A plate motion model around Japan

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Abstract

We estimated a precise plate motion model for tectonic plates surrounding Japan with the up-to-date GPS velocity fields which are alighned in ITRF 2000. Errors associated with velocity fields are estimated using the empirical relationship between WRMS and white and flicker noise amplitude. The obtained plate motion model generally agrees with those proposed in the previous study. We did not find deformation fields associated with the super plume under French Polynesia, presumably because of the decoupling between the low viscosity mantle and the plate or simply because hot mantle does not reach the above plate. TNGA, which lies on the Australia plate, has a significant differential velocity with the Australia plate. This is due to the rapid spreading of the Tonga-Lau basin. The site velocities at SUWN and DAEJ have significant differential velocities with the Eurasia plate. Therefore, we need to introduce the Amur plate or a regional block to explain these velocity fields. The site velocities at MAG0 and PETP have significant differential velocities with the North American plate. Therefore, we need to introduce the Okhotsk plate or some regional block motion to explain these velocity fields. Site 2003 seems to have significant differential velocities with the Philippine Sea plate. However, this is not conclusive since the GPS time series has a large WRMS.

1. Introduction

It is very important to obtain a precise plate motion model around Japan when one tries to evaluate the earthquake hazard potential in Japan. From relative Euler vectors, one may estimate the relative convergence rate across plate boundaries. Deviations from the estimation can be considered to come from slip deficits on plate boundaries (e.g. Sagiya and Thatcher, 1999). Then one may be able to infer the detailed distributions of slip deficits using sophisticated inversion techniques. A part of plate boundaries with large slip deficits correlates well with the distribution of the asperities, which have potentials to cause large earthquakes (e.g. Nishimura et al., 2004).

Historically, a plate motion model was constructed geologically mainly based on the spreading rates at the mid-ocean ridge estimated by magnetic stripes on the sea floor. NUVEL-1A model (DeMets et al., 1994) is a representative model. However, a problem in this geologic approach is that it is impossible to deal with small plates which do not have a spreading center. Instead, with a growing number of space geodetic measurements such as Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), and Satellite Laser Ranging (SLR), several models which are constructed solely by direct measurements of site displacements have been proposed (e.g. Sella et al., 2002; Prawirodirdjo and Bock, 2004).

A plate motion model around Japan, however, still involves several controversial aspects even after employing the sophisticated space geodetic measurements. In NUVEL-1A, it is assumed that Japan is covered by four plates. There are two continental plates, the North American plate and the Eurasia plate which cover northeast and southwest Japan, respectively. There are two oceanic plates, the Philippine plate and the Pacific plate, which subside under the continental plates at the Kuril-Japan trench, and the Sagami trough, Suruga trough and the Ryukyu trench respectively. Some studies (e.g. Cook et al.,1986; Seno et al., 1996) preferred the idea that northeast Japan belongs to the Okhotsk plate, which is independent from the North American plate, based on the analysis of seismicity, focal mechanism and slip vectors. However, the existence of the Okhotsk plate is not confirmed by the GPS measurements (e.g. Steblov et al., 2003). Some studies (e.g. Heki et al., 1999; Miyazaki and Heki, 2001) suggest that southwestern Japan belongs to the Amur plate instead of the Eurasia plate. However, other studies (e.g. Aoki and Scholz, 2003) favor the idea that southeastern Japan is still a part of the Eurasia plate. Thus it is necessary to construct a finer plate motion model with less ambiguity to clear up these controversial points, which this study tries to do with an updated GPS dataset.

2. GPS data and analysis

The data used in this study came from the following sources: the International GNSS service (IGS) continuous tracking stations, continuous GPS stations under the WING project (Kato et al., 1998), the University of Hawaii SW Pacific network (Bevis et al., 1995), the Geographical Survey Institute (GSI) South Pacific GPS network (Harada, 2000), and the GSI GPS Earth Observing Network (GEONET) (Hatanaka, 2003).

The GPS data were analyzed using the GIPSY-OASIS software with the PPP strategy (Zumberge et al., 1997). All station position timeseries are aligned in ITRF 2000 (Altamimi et al., 2002). We modeled the timeseries as a superposition of 1) linear trend, 2) annual and semi-annual sinusoidal variation, and 3) step motions due to antenna replacement etc.

It is well known that noise spectrum of the GPS position timeseries is dominated by colored noise at low frequencies (e.g. Langbein and Johnson, 1997; Mao et al., 1999). According to their study, if one ignores the colored noise, one will underestimate velocity uncertainty by a factor of 2 to 6. We assumed that the colored noise is flicker and estimated velocity uncertainty according to Mao et al. (1999). We adopted empirical relations between the weighted RMS of the GPS timeseries and standard deviations of white and flicker noise proposed by Dixon et al. (2000).

The Euler vector for each plate is estimated by fitting the velocity of each station within the plate in the least-squares sense. The stations used for determining each plate's motions are given in Table 1, together with velocities, their uncertainties and residuals after subtracting rigid plate motion. The map of the stations is given in Fig. 1. The estimated Euler poles are listed in Table 2.

3. Discussion

First of all, one can see that the chi^2 fits obtained in this study are generally larger than the previous studies. For example, Sella et al. (2002) reports chi^2 fits for Pacific and Eurasia plates which are 1.20 and 1.02, respectively. In this study, they are 2.26 and 3.40, respectively. This does not mean that our results suggest that these plates are less rigid than previously noted. The discrepancy is mostly due to the selection of error bars in the estimated velocity. In the velocity estimation, we discarded outliers to avoid distortion. We do not include these points in the WRMS calculation. This procedure may results in the underestimation of WRMS in our study, and lead to higher chi^2 values. We also adapted empirical relationship between white and colored noise proposed by Dixon (2000). However, this empirical relation is derived for a certain set of sites and does not necessarily hold for all stations. Considering these uncertainties in the velocity error estimation, the error bars in the velocity estimation and chi^2 of the plate motions should be treated with caution.

For the motion of the Pacific plate, we obtained the Euler vector (112.5E, -63.5N, 0.684deg/Myr). This value compares well with the (110.86E, -63.75N, 0.677deg/Myr) estimated by Beavan et al. (2002). From gravity and seismic studies, it is suggested that in the lower mantle below French Polynesia exists a large hot plume (e.g. Adam and Bonneville, 2005). However we do not observe notable velocity residuals in the vicinity (COOK, THTI, GAMB). This suggests either that the anomaly in the lower mantle does not extend up to the above crust or that the mantle and plate are dynamically decoupled and material properties in the mantle do not affect the plate motion (e.g. Forsyth and Uyeda, 1975).

TNGA is located on the Australian plate. However, the obtained velocity of TNGA is quite different from that expected from the Australian plate motion. This is due to the fast spreading of the Tonga-Lau basin (Bevis et al., 1995).

Our estimated Euler pole of the Eurasia plate is close to the (-99.7E, 57.2N, 0.262deg/Myr) estimated by Prawirodirdjo and Bock (2004), showing the robustness of the Euler vector to the selection of core stations and the method of GPS analysis. Relatively large residuals observed at KSTU may be due to the intermittent timeseries and will comply with the normal plate motion in the future.

Previously, several estimates are present for the motion of the Amur plate. For example, Heki et al. (1999) proposed the Euler vector of the Amur plate relative to Eurasia plate to be (-22.3E, 106.6N, 0.091deg/Myr), while Prawirodirdjo and Bock (2004) proposed the vector to be (-25.3E, 45.4N, 0.093deg/Myr). Sella et al. (2002) suggested the vector to be (159E, 44.1N, 0.103deg/Myr). This study suggests the vector to be (142.9E, 44.9N, 0.114deg/Myr), which is close to Sella et al. (2002). Note, however, this study and Sella et al. (2002) used GIPSY while Prawirodirdjo and Bock (2004) used GAMIT/GLOBK for the GPS analysis. Hence, these discrepancies may be due to the difference in the analysis strategy especially that in the reference frames realization. Further study will be needed to confirm this point.

Aoki et al. (2003) pointed out that the western part of Japan can be considered to be a part of the Eurasia plate, while Miyazaki and Heki (2001) considered it to be a part of the Amur plate. If we assume that the Amur plate is not independent and just a part of the Eurasia plate, we have large residuals around 3mm/yr at SUWN and DAEJ, which are well above the statistical significance. Therefore, if one assumes that the Amur plate is a part of the Eurasia plate, these residuals in the Korean peninsula need to be explained in some way, as discussed in Steblov et al. (2003).

Our estimated Euler pole of the North American plate is close to the (-84.7E, -3.6N, 0.200deg/Myr) estimated by Prawirodirdjo and Bock (2004). Residuals are generally very small (below 1mm/yr), reflecting the stability of the North American plate.

Seno et al. (1996) proposed a plate motion model where the southernmost tip of the North America plate moves independently as the Okhotsk plate based on earthquake slip vectors. However, from a geodetic point of view, its existence is still controversial (e.g. Steblov et al., 2003). We analyzed three GPS sites (MAG0, PETP, YSSK) which are on the proposed Okhotsk plate. If one assumes that these points are on the Eurasia plate, there are significant residuals. The residuals in YSSK may be explained by its lying in the proximity of the plate boundaries. However, the residuals of MAG0 and PETP need to be explained in some way, including the adoption of the Okhotsk plate.

As for the Philippine plate, our estimate of the Euler vector is pretty close to the (-30.4E, -46.5N, 0.910deg/Myr) from Sella et al. (2002). However, one can see significant residuals at 0602, 2003, and PBLS. The residual at 0602 may be due to the effect of volcanic activities on the island, and those of PBLS may due to the effect of the plate boundaries. For 2003, there is no explicit reason for the large residuals. Since the WRMS is relatively large at this site, we need more data to confirm whether the velocity of 2003 is consistent with the rest of the Philippine plate or not.

4. Conclusions

We estimated a precise plate motion model for tectonic plates surrounding Japan with the up-to-date GPS velocity fields which are alighned in ITRF 2000. The obtained plate motion model generally agrees with those proposed in the previous study. We did not find deformation fields associated with the super plume under French Polynesia. We found that TNGA does not move with the Australia plate due to the rapid spreading of the Tonga-Lau basin. We note that site velocities at SUWN and DAEJ have significant residuals if we assume they lie on the Eurasia plate. Therefore, we need to introduce the Amur plate or a regional block to explain these velocity fields. Site velocities at MAG0 and PETP have significant residuals if we assume they lie on the North American plate. We need to introduce the Okhotsk plate or some regional block motion to explain these velocity fields. 2003 seems to have significant residuals with the rest of the Philippine Sea plate. However, this is not conclusive since the GPS timeseries has a large WRMS.

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Table 1 Site positions and velocities relative to ITRF 2000. Braces in the site names denote that the sites are not used in the estimation. Braces in the residual velocities mean that those values are with respect to the plate motions by Prawirodirdjo and Bock (2004).

					WRMS(E)	WRMS(N)	ITRF2000 Velocity, mm/yr				Residual mm/yr	
Site	DT(years)	Data count	Longitude	Latitude			Ve	Vn	dVe	dVn	Re	Rn
Pacific plate												
CHAT	9.24	2438	-176.56	-43.96	3.87	2.59	-40.50	33.34	0.29	0.24	0.3	1.3
COOK	6.82	1974	-159.82	-21.20	6.48	4.16	-63.72	32.78	0.67	0.51	0.7	-1.1
FALE	7.13	981	-172.00	-13.83	4.75	3.11	-64.96	32.46	0.50	0.40	0.5	-0.4
GAMB	4.31	1280	-134.97	-23.13	4.83	2.77	-68.49	30.78	0.78	0.54	0.8	-0.6
KOKB	9.99	2440	-159.67	22.13	5.37	3.21	-63.35	33.00	0.38	0.28	0.4	-0.9
KRTM	7.59	1643	-157.45	2.05	8.07	3.37	-67.28	33.82	0.79	0.39	0.8	-0.1
KWJ1	6.34	1185	167.73	8.72	6.33	3.66	-70.07	26.49	0.74	0.51	0.7	-1.4
MIDW	2.63	360	-177.37	28.22	5.26	2.90	-64.42	34.54	1.54	1.02	1.5	-2.6
MKEA	7.58	2156	-155.46	19.80	4.53	3.02	-64.08	34.01	0.41	0.34	0.4	0.1
MNTR	9.45	1605	153.98	24.29	4.52	3.97	-73.52	21.17	0.35	0.37	0.3	-1.3
NIUC	5.12	550	-169.93	-19.06	4.59	2.95	-61.82	33.27	0.70	0.54	0.7	0.1
TARW	5.56	1240	172.92	1.36	8.36	2.90	-67.74	29.38	1.11	0.45	1.1	-0.1
THTI	6.57	1741	-149.61	-17.58	5.45	2.57	-66.64	33.09	0.59	0.34	0.6	-0.5
TRUK	6.81	763	151.89	7.48	6.18	3.04	-69.21	23.48	0.72	0.42	0.7	-2.0
Phillipine sea plate												
0602	7.78	2536	139.77	32.46	4.56	2.99	-21.67	12.43	0.40	0.32	3.8	0.0
0603	7.26	2515	142.16	26.64	4.70	5.00	-36.44	7.60	0.44	0.56	-0.8	-1.8
0746	7.86	2520	131.29	25.95	3.79	2.84	-39.06	22.64	0.33	0.30	-0.8	-0.5
2003	9.79	2725	142.19	27.10	6.06	3.66	-37.88	10.49	0.44	0.31	-3.0	1.2
PBLS	5.19	784	134.48	7.34	6.61	4.34	-63.21	18.89	0.97	0.75	-4.0	0.3
Amur plate												
BJFS	5.19	1626	115.89	39.61	3.00	2.00	29.02	-12.49	0.38	0.33	1.1	0.4
DAEJ	9.16	2925	127.37	36.37	5.19	2.81	27.53	-14.25	0.39	0.26	0.5	-0.2
KHAJ	2.55	687	135.05	48.52	4.10	2.52	21.06	-14.07	1.12	0.85	-0.9	0.5
SUWN	7.07	2019	127.05	37.38	3.50	2.43	26.32	-14.11	0.34	0.29	-0.5	-0.1
VLAD	4.86	1456	131.93	43.20	4.08	4.26	22.44	-14.16	0.58	0.73	-1.9	0.2
North American Plate												
AMC2	6.19	1976	-104.53	38.80	3.08	2.06	-15.62	-5.97	0.33	0.28	0.3	0.7
AOML	6.36	2094	-80.16	25.74	4.00	2.92	-10.94	2.69	0.43	0.38	0.4	0.4
BRMU	9.92	2967	-64.70	32.37	3.91	2.70	-12.61	7.95	0.27	0.23	0.3	0.0
GODE	9.99	3084	-76.83	39.02	3.08	3.10	-15.35	2.64	0.20	0.26	0.2	-0.9
MDO1	9.99	3093	-104.02	30.68	4.10	3.22	-12.57	-6.50	0.28	0.27	0.3	0.0
STJO	9.99	2926	-52.68	47.60	3.10	2.45	-15.40	12.07	0.21	0.21	0.2	0.2
USNO	7.66	2421	-77.07	38.92	3.09	2.69	-15.23	3.41	0.27	0.29	0.3	-0.1
(MAG0)	7.08	2343	150.77	59.58	4.05	4.59	6.95	-20.72	0.39	0.53	-1.7	-2.7
(PETP)	6.22	2090	158.61	53.07	3.30	2.61	-5.61	-8.38	0.35	0.35	-11.3	11.0
(YSSK)	5.42	1926	142.72	47.03	3.13	4.37	12.00	-17.24	0.38	0.66	3.5	-1.1
Eurasia plate												
ARTU	5.39	1770	58.56	56.43	2.23	2.11	24.94	5.11	0.26	0.33	0.0	-0.3
BOR1	9.86	3040	17.07	52.28	2.77	2.43	20.00	13.31	0.18	0.21	-0.1	-0.3
GLSV	6.78	2024	30.50	50.36	2.76	2.04	22.25	11.92	0.27	0.26	-0.6	0.4
JOZE	9.99	3099	21.03	52.10	3.13	4.31	21.37	13.63	0.21	0.36	0.5	0.6
KSTU	7.05	1404	92.79	55.99	3.34	2.51	24.41	-6.20	0.33	0.32	-1.1	-2.5
NYAL	9.99	2382	11.87	78.93	2.04	2.53	9.61	13.04	0.13	0.22	-0.8	-1.2
POTS	9.82	2959	13.07	52.38	2.55	2.22	19.33	14.49	0.17	0.19	0.1	0.4
TIXI	6.22	1951	128.87	71.64	3.56	3.26	16.62	-12.30	0.38	0.44	-0.2	-0.5
WTZR	8.96	2662	12.88	49.14	2.48	2.23	20.26	14.95	0.18	0.21	0.2	0.9
ZWEN	9.51	2247	36.76	55.70	4.00	3.13	23.86	10.28	0.29	0.28	1.2	-0.1
Australian plate												
(TNGA)	5.18	681	-175.18	-21.15	8.00	3.29	88.70	-8.63	1.21	0.58	70.7	-16.6

Table 2 Plate angular velocities relative to ITRF 2000. Rot denotes the angle of semi-major axis measured clockwise from north.

Longitude (deg)	Latitude (deg)	Rate (deg/Myr)	Smax	Smin	Rot(deg)	Sigma_rate	Chi2
112.5	-63.5	0.684	0.4	0.2	94.6	0.003	2.26
-30.6	-45.9	0.963	1.5	0.9	87.1	0.072	5.24
-125.5	64.2	0.303	4.9	3.1	13.0	0.016	1.96
-86.3	-7.1	0.194	1.3	0.5	99.0	0.004	1.78
-101.0	56.6	0.252	1.3	0.8	99.0	0.005	3.40

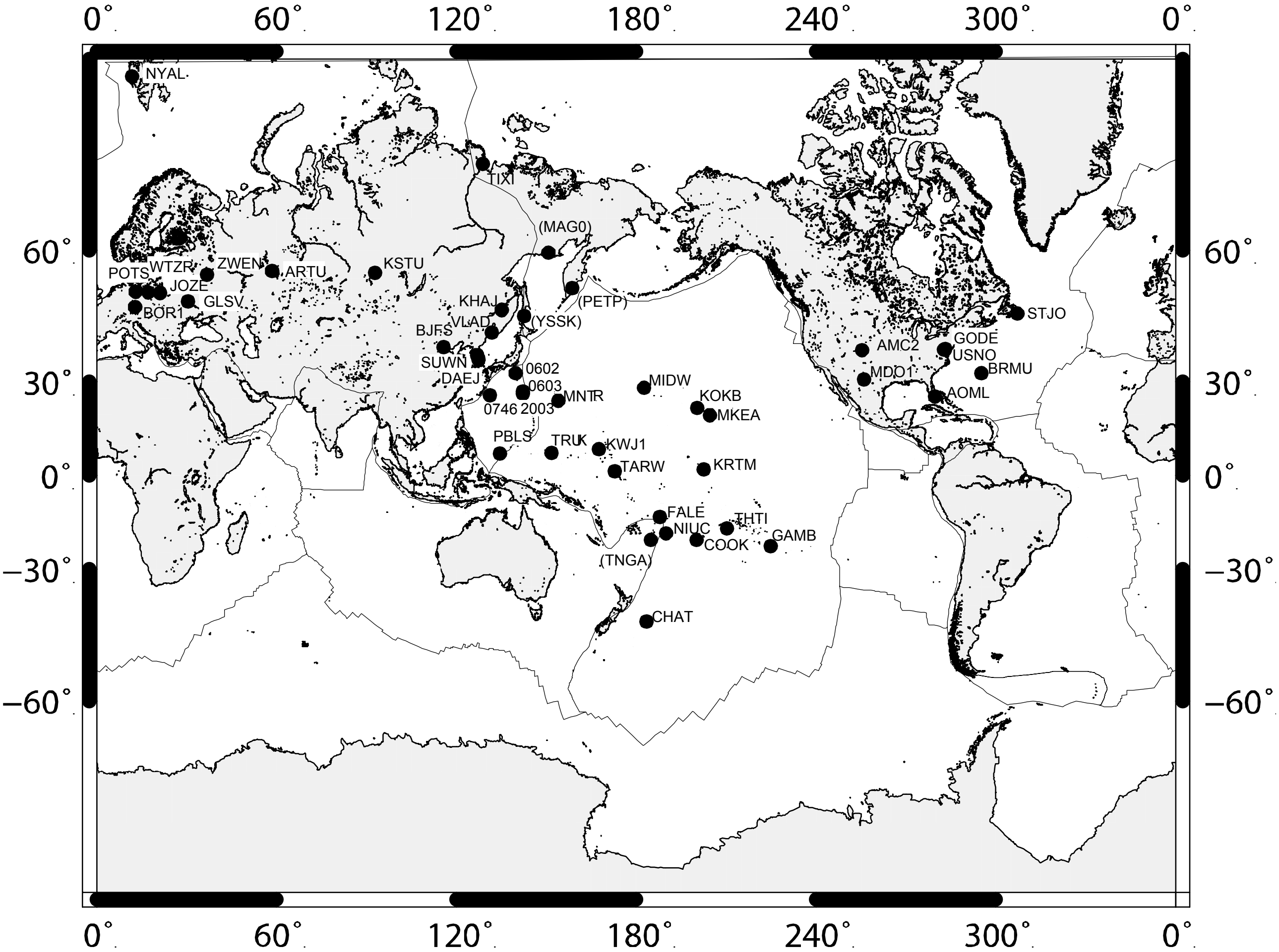

Fig. 1 The map of the GPS stations used in this study.