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NOTES AND CORRESPONDENCE

Source Parameters of Regional Earthquakes in Taiwan: January-December, 1997

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ABSTRACT

Establishment of the "Broadband Array in Taiwan for Seismology (BATS)" has enabled the systematic determination of reliable source parameters for regional earthquakes in Taiwan through waveform inversion technique. Using an improved algorithm by Kao et al. (1998) to overcome the generally higher background noise as well as the heterogeneous velocity structure resulted from the complex tectonic interactions near Taiwan, we report source parameters of 46 events that occurred in 1997. The inversion quality is classified by a combination of a letter (A-F) and a digit (1-4) reflecting the waveform misfit and the compensated linear vector dipole (CLVD) component, respectively. To make the results more accessible and useful to the academic community, both the table that summarizes the reported source parameters and the complete set of inversion results are available electronically from the BATS web site at

http://bats.earth.sinica.edu.tw/CMT_Solutions/cmtF1997.html.

(Key words: Broadband Array in Taiwan for Seismology, Earthquake source parameters, Waveform inversion, Taiwan)

1. INTRODUCTION

Systematic determination of earthquake source parameters (including centroid depths and moment tensor solutions) for global large and moderately-sized events ($m_b \geq 5.5$) is no longer a subject of research since mid-1980's due to the successful development of the centroid-moment-tensor (CMT) inversion technique and increasing coverage of global digital seismic networks (e.g., Dziewonski et al. 1981; Kawakatsu et al. 1995; Sipkin 1982). Since early 1990's, increasing knowledge of detailed velocity structures on a regional scale and the establishment of regional broadband networks both contribute to the success of extracting CMT

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solutions from regional waveforms (e.g., Dreger and Helmberger 1993; Fan and Wallace 1995; Lay et al. 1994; Thio and Kanamori 1995; Zhao and Helmberger 1994). Consequently, routine report of CMT solutions for smaller, regional earthquakes becomes standard practice for many regional broadband seismographic networks (e.g., Zhu and Helmberger 1996; Pasysnos et al. 1996).

The "Broadband Array in Taiwan for Seismology (BATS)" began its test operation in late 1994 (Fig. 1). Since then, significant amount of efforts have been made toward the systematic study and report of CMT solutions for the numerous earthquakes, both large and small, that occurred in the Taiwan region. However, the generally higher background noise as well as the heterogeneous velocity structure resulted from the complex tectonic interactions near Taiwan prevent the direct adoption of existing regional CMT algorithms. An improved inversion method utilizing the adjustable filtering bandwidth and allowing different velocity models for different station-source pairs finally overcomes the difficulty and makes the task a reality (Kao et al. 1998). A pilot study demonstrating the stability and tectonic implications of the source parameters for 7 earthquakes occurred east offshore of Taiwan was completed in 1998 (Kao et al. 1998), followed by a systematic presentation of source parameters for earthquakes in 1995 and 1996 (Kao and Jian 1999).

This work is a continuing effort to systematically present source parameters of regional events with which we were able to perform moment-tensor inversion using BATS data. Earthquakes that occurred in 1997 are included in this report and we intend to make future BATS CMT solutions available on a routine basis. Our results not only provide precise source parameters for smaller regional events that cannot be determined otherwise, but also serve as an alternative to independently examine solutions of large and moderate-sized events from other sources.

2. DATA AND METHOD

In this section, we review very briefly the data and method used in our determination of source parameters for regional earthquakes in Taiwan.

All BATS stations are equipped with state-of-the-art very-broadband (Streckeisen STS-1 or STS-2) and strong-motion (Terra Technology SSA-320) sensors and 24-bits digital recorders (Quanterra Q-680 or Q-4120). Data streams with high sampling rates ($\geq$80 samples per s) are recorded in triggering mode, while others are recorded in continuous mode on both hard disks and magnetic tapes. Data quality control is performed at the Data Management Center of the Institute of Earth Sciences (IES-DMC), Academia Sinica. The IES-DMC is also responsible for BATS data archiving and distribution afterwards. Meanwhile, one copy of BATS data is contributed to the Data Management Center of the Incorporated Research Institutions for Seismology (DMC, IRIS) for the same purpose.

The analysis begins with a background-noise evaluation that determines the frequency band used in the inversion. The cut-off frequency of the lower corner is usually at ~0.02 Hz, which is determined by comparing the power spectra of waveform windows 300 s before and after the *P* first arrival (Kao et al. 1998). The higher corner is set at 0.06-0.08 Hz to avoid the effect of lateral heterogeneity and to simplify the calculation of synthetics. We utilize a two-

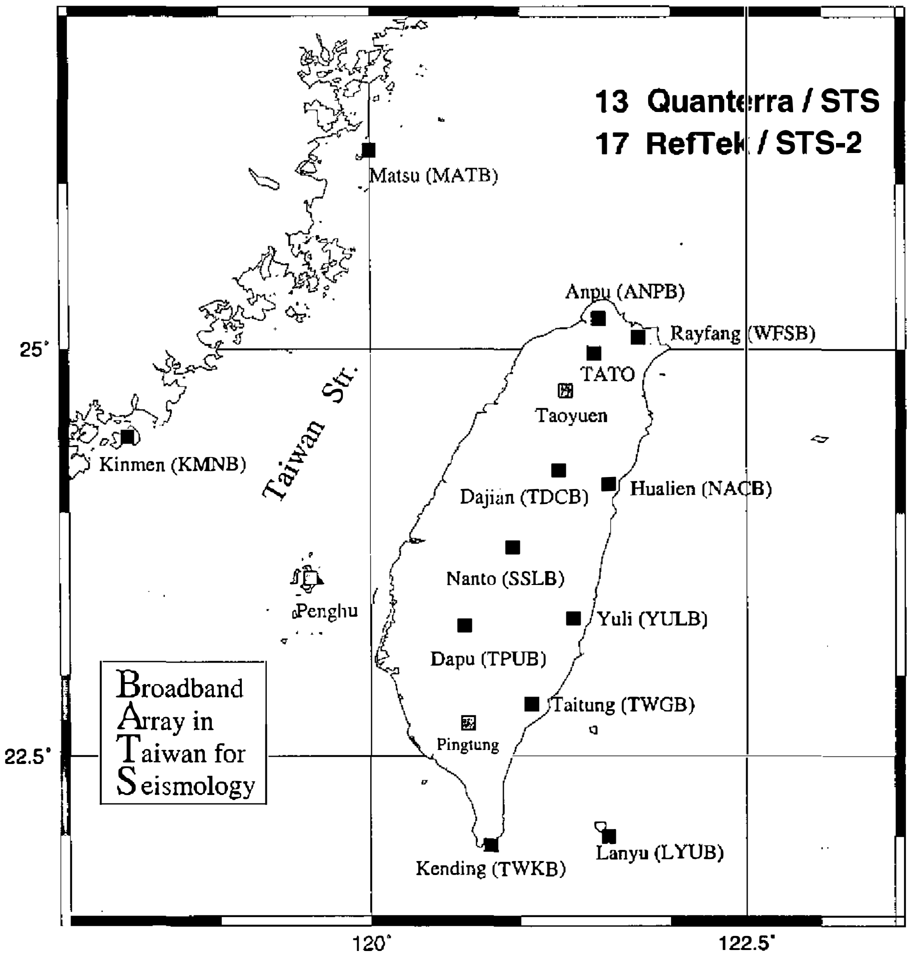


Fig. 1. Map of the "Broadband Array in Taiwan for Seismology (BATS)." Solid and gray squares show stations currently in operation and under construction, respectively. In addition to the permanent stations, BATS includes 17 portable stations that can be deployed for specific research tasks (as represented by symbols near the upper-right corner).

step procedure to allow different velocity models for different station-source pairs. This is to mimic the effect of heterogeneous velocity structures.

The inversion algorithm itself is based on the linear relationship between waveforms and the six elements of a moment tensor (Aki and Richards 1980). Computation of the Green's functions is done with the computational technique from Yao and Harkrider (1983) that efficiently combines the reflectivity method (Kennett 1980) and the discrete wavenumber summation method (Bouchon 1981).

The quality of inversion is evaluated by two parameters. The first is to measure the deviation from a pure double-couple source (Dziewonski et al. 1981),

$$\varepsilon = 2\ (\,|m^*|_{min} / |m^*|_{max}\,)\,, \tag{1}$$

$$m^* = m - (\textstyle\sum m_i / 3)\,,$$

where $\sum m_i$ is the sum of the three eigenvalues of the moment tensor and $|m^*|_{max}$ and $|m^*|_{min}$ are the largest and smallest absolute values, respectively. ε is 0 and 1 for a pure double couple and a CLVD source, respectively.

The second parameter is the misfit between the observed and synthetic waveforms, which is defined as

$$E = 1 - (f_{max} / g_{max}) \times \{\int f\, g\, dt / [(\int f^2\, dt)^{1/2} (\int g^2\, dt)^{1/2}]\}\,, \tag{2}$$

where f, f_{max}, g, and g_{max} are observed seismograms, the maximum amplitudes measured from observed seismograms, synthetic seismograms, and the maximum amplitudes measured from synthetic seismograms, respectively (Zeng and Anderson 1996). It is 0 if there is a perfect fit. This formula is an excellent compromise between the one that considers only the correlation between waveforms (e.g., Wallace et al. 1981) and the conventional root-mean-square (RMS) error that is determined completely by the amplitude differences. The quality of inversion is classified by a combination of a letter (A-F) and a digit (1-4). These are dictated by the waveform misfit (E) and the amount of CLVD component (ε), respectively, and are listed in Table 1.

3. RESULTS

Following the criteria defined in Kao and Jian (1999), we report source parameters only if they meet the following criteria: (1) 3-component waveforms from at least three stations are used in the inversion, and (2) the quality of inversion must be higher than C4. Here, inversion results for 46 earthquakes that satisfy these conditions are presented. The derived source parameters are listed in Table 2, whereas the corresponding best double-couple solutions and focal depths are plotted in Fig. 2.

Table 1. Quality Classification of Inversion results.

Class	Criteria
	Average Waveform Misfit (E)
A	$0 \le E < 0.3$
B	$0.3 < E \le 0.5$
C	$0.5 < E \le 0.7$
D	$0.7 < E \le 0.9$
E	$0.9 < E \le 1.1$
F	$E > 1.1$
	CLVD component (ε)
1	$\varepsilon \le 0.1$
2	$0.1 < \varepsilon \le 0.25$
3	$0.25 < \varepsilon \le 0.4$
4	$\varepsilon > 0.4$

Table 2. Source Parameters of Studies Earthquakes.

No	Origin Time[1]	Lat.[1]	Long.[1]	Dep.	M_{xx}[2]	M_{yy}[2]	M_{zz}[2]	M_{xy}[2]	M_{xz}[2]	M_{yz}[2]	M_w[2]	Strike[3]	Dip[3]	Rake[3]	E[4]	ε[4]	Class
1	97/01/02/06:31:42.4	22.42	121.09	27	-0.03	-2.15	1.90	1.15	0.40	-2.66	4.30	221	22	118	0.543	23.61	C2
2	97/01/05/10:34:16.9	24.62	122.53	27	55.50	-37.68	-14.57	38.03	30.55	-35.71	5.20	149	56	-17	0.535	24.98	C2
3	97/01/05/18:40:53.6	23.03	122.86	36	5.17	-6.56	0.75	4.48	-4.99	1.39	4.57	336	56	8	0.533	8.77	C1
4	97/01/06/01:51:12.2	24.65	122.34	15	3.22	-1.04	-1.53	1.53	0.27	-1.52	4.29	252	58	-146	0.599	12.83	C2
5	97/01/16/01:07:20.4	22.01	121.30	27	-0.52	-7.70	5.07	27.05	-15.09	10.98	4.95	353	61	-4	0.433	65.54	B4
6	97/01/16/09:45:44.4	21.56	121.38	24	-0.78	-0.04	0.98	-0.73	0.21	1.78	4.15	276	27	29	0.353	33.24	B3
7	97/01/18/17:13:47.8	23.93	122.44	18	-8.93	3.37	12.66	-1.10	23.58	-9.23	4.90	295	15	133	0.613	7.12	C1
8	97/01/20/05:53:00.4	24.07	121.85	36	-0.37	-0.86	1.24	0.69	-0.24	0.76	4.06	46	31	108	0.287	9.82	A1
9	97/01/26/19:18:00.3	24.09	121.63	39	-0.40	0.70	0.09	1.31	0.39	-1.57	4.16	282	41	-179	0.418	6.25	B1
10	97/02/09/21:42:21.9	23.51	121.70	36	-0.05	-1.75	1.40	0.44	-0.33	-0.09	4.09	207	47	109	0.351	12.44	B2
11	97/02/10/16:50:08.7	24.13	121.76	27	-0.55	0.39	0.23	1.32	0.64	-2.79	4.27	278	26	175	0.472	4.95	B1
12	97/02/13/08:29:54.2	23.21	121.46	18	0.10	-1.63	1.07	0.47	-0.75	-0.02	4.08	348	49	49	0.401	5.47	B1
13	97/02/19/09:49:21.2	23.90	121.56	21	-1.35	-0.21	1.07	1.18	0.27	0.79	4.12	88	52	138	0.416	11.36	B2
14	97/02/27/15:44:43.3	23.89	121.71	24	0.15	-1.40	1.98	0.88	-0.54	-2.04	4.24	227	29	136	0.371	14.28	B2
15	97/03/10/07:33:37.2	24.08	122.34	27	-11.88	6.16	7.29	-1.39	7.70	-5.81	4.71	309	39	151	0.441	17.49	B2
16	97/03/10/14:41:56.1	23.95	122.24	27	-5.10	2.24	5.35	-1.67	4.73	-2.41	4.53	310	33	140	0.516	4.17	C1
17	97/03/24/10:26:03.3	22.73	121.38	24	0.91	-1.31	0.18	0.50	-0.93	1.03	4.12	326	40	7	0.448	39.26	B3
18	97/03/24/23:32:20.1	24.16	121.72	42	4.57	-3.85	0.62	-2.44	4.73	-5.46	4.56	124	34	1	0.419	27.70	B3
19	97/04/13/17:45:14.0	23.81	121.71	48	26.00	-9.71	-13.69	-0.46	14.85	-24.69	4.98	119	35	-25	0.578	35.61	C3
20	97/04/15/21:33:22.6	23.99	122.30	27	-6.39	3.44	2.64	-2.49	3.96	-3.58	4.54	321	46	160	0.565	6.73	C1
21	97/04/27/23:59:32.6	24.61	121.96	60	-1.56	-0.32	1.83	4.15	0.90	3.09	4.43	87	54	159	0.541	8.20	C1
22	97/05/02/21:30:23.6	24.19	120.18	27	1.30	-1.19	0.23	-0.51	-0.61	0.11	4.05	212	74	163	0.518	19.16	C2
23	97/05/03/02:46:13.7	22.54	121.40	27	18.60	-43.94	20.77	2.79	-19.45	4.82	5.02	328	54	33	0.423	10.97	B2
24	97/05/15/10:43:47.7	24.79	121.93	108	-1.06	-0.03	0.31	-1.13	1.53	2.34	4.27	261	20	23	0.435	32.60	B3
25	97/05/23/10:41:20.1	21.21	122.04	180	-1.62	5.73	-4.15	-2.99	3.46	4.11	4.54	231	43	-31	0.394	19.37	B2
26	97/05/24/06:23:18.4	23.91	122.41	27	-0.77	0.50	0.12	-0.43	1.75	-0.92	4.15	328	21	174	0.610	4.15	C1
27	97/05/31/23:21:37.4	24.62	121.87	60	-0.09	0.45	-0.01	0.20	1.82	0.76	4.14	197	10	-7	0.437	10.10	B2

Table 2. continued.

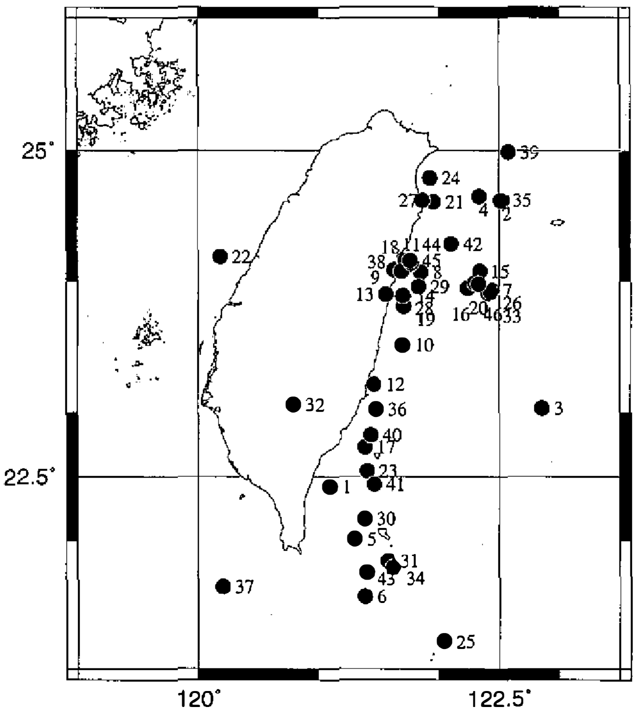
28	97/06/14/19:25:20.2	23.89	121.70	21	0.22	-1.29	1.95	0.69	1.07	-1.78	4.23	192	21	74	0.507	11.32	C2
29	97/06/18/02:03:30.6	23.96	121.83	39	5.58	-14.99	6.98	5.70	3.66	8.74	4.75	51	43	152	0.379	37.89	B3
30	97/06/22/09:36:04.1	22.17	121.38	21	8.38	-26.46	20.19	8.91	-8.23	-0.82	4.89	347	51	50	0.539	35.15	C3
31	97/06/27/15:53:27.5	21.84	121.58	36	-4.55	1.84	5.02	0.68	-4.36	5.13	4.55	109	27	144	0.551	20.94	C2
32	97/07/04/18:37:30.5	23.06	120.79	12	1.07	3.02	-9.56	10.00	-13.02	-12.76	4.83	327	16	-77	0.562	50.38	C4
33	97/07/08/16:26:27.3	23.92	122.43	21	-8.65	4.48	0.91	-3.33	6.46	-3.14	4.62	327	44	170	0.633	21.88	C2
34	97/07/10/08:19:53.6	21.79	121.62	15	3.77	5.42	-5.62	-0.17	-10.09	16.98	4.81	196	8	-103	0.526	26.08	C3
35	97/07/15/11:05:33.4	24.62	122.52	75	11.00	-21.97	9.19	15.14	3.43	161.80	5.41	63	6	155	0.426	12.95	B2
36	97/08/05/08:41:13.5	23.02	121.48	21	0.10	-1.41	1.23	0.69	-1.06	0.66	4.13	356	33	46	0.476	8.34	B1
37	97/08/24/12:17:40.0	21.64	120.20	54	-44.43	-19.24	67.30	27.05	-4.78	-11.32	5.15	247	45	104	0.524	15.44	C2
38	97/09/08/16:17:07.5	24.08	121.69	27	-0.19	-0.32	0.91	1.00	0.08	-1.33	4.11	257	34	152	0.446	10.56	B2
39	97/10/11/18:24:25.7	24.98	122.58	129	-72.82	139.95	-66.20	41.04	-58.62	68.56	5.40	132	48	-156	0.427	16.47	B2
40	97/10/17/13:14:16.8	22.82	121.43	24	1.97	0.49	-1.80	1.98	-2.04	-0.32	4.29	332	33	-46	0.434	39.11	B3
41	97/10/22/11:16:26.6	22.44	121.46	33	4.93	-13.18	5.56	5.30	-6.73	0.63	4.69	339	55	29	0.376	10.19	B2
42	97/10/25/02:40:15.9	24.29	122.11	36	-3.86	3.21	0.41	-0.55	0.83	-0.65	4.32	319	73	177	0.685	23.04	C2
43	97/11/12/00:09:35.8	21.75	121.40	69	-6.17	-6.81	12.57	10.76	9.18	-15.80	4.86	242	22	119	0.408	28.32	B3
44	97/11/12/22:36:45.2	24.14	121.77	30	-3.37	1.87	1.03	2.98	1.95	0.52	4.38	202	60	9	0.557	38.31	C3
45	97/11/14/04:29:50.8	24.16	121.76	24	-5.29	-29.04	16.68	18.08	21.59	-40.78	5.10	209	16	91	0.499	35.08	B3
46	97/12/23/02:35:45.7	23.98	122.33	30	-2.27	1.44	1.33	-1.55	3.28	-2.21	4.39	325	33	165	0.643	25.91	C3

[1] Origin time (Year/Month/Day/hr:min:sec) and epicentral locations (°N, °E) are reported by the Seismology Center, Central Weather Bureau, Taiwan.

[2] X, Y, Z point to north, east, and vertically down, respectively. All are in the unit of 1×10^{15} Nt m.

[3] Estimated best double-couple solutions in degrees.

[4] E and ε are defined by equations (2) and (1), respectively. ε is expressed in percent (%).



(b)

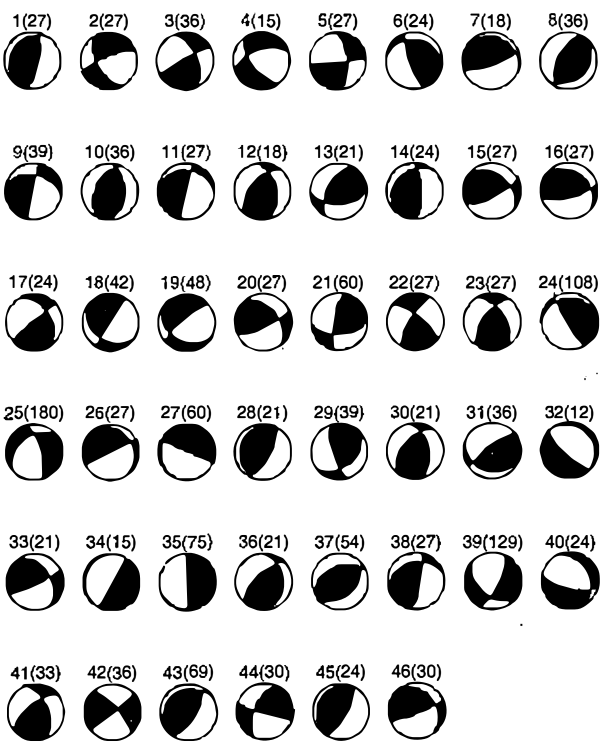


Fig. 2. Moment-tensor inversion results. (a) Map shows the epicenters of 46 earthquakes presented in this study. Numbers are according to Table 2. (b) Corresponding best double-couple solutions. The first number above each fault plane solution is the event number. The number in parenthesis is the best focal depth.

Due to the practical concern, the inversion results are presented as an electronic appendix to this report. Readers who are more interested in the technical aspect of our inversion can download the complete set from BATS web site at http://bats.earth.sinica.edu.tw/CMT_Solutions/cmtF1997.html. To make the results more accessible and useful to the academic community, Table 2 as well as the table in our previous report showing source parameters of earthquakes in late 1995 and 1996 are also available in our web site (http://bats.earth.sinica.edu.tw/CMT_Solutions/Solutions.html).

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APPENDIX Figures in this electronic appendix, numbered according to their order of appearance in Table 2, show the complete result of waveform inversion. Seismograms of three components (V: vertical; R: radial; T: transverse) from BATS stations are used. The station code, azimuth, epicentral distance, name of velocity model, and the frequency band used in the inversion are shown at the top of each set of seismograms. Thick and thin traces are observed and synthetic waveforms, respectively. The normalized maximum amplitude and corresponding misfit are near the beginning of each trace. The absolute amplitude scale is shown near the bottom. The focal mechanism is shown in lower-hemisphere projection with shaded area showing compressional *P* first motions. Dashed lines represent the corresponding best double couple solution. Solid dots mark the P, T, and B axes, while the open triangles show projected locations of used BATS stations. All figures are available from the BATS web site at http://bats.earth.sinica.edu.tw/CMT_Solutions/cmtF1997.html. Hard copies are also available directly from the authors upon request.

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