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[From the American Journal of Science, Vol. XXXV, Jan., 1888.]

Art. I.—*The Speed of Propagation of the Charleston Earthquake;* discussed by Professor Simon Newcomb, U. S. N., and Captain C. E. Dutton, U. S. A.

The investigation of the time data of the Charleston earthquake having been completed and a final result being reached, it is deemed proper, with the consent of the Director of the Geological Survey, to publish a brief abstract of the discussion. The full discussion will appear in the final report upon the earthquake, which report is now well advanced toward completion.

Immediately after the earthquake all practicable measures were taken to collect information, and special effort was directed to obtaining the largest amount of time data. Through the courtesy of the Associated Press, notices were published in nearly all the newspapers of the country requesting those who had made such observations to forward them to the Director of the Geological Survey. Many persons did so. The Chief Signal Officer instructed the observers of that bureau who had noted the time of the shock to report it, and he forwarded all such reports to the survey. The Western Union Telegraph Co. instructed its operators to forward reports and similar instructions were sent by the Lighthouse Board to light-keepers. Special effort was made to secure newspapers from as many localities as possible. Most of the leading papers of the country have an agent or reporter at Washington and he usually keeps a file of the paper he serves. The library of Congress keeps files of two or more papers from every State. As many of these as practicable were thoroughly examined. Many local papers were requested to furnish copies of their issues of Sept. 1st, 2d and 3d, and most of them complied. Many marked copies of papers were sent to the survey from unexpected sources. Altogether more than four hundred time reports were gathered.

As might be expected a portion of these were useless. In order that it may be apparent which were selected for consideration and which rejected, the following account is given. There were about thirty which stated that the shock occurred "about 10 o'clock" or "a few minutes before 10." As a single minute is a very important quantity here, all such reports were summarily rejected as too indefinite. The reports from lighthouses in most cases proved unavailable. These structures being situated most frequently where access to standard time is difficult, their clocks are regulated by the sun and an almanac. The uncertainties of this method of time keeping were evidently too great to justify any attempt to utilize them. But a few lighthouses keep standard time and in all such cases their reports were admitted to consideration. There were a few (nine or ten) which gave times so widely aberrant, differing by a quarter to half an hour from the great mass of records, that they were rejected. The whole number which received preliminary consideration was 316, many of which it was expected would also be rejected after a more thorough examination, due cause being assigned. These 316 observations were catalogued in alphabetical order, the latitudes and longitudes of the localities being roughly ascertained and also their distance from the centrum.

By far the most important time determination is that of the centrum, which was computed to be about six seconds earlier than that of Charleston. The time at Charleston is derived as follows. Among the numberless clocks stopped in that city by the earthquake, there were four which had compensated seconds pendulums and second hands and were of the pattern generally classed as "jewelers' regulators." All were compared daily with the time signal of the Western Union Telegraph Co., and the testimony is positive that none of them had errors on August 31st exceeding nine seconds, while the mean probable error of the four was certainly much less than this. The first was the regulator of James Allan & Co., Jewelers, No. 285 King street. It was regulated by means of a "sounder," which was daily put into circuit with the Western Union time signal wire. The clock was corrected only when its error exceeded nine seconds. Mr. Allan is authority for the statement that its reading next morning was 9:51 exactly. He had received the time signal on August 31st, but as the clock was within the limit of tolerance he did not correct it. Subject to this limit he had no knowledge of the exact error of his clock and his memory on this point did not serve him The second clock was the regulator which controls the time of the North Eastern Railway. This clock was compared with the time signal on August 31st, but was not corrected, its error being within the limit of tolerance, which was eight seconds. It had been reset two days previously. Its reading was 9:51:15. It was stopped by the point of the pendulum catching behind the metallic arc in front of which it properly vibrates. The third clock was that which regulates the time of the Charleston & Savannah Railroad. It had been reset two days previously and compared with the time signal on August 31st, and was within the limit of tolerance, eight seconds. Its reading was 9:51:16 and it was stopped in the same manner as the preceding one. The fourth clock was that of the South Carolina Railroad. It had been reset by the daily time signal on the day of the earthquake. Its reading was 9:51:48.

Although these records range through an interval of 48 seconds they may be reconciled. The azimuths of the planes of oscillation of their pendulums were as follows:

James Allan & Co's	N. 85° E.
North Eastern Railroad	N. 40° E.
Charleston & Savannah Railroad	N. 66° E.
South Carolina Railroad	N. 30° W.

These azimuths may be put into relation with what is now known concerning the varying phases of the shocks, their respective durations and directions of vibratory motion. The earthquake at Charleston began as a light tremor, steadily increasing in power through an interval estimated to be from 10 to 15 seconds' duration; then suddenly or by swift degrees it swelled into the full power of the first maximum, then subsided to a minimum, then swelled suddenly to a second maximum and lastly died away gradually. The interval from the beginning of the first maximum to the close of the second maximum is estimated at from 35 to 55 seconds; the subsiding tremors are estimated at about 6 to 8 seconds: the total duration from 55 to 75 seconds. It may be expressed graphically by the following curve in which the abscissas represent time and the ordinates an arbitrary scale of intensity.

In the first maximum the waves were mainly normal and came from N. 30° W. In the second maximum the direction of vibration was about at right angles with the foregoing or about N. 60° E. It will now be seen that the planes of oscillation of the first three clocks made wide angles with the direction of motion of the first maximum, while the plane of the fourth clock was almost exactly parallel with that direction and perpendicular to the direction of motion of the second maximum. The fourth clock, then, may easily have escaped arrest

until the second maximum while the other three would have little chance of escaping the first maximum, even if they did not stop during the lighter preliminary tremors. That the second and third clocks stopped during the first maximum is rendered probable by the way in which their pendulums were caught. It would require a considerable acceleration in a direction perpendicular to their planes of oscillation and at times when the pendulums were near the extremities of their arcs of vibration in order to throw their bobs far enough backward to catch in the manner they did. These two clocks are relied upon as giving the time of the first maximum. The chances are, however, that the pendulums were not caught in this particular way during the first three or four oscillations, but went staggering along for a very few beats until finally caught. An interval of three or four seconds was probably occupied in the rapid swelling of the quake from the preliminary milder phase into the full power of the maximum. If we assume for the beginning of the first maximum an instant of time about three or four seconds earlier than that indicated by the two railroad clocks, i. e. 9:51:12, our actual error, it is believed will not exceed four seconds. The clock of James Allan & Co. probably stopped at a slightly earlier phase. If it may be assumed to have been six or eight seconds slow, its stopping would have been easily possible at that phase; for many less sensitive clocks throughout the country were arrested by tremors no more forcible than those in Charleston at the particular phase thus indicated. We shall reach the same result, 9:51:12, if we throw out the fourth clock as relating to the second maximum and (giving the weight 2 to both the second and third clocks and the weight 1 to the first) take the mean readings of the three. The whole tenor of the evidence from other clocks in Charleston points strongly to a time a few seconds later than 9:51 for the first maximum.

It is plainly necessary to select some phase of the earthquake in Charleston or at the centrum as the beginning, with which the beginning in all other places must be compared. It must plainly be a phase at which the shocks had very great power, sufficient to make themselves felt hundreds of miles away. This phase should obviously be that which has been called the beginning of the first maximum. It still remains to find the corresponding time at the centrum. As the speed of propagation is now known to have been in the neighborhood of three miles a second and as the distance of Charleston from the theoretic centrum is 20 miles, the subtraction for the time at the centrum is taken to be six seconds, making the time of beginning at that point 9:51:06 standard time of the 75th meridian.

The full catalogue was next examined in order to ascertain what reports should be finally rejected. In the final report this catalogue will be published, together with a list of the rejected observations showing the grounds of rejection. For present purposes a summary view of these reports is given, showing the number of observations corresponding to specific minutes or falling betweeen consecutive minutes.

Table showing the numbers of reports corresponding to specified minutes or falling between consecutive minutes.

9:47 and seconds	1
9:48	3
9:50	32
9:51	6
9:51 and seconds	6
9:52	25
9:52 and seconds	9
9:53	28
9:53 and seconds	16
9:54	31
9:54 and seconds	9
9:55	86
9:55 and seconds	8
9:56	21
9:56 and seconds	2
9:57	8
9:58	5
9:58 and seconds	1
9:59	3
10:00	13
10:01	2
10:02	1
Total	316

There are thus four reports giving times earlier than 9:50 and three later than 10 o'clock. The synopsis illustrates well the tendency of people to give time in terms which are multiples of five minutes. Thus we have 32 giving 9:50, but none giving 9:49, and only six giving 9:51. There are 13 giving 10 o'clock and there would have been many more of them if the catalogue had included those which stated the time as being "about" 10 o'clock or "near" 10 o'clock. There are 86, or more than one fourth the whole number, which give 9:55. Every one of the 9:50 reports is rejected. It is certain that they all involve errors greater than one minute too early, and the large number of them would introduce a large systematic error into the mean; and as there is no apparent reason for rejecting or keeping one observation rather than another, all of them are thrown out. All of the 10 o'clock observations are thrown out. For, upon further examination, all giving 9:58 and seconds, 9:59, 10:01 and 10:02 will be rejected on their merits. This would leave the 10 o'clock reports as an isolated group in an otherwise comparatively orderly series, and its effect would be to introduce an error of unknown magnitude and of anomalous character. In dealing with those giving 9:55 there is more difficulty. The following course has been adopted. Wherever a report states clearly, or raises a strong presumption, that this was really the nearest minute observed, to the exclusion of any other, it is accepted if otherwise unobjectionable. Where this evidence is wanting the report is rejected. It is quite probable that some thus rejected are very good observations; but it is clearly better to reject many possibly good observations (provided a sufficient number remain) than to admit a few bad ones with the certainty of introducing an unknown error. The number of 9:55 reports thus rejected is 43, which happens to be just one half.

Still other observations are rejected on their merits. A majority of these are thrown out for what are presumed to be large unexplained errors. There are 29 of them, of which 15 are rejected for being two minutes or more too early and 14 for being as much, or more than as much, too late, when compared with a larger number of much better observations in the same locality or in the immediately surrounding region. The rejection of these 29 observations does not greatly affect the deduced speed, but it does diminish notably the computed probable error. The total number rejected for all causes is 130 and the number accepted is 186. These have been separated into four groups, each containing data which are considered to be as nearly homogeneous as possible; that is to say, in each group the observations are presumed to have the same sources of error, whether accidental or systematic.

The first group is required to fulfill the following conditions: (1) The report must specify the beginning, or the time when the tremors first became sensible. (2) It must give not only the minutes, but also the seconds, with an uncertainty not exceeding 15 seconds. (3) It must have been obtained from a clock kept running with accuracy upon standard time or equally reliable local time, or from a clock or watch compared with such time within a few hours of the occurrence. There are five observations besides that of Charleston which meet these requirements.

The second group will consist of those which fulfill the same conditions as the first, except that they will be required to give only the minute or half minute nearest to the beginning. There are eleven which answer to these requirements.

The third group will include all that remain after taking out groups I, II, and the stopped clocks. Some of these state that the time is that of the beginning, but fail to show that any attempt was made to ascertain the error of the time-piece. Some give a satisfactory account of the time-piece, but fail to state the phase to which the reported time refers. Many do neither the one nor the other. The number of reports in this group is 125.

The fourth group consists of accepted reports of clocks stopped by the first great shock. The clocks, however, must be stated to have been regulated carefully by standard time or by local time known to be equally accurate.

In all the groups there is more or less discordance among the several observations, no two giving the same speed. As the errors of the first two groups are believed to be mainly of the accidental class, the best method seems to be to submit them to the process of least squares. The equations of condition may be formed very simply in the following manner: The computed time of the beginning at the centrum (which has already been given) must be presumed to have some error, which may be designated by x. If t_0 be the computed time at the centrum (9:51:06) and t the reported time at any other locality, then $(t-t_0)$ = the number of seconds in the observed time-interval taken by the wave to travel from the centrum to the place of observation. If D be the distance in statute miles, and y the number of seconds or fraction of a second required to travel one mile, we may form the following equation: $x+Dy=t-t_0$, in which there are only two unknown quantities, x and y. This implies that the speed is uniform. If this implication differs widely from the truth, indications of it may be expected to appear in the residuals. It is necessary to put the equations of condition into a form in which a time and not a speed shall be the unknown quantity, because the times and not the distances are the data into which the greatest uncertainty enters. If, putting v for the speed of transmission, we put our equations into the form of $v(t-t_0)=D$, they would be subject to the objection that their uncertain quantities would be the coefficients of the unknown quantities and not the absolute terms. The distances from the centrum have been taken from the Land Office map of the United States by measurement with a scale. They are subject to possible errors as great as three or four miles, but this error is so small in comparison with the best times that the distances may be regarded as sensibly exact.

The following reports constitute the first group. For the sake of brevity the full accounts of these reports are here omitted. They will appear in the final work on the earthquake.

GROUP I.—*The best Observations.*

Locality.	State.	Distance.	Time 9h+ m.	s.	Weight.	Observer.
Centrum,	S. C.	0	51	06	2	
Washington,	D. C.	452	53	20	2	Prof. Newcomb
Washington,	D. C.	452	53	23	2	Alex. McAdie.
Baltimore,	Md.	487	53	20	1	R. Randolph.
New York,	N. Y.	645	54	30	2	M. C. Whitney.
Dyersburg,	Tenn.	569	54	00	1	Louis Hughes.

From these observations the following equations of condition may be formed.

	Wt.	Resid.
$x + 0y = 0$	2	$-2{\cdot}6$
$x + 452y = 135{\cdot}5$	4	$+1{\cdot}6$
$x + 487y = 134$	1	$+13{\cdot}9$
$x + 569y = 174$	1	$-0{\cdot}8$
$x + 645y = 204$	2	$-7{\cdot}3$

By the process of least squares the normal equations are:

$$10x + 4154 = 1258$$
$$4154x + 2210196 = 672408$$

The solution is, $x = -2{\cdot}6$s $\pm 4{\cdot}7$s. and $y = 0{\cdot}309 \pm 0{\cdot}01$. The resulting speed is, $3{\cdot}236 \pm 0{\cdot}105$ miles or 5205 ± 168 meters per second.

GROUP II.—*Good reports, giving the time of beginning to the nearest minute or half minute.*

Locality.	State.	Distance.	Time.	Weigh	Observer.
Centrum,	S. C.	0	51^m06^s	2	
Nashville,	Tenn.	438	53 30	1	J. D. Leonard.
Covington,	Ky.	488	53 41	1	Jos. Brookshaw.
Pikesville,	Md.	490	53 30	1	C. R. Goodwin.
Evansville,	Ind.	545	54	1	F. W. Norton.
Cleveland,	O.	604	54	1	Wm. Line.
Cleveland,	O.	604	54	1	G. H. Tower.
Crawfordsville,	Ind.	620	54	½	E. C. Simpson.
Belvidere,	N. J.	622	54	1	G. W. Holstein.
New York,	N. Y.	645	54 30	1	N. Y. Herald.
Stockbridge,	Mass.	765	56	½	J. O. Jacot.
Albany,	N. Y.	770	55	1	W. G. Tucker.

From these we may form the following equations.

Equation	Weight.	Residuals.
$x + 0y = 0$	2	$-1{\cdot}6$
$x + 438y = 144$	1	$-9{\cdot}8$
$x + 488y = 155$	1	$-5{\cdot}3$
$x + 490y = 144$	1	$+6{\cdot}3$
$x + 545y = 174$	1	$-6{\cdot}6$
$x + 604y = 174$	2	$+11{\cdot}6$
$x + 620y = 174$	$\frac{1}{2}$	$+16{\cdot}6$
$x + 622y = 174$	1	$+17{\cdot}2$
$x + 645y = 204$	1	$-5{\cdot}6$
$x + 705y = 294$	$\frac{1}{2}$	$-58{\cdot}4$
$x + 770y = 234$	1	$+3{\cdot}1$

The normal equations are:

$$12\,x + 5898{\cdot}5\;y = 1811.$$
$$5898{\cdot}5x + 3577366{\cdot}5\;y = 1100677.$$

The solution gives $x = -1{\cdot}6\text{s.} \pm 7{\cdot}7\text{s.}$ $y = 0{\cdot}31 \pm 0{\cdot}014\text{s.}$ The resulting speed is, $3{\cdot}226 \pm 0{\cdot}147$ miles or 5192 ± 236 meters per second.

Group III consists of reports which fail to give either the means of judging of the comparative accuracy of clocks and watches or of determining to what phase the observation refers. Many and indeed the majority of them are defective in both of these respects. Quite probably some of them are good observations but fail to give the evidence of it. So far as errors of clocks and watches are concerned the errors may be considered as belonging to the accidental class. But all errors as to the phase must be systematic. That some of them refer to more or less advanced phases is certain, and it becomes difficult to determine how many of them do so, and how great is the average tardiness. It is obvious that the effect of all such errors is to make the time too late and the resulting speed too slow. The general indications are, however, that this systematic error is not a large one. By comparing miscellaneous reports from those cities which have also given better verified reports belonging to groups I and II there seems to be a tendency of the average value of this error to fall between one-tenth and one-twentieth of the mean value of the time-interval.

In discussing this group it seems unnecessary to go to the length of formulating a hundred equations of condition, and an equally good result or even a better one may be obtained by the following more summary process. We may take them in sets, the first of which shall comprise all times within 200 miles of the centrum, the second set all between 200 and 300 miles, the third all between 300 and 400 miles, and so on until the last, which shall comprise all beyond 800 miles. In each set we may then take the weighted arithmetic means of the times and distances as if they were single observations.

GROUP III.—*List of* 125 *miscellaneous Time Reports.*

Locality.	State.	Distance.	Time.	W't.	Remarks.
Statesburg,	S. C.	80	51^m30^s	1	
Columbia,	S. C.	89	52	1	
Savannah,	Ga.	89	51 53	2	mean of 3 obs.
Augusta,	Ga.	111	51 30	2	mean of 2 obs.
Laurinburg,	N. C.	135	51	1	
Darien,	Ga.	138	52 30	1	
Brunswick,	Ga.	155	52	1	
Macon,	Ga.	203	52	1	
Jacksonville,	Fla.	211	52	2	mean of 3 obs.
Fernandina,	Fla.	225	53	1	
Olustee,	Fla.	355	53	1	
Palatka,	Fla.	255	53	1	
Thomasville,	Ga.	273	52 20	1	
Wytheville,	Va.	284	52 27	1	
Knoxville,	Tenn.	302	54	1	
Zellwood,	Fla.	306	53	1	
Chattanooga,	Tenn.	329	53	1	
Norfolk,	Va.	349	54	1	
University,	Ala.	363	52	1	
Ashland,	Va.	367	52	1	
Shelby Iron Works,	Ala.	377	54	1	
Catlettsburg,	Ky.	405	52 30	1	mean of 2 obs.
Pungoteague,	Va.	410	53	1	
Decatur,	Ala.	412	53	1	
Ironton,	O.	414	55	1	
Nashville,	Tenn.	438	54 30	1	
Washington,	D. C.	452	53 41	2	mean of 4 obs.
Louisville,	Ky.	485	54 38	1	mean of 2 obs.
Baltimore,	Md.	487	53	1	
Dayton,	Ky.	487	54 11	1	
Newport,	Ky.	488	53 21	1	
Cincinnati,	O.	491	53 41	4	mean of 6 obs.
Lancaster,	O.	491	54	1	
Wyoming,	O.	501	53 41	1	
Columbus,	O.	513	53 41	2	mean of 4 obs.
Hamilton,	O.	513	54 11	1	
Paris,	Tenn.	520	56	1	
Pittsburg,	Pa.	525	54 30	1	mean of 2 obs.
Brookville,	Ind	526	53	1	
New Philadelphia,	O.	532	54	1	
Sewickly,	Pa.	535	54	1	
Mt. Vernon,	O.	536	56	1	
Wellsville,	O.	538	55	1	
Oxford,	Miss.	548	56	1	
Paducah,	Ky.	558	52 15	1	
Philadelphia,	Pa.	566	53	1	
Burlington,	N. J.	584	53	1	
Indianapolis,	Ind.	584	55	2	mean of 3 obs.
Cairo,	Ill.	588	53	1	
Titusville,	Pa.	608	56	1	
Helena,	Ark.	609	55	1	
Toledo,	O.	637	55	1	
Newark,	N. J.	640	53	1	
Jamestown,	N. Y.	642	56	1	

Locality.	State.	Distance.	Time.	W't.	Remarks.
Brooklyn,	N. Y.	643	$54^m 30^s$	3	mean of 4 good obs.
New York,	N. Y.	645	54 12	6	mean of 10 obs.
Hackensack,	N. J.	654	54	1	
Warwick,	N. Y.	661	56	1	
Gowanda,	N. Y.	666	55	1	
Detroit,	Mich.	675	55 12	3	mean of 5 obs.
Valparaiso,	Ind.	705	53	1	
London,	Ont.	706	55	1	
Peoria,	Ill.	710	55	1	
New Haven,	Conn.	711	55 30	2	mean of 2 obs.
Port Huron,	Mich.	712	55	1	
Hudson,	N. Y.	747	57	1	
Hartford,	Conn.	747	54 45	2	mean of 2 good obs.
Stuyvesant,	N. Y.	760	57	1	
East Saginaw,	Mich.	766	58	1	
Albany,	N. Y.	770	56 40	1	
Fonda,	N. Y.	775	55	1	
Saratoga,	N. Y.	797	53	1	
Greenfield,	Mass.	799	55	1	
Keokuk,	Iowa.	810	56	2	2 obs.
Dighton,	Mass.	812	56	1	
Davenport,	Ia.	827	55	1	
Lake Placid,	N. Y.	827	55	1	
Jamaica Plain,	Mass.	828	57	1	
Blue Mt. Lake,	N. Y.	830	56	1	
Bellows Falls,	Vt.	832	53	1	
Boston,	Mass.	832	55 30	1	2 obs.
Dubuque,	Ia.	878	57	1	
Prairie du Chien,	Wis.	924	56 30	1	

Taking these in groups in the manner just indicated we have:

		Weight.	Residuals.
Centrum	$x + 0y = 0$	2	$+ 4{\cdot}06$
0 to 155	$x + 111y = 39$	9	$+ 1{\cdot}90$
203 to 284	$x + 240y = 84$	8	$- {\cdot}28$
302 to 377	$x + 342y = 122$	7	$- 4{\cdot}43$
405 to 491	$x + 462y = 158$	16	$- {\cdot}60$
501 to 588	$x + 542y = 184$	18	$- {\cdot}05$
608 to 675	$x + 647y = 217$	20	$+ 1{\cdot}80$
705 to 799	$x + 744y = 255$	15	$- 4{\cdot}00$
810 to 924	$x + 837y = 278$	11	$+ 3{\cdot}85$

The normal equations are:

$$106x + 55768y = 18940.$$
$$55768x + 34474772y = 11668675.$$

The solution gives $x = + 4{\cdot}06 \pm 1{\cdot}7$ seconds, $y = 0{\cdot}3319 \pm 0{\cdot}0029$. The resulting speed is, $3{\cdot}013 \pm 0{\cdot}027$ miles or 4848 $\pm$ 43 metres per second. To this result some correction must be applied for the systematic error, which, as already stated, there is reason to believe probably lies between one-tenth and one-twentieth of the mean time-interval and therefore of the speed. Suppose it be taken at one-fifteenth of the amount, with a probable error of one third of the correction. This would make the corrected result $3{\cdot}214 \pm 0{\cdot}072$ miles or 5171 ± 116 metres per second.

Stopped Clocks.

It is natural to suppose that if a clock were stopped by an earthquake and if its error at the time were known it would give the best possible record of the time of advent of the shock. An examination of the time reports of this earthquake, however, strongly contradicts this conclusion. A clock may stop at almost any phase of the disturbance. A sensitive one may pass through an earthquake of considerable violence and not stop at all. A jeweler's clock in Charleston was found going the next morning, and when the telegraph wires were re-opened its error was found to be small, showing that its escapement had missed very few beats, if any. Clocks in Columbia, Savannah, Augusta and Wilmington, N. C., in many cases kept going. Inquiry at Wilmington elicited the reply that no jewelers' clocks had been stopped. Several reports describe clocks whose rates are satisfactorily vouched for but whose times can be accounted for only upon the theory that they were stopped by the second powerful shock, which was felt at Charleston about five minutes after the principal one, *e. g.*, Branchville, S. C., Augusta, Rome, Ga., Cape Canaveral, Camden, Ala., Memphis, Tenn. There are some cities where the time of beginning is well established by independent observation and which also report stopped clocks. In every such case the time of the stopped clock is much later. Thus at Nashville the time of beginning was noted by a clock which continued going for 42 seconds and then stopped. Similar means of comparison come from Cincinnati, Covington, Ky., Pittsburg, Newark, N. J., Brooklyn and New York. And in general wherever stopped clocks can be compared with really good personal observations they invariably show a later time and usually a much later one. The difference is plainly due to the fact that it generally takes a considerable time and an accumulation of the effects of the vibrations of the building upon the pendulum to stop a clock. An attempt has been made to evaluate this difference by taking those cases where a comparison can be made between the readings of stopped clocks and independent determinations of the times of the beginning in the same locality.

Locality.	State.	Intervals by personal obs. Seconds.	Intervals by stopped clocks. Seconds.	Ratios.	Weights.
Nashville,	Tenn.	144	186	1·29	2
Covington,	Ky.	155	235	1·52	1
Cincinnati,	O.	155	195	1·26	2
Pittsburg,	Pa.	174	234	1·34	1
Brooklyn,	N. Y.	204	234	1·15	1
New York,	N. Y.	204	249	1·22	2
		Mean ratio,		1·28	

In the above table the comparison at Cincinnati takes account only of a single clock, whose error happened to be known exactly. The time of beginning in that city is also known with exceptional certainty and accuracy. It will not differ more than eight or ten seconds from 9h. 16m. (Cincinnati local mean time or 9h. 58m. 41s.). If we consider Cincinnati and suburban towns within fifteen miles of the city which are supplied with local time from the Cincinnati observatory, we have no less than twenty-two time reports, of which nine are stopped clocks. Two personal observations giving 9:15 local have been rejected because they are multiples of five. One report giving 9:17:45 has been rejected because its author, besides indicating that it refers to an advanced phase, throws doubt on his own observation. Of the remaining ten personal observations one gives 9:15:40, eight give 9:16, and one gives 9:16:30. Of the stopped clocks, three were in the central office of the Western Union Telegraph Co. They kept standard time and were read only to the nearest minute. All three are reported to have stopped at 9:54. The clock in the fire tower is the one whose error was known. Its corrected reading was 9:16:40. The remaining clocks gave (9:15), (9:16), (9:17), (9:17:20), and (9:19). Four of the latter were from the suburban town of Lockland Reducing to standard time and taking their mean, the ratio of the time-interval by stopped clocks to that by personal observation is 1.26, a result identical with that derived from the clock in the fire tower alone and nearly the same as that in the table. There is reason to believe, however, that this ratio is a little too great for the mean of stopped clocks throughout the entire country, and especially so for those of very distant localities; for if the ratio were uniform, the absolute differences between the two kinds of data would be very wide in remote regions and small near the centrum. This is not the case. The absolute differences at very remote localities are very little, if any, greater than those at the middle distances. This difficulty prevents us from assigning any specific value to the correction and from determining its probable error. Nevertheless the comparisons just made indicate that the systematic error is probably of such magnitude that, if due allowance were made for it, the corrected result for the stopped clocks would not differ much from those of the preceding groups. While this group furnishes evidence which strongly supports the approximate correctness of the results of the other three it cannot be a source of greater precision nor can it furnish the means of reducing the final probable error.

Group IV.—*Stopped Clocks.*

Locality.	State.	Distance.	Time.	No. of clocks.	W't.
Centrum,	S. C.	0	$51^m 06^s$		
Charleston,	S. C.	20	51 12	4	3
Columbia,	S. C.	89	51	2	2
Savannah,	Ga.	89	51 55	2	2
Langley,	S. C.	103	53	1	1
Augusta,	Ga.	111	52	1	1
Cochran,	Ga.	192	52	2	2
Macon,	Ga.	203	51 30	1	1
Jacksonville,	Fla.	211	52	1	1
Atlanta,	Ga.	252	52 22	4	3
Catlettsburg,	Ky.	405	53	1	1
Nashville,	Tenn.	438	54 12	1	1
Columbus,	Miss.	481	56	1	1
Covington,	Ky.	488	55	1	1
Cincinnati,	O.	491	54	3	2
Cincinnati,	O.	491	54 21	1	1
Meridian,	Miss.	500	54	1	1
Lockland,	O.	505	54 26	4	3
Havre de Grace,	Md.	515	55	1	1
Pittsburg,	Pa.	525	55	1	1
Newcastle,	Del.	538	54	1	1
Atlantic City,	N. J.	552	54	1	1
Wooster,	O.	558	55 45	1	1
Newcastle,	Pa.	565	55	1	1
Indianapolis,	Ind.	581	55	1	1
Memphis,	Tenn.	587	54 50	6	4
Cairo,	Ill.	588	53	1	1
Meadville,	Pa.	608	55	1	1
Newark,	N. J.	640	55	1	1
Brooklyn,	N. Y.	643	55	1	1
New York,	N. Y.	645	55 15	2	1
Ithaca,	N. Y.	696	55	1	1
Manistee,	Mich.	855	57	1	1

We may arrange these in groups or sets according to their distances, as was done in the discussion of group III, and obtain the following equations of condition.

		Weight.	Residuals.
0 to 89	$x + 59y = 15$	7	$+ 12{\cdot}29$
103 to 192	$x + 150y = 69$	4	$- 7{\cdot}21$
203 to 252	$x + 234y = 110$	5	$- 16{\cdot}37$
405 to 491	$x + 469y = 194$	7	$- 11{\cdot}29$
500 to 588	$x + 549y = 209$	16	$+ 4{\cdot}04$
608 to 696	$x + 642y = 237$	5	$+ 12{\cdot}80$
855	$x + 855y = 354$	1	$- 24{\cdot}97$

The normal equations are:

$$45x + 183335\,y = 7172.$$
$$18335x + 9567895\,y = 3717233.$$

From which $x = +5 \cdot 0$, $y = 0 \cdot 379$. The resulting speed is $2 \cdot 638 \pm 0 \cdot 105$ miles, or 4245 ± 168 meters per second. If the correction for the systematic error has a value approximately that which has been derived from the comparisons of the stopped clocks with well determined times of particular localities, or not less than one-fifth the amount, the corrected speed would be from 5100 to 5200 meters.

We may now proceed to combine the results of the first three groups and obtain from them a single mean. The probable error of the fourth group being uncertain it is necessary to omit it. Taking the weights inversely as the squares of the probable errors we have:

		W't.
Group I,	$5205^m \pm 168^m$	2
Group II,	$5192^m \pm 236^m$	1
Group III,	$5171^m \pm 116^m$	4
Mean result,	$5184^m \pm 80^m$	

It remains to inquire whether the data indicate any variation of the speed. The answer is in the negative. The data are inconsistent with any variation of a systematic character and there is no apparent means of detecting an unsystematic one. A small irregular variation, such as might be caused by varying density and elasticity of the propagating medium, would not be inconsistent with the data; but the evidence of it cannot be separated from the errors of observation.