Component azimuths of the CEArray stations estimated from P-wave particle motion*

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Abstract The recently built China Digital Seismic Network consists of the China National Digital Seismic Network (CNDSN), 31 regional seismic networks and several small aperture arrays with more than 1 000 stations including 850+ broadband stations. It forms a gigantic seismic array that provides an unprecedented opportunity to study the Earth's deep interior besides its routine task of seismic monitoring. Many modern seismic studies rely on rotation of vertical and horizontal components in order to separate different types of seismic waves. Knowledge of the orientations of the two horizontal components thus is important to perform a correction rotation. We analyzed particle motions of teleseismic P waves recorded by the network and used them to estimate the north-component azimuth of each station. An SNR-weighted-multi-event method was introduced to obtain component azimuths that best explain the P-wave particle motions of all the events recorded at a station. The method provides robust estimates including a measurement error calculated from background noise levels. We found that about one third of the stations have some sort of problems, including misorientation of the two horizontal components, mislabeling and polarity reversal in one or more components. These problems need to be taken into account for any rotation based seismic studies.

Key words: P-wave particle motion; back azimuth; component azimuth; CEArray

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1 Introduction

To better monitor seismic activities in Chinese mainland, the China Earthquake Administration (CEA), the former State Seismological Bureau, has gradually upgraded and expanded its national and regional digital seismic networks since the late 1990s (Chen et al., 2006). Completed in early 2007, the China Digital Seismic Network (CDSN) is now the largest permanent seismic network in the world, consisting of a backbone national seismograph network (CNDSN), 31 regional networks, and several small aperture arrays with more than 1 000 stations including 850+ broadband stations (Zheng et al., 2009). The 1 000+ stations formed a large 2D areal array with an aperture ~6 700

km from east to west and ~3 500 km from north to south. For the remainder of this paper, we will refer to these stations as the CEArray. Station spacing varies drastically with location and reaches to ~20–100 km in the eastern and central parts of China (Figure 1). While the CEArray is anticipated to play an important role in monitoring seismic activities, mapping rupture details of large earthquakes, providing early warning, seismic risk assessment and mitigation in China, it also opens a new window to directly “view” details of Earth's interior (Wang and Niu, 2010) to an unprecedented level and shed lights to fundamental processes that have shaped and are shaping the Earth.

Modern seismic studies rely heavily on precise three-component broadband observations. Just like travel time, three dimensional particle motion is an important information provided by a seismogram. It forms the basis of many analyses, such as shear-wave splitting, receiver function, surface and normal mode studies. Three component records are often rotated to isolate

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Figure 1 Location map showing the CEArray stations. We made no difference between the national and regional network stations. The two letters indicate the network code of the regional stations. Inset shows the locations of the 106 teleseismic events used in this study.

longitudinal, radial, and transverse motions. A critical parameter for performing rotation is the geographical orientations of the two horizontal components (usually named as BHN and BHE). Since the orthogonality between components of modern broadband instruments is accurate to a fraction of a degree, what really affects a correct rotation is the orientation of the BHN component, which could deviate from the true north direction.

Aligning a seismometer to true north is not an easy task even for a skilled field seismologist. Misorientation could occur for a variety of reasons during an installation. Estimating instrument orientation and identifying misoriented stations thus become very important for operating a modern seismic network. Based on polarization analysis of long-period surface wave, Laske (1995) found that four of the 37 Geoscope/IDA stations have orientation problem. Schulte-Pelkum et al. (2001) studied the particle motion of long-period P waves recorded by the Global Seismic Network (GSN) between 1976 and 1999, and concluded that at least 10 stations were misaligned by $>10^\circ$. The Transportable Array (TA) of the USArray was probably one of the best-installed seismic networks in the world. Despite an interferometric fiber-optic gyroscope, rather than a compass, was used in determining the sensor orientation during the installa-

tion, 7.4% of the TA stations were misoriented by $>7^\circ$, based on surface wave analysis by Ekstrom and Busby (2008).

Since July of 2007, large amount of continuous waveform data recorded by the CEArray has been archived at the Data Backup Center (DBC) of CEA and has been widely used in the Chinese and international seismological communities. As the CEArray is a conglomerate of national and regional, earthquake and volcanic monitoring networks equipped with more than seven types of sensors and digitizers, an important and urgent task is the validation of the waveform data, including orientations of the two horizontal components, response function of different components and different types of seismographs, before their being widely used. In this study, we analyzed intermediate-period (10 s) P-wave particle motions of $\sim$ one-year teleseismic events to estimate the orientations of the two horizontal components for a total of 803 broadband stations. We found 270 stations have either a misorientation $>8^\circ$ or a mistake in component naming or polarity. Our main goal is to provide users of the CEArray data a means of comparison and reference for their rotation-based seismic analyses.

2 Data and analysis

We visually examined a total of 126 earthquakes with magnitude greater than 5.5 and in the epicentral distance of 30° – 90° recorded between July of 2007 and early August of 2008, and chose 106 earthquakes (Table 1) with good signal-to-noise ratio (SNR). These earthquakes provide a reasonably good distance and azimuth coverage (Figure 1 inset), although a large portion of the events are located in the western Pacific and the Java trench, which lie in the back azimuthal range of 30° to 210° . We resampled the raw data to 20 samples per second. As mentioned above, the CEArray is a virtual array formed by national and regional seismic networks that are composed of a wide range of intermediate band to broadband sensors. The seismometers are a combination of STS2, GURALP3T, GURALP3ESP, KS2000 and Chinese national broadband sensors JCZ-1 (360 s–50 Hz), CTS-1 (120 s–50 Hz), FBS-3 (20 s–20 Hz) and some other types of sensors. To keep a consistent bandwidth among all the stations, we applied a two-pole Butterworth band-pass filter of 5–50 s to all the waveform data. To ensure our measurement statistically robust, we only kept stations with more than five records, which reduces the number of stations from 850+ to 803.

We define the sensor orientation, or component azimuth φ as the angle between the geographic north and the calculated direction of BHN axis, with the angle measured in clockwise direction from the north. Our calculation is based on a simple but reasonable assumption: for compressional P wave traveling in a horizontally stratified isotropic medium, its particle motion should be in the vertical plane containing the source and receiver, and its projection to the horizontal plane is parallel to the backazimuth of the source. We additionally assumed that the three components are orthogonal, with the vertical component strictly perpendicular to the horizontal plane.

Particle motions of teleseismic waves thus can be used to estimate the component azimuth of misoriented stations. As shown in the schematic Figure 2, if the “north” component is misaligned at φ degrees clockwise from the geographic north direction, the apparent back azimuth measured from P-wave particle motion $\theta_a = \theta_c - \varphi$, where θ_c is the back azimuth calculated from source-receiver geometry. To compute the apparent back azimuth, we first calculate the covariance matrix from the two horizontal components:

$$c_{ij} = \int_0^T u_i(t)u_j(t)dt, \quad i, j = 1, 2. \quad (1)$$

Figure 2 A schematic plot showing the relationship between “BHN” orientation (φ), measured polarization direction from BHN (θ_a) and station back azimuth (θ_c).

Here T is the time window length. In the absence of noise, the covariance matrix, $\mathbf{c}$, will possess one nonzero eigenvalue and θ_a is the direction of the corresponding eigenvector,

$$\theta_a = \cot^{-1} \frac{c_{22} - c_{11} + \sqrt{(c_{11} - c_{22})^2 + 4c_{12}^2}}{2c_{12}}. \quad (2)$$

When noise is present, $\mathbf{c}$ will have two nonzero eigenvalues λ_1, λ_2 . The ratio of the two eigenvalues, λ_2/λ_1 , defines the linearity of the particle motion, and is also an index of noise level and near station scattering that directly affect the error in the measurement of θ_a .

To better estimate φ , we have developed a method to solve for the best φ by minimizing the energy in the transverse components from a suite of events recorded at one station, which we refer as an SNR-weighted-multi-event method. For an assumed component azimuth, φ , we first rotated the two horizontal components into radial and transverse directions with the calculated back azimuth θ_c for each event. We then computed the weighted summation of the P wave energy in the transverse component from all the events,

$$E_T(\varphi) = \frac{\sum_{i=1}^N w_i E_T^i(\varphi)}{\sum_{i=1}^N w_i}. \quad (3)$$

Here $E_T^i(\varphi)$ is the energy in the transverse component computed within a manually picked time window of the i th event, and N is the total number of the events. The

Table 1 Earthquakes used in this study

Event ID	Lat. /°N	Long. /°E	Depth /km	M_W	Event ID	Lat. /°N	Long. /°E	Depth /km	M_W
08/01/07_17:08	−15.595	167.680	120	7.2	01/30/08_12:48	−0.169	125.083	70	5.5
08/02/07_03:21	51.307	−179.971	21	6.7	02/01/08_12:10	−21.495	−179.352	604	6.0
08/08/07_17:04	−5.926	107.681	291	6.1	02/07/08_20:58	−7.582	116.819	321	5.7
08/08/07_17:05	−5.859	107.419	280	7.5	02/14/08_10:09	36.501	21.670	29	6.9
08/11/07_18:04	−22.264	−179.493	606	5.6	02/14/08_12:08	36.345	21.863	28	6.5
08/16/07_08:39	−9.830	159.467	10	6.4	02/20/08_08:08	2.768	95.964	26	7.4
08/22/07_07:26	42.020	140.638	123	5.4	02/24/08_14:46	−2.405	99.931	22	6.5
08/23/07_11:34	−19.925	−177.718	553	5.1	02/25/08_08:36	−2.486	99.972	25	7.2
08/26/07_12:37	−17.457	−174.335	127	6.1	02/25/08_18:06	−2.332	99.891	25	6.6
08/28/07_01:16	49.690	154.290	115	5.6	02/25/08_21:02	−2.245	99.808	25	6.7
09/02/07_01:05	−11.610	165.762	35	7.2	03/01/08_18:51	53.886	159.295	112	5.4
09/03/07_16:14	45.836	150.060	94	6.2	03/03/08_09:31	46.406	153.175	10	6.5
09/06/07_17:51	24.340	122.219	53	6.2	03/03/08_14:11	13.351	125.630	24	6.9
09/12/07_11:10	−4.438	101.367	34	8.4	03/06/08_01:21	2.572	128.231	125	5.8
09/12/07_23:49	−2.625	100.841	35	7.9	03/20/08_14:10	6.178	126.930	82	6.1
09/13/07_02:30	−1.689	99.668	28	5.9	03/20/08_22:32	35.490	81.467	10	7.2
09/13/07_03:35	−2.130	99.627	22	7.0	03/22/08_21:24	52.176	−178.716	132	6.2
09/13/07_16:09	−3.158	101.533	48	6.0	03/26/08_20:06	13.594	144.879	70	5.6
09/14/07_11:51	−23.645	179.680	552	5.4	04/02/08_08:48	−4.346	102.717	67	5.7
09/20/07_08:31	−1.999	100.141	30	6.7	04/09/08_12:46	−20.071	168.892	33	7.3
09/25/07_05:16	−30.965	179.998	416	6.2	04/12/08_00:30	−55.664	158.453	16	7.1
09/26/07_12:36	−4.990	153.500	40	6.7	04/16/08_05:54	51.878	−179.165	13	6.6
09/28/07_01:35	−21.133	169.373	10	6.5	04/16/08_19:19	39.028	140.005	166	5.8
09/28/07_13:38	22.004	142.651	276	7.4	04/18/08_20:39	−17.342	−179.022	553	6.3
09/30/07_02:08	10.454	145.718	14	6.9	04/29/08_19:10	−6.108	127.484	404	5.9
09/30/07_05:23	−49.271	164.115	10	7.4	05/02/08_01:33	51.864	−177.528	14	6.6
09/30/07_09:47	−49.138	164.110	18	6.6	05/03/08_03:53	−3.015	101.319	50	5.3
10/05/07_07:17	−25.189	179.459	509	6.5	05/07/08_16:45	36.164	141.526	27	6.9
10/15/07_12:29	−44.785	167.583	25	6.8	05/09/08_21:51	12.516	143.181	76	6.7
10/16/07_21:05	−25.775	179.530	509	6.6	05/19/08_10:08	42.503	131.872	513	5.7
10/24/07_21:02	−3.896	101.017	20	6.8	05/23/08_03:33	51.638	177.916	55	5.3
10/25/07_03:44	−6.317	154.827	54	5.6	05/23/08_22:50	−7.061	129.483	125	5.7
10/31/07_03:30	18.896	145.363	223	7.2	06/03/08_16:20	−10.509	161.273	84	6.2
11/14/07_04:29	1.485	127.038	105	5.3	06/04/08_17:03	41.534	139.048	212	5.7
11/19/07_00:52	−21.185	−178.752	558	6.3	06/06/08_13:42	−7.495	127.885	122	6.0
11/20/07_12:52	−6.905	155.711	52	6.0	06/15/08_01:13	−17.735	−179.733	611	5.9
11/22/07_08:48	−5.756	147.103	53	6.7	06/19/08_00:36	−4.932	151.754	143	5.5
11/23/07_01:26	−4.630	151.869	150	5.9	06/25/08_23:37	41.937	142.486	55	5.5
11/25/07_02:51	−2.808	101.162	55	5.9	06/27/08_11:40	11.005	91.824	17	6.6
11/25/07_16:02	−8.258	118.343	52	6.5	06/29/08_20:53	45.161	137.422	287	6.0
11/25/07_19:53	−8.214	118.430	35	6.5	07/03/08_03:02	−23.370	−179.778	581	6.2
11/27/07_11:49	−10.990	162.225	16	6.6	07/05/08_02:12	53.882	152.886	632	7.7
12/07/07_00:47	29.916	141.045	78	5.9	07/07/08_04:44	−16.428	−174.047	116	5.5
12/09/07_07:28	−26.057	−177.518	143	7.8	07/09/08_08:24	−20.919	168.769	39	5.4
12/15/07_08:03	−7.522	127.482	147	6.0	07/15/08_03:26	35.800	27.860	52	6.4
12/15/07_09:39	−6.623	131.173	14	6.4	07/19/08_02:39	37.552	142.214	22	7.0
12/19/07_09:30	51.367	−179.549	29	7.1	07/19/08_09:27	−11.041	164.493	11	6.6
12/19/07_14:51	51.275	−179.528	35	5.3	07/19/08_22:39	−17.337	−177.312	391	6.4
12/20/07_07:55	−38.860	178.520	36	6.6	07/20/08_21:30	27.773	139.615	481	5.8
12/23/07_13:10	−8.942	123.730	117	5.2	07/25/08_20:11	−5.808	146.658	39	5.5
01/05/08_11:01	51.254	−130.746	15	6.6	08/01/08_10:35	13.505	120.782	135	5.6
01/06/08_05:14	37.216	22.693	75	6.2	08/04/08_04:42	49.860	156.380	74	5.8
01/15/08_17:52	−21.984	−179.535	597	6.5	08/04/08_20:45	−5.914	130.199	173	6.3

weight, w_i , is taken as the averaged signal-to-noise ratio (R) of the two horizontal components $w_i = 0.5 \cdot (R_{i,\text{BHN}} + R_{i,\text{BHE}})$. We also used the total P-wave energy recorded at the two horizontal components to normalize the traces before computing $E_T^i(\varphi)$.

We varied φ in the range of 0° to 180° with an increment of 1° . When the summed P-wave energy in the transverse component, $E_T(\varphi)$, reaches to its minimum value $E_T^{\min}$, we considered the azimuth as the station orientation. There are two possible azimuths, φ and $\varphi + 180^\circ$, in which transverse component reaches the minimum. We took the cross correlation between the vertical and radial components and chose the azimuth that shows a positive correlation. The method has been proved to be effective in obtaining the robust estimation of sensor orientation (Niu et al., 2007). For comparison we also estimated the component azimuth of the misoriented USArray stations identified by Ekstrom and Busby (2008). In general our measurements agree very well with the surface wave estimates (Figure 3).

As $E_T^{\min}$ is a sum-of-square Gaussian noise, it is expected to follow the χ^2 distribution. $E_T/E_T^{\min}$ thus follows a F-distribution if E_T does not include any P-wave energy. As shown by Jenkins and Watts (1968), for n degrees of freedom and k parameters, the confidence region at the α confidence level can be estimated as

$$\frac{E_T(\varphi)}{E_T^{\min}} \leq 1 + \frac{k}{n-k} f_{k,n-k}(1-\alpha). \quad (4)$$

In our case $k=1$, $\alpha=0.05$, and n is taken as 1 degree of freedom per second (Silver and Chan, 1991). Uncertainties estimated from equation (4) are not subjected to the noise level in the data. For noisy data, these could be significantly lower than the true level, as any φ with $E_T(\varphi)$ below the noise level should be considered as a possible solution of sensor orientation. So we replaced $E_T^{\min}$ with E^{noise} , which is taken to be the average of the noise level recorded in the two horizontal components prior to the direct P wave. We also used the revised equation (4) to estimate the upper and lower bounds of φ for each individual event and to confirm that minimum solution of equation (3) falls between them. Figure 4 shows an example of the measurement at station HE.WAT. The normalized energy projected to the transverse component is shown as a function of assumed sensor orientation (dashed line). The minimum solution (thick vertical line) falls well between the upper (pluses) and lower (minuses) bounds of φ estimated from individual events.

Figure 3 A comparison of BHN azimuths estimated at some USArray stations from surface wave analysis (Ekstrom and Busby, 2008) and P-wave particle motion of this study. Note values given by Ekstrom and Busby (2008) are corrections to the reported component azimuths. They were used to calculate the true component azimuths for the comparison. In general estimates from the two methods agree very well with each other.

Figure 4 An example showing multi-event measurement at station HE.WAT (thick vertical line), uncertainty range (vertical gray area), upper (pluses) and lower bands (minuses) from individual events. The dashed line indicates the summed energy in the P-wave time window normalized by pre-arrival noise levels projected to the transverse component. The normalized P-wave energy varies with the assumed BHN azimuth and reaches to the minimum at -3° .

3 Results and discussion

The CEArray data appears to be much more complicated than we expected. We found a fair amount of stations had a measurement error $>10^\circ$. Cross-correlation coefficients between the vertical and radial components of the P waves calculated from different events usually showed mixed signs. A close check of waveforms recorded at these stations indicated that they are very different from those registered at neighboring stations. This led to an identification of a set of stations whose components were mislabeled. We designed a special procedure to identify these stations and paid extra attentions in measuring their orientations.

For every station, we first form a virtual array of 15 to 30 stations from the neighboring stations. Depending on the station location, the virtual array can consist of stations from two or more regional networks. For each event recorded at the station, we manually picked the P-wave arrivals and then linearly stacked the waveforms to construct a reference waveform for all the three components:

$$u_j^0(t) = \frac{1}{M} \sum_{i=1}^M u_{ij}(t + \tau_i), \quad j = 1, 2, 3. \quad (5)$$

Here, $u_j^0(t)$ is the stacked waveform, τ_i is the delayed time of each station. M is the total number of stations, and j is the component index. Then we calculated the cross correlation coefficient (cc) between the station records and the reference waveforms. As expected, a normal station shows large positive ccs (most time >0.9) across the three components for all the events. For stations with a labeling problem in component name, cc usually appeared to be low with mixed signs. To estimate the sensor orientation of these stations, we used a trial and error method for all the three possible mislabeling, i.e., a switch between BHN and BHE, BHN and BHZ, and BHE and BHZ. With a proper switch between components, the measurement error drops drastically and the P wave particle motion becomes consistent with the source-receiver geometry. Besides the mislabeling problem, we also found a few stations whose BHN component was aligned in the EW direction, and some other stations whose one or more components have a reversed polarity. These types of problems are fortunately identifiable with the above analysis. Table 2 listed these special stations with the identified problems. To summarize, we found a total of eight types of problems: (1) polarity of BHE was reversed; (2) polarity of BHN was reversed; (3) polarity of both BHE and BHN was re-

versed; (4) BHN and BHE were switched; (5) BHE and BHZ were switched; (6) BHN was aligned in east direction; (7) BHN was aligned in west direction; (8) BHN and BHE were switched and their polarities were further reversed. Throughout this analysis, we noticed that the vertical component has almost no problem across the network. We found only three stations whose vertical component was mislabeled as east-west component.

After the above preprocessing for these special stations, the estimated orientation of the BHN component is expected to lie between $-45^\circ \sim 45^\circ$. Figure 5 shows the distribution of the measured azimuth of the BHN component for the 803 stations. Notice that the azimuth shown here is the absolute bearing that the BHN component carries; there is a sign difference between our values and the correction angles defined by Ekstrom and Busby (2008). The distribution is centered on -0.9° with a standard deviation of 6.5° . The maximum and minimum orientation angle is 42° and -43° , respectively. 44.7% of the stations are aligned within 3° from the north direction, and 28.3% stations fall in the azimuth range between $\pm 4^\circ$ and $\pm 7^\circ$. The other 27.0% deviates from the reported azimuths by 8° or more.

Figure 5 Histogram showing the distribution of the BHN component azimuths measured at the 803 CEArray stations.

Table 2 listed the 270 stations with a large misorientation ($\geq 8^\circ$) and those require a special processing, i.e., reversing polarities of one/two horizontal components, switching two components, and a combination of both operations. We also listed the number of events used in estimating the BHN azimuth and the measurement errors. Preprocessing details for the special stations are also included. In most cases, the problems identified from those special stations remain the same

Table 2 Misoriented stations

Station code	Number of events	φ / $^{\circ}$	Error / $^{\circ}$	Special operations	Station code	Number of events	φ / $^{\circ}$	Error / $^{\circ}$	Special operations
AH.BAS	43	10	3	E $\leftrightarrow$ N ($\rightarrow$ 20080503)	GS.HCH	26	10	3	
AH.BEB	38	-6	4	E $\leftrightarrow$ N ($\rightarrow$ 20080428)	GS.HJT	19	14	3	
AH.CHZ	37	-7	3	E $\leftrightarrow$ N ($\rightarrow$ 20080503)	GS.HXT	11	34	4	N $\rightarrow$ -E, E $\rightarrow$ N
AH.DYN	43	-23	3	N $\rightarrow$ E, E $\rightarrow$ -N (20070825 $\rightarrow$)	GS.HYS	19	10	3	
AH.FZL	34	2	3	E $\leftrightarrow$ N ($\rightarrow$ 20080302)	GS.JFS	28	12	4	
AH.HBE	41	13	3		GS.JNT	39	3	3	N $\rightarrow$ -E, E $\rightarrow$ N
AH.HEF	9	-9	4		GS.JYG	33	9	4	E $\leftrightarrow$ N
AH.HNA	50	3	3	E $\leftrightarrow$ N ($\rightarrow$ 20080428)	GS.LTT	16	9	4	
AH.HSH*	44	1	3	-E $\leftrightarrow$ -N ($\rightarrow$ 20080428)	GS.LYT	30	-11	3	
				N $\rightarrow$ -N, E $\rightarrow$ -E (20080428 $\rightarrow$)	GS.MIQ	12	-11	3	
AH.LAN	43	-30	4	N $\rightarrow$ E, E $\rightarrow$ -N	GS.NXT	5	-26	2	
AH.MAS	46	5	3	E $\leftrightarrow$ N ($\rightarrow$ 20080501)	GS.PLT	29	11	4	
AH.MCG [†]	24	1	1	E $\leftrightarrow$ N ($\rightarrow$ 20080501)	GS.SBC	20	17	4	
	5	-35	3	N $\rightarrow$ E, E $\rightarrow$ -N (20080701 $\rightarrow$)	GS.SNT	36	15	4	
AH.SCH	37	-1	3	E $\leftrightarrow$ N ($\rightarrow$ 20080501)	GS.ZHQ	21	9	5	
AH.SIX	49	1	3	E $\leftrightarrow$ N ($\rightarrow$ 20080501)	GS.ZHY	26	-11	3	
AH.TOL	45	-2	3	E $\leftrightarrow$ N ($\rightarrow$ 20080501)	GX.PXS	42	2	2	E $\rightarrow$ -E (20080302 $\rightarrow$)
BJ.LBP	26	-8	3		GX.WZD	26	-5	4	N $\rightarrow$ -N, E $\rightarrow$ -E
BJ.MIY	39	-10	3		GX.YLS	44	10	3	
BJ.NKY	42	-14	3		GX.YTT	34	-13	4	
BJ.XBZ	18	-13	4		GZ.YPT	9	-40	6	N $\rightarrow$ E, E $\rightarrow$ -N
BU.DOH	28	8	4	N $\rightarrow$ E, E $\rightarrow$ -N	GZ.ZFT	6	-8	4	
BU.HUA	19	-21	3		GZ.ZYT	9	-8	4	
BU.MDY	24	15	3		HA.DA	40	-41	3	
BU.TST	32	-4	4	N $\rightarrow$ -N, E $\rightarrow$ -E	HA.NY	50	1	3	E $\leftrightarrow$ N
BU.ZHL	35	5	3	N $\rightarrow$ E, E $\rightarrow$ -N	HB.DWU	37	-15	3	
BU.ZUH	25	-9	4		HB.ENS	9	-3	4	E $\leftrightarrow$ Z
CQ.CQT	40	6	3	E $\leftrightarrow$ N	HB.HME	41	-12	3	
CQ.FUL	31	-9	4		HB.JME	38	-11	3	
CQ.ROC	54	-13	2		HB.SYA	17	-1	4	E $\leftrightarrow$ N
CQ.SHZ	30	-7	3	N $\rightarrow$ -N, E $\rightarrow$ -E	HB.SZI	10	23	5	
CQ.SNB	9	36	3		HB.XNI	42	27	3	
CQ.WAZ	41	1	2	E $\leftrightarrow$ N	HB.ZUX	51	-10	4	
FJ.FZCM	13	5	3	E $\leftrightarrow$ N (20080704–20080710)	HE.CHD	13	4	4	N $\rightarrow$ E, E $\rightarrow$ -N
FJ.LJTL	33	-12	3		HE.HST	38	12	3	
FJ.NPDK	15	-8	4		HE.KAB	21	8	3	
FJ.PHSG	27	-20	5		HE.LOH	30	-13	2	
FJ.PTNR	31	-8	3		HE.LUQ	10	18	5	
FJ.TNSC	31	36	3	N $\rightarrow$ E, E $\rightarrow$ -N	HE.SHX	21	-17	4	N $\rightarrow$ -N
FJ.WYXF	42	29	4	N $\rightarrow$ -E, E $\rightarrow$ N	HE.WEC	38	-18	3	
FJ.YCTM	32	16	3		HE.YON	52	12	3	
FJ.YXBM	37	34	4		HE.ZJK	32	-8	2	
GD.DGD	28	-11	3		HI.QSL	27	0	3	E $\rightarrow$ -E
GD.LTK	25	13	3		HI.QZN	11	4	2	E $\leftrightarrow$ Z
GD.NAO	27	-24	4		HL.BEL	28	-16	3	
GD.SHD	26	11	4		HL.BJS	16	42	3	
GD.TIX	30	-8	3		HL.DNI	15	-25	4	
GD.XFJ	27	16	3		HL.FUY	18	-1	5	N $\rightarrow$ -N, E $\rightarrow$ -E
GD.YGX	21	-9	5		HL.HEG	38	-1	3	E $\rightarrow$ -E
GD.ZHH	29	-43	3	N $\rightarrow$ -E, E $\rightarrow$ N	HL.JMS	38	-28	4	N $\rightarrow$ -N, E $\rightarrow$ -E
GS.BKT	7	-19	6	N $\rightarrow$ -N, E $\rightarrow$ -E	HL.LIH	38	41	3	N $\rightarrow$ -E, E $\rightarrow$ N
GS.BYT	25	-10	4		HL.MOH	41	-11	3	
GS.DBT	31	8	4		HL.QAN	28	27	3	

Continued from Table 2

Station code	Number of events	φ / $^{\circ}$	Error / $^{\circ}$	Special operations	Station code	Number of events	φ / $^{\circ}$	Error / $^{\circ}$	Special operations
HL.QTH	18	-10	2		LN.YKO	50	-2	3	E $\leftrightarrow$ N
HL.TAH	29	-10	3		NM.BAC	40	8	3	
HL.WUC	26	-12	2		NM.BTO	21	-7	4	E $\leftrightarrow$ N
HL.XBH	18	-27	4		NM.CHR	25	11	3	
HL.XUK	13	-10	3		NM.DSH [†]	28	-37	2	N $\rightarrow$ E, E $\rightarrow$ -N ($\rightarrow$ 20080304)
HN.HOJ	5	11	4			9	-11	3	/ (20080304 $\rightarrow$)
HN.JIS	11	3	3	-E $\leftrightarrow$ -N	NM.GNH	41	-6	2	N $\rightarrow$ -E, E $\rightarrow$ N
HN.TAY	48	34	5	N $\rightarrow$ -N, E $\rightarrow$ -E	NM.HLH	18	-12	5	
JL.BCT	43	22	2	N $\rightarrow$ E, E $\rightarrow$ -N	NM.IDR	21	-13	2	
JL.CBS	46	-12	7		NM.JIN	29	-8	3	
JL.CBT	26	5	3	N $\rightarrow$ -E, E $\rightarrow$ N	NM.LCH	42	-42	3	
JL.CN2	8	-10	4		NM.LIX	11	10	3	
JL.DHT	40	0	3	N $\rightarrow$ -N, E $\rightarrow$ -E	NM.MDG	12	30	5	N $\rightarrow$ -E, E $\rightarrow$ N
JL.HNS	20	12	3	N $\rightarrow$ -E, E $\rightarrow$ N	NM.NIC	30	-9	3	
JL.HST	11	10	2	N $\rightarrow$ -E, E $\rightarrow$ N	NM.QSH	42	-30	2	
JL.JCT	30	21	3	N $\rightarrow$ E, E $\rightarrow$ -N ($\rightarrow$ 20080626)	NM.XIH	42	-34	3	N $\rightarrow$ -N, E $\rightarrow$ -E
JL.LHT	29	0	3	N $\rightarrow$ -N, E $\rightarrow$ -E	NM.XSZ	39	18	3	N $\rightarrow$ -N, E $\rightarrow$ -E
JL.LYT	39	25	3	N $\rightarrow$ E, E $\rightarrow$ -N	NM.ZLT	34	-11	4	
JL.MJT	37	45	4	N $\rightarrow$ -E, E $\rightarrow$ N	NX.LWU	33	23	5	
JL.PST	41	25	3	N $\rightarrow$ -N, E $\rightarrow$ -E	NX.TLE	30	9	3	
JL.SPT	43	-7	3	N $\rightarrow$ -E, E $\rightarrow$ N	NX.XSH	45	-27	3	
JL.SYZT	40	1	4	N $\rightarrow$ -E, E $\rightarrow$ N	NX.ZHW	46	-11	3	
JL.YFT	30	-17	3		QH.DCD	51	-13	6	
JL.YST	11	5	5	E $\leftrightarrow$ N	QH.DLH	49	-9	3	
JS.CZ	23	31	3		QH.HTG	8	8	4	
JS.HA	19	38	5	N $\rightarrow$ E, E $\rightarrow$ -N	QH.LED	43	27	3	N $\rightarrow$ -N, E $\rightarrow$ -E
JS.HUA	36	-14	5		QH.QIL	46	12	4	
JS.JJ	34	-8	4	N $\rightarrow$ E, E $\rightarrow$ -N	QH.TTH	38	0	6	E $\leftrightarrow$ N
JS.JT	30	-11	3		QH.YUS	56	2	4	E $\leftrightarrow$ N
JS.KS	21	-3	4	N $\rightarrow$ -E, E $\rightarrow$ N	SC.HLI	38	25	4	
JS.LAS	24	-7	3	N $\rightarrow$ -E, E $\rightarrow$ N	SC.HSH	47	9	4	
JS.LIS	34	-15	3		SC.JJS	40	-8	2	
JS.LYG	45	-23	3	E $\leftrightarrow$ N	SC.MEK	50	-10	4	
JS.NT	41	-21	3	N $\rightarrow$ -N, E $\rightarrow$ -E	SC.MGU	46	1	3	N $\rightarrow$ -N, E $\rightarrow$ -E ($\rightarrow$ 20070809)
JS.PX	21	8	3		SC.REG	53	-8	3	
JS.PZ	17	10	3		SC.SMI	51	12	7	
JS.RD	12	-27	3	N $\rightarrow$ -E, E $\rightarrow$ N	SC.XCE	43	-11	4	
JS.TZ	11	-5	4	N $\rightarrow$ -N, E $\rightarrow$ -E (20080408 $\rightarrow$)	SC.XCO	41	11	3	
JS.XH	13	-42	4	N $\rightarrow$ -E, E $\rightarrow$ N	SD.BHC	39	-10	3	
JS.XY	31	12	3		SD.CHD	46	-33	3	N $\rightarrow$ E, E $\rightarrow$ -N
JS.YX	23	32	3		SD.YTA	41	-5	3	E $\leftrightarrow$ N
JS.ZJ	33	-11	3		SH.NAH	8	-21	5	N $\rightarrow$ E, E $\rightarrow$ -N
JX.ANY	32	14	3		SH.QHS	20	-10	3	
JX.DAY	31	-11	3		SH.ZHY	20	-34	3	N $\rightarrow$ -N
LN.ANS	45	17	3		SN.HZHG	57	-9	5	E $\leftrightarrow$ N (20070911 $\rightarrow$)
LN.CHY	47	-1	3	N $\rightarrow$ -N, E $\rightarrow$ -E	SN.LOXT	50	10	4	
LN.FSH	43	-18	3		SN.SUDE	51	-12	4	
LN.GAX	47	3	3	N $\rightarrow$ E, E $\rightarrow$ -N (20080508 $\rightarrow$)	SN.YULG	26	0	4	E $\leftrightarrow$ N
LN.HUR	44	13	3		SX.DAX	38	-15	3	
LN.LYA	47	15	3		SX.DOS	33	-9	3	
LN.NAP	40	8	2		SX.HMA	55	-8	3	
LN.QYU	16	-16	5		SX.HSH	37	-15	4	
LN.TIL	41	-8	4		SX.KEL	50	-16	3	

Continued from Table 2

Station code	Number of events	φ / $^{\circ}$	Error / $^{\circ}$	Special operations	Station code	Number of events	φ / $^{\circ}$	Error / $^{\circ}$	Special operations
SX.LIF	55	-8	3		XJ.STZ	46	9	4	
SX.NIW	54	-15	3		XJ.TAC	43	-2	3	N $\rightarrow$ -N, E $\rightarrow$ -E
SX.PIG	44	-12	3		XJ.TAG	40	-10	4	
SX.SHZ	48	3	4	E $\leftrightarrow$ N	XJ.WMQ	15	-12	5	
SX.TAG	48	-9	3		XJ.WSC	20	15	5	
SX.XAX	53	-34	3	N $\rightarrow$ E, E $\rightarrow$ -N	XJ.YMS	5	16	3	
SX.XAY	43	-8	3		XZ.DXI	10	8	3	
SX.XIX	52	17	3		XZ.NMU	34	8	4	
SX.XIY	50	-9	4		XZ.PLA	26	4	4	N $\rightarrow$ -N, E $\rightarrow$ -E
SX.YJI	49	-33	4	N $\rightarrow$ E, E $\rightarrow$ -N	XZ.SNA	31	3	4	N $\rightarrow$ -N, E $\rightarrow$ -E
SX.ZOQ	54	28	3		XZ.SQHE	30	-12	4	
TJ.YGZ	32	22	3	N $\rightarrow$ E, E $\rightarrow$ -N	YN.BAS	6	0	3	E $\rightarrow$ -E (20080624 $\rightarrow$)
XJ.AHQ	45	12	5		YN.HEQ	18	-8	5	
XJ.ATS	31	10	6		YN.KMI	13	2	5	E $\leftrightarrow$ Z
XJ.BAC	39	8	4		YN.LUQ	27	15	3	
XJ.BTS	34	9	4		YN.MIL	30	-11	4	
XJ.CBC	37	15	3		YN.SIM	30	-10	5	
XJ.FUY	49	10	4		YN.WES	29	-19	3	
XJ.HBH	47	-24	4		YN.YAJ	33	11	4	
XJ.HTTZ0	9	15	4		YN.YOD	35	12	3	
XJ.KMY	38	0	3	N $\rightarrow$ E, E $\rightarrow$ -N (20080714 $\rightarrow$)	YN.YUM	8	12	4	
XJ.KOL	16	-10	5		YN.ZAT	47	12	5	
XJ.KSH	32	11	5		ZJ.CHA	47	-23	2	
XJ.KSZ	23	11	3		ZJ.JAX	46	-31	3	
XJ.LHG	48	12	5		ZJ.LIA	49	-8	3	
XJ.LSG	38	9	3		ZJ.NIH	41	-29	3	
XJ.QHE	47	-9	4		ZJ.WXJ	46	8	2	
XJ.RGN	40	-34	5	N $\rightarrow$ E, E $\rightarrow$ -N	ZJ.XAJ	13	-2	3	E $\leftrightarrow$ N
XJ.RUQ	5	12	4		ZJ.XIC	37	-14	3	
XJ.SHZ	30	12	6		ZJ.ZHS	47	-8	3	
XJ.SMY	36	17	4						

*: Station has one consistent sensor orientation through the study period after the special processing; †: Station has an inconsistent sensor orientation through the study period even after special operation. Two estimates were thus listed. YYYYMMDD $\rightarrow$: Special operation applied after YYYYMMDD; $\rightarrow$ YYYYMMDD: Special operation applied before YYYYMMDD.

during the $\sim$ one year period covered by our data. We have confirmed the misorientation with one provincial network. It appeared that the magnetic field around these stations was disturbed due to the steel reinforcement bars (rebars) incorporated inside the concrete pad for sensors. Under this circumstance, the north direction determined from a compass could be completely wrong. But for some stations, the problems disappeared after a point of time, which we assume, were fixed by maintenance (we confirmed this change from one of the provincial networks, the Anhui seismic network). The misorientation and mislabeling listed in Table 2 is extremely important for seismic analysis based on accurate rotation. This was well demonstrated by a recent shear-wave splitting study (Li and Niu, 2010), and receiver function analysis (Liu and Niu, 2011) using the same dataset.

In an isotropic 1D medium, P-waves produce displacement in the direction of wave propagation. In other words, it does not produce any displacement in the transverse direction. In the real data, significant P-wave energy could be found in the transverse component. Besides sensor misorientation and noise, there are several other sources, such as (1) seismic anisotropy, (2) lateral heterogeneities, and (3) dipping structures that can affect P-wave particle motion. The introduced deviation in particle motion, however, strongly depends on the back azimuth of the incoming waves, which is different from the effect caused by sensor misorientation. In principle, these effects can be isolated from sensor misorientation if a full back azimuth range of data is provided. On the other hand, the three types of structure predict different back azimuthal dependence. Those effects

are usually expressed in the following forms (Schulte-Pelkum et al., 2001; Davis, 2003; Fontaine et al., 2009):

$$\delta\phi = \phi_0 + a \sin\phi + b \cos\phi + c \sin(2\phi) + d \cos(2\phi), \quad (6)$$

where the $\sin 2\phi$, $\cos 2\phi$ terms represent the anisotropic effects, and $\sin\phi/\cos\phi$ terms show effects from dipping structure. A theoretical calculation by Davis (2003) indicated that possible deviation of particle motion resulting from mantle anisotropy is rather trivial (less than 1°). Schulte-Pelkum et al. (2001) analyzed long-period P-wave particle motions of 264 GSN stations and found a median deviation of 7.2° , which can be considered as a combined effect of subsurface structure and sensor misorientation. It is thus arguable that stations with azimuthal deviations $>8^\circ$ are misoriented.

We have not listed stations with an estimated azimuth between -7° and 7° for two reasons: (1) for receiver-function analysis and surface wave polarization studies, misorientation in this level is not expected to cause significant effects on the results; and (2) it is also possible that the deviation is caused by near station structure besides sensor misorientation. As we used teleseismic events here, error in particle motion due to source mislocation is, however, almost negligible. On the other hand, measurement error appears to be positively correlated with the linearity of P-wave particle motion

(Figure 6), suggesting that noise and scattering have certain contributions to the observed azimuthal deviations, as anisotropy and dipping structure have very little effects on the linearity of the P-wave particle motion.

4 Summary

In this study, we proposed a multi-event method to estimate sensor orientation of a seismic station, together with a way to identify problematic stations based array analysis. We applied this method to the newly built CEARray. With intermediate-period data, the method produces fairly robust estimate for stations with more than five records. We identified a total of 270 CEARray stations that have one or more problems in component azimuth, name and polarity. For these stations, a pre-processing of the data is required to correct these errors.

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Figure 6 Uncertainty in the measured BHN azimuth is shown as a function of the linearity of the P-wave particle motion. Both are calculated from a SNR weighted summation of all the seismograms recorded at a station. Note a weakly positive correlation exists between two, indicating contributions of noise and scattering to the observed azimuthal deviations.

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