which moves from west to east so as to track the star during exposures of 20 sec.

Four exposures are made of each star. The upper part of the PZT, which contains the lens and plate-carriage, is rotated as a unit through 180° between exposures. The distance between pairs of images, measured in the north–south direction, is twice the zenith distance.

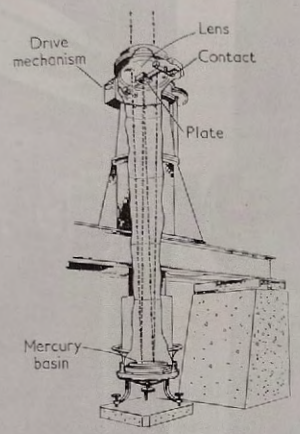

Fig. 2. Schematic view of PZT.

The moving plate-carriage initiates timing pulses during the exposures, which are recorded by a chronograph or directly compared with a clock. Measurement of the plate enables time to be determined.

The aperture of the Washington PZT is 8 in. and the focal length is 180 in. The PZT may be programmed for automatic operation during the night.

The probable errors for one night are 0″·06 in latitude and 0^s·005 in time.

C. *Danjon Astrolabe* [10]

The essential parts of this instrument are: an objective whose optical axis is horizontal, a 60° prism placed in front of the objec-

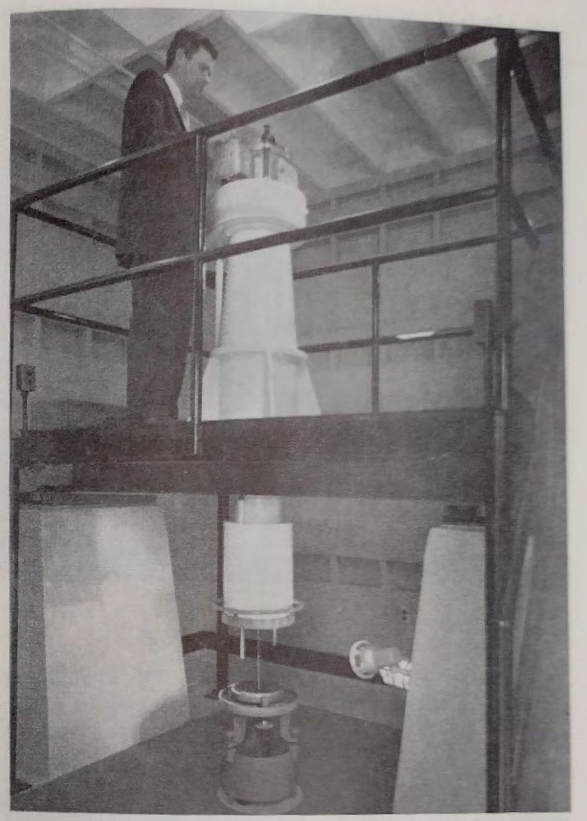

Fig. 3. PZT No. 3, U.S. Naval Observatory
(Official U.S. Navy Photograph).

tive, a basin of mercury, a Wollaston prism, and a viewing eyepiece. Direct and reflected rays from the star enter the 60° prism, forming two images. The diurnal motion of the star causes these images to move. The altitude of the star is 60° when the images coincide.

The moment of coincidence would be difficult to determine, so a Wollaston prism is placed in the optical path. Four images are produced, whose separation depends upon the position of the

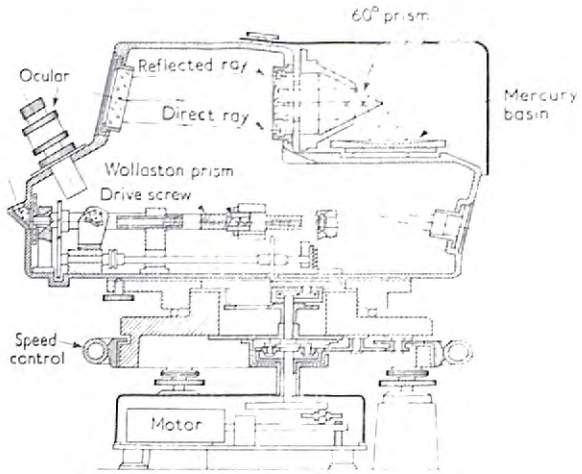

Fig. 4. Schematic view of Danjon astrolabe

Wollaston prism. Two images are suppressed. The separation of the two that remain depends upon both the position of the Wollaston prism and the altitude of the star. By moving the prism at the proper speed the motion in altitude may be cancelled and the separation remains fixed. In operation, the observer controls the speed of the Wollaston prism so that the images remain parallel to a pair of spider threads. Time markers are generated automatically by the motion of the prism.

The probable errors of the impersonal astrolabe are about the same as for the PZT.

Fig. 5. Astrolabe at Paris Observatory.

7. Corrections to Catalogue Positions

Positions of stars as given in catalogues contain random errors which would seriously affect the results obtained with the I.L.S. zenith telescopes, the PZT's, and the Danjon astrolabe. After observations have been made for a number of years the declinations are corrected internally by prescribing the condition that on any night all stars observed should give the same latitude. Corrections in right ascension are similarly obtained for the instruments which determine time.

The application of internal corrections does not affect any systematic errors in position or proper motion which the catalogue positions contain. Hence, the secular change in latitude derived

at an independent station will always be affected by a systematic error in proper motion of the catalogue declinations.

The situation is different for the chain of I.L.S. stations for it is the position of the pole which they determine. By using declinations which are relatively correct, the latitude derived at a station on any night is influenced but little if some star pairs are not observed. Hence, asymmetry of observation should have little effect on the determination of the position of the pole by the International Latitude Service.

III. THE SECULAR MOTION OF THE POLE

The question of the secular motion of the pole is one that has interested astronomers for more than a century. Many spirited controversies have occurred on this subject because of different interpretations made by various astronomers of nearly the same material. It is not feasible to give a complete history of this subject here, but some of the more important developments will be given.

It was shown by L. Euler in 1765 that the axis of rotation of a rigid earth could have an oscillation about the axis of figure which would be observed as a variation of latitude. Many attempts were made during the nineteenth century to observe this theoretical oscillation of the pole, whose period is 305 days, and also a secular motion, but without success.

In 1872 E. Fergola, Director of the Observatory of Capodimonte, Naples, attempted to show that decreases in latitude of about 1″ had occurred at several observatories. Fergola proposed in 1883 that a chain of stations be established on the same parallel of latitude in order to study the secular motion of the pole. Several investigations of existing series of latitude determinations were made shortly thereafter as a result. Despite apparent changes in latitude the conclusions generally drawn were that the changes indicated were within the errors of observation.

M. Nyrén, in 1888, listed the following determinations of the meridian circle at Pulkovo

Observer	Mean Epoch	Latitude
C. Peters	1843	59° 46′ 18″·727 ± 0″·013
H. Gyldén	1866	18·654 ± 0·014
M. Nyrén	1872	18·54 ± 0·014

Despite the small probable errors, he concluded: [11] 'Altogether, it is yet undecided if our instrument has really changed in latitude since the epoch of Peters.'

Asaph Hall,[12] in 1890, studied determinations of latitude of the U.S. Naval Observatory made at the old site. Some results follow.

Instrument	Mean Epoch	Latitude
Mural Circle	1846	38° 53′ 39″·23
Mural Circle	1863	38·78
Transit Circle	1875	38·38

Observations of Vega made with the prime vertical instrument from 1845 to 1866 had indicated an increase, in the seconds of arc, from 38″·38 to 38″·53. Hall concluded that, taking all the results into account, 'it is evident that there is no proof of a secular change in the latitude.'

S. C. Chandler,[13] who had thoroughly investigated several series of determinations of latitude at various observatories, remarked in 1892, 'if any secular change exists, it must be less than 0″·01 annually'.

About 1890, evidence of changes in latitude appeared, but not of the kind to be expected from the theory of Euler. In a paper published in 1890, F. Küstner [14] gave convincing proof that the latitude of Berlin had decreased by about 0″·4 from June, 1884 to March, 1885. This result was based on observations of the same four pairs of stars during this interval. He also showed that observations made with the vertical circles at Pulkovo in the interval from July 1884 to March 1885 gave nearly the same result.

In 1891 S. Chandler [15] announced that a periodic oscillation of the instantaneous pole about its mean position occurred in the period of about 427 days, instead of the 305 expected. The difference was explained by S. Newcomb as being due to the elastic deformation of the earth. In 1892 Chandler [16] announced that the motion of the pole was the resultant of two components, an annual as well as the 14-month period. Chandler's results were obtained from analyses of long series of observations made at various observatories dating back to about 1840.

To confirm the existence of the variation of latitude, an observing party was sent to Honolulu under the direction of A. Marcuse.

Observations of latitude made there and at Berlin simultaneously from May 1891 to May 1892 established the reality of the variation.

In order to study the phenomenon still further the International Latitude Service (I.L.S.) was established. Observations were begun in September 1899. Although the purpose of the I.L.S. was to study the periodic motion of the pole, it was realized that in the course of time the secular motion might also be determined.

The programmes of the I.L.S. generally extend over intervals of about six or twelve years. Changes in the list of stars observed were made at 1906.0, 1912.0, 1922.7, 1935.0, and 1955.0. Other changes were usually made at these times, namely, in the method of reductions and in the origin to which the instantaneous pole was referred. In addition, changes have been made in the star catalogues used and in the number of observing stations. Because of this inhomogeneity, it has been difficult to judge with confidence whether or not a secular motion of the pole exists.

The first attempt to determine the secular motion of the pole from the I.L.S. results was made by B. Wanach [17] in 1917, who found a motion of 0″·003 yr in the direction of Newfoundland. The material available to Wanach was, of course, scanty, and he noted that the motion found might be due to a variation of long period rather than to a progressive change.

Table 1 gives a list of secular motions found by various investigators, based on the I.L.S. results. The list is not complete, but is representative of the secular motions obtained for various intervals of observation.

Table 1. Secular motion of pole from observations of I.L.S.

	Interval	Rate seconds of arc/yr	Longitude W
(1) B. Wanach [17]	1900–1915	0″·003	55
(2) W. D. Lambert [18]	1900–1917	0·0048	78
(3) W. D. Lambert [19]	1900–1918	0·0066	81
(4) H. Mahnkopf [20]	1900–1922.7	0·0051	62
(5) H. Kimura [21]	1900–1923	0·0058	57
(6) B. Wanach [22]	1900–1925	0·0047	42
(7) N. Sekiguchi [23]	1922.7–1935.0	0·0103	91
(8) A. I. Orlov [24]	1900–1950	0·0042	69
(9) W. Markowitz	1900–1959	0·0032	60

1. Station Displacements

In 1921 A. C. Lawson noted that the latitude of the I.L.S. station at Ukiah, California, was increasing at the rate of 0″·0094/yr. In consequence, W. D. Lambert [18] made a study of the latitudes of all the I.L.S. stations. He concluded that the apparent motion of Ukiah could be explained by errors in proper motions combined with a secular motion of the pole.

F. Schlesinger,[25] in 1922, utilized improved proper motions to analyse the I.L.S. data. He found that the data could be interpreted as indicating either motion of the mean pole or, if the pole were fixed, an annual displacement to the south of Mizusawa of 0″·009. He favoured the second alternative. Lambert,[19] on geophysical grounds, argued against the possibility of a continuous displacement of nearly 1 ft/yr, and considered it to be more likely that the mean pole was moving.

In 1924 H. Kimura,[21] Director of the Mizusawa station, and at that time in charge of the Central Bureau of the I.L.S., found also that either the pole had moved or that Mizusawa had shifted in position. Later, in 1940, he wrote,[26] 'the most probable explanation is that the station Mizusawa alone has moved considerably under some causes while the remaining three stations remained steady for 35 years since 1900, and that the mean amount of the differences for the three stations is nothing more than the difference of the star systems used in the two volumes. In other words, there would be no displacement of the North Pole during the period 1900–1935.' He adopted −0″·12 as the change in the latitude of Mizusawa.

T. Hattori [27] attempted to place the results of the various I.L.S. programmes on a somewhat homogeneous system, in 1946, by utilizing the *General Catalogue*. He found that the mean pole moved in the general direction of longitude 90° W from 1900 to 1919, and then along the meridian 30° E for one year. After 1920 it resumed a motion in the general direction of longitude 130° W. Hattori decided that the apparent motion of the pole was due principally to displacements of the stations. He states, 'Secular movement . . . relative to the figure axis of the Earth, if it exists, is considered very small compared with the continental movements. But the rapid change during 1919–1920 is surely the real change of the rotation pole.'

G. Cecchini became Director of the Central Bureau of the I.L.S. in 1949. In a paper [28] published in 1950 he decided that there was no secular motion of the pole from 1900 to 1935, and a slight motion thereafter. Also, he decided that the displacement of 0″·12 of Mizusawa found by Kimura was real. In computing the position of the pole he used an adopted value of the latitude of Mizusawa which differed by 0″·12 from the value used before 1923. Later, however, in a report [29] issued in August 1958 he stated that it was impossible to decide with certainty whether the position of only Mizusawa (or its vertical) had changed since 1900.

A. I. Orlov,[30] in 1954, decided that there was both a secular motion of the pole and a southward drift of Mizusawa of 0″·006 yr. He remarked that this was one of the rare cases of systematic change in latitude not due to polar motion.

2. Random Motion of Mean Pole

Lambert had noted in his early studies that the mean pole moved along one direction and then abruptly changed course. Hattori observed the same phenomenon, but in somewhat more detail.

The apparent random motion was brought out clearly by N.

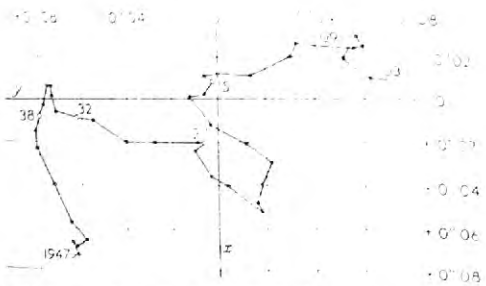

Fig. 6. Motion of Mean Pole 1903–1947, derived by Sekiguchi.

Sekiguchi [31] in 1954. He formed 6-year running means of x and y, so as to obtain yearly positions of the mean pole. He found that there were changes in direction in the motion of the pole, as shown in Fig. 6. P. Melchior [32] pointed out that the sudden changes in

direction of the movement of the mean pole were contemporary with changes in programmes of the I.L.S. Hence, he considered that the changes found by Sekiguchi indicated the effects of discontinuities in the programme, and not a real motion of the pole.

Sekiguchi [23] made a new study so as to eliminate the effects of changes in programme and asymmetry of observation, utilizing the results of a single programme, 1922.7 to 1935.0. He found that the motion of the mean pole was practically the same as previously derived. A study by A. Philippov [33] confirmed the conclusion that programme changes and asymmetry of observation could not account for the erratic motion of the pole. Melchior [34] agreed with this result.

Cecchini [29] derived positions of the pole in 1958 for mean epochs 1903 to 1952. He found that the mean pole moved erratically and that the positions obtained depended upon the combination of stations used.

Various explanations were offered for the apparent motion of the pole. Sekiguchi [31] considered the motion to be real, and suggested that a connection existed with variations in the speed of rotation of the earth. D. Brouwer [35] had suggested that changes in speed of rotation could be due to the cumulative effect of small random variations, and Sekiguchi thought a similar process might account for the motion of the mean pole along segments of straight lines.

Philippov and E. P. Fedorov [33] ascribed the changes to variations in latitude, of obscure origin, and not to motion of the pole.

Cecchini [29] ascribed the erratic motion to individual displacements of the stations, possibly of a periodic nature.

Although the indications are that changes in programme have had little effect on the position of the mean pole, it would be desirable to reduce all the I.L.S. observations made since 1900 with a single catalogue of high accuracy. A project for this purpose was started by the Observatoire Royal de Belgique in 1951. The I.L.S. stars were observed with the transit circle by G. Becq and P. Melchior at Uccle, and a catalogue of declinations with epoch about 1955 was formed.[36] Melchior is combining these declinations with those obtained at various observatories for earlier epochs to obtain the proper motions.

3. New Origin

In June 1959 Cecchini [4] apparently abandoned the hypothesis that Mizusawa had shifted and he returned to the initial value of its adopted mean latitude for determining the position of the pole since 1900. He adopted an origin which he calls the 'new system, 1900–05'. This origin, denoted by P_0, is defined by the latitudes given in Table 2, which we call *initial latitudes*.

Table 2. Initial latitudes, 'New system, 1900–05'

	ϕ_{i0}	λ_i
Mizusawa	39° 8′·3 ±·602	141
Kitab	1·850	67
Carloforte	8·941	8
Gaithersburg	13·202	77
Ukiah	12·096	123

The latitudes of Table 2, except for Kitab, are the mean latitudes for the initial 6-year programme of the I.L.S., 1899.9 to

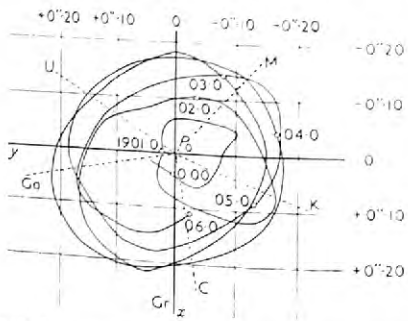

Fig. 7. Motion of the instantaneous pole (Albrecht, Wanach), referred to 'new system, 1900–05' of Cecchini, 1899.9 to 1906.0.

1906.0. Kitab, which replaced one of the original I.L.S. Stations, Tchardjui, was placed in operation in 1930, so that the value 1″·850 was obtained by Cecchini by a process which involves extrapolation.

The polar motion from 1899.9 to 1906.0 and from 1954.4 to 1959.2 with respect to the 'new system' is shown in Figs. 7 and 8,

respectively. It is evident that the centre about which the instantaneous pole moves has changed position. This, of itself, does not prove, however, that a real change has occurred.

Cecchini derived the position of the mean pole for epochs from

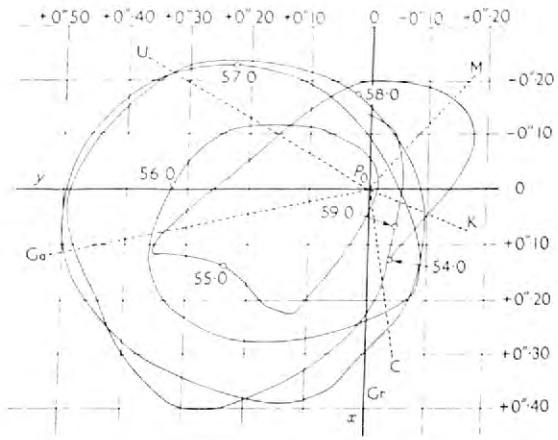

Fig. 8. Motion of instantaneous pole (Cecchini) referred to 'new system, 1900–05', 1954.0 to 1959.20.

1903 to 1952 and of the instantaneous pole from 1949.00 to 1959.20, with respect to the new origin. By referring all the I.L.S. results to the same origin, Cecchini made an important contribution; he removed what was perhaps the major source of uncertainty in studying the polar motion. This led me to undertake a new study of the motion of the mean pole, given below.

4. Definitions

It is desirable, at this point, to define the terms concerning latitude which are used here. The term mean latitude, for example, has been used in different senses by various authors. Latitudes will be defined with respect to the instantaneous pole and a fixed pole.

The *instantaneous latitude*, ϕ_i, of a station, S_i, is the complement

of the angle between the vertical and a line parallel to the instantaneous axis of rotation which passes through S.

The *station latitude*, Φ_s, is defined as the latitude with respect to a particular axis, fixed in the earth. The axis used here is the one for which the pole is P_0, defined by the 'new system, 1900–05'.

The *programme mean latitude* is defined as the mean value of ϕ_t for a specific observing programme or interval. Means are most often formed for one year or six years.

The observed *variation of latitude* is defined as $\Delta\phi = \phi_t - \phi_{t0}$, where ϕ_{t0} is a constant called the initial latitude. The values of ϕ_{t0} used here are equal to the programme mean latitudes for 1900–1905.

Analagous definitions may be formed for longitude. Evidently, the instantaneous latitude and longitude of a fixed station are continually varying quantities, but the station latitude and longitude are constants.

5. Motion of Mean Pole

The programme mean latitudes of the I.L.S. stations are given by Cecchini in Table XII of his 1958 report.[29]

Table 3 reproduces the values for Mizusawa, Kitab, Carloforte, Gaithersburg, and Ukiah. It should be noted that the quantities given are the mean latitudes obtained by observation. Results not based on the complete interval are marked by parentheses.

Table 3. Observed mean latitudes of I.L.S. stations

Interval	Mean epoch	Mizusawa	Kitab	Carloforte	Gaithersburg	Ukiah
1900–05	1903	3″·602		8″·941	13″·202	12″·096
1906–11	1909	·587		·923	·257	·122
1912–17	1915	·522		·901	·246	·131
1923–30	1927	·397	4″·669	·855	·156	·031
1929–34	1932	·377	·619	·837	·204	·079
1935–40	1938	·449	·727	·905	·318	·175
1949–54	1952	·389	·690	·928	·294	·114

The latitude of a station, S, when the instantaneous pole of rotation is at a point on the surface of the earth denoted P_0 is ϕ_{t0}. Let the pole move later to a new position, P, whose rectangular coordinates are x and y, measured along the meridians of Greenwich

and longitude 90° W, respectively. The variation in latitude which results, as may be seen from Fig. 9, is $x \cos \lambda_s + y \sin \lambda_s$, where λ_s is the longitude of the station.

Let the systematic error in declination of the stars observed when the pole is at P exceed that when at P_0 by the amount z. Then there will be an additional change in the observed latitude,

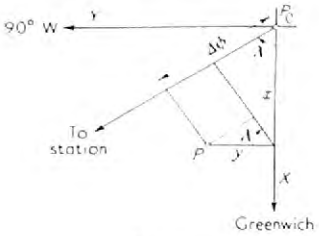

Fig. 9.

equal to z, which is not due to the polar motion. Hence, the observed variation in latitude, $\Delta\phi_s$, is

$$\phi_s - \phi_{t0} = x \cos \lambda_s + y \sin \lambda_s + z \qquad (1)$$

where ϕ_s is the observed latitude of the station.

If observations are made at three or more stations it is possible to determine x, y and z. Hence, it is possible to determine the coordinates of the instantaneous pole of rotation, x and y, independently of errors in the positions or proper motions of the stars. In using equation 1 the implicit assumption is made that the positions of the stations with respect to P_0 are fixed, that is, there are no displacements of the stations relative to the crust of the earth.

Cecchini determined mean values of x, y and z for each I.L.S. programme by means of equation 1. The results are given in Table 4.

Table 4. Position of mean pole, P_1

Mean epoch	x_1	y_1	z
1903	0″·000	0″·000	0″·000
1909	0·007	0·043	−0·001
1915	+0·001	−0·076	−0·028
1927	+0·039	−0·080	−0·117
1932	+0·027	0·130	−0·116
1938	+0·031	+0·139	−0·037
1952	+0·074	+0·142	−0·064
1957	+0·071	+0·178	