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ORIENTATION ERROR ESTIMATION OF BURIED SEISMOGRAPHS IN ARRAY OBSERVATION

FUMIO YAMAZAKI,[*] LIN LU[†] AND TSUNEO KATAYAMA[‡]

Institute of Industrial Science, The University of Tokyo, 7-22-1 Roppongi, Minato-ku, Tokyo 106, Japan

SUMMARY

Array observation is an efficient tool to investigate various characteristics of earthquake ground motion. However, seismographs used in arrays may involve unexpected errors in their orientations. Methods of orientation error estimation were developed in three-dimensional space by comparing recorded ground motions at a reference point with those at a checking point. A maximum cross-correlation method and a maximum coherence method were proposed and their accuracy was demonstrated. The earthquake ground motions recorded in the Chiba array and in two other arrays were used in numerical examples. Non-trivial orientation errors were detected for all these arrays. The cross-correlation coefficients and the coherence values between two points increased significantly by correcting the estimated orientation errors.

INTRODUCTION

In recent years, a large number of seismograph arrays[1–3] have been installed at many places in the world in order to evaluate various engineering and seismological characteristics of earthquake ground motions. In array observations, an unexpected problem which had not been considered seriously for autonomous (stand alone) seismograph stations may be encountered, that is, orientation errors of seismographs from their preassigned directions. Recorded ground motions from seismograph arrays are often used in wave propagation and spatial variation analyses[4–6] and in soil amplification studies,[7–9] among other things. In these cases, the correlation of earthquake ground motions among different locations or depths is of major concern. Thus, the arrayed seismographs must have correct orientations; otherwise such studies cannot be made precisely.

It may be rather easy to place seismographs on the ground surface to a preassigned orientation, but it is not so easy to set them correctly in boreholes. It is also noted that once a downhole seismograph is buried, it is extremely difficult to confirm its orientation visually and to reposition it when an error is found. In such a case, estimating the instrument orientation error using recorded motions and then correcting the records by a coordinate transform may be the best remedy.

Actually, orientation errors have been reported for several arrays, e.g. the Chiba array[10] in Japan and the Turkey Flat array[11] in the U.S.A. In these cases, orientation errors were detected from particle orbit plots of two horizontal components and were estimated by maximizing the cross-correlation coefficients between the horizontal components of two points. This means that the orientation error is considered to be a rotation angle about the vertical axis of the instrument.

However, there are generally three components in earthquake ground motion. Hence, for the orientation error of a three-component seismograph, three rotation angles exist about three spatial coordinates. The two additional angles are the rotations about the two horizontal axes which correspond to the tilts of the

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[*] Associate Professor.
[†] Graduate Student.
[‡] Professor.

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instruments in boreholes. To estimate these three angles accurately for a buried seismograph, two methods which use recorded ground motions at this checking point and at a reference point are proposed in this paper. The maximum cross-correlation method compares the three pairs of cross-covariance functions in the time domain, while the maximum coherence method employs the three pairs of coherence functions in the frequency domain. These techniques are described and their accuracy is discussed. Three seismograph array systems are considered as examples, and orientation errors are detected in all the three arrays from their recorded motions.

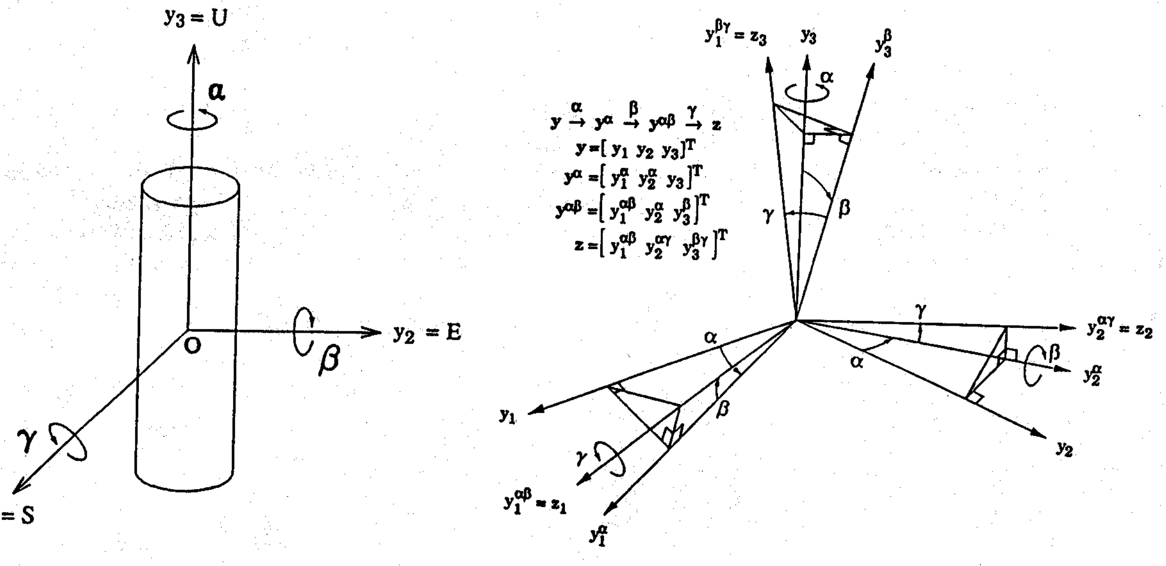
METHODS OF ORIENTATION ERROR ESTIMATION

Orientation error in three-dimensional space

There are many kinds of seismographs in the world. Among these, consider a three-component seismograph to be installed in a borehole. For such an instrument, three transducers corresponding to the three orthogonal directions are placed in a casing. The orthogonality of the three transducers in the casing is first assumed. When setting the seismograph in a borehole, extreme care is taken to give it the correct orientation. However, since it is difficult to confirm visually the position of the instrument from the ground surface, an orientation error may still result in some cases.

Suppose the earthquake ground motion at a point is represented by the vector process $\mathbf{z}(t) = [z_1(t), z_2(t), z_3(t)]^{\mathrm{T}}$ with $z_1(t)$, $z_2(t)$ and $z_3(t)$ indicating the ground motion components to the preassigned directions, i.e. the north–south (NS), east–west (EW) and up–down (UD). Each component may have a dimension of acceleration, velocity or displacement. Also, it could be a filtered wave for a selected frequency range where high spatial coherence is observed. Similarly, the ground motion recorded by an instrument having an orientation error is denoted by $\mathbf{y}(t) = [y_1(t), y_2(t), y_3(t)]^{\mathrm{T}}$. A direct measurement of $\mathbf{z}(t)$ is desired, but only $\mathbf{y}(t)$ can be observed by the seismograph. Hence it becomes necessary to estimate the orientation error and to calculate $\mathbf{z}(t)$ from the observed $\mathbf{y}(t)$.

The possible orientation error of a three-component seismograph can be expressed by three independent angles α, β and γ, as shown in Figure 1(a). Angle α describes the rotation of the casing about the vertical axis y_3. Angles β and γ define the rotations of the casing about the horizontal axes y_2 and y_1, respectively. The



(a) rotation of α, β and γ independently

(b) rotation of α, β and γ in turn

Figure 1. Three rotation angles in a three-dimensional space

two latter angles are usually smaller than α because they may be restricted by the wall of a borehole. If these three rotations occur simultaneously, the three rotations in turn must be considered as depicted in Figure 1(b). If $\mathbf{y}(t)$ is rotated in the order of α, β and γ, the corresponding three-dimensional coordinate transform matrix $\mathbf{T}$ is obtained by the product of three transform matrices as

$$\mathbf{T}(\alpha, \beta, \gamma) = \mathbf{T}_\gamma \mathbf{T}_\beta \mathbf{T}_\alpha \tag{1}$$

with

$$\mathbf{T} = \begin{bmatrix} \cos\alpha\cos\beta & \sin\alpha\cos\beta & \sin\beta \\ -\sin\alpha\cos\gamma - \cos\alpha\sin\beta\sin\gamma & \cos\alpha\cos\gamma - \sin\alpha\sin\beta\sin\gamma & \cos\beta\sin\gamma \\ \sin\alpha\sin\gamma - \cos\alpha\sin\beta\cos\gamma & -\cos\alpha\sin\gamma - \sin\alpha\sin\beta\cos\gamma & \cos\beta\cos\gamma \end{bmatrix} \tag{2}$$

where angles α, β and γ are the orientation error to be estimated. By applying the three-dimensional transform, $\mathbf{y}(t)$ is converted to $\mathbf{z}(t)$, which has the correct orientation:

$$\mathbf{z}(t) = \mathbf{T}(\alpha, \beta, \gamma)\mathbf{y}(t) \tag{3}$$

In order to estimate the orientation error of a dubious instrument, a reference instrument whose orientation is correct or known is necessary. Consider a ground motion vector process at the reference point as $\mathbf{x}(t) = [x_1(t), x_2(t), x_3(t)]^{\mathrm{T}}$. If the reference point and the checking point are not far apart, say within a few hundred metres, the existence of coherently propagating waves between the two points can be assumed. Also, effects of topographical irregularity or structural response should not be so large for the two points, otherwise seismic waves may be scattered or distorted and they become very different at the two points. If these conditions are satisfied, the angles α, β and γ which give the highest cross-correlation between vector processes $\mathbf{x}(t)$ and $\mathbf{z}(t)$ can be estimated. To perform this, two methods are proposed hereafter.

Maximum cross-correlation method

The orientation error involved in $\mathbf{y}(t)$ may be estimated by maximizing the cross-correlation between $\mathbf{x}(t)$ and $\mathbf{z}(t)$ in the time domain. Since there are three components in these vectors, a sum of three cross-covariance functions is considered:

$$S(\alpha, \beta, \gamma, \tau) = \sum_{i=1}^{3} R_{x_i z_i}(\tau) = \sum_{i=1}^{3} E[(x_i(t) - \bar{x}_i)(z_i(t+\tau) - \bar{z}_i)] \tag{4}$$

in which an overbar indicates a mean value, $E[\cdot]$ means the ensemble average and τ is the time lag between $\mathbf{x}(t)$ and $\mathbf{z}(t)$. Substituting equation (3) into equation (4) results in

$$S(\alpha, \beta, \gamma, \tau) = \sum_{i=1}^{3}\sum_{j=1}^{3} t_{ij} R_{x_i y_j}(\tau) \tag{5}$$

where t_{ij} is the element of the transformation matrix $\mathbf{T}$ in equation (2) and $R_{x_i y_j}(\tau)$ is defined as

$$R_{x_i y_j}(\tau) = E[(x_i(t) - \bar{x}_i)(y_j(t+\tau) - \bar{y}_j)] \tag{6}$$

In evaluating equations (5) and (6) for the sample processes of $\mathbf{x}(t)$ and $\mathbf{y}(t)$, the temporal average is used instead of the ensemble average for convenience. Then equation (6) is replaced by

$$R_{x_i y_j}(\tau) = \frac{1}{n}\sum_{k=1}^{n} x_i(t_k) y_j(t_k + \tau) - \bar{x}_i \bar{y}_j \tag{7}$$

and

$$\bar{x}_i = \frac{1}{n}\sum_{k=1}^{n} x_i(t_k); \qquad \bar{y}_j = \frac{1}{n}\sum_{k=1}^{n} y_j(t_k + \tau) \tag{8}$$

where n is the number of discretized time steps.

Since S in equation (5) is a function of variables α, β, γ and τ, the estimation of orientation error becomes a multi-variable maximization problem. The revised quasi-Newton method[12] is employed by converting the original problem to a minimization problem by multiplying both sides of equation (5) by -1. According to the method, for a given real function $f(\mathbf{x})$ with n variables and initial vector $\mathbf{x}_0$, vector $\mathbf{x}^*$, which gives the minimum value of $f(\mathbf{x})$, can be obtained by an iterative process for a given allowable error. For an assumed value of time lag τ, the quasi-Newton method finds α, β and γ which minimize S. This process is repeated for a possible range of time lag in which τ is taken discretely considering a sampling time interval. A combination of α, β, γ and τ which maximizes S among the possible candidates is a final solution.

It is known that high frequency contents of ground motion are less coherent than low frequency contents. Thus, a filtered wave having only low frequency contents will give a better estimate in this method.

The method was verified by solving sample sets of waves which have artificially introduced orientation errors. Earthquake ground motions during the 1987 Chibaken–Toho–Oki event[13] recorded by the Chiba array were used for this purpose. The three components of motion at a point were rotated for several sets of given angles α, β and γ. Then the original time histories, $\mathbf{x}(t)$, and the rotated time histories, $\mathbf{y}(t)$, were employed to estimate the artificially rotated angles. The results showed that the estimated and given angles agreed almost perfectly for the three angles. Therefore for cases where no noise exists between the two sets of time histories, the accuracy of this numerical technique was demonstrated. The effects of initial values in the revised quasi-Newton method were also examined. Several sets of initial values were used for a set of records at two points in the Chiba array. For different initial values, almost the same results were obtained. Thus the effect of initial values may be small if they are given within a reasonable range.

Note that, in the maximum cross-correlation method, the maximum positive cross-correlation is sought. Thus, frequency contents lower than the first predominant peak between the two points should be selected. It is only in this range that positive cross-correlation is always guaranteed. Hence band-pass filtered waves should be used considering also the accuracy of the instrument in the low frequency range.

Maximum coherence method

The cross-covariance function gives the correlation of ground motions at two points in the time domain, while the coherence function provides that in the frequency domain. In this method, the coherence function is employed instead of the cross-covariance function for detecting orientation error. Using the same notations as before, the coherence function between the ith components, $x_i(t)$ and $z_i(t)$, of two vector processes is defined as

$$\mathrm{coh}^2_{x_i z_i}(f) = \frac{|S_{x_i z_i}(f)|^2}{S_{x_i x_i}(f) S_{z_i z_i}(f)} \tag{9}$$

in which $S_{x_i x_i}(f)$ and $S_{z_i z_i}(f)$ are the power spectra of $x_i(t)$ and $z_i(t)$, respectively, and $S_{x_i z_i}(f)$ denotes the cross spectrum between them. Three sets of coherence functions exist between the three-component vector processes. Then consider the sum of these as the quantity to be maximized:

$$C(\alpha, \beta, \gamma) = \sum_{i=1}^{3} \int_{f_1}^{f_2} \mathrm{coh}^2_{x_i z_i}(f)\,\mathrm{d}f \tag{10}$$

where f_1 and f_2 indicate the range of frequency to be considered. Hence, in this method, frequency filtering for recorded motions is not necessary in advance. Obtaining a set of α, β and γ which gives the maximum value of C also becomes a multi-variable maximization problem.

The power and cross spectra can be evaluated in two ways, i.e. by taking the ensemble average or by applying smoothing to their sample estimates. The latter method is more convenient for orientation error estimation. Because of the smoothing procedure used in calculating the power and cross spectra, it is difficult to deal with this problem analytically. Hence, the problem is solved numerically.

For a given combination of α, β and γ in matrix $\mathbf{T}$, a value of C can be obtained by equation (10). Conducting such trials many times gives the set in which $\mathbf{x}(t)$ and $\mathbf{y}(t)$ become closest. Assuming m_α cases for α, m_β cases for β and m_γ cases for γ, the total number of combinations becomes $m_\alpha \times m_\beta \times m_\gamma$. This is obviously not an efficient way to find the maximum value of C because it entails too many trials. Instead, by firstly setting $\beta = \gamma = 0$, α_1, which maximizes C, is determined. This is because error α is more likely to occur and it is usually larger than errors β and γ. Secondly, by using the α_1 thus determined, the first approximations for the two other angles, β_1 and γ_1, are obtained. Finally, by using these α_1, β_1 and γ_1 as initial values, a narrow range is searched for the most appropriate error angles.

Note that the estimates of α, β and γ by the maximum coherence method are within the range $-90°$ to $90°$ because the coherence function can take only non-negative values. Hence, if an error angle is out of this range, examination of the phase delay between the two time histories is necessary. Also, because the coherence function generally decreases at the peaks of the transfer function, it is better to select the frequency range for the estimation between a very low frequency and the first natural frequency.

ORIENTATION ERROR ESTIMATION FOR THE CHIBA ARRAY

The Chiba array and status of its instruments

A dense three-dimensional array[10,13] has been in operation since 1982 in the Chiba Experiment Station of the Institute of Industrial Science, the University of Tokyo. In this array, 44 accelerographs are buried at several depths in 15 boreholes which are located within a space of approximately 300 m × 300 m. The number of instruments buried at each depth is 15 at GL $-$ 1 m, 5 at GL $-$ 5 m, 11 at GL $-$ 10 m, 11 at GL $-$ 20 m and 2 at GL $-$ 40 m. In addition, one accelerograph is placed on the first floor of the building where the recording system is located.

The accelerographs used in the Chiba array have piezoelectric type acceleration transducers. The three transducers and their amplifiers are encased in a cylindrical steel casing with an external diameter of 65 mm and a length of 335 mm. The casing was installed in a borehole with a diameter of 116 mm. A cable was connected to the casing at its cap for output signals and power supply. When the instrument reached a predetermined depth, it was fixed in place using cement mortar. Although it is almost certain that the three transducers were set perpendicular to one another, it is difficult to ensure the actual orientation of the instrument in spite of the meticulous care taken during the installation.

Soon after the start of the observation, orientation errors for most of the accelerographs were found[10] from recorded motions. The Lissajous figures formed by two horizontal components at each point had similar shapes but different directivities. Then eleven instruments buried at GL $-$ 1 m were exposed by excavation and their directions were measured by a compass and a weight. Since the errors were found to be large, five of the eleven excavated instruments were repositioned[10] after the inspection. It was practically impossible to excavate and reposition all the instruments, especially those buried deeply in the ground.

Recently, the authors developed the Chiba array database[13] comprising strong ground motions from 27 major events. At that time, the three-dimensional orientation error estimation was conducted and the results were utilized to correct the records for the database.

Estimation of orientation error

Using the two proposed methods, orientation errors for all the Chiba array instruments were examined. C001 point (GL $-$ 1 m in borehole C0) is used as a reference point because it is located at the centre of the Chiba array. Since the instrument at C001 was repositioned to have the correct orientation as mentioned above, the relative orientation error to C001 can be considered as an absolute one.

It is possible to estimate the orientation error from the records of a single event. If close results for several events can be obtained, however, the estimation becomes more reliable and more objective. Therefore seven events which showed relatively strong intensity at the site were selected. It is considered that the stronger the ground motion is, the higher the signal-to-noise ratio becomes. The epicentres of the seven earthquakes are shown in Figure 2. Table I summarizes basic information on the selected events.

The EW-components recorded at C001 for the seven events are shown in Figure 3, where the time spans adopted in the calculation are marked. The beginning and main shaking parts were selected. The beginning part, where vertical motion is strong, is useful when estimating β and γ, while the main part, where horizontal motion is dominant, is useful when estimating α. In the maximum cross-correlation method, time lag τ was

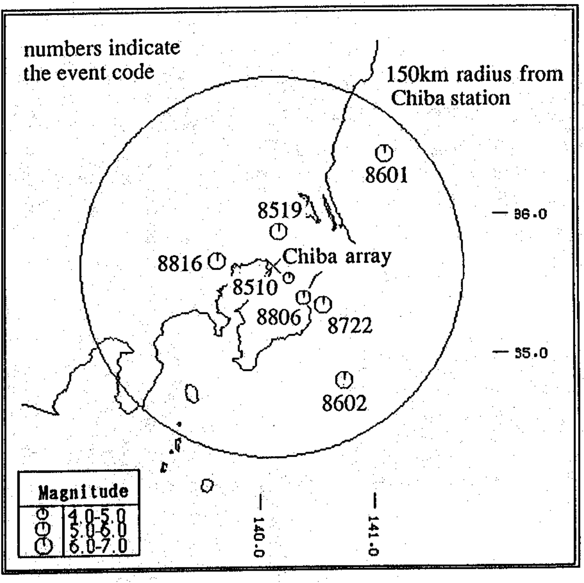


Figure 2. Epicentres of seven earthquake events used for orientation error estimation of the Chiba array

Table I. Information on the seven earthquake events

No.	IEQK	JMA M	d (km)	Δ (km)	Azimuth (deg.)	Max. Acc. at C001 (cm/s^2) EW	NS	UD
1	8510	4·8	64	16	126·1	27·4	29·6	12·6
2	8519	6·1	78	28	9·0	59·2	82·2	23·5
3	8601	6·1	44	125	44·5	15·4	14·3	5·2
4	8602	6·5	73	105	147·7	54·0	40·7	21·5
5	8722	6·7	58	45	128·1	213·6	327·1	124·8
6	8806	5·2	48	38	133·3	54·9	97·8	19·8
7	8816	6·0	96	42	276·3	48·4	59·8	15·2

JMA = the Japan Meteorological Agency; M = magnitude; d = focal depth; Δ = epicentral distance. Azimuth: clockwise from north.

treated discretely in steps of 0·005 s for the range − 0·25 to 0·25 s. In the maximum coherence method, a Parzen window with a bandwidth of 0·4 Hz was employed for smoothing.

For both proposed methods, the frequency range between 0·1 and 1·5 Hz was used for the calculation. The lower cut-off frequency was determined by the frequency-response characteristics[10] of the accelerographs. The upper cut-off frequency was determined by considering the spatial correlation characteristics of the ground motions. In the horizontal direction, the maximum separation distance between the reference and other instruments is about 250 m. Within this distance, ground motions were found to be strongly coherent for frequencies under around 1·5 Hz.[13] In the vertical direction, the deepest instruments are located at GL − 40 m. The fundamental period for the 40 m soil column was found to be about 2·3 Hz.[13] This means that the ground motion recorded at the ground surface has positive correlation with that recorded at GL − 40 m for frequencies lower than 2·3 Hz. The frequency range to use was determined from these observations.

Using the records of the 1987 Chibaken-Toho-Oki earthquake, the results obtained by the two methods are compared in Figure 4 under the same conditions of time segment (t = 0–16 s) and frequency range

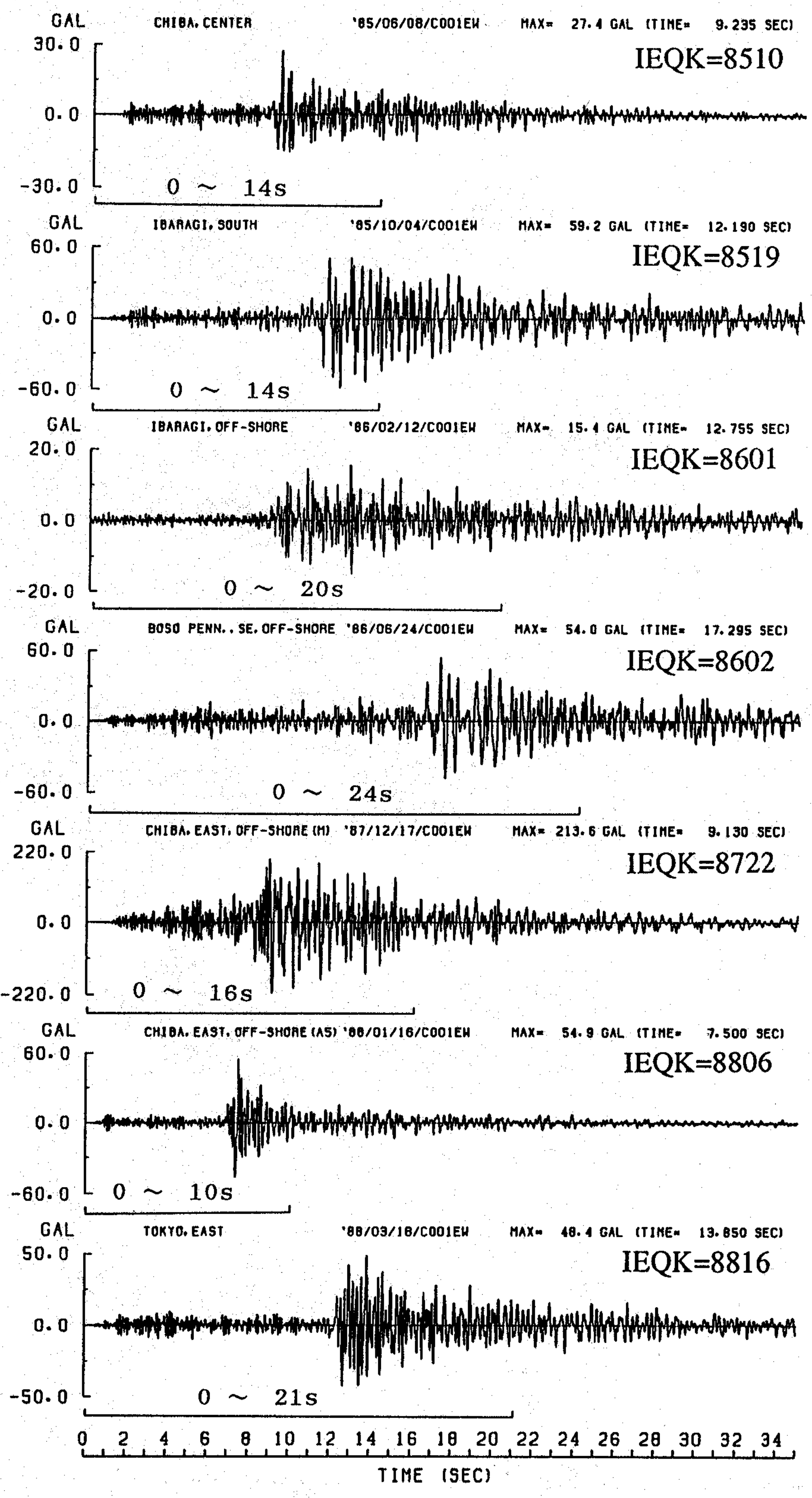


Figure 3. Time histories and selected time spans used for orientation error estimation (EW-components at C001)

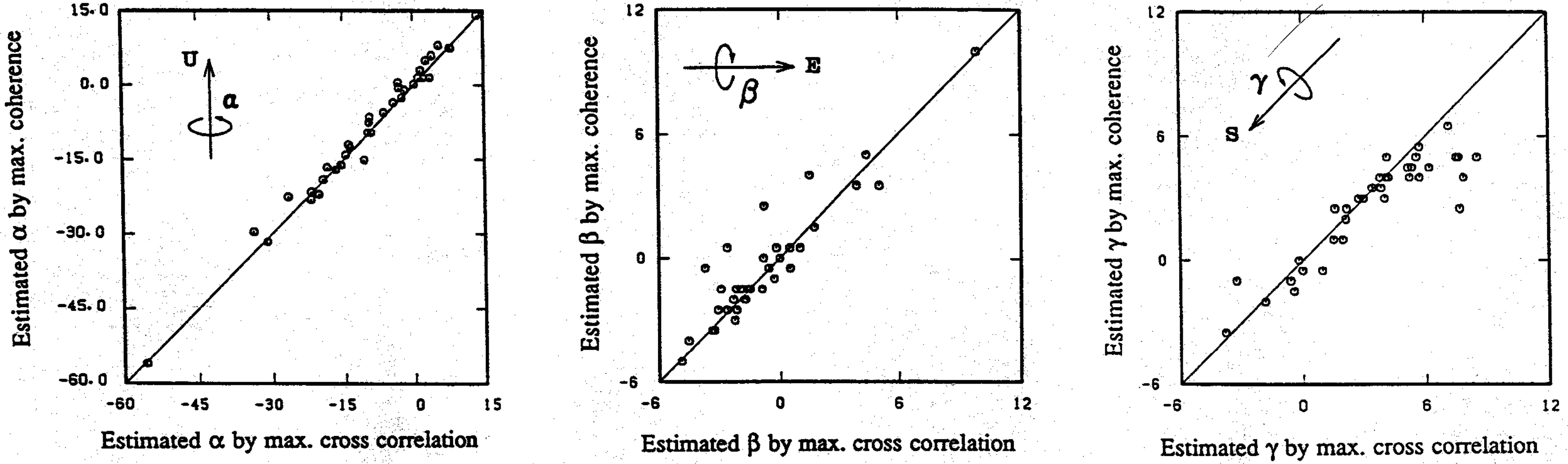
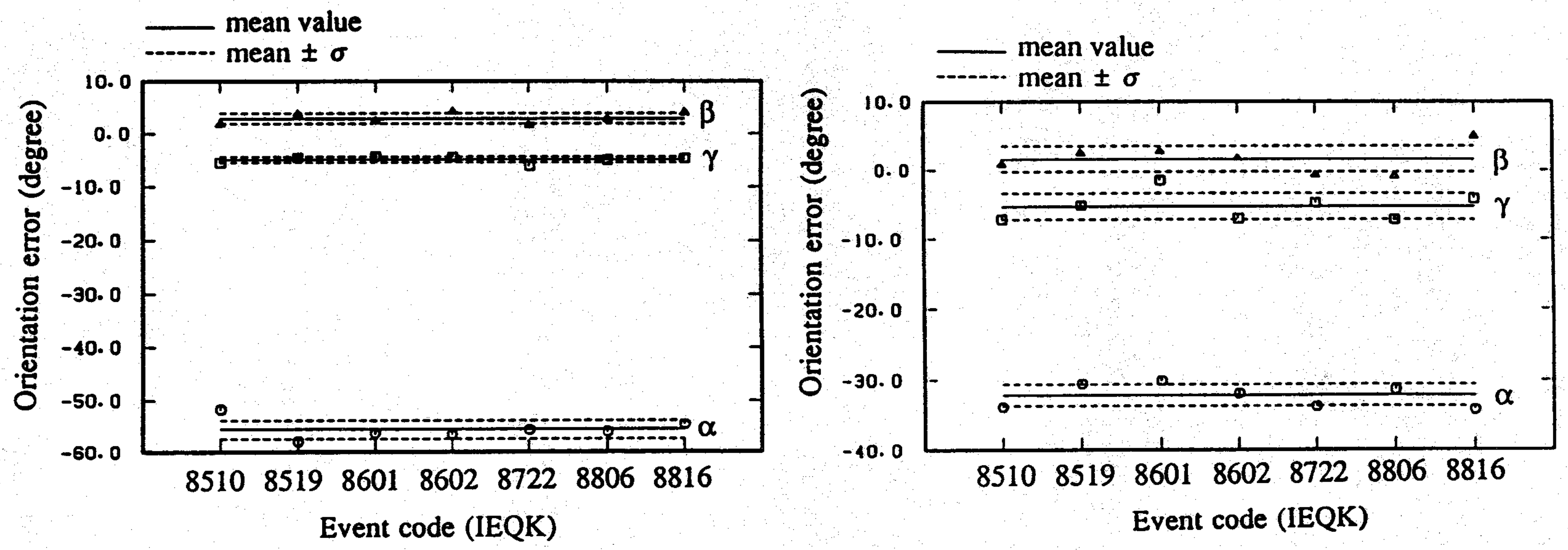


Figure 4. Comparison of estimated orientation errors for the 44 instruments of the Chiba array by the maximum cross-correlation method and the maximum coherence method (the 1987 Chibaken-Toho-Oki event, IEQK = 8722 in Table I)



(a) accelerograph C405

(b) accelerograph P610

Figure 5. Mean values and standard deviations of the estimated error angles for the seven events

($f = 0{\cdot}1$–$1{\cdot}5$ Hz). The two methods gave close values of α, β and γ for all 44 points. Hence either method may be used for orientation error estimation. The maximum cross-correlation method was employed in examples hereafter.

Orientation errors were estimated for the seven events and typical results for two points, C405 and P610, are plotted in Figure 5. The separation between C405 and C001 is 5 m in the horizontal direction and 4 m in the vertical direction, while the separation between P610 and C001 is 143 m horizontally and 9 m vertically. The figure indicates that each estimated angle is within a narrow range. For the other instruments, the standard deviations of the estimated angles for the seven events were mostly less than 1° or 2°. It was found that the standard deviation becomes larger as the separation between the checking point and the reference point (C001) increases. However, the maximum value was still less than 3°. Since the estimated angles for the seven events were stable, their average was considered as the instrument orientation error.

Examination of estimated results

The results obtained above were examined further. First, the accelerograph installed in the observation building was considered since its position can be confirmed visually. The Y_1 axis of the instrument was set along an axis of the building. By surveying the building, the Y_1 axis was measured as S54°E. By the orientation error estimation, α of the building accelerograph was obtained as S53·7°E with respect to C001, which is about 100 m from the building. The closeness of these two angles validates the proposed methods.

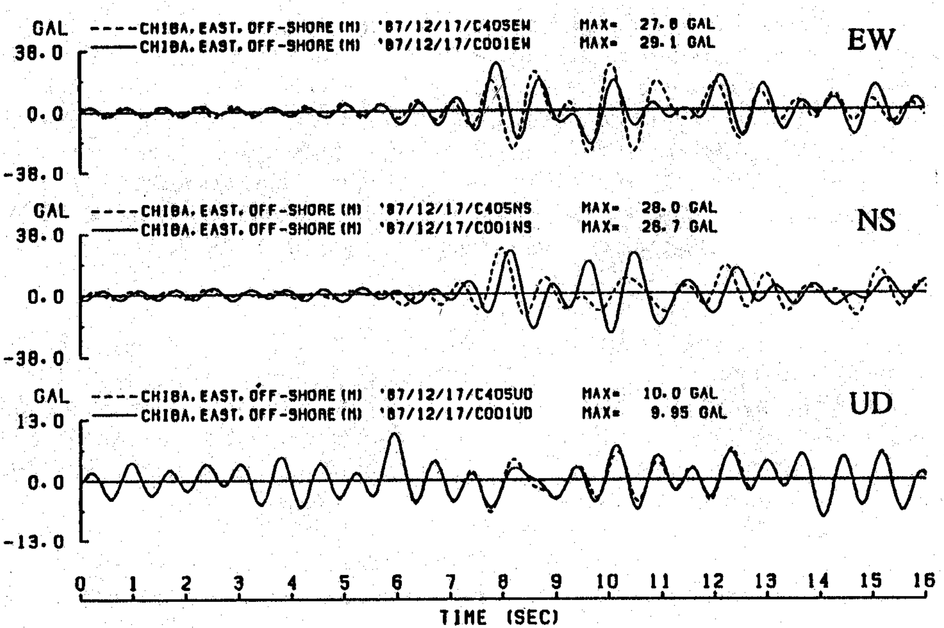
As mentioned previously, the actual orientations of 11 instruments at GL − 1 m were inspected visually. In Table II, these results were compared with the estimated orientation errors. Although slight differences exist between them, the overall agreements for α, β and γ were fairly good and satisfactory. The differences may be attributed to the accuracy of both the measurement and the estimation method.

Note that, in Table II, γ for C001 is given as − 3°. This is for the following reasons: (1) the estimated γ for the building instrument was obtained as 3°, although by visual inspection, it seemed correct; (2) the average of the estimated γ for the other 43 instruments was 3·1°, although β and γ are considered to occur randomly. In fact, the corresponding average for β was close to 0°. From these two facts, it was concluded that it is more reasonable to assume that the reference accelerograph C001 contains the error $\gamma = -3°$. Hence, the estimated angles of γ for all the other instruments were decreased by 3° for constructing the Chiba array database.

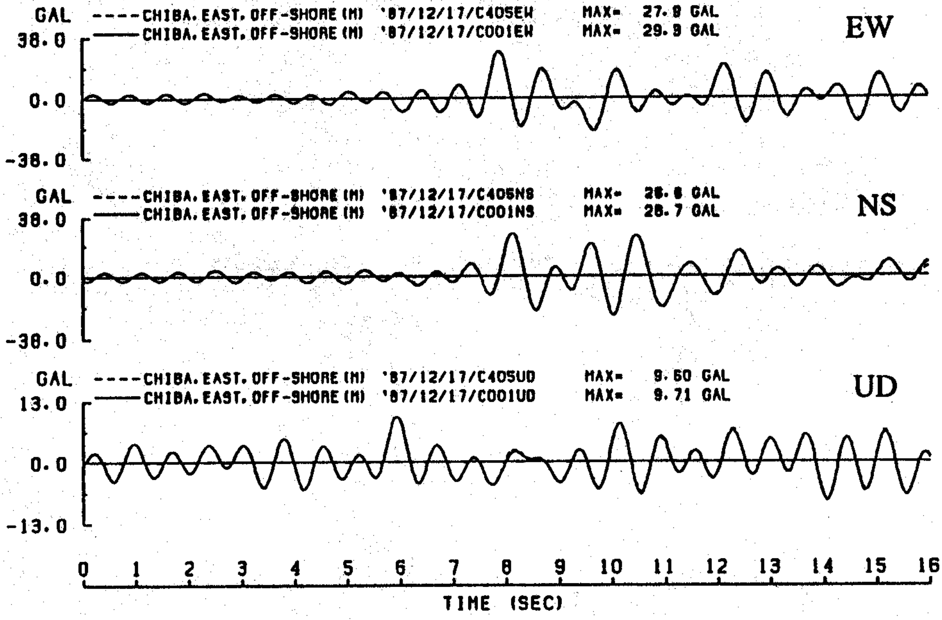
Table II. Comparison between measured and estimated orientation errors for 11 instruments buried at GL − 1 m of the Chiba array

Seismometer	α (degree)		β (degree)		γ (degree)	
	Meas.	Est.	Meas.	Est.	Meas.	Est.
C001*	0	0	0	0·0	0	− 3·0
C101	− 13	− 15·4	− 2	− 4·6	0	1·7
C201	− 12	− 10·6	0	0·2	− 2	− 3·2
C301*	0	− 1·0	0	1·2	0	− 0·2
C401*	0	− 1·7	0	− 2·2	0	0·2
P101	7	8·2	0	− 0·5	0	− 1·1
P201	− 7	− 8·9	0	0·0	0	2·1
P301	13	13·9	0	− 2·5	0	− 3·3
P401	− 20	− 20·6	− 3	− 1·3	0	1·1
P501*	0	2·0	0	2·4	0	2·8
P601*	0	− 2·6	0	− 1·5	0	− 0·8

*: Re-orientated; Meas. = measured; Est. = estimated.



(a) before orientation error correction



(b) after orientation error correction

Figure 6. Comparison of filtered waves at C001 and C405 before and after the orientation error correction

Correction of orientation error

The ground motions recorded by the Chiba array were corrected by equation (3) using the mean angles of the seven events. The effects of the correction were demonstrated using time histories, cross-correlation functions and coherence functions.

Figure 6 compares the filtered waves at two points, C001 and C405, for two cases, before and after the orientation error correction. The estimated α, β and γ for C405 are $-55{\cdot}6°$, $2{\cdot}8°$ and $-5{\cdot}0°$, respectively. It is found that the pairs of waveforms in the frequency range 0·1 to 1·5 Hz became very close after the correction, although these were clearly different before the correction. Note that a slight difference between the vertical components also diminished. This fact suggests that the tilting angles, β and γ, are also meaningful.

The cross-correlation coefficients of the filtered waves at C001 and C405 are shown in Figure 7. This figure shows that the orientation error causes a decrease in the maximum cross-correlation and a shift in the time lag at which it occurs. This fact is important because the time lag is often utilized to evaluate the apparent velocity of seismic waves.

The corresponding coherence functions are shown in Figure 8. The coherence increases for all the three components, especially in the low frequency range. Because α is very large for this case, the correction drastically improved the coherence.

Figure 9 explains the change of the maximum cross-correlation coefficients for eight instruments. All the cross-correlation coefficients became larger after the correction for orientation error. Through all these comparisons, the instrument orientation error is found to have a significant influence on time histories, cross-correlation functions and coherence functions.

ORIENTATION ERROR ESTIMATION FOR OTHER ARRAYS

With the aid of the proposed techniques, the orientation error for the Chiba array was evaluated successfully. It must be emphasized that this kind of problem is not unique to the Chiba array. Other arrays may also have the same problem. Two other arrays were inspected to demonstrate this fact and to validate further the applicability of the proposed methods.

Orientation error in L array

The L array is a three-dimensional array located at alluvial ground. It is aimed primarily at observing soil–structure interaction. In this array, several accelerographs are laid on the ground surface along three lines which are extended from a model structure to free field. Orientation error was inspected for three instruments at the tips of the three lines. The three points constitute a triangle with mutual distances of approximately 90 m.

When the accelerograms recorded by the array were used to investigate the spatial variation of earthquake ground motions, a strange trend was seen in the coherence functions for the three points. When the record from one of the three points was involved in the calculation, the coherence function became considerably lower than that obtained without involving that point. The difference of the ground motion at that particular point had been considered as probably due to a difference in soil condition.

Orientation error estimation was also conducted for these three points in the L array. The ground motion records from two events were employed with a frequency filter of 0·1–2·0 Hz. Using the maximum cross-correlation method, error angles, α, β and γ, of the dubious instrument were obtained for one event as 30·3°, 1·2° and 0·4°, respectively, and for another event as 32·6°, 1·2° and 1·3°, respectively. Figure 10 shows the coherence functions between this point and a reference point. A clear increase in coherence values can be seen in the two horizontal components.

Afterwards, misorientation of the instrument about the vertical axis was confirmed by the array owners through visual inspection, and it was reported to be about 30°. The problem for this array indicates that the orientation error may occur even for seismographs installed on the ground surface and that it should be first inspected when using array records.

Orientation error in Y array

The Y array is a one-dimensional vertical array installed at a soft reclaimed land. It is composed of three downhole accelerographs located at 1, 18 and 89 m from the ground surface. Pore pressure gauges are also buried in a near-surface sandy layer to measure pore pressure buildup during strong earthquakes. We

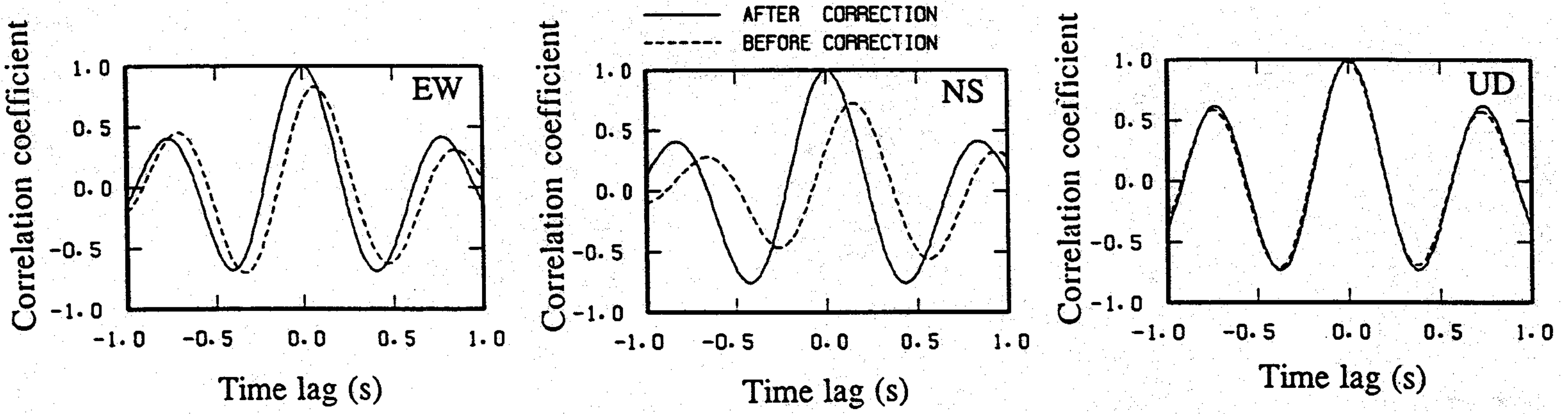


Figure 7. Comparison of cross-correlation coefficients between C001 and C405 before and after the orientation error correction

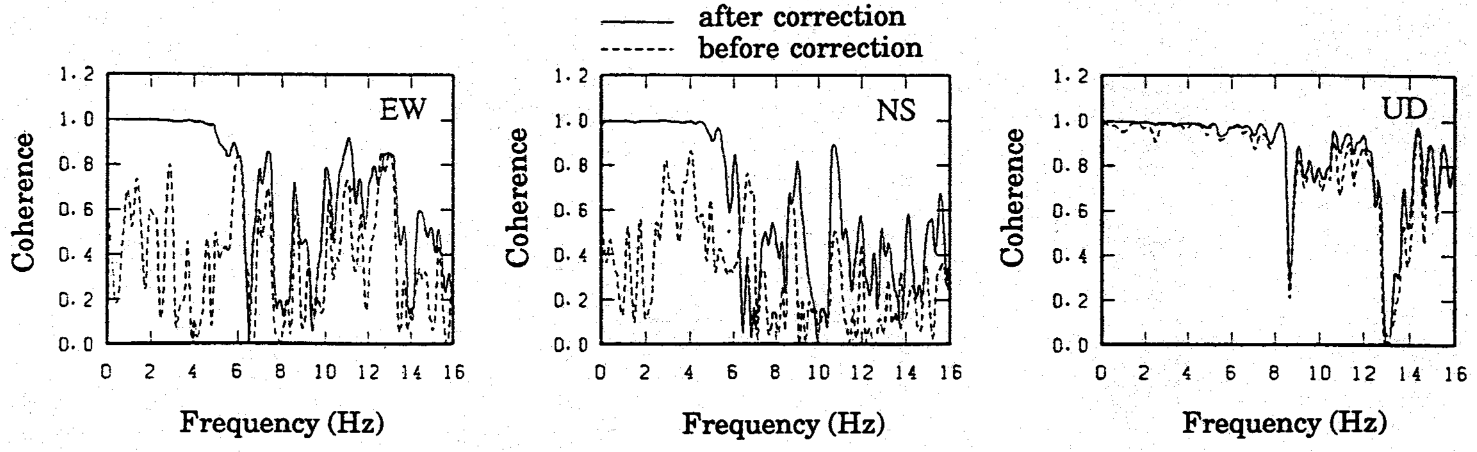
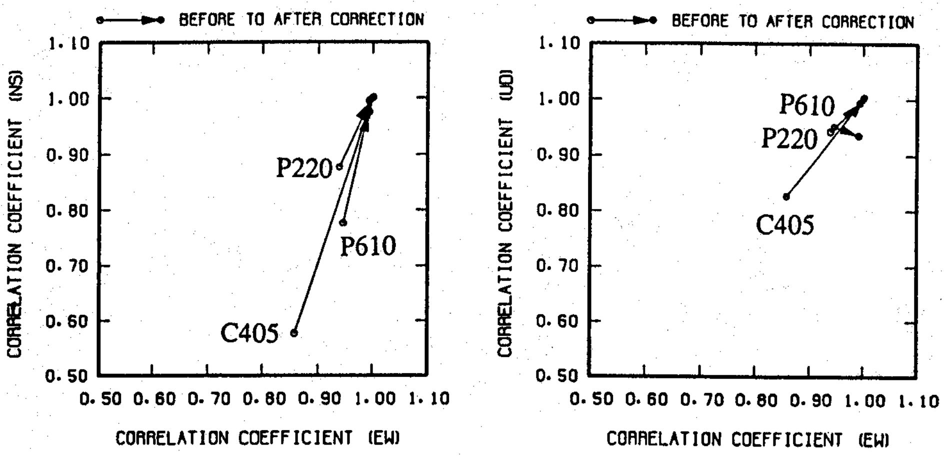
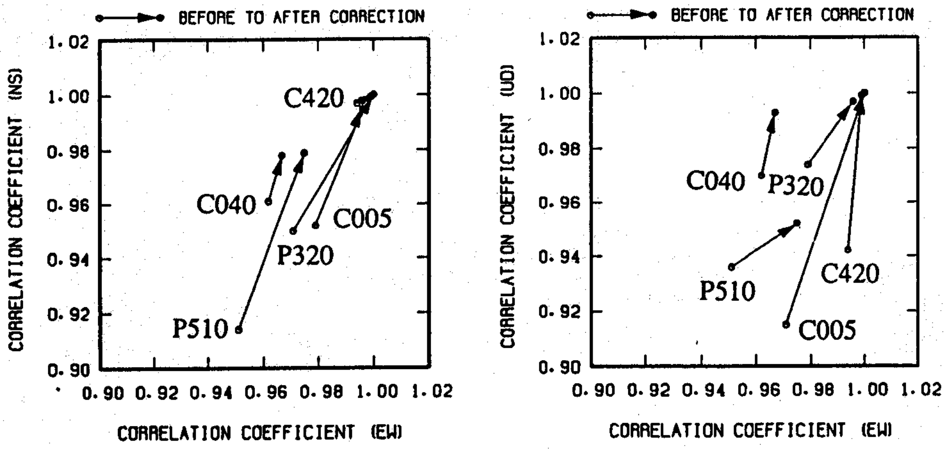


Figure 8. Comparison of coherence functions between C001 and C405 before and after the orientation error correction



(a) C405, P220 and P610 points



(b) C005, C040, C420, P320 and P510 points

Figure 9. Change of the maximum cross-correlation coefficients between C001 and eight other instruments by orientation error correction

requested the array owner for the use of records to investigate instrument orientation error. Ground motion records from three events were used for the examination.

Taking the instrument at GL − 1 m as a reference, the orientation errors of the other two instruments were estimated by the maximum cross-correlation method. The frequency range 0·1 to 0·6 Hz was utilized considering the first natural frequency of the 89 m soil column. The estimated orientation errors were $\alpha = -11{\cdot}3°$, $\beta = -2{\cdot}2°$ and $\gamma = 0{\cdot}8°$ for the instrument at GL − 18 m, and $\alpha = -10{\cdot}9°$, $\beta = -8{\cdot}6°$ and $\gamma = 4{\cdot}9°$ for that at GL − 89 m. These angles were the averages of the three events and their deviations were small with respect to the different events.

The coherence functions between the records at GL − 1 m and GL − 18 m before and after the orientation error correction are plotted in Figure 11. The increase in coherence values, which is clearly seen in the low frequency range, indicates the validity of the estimation.

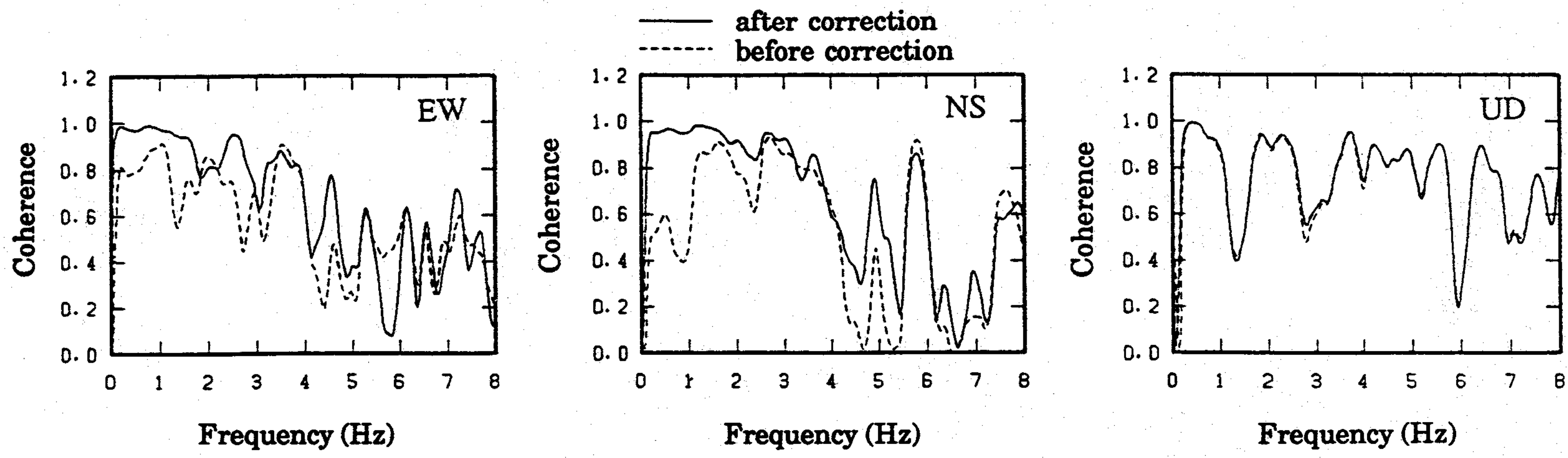


Figure 10. Comparison of coherence functions between the reference point and the dubious point in the L array before and after the orientation error correction

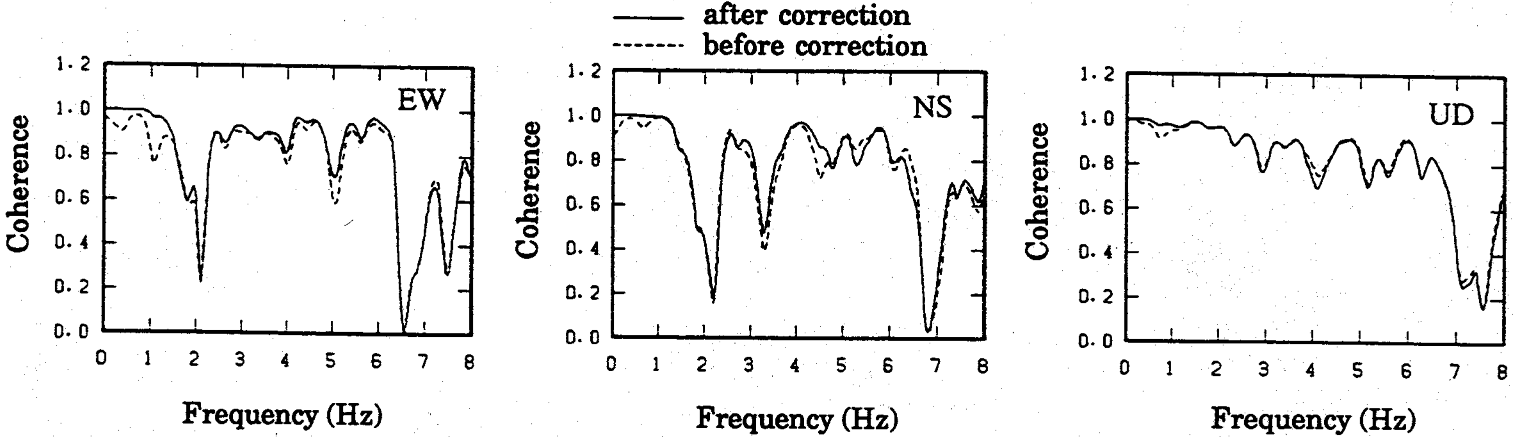


Figure 11. Comparison of coherence functions between the reference point (GL − 1 m) and the dubious point (GL − 18 m) in the Y array before and after the orientation error correction

CONCLUSIONS

The problem of instrument orientation error was highlighted for seismographs used in array observations. Because ground motions recorded by arrays are often used by taking into account their mutual correlation, the orientation error, if it exists, gives inaccurate results in such analyses. The orientation error is more likely to occur for downhole instruments than for those on the ground surface. Even when extreme care is taken in their installation, errors may still occur because their positions cannot be confirmed visually.

Once a seismograph is installed in a borehole, it is almost impossible to reposition it even if an orientation error is found. To overcome this difficulty, this paper proposed two methods to estimate the orientation error in a three-dimensional space using recorded motions.

Consider a checking point whose instrument orientation is dubious and a reference point whose instrument orientation is known. Using three component pairs of ground motions at the two points, the maximum cross-correlation method seeks the maximum of the sum of the three cross-covariance functions, while the maximum coherence method searches the maximum of the sum of three coherence functions. In these methods, low frequency contents where spatial coherency of ground motion is strong must be used. Also the two points should not be far apart, say within a few hundred metres, otherwise strong spatial coherency cannot be expected.

The methods were first applied to the Chiba array. The two methods gave very close results for the three error angles of all 44 points. For seven events, the estimated results were in narrow ranges. Also, for several points, the estimated angles were compared with those by visual inspection and these agreed very well. These comparisons showed satisfactory accuracy for both proposed methods. By correcting the estimated orientation error, the cross-correlation coefficients and the coherence functions between two point pairs increased significantly.

The methods were further applied to two other arrays. In a three-dimensional array, an orientation error of about 30° with respect to the vertical axis was found for an instrument on the ground surface. This orientation error was confirmed later by array owners. In a one-dimensional vertical array, a non-negligible error was also detected.

Through inspection of the three arrays, the orientation error is found to occur often in the instrument installation stage. Hence it is suggested that before using array records, orientation error should be first examined.

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