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EARTH ROTATION AND GEODYNAMICS

Early Latitude Observations at the Pulkovo Observatory

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Abstract—Pulkovo astrometric observations began in the 1840s using the Repsold transit instrument in the prime vertical and Ertel vertical circle. The first observers on these instruments were W.I. Struve, 1840–1856, and Kh.I. Peters, 1842–1849. In the present work, we collected and analyzed different series of latitude variations from observations made by M.O. Nuren, B. Wanach, A.A. Ivanov, I.N. Bonsdorf, and A.Ya. Orlov. In addition, results are given of investigations of a specific behavior of the Chandler polar motion in this interval, obtained by C. Chandler, Ivanov, Kh. Kimura, Orlov, and N. Sekiguchi. The aim of this paper is to search for and analyze the earliest series of Pulkovo latitudes, in order to evaluate the possibility of their use to study the motion of the pole at the maximum available range of observations. Different methods were used to isolate and analyze the sum of Chandler and annual latitude variations. The annex provides a series of Pulkovo latitude variations for 1840–1848, which may be used to extend latitude variation back to 1840.

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INTRODUCTION

In the study of the Chandler polar motion, three areas of abrupt change in amplitude were found, accompanied by the phase change by almost 180° [5]. This feature of the behavior of the Chandler motion of the pole in the middle of the observation interval, around 1930, is well known. The other two intervals are at the ends of the series, and, therefore, there is a need to extend the series back as far as possible. On the example of comparing the behavior of the Chandler polar motion derived from the data of IERS C01 series (http://hpiers.obspm.fr/) and from observations of the Pulkovo latitude (ZTF–135) in the interval 1904–2006, it was shown that the Chandler polar motion may be studied using a long series of latitude variations from one observatory [6]. The purpose of this study is to investigate the early series of Pulkovo latitude variations in the interval 1840–1855 and compare them with a series obtained from IERS C01 in the interval 1846–1855.

Pulkovo observations began in the 1840s on the large vertical circle of Ertel and Repsold transit instrument in the prime vertical. Both instruments were manufactured specifically for Pulkovo and installed in the year of opening of the observatory (1839). They were designed for absolute positioning of the stars. In determining the series of absolute declination of stars, a series of latitude determinations are also formed. They may be used to study the motion of the poles.

We collected historical material relating to the observations, processing, and calculating of Pulkovo latitude variations using the transit instrument for 1840–1856 and the large vertical circle of Ertel for 1840–1875, as well as the curves of latitude variations for these two instruments constructed by a series of B. Wanach and A.A. Ivanov. A short review is given of the results of studying the variability of latitude in the interval 1840–1855 by different researchers, as well as the analysis of Pulkovo latitude variations based on three series of observations made by Ivanov (1842.3–1849.5), Wanach (1840–1856.5), and a series of L.V. Rykhlova (1846–1856.5).

OBSERVATIONS ON THE LARGE TRANSIT INSTRUMENT IN THE PRIME VERTICAL

The Repsold large transit instrument at Pulkovo was specially installed in the prime vertical to determine constants of aberration and nutation. All the observations in the interval 1840–1855 were made by W.I. Struve. He also developed a method of observation and data processing. The method of observation consisted in fixing the time of passage of the same star through the filament in the eastern and western parts of the prime vertical. A detailed description of this observation method and how to obtain latitudes from observations (Struve method) is described in [10].

Observations on the interval of 1840–1855 are divided into two series, i.e., 1840.3–1843.0 and 1843.0–1855.0. In the first series, approximately 300 observations of seven stars are included, distributed over all

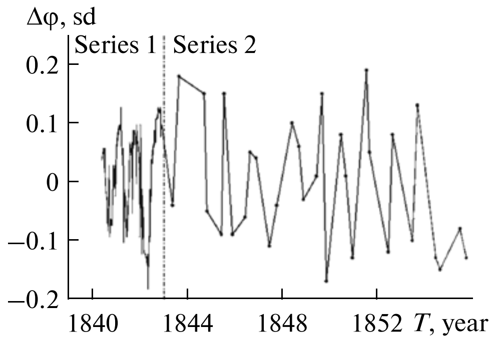

Fig. 1. The series obtained by Wanach [18] from two series of observations made by Struve using the transit instrument in the prime vertical in 1840–1843 and 1844–1855.

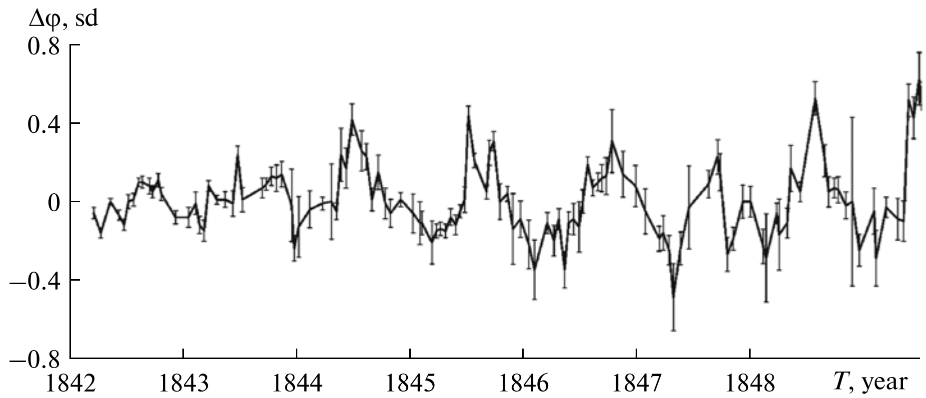

Fig. 2. The series obtained by Ivanov [3] from observations made by Peters on the Ertel vertical circle in 1842–1849.

hours of right ascension. This series was used by Struve to determine the constant of aberration. In the second series, only three stars were observed, and for 12 years 169 observations were carried out. This series of observations (1843–1862) was used by M.O. Nuren to determine the constant of nutation [1]. Figure 1 provides a graph showing Pulkovo latitude variations built on the basis of the latitude calculated by Wanach [18] from two series of observations made by Struve. Both series differ greatly among themselves in density. On average, in the first series, there were three observations per month, while, in the second series, there were only two or three observations per year. The analysis of the first series of latitude variations was made by Chandler, and his results agree well with results obtained by Orlov for the vertical circle (see below). Observations of the second series are rarely used for that purpose, and attempts to analyze by old methods did not give the desired results [18].

OBSERVATIONS ON THE LARGE ERTEL VERTICAL CIRCLE

The Ertel vertical circle was proposed by Struve for refractive research, compilation of the fundamental catalog of declinations, and observation of solar zenith distances at all points of its orbit in order to determine the position of the ecliptic [8]. Observations on this instrument at two positions of the circle make it possible to directly get the zenith distance circumpolar stars in the upper and lower culminations, and then to calculate the latitude of observation. The first observer on this instrument was Kh.I. Peters, who started observations in the fall of 1839 and finished them in July 1849, having made more than 5000 observations.

In 1895, Ivanov revised the observations made by Peters using the method described in detail in [3, 4]. In the analysis of observations made in 1842–1849, Ivanov [3] selected all of the common stars in the first (1845) and second (1865) Pulkovo absolute catalogs. Then, the declination of these stars from the catalog of 1865 he brought to the era of 1845 and used these values in his calculations as true. For the North Star and seven stars observed to determine their parallax, declinations from the catalog of 1845 were adopted. In addition, series of latitude variations did not include zenith stars with a very high proper motion and stars with the zenith distance greater than 76°. Figure 2 shows the Pulkovo latitude curve for 1842–1849 according to data calculated by Ivanov [3], derived from 3119 observations.

REVIEW OF RESEARCH ON THE PULKOVO LATITUDE VARIATIONS IN 1840–1855

At Pulkovo Observatory, the first observer who calculated latitude on the basis of his observations of zenith distances of the North Star on the large vertical circle of Ertel for 1842–1843 and established its variation was Peters [3]. The following studies of the latitude variation were carried out thirty years later by Nuren [16]. For this purpose, he used observations made by Struve on the transit instrument installed in the prime vertical and observations made by Peters, Gulden, and himself on the vertical circle. In their studies, Peters and Nuren did not notice latitude variations with a period longer than one year, as they a priori assumed the existence of the Euler period equal to 305 days, and used this value in calculations. And only in the analysis of all observations made to create a catalog in 1885 on a vertical circle, Nuren got the period close to 430 days [4].

These studies preceded works of Chandler, who, in 1891, began publishing his researches of latitude variability and for the first time announced the period of approximately 428 days in observations of latitude [11]. For three years (1891–1893), he published eight articles under the title *On the Variation of Latitudes*. He analyzed 45 short series of observations, containing over thirty thousand individual observations made in various observatories of the world from 1841 to 1890 [12]. As a result, in latitude variations after the exclusion of the annual term an interval of a sharp decrease in amplitude was isolated, the minimum of which fell within the interval 1840–1856. In addition, he later concluded that this oscillation consists of at least two harmonics, i.e., the first with a period of 428.5 days (1.17 h) and the amplitude of 0.14″, and the second with a period of 436 days (1.19 h) and the amplitude of 0.09″ [13]. Based on the assumption that there were two harmonics and taking into account the values of their periods, Chandler proposed a model in which a new decrease in the amplitude of this oscillation was going to happen around 1910 [14]. In fact, a sharp decrease in amplitude occurred somewhat later (around 1930). Currently, this oscillation is called the Chandler wobble.

In 1892, Wanach revised the observations made on the transit instrument in the Pulkovo prime vertical by Struve, F. Oom, and Nuren during 1840–1880. He calculated latitude variations using declination and proper motions derived from his observations in 1891, and compared with the results from [18]. Observations of Nuren in 1879–1882 showed an increase in the amplitude of periodic latitude variations compared with the previous observations by Struve.

In 1895, Ivanov handled nearly 3000 observations made on a vertical circle. In the interval of 1863–1871, the value of a period was 433 days, and it was 358 days in the interval 1842–1849 [3]. Chandler also found that the studied period is almost equal to the annual one in the interval 1842–1849 [11].

In 1917, Kimura [15] studied the polar vibration from 1828 to 1922 and calculated the variation of the period and amplitude of the Chandler wobble. For his analysis, he used observations made at Greenwich and Pulkovo observatories. His results also showed a significant decrease in 1840 both in the amplitude and period, confirming the results of Chandler, Wanach, and Ivanov.

In 1937, Orlov turned to early observations and reviewed the series latitude variations obtained by Ivanov, Wanach, and Bonsdorf from observations of Peters at Pulkovo vertical circle of Ertel [7]. As a result, Orlov developed the following expressions for the Chandler wave in the epoch 1845.0

$$\varphi_C = 0.08''\cos(\mu t + 143°), \quad (1)$$

$$\varphi_C = 0.08''\cos(\mu t + 147°), \quad (2)$$

where $\mu = 2\pi/P$ and $P = 1.184$ h.

The expression (1) describes the observations of Peters (1842–1849) on the vertical circle, and the expression (2) refers to observations made by Struve on the transit instrument in the prime vertical (1840–1842).

For a vertical circle, he calculated this expression from the above three series of observations, and for the transit instrument in the prime vertical he used the expression obtained by Chandler, transferring it to the epoch 1845.0. Good agreement between the two expressions is evident. After comparing the observations of latitude of this period with later ones, Orlov noted some characteristics of behavior of the amplitude and phase of the Chandler wobble at the first interval of observations. He wrote that the amplitude of

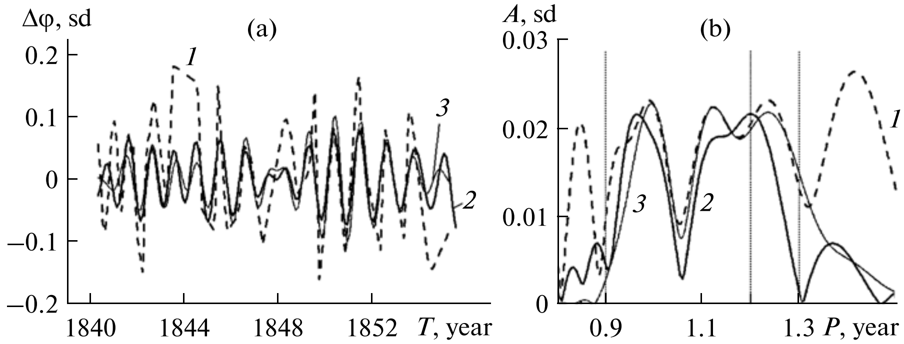

Fig. 3. (a) is the Pulkovo latitude variation obtained from the Wanach series (*1* is the original series, *2* and *3* are series selected by methods of SSA and Ellip, respectively); (b) indicates corresponding spectra.

this vibration was constantly changing, and, for the first series of observations (1842–1849), it was three times smaller than that for the last (1908–1912).

The initial phase in 1868 was by nearly 40° different from its values in 1846, 1887, and 1910. These differences cannot be explained by errors of observation. Thus, Orlov concluded that "between 1847 and 1868, the motion of the pole seemed to slow down and then regained its speed" [7].

In 1975, Sekiguchi conducted a study of variations of amplitude and frequency of the Chandler wobble in the interval 1840–1860, also derived from observations made at Greenwich and Pulkovo observatories. As a result, it was found that the Chandler period at this interval had a value of 423.3 days with minimum amplitude of 0.072″ ± 0.014″ around 1845. On this basis, he made a conclusion of the similarity of this feature with the one that took place around 1930 [17].

Thus, from the analysis of the results obtained by different researchers, we can conclude that, in the interval 1840–1855, there was a decrease of the amplitude to approximately 0.08″. In addition, there is an indication of the change in the phase of the Chandler polar motion on the interval 1847–1868.

DESCRIPTION OF DATA AND THEIR ANALYSIS

To analyze latitude variations, we used the following three series in this study.

(1) The 1840–1855 series obtained by Wanach from observations made by Struve the Repsold transit instrument installed in the prime vertical.

(2) The 1842–1849 series obtained by Ivanov from observations made by Peters on the large vertical circle of Ertel.

(3) The 1846–1858 IERS C01 series obtained from the series of Rykhlova [9]. This series of observations was created from Pulkovo vertical circle of Ertel, treated by Orlov and from Greenwich on two mural circles, treated by Chandler, in Washington on the mural circle.

The first two series were smoothed and interpolated with a step of 0.1 h. The latitude variation for the third series was calculated using the Kostinski formula

$$\Delta\varphi = \varphi - \varphi_0 = X_p\cos\lambda - Y_p\sin\lambda = 0.863X_p - 0.505Y_p,$$

where X_p and Y_p are coordinates of the pole and λ is the Pulkovo longitude.

The isolation of the Chandler and annual oscillation was performed using two methods of analysis: the method of singular spectrum analysis (Caterpillar–SSA method) [http://www.gistatgroup.com/gus/] and the filtration method (Ellip) with a bandwidth of 0.77–1.05 year^{-1}. Filtering was performed using a frequency bandpass elliptic filter of Zolotarev–Cauer of the fifth-order (the ellip Matlab Signal Processing Toolbox function).

When using the SSA, all series were processed twice. First, using SSA, slow latitude variations and noise components were eliminated, and then the SSA decomposition of the remaining series was carried out again. The length of the window M was assumed to be equal to a half of the series length. The series was restored by first basic components with frequencies close to frequencies of Chandler and annual oscillations. The rationale for the use of SSA to eliminate slow latitude variations, and the comparison of results with other commonly used methods of filtration are given in [2].

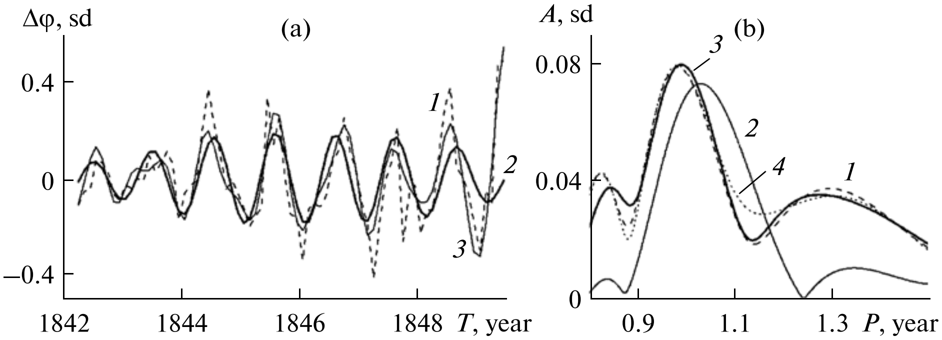

Fig. 4. (a) is the Pulkovo latitude variation obtained from the Ivanov series (*1* is the original series, *2* and *3* are series, selected by methods of SSA and Ellip, respectively); (b) indicates corresponding spectra.

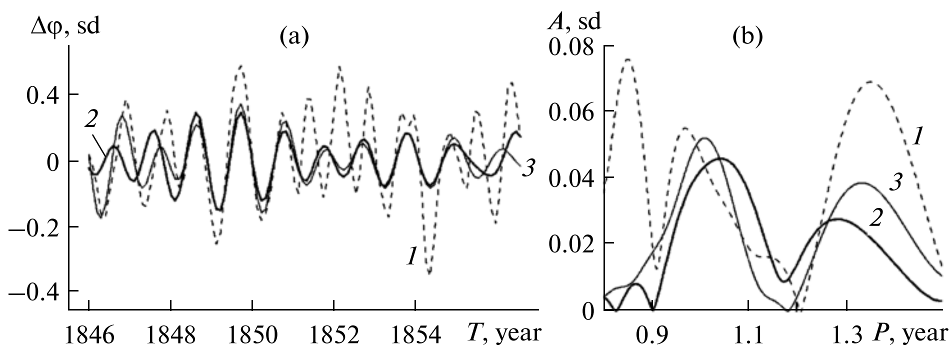

Fig. 5. (a) is the Pulkovo latitude variation calculated from the pole coordinates IERS C01 (*1* is the original series, *2* and *3* are series, selected by methods of SSA and Ellip, respectively), (b) indicates corresponding spectra.

Figures 3a, 4a, and 5a show investigated series with a uniform step of 0.1 h and filtering results obtained by both methods. Figures 3b, 4b, and 5b depict the results of the spectral analysis of these series.

As a result of observations on the transit instrument in the prime vertical by the two methods, similar latitude curves were obtained with a six-year modulation, usual for the sum of the Chandler and annual components (Fig. 3). The minimum value of amplitude fell on 1848. For a series C01 after filtration (Fig. 5), a slight decrease in the amplitude at approximately 1850 was also observed. It is interesting to note that the spectrum obtained for the sum of Chandler and annual components by the SSA method is very close to spectra of the original series and the series obtained by Orlov from the data collected by Ivanov [7].

From the spectra in Figs. 4 and 5, it is clear that the amplitude of the annual component is greater than the amplitude of the Chandler component for the second (vertical circle) and third (IERS C01) series. The spectrum of observation series made using the transit instrument has a peak of annual and two peaks of the Chandler wobble with close amplitude. This series is longer (16 years) than the series of Ivanov (seven years), but it contains a very small number of observations, except for the first three years (1840–1843).

The analysis of spectra (Figs. 3–5) shows that the annual period of latitude variations is stable, and it can be explained by the fact that the annual fluctuation is mainly determined by seasonal changes in the atmosphere. The period of the Chandler wobble is less stable, because, as shown above, the amplitude of this component in the target range is not very large. In addition, the accuracy of observations is low, and observations on the transit instrument in the prime vertical in this range are of low density.

Figure 6 presents a comparison of amounts of Chandler and annual components obtained by two different methods for all three series. Good agreement is observed between the epochs of minima and maxima for the series calculated from observations on two different instruments of the Pulkovo Observatory in the interval 1843–1846. In the interval 1846–1849.5, curves obtained from a series of Ivanov and Rykhlova are also in agreement. For a series of observations on the transit instrument in the prime vertical derived from the data obtained by Wanach, there is a region near 1848 that is characterized by a significant decrease in amplitude. A similar decrease in amplitude, but to a lesser extent, may be traced in a series C01

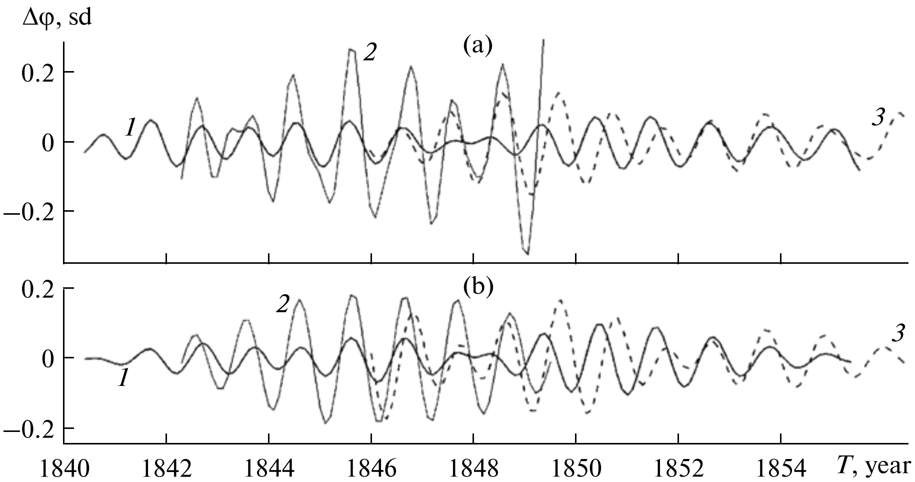

Fig. 6. Series latitude variations obtained by two methods of filtration: (a) is the SSA method; (b) is the Ellip method from the series of (*1*) Wanach, (*2*) Ivanov, and a series C01 of (*3*) Rykhlova.

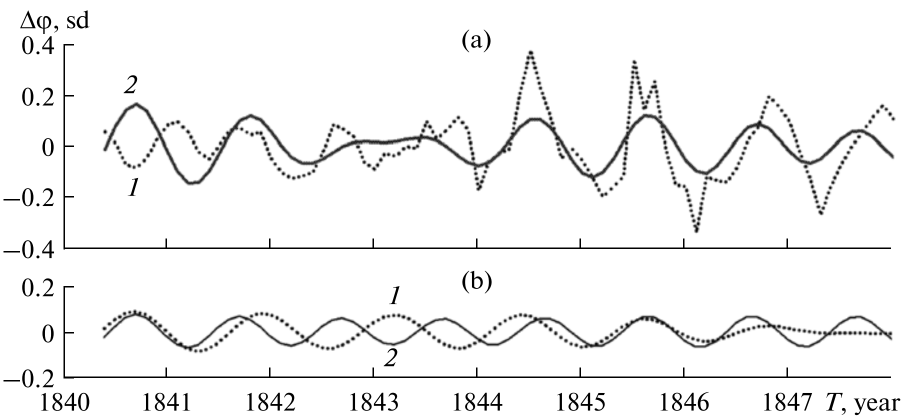

Fig. 7.

using the filtration method. The oscillation amplitude for a series derived from observations on the transit instrument is very small. Nevertheless, since 1852, not only almost complete overlap of the phase for this series and of the C01 series is observed but also close values of amplitudes. On the contrary, in the interval 1849–1852, there is no overlap of the phase of these two series. In general, it should be noted that both filtering methods give similar results in the processing of the series of latitude variations. But since the results obtained by the SSA method are closer to the results obtained by Orlov, it is appropriate to use the SSA method to calculate the annual and Chandler wobble of latitude variations.

Figure 7 and the table show the combined series for 1840–1848, which may be used to extend the series of Pulkovo latitude variations back to 1840. This series consists of Pulkovo latitude variations obtained from observations on the transit instrument in the prime vertical for 1840.3–1843 and on the large vertical circle of Ertel for 1842.4–1846.5. From the expressions (1) and (2) obtained by Orlov and the analysis carried out in our work, it is implied that these two series agree with each other over the interval 1842.4–1843. Therefore, they were combined in this interval by a simple averaging. The appendix contains the Chandler and annual components of Pulkovo latitude variations for 1842.4–1846.5 obtained by the SSA method.

CONCLUSIONS

In the present paper, historical material was collected related to observations, treatment, and research of Pulkovo latitude obtained on two instruments at the Pulkovo Observatory in 1840–1856. All materials were selected and analyzed to search for data, methods of their processing, and analysis for the extension

The combined series Δφ of Pulkovo latitude variations, as well as Chandler ($\Delta\varphi_c$) and annual ($\Delta\varphi_h$) components

Year	Δφ, sd	$\Delta\varphi_c$, sd	$\Delta\varphi_h$, sd	Year	Δφ, sd	$\Delta\varphi_c$, sd	$\Delta\varphi_h$, sd
1840.4	0.05	0.01	–0.02	1843.5	0.10	0.00	0.03
1840.5	0.01	0.05	0.02	1843.6	0.03	–0.03	0.05
1840.6	–0.07	0.08	0.06	1843.7	0.06	–0.06	0.05
1840.7	–0.09	0.09	0.08	1843.8	0.11	–0.07	0.04
1840.8	–0.05	0.07	0.06	1843.9	0.06	–0.07	0.00
1840.9	0.02	0.04	0.02	1844.0	–0.17	–0.05	–0.03
1841.0	0.08	0.00	–0.02	1844.1	–0.06	–0.01	–0.05
1841.1	0.09	–0.04	–0.06	1844.2	–0.03	0.03	–0.06
1841.2	0.05	–0.07	–0.07	1844.3	–0.01	0.06	–0.03
1841.3	–0.02	–0.09	–0.06	1844.4	0.21	0.07	0.00
1841.4	–0.05	–0.08	–0.02	1844.5	0.38	0.07	0.04
1841.5	0.00	–0.05	0.02	1844.6	0.23	0.05	0.06
1841.6	0.06	–0.01	0.05	1844.7	0.11	0.01	0.06
1841.7	0.07	0.03	0.07	1844.8	–0.05	–0.02	0.04
1841.8	0.04	0.06	0.05	1844.9	–0.01	–0.05	0.00
1841.9	0.05	0.08	0.02	1845.0	–0.06	–0.07	–0.04
1842.0	–0.05	0.07	–0.02	1845.1	–0.12	–0.06	–0.06
1842.1	–0.10	0.05	–0.05	1845.2	–0.20	–0.04	–0.06
1842.2	–0.13	0.02	–0.06	1845.3	–0.16	–0.01	–0.04
1842.3	–0.12	–0.02	–0.05	1845.4	–0.12	0.02	0.00
1842.4	–0.10	–0.05	–0.02	1845.5	0.34	0.05	0.04
1842.5	–0.02	–0.07	0.02	1845.6	0.14	0.06	0.06
1842.6	0.08	–0.07	0.05	1845.7	0.25	0.05	0.06
1842.7	0.07	–0.06	0.06	1845.8	0.00	0.03	0.04
1842.8	0.04	–0.03	0.04	1845.9	–0.15	0.01	0.00
1842.9	–0.06	0.01	0.01	1846.0	–0.16	–0.02	–0.04
1843.0	–0.09	0.04	–0.02	1846.1	–0.34	–0.03	–0.06
1843.1	–0.03	0.06	–0.05	1846.2	–0.12	–0.04	–0.06
1843.2	–0.04	0.07	–0.06	1846.3	–0.13	–0.04	–0.04
1843.3	0.00	0.06	–0.04	1846.4	–0.14	–0.02	0.00
1843.4	–0.01	0.04	–0.01	1846.5	–0.08	–0.01	0.04

of the series of latitude variations back to 1840. Latitude variations derived by Ivanov and Wanach from earlier observations on the vertical circle of Ertel and on the transit instrument established in the prime vertical were investigated. By means of SSA and filtration methods, despite the omissions, heterogeneity of the series, and relatively small number of observations, latitude variations were obtained in the frequency range corresponding to the annual and Chandler wobble. Then we compared this series with each other and with the similar series obtained in the same method from IERS C01 in the interval 1846–1858. When comparing the series with each other, overlap of the phase of oscillation was noted, especially in the interval up to 1846. This was also noted by Orlov.

The comparison of latitude variations calculated from observations on the transit instrument in the prime vertical, with the change in latitude calculated from the series C01, shows the overlap of peaks in the intervals 1846–1848 and 1852–1856 and the mismatch in the remaining interval 1848–1852. In the analysis of observations on different instruments at Pulkovo and Greenwich observatories in [17], the mismatch of the phase of the Chandler polar motion of the C01 series with the phase of series in the interval up to 1853 was analyzed in this study.

In this paper, we collected the results of various studies, indirectly confirming the existence of a sharp decrease in amplitude of the Chandler motion of the pole with a simultaneous phase change in the interval 1840–1852.

The table contains the final series Pulkovo latitude variations in 1840–1846.5, which may be used to study Pulkovo latitude variations for 170 years from 1840 to 2009.

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