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Seismology in St. Louis University.

PART II.

During the year 1911 the Seismological Department was conducted, as in the preceding year, along the lines sketched in the December Bulletin of the St. Louis University.[1] Hence we respectfully refer our readers to that publication for a discussion of our instrument and methods, as the present report will be supplementary to it.

The earthquakes registered during the year were thirty-seven in number, as tabulated further on. Among these, two are especially worthy of further study. The earthquakes of June 7th and December 16th are both said to have caused considerable damage throughout the central portion of the Republic of Mexico. A comparison of the seismograms, however, reveals decided differences. Hence it will be of the greatest interest to determine as accurately as possible the position of the two epicenters. To this end we made use of each of the three methods now in vogue, that of Prince Galitzin,[2] that of Dr. Klotz, to which we referred in the December Bulletin, and the least square method applied by Dr. Geiger.[3]

THE METHOD OF PRINCE GALITZIN.

The method of Prince Galitzin consists in reducing the first maximum amplitude of the P-waves, which appears on the record of each component to the corresponding earth-motion amplitudes (A_E and A_N), and applying the formula: $\tan x = \dfrac{A_E}{A_N}$, in which x is the angle of azimuth. In this formula we give the positive sign to an earth-displacement toward the north or east, and the negative sign to a displacement toward the south or west. The arrows on the seismogram for December 16th indicate the corresponding displacements of the pen on our seismograph when the inertia of the pendulum and pillar does not come into play, as would be the case in very rapid oscillations. Since the first preliminary waves are longitudinal, they must of necessity impinge upon the seismograph in a line parallel to the direction of motion of the wave front; and, if the components are properly recorded, this line will be indicated by the seismograph. But the *direction* of the impulse communicated by the wave-front will be toward the epicenter or away from it according as the wave is *dilatational* or *condensational,* that is, a *contraction toward the hypocenter or an outward compression away from it,* as Prince Galitzin has well pointed out. This ambiguity is at once removed by noting whether the vertical component is upward, as would be the case in a condensation wave, or downward, as in a dilatation wave. If the latter is true, then the epicenter lies in the opposite direction from that indicated by the seismograph. Prince Galitzin has demonstrated to evidence that this method of locating epicenters is capable of great accuracy when applied, with proper precautions, to the records of his specially designed aperiodic pendulums with photo-galvanometric registration. To what extent it may be relied upon in the case of a small machine like ours with all its friction may be seen from the following results. The constants of our Wiechert 80 kg. horizontal seismograph, as determined June 6th, the day before the first of the two Mexican earthquakes, were: $T_0E = 7$ sec., $T_0N = 7$ sec., $V_E = 67$, $V_N = 79$. Taking the first impulse which appears on both components, the respective amplitudes reduced to earth motion, were: $A_E = 7.8\ \mu$, $A_N = 67.9\ \mu$, which give an azimuth for the epicenter $= \tan^{-1} .1149 =$ S 6° 33′ W. Taking this value together with the distance $\Delta = 2600$ km., and solving the corresponding spherical triangle, we obtain as co-ordinates of the epicenter: $\phi = 15^\circ.3$ N, $\lambda = 92^\circ.9$ W. As a check on this result we do the same for the first impulse in the reflection 24 sec. later and obtain as azimuth S 17° 6′ W. This gives us as co-ordinates: $\phi = 16^\circ.1$ N, $\lambda = 97^\circ.2$ W. Prince Galitzin obtained by his method from the observations of Pulkowa, $\phi = 19^\circ\ 34'$ N, $\lambda = 97^\circ\ 59'$ W.[4]

The constants for December 16th, as determined the following day, were: $= T_0E = 6.8$ sec., $T_0N = 7$ sec., $V_E = 88$, $V_N = 83$. The earth amplitudes of the initial impulse were: $A_E = 12.5\ \mu$, $A_N = 22.7\ \mu$. This gives as azimuth S 28° 50′ W. Taking the distance as 2690 km., we obtain as co-ordinates: $\phi = 16^\circ.8$ N, $\lambda = 102^\circ.9$ W. However, if we take as horizontal components the average maximum amplitude of

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[1] *Seismology in St. Louis University,* Bulletin, Vol. VII, No. 5, December, 1911.

[2] *Bestimmung der Lage des Epicentrums eines Bebens aus den Angaben einer einzelnen Station,* St. Petersburg, 1911.

[3] Dr. L. Geiger.—*Herdbestimmung bei Erdbeben aus den Ankunftszeiten,* Goettingen, 1910.

[4] Op. cit. See Note 3.

several of the waves immediately following the initial impulse, we obtain as azimuth S 18° 26′ W. This places the epicenter at $\phi = 15^\circ.4$ N, $\lambda = 98^\circ$ W.

Dr. Tams obtained from the observations of Hamburg, by the same method: $\phi = 16^\circ$ N, $\lambda = 97^\circ$ W.[5]

By another method Dr. Zeissig obtained as co-ordinates: $\phi = 15^\circ.6$ N, $\lambda = 96^\circ.4$ W.

It will be seen from these results that the Galitzin method, even with a small machine like ours, will give a very fair approximation.

STEREOGRAPHIC METHOD OF DR. KLOTZ.

Applying the method of Dr. Klotz[6] to the earthquake of June 7, we obtain three approximate intersections of three circles. (Fig. 1.)

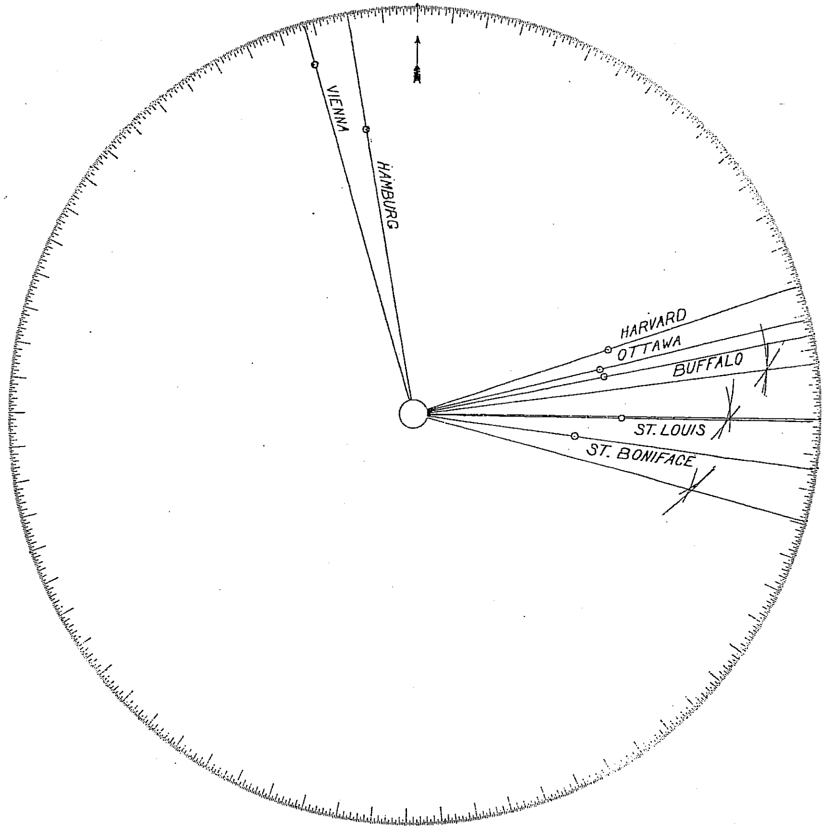

Fig. 1.

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[5] *Mitteilungen*, No. 44.

[6] Dr. Otto Klotz, F. R. A. S.—*Earthquake Epicenters.* Journal of the Astronomical Society of Canada, May-June, 1910.

The lower intersection determined by data from Hamburg, Harvard and St. Boniface places the epicenter at $\lambda = 104^\circ.6$ W, $\phi = 19^\circ.8$ N. The middle one, from Vienna, Buffalo and St. Louis, gives $\lambda = 89^\circ.9$ W, $\phi = 14^\circ.5$ N. According to the upper one, due to Vienna, Ottawa and Harvard, $\lambda = 82^\circ$ W and $\phi = 7^\circ.7$ N.

Applying the method to the earthquake of Dec. 16, we obtain but one intersection of three circles, as seen in Fig. 2. This would place the epicenter at $\lambda = 95^\circ$ W, $\phi = 15^\circ$ N.

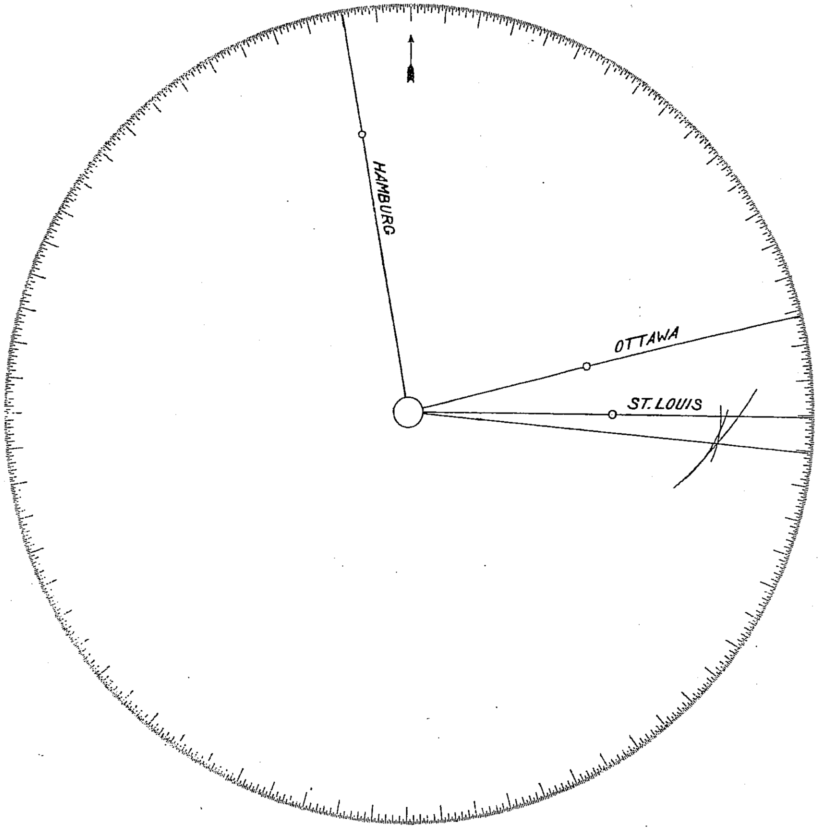

Fig. 2.

The discrepancies which appear in the values thus obtained for the epicenter of the June earthquake would seem to indicate that the epicentric area was of considerable extent. A further reason for suspecting this may be found in the fact that, though the epicenter was evidently somewhere beneath the Pacific, the whole of Central Mexico was included in the megaseismic district. In order to ascertain what point was probably nearest the center of the epicentric area we may now apply the method of Dr. Geiger.[7]

PROBABILITY METHOD FOR THE DETERMINATION OF EARTHQUAKE EPICENTERS FROM THE ARRIVAL TIME ONLY.

F. W. L. Peebles

Nomenclature: λ = longitude, ϕ = latitude, t = time in hours, minutes and seconds of an occurrence. T = a period of time in minutes and seconds for wave translation. * indicates that the accompanying value is assumed, subject to correction. Δ is angular distance on the earth's surface. † is used but once, and indicates observation, and as attached to time means observation time of arrival at a station. Numeral subscripts and the general subscript $_n$ designate the station data, either assumed or absolute. Subscript $_0$ indicates an epicentric function.

To make use of this third method, we must first assume an approximate location of the epicenter, and the closer this assumption is to the ultimate location the smaller will be the corrections and the more accurate the work; but a very fair localization may be computed with an error of several degrees in the first assumption. The process depends to a great extent on the translation time of the first preliminaries, which is, of course, not a linear function of the distance.

If we assume $^*\lambda_0$, $^*\phi_0$ and $^*t_0$ by any convenient method, and assume that in each there is an error which we will designate by $\delta^*\lambda_0$, by $\delta^*\phi_0$ and by δ^*t_0, equation (1) follows:

$$\lambda_0 = {}^*\lambda_0 + \delta^*\lambda_0$$
$$\phi_0 = {}^*\phi_0 + \delta^*\phi_0 \text{ and } t_0 = {}^*t_0 + \delta^*t_0$$

In these equations the left-hand members are the ones primarily sought, and the first terms of the right-hand members are unvarying assumed quantities subject to variation by their second terms, which are the corrections. Here the case resolves itself into a determination of the δ quantities. To determine these we proceed as follows:

We first calculate the distance from the assumed epicenter to each station, by means of the spherical cosine law:

$$\text{Cos } \Delta_n = \sin \phi_0 \sin \phi_n + \cos \phi_0 \cos \phi_n \cos \ (\lambda_0 - \lambda_n) \quad . \qquad (2)$$

In our tabular work at the end of the discussion this is done logarithmically, and the two terms of the right-hand member of the cosine law are designated by I and II. These are to be added. After obtaining in this way cos $^*\Delta_n$, the corresponding $^*\Delta_n$ in angular measurement is taken from a table of natural cosines.

Having now the angular or arcual distance approximately, from station $_n$ to an assumed location of the epicenter, we take from Table 1[8] an approximate translation time. This translation time is called, according to our symbols, $^*T_n$. An approximate translation time added to an approximate occurrence time will give an approximate arrival time, *i. e.*—

$$^*t_n = {}^*t_0 + {}^*T_n \quad . \quad . \quad . \qquad (3)$$

Were there no error in our assumed location, and no error in recorded times, and no error in observation, this $^*t_n$ would be our observation time, $\dagger t_n$. But there are errors, so that there will be a difference, F_n, between the two, *i. e.*—

$$F_n = {}^*t_n - \dagger t_n \quad . \quad . \quad . \qquad (4)$$

The foregoing makes it clear that if there were no errors such as $\delta^*\lambda_0$, $\delta^*\phi_0$ and δ^*t_0, and the $\dagger t_n$ were accurate, there could be no F_n.

Our next step is to establish a relationship between F_n and the errors in assumption which occasion its existence.

Assuming for the moment that all data were correct for location and time at the epicenter except the longitude, and that an F_n existed because of a difference in longitudes, then

$$F_n = \delta^*\lambda_0 \frac{\delta^*t_n}{\delta^*\lambda_0},$$

that is, F_n would be a time correction equal to the time correction per unit of longitude, multiplied by the number of units of longitude correction. If we were to examine the rate of change in translation time per degree of longitude, and with this ratio correct our time by an amount equal to that ratio multiplied by the actual longitude correction in the same units, this would satisfy F_n in so far as the longitude variation is concerned. Now, all that has been said about longitude will apply with equal force to latitude independently, and we shall have $\delta^*\phi_0$ $(\delta^*t_n/\delta^*\phi_0)$. On the other hand, if we suppose a change in time of occurrence, $^*t_0$, there must be a similar change in time of arrival, $^*t_n$, so that the rate of change of arrival time with respect to occurrence time, δ^*t_n/δ^*t_0, is always unity. In order, however, to handle the matter mathematically this time ratio is treated as are the others, and hence a third correction appears as δ^*t_0 $(\delta^*t_n/\delta^*t_0)$, though its value is merely δ^*t_0. From this consideration

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[7] See Note 4.

[8] Taken from Dr. L. Geiger's *Herdbestimmung.* See Note 4.

it follows that F_n is essentially a differential by existence, for it may be equated to differentials as has been done above; and hence approaches 0 as a limit when δ-terms are made indefinitely small. Now it may be shown by Taylor's Theorem that if F_n depend separately upon $(\delta^*t_n/\delta^*\lambda_0)\ \delta^*\lambda_0$, $(\delta^*t_n/\delta^*\phi_0)\ \delta^*\phi_0$, and $(\delta^*t_n/\delta^*t_0)\ \delta^*t_0$, it may be equated to their sum. In forming this equation, the partial differential sign, ∂, replaces δ in the ratio to indicate that each is treated as if the others were constants and that in the end the sum total is used. In our work tabulated later it will be seen that this is exactly followed out with respect to latitude and longitude, and the same would have been done with respect to time, but for the fact that the time ratio is everywhere equal to 1, and hence would only have introduced useless work.

$$\text{Therefore}\quad F_n = \frac{\partial^*t_n}{\partial^*\lambda_0}.\ \delta^*\lambda_0 + \frac{\partial^*t_n}{\partial^*\phi_0}.\ \delta^*\phi_0 + \frac{\partial^*t_n}{\partial^*t_0}.\ \delta^*t_0 \qquad . \qquad . \qquad (5)$$

From relations established in (3) it follows that any increment given to $^*t_n$ will have to be given to $^*T_n$, otherwise the translation time would be a variable with the hour of the day, so that ∂^*T_n may replace ∂^*t_n in any ratios.

Therefore we may substitute in (5)

$$F_n = \frac{\partial^*T_n}{\partial^*\lambda_0}.\ \delta^*\lambda_0 + \frac{\partial^*T_n}{\partial\phi_0}.\ \delta^*\phi_0 + \delta^*t_0 \qquad . \qquad . \qquad (6)$$

By replacing the ratios in (6) with a_n, b_n and c_n, and remembering that c_n must be = 1, we obtain at once

$$F_n = a_n\,\delta^*\lambda_0 + b_n\,\delta^*\phi_0 + c_n.\ \delta^*t_0 \qquad . \qquad . \qquad (7)$$

After equation (6) we placed $a_n = \frac{\partial^*T_n}{\partial^*\lambda_0}$, $b_n = \frac{\partial^*T_n}{\partial^*\phi_0}$. Introducing now $\partial^*\Delta_n$ in both numerator and denominator of each of these ratios, and factoring the resulting fraction, we get:

$$a_n = \frac{\partial^*T_n}{\partial^*\Delta_n}.\frac{\partial^*\Delta_n}{\partial^*\lambda_0} \quad\text{and}\quad b_n = \frac{\partial^*T_n}{\partial^*\Delta_n}.\frac{\partial^*\Delta_n}{\partial^*\phi_0} \qquad . \qquad . \qquad (8)$$

Now, if we reckon ∂^*T_n in seconds of time and $\partial^*\Delta_n$ in minutes of arc, the first ratio in the above will express the difference in the translation time per minute of arc change in the $^*\Delta_n$. This may be calculated from Table I as follows: Take the time difference, d^s_n, for each station in seconds corresponding to a change of one degree at the given distance, $^*\Delta_n$, and divide it by 60 to obtain the time difference for 1′.

$$\text{Thus,}\quad \frac{\partial^*T_n}{\partial^*\Delta_n} = \frac{d^s_n}{60'} \qquad . \qquad . \qquad . \qquad . \qquad (9)$$

The second ratio in each case will obviously be the quotient of the change produced in the distance, $^*\Delta_n$, by giving an increment to the longitude or latitude of the assumed epicenter, divided by that increment, that is, the change in $^*\Delta_n$ per unit change in $^*\lambda_0$ or $^*\phi_0$. This ratio may readily be obtained in the following manner: Assign an arbitrary increment, $\delta^*\lambda_0$, say of 1° or more, to the longitude of the assumed epicenter. The co-ordinates of this new point will be $[(^*\lambda_0 + \delta^*\lambda_0),\ ^*\phi_0]$. By means of the spherical cosine law, (2), calculate the distance from each station to that point. Call this distance $^*\Delta_n\lambda$. Then, evidently, $^*\Delta_n\lambda - {}^*\Delta_n = \delta^*\Delta_n$, the change produced in $^*\Delta_n$ by assigning the increment to $^*\Delta_0$. Divide this total change, $\delta^*\Delta_n$, by the increment assigned to $^*\lambda_0$, and the quotient will be the approximate change in $^*\Delta_n$ per unit change in $^*\lambda_0$, which is the desired ratio, $\partial^*\Delta_n/\partial^*\lambda_0$. The products of $\partial^*\Delta_n/\partial^*\lambda_0$ and $d^s_n/60'$ for each station (8) will give the coefficient a_n in (7).

Proceeding in a similar way to obtain

$$\frac{\partial^*\Delta_n}{\partial^*\phi_0},$$

we assign the same arbitrary increment of 1° or more to $^*\phi_0$, calculate the distance, $^*\Delta_n\phi$, from each station to the new point, $[^*\lambda_0,\ (^*\phi_0 + \delta^*\phi_0)]$, find the difference $^*\Delta_n\phi - {}^*\Delta_n$, and divide it by the latitude increment $\delta^*\phi_0$. The result will again be the desired ratio $\partial^*\Delta_n/\partial^*\phi_0$, which, when multiplied by the interpolation factor $d^s_n/60'$ from (9) will give the second coefficient b_n in (7). This work will be found tabulated with $^*\Delta_n$, the distance from each station to the assumed epicenter, in Table 2.

We have now real numerical values for a_n and b_n as well as for $c_n = 1$. But $_n$ denotes any one of the stations, so that by (7) we see that we have an F-value, F_n, for each station. Thus we have as many error equations as there are stations whose data we used. Now it is shown in the theory[9] of the least square method, that the most probable val-

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[9] For proofs the reader may consult:
Bartlett, *Method of Least Squares;*
Merriman, *Method of Least Squares*, New York, 1884;
Woodward, *Geographical Tables*, Smith. Inst. Publ., 1894;
Doolittle, *Practical Astronomy, 5th Ed.*, 1910;
Helmert, *Ausgleichungsrechnung nach der Methode der kleinsten Quadrate*, 2 *Aufl.* 1907.

ues of the required unknowns are those which will make the sum of the squares of the single errors a minimum. Let x be some quantity which added to each of the assumed errors will make the sum of the squares of the resulting quantities, $(F_1 + x)^2 + (F_2{}^2 + x)^2 + \quad . \quad . + (F_n + x)^2$, a minimum.

Then it follows from the Calculus that, as the function under consideration tends toward a minimum and not a maximum, that value of x will make the function a minimum which will make the first derivative equal to 0. Therefore differentiating, equating to 0 and solving for x, we obtain the correction which must be added to each station error so as to make the mean error a minimum. Our general error equation now becomes:

$$(F_n + x) = a_n\delta^*\lambda_0 + b_n\delta^*\phi_0 + c_n\delta^*t_0 \qquad . \qquad . \qquad (10)$$

This gives the greatest weight to those stations whose observations most nearly agree, and least weight to those whose error differs most from the mean. Each of the three unknown quantities will have thus to adjust themselves to that value which will give the least mean error. We now tabulate as in Table 3, the numerical values of the three coefficients a, b and c, and their sum S, which will be needed in further work, together with the "weighted error" $(F + x)$ for each station. This latter value, $(F + x)_n$, we shall call simply F_n. For convenience also we shall set the first unknown $\delta^*\lambda_0 = x$; the second, $\delta^*\phi_0 = y$; and the third, $\delta^*t_0 = z$. We are now ready to form and to solve the so-called normal equations.

FORMATION AND SOLUTION OF THE NORMAL EQUATIONS.

If there be a given number of simultaneous equations and that number is in excess of the number of unknowns, as in our case, then, in attempting a solution, it may be impossible to justify all the results obtained on account of inaccuracies in the original data. The values of the quantities depend upon the values of the coefficients and if it be possible to adjust these to a most probable value for each, then one result for each unknown may be obtained. For most physical purposes, where the best result that can be obtained is an approximation, such a proceeding is very useful. The method, with an arrangement of detached coefficients, is as follows:

We are given the following five equations:

$$\begin{aligned} a_1x + b_1y + c_1z &= F_1 \\ a_2x + b_2y + c_2z &= F_2 \\ a_3x + b_3y + c_3z &= F_3 \\ a_4x + b_4y + c_4z &= F_4 \\ a_5x + b_5y + c_5z &= F_5 \end{aligned}$$

From these we are to find the value of the three unknown quantities. If the five equations are added term by term an equality will remain and may be written, $[a]x + [b]y + [c]z = [F]$, in which the sign [ ] means simply that the term enclosed by it is a sum of all such quantities.

This single equation will give one in which the inaccuracies are averaged and, if the errors are equal, or if equal reliance may be placed on each element of the data, it is the most reasonable approximation that we can select.

The one equation given above will not suffice for the solution of the three unknowns, so a method must be given that will provide at least three equations. If, before making the addition above, each of the N equations had been multiplied by a_n, where $_n$ is a general subscript, our sum would have been, by the notation that we are using,

$[aa]x + [ab]y + [ac]z = [aF]$ and similarly multiplying by b_n

$[ab]x + [bb]y + [bc]z = [bF]$ and similarly multiplying by c_n

$[ac]x + [bc]y + [cc]z = [bF]$.

These are known as normal equations and are treated as any other simultaneous equations. There are but three of them for a solution of three unknowns, so that there can be no interference from a number of different answers. In other words, we have averaged our error before the computation began.

In the following work we will omit, for the greater part, the sign [ ], which means the sum of all such terms as are enclosed by it, though account of it must be made. We need:

$$\begin{array}{cccc} aa & ab & ac & aF \\ & bb & bc & bF \\ & & cc & cF \\ & & & FF \end{array}$$

From these we calculate, $bb - \frac{ab}{aa}.\,ab = bb_1$

$$bc - \frac{ab}{aa}.\,ac = bc_1$$

$$bF - \frac{ab}{aa}.\,aF = bF_1$$

$$cc - \frac{ac}{aa}.\,ac = cc_1$$

$$cF - \frac{ac}{aa}.\,aF = cF_1$$

And from these in turn,

$$cc_1 - \frac{bc_1}{bb_1}.\,bc_1 = cc_2$$

$$cF_1 - \frac{bc_1}{bb_1}.\,bF_1 = cF_2$$

In order to check the numerical work from time to time an independent calculation is carried on. This independent work has enough totals in common with the regular work to be of service as a check, but the determination should be carried out as above, with the following as a check and nothing else:

Let $a + b + c = S$

$a_1S_1 + b_2S_2 + a_3S_3 \;\; . \;\; . \;\; . \;\; a_nS_n = aS$
$b_1S_1 + b_2S_2 + b_3S_3 \;\; . \;\; . \;\; . \;\; b_nS_n = bS$
etc.

Then

$aa + ab + ac = aS$
$ab + bb + bc = bS$
$ac + bc + cc = cS$
$aF + bF + cF = FS$

From this we can calculate

$bS - \frac{ab}{aa}.\,aS = bS_1$, and it follows that $bS_1 = bb_1 + bc_1$, which checks two of our other determinations.

$cS - \frac{ac}{aa}.\,aS = cS_1$ and so $cS_1 = bc_1 + cc_1$

$FS - \frac{aF}{aa}.\,aS = FS_1$ and so $FS_1 = bF_1 + cF_1$

And, furthermore, $cS_1 - \frac{bc_1}{bb_1}.\,bS_1 = cS_2$ and $cS_2 = cc_2$

$$FS_1 - \frac{bF_1}{bb_1}.\,bS_1 = FS_2 \text{ and } FS_2 = cF_2$$

As a matter of final check we return to our original equations like, $a_1x + b_1y + c_1z = F$, and substitute, when the real error will appear. We will proceed with the solution of the general case.

(1) $aax + aby + acz = aF$
(2) $abx + bby + bcz = bF$
(3) $acx + bcy + ccz = cF.$

Eliminating x from (1) and (2) we have:

$aa.abx + ab.aby + ab.acz = ab.aF$
$aa.abx + aa.bby + aa.bcz = aa.bF$

Subtracting the one from the other and dividing by aa, we obtain:

$$(4)\quad (bb - \frac{ab}{aa}.\,ab)\,y + (bc - \frac{ab}{aa}.\,ac)\,z = (bF - \frac{ab}{aa}.\,aF)$$

Transforming by substitution, we have:

(5) $bb_1y + bc_1z = bF_1$

Eliminating x from (1) and (3) we have:

$aa.acx + ab.acy + ac.acz = ac.aF$
$aa.acx + aa.bcy + aa.ccz = aa.cF$. By repeating the subtraction, division by aa, and the transforming by substitution, we also have

(6) $bc_1y + cc_1z = cF_1$, in which bc_1 is the same as in (5).

Eliminating y from (5) and (6),

$$\begin{aligned} bb_1y + bc_1z = bF_1 &= (bb_1.bc_1)y + (bc_1.bc_1)z = bc_1bF_1 \\ bc_1y + cc_1z = cF_1 &= (bb_1.bc_1)y + (bb_1.cc_1)z = bb_1cF_1 \\ (bc_1.bc_1 - bb_1.cc_1)z &= (bc_1bF_1 - bb_1.cF_1) \end{aligned}$$

Dividing by $-\ bb_1$. transforming and substituting, we obtain:

$$(7)\quad cc_2z = cF_2$$

$$(8)\qquad z = \frac{cF_2}{cc_2}$$

Substituting z in (5) and transposing, we obtain:

$$(9)\qquad y = \frac{bF_1}{bb_1}. - \frac{bc_1}{bb_1}. z$$

Evaluating (1) for x we have:

$$(10)\qquad x = \frac{aF}{aa} - \frac{ab}{aa}y - \frac{ac}{aa}z.$$

Substituting for x, y and z, their original symbols $\delta^*\lambda_0$, $\delta^*\phi_0$, δ^*t_0, and replacing these in equation (1) by the values here found, we obtain the co-ordinates of the corrected epicenter, λ_0, ϕ_0 and t_0. By the method of detached coefficients outlined above, the value of the three unknowns may be calculated directly, without solving the simultaneous equations, by substituting the required coefficients in the final formulas.

As a final check on the entire calculation we substitute the values of $\delta^*\lambda_0$, $\delta^*\phi_0$ and δ^*t_0 in each of the N error equations, and thus obtain the N "error corrections."

$$f_n = a_n\delta^*\lambda_0 + b_n\delta^*\phi_0 + c_n\delta^*t_0 - F_n \quad . \quad . \qquad (11)$$

The sum of these "error corrections" must then be:

$$ff = FF - \frac{aF}{aa}.\ aF - \frac{bF_1}{bb_1}.\ bF_1 - \frac{cF_2}{cc_2}.\ cF_2 \quad . \qquad (12)$$

These quantities will be found in Table 5.

METHOD OF DETERMINING THE ACCURACY ATTAINED.

We should not be satisfied with the values we have obtained for λ_0, ϕ_0 and t_0, without some precision measure to test their accuracy. By this we mean, however, their relative accuracy, for if there be a constant error in the observations of all the stations whose data we have used then there will also be an absolute error in the above quantities, which only new station data will detect. With this distinction clearly in mind we proceed to determine the so-called mean error, $\mu\lambda$, $\mu\phi$ and μt, which is to be feared in the three quantities, λ_0, ϕ_0 and t_0. This Dr. Geiger does in the following way:[10]

First calculate the six coefficients of weight, as they are called, $Q\lambda\lambda$, $Q\phi\phi$, Qtt, $Q\lambda\phi$, $Q\lambda$t, $Q\phi$t,

$$\begin{aligned} Q\lambda\lambda &= \frac{bb.cc - bc.bc}{[aa].[bb_1].[cc_2]} = \frac{Z\lambda\lambda}{D} \\ Q\phi\phi &= \frac{aa.cc - ac.ac}{[aa].[bb_1].[cc_2]} = \frac{Z\phi\phi}{D} \\ Q\mathrm{tt} &= \frac{aa.bb - ab.ab}{[aa].[bb_1].[cc_2]} = \frac{Z\mathrm{tt}}{D} \\ Q\lambda\phi &= -\frac{ab.cc - ac.bc}{[aa].[bb_1].[cc_2]} = \frac{Z\lambda\phi}{D} \\ Q\lambda t &= -\frac{ac.bb - ab.bc}{[aa].[bb_1].[cc_2]} = \frac{Z\lambda\mathrm{t}}{D} \\ Q\phi t &= -\frac{bc.aa - ab.ac}{[aa].[bb_1].[cc_2]} = \frac{Z\phi\mathrm{t}}{D} \quad . \quad . \qquad (13) \end{aligned}$$

As a check on these calculations we test the truth of the following:

$$\begin{aligned} [aS].(Q\lambda\lambda + Q\lambda\phi + Q\lambda t) + [bS].(Q\lambda\phi + Q\phi\phi + Q\phi t) \\ + [cS].(Q\lambda t + Q\phi t + Qtt) = 3 \quad . \quad . \quad . \qquad (14) \end{aligned}$$

The number 3 is the number of the unknowns. These values will be found in Table 4.

---

[10] See Note 4.

Next we need the error of unit weight, μ. This we find by the formula:

$$\mu = \sqrt{\frac{ff}{N\text{-}3}} \quad . \quad . \quad . \quad . \qquad (15)$$

ff being the value obtained in (12), N the number of stations, and 3 the number of unknowns as above. Then the mean errors are:

$$\mu\lambda = \pm\,\mu\sqrt{Q\lambda\lambda},\ \mu\phi = \pm\,\mu\sqrt{Q\phi\phi},\ \mu t = \pm\,\mu\sqrt{Qtt} \quad . \qquad (16)$$

The relative accuracy of the entire determination may now be graphically characterized by constructing the so-called mean error ellipse. To this end we must first reduce the above longitude and latitude error values to the same absolute units. As the absolute length of a latitude unit is practically invariable, being always measured on great circles, while that of the unit of longitude varies with the cosine of the latitude, it follows that $\mu\phi$, on this basis will remain $\mu\phi$, while $\mu\lambda$ will become $\mu\lambda \cos \phi_0$. So, too, if we denote the coefficient of longitude on itself, reduced to this basis, by Q_{11}, of latitude on itself by Q_{22} and the coefficient of mutual weight by Q_{12}, then it is evident that Q_{22} will be the same as above, $Q\phi\phi$, while Q_{12} will contain $\cos \phi_0$ once as a factor and Q_{11} twice. Hence

$$Q_{11} = Q\lambda\lambda \cos^2\phi_0,\ Q_{12} = Q\lambda\phi \cos \phi_0,\ Q_{22} = Q\phi\phi \quad . \qquad (17)$$

Now the angle ω, at which the longitude semi-axis $\mu\omega_1$, is inclined to the parallel in the Figure 3, is given by the equation

$$\tan 2\omega = \frac{2Q_{12}}{Q_{11} - Q_{22}} \quad . \quad . \quad . \qquad (18)$$

From this we obtain the angle ω_2 at which the latitude semi-axis $\mu\omega_2$ is inclined to the meridian, for evidently

$$\omega_2 = \omega_1 + 90^\circ \quad . \quad . \quad . \quad . \qquad (19)$$

The only values that still remain to be determined are the lengths of the two semi-axis $\mu\omega_1$ and $\mu\omega_2$. These are given by:

$$\mu\omega_1 = \pm\,\mu\sqrt{Q_{11} + Q_{12} \tan \omega_1}$$
$$\mu\omega_2 = \pm\,\mu\sqrt{Q_{11} + Q_{12} \tan \omega_2} \quad . \quad . \qquad (20)$$

μ being the error of unit weight from (15).

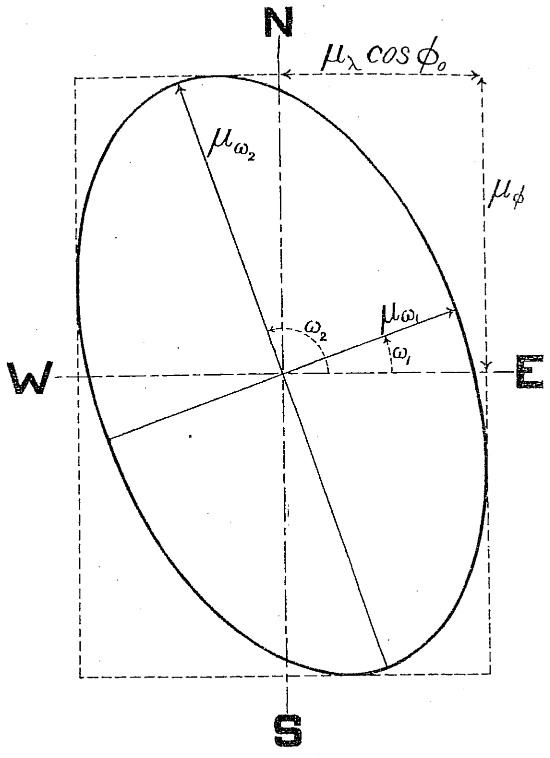


Fig. 3.

The projections of the ellipse on the meridian and parallel, and hence the sides of the tangent quadrangle enclosing the ellipse are $2\mu\phi$ and $2\mu\lambda \cos \phi_0$. The relative probability that the epicenter lies within the ellipse is $1 - \sqrt{e} = 0.393$.

PROBABILITY METHOD APPLIED TO THE EARTHQUAKE OF JUNE 7, 1911.

[illegible]

The first step to be taken in applying this third method is, as we have said, to assume a probable location for the epicenter. Now, in the case of the June 7th earthquake, we shall take as probable coordinates: $\lambda = 103°$ W, $\phi = 19°$ N, which would place the epicenter between $\lambda = 97° \, 59'$ W, $\phi = 19° \, 34'$ N, as given by Prince Galitzin, and $\lambda = 104°.6$ W, $\phi = 19°.8$ N, as obtained from the Hamburg-Harvard-St. Boniface intersection according to the method of Dr. Klotz.

On account of what seems to be a considerable disagreement in the arrival times of stations at a greater distance, we shall choose the following five stations as being close to the earthquake, and still sufficiently scattered for our purpose: Buffalo, Harvard, Ottawa, St. Boniface, Santa Clara, St. Louis.

Place.	Station No.	Longitude.	Latitude.	Arrival Time of P-Waves.
Epicenter	0	103° 00′ 00″	19° 00′ 00″	11 h. 2 m. 32 s.
St. Louis	1	90° 13′ 58″.5	38° 38′ 17″	11 h. 7 m. 46 s.
St. Boniface	2	97° 6′ 39″	49° 53′ 31″	11 h. 9 m. 9 s.
Harvard	3	71° 6′ 59″	42° 22′ 56″	11 h. 9 m. 50 s.
Buffalo	4	78° 52′ 40″	42° 53′ 2″	11 h. 9 m. 9 s.
Santa Clara	5	121° 57′ 3″	37° 26′ 36″	11 h. 8 m. 12 s.
Ottawa	6	75° 42′ 57″	45° 23′ 38″	11 h. 9 m. 43 s.

With these we calculate Table II for each station (of which we give only one example), and Tables III, IV and V. We see from Table IV that the corrected position of the epicenter is: $\lambda_0 = 102° \, 39' \pm 23'$ W, $\phi = 18° \, 30' \pm 96'$ N. The next step will be to calculate and construct the mean error ellipse about this point as center.

From (17), $Q_{11} = + 36.35$, $Q_{12} = - 68.15$, $Q_{22} = + 682.67$. Hence $\tan 2\omega_1 = + .2087$, $\omega_1 = 5° \, 57'.3$, $\omega_2 = 95° \, 57'.3$ and

$$\mu\omega_1 = 3.66 \; 36.35 - 68.15 \times .1043 = 19.9 \text{ Geogr. miles,}$$
$$\mu\omega_2 = 3.66 \; 36.35 + 68.15 \times 9.5878 = 96.5 \text{ Geogr. miles.}$$

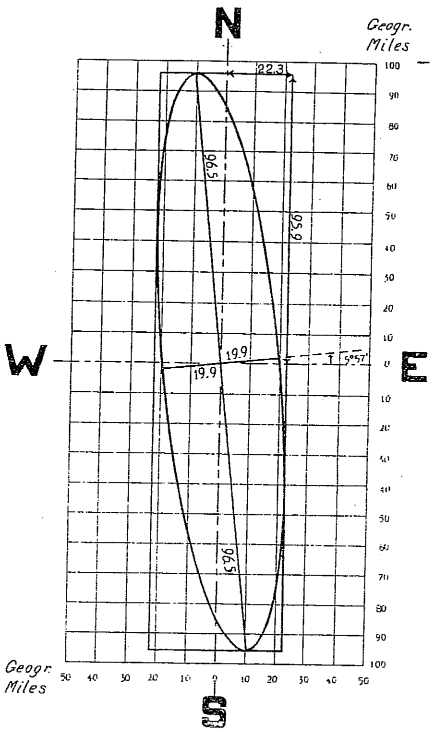


Fig. 4.

The ellipse is seen to be very elongated in the direction of latitude and any further stations which would be brought into the calculations should be chosen along the N-S axis, so as to diminish the eccentricity of the figure and thereby greatly increase the reliability of the results.

TABLE I.

Δ	T	d	Δ	T	d	Δ	T	d	Δ	T	d
0°	0s	15s	30°	388s	10s	60°	611s	7s	90°	795s	6s
1	15	16	31	398	9	61	618	6	91	801	5
2	31	16	32	407	9	62	624	7	92	806	6
3	47	15	33	416	9	63	631	6	93	812	5
4	62	15	34	425	8	64	637	7	94	817	6
5	77	15	35	433	9	65	644	6	95	823	5
6	92	15	36	442	8	66	650	6	96	828	6
7	107	14	37	450	8	67	656	7	97	834	5
8	121	15	38	458	8	68	663	6	98	839	5
9	136	14	39	466	8	69	669	6	99	844	5
10	150	14	40	474	8	70	675	7	100	849	6
11	164	14	41	482	7	71	682	6	101	855	5
12	178	14	42	489	8	72	688	6	102	860	5
13	192	14	43	497	7	73	694	7	103	865	5
14	206	13	44	504	7	74	701	6	104	870	4
15	219	13	45	511	7	75	707	6	105	874	5
16	232	12	46	518	7	76	713	6	106	879	5
17	244	13	47	525	7	77	719	6	107	884	4
18	257	12	48	532	7	78	725	6	108	888	5
19	269	12	49	539	7	79	731	6	109	893	5
20	281	12	50	546	6	80	737	6	110	898	5
21	293	11	51	552	7	81	743	6	111	903	4
22	304	11	52	559	6	82	749	6	112	907	5
23	315	11	53	565	7	83	755	5	113	912	4
24	326	11	54	572	6	84	760	6	114	916	4
25	337	11	55	578	7	85	766	6	115	920	5
26	348	10	56	585	6	86	772	6	116	925	4
27	358	10	57	591	7	87	778	5	117	929	4
28	368	10	58	598	6	88	683	6	118	933	5
29	378	10	59	604	5	89	789	6	119	938	4
30	388		60	611		90	795		120	942	

TABLE II.

STATION 1, SAINT LOUIS UNIVERSITY.

	$^*\lambda_0,\ ^*\varphi_0.$	$(^*\lambda_0+\partial^*\lambda_0),^*\varphi_0.$	$^*\lambda_0,\ (\varphi_0+\partial^*\varphi_0)$
Epicentric Latitude, φ_0	19° 00' 00"	19° 00' 00"	20° 00' 00"
Station Latitude, φ_1	38 38 15	38 38 15	38 38 15
Epicentric Longitude, λ_0	103 00 00	104 00 00	103 00 00
Station Longitude, λ_1	90 13 58.5	90 13 58.5	90 13 58.5
$\lambda_0 - \lambda_1$	12 46 2	13 46 2	12 46 2
Log. cos.$(\lambda_0-\lambda_1)$	9.9891	9.9873	9.9891
Log. cos φ_0	9.9757	9.9757	9.9729
Log. cos φ_1	9.8927	9.8927	9.8927
Log. II	29.8575	29.8557	29.8575
Log. sin φ_0	9.5126	9.5126	9.5340
Log. sin φ_1	9.7954	9.7954	9.7954
Log. I	19.3080	19.3080	19.3294
II	.7203	.7173	.7157
I	.2033	.2033	.2135
Cos.$^*\Delta_1$	.9236	.9206	.9292
$^*\Delta_1$	22° 32'	$^*\Delta_{1_\lambda}$ = 22° 59'	$^*\Delta_{1_\varphi}$ = 21° 41'
$(\partial^*\Delta_1 \div \partial^*\lambda_0)\cdot\delta^*\lambda_0$	−7'.76	$^*\Delta_1$ = 22° 32'	$^*\Delta_1$ = 22° 32'
$(\partial^*\Delta_1 \div \partial^*\varphi_0)\cdot\delta^*\varphi_0$	+39'.00	$\partial^*\Delta_{1_\lambda}$ = 27'	$\partial^*\Delta_{1_\varphi}$ = −51'
Δ_1	23° 3'.24		
		$\frac{\partial^*\Delta_1}{\partial^*\lambda_0}$ = +.45	$\frac{\partial^*\Delta_1}{\partial^*\varphi_0}$ = −.85
$^*T_1$	0° 5' 10"	$\mathfrak{a}_1$ = .081	
$^*\mathfrak{t}_0$	11h 2m 32s	$\mathfrak{b}_1$ =−.153	
$^*\mathfrak{t}_1 = {}^*T_1 + {}^*\mathfrak{t}_0$	11h 7m 42s	$\mathfrak{c}_1$ = 1	
$^*\mathfrak{r}_1 = \mathfrak{t}_1\dagger - {}^*\mathfrak{t}_1$	4s	$\mathfrak{s}_1$ = .928	
$\mathfrak{d}^s_1 \div 60 = .18$			

TABLE III.

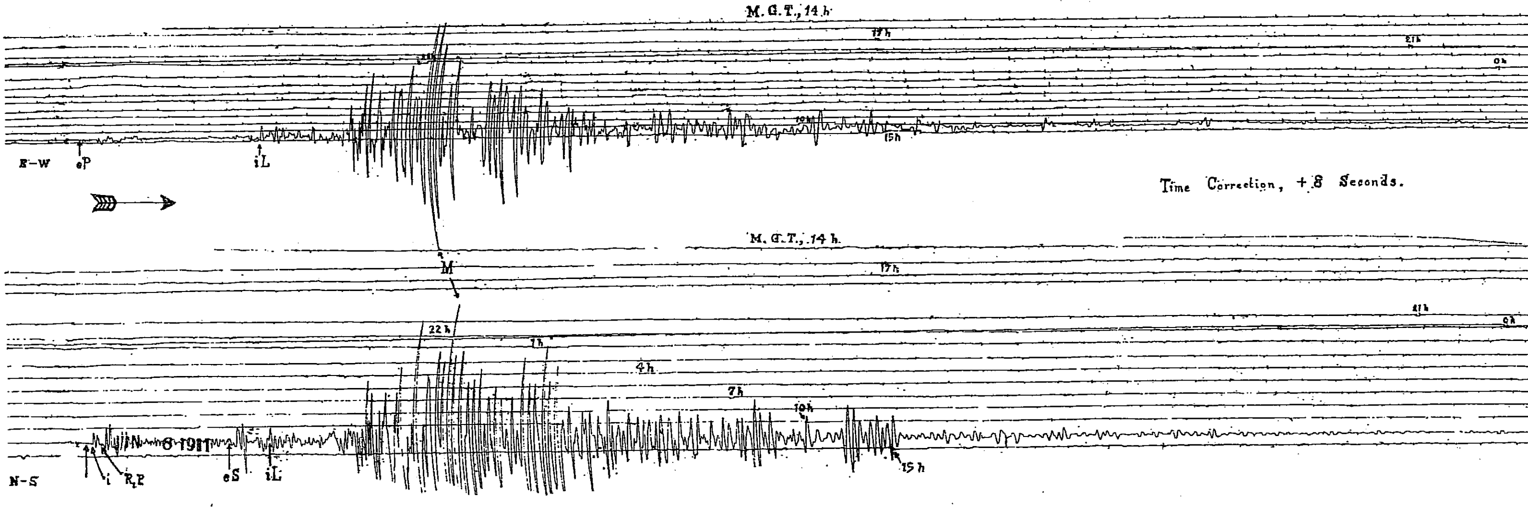
$\mathfrak{n}$	$\mathfrak{a}$	$\mathfrak{b}$	$\mathfrak{c}$	$\mathfrak{s}$	$\mathfrak{r}$
1	+.08	−.15	+1	+.93	+4
2	+.02	−.15	+1	+.87	−3
3	+.09	−.11	+1	+.98	−1
4	+.09	−.12	+1	+.97	−3
5	−.11	−.14	+1	+.76	+5
6	+.07	−.11	+1	+.96	0

TABLE V.

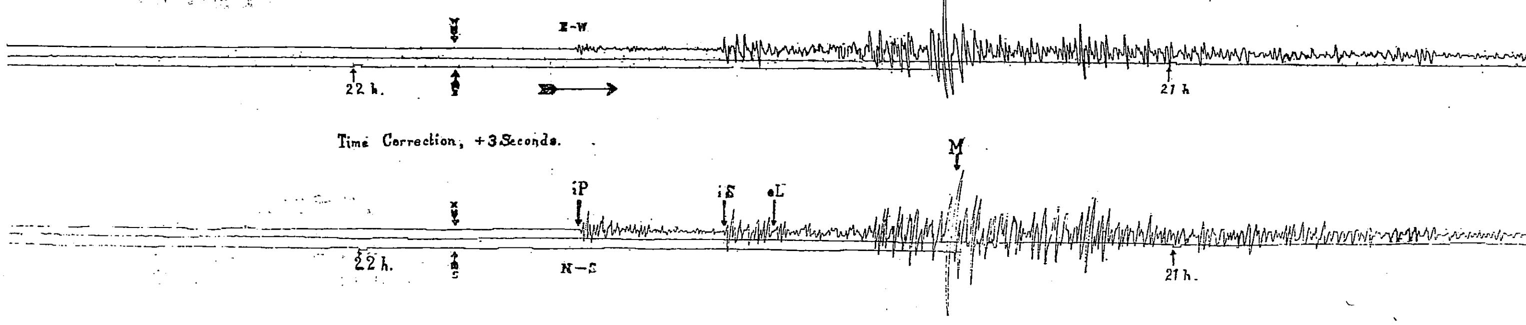
	St. Louis	St. Boniface	Harvard	Buffalo	Santa Clara	Ottawa
$\mathfrak{a}_n$	+.08	+.02	+.09	+.09	−.11	+.07
$\mathfrak{b}_n$	−.15	−.15	−.11	−.12	−.14	−.11
$\mathfrak{a}_n\cdot\delta\lambda_0$	−1.7	−.4	−1.9	−1.9	+2.3	−1.5
$\mathfrak{b}_n\cdot\delta\varphi_0$	+4.6	+4.6	+3.4	+3.7	+4.3	+3.4
$\delta\mathfrak{t}_0$	−2.8	−2.8	−2.8	−2.8	−2.8	−2.8
$-\ \mathfrak{r}$	−4.	+3.	+1.	+3.	−5.	0.
$\mathfrak{r}_n$	−3.9	+4.5	−.3	+2.	−1.2	−.9

aa= .04	ab= −.0280 bb= +.1032 $\frac{ab}{aa}$ab= +.0196	ac +.2400 bc= −.7800 $\frac{ab}{aa}$ac= −.1680	aS= +.2509 bS= −.7062 $\frac{ab}{aa}$aS= −.1756	aF= −.6500 bF= −.3800 $\frac{ab}{aa}$aF= +.4550	TABLE IV.	
$\frac{ab}{aa}$= −.7000 $\frac{ac}{aa}$= +6.0000 $\frac{aF}{aa}$= −16.2500 $\frac{1}{D}$= +3742.7200	bb_1= +.0836 $\frac{bc_1}{bb_1}$= −7.3205 $\frac{bF_1}{bb_1}$= −9.9880 $\frac{cF_2}{cc_2}$= −2.6608 μ= ±3.6755	bc_1= −.6120 cc = +6.0000 $\frac{ac}{aa}$ac= +1.4400 cc_1 = +4.5600 $\frac{bc_1}{bb_1}bc_1$= +4.4801 cc_2= .0799	bS_1= −.5306 cS = +5.4700 $\frac{ac}{aa}$aS= +1.5054 cS_1 = +3.9646 $\frac{bc_1}{bb_1}bS_1$= +3.8843 cS_2= .0803	bF_1= −.8350 cF = +2.0000 $\frac{ac}{aa}$aF= −3.9000 cF_1 = +5.9000 $\frac{bc_1}{bb_1}bF_1$= +6.1126 cF_2= −.2126	FS= +1.0200 $\frac{aF}{aa}$·aS= −4.0771 FS_1= +5.0971 $\frac{bF_1}{bb_1}bS_1$=+5.2996 FS_2= −.2025	FF= +60.0000 $\frac{aF}{aa}$·aF=+10.0000 $\frac{bF_1}{bb_1}bF_1$=+8.3400
bb·cc= +.6192 bc·bc= +.6084	aa·cc= +.2400 ac·ac= +.0576	aa·bb= +.004128 ab·ab= +.000784	ab·cc= −.1680 ac·bc= −.1872	ac·bb= +.024792 ab·bc= +.021840	bc·aa=−.031200 ab·ac=−.006720	$\frac{cF_2}{cc_2}cF_2$= +.5657
$Z_{\lambda\lambda}$= +.0108 $Q_{\lambda\lambda}$= +40.4214 $\sqrt{Q_{\lambda\lambda}}$ = ±6.3586 μ_λ= ±23'.37	$Z_{\varphi\varphi}$= +.1824 $Q_{\varphi\varphi}$= +682.6721 $\sqrt{Q_{\varphi\varphi}}$ = ±26.1279 μ_φ= ±96'.13	Z_{tt}= +.003344 Q_{tt}= +12.5157 $\sqrt{Q_{tt}}$ =±3.5377 μ_t= ±13s	$-Z_{\lambda\varphi}$= −.0192 $Q_{\lambda\varphi}$ = −71.8602 $Q_{\lambda\lambda}$ = +40.4214 $Q_{\lambda\varphi}$ = −71.8602 $Q_{\lambda t}$= −11.0485 Q_λ = −42.4873 aS·Q_λ = −10.6601	$-Z_{\lambda t}$ = −.002952 $Q_{\lambda t}$ =−11.048500 $Q_{\lambda\varphi}$ = −71.860200 $Q_{\varphi\varphi}$=+682.672100 $Q_{\varphi t}$= +91.621800 Q_φ = +702.433700 bS·Q_φ=−496.0587	$-Z_{\varphi t}$= +.024480 $Q_{\varphi t}$ +91.621800 $Q_{\lambda t}$ =−11.048500 $Q_{\varphi t}$=+91.621800 Q_{tt}=+12.515700 Q_t= +93.0890 cS·Q_t= +509.1968	ff= +40.5300 $\delta\lambda_o$= −20'.9 $\delta\varphi_o$= −29'.5 δt_o= −2.7sec λ_o= 102°39'±23' φ_o= 18°30'±96' t_o= 11h 2m 29s ± 13s

Mexican Earthquake, June 7, 1911.



Mexican Earthquake, December 16, 1911.



Jesuit Seismological Service Record of the Earthquake Station, St. Louis University.

ST. LOUIS, MO., U. S. A.

LATITUDE: 38° 38′ 17″ N.
LONGITUDE: 90° 13′ 58″.5 or 6^h. 0^m. 55^s.9 W. Gr.
ALTITUDE: 160.36 m.

TIME: Mean Greenwich, midnight to midnight.
INSTRUMENT: Wiechert 80 kg., astatic, horizontal pendulum.

NOMENCLATURE: International.

The symbols used in the following records are those of the *International* Nomenclature, which is identical with that given by us in the December Bulletin of the University (1911). For the sake of those who may wish to make further use of our data, we preface the records with the list of constants for the year.

Date.	E			N		
	T	V	ε	T	V	ε
	s			s		
Jan. 3..	7.	85	5.	7.	97	5.4
Jan. 7..	7.	85	5.1	7.	79	5.1
Jan. 21..	6.9	89	5.4	6.3	98	5.
Feb. 17..	7.	94	5.	7.	98	4.9
Feb. 21..	7.	82	5.	7.	86	5.
May 1..	6.7	91	4.1	7.	89	5.7
June 6..	7.	67	5.	7.	79	5.
Aug. 17..	7.	..	...	7.	..	...
Sept. 17..	6.5	85	5.	7.	90	5.
Sept. 22..	7.	93	5.6	7.	83	6.2
Oct. 10..	7.	79	5.	7.	86	5.
Nov. 21..	7.	88	...	6.5	84	...
Dec. 17..	6.8	88	5.	7.	83	6.

EARTHQUAKE RECORDS FOR 1911.

DATE	CHARACTER	PHASE	TIME	PERIOD T	AMPLITUDE		REMARKS
			h m s	s	A_E μ	A_N μ	
Jan.3-4	III_u	S_E	23 50				P, if present on either component, cannot be recognized on account of microseismic disturbances. The waves in S and first part of L are too irregular for accurate determination of amplitude or period; the earth motion was apparently very complicated. A short train of large irregular waves appeared on N-S component at 23^h 57^m .7 between time for RS_1 and RS_2; cannot identify them. Turkestan.
		S_N	23 50.6				
		L_E	0 12				
		L_N	0 13.4				
		M_E	0 16	34	347		
		M_N	0 27.9	21		488	
		F_E	2				
		F_N	2				
Feb.4	I	eL_N	4 29.7				E-W component shows no distinct M.
		M_N	5 06.5	30		6	
		eL_E	5 38.6				
		F_E	7 24.1				
Feb.4	I	eL_N	8 51.6				No decided M on E-W.
		M_N	9 07.8	12		1	
		eL_E	9 22.6				
		F_N	9 46.6				
		F_E	9.48.6				
Feb. 5	Ir	iP_N	4 29.4	3		5	No trace on P on E-W component. The train of waves at 4; 31.5 seems to be PS. Distance calculated 2690 km. Co-ordinates of the epicenter, as determined from data supplied by Ottawa, Harvard, St. Boniface and St. Louis, were λ=89°, φ=14°23′, near San Salvador, Central America.
		i_N	4 29.6	3.9		4	
		RP_N	4 29.7				
		PS?	4 31.5				
		iS_N	4 33.7	4		6	
		eS_E	4 33.7				
		i_E	4 34.1				
		i_N	4 34.6	6		6	
		eL_E	4 35				
		M_N	4 39.7	6		9	

DATE	CHARACTER	PHASE	TIME h m s	PERIOD T s	AMPLITUDE A_E μ	A_N μ	REMARKS
Feb. 5		M_E	4 39.7	5.1	13		
		C_E	4 42.7				
		F_N	4 51.2				
		F_E	4 54				
Feb. 17	I	eP_E	14 28.8				
		eP_N	14 29.8				
		eS_E	14 32.8				
		L	14 33.8				
		M_E	14 34.9	6	12		
		M_N	14 35.6	7.8		18	
		F	15 01				
Feb. 18	I	eL_N	2 03				
		eL_E	2 04.5				
		M	2 06.4	9.6	14	16	
		F_E	2 16				
		F_N	2 20				
Feb. 18	IIu	e_E	19 22.1				Up to 19h 43^m the motion on both components was very complicated and irregular. Central Asia.
		e_N	19 25.6				
		S_E	19 27.4				
		L_E	19 34.1				
		eL_N	19 36.1				
		M_E	19 38.6	18	102		
		M_N	19 45.1	18		211	
		F	20 10				
Feb. 28	I	eL_E	4 24.6				
		F	6 00.6				

DATE	CHARACTER	PHASE	TIME h m s	PERIOD T s	AMPLITUDE A_E μ	A_N μ	REMARKS
Mar. 10	I	eL_N	1 28				
		M_N	1 34.7	17		6	
		F_N	3 18				
Mar. 10	I	eL_E	11 2.7				
		F_E	11 45				
Mar. 22	I	eL_N	7 02				
		F_N	8 37				
Apr. 10	Ir	P	18 49.2				Distance 3660 km. According to reports received from northern Columbia by the Jesuit Observatory of Havana, the epicenter of the earthquake was between Bogota and Cartagena. The macroseismic data furnished by Havana, Ottawa, Trieste and Saint Louis, place the epicenter at: Long. 75° 50' W., Lat. 8° 36' N.
		S_E	54.6	7	8		
		S_N	54.6	9		11	
		L	57.2				
		M_E	19 3.5	14	22		
		M_N	4.2	15		34	
		F	23				
Apr. 28	IIr	P	10 0.4				
		L_N	7				
		L_E	7.1				
		M_E	7.2	6	13		
		M_N	7.2	5.5		15	
		F_E	22				
		F_N	51				

DATE	CHARACTER	PHASE	TIME	PERIOD T	AMPLITUDE		REMARKS
			h m s	s	A_E μ	A_N μ	
May 4–5	IIu	P	23 48.1				
		iS_N	57.5	6		25	$(S-P)_N$ = 9m31s Distance 8200 km.
		iS_E	58.1	6	8		$(S-P)_E$ = 10m6s Distance 8900 km.
		L	0 10.6				The co-ordinates calculated from
		M_E	11.6	24	105		data furnished by Darmstadt, Vi-
		M_N	12.2	21		95	enna and Saint Louis, are:
		F_E	14				Long. 152° 30'E
		F_N	19				Lat. 51° N.
							Kamtchatka.
Jun. 7	IIIr	eP_N	11 07.7+				$(S-P)_N = 4^m\ 13^s$
		eP_E	07.8	T_e 7.4			Δ= 2600 km.
		iP	07.9		8	68	Mexico
		R_1P	08.2	T_n 8.3			
		iS	11.9				
		iL	13.2				
		M_{1N}	17.4	15		1580	
		M	18	12	1306	1265	
		F	13 35				
Jun. 15	II	i_{1E}	14 47.1	7.8	75		Phases are doubtful owing to
		i_{1N}	47.1	8.4		90	interference of two quakes.
		i_2	53.3	6	42	36	China Sea and Mexico
		F	15 33				
Jul. 1	Ir	eP_E	22 9.9				Epicenter near San Francisco.
		L	16.5				
		M	16.6	10.8	55	60	
		F_E	47.1				
		F_N	55.5				

DATE	CHARACTER	PHASE	TIME	PERIOD T	AMPLITUDE		REMARKS
			h m s	s	A_E μ	A_N μ	
Jul. 4	I	e_N	13 56.2				Turkestan.
		e_E	56.3				
		F_E	14 42.4				
		F_N	47.2				
Jul. 12	I	i_1	4 28.3				Japan.
		i_{2E}	38.1				
		i_{2N}	38.2	12	77		
		F_N	5 54.6				
		F_E	5 54.8				
Aug. 16	Iu	eP	22 57 42				Guam.
		S	23 10 12				
		L	33 36				
		M_E	0 01 09	19	90		M_N indistinct.
		F	1 11 00				
Aug. 21	I	i	16 52 12				Near Kamtchatka?
		F	17 10 00				
Aug. 27	I	e	11 02 50				P and S too doubtful for deter-
		eL	08 08				mination. Mexico
		F	37 00				
Sep. 15	Iu	P	13 28 35				(S-P) = 7m 10s
		S	35 45				Distance 5550 km.
		eL_E	41 18				
		eL_N	42 18				
		M_N	45 08	27		81	
		M_E	47 38	18	32		
		F	15 30				
Sep. 17	Iu	iP	3 40 23				$(S-P)_N = 8^m\ 30^s$
		S_N	48 53				Distance 7000 km. Chili.

DATE	CHARACTER	PHASE	TIME	PERIOD T	AMPLITUDE		REMARKS
			h m s	S	A_E μ	A_N μ	
		S_E	3 49 11				
		eL_N	59 23				
		eL_E	4 00 53				
		M_E	01 17	15	49		
		M_N	06 20	17		78	
		F	42				
Sep. 22	Iu	eP_N	5 15 29				$(S-P) = 7^m$
		eP_E	15 35				Distance 5300 km. Alaska.
		eS_N	22 29				
		eS_E	22 35				
		L_N	27 59				
		L_E	28 53				
		M_N	29.08	8		1mm	
		M_E	29 09	9	1mm		
		F	53				
Oct. 6	IIr	iP	10 21 53				$(S-P)_E = 4^m 42^s$.
		iS_N	26 33				Distance 3000 km. Haiti
		iS_E	26 35				
		L_N	29 39				
		L_E	29 44				
		M_N	31 30	15		204	
		M_E	5.1 30	15	172		
		F	14 14				
Oct. 10	Ir	iP	13 18 03				Same determination as for
		iS	22 45				October 6.
		L_N	25 33				
		L_E	26 00				
		M_N	35 00	12		30	
		M_E	35 45	12	25		
		F	14 00				

DATE	CHARACTER	PHASE	TIME	PERIOD T	AMPLITUDE		REMARKS.
			h m s	s	A_E μ	A_N μ	
Oct. 15	I	e	16 58?				S and P could not be determined on account of microseismic disturbances.
		L_E	09				
		L_N	11.9				
		M_E	12.5	15	25		
		F	18 02				
Oct. 29	Ir	P_N	18 20.9				
		P_E	21				
		S_E	25.9				
		S_N	26				No distinct Maximums.
		L_E	28.1				
		L_N	28.9				
		F	46				
Nov. 18	I	P_N	7 38.2				P_E and S_E not distinct.
		S_N	43				
		L_N	48				
		F	8 06				
Nov. 20	I	P_N	13 54.7				Distance 3150 km.
		P_E	55.5				
		S_N	58.5				
		L_N	14 05				
		L_E	06.5				
		M_E	08	15	18		
		M_N	08.5	15		44	
		F	16.5				
Nov. 22	I	e	10 20.4				E-W too indistinct.
		L_N	21				
		F	27.3				
Nov. 25		P_E	19 35.8?				
		P_N	37 ?				
		S_E	39.8				
		S_N	42				
		L_E	42.8				
		L_N	43				
		M_N	43.6	12		35	
		M_E	45	12	15		F lost in microseisms.

DATE	CHARACTER	PHASE	TIME	PERIOD T	AMPLITUDE		REMARKS.
			h m s	s	A_E μ	A_N μ	
Dec. 16	IIIr	iP_E	19 19.4	638	12		
		iP_N	19.5	638		23	$(S-P)_N=4^m\ 20^s$.
		iS_E	23.8	8.7	3		Distance 2690 km. Mexico.
		iS_N	23.8	8.7		49	
		L_E	25.2				
		L_N	25.3	14.5			
		M_N	19 30			1064	
		M_E	30	12	546		
		F_N	21 06.5				
		F_E	12.5				
Dec. 22	I	P	13 00.1				
		S_E	04.6				$(S-P)_N = 4^m\ 30^s$
		S_N	04.6				Distance 2830 km.
		L_N	08.1				
		L_E	08.2				
		M_N	20.6	13		45	
		M_E	20.7	13	34		
		F	38				
Dec. 23	I	e	7 57.9				
		L_N	58.8				
		L_E	58.7				F overlapped by following quake
Dec. 23	I	e_N	8 08.6				
		e_E	07.5				
		F	43				

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