Strings and things for locating Earthquakes

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Abstract

When one hears that an earthquake has occurred, one of the first questions is “where was it?” For the general public, this question oftentimes determines the importance of another important question, “how big was it?” Once learning the location and size, some might wonder how this information was determined. We present here an interactive, three-dimensional analog computer that uses a map, strings, and a time-distance scale to find the location of an earthquake (lat, long and depth) based on seismic wave arrival times. We have also developed a set of lesson plans to present the ideas used for locating earthquakes to grade and high school students and the general public. The device is suitable for both permanent mounting in a science museum or can be easily transported to schools or other places. The analog earthquake locator is located in the Public Earthquake Resource Center, PERC, at the Center for Earthquake Research and Information at The University of Memphis and is taken to classrooms for education outreach.

Introduction

In many cases, the public’s first concern after hearing that an earthquake has occurred is its location. For those who are also interested in how the answer is obtained, we have built a three dimensional analog computer that can be used not only to locate earthquakes but also illustrate many of the ideas associated with this process. We have installed this analog computer in the Public Earthquake Resource Center, PERC, at The University of Memphis, but it can be easily transported to classrooms or other locations. We have also developed a set of instructional materials which we use with the locator in presentations to grade school and high school students.

The most popular introductory method for showing how earthquakes are located is based on drawing circles about seismic stations on a map or globe (Figure 1). The circles' radii are determined by using the difference between the arrival times of the P and S waves. This time difference is converted to a distance that can be measured on the map. Undergraduate Physical Geology laboratory exercises and presentations about earthquakes to grade and high school groups typically use this method with a compass, regional map, and data from at least three seismic stations. By drawing circles with appropriate radii around the seismic stations, the surface location, or epicenter, of the earthquake is found where the three circles intersect at a point. This demonstration "works" perfectly for earthquakes at the surface and synthetic, noiseless P and S wave arrival time data. Most earthquakes, however, do not occur at the surface. In this case, the circles drawn on the map will not intersect at one point. We can fix this problem if we modify the method whereby the radii found from the T_s-T_p arrival times are used to create spheres in three-dimensions (Figure 2), instead of two-dimensional circles on the surface. We now find that there are two points of intersection of the three radii. Both points are equidistant to the earth's surface. One is located within the earth and the other above the ground surface. The point of intersection beneath the surface is the focal location of the earthquake; hence the distance from the surface to the point of intersection above the earth's surface also denotes the depth of the earthquake. The radii represent the ray paths of the seismic rays traveling through a homogeneous media. The analog earthquake locator forms the intersection of the radii of spheres in three dimensions above the surface of a map, demonstrating not only the epicentral location on the surface directly beneath the intersection, but the depth of the earthquake as well.

Analog Computing

The term analog is now oftentimes used to mean continuous, as opposed to discrete. While many analog computers use continuously varying quantities to perform their calculations, this is not a requirement for analog computing. The fundamental principal behind analog computing is based on the observation that many seemingly different physical systems can be described mathematically by equations of the same form, differing only in the interpretation of the parameters and variables. If two systems are equivalent mathematically, we can investigate the behavior of one system in terms of the other. Electrical and plumbing circuits are an example of analogous systems. In these two systems the mathematical relationships between the conservation of current or fluid flow, or the voltage and pressure, electrical current and water flow, and resistance to electrical or fluid flow are the same. One could therefore use electric circuits to simulate plumbing systems. Analog electrical computers were a popular method for solving large differential equations before the digital computer revolution. Another example of an analog computer, this time a mechanical one, is the simple slide rule. There are an incredible number of interesting non-electrical analog computing devices, such as the famous Norden bombsight of WW II. Before the advent of the digital computer, the

USGS used the circle method to locate teleseisms by finding the intersection of circles on a globe (Figure 3).

The Analog Earthquake Locator

The analog computer method for locating earthquakes provides students and visitors of the PERC at CERI a hands-on visual presentation to help understand how to determine earthquake focal locations in three-dimensions. It also introduces some of the physical ideas, such as ray paths, associated with this process. The locator was inspired by a device built and used by the late Argentine seismologist F. Volponi, of the Instituto Geofísico Sismológico Zonda (now Instituto Sismológico "Fernando Volponi") of the Universidad Nacional de San Juan in San Juan, Argentina. S. Sacks suggested the device to Volponi to address the issue of locating intermediate depth earthquakes beneath San Juan, where the circle method fails due to the 100+ km depth of earthquakes whose epicentral distances for events immediately beneath the network were oftentimes much smaller than their depths. The size of our device is scaled for determining the epicenter and depth for earthquakes within a small part of the New Madrid Seismic Zone, where earthquake depths up to 21 km can be equal to or larger than the epicentral distances.

Figure 4 shows a schematic of the locator construction and use. The front of the display contains a set of educational materials and instructional activities, a map showing four seismic stations to be used in the exercises, a time-distance scale with adjustable markers, and several seismograms. The time-distance scale shows both the T_s-T_p times and the corresponding distances traveled by the seismic waves. The distance portion of the time-distance scale is at the same scale as the map and the corresponding T_s-T_p times are found from the P and S wave velocity model. The map is approximately 0.5 m by 0.5 m and covers a 40 km^2 area over the thrust arm of the New Madrid seismic zone. In this region the seismic stations have a spacing of 10 to 30 km and the earthquakes vary from 5 to 21 km in depth. The region includes Reelfoot Lake, located in the northwest corner of TN, and a section of the Mississippi River. Holes are drilled through the map at four seismic stations (shown by stars). A metallic loop is connected to the end of a string that can be pulled out of the hole, away from the surface of the map. The string passes over the time-distance scale where markers show the distance the end of the string has moved. Retracting mechanisms mounted to the back of the locater keep the strings taut and retract the string when the end is moved back towards the hole. In Volponi's original analog locator, the map was mounted on the top of a table and short sections of pipe were slipped onto the four table legs. The strings were connected to these pipes which served as weights to maintain the tension as the pipes slid up and down the table legs with the change in the position of the other end of the string.

The components of the locater are very simple. It consists of a wooden frame and board, a laminated and mounted map, a scale marked in T_s–T_p time and distance, strings, metallic loops, key-ring retractors, and a device for holding the ends of the strings together (Figure 5). The time markings on the scale are based on the equation:

$$D = [(V_p\ V_s)/(V_p - V_s)](T_s - T_p)$$

$$D = VT$$

where D is the distance of one ray path, T_s is the S wave arrival time, T_p is the P wave arrival time, V_s is the S wave velocity, and V_p is the P wave velocity. For this implementation of the locater we used a homogeneous half space model for the New Madrid seismic zone with a V_p of 6 km/sec and V_s of 3.5= $V_p/(\sqrt{3})$ km/sec. The markers are placed on the string associated with each seismic station based on the T_s-T_p time for that station. The position of the marker on the string is also equal to the distance the seismic waves traveled from the focus to the respective seismic station; this distance can be read off the distance scale.

By using T_s-T_p times, the locator can be operated several ways. In the first method the markers for the T_s-T_p arrival times are placed at the appropriate positions on the scale for each seismic station, the ends of the strings are pulled together and joined, and this union is moved around in 3-D until the T_s-T_p markers line up on the time scale (Figure 6). Since the markers are initially at the distance the seismic waves traveled to each station, they will line up at zero. In most cases, the union of the ends of the strings must be pulled away from the map for the markers to line-up. When the markers line up, the position of the union represents the earthquake focus and the strings signify the ray paths to each station. The distance of the union of the strings above the map, obtained using a measuring device that has the same scale as the map, gives the depth of the earthquake. The point on the map directly beneath the union is the epicenter. This is the method one would use if the analog earthquake locator was the principal method of locating an earthquake.

The next method we present is more didactic but still uses the distance traveled by each of three seismic waves through conversion of the T_s-T_p arrival times to distance through the time-distance scale. Start with all the strings retracted so their ends are at the seismic stations. Next, place the time markers at the appropriate places on the strings using the T_s-T_p scale. Then pull the end of each string away from the station to bring its individual marker to zero. Now lock or hold down all the strings. Finally connect the ends of the strings together to find the solution. Using data from three stations, the solution will be the unique place where all the strings are taut. As with the first method, the location will be above the surface of the map, indicating the depth of the earthquake's focus and the epicenter beneath the intersection.

A variation of the previously discussed method, with additional teaching opportunities, is to start manipulating only one of the locked strings. Demonstrate that this defines a hemisphere above the map by moving the string in all directions while keeping it taut. A similar hemisphere could also be defined below the map. Each string defines its own hemisphere about its seismic station. Now one can hold the ends of two of the strings together and find that this limits the allowed motion of the union of the two strings to following an arc. This arc is half of the circle that is defined by the intersection of two spheres. Each pair of strings defines an arc. Finally, by connecting all three strings together we find that there is a unique place (actually there is also one below the map) where all three strings are taut and this single place, where all the strings intersect, is the focus and hypocentral location of the earthquake. This point is the intersection of the three spheres and the three arcs of circles we round with individual strings and pairs of strings. If we have more data (more seismic stations with strings strung to them) we will again find a place where all the strings are taut, but only if the data are perfect. If the data are not perfect, we will always be able to keep at least three strings taut at any time.

By changing the time-distance scale, the analog computer can also be used to locate earthquakes using P wave arrival times only. The time-distance scale is changed from T_s-T_p times and the corresponding distances to a scale marked in P wave travel times and the corresponding distances P waves travel. Unlike the case for using T_s-T_p, where the velocity used to scale time to distance does not represent a physical velocity, the velocity used to generate the new scale is the actual P wave velocity. In this method one does not know the distance to the hypocenter beforehand so one cannot lock the strings at a fixed distance or know where they should line up. The direction of the time and distance marks on the scale now run the other direction and one places the time markers based on their relative P wave arrival times. The last arrival defines zero time and distance. The earlier arrivals are marked at their relative arrival times/distances ahead of the last arrival. The ends of the string are again joined and the union moved around until the markers line up. In contrast to the case of using T_s-T_p, the markers will now line up at some arbitrary position. The distance from the station with the latest P arrival time to the earthquake is read directly from the distance portion of the scale and the distances to the other stations can be determined by the relative arrival times and corresponding distances. For this method, P arrivals from at least four seismic stations are required to estimate the four parameters – latitude, longitude, depth, and origin time (There are actually six data measurements in the T_s-T_p method as we need both a P and S wave arrival data at each of the three stations. In addition in the T_s-T_p method, we are estimating one less parameter since the origin time is determined from the known distance to each station.). The concepts associated with using P wave arrival times only are more advanced than those associated with the T_s-T_p method and would be suited for undergraduate or graduate class presentations.

College level classes may benefit from demonstrations of other concepts that are more advanced than those presented with the museum display. The analog locator can be used to illustrate the idea of a “best fit” when one has more than the minimum number of data and one introduces noise or errors into the arrival time measurements. This can be demonstrated using four sets of T_s-T_p times. For perfect data, the four markers will all line up at zero. For data with errors, the user will have to find a “best” arrangement of the markers near zero. The analog locator can also be used to show how the determination of origin time and depth are coupled when one has only P wave arrival times. As the union is moved vertically over the epicenter, there is very little relative movement between the markers, so it is difficult to decide when they are best lined up. The device is also well suited to illustrate problems arising when the earthquake to be located is well outside the network. In this case, with either type data (T_s-T_p or P), one can move the union perpendicular to the line connecting the union to the stations a considerable amount with very little variation in the position of the markers.

Explanatory and Educational Materials

About 2000 people visit the PERC yearly and the average visitor is between the ages of 8 and 15. Those who visit the PERC learn about paleoseismology, plate tectonics, geology, earthquake hazards – especially in the New Madrid area, and how CERI records earthquakes in the New Madrid Zone. The PERC has several activities involving seismology, but no display dedicated to the subject of locating earthquakes. Our physical analog model provides a hands-on, interesting and fun way to obtain a basic understanding of the process of locating earthquakes.

Explanatory materials are displayed on the locator to give an introduction to the process of locating earthquakes. Given the diverse target audience of the PERC and the relatively complex nature of earthquake location, importance was placed on selecting development material that was both rich in content and suitable for both adults and children. The goal was to create a model that would appeal to the average visitor (8-15) and to visitors that we hope to do a better job of attracting (15-24). The introductory materials introduce the ideas behind locating earthquakes using the travel time of waves by analogy to the common method of estimating the distance to a lightning bolt by counting the seconds between the flash and the thunder. Several example seismograms are shown with the P and S arrivals marked. These seismograms are used to provide the data for the hands-on exercise. Finally there is a short discussion with a simple explanation of seismic waves, their velocities, the idea of ray paths, and the relation of the elements of the analog model to the actual physics of the problem.

We have prepared additional materials that teachers can use to prepare their class before the visit and that teachers and students can take with them when they leave. Importance was placed on tying our subject matter to the State of Tennessee science standards. Earth and space science, physical science, geography, and science as inquiry are the main connections to the curriculum. Academic “bullets” (and grade levels) addressed in the display include:

- energy (K-12)
- Earth’s features and structure (K-12)

- waves (4-12)
- position and motion of objects (3-12)
- force and motion (K-12)
- measurement skills and tools (K-12)
- map reading (3-12)
- properties of objects and materials (K-12)
- what is scientific inquiry (3-12)
- what abilities are necessary to do scientific inquiry (3-12)

Construction

In order to create a functional earthquake locator for use by children, several factors were taken into consideration such as cost, durability, accessibility, and portability. To make the hands-on exercise interesting to local visitors, the locator was designed to work in the New Madrid region. We used sites from the New Madrid Cooperative Seismic Network and selected a region of the seismic zone with the deepest events. We were very concerned with durability because the PERC, as with all children's museums, has a history of broken displays due to over enthusiastic use by visitors.

We constructed the base of the display from a sturdy, solid wood frame and a plywood display board. Key ring retractors provide the tension and retraction needed for the strings. The coiling mechanism in the key ring retractors provides the constant tension needed. All of these parts are relatively inexpensive and easy to obtain.

Explanatory materials are laminated and mounted on foam core and they can be changed or replaced easily and inexpensively. The scale, also laminated and mounted on foam core, with marked strings is enclosed in a case with a Plexiglas front panel. The

Plexiglass panel can be easily removed to allow scale changes, to use P wave arrival times for example, or for changing the positions of the markers to use other sets of T_s-T_p arrival times. This allows the markers to be set up beforehand and prevents them from being modified by the user. For normal presentations to grade school groups, the markers are preset and not accessible by the students.

The physical dimensions of the analog locator and associated display material were determined by the space available in the PERC and the desire for portability. In the PERC the locator is mounted such that the base is about three feet from the floor. This allows easy accessibility and use by grade school students. The scale is horizontal and positioned above the map at about eye level for grade school students.

Simple operation requires pulling on the strings, connecting them together, and moving the union of the strings around and above the map until the markers line up. We used sturdy, 20 lb fishing line secured to stainless steel thumb bolts at four of the seismic station locations. We constructed a connecter from ten gauge copper wire by bending it into an appropriate shape. The 20 lb string is orange, has low friction, and has little elasticity. The orange color allows the string to be seen by viewers throughout a classroom or display area. Keeping friction at a minimum was important so we installed plastic female banana plugs, with the electrical interior part removed, into the holes the strings pass through. The composition of the banana plugs reduces friction considerably. Tension in the strings is necessary to keep the strings taut, in a straight line, and also to retract the strings when the end is moved closer to its hole. String tension is provided by key ring retractors. When a string is pulled out from the board, the appropriate marker moves the same distance horizontally along the scale as the distance the end of the string is moved. The markers are light-weight foam cylinders about 1 cm in length and 1 cm diameter. The markers had to be light enough not to weigh down the string, small enough not to interfere while moving past one another as the strings are moved, and large enough to be seen from a distance.

Another factor in the design is portability. We need to be able to bring the analog locator to schools, science fairs, etc. for education and outreach activities. The space available for installing the locator in the PERC requires a wall-mounted display. When used outside the PERC, the analog locator must be freestanding and stable with respect to users tugging on the strings. To address this, we made a support that can be temporarily clamped onto a table. With this design, participants can operate the locator without it moving or falling over on them when they pull on the strings. The base is quick to set up and easy to disassemble. The display itself is manageable by one person.

It is important that the earthquake used in the exercises requires that the union of the strings be pulled away from the map surface in order to locate the earthquake. We therefore chose a sub-region of the network with dense station spacing such that earthquakes with depths greater than ~5 km will require the union of the strings to be noticeably lifted away from the surface of the map in order to locate the earthquake. Finding an example earthquake at a good location and with sufficient depth was not difficult. Finding an appropriate seismogram, however, was problematic due to the location of the New Madrid seismic zone and the seismic network in the Mississippi Embayment. The low velocity unconsolidated sediments of the Mississippi Embayment lie above high velocity basement rocks causing several complications. The S wave, for example, typically does not show up on the vertical component seismogram, where a strong S to P conversion from the bottom of the embayment sediments is evident. Having to look at multiple seismogram components and deal with mode conversions to obtain the P and S waves arrival times is too complex for the didactic purposes of the locator in the PERC. Instead of using the real seismograms for the earthquake we therefore altered a few seismograms to “fit” the T_s-T_p times needed.

Conclusion

Analog devices provide an excellent format to present complex physical phenomena in an easy to understand manner that is oftentimes very true to the original physics. The hands-on control of the locator also adds to the educational experience. Building the locator also provided an interesting undergraduate project that spanned simple carpentry, to elementary education standards and simple seismological theory.

Acknowledgements

We would like to thank the late F. Volpini for showing us the locator in use at the Instituto Geofísico Sismológico Zonda in San Juan, Argentina, and S. Sacks for his advice about using analog devices to solve problems in geophysics. We would like to thank XX for helpful reviews. This work was supported primarily by the Mid America Earthquake Center of the Earthquake Engineering Research Centers Program of the National Science foundation under Award Number EEC-9701785. We had additional support through matching funds from the Center for Earthquake Research and Information of the University of Memphis.

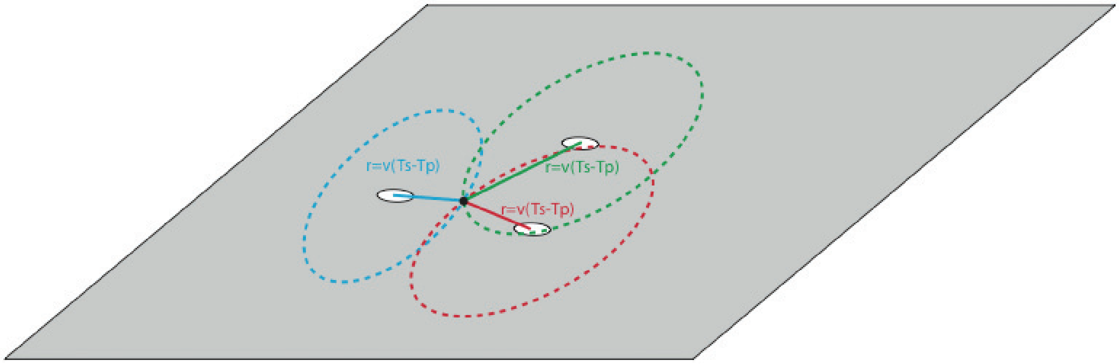

Figure 1. This figure illustrates the circle method for locating earthquakes. Circles of appropriate radius, based on the T_s–T_p time, are drawn around each station and their intersection is the location of the earthquake.

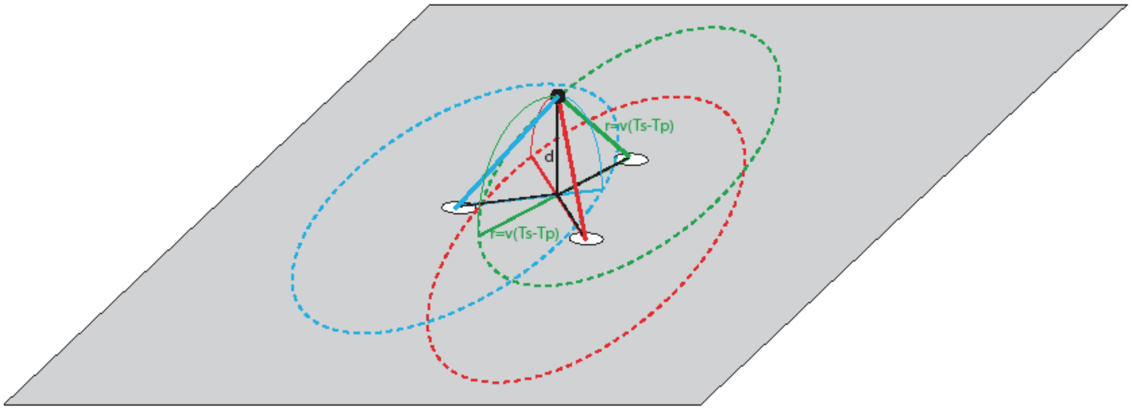

Figure 2. This figure illustrates the failure of the circle method when the earthquake does not occur at the surface. The three radii are shown intersecting at a single point, the hypocenter. The failure of the circle method gets more pronounced as the depth of the earthquake becomes equal to or greater than the epicentral distance (the distance from the epicenter, on the surface, to the seismic stations). The distance the seismic waves travel between the earthquake and the stations, given by $T_s – T_p$, determines the radii of spheres. Since the waves travel the distances shown by the solid lines, when the radii (dashed colored lines) are rotated to make circles on the surface, they are all too long and the three circles do not intersect at a single point.

Courtesy of the USGS

Figure 3. Dr. Waverly Person (right) and an unidentified coworker use a large wooden compass and globe to locate a teleseism at the USGS NEIC. The spacing of the compass legs is based on the time difference between the arrival of the P and S seismic waves. For teleseisms, the relationship between the distance, D, and T_s–T_p is not linear and is read from a table (there is no single velocity to scale T_s–T_p to D). The compass is used to draw arcs of circles in chalk on the globe about a number of seismic stations. Again, the intersection of the circles gives the earthquake epicenter.

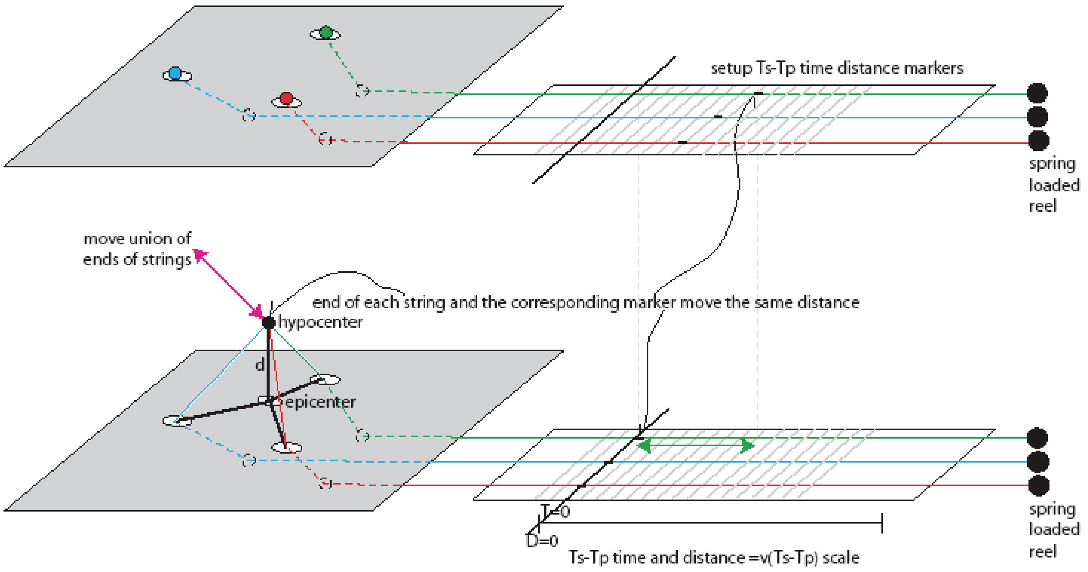

Figure 4. This figure shows a schematic diagram of both construction and use of the analog earthquake locator. For clarity, only three stations are shown for the method using T_s-T_p times. As the ends of the strings are pulled from the locations of the seismic stations, the markers on each string move the same physical distance as the end of the string. One can determine the distance the end of the string moved using the distance scale, which is the same as the map scale. The time scale is produced using the corresponding T_s–T_p time for each distance based on the velocity model. To use the locator, one lets all the strings retract so that the end of each string is at the location of the seismic station. One then places the marker at the T_s–T_p time for a given station on the string that corresponds to that station. Next, the ends of the strings are joined together and

the union is moved about until all the markers line up at zero. For earthquakes with depths similar to or larger than their epicentral distances, the union has to be moved noticeably away from the map surface. One can then determine the depth of the earthquake by measuring the distance from the union of the ends of the strings from the map, using a ruler that is marked at the same scale as the map. The epicenter is the point directly below the union.

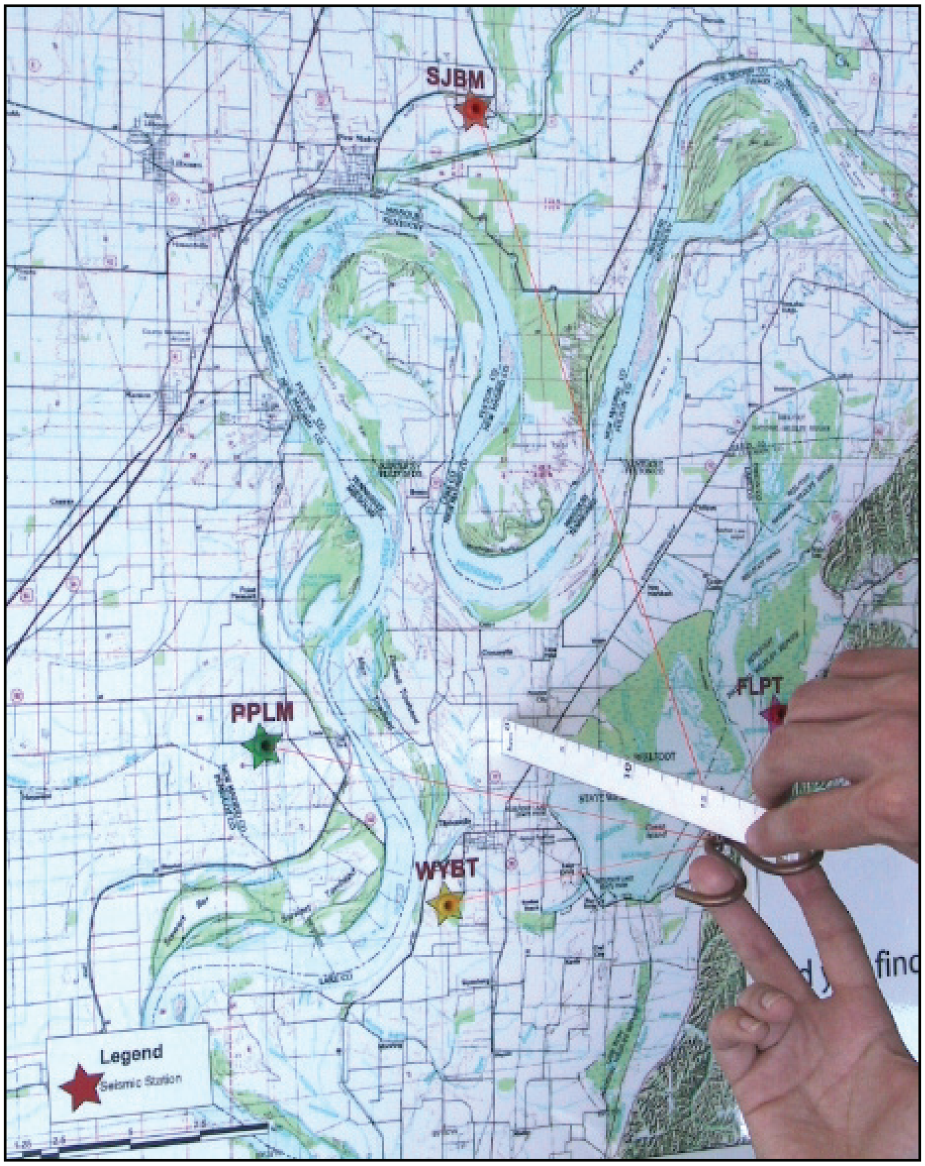

Figure 5. This figure shows the earthquake locator in use. Four strings are connected, brought to a point above the map where all markers line up on the scale, and the distance off of the map is measured with a provided ruler scaled the same as the map scale.

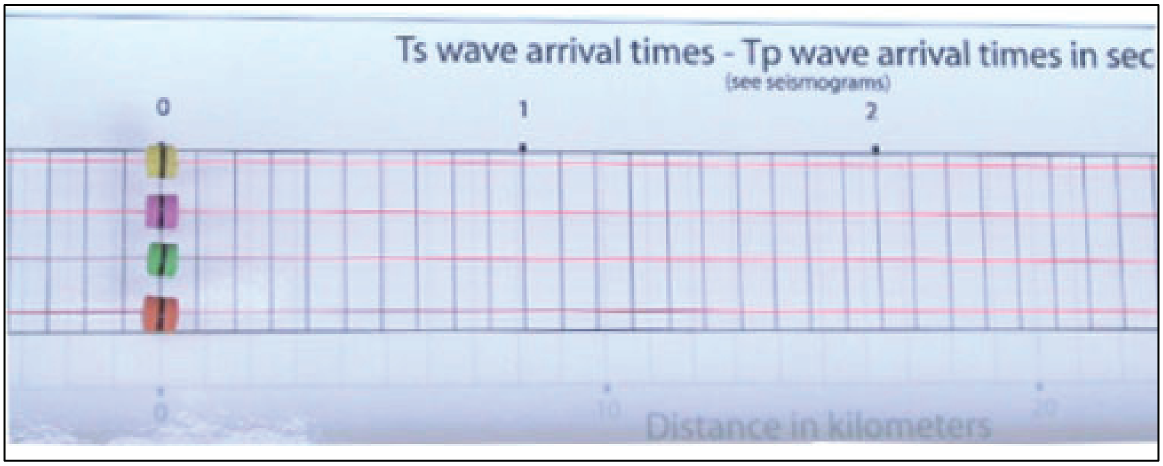

Figure 6. Markers lined up at zero on the time distance scale indicating the earthquake has been located. Seismic wave arrival times are in seconds and distances are in kilometers.