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Short Note

Array Deployment to Observe Rotational and Translational Ground Motions along the Meishan Fault, Taiwan: A Progress Report

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Abstract Measurements in the near field of earthquakes in Japan (Takeo, 1998) and in Taiwan (Huang *et al.*, 2006; Liu *et al.*, 2009) indicate that rotational ground motions are many times larger than expected from the classical elasticity theory. The Central Weather Bureau (CWB) deployed four instrumentation sets on the campus of the National Chung-Cheng University, Chia-yi, Taiwan, in order to study in detail earthquakes in the near field for both seismology and earthquake engineering. Both rotational and translational ground motions are being monitored along the active Meishan fault, where a major earthquake occurred in 1906, more than a century ago. The deployed instruments are: (1) a 32-element seismic array in the free field, (2) a 32-element seismic array in a building, (3) a six-channel unit with a broadband seismometer and an accelerometer, and (4) a six-channel unit with an accelerometer and an external rotational velocity sensor.

This short note is a progress report on this array deployment. Although 24 local earthquakes were recorded by one or more of the four instrumentation sets from 12 December 2007 to 3 July 2008, we are still in the process of upgrading equipment and improving field operations.

Introduction

Taiwan is located in the complex collision zone of the Philippine Sea plate and the Eurasia plate. The Philippine Sea plate is subducting below the Ryukyu trench in the northeast. The Eurasia plate is subducting below the Manila trench in the southwest. The Meishan earthquake of 17 March 1906 was a major earthquake (magnitude 7.1) having a rupture length of about 25 km and is one of the ten most disastrous earthquakes in Taiwan (Cheng *et al.*, 1999). However, the surface rupture of the Meishan earthquake was only partially observed (see Fig. 1) because Omori (1907) did not trace the rupture to the eastern end due to access difficulties; the Meishan fault is buried under thick sediments to the west of the 1906 mapped fault rupture. Because the historical earthquakes in Taiwan were not well documented until a century ago, we are not sure about the recurrence interval of earthquakes along the Meishan fault.

To the northeast of the Meishan fault, the surface rupture of the Chelungpu fault during the 1999 Chi-Chi earthquake (magnitude 7.6) has been mapped by the Central Geological Survey (1999). To the southwest of the Meishan fault, the Manila trench marks a large subduction zone extending about 1000 km to the south into the offshore region of the west coast of Luzon and beyond. Many magnitude 7 earthquakes have occurred in this subduction zone. For example, two recent magnitude 7 earthquakes occurred offshore of Pingtung at the southern tip of Taiwan on 26 December 2006 (Ma and Liang, 2008).

Existing instruments in the vicinity of the Meishan fault are also shown in Figure 1. It is already heavily instrumented. However, to capture a large earthquake in detail, more instruments are needed, especially instruments that are not routinely deployed, such as rotational sensors, low-gain broadband seismometers, and high-rate Global Positioning System instruments. Our approach is to deploy an array of rotational and translational sensors, so that rotational motions can be observed directly and inferred indirectly, as discussed in Lee *et al.* (2009).

Because rotational motions will be most pronounced in the near field of earthquakes, we chose a site where a large earthquake is anticipated. Deployments in both free-field sites and in buildings are critical in order to understand the impact of rotational motions on the built environment. In addition, a broadband seismometer that can record onscale up to ground acceleration of $2g$ will help to verify the ground velocity deduced from ground acceleration because traditional broadband seismometers will be offscale at $\sim 0.01g$.

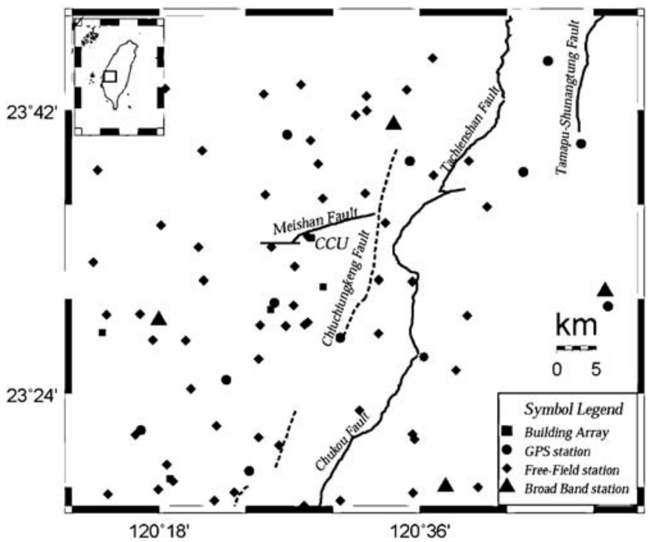

Figure 1. Existing instruments in the vicinity of the Meishan fault before deployments of additional instruments at the NCCU campus site (marked CCU in the figure) in December 2007.

The Deployed Instruments

We chose the National Chung-Cheng University (NCCU) campus site because the Meishan fault cuts across the campus, and there is already an existing accelerometer array (CHYBA1) in the building of its Institute of Seismology. Locations of CHYBA1 and the free-field accelerometer array (CHYARJ) are shown in Figure 2. The CHYARJ, deployed in mid-December 2007, is an array of nine stations (1–9), offset about 300 m northwest from CHYBA1. Two more sets of instruments (CHY130G and CHY130R) were deployed at the central station of CHYARJ (station 3). The topography in the area shown in Figure 2 is nearly flat, as the site was leveled for use as a university campus. Station elevation for the free-field array varies from 53 to 59 m.

CHYBA1 Array in a Building

An accelerometer array was installed in the Institute of Seismology Building in 1993 using a duplex personal computer-based (PC-based) real time, 16-bit, 32-channel seismic data acquisition system (Lee and Shin, 1997). This array consists of 20 uniaxial accelerometers (Model SV-555 by Tokyo Sokushin) and 1 three-component accelerometer (Model SV-355P by Tokyo Sokushin) just outside the building. Accelerometers are installed at different levels of the building. All sensors are connected to the data acquisition system by cables for simultaneous digitization and recording. It has been in continuous operation and has recorded hundreds of earthquakes. The PC-based data acquisition system was recently replaced by a real time, 24-bit, 32-channel datalogger (Model SAMTAC 700 by Tokyo Sokushin) in October 2007. This datalogger has 256 MB memory and has automatic backup of the recorded data to a hard disk of 80 GB. The triggering threshold level is set at 4 mv (~0.8 gal). After it is triggered, the datalogger records the event at 200 samples/sec with 20 sec pre-event and 15 sec post-event data.

CHYARJ Array in the Free Field

A free-field accelerometer array was installed at the northwestern part of the NCCU campus, about 300 m northwest of CHYBA1. This array consists of nine stations, each equipped with a three-component accelerometer

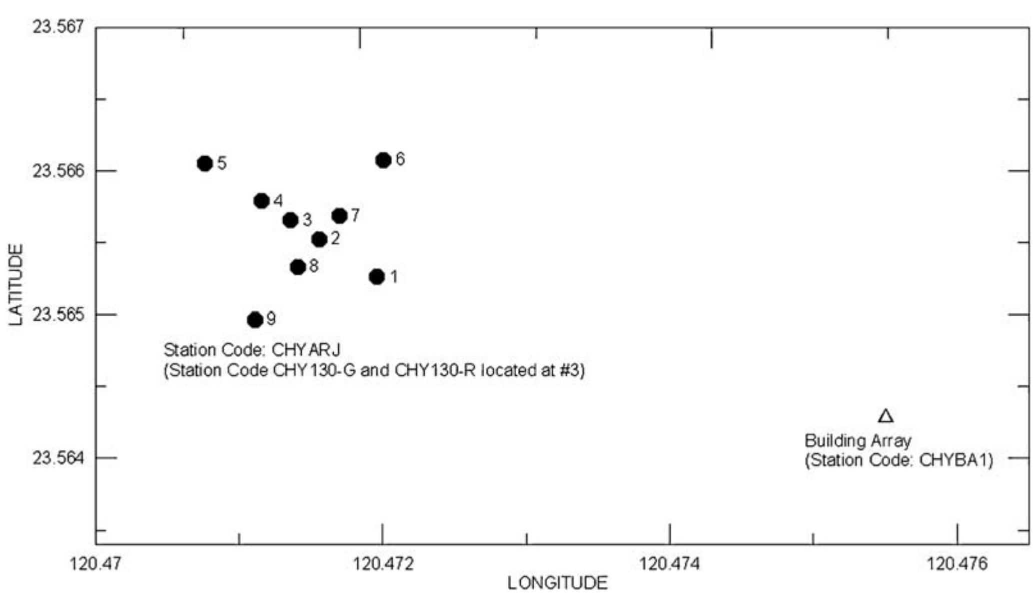

Figure 2. Relative locations of the nine stations of the CHYARJ array and CHYBA1 building array. The CHYARJ array with stations 1, 2, 3, 4, and 5 along an approximately straight line oriented approximately southeast–northwest, and stations 6, 7, 8, and 9 oriented northeast–southwest. Station CHY130G and station CHY130R are colocated with station 3 of CHYARJ. Station spacing is either 25 or 50 m.

(Model FBA-23 of Kinemetrics). These accelerometers are connected to a datalogger by cables. The initial datalogger is a temporary unit of 32-channels with a 16-bit digitizer. This temporary datalogger was replaced by a 24-bit, 32-channel datalogger (Model SAMTAC 700 by Tokyo Sokushin) on 12 February 2008. In addition, eight short-period, three-component seismometers (Model L22 by Mark Products) are also placed at eight stations of the CHYARJ array (except station 3). However, only five vertical components from stations 1, 2, 4, 7, and 8 are now connected to the datalogger by cables. The triggering threshold level is set at 4 mv (~0.8 gal). After it is triggered, the datalogger records the event at 200 samples/sec with 20 sec pre-event and 15 sec post-event data. The relative locations of these nine stations are shown in Figure 2. Each arm of the array is 150 m in length, and the station separation is either 25 or 50 m.

Station CHY130R: Accelerometer and Rotational Velocity Sensor

A six-channel, 24-bit recording accelerograph (Model K2 by Kinemetrics) was upgraded to include an external three-component rotational velocity sensor (Model R-1 by eentec). We call this instrument "K2 + R1." The K2 is a well-known accelerograph made by Kinemetrics, and detailed description and technical specifications can be found at the manufacturer's web site (see the Data and Resources section). This instrument (tested by Nigbor and Lee, 2006) was installed at the central station of the CHYARJ array in the free field, that is, colocated with station 3. The triggering threshold level is set at 1.92 gal for the internal accelerometer. After it is triggered, the accelerograph records the event at 200 samples/sec with 20 sec pre-event and 15 sec post-event data.

Very recently, Nigbor *et al.* (2009) carried out extensive tests on commercial rotational sensors and concluded that the R-1 sensor generally meets the specifications given by the manufacturer but that clip level and frequency response vary enough that more detailed calibrations are warranted for individual units. The transfer function of the R-1 sensor can be found at the manufacturer's website (see the Data and Resources section). The instrument response is nearly flat from 0.1 to 20 Hz, and its self noise is $< 10^{-6}$ rad/sec rms in the same frequency band, as confirmed by Nigbor *et al.* (2009).

Station CHY130G: Accelerometer and Low-Gain Broadband Seismometer

A six-channel, 24-bit recording datalogger (Model 802H by Tokyo Sokushin) was also installed at the central station of the CHYARJ array (i.e., colocated with CHY130R). This datalogger has two connected external sensors: a three-component accelerometer (Model AS-3257 by Tokyo Sokushin) and a broadband velocity seismometer (Model VSE-355G3 by Tokyo Sokushin) that are capable of recording onscale for ground motions up to 2*g* in acceleration. A VSE-355G3 seismometer was recently tested by Hutt *et al.* (2008). The triggering threshold level is set at 10 mv (~2 gal) for the accelerometer. After it is triggered, the datalogger records the event at 200 samples/sec with 20 sec pre-event and 15 sec post-event data.

The Recorded Data

After the instruments were deployed in the free-field site in mid-December 2007, 24 earthquakes were recorded by 1 or more of the 4 sets of instruments by early July 2008. Locations for these 24 earthquakes are shown in Figure 3. Because of reasons such as power failures and threshold trigger levels, not all the instruments were triggered by these earthquakes. A summary of the recorded data is given in Table 1. Most of the earthquakes are small ($M_L < 4$). The nearest earthquake (M_L 2.5) has an epicentral distance of 5 km, and the largest earthquake (M_L 6.4) has an epicentral distance of 461 km.

For illustrative purposes, we plotted some of the recorded data from the first earthquake on 4 March 2008 (earthquake number 12 in Table 1). Figure 4 shows the ground translational acceleration (left-hand panel) and the

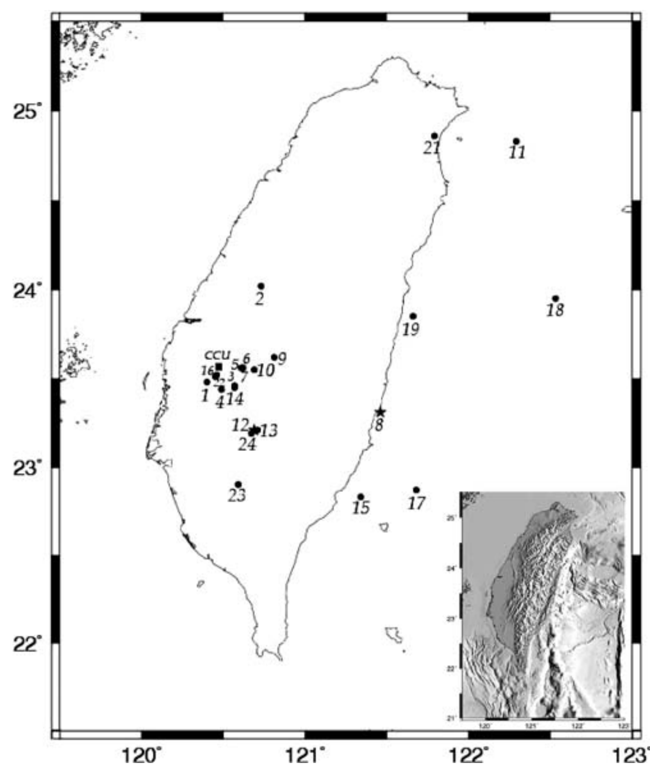

Figure 3. Locations of 24 earthquakes recorded by 1 or more of the 4 instrumentation sets at the NCCU (CCU in the figure). The insert in the lower right-hand corner is a topographic relief map of Taiwan. The numbers correspond to the event numbers in Table 1. The black square is the NCCU site. The stars indicate the location of earthquakes recorded by all four instrumentation sets and the dots indicate the other events. Earthquake number 20 is located too far south to be included in the figure.

Table 1

Summary of Earthquakes Observed from Late December 2007 to Early July 2008*

Number	Date (yy/mm/dd)	Time (hh:mm UTC)	Latitude (North)	Longitude (East)	Depth (km)	Magnitude	Delta† (km)	CHYBA1	CHYARJ	CHY130G	CHY130R
1	07/12/23	02:12	23.48°	120.43°	10.0	3.4	11.8		12230212.txt		IB033.evt
2	07/12/24	18:48	24.02°	120.73°	23.4	4.9	56.8	12241848.46w	12241848.txt		IB034.evt
3	07/12/29	17:47	23.46°	120.57°	9.4	3.7	16.7	12291747.14w			IB035.evt
4	08/01/23	19:14	23.44°	120.50°	6.1	3.6	14.8	01231914.16w			IB118.evt
5	08/02/04	08:59	23.56°	120.61°	12.2	3.6	14.3				IB129.evt
6	08/02/04	11:16	23.56°	120.62°	10.8	3.1	15.2				IB130.evt
7	08/02/09	13:52	23.56°	120.62°	11.6	3.2	15.0				IB131.evt
8	08/02/17	20:33	23.31°	121.46°	28.3	5.4	105.1	02172033.08w	02172033.37w	28A34850.06d	IC001.evt
9	08/02/22	00:22	23.62°	120.81°	5.0	4.1	24.9	02220022.02w		28AC0580.06d	IC002.evt
10	08/02/23	07:03	23.55°	120.70°	19.4	2.4	23.5			80205400.cva	
11	08/02/27	18:54	24.83°	122.29°	14.4	4.8	231.5			80205800.cva	
12	08/03/04	17:31	23.21°	120.70°	11.3	5.2	45.9	03041731.43w	03041648.06w	28C917E8.06d	IL005.evt
13	08/03/04	22:42	23.21°	120.71°	11.9	4.6	45.9	03042242.35w			IL006.evt
14	08/04/02	21:44	23.45°	120.59°	8.1	2.6	17.3			29055B2C.06d	
15	08/04/14	15:47	22.83°	121.34°	27.0	4.3	120.5			291CFBC7.06d	
16	08/04/19	19:23	23.52°	120.46°	9.8	2.5	5.4				IM018.evt
17	08/04/23	18:28	22.87°	121.68°	11.1	5.6	145.5	04231829.11w			IM019.evt
18	08/05/10	19:42	23.95°	122.53°	25.0	5.6	214.3	05101942.43w	29553AB9.06f		IM030.evt
19	08/05/10	21:11	23.85°	121.66°	40.9	4.0	125.1			295552A3.06d	
20	08/06/01	01:57	19.45°	121.10°	41.9	6.4	460.5				VO013.evt
21	08/06/01	16:59	24.86°	121.79°	92.3	5.8	196.3				VO014.evt
22	08/06/14	16:24	23.51°	120.45°	7.6	2.6	6.9			299D0613.06d	
23	08/06/14	23:59	22.90°	120.59°	16.9	4.8	74.3			299D775D.06d	VO015.evt
24	08/07/03	00:05	23.19°	120.67°	15.1	4.3	46.3				VO016.evt

*If a data filename is shown, it indicates that a successful recording was obtained.

†Delta is the epicentral distance.

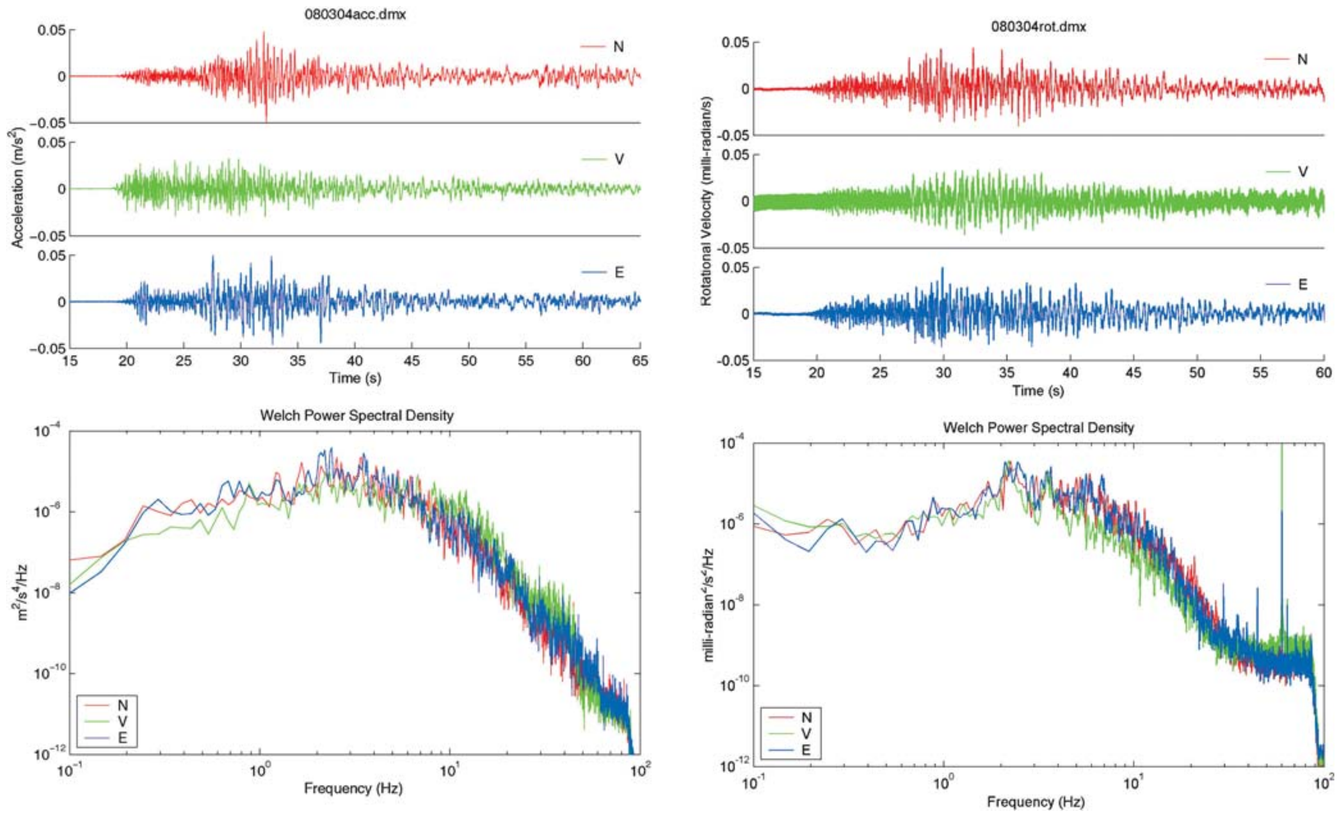

Figure 4. Translational acceleration (left-hand panel) and rotational velocity (right-hand panel) from the first 4 March 2008 earthquake recorded by the K2 + R1 unit at CHY130R. See the text for explanation.

ground rotational velocity (right-hand panel) recorded by the K2 + R1 unit at station CHY130R. For each panel, the waveform time histories (for three components) are shown in the top frame and the Welch spectral densities (for the corresponding three components) as a function of frequency are shown in the bottom frame. The plotted waveform data have not been corrected for instrument response. Please note that the rotational velocity sensor is a much more narrowband instrument (0.1–20 Hz) than the accelerometer (DC to 50 Hz). Figure 5 shows the ground acceleration (Ch01–Ch27) and ground velocity (Ch28–Ch32) recorded by the CHYARJ array in the free field. Each trace in Figure 5 is scaled to its peak amplitude in order to fit within the allocated plot space for each channel data.

Because this project is recently underway, we are learning how to deploy four different types of sensors in arrays using three different types of dataloggers. We have not had sufficient time to analyze the recorded data as new software is required to handle different types of sensors and dataloggers. Detailed data analysis will follow in future publications after more data are collected.

Discussion

A plan to intensify earthquake monitoring along the Meishan fault was proposed and accepted by the Central Weather Bureau (CWB) in June 2008, but it is currently waiting for funding. Presently, we had to make use of existing instruments (including some delivered in 2007 and 2008). As a result, instrument deployments took place in several stages and were often not optimal. A 32-channel array (CHYBA1) with one three-component and 20 single-component accelerometers was previously deployed in the Institute of Seismology Building in 1993 using a 16-bit PC-based system, and its recording system was replaced in October 2007 by a modern 24-bit system. A K2 + R1 instrument was deployed in the same building in late June 2008. Because only 23 channels were connected to accelerometers, three R-1 rotational velocity sensors were added to the CHYBA1 array in October 2008. We have also requested funding for 20 K2 + R1 instruments in 2009. If approved, they will be deployed at about 1 km spacing along the Meishan and nearby faults.

Twenty-five earthquakes were recorded within 7 months after the initial instrument deployment (from 12 December 2007 to 3 July 2008) when this manuscript was first submitted. Since then (from 4 July to 31 October 2008), 13 more earthquakes were recorded but were not included in this article. Most of these earthquakes are small local events. Because of the field deployment schedule and various operational problems, only 2 of these 24 earthquakes were recorded by all of the instruments, and the K2 + R1 instrument

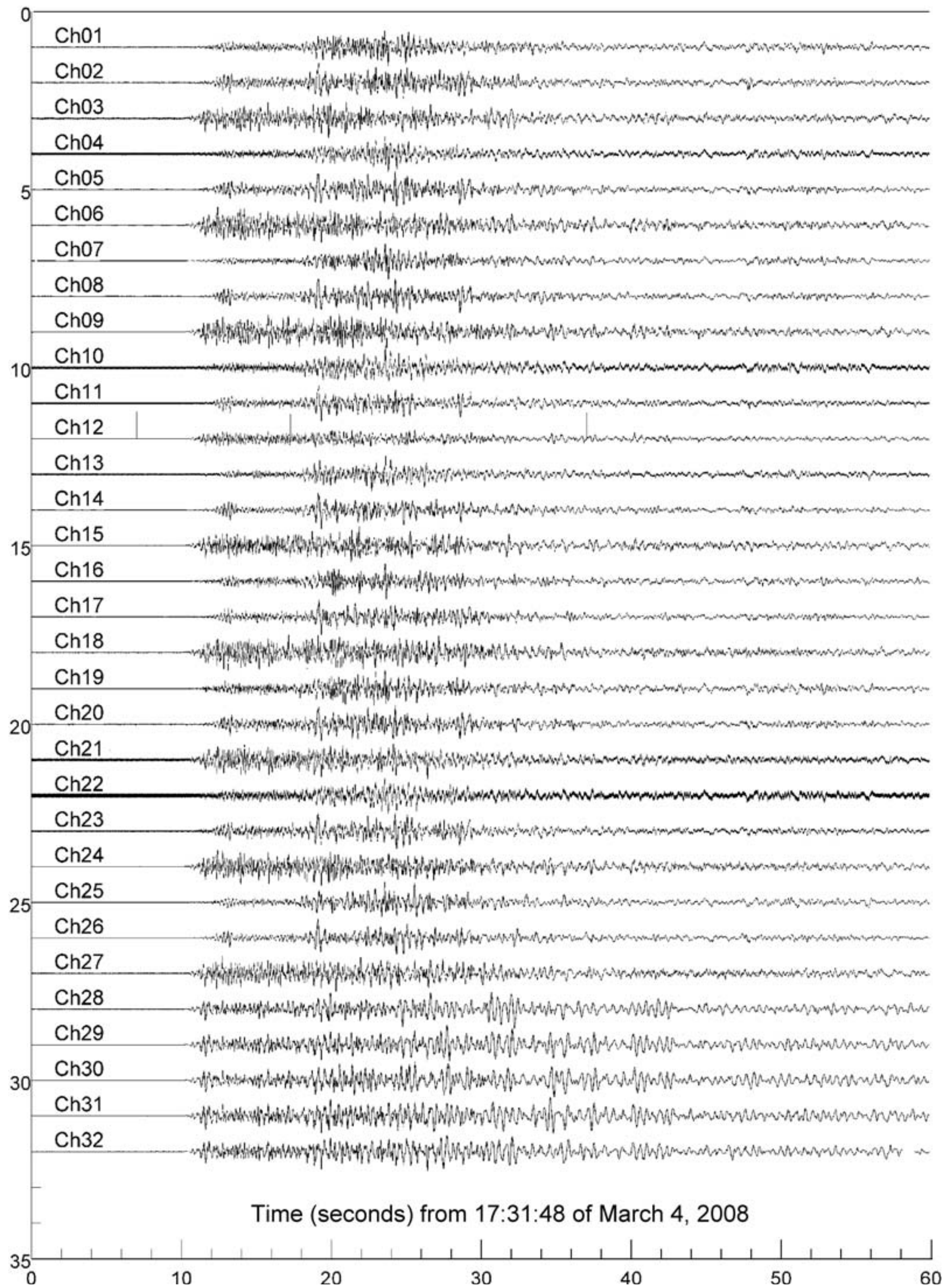

Figure 5. Acceleration (Ch01–Ch27) and translational velocity (Ch28–Ch32) from the 4 March 2008 (17:31 UTC) earthquake recorded by the CHYARJ array in the free field. Scale is arbitrary in order to fit the waveforms within the allocated space for each channel data.

recorded the most, 18 of the total. Nevertheless, we expect to have better field results when the field operation problems are resolved.

Data and Resources

All translational and rotational seismograms described in this article were collected by us and all other data used were published. We will release our recorded data at the web site of the International Working Group on Rotational Seismology (http://www.rotational-seismology.org/, last accessed January 2009).

For information on the Kinematics and eentec instruments, see http://www.kinemetrics.com/ (last accessed January 2009) and http://www.eentec.com/ (last accessed January 2009), respectively.

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