude and is thus the quantity that is of interest. The time correction attributable to the polar variation can be determined by dividing Equation (2) by 15. In this way longitude is measured in hour angle instead of degrees. Substituting UT1 for Λ and UT0 for Λ_{obs} and noting $\tan \phi_{Gr} \cong 0$, Equation (2) becomes

$$UT1 = UT0 - \frac{1}{15}(x \sin \lambda + y \cos \lambda) \tan \phi \quad (3)$$

[6]

UT1 is the time measured by correcting the rotation of the earth for polar variation. Notice that several observatories' evaluations of time cannot be compared until Equation (3) is applied to the observation UT0 for each observatory because the observation is dependent on position.

3. UT2

UT2 makes corrections for the empirically-determined seasonal variation in the UT1 time scale.

a. <u>Seasonal Variation</u>. Many of the earth's mass redistributions are seasonal. Some of these seasonal redistributions are due to polar ice movement and ocean displacement. Another obvious effect having seasonal dependence is caused by vegetation, although it does not involve as much mass as the previously mentioned factors.[11] These redistributions of mass cause a change in the earth's moment of inertia.

b. <u>Measurement of UT2</u>. The seasonal effects resulting in redistribution of mass have led to a corresponding seasonal deviation in the universal time scale. The seasonal periodicity in the UT1 scale has been empirically corrected (see Figure 4). For the interval 1962-1968, the correction is given by

$$UT2 - UT1 = 0.022 \sin 2\pi T - 0.012 \cos 2\pi T - 0.006 \sin 4\pi T + 0.007 \cos 4\pi T \quad (4)$$

[12]

where T is measured in fractions of Besselian years.*

C. UTC

1. UTC as a Compromise Time Scale

As mentioned previously, universal time is not a uniform time scale. Consequently, by using an off-set frequency to adjust the rate of an atomic frequency device to that of the long-term trend of UT2, and applying step-time corrections as necessary, a uniform time scale, UTC, is formed which approximates UT2. In creating UTC, one accomplished two things:

(a) A working universal time is created, one which can be used at the moment it occurs instead of being measured afterward when star readings have been made.

(b) A link is provided between the universal time scale and an atomic time scale.

2. Generation of UTC

Coordinated Universal Time (UTC) is generated by applying a frequency offset, announced each year by the Bureau Internationale de l'Heure (BIH), to an oscillator employing the hyperfine resonance of the cesium 133 isotope as its frequency base. In addition to the offset, step corrections as shown in Figure 5 are used to maintain UTC as closely as possible to UT2. The step corrections are announced at the beginning of a month by the BIH. The BIH also announces the offset to be used each year. Changes in offset are made if a different offset will result in fewer step corrections. Changes in offset are made in multiples of 50×10^{-10} and are applied only at the beginning of a year.

3. History of the Frequency Offset

When it was considered desirable to establish a coordinated universal time as discussed in the preceding section, it was necessary to determine a good frequency offset. Individual laboratories had their own conceptions of the best offset and used ones which they thought were appropriate for their purposes. Consequently, to attain a uniform worldwide offset, it is necessary after international agreement on the offset to consolidate to one offset which is announced each year

*The Besselian year begins at the time closest to the beginning of the Ephemeris year at which the right ascension of the fictitious mean sun is 18^h40^m.[13]

by the BIH. Table 2 indicates the offsets used by two laboratories in the United States, NBS and USNO. Notice that they do not agree until 1961 when the BIH became the spokesman for the offset.

4. Change of Format of UTC

While on the subject of UTC, one should mention that consideration is being given to changing the UTC format. The format being considered calls for no offset and step-time corrections to be made whenever UTC differs from UT2 by one second.

D. APPLICATION OF POLAR MOTION AND SEASONAL CORRECTIONS

As an example of the corrections used to refine universal time, consider the Naval Observatory Bulletin, Series 7 of 31 July 1969 (Figure 6), containing the following data:

$$\begin{aligned} UT0 - UTC &= 18 \text{ ms} \qquad &(i) \\ UT1 - UTC &= 23 \text{ ms} \qquad &(ii) \\ UT2 - UTC &= 22 \text{ ms} \qquad &(iii) \end{aligned}$$

$$\begin{array}{cc} x & y \\ +0''.161 & +0''.241 \end{array}$$ [14]

The Bulletin values contained in (ii) and (iii) are the averaged values of three stations located at Washington, D.C.; Richmond, Fla.; and Herstmonceux, England.[14]

Beginning with the observed values of UT0-UTC measured at the Naval Observatory, Washington, D.C., and the x and y coordinates of the pole, one can compute the other Universal times. Using the coordinates of the Naval Observatory, 38°55' N., 77°04' W., Equation (3) is applied to remove polar fluctuation:

$$\begin{aligned} UT1 - UT0 &= -\frac{1}{15}\left\{ x \sin\lambda + y \cos\lambda \right\} \tan\phi \\ &= -\frac{1}{15}\left\{ (.161) \sin(282°56') + (.241) \cos(282°56') \right\} \tan 38°55' \\ &= -\frac{1}{15}\left\{ (.161)(-.97463) + (.241)(.22382) \right\} (.80738) \\ &= .00554^{s.} \approx 6 \text{ ms.} \end{aligned}$$

Combining this result with (i) gives a value for UT1 - UTC of 24 ms which differs from (ii) by 1 ms. It is not at ali unreasonable that one station's value should differ from the three-station mean by an order of 1 millisecond.

Equation (4) allows correction for seasonal fluctuations. For 31 July 1969, T = .578.

$$
\begin{aligned}
UT2 - UT1 &= .022 \sin 2\pi T - .012 \cos 2\pi T - .006 \sin 4\pi T + .007 \cos 4\pi T \\
&= (.022) \sin 2\pi(.578) - (.012) \cos 2\pi(.578) - (.006) \sin 4\pi(.578) \\
&\qquad + (.007) \cos 4\pi(.578) \\
&= (.022)(-.46974) - (.012)(-.88184) - (.006)(.82882) + (.007)(.55950) \\
&= -.00080^{5} \approx -1 \text{ ms.}
\end{aligned}
$$

Combining (ii) with the above result gives

$$UT2 - UTC = 22 \text{ ms}$$

which is in agreement with (iii).

III. UTILIZATION OF U.S.N.O. STORED DATA ON TIME SCALES

Values of universal time and atomic time along with coordinates of the pole have been published by the Naval Observatory. They are presented here in tabular and graphical forms and provide interesting insights into the time scales.

A. USE OF NAVAL OBSERVATORY BULLETINS[14]

Preliminary times, predictions issued two weeks in advance based on observations of UT2, contained in U.S.N.O. Bulletin, Series 7 (Figure 6) are presented in Figure 7. The tables of data compiled from these bulletins are available upon request.

There are six step corrections to UTC in the years 1964-1965. It is obvious from Figure 7 that these step corrections were necessitated by the rather rapid drift of UT2 with respect to UTC. Referring to Figure 5, the increased difference of UT2 and UTC, as shown by the given 100 ms step corrections from 1963 to 1965, can be explained by the change in slope of UT2 - A.1; the offset -150×10^{-10} ceased to be a good approximation to this slope after the middle of 1963. Consequently, at the beginning of 1966, the frequency offset was changed to -300×10^{-10}. As a result of the change, the next step-correction was not required until February, 1968, twenty-five months later. From January, 1966 to February, 1968 the value of UT2-UTC increased 155 milliseconds, from -75 ms to +80 ms. This rather slow increase, compared to the rapid change before 1966, indicates that the offset change was warranted.

Another interesting observation concerning UT2 can be made from Figure 7. From February 14, 1968 to February 12, 1969, an entire period of seasonal variation of UT1 can be observed. Notice, however, that UTC, as represented by a straight line, is still not a close approximation of UT2, indicating that some residual effect still remains in the UT2 time scale.

B. USE OF DATA STORED AT NAVAL OBSERVATORY[7]

The previous discussion was based on predicted times. Accurate ex post facto data regarding the time scales is kept by the Naval Observatory and has been obtained from them in the form of a computer print-out[7]. The data is given daily in the print-out for the years 1956-1969.

Figure 5, previously cited, presents plots of UTC and UT2 vs. A.1, demonstrating the relationships of these time scales. Compared to A.1, UTC approximates UT2 very closely. The frequency offset is just the slope of the UTC curve in Figure 5.

Monthly values of UT1 and UT2 measured against UTC for the years 1956 to 1969 are plotted in Figure 8. The frequent spikelike patterns are due to the step corrections imposed on the UTC system. The spikes were especially evident in the years 1963 to 1965 where numerous one hundred millisecond steps were made. The dashed horizontal lines define the region where UT1 and UT2 are within ±100 milliseconds of UTC. Notice that the step corrections are made to maintain UT2 within this region on the graph. Expressed differently, the step corrections are made on UTC so that the difference between UTC and UT2 remains less than one hundred milliseconds in magnitude.

The regularity of the seasonal correction to UT1 can be observed in Figure 4 where the difference UT2-UT1[7] has been plotted for the three-year period 1956 to 1958. Almost exact repeatability of the yearly pattern is observed through year 1969.

Observed step-time corrections made on UTC are listed as jumps in Table 3. It should be noted that these values are opposite in sign to the step corrections made on the UTC scale. The negative step-time correction in this table means advance of the UTC time.

Knowing the long-term difference between A.1 and UTC[7] and also the step corrections that were made on UTC[7], one can compute, for any given year, the post-corrected frequency-offset that should be used. The procedure is to calculate the rate of the net time deviation, adjusted for the step-time corrections, for a given time interval. The values thus calculated compare favorably with the offsets which were listed by N.B.S. for the years 1958 to 1968. Additionally, the exercise shows the experimental offsets used by N.B.S. for the years 1956 and 1957, which are calculated to be -81×10^{-10} and -88×10^{-10} respectively.

ACKNOWLEDGMENTS

The author is grateful to Dr. R. Glenn Hall of the U.S. Naval Observatory who provided useful information on the offsets used by different laboratories and also provided the author with the computer print-out vital in the presentation of this document. Guidance and encouragement provided by Mr. Andrew R. Chi of Goddard Space Flight Center as well as extensive conversations with him providing information pertinent to the material contained in the report is gratefully acknowledged. A plot similar to Figure 7 was originally released by N.B.S.

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APPENDIX

Briefly, there are two refinements to the topographical surface of the earth, from which the different coordinate systems arise:

(i) the geoid, an equipotential surface, everywhere perpendicular to the force of gravity, which coincides with mean sea level.

(ii) the spheroid, a mathematical figure approximating the geoid formed by revolving an ellipse about its minor, or polar axis.

Geodetic coordinates of a point are determined by the normal at the point to the spheroid.

(i) Geodetic latitude is the angle the normal makes with the equator.

(ii) Geodetic longitude is the angle that the projection of the normal on the equator makes with the projection of some arbitrary fixed origin (usually Greenwich).

Astronomic coordinates of a point are determined by the normal (vertical) at the point to the geoid.

(i) Astronomic latitude is the angle the vertical makes with the equator.

(ii) Astronomic longitude is the angle the projection of the vertical on the equator makes with the projection of some arbitrary fixed point (usually Greenwich).

Further description can be obtained from (9). Figure 3 illustrates the latitudes of the different coordinate systems.

Table 1

Original Contributors to the 1962 A.1 Time Scale Determination by U.S. Naval Observatory

Station	Standard	Weighing Factor* (1962)
U.S. Naval Observatory, Washington, D.C.	A	2
U.S. Naval Observatory, Richmond, Florida	A	2
Naval Research Laboratory	A	1
National Bureau of Standards	L	10
Cruft Laboratory (Harvard University)	A	2
National Physical Laboratory (United Kingdom)	L	10
Swiss Watch Research Lab. (Neuchatel, Switzerland)	L	10
Bagneux (France)	A	1
National Research Council (Canada)	L	0
A: Atomichrons manufactured by National Co.		
L: Laboratory Model of Cs beam standard		

*Weighing factors were subject to change from year to year depending on the status of the cesium standards; i.e. whether they were used for other research studies or just used as frequency standards. Laboratory made cesium standards were given a weighing factor 10 if used as a frequency standard. (Courtesy U.S. Naval Observatory)

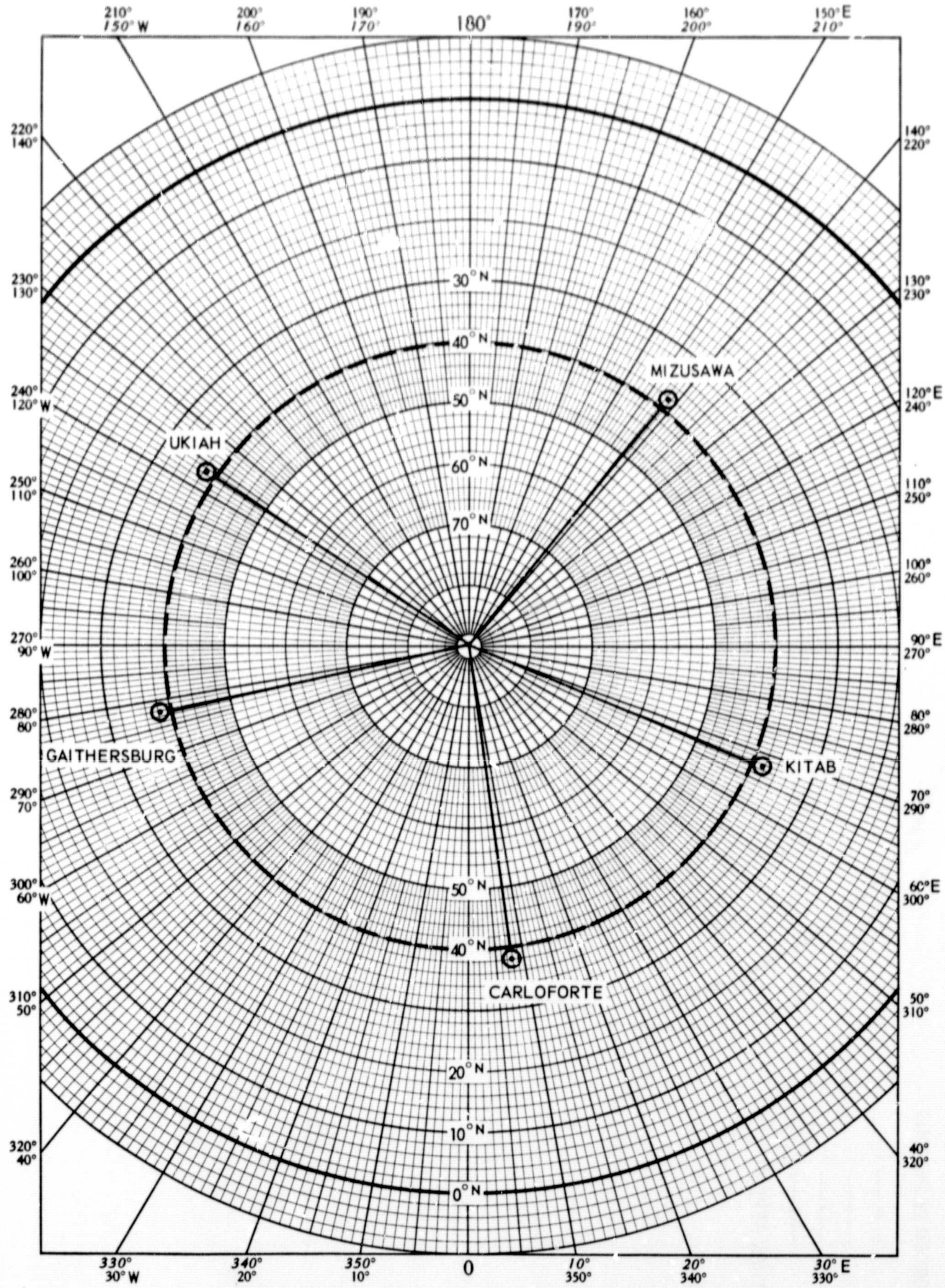

Figure 1. Relative Location of Polar Motion Observation Sites

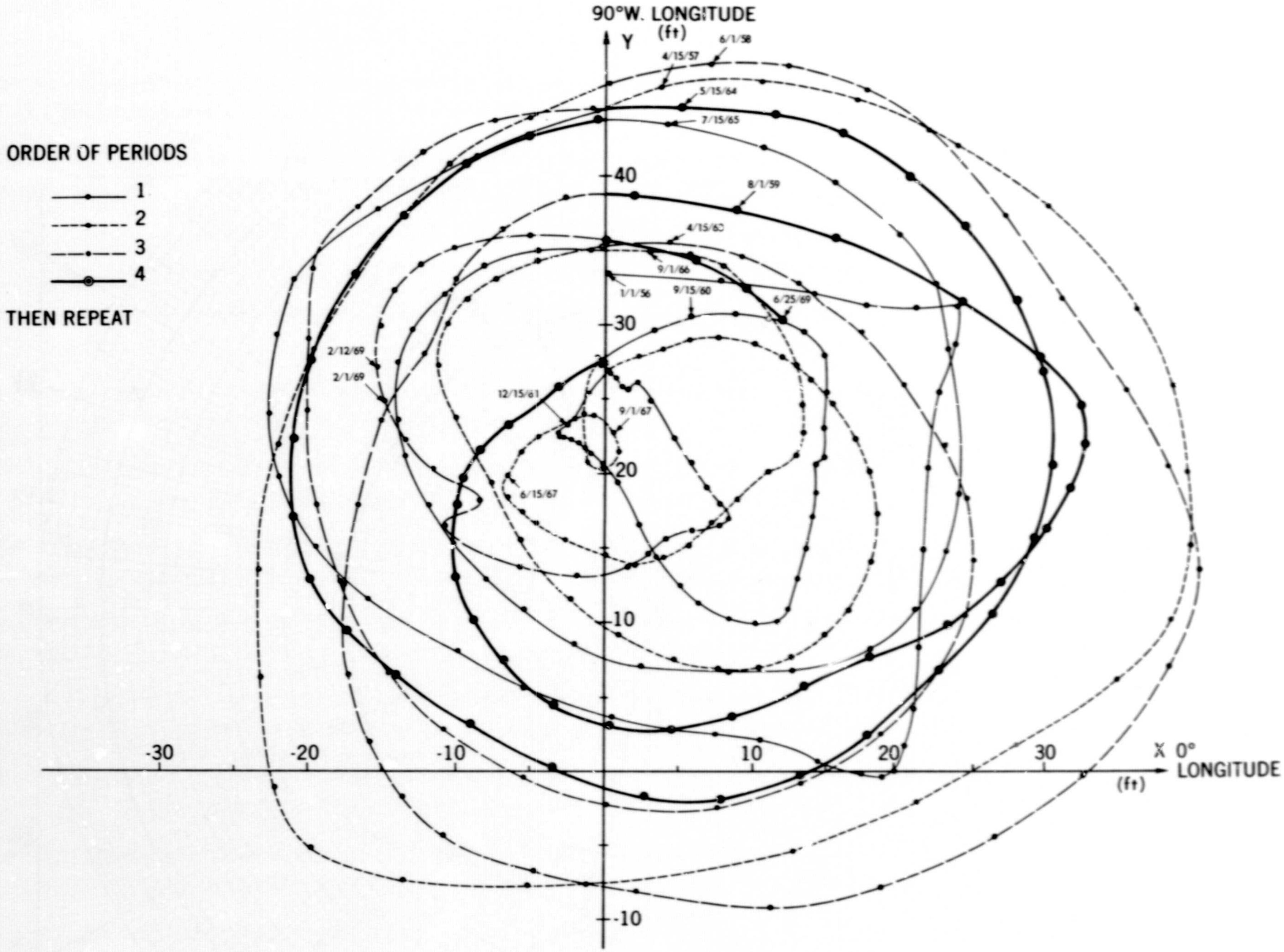

Figure 2. Coordinates of the Pole with Respect to Mean Pole of 1900-1905

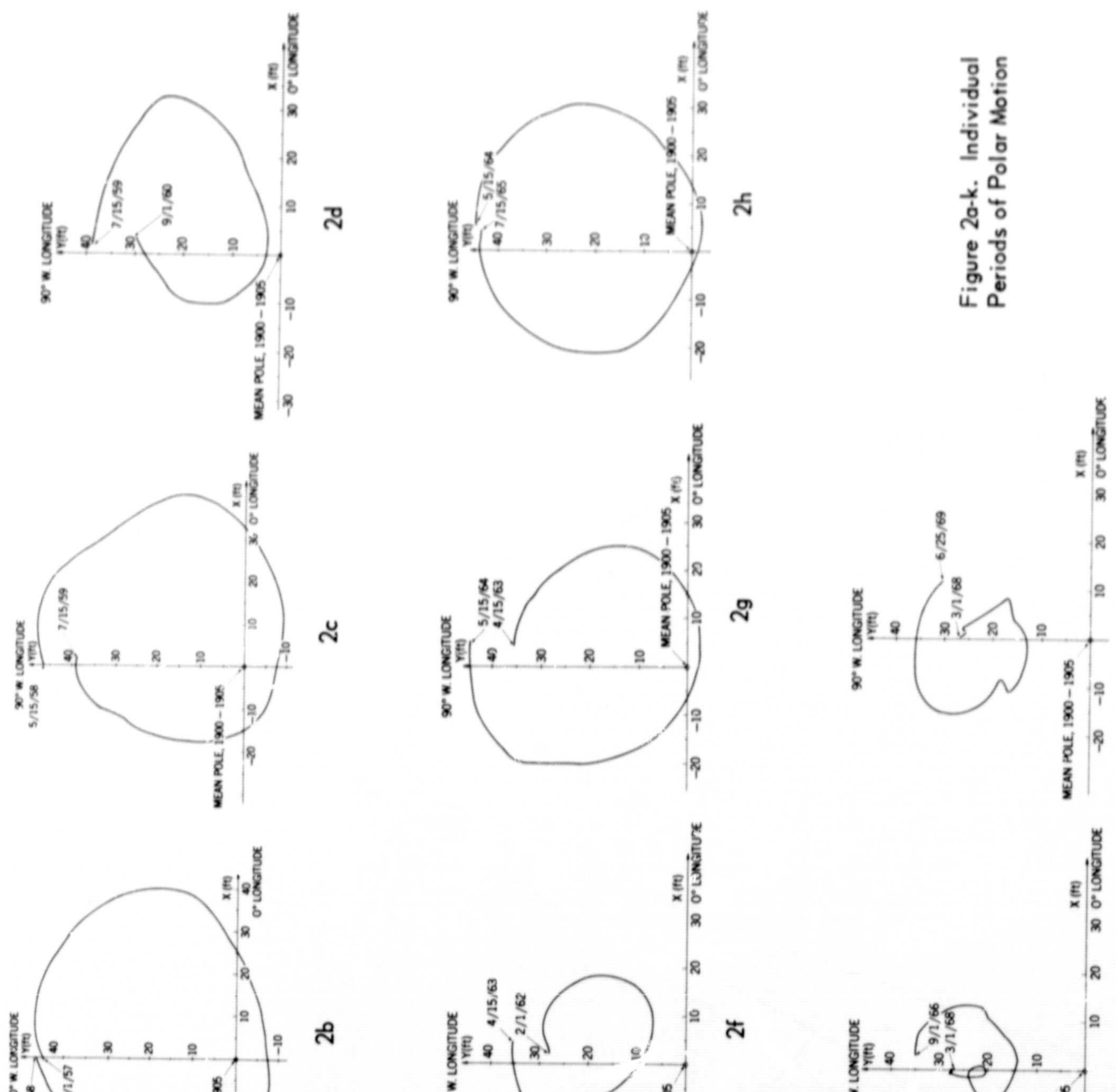

Figure 2a-k. Individual Periods of Polar Motion

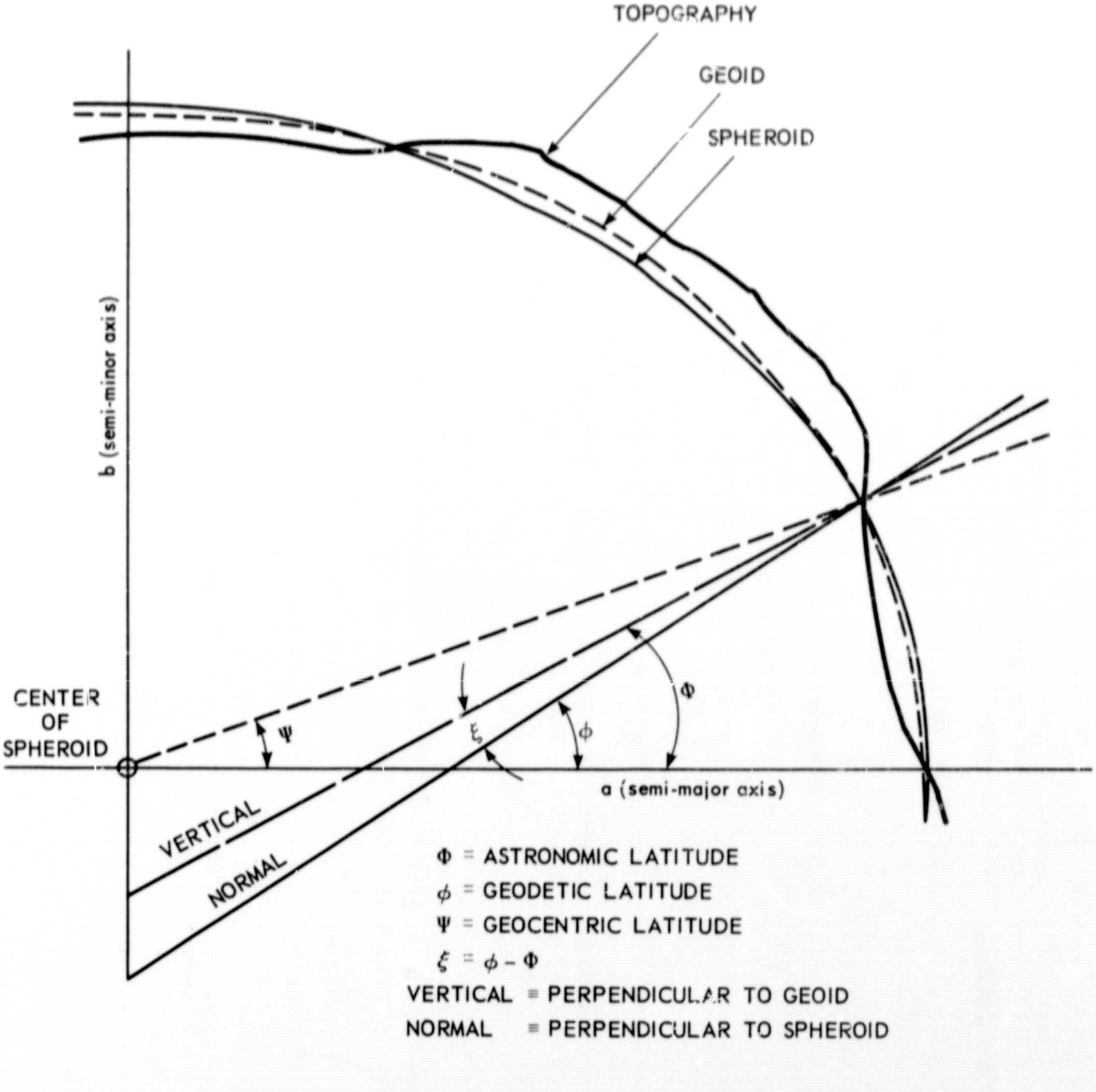

Figure 3. Earth Coordinate Systems

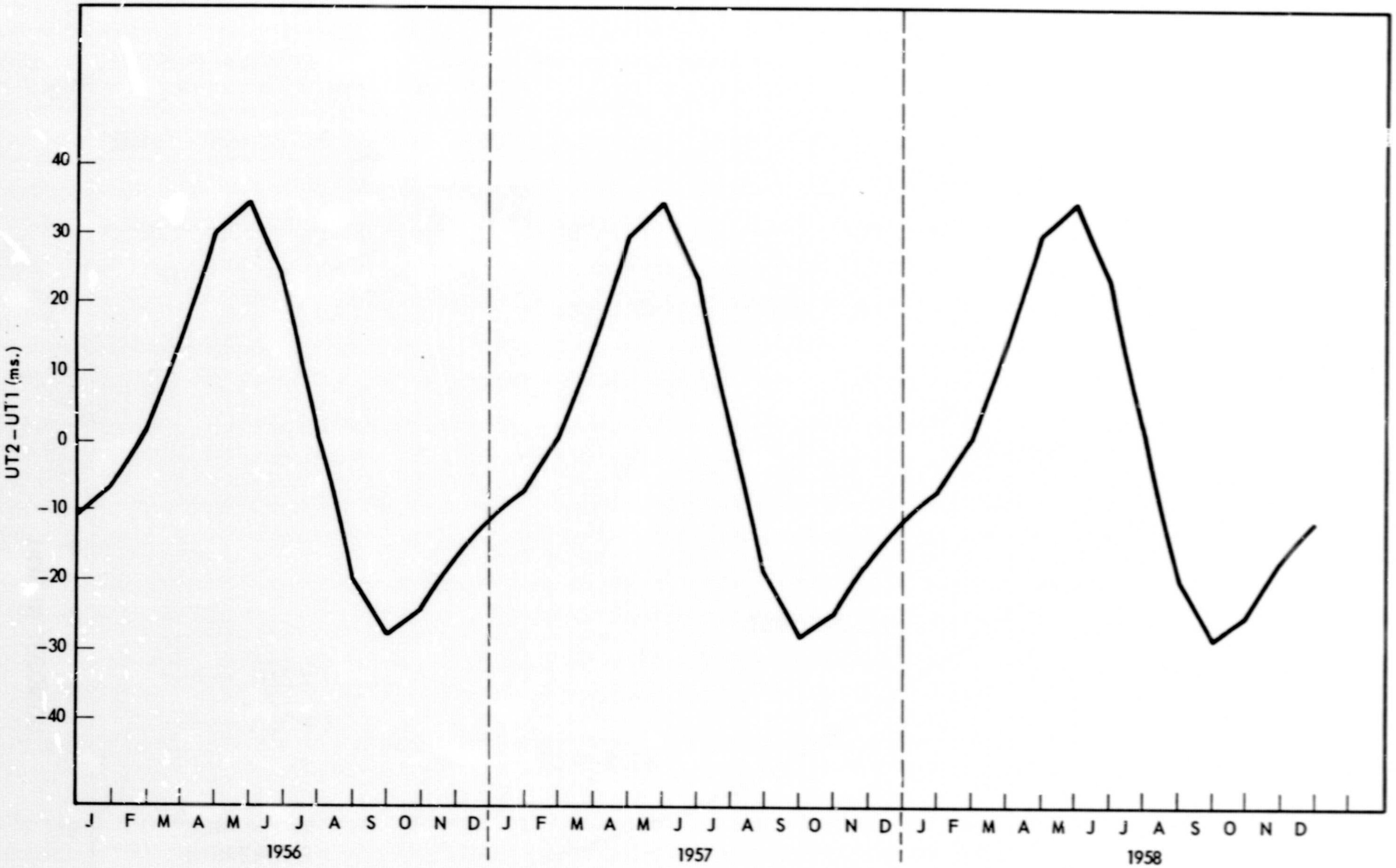

Figure 4. Seasonal Variation of Universal Time (UT2-UT1)

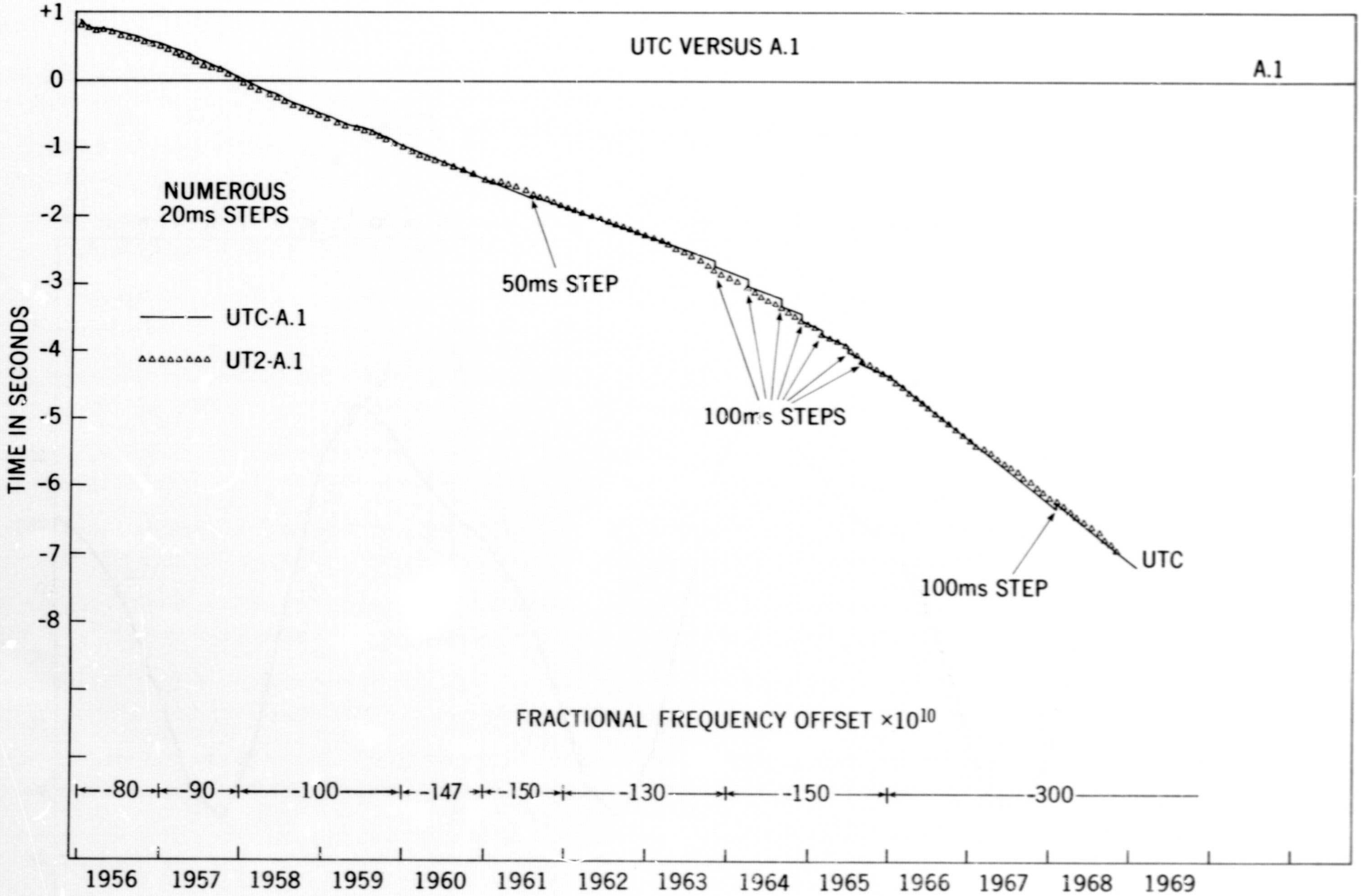

Figure 5. Step-time corrected UTC vs. A.1 Time. The offset frequencies given in lower portion of the figure are those used by NBS, prior to international coordination. See text on pp. 6 and 7.

Table 2

Frequency Offset ($\times 10^{10}$) as Applied to Atomic Time to Generate UTC Time

	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
United States Naval Observatory	-170	-150	-150	-150	-130	-130	-150	-150	-300	-300	-300	-300	-300
National Bureau of Standards (U.S.)	-100	-100	-147	-150	-130	-130	-150	-150	-300	-300	-300	-300	-300
International Agreement Through BIH	—	—	—	-150	-130	-130	-150	-150	-300	-300	-300	-300	-300

U.S. NAVAL OBSERVATORY
WASHINGTON, D.C. 20390

1969 July 31

PRELIMINARY TIMES AND COORDINATES
OF THE POLE, SERIES 7 NO. 83

I. EXTRAPOLATED CORRECTIONS

Extrapolated corrections of coordinated time signals are issued by the U.S. Naval Observatory weekly with the predictions two weeks in advance.

These predictions are based on observations of UT2 made at Washington and Richmond. Linear curves are fitted to the unweighted, nightly results of 1, 2, and 3 months observations at each station separately. The curves are extrapolated and combined into a single value giving Richmond a weight of two and Washington a weight of one. Experience and judgment are used if the results from the 1, 2, and 3 months curve fitting differ extensively, the last observed month being given the largest weight.

Thus the predictions are differences UT2 – UTC(USNO). However, they are usually accurate for all coordinated time signals. The estimated accuracy is about .005 seconds.

Date 0^h UT		MJD	A.1-UTC(USNO)	Extrapolated UT2-UTC(USNO) Rate = 0 ms/day
1969 Aug	7	40440	$7^s.653\ 597\ 7$	$+0^s.020$
	8	40441	7.656 189 7	+ 0.020
	9	40442	7.658 781 7	+ 0.020
	10	40443	7.661 373 7	+ 0.020
	11	40444	7.663 965 7	+ 0.020
	12	40445	7.666 557 7	+ 0.020
	13	40446	7.669 149 7	+ 0.020

JD = MJD +2,400,000.5
ET = A.1 $+32^s.15$

II. PRELIMINARY EMISSION TIMES for Signals from NSS, NBA, GBR, WWV, CHU, and Other Coordinated Stations

The following times for coordinated stations are derived by averaging observations of UT2 – UTC made at Richmond, Florida; Washington, D.C.; and Herstmonceux, England. B.I.H. corrections for each station are used to reduce the individual values of UT0 – UTC to UT2 – UTC before averaging.

The following table gives values of UT0 – UTC, UT1 – UTC, and UT2 – UTC as the differences in the readings of clocks. B.I.H. corrections are used to reduce UT2 – UTC to UT1 – UTC. The value of UT0 – UTC is obtained from UT1 – UTC by correcting for the variation in longitude of Washington as given by the B.I.H. (Conventional Pole.)

UT0 is the reading of a clock which indicates time UT0. Similarly for UT1, UT2, and A.1 "UTC" is the reading of the transmitting clock.

For 30 July 1969 at 1500 UT

UT0 – UTC, $+0^s.018$

UT1 – UTC, + 0.023

UT2 – UTC, + 0.022

A.1 – UTC, 7.634

III. PROVISIONAL COORDINATES OF THE POLE

For 30 July 1969

B.I.H.	x	y
Conventional International Pole	$+0''.161$	$+0''.241$

Figure 6. Naval Observatory Bulletin Series 7 Giving Preliminary Times and Coordinates of the Pole

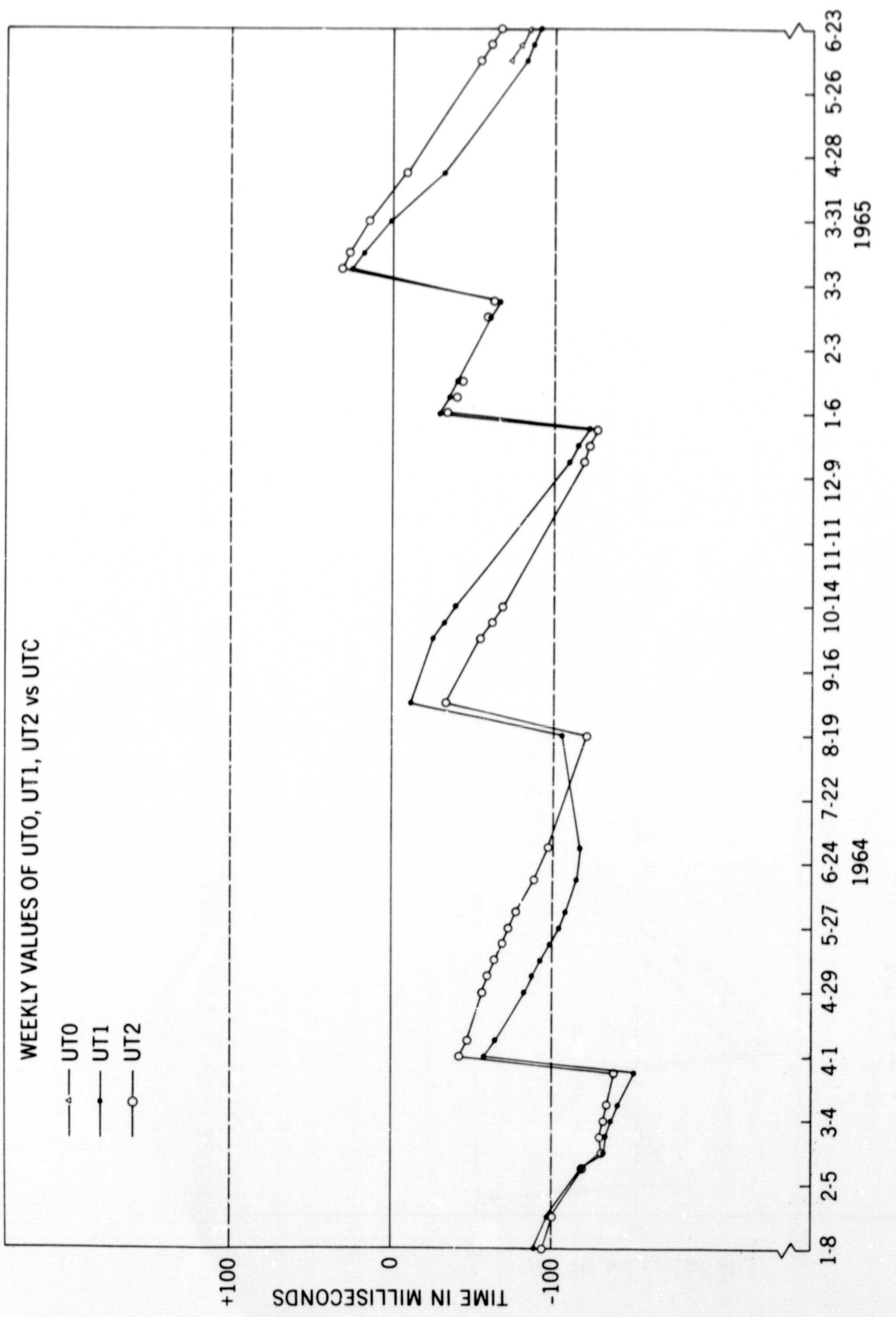

Figure 7a. Weekly Values of UT0, UT1, UT2 vs. UTC

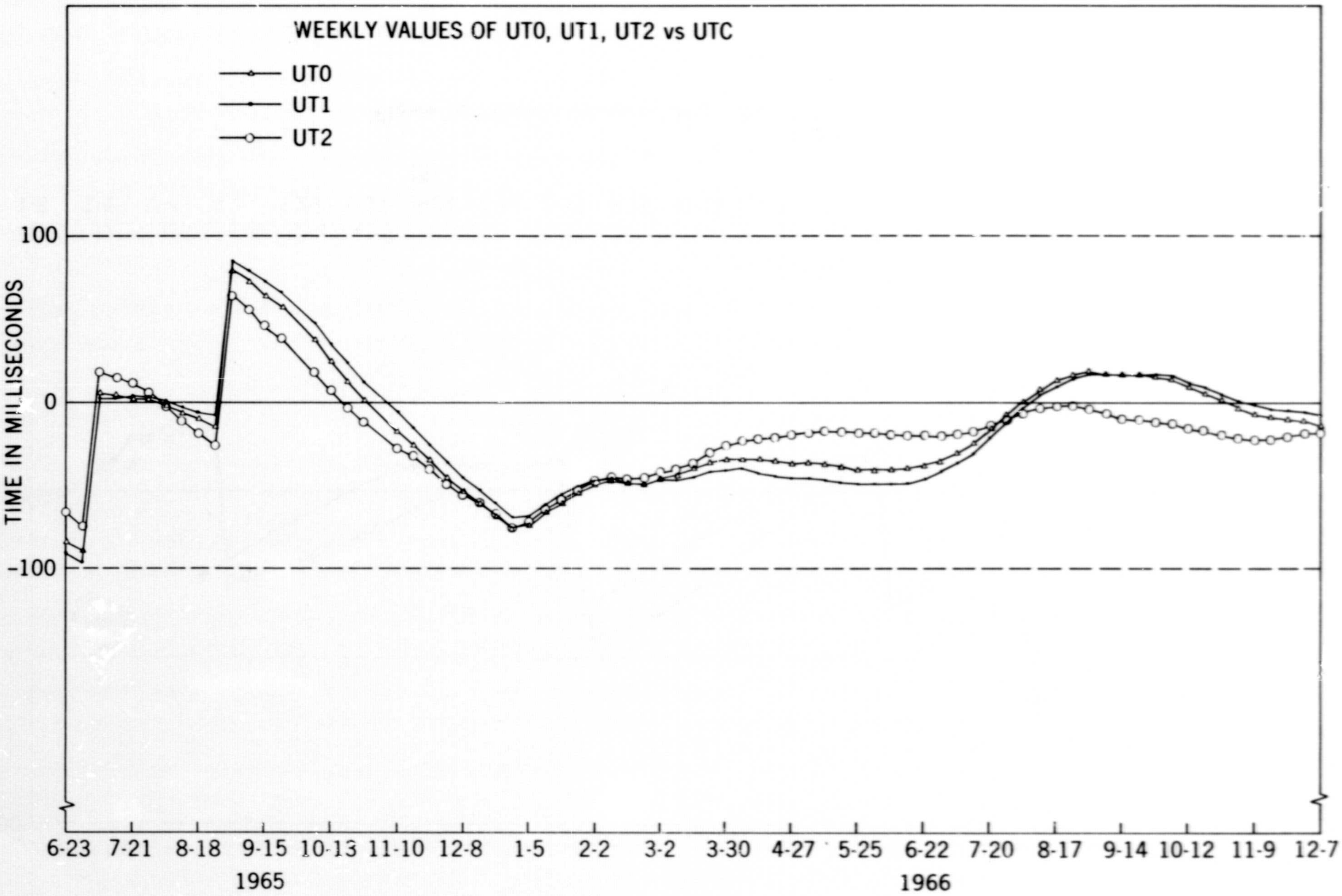

Figure 7b. Weekly Values of UT0, UT1, UT2 vs. UTC

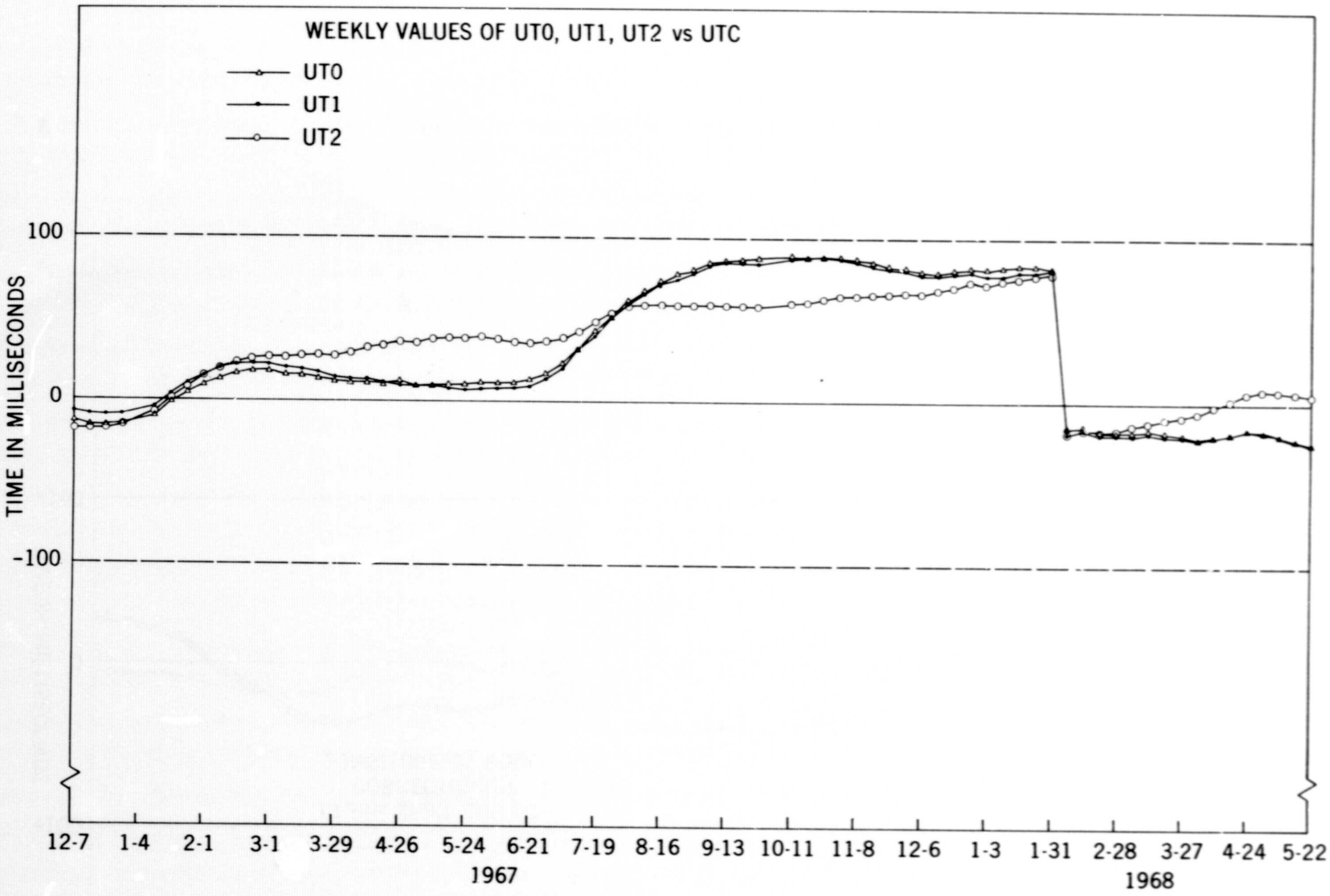

Figure 7c. Weekly Values of UT0, UT1, UT2 vs. UTC

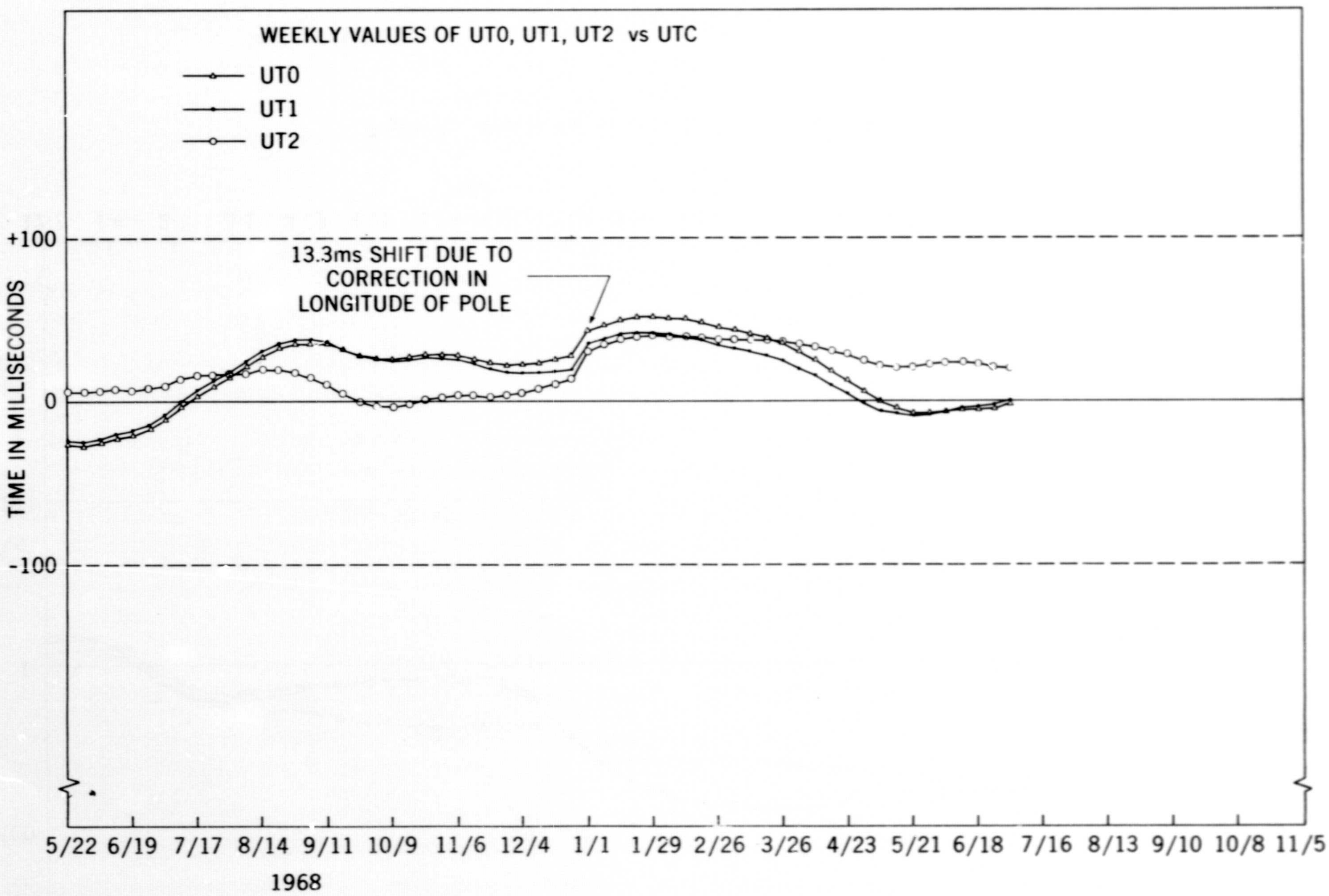

Figure 7d. Weekly Values of UT0, UT1, UT2 vs. UTC

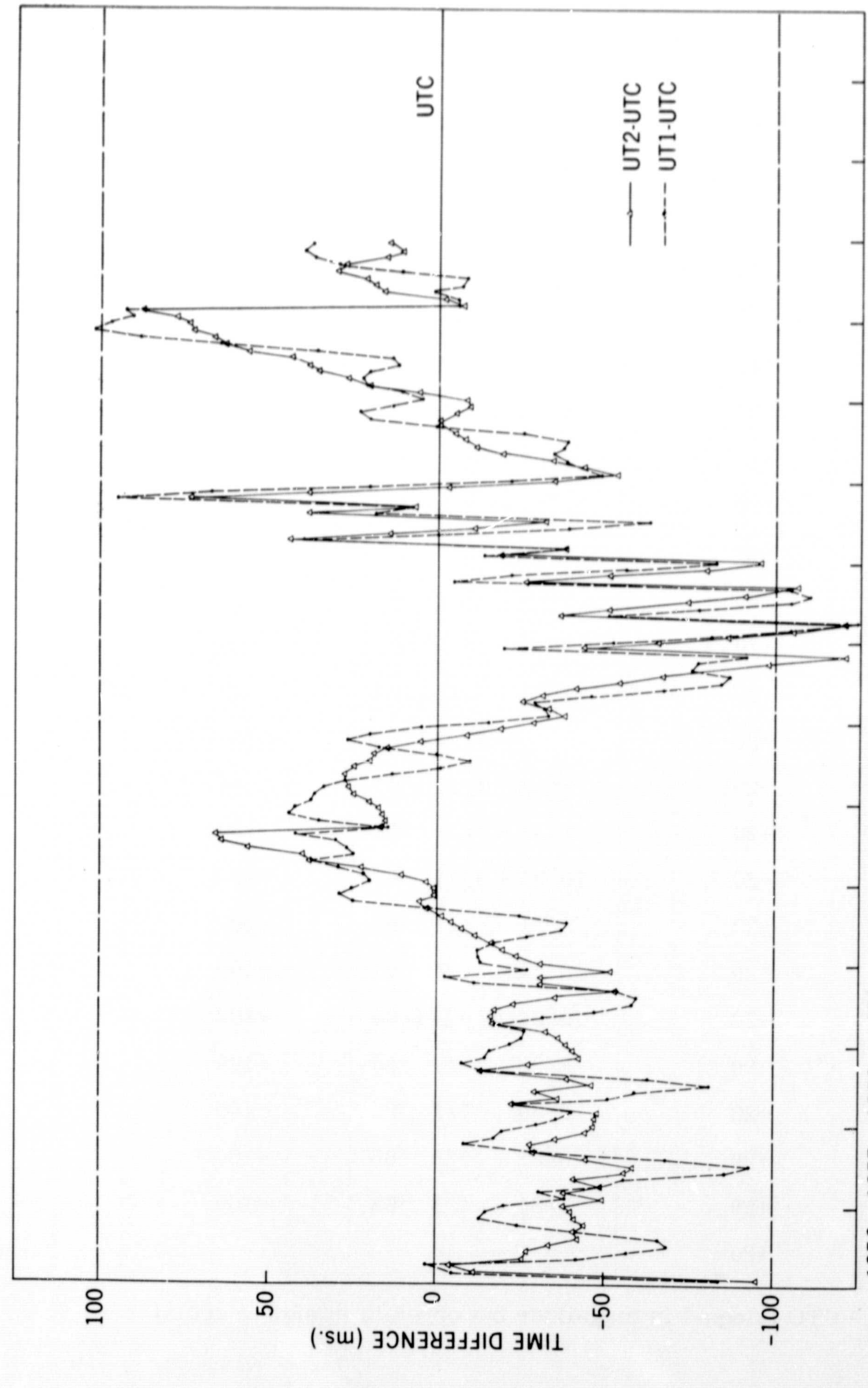

Figure 8. UT1 & UT2 vs. UTC

Table 3

Observed Jumps In Values of A.1 - UTC (UTC Step Corrections)

Interval	Magnitude (ms)	Interval	Magnitude (ms)
1/4 - 1/5 '56	+60	7/2 - 7/3 '58	+20
3/7 - 3/8 '56	-20	7/16 - 7/17 '58	+20
3/28 - 3/29 '56	-20	10/22 - 10/23 '58	+20
7/25 - 7/26 '56	+20	11/26 - 11/27 '58	+20
8/22 - 8/23 '56	+20	12/24 - 12/25 '58	+20
9/19 - 9/20 '56	+20	1/28 - 1/29 '59	+20
10/31 - 11/1 '56	+20	2/25 - 2/26 '59	+20
11/14 - 11/15 '56	+20	8/5 - 8/6 '59	+20
1/23 - 1/24 '57	+20	8/26 - 8/27 '59	+20
3/13 - 3/14 '57	+20	9/30 - 10/1 '59	+20
5/1 - 5/2 '57	+20	11/4 - 11/5 '59	+20
6/5 - 6/6 '57	+20	11/18 - 11/19 '59	+20
6/19 - 6/20 '57	+20	12/16 - 12/17 '59	+20
7/13 - 7/14 '57	+20	12/31/60 - 1/1/61	+5
7/17 - 7/18 '57	+20	7/31 - 8/1 '61	-50
8/14 - 8/15 '57	+20	10/31 - 11/1 '63	+100
10/16 - 10/17 '57	+20	3/31 - 4/1 '64	+100
11/6 - 11/7 '57	+20	8/31 - 9/1 '64	+100
12/11 - 12/12 '57	+20	12/31/64 - 1/1/65	+100
1/15 - 1/16 '58	+20	2/28 - 3/1 '65	+100
2/5 - 2/6 '58	+20	6/30 - 7/1 '65	+100
2/19 - 2/20 '58	+20	8/31 - 9/1 '65	+100
4/9 - 4/10 '58	+20	1/31 - 2/1 '68	-100
6/11 - 6/12 '58	+20		

Note: Change of A.1 - UTC is equal in magnitude but opposite in sign to actual change of UTC.