

*EqLocate Tutorial*¹

(L. Braile, July 2002, revised November, 2004)

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About EqLocate: EqLocate is an interactive earthquake location program that uses actual seismograms and user-selected P-wave arrival times to locate the earthquake. The program uses a method that is similar to the approach that is used by seismologists to routinely determine the location of earthquakes from around the world. In the standard method, tens to hundreds of arrival times (each from an individual seismogram corresponding to a seismograph station) are used by a computer program to automatically find an optimum solution (location and origin time of the earthquake determined such that the observed arrival times match the theoretical arrival times calculated using a well-known seismic velocity model for the Earth). In EqLocate, a limited number of seismograms (3 to 10, or more) and corresponding arrival times are used, and the solution is found by the user selecting trial locations on a map until an optimum location is found. The user is guided in the selection of trial epicenters by graphical information generated by EqLocate from the previous trial location. Once a close epicenter is found, the depth of focus of the earthquake can be estimated by changing the trial depth and selecting additional trial epicenters. (The epicenter is the location on the surface of the Earth above the earthquake focus and is identified by latitude and longitude. The location of the earthquake focus is called the hypocenter and is identified by the latitude, longitude and the depth of the focus.) A measure of the quality of the final solution is provided by calculation of the differences between observed and theoretical arrival times and by a color coded display of solutions that are close to the optimum location.



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The web page for this document is:

<http://web.ics.purdue.edu/~braile/edumod/eqlocate/tutorial.htm>.

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Several data sets (seismograms) for selected earthquakes are provided with EqLocate. Additional data can be added to the EqLocate folder at any time. Although EqLocate can be used to locate many earthquakes, and the resulting locations are reasonably accurate, the primary objective of the program is to illustrate the important concepts of earthquake location for educational purposes.

The EqLocate program was written by Alan Jones based on a concept developed by Larry Braile. John Lahr and Larry Braile provided testing and suggestions during program development. Support for development of the program was provided by the NSF-sponsored IRIS (Incorporated Research Institutions for Seismology) Consortium.

Four sections of this tutorial (**Running EqLocate, How EqLocate Works, Importing Data into EqLocate, and Data Sets**) are provided below to explain the use of the program to locate earthquakes, to understand the method used by the program, and to learn about earthquake data (including importing data into EqLocate) and earthquake location.

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1. Running EqLocate: This section describes how to install and operate the EqLocate program on your computer. EqLocate runs on the Windows operating system.

1.1 Installing EqLocate: To install EqLocate on your computer, use your Netscape or Internet Explorer browser to link to: www.geol.binghamton.edu/faculty/jones/EqLocateSetup.exe. Download the file EqLocateSetup.exe to your computer (saving it in a folder called "Downloads" is convenient as you can reinstall at some later time or copy or send the file for another computer) and double click on EqLocateSetup.exe. The setup program will install EqLocate on your computer in a folder called EqLocate. In the EqLocate folder, right click on the EqLocate.exe file and create a shortcut to EqLocate.exe. Drag the shortcut to your desktop.



1.2 Starting EqLocate: To start EqLocate, double click on the EqLocate.exe shortcut on your desktop. A “splash screen” with information about the program will appear. Click continue. A world map similar to that shown in Figure 1 will appear. You can change the map view and zoom in using the arrow and plus and minus controls as illustrated in Figure 2. Zoom in on the map and adjust the view to the approximate area of the earthquake that you wish to view. You can select one of the standard earthquake data sets (seismograms located in folders organized by event) provided with the program or generate your own seismogram folder by downloading data from the IRIS Data Management Center using WILBER (see **Importing Data Into EqLocate** below) or other source of SAC binary seismogram files such as AS-1 or PEPP.

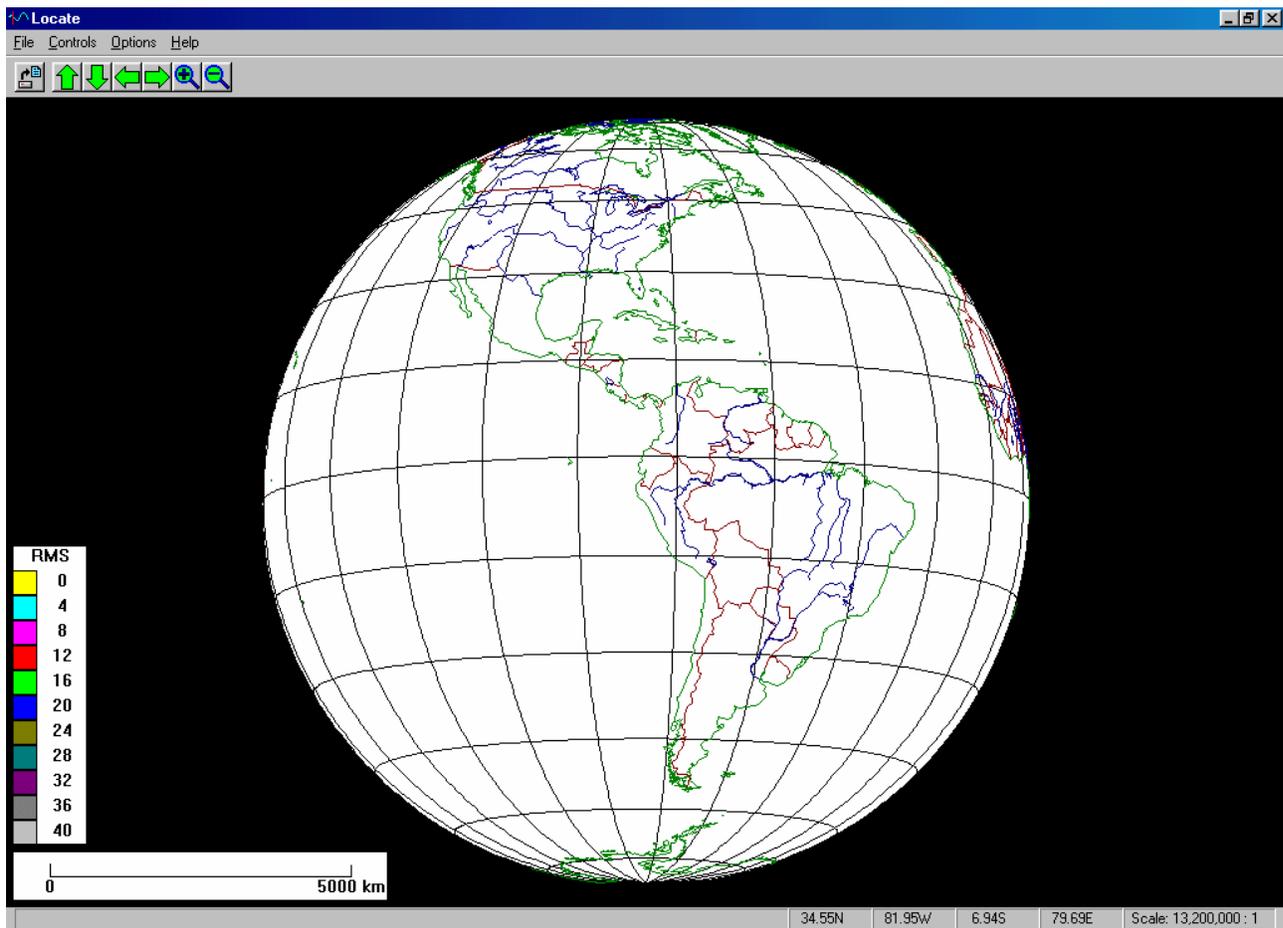


Figure 1. Screen image of the EqLocate program showing world map display. Any area of the world can be displayed and the user can zoom in to focus on the area that included the seismograph stations of interest. Latitude and longitude lines at 15 degree intervals are shown on the map.

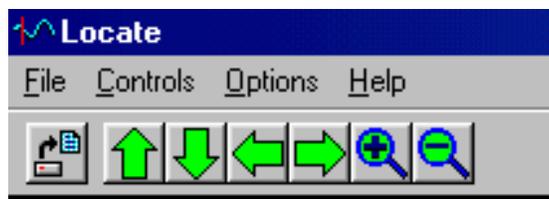


Figure 2. Close-up of the EqLocate controls for moving around the world map and zooming. The up arrow causes the world view to move to the north. The down arrow causes the world view to move to the south. The left arrow causes the world view to move to the west. The right arrow causes the world view to move to the east. The plus symbol causes zooming in (smaller area displayed) on the view. The minus symbol causes zooming out (larger area displayed).



1.3 EqLocate menus: Pull-down menus in EqLocate (at the upper left hand corner of the screen) provide controls and program information. Using the **File** menu, one can open or close seismogram files for events, print the current screen, and exit the program. In the **Controls** menu, one can set the depth of focus (a dialog box appears that allows the user to select from several standard depths or input an arbitrary depth – the travel time tables are limited to a maximum depth of about 650 km because only a few earthquakes deeper than that depth have ever been recorded) of an earthquake to iteratively determine the depth as well as the epicenter; set the maximum RMS value for the color coding on the color bar at the lower left hand corner of the screen – for most regional and distant (teleseismic) events, a value of 30 or 40 works well; use the zoom and arrow controls equivalent to the arrow and plus/minus symbols in the upper left hand corner of the screen (Figure 2). In the **Options** menu, one can turn on the Hints window that provides a shorter version of the instructions that are provided here; select multiple seismogram windows (small windows displaying one seismogram for each station that can be moved to be located adjacent to the station location), or seismograms in one window. In the **Help** menu one can determine the version of EqLocate that is installed and some information about the program. During program operation, **Hints** windows appear that help guide the user through program operation.



1.4 Opening seismograms from an earthquake folder: To open seismograms for an earthquake, select **Open Event** from the **File** menu and select the event of interest. The seismograms for each standard event are saved in a folder named for the event. Open the folder by double clicking or selecting and clicking on **Open** and select the seismograms using the mouse. Hold the **Control key** down to select multiple seismograms. Hold the **Shift key** down and select the first seismogram and the last seismogram to select all seismograms in the folder. Click **Open**. At least three seismograms should be selected for each event.

New seismograms for additional earthquakes can be added. Place seismograms in folders to organize the data by event as has been done with the standard earthquakes provided with EqLocate. Occasionally, an opened seismogram will have an arrival time that cannot be matched with a theoretical travel time. In this case, it is possible that a timing error exists with that seismogram and station and therefore, that seismogram should not be used for locating the earthquake. For more information on adding seismograms, see **Importing Data Into EqLocate** below.

An example of opening seismograms for an event is shown in Figure 3. In this example, the Northern Bolivia, deep-focus earthquake has been selected and opened. The station locations and seismograms appear on the screen. After some adjustment of the map view (moving north

or south, east or west, and zooming), the screen looks like that shown in Figure 3. The seismograms are all plotted with the same maximum amplitude (called “trace normalized”). In this case the seismograms are in a single window. Initially, they are ordered according to their file position in the folder. After an initial trial epicenter is selected, they are ordered according to distance from the epicenter.

One can also select multiple seismogram windows (use the **Options** menu) in which case there will be one window for each seismogram. The seismogram windows can be moved around on the screen to place them adjacent to the corresponding station. Time and amplitude expansion of the traces is also provided by the arrows in each of the multiple seismogram windows.

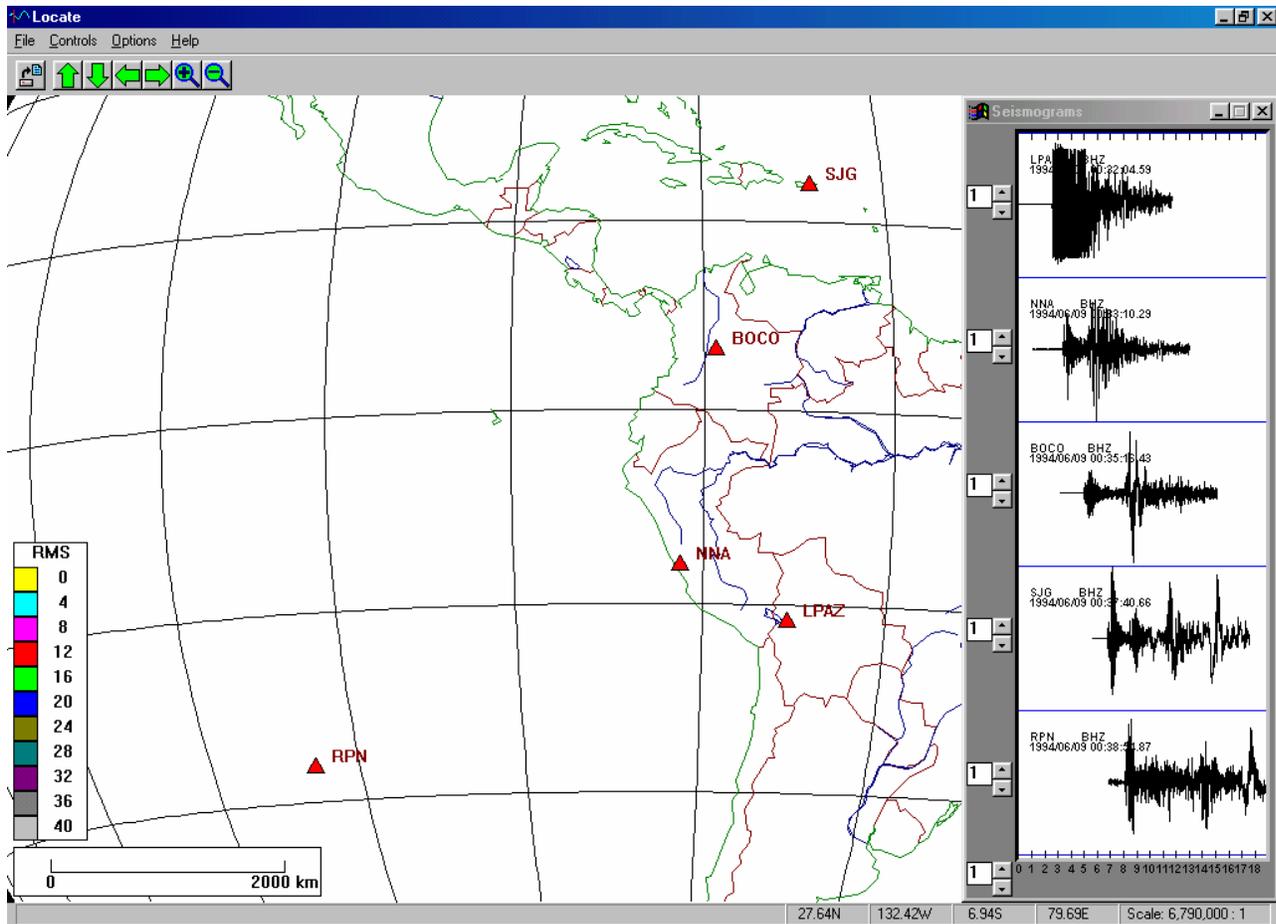


Figure 3. Screen image of the EqLocate program after an earthquake data set (in this case the June 9, 1994, magnitude 8.2 (M8.2), deep-focus Bolivia earthquake) has been opened. Selected seismograph stations are shown by the red triangles. Seismograms from these stations are shown in the “record section” display in the window at the right side of the screen.

With the single window view, as in Figure 3, one can enlarge the seismograms window by dragging the lower left hand corner of the window with the mouse cursor. The time scale can then be expanded if desired and the amplitude of each trace can be expanded as needed. Then, placing the cursor at the interpreted first arrival (P-wave) of each seismogram, clicking the mouse selects the arrival time (indicated by a red vertical line). The resulting display for the Bolivia earthquake data is shown in Figure 4. The seismogram window can then be scaled back to its original size or minimized. Enlarging the time and amplitude scales during interpretation of

the arrival times (“picking” the times using the cursor) of the seismograms allows one to very accurately determine the observed arrival times (and thus improve the accuracy of the earthquake location). An example of an enlarged seismogram display is shown in Figure 9 (lower diagram).

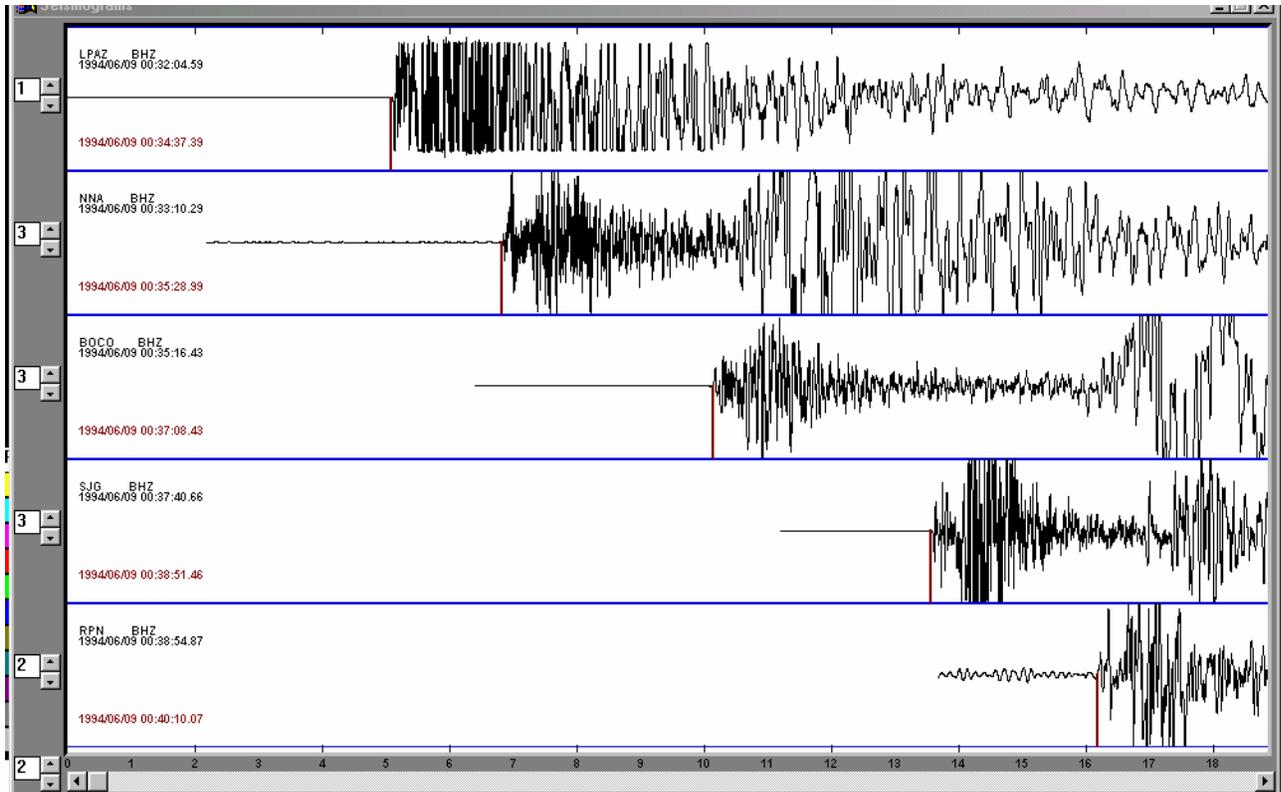


Figure 4. Screen image of the EqLocate program seismogram window. The window has been enlarged on the screen by dragging the lower left hand corner of the window to the left. Also, the time scale has been expanded by a factor of 2 using the up arrow in the lower left hand corner of the seismogram window. Amplitude scales of some of the seismograms have been enlarged (for easier interpretation of the first arrival) using the up arrows located to the left of each seismogram. Arrival times for each seismogram have been picked by clicking the mouse with the cursor positioned at the user-selected arrival time. The selected arrival times are marked by a red line extending downward from the seismograms. The scale at the bottom of the window is relative time in minutes. To the left of each seismogram is information about the station and seismogram. The station name is a 3, 4 or 5 letter code. BHZ indicates the vertical component of motion from a broadband seismograph. The second line of text lists the date (YYYY/MO/DA) and the time of the start of the seismogram (HR:MN:SS.ss). The next line gives the date (YYYY/MO/DA) and the arrival time (HR:MN:SS.ss).



1.5 Finding the earthquake epicenter: Next, the initial trial epicenter is selected by clicking on the map display. In practice, any location will work to start the process, but because we have seismograms that are all recorded and displayed in absolute time, we know that the epicenter must be closest to the station corresponding to the seismogram with the earliest travel time. Therefore, one should select an initial trial epicenter near the station with the earliest arrival

time. For the Bolivia event, an initial trial epicenter was selected as shown in Figure 5. We know that this epicenter won't be correct but it provides us with information (calculated by the program based on standard Earth models and travel time curves – see **How EqLocate Works**, below) on how well the location fits the arrival times and an indication of the adjustments in the location needed to obtain a better fit to the data.

The degree to which the data from the trial epicenters fits the observed arrival times (“the quality of the solution”) can be visualized and understood with three different but related displays. After the trial epicenter is selected, the epicenter-to-station distances are calculated by the program and theoretical travel times for each of these distances can be calculated by interpolation of the standard travel time curves, and an origin time for the earthquake estimated. The theoretical arrival times are then calculated and compared with the observed (user-selected, or, “picked”) arrival times. A consistent measure of the fit of all the arrival time data is the *RMS* (Root Mean Square) *error* (the *RMS error* is a measure of the average error of the observed minus theoretical arrival times) shown on the yellow bar near the upper left hand corner of the map display. For the Bolivia data, the *RMS error* for the initial trial epicenter (Figure 5) is 47.74 s, indicating fairly large time differences between the observed and theoretical arrival times. One can also view these time differences on the seismogram window by comparing the observed and theoretical arrival time marks (red and blue vertical lines extending from each seismogram).

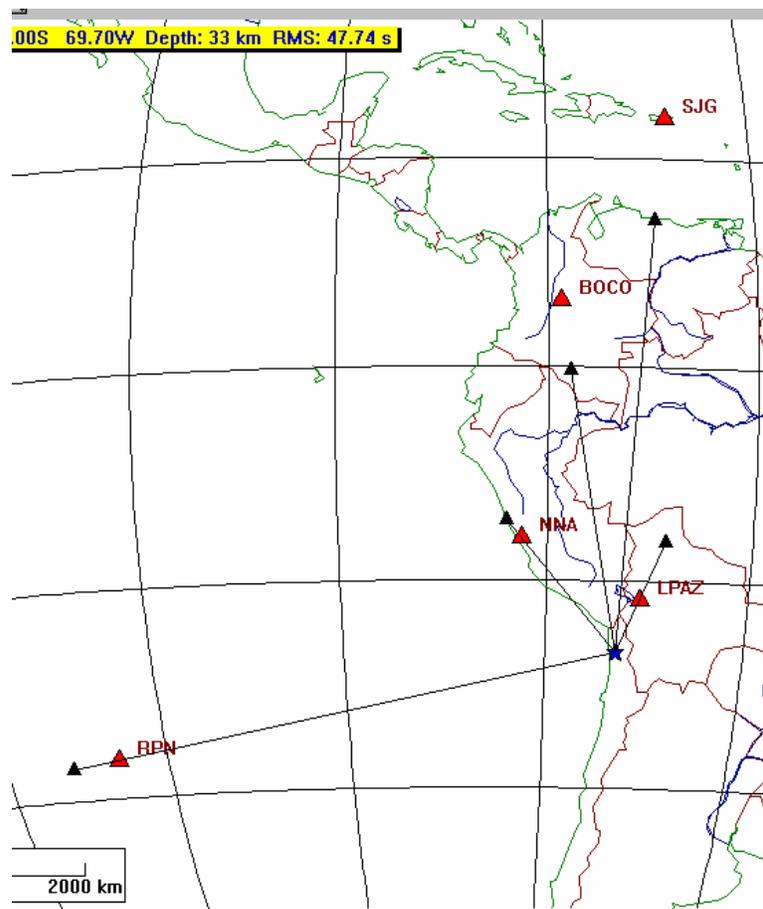


Figure 5. Portion of the EqLocate screen after the initial trial epicenter (small blue star) has been selected. A depth of 33 km was chosen for the initial trial epicenter. The small black triangles and lines extending from the trial epicenter toward the stations indicate the estimated distance to each

station based on the arrival times and the origin time estimated from an average of the time information (see **How EgLocate Works**, section 2, below). The black lines are simply straight lines connecting the epicenter with the estimated epicenter-to-station distance (from the observations – not the distance calculated from the coordinates of the trial epicenter and the stations). These lines do not represent the paths that the seismic waves would travel. The paths would be slightly curved lines on this map projection connecting the trial epicenter and the station. The RMS error (in this case 47.74 s) indicates that our trial epicenter is not a good solution. The fact that the calculated epicenter-to-station distances (from epicenter to each station – red triangle) do not match the estimated distances (epicenter to small black triangles) also indicates that the initial epicenter is not correct. Comparing the observed and theoretical arrival times in the seismogram window also confirms that the trial epicenter is not correct.

Theoretical arrival times that are earlier than the observed arrival time indicate that the trial epicenter needs to be moved farther from that station. Similarly, theoretical arrival times that are later than the observed arrival time indicate that the trial epicenter needs to be moved closer to that station.

An additional display of the fit of the trial epicenter and of the direction to move the epicenter for a better fit is provided by the black triangles and lines on the map display. The positions of the small black triangles and the lengths of the lines are calculated by the program and represent the expected distance to the corresponding station *if* the trial epicenter is correct. A mismatch in the positions of the triangles means that the trial epicenter needs to be moved. If the estimated distance is less than the epicenter-to-station distance (the line connecting the epicenter to the small black triangle does not reach the station), **the epicenter needs to be moved toward that station**. Similarly, if the estimated distance is greater than the epicenter-to-station distance (the line connecting the epicenter to the small black triangle goes through the station), **the epicenter needs to be moved farther from that station**. For example, for the initial trial epicenter for the Bolivia earthquake (Figure 5), the mismatch of the triangles for both stations SJG and BOCO is significant, so the trial epicenter is moved to the north (toward stations SJG and BOCO). The result is shown in Figure 6. Note that the estimated distances (thin black lines) are much closer to the actual distances and that the *RMS error* has been reduced. Therefore the second trial epicenter has resulted in a better solution (the theoretical data more closely fit the observed data). Also note that the calculations described above associated with selecting the new trial epicenter are performed very rapidly by the program so many trial epicenters can be tried very quickly.

An additional feature appears in the map display for the second trial epicenter (Figure 6). Because the *RMS error* is less than the maximum *RMS error* that we have set for the color bar on the map (in this case, 40 s; use the **Controls** menus to set the maximum *RMS error* for the color bar display), the second trial epicenter is color-coded, providing a quick, visual indication of the degree of fit of the location. However, in this case, the relatively high *RMS error*, the mismatch of the estimated and actual station locations, and the mismatch of the observed and theoretical arrival times (visible in the seismogram window) all indicate that the trial epicenter is still not good enough.

The search can be continued by selecting another trial epicenter using the positions of the small black triangles as guides to which direction to move the epicenter. A relatively small *RMS error* solution can usually be found with a few more trials using this approach. However, a very effective alternative, and one that provides additional insight into the solution, is to simply try

many epicenters near the location where a relatively low *RMS error* solution has been found. Because the program calculates new solutions so rapidly, it is very fast and easy to search for the optimum location using this method. For example, for the Bolivia earthquake, many trial epicenters near the location selected in Figure 6 were selected with many rapid clicks of the mouse. The result is shown in Figure 7.

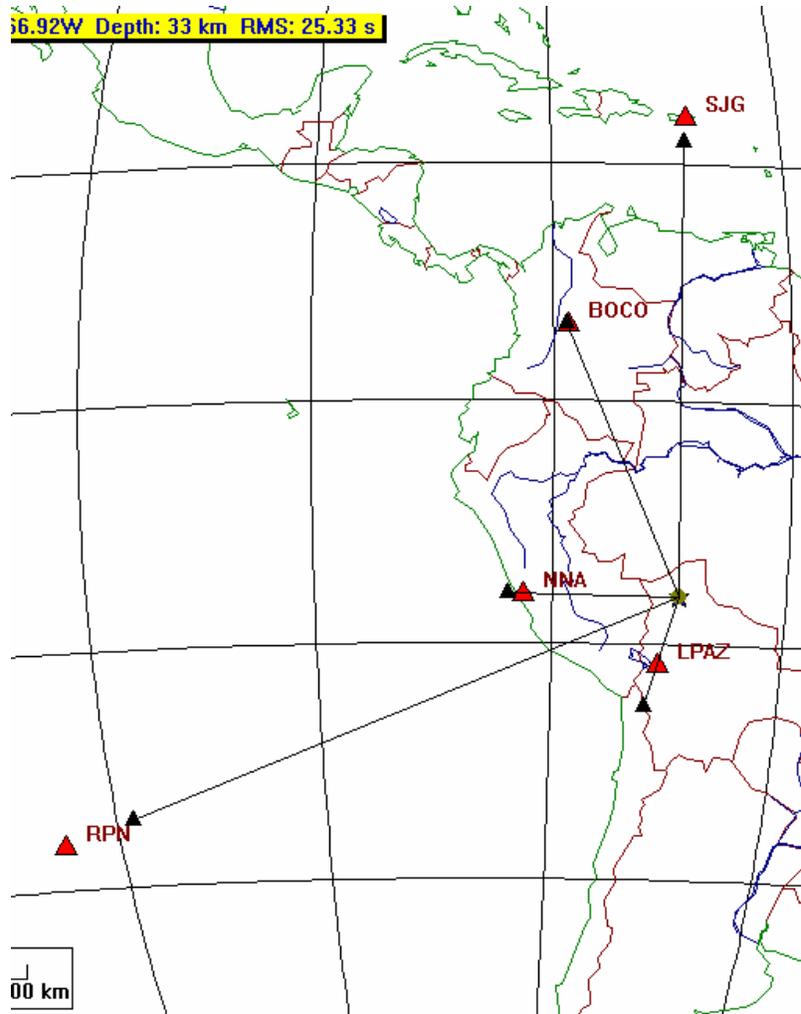


Figure 6. Portion of the EgLocate screen after the second trial epicenter (small blue star) has been selected. The location is improved – the estimated epicenter-to-station distances derived from the arrival time data (small black triangles connected to the epicenter by thin lines) are closer to the theoretical distances (epicenter to station), and the RMS error has decreased significantly.

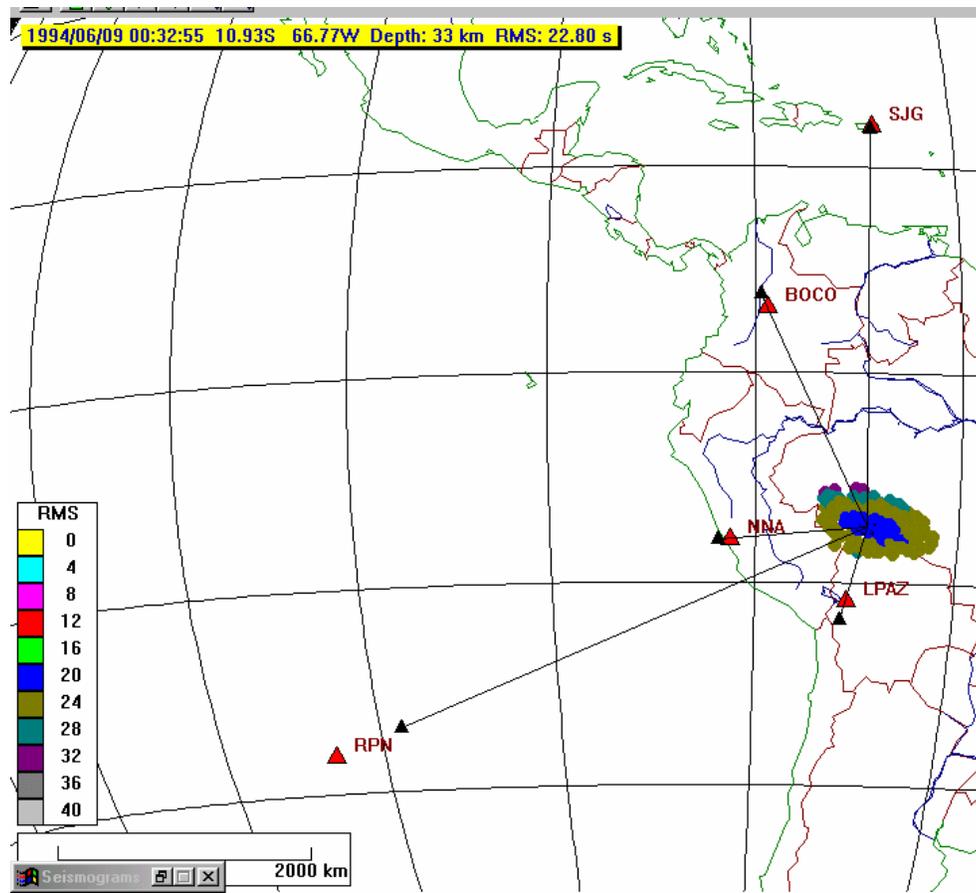


Figure 7. Portion of the EgLocate screen after the best solution has been found for the initial depth of focus – 33 km. The RMS error has been reduced but it is still large. This error corresponds to an average of many seconds of error per station, whereas arrival time accuracy is about one second or less. The mismatch of the small black triangles and the station locations also indicates that the solution is not very good. However, by selecting epicenters all around the lowest RMS error epicenter, the RMS color pattern shows that this epicenter is optimum for the chosen depth. This pattern also provides an estimation of the uncertainty in the epicenter location.



1.6 Estimating the possible error in the derived epicenter: For the depth of focus that was originally selected (33 km), the best solution found corresponded to an *RMS error* of 22.8 s (Figure 7). Furthermore, by selecting many trial epicenters, an approximately elliptical-shaped area has been outlined by the colors on the map. The colors show that the lowest *RMS error* epicenter is near the center of this ellipse and the size of the ellipse gives an indication of the possible error in the derived solution. For example, one can see that the central blue area (corresponding to an *RMS error* that is somewhat less than the solutions in the surrounding area) is about 600 km wide. Because any epicenter in the blue area has about the same *RMS error* (in this case, between 20 and 24 s), the different locations are not *significantly* different in the degree of fit to the observed data. Thus we might conclude that the accuracy of our epicenter is about +/- 300 km. A more complete estimation of the possible inaccuracy of the epicenter is somewhat more complicated and requires the knowledge (or reasonable assumption) of the accuracy of the data including the observed arrival time accuracy, the accuracy of the locations

of the stations, and the validity of the Earth model that is used to calculate the travel time curves. However, color-coding of regions of error in the earthquake location, as shown in Figure 7, is at least a useful relative indicator of the accuracy of the solution.



1.7 Determining the depth of focus of the earthquake: The *RMS error* for the best solution shown in Figure 7 is still relatively large. More data (seismograms from additional stations) might help, but a likely problem that we have not addressed thus far is the depth of focus of this earthquake. The depth of 33 km was chosen arbitrarily as a starting depth because most earthquakes are relatively shallow. However, the large *RMS error* and the significant mismatch in the distances (as indicated by the triangles on the map in Figure 7) suggest that the depth of focus might be significantly different than 33 km. We can easily test this hypothesis by selecting other depths and then selecting new trial epicenters. Setting the depth is easily accomplished using the Depth window that is opened from the **Control** menu. Performing multiple epicenter searches as illustrated in Figure 7 for a variety of depths yields locations with *RMS errors* that are shown in Table 1. The errors decrease significantly for the optimum trial epicenters corresponding to greater depth of focus. The minimum *RMS error* is found for a depth of focus of 650 km although there is very little difference in the errors found for any depth from about 580 km to 650 km. The resulting solution is shown in Figure 8.

Table 1. Depth of focus and minimum RMS error for the June 9, 1994 Bolivia earthquake.

Depth of Focus (km)	Minimum <i>RMS Error</i> (s)
33	22.8
100	21.1
200	18.9
300	14.5
400	9.3
500	6.7
600	1.8
650	1.7

The small *RMS error*, the comparison of the estimated and calculated distances to each station (correspondence of the small black triangles and the red triangles), and the match of the observed and theoretical arrival times in the seismogram window (Figure 9), all indicate that the epicenter shown in Figure 8 provides a very good fit to the observed arrival times. Furthermore, the small error ellipse (the yellow area outlined in Figure 8 representing epicenters corresponding to *RMS errors* of less than 4 s) suggests that the derived location is reasonably accurate (about +/- 50 km in epicenter location and +/- 70 km in depth).

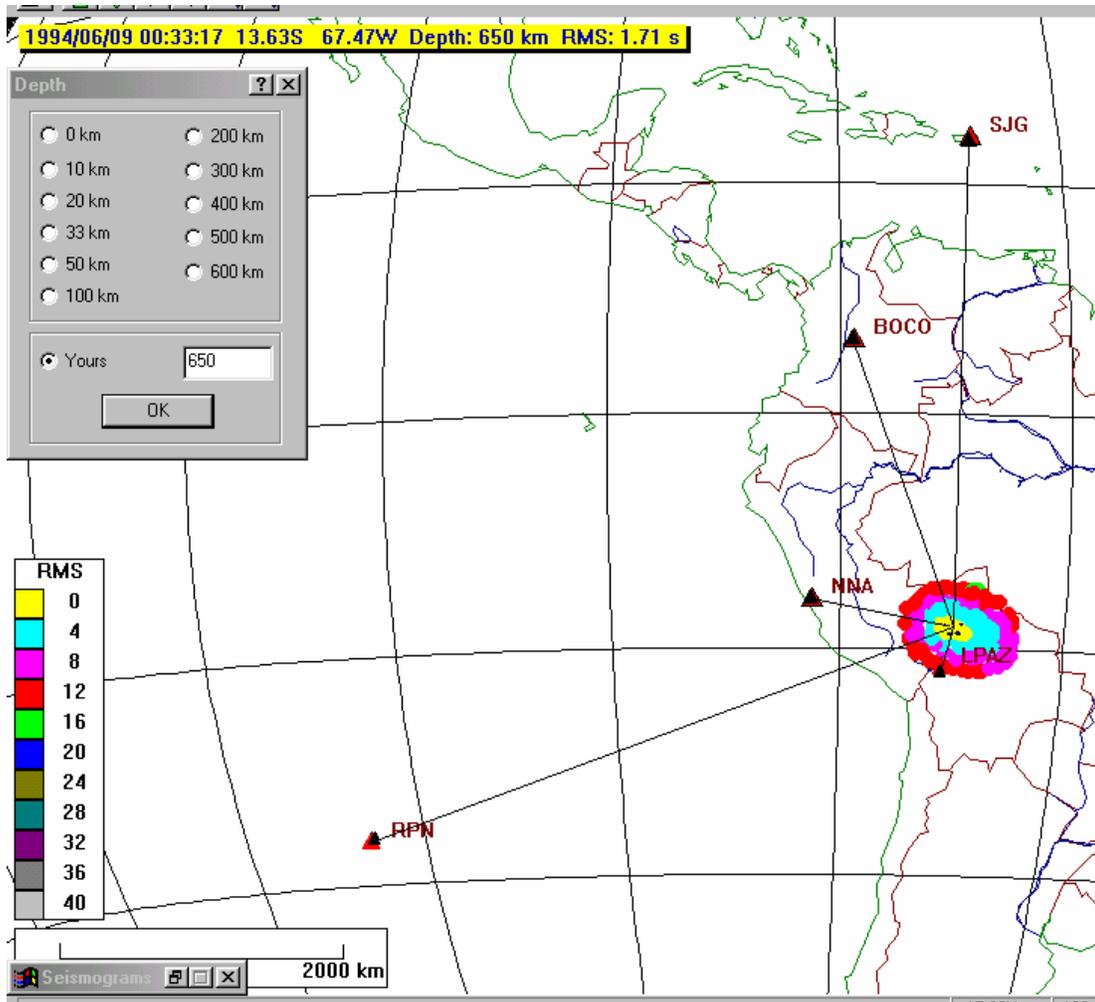


Figure 8. Portion of the EQLocate screen after the final trial epicenter (small blue star) has been selected. Various depth of focus values were tried up to 650 km (very few earthquakes have been recorded that have depths greater than 650 km). The small RMS error (1.71 s), the match of the estimated distances and the theoretical distances (black and red triangles are almost at the same location), the small error ellipse defined by the colors, and the small observed minus theoretical arrival time differences seen on the seismogram display, indicate that the earthquake location (latitude, longitude, depth of focus and origin time) determined using these seismograms and EQLocate is accurate.

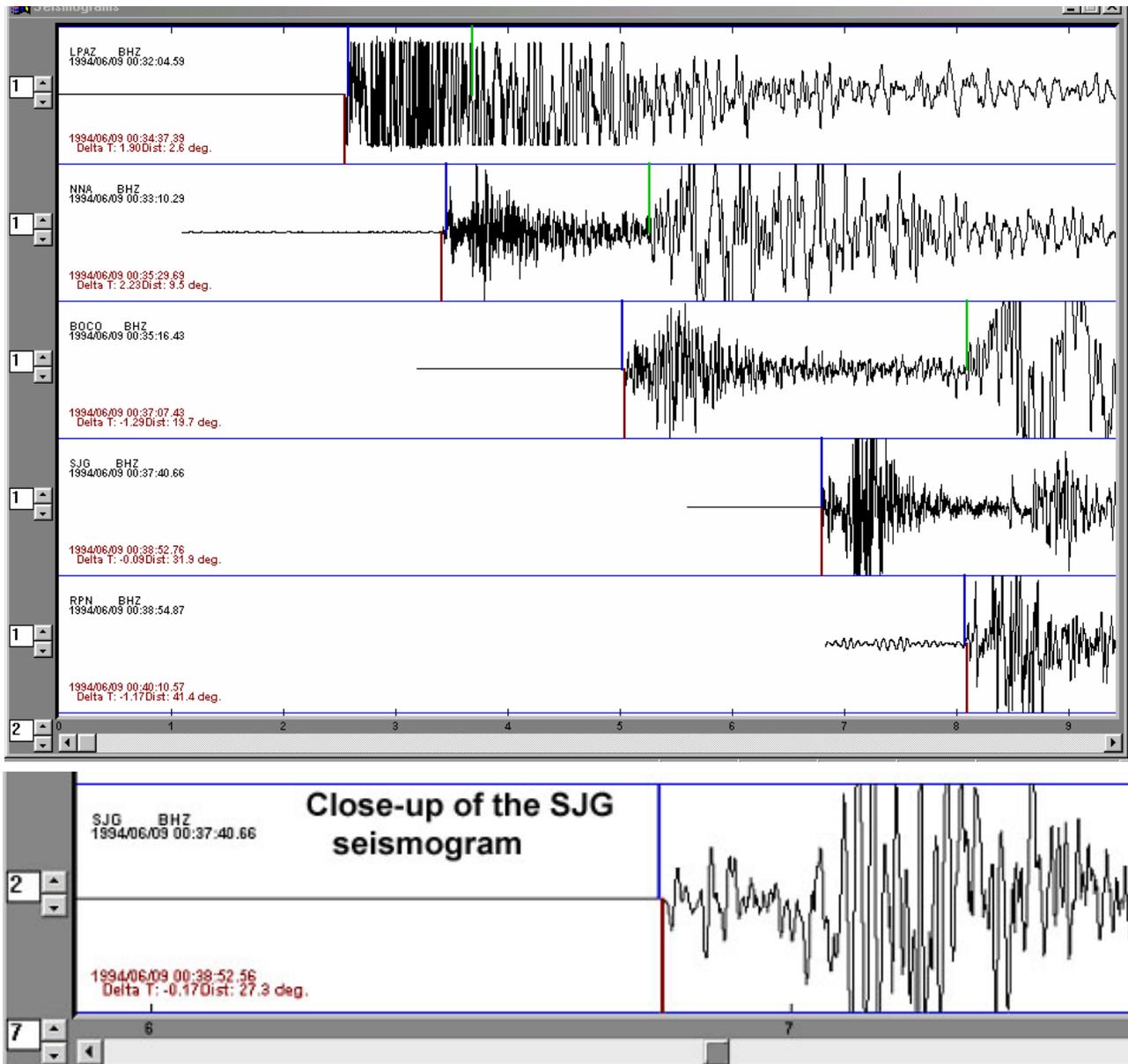


Figure 9. EqLocate seismogram window (upper diagram) for the June 9, 1994 Bolivia earthquake after optimum location has been determined. The vertical blue lines extending up from each seismogram marks the theoretical arrival time of the P-wave, which is the origin time estimated by the program plus the travel time from the travel time curves. Note that the observed and theoretical arrival times are nearly identical. For comparison with the seismogram, the vertical green lines indicate the theoretical S-wave arrival times. After the first trial epicenter has been selected, the last line of the text display for each seismogram is added to the window. This line lists the difference between the observed and theoretical arrival time (Delta T) and the epicenter-to-station distance (Dist) in degrees (geocentric angle; one degree = 111.19 km along the Earth's surface). A close-up view (lower diagram) of the SJG seismogram is also shown that illustrates the accuracy of the fit and the fact that the measurement of the arrival times (interpreted from the first arriving P wave signal) can be made with excellent time precision (note the time scale at the bottom showing one minute of time between the tic marks labeled 6 and 7).



1.8 Checking the accuracy of the solution: To check the accuracy of the location, a comparison between the “official” location and the location determined using the five seismograms and EqLocate is shown in Table 2. As can be seen from Table 2, the EqLocate solution is very good. The official location information for earthquakes can be found from the earthquake search tool on the US Geological Survey web page (<http://earthquake.usgs.gov>) or using the event search tool on the IRIS DMC web page (<http://www.iris.edu>). Detailed instructions (including examples) for accessing earthquake information from the Internet for recent and historical events are provided at: <http://web.ics.purdue.edu/~braile/edumod/eqdata/eqdata.htm> (see section 2.3).

Table 2. Comparison of the official (USGS) location (latitude, longitude, depth and origin time) for the Bolivia earthquake determined from over a hundred arrival times, with the EqLocate location determined from the five seismograms shown here.

<i>Bolivia Earthquake (June 9, 1994)</i>	<i>Official Location</i>	<i>EqLocate Location</i>
Latitude (degrees S)	13.84	13.63
Longitude (degrees W)	67.55	67.47
Depth of focus (km)	631	650
Origin Time (HR:MN:SS, GMT/UTC)	00:33:16	00:33:16



1.9 Selection of seismograms: In selecting seismograms to use in EqLocate to determine the epicenter or hypocenter of an earthquake, one should select at least 3 seismograms to obtain an estimate of the epicenter (there are 3 unknowns to determine – latitude, longitude and origin time) and at least 4 seismograms to obtain an estimate of the hypocenter (there are 4 unknowns to determine – latitude, longitude, origin time and depth of focus). Using additional seismograms (stations) will generally improve the accuracy of the solution. In practice, using about 5-8 seismograms will provide for a rapid and reasonably accurate solution. Selecting at least one station that is reasonably close to the epicenter (one usually knows the approximate location for significant events from damage or felt reports even before a calculated location is available, although calculated locations are sometimes available on the Internet just a few minutes after the earthquake), will improve the solution, especially for deep focus earthquakes. Also, the seismograph stations should approximately “surround” the epicenter, and especially not be all from the same direction. As an example of this problem, three seismograms were used to locate the Northridge earthquake using EqLocate (Figure 10). Because the stations selected and the epicenter are located approximately along a line, the resulting location is very poorly determined. The best fitting epicenter corresponds to a very low *RMS error* (0.39 s), but solutions (epicenters) that are almost as good are found in a very broad region outlined in Figure 10 by the color-coded *RMS errors* for many trial epicenters. The “banana” shape of this region is caused by the station locations with respect to the epicenter. Because the stations are located approximately along a line, the arrival time data for the three stations provide a very poor “triangularization” of the epicenter. For this set of stations, a small error in one of the observed arrival times (from “picking” the wrong arrival, from noise on the seismogram, or from timing errors in the seismograph station) could result in a fairly large error in the epicentral solution.

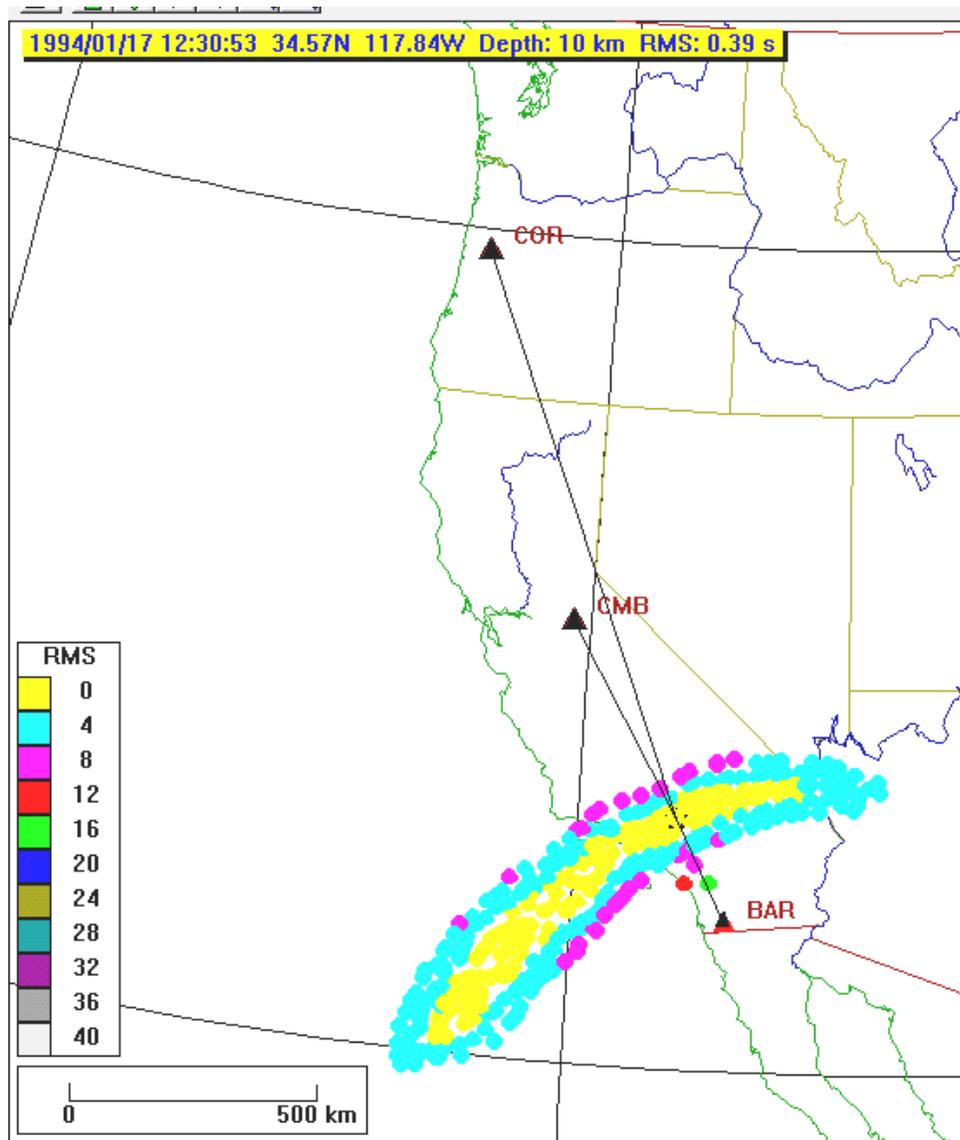


Figure 10. Color-coded RMS errors for trial epicenters for the Northridge (January 17, 1994) earthquake using EqLocate and only three seismograms. Epicenters corresponding to solutions with RMS errors less than 4 s are indicated by the yellow area.



2. How EqLocate Works:

2.1 Monitoring earthquakes: Seismograph stations around the world continuously record seismic data (vibrations of the ground) to monitor earthquake activity and detect and record the signals from explosions. These seismographs also record seismic signals from various noise sources such as ocean waves hitting the coastline (a primary cause of microseisms), wind, nearby traffic, sonic booms, volcanic eruptions, lightning and thunder, and other sources of ground vibration. When a significant earthquake occurs, seismic waves travel through the

Earth's interior and the waves are recorded on seismographs around the world. A seismogram from a single seismograph station cannot be used to determine where the earthquake occurred. In fact, from the compressional or P-wave arrival time (the compressional wave is the earliest arrival and its time is usually accurately determined) recorded on a single seismogram, we cannot determine the location, distance or origin time of the event. If an S-wave is also identifiable on the seismogram, the distance from the station to the earthquake and the origin time can be estimated from the single station record using the difference in the time of arrival of the S- and P-waves. This difference is proportional to the distance from the station. If S- and P-wave arrival times are available from three or more stations, it is possible to determine the epicenter (with some accuracy) by triangulation using the S minus P times. This S minus P method is relatively easy to use and the method is instructive for learning about earthquake location and seismic waves. More information about earthquake location methods and the S minus P method can be found in Bolt (1993, p. xxx), and the following Internet sites:

<http://quake.wr.usgs.gov/info/eqlocation/>, <http://www.scecdc.scec.org/Module/s3act03.html>,

<http://www.geo.mtu.edu/UPSeis/locating.html>,

http://www.geol.vt.edu/outreach/vtso/anonftp/iasphand/CD_volume/8517Lee/,

<http://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-99-0023> (description of the HYPOELLIPSE program), and

<http://www.seismo.unr.edu/ftp/pub/louie/class/100/seismic-waves.html>.

Earthquake location teaching modules can be found at:

<http://www.geol.binghamton.edu/~barker/labs/lab3.html> (S minus P with actual seismograms),

<http://www.sciencecourseware.com/eec/Earthquake/> (the *Virtual Earthquake* activity),

<http://web.ics.purdue.edu/~braile/edumod/walkrun/walkrun.htm> (an earthquake location simulation using walking to represent S waves and running to represent P waves), and

<http://web.ics.purdue.edu/~braile/edumod/as1lessons/EQlocation/EQlocation.htm> (an S minus P earthquake location exercise that uses real seismograms (paper copies or viewed and interpreted on your computer using the AmaSeis program) and instructions for mapping the location on a globe or using an online mapping tool (also see

<http://web.ics.purdue.edu/~braile/edumod/eqdata/eqdata.htm> for an example of the use of the online mapping tool).

However, the S minus P method is not the approach that is generally used by seismologists to locate earthquakes. Normally the P-wave arrivals are used. There are several reasons for this choice. Because the S wave is always a secondary arrival and other waves may interfere with identifying the first S-wave arrival, the accuracy of the S-wave arrival time is often significantly lower than for the P wave. Also, the S-wave arrival is often less distinct (and, therefore, the arrival times may be subject to considerable uncertainty) than the first P arrival, especially on vertical component seismograms. It is easier to include arrival times from many seismograph stations and to analyze the possible uncertainties in the solution with the P-wave method. Estimating the depth of focus of the earthquake is also much easier using the P waves.



2.2 Seismograms recorded at seismograph stations: An example of a seismogram recorded at a standard seismograph station from seismic waves generated by an earthquake is shown in Figure 11. The approximate raypath that the P- and S-waves have traveled through the Earth to reach the seismograph station is shown. The P- and the S-wave arrivals are identified on the seismogram. In the EqLocate program, only the P-wave arrival time is used. Note that for a

single station and seismogram, the origin time of the earthquake and the distance to the station is unknown until determined by analysis of several arrival times (data from several stations).

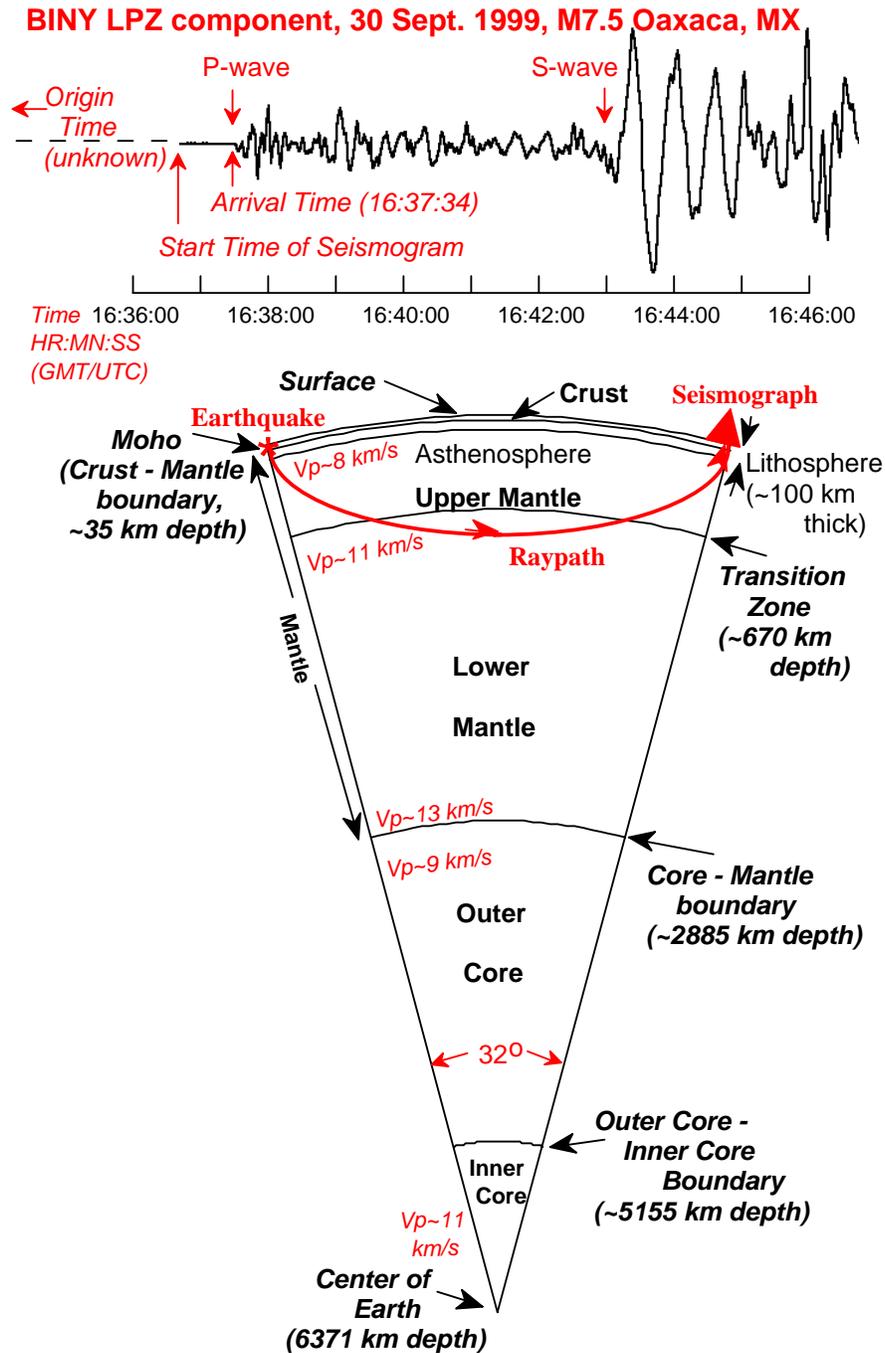


Figure 11. Segment of Earth model showing main boundaries and layers, and approximate compressional- or P-wave velocity with depth. Raypath shows approximate travel path for the first arriving P-wave for the seismogram shown above. The seismogram was recorded by the Binghamton, NY (BINY) station and is the record of the long period, vertical component (LPZ) of motion. The source was the M7.5, Oaxaca, Mexico earthquake of September 30, 1999. The distance from the earthquake epicenter to the seismograph station was approximately 32 degrees geocentric angle, corresponding to about 3560 km along the Earth's surface.



2.3 Flow chart for the EqLocate program: A flow chart that illustrates how the computer program EqLocate works is shown in Figure 12. The user selects earthquake data (seismograms) for a specific event and opens the records. The map display is then adjusted, arrival times of seismograms picked (arrival times measured) and a trial hypocenter selected as illustrated in the **Running EqLocate** section of this tutorial. The EqLocate program then calculates the trial epicenter-to-station distances and uses these distances to determine theoretical travel times using interpolation of the standard travel time curves as shown in Figure 13.

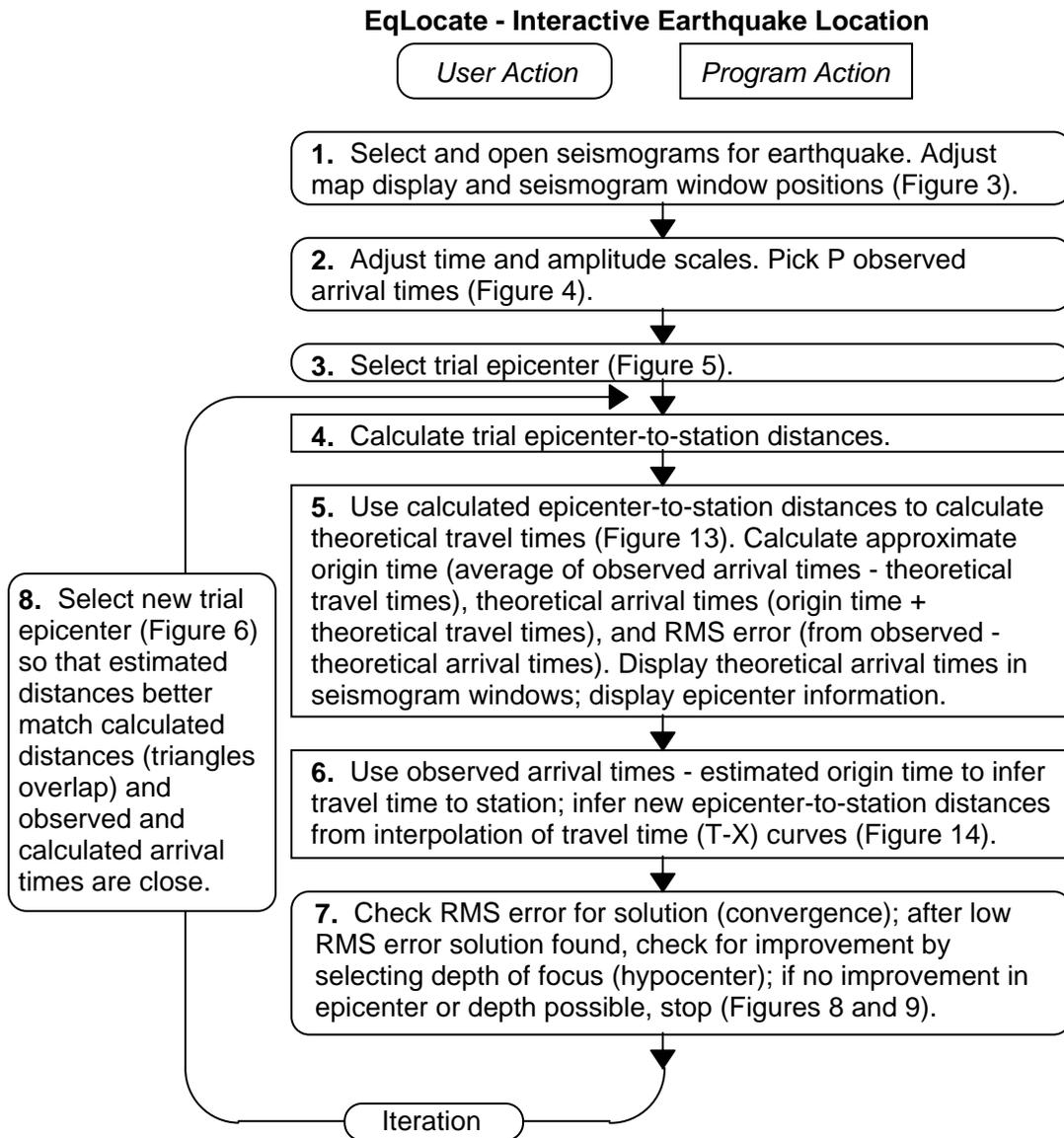


Figure 12. Flowchart for the EqLocate program. Steps 1, 2, 3, 7, and 8 are performed by the user. Steps 4, 5 and 6 are performed by the program by calculations and adjusting the map display and data displayed in the map and seismogram windows. Step 8, connected by the long, curved arrows, represents multiple selections of the trial epicenter (iteration) to improve the fit until an optimum location is found.

An approximate origin time for the earthquake is then calculated by subtracting the theoretical travel times from the observed arrival times for each station and averaging these origin time estimates. This approximate origin time will not be exact, but because it is likely that the trial epicenter is too close to some stations and too far from others, the average of the origin times determined from each station will provide a reasonable “first approximation”. This approximate origin time provides the best possible estimate corresponding to the current trial epicenter. As new trial hypocenters are selected (using the EqLocate display that indicates the direction to move the epicenter to obtain a better location; described in section [1.5](#), above), the hypocenter solution will be improved through the very rapid trial and error process and the color coded location estimates will indicate the best location estimate. Theoretical arrival times are then calculated for each station by adding the theoretical travel times to the approximate origin time. The theoretical arrival times are displayed on the seismograms in the seismogram window for comparison with the observed arrival times.

A good quantitative measure of the error in the arrival times (differences between observed and theoretical arrival times and therefore of the accuracy of the trial epicenter) is provided by the *RMS* (Root Mean Square) *error* defined as:

$$RMS\ error = Sqrt[(Sum(obs - the)^2) / n],$$

where *Sqrt* is the square root operation, *Sum* is the sum of all squared differences between the observed (*obs*) and theoretical (*the*) arrival times, and *n* is the number of arrival times (seismograms). The *RMS error* can be interpreted as an “average” error of the arrival times. For example, if there are four seismograms and the arrival time errors (observed times minus theoretical times) are -0.55, 3.71, 6.73, and 7.54 seconds, the *RMS error* is 5.39 s. The size of the *RMS error* can be compared to an estimate of the accuracy of the measurement of the arrival times from the seismograms to evaluate the quality of the location solution. For example, it is often possible to measure the arrival times with an accuracy of about 1 second or less (an example is shown in Figure 9, lower diagram, for the June 9, 1994 Bolivia earthquake) suggesting that the *RMS error* in a location solution should also be of similar size (depending on number of stations used, noise on the seismograms, possible errors in timing for one or more seismograph stations, and other sometimes unknown factors such as local variations in Earth structure that affect the observed arrival times for some stations).

After a trial epicenter has been selected, and estimates of the origin time and error in the solution (*RMS error*) calculated (as described above), the EqLocate program provides a display (for example, Figure 5) of the stations and trial epicenter locations as well as calculated distances (based on the provisional origin time and the observed arrival times) as illustrated in Figure 14. The calculated distances (assuming that the origin time is correct) are displayed on the EqLocate map view as triangles that are connected to the epicenter by thin black lines drawn from the epicenter toward the station. The calculated distances (estimated from the travel times by the method illustrated in Figure 14) provide an indication of which direction to move the epicenter to produce a better location solution. For example, if the black line from the epicenter to the station does not extend all the way to the station, the epicenter needs to be moved toward that station (the distance inferred from the calculated travel times is too small because of the location of the trial epicenter). In contrast, if the black line from the epicenter to the station extends beyond the station, then the epicenter needs to be moved away from that station to produce a better location solution. In the example shown in Figure 5, the trial epicenter needs to

be moved away from stations RPN, NNA and LPAZ and toward stations BOCO and SJG where the largest distance errors are observed. The only direction to move the epicenter that will satisfy these constraints is to the northeast. In the Bolivia earthquake example (Figure 5), moving the trial epicenter to the northeast results in a trial solution shown in Figure 6. This trial epicenter is still not correct but is an improvement. In practice, the trial and error procedure, with “guidance” from the EqLocate program (positions of small black triangles relative to the station locations), is very rapid and intuitive after the first few trials and the optimum epicenter is determined efficiently. The lowest RMS error solution will be visibly evident on the EqLocate map as the locations of the black triangles overlap the station locations (as in Figure 8). It may be necessary to vary the depth of the earthquake (as described in section 1.7, above) in order to obtain the lowest *RMS error* solution. However, for some station locations and data sets, it will not be possible to accurately determine the earthquake depth.

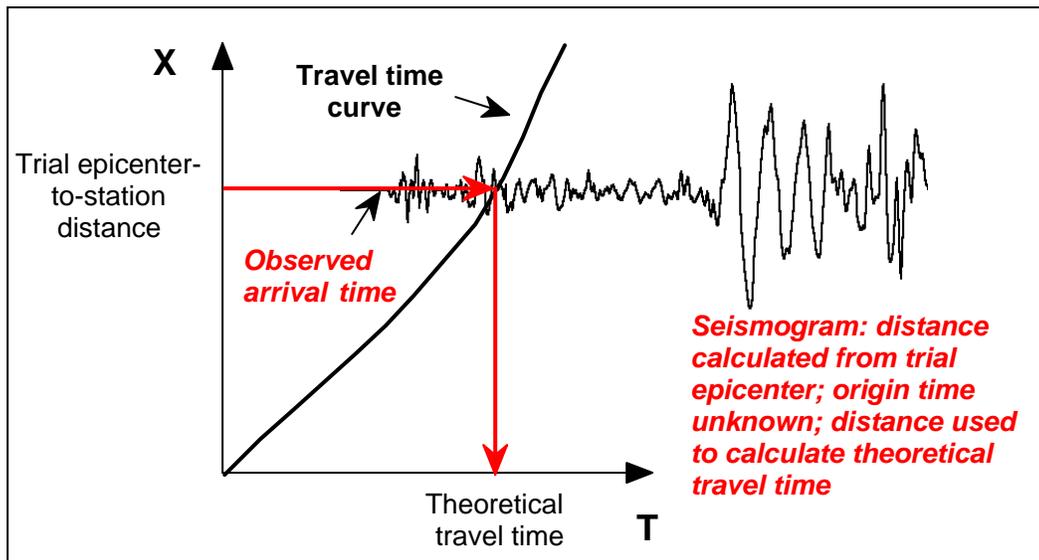


Figure 13. Interpolation of the travel time curve to obtain theoretical travel time (for the trial epicenter). The X axis is distance from the epicenter. The T axis is travel time. This travel time curve marks the travel time of the P-wave with distance. When a trial epicenter is selected, the trial epicenter-to-station distance can be calculated for each station (from the trial epicenter and station coordinates). The theoretical travel time is found (follow red arrows for interpolation) by using the standard travel time curve (for the depth of focus selected) corresponding to the well-known seismic velocity model of the Earth. Because from a single station, we do not know the origin time of the earthquake (only the location of the station and the arrival times of the seismic waves, such as the P-wave, are known), the seismogram can be overlain on the travel time graph at the appropriate distance as shown, but the horizontal position (time with respect to the origin time) is not known. Note that the standard travel time curve (for the first P wave arrival time for a standard Earth velocity model) for this diagram has been plotted with the time scale on the horizontal axis and the distance scale on the vertical axis. This choice of axes is different than the conventional travel time curve plot (Figure 15) in which the distance scale is the horizontal axis and the travel time scale is the vertical axis. The choice of axes for this Figure (and Figure 14) allows the seismograms to be plotted horizontally as they are in the EqLocate seismograms window display (Figures 4 and 9, for example) and makes it easier to measure the arrival times and visualize the observed and theoretical arrival time differences.

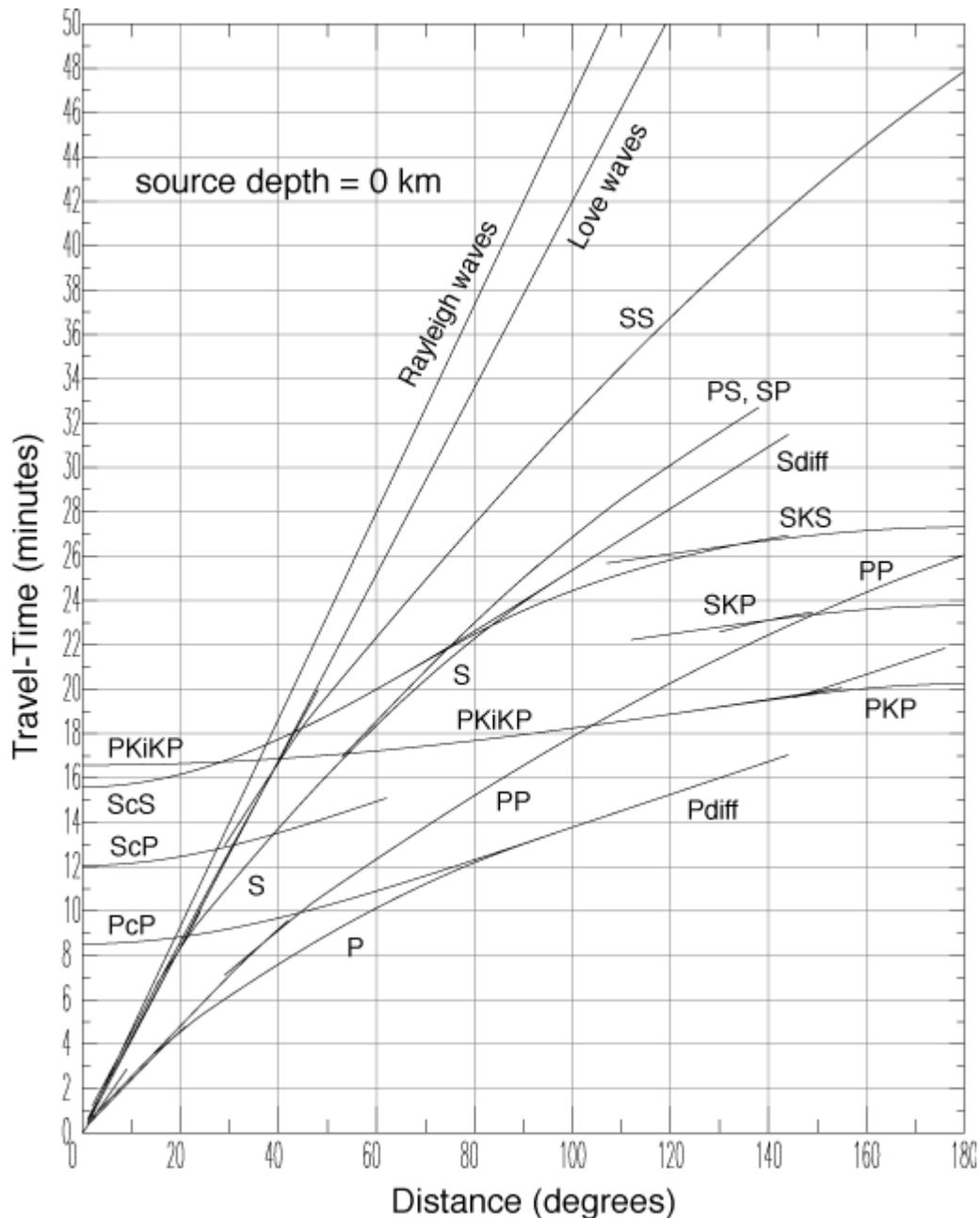


Figure 15. Standard travel time curves for various seismic arrivals for a standard Earth model and a zero depth of focus (from the Princeton PEPP page: <http://lasker.princeton.edu/index.shtml>). The P-wave travel times are used for EqLocate and the standard programs used by the US Geological Survey and by other seismologists to locate earthquakes from around the world. The P- and S-wave travel times (actually the time differences, S minus P travel times; also see http://neic.usgs.gov/neis/travel_times/ and the links included in section 2.1 above) are used in the S minus P method.

2.4 An additional example of the use of EqLocate (a local event – the June 18, 2002 southern Indiana earthquake): An additional example, in this case a regional event that involves a substantially smaller map area, is shown below. The selected seismograms are stations CCM, WCI, OXF (GSN stations), PPNVW (a PEPP station), and WLIN (an AS-1 station). The seismograms are available in the pre-assembled data set (Number 8, Central US 1)

in section 4, below. The earthquake location is illustrated in Figure 16 after many trial locations using EgLocate. The seismograms for the selected stations are shown in Figure 17.

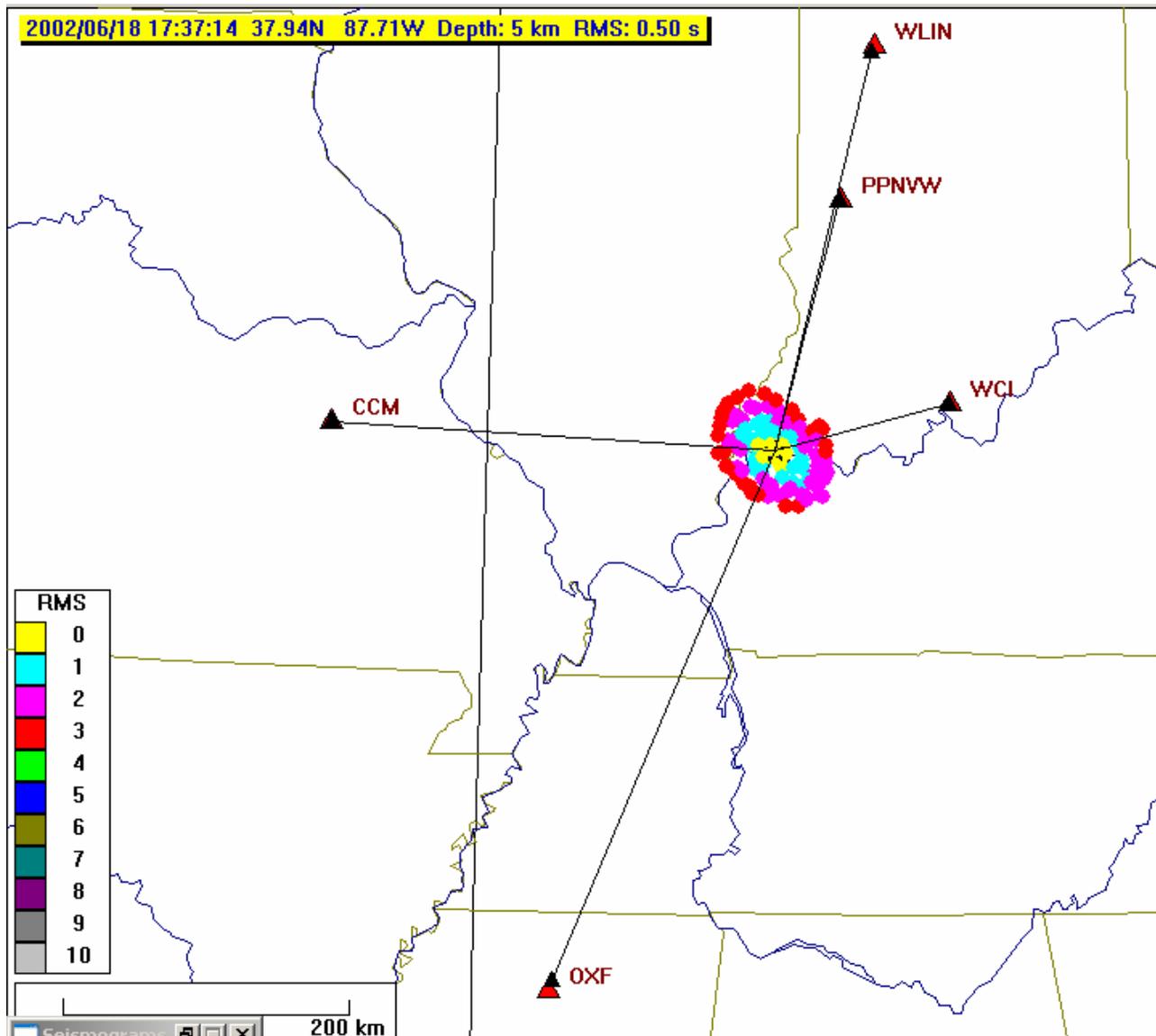


Figure 16. Stations (red triangles) and trial epicenters (colored dots) for the June 18, 2002 southern Indiana earthquake. The small error ellipse and small RMS error indicate that a reasonably accurate location has been determined. Because there are no stations that are very close to the earthquake, the depth of focus is likely to be less well determined. Seismograms for the stations shown here, and arrival time information are illustrated in Figure 17.

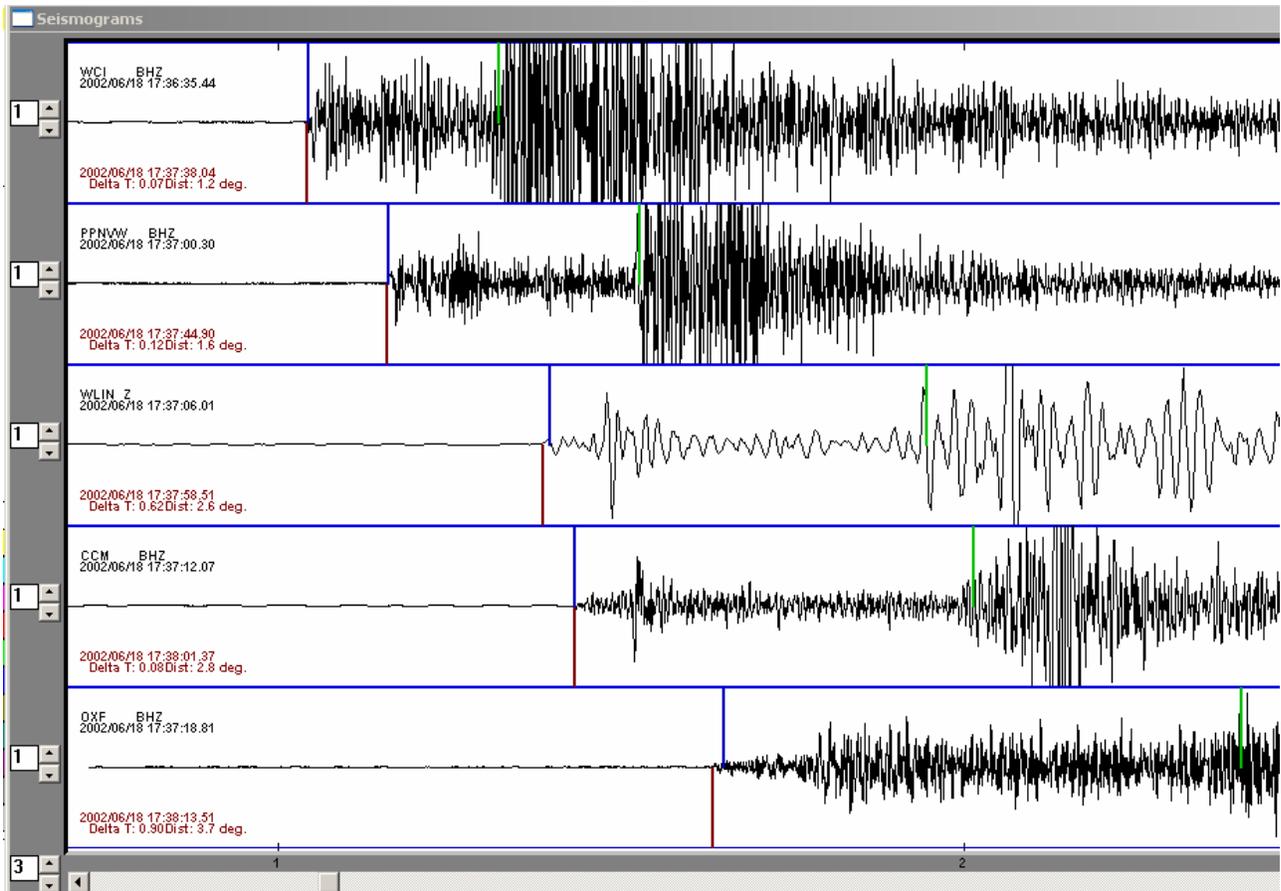


Figure 17. Seismograms, interpreted arrival times (“picks”; downward red lines), theoretical arrival times (calculated for the hypocenter shown in Figure 16; upward blue lines), a calculated S-wave arrival times (upward green lines) for the southern Indiana earthquake.



3. Importing Data into EqLocate: Detailed instructions for accessing data (SAC-format seismograms) from SpiNet (primarily AS-1 seismograms) and from the IRIS DMC archive (GSN, PEPP and other seismograms that can be downloaded in SAC format) using the WILBER II online tool are provided at: <http://web.ics.purdue.edu/~braile/edumod/as1lessons/UsingAmaSeis/UsingAmaSeis.htm> (see section 5).

When adding data to EqLocate data folders use the WILBER II SAC binary, individual files option. Also, rename the seismogram files to use a short file name (similar to the file names used in this tutorial) so that many seismograms can be opened by the EqLocate **Open** command. PEPP and AS-1 records in SAC format can also be added.

Pre-assembled data sets for use in EqLocate are provided in section 4, below.



4. Data Sets: Some data sets (including some of those shown below) are included in the download of EqLocate (from Alan Jones' website). To download seismograms for the events shown in Table 3, select the seismograms from the lists for the following events and place the downloaded .sac files in folders (named for the events) in your EqLocate folder.

Table 3. EqLocate earthquakes. Folders contain seismograms. Event is earthquake name. Origin time (UTC/GMT), hypocenter and magnitude information in column to right (Yr = Year, Mo = Month, Da = Day, Hr = Hour, Mn = Minutes, SS.ss = Seconds and decimal seconds, Lat = Latitude in degrees [South is negative], Lon = Longitude in degrees [West is negative], Dep = Depth of focus in kilometers, M = Magnitude).

Folder	Event	Yr	Mo	Da	HrMnSS.ss	Lat	Lon	Dep	M
1. S. America 1	N. Bolivia	1994	06	09	003316.23	-13.84	-67.55	631	8.2
2. S. America 2	Argentina	2000	04	23	092723.32	-28.31	-62.99	608	7.0
3. Cent. Amer. 1	Oaxaca	1999	09	30	163115.69	16.06	-96.93	60	7.5
4. Pacific NW 1	Nisqually, WA	2001	02	28	185432.83	47.15	-122.73	51	6.8
5. Eastern US 1	Ausable, NY	2002	04	20	105047.50	44.51	-73.70	11	5.2
6. W. Pacific 1	Kobe	1995	01	16	204652.12	34.58	135.02	21	6.9
7. California 1	Northridge	1994	01	17	123055.39	34.21	-118.54	18	6.8
8. Central US 1	So. Indiana	2002	06	18	173715.20	37.99	-87.78	5	5.0
9. Western US 1	Idaho	2001	04	21	171856.95	42.92	-111.39	0	5.4
10. Alaska 1	Kodiak Is. Reg	2001	01	10	160244.23	57.08	-153.21	33	7.0

- Folder/Event = "S. America 1":** [BOCO.BHZ.SAC](#), [NNA.BHZ.SAC](#), [SJG.BHZ.SAC](#), [LPAZ.BHZ.SAC](#), [RPN.BHZ.SAC](#).
- Folder/Event = "S. America 2":** [BDFB.BHZ.SAC](#), [NNA.BHZ.SAC](#), [SJG.BHZ.SAC](#), [PLCA.BHZ.SAC](#), [RCBR.BHZ.SAC](#).
- Folder/Event = "Central America 1":** [AMNO.LHZ.SAC](#), [COLA.LHZ.SAC](#), [KIP.LHZ.SAC](#), [BINY.LHZ.SAC](#), [HKT.BHZ.SAC](#); for a relatively simple data set, try stations AMNO, COLA, KIP and BINY.
- Folder/Event = "Pacific NW 1":** [ADK.BHZ.SAC](#), [COR.BHZ.SAC](#), [FFC.BHZ.SAC](#), [KDAK.BHZ.SAC](#), [NEW.BHZ.SAC](#), [TUC.BHZ.SAC](#), [AMNO.BHZ.SAC](#), [DUG.BHZ.SAC](#), [INK.BHZ.SAC](#), [MA2.BHZ.SAC](#), [SFJ.BHZ.SAC](#); for a relatively simple data set, try stations COR, FFC, KDAK, NEW, TUC and AMNO.
- Folder/Event = "Eastern US 1":** [BINY.BHZ.SAC](#), [LBNH.BHZ.SAC](#), [NCB.BHZ.SAC](#), [HRV.BHZ.SAC](#), [MCWV.BHZ.SAC](#).
- Folder/Event = "Western Pacific 1":** [ARU.BHZ.SAC](#), [GUMO.BHZ.SAC](#), [MA2.BHZ.SAC](#), [TUC.BHZ.SAC](#), [YSS.BHZ.SAC](#), [FFC.BHZ.SAC](#), [NAI.BHZ.SAC](#), [NWA0.BHZ.SAC](#), [ULN.BHZ.SAC](#); for a relatively simple data set, try stations GUMO, MA2, YSS and ULN.
- Folder/Event = "California 1":** [BAR.BHZ.SAC](#), [COR.BHZ.SAC](#), [NEE.BHZ.SAC](#), [PFO.BHZ.SAC](#), [TUC.BHZ.SAC](#), [CMB.BHZ.SAC](#), [ISA.BHZ.SAC](#), [PAS.BHZ.SAC](#),

[SBC.BHZ.SAC](#), [VTV.BHZ.SAC](#); for a relatively simple data set, try stations BAR, PFO, CMB, ISA, SBC and VTV.

8. **Folder/Event = “Central US 1”:** [ACSO.BHZ.SAC](#), [JFWS.BHZ.SAC](#), [MYNC.BHZ.SAC](#), [PPBNL.BHZ.SAC](#), [PPMUN.BHZ.SAC](#), [PPPCH.BHZ.SAC](#), [WLIN.AS1.SAC](#), [CCM.BHZ.SAC](#), [MCWV.BHZ.SAC](#), [OXF.BHZ.SAC](#), [PPEGH.BHZ.SAC](#), [PPNVW.BHZ.SAC](#), [SSPA.BHZ.SAC](#), [WMOK.BHZ.SAC](#), [GOGA.BHZ.SAC](#), [MIAR.BHZ.SAC](#), [PPBLO.BHZ.SAC](#), [PPFAY.BHZ.SAC](#), [PPPCC.BHZ.SAC](#), [WCI.BHZ.SAC](#); for a relatively simple data set, try stations WLIN, CCM, OXF, PPNVW and WCI.
9. **Folder/Event = “Western US 1”:** [AMNO.BHZ.SAC](#), [COLA.BHZ.SAC](#), [NEW.BHZ.SAC](#), [CCM.BHZ.SAC](#), [COR.BHZ.SAC](#), [SSPA.BHZ.SAC](#), [CMB.BHZ.SAC](#), [DUG.BHZ.SAC](#); for a relatively simple data set, try stations NEW, COR, CMB and DUG.
10. **Folder/Event = “Alaska 1”:** [COLA.BHZ.SAC](#), [HKT.BHZ.SAC](#), [NEW.BHZ.SAC](#), [TLY.BHZ.SAC](#), [DUG.BHZ.SAC](#), [INK.BHZ.SAC](#), [RES.BHZ.SAC](#), [TUC.BHZ.SAC](#), [HIA.BHZ.SAC](#), [MDJ.BHZ.SAC](#), [SSE.BHZ.SAC](#); for a relatively simple data set, try stations COLA, INK, RES, TUC and MDJ.

Notes for additional development of tutorial:

Add Denali event? Add an example with only AS-1 seismograms?

Add intermediate depth event to show minimum RMS error (larger errors for both shallower and deeper hypocenters) ?

Questions

Teaching strategies



5. References:

Bolt, B.A., *Earthquakes and Geological Discovery*, Scientific American Library, W.H. Freeman, New York, 229 pp., 1993.

Herrmann, R.B., FASTHYPO: A hypocenter location program, *Earthquake Notes*, **50** (2), 25-37, 1979.



6. Acknowledgements:

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