Strings and Things for Locating Earthquakes

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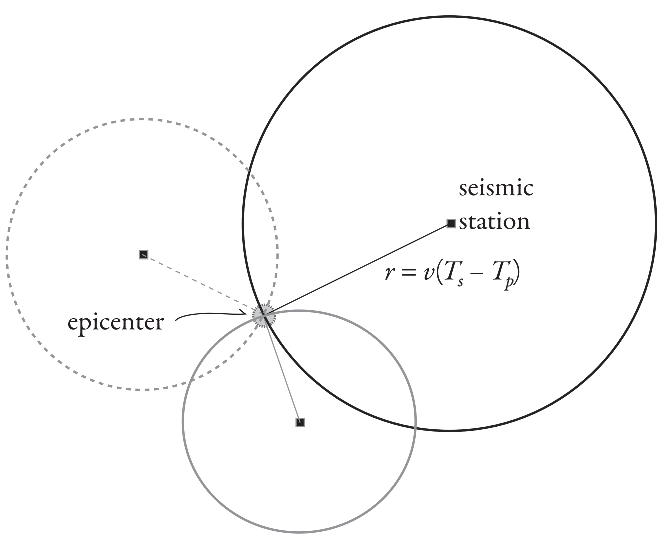
INTRODUCTION

When one hears that an earthquake has occurred, one of the first questions is, "Where was it?" For the general public, this question often determines the importance of another question, "How big was it?" Upon learning the location and size, one may wonder how this information was determined. For those interested in how earthquakes are located, we have developed an interactive, three-dimensional analog computer that uses a map, strings, and a time-distance scale to find the location of an earthquake (latitude, longitude, and depth) based on seismic wave arrival times. We also have developed a set of lesson plans to present the ideas used for locating earthquakes to grade-school students, college classes, and the general public. The device is suitable for both permanent mounting in a science museum or can be transported easily to schools or other educational and outreach venues. Our prototype analog earthquake locator is housed in the Public Earthquake Resource Center (PERC) at the University of Memphis and also is taken to local classrooms.

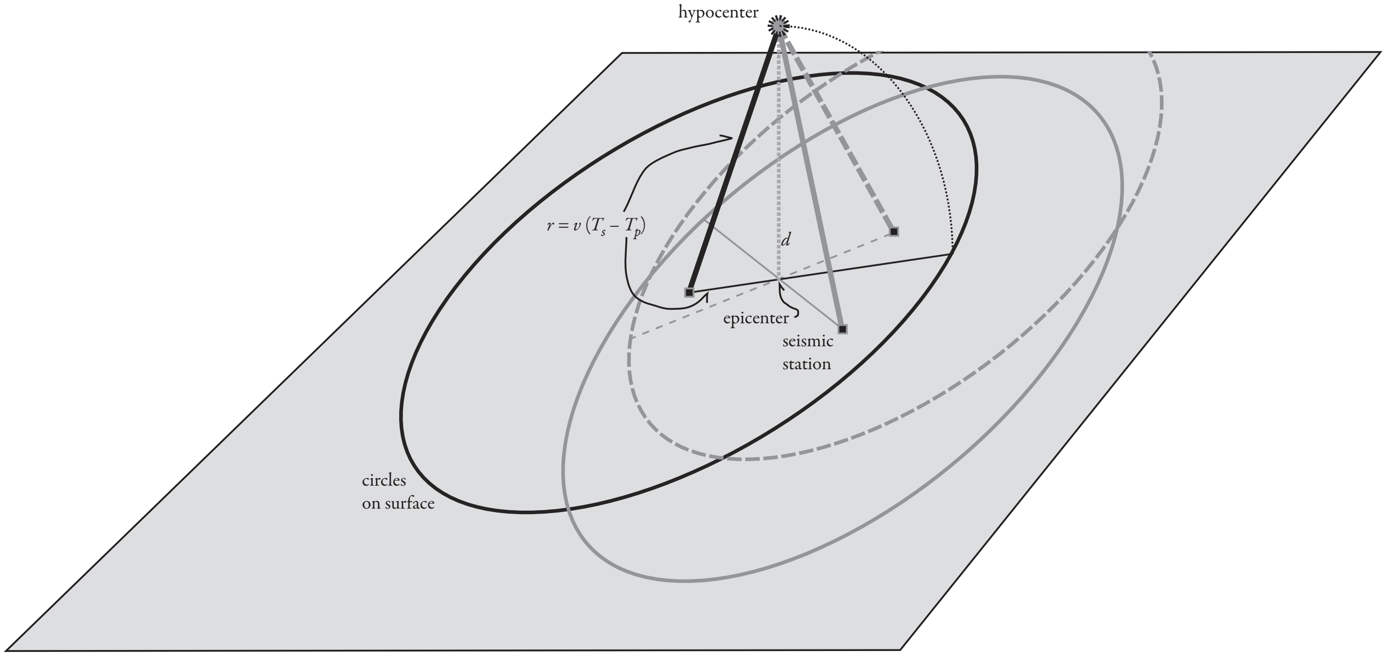
The most popular introductory method for showing how to locate earthquakes is the circle method, which is based on drawing circles around seismic stations on a map or a globe (figure 1). The circles' radii are based on the length of time between the arrival of the *P* and *S* waves, $T_s - T_p$, at each station. This time difference is converted to a distance by using a table or multiplying by a given velocity. How the velocity or the values in the table are determined is usually not discussed. The distance determined from the $T_s - T_p$ time is used as the radius of a circle that can be drawn on the map or globe by a student using a compass. Laboratory exercises and presentations about earthquakes to elementary, middle, and high-school groups typically apply this method with a compass, a regional map, and data from at least three stations. In this exercise, the distance between the earthquake and the seismic stations has to be small enough that the Earth can be considered flat. Drawing circles with appropriate radii around the seismic stations produces a point where the three circles intersect. The intersection point is the surface location, or epicenter, of the earthquake. This demonstration works perfectly for earthquakes at the surface and noiseless *P*- and *S*-wave arrival time data. Real earthquakes, however, occur inside the Earth at some depth, not at the surface. In this case, the circles drawn on the map will not intersect at one point because the distances determined using the $T_s - T_p$ arrival times are the distances from the earthquake to the stations, not the distances from the point on the Earth's surface above the earthquake to the stations (figure 2). The problem can be fixed by using the distances found from the $T_s - T_p$ arrival times as the radii of spheres in three dimensions, instead of two-dimensional circles on the surface. The three radii now create two points of intersection. Both points are equidistant to the Earth's surface. One is located within the Earth and the other above the Earth's 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 medium. 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.



▲ **Figure 1.** This figure illustrates the circle method for locating earthquakes. First draw circles of appropriate radii, based on the $T_s - T_p$ times, around each station on a map. Data from one station locates the earthquake somewhere on the circle drawn about that station. Data from two stations further restricts the earthquake location to one of the two places where the two circles intersect. Finally, the intersection of the three circles gives the unique location of the earthquake.

ANALOG COMPUTING

The term "analog" has two meanings that are relevant to the earthquake locator. The fundamental principle behind the application of analog computing is 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



▲ **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, but this point is not on the surface. 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 about the hypocenter. Because the waves travel the distances shown by the heavy lines, when the radii are rotated to make circles on the surface (fine lines on surface), the radii are all too long and the three circles do not intersect at a single point.

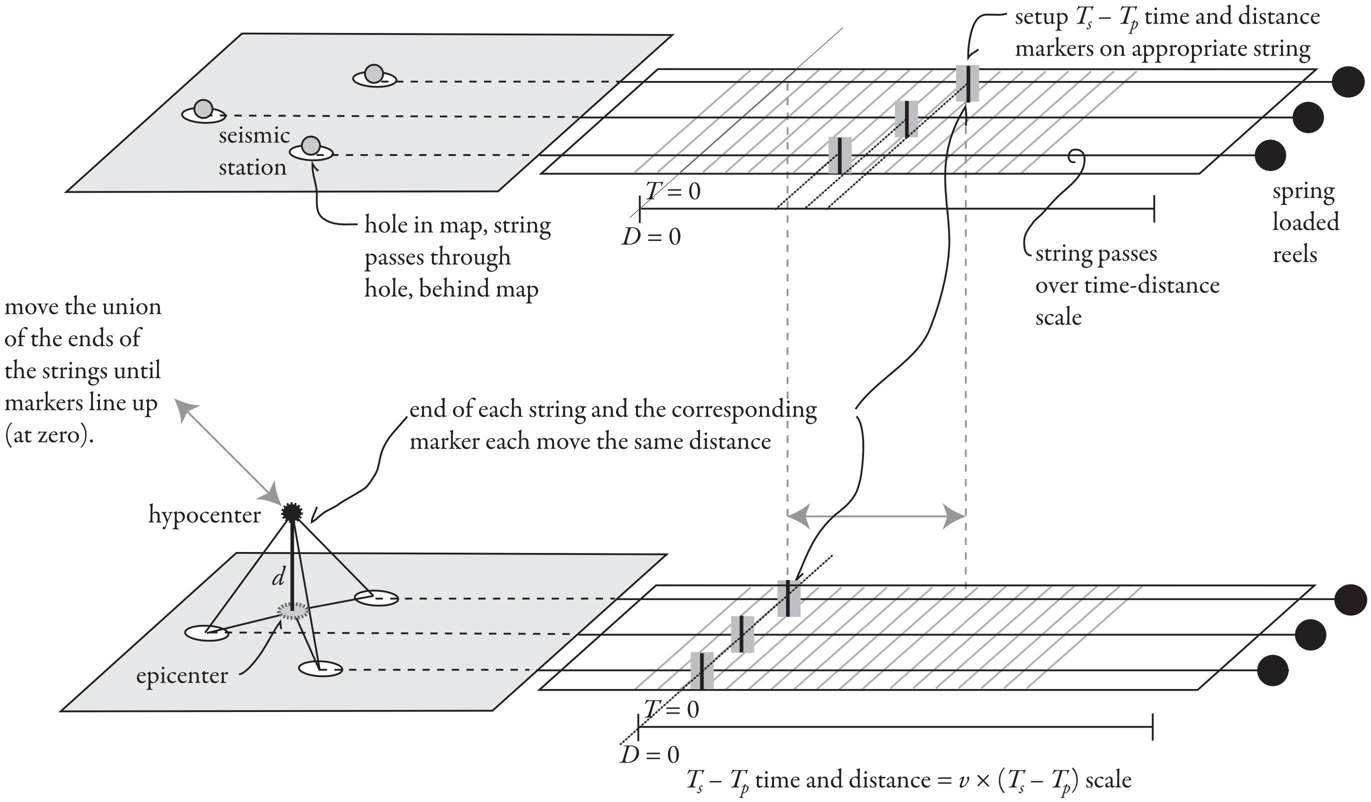
are equivalent mathematically, we can investigate the behavior of one system in terms of the other. Electrical and plumbing circuits are an example of analogous systems. In these two systems the mathematical relationships between current and fluid flow, and voltage and pressure, are the same. One could therefore use electric circuits to simulate plumbing systems and determine the pressure, current, and resistance for a given plumbing system by making measurements on the analogous electrical circuit. The second meaning refers to the use of continuous, as opposed to digital, quantities. Analog computers use continuously varying quantities to perform their calculations, although the actual calculation may depend on discrete rather than continuous levels.

Analog computers have had numerous applications. Electrical analog computers were once a popular method for solving large differential equations. Another example of an analog computer is the simple slide rule. There are an incredible number of interesting nonelectrical analog computing devices, such as the famous Norden bombsight of World War II. At one time the U.S. Geological Survey used the circle method to locate teleseisms by finding the intersection of circles on a globe. Although analog systems have been replaced by digital computers, the earthquake locator is a useful, appropriate device because its purpose is education rather than speed.

THE ANALOG EARTHQUAKE LOCATOR

The analog computer method for locating earthquakes provides students and visitors of the PERC at the Center for Research Information (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 Fernando Volponi, of the Instituto Geofísico Sismológico Zonda (now Instituto Sismológico "Fernando Volponi") of the Universidad Nacional de San Juan in San Juan, Argentina. I. Selwyn 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; epicentral distances for events immediately beneath the network were often 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 3 shows a schematic of the locator construction and operation, and figure 4 shows the locator in 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, their seismograms, and a time-distance scale with adjustable markers. 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. The $T_s - T_p$ times on the scale are based on the equation:



▲ **Figure 3.** 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 based on $T_s - T_p$ times. The time and distance scale bar is produced by using the map scale for the distance part of the scale and the corresponding $T_s - T_p$ time as a function of distance based on the velocity model. Both the time and distance scales are printed on the scale bar. 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 (top). Next, the ends of the strings are joined together and the union is moved until all the markers line up at zero (bottom). 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 each string moves using the distance scale. 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 surface with a ruler that is marked at the same scale as the map. The epicenter is the point directly below the union.

$$D = \left(\frac{V_p V_s}{V_p - V_s}\right)\left(T_s - T_p\right)$$

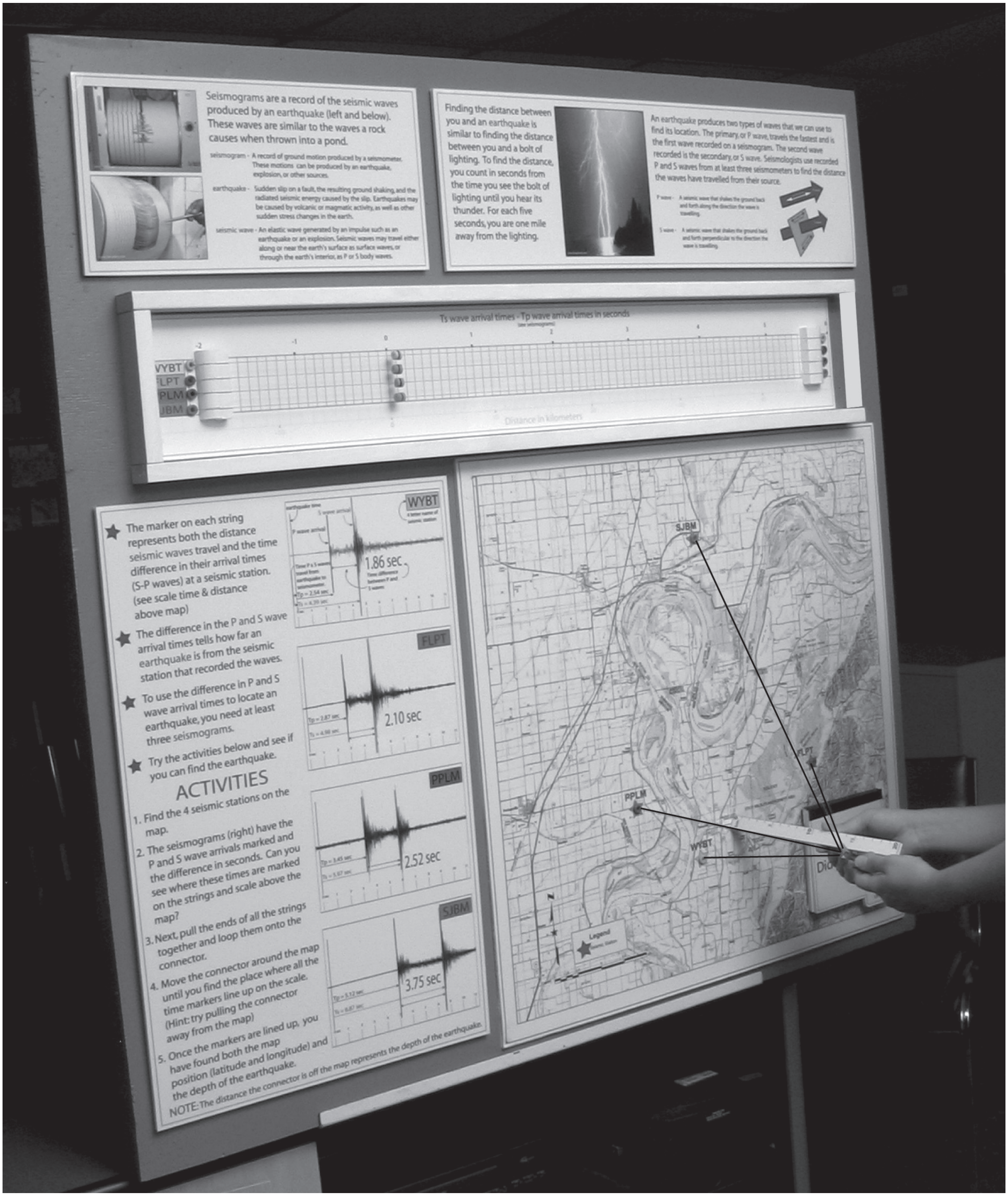
$$D = VT$$

where D is the length of the 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 locator we used a homogeneous half-space model for the New Madrid seismic zone with $V_p = 6$ km/s and

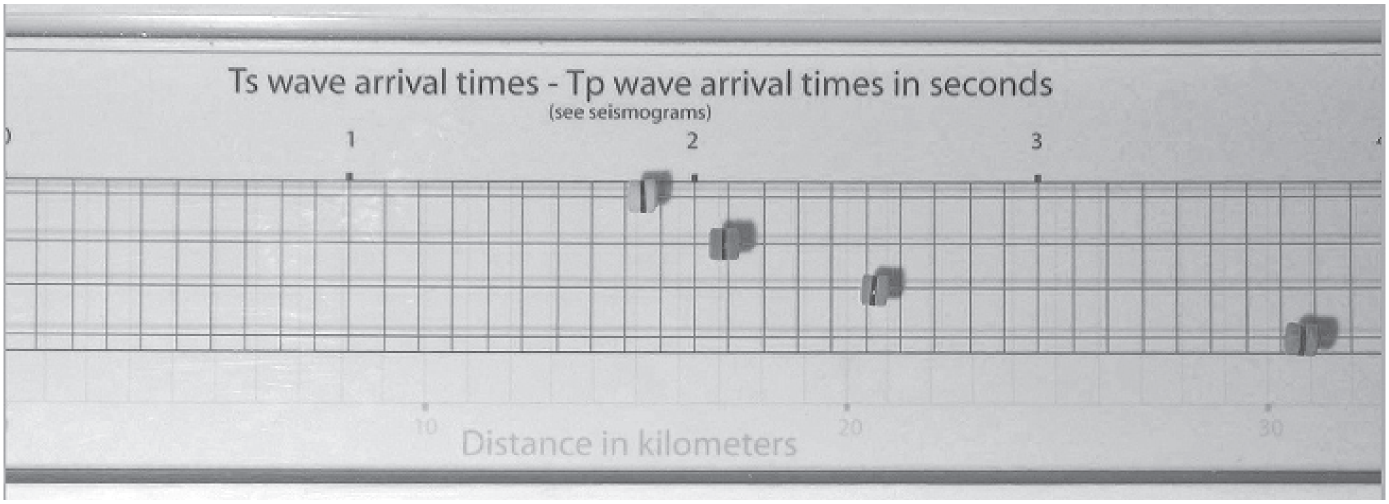
$$V_s = 3.5 = \frac{V_p}{\sqrt{3}} \text{ km/s.}$$

The map is approximately 0.5 m by 0.5 m and covers a 40 km² area over the thrust arm of the New Madrid seismic zone. In this region the seismic stations have a spacing of 10 to 20 km, and the earthquakes vary from 5 to 21 km in depth. The region includes Reelfoot Lake, located in the northwest corner of Tennessee, and a section of the Mississippi River. Holes are drilled through the map at four seismic stations (shown by stars). At each hole, a metal loop is attached to a string that can be pulled out of the hole away from the surface of the map. The other end of 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 locator keep the strings taut and retract the string when the end is moved back toward the hole. In Volponi's original analog locator, the map was mounted on the top of a table. Short sections of pipe, to which the ends of the strings were attached, were slipped over the four table legs and provided tension in the strings as the pipes slid up and down the table legs with movement of the other end of the string.

The components of the locator are very simple, consisting 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 4). The markers are placed on the



▲ **Figure 4.** This figure shows the earthquake locator in use, its size, and the presentation of the explanatory material. The four strings are connected and brought to a point above the map where all the markers line up on the scale at zero time and distance. This point is the hypocenter. The distance of the union from the map is measured with a ruler that is marked at the same scale as the map. The epicenter is the point directly under the union where the ruler touches the map.



▲ **Figure 5.** This figure shows the initial placement of the markers at the $T_s - T_p$ times and the dual time and distance scale.

string associated with each seismic station based on the $T_s - T_p$ time for that station (figure 5). 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.

The locator can be operated several ways using the $T_s - T_p$ times. 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. In most cases, the union of the ends of the strings must be pulled away from the map to accomplish this. Because the markers are initially at the distance the seismic waves traveled to each station, the markers also line up at zero. When the markers are lined up, the position of the union represents the earthquake focus and the strings represent the ray paths to each station. The distance of the union of the strings above the map, obtained using a ruler 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 were the principal method of locating an earthquake.

The next method is more didactic but still uses the distance traveled by each of the three seismic waves obtained by 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 positions 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 begin by working with only one of the locked strings. Demonstrate this string defines a hemisphere of a given radius by moving the end in all directions above the map while keeping it taut. With data from one station, the earthquake will therefore lie somewhere on this hemisphere. A similar hemisphere can also be found below the map, defining a full sphere. Next, join the ends of two locked strings keeping in mind that each string defines a sphere. With the strings taut, the motion of their union above and below the map is restricted to a circle, defining the intersection of the two spheres, on which the earthquake is now constrained to lie. Finally, connecting the ends of all three locked strings together one finds a single place above the map where all the strings are taut. This place represents the earthquake focus or hypocentral location. It is much easier to see this intersection using the strings as radii, rather than trying to draw the intersection of the three spheres. If more data are available (more seismic stations with locked, measured strings attached), there will still be only one place where all the strings are taut, but only if the data are perfect. If the data are not perfect there will be at least one, and possibly several, places where at least three of the strings will be taut.

The analog computer can also be used to locate earthquakes using *P*-wave arrival times only. This is accomplished by changing the time-distance scale to one showing *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 strings 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-wave 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 both P- and S-wave arrival data are needed at each of the three stations. In addition, in the $T_s - T_p$ method we are estimating one less parameter because the origin time is determined from the known distance to each station.) The concepts associated with using only P-wave arrival times are more advanced than those associated with the $T_s - T_p$ method and would be better suited for undergraduate or graduate class presentations. An interesting note is that by properly redefining things (stations become satellites and the earthquake becomes the observation point), this analog computer can also can be used to demonstrate how one locates oneself using the global positioning system (GPS).

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 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 deciding where they best line up is difficult. The device is also well suited to illustrate problems arising when the earthquake is well outside the network. In this case, with either type of 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 2,000 people visit the PERC yearly and the average visitor is between the ages of 8 and 15. The PERC has presentations about paleoseismology, plate tectonics, geology, earthquake hazards—especially in the New Madrid area—and how CERI records earthquakes in the New Madrid seismic zone. While several of the activities involve seismology, none are dedicated to the subject of locating earthquakes. The physical analog model provides a hands-on, interesting, and fun way to obtain a basic understanding of the earthquake location process.

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, it was important to select and develop material that was rich in content and suitable for both adults and children. The goal was to create a model that would appeal to the average 8- to 15-year-old visitor and also to visitors that we hope to do a better job of attracting (ages 15 to 24). The introductory materials describe the concept of locating earthquakes using the travel time of waves, which is analogous to the common method of estimating the distance to a lightning bolt by counting the seconds between the flash and the thunder and dividing by five to get miles. Several examples of 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.

Additional materials are available that teachers can use to prepare their classes before the visit and that teachers and students can take with them when they leave. Importance was placed on tying the 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

Creating a functional earthquake locator for use by children requires considering factors such as cost, durability, accessibility, and portability. Designing the locator to work in the New Madrid region makes the hands-on exercise more interesting to local visitors. Using sites from the New Madrid Cooperative Seismic Network in the region of the seismic zone with the deepest events ensures that the union will be noticeably above the map surface. Durability is also a primary concern because the PERC, like all children's museums, has a history of broken displays due to over-enthusiastic use by visitors.

The parts of the display are all relatively inexpensive and easy to obtain. The base of the display is a sturdy, solid wood frame with a plywood display board. Tensioning and retracting the strings is performed by a set of key-ring retractors. Explanatory materials are laminated and mounted on foam core. The scale, also laminated and mounted on foam core and with marked strings, is enclosed in a case with a Plexiglas front panel. The Plexiglas panel can be removed easily to change the scale to another velocity model or to use P-wave arrival times, or to change the positions of the markers to use other sets of $T_s - T_p$ arrival times. The removable panel allows the markers to be set up beforehand and once reinstalled prevents the markers from being modified by the user. For normal presentations to grade-school groups, the markers are preset and not accessible.

The space available in the PERC and the desire for portability determined the dimensions of the display. In the PERC, the locator is mounted so that the base is about three feet from the floor. The scale is horizontal and positioned above the map at about eye level so it is easily accessible for grade-school students.

The strings are sturdy, 20-lb. fishing line with one end connected to the key-ring retractor and the other secured to stainless steel thumb bolts at the seismic station locations. The strings run behind the locator, come up to the top where they pass over the time-distance scale, and continue to the key-ring retractors. The string is orange and has low friction and little elasticity. The orange color allows the string to be seen by viewers throughout a classroom or display area. Plastic female banana plugs, with the electrical interior part removed, keep friction at a minimum where the strings pass through the holes in the map. Tension, provided by the key-ring retractors, is necessary to keep the strings taut and to retract them when the end is moved closer to its hole. When a string is pulled out from the board, the appropriate marker moves the same distance horizontally along the time-distance scale as the distance the end of the string is moved. The markers are lightweight foam cylinders about 1 cm in length and diameter. The markers need 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. Finally, copper wire was used to fashion a simple connector to hold the thumb bolts at the ends of the strings together.

CERI makes presentations at schools, science fairs, and other venues as part of its education and outreach activities. Demonstrations and hands-on activities are part of these presentations. The locator is well suited for such activities. In the PERC, the only available space requires a wall-mounted display. When used outside the PERC, the analog locator must be freestanding and stable as users pull on the strings. The locator therefore has a support that can be temporarily clamped onto a table to allow safe operation. The base is quickly set up and easily disassembled. 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 to locate the earthquake. Choosing a sub-region of the network with both dense station spacing and relatively deep earthquakes ensures 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. Finding an example earthquake at such a 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, where 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, whereas a strong *S* to *P* conversion from the bottom of the embayment sediments is evident. Looking at multiple seismogram components and dealing with mode conversions to obtain the *P*- and *S*-wave arrival times is too complex for the didactic purposes of the locator in the PERC. Selecting a few seismograms that provide appropriate $T_s - T_p$ values solved this problem.

CONCLUSION

Analog devices provide an excellent format to present complex physical phenomena in an easy to understand manner that is often very true to the original physics. The hands-on control of the locator also makes it a more engaging educational experience. Building the locator provided an interesting undergraduate project that spanned tasks from basic carpentry to elementary education standards to simple seismological theory.

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