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Short Note

Rotational Motions Observed during an Earthquake Swarm in April 1998 Offshore Ito, Japan

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Abstract We observed six components of ground rotational and translational motions in a near-field region during an earthquake swarm in April 1998 offshore Ito, Izu Peninsula, Japan. To check the reliability of our observation using a MotionPack sensor, we installed an 8301F sensor, which is an inertial angular displacement sensor with a higher sensitivity than MotionPack. The noise level of the MotionPack is much higher than that of the 8301F, but the waveforms of these signal components are quite similar to each other, suggesting that the MotionPack records rotational rate correctly but with higher noise. Our observation made known a linear correlation between the maximum rotational displacements around the vertical axis and the maximum translational velocities. The waveforms of rotational motion around the vertical axis are analogous to those of translational horizontal velocities, suggesting the linear correlation between maximum values. These rotational motions are much larger than those calculated by array data at the San Andreas fault. This large discrepancy might be explained by one or more of the following effects: the difference in the spatial scale of rotational motion by single gyro measurement and by array observation, the effect of the precipitous topography at the station of the offshore Ito swarm, and the difference of the degree of maturation between the San Andreas fault and the swarm regions of offshore Ito.

Introduction

It has been recognized progressively by seismologists and earthquake engineers that ground rotational motions should be recorded together with ground translational motions to get more reliable information concerning torsion and distortion of buildings and long structures, seismic velocity structure, stress induction due to seismic waves, and the rupture process of an earthquake. Recently, Igel *et al.* (2005) succeeded in recording weak rotational motion excited by the 2003 Tokachi-oki, Japan, earthquake at a far-field station using a ring laser gyro. In the near-field region, several observations on ground rotational motions had been reported based on different measurement methods, observations using a single gyro sensor (e.g., Nigbor, 1994; Takeo, 1998), array observations (Spudich *et al.*, 1995; Huang, 2003; Spudich and Fletcher, 2008), and both (Suryanto *et al.*, 2006).

In this short note, we report an observation of six components of ground rotational and translational motions in a near-field region with hypocentral distances less than 8 km during an earthquake swarm in April 1998 offshore Ito, Izu Peninsula, Japan. In this observation, we installed not only a gyro sensor, which was used in the rotational motion observation during a swarm of March 1997 (Takeo, 1998) but also high-sensitivity angular displacement sensors to check the reliability of observations. Using these high-sensitivity sensors, we obtained more than 200 records of ground rotational displacements ranging from 1×10^{-7} rad to 1×10^{-3} rad.

Observational System

The observational system consists of a Kinemetrics FBA-23 triaxial accelerometer (up–down, north–south, and east–west components), a Systron Donner MotionPak triaxial gyro sensor (rotational components around the vertical axis, north–south axis, and east–west axis), a triaxial high-sensitive angular displacement sensor, and two six-channel digital data loggers. The inertial angular displacement sensor, a Systron Donner 8301F, has a higher sensitivity and a lower internal noise than those of MotionPack. Three 8301F sensors were mounted on a triaxial base forming a triaxial angular displacement sensor.

Full-scale outputs of the FBA-23 and the MotionPack are ± 1 G and $\pm 8.73 \times 10^{-1}$ rad/sec, respectively. The scale range and the internal noise level of the 8301F are $\pm 2 \times 10^{-4}$ rad and 3×10^{-8} rad rms, respectively. The MotionPak

has a internal noise of 7×10^{-5} rad/sec (rms). The FBA23 sensor has a flat frequency response to translational acceleration from static component to 50 Hz. The MotionPack also has a flat frequency response to rotational velocities around three perpendicular axes from static component to 75 Hz. The 8301F sensor has a flat response to angular displacement in a frequency range higher than 2 Hz, but the sensitivity decays 12 dB in octave in frequency range from 2 to 0.07 Hz. The digital data logger used in this observational system is a LS7000XT manufactured by Hakusan Co., Ltd., which has a six-channel, 24-bit resolution digitizer. The sampling rate of this logger is 50 samples/sec under a continuous recording mode using an antialias filter with a cutoff frequency of 20 Hz.

Near-Field Ground Rotational Motions

Repeating seismic swarm activities at offshore Ito on the Izu Peninsula, Japan, occurred every spring from 1995 to 1998. In 1998, the earthquake swarm started on 20 April and lasted for 10 days. The source area was located about 3 km east of Cape Kawana extending about 5 km long east to west. We installed the observational system at Cape Kawana (station KAW) on 21 April 1998, one day after the start of the swarm activity, and had operated until the end of the swarm activity. Figure 1 shows the distribution of the hypocenters of all swarm activities from 1995 to 1998 (left panel) and that of the 1998 swarm activity (right panel). The swarm source regions were shifted slightly to each other, and each swarm seemed to occur while rupturing a new region every time.

The accelerometer (FBA-23) and the angular displacement sensor (8301F) of the observational system detected 943 events and 216 events, respectively. All events whose angular displacements were recorded are listed in Table 1 with the magnitudes, the epicentral distances, the maximum values of translational acceleration, translational velocity, rotational displacement, rotational rate, and the location of hypocenters. The magnitudes and the epicentral distances ranged from 5.0 to 1.2 and from 1.5 to 10 km, respectively.

In Figure 2 rotational rates around the vertical axis recorded by the MotionPack are compared with those calculated from the 8301F records. This event occurred at 6:09 Japanese Standard Time, 27 April 1998, with depth, epicentral distance, and magnitude of 5.0 km, 4.5 km, and 4.8, respectively. The noise level of the MotionPack is higher than that of the 8301F, but the waveforms are quite similar to each other. This suggests that the MotionPack measured rotational rates correctly even with its higher noise level.

The maximum rotational displacements around the vertical axis are compared with the horizontal peak-to-peak maximum translational velocities in Figure 3. We can recognize a linear correlation between these two measures.

Accelerations, velocities, rotational displacements, and rotational rates, which were excited by four earthquakes with magnitudes ranging from 2.4 to 5.0, are compared in Fig-

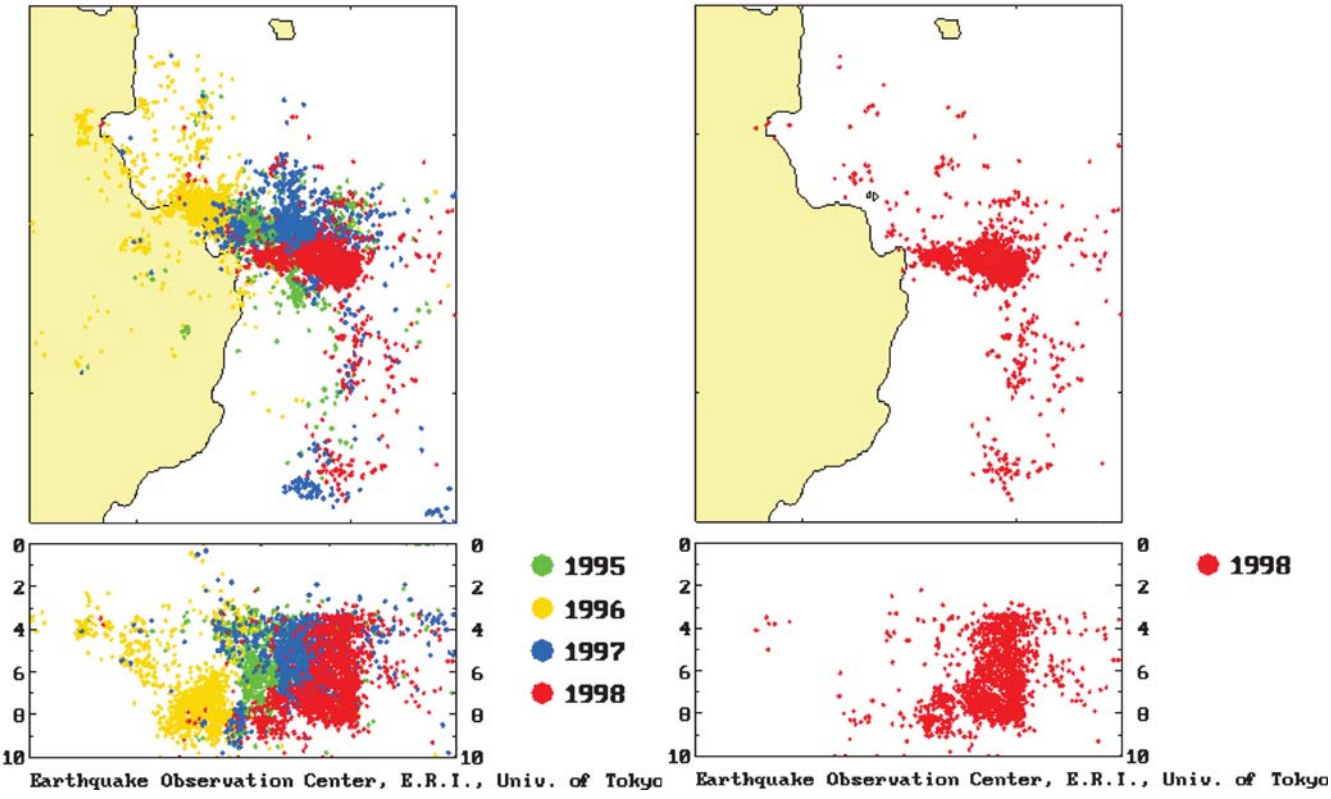

Figure 1. Epicenters of four offshore Ito swarm activities from 1995 to 1998 (left panel) and that of the 1998 swarm activity (right panel).

Table 1

List of Rotational Displacements, Accelerations, and Velocities of the 1998 Offshore Ito Swarm Activity

Date	Time	Latitude	Longitude	Distance (km)	Azimuth	Depth (km)	M	Accelerations (10 m/sec^2)	Velocities (m/sec)	Rotational (rad)	Rotational Rate (rad/sec)
26 April 1998	07:37:36.7	34.9615N	139.1816E	3.477	251.541	5.3	5.0	2.98×10^{-01}	2.81×10^{-01}	3.57×10^{-04}	4.45×10^{-03}
26 April 1998	15:03:45.7	34.9728N	139.2009E	5.582	245.055	3.5	5.0	3.41×10^{-01}	2.22×10^{-01}	2.89×10^{-04}	4.79×10^{-03}
27 April 1998	06:09:22.0	34.9510N	139.1945E	4.478	270.815	5.0	4.8	2.25×10^{-01}	1.47×10^{-01}	2.09×10^{-04}	3.46×10^{-03}
22 April 1998	10:40:55.7	34.9498N	139.1875E	3.842	272.933	5.7	4.6	1.72×10^{-01}	5.62×10^{-02}	8.88×10^{-05}	2.69×10^{-03}
25 April 1998	18:34:10.4	34.9563N	139.2234E	7.137	265.805	6.6	4.5	1.41×10^{-01}	4.26×10^{-02}	8.07×10^{-05}	2.02×10^{-03}
26 April 1998	18:00:55.8	34.8805N	139.1872E	8.756	334.209	1.5	4.5	6.42×10^{-02}	3.03×10^{-02}	3.36×10^{-05}	1.01×10^{-03}
22 April 1998	04:41:49.8	34.9545N	139.1946E	4.498	265.869	4.7	4.4	1.12×10^{-01}	6.25×10^{-02}	9.04×10^{-05}	1.68×10^{-03}
22 April 1998	17:49:58.2	34.9527N	139.1918E	4.232	268.307	6.0	4.4	7.76×10^{-02}	2.54×10^{-02}	3.64×10^{-05}	1.09×10^{-03}
26 April 1998	22:02:59.7	34.9464N	139.1907E	4.170	277.915	5.0	4.4	1.41×10^{-01}	5.41×10^{-02}	7.86×10^{-05}	2.18×10^{-03}
21 April 1998	20:45:39.2	34.9603N	139.1839E	3.640	254.572	4.5	4.3	1.04×10^{-01}	3.62×10^{-02}	4.76×10^{-05}	1.38×10^{-03}
23 April 1998	05:28:55.7	34.9488N	139.1948E	4.514	273.913	6.0	4.2	1.24×10^{-01}	3.74×10^{-02}	5.13×10^{-05}	1.63×10^{-03}
23 April 1998	11:03:29.7	34.9524N	139.1915E	4.203	268.750	6.8	4.1	2.57×10^{-02}	1.38×10^{-02}	2.09×10^{-05}	4.20×10^{-04}
27 April 1998	20:39:07.5	34.9052N	139.1944E	6.813	319.032	6.0	4.1	3.14×10^{-02}	1.35×10^{-02}	1.83×10^{-05}	4.78×10^{-04}
21 April 1998	23:41:32.1	34.9600N	139.1866E	3.869	256.019	4.1	4.0	5.18×10^{-02}	1.79×10^{-02}	2.40×10^{-05}	5.24×10^{-04}
22 April 1998	01:16:22.5	34.9539N	139.1915E	4.210	266.485	5.9	4.0	4.19×10^{-02}	1.52×10^{-02}	2.28×10^{-05}	6.29×10^{-04}
22 April 1998	02:57:53.2	34.9527N	139.1927E	4.314	268.340	6.1	4.0	4.24×10^{-02}	1.19×10^{-02}	1.49×10^{-05}	4.63×10^{-04}
22 April 1998	19:35:53.9	34.9236N	139.1986E	5.758	302.615	5.5	4.0	3.88×10^{-02}	1.35×10^{-02}	1.67×10^{-05}	5.60×10^{-04}
23 April 1998	07:19:07.8	34.9512N	139.1909E	4.148	270.582	6.3	4.0	5.02×10^{-02}	1.31×10^{-02}	1.86×10^{-05}	5.28×10^{-04}
24 April 1998	05:45:53.3	34.9594N	139.1810E	3.358	255.012	3.8	3.9	3.98×10^{-02}	1.92×10^{-02}	2.40×10^{-05}	4.38×10^{-04}
26 April 1998	17:31:02.3	34.9585N	139.1868E	3.851	258.491	4.1	3.9	7.47×10^{-02}	2.92×10^{-02}	4.12×10^{-05}	8.91×10^{-04}
30 April 1998	05:13:23.3	34.9527N	139.1732E	2.535	267.159	6.6	3.9	3.10×10^{-02}	1.32×10^{-02}	1.98×10^{-05}	3.25×10^{-04}
21 April 1998	20:10:01.8	34.9544N	139.1839E	3.523	264.890	4.8	3.8	5.59×10^{-02}	1.85×10^{-02}	2.67×10^{-05}	7.70×10^{-04}
21 April 1998	23:39:27.3	34.9572N	139.1929E	4.376	261.805	4.0	3.8	3.28×10^{-02}	1.29×10^{-02}	1.84×10^{-05}	4.82×10^{-04}
22 April 1998	03:27:39.1	34.9540N	139.1939E	4.429	266.521	5.0	3.8	4.08×10^{-02}	1.20×10^{-02}	1.96×10^{-05}	5.46×10^{-04}
22 April 1998	10:21:01.0	34.9536N	139.1826E	3.398	266.199	6.5	3.8	1.63×10^{-02}	6.73×10^{-03}	8.54×10^{-06}	1.45×10^{-04}
26 April 1998	18:22:58.1	34.9581N	139.1838E	3.574	258.314	4.8	3.8	5.03×10^{-02}	1.30×10^{-02}	1.54×10^{-05}	4.55×10^{-04}
26 April 1998	18:37:56.7	34.9575N	139.1880E	3.938	260.394	4.1	3.8	4.62×10^{-02}	1.70×10^{-02}	2.36×10^{-05}	4.70×10^{-04}
26 April 1998	19:46:08.5	34.9588N	139.1829E	3.511	256.795	4.8	3.8	1.89×10^{-02}	7.10×10^{-03}	9.83×10^{-06}	2.23×10^{-04}
28 April 1998	11:09:13.5	34.9217N	139.2117E	6.897	298.726	5.9	3.8	2.14×10^{-02}	7.02×10^{-03}	1.09×10^{-05}	3.28×10^{-04}
21 April 1998	21:31:15.5	34.9582N	139.1897E	4.104	259.684	4.0	3.7	1.73×10^{-02}	6.29×10^{-03}	9.72×10^{-06}	2.30×10^{-04}
22 April 1998	01:34:17.0	34.9585N	139.1983E	4.885	260.956	3.7	3.7	3.70×10^{-02}	1.15×10^{-02}	1.62×10^{-05}	3.36×10^{-04}
22 April 1998	11:38:21.9	34.9531N	139.1929E	4.334	267.766	6.3	3.7	1.84×10^{-02}	4.82×10^{-03}	7.99×10^{-06}	2.39×10^{-04}
24 April 1998	08:48:36.8	34.9522N	139.1947E	4.496	269.113	7.1	3.7	1.22×10^{-02}	4.39×10^{-03}	6.80×10^{-06}	2.02×10^{-04}
25 April 1998	01:51:53.0	34.9514N	139.1911E	4.167	270.268	4.5	3.7	2.37×10^{-02}	9.11×10^{-03}	1.36×10^{-05}	3.03×10^{-04}
26 April 1998	22:07:16.8	34.9456N	139.1936E	4.445	278.586	6.1	3.7	1.33×10^{-02}	5.73×10^{-03}	8.94×10^{-06}	1.65×10^{-04}
21 April 1998	23:45:54.9	34.9552N	139.1899E	4.077	264.338	3.7	3.6	4.34×10^{-02}	1.34×10^{-02}	2.02×10^{-05}	5.36×10^{-04}
22 April 1998	12:35:09.7	34.9484N	139.1943E	4.474	274.520	7.2	3.6	1.54×10^{-02}	4.93×10^{-03}	7.04×10^{-06}	2.24×10^{-04}
22 April 1998	16:06:50.4	34.9540N	139.1776E	2.945	264.752	6.7	3.6	1.42×10^{-02}	5.13×10^{-03}	6.61×10^{-06}	1.68×10^{-04}
26 April 1998	08:57:13.0	34.9576N	139.1841E	3.589	259.265	4.8	3.6	3.10×10^{-02}	9.39×10^{-03}	1.41×10^{-05}	4.02×10^{-04}
26 April 1998	18:18:30.8	34.9128N	139.1904E	5.944	316.356	5.5	3.6	4.83×10^{-02}	9.24×10^{-03}	1.29×10^{-05}	3.58×10^{-04}
26 April 1998	21:18:42.5	34.9581N	139.1864E	3.807	259.037	4.3	3.6	3.58×10^{-02}	8.73×10^{-03}	1.29×10^{-05}	3.99×10^{-04}
29 April 1998	16:43:25.6	35.0004N	139.2380E	10.036	237.361	3.9	3.6	5.13×10^{-03}	2.20×10^{-03}	2.37×10^{-06}	4.86×10^{-05}
30 April 1998	07:04:15.7	34.9521N	139.1741E	2.615	268.708	7.0	3.6	1.90×10^{-02}	3.78×10^{-03}	5.67×10^{-06}	1.55×10^{-04}

(*continued*)

Table 1 (*Continued*)

Date	Time	Latitude	Longitude	Distance (km)	Azimuth	Depth (km)	M	Accelerations (10 m/sec^2)	Velocities (m/sec)	Rotational (rad)	Rotational Rate (rad/sec)
21 April 1998	21:38:58.7	34.9568N	139.1913E	4.225	262.112	4.0	3.5	2.66×10^{-02}	9.36×10^{-03}	1.17×10^{-05}	3.20×10^{-04}
22 April 1998	05:48:42.6	34.9567N	139.1833E	3.500	260.648	5.0	3.5	2.65×10^{-02}	7.34×10^{-03}	9.33×10^{-06}	2.84×10^{-04}
22 April 1998	08:17:57.4	34.9617N	139.1889E	4.122	254.184	4.6	3.5	2.69×10^{-02}	6.55×10^{-03}	9.31×10^{-06}	3.06×10^{-04}
26 April 1998	19:28:15.2	34.9577N	139.1877E	3.915	260.010	4.0	3.5	2.72×10^{-02}	1.28×10^{-02}	1.92×10^{-05}	3.42×10^{-04}
27 April 1998	08:29:59.3	34.9555N	139.1934E	4.399	264.313	4.0	3.5	1.66×10^{-02}	8.44×10^{-03}	1.16×10^{-05}	2.14×10^{-04}
27 April 1998	08:33:14.2	34.9564N	139.1924E	4.318	262.872	4.0	3.5	3.09×10^{-02}	1.02×10^{-02}	1.37×10^{-05}	4.01×10^{-04}
22 April 1998	08:25:39.3	34.9612N	139.1901E	4.212	255.313	4.5	3.4	1.84×10^{-02}	7.67×10^{-03}	1.15×10^{-05}	2.02×10^{-04}
25 April 1998	01:53:35.7	34.9532N	139.1933E	4.371	267.637	4.0	3.4	1.77×10^{-02}	4.94×10^{-03}	7.86×10^{-06}	2.24×10^{-04}
25 April 1998	02:08:07.9	34.9469N	139.1907E	4.163	277.153	5.9	3.4	7.57×10^{-03}	1.86×10^{-03}	3.17×10^{-06}	8.91×10^{-05}
26 April 1998	08:23:13.8	34.9580N	139.1844E	3.626	258.655	5.0	3.4	1.96×10^{-02}	5.20×10^{-03}	7.17×10^{-06}	1.97×10^{-04}
26 April 1998	18:23:34.0	34.9606N	139.1804E	3.343	252.564	5.4	3.4	1.97×10^{-02}	5.71×10^{-03}	6.95×10^{-06}	1.98×10^{-04}
29 April 1998	02:51:22.9	34.9602N	139.1739E	2.766	249.741	3.8	3.4	3.47×10^{-02}	8.69×10^{-03}	1.29×10^{-05}	2.72×10^{-04}
25 April 1998	08:36:00.2	34.9565N	139.1713E	2.420	256.931	5.5	3.3	1.24×10^{-02}	2.49×10^{-03}	3.42×10^{-06}	9.57×10^{-05}
26 April 1998	08:56:29.1	34.9556N	139.1956E	4.600	264.431	3.0	3.3	2.23×10^{-02}	6.87×10^{-03}	1.11×10^{-05}	2.67×10^{-04}
26 April 1998	17:46:57.2	34.9578N	139.1844E	3.622	258.995	4.4	3.3	1.52×10^{-02}	6.52×10^{-03}	9.04×10^{-06}	1.46×10^{-04}
26 April 1998	18:26:08.9	34.8900N	139.1839E	7.679	332.809	3.9	3.3	7.70×10^{-03}	2.86×10^{-03}	3.58×10^{-06}	9.80×10^{-05}
26 April 1998	18:56:08.3	34.9591N	139.1835E	3.572	256.477	4.8	3.3	1.29×10^{-02}	2.97×10^{-03}	4.09×10^{-06}	1.28×10^{-04}
27 April 1998	09:20:01.3	34.9568N	139.1934E	4.415	262.456	3.9	3.3	1.42×10^{-02}	5.42×10^{-03}	7.08×10^{-06}	1.78×10^{-04}
29 April 1998	01:24:27.7	34.9477N	139.1904E	4.125	275.980	4.2	3.3	1.70×10^{-02}	3.52×10^{-03}	5.12×10^{-06}	1.48×10^{-04}
29 April 1998	03:34:54.7	34.9576N	139.1770E	2.955	256.922	4.9	3.3	1.36×10^{-02}	6.20×10^{-03}	7.52×10^{-06}	1.24×10^{-04}
21 April 1998	21:29:41.2	34.9590N	139.1831E	3.534	256.519	4.0	3.2	1.55×10^{-02}	6.22×10^{-03}	8.84×10^{-06}	2.20×10^{-04}
21 April 1998	22:28:31.2	34.9605N	139.1948E	4.611	257.604	3.9	3.2	1.09×10^{-02}	4.08×10^{-03}	5.06×10^{-06}	1.16×10^{-04}
26 April 1998	09:16:08.0	34.9585N	139.1816E	3.386	256.883	5.0	3.2	1.54×10^{-02}	3.22×10^{-03}	4.31×10^{-06}	1.33×10^{-04}
26 April 1998	22:14:00.1	34.9496N	139.1920E	4.255	272.955	4.7	3.2	8.35×10^{-03}	1.74×10^{-03}	2.45×10^{-06}	7.60×10^{-05}
27 April 1998	06:07:18.5	34.9534N	139.1931E	4.353	267.330	4.0	3.2	1.13×10^{-02}	3.44×10^{-03}	5.19×10^{-06}	1.44×10^{-04}
29 April 1998	08:07:11.0	34.9174N	139.2088E	6.916	303.250	4.9	3.2	5.85×10^{-03}	1.36×10^{-03}	2.35×10^{-06}	8.06×10^{-05}
21 April 1998	21:24:04.5	34.9539N	139.1840E	3.528	265.799	5.5	3.1	9.30×10^{-03}	2.29×10^{-03}	3.11×10^{-06}	9.65×10^{-05}
21 April 1998	22:41:08.6	34.9534N	139.1870E	3.797	266.934	5.5	3.1	1.09×10^{-02}	3.16×10^{-03}	4.66×10^{-06}	1.53×10^{-04}
21 April 1998	20:44:00.8	34.9574N	139.1866E	3.810	260.230	3.9	3.0	9.06×10^{-03}	3.37×10^{-03}	4.75×10^{-06}	1.20×10^{-04}
21 April 1998	21:33:31.6	34.9560N	139.1877E	3.887	262.746	4.0	3.0	9.75×10^{-03}	3.30×10^{-03}	4.25×10^{-06}	1.36×10^{-04}
22 April 1998	05:12:23.0	34.9509N	139.1933E	4.368	270.982	4.0	3.0	1.78×10^{-02}	4.03×10^{-03}	5.67×10^{-06}	1.82×10^{-04}
25 April 1998	08:07:07.8	34.9547N	139.1713E	2.382	261.618	6.4	3.0	5.96×10^{-03}	1.84×10^{-03}	2.80×10^{-06}	4.93×10^{-05}
25 April 1998	19:17:07.3	34.9552N	139.2037E	5.333	265.683	4.0	3.0	8.26×10^{-03}	3.98×10^{-03}	4.38×10^{-06}	9.47×10^{-05}
26 April 1998	07:37:00.7	34.9659N	139.1824E	3.727	244.758	5.5	3.0	8.18×10^{-03}	2.34×10^{-03}	2.98×10^{-06}	8.92×10^{-05}
26 April 1998	07:47:21.4	34.9585N	139.1842E	3.619	257.741	5.5	3.0	1.07×10^{-02}	2.12×10^{-03}	2.83×10^{-06}	8.96×10^{-05}
26 April 1998	17:04:19.4	34.9596N	139.1861E	3.815	256.505	4.5	3.0	2.96×10^{-02}	6.20×10^{-03}	9.73×10^{-06}	2.69×10^{-04}
26 April 1998	18:00:43.2	34.9562N	139.1877E	3.890	262.425	4.3	3.0	1.05×10^{-02}	2.50×10^{-03}	3.69×10^{-06}	8.02×10^{-05}
26 April 1998	18:45:42.1	34.9589N	139.1810E	3.344	255.938	4.4	3.0	1.30×10^{-02}	3.82×10^{-03}	5.10×10^{-06}	1.62×10^{-04}
27 April 1998	05:54:12.1	34.9509N	139.1938E	4.414	270.972	4.0	3.0	1.22×10^{-02}	2.56×10^{-03}	3.04×10^{-06}	9.87×10^{-05}
27 April 1998	05:54:58.9	34.9519N	139.1951E	4.532	269.543	5.0	3.0	9.78×10^{-03}	2.24×10^{-03}	3.41×10^{-06}	1.09×10^{-04}
29 April 1998	04:44:34.2	34.9575N	139.2309E	7.829	265.203	3.6	3.0	5.07×10^{-03}	2.37×10^{-03}	2.82×10^{-06}	5.76×10^{-05}
21 April 1998	21:20:46.8	34.9605N	139.1867E	3.893	255.265	4.7	2.9	7.64×10^{-03}	1.79×10^{-03}	2.84×10^{-06}	7.89×10^{-05}
21 April 1998	22:19:03.0	34.9542N	139.1921E	4.267	266.085	5.0	2.9	1.45×10^{-02}	2.74×10^{-03}	3.73×10^{-06}	1.29×10^{-04}
25 April 1998	08:00:32.6	34.9542N	139.1728E	2.513	263.324	6.4	2.9	6.65×10^{-03}	1.29×10^{-03}	1.85×10^{-06}	5.22×10^{-05}
25 April 1998	08:11:28.9	34.9565N	139.1746E	2.716	258.380	5.9	2.9	8.17×10^{-03}	1.07×10^{-03}	2.02×10^{-06}	6.21×10^{-05}

(*continued*)

Table 1 (*Continued*)

Date	Time	Latitude	Longitude	Distance (km)	Azimuth	Depth (km)	M	Accelerations (10 m/sec^2)	Velocities (m/sec)	Rotational (rad)	Rotational Rate (rad/sec)
26 April 1998	08:29:24.0	34.9587N	139.1792E	3.179	255.600	5.2	2.9	1.06×10^{-02}	1.80×10^{-03}	2.37×10^{-06}	6.93×10^{-05}
26 April 1998	13:10:11.6	34.9551N	139.1900E	4.085	264.503	3.9	2.9	1.91×10^{-02}	5.60×10^{-03}	8.01×10^{-06}	1.97×10^{-04}
26 April 1998	17:48:45.8	34.9584N	139.1814E	3.367	256.991	4.3	2.9	9.70×10^{-03}	2.05×10^{-03}	2.41×10^{-06}	8.02×10^{-05}
27 April 1998	05:55:19.6	34.9518N	139.1921E	4.258	269.655	4.1	2.9	7.66×10^{-03}	1.72×10^{-03}	2.22×10^{-06}	6.09×10^{-05}
27 April 1998	06:29:41.0	34.9472N	139.1865E	3.777	277.376	3.2	2.9	1.25×10^{-02}	5.00×10^{-03}	4.67×10^{-06}	1.29×10^{-04}
21 April 1998	20:36:35.0	34.9566N	139.1895E	4.059	262.100	4.5	2.8	7.19×10^{-03}	1.69×10^{-03}	2.64×10^{-06}	7.83×10^{-05}
21 April 1998	20:57:32.7	34.9570N	139.1881E	3.938	261.209	4.1	2.8	6.54×10^{-03}	1.81×10^{-03}	2.84×10^{-06}	7.59×10^{-05}
26 April 1998	08:27:34.3	34.9590N	139.1923E	4.355	259.099	4.5	2.8	7.24×10^{-03}	1.52×10^{-03}	2.24×10^{-06}	6.33×10^{-05}
26 April 1998	15:16:19.0	34.9731N	139.2067E	6.080	246.882	3.9	2.8	7.29×10^{-03}	1.71×10^{-03}	2.41×10^{-06}	7.43×10^{-05}
26 April 1998	17:10:53.8	34.9728N	139.1983E	5.368	243.985	3.6	2.8	7.35×10^{-03}	1.24×10^{-03}	1.23×10^{-06}	4.93×10^{-05}
26 April 1998	17:28:15.0	34.9589N	139.1835E	3.566	256.830	4.9	2.8	9.11×10^{-03}	1.72×10^{-03}	2.38×10^{-06}	5.36×10^{-05}
26 April 1998	17:43:09.2	34.9591N	139.1834E	3.562	256.440	4.4	2.8	8.72×10^{-03}	2.54×10^{-03}	3.35×10^{-03}	8.28×10^{-03}
26 April 1998	17:56:44.0	34.9571N	139.1832E	3.498	259.901	4.3	2.8	8.76×10^{-03}	2.66×10^{-03}	3.63×10^{-06}	1.06×10^{-04}
27 April 1998	05:33:20.1	34.9545N	139.1937E	4.415	265.792	4.5	2.8	6.63×10^{-03}	1.64×10^{-03}	2.42×10^{-06}	7.60×10^{-05}
27 April 1998	06:22:13.2	34.9542N	139.1947E	4.505	266.293	4.0	2.8	6.53×10^{-03}	1.90×10^{-03}	2.57×10^{-06}	5.69×10^{-05}
21 April 1998	19:48:12.9	34.9587N	139.1891E	4.062	258.780	5.0	2.7	5.26×10^{-03}	1.30×10^{-03}	1.82×10^{-06}	5.64×10^{-05}
21 April 1998	20:19:36.9	34.9564N	139.1900E	4.102	262.492	5.6	2.7	4.34×10^{-03}	1.11×10^{-03}	1.67×10^{-06}	4.78×10^{-05}
21 April 1998	20:29:04.9	34.9578N	139.1912E	4.232	260.602	5.4	2.7	4.34×10^{-03}	1.40×10^{-03}	2.09×10^{-06}	5.43×10^{-05}
21 April 1998	21:37:58.4	34.9612N	139.1958E	4.718	256.920	5.2	2.7	4.41×10^{-03}	1.43×10^{-03}	2.03×10^{-06}	5.58×10^{-05}
26 April 1998	07:48:08.3	34.9550N	139.1784E	3.031	262.786	6.1	2.7	4.15×10^{-03}	7.79×10^{-04}	1.40×10^{-06}	3.40×10^{-05}
26 April 1998	07:56:18.9	34.9575N	139.1807E	3.282	258.446	5.2	2.7	4.92×10^{-03}	1.20×10^{-03}	1.43×10^{-06}	3.83×10^{-05}
26 April 1998	07:57:40.8	34.9579N	139.1754E	2.821	255.588	6.0	2.7	5.67×10^{-03}	9.29×10^{-04}	1.55×10^{-06}	4.31×10^{-05}
26 April 1998	08:07:15.9	34.9563N	139.1724E	2.514	257.957	6.2	2.7	3.56×10^{-03}	7.20×10^{-04}	1.17×10^{-06}	3.12×10^{-05}
26 April 1998	15:26:55.1	34.9710N	139.1835E	4.087	238.173	4.0	2.7	1.06×10^{-02}	2.49×10^{-03}	2.71×10^{-06}	1.06×10^{-04}
26 April 1998	17:10:32.8	34.9584N	139.1857E	3.751	258.345	4.3	2.7	5.08×10^{-03}	1.43×10^{-03}	1.77×10^{-06}	4.52×10^{-05}
26 April 1998	17:40:48.4	34.9578N	139.1838E	3.568	258.827	5.0	2.7	7.76×10^{-03}	1.47×10^{-03}	2.07×10^{-06}	6.83×10^{-05}
26 April 1998	19:13:50.5	34.9578N	139.1806E	3.281	257.834	4.8	2.7	7.82×10^{-03}	1.03×10^{-03}	1.17×10^{-06}	3.08×10^{-05}
27 April 1998	06:18:46.9	34.9539N	139.1931E	4.356	266.604	4.4	2.7	5.71×10^{-03}	1.31×10^{-03}	2.19×10^{-06}	6.40×10^{-05}
21 April 1998	21:06:52.9	34.9580N	139.1862E	3.786	259.144	4.0	2.6	5.46×10^{-03}	1.75×10^{-03}	2.17×10^{-06}	6.45×10^{-05}
21 April 1998	21:07:08.0	34.9558N	139.1902E	4.111	263.454	4.4	2.6	4.46×10^{-03}	1.72×10^{-03}	2.26×10^{-06}	4.49×10^{-05}
21 April 1998	21:16:39.8	34.9581N	139.1842E	3.610	258.430	5.5	2.6	3.64×10^{-03}	8.71×10^{-04}	1.25×10^{-06}	3.89×10^{-05}
21 April 1998	21:25:25.6	34.9594N	139.1908E	4.229	258.154	4.7	2.6	1.30×10^{-02}	4.64×10^{-03}	6.07×10^{-06}	1.70×10^{-04}
26 April 1998	17:40:23.8	34.9562N	139.1837E	3.528	261.640	4.6	2.6	5.96×10^{-03}	1.60×10^{-03}	2.19×10^{-06}	5.23×10^{-05}
21 April 1998	20:34:50.7	34.9565N	139.1905E	4.148	262.427	5.0	2.5	3.07×10^{-03}	6.69×10^{-04}	8.38×10^{-07}	2.61×10^{-05}
21 April 1998	20:58:58.8	34.9542N	139.1880E	3.894	265.706	5.7	2.5	3.05×10^{-03}	6.48×10^{-04}	7.92×10^{-07}	2.86×10^{-05}
21 April 1998	21:12:42.7	34.9558N	139.1855E	3.685	262.689	4.8	2.5	2.98×10^{-03}	6.75×10^{-04}	8.89×10^{-07}	2.81×10^{-05}
21 April 1998	21:17:02.2	34.9539N	139.1931E	4.356	266.604	3.6	2.5	3.31×10^{-03}	8.85×10^{-04}	1.27×10^{-06}	3.27×10^{-05}
21 April 1998	21:53:15.4	34.9583N	139.1879E	3.944	259.092	4.0	2.5	3.02×10^{-03}	1.06×10^{-03}	1.45×10^{-06}	3.56×10^{-05}
26 April 1998	08:03:04.7	34.9568N	139.1788E	3.098	259.205	5.1	2.5	3.25×10^{-03}	6.32×10^{-04}	6.67×10^{-07}	2.34×10^{-05}
26 April 1998	08:18:26.7	34.9583N	139.1790E	3.151	256.292	5.1	2.5	4.80×10^{-03}	8.78×10^{-04}	9.39×10^{-07}	2.45×10^{-05}
26 April 1998	09:54:45.6	34.9737N	139.1958E	5.210	241.895	3.4	2.5	2.45×10^{-03}	5.83×10^{-04}	8.99×10^{-07}	3.50×10^{-05}
26 April 1998	15:26:19.2	34.9707N	139.1764E	3.532	233.072	3.8	2.5	7.40×10^{-03}	1.56×10^{-03}	1.34×10^{-06}	4.54×10^{-05}
26 April 1998	16:34:14.8	34.9698N	139.1953E	4.978	246.041	3.5	2.5	1.11×10^{-02}	2.25×10^{-03}	2.16×10^{-06}	7.82×10^{-05}
26 April 1998	17:20:34.1	34.9593N	139.1868E	3.870	257.196	4.0	2.5	4.62×10^{-03}	1.03×10^{-03}	1.58×10^{-06}	4.66×10^{-05}
26 April 1998	17:40:06.1	34.9590N	139.1835E	3.569	256.652	5.0	2.5	7.12×10^{-03}	9.21×10^{-04}	1.46×10^{-06}	4.39×10^{-05}

(*continued*)

Table 1 (*Continued*)

Date	Time	Latitude	Longitude	Distance (km)	Azimuth	Depth (km)	M	Accelerations (10 m/sec^2)	Velocities (m/sec)	Rotational (rad)	Rotational Rate (rad/sec)
26 April 1998	17:46:02.0	34.9581N	139.1861E	3.780	258.959	4.8	2.5	5.63×10^{-03}	1.00×10^{-03}	1.31×10^{-06}	4.83×10^{-05}
26 April 1998	19:08:22.7	34.8843N	139.1812E	8.144	336.389	3.7	2.5	1.75×10^{-03}	4.46×10^{-04}	6.24×10^{-07}	1.94×10^{-05}
26 April 1998	19:08:45.8	34.9570N	139.1875E	3.884	261.084	4.3	2.5	4.55×10^{-03}	1.41×10^{-03}	1.92×10^{-06}	4.76×10^{-05}
27 April 1998	06:19:19.6	34.9571N	139.1929E	4.374	261.943	3.3	2.5	1.08×10^{-02}	1.91×10^{-03}	2.27×10^{-06}	5.81×10^{-05}
27 April 1998	06:26:22.5	34.9553N	139.1922E	4.286	264.467	4.0	2.5	3.67×10^{-03}	9.21×10^{-04}	1.20×10^{-06}	2.61×10^{-05}
27 April 1998	08:26:42.8	34.9561N	139.1949E	4.541	263.656	4.0	2.5	2.94×10^{-03}	7.90×10^{-04}	1.33×10^{-06}	4.47×10^{-05}
21 April 1998	20:34:08.6	34.9555N	139.1891E	4.008	263.754	4.7	2.4	2.96×10^{-03}	1.06×10^{-03}	1.18×10^{-06}	3.89×10^{-05}
21 April 1998	21:17:47.1	34.9560N	139.1904E	4.132	263.180	4.2	2.4	3.00×10^{-03}	9.43×10^{-04}	1.29×10^{-06}	3.95×10^{-05}
21 April 1998	21:44:33.9	34.9587N	139.1890E	4.052	258.751	3.8	2.4	3.33×10^{-03}	9.54×10^{-04}	1.08×10^{-06}	3.00×10^{-05}
26 April 1998	08:08:02.3	34.9529N	139.1990E	4.891	268.282	3.0	2.4	5.36×10^{-03}	1.67×10^{-03}	2.20×10^{-06}	5.81×10^{-05}
26 April 1998	08:41:41.9	34.9567N	139.1742E	2.683	257.752	6.0	2.4	3.76×10^{-03}	5.89×10^{-04}	7.91×10^{-07}	1.71×10^{-05}
26 April 1998	10:33:24.5	34.9547N	139.1919E	4.253	265.325	4.0	2.4	2.46×10^{-03}	5.81×10^{-04}	9.50×10^{-07}	2.66×10^{-05}
27 April 1998	06:00:47.5	34.9546N	139.1942E	4.462	265.690	4.5	2.4	3.69×10^{-03}	9.34×10^{-04}	1.32×10^{-06}	4.41×10^{-05}
27 April 1998	06:26:43.0	34.9544N	139.1942E	4.461	265.972	4.0	2.4	3.65×10^{-03}	6.04×10^{-04}	1.08×10^{-06}	3.38×10^{-05}
21 April 1998	20:01:20.7	34.9574N	139.1909E	4.198	261.142	5.6	2.3	2.46×10^{-03}	4.40×10^{-04}	6.59×10^{-07}	1.98×10^{-05}
21 April 1998	20:33:19.3	34.9576N	139.1810E	3.312	258.353	6.3	2.3	1.52×10^{-03}	3.82×10^{-04}	5.91×10^{-07}	1.81×10^{-05}
21 April 1998	21:13:18.1	34.9576N	139.1889E	4.021	260.432	4.3	2.3	3.13×10^{-03}	4.92×10^{-04}	7.57×10^{-07}	2.42×10^{-05}
21 April 1998	21:23:43.8	34.9541N	139.1904E	4.112	266.092	4.4	2.3	3.13×10^{-03}	6.18×10^{-04}	8.78×10^{-07}	2.70×10^{-05}
21 April 1998	21:34:06.4	34.9558N	139.1903E	4.121	263.469	4.4	2.3	2.20×10^{-03}	5.90×10^{-04}	8.82×10^{-07}	2.34×10^{-05}
21 April 1998	21:52:46.0	34.9538N	139.1888E	3.963	266.418	4.5	2.3	2.65×10^{-03}	7.37×10^{-04}	9.56×10^{-07}	2.97×10^{-05}
21 April 1998	21:53:44.6	34.9560N	139.1901E	4.104	263.133	4.3	2.3	2.54×10^{-03}	7.22×10^{-04}	9.64×10^{-07}	3.32×10^{-05}
26 April 1998	08:13:16.0	34.9583N	139.1843E	3.623	258.108	4.8	2.3	3.19×10^{-03}	5.61×10^{-04}	7.18×10^{-07}	2.33×10^{-05}
26 April 1998	08:28:19.4	34.9566N	139.1757E	2.816	258.565	6.0	2.3	2.41×10^{-03}	3.78×10^{-04}	7.12×10^{-07}	2.02×10^{-05}
26 April 1998	09:02:59.4	34.9583N	139.1833E	3.534	257.803	4.8	2.3	2.22×10^{-03}	3.73×10^{-04}	5.11×10^{-07}	1.68×10^{-05}
26 April 1998	09:45:37.9	34.9474N	139.1903E	4.120	276.451	2.9	2.3	6.16×10^{-03}	1.52×10^{-03}	2.02×10^{-06}	6.54×10^{-05}
26 April 1998	17:44:12.2	34.9602N	139.1874E	3.946	255.958	3.6	2.3	3.35×10^{-03}	1.06×10^{-03}	1.57×10^{-06}	3.16×10^{-05}
27 April 1998	05:39:46.1	34.9554N	139.1976E	4.779	264.913	4.0	2.3	3.05×10^{-03}	7.78×10^{-04}	9.11×10^{-07}	2.20×10^{-05}
27 April 1998	06:06:08.1	34.9487N	139.1877E	3.869	274.729	5.4	2.3	2.60×10^{-03}	4.91×10^{-04}	5.65×10^{-07}	1.64×10^{-05}
21 April 1998	20:00:35.1	34.9574N	139.1894E	4.063	260.846	5.8	2.2	1.81×10^{-03}	3.66×10^{-04}	4.60×10^{-07}	1.68×10^{-05}
21 April 1998	20:01:44.8	34.9588N	139.1883E	3.991	258.411	5.0	2.2	2.00×10^{-03}	4.55×10^{-04}	6.20×10^{-07}	1.98×10^{-05}
21 April 1998	21:16:22.3	34.9625N	139.1939E	4.584	254.666	4.6	2.2	2.27×10^{-03}	4.79×10^{-04}	8.09×10^{-07}	2.14×10^{-05}
21 April 1998	21:54:40.9	34.9552N	139.1940E	4.449	264.817	4.7	2.2	1.87×10^{-03}	4.86×10^{-04}	7.60×10^{-07}	2.37×10^{-05}
26 April 1998	17:20:16.4	34.9579N	139.1835E	3.543	258.571	4.4	2.2	3.47×10^{-03}	7.65×10^{-04}	9.88×10^{-07}	3.32×10^{-05}
26 April 1998	17:27:38.5	34.9583N	139.1842E	3.614	258.080	4.3	2.2	2.71×10^{-03}	5.68×10^{-04}	9.65×10^{-07}	2.50×10^{-05}
26 April 1998	19:07:47.6	34.9589N	139.1828E	3.503	256.589	4.7	2.2	3.71×10^{-03}	4.52×10^{-04}	7.17×10^{-07}	2.13×10^{-05}
26 April 1998	21:44:29.9	34.8876N	139.1772E	7.665	337.799	3.8	2.2	1.13×10^{-03}	2.04×10^{-04}	3.00×10^{-07}	1.04×10^{-05}
21 April 1998	19:53:28.9	34.9590N	139.1882E	3.988	258.080	5.1	2.1	1.84×10^{-03}	4.21×10^{-04}	6.17×10^{-07}	1.72×10^{-05}
21 April 1998	20:18:34.8	34.9594N	139.1848E	3.695	256.406	5.1	2.1	1.63×10^{-03}	4.35×10^{-04}	5.53×10^{-07}	1.64×10^{-05}
21 April 1998	20:27:56.3	34.9636N	139.1904E	4.314	251.993	6.1	2.1	1.16×10^{-03}	3.27×10^{-04}	4.56×10^{-07}	1.39×10^{-05}
21 April 1998	20:36:21.2	34.9578N	139.1826E	3.460	258.475	5.2	2.1	2.17×10^{-03}	3.77×10^{-04}	5.28×10^{-07}	1.92×10^{-05}
26 April 1998	09:05:10.8	34.9579N	139.1797E	3.204	257.341	4.9	2.1	1.35×10^{-03}	2.79×10^{-04}	4.23×10^{-07}	1.05×10^{-05}
26 April 1998	13:39:07.6	34.9366N	139.2030E	5.510	287.555	3.7	2.1	1.10×10^{-03}	2.93×10^{-04}	3.92×10^{-07}	1.09×10^{-05}
26 April 1998	15:25:45.3	34.9705N	139.1760E	3.489	233.002	3.8	2.1	3.26×10^{-03}	9.62×10^{-04}	9.77×10^{-07}	2.48×10^{-05}
26 April 1998	16:33:58.0	34.9733N	139.1932E	4.981	241.056	2.9	2.1	4.42×10^{-03}	1.01×10^{-03}	9.02×10^{-07}	3.24×10^{-05}
27 April 1998	06:00:25.0	34.9550N	139.1932E	4.375	265.017	4.3	2.1	1.53×10^{-03}	3.70×10^{-04}	5.26×10^{-07}	1.67×10^{-05}

(*continued*)

Table 1 (*Continued*)

Date	Time	Latitude	Longitude	Distance (km)	Azimuth	Depth (km)	M	Accelerations (10 m/sec^2)	Velocities (m/sec)	Rotational (rad)	Rotational Rate (rad/sec)
27 April 1998	06:05:49.0	34.9476N	139.1935E	4.407	275.744	5.4	2.1	1.24×10^{-03}	3.01×10^{-04}	4.44×10^{-07}	1.36×10^{-05}
21 April 1998	20:43:16.2	34.9563N	139.1896E	4.064	262.594	4.4	2.0	1.28×10^{-03}	3.57×10^{-04}	4.82×10^{-07}	1.29×10^{-05}
21 April 1998	20:59:27.8	34.9524N	139.1870E	3.793	268.612	6.9	2.0	6.31×10^{-04}	1.34×10^{-04}	1.88×10^{-07}	5.70×10^{-06}
21 April 1998	21:18:30.7	34.9531N	139.1865E	3.750	267.413	5.6	2.0	1.33×10^{-03}	2.39×10^{-04}	3.45×10^{-07}	1.29×10^{-05}
26 April 1998	08:04:14.8	34.9569N	139.1704E	2.351	255.432	5.6	2.0	1.62×10^{-03}	2.45×10^{-04}	2.57×10^{-07}	1.07×10^{-05}
26 April 1998	08:26:56.4	34.9570N	139.1739E	2.664	256.931	5.8	2.0	1.99×10^{-03}	1.82×10^{-04}	2.45×10^{-07}	1.02×10^{-05}
26 April 1998	08:27:20.2	34.9550N	139.1744E	2.668	261.794	5.9	2.0	1.05×10^{-03}	1.00×10^{-04}	1.36×10^{-07}	5.01×10^{-06}
26 April 1998	08:38:47.9	34.9566N	139.1838E	3.544	260.941	5.0	2.0	1.67×10^{-03}	3.60×10^{-04}	4.40×10^{-07}	1.46×10^{-05}
26 April 1998	09:45:17.2	34.9501N	139.1916E	4.216	272.222	3.0	2.0	4.89×10^{-03}	8.57×10^{-04}	1.31×10^{-06}	3.99×10^{-05}
26 April 1998	19:26:26.8	34.9590N	139.1832E	3.541	256.547	4.7	2.0	1.94×10^{-03}	2.71×10^{-04}	3.52×10^{-07}	1.34×10^{-05}
21 April 1998	20:09:19.1	34.9566N	139.1871E	3.842	261.649	4.7	1.9	1.23×10^{-03}	3.61×10^{-04}	4.69×10^{-07}	1.52×10^{-05}
26 April 1998	07:55:55.8	34.9574N	139.1760E	2.861	256.930	5.6	1.9	1.64×10^{-03}	1.52×10^{-04}	2.32×10^{-07}	6.82×10^{-06}
26 April 1998	08:03:57.4	34.9584N	139.1722E	2.554	252.735	6.3	1.9	1.40×10^{-03}	1.61×10^{-04}	3.06×10^{-07}	9.27×10^{-06}
26 April 1998	08:14:07.6	34.9632N	139.1545E	1.530	212.506	1.8	1.9	3.90×10^{-03}	8.64×10^{-04}	9.54×10^{-07}	2.75×10^{-05}
26 April 1998	08:41:09.5	34.9587N	139.1811E	3.348	256.340	5.0	1.9	1.56×10^{-03}	2.31×10^{-04}	3.21×10^{-07}	1.04×10^{-05}
26 April 1998	11:06:59.2	34.9716N	139.1881E	4.481	240.282	3.6	1.9	3.18×10^{-03}	5.62×10^{-04}	5.41×10^{-07}	2.09×10^{-05}
26 April 1998	21:44:52.9	34.9747N	139.1991E	5.528	242.355	3.3	1.9	2.77×10^{-03}	5.30×10^{-04}	4.64×10^{-07}	1.62×10^{-05}
27 April 1998	06:21:47.1	34.9522N	139.1940E	4.432	269.100	4.5	1.9	1.34×10^{-03}	2.65×10^{-04}	3.36×10^{-037}	1.22×10^{-05}
21 April 1998	20:08:07.8	34.9554N	139.1877E	3.879	263.721	4.7	1.8	8.24×10^{-04}	2.30×10^{-04}	3.66×10^{-07}	1.19×10^{-05}
21 April 1998	20:52:30.6	34.9592N	139.1896E	4.118	258.143	4.6	1.8	1.11×10^{-03}	2.10×10^{-04}	3.63×10^{-07}	1.00×10^{-05}
26 April 1998	12:59:20.6	34.9532N	139.2182E	6.645	268.458	6.5	1.8	4.59×10^{-04}	1.33×10^{-04}	1.90×10^{-07}	6.18×10^{-06}
26 April 1998	15:41:53.0	34.9741N	139.1983E	5.432	242.622	3.4	1.8	1.89×10^{-03}	3.87×10^{-04}	3.54×10^{-07}	1.14×10^{-05}
21 April 1998	20:08:54.5	34.9558N	139.1875E	3.865	263.034	4.7	1.7	1.01×10^{-03}	1.83×10^{-04}	2.93×10^{-07}	8.99×10^{-06}
21 April 1998	20:19:11.4	34.9543N	139.1856E	3.676	265.282	3.6	1.7	8.23×10^{-04}	1.33×10^{-04}	1.86×10^{-07}	7.62×10^{-06}
21 April 1998	21:06:34.5	34.9583N	139.1860E	3.775	258.596	4.1	1.7	1.04×10^{-03}	2.22×10^{-04}	3.46×10^{-07}	1.00×10^{-05}
21 April 1998	21:22:27.5	34.9587N	139.1913E	4.259	259.306	4.8	1.7	8.73×10^{-04}	1.55×10^{-04}	2.51×10^{-07}	7.18×10^{-06}
26 April 1998	08:38:21.0	34.9580N	139.1849E	3.670	258.793	4.7	1.7	1.06×10^{-03}	1.47×10^{-04}	2.68×10^{-07}	7.25×10^{-06}
26 April 1998	16:51:40.6	34.9580N	139.1876E	3.913	259.499	4.4	1.7	1.47×10^{-03}	2.48×10^{-04}	3.44×10^{-07}	1.18×10^{-05}
26 April 1998	17:45:47.8	34.9588N	139.1845E	3.651	257.315	4.6	1.7	1.43×10^{-03}	2.00×10^{-04}	3.18×10^{-07}	1.09×10^{-05}
26 April 1998	17:58:02.5	34.9563N	139.1903E	4.127	262.708	4.0	1.7	1.03×10^{-03}	2.05×10^{-04}	2.47×10^{-07}	8.61×10^{-06}
21 April 1998	21:08:32.0	34.9582N	139.1805E	3.282	257.049	4.0	1.6	7.96×10^{-04}	1.16×10^{-04}	2.19×10^{-07}	6.02×10^{-06}
26 April 1998	09:02:29.4	34.9575N	139.1852E	3.686	259.730	4.7	1.6	1.07×10^{-03}	1.83×10^{-04}	2.45×10^{-07}	7.84×10^{-06}
26 April 1998	11:41:03.4	34.9638N	139.1965E	4.853	253.775	3.4	1.6	1.07×10^{-03}	1.87×10^{-04}	1.85×10^{-07}	6.11×10^{-06}
26 April 1998	15:30:36.5	34.9755N	139.2046E	6.017	243.838	3.3	1.6	4.55×10^{-04}	8.68×10^{-05}	1.49×10^{-07}	4.42×10^{-06}
26 April 1998	18:53:37.7	34.9585N	139.1803E	3.271	256.410	4.4	1.6	7.30×10^{-04}	1.48×10^{-04}	2.09×10^{-07}	5.98×10^{-06}
26 April 1998	20:22:45.2	34.9600N	139.1811E	3.385	253.963	4.0	1.6	7.07×10^{-04}	1.35×10^{-04}	2.82×10^{-07}	6.75×10^{-06}
27 April 1998	06:00:09.7	34.9563N	139.1922E	4.298	263.000	4.0	1.4	5.72×10^{-04}	1.01×10^{-04}	1.49×10^{-07}	4.52×10^{-06}
26 April 1998	09:05:02.9	34.9554N	139.1977E	4.788	264.922	3.5	1.2	5.74×10^{-04}	1.16×10^{-04}	1.63×10^{-07}	4.65×10^{-06}

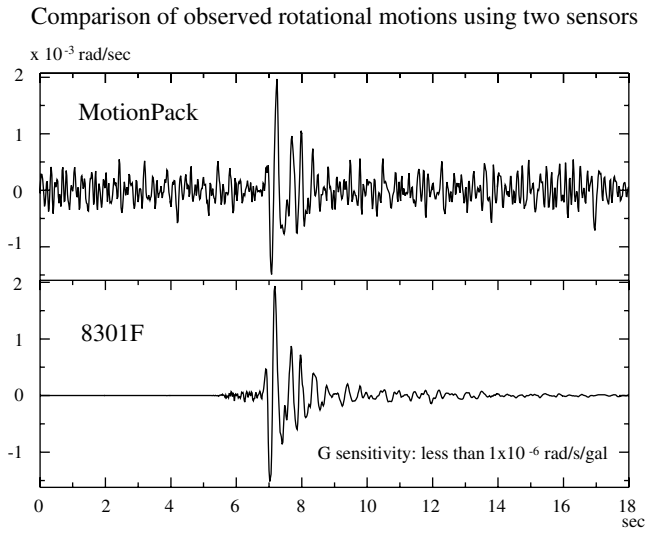

Figure 2. Comparison of rotational rates around the vertical axis observed by the MotionPack and by the 8301F. The noise level of the MotionPack is higher than that of the 8301F, but the waveforms are quite similar to each other. This suggests that MotionPack records rotational rate correctly even with its higher noise level.

ure 4. The rotational motions around the vertical axis resemble the translational velocities of horizontal components, suggesting the linear correlation between the maximum values of rotational displacements around the vertical axis and the maximum values of translational velocities.

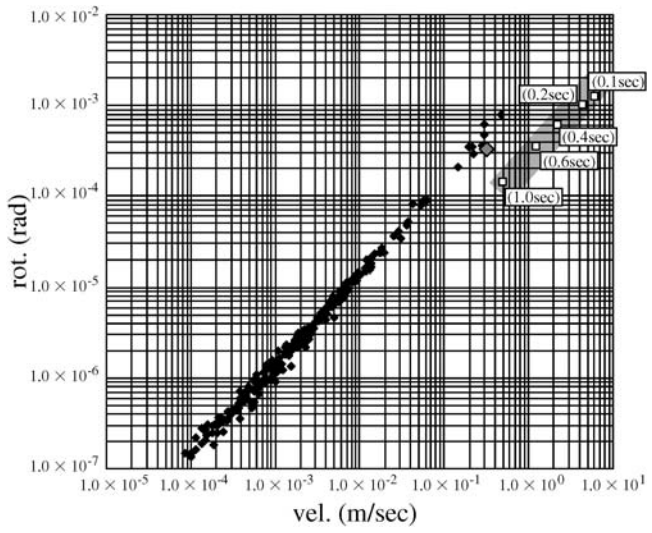

Figure 3. Comparison of the maximum rotational displacements around a vertical axis with the horizontal peak-to-peak maximum translational velocities. Black squares represent observed values during the 1998 offshore Ito swarm activity. A gray square indicates the maximum values of the largest earthquake in the 1997 swarm activity. Synthetic values of maximum rotational displacements around the vertical axis and of horizontal peak-to-peak maximum translational velocities changing the length of source time are shown by white squares in a gray zone, whose moment magnitude and the location of point source are same as those of the largest earthquake in 1997 swarm activity.

Discussion

We calculated a maximum rotational displacement and a maximum translational velocity of the largest earthquake in the 1997 swarm activity of the offshore Ito region whose moment magnitude was 5.3. The data point is plotted by a gray rhombus in Figure 3. Assuming a simple dislocation point source with a triangle source time function, we calculated ground rotational displacements and ground translational velocities while changing the lengths of source time function from 0.1 to 1.0 sec. The reflection-transmission matrices (Kennett and Kerry, 1979) and the discrete wavenumber method (Bouchon, 1981) are used in the calculation of ground motion, assuming the anelastic layered half-space structure listed in Table 2 (Yoshii *et al.*, 1985; Takeo, 1992). These maximum rotational displacements and maximum translational velocities are plotted by white squares in Figure 3 with lengths of source time function. The moment magnitude and the location of point source were the same as those of the largest earthquake in the 1997 swarm activity; therefore, these white squares should be compared with the gray rhombus. The maximum velocity of synthetics with the source time of 1.0 sec achieves the observed value of maximum translational velocity, but the maximum rotational displacement of the synthetics is about one third of the observation. Takeo and Ito (1997) derived a general expression for rotational motion of seismic waves as a function of the geometrical quantities, a torsion tensor, and a curvature tensor, showing that not only the plastic strain, but also the rotational strain, and the spatial variation of slip at earthquake sources directly generates rotational motions in seismic waves. On the other hand, translational motions in seismic waves are only excited by the plastic strain, which can be transformed into a dislocation in case of a simple fault plane. The source time of 1.0 sec is about half of the typical source times of earthquakes with magnitudes of 5.3 (Utsu, 2001). This indicates the existence of asperity; the slip is localized in a smaller region than a typical source region with the same magnitude. The localization of slip induced the large spatial change of slip in the source region, which might excite the rotational motion effectively. Every swarm that occurred from 1995 to 1998 seemed to rupture an intact region, in each case producing an inhomogeneous rupture zone. It seems possible that the small-scale asperity and the large spatial change of slip could be attributed to the inhomogeneity.

Spudich and Fletcher (2008) analyzed the U.S. Geological Survey Parkfield Seismic Array data of the 2004 Parkfield earthquake (M_w 6.0) and four aftershocks (M_w 4.7–5.1) to determine both time variance and peak values of ground strain, torsions, and tilts. Huang (2003) also estimated ground rotations based on array measurements of the 1999 Chi-Chi, Taiwan earthquake (M_w 7.6). Our observations of peak rotation values are about 100 times larger than their observations for earthquakes with similar magnitudes.

There are several prospects to explain this discrepancy. The first possibility is the difference in the spatial scale of

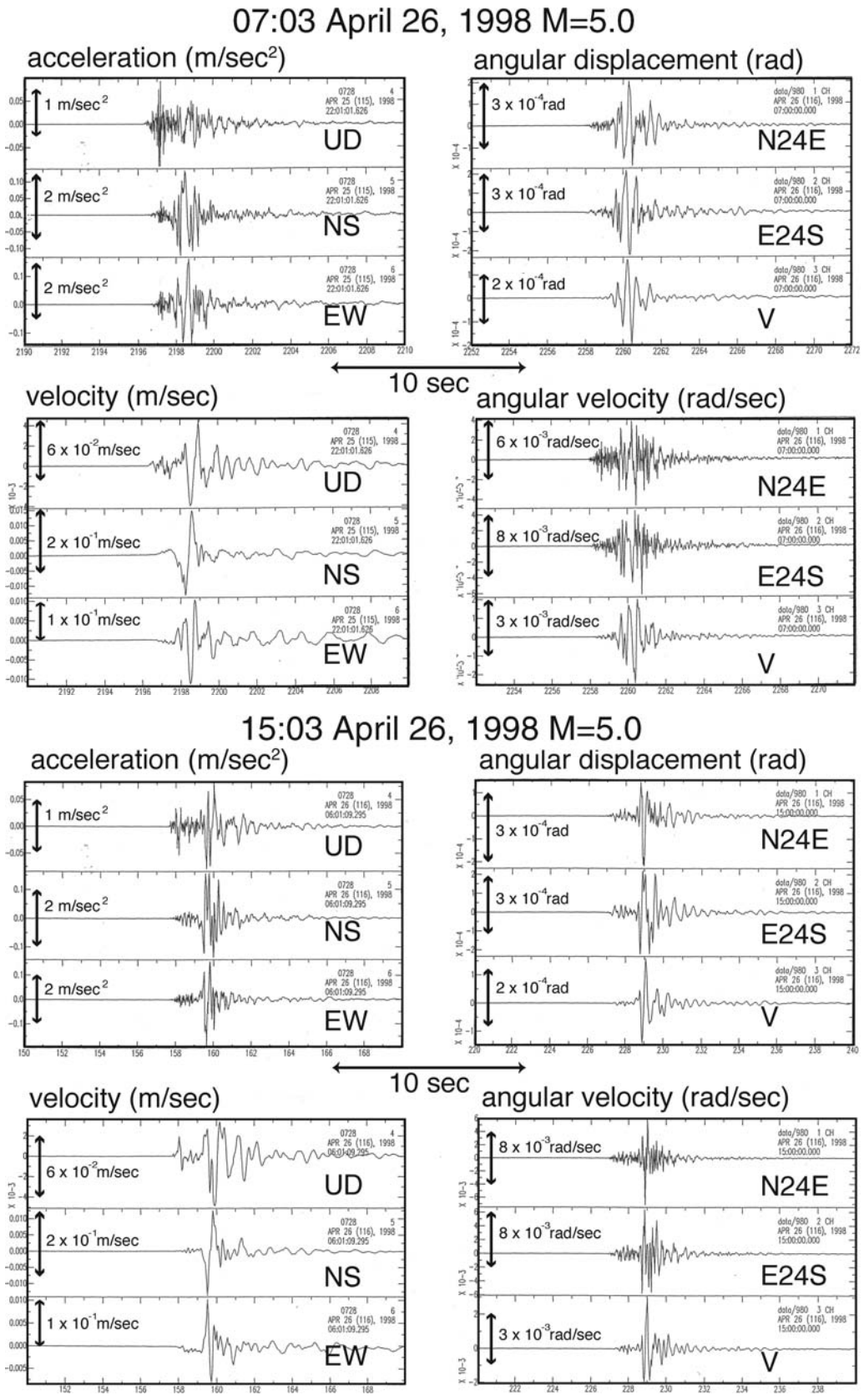

Figure 4. Accelerations, velocities, rotational displacements, and rotational rates, which were excited by earthquakes with magnitudes ranging from 2.4 to 5.0, are compared in the four panels. The rotational motions around the vertical axis resemble translational velocities of horizontal components in the waveform, suggesting the linear correlation between the maximum values of rotational displacements around the vertical axis and the maximum values of translational velocities. (*Continued*)

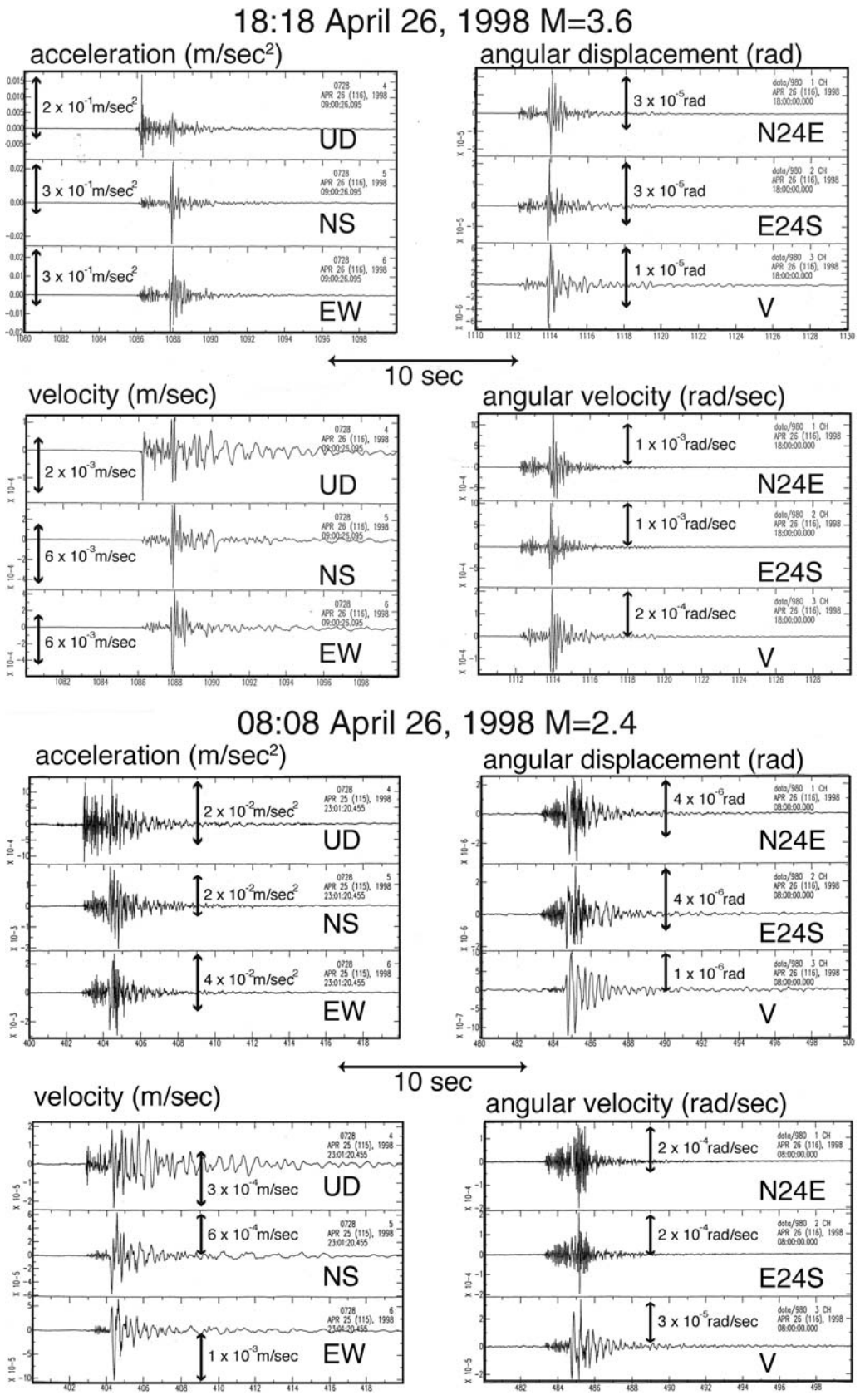

Figure 4. Continued.

Table 2

Velocity Structure Used in the Calculation of Synthetic Waveforms*

V_P (km/sec)	V_S (km/sec)	Density (g/cm^3)	H (km)	Q_P	Q_S
1.95	0.23	2.00	0.00	50	30
2.05	0.48	2.00	0.04	50	30
2.15	0.73	2.00	0.08	50	30
2.25	0.98	2.00	0.12	50	30
2.60	1.30	2.00	0.16	100	50
4.20	2.20	2.30	0.36	300	200
5.30	3.10	2.50	1.86	500	300
6.00	3.46	2.70	4.30	1000	500
6.80	3.93	3.00	15.0	1000	500
7.80	4.50	3.20	30.0	2000	1000

*(Yoshii *et al.*, 1985; Takeo, 1992)

rotational motion measurement as pointed out by Spudich and Fletcher (2008). The results of Spudich and Fletcher (2008) and Huang (2003) were based on the array measurements, so that their rotational motions were averaged over tens of or over 100 m. Our measurements were performed using the gyro sensors, and these point measurements must be sensitive to the local structure around the station. The two gyro sensors, the MotionPack and the 8301F, were separated by several meters, and their instrumental foundations were separated from each other. The coherence of both gyro observations, as shown in Figure 2, infers that the observed rotational motions were not affected by the rocking behavior of the foundations. A short wavelength rotational motion could be amplified easily due to local heterogeneities such as topography and/or surface soil structure. The KAW station is located at the headland of Cape Kawana. Therefore, another possible explanation of large rotational motions is the effect of the precipitous topography.

On the other hand, the high levels of rotational motions are obtained at the low levels of acceleration (10^{-3} G) as listed in Table 1. The wide range linear correlation between the maximum values of rotational displacement and of translational velocity suggests that the soil nonlinearity beneath the station cannot explain the disagreement between our measurements and those of the other researchers. The other possible explanation is the difference of the degree of maturation between the San Andreas fault and the swarm regions of offshore Ito. Every offshore Ito swarm activity ruptured an intact region in each case, so the degree of heterogeneity in the swarm source regions seemed to be higher than those along the San Andreas fault. This difference presumably produced a severe change of spatial variation between the earthquakes in these two regions. We need more examples of near-field observations of rotational motion within a distance of several kilometers to progress the discussion concerning this large discrepancy. We also need a broadband (from static component to several hundred hertz) observation to reveal the relations between amplitude and wavelength of rotational motions.

Data and Resources

Seismograms used in this study were collected using the observational system explained in this article. The data are available from the author.

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