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Relative motions of the Australian, Pacific and Antarctic plates estimated by the Global Positioning System

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Abstract. GPS measurements spanning ~3 years have been used to determine velocities for 7 sites on the Australian, Pacific and Antarctic plates. The site velocities agree with both plate model predictions and other space geodetic techniques. We find no evidence for internal deformation of the interior of the Australian plate. Wellington, New Zealand, located in the Australian-Pacific plate boundary zone, moves 20±5 mm/yr west-southwest relative to the Australian plate. Its velocity lies midway between the predicted velocities of the two plates. Relative Euler vectors for the Australia-Antarctica and Pacific-Antarctica plates agree within one standard deviation with the NUVEL-1A predictions.

Introduction

One goal of space geodesy in the past two decades has been to measure current values of relative plate motions and compare them with plate motions averaged over the last three million years [*DeMets et al.*, 1990]. Over the past decade, satellite laser ranging (SLR) and very long baseline interferometry (VLBI) have measured precise velocities for several plates, principally the North American, Pacific, and Eurasian plates [*Robaudo and Harrison*, 1993; *Robbins et al.*, 1993, *Ryan et al.*, 1993]. The Global Positioning System (GPS) has opened up most of the world to plate motion studies. We use the International GPS Service for geodynamics (IGS) permanent network [*Beutler and Brockmann*, 1993] to estimate velocities for sites on the Australian, Pacific and Antarctic plates (Figure 1), and use these site velocities to determine the relative motions of these three plates. Although the relative motion of Antarctica is well constrained by geologic data, to date there have been no published geodetic estimates of its motion.

Measurements and Analysis

Space geodetic observations have been made in Australia since the 1970's [*Christodoulidis et al.*, 1985; *Herring et al.*, 1986]. SLR estimates of Australian station velocities agree with NNR-NUVEL1 [*Argus and Gordon*, 1991] in direction, but are slower by ~10% [*Robbins et al.*, 1993]. The first permanent GPS receivers on the Australian plate were installed in early 1990, and there have been long-term GPS measurements at a total of 5 sites on the plate (Figure 1). There are two IGS sites on the Pacific plate, Kokee, Hawaii (since 1987) and Pamatai, French Polynesia (since 1992). A permanent site at McMurdo, Antarctica was established in February 1992.

The earliest data used in this study were collected during the GIG '91 experiment (January-February 1991) [*Heflin et al.*, 1992]. We also used global station coordinates estimated approximately once per week for the IGS network from February 1992 through November 1993, at which time the antenna at McMurdo was moved. Except for small data gaps associated with receiver malfunctions in the Australia/Antarctica area, the time series of station coordinates is distributed fairly evenly in time over this 20 month period. Our data set includes most of the sites in the global network, but for this paper we will concentrate on the results for our 'regional network' (Table 1). Figure 2 shows the location of the global sites we used over the course of this study for orbit estimation. Due to improved station coverage and an increasing number of satellites, the precision of a daily GPS solution increased steadily during the period of this study.

The GPS data were analyzed with the Gipsy 2.0 software developed by the Jet Propulsion Laboratory. Each position estimate is based on 24 hours of pseudorange and phase data decimated to 6 minute points. We generally followed the strategy described by *Heflin et al.* [1992]. The coordinates of 6 globally distributed sites were constrained to agree with VLBI/SLR coordinates with an a priori uncertainty of 10 meters, while the remaining sites were unconstrained.

We apply *a posteriori* reference frame constraints by transforming the station coordinates from each GPS solution to agree on average with the ITRF92 reference frame [*Boucher et al.*, 1993]. The fit is weighted by the formal errors of the GPS solution scaled by 2.5 and by the formal errors for the ITRF92 station coordinates. The scale factor was chosen to reduce the chi square per degrees of freedom to 1.

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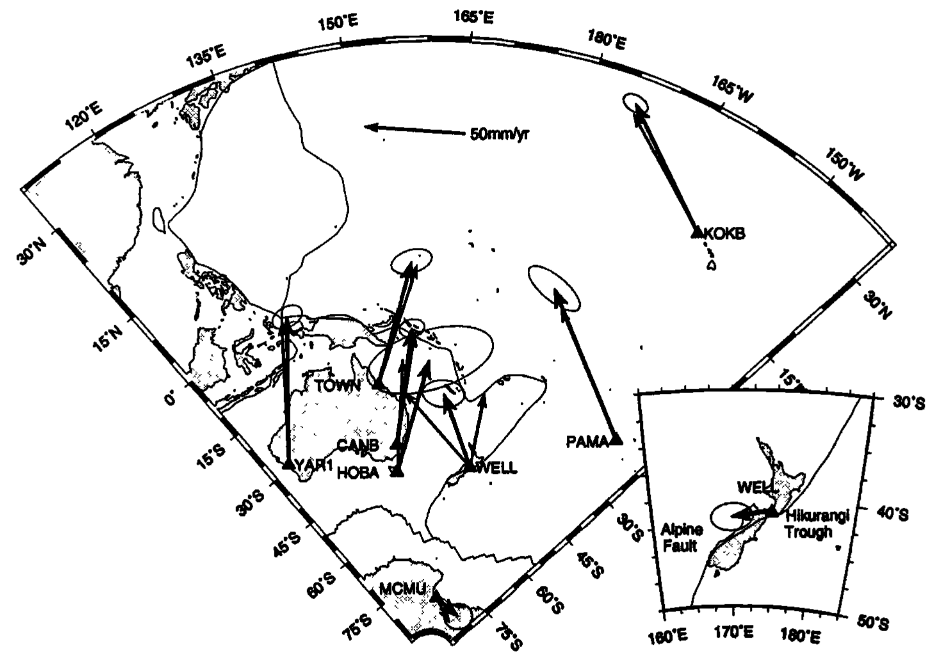

Figure 1. Horizontal station velocities with 95% confidence ellipses. The vectors without sigmas are the NNR-A predictions. Wellington predictions for both the Pacific and Australian plates are shown. The inset shows Wellington's motion relative to the Australian plate.

We selected a subset of 11 sites from the ITRF92 model as reference sites to define each day's transformation (Figure 2). The choice of reference sites was dictated by the quality of each site's position and velocity, it's temporal continuity, and by the geometry of the reference network. There are multiple sites which fit these criteria in Europe and North America. However, the choices are limited in the southern hemisphere, and we chose nearly all available sites. This method of specifying the reference frame does not constrain the position or velocity of any one site; it constrains the weighted average of all the reference sites. Only one of the regional sites, Yaragadee, was used as a reference site, so estimates of relative velocities between regional sites were not constrained *a priori*.

ITRF92 positions and velocities are derived from SLR and VLBI measurements with a no-net-rotation constraint with respect to NNR-NUVEL-1 [*Argus and Gordon*, 1991]. Recent revisions of the magnetic time scale have shown that the velocities in the NUVEL-1 model are systematically too fast by about 4 %. The NUVEL-1A model has been computed based on these revisions [*DeMets et al.*, in press]. This new model, NNR-NUVEL-1A (hereafter called NNR-A), scales NNR by 0.9562. Note that our reference frame constraint is based on NNR-NUVEL-1, not NNR-A. The agreement of our results with NNR-A suggests that the effect of this inconsistency in the reference frame is small.

Table 1. Local Site Information

Site	ID	Obs.	Time Span
Canberra	CANB	77	1991.06-1993.81
Hobart	HOBA	23	1993.21-1993.81
Kokee Park	KOKB	73	1991.06-1993.81
McMurdo	MCMU	76	1991.06-1993.81
Pamatai	PAMA	60	1992.17-1993.81
Townsville	TOWN	51	1991.06-1992.88
Wellington	WELL	53	1991.06-1992.88
Yaragadee	YAR1	89	1991.06-1993.81

Geodetic Results

The horizontal components of the McMurdo-Yaragadee interstation vector (5780 km) are depicted in Figure 3. The north-south extension of the baseline is clearly shown. Using the weighted rms scatter about the best fit line to define precision for all baselines in the regional network, horizontal precision can be characterized as 3-4 mm + 3 parts in 10^9, with a larger constant term for the vertical component.

Station velocities are determined from the individual station positions assuming linear motion with time. Figure 1 shows the estimated horizontal velocities at the network sites, along with the NNR-A predictions. Our velocities are in excellent agreement with the predictions of the NNR-A model (Table 2). With the exception of the north component of Kokee, the individual GPS velocity components are all within two standard deviations of NNR-A. Again, except for Kokee, the velocities agree well with the ITRF92 model, which is based on independent VLBI and SLR data. Plate tectonic models predict no vertical motions, and we observe significant vertical deformation only at Wellington, which is located in a plate boundary zone.

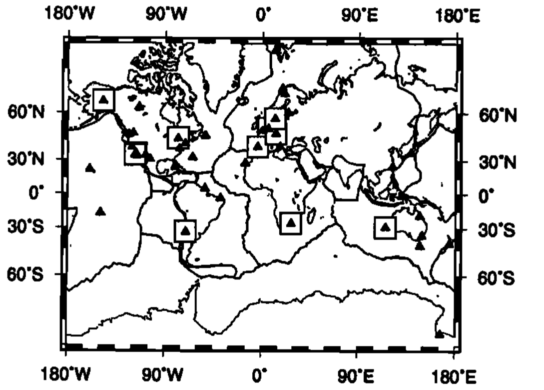

Figure 2. Global GPS tracking stations (IGS network) used in this study. Open squares represent stations used to define the reference frame.

Discussion

Plate tectonic models predict no change in baseline length between stations situated on the same plate. The GPS length estimates for interstation vectors between Canberra and Yaragadee, Townsville, and Hobart (-3±3, 3±7, and 3±7 mm/yr respectively) show no significant change at the one standard deviation level. Likewise, there is no significant (6±6 mm/yr) lengthening of the Pamatai to Kokee baseline on the Pacific Plate.

Wellington (New Zealand) is located on the margin of the Australian plate, 85 km from the Hikurangi Trough, which represents the boundary with the Pacific plate. Its velocity lies midway between the predicted velocities of the Australian and Pacific plates (Figure 1), 20±5 mm/yr to the west relative to the Australian plate. *Bibby et al.* [1986] estimated the velocity field of New Zealand based on integration of the strain rates observed by surface geodetic measurements. They predicted that Wellington moves 20±4 mm/yr west-southwest relative to the Australian plate. The agreement is remarkable, considering the difference in the methods used to obtain the velocities. It has been noted before that the velocities of sites in plate boundary zones are, to first order, linear combinations of the velocities of the plates involved [*Ward*, 1988; *Smith et al.*, 1990].

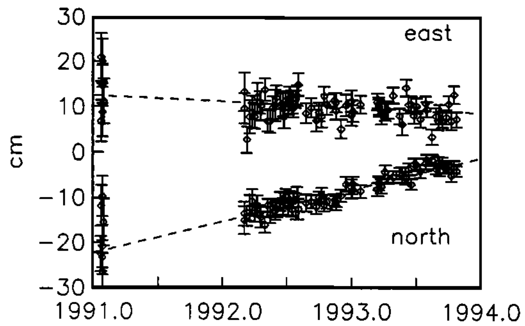

Figure 3. East and north components for the Yaragadee-McMurdo interstation vector. Error bars are one standard deviation.

The motion of a rigid plate on a spherical earth can be specified by an Euler vector, representing a rotation about an axis passing through the geocenter. Plate velocities (relative to the geodetic reference frame) are estimated by inverting the relation $v = \Omega \times r$ where Ω is the plate's Euler vector, v is the station velocity, and r is the position of the station. The inversion is weighted by the full covariance of the velocities. The Euler vector for a tectonic plate cannot be resolved with only one site velocity.

The Australian and Pacific Euler vectors are uniquely determined by the GPS data, but the Antarctica Euler vector is not. We must apply *a priori* information to be able to determine this Euler vector. Because McMurdo is near the Earth's spin axis, the z component of the Antarctica Euler vector is poorly determined by the data. Thus, we constrain the z component of the Antarctica Euler vector to its NNR-A value with an *a priori* uncertainty of 0.05 degrees/million year. For comparison, the uncertainty in the NUVEL-1A relative Euler vector between the Antarctic and Australian plates is less than 0.009 degrees/million year. The estimated value that results for the z component is equivalent to the prior value (Table 3).

The Euler vectors for Australia-Antarctica and Pacific-Antarctica agree with NUVEL-1A within one standard deviation. Of the three plates, the Pacific plate Euler vector agrees least well with NNR-A, although still within two standard deviations. This not surprising, given that both sites on the Pacific plate, Kokee and Pamatai, were moving significantly faster than NNR-A predictions. It is not yet clear whether these Pacific plate results are due to a true difference in the motion of the Pacific plate, internal deformation of the Pacific

Table 2. Station Velocities - mm/yr

	GPS			NNR-A			ITRF92		
	North	East	Vert.	North	East	Vert.	North	East	Vert.
Canberra	55.8±1.8	16.6±2.6	1.2±4.2	53.7	17.7	0	54.9	16.6	5.0
Hobart	51.7±6.1	25.8±13.0	24.1±27.0	54.4	12.8	0	58.9	11.1	4.7
Kokee Park	37.0±1.6	-60.1±2.7	-2.4±4.6	32.3	-58.3	0	33.5	-61.5	-1.4
McMurdo	-8.3±2.5	11.6±2.8	-9.5±6.8	-11.7	7.5	0	-	-	-
Pamatai	36.9±2.5	-71.9±6.4	-8.0±10.2	31.5	-62.9	0	-	-	-
Townsville	56.9±2.3	27.6±4.2	17.9±8.3	54.7	30.0	0	-	-	-
Wellington	32.9±0.8	-20.2±4.2	24.4±7.7	37.1	-0.6	0	-	-	-
Yaragadee	59.6±2.1	42.6±3.1	7.3±4.7	59.1	39.0	0	59.0	37.4	-2.6

Table 3. Euler Vector Components - degrees/million years

	X	Y	Z
Antarctica	-0.074±0.027 (-0.047)	-0.060±0.022 (-0.097)	0.212±0.050 (0.212)
Australia	0.440±0.021 (0.449)	0.316±0.018 (0.294)	0.359±0.022 (0.360)
Pacific	-0.078±0.069 (-0.087)	0.327±0.031 (0.277)	-0.620±0.031(-0.571)
ANTA-AUST	-0.514±0.032 (-0.496±0.007)	-0.376±0.025 (-0.391±0.010)	-0.147±0.054 (-0.148±0.008)
ANTA-PCFC	0.004±0.070 (0.040±0.013)	-0.387±0.039 (-0.375±0.010)	0.832±0.059 (0.784±0.011)

NNR-A predictions in parentheses.

plate, local deformation, or simply an inconsistency of the reference frames.

Conclusions

With a nearly three year time span of GPS observations, we were able to estimate coordinate velocities with an accuracy of 3 mm/yr (comparison with ITRF92). We find no geodetic evidence for internal deformation of the Australian plate. We have estimated Euler vectors for the Pacific, Australian, and Antarctic plates. Relative Euler vectors for Australia-Antarctica and Pacific-Antarctica agree within one standard deviation with NUVEL-1A. The site at Wellington (New Zealand) is moving with a velocity intermediate between the Australian and Pacific plates, consistent with its location in the plate boundary zone. Velocities for sites on the Pacific plate are slightly faster than NNR-A, and future data will show whether this disagreement is significant.

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