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STUDY OF TIME ERRORS IN PRECISE LONGITUDE DETERMINATIONS BY THE U. S. COAST AND GEODETIC SURVEY

BY

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By William Bowie, *Chief, Division of Geodesy, U. S. Coast and Geodetic Survey.*

INTERNATIONAL LONGITUDE DETERMINATIONS.

During the meeting of the International Astronomical Union at Rome in May, 1922, there was discussed at some length the plan of General Ferrie for the determination of a net of longitude differences to circle the globe. It was proposed that these determinations should depend upon radio signals and the determination of time at a number of astronomical observatories. This plan has been under discussion for a number of years and its advocates have held the view that it would furnish a means of determining the longitude of each of a number of primary stations with a far greater accuracy than longitude determinations by means of cables and land wires. There seemed to be only one question involved, and that was the method by which the radio signals would be received and compared with the local timepieces. Apparently this question is being satisfactorily solved, for now the radio signals can be received with little or no error by photographic methods or by having them actuate the pen of an ordinary chronograph.

At the Rome meeting it was found that the most serious problem involved in this proposed plan of Ferrie's is not the receiving of radio signals, but rather the uncertainty in the determination of time at the astronomical observatories.

Prof. R. A. Sampson, of the University of Edinburgh, presented to the Astronomical Union his article, entitled "On the determination of time at different observatories," which had been printed in the Monthly Notices of the Royal Astronomical Society of January, 1922. In that paper Sampson calls attention to the fact that—

> When several observatories are linked together in this way, whether by means of the same signal or of different signals, it becomes possible by a simple step to compare the time determination of each observatory with the mean of all, and so to assign to each with some considerable certainty the amount by which its own determination on any occasion was astray, at any rate in so far as fluctuations from a datum line are concerned.

In November, 1920, Sampson published the results of comparisons between Paris and Edinburgh from March, 1914, to August, 1920.[1] The recent paper of Sampson's gives the results of additional studies.

ERRORS IN TIME DETERMINATIONS AT FIXED OBSERVATORIES.

Sampson's work leads to the astonishing conclusion that there is a range in the time determinations of about $0^s.4$ at each of the six observatories considered by him. This is a range which would make

[1] Monthly Notices of the Royal Astronomical Society, Vol. LXXXI, No. 1.

it impossible to determine a difference of longitude by radio signals between fixed observatories with an accuracy comparable with that obtained by the older methods which depended upon observations at field stations.

Sampson gives the results of some of his investigations to show, if possible, the cause of the large range at the several observatories, but none of the causes outlined by him would be sufficient to account for the errors. He mentioned anomalous refraction, but he is inclined to think that this is not sufficient to cause all of the errors.

The present paper is prepared for the purpose of setting forth the results of the time determinations made by the U. S. Coast and Geodetic Survey in its longitude work. There are a number of closed loops of longitude differences in the United States, and as the work on any loop occupied a number of months and at times several years, the loop closures should throw some light on the errors in the time work. They should also indicate whether seasonal effects such as Sampson found are present.

In 1897 an adjustment was made of the net of connected differences of longitude determined astronomically in the United States by the U. S. Coast and Geodetic Survey. Since that date differences of longitude determined by that organization have been fitted into the 1897 net without changing the values for the stations involved in that adjustment.

METHODS AND INSTRUMENTS USED ON LONGITUDE WORK BY THE U. S. COAST AND GEODETIC SURVEY.

Prior to 1905, time determinations were made either by the eye-and-ear method or by the key-and-chronograph method. Since that date all determinations have been made with instruments fitted with the transit micrometer.

Before 1914 all longitude work depended upon observations made with the straight telescope portable transit.[2] From 1914 to date the time observations, with few exceptions, have been made with the broken-telescope type of portable transit.[3]

The instruments have been mounted on brick, stone, concrete, or wooden piers or stands. The shelter has consisted of a tent or a frail wooden shelter just large enough to enable the observer to operate the transit and the chronograph. (See Figs. 1 and 2.)

Most of the longitude stations have been established in open lots in small settlements or out in the fields within easy reach of a telegraph line.

Before the introduction of the transit micrometer personal equation in the determination of a difference of longitude of the first class was eliminated by exchange of observers. There have been only a few cases of an exchange of observers since the transit micrometer has been used. Several years ago a severe test of the transit micrometer was made at the Washington office of the U. S. Coast and Geodetic Survey, which showed there is no personal equation present of such magnitude as to justify the expense of making an exchange of observers in the field.[4] Later a field test was made for relative personal equa-

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[2] Described in U. S. Coast and Geodetic Survey Special Publication No. 14.
[3] Described in U. S. Coast and Geodetic Survey Special Publication No. 35.
[4] A Test of a Transit Micrometer, by John F. Hayford. Appendix 8, Report for 1904.

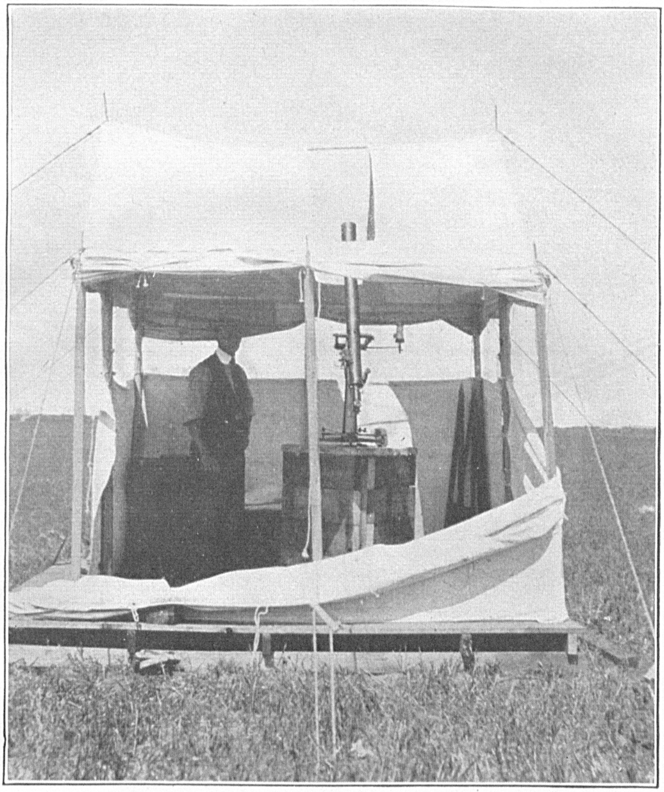

FIG. 1.—TENT USED AS INSTRUMENT SHELTER.

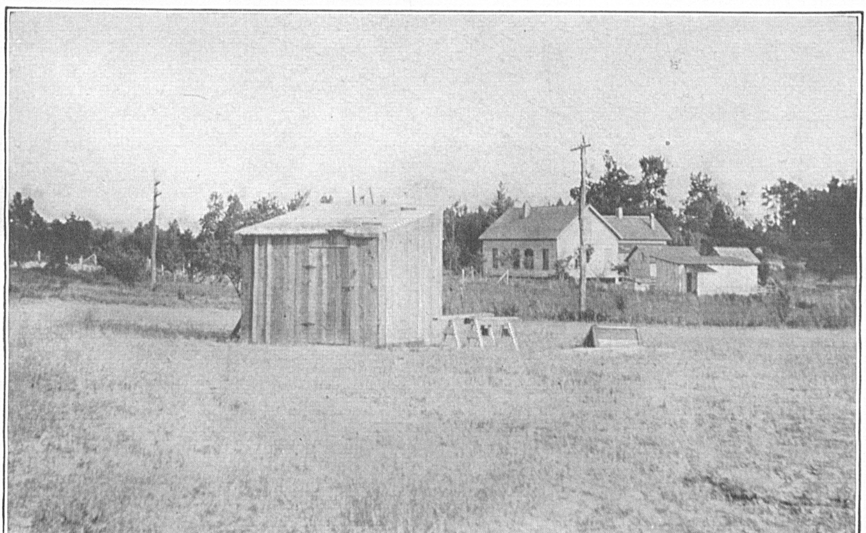

FIG. 2.—TEMPORARY WOODEN OBSERVATORY.

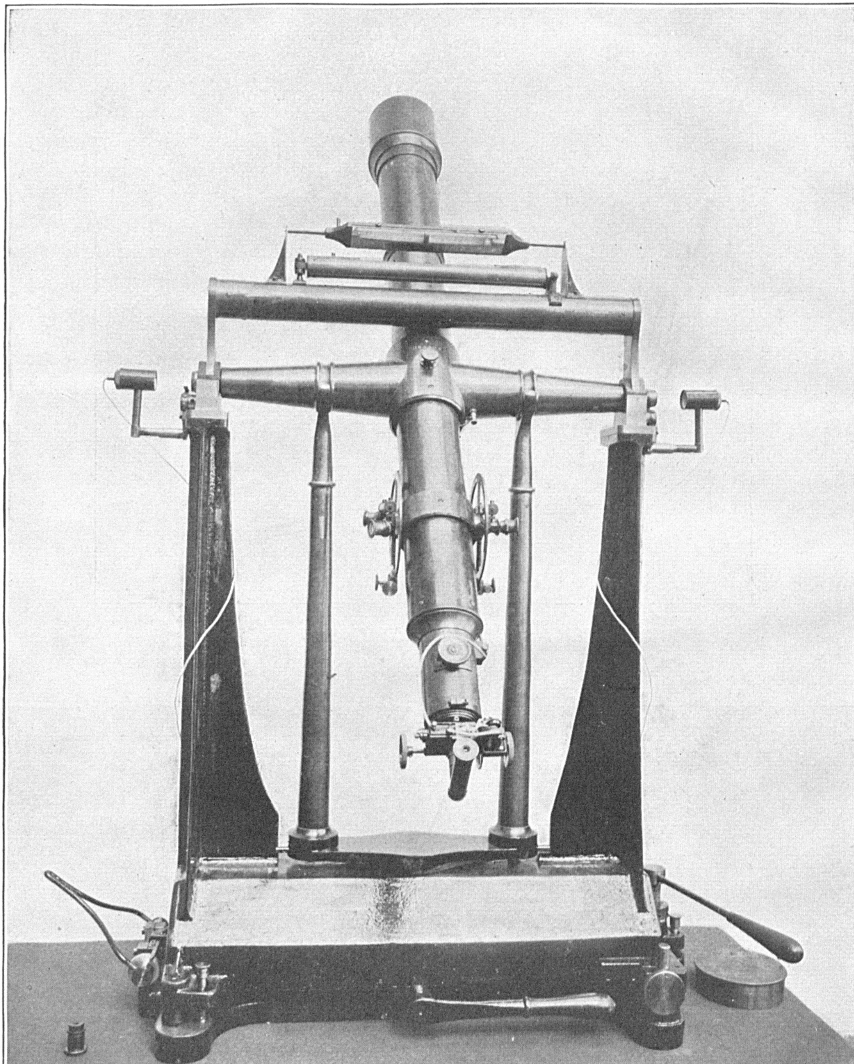

FIG. 3.—STRAIGHT TELESCOPE TRANSIT.

tion between two observers, which confirmed the office test. If there is a relative personal equation present with the transit micrometers used by the U. S. Coast and Geodetic Survey, it is probably not larger than $0^s.01$. This is too small to justify an exchange of observers, except in unusual cases, such as the determination of the differences between the stations Washington, Cambridge, and Far Rockaway.[5]

Figure 3 shows a second-sized portable straight-telescope transit used by the U. S. Coast and Geodetic Survey. It has a focal length of 94 cm. and a clear aperture of 76 mm. The magnifying power of the eyepiece ordinarily used is 104 diameters. The value of one division of the striding level is about 1″.5. The instrument is provided with a sub-base which is firmly secured to the supporting pier and with a convenient reversing apparatus. It has the usual arrangements for bringing the instrument into the meridian and for clamping it thereafter.

The portable broken-telescope transit used by the U. S. Coast and Geodetic Survey, shown in Figure 4, has a clear aperture of 7 cm. and a focal length of 67 cm.

SPECIFICATIONS FOR LONGITUDE DETERMINATIONS.

A primary determination of the differences in longitude before the advent of the transit micrometer depended upon at least six nights of successful exchange of signals, with an exchange of the observers after the first three or four successful nights.

After the transits were fitted with the transit micrometers there were required at least three nights of successful exchange of signals with no exchange of observers, provided that no difference of longitude should depend upon only three nights if the value for any night differed as much as $0^s.07$ from the mean of all of the nights.

During 1907, when 10 differences of longitude were determined, the same observer occupied the forward or new station for each difference in order to discover the magnitude of the personal equation when using the transit micrometer. Six of the differences formed one closed loop, while the other four made a second loop. The correction to a difference to close the loops was less than $0^s.01$ in each case. These corrections accounted for the personal equation and all systematic and accidental errors. After this successful field test and in view of the office tests previously mentioned, it was decided that no particular order need be followed in the placing of the observers.

The difference in geographic position of the two stations involved in a determination of the difference of longitude has usually been so small that the same set of stars could have been used at each station. In general, no attempt has been made to use identical sets, though many of the stars would necessarily be used at both stations.

During the past two decades a time set used in longitude work has, with few exceptions, included only those stars having an azimuth factor less than unity. The number of stars in a set is usually 12 and never less than 8 for the straight-telescope instrument, and is usually 6 with a minimum of 4 for the broken-telescope type. The algebraic sum of the several azimuth factors must not be greater

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[5] Determination of Differences in Longitude Between Each Two of the Stations, Washington, Cambridge, and Far Rockaway, by Fremont Morse and O. B. French. U. S. Coast and Geodetic Survey Special Publication No. 35.

than unity for a set. The straight-telescope transit is reversed in the middle of each set of stars, but the broken-telescope instrument is reversed in the middle of the observations on each star. With either type of instrument, a night's work at a station consists of observations on two sets of stars and an exchange of signals by telegraph with the other station. The exchange occurs as close as practicable to the mean epoch of the observations for the night.

Details regarding methods employed by the U. S. Coast and Geodetic Survey in the astronomic work involving time and longitude are given in Special Publications Nos. 14 and 35 of that organization.

ACCURACY OF TIME OBSERVATIONS.

An estimate of the accuracy of the observations on the individual stars may be obtained from the tables given below. The first one gives the azimuth factors and the residuals resulting from the computation of two sets of stars observed in connection with the determination of a difference of longitude in Florida. In this case the straight-telescope transit was used.

The second table gives the azimuth factors and residuals for stars used in the determination of a difference of longitude in Texas with the broken-telescope transit.

The time required for the observations on any one night is about two hours with either type of instrument.

Residuals of time determinations, straight-telescope transit with transit micrometer.

[Sebastian, Fla. Latitude, 27° 40′. March 7, 1907.]

Set number 1.			Set number 2.		
Star number.	A factor.	Residual.	Star number.	A factor.	Residual.
		Second.			*Second.*
1	+0.31	−0.06	1	+0.06	−0.02
2	− .38	− .09	2	− .13	+ .02
3	+ .43	+ .02	3	− .51	− .02
4	+ .13	+ .03	4	+ .04	+ .02
5	− .26	+ .09	5	− .02	+ .02
Telescope reversed.			Telescope reversed.		
6	+ .20	+ .04	6	− .66	.00
7	− .82	− .05	7	+ .19	− .06
8	− .02	+ .03	8	+ .32	+ .06
9	+ .34	− .04	9	− .37	+ .01
10	− .08	+ .02	10	− .23	+ .01

Residuals of time determinations, Bamberg broken-telescope transit with transit micrometer.

[Johnstone, Tex. Latitude, 29° 23′. July 13, 1919.]

Set number 1.			Set number 2.		
Star number.	A factor.	Residual.	Star number.	A factor.	Residual.
		Second.			*Second.*
1	−0.03	+0.01	1	+0.05	−0.04
2	+ .04	− .09	2	− .10	− .05
3	+ .04	.00	3	+ .18	+ .05
4	− .09	+ .03	4	+ .14	− .01
5	− .18	− .04	5	− .05	+ .02
6	.00	+ .05	6	− .03	+ .02

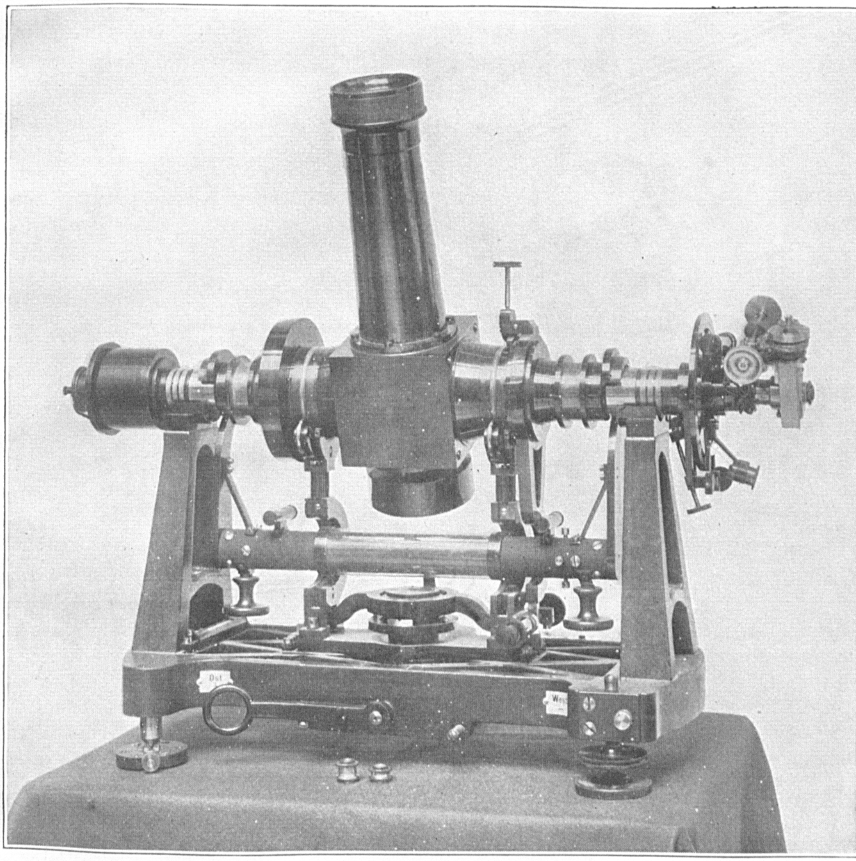

FIG. 4.—BROKEN TELESCOPE TRANSIT.

The residuals for the individual stars can not be held to be the actual errors. It is probable that any tilting of the meridian plane due to refraction will affect each star a similar amount and mask the constant error resulting thereby. Nor will any constant error in the catalogue right ascension show in the residuals. In the solution of the equations of a set of stars there is a tendency for the derived residuals to differ somewhat from the actual errors. Since the correction to the clock is computed for the mean epoch for the set the residuals are affected by the clock rate and its irregularities. Any personal equation of the observer will affect all the stars nearly the same amount, since the azimuth factor of any star used is never greater than unity and all of the stars are, therefore, comparatively close to the zenith. The other errors affecting the residuals are those due to pointing, reading the chronograph sheet, irregular refraction, unequal heating of the instrument, and level errors.

One hundred time sets actually used in longitude work by the U. S. Coast and Geodetic Survey were taken at random and it was found that in only 24 sets was there a residual on a single star as great as $0^s.10$. The probable error of the clock correction as determined by observations on a set of stars, with either of the two types of transits used, is seldom greater than $0^s.02$.

The timepiece used in the longitude work of the U. S. Coast and Geodetic Survey is the well-known chronometer. The exchange of signals between the two observers nearly always occurs about midway between the epochs of the two time sets, and in consequence the accuracy of the determination of the difference in longitude will be affected by irregularity in the rates of the chronometers between the epochs of the sets. Ordinarily the error from this source will be very small, but it may be large if the chronometers are not in good order.

In all recent work the determination of a difference in longitude is based upon not more than four nights of successful observations and exchange of signals between the two observers, though three nights are acceptable if the value of the difference for any one night does not stand out more than $0^s.07$ from the mean of the three. The probable error of the determination of a difference in longitude, since the introduction of the transit micrometer, is greater than $0^s.020$ in only 17 per cent of the cases.

As the time signals are exchanged in both directions the transmission time is largely eliminated. But at times some error may result from having a repeater in the line if the repeater does not have its two magnets adjusted exactly alike. The error entering into the difference in longitude from the difference in the transmission times in the two directions is no doubt small in nearly every case.

A lengthy discussion of the causes of error in time and longitude work may be found in U. S. Coast and Geodetic Survey Special Publication No. 14, pages 48–51 and 85–87.

CLOSING ERRORS OF LONGITUDE LOOPS IN THE UNITED STATES.

It is believed that the severest test of the accuracy of the determination of the clock corrections is furnished by the closing error of loops of differences in longitude.

Figure 5 shows graphically the location of differences in longitude determined in recent years, which form 17 closed loops. A loop may consist of recent differences tied into two adjusted stations of the

LONGITUDE LOOPS CLOSED DURING THE PERIOD 1905-1920

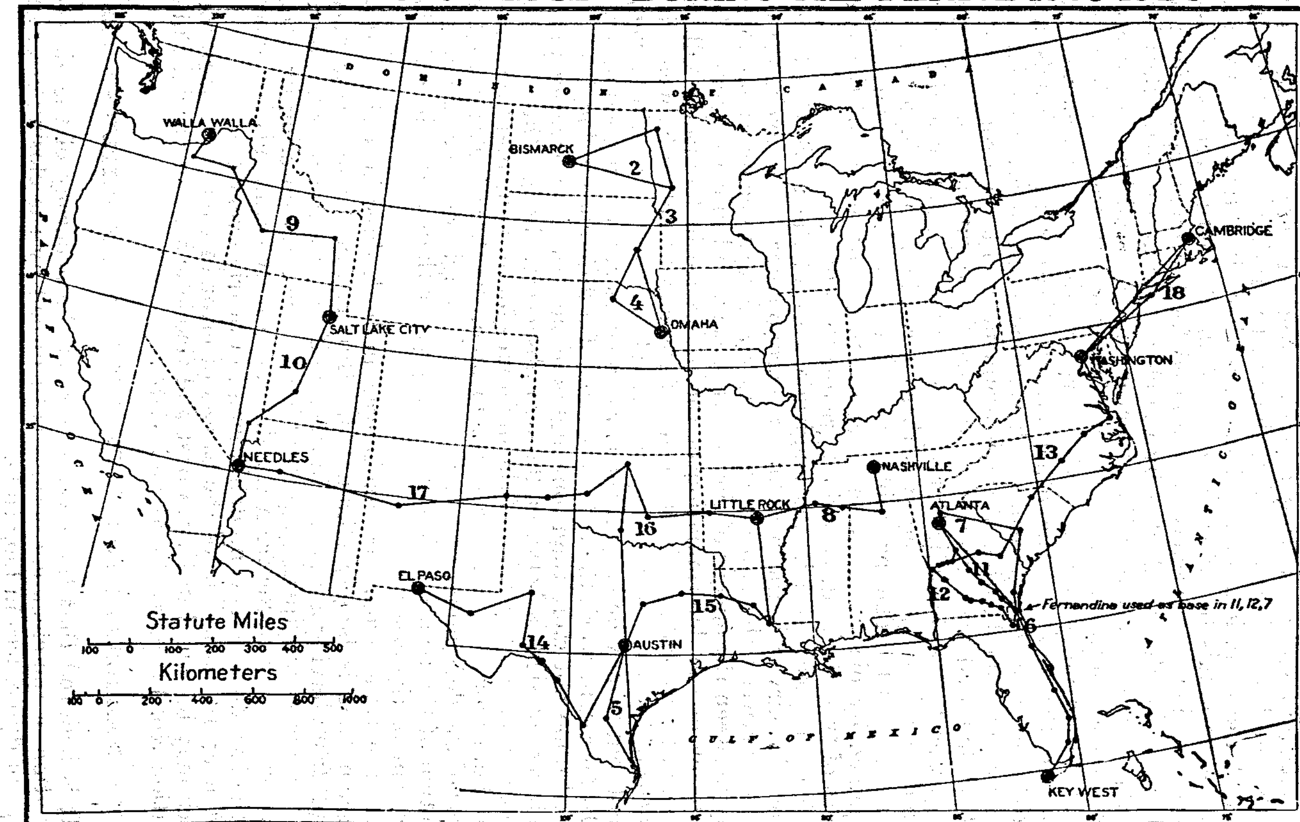

FIG. 5.

1897 longitude net adjustment in the United States[6] or may consist of differences which close on a single station. In some cases a difference is involved in more than one closed loop.

In the following table are given data for the several loops. Loops Nos. 2–18 are shown in Figure 5. Loop 1 is between Seattle and Boundary and so beyond the limits of the illustration.

The correction to a difference shown in the last column deviates in several cases from that actually applied where the adjustment involves an interlacing of loops.

Longitude loop closures.

Loop number.	Base stations.	Number of longitude differences.	Loop closure.	Correction to a difference to close loop.
			Second.	*Second.*
1	Seattle, Wash.-Boundary, Yukon Territory	4	0.033	0.008
2	Bismarck, N. Dak	3	.030	.010
3	Bismarck, N. Dak.-Omaha, Nebr	3	.024	.008
4	Omaha, Nebr	3	.071	.024
5	Austin, Tex	3	.038	.013
6	Atlanta, Ga.-Key West, Fla	6	.055	.009
7	Atlanta, Ga.-Fernandina, Fla	4	.032	.008
8	Little Rock, Ark.-Nashville, Tenn	4	.064	.016
9	Walla Walla, Wash.-Salt Lake City, Utah	5	.030	.006
10	Needles, Calif.-Salt Lake City, Utah	3	.046	.015
11	Atlanta, Ga.-Fernandina, Fla	7	.074	.011
12	Fernandina, Fla.-Atlanta, Ga	14	.273	.019
13	Atlanta, Ga.-Washington, D. C	9	.014	.002
14	El Paso, Tex.-Austin, Tex	7	.054	.008
15	Austin, Tex.-Little Rock, Ark	6	.175	.029
16	Little Rock, Ark.-Austin, Tex	5	.029	.006
17	Little Rock, Ark.-Needles, Calif	9	.003	.000
18	Washington, D. C.-Cambridge, Mass	3	.003	.001

In each of the loops Nos. 14 and 16 there was one difference in which transits without transit micrometers were used, but in these cases there was an exchange of the observers to eliminate personal equation. There was an exchange of observers in the three differences forming loop No. 18, though the instruments were equipped with the transit micrometers.

There are 98 differences[7] shown in the table with an average correction to a difference of $0^s.011$. The correction per difference for 10 of the loops is less than $0^s.010$, and only four loops have corrections per difference greater than $0^s.015$.

The number of corrections of different sizes is shown below.

Loop closure corrections since 1897.

Number of corrections.	Range of corrections.	Number of corrections.	Range of corrections.
	Second.		*Second.*
21	0.000-0.005	18	0.016-0.020
37	.006- .010	3	.021- .025
13	.011- .015	6	.026- .030

[6] The telegraphic longitude net of the United States and its connection with that of Europe, 1866–1896, by C. A. Schott. Appendix 2, Report 1897.

[7] The actual number of differences is 90. Some of these are listed in the table for two groups, hence the number 98 shown therein.

In the 1897 adjustment of the longitude net of the United States there are 72 differences in longitude. Land lines were used for 63 of these differences, cables for the remaining 9. The following table shows the number of corrections of the 1897 adjustment falling between various limiting values:

Loop closure corrections, 1897 adjustment.

Signals exchanged over land lines.		Signals exchanged over ocean cables.	
Number of corrections.	Range of corrections.	Number of corrections.	Range of corrections.
	Second.		*Second.*
24	0.000-0.010	1	0.000-0.010
12	.010- .020	4	.010- .020
9	.020- .030	0	.020- .030
15	.030- .040	2	.030- .040
1	.040- .050	0	.040- .050
2	.050- .060	0	.050- .060
		2	.060- .070

Even though no transit micrometers had been used in the observations for time in connection with the differences of longitude prior to 1897, the net adjustment that year showed corrections which are really small. Of 63 differences over land, 36 have corrections for loop closure less than $0^s.020$, while only 3 of the corrections are more than $0^s.040$.

The 9 differences involving cables show 5 corrections less than $0^s.020$, 2 between $0^s.030$ and $0^s.040$, and 2 between $0^s.060$ and $0^s.070$.

The accuracy of the adopted longitudes of the stations involved in the 1897 adjustment is indicated by the closing errors of the loops of longitude differences determined since that date which close on these stations. There is a chain of new determinations from Cambridge, Mass., to Walla Walla, Wash., with the exception of the differences in longitude between Atlanta and Nashville and between the New Naval Observatory and the U. S. Coast and Geodetic Survey. For those two differences there was an exchange of observers. There are 33 links in this chain, and the sum of the differences of longitude is only $0^s.012$ less than the difference between those stations derived by the 1897 adjustment. The correction per difference in longitude to close this loop is, therefore, only $0^s.0004$.

It is believed that the evidence given above regarding the longitude work by the U. S. Coast and Geodetic Survey since the introduction of the telegraph many years ago will enable anyone to arrive at the conclusion that errors of the magnitude of several tenths of a second of time do not exist in the determination of the clock corrections used in the longitude work. The small average probable error ($\pm 0^s.010$) of the determination of time with a set of stars, the small probable error (about $\pm 0^s.02$ on an average) in the determination of a difference in longitude, and finally the exceedingly small correction (about $0^s.011$ on an average) necessary to close loops of longitude differences, all indicate clearly that the total range in the errors in the time determinations is seldom greater than $0^s.10$ at a longitude station.

CAUSES OF ERRORS IN TIME DETERMINATIONS.

There have been many articles published dealing with clock errors and rates and what causes affect them. It is not intended that this paper shall go into this vast field. It is certain that such errors in time values as were found by Sampson[8] in determinations at the large observatories do not exist even in the older work of the U. S. Coast and Geodetic Survey, and they certainly are not present in the time work done since the instruments were fitted with the transit micrometers.

There are fundamental differences in the longitude methods investigated by Sampson and those of the U. S. Coast and Geodetic Survey. Sampson received the time signals by radio, but on the work of the U. S. Coast and Geodetic Survey wires and cables were employed. The observations involved in Sampson's investigations were made at permanent observatories, presumably with large transit instruments housed or surrounded by permanent structures. The time observations of the U. S. Coast and Geodetic Survey are made with portable transits, necessarily small, installed in tents or small temporary wooden shelters. The observatories are probably in or very close to large cities or settlements, but the longitude stations of the Coast and Geodetic Survey are usually out in the fields or in vacant lots in small villages. The movement of the warmer air from a city across an observatory may result in some lateral refraction and displacement of the meridian.

It is probable that some of the trouble discovered by Sampson is due to the radio signals. Some of the trouble may be due to the presence of large buildings around the transits. There may be lateral refraction caused by the rising air currents from the buildings during the early hours of the night. The work of the U. S. Coast and Geodetic Survey is free from any such troubles.

With such large uncertainties in the time determinations at a number of the largest observatories in the world, as are indicated in Sampson's studies, it would hardly seem advisable to embark now on such a campaign of longitude determinations by the aid of radio signals as Ferrie proposes.

The errors incident to sending time signals by radio should be carefully studied, and a careful comparison should be made of the time observations at a large observatory with those at a field station. The results of such tests would be most interesting and valuable to a large number of persons.

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[8] On the determination of time at different observatories. Monthly Notices of Royal Astronomical Society, January, 1922.

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