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Seismological and Meteorological Departments

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PART I.

SEISMOLOGY

On the Epicenter Problem.

1. INTRODUCTORY.

We present herewith two papers on the subject announced. The section headings of the two papers are numbered consecutively, to facilitate reference. The second paper comprises sections 12—14.

At first our ambitions did not soar above the modest purpose indicated in the subtitle of the first paper. We were soon compelled to recognise the gruesomeness of the charts our method was producing. The apologetic tone of our first paper is due to that circumstance. It seemed unnecessary to withdraw the apologies, when the very gruesomeness of the product led to quite unexpected results.

As our work progressed we became more and more convinced that an epicenter could be located with considerable certainty, if three conditions were fulfilled, namely:

1. If the theory of the W & Z curve (Sect. 3) is correct.

2. Supposing the first condition, if data were available, which conformed accurately to that theory.

3. If there were available a not too laborious way of translating such accurate data into curves, of which the roughly sketched curves of our charts may serve as diagrams.

The first condition seems to be generally assumed. Over the second we have no immediate control, but we thought that our idea of Time-Difference Charts might aid in procuring a greater number of reliable records, and thus contribute toward the realisation of the second condition. We encountered a seeming fulfilment of the third condition in the course of our work, and that fulfilment, such as it is, we present in the second paper, on the somewhat doubtful supposition that the scheme is unknown or untried, in seismology at least, since we can find no reference to it in the seismological literature now in our hands.

In consequence we respectfully submit for consideration the claim that Time-Difference Charts, of the species described in our first paper, but computed by one of the methods presented in our second paper from data, representing accurately the theory of the W & Z curve, solves the

PROBLEM: To locate an epicenter; given the correct arrival times of the P tremors at the chart stations.

Of this problem Dr. Geiger wrote in 1910: "Wenn es nun moeglich waere, eine Methode der Herdbestimmung anzugeben, die einzig auf Ankunftszeiten und auf der Laufzeitfunktion der I Vorlaeufer beruht, dann koennte der Herd jedes noch so komplizierten Bebens mit sehr grosser Schaerfe angegeben werden, sobald der Anfang der I Vorlaeufer scharf bekannt ist. Nimmt man wieder an, dass die Ankunftszeiten eine Unsicherheit von ±1 Sekunde enthalten &c."*

We assumed, of course, that the arrival times can be, and are, determined with rather great precision. And then we found that charts, even our rough diagrams, supply a rather searching test of the accuracy of the arrival times, reported by the stations.

The effective formulæ of our second paper may be described as parametric equations of our Time-Difference Loci, and of all sorts of cognate loci. On this fact a second claim may be based, namely:

The method, suggested in our second paper, in connection with even rougher Time-Difference Charts than ours, gives a solution of the

PROBLEM: To locate the epicenter; given the correct S-P of any two stations whatever, and the fairly correct arrival times P for the three stations of a single chart, in very many instances, and in all instances, practically, if a second chart is available, one of whose stations, at least, differs from those of the first chart.

To what extent the accuracy obtainable by the methods suggested, may warrant the labor required, we must leave to others to decide. And that seems to call for a few remarks on the mathematical method. As stated before, we could find no reference to it in our seismological literature, not even in the resume of methods by Dr. Tams, published in 1913.** The formulæ presented themselves so readily, at our very first attempt, that we could scarcely suppose them unknown. That would mean that they had been tried and abandoned as impracticable. Still, the little trial we were able to give the scheme seemed to indicate that it was practical, and the way we happened upon the formulæ might explain why they were not known in seismology.

Our chart making led up to the formulæ. In that process we used the transfer time as the independent variable. Hitherto the

*_Herdbestimmung bei Erdbeben aus den Ankunftszeiten._ _L. Geiger_, 1910.

**_Neuere Fortschritte auf dem Gebiete der Erdbebenforschung._ Dr. E. Tams, 1913.

transfer distance seems to have been used thus. The W & Z curve will give the distance corresponding to a given time, or the time corresponding to a given distance with equal ease (or difficulty). But Dr. Geiger makes use of distance as the independent variable, in all his tables. For this reason, by the by, we could not use his tables directly in our work. If attention had been directed away from the realm we were working, then the formulæ might still be unknown. On this assumption, and to establish, if possible, the rather brave claims we just preferred, we publish our second paper.

In the first section of that paper we deduce the formulæ. If that work should seem rather elementary, we suggest in extenuation that it is also quite brief, and that it seemed the simplest means, whereby we could define both the meaning of the formulæ and the terms they contain.

Much might be said, on general principles, to commend the formulæ.

The manner of deducing them guarantees their accuracy.

The method, on which our second claim is based, is direct.

The result obtained by this method is unequivocal. For the S-P from one pair of stations, one latitude and one longitude is returned for the epicenter.

The work is simple in several senses. After the constants for the pair of stations have been prepared, once for all, the work is entered by means of the cosines of the S-P. After that the work is purely numerical until sine latitude and tangent longitude are obtained.

The formulæ themselves provide unexceptionable guidance for the work.

The obvious objection, that the formulæ are not suitable for logarithmic work, we have tried to meet fairly in the conclusion to the second paper. In the same place we have indicated the real difficulty in the work, with its compensating advantage. The difficulty is that large tables must be used if a high degree of precision is demanded, the advantage, that it is easy to gauge the size of the tables required, for any degrees of precision demanded. And we might add that the nearest minute (arc) of latitude and longitude can be obtained with five place tables, unless the epicenter should happen to be in a very high latitude, or unless the pair of stations should be very close together.

This does not interfere with the original purpose of our charts. Hence we publish our first paper in almost its original form, apologies and all. The purpose of the paper is to explain the idea, which the charts are to illustrate practically; also to explain the manner of constructing the charts in such wise, that anyone interested might be able to construct for himself similar ones for any set or sets of three stations, with the least possible trouble and the greatest possible speed. Hence, wherever it seemed to us that fewer words might make our meaning at all doubtful, we elected to use the greater number of words. But we have tried to omit from the story all that did not serve directly the purposes just indicated.

We also found that the same explanations serve the purposes of our second paper admirably. The first paper being supposed, the second could attend strictly to its proper business, all explanations being disposed of by reference to the pertinent section of the first paper.

The first chart we undertook is the European one, and almost all references in the first paper are to that chart, since our time limit might have precluded publication of the American charts. It does not seem necessary to alter the references.

Our thanks are hereby tendered to Rev. C. J. Borgmeyer, S. J., Professor of Mathematics in St. Louis University, for mathematical work done in connection with this bulletin.

FIRST PAPER.

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2. TIME-DIFFERENCE CHARTS.

TO DETERMINE APPROXIMATELY THE EPICENTER OF AN EARTHQUAKE, WHEN THE ARRIVAL TIMES P AT ONE OR MORE SETS OF THREE SELECTED STATIONS ARE KNOWN.

The calculation required to locate an epicenter is not easy. The mathematical methods, with which we have become acquainted, are long, and, for the most part, involved. In the Publications of The Geophysical Observatory of The St. Louis University, for 1911 and 1912, we presented the methods of Prince Galitzin, Dr. Geiger and Dr. Klotz. Before submitting our charts we wish to refer our readers to the methods proposed by Dr. C. Zeissig. Two of these methods he published in Gerland's Beitraege zur Geophysik, XI Band, 2/4 Heft. Dr. Zeissig has used these methods since 1910, and he reported on them at the Manchester Convention in July, 1911*. These methods make the solution of the epicenter problem comparatively simple, but they afford only an approximate location of the point sought.

Both these methods of Dr. Zeissig aim directly at determining the azimuth of the epicenter in relation to some seismic station. This azimuth, and the epicentral distance, (the latter obtained from the

Comptes Rendus Des Seances·····... De L' Association Internationale de Seismologie. Manchester, 1911.

S-P in the well known transfer time tables), are then employed to fix the geographical coordinates of the epicenter. The author provides tables, from which these coordinates may be obtained, when the data, azimuth and epicentral distance, are known.

In the first of these methods Dr. Zeissig makes use of the differences of arrival times at two or more stations. These, with the known velocities of the incident longitudinal waves, determine the normals to the several wave fronts. The azimuth of the epicenter, in relation to one of the stations, is obtained from these normals.

In the second method Dr. Zeissig makes use of the epicentral distances, obtained from the S-P of the transfer time tables. The direction angle of the epicenter is then considered as a function of the difference between two station distances of the epicenter, and thus the azimuth of the epicenter is arrived at.

July 1, 1912, Dr. Zeissig sent a third method to the Physikalische Zeitschrift. This method he entitles "Graphische Bestimmung

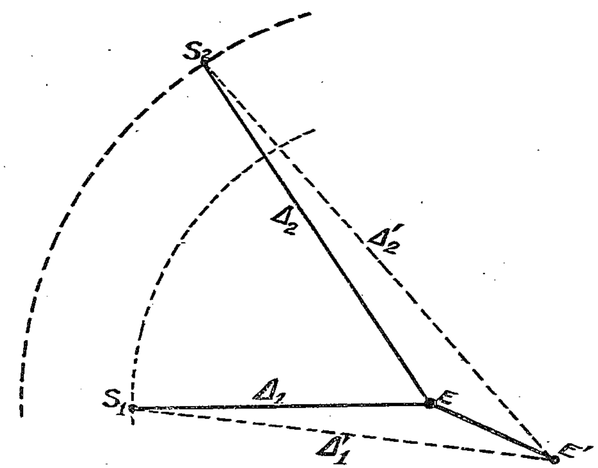

Fig. 1

eines Erdbeben Epizentrums aus den Ankunftszeiten P." The article appeared in the Physikalische Zeitschrift, 13 Jahrgang, 1912, p. 767. In this method Dr. Zeissig discards the use of the epicentral distances, obtained from the S-P. Instead he assumes two epicentral distances, one somewhat less, the other somewhat greater, than the probably true one. He calculates the $\Delta_2=\Delta_1+\delta$ from the difference $P_2—P_1$, (Fig. 1.) Thus he determines the points E and E_1, between which the epicenter will be found. The latter can then be determined by introducing the elements, obtained in a similar manner, from the records of a third station. Dr. Zeissig calls attention to the fact that the three stations should be chosen with a view to obtaining lines, intersecting at right angles, or nearly so. If the stations, chosen or available, do not fulfil this condition, then he recommends one or other of the methods previously published by him.

With all these methods at our disposal we desired something "easier" and "quicker", even if it were lacking a trifle, or so, in accuracy. Perhaps others have cherished similar desires. The methods just referred to, employ, for the most part, the published information about the transfer times of seismic disturbances. This information is published both in tabular form and graphically. The mathematician prefers his data in one of these forms, and his methods alone can locate an epicenter definitively. But it seemed to us that the same data could be presented in a form which would locate an epicenter approximately without the further intervention of any calculation. We present the result in our TIME-DIFFERENCE CHARTS, and we present them with all the apology, which their wildly tangled snakiness may seem to demand.

3. THE W & Z CURVE.

For our experiment we selected the "Laufzeitkurve No. 2" of Wiechert and Zoeppritz, given in Tafel I of their book "Ueber Erdbebenwellen" 2ter Teil, published in 1907. This curve gives transfer times of the preliminary tremors P for epicentral distances up to about 13,000 km. In the following we refer to this curve simply as "The W & Z Curve."

The correctness of the information, condensed in this curve, is called in question. The authors do not claim that it is correct. The best way to test its accuracy is to apply its data as often and as extensively as possible. An easier way of locating epicenters, even approximately, may secure a larger number of reliable records, and thus help to secure more reliable data.

We were less concerned with the accuracy of the information than with the form of its presentation. Should the form we had devised commend itself (on explanation), then means might be devised to present these, or any more accurate data, in a similar form, to any degree of exactness and of minuteness of detail that might seem desirable.

The explanation of such seemingly lawless tangles of lines has difficulties of its own. Telling the story of the genesis of one of them seems to be about the only possible explanation, which offers any prospect of success. This will also enable anyone interested, to construct for himself similar tangles for any other set or sets of three

stations, which he may find serviceable—his own included, of course. The labor will not be very great.

We claim very little that is new in our scheme. The numerical data are public property. In charting them we employed only the simplest geometrical principles. Even this geometrical treatment of the data has not only been suggested, but has been actually employed in locating epicenters. To the best of our knowledge, the actual charting of the data on these principles has not been presented hitherto, though even this is in line with suggestions contained in our previous Publications. The idea of some such chart must have presented itself to many a one before, perhaps only to be dismissed for its seeming difficulties, or for other reasons, and, for all we know, such dismissal may have been the more prudent course.

4. IDEAS INVOLVED IN THE CONSTRUCTION OF OUR CHART.

According to the W & Z curve, the preliminary tremors of a seismic disturbance will travel 390 km in 1 minute, 855 km in 2 minutes, and so on. Suppose a list made of all whole minute transfer times with the corresponding distances, which can be read from the W & Z curve. Then suppose the following operations:

On a terrestrial globe locate a seismograph station, H (Hamburg) in its exact latitude and longitude. Open a pair of dividers to span the 1 minute distance (an arc representing 390 km on the globe). Place the pivot leg of the dividers on the station, H, and with the marking leg draw the small circle, with 1 minute transfer distance about H as a pole. Call that circle H_1. In like manner draw H_2, with H-polar distance equal to 2 minutes of transfer-time distance. Continue thus to the end of the distance list, say to circle H_{15}.

Select anyone of the circles, say H_n. Then, from any point on H_n, the preliminary tremors P of an earthquake would pass to the instrument at H in just n minutes of time, i.e. in as many minutes as there are units in the subscript of the symbol of the circle selected. Such a set of circles, if drawn, would cover distinctly more than half the surface of the sphere, and, an earthquake, recorded on the instrument at H, would have its epicenter somewhere within that area, unless the epicenter should be so far from H, that its location could not be attempted by means of the W & Z curve, as we have it. More than this cannot be claimed for such a set of circles, so long as nothing further is provided.

Now select another seismograph station, V (Vienna), which, on earth, is at a serviceable distance from H. We are not prepared to define this "serviceable distance." It may be that close stations are better in the case of epicenters at small distances, distant stations, better in the case of distant epicenters. But small distances are apt to crowd the lines in some regions of the chart, distances greater than would correspond to 6 or 7 minutes of transfer time, reduce the area of the chart. Suppose the station V selected, located on the same globe, and surrounded by a set of circles, V_1, V_2, and so on, similar to the set of H circles. The letter, then, will indicate the set, to which any circle belongs, and the subscript the transfer time in minutes from a point on the circumference to the station, which names the circle.

Unless the stations are very far apart, the two sets of circles will intersect in numerous points. We must now classify these intersections. H_1 will not cut V_1, as a matter of fact. Should these circles cut each other in any other set, then the stations are rather too close together. But, moving outward from H a circle, H_n, will soon be found, which is tangent to, or which intersects a circle of the V set, with the same subscript, V_n. Mark these intersections. Every circle of the H set, with subscript greater than n, say H_{n+m} will then intersect the circle of the V set with the same subscript, V_{n+m}. Mark all such intersections. Each of the points, so determined is as far from H as from V. A uniform curve, drawn through all these points will be a large part of the great circle, which perpendicularly bisects the arc HV. Every point on this great circle is as far from H as from V, and, conversely, all such equidistant points are on that great circle. Hence, a tremor, recorded simultaneously at H and V can come only from some point on this great circle. Call this locus: H—V=0.

The next intersections to be looked for are those of circles of the two sets, whose subscripts differ by unity. Some circle, say H_n, will touch or intersect V_{n+1}. Every circle of the H set with subscript larger than n, say H_m, will then cut the V circle, with the next larger subscript, namely V_{m+1}, in two points, until a certain upper limit is reached, which is discussed in Sect. 7. Third. A uniform curve, drawn through all the intersections just specified, would be the locus of all the points, which, as epicenters, would send P tremors to H and V, that would record themselves at H just one minute sooner than at V. Call the locus: V—H=1 minute.

Drawing a similar curve through all the intersections of V circles, V_m, with circles H_{m+1}, would give a locus: H—V=1 minute. A P-tremor from an epicenter anywhere on this locus would reach H just one minute after recording its arrival at V.

Similarly, intersections of circles of H_n with circles V_{n+2}, and of circles V_n with circles H_{n+2}, would give respectively the loci: H—V=2, and V—H=2. In like manner, loci H—V=3, 4, 5 and so on

minutes, and V—H=3, 4, 5 and so on, minutes should be drawn until the limit of the intersections is reached, which will be very soon if the stations are close together. In the case of the VH set the greatest possible difference in whole minutes is 2, and that 2 minute locus is a very small affair.

Suppose all such loci drawn on the globe, and then suppose that P-tremors from an earthquake are recorded at H just r minutes sooner than at V, then the epicenter must be on the locus V—H=r minutes, if such a locus is possible. Also, if r is an integer and within the proper limit as to size, then the locus will be found on the globe, and some point, of the line actually drawn will be the epicenter.

But the locus V—H=r may sprawl widely over the globe. It will sprawl most surprisingly, if r is small and the stations close together. Hence we would still be far from even an approximate location of the epicenter. We would have gained merely this, that in our search for the epicenter we could confine our attention to a single line, instead of having to worry over the entire surface of the globe.

The epicenter may be located more definitely by calling in the aid of a third station P (Pulkowa), which should be at serviceable distances from both H and V. Suppose such a station selected, located on the same globe, surrounded by its set of circles P_1, P_2 and so on, and also suppose drawn the loci H—P=0, 1, 2, and so on and the loci P—H=1, 2 and so on. If now it should be found, that the epicenter, which we just located on the V—H=r locus, recorded itself at P just s minutes sooner than at H, then the epicenter would also be on the locus H—P=s minutes. These two loci should, therefore intersect, and evidently some one of the intersections must be the epicenter.

In planning our charts we had calculated on two intersections at most—but the only statement we can now venture is that the intersections come in pairs, and that there will not be many pairs of them, if the loci intersect at all. This would reduce the problem to deciding which one of a comparatively few points is the epicentral point. In some instances the selection can be made by means of the data furnished by a single chart. In most instances by the data just referred to together with some S-P value, which need not be very accurate either. In all instances, practically, the selection is determined by the data of a second chart, one of whose stations, at least, differs from the stations of the first chart. (Some one will suggest that there are no "epicentral points". Well, to be precise we must deal with "points". A little widening, in practice, will take care of the "areas".)

The P-circles intersect the V-circles also. Hence we can also draw the loci V—P=0, 1, 2, and so on, and P—V=1, 2, and so on. Should we then find that the same tremors were recorded t minutes earlier at V than at P, then the epicenter must also be on the locus P—V=t. This third locus will pass through all of the intersections of the other two loci. The epicenter will be one of these intersections —if the W & Z curve is correct in all respects, and if it is charted correctly, and if the three arrival times are recorded and then read correctly, and if the first preliminary tremors met with no accidents on the way, and any other ifs, which do not occur to us just now.

Some one may think that this third set of loci cumbers the wild chart with a great deal of additional confusion, and to very little purpose. Its service is not as trifling as it seems to be.

It will be found that the VP locus, after condescending to the other two in the slight matter just mentioned, as a rule pursues a quite independent course over quite distinct areas of the chart. This alone might indicate that it can serve purposes of its own. It seems that some of these purposes should be indicated here.

1. At best only a few of the loci of any three-station set can be drawn on a chart. Hence an epicenter will be found but rarely on a locus actually drawn. And therefore to locate the epicenter we must have recourse to interpolation in most instances. This process will be both more easy and more reliable, the nearer an epicenter is to some locus on the chart. Drawing the third set of loci will increase by about 50 per cent the chances that some locus of one of the sets may pass near the epicenter.

2. As we shall show in Sect. 7, the loci of each set define areas within which the epicenter must lie, if the arrival times are recorded correctly at the two stations, which name the locus.

3. In Sect. 9 we show that this third set of loci gives most welcome, visible evidence of the wholly unexpected accuracy of our "easy" charting method.

4. That the third set enables us in some cases to locate the epicenter with considerable precision, by means of a single chart, we shall illustrate in Sect. 11. That the same set supplies a very searching test to the consistency of the arrival times, reported by the three chart stations, we shall indicate more precisely in Sect. 10. We are not prepared to state the lower limit of such inconsistency that can be thus detected, but we shall illustrate in Sect. 11 that the chart does rule out peremptorily some sets of data, which look quite proper as presented.

5. FROM THESE IDEAS TO THE CHART.

We are evidently placing a heavy burden on the accuracy of a chart, drawn as described in the preceding section. For us this difficulty had been solved by a previous venture. Our first plan was to produce our Berkeley-St. Louis-Ottawa chart, on a large scale and with all the precision obtainable. Just that, and nothing more. (Publication to be dependent on circumstances.) For this purpose a sufficient number of points had to be determined somehow, but with such accuracy, that the loci, drawn to their guidance, would realise our intentions, or nearly so.

The only safe way to make these determinations seemed to be the solution, for each point, of the terrible series of triangles, whereby every text of elementary Spherical Trigonometry solves problems of the kind. Such a gigantic task could be justified only by some very good evidence that the result would prove eminently useful. Prof. F. W. L. Peebles, E. E., faced the task for us, and computed points for a rather small portion of the intended chart.

We had a 12 inch (305 mm) spherical blackboard handy, and this suggested the circle method, detailed in the preceding section. On this globe we drew the first five or six circles of each of the B, S and O sets, and sketched in the loci, in the manner just detailed. The results of this venture agreed so remarkably well with the calculated data, that we promptly concluded to eliminate all calculation, and construct the entire chart by the "easy" method, found so opportunely. We also concluded that this graphic way would not give the accurate result which we had intended, but it would supply an extended working model, which might determine whether resumption of the abandoned calculation would be justifiable.

Although our "easy" method was thus developed on a globe, a globe chart was undesirable for a number of reasons. Since every chart of the kind covers a good deal more than half the globe, every new three-station chart would require a new globe. Now, not to dwell on volumetric considerations, a new paper chart is apt to be less expensive than a new globe. Again, a flat, well-behaved chart is ever so much easier to study than a globe, fidgeting on a pivot. A globe area, moreover, is strictly limited in size, a paper chart can be expanded ad libitum. Finally, and especially, we wanted to publish our idea, diagram and all, for criticism, approving or otherwise, and a globe cannot be published conveniently.

So the points, determined on the globe had to be transferred to the chart. But even the work on the globe had its difficulties. Even the few circles we actually drew on the globe formed a perfect wilderness of intersections. Yet at least forty-five circles to each set would be required to secure loci for every twenty seconds of transfer time difference. To that limit the W & Z curve can be read with comparative ease. Worse still, even the outermost circles of our very limited collection showed quite indeterminable interesctions, as a matter of course. We avoided all these difficulties by drawing no circles at all, when we took the chart in hand.

For reasons of no interest now, we passed to the other Continent for a first trial, and selected the trio of stations, Hamburg, Vienna and Pulkowa, which supplied the capital letters of the preceding section. One inconvenience, which arises from the proximity of H to V, is that the loci are crowded together about the longitudes 80° and 280°. But with the three charts, which we are now able to present, we illustrate effects of varying distance and varying position in considerable variety, and that may make judicious selections of chart stations possible.

To determine points for the loci we procured an 18 inch (458mm) terrestrial globe. It rotates on an iron pivot, which pierces the shell in the polar regions, has an equator, divided into single degrees of longitude, and has parallels of latitude drawn for every 10°. We compared the positions of H, V and P on the map, with the latitudes and longitudes of the respective Observatories given in the Bulletin of the British Association*, and concluded that the map located the stations about as accurately as we could. At each of the stations a pinhole was bored right through the papier mache shell of the globe.

After trying various materials we finally procured narrow strips of thin spring brass. Ours are about 7mm wide. A line was drawn down the middle of two of these strips, and a pinhole pierced near one end of each strip, the center of the pinhole being on this line. Along the mid-line of each strip were laid off, and marked clearly, distances from the middle of the pinhole, corresponding to epicenter distances (as represented on our globe) requiring 20 seconds, 40 seconds and so forth of transfer time, up to the limit of the W & Z curve. Pinholes were then pierced through each strip, at the intersections of the mid-line with each mark. These distances we read from the W & Z curve, estimating to the nearest hundredth of a megameter. We accommodated these distances to our globe by means of the relation: 1 megameter equals 9° of a great circle. To determine the length in mm of 1° on the globe, three great circles were measured with a mm tape line, namely, the equator, a meridian and the inevitable ecliptic. Dividing each of these measures by 360, gave us three values of the great circle degree. We took the mean of the three values, and made no further investigation of the peculiar sphericity of our globe.

The end pinhole of one of the strips was then placed over the hole pierced at H, and an ordinary pin inserted, to serve as pivot. The other strip was similarly pivoted at P. The papier mache endured the consequent abuse remarkably well. The pivot pins were gripped firmly even after numerous insertions and removals. These details are trivial, but, had we known them to begin with, we would have been saved a good deal of time and trouble.

We could now mark on the globe a large number of points, belonging to loci of the HP group. To mark points on the locus H—P=0 (the great circle, which perpendicularly bisects the arc HP), the pinhole at 2 minutes of transfer time distance on the H-strip was placed over the 2 minute hole on the P-strip, a pin inserted, and the rigid triangle, so determined, laid on the globe surface. A (not indelible) mark was made at the point indicated. Similarly, marks were made by means of the 3 minute, 4 minute and so on pinholes, to the end of the graduation. Then the strips were swung around to the other side of the HP arc, and the part of the bisecting great circle marked out on that side.

To mark points on the locus H—P=1 minute, the mark at 3 minutes from H was matched with the mark at 2 minutes from P, the mark at 4 minutes from H with that at 3 minutes from P, and so on and points marked on both sides of the HP arc. This should suffice to indicate the method followed. We certainly found a very easy and rapid way of locating points for our intended chart. On the accuracy of the resulting chart we shall comment in Sect. 9.

But to transfer the points so determined from globe to chart, the location of the points in terms of latitude and longitude had to be determined. Another brass strip served this purpose. Its length is about 150° of our globe. It was pivoted (removably) at the pole in such wise that one edge of the strip, produced, would pass through the center of the pivot hole. This edge was graduated to degrees, to suit our globe, and the graduation numbered each way from the equator. The location of the previously marked points is then quite simple. The meridian strip is pivoted, and its meridian edge is placed through the point to be determined. The same meridian edge of the strip then marks off on the equator (divided into degrees) the longitude of the point, and, after that has been recorded, the latitude is read directly from the strip. It will be news to few that greater uncertainty attaches to this determination of the longitude than to any other step in the process.

6. THE CHARTING.

To chart the points so determined, a convenient set of coordinates had to be selected. The entire loci, belonging to any three-station set, cover an area, which involves at least one of the poles. An attempt to plot such loci to rectangular coordinates leads to unmanageable distortion near the pole, the pole itself develops into a straight line, stretching across the entire width of the chart, and it is very difficult

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to trace any locus from its deformed ending on one side of the pole, into its deformed continuance on the other side. Of course, if the set of three stations is near the equator, both the poles will be involved in the area, and then simple squared paper would seem to furnish the most convenient coordinates. The polar distortion will occur, as a matter of course, but it will affect only the fag-ends of some loci, and they may be useless anyway.

Our stations are not equatorial, and so we selected a simple set of polar coordinates, radiating from the pole involved in the area. We drew them ourselves, to suit our special purposes. Straight lines, intersecting at the pole, are the meridians. Circles, with the pole as center, and spaced equal distances apart figure as parallels of latitude. The longitude numbering adopted has its zero on the Greenwich meridian, and increases eastward, continuously, to 360°. This is analogous to the R. A. numbering in astronomy. The continuous numbering is by all means the more convenient, and carrying the numbers the other way about introduces difficulties.

Since we are not much concerned with area on the chart, but only, or chiefly, with latitudes and longitudes, such a set of coordinates seems admissible. Beyond the equator things acquire an unfamiliar look, but the meridians and circles provide all needed guidance even in that region.

It might be well to call attention to one other little practical trifle. The pole of the earth must, of course, remain the pole of coordinates too, but the station triangle is, of necessity, the center of the chart. Hence, if the coordinate lines are drawn with the pole in the center of the paper, and if a generous scale of latitude is then adopted, a chart for a low latitude station set might find itself mostly off the paper. The full size of the drawing paper may be best utilised by reserving the center of the paper for what might be called the center of gravity of the station triangle. Proceed as follows. Mark the center of the paper. Subtract one-third the sum of the latitudes of the stations from 90°. Select some point at this complementary distance from the center of the paper, to serve as pole. Draw the coordinate lines with reference to the pole point so selected. Then the longitude numbering must begin on the meridian, which passes nearest the center of the paper. Assign to that meridian the nearest 5° or 10° to the number obtained by dividing the sum of the longitudes of the stations by 3. Then continue the longitude numbering eastward.

Beyond this, the plotting of the loci should need no remarks. After the points have all been plotted for any one locus, the locus is drawn (as usual in such cases) to form "a uniform curve, best satisfying the position of the points". A glance at our charts may suggest the idea that "uniformity" has a peculiar meaning with us.

But all our loci were not drawn in this manner. On the European chart all the loci for 0, 1 and 2 minute differences were so plotted, also the H-V loci for 20 and 40 second differences—and two more loci. After plotting the V—P=0, and V—P=1 minute loci, it occurred to us to fill the gaping void between them, by plotting in the 20 and 40 seconds difference loci, which belong there. But another very definite purpose of this proceeding was to test the reliability of our method. We plotted both these loci, in both directions from the VP line, only omitting the parts within and near the station triangle, since that area was showing signs of overcrowding even then. As may be seen the loci fairly trisect the area between the 0 and 1 minute loci. This is done so definitely that we could evidently have plotted in the loci for the remaining 10 seconds difference loci, without any of the lines fouling each other.

Since we were professedly in quest of "the easy" we promptly took a hint from this experience. All other similarly situated loci (when drawn at all) were just sketched in very simply. To illustrate the process let us take the area between the P—H=1, and P—H=2 minute difference loci. The pivot leg of the dividers is set on H (on the chart). H is the nearer station. The marking leg is then spread until it reaches into a region where there seems to be room for more lines. Swing a light, leadpencil arc from the 2 minute to the 1 minute locus. Draw other such arcs at increasing distances from H, wherever they may seem convenient or useful—until the 2 minute locus tumbles towards its closing point. Trisect each of these pencilled arcs after this manner. Estimate a third of the arc in hand. Spread the dividers to that extent. Test the "guess" by "stepping off" on the arc. Correct, and then mark the two points of trisection. "Uniform" curves drawn to the guidance of these two sets of points will represent the 20 and 40 seconds difference loci, belonging to that space, about as well as the same loci could be plotted from the globe, and they will cost distinctly less labor. Both the loci, so constructed, may be continued for some distance into the void beyond, in the general direction hinted at by the last few trisection points, and the course of the curve with the smaller time difference. Hence the 20 seconds locus can be produced further than the other—but this proceeding can be easily overdone.

This work is not accurate. Certainly not. But it is more correct than a mere eye estimate would be. Furthermore, as indicated at the close of the second paper, a really reliable method of interpolation may be derived from this method, for loci calculated with all precision desirable.

Our delirious charts were constant reminders, in the course of their growth, that it would be a very difficult matter to follow the course of any individual locus, in an attempt to locate an epicenter. Hence, in the first place, we adopted the simple device of inking one of the sets as continuous lines, the other two in short and long dashes, respectively. Perhaps a color scheme would be better, if a detailed and accurate chart should ever be produced. At the same time we kept in view the diagrammatic character we attribute to the charts presented. Hence we introduced as few of the loci as would be consistent with the idea of a working diagram. Our two American charts interlock very thoroughly over the entire region of North and Central America, and almost the whole of South America. The NSO chart interlocks very thoroughly with the European chart over almost the whole of the Atlantic basin, and, to a slightly less extent over the two Americas and Europe as well. The recorded arrival times of tremors from epicenters situated within this very large area of the earth's surface can be tested by means of these diagrams—or the diagrams can be tested by means of these tremors. No very elaborate interpolation will be required for that purpose, but the results should decide as to the value, or otherwise, of our device either for the original purpose we had in view, or for numerous other purposes, suggested by the completed diagrams and their by-products. If we had been able to carry out our plan of a second European chart, combining either Stonyhurst or Shide with either Hamburg and Vienna or Pulkowa and Vienna, the combination of the diagrams would have been still more effective. But it is not for us to make and evaluate the tests. Should anyone be sufficiently interested in the matter to institute some tests of the kind, then he may find a few sample locations of epicenters in the last section of this first paper. Meanwhile we shall try to indicate a few of the "by-products" developed in the production of the charts.

7. CHARACTERS OF THE LOCI.

Some characteristics of our loci are due to the simple geometric basis of our scheme, others are due to the brusk way, in which we reduced the earth's surface to a plane, the rest, and, in particular the "kinks" derive from the W & Z curve. We bargained for all the distortion consequent on our unlawful projection, and have no further comment to offer on that matter. The "kinks" we reserve for the next section. The geometric peculiarities are due to just elementary

geometry. In the present section we shall offer some remarks on them, just to call attention to the salient points visualised in the charts.

First. Every point on any one of our loci represents the vertex of a spherical triangle, whose base is the distance between the two stations, which name the locus, and whose sides differ by a length, varying from point to point, but determined in each case by the condition that the transfer time from that point to the more distant station shall exceed the transfer time to the nearer station by the constant time difference, which specifies the locus. This description applies to the zero loci only if the fact that they are limiting cases is remembered.

For further illustration we shall remark on the VP loci. For any point, X, on the locus V—P=0, the triangle VPX is isosceles. For any locus V—P greater than zero, the side VX exceeds the side PX. Hence all such loci lie entirely on the Pulkowa side of the 0 locus. Similarly, every locus P—V greater than 0, lies wholly on the Vienna side of the same 0 locus.

Second. Through any two stations, say V and P, we can pass one and only one great circle. This circle is not shown on our charts, because tremors from different points on that circle would not have the same differences of arrival times at the two stations. For other purposes, even for the construction of the charts, it might be convenient to draw this circle, but another graphic method would be required for that. The method required is given in the geometry of the sphere.

With respect to this great circle all PV loci are disposed symmetrically (on the globe, not on our charts). Because, for any triangle VPX, with its vertex X on the north pole side of this greater circle, there is another triangle VPX′, symmetrical to the former triangle, and therefore with its vertex on the other side of the same great circle.

Third. All the loci are closed curves, and each encloses one of the base stations. Also, in any locus, the point nearest to, and the point furthest from, the enclosed station is on the great circle through the stations. These assertions derive from the simple principle that in any triangle the sum of two sides cannot be less, nor the difference of two sides greater, than the third side. For illustration let us consider a locus V—P=d. Let a circle with V as pole begin with zero radius. (For the sake of brevity we use radius here instead of V-polar distance). Let this circle grow continuously by increasing its radius continuously, the increase per second of time being the corresponding increase of transfer distance according to the W & Z curve. This radius will soon reach a value, such that a tremor from its endpoint would require d seconds to reach V. Just when this radius is passing through that value, start another similar circle from zero at P, with the same law of increase as that of the former circle. The difference of transfer times from their ends to their respective poles will then always remain d seconds.

The two circles will be tangent just when the sum of their actual (not transfer time) radii equals the distance VP. This point of tangency clearly belongs to the locus V—P=d, and is on the arc VP. No point on this locus can be nearer to P, for this is the first point reached by the increasing radius (from P) to which the law of the locus applies. All other points on the locus must be farther from P, because at all these points the two supposed circles intersect in two points. Hence both radii must have increased from their value at the point of tangency.

Since both the radii are increasing, the locus will, at first, depart rapidly from the great circle through V and P. But the radius of the V-circle must increase more rapidly than the radius of the P-circle, since the former is increasing at the rate of a further part of the W & Z curve. Hence somewhere the locus will reach a point, (or rather two points) of maximum divergence, and from there on, the two points of intersection will approach the great circle through V and P, more rapidly than they departed. When the varying rates of increase of the two radii has made the actual (not transfer time) difference of the radii equal to the distance VP, the circles will again become tangent, evidently on the great circle through V and P. That point of tangency will be further from P than any other point on the locus. After that point has been reached, the P-circle will be and remain wholly inside the V-circle, and no further intersections will be possible.

Fourth. The greater the difference of transfer time for points on any locus, the nearer will be the extreme points of that locus to the station, which it encloses. This follows very simply from the preceding demonstration, and was shown, in fact, for the point on the arc VP between the stations. The statement is equally evident for the more distant point of tangency of the increasing circles. For, the greater is the time difference of the locus V—P=d, the greater will be the start of the V-radius on the P-radius. The more, therefore, will the rate of increase of the V-radius exceed that of the P-radius, and therefore, the sooner will the actual distance VX exceed the actual distance PX by just the length of the arc VP.

Thus, our locus V—P=1 closes beyond the limits of the chart. V—P=2 extends quite far, but closes well within the limits of the chart, V—P=3 is very small. We had drawn it, but abandoned it, on account of the uncertainty of its course, due to the few points on it, which we could determine by our method, and also on account of the crowded condition of the region where it belongs. In cases where loci of this character cover earthquake regions, these small ones must be determined by calculating a sufficient number of points. There can be no locus for these two stations with a time-difference exceeding 3 minutes by more than a few seconds, and the maximum difference of arrival times of a seismic disturbance at the two stations would be shown by tremors due to an earthquake at one of the stations.

Hence the fact, already well known, that if the difference of arrival times exceeds the transfer time between the two stations, then there is something wrong with the records. This fact is here deduced from the data of the W & Z curve. The physical reason for the same statement has, we think, been presented before.

Fifth. Every locus, as V—P=t, encloses all the points on the chart, from which a seismic disturbance can reach the stations, which name the locus, with a time difference greater than t. This follows necessarily from the preceding demonstrations, and each of our charts offers abundant illustrations of the fact.

8. THE "KINKS" AND "CURLS".

We began our charting with the H—P=0 locus, and encountered no difficulty. When we came to the HP one-minute-difference loci our troubles began. We had used only the whole minute distance marks, and the points near the stations arranged themselves in a very promising order on the chart up to station distances corresponding to 5 and 6 minutes from the respective stations. Beyond the 8 minute distances the plotted points again showed good behavior. Besides, the uniform curves, drawn through the terminal sections, could be connected with that through the section near the stations by a very neat, uniform curve—but the intermediate points bore no relation to this pretty curve, except one of irregular distance. Naturally, our suspicion of our easy method dictated our next moves. We relocated the points, and they remained just where they were before. We reread the W & Z curve, repeated our multiplications, remeasured our strips—and the points maintained their positions. They showed no inclination to move at all. So we were finally forced to conclude that they were in their proper positions, or thereabouts.

Once we had to admit that we could found no serious charge against our "easy" method by reapplying it, the explanation was of course, ridiculously obvious. The distances, read from the W & Z curve, for transfer times of 1, 2, 3, 4 and 5 minutes, increase at an increasing rate, but the change in rate is fairly uniform. At about the 5 minute distance the slope of the curve decreases very decidedly, and the increase of distance for the interval 5 to 6 minutes and thereafter is much greater than in the earlier part of the curve, though the change again approaches a somewhat uniformly increasing rate. These conditions could produce no effect on the bisecting great circle, nor on the initial points of the 1 minute difference loci. But when the 5 minute mark on the H strip was matched with the 6 minute mark on the P strip, there resulted a triangle, whose side PX had increased abnormally as compared to the side HX. Hence the vertex was thrown very notably in the direction away from P. In the case of the 6 and 7 minute match, the HX side of the triangle had received one abnormal increase, but the corresponding side PX boasted two such increases, hence the vertex kept its H-ward inclination. After this these increases tone down their effects slowly, and lead to the well behaved outer reaches of the loci. When we plotted the points corresponding to the 20 seconds and 40 seconds increases between the uniform curve and the first of the outstanding points, the additional points marked out a very neat curve "kinking" the regular curve over to the displaced point, and, in the same manner we could "kink" back into the regular curve further out.

The 3-minute-difference curves, which were drawn, did not show the kinks. Neither do they appear in the HV 2-minute-difference curves. All these lie on the station side of the region where trouble is due. In the HV and PV 2-minute-difference curves the kinks appear, but are mostly obliterated by the swing toward the closing point, which begins almost at the trouble point.

This closing swing, by the by, has to be drawn with very little assistance from the measuring strips. Almost the whole of the swing, in the case of these close stations, lies within a single 20 seconds transfer distance, and the actual closing point has to be estimated with very little to base the estimate on. Of course, the point lies beyond the mark (from either station) which was matched with a mark from the other station for the last determinable point—also, the closing point lies nearer either station than the next 20 seconds marks. In our American charts the parts of the loci between the two points last determined on either side, has been omitted for the present. The part of the locus drawn, indicates the form of the closing part so clearly that this may be readily drawn in. Meanwhile the matter is not a very serious one. If the closing point should be jotted down almost anywhere between the limits of its position, which are easily determinable, it would not be far out of place. In the early part of the W & Z curve the 20 seconds differences amount to about 1°, and toward the very end of the old curve they do not reach 4° in length.

For the intermediate loci this kinking matter gets to be far more tangled. To locate points on these loci graphically, 20-second, or 40-second difference marks have to be matched with whole minute marks—or with each other, if all available points are to be determined, as was done for most of our plotted loci. The unequal minute increments are unequally distributed among the subdivisions. The consequences may be appreciated from the snakiness of the resulting loci. But even these extravagances scarcely do justice to the subject when all available points are plotted for a 20-seconds, or 40-seconds difference locus, which depends on a small base besides. For instance, the HV loci for these differences had to be plotted in, if we were to show any HV locus in the vast space between the small 1-minute-difference ovals, and the majestic sweep of the bisector. All the points for these loci were plotted and then connected serially by faint leadpencil lines, preparatory to a generous "smoothing" process. The result looked like an exaggerated instance of the conventional picture of "jagged lightning".

And of course the next question is: what business had we to do any "smoothing"? There were two good reasons for such smoothing as was done. First, we wished to make it possible to follow our loci across the chart, and since it was permissible, we indulged our preference. Secondly, it was permissible since these wild oscillations are certainly exaggerations, and, so far, we have no means to estimate the extent of the exaggeration. For this second reason, especially, the smoothing process was conducted with all convenient deference to the dancing set of points, but more respect was paid to the probalities. Of course, if one or more points persisted in a peculiarly outrageous situation, the curve was adapted to suit their peculiar humor.

The cause of these exaggerations is obvious enough, though we have no means at present to gauge their extent.

The basic cause of all pronounced irregularity in the loci, is of course, the varying rate of the W & Z curve. That irregularity is part of the truth we undertook to represent, and should be maintained as far as it is known.

But our reading of the curve introduced a factor of a different order. We endeavored to estimate the distance to the nearest tenth of the coordinate division of the W & Z chart at our disposal, i. e. to the nearest hundredth of a megameter. We do not claim that we secured the nearest hundredths. One hundredth megameter is 10 km. If in our readings we estimated one distance short by even 10 km, and another distance too long by the same amount, then, if two such marks are matched in locating a point, that point will be swung vigorously over to the "short" side, especially when the base line is short.

As stated in the introduction, we could not use Dr. Geiger's interpolation directly, but we compared our readings with his tables, and the agreement was quite satisfactory with the first interpolation throughout. Our readings agreed even better with the second interpolation (of 1912), up to a transfer time of about 520 seconds, or a distance of 46°. In the succeeding stretch Dr. Geiger used a slightly steeper curve for the second table, and so the transfer times for the same distances increase up to a distance of 69°, for which distance the transfer time exceeds that of the old table by 14 seconds. This maximum differences is maintained to distance 73°. After that the new values approach the old ones to the end of the new table at distance 82°, for which the time exceeds that of the old table by only 6 seconds.

Our charts were to serve as diagrams, hence we wished to make them as extensive as the W & Z curve permitted. The terminal portions of that curve are not considered in Dr. Geiger's new table, nor does the latter connect up with them. Hence we adhered to our readings. This we could do the more readily since loci, plotted to Dr. Geiger's new readings would not differ to any serious extent from those we present. In the part of the curve affected by the new table, each point would be moved toward the stations by an amount corresponding to the change, but the displacement sideways would amount to very little.

Since we could not determine the distances more precisely we had to use the values as we had them. Calculation is no remedy, for only the same defective readings can be fed into the calculation. If an equation of the curve could be produced, or if there were available a set of values adjusted to each other by the masters in this realm, then a chart could be produced—not without kinks, to be sure, but with every kink in its proper place and of the proper size, and no impromptu affairs to add to the natural spiciness of the chart.

A seemingly more serious difficulty is inherent in the graphic method itself, and its effects must become more and more pronounced the closer the stations are to each other, and the further the plotted loci extend from their stations. If the station holes are not bored so that their centers coincide exactly with the geographical position of the stations in question, then the base line of the system of triangles, which depends on these station holes, may be a little too short or a little too long—also it may get a slight tilt out of its proper direction. The actual line determined by the holes, will not differ much in either respect from the line it is to represent, but the vertex of a triangle on such a base, and with sides stretching out to 10 or 12 thousand km will be at quite different distances from the base, according as the latter has its true value, or has been taken too long or too short. A slight tilt of the base might also seem able to give a notable jolt to a vertex at such distances.

And now we have said about all the bad things of our loci that we could think of. We had good reason to think of them. The wild tangle of lines on the charts seemed to be necessities of the case. We could remedy neither their lawless courses nor their crowding here and there. But if the entire show was out of its proper position, that was quite another matter. We had no desire to publish a seeming nightmare without some tangible assurance that it was more than just the figment of a dream and of a very troubled dream at that. We never lost sight of these possibilities throughout our work, and our digressions referring to tests by the way were intended to reassure any reader kind enough to examine the work. But the appearance of our product, when near completion, seemed to demand more searching tests.

9. ACCURACY OF THE CHARTS.

We refer only to the accuracy, with which the charts represent the data of the W & Z curve employed. A host of triple intersections gave welcome evidence of the consistency of the work, and this evidence we shall specify a little more at the end of this section. To determine whether the loci were of the proper size and in their proper places, at least approximately, a mathematical test offered the only recourse. The old trigonometric way was not inviting, and so we went in search of another way. This we found so soon and so easily that we certainly cannot guarantee its novelty, but, such as it, we present it in the second paper.

This seems to be the proper place to give a few practical data about this mathematical scheme. Since we also propose it as a method for computing points for our kind of loci, we gave it a time and space trial. A tabulation of the work was devised, and after the data had been entered, we did the work required to determine the latitudes and longitudes of over fifty points on one of our loci. We used five place logarithms, but worked only to the nearest fourth place of the numerical values. The area of paper covered measures 61 by 40 cm, but the long dimension includes the width of two colums of tabulation text. The space occupied by determining the latitudes and longitudes of a pair of points measures 40 cm by 19mm. A single point requires about 30 cm by 19 mm. The time consumed in covering the 61 by 40 area was about four hours.

This time requirement is a very generous upper limit. The use of more extensive tables would widen the columns proportionately, but would not increase the time proportionately, and, an expert computer would also shorten the columns.

Incidentally this trial was to give some evidence about the particularly wild V—H=40 seconds locus. Three-fourths of our points measured up into comforting nearness to that deformed cripple. The other fourth failed to make connection, because they belonged to the neighborhood of the pole, and the extent of our numerical basis was too slight to determine points in that high latitude.

A previous trial, undertaken for the purpose of getting the tabulation into manageable shape, was carried out on the HP bisecting circle. All the points (20 seconds intervals) were taken to the limit of the paper employed. The most distant points reached were at 6 minutes transfer time distances from the two stations. Every one of the 26 or 28 locations obtained fitted squarely on the locus, though the same tables mentioned above were employed.

A still earlier trial, instituted for the special purpose of testing position and shape of H—P=1 minute, gave an even more reassuring result. In that trial the nearest fifth place of the numerical values was aimed at. Distances from the stations were selected almost at random, and the results of the computation were compared with the locus, already drawn in ink on the chart. The following table gives the computed latitudes and longitudes, on the north and south branches respectively of this locus, under the pertinent transfer times to Hamburg.

Transfer time to H.	460s	480s	500s	720s	780 seconds
North Branch Lat.	88°	86°	84°	46.5°	37°
North Branch Long.	145°	171.5°	168°	171.75°	167°
South Branch Lat.	33.5°	31°	30.5°	8.5°	3.75°
South Branch Long.	56°	58°	61.25°	89.75°	101.75°

The locus is on our European chart, and the coordinates may be compared with it. Only two of the points fail to register closely with the locus as drawn, namely the point in Lat. 88° and one of the last two points on the south branch. The numerical values employed in this work could not give a definite location so near the pole, and even the nice fit of the point at Lat. 86° may be more or less accidental. The failure on the south branch may be due to a miscalculation, but it is more likely that an outstanding point did not get sufficient consideration in drawing the locus in this neighborhood. The three sets of results seem to give a satisfactory reply to the suspicions frequently expressed in these pages as to the reliability of the method of plotting we employed.

And now we must attempt a short discussion of our formulæ from another point of view. In Sect. 4 we stated that, if two of our loci intersected they would do so in pairs of points, and then some locus of the third set would pass through all these points of intersection. This may not be self evident, and a thoroughgoing discussion of the matter is too complex an undertaking, so long as the prospects

of our scheme are so doubtful. Something in that direction must be undertaken, if an intelligible account of our charts is to be presented.

Our formulæ are derived from the equations of two cones, namely (4) and (6) of Sect. 12. An equation of similar form will give the cone about a third station. Our formulæ are derived from (4) and (6) by using those equations as simultaneous equations. The same equations can be so used in another way, and will then give an equation of the WE loci, having the general form:

$$Auv+Bu+Cv+D=0$$

In this equation u is the sine of the latitude and v the tangent of the longitude of the tracing point. A and B are constants for the stations selected. C and D are functions of the distances of the tracing point from the same two stations.

Let Q be the third station. Then combining the cone about Q, first with (4) and then with (6) will give the equations of the loci QW and QE respectively, and each will be of exactly the same form as the one given above. Anyone of these three equations can, of course, be derived from the other two. Hence, any solution, derived from any two of them must be a similar solution of the third. It would be impossible to plot the loci from these equations, because each of them contains four variables. The same fact explains why an equation of so pronounced a hyperbolic form does not plot as a hyperbola.

If we disregard, for the moment, the variable distances involved in the coefficients, symbolised by C and D, then each of the equations involves only two variables, namely the latitude and longitude of the point which traces the locus. Select one locus from each of two of these sets, but so situated that they will intersect. This involves the condition that only such variable distances shall enter the coefficients C and D, as are determined by points on the particular loci selected. Solving these two equations, so modified, as simultaneous equations, must give us the latitudes and longitudes of their points of intersection. This can be done most readily by solving each equation for u, and equating the values of u so obtained. The result is an equation of the second degree in v. Under the stringent conditions of the problem each of these values of v can refer only to the longitude of a single point. Hence, so far it would seem that the two loci can intersect in but two points, since a single longitude value means a single value of the corresponding latitude.

But we encounter first of all the fact that the two longitude values are presented in terms of the same symbols of the distances of the points. It may be that one of these solutions gives an impossible value of the sine. For several reasons the following seems to us the correct explanation.

The only law we have imposed on these distance symbols, so far, is that they must be only such distances as apply to points on the loci selected. Hence each of the points obtained in the solution will require its own set of the three distances.

Suppose the set of distances, determined by one of these points, and select that locus of the third set, which will pass through that point. That determines the time-difference of this locus, and so identifies the locus required. Using this equation with the equation of either of the intersecting loci, must give as one solution the point, by means of which the third equation was selected. But the second point of intersection involves distances, which correspond to the time-difference of this third locus. Hence, if it passes through one of the two intersections, it must also pass through the other.

From the manner, in which our loci were plotted, there should be a number of such double triplets of intersection. After two sets of loci have been drawn, and after all their points of intersection are clearly marked, it would not be difficult to name the third locus, which must pass through any pair of such intersections. But the only feasible proceeding is to draw the third set of loci. They will mark out the intersections. Our third sets—all of them—were drawn in just that way. They were plotted in, without any reference to existing intersections. All the charts show numbers of pairs of close triplets. Towards the limits of the charts the "triangle of error", to be expected, becomes rather evident, but, all in all, these triple intersections approve the consistency of the work to a very satisfactory extent, at least compared to the accuracy we expected.

But we meet with another trouble on the chart, when two loci run close together for long distances, intersect time and again, no third locus follows their lead, and our second degree equation, leaves room for only two intersections. Our second degree equation shows only that the uncontrollable distances determine the number of intersections of the two loci. That the intersections must come in pairs is due to the ovoid shape of our loci. Two regular ovals can intersect in four points. It may be that the second degree equation also indicates that one of these expected pairs of intersection is in abeyance in the case of our loci. This is no demonstration, but a conclusion, suggested, and seemingly borne out by a study of the position, size and form of our loci. The intersections of rambling loci are not of this regularly expected kind.

As a matter of fact two loci, each of a different set, often run long distances, in quite close proximity to each other. Taking any two close parts of such loci it will be readily seen that one is distinctly further from its base than the other, that one, therefore, is subject to a variety of kinking, which the other meets with somewhere else. Hence it seems quite necessary that they kink into each other here and there. The uniqueness of our solution of the second degree equation is then only apparent, and the source of the discrepancy is to be found in those varying distances, which cannot be eliminated from these equations. But if we find one such intersection, then there must be another. They must come in pairs. The dependence of the equation of the third locus on the two intersecting ones demands also that the same previous locus of the third set pass through both these new intersections. If all available loci had been drawn on our charts, all intersections would have been triple ones. Of course, a proceeding like the one just presented is hardly mathematical. It is partly based on unmanageable equations, partly on inspection of diagrams. If anything should come of our work, then a more rigid investigation may be worth while. Meanwhile this may serve as a temporary attempt at explanation. But, whatever value these surmises may have or not have, it is demonstrably certain that if two of our loci intersect at all, then they intersect in one or more pairs of points, and through all such intersections the same locus of the third set passes.

10. PROCESS OF LOCATING AN EPICENTER.

The first proceeding we suggest is based on the fact specified in the concluding sentence of the preceding section. We rely on the arrival times of the P tremors, to locate an earthquake.* If those times are not consistent, then a location of an epicenter by means of them is impossible. The principle, on which we tried to laud the consistency of our chart, serves also to test the consistency of these arrival times. Only in their case the demonstration is easy and peremptory.

As stated, the cones, with which our mathematical study begins, can be used to produce equations of our loci of the general form

$$Auv+Bu+Cv+D=0$$

Using the three cones pairwise gives three of these equations. We could do so little with them before, because they had so many irremovable variables. Now, when the three chart stations report the P tremors of an earthquake, these variables are ipso facto fixed. It happens thus. (To be definite, we must keep to the epicentral "point".) The epicenter is definitely somewhere. Therefore it is at a very definite distance from each of the three stations, and hence

*The arrival times of P tremors are taken from the Shide Bulletins. See Note 4.

the transfer times to the three stations are very strictly determined. The actual distances do not appear on the face of the returns of the P arrival times. But the P arrival times indicate the locus of each set, on which the epicenter is to be sought. These three loci intersect mutually in two points at least, and these two points are determined by the simultaneous solution of the three equations, of the above form —or they appear as actual intersections on our chart, or as interpolated locations. Now suppose that two of the stations report the arrival time correctly, but the third is distinctly late. Such a time record or report would mean an epicenter at a distance greater than the true one. This would promptly introduce arbitrary changes in the constants C and D of two of the three equations—and the chances are slim that the three equations will then be simultaneously satisfied. In the case of our chart, the effect will be that the epicenter is referred to two wrong loci, each further away from the station with the false report, whilst the two stations with the correct report, keep the epicenter on the locus where it belongs. The three loci so assigned will not show pairs of triple interesections.

The same principle can be used with the same or even a better effect, if the epicenter is to be located by means of the S—P from three stations. The S—P is the actual distance from the station, which presents it, to the epicenter it should refer to. These actual distances enter into the coefficients C and D of the equations. If they are entered, and the three equations solved, the triangle of error will show an inadmissible magnitude, if one or other of the S—P values is greatly in error.

Theoretically this imports that the consistency of the (S—P)s, reported by any three stations whatever, can be tested by means of a single third order determinant placed equal to 0. In practice, the coefficients may deter one from a trial. Solved in this manner, and supposing correct distances, only one set of coordinates results.

Supposing the arrival times known correctly, the process of locating an epicenter on our chart, is merely one of tracing lines in that labyrinth. The differences of the arrival times will specify one locus of each set. One of the time-differences, it is hoped, is somewhere near the designation of a locus on the chart. If a locus with small time-difference, its frayed ends will be found somewhere on the outer limits of the chart. Find both its ends, and place a marker on them. Then find the next easiest locus to follow. Follow up both, until points of intersection are reached. Mark all such points of intersection.

As a rule, none of the time-differences obtained will refer to a locus, actually on the chart. In that case, the two loci, nearest to the epicenter are followed, until a rough interpolation shows that the neighborhood of the point sought is reached. Mark the neighborhood. The third locus, tracked into the same vicinity may then settle the matter, as we shall show in a few examples in the next section.

Again, one of only two sets of triple intersections may be off the chart, or so very far away as not to come into consideration. Then the near epicenter of a pair is probably the one sought.

If all intersections are near the stations, then anyone of them may be the point sought.

In that case a second chart, covering the same region, but having at least one of its three stations different from the set employed in the first chart will determine which is the point sought.

Should that third chart not be in existence, then one of the three chart stations at least, should be able to produce an S—P of some value. Even a roughly accurate value of that datum should enable one to pick out which of such points should be called the epicenter. The idea of earthquake regions may also be invoked, though what certainty can be claimed for that proceeding we are unable to specify.

In the succeeding section we shall try to apply these principles to some earthquakes, for which we have arrival times available. Should the process commend itself as in any way helpful or useful, we shall consider our labor as amply rewarded.

11. LOCATION OF SOME EPICENTERS.

Locations are given in just the order, in which we made them.

1. March 24, 1913.

Reported	at Hamburg	10h 42.4m	Hence	P—V=0.1 minute
	at Vienna	10h 41.3m		H—P=1.0 "
	at Pulkowa	10h 41.4m		H—V=1.1 "

Ends of H—P=1, found in Longs. 120 and 160; of V—P=0, in Longs. 255 and 80.

These two loci do not intersect. They run close to each other for quite a distance. Near Long. 40, Lat. 45. P—V=0.1 minute, is on the V side of the bisector, hence still further away from H—P=1. Our times are given only to the nearest tenth of a minute. Hence .4m may be anything from 21 to 27 seconds, .3m, anything from 15 to 21 seconds. If the precise times were available, the loci they would indicate would intersect. However, place a marker in that parallel region, and find third locus. Small oval, H—V=1 pushes one little corner accross the PV bisector in just the parallel region marked. The third locus, H—V=1.1 is inside the oval, but near the line on the chart.

The location of epicenter, suggested by the three loci is very evidently the immediate neighborhood of Long. 39°, Lat. 44°.

The three loci diverge rapidly from that region, hence epicenter must be just there. The region is near the western end of the Caucasus Mts.

2. March 3, 1913.

Reported at Hamburg	20h 14.3m	Hence	V—H=1.0	minute
at Vienna	20h 15.3m		V—P=2.2	"
at Pulkowa	20h 13.1m		H—P=1.2	"

Ends of H—P=1 in Longs. 120 and 160; of V—H=1; small oval, between Longs. 315 and 20, and between Lats. 50 and 75. H—P=1.2 is inside H—P=1. Hence it would intersect H—P=1 not far from extreme kink in Long. 18°, Lat. 68°.

V—P=2 forms triple intersections with V—H=1. V—P=2.2 is inside V—P=2. Hence indicates same as other two loci. Epicenter is near Long. 18°, Lat. 68°.

Rapid divergence of three loci permits no other location. Large time differences, for the stations in question indicate nearby epicenter. The reverse of this last statement does not hold. Region, Scandinavian Mts. near n. w. corner of Sweden.

3. March 27, 1913.

Hamburg reports	3h 21m	Hence	H—V=0.7m.
Vienna	3h 20.3m		P—H=0.2m.
Pulkowa	3h 21.2m		P—V=0.9m.

Ends of P—V=1 in Longs. 305 and 30; of P—H=0 in Longs. 230 and 60.

H—V= .7 = 42 seconds. Our locus H—V=40 seconds satisfies this requirement about as well as our time data permit. This locus is named in Long. 20°, Lat. 10°, is a closed locus, and is easy to follow.

P—H=.2m = 12 seconds is midway between H—P=0 and P—H=20 seconds.

This locus would intersect P—V=40 seconds in about Long. 39° and Lat. —8°.

P-V=.9m=54 seconds is about trisector nearest P—V=1 minute of area between P—V=1m and P—V=40 seconds. Intersects H—V=40 seconds in about same point as above.

Hence one triple intersection is in Long. 39°, Lat. —8°.

Region, near e. coast Africa, south of Monfia Is.

Same three loci have common intersection in about Long. 23°, Lat. 51°.

Region, near n. e. corner Hungary.

No other intersections of these loci possible. A second chart would easily decide which of these two points is the epicenter. Even one S—P, at all reliable, would also decide the matter.

Service of third locus is shown well in case of southern point. H—V=40 seconds is cut almost normally by other two loci, and the latter run parallel courses through region. More loci in southern region would render location easy and certain.

4. March 31, 1913.

Hamburg reports	3h 52.8m	Hence	V—H = .5m
Vienna	3h 53.3m		H—P = .9m
Pulkowa	3h 51.9m		V—P = 1.4m

One triple intersection can be made out with comparative ease in about Long. 24° and Lat. 57°. Region, well within station triangle.

The other intersection is difficult to locate. Somehow our "exercises" came to us in "graded" order, without any attempt on our part to make them so.

V—H=20 seconds ends in Longs. 180 and 290.

V—H=40 seconds, is closed, named in Long. 215, Lat. 65.

V—H=.5m = 30 seconds is midway between the two loci just named.

H—P=.9m = 54 seconds is trisector, nearest H—P=1m of area between H—P=1m and H—P= 40 seconds.

This locus would seem to intersect V—H=30 seconds in about Long. 180° and between Latitudes 47° and 57°.

V—P=1.4m = 1m 24 seconds. If our locus V—P=1m 20 seconds had been drawn, it would determine the intersection quite definitely. It certainly passes through the region specified above. If we accept the location named: Long. 180° Lat. between 47° and 57°, we would include the region named rather indefinitely by several locators as "Aleutian Isds."

These attempts at location seem to indicate the following

RULE, for loci to be drawn on chart.

1. All whole minute difference loci should be drawn entire.
2. The 20 and 40 seconds difference loci should begin near the station triangle, and should be continued thence to the limits of the chart.
3. The intermediate, 10 seconds difference loci should begin further out from the station triangle than the loci mentioned in 2.
4. 5 seconds difference loci would be very convenient near the limits of the chart.
5. Loci referring to smaller time-differences would be useless, so long as the ± 1 seconds error of the arrival times must be reckoned with.
6. The loci, specified in 4 certainly, and probably those specified

in 3 could be interpolated by the method suggested at the conclusion of our second paper.

There are two more things we wish to illustrate. We did not select the order, in which the earthquakes, located above, were studied. We did reject, though, several, whose time returns were impossible, on the face of the reports. For instance:

5. March 18, 1913.

Hamburg reports 1h 54m.
Vienna 1h 31.4m H—P=15m
Pulkowa 1h 29m H—V=12m and more, quite impossible.

Same trouble, only less pronounced on March 23, 1913.

6. Sept. 17, 1911.

Berkeley reports 3h 35m 21s Hence S—B=5m.
St. Louis 3h 40m 23s S—O=3m.
Ottawa 3h 37m 23s O—B=2m.

All these loci are possible.
S—B=5m, small oval about B. Not on chart.
S—O=3m, small oval about O. Not on chart.
O—B=2m, almost bisects line Berkeley Ottawa.

From the data, as given in 5 and 6, it is impossible to decide which station made the return to which the trouble is due. A second chart, or rather, a set of second charts, would decide that matter.

7. One example of the use of a second chart.

Oct. 6, 1911.

Berkeley reports 10h 24m 55s Hence B—S=3m 2s
St. Louis 10h 21m 53s B—O=3m 4s
Ottawa 10h 21m 51s S—O=0m 2s

We can afford to neglect the odd seconds.

The three loci determined on our chart, by such omission, form two "triangles of error", one with its center in about Long. 290, Lat. 18; the other in about Long. 270, Lat. 48.

For the same earthquake, New Orleans reports 10h 20m.

O—N=1m 51s, is midway between O—N=2m and O—N=1m40s, both on the St. Louis-New Orleans-Ottawa chart. Both the loci mentioned are close together in the immediate neighborhood of the southern of the two points, located on the other American chart, whilst the same loci are nowhere near the northern point. This decides the case in favor of the southern point.

Location Haiti.

SECOND PAPER.

12. THE FORMULAE AND DEFINITIONS OF THEIR SYMBOLS.

Assume a spherical earth (Fig. 2). Through center O pass three axes: ON, passing through north pole of earth, OB, through intersection of Greenwich meridian with equator, and OQ cutting equator 90° east of B. Number longitudes from Greenwich eastward to 360°.

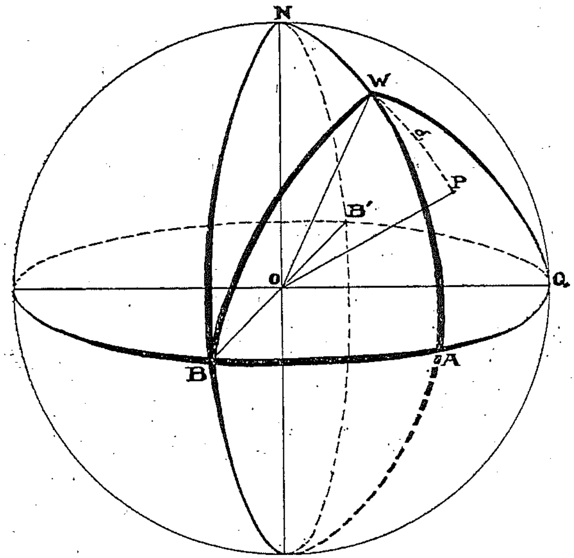

Fig. 2

A point, W, fixed in ϕ_1, λ_1, (AW, BA), is fixed with reference to the axes by the three position angles: α_1=WOQ, β_1=WOB and γ_1=WON.

From right triangles WAQ, and WAB, we get, by "Napier's Rules":

For W, fixed in ϕ_1, λ_1, and for E, fixed in ϕ_2, λ_2,

$$\begin{aligned} \cos\alpha_1 &= \cos\phi_1 \sin\lambda_1 = l_1 & \cos\alpha_2 &= \cos\phi_2 \sin\lambda_2 = l_2 \\ \cos\beta_1 &= \cos\phi_1 \cos\lambda_1 = m_1 & \cos\beta_2 &= \cos\phi_2 \cos\lambda_2 = m_2 \quad (1) \\ \text{also } \cos\gamma_1 &= \sin\phi_1 = n_1 & \text{and } \cos\gamma_2 &= \sin\phi_2 = n_2 \end{aligned}$$

The point E is not shown in the figure. The relations for E follow from those for W, since the latter hold for any point on the globe.

Hence also for a point, P, in ϕ, λ, and with position angles α, β, γ,

$$\cos\alpha = \cos\phi \sin\lambda = x$$
$$\cos\beta = \cos\phi \cos\lambda = y \qquad (2)$$
$$\text{and } \cos\gamma = \sin\phi.$$

Radii WO and PO form angle WOP=δ_1. Let $\cos\delta_1 = z_1$ (3)

Then angle WOP is determined by the relation:

$$\cos\delta_1 = \cos\alpha \cos\alpha_1 + \cos\beta \cos\beta_1 + \cos\gamma \cos\gamma_1,$$

or, replacing these terms by their symbols from (1), (2) and (3)

$$z_1 = l_1x + m_1y + n_1 \sin\phi. \qquad (4)$$

If we impose on radius OP no condition except (3), then will (4) be the equation of a right circular cone, with vertex at O and axis OW. This conical surface will cut the spherical surface in a circle, whose pole is W.

With radius OE, of station E, a second radius OP, for whose position cosines we adopt the values and symbols of (2), makes the angle EOP=δ_2. Let $\cos\delta_2 = z_2$. (5)

Then will this second OP describe about axis OE the right circular cone

$$z_2 = l_2x + m_2y + n_2 \sin\phi. \qquad (6)$$

Now impose on δ_1 and δ_2, or, what comes to the same thing, on the arcs WP and EP, respectively, the law of growth, detailed in Sect. 7, Third. The intersections of the two cones (4) and (6) will then trace on the spherical surface one of the Time-Difference loci, of the set WE. For the coincident elements of the intersecting conical surfaces, the x, y and ϕ of (4) and (6) will have identical values.

Regarding (4) and (6) as simultaneous equations, we readily get:

$$x = \frac{m_2z_1 - m_1z_2 - (m_2n_1 - m_1n_2) \sin\phi}{m_2l_1 - m_1l_2} = \frac{M - N \sin\phi}{L} \qquad (7)$$

$$y = \frac{l_2z_1 - l_1z_2 - (l_2n_1 - l_1n_2) \sin\phi}{l_2m_1 - l_1m_2} = \frac{M' - N' \sin\phi}{-L} \qquad (8)$$

Next we obtain from (2): $x^2 + y^2 = \cos^2\phi$ (9)
and $x/y = \tan\lambda$ (10)

Combining (7) and (8) by (9), gives a simple second degree equation, with $\sin\phi$ as the sole variable, and this gives a solution of the form:

$$\sin\phi = \frac{A \pm [L^2(D-B) - C^2]^{\frac{1}{2}}}{D} \qquad (11)$$

For every value of $\sin\phi$, so determined, (7) and (8) by (10) give

$$\tan\lambda = -\frac{M - N\sin\phi}{M' - N'\sin\phi} \qquad (12)$$

From (2), (3) and (5) and the note following (6), it will be clear that the ϕ and λ, obtained in (11) and (12) are the geographical coordinates of points on that time-difference locus of the set WE, whose time-difference is the difference of the times, proper to the two deltas selected.

13. LOCATING AN EPICENTER BY MEANS OF A TIME-DIFFERENCE CHART AND THE S-P OF TWO STATIONS.

From (11) it is evident that A/D is the mean of the latitude sines of two points, each of which is at the distance δ_1 from W and δ_2 from E. Both the points are situated on the W side or on the E side of the great circle W—E=0, according as $\delta_2 - \delta_1$ is greater or less than 0. If we represent the radical by R, then will (A+R)/D be the latitude sine of the point on the north pole side of the great circle through W and E, and (A—R)/D will be the latitude sine of the point on the other side of the same great circle. This azimuth requirement can evidently be obtained from even a very rough Time-Difference Chart.

If the stations, from which the S-P values are obtained are both chart stations, there is no further difficulty. Otherwise a chart can be readily improvised for them, by roughly locating on a terrestrial globe the great circle through the stations, and the great circle bisecting the arc connecting the two stations. The former great circle will then decide, which sign of the radical is to be employed. This determined, the S-P of the two stations will be the two deltas of (3) and (5) respectively, and by means of them and the constants of the two stations, the terms of (11) and (12) can be produced readily.

The first paragraph of this section secures a single-valued sine of the latitude, and hence the latitude is determined unequivocally.

In case a series of points is determined, say with a view to constructing one of the loci of a Time-Difference Chart, the sequence of the longitudes would decide the matter of quadrants. When a single point is to be located, the longitude may be doubtful, so long as the matter is dealt with in this very general way. A few working directions will simplify the work considerably, and remove this difficulty as well.

14. SIMPLIFICATIONS FOR THE PURPOSE OF WORK.

The zero of longitudes is arbitrary, and for the purposes of this computation may be assumed anywhere.

Hence, proceed as follows:

Make no change whatever in the definitions and formulæ of section 12.

For W take the Western of the two stations, and for E take the Eastern station. These two letters were selected for that particular purpose. All the symbols with subscript 1 belong to the W camp, those with subscript 2 belong to the E camp.

Make the meridan of W the zero meridian, for the purpose of this work only.

This is done very simply by USING different values for λ_1 and λ_2. Namely, instead of λ_1, USE $\lambda'_1=0$, and instead of λ_2 USE $\lambda'_2=\lambda_2-\lambda_1$. When the work is done according to the formulæ, add to the longitude obtained the longitude of W, or if that should give a sum with a negative sign, add 360° more.

The longitude so obtained will be unambiguous, as a rule. Only, if the epicenter is in a very high latitude, it might be doubtful, whether a positive tangent longitude indicates the first or third quadrant, or whether a negative tangent indicates the second or fourth quadrant. A Time-Difference Chart may then decide the matter.

A brief outline of the numerical work may tempt some kindly disposed critic to give the formulæ an actual trial. The symbols of (1) are constants for their respective stations. Hence L, N and N′ of (7), (8), (11) and (12), and therefore D ($=L^2+N^2+N'^2$) of (11) are constants for any pair of stations. Hence, for any pair of stations prepare logs of m_2, m_1, l_2, N, N′ and L^2, also D and its colog. Dispose these eight constants (computer fashion) about the edges of a card. M and M′ are determined by means of the first three of these constants and the cosines of the two deltas. Then $A=MN+M'N'$; $B=M^2+M'^2$ and $C=MN'-M'N$. The rest of the work is marked out unmistakably in (11) and (12).

Formula (11) indicates just how far the results are reliable. If the nth place in the value of D is certain, and if that value contains q significant figures, then the qth place of the sine latitude obtained is fairly certain, provided the nth place in A+R is certain. But to secure certainty about the nth place of A+R, several more places under the radical must be made certain. From the character of the operations required it is evident that if the work is based on an m-place table of sine functions (natural), then the mth place of the first derived result may be in error by ±1, or nearly that. Any figures beyond the mth place are not even ornamental, they are simply deceptive.

This very clear cut program is very satisfactory if known accuracy is the sole result aimed at. Any degree of precision may be secured by employing tables of the requisite amplitude. The usefulness of the formulæ ceases just where the precision aimed at ceases to warrant the extent of the work required.

The critical item is the value of D. It is always greater than zero, but its possible maximum does not seem to exceed .5 by much In general D increases as the latitudes decrease, though this rule seems to reverse near the equator. Again, D increases as the longitude difference of the two stations approaches 45°. For the short Hamburg-Vienna base, in a rather high latitude besides, D is not much greater than .01; for the St. Louis-Ottawa base it is more than .04; for the splendid Berkeley-Ottawa base it is more than .33. For two stations on the equator, and 45° apart D=.5 exactly.

The purpose of this last section is to simplify the work demanded by our formulæ. If the work is undertaken for the purpose considered in the preceding section, no more can be added now. If the work should be undertaken for the sake of computing a Chart, a further simplification suggests itself, which would supply besides a stringent test of the accuracy of the work, and also supply means for interpolating loci among those calculated.

This proposed simplification contemplates the computation, in one operation, of all the points at the same distance from the W station (instead of all the points on the same locus.) Here a number of other terms would become constant for just that operation, namely: m_2z_1, l_2z_1, and therefore M′, M′N′, M'^2, M′N, would all be constant for any single operation. All these could be computed together as a preliminary to the work for the set, and then, for any operation, the pertinent constants could be "carded". This would shorten the columns very decidedly, in the first place. Then, plotting the points, derived from any single operation on a globe, should dispose them all on a circle, with W as pole. On the chart, therefore, they should lie on some sort of a battered ellipse, which would, however, be sufficiently regular to indicate instantly any delinquent calculation. No amount of "kinking" could interfere with such a reminiscence of an ellipse.

Suppose the calculated points measure up to the proper ellipse. Then, the latitudes, first, and the longitudes next, will be disposed in a sequence of numbers, which should show sufficient serial regularity to admit of a definitely determined interpolation. And herewith we must leave our work to its own devices.

Seismology and the Seismograph.*

Seismology, as we know it today, is the Benjamin of the Sciences. It has grown up within our memory. Fifty years ago it was believed that earthquakes were caused by explosions within a cavity in the earth's crust called the focus or centrum, and that the energy of these explosions travelled outward in straight lines as earthquake shocks which were soon dissipated.

In accordance with this theory Robert Mallet was commissioned by the Royal Society of Great Britain to determine the position and depth of the supposed cavity in the case of the great Italian earthquake of 1857. This he tried to do by establishing the normals to the fissure planes in the walls of damaged buildings and noting the directions in which debris had been thrown. These lines, he argued, should give the direction of propagation of the shock and should all intersect at the centrum.

Mallet's exhaustive report† was more than satisfactory to his own contemporaries, though it actually contains enough material to refute the centrum theory completely. Mallet did another great service to science. He introduced a number of needed terms which are still in use. The point on the earth's surface immediately above the focal cavity or centrum he called epicenter or epicentrum. The region about this point within which the shocks were most violent and destructive he called the meizoseismal area. About the epicenter he drew a system of closed curves; each curve passing through all places which suffered shocks of a given intensity. These lines of equal intensity, he called isoseisms or isoseismal lines after the manner of isotherms and isobars on the weather map.

The centrum or semi-volcanic theory of earthquakes accepted in Mallet's time was substantially that advanced by Artistotle 2000 years before, and it was given a new lease of life in 1872 by Prof. von Seebach‡ in his studies on the Central German Earthquake of that year. But in the same year the first bomb was thrown into the centrum camp. In his work on the Calabrian and Austrian series of earthquakes, the great Viennese geologist Prof. Suess§ showed conclusively that the epicenters of all the destructive earthquakes of both regions

*A lecture delivered before the Academy of Science, of St. Louis, Mo., by Prof. J. B. Macelwane, S. J., Professor of Physics in the St. Louis University.

†Robert Mallet, *The Neapolitan Earthquake of* 1857. 2 vols., London 1862.

‡K. von Seebach, *Das mitteldeutsche Erdbeben von 6 Marz* 1872. Leipsic, 1873.

§Edward Suess, Die Erdbeben des suedlichen Italien. *Denkschr. d. K-k. Akad. d. Wissensch. z. Wien; Math.-nathurw. Kl.*, vol. xxxiv, 1872, pp. 1-32, 3 pls. Die Erbeben Niederosterreichs, *ibid.*, vol. xxxiii, 1873, pp. 1-38, maps.

were ranged upon straight lines which marked the position of geological fault planes in the crust. Hence he divided earthquakes into two classes, tectonic quakes due to the slipping of vast masses or blocks of the earth's crust upon one another, and volcanic quakes or the minor, local shocks which accompany volcanic eruptions. The more earthquakes were studied the more evident did it become that Prof. Suess' classification was correct.

To illustrate the manner in which this readjustment of the earth's crust along fault planes takes place, Prof. Hobbs* has devised an experiment with blocks, to represent the blocks into which the earth's crust is divided.

A long rectangular tank or trough has one side of heavy plate glass which permits us to see what takes place within the tank. Across the trough near one end is a loosely fitting false end which is hinged to the bottom of the tank. An iron rod is so fitted through the false end and the opposite fixed end that objects fitting loosely between the two may be compressed as in a vise by tightening the bur on the rod. The tank is partly filled with water and a set of wooden blocks of varying lengths are floated loosely between. If the blocks are pushed down with a board until their tops are even and the bur is then tightened, they will be held in position by lateral pressure. This position is supposed to represent the unstable condition of the blocks of the earth's crust before an earthquake. There is a tension at many of the planes between the blocks and it is only the lateral pressure which prevents slipping. If this lateral pressure is slowly relieved by unscrewing the nut which holds the hinged end, there will come a time when readjustment will take place. The deeper blocks will slide upward and the shallower blocks will slide downward. This readjustment is what is conceived to take place in an earthquake. The illustration is, however, incomplete. Such blocks are far more rigid under the small stresses to which they are subjected than the earth blocks could possibly be under their stresses. A state of elastic strain is set up along the fault plane which causes a corresponding rebound when the rock gives way. This is aptly illustrated by an experiment of Prof. Reid.†

A sheet of gelatine three inches long, two inches wide and one-half inch thick was set between two small blocks of wood. A straight line, AC was drawn in ink on the jelly. The jelly was cut along the line tt′ and pressed together while the block on the left was shifted upward one-half inch. This sheared the jelly and the line AC took up the slanting position seen dotted in Fig. 4 On reliev-

*William H. Hobbs, *Earthquakes*, New York, 1907.

†Harry Fielding Reid, The Elastic-Rebound Theory. *Univ. of Cal. Publ., Bull. of the Dept. of Geol.*, vol. 6, No. 19, pp. 413-444' Berkeley, 1911.

ing the side pressure so that the friction could no longer keep the jelly in its strained position, the two sides slipped along the plane tt′ and the line AC broke into the two lines AB and DC. The distance between D and B being the distance the left block was originally shifted. A second experiment consisted in drawing a straight line A′C′ while the jelly was under strain. When the slip took place the line separated into the two parts A′B′ and D′C′, the distance D′B′ being the original displacement of the left side block. A third experiment was this: The left block was shifted one-half inch, thus straining the jelly. Then the straight line A′C′ was drawn upon it as before and the block shifted a quarter inch further, thus causing the line to take the position A″C′. When the slip took place along the line tt′ the line separated into the parts A″B″ and D″C′. In this last experiment notice that the total slip at the fracture was the sum of the two displacements of the left block; that the movement gradually decreases to zero at C′ on the right side of the fracture, while on the left it never becomes less than A′A″ the motion of the left block after A′C′ was drawn.

This experiment illustrates very well what took place in the California earthquake. This region has been surveyed three times by the U. S. Coast and Geodetic Survey; once between 1851 and 1866, again between 1874 and 1892, and a third time after the last earthquake in 1906-7. In 1868, between the first and second surveys, a severe earthquake is known to have occurred in this region. Now the report of the U. S. Coast and Geodetic Survey for 1907 furnished us with the following facts: During the quake of 1868, or about that time, over 1000 sq. mi. of the earth's crust between Mt. Tamalpais, Farallon Light House, Ross Mt. and probably Sonoma Mt. moved northward as a block, a distance of about five feet. Mt. Diablo was not on this block and did not move. After this displacement, let us imagine a straight line drawn on the earth from Mt. Diablo to Farallon Light House, for the position of this line was actually determined by triangulation with a line from Mt. Tamalpais to Sierra Morena as a base. The survey of 1906-7 shows a further displacement of the Farallon Light House, after our imaginary Mt. Diablo-Farallon line was drawn, of about six feet to the northwest. Now what took place during the earthquake of 1906? Every road, every fence or row of trees that cross the fault shows a relative displacement parallel to the fault of from 7 to 21 ft., or about ten feet on the average for a distance of 185 miles. Regarding the absolute motion at any distance from the fault, the U. S. Survey officials, Hayford and Baldwin*, have deduced the following four characteristics or laws (pages 81, 82). "First: Points on opposite sides of the fault moved in opposite directions, those to the eastward of the fault in a southerly direction, and those to the westward in a northerly direction. Secondly: The displacements of all points were approximately parallel to the fault. Thirdly: The displacements on each side of the fault were less the greater the distance of the displaced points from the fault. Fourthly: For points on opposite sides of the fault and at the same distance from it, those on the western side were displaced on an average about twice as much as those on the eastern side." Mt. Diablo, 33 miles east of the fault line, did not move. In fact no displacement could be detected with certainty at a distance greater than four miles east of the fault. Farallon Light House, 23 mi. west of the fault, moved about 6 ft. and the displacements of all points west of the fault apparently became equal to this amount at a distance of 6 to 10 mi. from the fault line. The total combined displacement of Farallon Light House for 1868 and 1906 was about 10 ft. The average relative displacement of points immediately adjoining the fault line on opposite sides was 10 ft. Thus far there is a perfect parallel between Prof. Reid's jelly experiment and the earthquake of 1906. But there is also a difference. The lines on the jelly after the slip were straight. The two parts of our imaginary Mt. Diablo-Farallon line were curved, the eastern portion being concave southward and the western portion concave northward. This is probably due, as Prof. Reid suggests, to the fact that the elastic forces are not applied at the outside edges, as in the case of the jelly, but are distributed throughout the entire strained portion of the crust.

***John F. Hayford and A. L. Baldwin, The Earth Movements in the California Earthquake of 1906, *Rep. of the Supt. of the U. S. Coast and Good Surv.*, Append. 3, pp. 69-104. Washington, 1907.**

The rapid tearing of a rift in the earth for a distance of over 200 mi. and a sudden slip of 7 to 20 feet would naturally cause a series of gigantic vibrations or waves in the solid earth. Such waves had often been seen, but it was thought that they were merely local phenomena associated with the meizoseimal area and never travelled to any distance. But a new era in the history of earthquake science was ushered in ,when in 1894, Prof. von Rebeur-Paschwitz noticed that his delicate pendulums were disturbed by earthquakes on the other side of the planet. This discovery marked the birth of the New Seismology. It was now possible, by suitably designed instruments, to observe earthquakes occurring anywhere on the globe. It is true that instruments had been used before, in regions of frequent earthquakes, to record the exact time at which a shock began. Such for instance, was the Chinese Seismoscope built by Chi-o-cho in the year 136 B. C. Inside a brass globe was suspended a pendulum. On the outside of the globe were eight dragons' heads, corresponding to the four cardinal points and four intermediate directions of the compass. In the throat of each was a ball which would be set in motion by any movement of the pendulum in that direction and would roll down and fall into the upturned, open mouth of a frog sitting below, thus indicating the direction of the shock. But such instruments were useless outside of the area affected by the shock and besides, told little of the nature of the motion. Prof. von Rebeur-Paschwitz' discovery, on the other hand, led immediately to the construction of the far more useful seismographs, which were to spread and increase in number until in 1912 there were 265 seismograph stations scattered over the globe.* Of the various countries Italy leads with 41 stations, the United States and the British Empire are next, each with 33 stations; then come Japan with 27, Germany with 25, Russia with 23 and Austria-Hungary with 18. The other 65 are scattered over 24 different countries.

The seismographs in use at these various stations may be divided into two general classes; the double horizontal and the single vertical pendulums. To the first class belong the von Rebeur-Ehlert, Milne, Omori, Mainka, and Galitzin types, and to the second the Vicentini, Agamennone, O'Leary and Wiechert types. The inverted types of the verticals such as the O'Leary and Wiechert, all depend on the action of springs, and are really intermediate between the horizontal and true vertical.

All of the horizontal pendulum seismographs require two separate instruments, one for each of the components, N-S and E-W. The object in using a horizontal pendulum instead of a vertical one is to lessen the effective component of gravity and thus to increase the period of vibration without unduly lengthening the pendulum itself. For if a horizontal pendulum with a period of 10 sec. were to be replaced by an ordinary vertical one with the same period, that vertical pendulum would have to be 81 ft. long. Still 10 seconds is not, by any means, a long period for a seismograph.

Seismographs in which the pendulum is vertical are either inverted or not. Examples of the latter class are the Agamennone and Vicentini. These seismographs are a compromise between length and period.

The O'Leary seismograph consists essentially of a heavy weight surmounting a long stem, supported in an upright position by a system of three steel wires attached firmly to a collar which surrounds the well in which the pendulum rests. The upright stands directly in the vertical and the restoring force which causes it to vibrate as a pendulum depends on the fact that the elastic stress in the wire increases faster than the effective component of gravity.

Siegmund Szirtes, Geographische Koordinaten der seismischen Stationen nebst Hilfstabellen.** ***G. Gerlands Beitr. z. Geophys., **XI. Band, 2./4. Heft. Leipzig, 1912.**

The Wiechert seismographs also contain an inverted pendulum. But the pendulum is not vertical. It is tilted just out of the vertical and is supported by delicate springs.

Now we come to the seismograph we have here in St. Louis. It was installed in a carefully insulated vault under the administration building of the St. Louis University, October 18, 1909. The instrument rests on a concrete pier 4x4x5.8 ft. walled off from the earth around it, leaving an air space of about two inches on all sides. Let me give you a more detailed description of the mechanism. Like other Wiechert seismographs it is an inverted pendulum tilted slightly out of the vertical. This pendulum consists of a heavy mass, weighing 80 kg. or 176 lbs. poised on a stiff rod about a yard long. The lower end of this rod terminates in a frictionless, universal joint formed by a Cardanic system of thin, flat springs. When the pier on which the instrument rests is set in motion by an earthquake, the cardanic hinge at the bottom and the entire frame of the machine move with the pier while the large mass at the top tends to remain at rest on account of its inertia. Archimedes said "Give me a place to stand and I will move the earth." Here we have a place to stand and watch the earth move around us, and if we want a record of this motion all we shall have to do is attach a pen to the stationary mass and it will make a trace on the moving frame.

But the pendulum will not remain upright in this unstable position without some means of support. It must be attached to the frame, yet so that it can remain stationary when the frame moves. This is ingeniously contrived by means of two thrust rods meeting at right angles in the center of percussion.

The instrument is so placed on the pier that the right thrust rod extends southward and the left one westward. Perpendicular to each thrust rod and in the same plane is a truss-like double lever. This lever is attached at its mid-point by means of a Cardanic hinge to an upward projection of the iron frame. This is the fulcrum of the lever. On either side are arms of equal length. One arm goes to the damping device, of which we shall have occasion to speak soon. The outer end of each thrust rod is fastened to this arm a short distance from the fulcrum. The arm on the other side leads to the mechanism which governs the motion of the pens.

By means of levelling screws in the base of the instrument, the pendulum with its large mass is tilted slightly toward the N-E. The force of gravity thus obtains an effective component and tends to make the pendulum fall over completely in that direction. The mass then pulls on the thrust rods and rotates the truss-like levers, pushing on their further ends. This push is transmitted through two little telescope rods which engage with the ends of their respective levers and with two other short levers which are pushed in the opposite direction by the torsion of two spiral springs on the axis of rotation of the pens. If either force is stronger than the other, it will rotate the pens and make a mark on the paper. If the effective component of the two forces due to gravity and the spring are equal the pendulum will be in equilibrium. Now if we take care that the effective component of the spring's force always increases and decreases faster than that of gravity, we shall always have a restoring force which will tend to bring the pendulum back to the position of equilibrium. But this same restoring force will keep the pendulum vibrating harmonically when once it is set in motion. This is a disturbing factor and will spoil our record of the relative motion between the earth and the stationary mass. For the mass will no longer be stationary when the earth moves. To obviate this difficulty as far as possible the damping cylinders are introduced. They consist of an air chamber inside which a piston is so suspended by little wire stays that it can move freely to and fro without touching the sides of the cylinder. But, in moving, this piston must overcome the resistance of the air. The air is sucked in behind the piston and driven out ahead of it through two holes whose size can be regulated. The resistance thus offered becomes greater, the faster the pendulum is moving. In this it differs from ordinary mechanical friction which must always be kept at a minimum. Mechanical friction curtails each stroke of the pen by a constant amount. The air damping does not. It makes each successive stroke of the pen on the paper bear a constant ratio to the preceding. This ratio is in our case 5:1, so that, if the pendulum be set in motion and cause the pen to mark one inch long the first time, the next mark will only be one-fifth of an inch long, the next one twenty-fifth, etc., and the pendulum will soon be practically at rest.

Such a contrivance becomes the more necessary the more closely the period of the earth waves approaches the natural period of the pendulum, which is in our case 7 seconds. I have here a wire with a loop which I place over my finger. Some distance down the wire I have attached a heavy ball of metal. My hand represents the earth. The loop represents the Cardanic hinge; the upper part of the wire is the pendulum, and the ball the heavy mass; while the long piece of wire extending below the ball represents the lever system and pens. If I move my hand back and forth very fast, the mass remains stationary and the pointer below indicates the motion, magnified, of course, in the ratio of the long wire to the short one. Now there is actually some length which we could give to a purely gravitational pendulum which would cause it to vibrate with the same period as our seismograph pendulum. That length would be about 40 feet. It would also be possible to attach a pointer to the pendulum which would be so

long that it would magnify the motion of my hand to the same extent that the lever system of the seismograph magnifies the motion of the earth. The length of that pointer would be about three-fifths of a mile. Now suppose I move my hand more slowly. The pendulum mass no longer remains stationary and the motion of the pointer becomes exaggerated. The more closely I conform the motion of my hand to the natural period of vibration of the pendulum, the more violently does the pendulum swing. This is the phenomenon called resonance. From this demonstration I think you can see the necessity for damping, if we are to have a record of the earth's motion which is in any way faithful.

The demonstration also gives an idea how the true magnification changes with the period of the earth waves. If I move my hand very slowly the pendulum will follow my hand and there will be no relative motion recorded at all. The number of times the pointer is longer than the pendulum we call the indicator magnification or magnification for very rapid vibrations. Prof. Wiechert's chart will show the relation of the true magnification to the indicator magnification for various earth-wave periods and damping ratios.

We often wish to know the exact distance through which each particle in the earth under the seismograph has moved. But, as we have seen, the magnification for each wave may be different. Hence the calculation of the earth motion is a tedious process, but is very much shortened by the use of a logarithmic chart made by Dr. Geiger of Gœttingen, Germany, which gives us the earth-motion corresponding to one millimeter on the trace or seismogram for any particular wave.

Any of you who are interested in the physics of the Seismograph I would refer to the Bulletin of the St. Louis University for December, 1911, as time will not permit us to treat the matter further tonight. Standard works on the mathematics of the subject are Wiechert's *Theory of Automatic Seismographs* in German, and Reid's *Theory of Seismographs* in the second volume of the Report of the State Earthquake Investigation Commission on the California Earthquake of 1906.

Let us proceed now to the trace made by the Seismograph.

We take a sheet of paper about one yard long, bend it around, paste the two ends together, put it on rollers and rotate it over a long kerosene flame until it is covered with a fine film of soot. It is then placed on the recording cylinder of the seismograph and rotated uniformly by clockwork at the rate of one centimeter per minute, that is about two inches every five minutes. The fine aluminum recording pens rest lightly upon it. In fact the pressure is not greater than 1 milligram or .00004 of an ounce.

Suppose now that the waves from a distant earthquake strike the seismograph. The motion will be split up into two components, N-S and E-W, by the two thrust rods. Near the earthquake epicenter the waves will all be crowded together. But if the waves have come from a distance they will be separated out into definite groups. There are three distinct sets, the first preliminaries, second preliminaries and main waves. We have the same groups or phases in the record of the Persian earthquake of Jan. 23, 1909, made by the large Wiechert seismograph at his own station in Gœttingen and also in the seismogram of the Mexican earthquake of June 7, 1911, recorded at the St. Louis University. Each of these sets of waves on the record corresponds to a particular kind of wave in the earth. The first preliminary waves are longitudinal waves of compression and rarefaction like sound waves. The second preliminaries are transverse waves of distortion like light waves. Both of these go through the interior of the earth. The main waves are complex surface waves like water waves which go around the outside of the earth. All three sets started out together but the longitudinal waves travel faster than the transverse waves, and these again faster than the surface waves. So the farther the earthquake station is from the epicenter, the greater distance there will be between their records on the seismograph. If we know the time it takes for each to travel a certain distance and hence the amount by which each falls behind the other for a given distance, we need only observe the number of minutes by which the second preliminaries have fallen behind the first and we have the distance of the earthquake. Tables are used for this purpose which are derived from the Weichert-Zoeppritz transmission curves. The ordinates or vertical lines to each curve represent the time in seconds required for that kind of waves to reach a station whose epicentral distance around the surface of the earth is represented by the abscissae, each large vertical space representing 500 seconds and each large horizontal space representing one megameter or about 621 miles. Curve No. 2 gives the transmission time for the first preliminaries. Curve No. 3 for the second preliminaries and Curve No. 5 for the surface or main waves.

Now it is not always possible to distinguish the phases with certainty, as in the record of an earthquake in Swan Island in the Caribbean Sea obtained at the University Jan. 1, 1910.

Even in the case of such records as the three we had before and also the one of the Mexican earthquake of Dec. 16, 1911, in which the phases are very clear and distinct, we have not yet *located* the earthquake by the mere fact that we have determined the distance. For this condition would hold equally well for all points on a circle with St. Louis as center and that distance as radius.

In certain exceptional cases, however, in which the earthquake record begins with a decided impulse, as in the one now on the screen,

we may proceed in this way. The two sets of lines represent the two components into which the motion is broken up by the thrust rods. An impulse from the west will make a downward stroke on the upper line and one from the east an upward stroke. Also an impulse from the north will make a downward stroke on the lower line and one from the south an upward one. In this case we find an upward impulse on the upper line and a downward impulse on the lower. This means that the shock came from somewhere between north and east. This might have been produced either by a condensation from the northeast or a rarefaction from the southwest. The distance given by the interval between the first and second preliminaries was 2690 km, or about 1670 miles. Now we know by experience that we do not get earthquakes of this character from Labrador. This record bears a decided Mexican stamp. So we take our microscope, measure each impulse exactly, and calculate the corresponding earth motion. We find them to be .0005 inch W, and .001 inch S. approximately. Combining these two values in the parallelogram of forces and calculating the exact azimuth or direction, we can go to our map on which we have direction lines and distance circles plotted for St. Louis and put our fingers on the exact spot off the west coast of Mexico between Acapulco and Colima. This we telephoned to the newspapers within an hour after the record was removed from the machine. This method is known as that of Prince Galitzin. Other methods required data from at least three stations before they can be applied.

I would respectfully refer anyone who is interested in these methods to the Bulletin of St. Louis University for April, 1912, and also to the forthcoming April Bulletin.

Before leaving this subject, I wish to call your attention to the fact that if we had the Wiechert instrument for the vertical component when we were working out the data for that Mexican earthquake there would not have been any ambiguity, for the impulse would have been downward and earthquakes do not come from the sky.

Like all vertical seismographs, the Wiechert consists of a heavy mass, in this case 80 Kg. or 176 lbs., supported by springs and free to vibrate in a vertical plane.

People nowadays are always looking for results from Science. By this they usually mean applications of the knowledge gained to the problems of other fields of endeavor. Judged from this standpoint has seismology any results to offer? From a practical and economic point of veiw, the knowledge of the nature of seismic vibrations has been of material assistance to the building engineer and is leading to saner and safer construction, especially in those regions that are exposed to earthquakes. But it is to the geologist and geophysicist that seismology has been the greatest boon. Before the advent of seismology the interior of the earth was a sealed book. The depth which was reached by mines and borings can scarcely be called a scratch on the surface. According to various vague assumptions we were led now to a molten liquid earth surrounded by a thin crust, now to a gaseous interior. Seismology proves beyond doubt that the interior of the earth, whatever its condition, behaves as if it were a solid more than twice as rigid as steel. The earth seems to be made up of an outer mantle of rock in which the velocity of seismic waves rapidly increases down to a depth of 1200 km; a layer of metal, apparently nickel steel, in which the velocity increases very slowly, and an inner metallic core at a depth of 3000 km., which casts a seismic shadow on the other side of the globe and in which the velocity seems to be somewhat less, though it is very hard to study. Thus like the rays of light from the distant stars that bring us, through their spectra, some knowledge of the chemical constitution of the bodies from which they come, the seismic rays from the interior of our planet seem destined to open before our mental vision those dark and mysterious depths.

Record of Earthquake Station, St. Louis University for 1913.

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: 160.36m.
TIME: Mean Greenwich, midnight to midnight.

INSTRUMENT: Wiechert 80 kg., astatic, horizontal pendulum.
FOUNDATION: 12 ft. of tough clay over limestone of Mississippi System; thickness of latter about 300 ft.

NOMENCLATURE: International.

The symbols used in the following record are those of the *International* Nomenclature, which is identical with that given by us in the December Bulletin of the University (1911).

SYMBOLS.

CHARACTER OF THE EARTHQUAKE.

I = noticeable, II = striking, III = violent.

d = terrae motus domesticus) = local earthquake (felt at station).

v = (terrae motus vicinus) = nearby earthquake (less than 1000 km.).

r = (terrae motus remotus) = distant earthquake (1000-5000 km.).

u = (terrae motus ultimus) = very distant earthquake (more than 5000 km.).

PHASES:

P = (undae primae) = first preliminary tremors (longitudinal waves through the earth's interior.)

PRn = P waves reflected n times at the earth's surface.

S = (undae secundae) = second preliminary tremors (transverse waves through the earth's interior).

SRn = S waves reflected n times at the earth's surface.

PS = transformed waves, i. e., waves which, in their reflection at the earth's surface, have been changed from longitude to transverse, or vice versa.

L = (undae longae) = long or "Rayleigh" waves (first phase of main or principal portion—surface waves).

M = (undae maximae) = greatest motion in the main or principal portion (complicated surface waves).

C = (cauda) after-shocks or trailers.

F = (finis) = end of visible motion.

NATURE OF THE MOTION:

i = (impetus) = sudden impulse.

e = (emersio) = gradual development (beginning uncertain).

T = period =time of complete vibration to and fro.

A = amplitude of earth motion—reckoned from the line of rest and measured in microns, (μ = 1/1000 mm).

E or N attached to a symbol refers it to the E-W or N-S component.

EARTHQUAKE RECORDS FOR 1913.

Date	Char.	Phase	Time	Period T	Amplitude .AE	Amplitude .AN	Remarks.
			h. m. s.	s.	mm	mm	
Jan. 11	I	$?P_E$	13: 39.				Contact clock
		$?P_N$	13: 39: 05				slightly inaccurate
		L_N	13: 54. 18				
		L_E	13: 54.				
		F_E	15: 37.				
Jan. 15	Ir	iP_N	18: 58: 3	3		.6	E-W very faint
		eP_E	18: 58: 4				Distance about 3000 km.
		PR_{1N}	18: 58: 8	4-6		1.	
		S_E	19: 02: 8				
		S_N	19: 02: 8	5		.5	
		L_E	19: 03: 8	6-9			
		F_E	19: 40.				
Feb. 18	I	$?e_N$	00: 47: 1				
		L_N	00: 52: 7	9			
		F	8: 15: 5				
Mar. 3	II	e	3: 12: (?)				Record very imperfect.
		$?S_E$					
		L_N	3: 18: 5	10-12			T_E = 6.8 sec.
		L_E	3: 19: 8	10-11			T_N = 7.3 sec.
		M_N	3: 20:	10		8	ε_E = 5.1
		F	3: 48: 5				ε_N = 6.2
Mar. 4	Iu	S_N	11: 29: 50				
		S_E	11: 30: 14				Distance = 4450 km.
		$?SR_E$	11: 32: 15				Periods and amplitudes
		L	11: 34:				exceedingly slight.
		F	11: 50:				
Mar. 8	IIr	$?P_N$	15: 57: 01				
		S	16: 02: 41	4-10			Distance = 3800 km.
		M_N	16: 02: 50	10			Beginning of Phases indistinct.

Date	Char.	Phase	Time	Period T	Amplitude .AE	Amplitude .AN	Remarks.
			h. m. s.	s.	mm	mm	
Mar. 8		eL	16: 06: 12				continued.
		L_N	16: 11: 36	10		.4	T = 7 sec.
		C_N	16: 12: 36	10			ε_N = 6.2
		F	16: 33: ca				ε_E = 6.1
Mar. 9		L	16: 30: 24				
Mar. 14	IIu	P	9: 05: 58				
		S	9: 15: 59				
		$?eL_N$	9: 27: 55				
		$?eL_E$	9: 32: 01	12			
		L_E	9: 41: 07	40	.4		
		L_E	10: 04: 44	15	.5		
		F	11: 14: 00				
Mar. 15	I	?e	22: 29.7				N-S disturbed by wind-quakes.
		eL_E	22: 33: 22	6			
		F_E	22: 52				
Mar. 31	IIu	P	3: 51: 14				
		S_E	3: 59: 31				Distance = 6800 km.
		S_N	3: 59: 33				On N-S there are
		L	4: 022: 12	33			seven distinct main
		M_{N1}	4: 15: 35	20		.7	shocks and three
		M_{E1}	4: 15: 59	19	4		after shocks.
		M_{N2}	4: 17: 37	13		.9	T_E = 7 sec.
		M_{E2}	4: 17: 45	14	.7		T_N = 7.2 sec.
		M_{N3}	4: 19: 48	14		1.	ε_E = 5.8
		M_{E3}	4: 19: 48	16	.8		ε_N = 6.3
		M_{E4}	4: 22: 49	11	.6		
		M_{N4}	4: 23: 21	13		.9	
		M_{N5}	4: 27: 58	12		.6	
		C_N	5: 03: 45	10		.4	
		C_{E1}	5: 03: 45	10	.2		

Date	Char.	Phase	Time	Period T	Amplitude AE	Amplitude AN	Remarks.
			h. m. s.	s.	mm	mm	
		C_{E2}	5: 09: 14	10	.2		
		F_N	5: 13: 30				
		F_E	5: 30: 00				
Apr. 25	I'	?e	18: 23: 42				
		L_E	19: 00: 30				
		L_N	19: 02: 07	20			
		L_E	19: 11: 06	18			
		F	19: 59:				
Apr. 26	Ir	P_E	12: 43: 49				No. L on E-W.
		P_N	12: 43: 51				
		S	12: 48: 50				Distance 3250 km.
		$?eL_N$	12: 51: 00				
		L_N	12: 54: 14	15			
		?F	13: 15:				
Apr. 28		i_E	00: 34: 27				Local earthquakes
		i_N	00: 34: 35				felt along the St.
							Lawrence.
Apr. 29		L_E	00: 05: 30	15			
		L_N	00: 07: 25	15			
		?F	00: 25				
Apr. 30	Iu	?S	11: 52: 15				Distance 8000?km.
		L_N	12: 04: 58	17			
		L_E	12: 04: 59	14-16			
		F	13: 57.				
May 8		e_E	18: 51: 48				Record very slight. Masked by local microseisms.

Date	Char.	Phase	Time	Period T	Amplitude AE	Amplitude AN	Remarks.
			h. m. s.	s.	mm	mm	
May 16	I	$?eL_E$	12: 11: 15	10			
		$?eL_N$	12: 11: 17				
		F	12: 30: 00				
May 30	Iu	$?eP_N$	11: 54: 53				Distance = 13000? km.
		$?eP_E$	11: 58. 18				T = 7 sec.
		e_E	12: 02: 35				ε_E = 4.5
		e_N	12: 02. 42				ε_N = 6.3
		eL_N	12: 34: 20	54		.4	
		eL_E	12: 35. 30				
		L_E	12: 50: 32	20	.5		
		L_N	12: 53: 36	15		.6	
		F_E	14: 08: 30				
		F_N	14: 09: 55				
Jun. 22	Ir	eP	13: 59: 36				
		R_1P_N	14: 02: 12				Distance = 6500 km.
		eS	14: 07: 42				Quake reported from the
		$?R_1S_N$	14: 12				Aleutian Islands.
		$?eL_N$	14: 17. 24				
		$?eL_E$	14: 17. 48				
		M_E	14: 26	17	.5		
		M_N	14: 27. 30	16		.7	
		F	15: 12.				
Jun. 26	Ir	?eP	5: 11: 30				
		$?eS_E$	5: 18				Distance = 4900 km.
		R_1P_E	5: 13: 15				Microseisms on N-S
		eL_E	5: 23: 01				render determination
		$?eL_N$	5: 23: 50				of S impossible.
		M_E	5: 45: 18	26	.8		
		M_N	5: 43: 54	21		.7	
		F	7: 36.				

Date	Char.	Phase	Time	Period T	Amplitude AE	Amplitude AN	Remarks.
			h. m. s.	s.	mm	mm	
Jul. 8	Ir	eP_N	00: 17:				
		$?eP_E$	00: 17: 05				Distance = 1900 km.
		eS_N	00: 20: 16				
		eS_E	00: 20: 23				
		eL_E	00: 20: 59				
		eL_N	00: 21: 58				
		M_N	00: 23: 17	10		.7	
		M_E	00: 25: 39	8	.4		
		F_N	00: 40:				
		F_E	00: 42:				
Aug. 1	II	?e	17: 33: 02				
		?eL	17; 52: 50				
		F	18: 30				
Aug. 6	II	$?eP_E$					
		e	21: 21: 15				Distance = 3600 km.
		$?eP_E$	21: 24: 06				Quake reported from
		P_N	21: 24: 22				Peru.
		$?S_N$	21: 29: 19				
		$?eS_E$	21: 29: 30				
		eL_E	21: 31: 58				
		L_N	21: 32: 12	12			
		M_E	21: 44: 55	30	.9		
		M_N	21: 48:	21		2.1	
		M_{E2}	21: 50: 01	20	1.2		
		F	22: 50				
Sep. 3	I	$?E_N$	21: 13; 46				Reported in Sicily.
		$eS_E?$	21: 18: 58				No decided M.
		eL_E	21: 47: 58				
		F	22: 27:				

Date	Char.	Phase	Time	Period T	Amplitude AE	Amplitude AN	Remarks
			h. m. s.	s.	mm	mm	
Oct. 2	IIr	eP_N	4: 29; 47				
		$?PR_{1N}$	4: 30: 41				Distance = 3100 km.
		eS_N	4: 34: 13				Panama
		$?S_E$	4: 35: 53				
		eL_N	4: 36: 17				
		$?eL_E$	4: 39: 04				
		M_{N1}	4: 41: 11	9		.5	
		M_E	4: 41: 15	8	.4		
		M_{N2}	4: 46: 09	11		.6	
		F_N	5: 03.				
		F_E	5: 18				
Oct. 4		e_N	22: 11: 39				Microseisms especially
		e_E	22: 11: 06				on E-W.
		F	22: 29.				
Oct. 11		$?eP_E$	2: 03: 16				
		$?eL_e$	2: 35:				
		eL_e	2: 43:				
		F	2: 57				
Oct. 11	IIr	eL_N	5: 05: 38				
		eL_E	5: 16: 42				
		F	5: 35				
Oct. 14	Ir	eP_E	8: 27: 38				
		R_2P_E	8: 33: 12;				
		R_3P_E	8: 34: 22				
		$?eS_E$	8: 38: 08				
		R_1S_E	8: 44: ?				
		F	8: 55;				

Date	Char.	Phase	Time	Period T	Amplitude AE	Amplitude AN	Remarks.
			h. m. s.	s.	mm	mm	
Oct 23	Ir	?eP	15: 03: 26				
		eS	15: 13: 14				
		eL	15: 15: 25				
		M_E	15: 16: 19	9	.3		
		F	15: 44				
Nov 23		e_E	21: 34: 17				
Nov 26		$?i_N$	7: 01: 00				Microseisms prevail
		?e	7: 04				
Dec 6		e_E	0: 26				
		e_E	0: 31: 12				
Dec 6		?e	11: 08: 35				
		$?i_E$	11: 14: 46				
		?e	11: 19: 27				
Dec 15			23: 59				Microseisms continually before midnight
			24: 14: 06				
			24: 48: 02				
Dec 21		$?eL_E$	16: 42: 25				Microseisms
		eL_N	16: 43				
		M_N	16: 46: 12		.3		
		F	17: 00				
Dec 28		?e	12: 08: 12				Microseisms prevail remarkably from Dec. 26th to Jan. 1st 1914
		?i	12: 18: 49				