# 2.1. CONCURRENT ASTRONOMICAL OBSERVATIONS FOR STUDYING CONTINENTAL DRIFT, POLAR MOTION, AND THE ROTATION OF THE EARTH

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ABSTRACT

The analysis of 66 years of concurrent latitude observations of the ILS shows that the mean pole has a secular motion which consists of a progressive component of about $0\overset{''}{.}0035$/yr (10 cm/yr) along the meridian 65°W and a librational component (oscillation) of 24-year period along the meridian 122°W (or 58°E). Crustal displacements in latitude are not found within the errors of observation, about 1 cm/yr.

Comparable, concurrent observations for time (longitude) have not been made but programs are being organized. From 30 to 50 years will be needed for detection of continental drift with PZT's and astrolabes if relative drifts in longitude of 3 cm/yr are occurring.

RÉSUMÉ

L'analyse de 66 années d'observations de latitude par le SIL montre que le pôle moyen a un mouvement séculaire qui consiste en une composante linéaire d'environ $0\overset{''}{.}0035$ par an (10 cm/an) le long du méridien +65° et en une libration de 24 ans de période le long du méridien +122° (ou −58°). On n'a pas trouvé de déplacements de la croûte dans la limite des erreurs d'observation, soit environ 1 cm/an. Des observations associées comparables, pour le temps (longitude), n'ont jamais été faites, mais on est en train d'organiser des programmes. 30 à 50 ans seront nécessaires pour mettre en évidence des dérives continentales avec des lunettes photographiques zénithales et des astrolabes, si des dérives en longitude de 3 cm/an se produisent.

## 1. Introduction

Concurrent observations are defined to be those made by the stations of a chain which observe stars in common. Such observations are important because the polar motion derived from a chain with sufficient stations is independent of errors in the star positions. Three stations suffice if latitude only is determined.

This paper analyzes the concurrent observations made during 66 years, 1900·0 to 1966·0, by the International Latitude Service chain (ILS) at latitude +39°. The progressive and 24-year librational components of the secular motion found in 1960 (Markowitz, 1960, 1961) have continued since then. Relative crustal displacements are not found. However, continental drift may be occurring in longitude. No long series of concurrent time (or longitude) observations exists, however.

Concurrent observations in longitude may be obtained with PZT's and astrolabes

*Markowitz and Guinot (eds.), Continental Drift*, 25–32. © *I.A.U.*

by revising the observing programs of instruments which are suitably located in latitude. The errors of observation and the time required for detection are discussed.

## 2. Independence from Declinations Used

It has been stated often that errors in star positions (and proper motions) effect the determination of the pole by the ILS. Let us analyze the equations used to determine the coordinates of the pole, $x$ and $y$, from three or more stations.

Let $\delta$ be the average apparent declination of a star pair and let $\zeta_i$ be the average north Zenith distance as observed at station $i$. Then the observed latitude is

$$\varphi_i = \delta - \zeta_i . \tag{1}$$

Let $\varphi_{i0}$ be a set of adopted constants, called the initial latitudes. Then, by definition, the variation in latitude is

$$\Delta\varphi_i = \varphi_i - \varphi_{i0} . \tag{2}$$

The equation of condition used in the least squares solution is

$$\Delta\varphi_i = x \cos \lambda_i + y \sin \lambda_i + z , \tag{3}$$

where $\lambda_i$ is the longitude of station $i$, and $z$ is a constant. The solutions are

$$x = \Sigma a_i \, \Delta\varphi_i , \quad y = \Sigma b_i \, \Delta\varphi_i , \quad z = \Sigma c_i \, \Delta\varphi_i . \tag{4}$$

The coefficients have the properties, for $i \geqq 3$,

$$\Sigma a_i = 0 , \quad \Sigma b_i = 0 , \quad \Sigma c_i = 1 . \tag{5}$$

It can be shown from Equations (2), (4), and (5) that

$$x = A - \Sigma a_i \zeta_i , \quad y = B - \Sigma b_i \zeta_i , \quad z = C - \Sigma c_i \zeta_i , \tag{6}$$

where

$$A = - \Sigma a_i \varphi_{i0} , \quad B = - \Sigma b_i \varphi_{i0} , \quad C = \delta - \Sigma c_i \varphi_{i0} . \tag{7}$$

Hence, $x$ and $y$ do not depend upon the $\delta$'s used.

## 3. Secular Motion of the Pole

The secular motion of the pole previously found consists of a progressive motion of 0''.0032/yr (10 cm/yr) along the meridian 60° West and an oscillating (librational) motion of 24-year period along the meridian 122°W (or 58°E). See page 350 of (**1**).

The position of the mean pole at 6-year intervals up to 1957·0 as shown in Figure 10 of (**1**) was based on results published by G. Cecchini. Figure 1 of this paper shows an additional point, for 1963·0, based on results published by Yumi and Wakō (**3**). The

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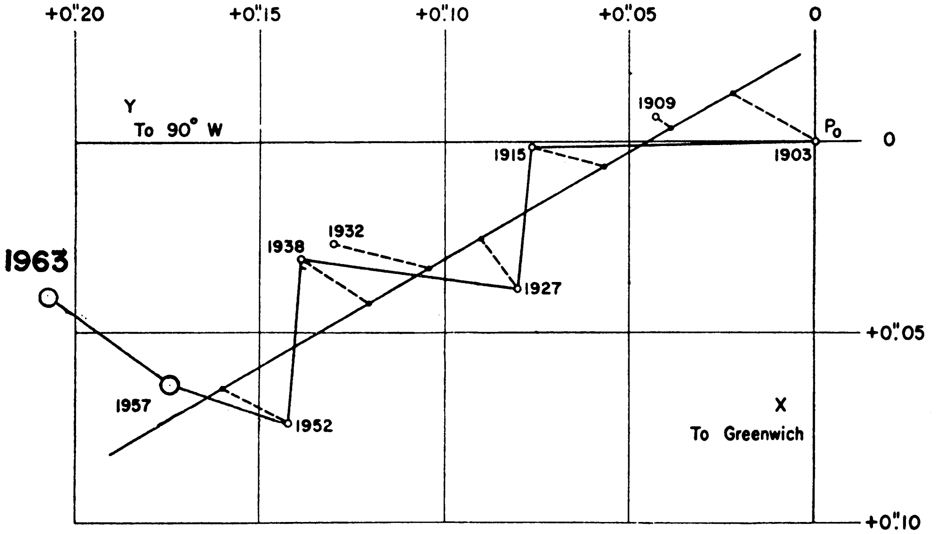


FIG. 1. *Motion of mean pole for 6-year intervals. Origin is pole of 1903·0. The 1963 point was added to a figure drawn previously. The 1957 point was moved slightly.*

location of the 1963·0 point agrees very well with that to be expected from the motions previously found. The presence of the 24-year term is surprising. It is purely empirical, since we do not know of any geophysical phenomenon with this period.

## 4. Variations in Latitude

Table 1 gives mean values of the $\Delta\varphi_i$, $x$, $y$, and $z$ for 6-year intervals for Mizusawa, Kitab, Carloforte, Gaithersburg, and Ukiah. (Kitab was not in operation until about 1930, so that $\Delta\varphi_k$ for 1903 is not an observed value.)

**Table 1**

**Variations in latitude, $\Delta\varphi_i$, and solutions**

(Unit $= 0''.001$)

| Nominal epoch | *M* | *K* | *C* | *G* | *U* | *x* | *y* | *z* |
|---|---|---|---|---|---|---|---|---|
| 1903·0 | 0 | (0) | 0 | 0 | 0 | 0 | 0 | 0 |
| 27 | −205 | −181 | − 85 | − 46 | −65 | +39 | + 80 | −117 |
| 32 | −225 | −231 | −104 | + 2 | −17 | +27 | +130 | −116 |
| 38 | −153 | −123 | − 36 | +116 | +79 | +31 | +139 | − 37 |
| 52 | −213 | −160 | − 13 | + 92 | +18 | +74 | +142 | − 64 |
| 57 | −277 | −248 | − 80 | + 65 | − 3 | +63 | +173 | −116 |
| 63 | −340 | −274 | −131 | + 45 | +74 | +40 | +207 | −132 |

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## Table 2

**Corrected Variations, $\Delta\varphi_i'$**
(Unit = 0″.001)

| Nominal epoch | *M* | *K* | *C* | *G* | *U* |
|---|---|---|---|---|---|
| 1903.0 | 0 | (0) | 0 | 0 | 0 |
| 27 | − 88 | − 64 | +32 | + 71 | + 52 |
| 32 | −109 | −115 | +12 | +118 | + 99 |
| 38 | −116 | − 86 | + 1 | +153 | +116 |
| 52 | −149 | − 96 | +51 | +156 | + 82 |
| 57 | −161 | −132 | +36 | +181 | +113 |
| 63 | −208 | −142 | + 1 | +177 | +206 |

Essentially, $z$ represents the error in the variation of latitude due to the average error in the star places for the interval. We can correct this by subtracting $z$. Table 2 gives $\Delta\varphi_i' = \Delta\varphi_i - z$.

The corrected variations in latitude are plotted in Figure 2. The dashed lines are the

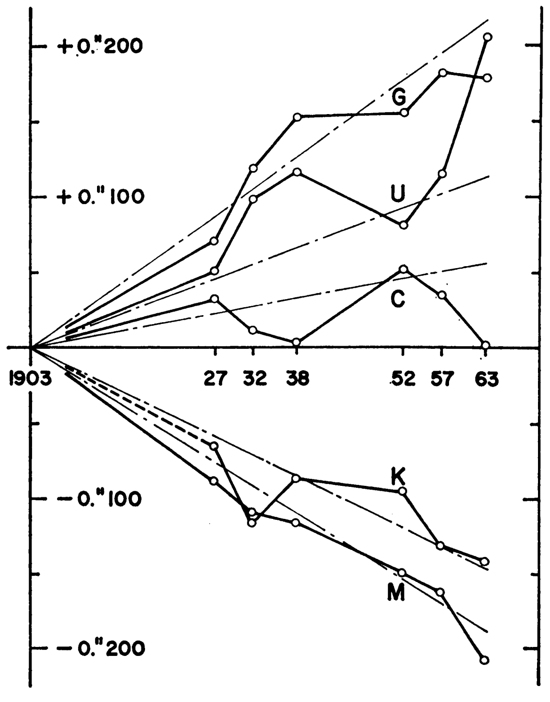


FIG. 2. *Variation in latitude for 6-year intervals. Origin is pole of 1903·0. The ordinates are $\Delta\varphi_i' = \Delta\varphi_i - z$. The dashed lines represent the variations which would have occurred if the mean pole had moved 0″.210 in 60 years along longitude 65° W.*

variations which would have occurred if the mean pole had moved 0″.210 in 60 years along a straight line inclined $+65°$ to the $x$-axis. The average speed is 0″.0035/yr (10 cm/yr).

If the pole moves an amount $H$ in the direction 122°W then the latitudes will change by $H$ times the following factors: $M, -\cdot 12$; $K, -\cdot 99$; $C, -\cdot 64$; $G, +\cdot 71$; $U, +1\cdot 00$. Hence, the librational motion should produce oscillations in the variation of latitude of the same phase for Mizusawa, Kitab and Carloforte, and of the opposite phase for Gaithersburg and Ukiah. Furthermore, the oscillation for Mizusawa should be very small. This is what Figure 2 shows. The small amplitude for Mizusawa is noteworthy, because it has been frequently asserted that this station undergoes crustal displacements.

## 5. Non-polar Variations

Observed variations in latitude could be due to effects other than polar motion. We divide these into two classes: Type 1, which would necessarily affect all instruments on a station alike, and Type 2, which would not. Examples are:

1a. Crustal displacements.
1b. Changes in direction of gravity.
2a. Changes in refraction.
2b. Changes in properties of instruments.
2c. Changes in observers, or in their personal equations.

Instruments on the same station, such as meridian circles, Zenith telescopes, PZT's, and astrolabes exhibit systematic variations which persist for weeks, months, and longer. Hence, Type 2 effects exist. Type 1 are only conjectured – as yet.

## 6. Errors of Observation

When comparing observed motions with probable errors to judge whether the pole has moved secularly or whether crustal displacements have occurred it is necessary that external probable errors be used, and not theoretical, internal probable errors. If $e_1$ is the p.e. for one observation then the theoretical p.e. for $n$ observations, $e_n = e_1/n^{\frac{1}{2}}$, is the correct probable error to use only if the observations are independent. Experience shows, however, that systematic effects generally occur, such as type 2, and the external p.e. is greater than $e_n$.

I have obtained probable errors for mean $\Delta\varphi_i$ as follows:

| *Interval* | *Internal* | *External* |
|---|---|---|
| 1 night | — | 0″.05 |
| 1 year | 0″.004 | 0″.022 |
| 6 years | 0″.009 | 0″.015 |

The external value for one night was obtained from the night to night differences within a month (same groups observed during the month). The external value for one year was obtained from residuals $v_i = (o-c)_i$, published by Yumi and Wako (3). A residual is the difference between the observed $\Delta\varphi_i$ and the computed value obtained by the use of equation (3) and the yearly solutions for $x$, $y$, and $z$. The external value for six years was obtained similarly from Table 1, above. The internal errors were based on the number of nights or the years in the interval.

The p.e. of a coordinate is obtained from equation (4). Using 0″.015 for the p.e. of a 6-year mean $\Delta\varphi_i$ we obtain p.e.'s of 0″.011 for $x$ and 0″.009 for $y$ for a 6-year interval. These values indicate that the progressive and librational motions shown in Figure 1 are not due to accidental causes.

Crustal displacements would be indicated by systematic departures in Figure 2 of the observed variations in latitude from the dashed lines. The existence of the 24-year oscillation of the pole increases the uncertainty of detecting such displacements. A study of the results indicates that crustal displacements in latitude, if they exist, were less than 0″.02 in 60 years. This rate is 0″.00033/yr, or 1 cm/yr.

## 7. Choice of Origin

A fixed origin for describing the polar motion is a necessity from a computational standpoint. The ILS pole, which is independent of errors in star positions, provides the fundamental polar motion. Determinations made with other instruments must be adjusted systematically so as to be in accord with the ILS system.

An examination of the equations in Section 2 shows that the origin for the ILS polar motion is defined by the constants $\varphi_{i0}$. In 1959 G. Cecchini adopted the following $\varphi_{i0}$:

| | $\varphi_{0i}$ | $\lambda_i$ |
|---|---|---|
| Mizusawa | 39° 8′ 3″.602 | − 141° |
| Kitab | 1″.850 | − 67° |
| Carloforte | 8″.941 | − 8° |
| Gaithersburg | 13″.202 | + 77° |
| Ukiah | 12″.096 | + 123° |

These define an origin which he called the "new system, 1900–05". It is called the pole of 1903·0 for short. This origin has been widely used for some time, and is a logical choice for the fixed origin.

## 8. Detection of Continental Drift

The p.e. for one year of observation in latitude by an ILS station is 0″.022. I have previously found a p.e. of 0ˢ.002 (in time) for one year of observation with a PZT (4).

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This corresponds to about 0".02 along a great circle, so that the probable errors are similar. The equivalent distance is 0·6 m. The probable error of the difference in latitude or longitude for a pair of stations is thus about 1 m.

Although we have not detected continental drift in latitude from the ILS results, such drift may occur in longitude. Assuming a drift rate of 3 cm/yr, it will require 33 years for a drift of 1 m, which corresponds to 0".03. This is a small quantity to detect definitely, because of possible systematic effects. It might not be possible to be assured that drift had occurred until the total drift was about 2 m or 0".06. Thus, a chain of PZT's or astrolabes would require about 50 years to detect continental drift if the rate is 3 cm/yr. The time would be diminished, perhaps to 30 years, if a number of chains were in operation. It is not necessary that observations be made continuously. The astrolabe is a portable instrument and it could be used at several latitudes in a cyclic manner.

A complicating factor in detecting continental drift is that secular changes in latitude and longitude due to drift must be separated from those due to the secular motion of the pole. For this reason, continued observations by the ILS are necessary. The preceding consideration does not apply in the satellite methods in which the distances between stations are determined directly, as in the corner-reflector laser method.

## 9. Speed of Rotation

A comparison of UT2 obtained with the Washington and Richmond PZT's versus atomic time, A.1, shows that the earth's rotation is subject to sudden changes in acceleration but not in speed. Sudden changes in acceleration occurred about September 1957 and January 1962. No correlation with the motion of the mean pole is evident. However, another 20 years of additional observation are needed for more detailed study.

## 10. Discussion

Numerous attempts have been made to explain the observed secular changes in latitude of the ILS stations by crustal displacements, in whole or in part, rather than by a secular motion of the pole. The stations most frequently supposed to be drifting are Mizusawa and Ukiah. A test of this hypothesis is to compute the polar motion for various combinations of two stations at a time using the data in Table 2. In all cases, including the Carloforte–Gaithersburg combination, which makes no use of either Mizusawa or Ukiah, the motion obtained is similar to that shown in Figure 1. Hence, crustal displacements cannot cause the motion shown by Figure 1.

Yumi and Wako (3) have assigned about half the secular change in latitude of Mizusawa and Ukiah to progressive crustal drifts of opposite sign. They base this hypothesis on the fact that the residuals $v_i$ for the years near 1963 are larger than for the years near 1936. However, the $v_i$ during the 10-year interval from 1950·0 to 1960·0 are the smallest of any similar interval from 1900·0 to 1966·0. If the hypothesis were correct it would mean that from 1950 to 1960 the two stations were back in their initial positions.

Hypotheses of crustal displacement, moreover, cannot account for the agreement (or opposition) of phase shown by Figure 2 and for the small amplitude shown by Mizusawa.

The secular motion of the pole is judged to be real and has been detected because it is relatively large, about 10 cm/yr. Crustal drifts have not been detected because the drift rate in latitude for the ILS stations is small, 1 cm/year or less.

Attempts have been made to prove that secular changes in longitude, not due to polar motion, have occurred. The observations used were non-concurrent. Also, different instruments, star lists, and methods of receiving time signals have been changed from time to time, and instruments were changed in location, as at Washington, Richmond, and Ottawa (**5**).

Such heterogeneous data cannot be used to detect continental drift. However, concurrent observations for time and latitude, made in the future with PZT's and astrolabes, and combined with continuing ILS observations may detect continental drift in the next 30 to 50 years. There is the possibility of course, that the laser method may detect such drift much sooner.

Additional details of the topics discussed here will be published in the *Bulletin Géodésique*.

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