

Article

An Interactive System Based on the IASP91 Earth Model for Earthquake Data Processing

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Abstract: System software for interactive human–computer data processing based on the IASP91 Earth model was designed. An interactive data processing system for visualizing earthquake data was designed and implemented via the Intel Fortran platform. The system reads and processes broadband seismic data acquired by field stations, mainly including the reading and import of raw data, pre-processing, identification of seismic phases and inter-correlation traveltimes picking. In the data processing step, shortcomings have been improved and functions have been gradually refined and enhanced, making it easier and faster to process data. It has already processed more than 1000 large seismic events received by the station from 2013 to 2018. The practical application shows that the human–computer interaction system is easy to operate, accurate, fast and flexible, and is an effective tool for processing seismic data.

Keywords: seismic data; IASP91 earth model; data processing; Traveltimes; system software



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1. Introduction

One of the tasks of seismology is to analyze natural earthquake observations and seismic data. This allows us to gain information on the propagation characteristics and traveltimes of the different seismic phases generated by each seismic event, and thus to study the structural characteristics of the Earth's interior [1–3]. However, the amount of observed data is staggering. Finding the natural seismic signal in the vast amount of natural seismic observations and identifying the individual phases in the seismic record of that event is a single, repetitive and very time-consuming task. The development of an efficient natural seismic data processing system has become necessary.

Programming environments for distributed computing are provided to application programmers, usually to provide tools for the development and testing of a single application [4–6]. Seismic Unix is a large collection of subroutine libraries, graphics tools and fundamental seismic data processing applications [7,8]. Distributed Seismic Unix is designed to help geophysicists develop and execute Seismic Unix application sequences on clusters of workstations as well as on tightly coupled multiprocessor machines, providing tools to create and execute application sequences in several types of multiprocessor environment [9,10]. The SeisLab toolbox has been developed as a Matlab-based seismic data processing package [11,12]. Lima proposed a new graphical user interface, called BotoSeis, written in the Java programming language [13]. The Application Visualization System provides excellent integration of a single application with a graphics program and has been oriented towards optimizing the parallel performance of the graphics components [14]. Local Earthquake Single-Station Location Analyser (LESSLA) used an automated matching approach to identify local/regional events based on a weighting scheme applied to triggers in different sampling streams [15]. However, executing some seismic processing scripts can still be a challenge, especially for inexperienced users. Our software has been created as an .exe file that can be installed directly into Windows using a password; no

programming skills are required to use the functions of the software and no additional files need to be copied. The names of the functions are simple and can be easily found and used by the user.

Based on a preliminary Earth reference model, the International Association of Seismology and Physics of the Earth's Interior developed a model of the Earth that reflects global average properties, called the IASP91 earth model, in 1991. Australian seismologist Kennett calculated the travel schedules of seismic waves of different phases propagating through the Earth's interior based on this model [16]. Focusing on the kinematic information of seismic wave propagation reduces the theory of seismic wave fluctuations to ray theory, which facilitates the study of seismic wave propagation [17]. The continuous research and study of ray tracing methods has led to a variety of ray tracing methods being constantly updated and improved. With this research, the kinematic and dynamical characteristics of seismic waves propagating in the Earth's internal medium are gradually becoming clearer. Ray tracing has become an indispensable and important tool for studying the physical properties and velocity structure of the Earth's inner medium [18–24].

Accurate seismic phase picking is a prerequisite for seismic data processing methods such as seismic wave velocity imaging. This work has included building a Windows-based graphic user interface to visualize the natural seismic data in a simple and efficient way, and to make the human–computer interaction more intuitive and smooth [25]. Similarly, the human–computer interface enables the accurate identification and picking of seismic phases and other functions.

2. Data Pre-Processing

- (1) Filtering. The filtering settings are Gaussian filtering and band-pass filtering [26]. The filtering function can be achieved by setting the low cut-off frequency Flow and the high cut-off frequency Fhigh for the band-pass filter in the Filtering section of Setting and selecting Filtering, and then running Display→Display Seismograms. If a Gaussian filter is selected, the Gaussian filter is additionally selected with a center frequency of $f_c = (Flow + Fhigh)/2$. A is the amplitude, α is the smoothing factor and f_c is the center frequency of the Gaussian filter.
- (2) Time correction. If a seismic trace has a known time delay or advance, the trace can be corrected in the Settings display by setting dTcorrect = dT and running Processing→Correct trace time. dT can be positive or negative, with dT > 0 corresponding to a time delay and dT < 0 corresponding to a time advance.
- (3) Removing bad traces. Due to a variety of interferences, such as random noise from the environment, industrial interference, low-frequency linear interference, etc., there are some recording traces with a too low signal-to-noise ratio in the seismic records, commonly known as bad traces. They cannot be used and therefore need to be removed. To remove some bad traces, make sure that Picking is selected in the Settings display, then select the bad trace by moving and clicking the mouse, and finally run Processing→Remove Bad Traces to remove the bad trace. The removal process actually marks the traces and is not called up again during the process; the data remains in the computer memory. If deleted by mistake, you can run Processing→Recover traces removed to recover all the removed bad traces and remove them again. The bad trace removal function can remove multiple bad traces at the same time.
- (4) Resampling. In the seismic data processing process, it is sometimes necessary to resample the data according to practical needs, encrypting or pumping thin seismic data. This system uses the cubic spline algorithm for interpolation [27–29] to realize the resampling of seismic data.

3. Major Functions

3.1. Data Rotation

The place within the Earth where the rupture of a rock formation causes vibrations is called the seismic source. It is an area of a certain size, also known as the epicenter zone or

source body, where the energy of an earthquake is accumulated and released. The vertical projection of the source on the Earth's surface is the epicenter, and the distance in an arc between the epicenter and the observation point is the epicenter distance. The azimuth (α) is the clockwise angle between the longitude line where the epicenter is located and the large circular arc pointing from the epicenter to the station (as shown in Figure 1), and the inverse azimuth (β) is the clockwise angle between the longitude line where the station is located and the large circular arc pointing from the station to the epicenter.

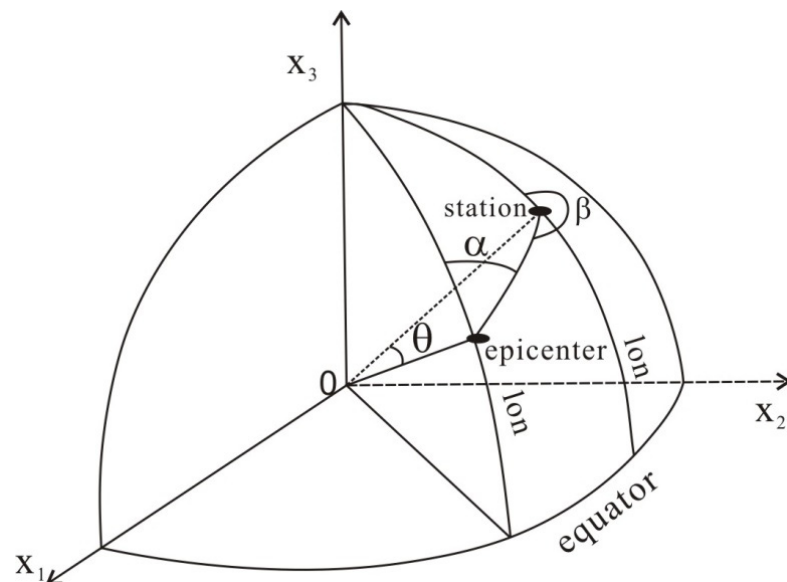


Figure 1. Diagram of azimuthal correction.

Supposing the longitude and latitude coordinates of the epicenter are (φ_s, ψ_s) and the longitude and latitude coordinates of the observation station are (φ_E, ψ_E) , the location of the epicenter and the observation station of the earthquake in Cartesian coordinates can be expressed as

$$X = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} R \cos \varphi \cos \psi \\ R \sin \varphi \cos \psi \\ R \sin \psi \end{pmatrix} \quad (1)$$

$$\begin{cases} X_E = (R \cos \varphi_E \cos \psi_E, R \sin \varphi_E \cos \psi_E, R \sin \psi_E) \\ X_S = (R \cos \varphi_S \cos \psi_S, R \sin \varphi_S \cos \psi_S, R \sin \psi_S) \end{cases} \quad (2)$$

In addition, if the angle between X_E and X_S is θ , then

$$X_E \cdot X_S = R^2 \cos \theta \quad (3)$$

$$\theta = \cos^{-1} [\cos \psi_E \cos \psi_S (\cos(\varphi_S - \varphi_E) + \sin \psi_E + \sin \psi_S)] \quad (4)$$

To calculate the azimuth and inverse azimuth of an observation station relative to the epicenter of an earthquake, we construct a unit vector in the ground plane where the epicenter of the earthquake is located, and make

$$X_E \times X_S = b R^2 \sin \theta \quad (5)$$

So

$$b = \frac{1}{\sin \theta} \begin{pmatrix} \sin \varphi_S \cos \psi_S \sin \psi_E - \sin \varphi_E \cos \psi_E \sin \psi_S \\ \cos \varphi_S \sin \psi_S \cos \psi_E - \cos \varphi_E \sin \psi_E \cos \psi_S \\ \cos \psi_S \cos \psi_E \sin(\varphi_E - \varphi_S) \end{pmatrix} \quad (6)$$

The vector b is perpendicular to the ray plane and lies in the same plane (ground plane) as the vector bases e_φ and e_ψ of the spherical coordinates, and thus the azimuth α of

the station relative to the epicenter of the earthquake is the angle between the vector b and $e_{\varnothing}$, which gives

$$\cos\alpha = \mathbf{b} \cdot \mathbf{e}_{\varnothing} = \frac{\sin\psi_S \cos\psi_E - \cos\psi_S \sin\psi_E \cos(\varnothing_S - \varnothing_E)}{\sin\theta} \quad (7)$$

Or

$$\sin\alpha = \mathbf{b} \cdot \mathbf{e}_{\psi} = \frac{\cos\psi_S \sin(\varnothing_S - \varnothing_E)}{\cos\theta} \quad (8)$$

The formula for the inverse azimuth can be obtained by simply swapping the subscripts for the longitude and latitude of the earthquake epicenter and the observatory station, i.e.,

$$\cos\beta = \frac{\sin\psi_E \cos\psi_S - \cos\psi_E \sin\psi_S \cos(\varnothing_E - \varnothing_S)}{\sin\theta} \quad (9)$$

The three components $Z(t)$, $N(t)$ and $E(t)$ of the observed seismic record represent, in turn, the vertical component (VZ) record, the north-south component (NS) record and the east-west component (EW) record. In research work on seismic data (e.g., reception functions, transverse wave splitting, etc.), the two components $R(t)$ and $T(t)$ represent the two horizontal components of the seismic record obtained after rotation of the radial component (SV wave) and the tangential component (SH wave). Then, under the condition that the earthquake has been determined according to the inverse azimuth β , the actual observed north-south component $N(t)$ and east-west component $E(t)$ can be rotated to obtain the radial component $R(t)$ and the lateral component $T(t)$ as

$$\begin{cases} R(t) = N(t)\cos\beta + E(t)\sin\beta \\ T(t) = -N(t)\sin\beta + E(t)\cos\beta \end{cases} \quad (10)$$

3.2. Ray Tracing

The ray tracing in this system is based on the IASP91 standard Earth velocity model [16,30]. The common seismic phases in natural seismic signals, as determined by the International Association of Seismology and Internal Geophysics, are P, S, PcP, ScS, PKP, SKS, etc. Using the ray tracing method adopted in this system, by setting the Phase and the Depth of the source in the Settings and executing Processing→RayTracer, the theoretical traveltimes of the various seismic phases can be calculated and adopted as a reference for phase identification.

3.3. Seismic Phase Identification

For the massive amount of broadband seismic observations, download the seismic catalogues for the appropriate time period according to the USGS seismic catalogue search engine (<https://earthquake.usgs.gov/earthquakes/search/> (accessed on 1 September 2022)) [31] and create the seismic event catalogue file *.evt for this project. The seismic event catalogue file *.evt will be placed under the catalogue for this project for later use; then, the seismic wave phase identification process can begin.

Search the seismic event catalogue for the time of the possible event and determine the location of the earthquake in the data record, such as date and time, based on the location of the source, magnitude and distance of the observation area from the earthquake source, and the desired length of the imported data record (in minutes), the time system used for the region where the data is to be observed (UTC), etc. Finally, you can start reading the desired import data by executing File→Open and selecting the appropriate data type.

If the imported data is from a different format and thus may have different sampling intervals, the system will resample all the data to the dTsamp sampling interval in the Settings display to create seismic data with the same sampling rate.

Once the data has been imported, the parameters are displayed in the Data Information section of the Setting area, including the sampling rate (Rate × 1000) and the total number of stations (Ntrace/3), the length of the data in seconds (Xmax), the start time in T0 (yyymmddhhmmss), and the total number of stations in Nstat.

Since earthquakes occur every minute on Earth, the seismic catalogue downloaded from the above website is a large amount of data and reading them all into memory would affect the speed of the system. Generally speaking, the time between the occurrence of an earthquake and the observation of that seismic signal anywhere on Earth is no more than one hour, so this system uses a process to run Processing→Load Events, which reads the event information for a time range of one hour before and one hour after the start time of the imported data into the system, and stores it in the Setting.

Select the event in the drop-down menu and the parameters of the selected event will be displayed in the Event Selection with the date, time, epicenter location (Lon., Lat.), depth and magnitude (Mag) of the event.

Once the source parameters have been determined, Processing→Parameterizing Stations is run to calculate the center distance of each station, followed by ray tracing to calculate the theoretical traveltimes of the selected phase. Once the ray tracing is complete, the theoretical traveltime curve is displayed on the seismogram and the average epicenter distance from all stations is also displayed in the Event Selection section of the Delt within the Settings display.

If the ray tracing fails due to the selection of the phase, then the phase can be reselected according to the Delt value in the Event Selection column in the Settings display and the ray tracing can be performed again until successful.

Once the theoretical traveltime has been calculated, the seismic records can be displayed by selecting Display→Align in the Plotting Frame Parameters section within the Settings.

3.4. Cross-Correlation for Automatialy Picking Seismic Phase Arrivals

Let the seismic record of a given seismic event received by N stations be $x_i(t)$, and its discrete signal be x_{ij} ($i = 1, 2, 3, \dots, N, j = 1, 2, 3, \dots, N_x$); the wavelet of a given seismic phase of that event be $s(t)$, and its discrete signal be s_k ($k = 1, 2, 3, \dots, N_s$), and that wavelet can be extracted from the best seismic record among N stations. Also, assuming that the theoretical arrival time of this seismic phase is t_i , then the correlation coefficient between the seismic record of the i th station after moment t and the specified wavelet can be expressed as

$$R_i(\tau) = \frac{\sum x_i(t + \tau)s(t)}{\sqrt{\sum x_i^2(t) \sum s^2(t)}} \quad (11)$$

The discrete form can be expressed as

$$R_i(k) = \frac{\sum_{j=k}^{k+N_s-1} x_{ij}s_j}{\sqrt{\sum_{j=k}^{k+N_s-1} x_{ij}^2 \sum_{j=k}^{k+N_s-1} s_j^2}} \quad (12)$$

$t = (k - 1)\Delta t, k = 1, 2, 3, \dots, N_x$, and Δt is the sampling interval of the seismic waveform. According to the definition of correlation coefficient, the value of R_i can be taken between 0 and 1. When $R_i = 1$, it means that the two series are identical; when $R_i = 0$, it means that the two series are completely unrelated; the larger the value of R_i , the greater the similarity of the two waveforms is characterized [32].

If the correlation coefficient between the seismic record of the i th station after moment t and the specified wavelet is maximum, then the corresponding $t = (k - 1)\Delta t$ is the arrival time of the specified phase received by that station, and the seismic wave traveltime t_i of that phase can be obtained according to the seismic event's moment of origin t_0 .

In Figure 2, $x(t)$ and $s(t)$ are two artificially shifted sequences of the same signal, where $x(t)$ is obtained by shifting $s(t)$ to the right for 10 s, when R_i reaches its maximum value.

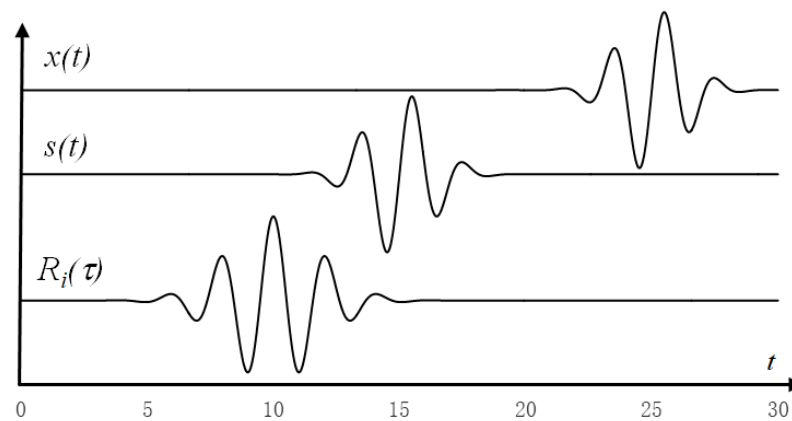


Figure 2. Two time series and their cross-correlation functions.

(1) Wavelet selection

In general, the shorter the time period, the better the waveform characteristics are identified. Therefore, when picking the seismic phase, the length of the display should not exceed 300 s. When picking the seismogram, select Picking in the Settings menu to select a recorder with a good signal-to-noise ratio, then select Pick Wavelet in the Settings menu to select the wavelet (the most distinctive part of the seismogram, e.g., station WQ01). Run Display→Display Seismograms to select the wavelet. Always refresh the screen by running Display Seismograms before the wavelet is selected. Also, to ensure the accuracy of the seismogram picking, use as short a wavelet as possible to prevent the wavelet from including another seismogram and affecting the accuracy of the picking. The length of the wavelet should not exceed 30 s.

(2) Automatic Arrival-Picking by using the cross-correlation technique

In the Settings menu, the Pick Wavelet is unchecked and then Auto Picking is selected, and the start position of the cross-correlation is given in the Settings by setting Tstart according to the proximity of most of the phases to the theoretical walk time, where when Tstart < 0, the interoff starts at Tstart on the left side of the theoretical walk time, and vice versa, when Tstart > 0, the interoff starts at Tstart on the right side of the theoretical walk. Once the parameters are set, the correlation between the seismic waveforms at other stations and the selected sub-waves at station WQ01 is achieved by running Functions→Phase correlation.

If the correlation is not good for individual stations, the system can be fine-tuned manually by unchecking Auto Picking in the Settings option, then determining the best arrival time by mouse picking, and running Functions→Phase correlation to refresh until satisfied.

After confirming that the cross-correlation results meet the requirements, the time corresponding to the theoretical traveltime is set in the Settings by setting Tstart and Tlength as the start time of the data segment and running Functions→Plot correlation to map the cross-correlation effect, whereby the accuracy of the cross-correlation traveltime picking can be further evaluated.

3.5. Cross-Correlation Traveltime Picking of Numerical Simulation Records

Based on the IASP91 standard earth velocity model and setting the source depth to 0 km, the validity of the traveltime picking using cross-correlation was verified by adding a 5% random time error to the theoretically calculated traveltimes after calculating the theoretical traveltimes of seismic phase P using ray tracing (see Table 1) and by using Leks wavelets in order to simulate the actual observed seismic data.

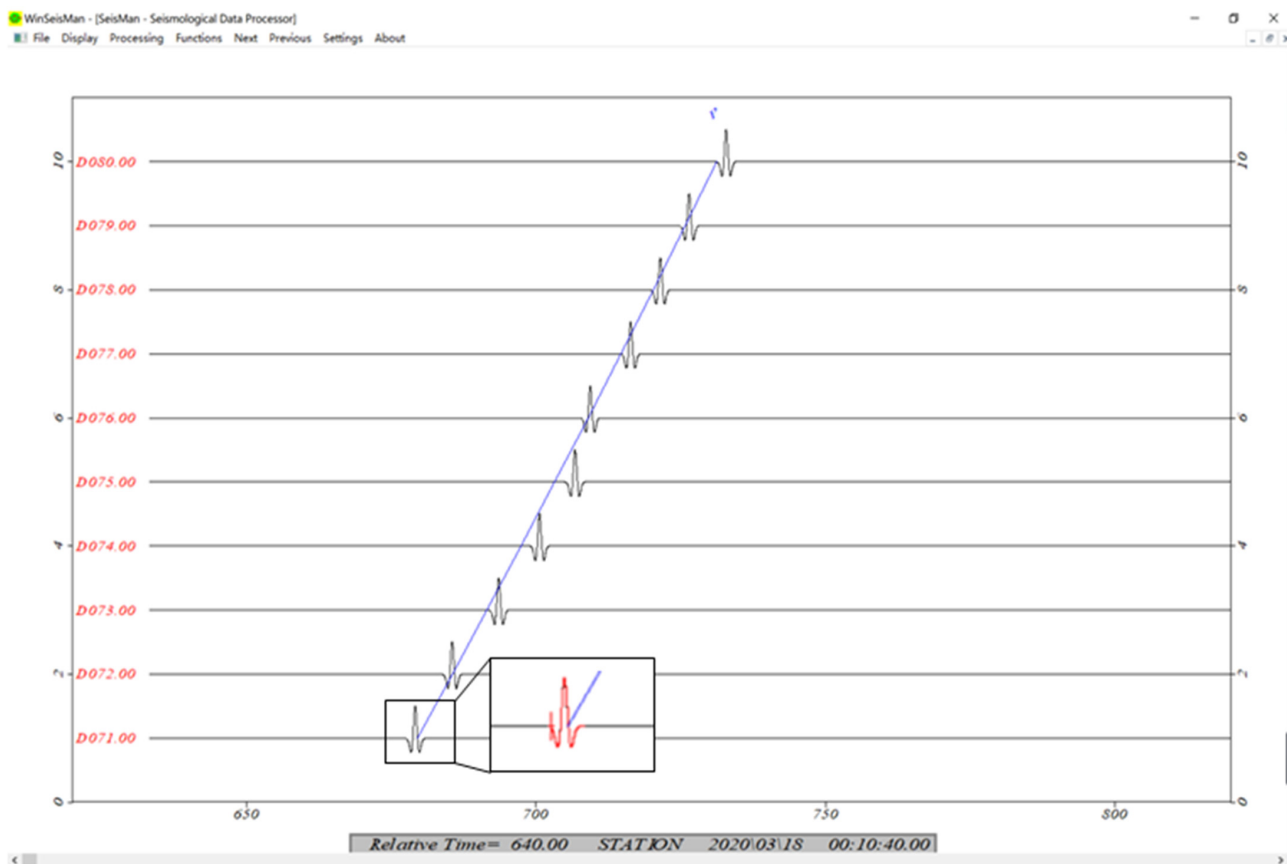
$$R(t) = af_0[1 - 2b(cf_0t - 1)^2]e^{-b(cf_0t - 1)^2} \quad (13)$$

Table 1. Random time error of adding 5% to the traveltime.

Epicentral Distances (Deg.)	Theoretical Travel Time (s)	Random Error (s)	Travel-Time Residual (s)	Theoretical Error (s)
71	679.520	−1.738	−1.740	−0.002
72	685.560	−1.403	−1.400	0.003
73	691.530	0.669	0.670	0.001
74	697.420	1.817	1.820	0.003
75	703.230	2.133	2.130	−0.003
76	708.975	−0.981	−0.980	0.001
77	714.648	0.316	0.320	0.004
78	720.241	−0.148	−0.150	−0.002
79	725.760	−0.678	−0.680	−0.002
80	731.200	0.256	0.260	0.004

Based on the IASP91 standard earth velocity model, and with a source depth of 0 km, the validity of the traveltimes picking using cross-correlation was verified by adding a 5% random time error to the theoretical traveltimes calculated using ray tracing for the seismic phase P (see Table 1), and using a Rake wavelet as the source in order to simulate the actual observed seismic data.

Where f_0 is the center frequency, take $a = -0.576$, $b = 8$, $c = 0.6$ and set the sampling rate $dT_{\text{samp}} = 10$ ms in the Settings; the result of the constituted synthetic seismic waveform recording is shown in Figure 3.

**Figure 3.** Synthetic seismic waveform recordings with random noise added and theoretical traveltime curves and wavelet selection.

Select Picking and Pick Wavelet in the Settings to select a wavelet. As this is a numerical simulation recording, there is no interference, so the P-wave signal from any of the stations can be selected as a wavelet, e.g., station D075.00. At the same time, the length of the wavelet is adjusted by Tlength in the Settings, and then Display→Display Seismograms is run for wavelet selection.

In the Settings, the Pick Wavelet is unchecked and Auto Picking is selected. The starting position of the correlation is set in the Settings by setting Tstart according to the distance of most of the phases from the theoretical traveltime. Then run Functions→Phase correlation to correlate the seismic waveforms of other stations with the selected sub-waves.

After confirming that the correlation results meet the requirements, set the start time of the data segment by Tstart and Tlength in the Settings, and run Functions→Plot correlation to output the correlation effect as shown in Figure 4.

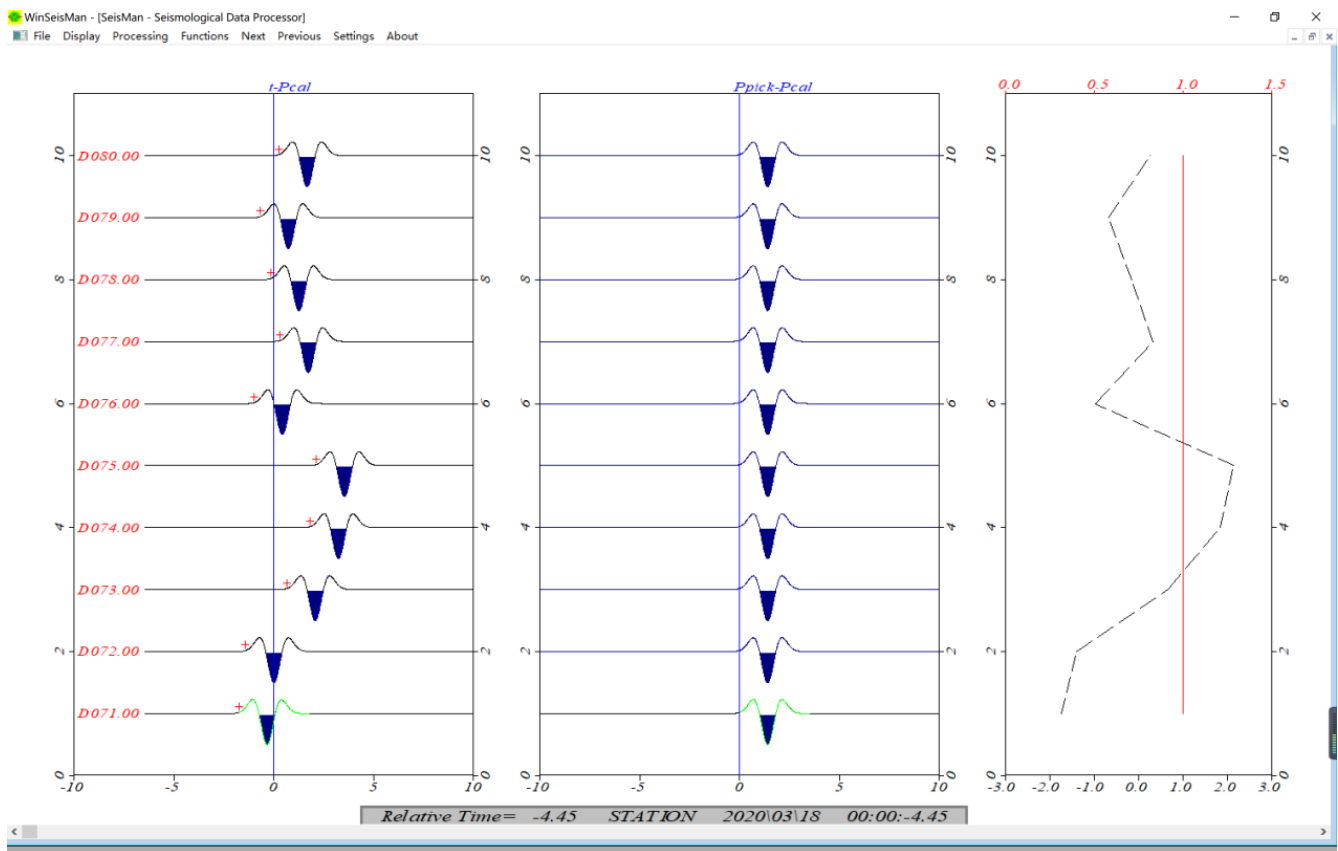


Figure 4. Cross-correlation evaluation system. The left and middle panels show the seismic waveforms centered on the theoretical and measured traveltimes. The red line on the rightmost graph is the correlation coefficient, and the corresponding numbers are the upper red axis. The black line shows the residual difference between the measured traveltime and the theoretical traveltime; the corresponding numbers are the lower black coordinates in seconds.

After correcting the P-wave seismic phase for arrival residuals at each station (middle panel of Figure 4), it can be seen that the signal maxima of the P-wave seismic phase at all stations lie on a straight line; at the same time, the correlation coefficient curve (right panel of Figure 4) also shows that the picking of traveltimes is effective.

The results are shown in Table 1, and the correlation results and traveltimes are automatically stored in the Pick directory under this project. The file name is composed of the date, end time (hour, minute, second) and phase of this numerical calculation. The exported file is 20200318000000P.pic.

As can be seen from Table 1, the absolute value of the theoretical error in the traveltime picking of seismic phases using the cross-correlation technique is less than 0.005 s, which is consistent with the adopted interval and possible error direction used in the manual synthesis of seismic data.

4. Case Application of the Earthquake Data Processing System

The majority of the seismic station distribution is located in the Guangxi region of China, covering the range of 21° to 26° N and 105° to 112° E. Between October 2013 and December 2018, 150 mobile broadband seismometers were deployed in the study area, and the station distribution map is shown in Figure 5. The seismic data used in this paper were received by the mobile stations, which received seismic data from 2013 to the end of 2018, with 1347 data sets available for display in this system. Globally, 85% of earthquakes occur on plate boundaries and only 15% of earthquakes are not clearly related to plate boundaries [33].

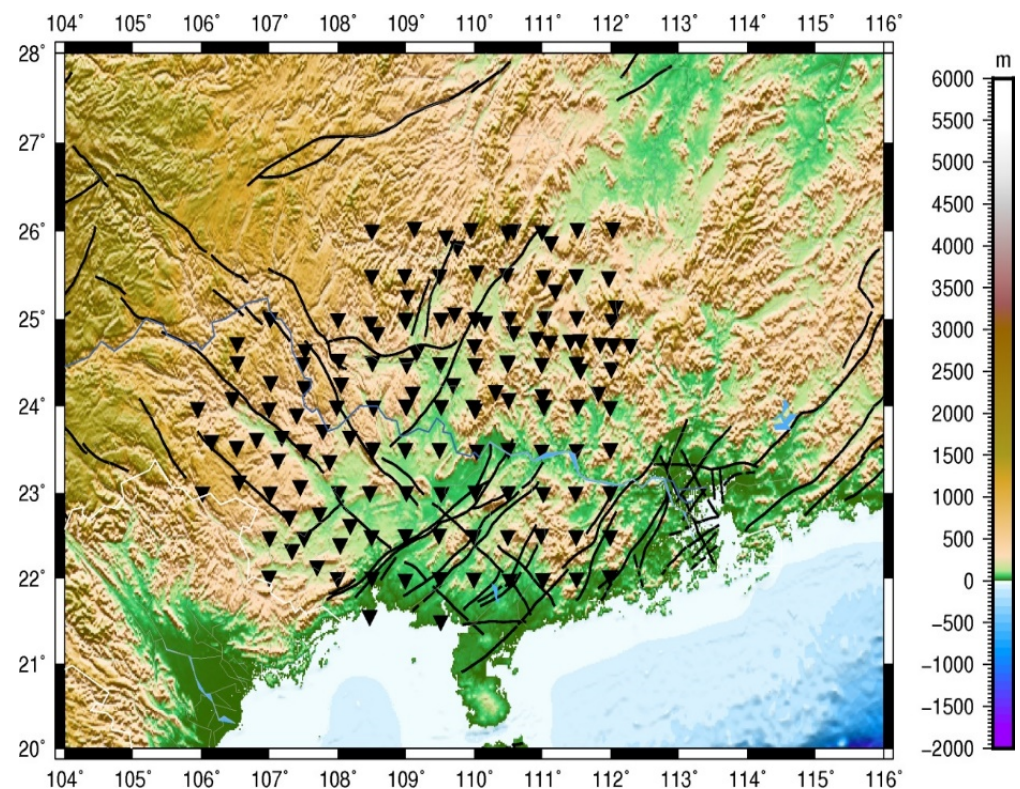


Figure 5. Map of stations.

4.1. Data Import and Pre-Processing

In this paper, an earthquake record is used as an example for its application and analysis using this system. The magnitude 6.5 earthquake in Java, Indonesia occurred on 15 December 2017 at 16:47:58.23 GMT (UTC = 0) with a source depth of 90 km. Since the distance from Guangxi to Java, Indonesia is about 3000 km, the first-to-wave phase of this earthquake should be a P-wave and the traveltime of this phase is about 10 min; therefore, it can be selected to import. The starting moment of the data is 16:51:00 and the record length is 13 min (Figure 6).

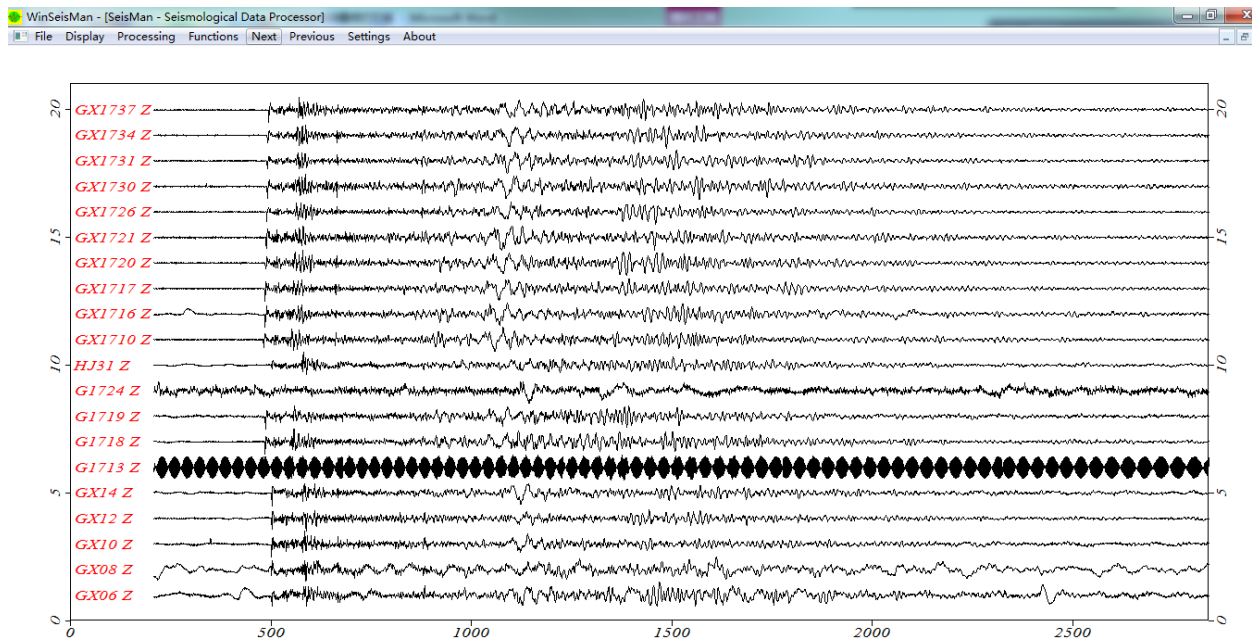


Figure 6. Data import (unfiltered).

From the imported data (Figure 6), stations G1713 and GX1724 are bad channels and need to be removed; meanwhile, stations GX08 and GX06 also have some interference and need to be filtered. Based on the frequency characteristics of natural earthquakes, Filtering parameters is low = 0.1 Hz and high = 2 Hz. The pre-processed seismic data are shown in Figure 7.

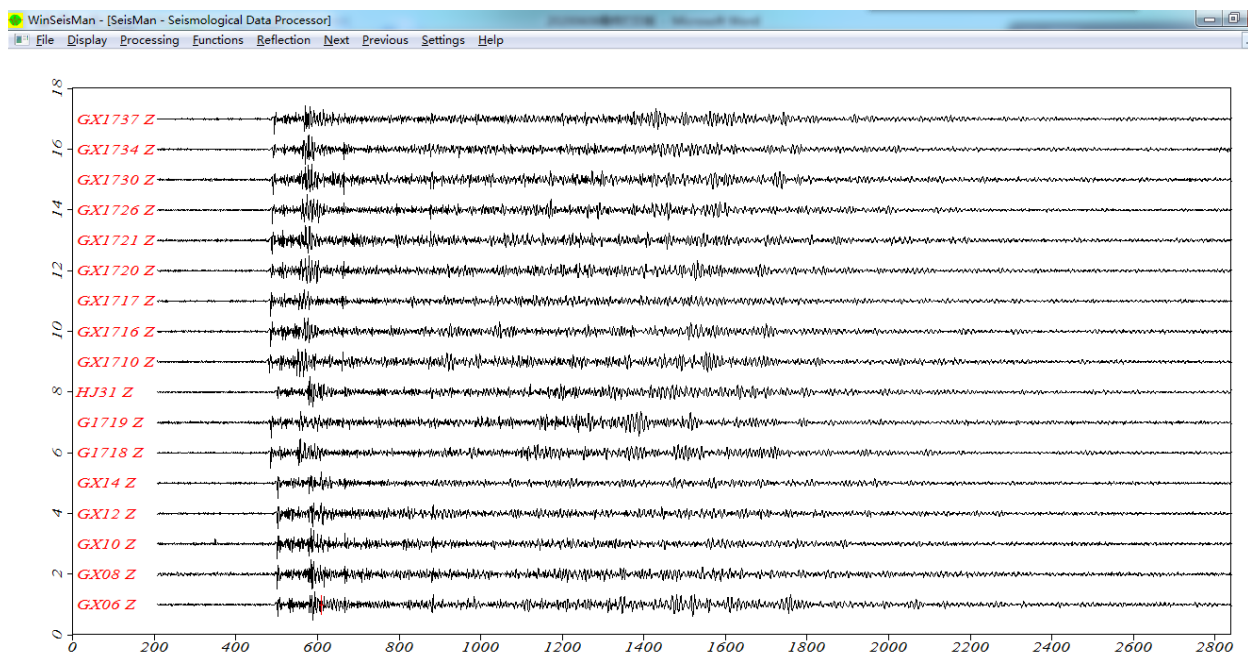


Figure 7. Seismic data after removal of bad traces and filtering.

4.2. Seismic Phase Identification and Traveltime Picking

Run Processing→Load Events to load the seismic event information, then set the possible phases, run Processing→Parameterizing Stations to calculate the epicenter distance of each station from the epicenter and perform ray tracing to calculate the theoretical traveltime for a given phase, the results of which are shown in Figure 8.

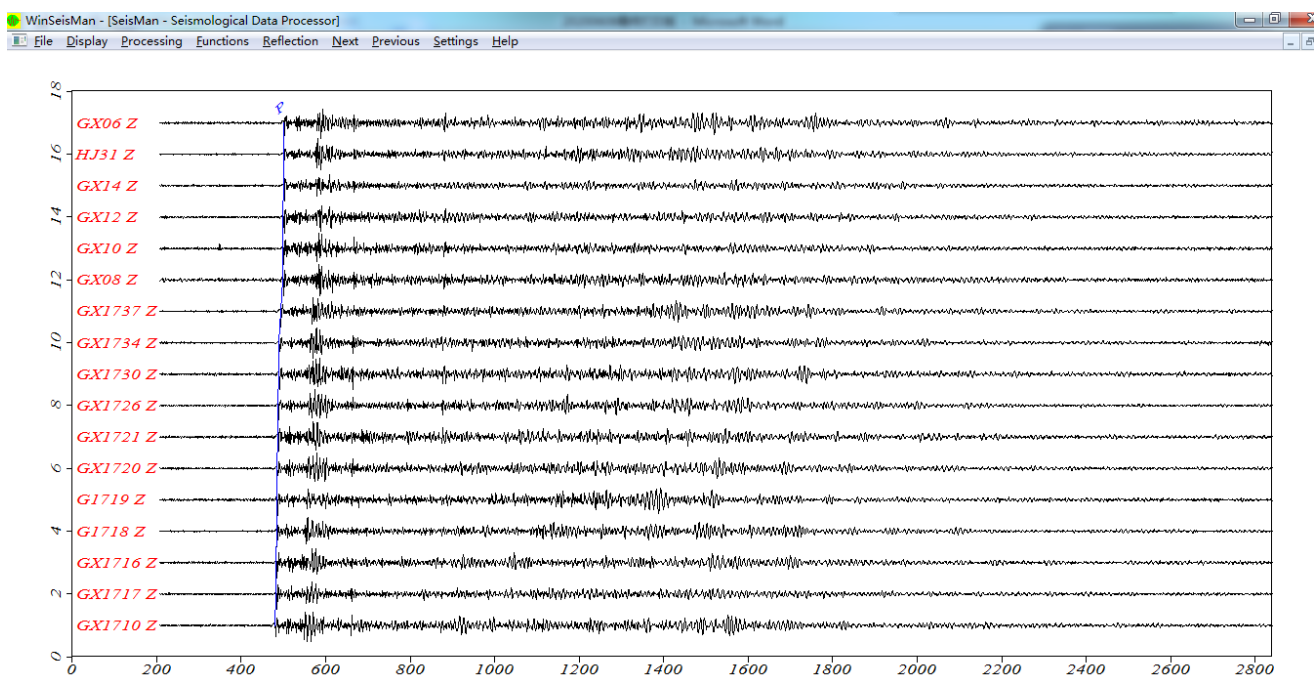


Figure 8. Seismic data and theoretical traveltimes (band-pass filtered).

As can be seen from Figure 8, the observed P-wave phases are very close to the theoretical traveltimes, which prove that the phases are correctly identified. Of course, we can also calculate the theoretical traveltimes for the subsequent phases and the results are shown in Figure 9.

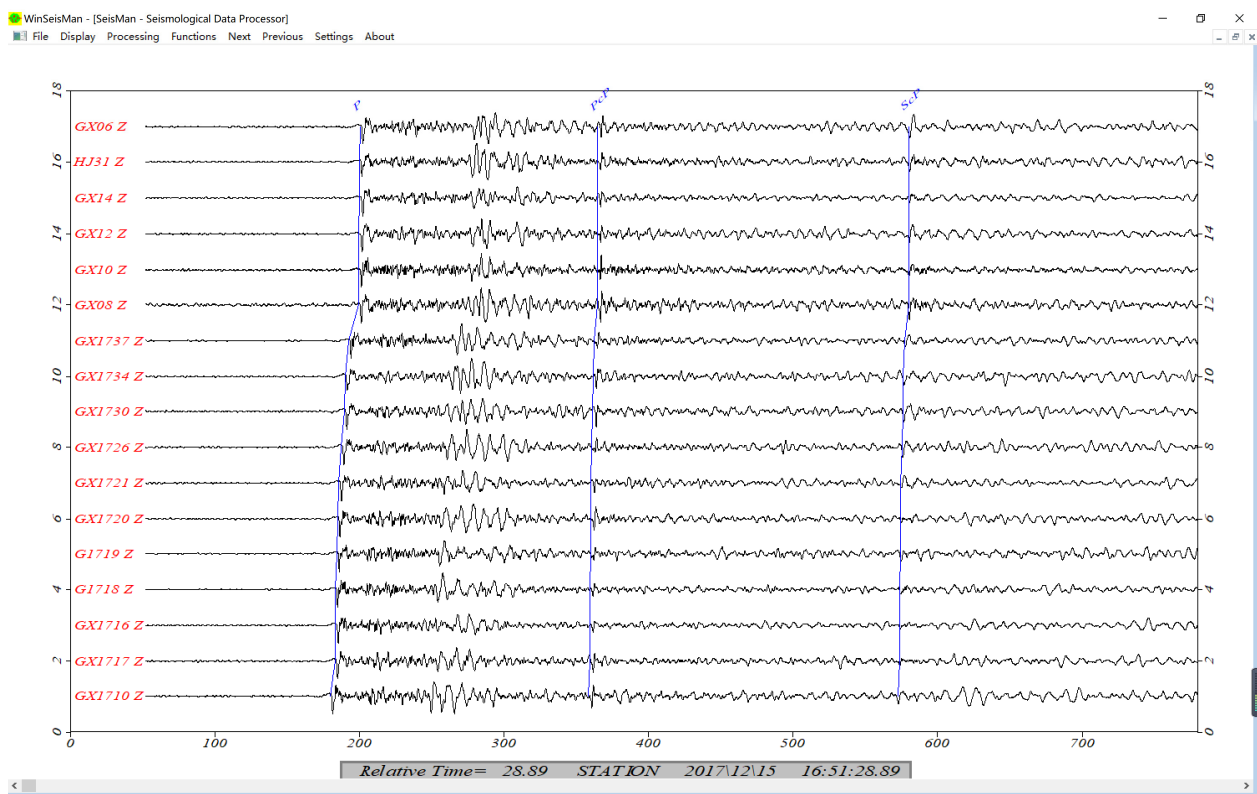


Figure 9. Multiple phases of this earthquake and their theoretical traveltimes (band-pass filtered).

Once the seismic phase has been correctly identified, we can start picking the measured phase traveltime.

(1) Wavelet selection

Generally speaking, the shorter the time period, the better the waveform characteristics can be identified. Therefore, when picking the seismic phase, the length of the display should not exceed 300 s. When picking the seismograms, select Picking in the Settings to select a recorder with a good signal-to-noise ratio, then select Pick Wavelet in the Settings to select the wavelet (the most distinctive part of the seismogram). Use Display→Display Seismograms for wavelet selection (Figure 10).

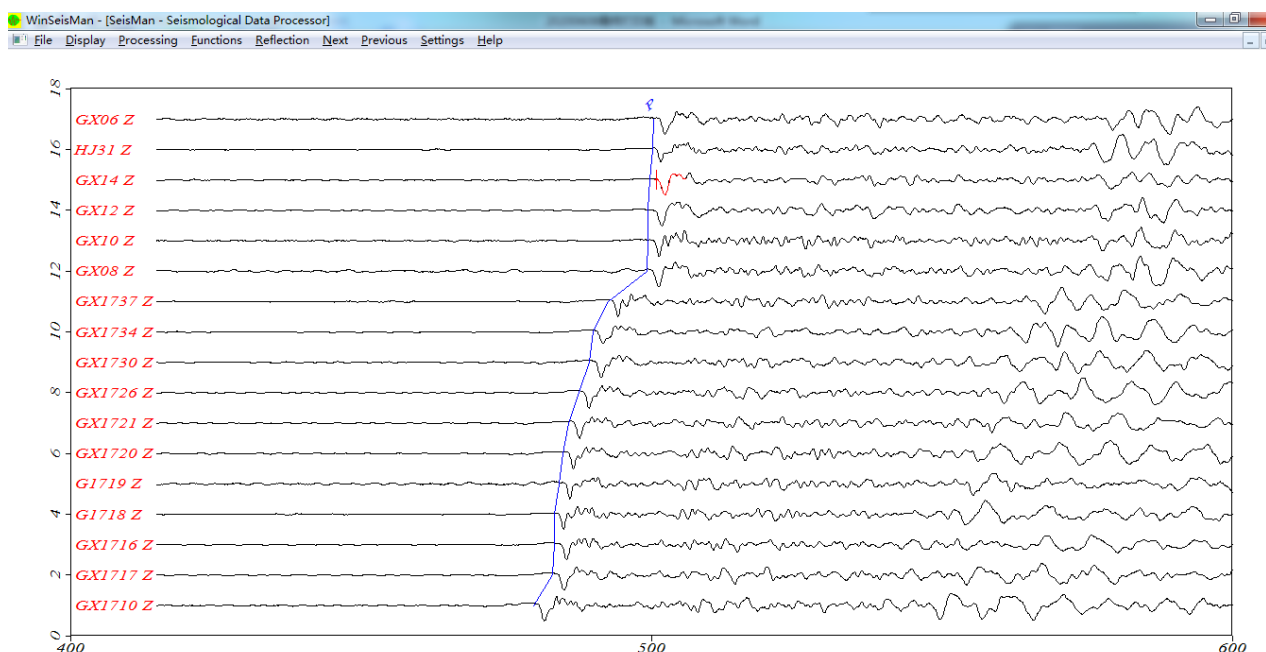


Figure 10. Wavelet selection (band-pass filtered).

Always refresh the screen by running Display→Display Seismograms before wavelets are selected. In addition, to ensure the accuracy of the seismogram picking, use as short a wavelet as possible to prevent the wavelet from including another seismogram and affecting the accuracy of the traveltime picking. The length of the wavelet should not exceed 30 s.

(2) Automatic Arrival-Picking by using the cross-correlation technique

In the Settings, the Pick Wavelet is unchecked and then Auto Picking is selected, and the start position of the cross-correlation is given in the Settings by setting Tstart according to the distance of most of the phases from the theoretical walk time, where when Tstart < 0, the cross-correlation starts at Tstart on the left side of the theoretical walk time, and vice versa: when Tstart > 0, the cross-correlation starts at Tstart on the right side of the theoretical walk. After setting the parameters, run Functions→Phase correlation to correlate the seismic waveforms of other stations with the selected wavelet. If individual stations have poor correlation due to a relatively low signal-to-noise ratios, the system can be used to determine the optimum arrival time by setting a range of inter-correlation time periods between the wavelet and other waveforms after setting Auto picking in the setup options and then running Function→Phase correlation until satisfied (Figure 11). If the selection is simply undertaken manually, different people picking will generate different errors that will affect the final result. During the picking of wavelets and subsequent interdependent picking, the waveform is enlarged and the length of time displayed is set in the window to

shorten the time taken for the automatic picking to begin, which takes only a few seconds after running Auto Picking, which is very fast.

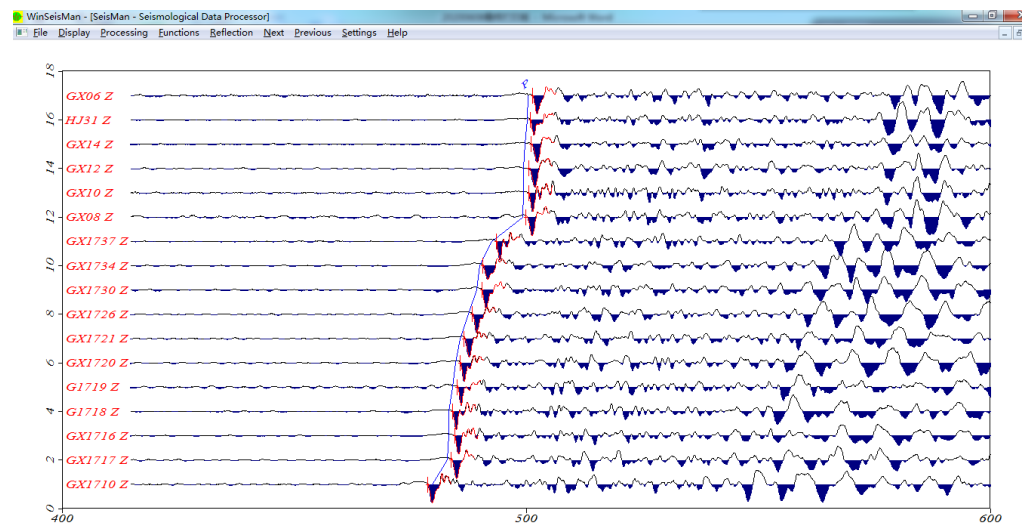


Figure 11. Results of fine-tuned cross-correlation.

After confirming that the correlation results meet the requirements, the correlation effect is plotted by running Functions→Plot correlation (Figure 12) and the accuracy of the seismic phase picking is further evaluated based on the correlation coefficients. The time period for displaying the seismic data is set in the Settings by setting Tstart and Tlength to correspond to the time of the theoretical traveltime as the start of the data period.

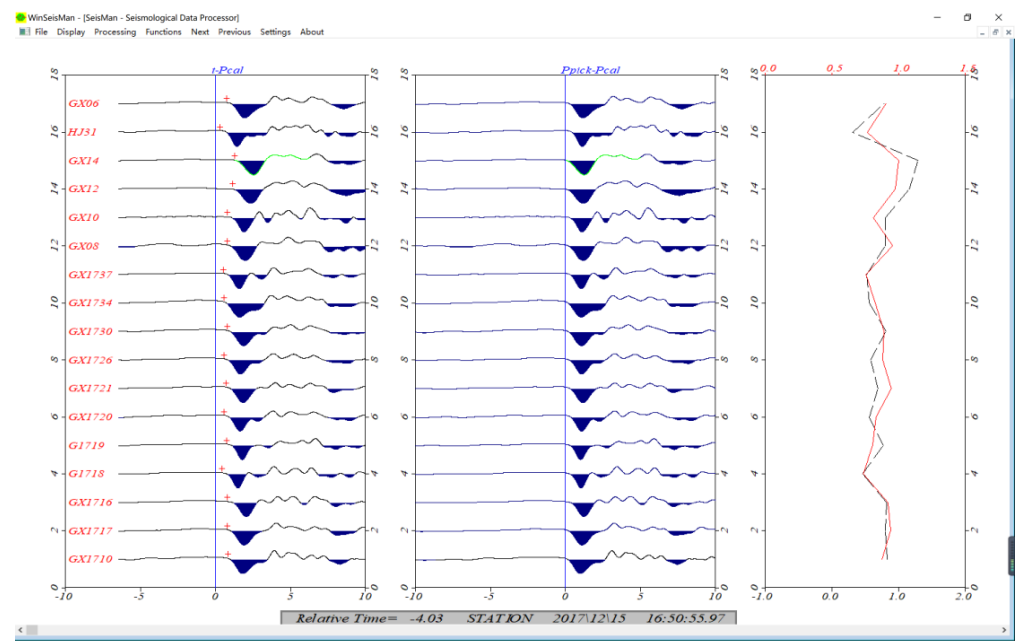


Figure 12. Cross-correlation evaluation system. The left and middle panels show the seismic waveforms centered on the theoretical and measured traveltimes. The red line on the rightmost graph is the correlation coefficient, and the corresponding numbers are the upper red axis. The black line shows the residual difference between the measured traveltime and the theoretical traveltime; the corresponding numbers are the lower black coordinates in seconds.

The middle panel of Figure 12 is actually the result of correcting the P-wave seismic phase in terms of arrival residuals for the observed arrival times at each station. Combined

with the correlation coefficient curves (all correlation coefficients are greater than 0.76), it can be seen that the inter-correlation traveltime picking works well. At this point, File→Save Picked Traveltimes can be run to store the picked P-wave traveltimes. The results are shown in Table 2 and are automatically stored in the Pick directory under this project. The file name is composed of the date, time (hour, minute, second) and phase of this earthquake. The P-phase file is 20171215164758P.pic.

Table 2. P-wave traveltime data table for the 6.5 magnitude earthquake in Java, Indonesia on 15 December 2017.

Station	Latitude (Deg.)	Longitude (Deg.)	Altitude (m)	Epicentral Distances (Deg.)	Actual Arrival Time (s)	Theoretical Traveltime (s)	Traveltime Residual (s)	Correlation Coefficient
GX1710	22.6105	109.9730	86	30.1540	362.1960	361.3660	0.8300	0.8745
GX1717	22.9972	109.7620	82	30.5290	365.4700	364.6700	0.8000	0.9395
GX1716	22.9932	110.4080	256	30.5630	365.7950	364.9750	0.8200	0.9179
G1718	23.0755	107.4500	259	30.5760	365.5470	365.0840	0.4631	0.7351
G1719	23.1336	106.5540	718	30.6670	366.6580	365.8840	0.7741	0.8036
GX1720	23.2307	109.2740	113	30.7420	367.1030	366.5430	0.5600	0.8277
GX1721	23.2856	110.1760	115	30.8400	368.0970	367.4070	0.6900	0.9434
GX1726	23.5434	109.0620	154	31.0480	369.8130	369.2330	0.5800	0.8777
GX1730	23.6780	110.5910	120	31.2590	371.9030	371.0930	0.8100	0.8894
GX1734	23.8064	109.4530	95	31.3230	372.2140	371.6550	0.5595	0.8258
GX1737	24.1285	108.5920	174	31.6230	374.8070	374.2830	0.5234	0.7526
GX08	24.7880	110.9080	244	32.3900	381.7850	380.9850	0.8000	0.9526
GX10	24.7597	111.4050	228	32.4050	381.9180	381.1180	0.7995	0.8113
GX12	24.7214	111.8410	267	32.4110	382.3310	381.1710	1.1600	0.9745
GX14	24.7098	112.2870	129	32.4500	382.8070	381.5130	1.2941	1.0000
HJ31	25.0025	108.0050	368	32.4950	382.2140	381.9020	0.3118	0.7630
GX06	24.9686	110.1580	471	32.5180	382.8810	382.1040	0.7770	0.9047

5. Conclusions

This paper designs and implements a natural seismic data processing system based on the Inter Fortran development platform for the Windows environment. The system reads and processes broadband seismic data collected from field stations, mainly including data import, pre-processing, data conversion, merging and exporting, seismic phase identification, and traveltime cross-correlation picking.

In the process of processing over 1000 large seismic events received by the station from 2013 to 2018, the system has been continuously improved and updated with functions such as cross-correlation traveltime picking. The entire system design is a process of refinement as the data is processed. Practical tests have shown that the human–computer interaction system is easy to operate and processes data well. As the system continues to improve and update its functionality, it paves the way for our future research into the internal structure of the Earth.

The specific work is summarized as follows.

- (1) Research into commonly used seismic data formats, realizing the reading, writing, merging, converting and exporting of different seismic data format files for storage, and programming the original seismic data for a one-time reading time of 24 h based on in-depth research. The data is normalized so that each station record is perfectly mapped out in the main window and a jump point waveform is used for fast plotting,

greatly saving plotting time. To suppress interference from the external environment and processing methods, data rounding is achieved with filter design, time correction and bad trace rejection.

- (2) To identify the seismic phases in the mobile array seismic data, the traveltimes of different phases propagating in the Earth's interior are simulated numerically using ray tracing techniques based on the IASP91 Earth velocity model, and the simulation results of the orthogonal traveltimes of each phase can match well with the travel schedules of seismic waves of the corresponding phases calculated by Kennett, and the calculation speed can be guaranteed. After the correct identification of the seismic phases, the traveltime picking using the cross-correlation technique greatly improves the picking accuracy, and the cross-correlation data can clearly reflect the good and bad quality of the waveforms at each station, reducing the errors in the qualitative analysis, which works well in the cross-correlation evaluation system through the system's interactive picking work.
- (3) The system provides good performance and has its own unique features in both seismic phase identification and traveltime picking calculations. The deviation between the theoretical and actual arrival times of the seismic phases calculated from the numerical simulations is mainly due to the non-uniformity of the velocity structure within the Earth, both in the radial and lateral directions. It is this deviation that opens up the possibility of studying the complex structure of the Earth's interior.

The integration of seismic data processing and interpretation methods is one of the challenging and practical fundamental studies in geophysics today. Some of the functions of this system need to be further supplemented and improved, and the data processing and interpretation work is not deep enough and needs to be certified by further practical processing and interpretation work. In addition, more in-depth issues need to be explored in future efforts, and the study of seismic attribute methods is an important tool for future fine stratigraphic studies. Therefore, it is hoped that more people will carry out research on new methods and techniques for seismic attribute processing and interpretation based on existing platforms.

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