An interactive program on digitizing historical seismograms

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ABSTRACT

Retrieving information from analog seismograms is of great importance since they are considered as the unique sources that provide quantitative information of historical earthquakes. We present an algorithm for automatic digitization of the seismograms as an inversion problem that forms an interactive program using Matlab® GUI. The program integrates automatic digitization with manual digitization and users can easily switch between the two modalities and carry out different combinations for the optimal results. Several examples about applying the interactive program are given to illustrate the merits of the method.

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1. Introduction

Analog seismograms are barely used nowadays, but the importance of them cannot be denied. It has only been around 70 years since the digital seismological data was recorded in the 1960s as well as the advent of WWSSN, while analog records of teleseismic data can be dated back to 1889 (Stein et al., 1988).If quantitative information could be extracted from these records, seismic events recorded during more than 70 years could be used by Geophysicists (Cadek, 1987; Samardjieva et al., 1998; Baskoutas et al., 2000; Bungum et al., 2003; Lee and Benson, 2008; Mezcua et al., 2013). New understandings may be obtained if the seismicity history is considered, because these seismic data have a longer period of time and are crucial for seismological research (Kanamori, 1988).

Digitizing analog seismograms is essential for employing historical recordings but the digitization quality directly affects the validity of final results and interpretation of the historical earthquakes. Adams and Allen (1961) used a device that is originally applied to digitize weather maps for data processing. Bogert (1961) employed equipment that processes speech and visual data for digital versions of seismograms. With the development of computers' technology and scanning and image processing techniques, digitization based on raster images scanned from photographic records was presented by Trifunac et al. (1999). Teves-Costa et al. (1999) demonstrated use of CADcore to vectorize analog seismograms and then converted the images into unevenly spaced (x, y) pairs by AUTOCAD so as to obtain the digitized seismograms. Pintore et al. (2005) developed a vectorization of historical seismograms, named Teseo, which bases on neural networks and Bezier fitting algorithm and provides both manual and automatic trace vectorizations of seismograms,

Although several attempts have been made for more than 70 years, and great improvements have been achieved, results from the automatic digitizing programs still have defects in some particular situations (Trifunac et al., 1973, 1999), which need subsequent corrections. It may be possible to remove these defects by purely automatic digitalization, but it needs extreme works and results in lengthy codes. The automatic tracing is faster, but its result may not be able to reach the desired quality. Manual digitization may give the best resolution, but it is time-consuming. The optimal way to digitalize analog seismograms is combination of manual and automatic tracing techniques. In this paper, we present a computer program that achieves the combination and offers a friendly graphical user interface, which allows user easily switch between the manual and automatic digitization modalities.

In the following sections, we first talk about the data we used in testing our programs, then give a general principle of automatic digitization. We described the digitization of seismograms as an inversion problem, in which the raster image acquired from scanning the historical seismograms are considered as the "observed data", and the digital seismological data saved in a sequence of amplitude data on evenly spaced time, as the "model parameters". Finally, we draw some conclusions from our implementations of the computer program and actual digitization results.

2. Data

The first step of historical seismograms digitization is scanning the analog seismograms (Trifunac et al., 1999). The output of

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scanners is raster images, which are made up of two-dimensional arrays of pixels. Each pixel could be represented by either one scaled number of grayscale of pixel, or a color triplet with red, green and blue. The historical seismograms, whether it is on the smoked paper or the photographic record, are often given in grayscale colors with which our algorithm starts. Any other kinds of images could be converted into the grayscale images in terms of the values of red color. The resolution of the scanned image should be high enough to retain information sufficient for the later processing of digitization. In this study, we focused on the images that have 300 dpi and higher, since they may hold sufficient details for refinement of digitization results.

The historical seismograms are recorded by mechanical instruments, and result in images that have several characteristics, some of which increase the complexity of the problem, e.g. curvature distortion. The algorithm we presented here is based on the assumption that amplitude of seismic traces has a bijective relationship with the ordinate values, which corresponds to time. This assumption fails when dealing with the seismograms on smoked paper due to the curvature distortion (Batlló et al., 2008; Batlló, 2010; Schlupp and Cisternas, 2007). Therefore, the seismograms on the smoked paper must be particularly processed, e.g. migrating the pixels to the corrected position to reduce curvature distortion. The amount of correction of a pixel is a function of the distance between the pixel and the base line of the trace. The function might be obtained from analysis of the structure of the seismometer, or the curvature of the seismogram. We assume that the correction is already completed so that the seismograms satisfy the "bijective" assumption. We gave two examples to show capability of our program. One is a seismogram (Fig. 7) on the photographic record obtained from the paper of Pintore et al. (2005), another comes from rasterization of vector image of wide angle reflection/refraction data (Fig. 6). Although it is not historical seismograms, it has similar characteristics to the historical ones (those characteristics are discussed in the Section 3). The two examples may represent two kinds of seismograms which can be processed by our computer program. It should be mentioned that some modern seismograms may also need re-digitization to recover partial miss in the original data. Our program was originally developed to digitize wide-angle seismic reflection/refraction data.

3. Digitization

3.1. Principle

Considering the digitizing process of seismograms as a black box shown in Fig. 1, the input of the black box is a grayscale raster image and the output is seismic data. Since we need computers to do the work for us, we should offer a mathematical explanation of digitization to the computer. A grayscale raster image is merely a two-dimensional matrix of which each element has the value ranging from 0 (pure black) to 255 (pure white), and seismic traces are either parameterized lines (Pintore et al., 2005) or sequences of time–amplitude pairs (Teves-Costa et al., 1999). Modern seismological recording techniques are commonly designed for digital seismograms that contain amplitude data on evenly spaced time. The sequences of time–amplitude pairs become the format of the digital seismograms and provide possibility for further numerical process and analysis. Hence, the digitization of analog seismograms may be simply considered as a procedure that constructs a sequence or sequences of doublets from a matrix (image). If we take the matrix as "observed data" and the sequences of doublets as "model parameters", the digitalization becomes an inversion problem.
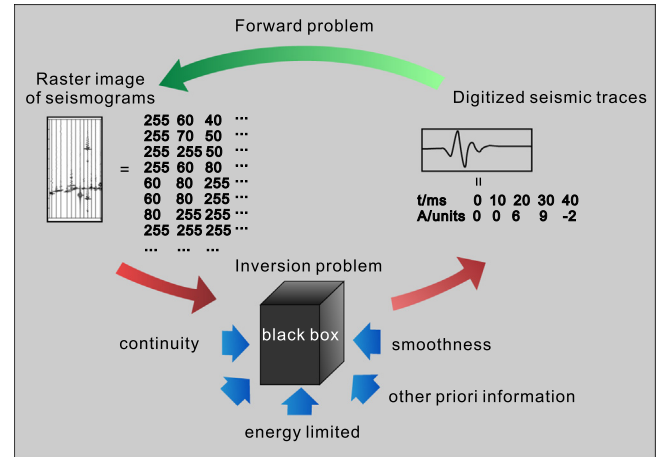

Fig. 1. The inversion problem arising in the digitization of historical seismograms. The historical seismograms can be represented by a matrix, whose elements are the grayscale value of each pixel in the scanned seismograms. The digitized seismic traces are essentially sequences of time–amplitude pairs, which contain the amplitude information in each time point. The black box can refer to any method which can retrieve seismological information from the matrix, and these methods should consider the constraints arising from the priori information.
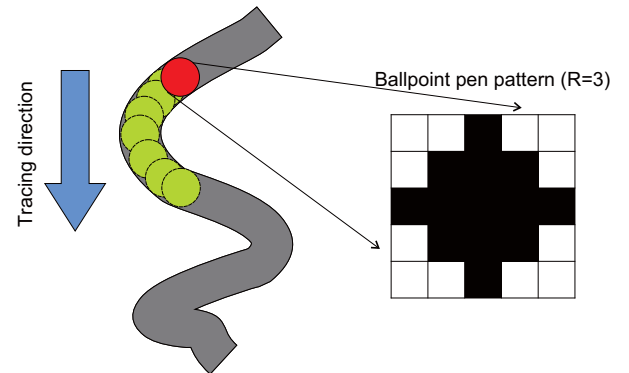

Fig. 2. Illustration of ballpoint pen assumption. The red and green balls represent ballpoint pen patterns. The red ball is the starting point, and the green ones are automatic digitization results. An example of pixel representation of ballpoint pattern is shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The relationship between the model parameters and the observed data is often defined by a mathematical operator. Mathematically, the operators must be uniquely determined by the input matrix and the output of time–amplitude pairs. However, it is difficult to give a general and explicit formula of the operator because of the requirement of detailed knowledge of the instrument structure that the authors do not have. Alternatively, we choose a simpler way that regards the forward problem of converting the seismic data to analog seismograms as moving a ballpoint pen along the traces on digital seismograms, as shown in Fig. 2. The diameter and shape of the ballpoint pen may vary as it moves. In addition, abrupt shift should be involved in case of time marks. Let $\mathbf{m}^k$ be the kth seismic traces and $\mathbf{B}$ be the ballpoint pattern, given by

$$\mathbf{m}^k = \sum_{p=1}^{Np} \delta_{im_{p1}^k} \delta_{im_{p2}^k}, \tag{1}$$

and

$$B = [b_{ij}], \quad b_{ij} = \begin{cases} 1, & \text{if} \quad i^2 + j^2 \leq R^2 \\ 0, & \text{if} \quad i^2 + j^2 > R^2 \end{cases}, \quad i, j = 0, \pm 1, \pm 2, \cdots, \tag{2}$$

respectively. m_{p1}^k and m_{p2}^k are both integers, and denote the abscissa and the ordinate of the pth point in the kth trace. The raster

seismogram $\mathbf{S}$ therefore can be obtained by the convolution of $\mathbf{m}^k$ and $\mathbf{B}$, that is

$$\mathbf{S} = \sum_{k=1}^{K} \mathbf{S}_k = \sum_{k=1}^{K} \mathbf{m}^k * \mathbf{B}. \tag{3}$$

Before comparing the raster seismogram $\mathbf{S}$ with the real raster grayscale seismogram, the following procedures are required. From Eq. (3), we know that the nonzero elements of $\mathbf{S}$ correspond to the pixels on the seismic traces. These pixels relates to the black pixels in common digital seismograms and seismograms on photographic records, as well to the white pixels in seismograms on smoked papers. For simplicity, we assume that the black pixels contain seismic information and the white pixels are the background. Assigning 0 and 255 to the nonzero and zero elements respectively, one can obtain the result of the forward problem. The inversion problem is solved by iteratively evaluating the difference between the calculated seismograms and the real seismograms and modifying the traces data until reaching desirable results.

However, there are several factors that affect the inversion results, e.g. intersections between seismic traces and undermined widths of seismic traces. $\mathbf{S}_k$ in Eq. (3) denotes the seismogram keeping merely the kth trace, and has the following explicit expression

$$(\mathbf{S}_k)_{ij} = \sum_{p=1}^{N_p} (\delta_{i m_{p1}^k} \delta_{j m_{p2}^k}) * (\mathbf{B}_{ij}) = \sum_{p=1}^{N_p} \mathbf{B}_{i - m_{p1}^k, j - m_{p2}^k}. \tag{4}$$

m_{p1}^k and m_{p2}^k can be simply obtained by deconvolution of $\mathbf{S}_k$. However, if more than one trace is recorded in the seismogram, deconvolution can only obtain the points of the traces without determining which trace each point belongs to. We therefore adopt an iterative tracing method to the case. The method starts the tracing with a point on a trace and tracks down the entire trace. In each iteration, one new point is selected according to the traced points and some criteria. These points are considered to be of the same trace. Applying the same method to points on other traces, one obtains the digitized seismic data. Manual digitization modality is also provided in case of any setbacks of the automatic digitization. We need to emphasize that the application provides a graphic user interface and easy switch between the automatic and manual digitization modalities. This interactive feature can significantly reduce the time on digitization and improve the quality of the final digitized seismograms.

3.2. Automatic digitization

The digitization described above is an underdetermined problem that has nonunique solutions. To overcome this problem, our iterative algorithm contains a selection of the next point on the trace in each iteration. The selection is accomplished according to the following features:

1. Amplitude of seismic traces are bijective functions of time;
2. Seismic traces are continuous;
3. Seismic traces are smooth (this feature will be lost in low resolution scanned images of seismograms);
4. Seismic traces are energy-limited, i.e. amplitude should be limited within a proper bound;
5. Seismic traces may have varied width;
6. Some seismographs give constant width of traces.

These points are common characteristics of seismic traces, despite that they may fail due to some reasons. Consequently, we follow these features and construct the method to select the next point along the trace.

The algorithm we present here takes a raster image obtained by scanning the analog seismograms or rasterizing of the digital seismograms as an input. The image often has many blemishes,

so we have to "clean" the image by applying a threshold value to the values. We applied the principle of Section 3.1 to black pixels that refer to the seismic traces and check the grayscale values of the pixels. If their grayscale values are greater than the threshold, they are forcibly set to 255 (pure white), and the non-white pixels left are set to 0. After such "clean" operation, the image remains the same format of the raster seismogram $\mathbf{S}$. Selection of the threshold value should be careful, since the digitized result highly depends upon it. The proper threshold should reach a balance between reducing the background noise and keeping the information in the seismogram (Fig. 3). Seismographs record the displacement, or velocity, or acceleration of the ground motion. Only one value is recorded at each time. No mater whatever the recording are, the traces aligned together and give several continuous series of black pixels, rather than one series, at each time point. Each group of black pixels may correspond to a trace, and the accurate amplitude can be obtained by deconvolution of the surrounding pixels. However, deconvolution cannot deal with crossing traces as mentioned in Section 3.3. We therefore developed another method to solve the trace-crossing problem. First, we obtain an approximation of the amplitude by calculating the middle point of each continuous series. This procedure can be considered as a rough approximation of inverse operator of the digitization problem. Next, modify the approximation result to more proper value based on the features mentioned above. We refer to the first step as "tracing" and the second step as "refinement", and the selection of the next point is included in the first step.

3.2.1. Tracing

"Tracing" means to trace down a trace from a point to point along the whole trace. To start the tracing, one needs the starting point, which can be assigned manually by the manual digitization modality. However, simply drawing a straight line perpendicular to the time direction, the cross points of the line and the traces can also be the starting points for the traces. The digitized data obtained from tracing of one particular starting point is considered as the seismic trace to which the starting point belongs. Although the straight line may intersect with two or more seismic traces at the same point if the traces cross, new starting points can be assigned manually.

After choosing the starting points, one needs to determine the next point that belongs to the same trace. Once the next point is picked up, the whole trace can be traced out by repeating the determination of the next point. Let (m_{p1}^k, m_{p2}^k) be the starting point in the seismic trace, the next point is determined under the constraints of the second, third, and fourth features listed in Section 3.2. We refer to the three features as Continuous Rule (C rule), Smooth Rule (S rule) and Energy limited Rule (E rule) respectively. To search for the next point, we restrain the search area to the time point right after the starting point, and denote the position of traces by (i_q, j_q), $q = 1, 2, \dots j_p$ remains constant during each iteration while i_q varies and corresponds to the abscissa of the traces. In these denotations, the C-rule method can be formulated as

$$m_{p+1,1}^k = \{i_Q \in \{i_q, q = 1, 2, \cdots\} | |i_Q - m_{p1}^k| = \min(|i_q - m_{p1}^k|), q = 1, 2, \cdots\},$$

$$m_{p+1,2}^k = j_q. \tag{5}$$

The E-rule method is covered by the C-rule method, which limits the search area of the next point within preset distance unless no trace is in the area. For simplicity, we refer to the C- and E-rule method as "the C-rule method". To maintain the continuity of the trace, the C-rule method prefers to choose the nearest point as the next point of the trace. Alternatively, the S-rule method selects the next point that mostly preserves the direction of the
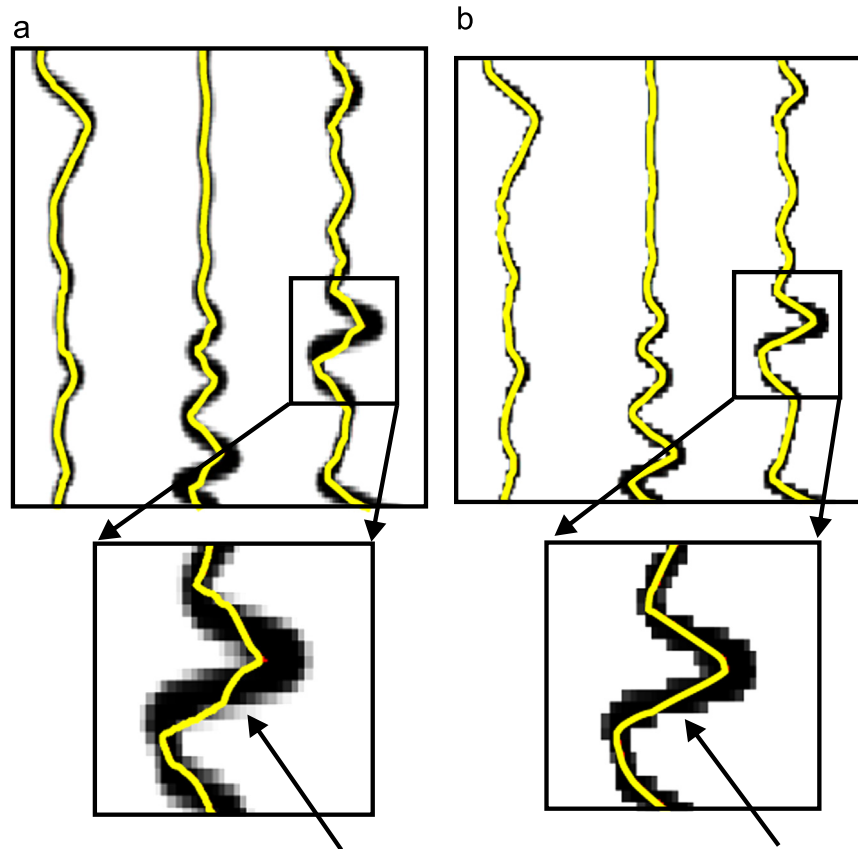
Fig. 3. Comparison of digitized results obtained before (a) and after (b) applying the threshold to the grayscale value. Both of the results are obtained by automatic digitization based on the C-rule method, without any following correction. The yellow lines represent the digitized traces. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

trace, for which the mathematical formula is

$$m_{p+1,1}^k = \{i_Q \in \{i_q, q = 1, 2, \cdots\} || i_Q - s_{p1}^k | = \min(|i_q - s_{p1}^k|), q = 1, 2, \cdots\}$$

$$m_{p+1,2}^k = j_q \tag{6}$$

Here s_{p1}^k represents the predicted abscissa value of the next point based on the last few points of the trace. We used linear regression of at most twenty points to obtain the direction of the trace and then predicted the position of the next point in our program. Users can switch between the two methods by clicking the checkbox "Smooth" in the program.

The direction of tracing can be set to the direction of time increasing or decreasing by assigning $m_{p,2}^k + 1$ or $m_{p,2}^k - 1$ to j_q, respectively. Hence, the whole seismic trace can be obtained wherever the starting point is. We included both two-direction tracing method to automatically find the starting points and digitize all the traces, and one-direction tracing method to integrate with the manual digitization of complicated traces. When the automatic digitization fails, we use the manual digitization to lead the process through the difficult area and then continue the automatic digitization.

Both the C- and S-rule methods can get good results for *simple* seismograms, in which each seismic trace is isolated from others (Fig. 3). However, such *simple* traces barely exist in practice. In most of the seismograms, the amplitude of a trace increases and intersects with other traces when a signal arrives, e.g., primary waves. Applying the S-rule method to these cases may solve most of the intersection problems. Similar methods have been performed well on digitizing historical seismograms (Pintore et al., 2005). Although the S-rule method seems better and more natural than the C-rule method, we included the C-rule method in our program for completeness, because that the C-rule method

essentially depends upon the first-order feature of the traces, while the S-rule method rests on the second-order feature of the trace. If the raster image has infinite high resolution, the S-rule method is the only right choice. However, as the resolution decreases, the reliability of the second-order feature diminishes. It changes the smooth seismic traces into pulse-like curves, which reduce or completely eliminate the smooth characteristic of the traces. In this case, the S-rule method maybe come even worse than the C-rule method, which may yields acceptable results in most of the cases. Therefore, the C-rule method is the default automatic digitization method of our program. The S-rule method is provided as an additional option for better results in some particular cases.

3.2.2. Refinement

After the "tracing" step, we obtain a primary result of automatic digitization. The quality of the primary results varies among different images, and few of them are satisfactory. Further refinements are needed to improve the quality to meet the requirement of the modern seismological techniques. Actually, our digitalization described above is based on the abstraction that seismograms are convolution of seismic data and ball-like patterns. The automatic refinements also apply this principle.

In the primary result, at least one drawback may be found in the digitization results of both the historical seismogram and the digital seismogram. The primarily digitized trace distorts from the correct trace when reaching a sharp turn of the seismic trace (Fig. 4b). This distortion is due to the significant error of the "middle point" approximation in "tracing" step. As shown in Fig. 5a, the approximation radius of the ballpoint is far larger than the radius of the correct
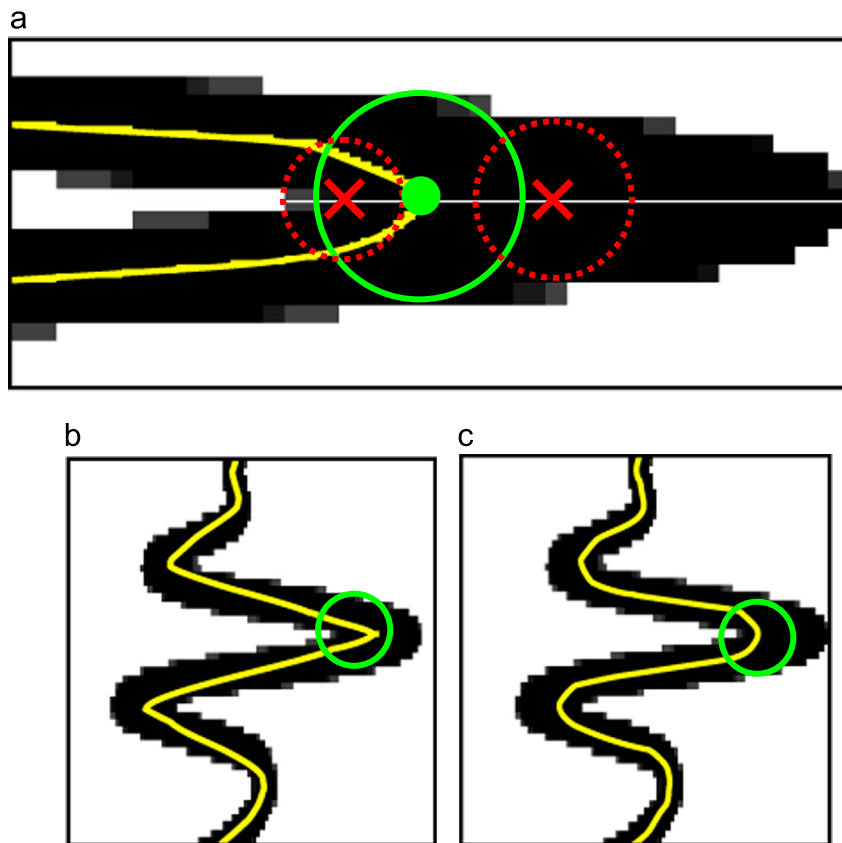
Fig. 4. The "varied width correction". Panel (a) illustrates how the refinement works. The red dotted circles with an " × " at their centers represent solutions during the bisection search, while the green solid circle with a ball at its center represents the final solution. Panels (b) and (c) show the difference between digitization results before and after the correction respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
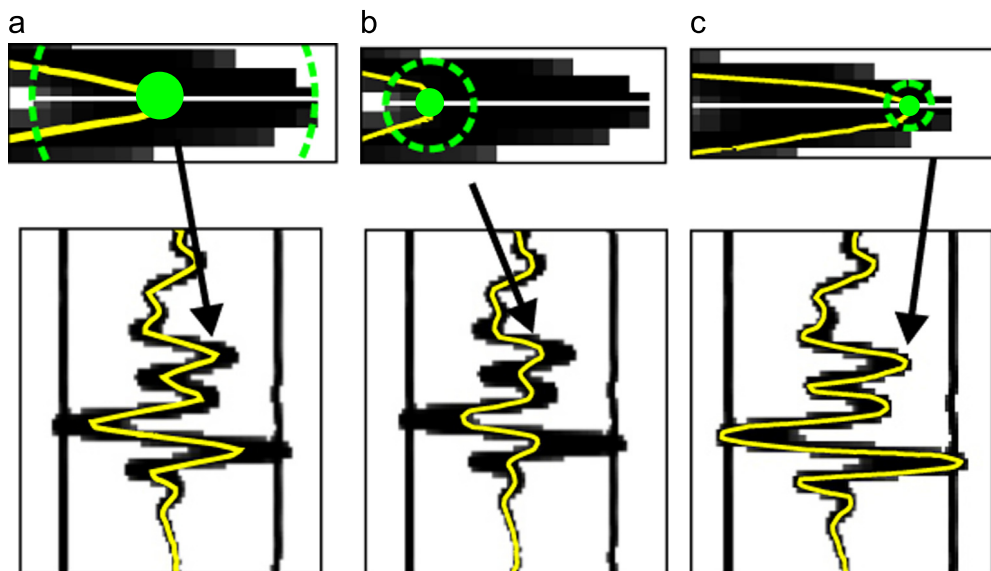
Fig. 5. The "fixed width correction". The digitization result obtained after "fixed width correction", is compared to the result of the C-rule method and after only the "varied width correction". The enlarged pictures show the differences among them. An essential difference between digitized results after only the "varied width correction" and the "fixed width correction" is that the radii of the circles in the former vary along the trace, while those in the latter remain the same.

ballpoint (Fig. 5c). Applying variable radii of the ballpoint patterns along the trace, we obtain the results of "varied width correction". This correction is the first choice of refinement, which finds the largest ballpoint pattern internally tangential to the trace with the origin of the ballpoint at the same time point. "Internally tangential" means that these balls locate inside seismic traces and are infinitely

close to the two boundary lines of the traces (Fig. 5b). This correction is implemented by bisection search so as to greatly improve the result near the peaks or valleys of the seismic traces (Fig. 4). It is suitable for both the historical seismogram and the modern digital seismograms. The digitized result of historical seismograms after the "varied width correction" now becomes the best one of the automatic digitization.

Any other distortions are left to manual digitization and the additional correction may be applied.

However, further refinement could be employed to the modern digital seismograms. Applying a constant radius of the ballpoint pattern, we obtain the results of "fixed width correction", which is also set up in the program as the second choice of the refinement. The fixed radius takes the dominant radius of the "varied width correction". Generally, the dominant radius should be smaller than any other radii. Since the ballpoint patterns after the "varied width correction" are internally tangential to the traces, reduction in the radii makes them close to one boundary of the traces. In order to keep the amplitude information, we make the ballpoint patterns remain touching the farther boundary away from zero base lines of the seismic traces (Fig. 5c). The base line may be obtained in different ways, such as mean of the silent part of the trace and the mode of the amplitude of the trace. We prefer the second method..

In summary, the automatic digitization algorithm consists of four steps.

Step 1: find the starting point;
Step 2: trace along the seismic trace;
Step 3: the refinement based on the "varied width correction" (optional);
Step 4: the further refinement based on the "varied width correction" (optional).

3.3. Manual digitization

Although the automatic digitization algorithm performs well on most of the cases, it fails sometimes due to complexity of real seismograms. Leaving the rotation and tilt problem to the pre-digitization process, we concentrate on the problems of the trace-crossing and discontinuity. We have tried to solve the problems in automatic tracing step by predicting the position of the next point based on smoothness feature and have obtained good results.

However, we fail in some complex cases. The problems seem unable to be completely solved by any single algorithm. We therefore put a manual digitization into the program to make the final refinement to the digitized seismograms. The manual digitization simply records the positions of mouse clicks and interpolates the positions into a sequence of amplitude–time pairs. It then updates the amplitude data of the corresponding time. The programs provide a smooth switch between manual digitization and automatic one. After the manual digitization, the program can perform a new automatic digitization that starts with the last point of the manual digitization. Then, users can make new manual correction and automatic digitization. The automatic digitization here is implemented with one-direction digitization of a trace. The preferred direction is consistent with the direction of time-increasing.

4. Examples

The first example is to digitize a wide-angle seismic profile (Fig. 6). First, we choose 80 as the threshold to "clean" the image because that the seismogram has little blemish. Next, we select the C-rule method by unchecking the "Smooth" checkbox in the "Digitize All Trace" panel, and choose the "fixed width correction" as the refinement method by checking both the "Varied Width Correction" and "Fixed Width Correction". Leaving the "Custom Fixed Width" unchecked and then clicking the "Digitize All Traces" button, an automatic digitization is started. The automatically digitized results fit the original seismogram well, because the seismogram satisfies the assumption with the ball patterns have same fixed radius (Fig. 6a). The manual digitization can be used to correct the results, i.e. selecting the trace, clicking the "Manually Digitize" in the toolbar and digitizing the wrong part manually. If digitized result mistakenly follows the wrong trace from one point, a new automatic search can be started for the trace after
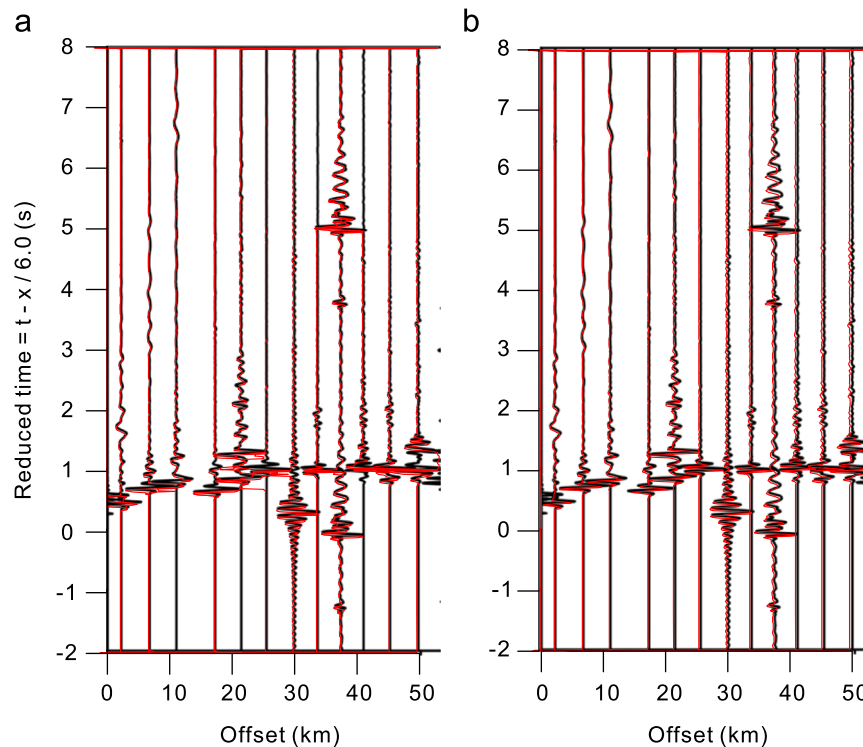
Fig. 6. Digitization of a wide-angle seismogram. Original seismograms are used as the background, and the digitized results are shown in red lines. (a) shows the results of automatic digitization, and (b) shows the results after manual corrections. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a	b
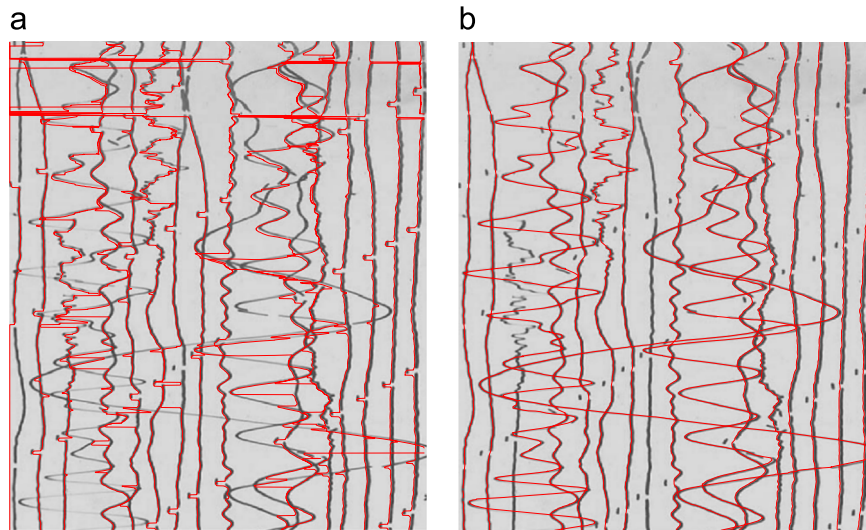
Fig. 7. Digitization of a seismogram on photographic record (from Pintore et al., 2005). Original seismograms are used as the background, and the digitized results are shown in red lines. (a) shows the results of automatic digitization, and (b) shows the results after manual corrections. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

adjusting the digitized result to the right trace manually. The final result of the digitized seismogram is given in Fig. 6b, which shows the digitalization matches well with the original seismogram (red lines).

The second example is to digitalize a seismogram on photographic record (from Pintore et al., 2005). In this experiment, a higher threshold value, i.e. 180, is chose because of the dark background. The options of the automatic digitization are the same as the first example except setting the "Fixed Width Correction" to unchecked, since this refinement is too strong for this kind of seismogram. The automatic result as shown in Fig. 7a is worse than one in the first example. The program cannot find the right traces except for the several isolated traces. However, manual digitization together with the S-rule method can be used to improve the quality of the digitized result (Fig. 7b). Although the program fails in obtaining excellent result by purely automatic digitization, it offers an interactive automatic way that does significantly improve the efficiency and accuracy of the digitization of seismograms. One may notice that two traces have not been digitized in Fig. 7b. The reason is that the program identified only 16 traces out of the all 18 traces in the seismogram. Then only 16 arrays were created to store the digitized trace. Consequently, the two unprocessed traces have to be left for the following single trace digitization. To start a single trace digitization, one should save the digitized data in a file and clear memory, then use manual digitization to set the starting point for the trace and carry out the automatic digitization. After that, use the same technique as manual correction to digitize the trace and save it in a different file. Repeating the same procedure to the other trace, one completely digitized the whole seismograms.

5. Conclusion

This paper tackles the digitization of analog seismograms by solving an inversion problem. Although we eventually have not used any classical method (such as steepest descent method or simulated annealing method) to the digitization problem, we demonstrated a new algorithm to resolve the problem. The new method is actually to find optimized solutions under the constraints obtained from the basic features of historical seismograms. The presented method first finds an approximation of seismic traces, and then iteratively improves the result by adding new

constraints of C-rule or S-rule. The more features are added into the program, the better results are obtained by the automatic digitization.

Our computer program achieves a balance between correctness and efficiency by offering a manual digitization modality along with automatic one. Most of this paper presents the automatic digitization algorithm, but the manual digitalization is crucial when using the program to digitize a seismogram. It is the same as driving a vehicle. The automatic algorithm is the vehicle, and the manual digitalization is the driver who adjusts the searching direction and makes corrections. Users are not constrained in the results of computers but can easily make corrections wherever needed. It makes the interactive program work pretty well on practical seismograms.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.cageo.2013.11.001.

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