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단일지진관측 방위각 결정을 위한 시간－방향 스태킹 방법
Time－Direction Stacking Method for a Single－Station Azimuth Estimation

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요약/Abstract

3성분 단일 지진관측의 방위각 결정에서 때때로 결과는 파형에 의존하고, 자동 관측은 불편하게 만든다. 본 연구에서는 시간－방향 스태킹 기술에 의해서 방위각이 아주 긴 파열(wave train) 관측으로부터 더 정확하게 결정되는 대안을 제안한다. 한반도 지진관측으로 취득한 디지털 파형을 가지고 시험한 결과 단순한 알고리즘은 광역거리에서 지진 진원의 방위각을 더 정확하게 결정하여 주는 것을 보여준다.

In estimating the azimuth of regional earthquakes with single－station three－component data, in some cases the result is dependent on the selection of waveforms, making the measurement subjective and inconvenient in automatic detection. In this paper an alternative approach is proposed in which the azimuth is measured from quite a long wave train by time－direction stacking technique. Test with digital waveform data from Korean seimic stations shows that the simple algorithm seems to be able to give a better estimation of azimuth of earthquakes at regional distances.

Key words : single－station, azimuth, stacking, regional earthquakes

Introduction

There are three important reasons why the problem of a single－station earthquake location, one of the oldest problems in seismology, keeps attracting research interest among seismologists. Firstly, the problem how many stations at least are needed to determine certain parameters of an earthquake is a fundamental one, and a single－station is an extreme of such problem. Secondly, in seismological observation, as the distance from the source to the receiver becomes much larger than the dimension of the coverage area of a seismic station network, the problem of source parameter estimation degenerates into a single－station problem. Even when the source－station distance is comparable to the aperture of the seismic network, in dealing with earthquakes outside the network coverage, the location is also near to the single−station problem (Kim and Lee, 1995). Finally, in regions with insufficient communication facilities, the single−station response to local and regional earthquakes is crucial in the social endeavor of the preparedness and mitigation of seismic disasters. It is natural, therefore, once a new generation of seismometer is developed, the single−station problem will be discussed using the new data and new techniques. In recent years, the single−station problem has attracted renewed attention in seismology, mainly because of the developments of digital seismological observation and automatic detection technique (*e.g.*, Magotra et al., 1987;Jurkevics, 1988;Roberts et al., 1989;Roberts and Christoffersson, 1990;Kim and Lee, 1995).

In the single−station location of regional earthquakes, the azimuth is an important parameter. In estimating the azimuth of regional earthquakes with a single−station three−component data, one of the problems is that in some cases the result seems dependent on the selection of waveforms, and sometimes the dependence is quite sensitive (e.g., Kim and Lee, 1995). Such dependence makes the measurement subjective and, as a result, causes inconvenience in automatic detection, naturally rising the question whether it is possible to extract the overall polarization properties from longer wave trains and make the result more robust with some statistical operations. In this paper an alternative approach is proposed in which the azimuth is measured by time−direction stacking. The algorithm, being straightforward in principle and very simple in data processing, seems effective in estimating the azimuths of earthquakes at regional distances.

Time−direction stacking

The methodology of the approach is straightforward. It is assumed that the signals contained in regional seismograms mainly consist of two types : the P−type motion paralell to the direction of the source−station vector, and the S−type motion perpendicular to the source−station vector, no matter what phases they belong to. In this case there is a unique P−direction and many S−directions. What is going to be done is to take the average direction of motion for all samples (the time stacking) and to add the motion vectors in the P−direction and in all of the S−directions altogether (the direction stacking). It is also assumed that the apparent noise, including both the noise itself and the scattered signals which have the polarization properties of neither P−type nor S−type, is stochastic and can be eliminated through the stacking.

The data processing is extremely simple. For a time series of three component ground motion $x_1(i)$, $x_2(i)$ and $x_3(i)$, $i=1,2,\ldots, N$, in which $x_1(i)$ denotes the ground motion along the vertical direction at time $i\triangle t$, where $\triangle t$ is the time step, $x_2(i)$ denotes the motion along the north−south direction, and $x_3(i)$ denotes the motion along the east−west direction, taking a time window $m\triangle t$, the mean square roots over the time window can be calculated as

$$X_k(i)=\frac{1}{m}\sqrt{\sum_{j=1}^{m}x_k^2(i-j)} \qquad k=1,2,3 \tag{1}$$

One can determine the azimuth Az and apparent incidence angle i_a at time $i\triangle t$ by

$$Az(i)=\arg\tan\left[\frac{X_3(i)}{X_2(i)}\right] \tag{2}$$

$$i_a(i)=\arg\tan\left[\frac{\sqrt{X_2^2(i)+X_3^2(i)}}{X_1(i)}\right] \tag{3}$$

Generally, the average over the time window is adopted to depress the noise. On the other hand, however, the time window $m\triangle t$ can not be too long, because within a long time window, the result will be affected by the mechanism and complexity of the earthquake.

As the next step, the number of samples with certain Az and i_a, represented by $R(Az, i_a)$, is counted over the given time span $N\triangle t$. Then the direction stacking

$$R_a(Az, i_a) = R(Az, i_a) + R(\frac{\pi}{2} - Az, i_a) \qquad (4)$$

is undertaken. Seen in a 2-dimentional view, this algorithm equals to stack all of the eight directions, P, S_1, S_2, a, b, c, d and e altogether, as shown in Figure 1. However, as directions a, b, c, d and e contain mainly apparent noises, the stacking is only effective for directions P, S_1 and S_2. In practical analysis, whether the final azimuth takes the value of Az or $\frac{\pi}{2} - Az$ is determined by whether the motions are mainly S-type or P-type, which is simple at regional distances : for indigenous earthquakes the motion is mainly S-type ; for underground explosions the motion is mainly P-type. In the estimation of azimuth, the value $R_a(az, i_a)$ is normalized by

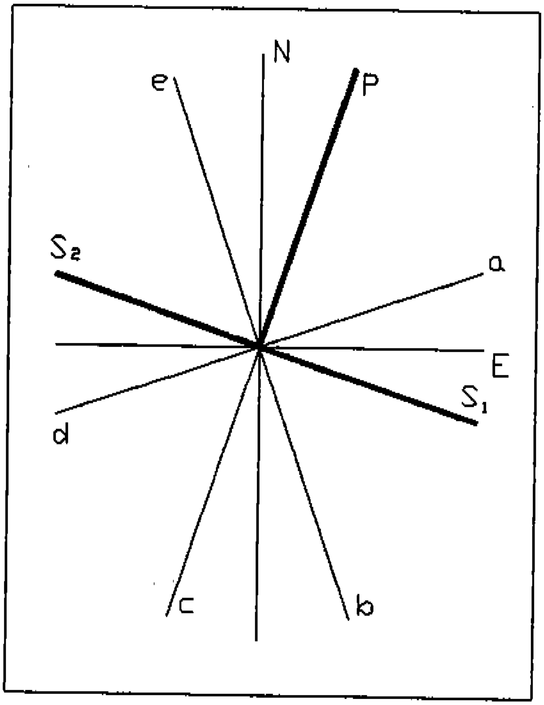

Figure 1 Direction stacking. See text for details.

$$S(Az, i_a) = \frac{R_a(Az, i_a)}{\max[\ R_a(Az, i_a)]} \qquad (5)$$

The centroid location of the distribution

$$Az_0 = \sum_S [\ Az \cdot S(Az, i_a)] \ / \sum_S S(Az, i_a) \qquad (6)$$

$$i_{a_0} = \sum_S [\ i_a \cdot S(Az, i_a)] \ / \sum_S S(Az, i_a) \qquad (7)$$

is taken as the final result. From the distribution of $S(Az, i_o)$ along the $Az - i_a$ plane the uncertainty of the estimation can also be obtained. For instance, one can use

$$(\delta Az)^2 = \sum_S [\ (Az - Az_0)^2 \cdot S(Az, i_a)] \ / \sum_S S(Az, i_a) \qquad (8)$$

$$(\delta i_a)^2 = \sum_S [\ (i_a - i_{a_0})^2 \cdot S(Az, i_a)] \ / \sum_S S(Az, i_a) \qquad (9)$$

which gives the upper limit of the uncertainty. As a result, such a statistics gives four possible values within the four quadrants, respectively. Using other information, such as first motions, it is easy to determine the choice. Finally, if, as indicated by the first motions, the azimuth is near to $\frac{\pi}{2}$ or $\frac{3\pi}{2}$, in the small denominator in equation (2) will cause instabilities in the calculation. In this case, a simple trick is to rotate the coordinate axis by $\frac{\pi}{4}$, then the result will be obtained with more stability.

Test with seismic records

As a test of the algorithm proposed in this paper, a test with seismic records was undertaken. Figure 2 shows the stations and earthquakes involved in this study. The parameters of the stations and earthquakes are given in Tables 1 and 2. In the figure the line between a station and an earthquake indicates that the seismogram of the earthquake recorded at the station is chosen for the analysis. The events include two earthquakes and two explosions, with the azimuth coverage of the seismic rays over 200°.

Figure 3 shows the result for the Yellow Sea earthquake recorded at Guntan station. The three component seismogram is shown in the lower plot, in which the vertical bars denote the time span, $N \triangle t$, chosen for the analysis. The upper plot shows the $S(Az, i_a)$ function in the $Az-i_a$ plane. Cross indicates the centroid as calculated in equations (6) and (7). The coordinates of the centriod is taken as the final result of Az and i_a. From the distribution of $S(Az, i_a)$ the uncertainty of the result can also be estimated by (8) and (9). The result from ellipsoid analysis (Kim and Lee, 1995) is taken as the reference result to determine the quadrant. The stacking gives the result of $Az \approx 219°$, near to the actual value 216.5°. In contrast, traditional polarization analysis using P waves gave the result $Az \approx 243°$ (Kim and Lee, 1995), with the deviation much larger than that in this approach. In fact, it may be seen from Figure 3 that as the seismogram is complex in its appearance, it is hard to extract the P-phase, and the selection of certain phases is quite subjective. In this case the statistical approach shows its advantage that it is able to extract the overall information from a long wave train. Experiments also show that the result is stable against different lengths and different endings of the waveform except that the time span is taken to be too short or too long. For instance, in the analysis of the Yellow Sea earthquake with the seismic records at Guntan station, for 40%, 60% and 80% of the time span shown in Figure 3, the measured

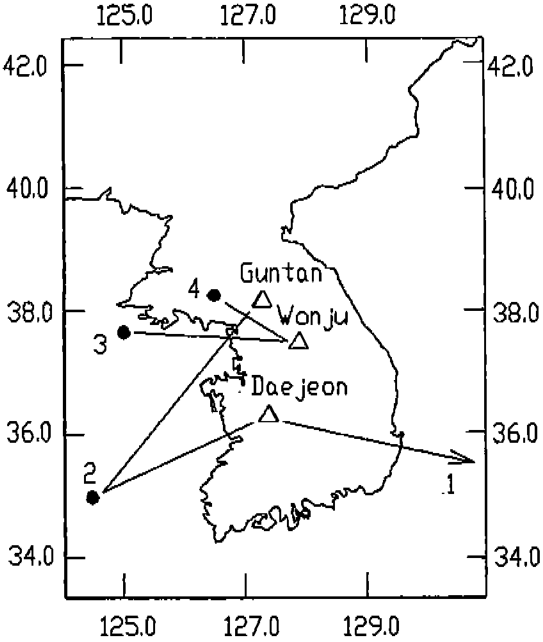

Figure 2 Stations and earthquakes in this study. Triangles denote stations, and points denote earthquakes. Earthquakes are numbered according to their azimuths. Line between station and earthquake indicates that the seismogram of the earthquake recorded at the station is chosen for the analysis. Parameters of stations and earthquakes are given in Tables 1 and 2. Earthquake no. 1 is out of the range of the figure, yet its azimuth relative to the recording station is shown.

Table 1. Parameters of stations in this study

Station	Latitude	Longitude	Sampling rate	Record Type
Daejeon	36.30	127.40	100	Velocity
Guntan	38.15	127.32	50	Velocity
Wonju	37.48	127.90	20	Velocity

Table 2. Parameters of earthquakes in this study

Event No.	Date	Time	Latitude	Longitude	Depth(km)	Magnitude	Note
1	95-01-17	05 : 46 : 54	34.67	135.04	16	mb6.0	Kobe
2	94-07-26	02 : 41 : 50	34.91	124.43	10	M4.9	Yellow Sea
3	88-01-26	16 : 59 : 02	37.69	124.99		M2.4	Explosion
4	88-01-24	13 : 14 : 29	38.26	126.51		M2.7	Explosion

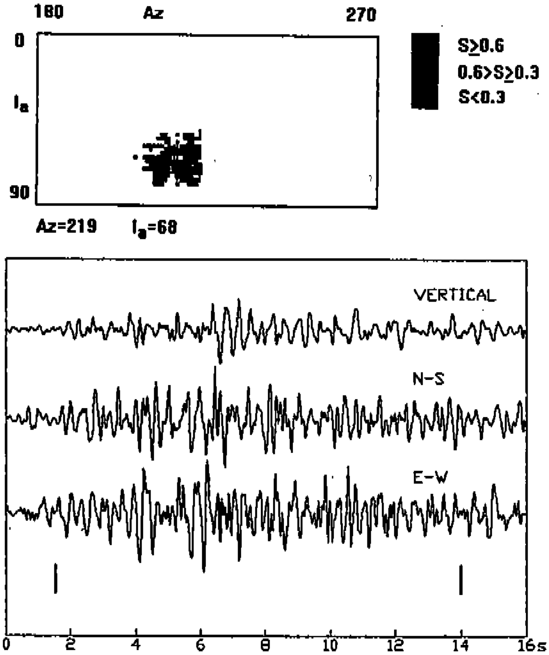

Figure 3 Time-direction stacking result for the Yellow Sea earthquake recorded at Guntan station. The three component seismogram is shown in the lower plot, in which the vertical bars denote the time span chosen for analysis. The upper plot shows the $S(Az, i_a)$ function in the Az-i_a plane. Cross indicates the centroid. The coordinates of the centriod is taken as the final result of Az and i_a. From the distribution of $S(Az, i_a)$ the uncertainty of the estimation can also be obtained. See text for details.

azimuth varies within 2°. As for the same earthquake recorded at Daejeon station, the polarization analysis using P_n wave gave the result of $Az \approx 252°$ (Kim and Lee, 1995), while the present approach (Figure 4) results $Az \approx 239°$, much nearer to the actual azimuth 241°. As another example, Figure 5 shows the result for the 88/01/26 explosion recorded at Wonju station. Using first motion to determine the quadrant, the result $Az \approx 279°$ is near to the actual azimuth 275.5°, implying that the algorithm seems approporiate for both earthquakes and explosions.

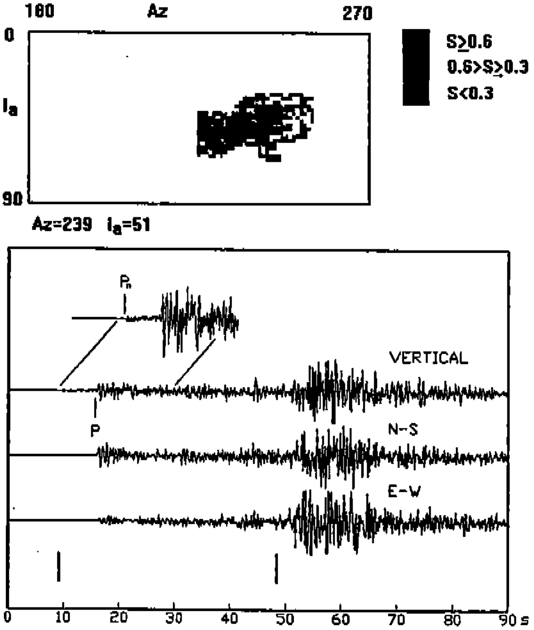

Figure 4 Time-direction stacking result for the Yellow Sea earthquake recorded at Daejeon station. Symbols have the same meaning as in Figure 3.

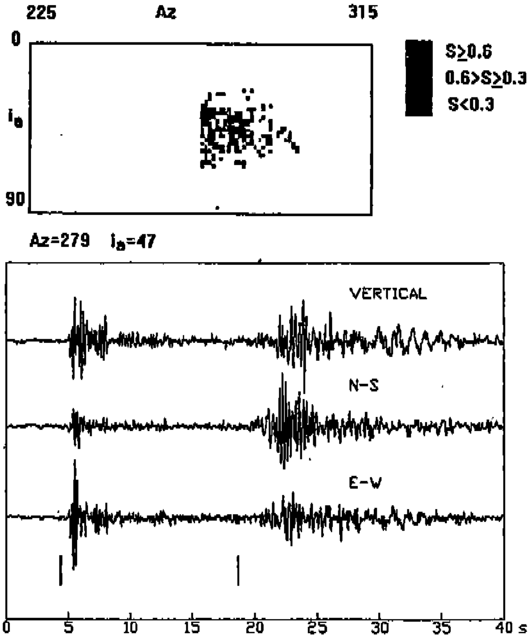

Figure 5 Time-direction stacking result for the 88/01/26 explosion recorded at Wonju station. Symbols have the same meaning as in Figure 3.

As an overall look at the results, Figure 6 shows the comparison between the azimuths obtained by stacking (the vertical axis) and the 'true' azimuth (the horizontal axis). The results are listed in Table 3 in detail. In the figure the solid points denote the result given by the centroid location, while the bars give the uncertainty of the estimation. It may be seen from the figure that the simple approach proposed in this paper seems effective in estimating the single-station azimuths at regional distances.

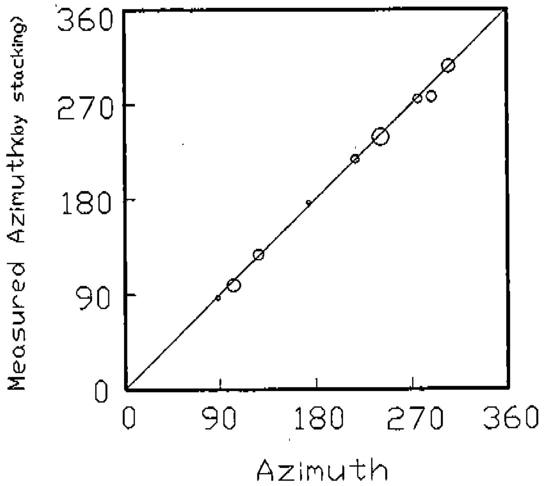

Figure 6 Azimuths obtained by stacking (vertical axis) versus the actual azimuth (horizontal axis). Numbers denote the serial number of earthquakes, bars give the uncertainty of the stacking estimation. See Tables 2 and 3.

Table 3. Results of T-D stacking

Earthquake	Station	Azimuth	Azimuth by stacking
1 Kobe eq.	Daejeon	102.5	96
2 Yellow Sea eq.	Guntan	216.5	219
2 Yellow Sea eq.	Daejeon	241.0	239
3 Explosion	Wonju	275.5	279
4 Explosion	Wonju	305.0	307

Discussion

At regional distances, the propagation of seismic waves is quite complex. Different phases may be affected by the heterogeneities within the Earth to different extent. As a result, it is natural that the azimuth calculated from the polarization analysis of a single phase or a few phases may deviate from the true value. Or to be more exact, the seismic waves of some phases may propagate along the path different from that predicted by homogeneous structure model. Therefore, in locating earthquakes at regional distances, it is possible that the result be dependent on the selection of different phases. Sometimes such dependence may be sensitive. This effect may cause considerable deviations in the single-station azimuth determination, as demonstrated in previous experiments (e.g., Kim and Lee, 1995).

The statistical properties of regional seismic waves, on the other hand, mainly depend on the overall structure between the source and the station. As the signals of different phases are stacked altogether, it may be expected that the noise would be depressed and the deviations would be smoothed out. In methodology, the idea of this approach is the same as those of other stackings carried out in seismic analysis. However, our result shows that stacking as a useful tool in seismic data analysis can be undertaken even to a single-station data.

It may be seen from the result that the technique proposed in this paper seems to be able to provide a better estimate of the azimuth and the apparent incidence angle. On the other hand, however, the estimation of azimuths by the time-direction stacking cannot determine the quadrant of the azimuth, which should be determined by other information such as first motions. More often one may use the result of ellipsoid analysis (e.g., Jurkevics, 1988;Kim and Lee, 1995) as the reference to determine the quadrant, as has been done in this approach. That means what has been done through stacking is only to enhance the quality of azimuth estimation, while in the enhancement of the quality, a price has been paid that the information about the quadrant is lost. Moreover, to obtain the location of an earthquake, other information such as the arrival time differences of different phases is also necessary.

This is the limit of the stacking method. Nevertheless, as one of the approaches to get better parameter estimation from a single−station, the simple technique proposed in this paper has provided more confidence on the potential of a single−station of three−components in the monitoring of earthquakes and can be used at least as a reference to other results obtained from other methods.

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