Limitations in the NZGD2000 Deformation Model

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Abstract. The New Zealand Geodetic Datum 2000 (NZGD2000) is a semi-dynamic datum, in that coordinates are fixed to their values at 1 January 2000 and velocities from a horizontal deformation model are used to transform the coordinates of data collected before or after that date.

The deformation model was calculated from GPS campaign data collected between 1992 and 1998, and was aligned with ITRF96. We examine the performance of this model in 2005 from two points of view: (1) how different are the ITRF2000 velocities from ITRF96, and (2) for new stations, and older stations where additional data have been collected, how well do the newly estimated velocities match those in the deformation model (after the ITRF96-ITRF2000 transformation)?

We have calculated ITRF2000 velocities at points throughout New Zealand. The ITRF96 and ITRF2000 velocities differ by 4.8 mm/yr at azimuth -101° in the southwest of the country, and by 5.4 mm/yr at azimuth -111° in the northeast.

The differences between newly-calculated ITRF2000 site velocities and velocities from the deformation model transformed to ITRF2000 range between zero and about 4 mm/yr. Velocities of some continuous GPS stations installed in the past few years differ by more than this (in two cases by >7 mm/yr), in part because the new velocities cannot be estimated reliably from relatively short spans of data, and in part because the velocities at some sites are not linear. Significant vertical velocities up to a few mm/yr are estimated for continuous GPS stations that have been established for at least four years. These comparisons suggest that an upgrade to the deformation model should be considered. Alignment of the deformation model with ITRF2000 (or its successors) will have benefits in combining newly collected data with existing data, as the ITRF96 to ITRF2000 transformation step will no longer be needed.

Keywords. Geodetic datum, deformation model, crustal deformation, New Zealand

1 Introduction

In 1998 Land Information New Zealand (LINZ) implemented a new geocentric datum for New Zealand, New Zealand Geodetic Datum 2000 (NZGD2000) with a reference epoch of 1 January 2000 (2000.0). NZGD2000 is realised in terms of ITRF96 and uses the GRS80 ellipsoid; (see Grant et al., 1999; Blick et al., 2003; Office of the Surveyor-General, 2003a).

A major conceptual departure from the definition of the previous national datum (New Zealand Geodetic Datum 1949) and other international datums is that NZGD2000 accommodates the effects of crustal deformation. This is achieved by applying a deformation model when generating new coordinates, enabling them to be transformed from one epoch to another following a method similar to that described by Snay (1999). For most users, it has the appearance of a static datum.

The accuracy criteria aimed at for NZGD2000 are that a mark’s coordinate accuracy relative to adjacent marks of the next highest order shall not exceed 0.05 m horizontally and 0.15 m vertically (Office of the Surveyor-General, 2003b). The deformation model must be of sufficient accuracy to enable these accuracy requirements to continue to be achieved over time. Where the computed positions of marks using the deformation model differ from the surveyed positions by greater than these limits, consideration will need to be given to refining the deformation model.

The deformation model must be able to reflect the true deformation field with adequate accuracy and resolution. A model should include both the long term deformation trends and, potentially, discrete events such as earthquakes, where the model definition could include surface fault ruptures. This would depend on the extent to which fault movement should be reflected by the deformation field, and the extent to which it should be represented by changing the coordinates of survey marks.

The deformation model used in NZGD2000 (Figure 1) is now seven years old and it is time to consider if the accuracy requirements of the datum are still being met. This paper examines the performance of the current model in 2005 from two points of view: (1) how different are the ITRF2000 velocities from ITRF96, and (2) for new stations, and older stations where additional data have been collected, how well do the newly estimated velocities match those in the deformation model (after the ITRF96-ITRF2000 transformation)?

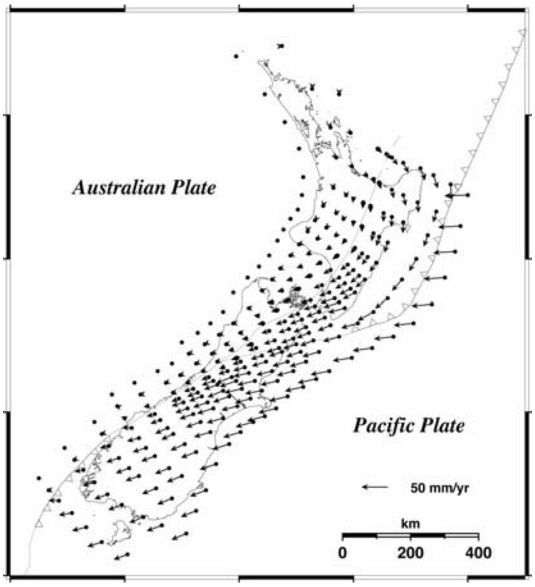

Fig 1. NZGD2000 deformation model, with horizontal velocities relative to the Australian plate plotted at the nodes of the model.

2 Limitations of the NZGD2000 Deformation Model

Coordinates and velocities for 29 primary 1st-order network stations were generated from 4 to 6 repeat GPS surveys made between 1993 and 1998 (Office of the Surveyor-General, 2000). Data from these and other repeat surveys observed between 1991 and 1998 were used to generate a horizontal deformation model relative to the Australian tectonic plate (Figure 1), assuming constant site velocities (Beavan and Haines, 2001).

The velocities at the 29 primary points were also calculated relative to ITRF96 by including their data in global (Morgan and Pearse, 1999) and regional (Beavan, 1998) GPS analyses. In these analyses, a number of global or regional GPS stations are constrained to their ITRF96 positions and velocities, allowing the estimation of ITRF96 coordinates and velocities for all other stations in the solution. A 3-parameter (3 orthogonal rotations) transformation was derived by comparing the horizontal velocities of these 29 points in the deformation model with their estimated ITRF96 values. This transformation was used to convert the Australia-fixed deformation model into ITRF96, and this is the model used by LINZ for the NZGD2000 datum.

The surveys used to determine the deformation model are now on average nearly 10 years old. As time passes, errors in the determination of the velocities used in the deformation model lead to increasing errors in the calculated position of marks in terms of the reference epoch of 2000.0. In effect, the spatial accuracy of the datum is steadily degrading. Also, the datum and the effectiveness of the deformation model may be degraded by localised and temporally non-linear deformation, for example earthquakes and recently observed “slow earthquakes” (e.g., Douglas et al., 2005; Beavan et al., 2006).

In addition, the current deformation model is aligned with ITRF96, and NZGD2000 will therefore drift from future and more accurate realisations of the ITRF. These limitations are shown schematically in Figure 2.

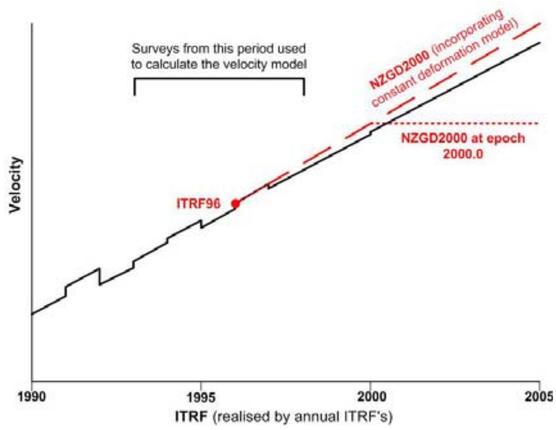

Fig 2. Relationship between ITRF and NZGD2000.

3 Reference Frame Improvements

We can easily convert the deformation model used in NZGD2000 from ITRF96 to ITRF2000 (or another realisation of the ITRF). We simply need to repeat the global or regional GPS analysis of the 29 1st order stations using exactly the same data that went into the original analysis, but with the positions and velocities of the global or regional reference stations constrained to ITRF2000 rather than ITRF96.

Figure 3 shows the differences between the ITRF96 and ITRF2000 positions of the 29 1st order stations between epochs 2000.0 and 2010.0. The differences have grown by ~50 mm over this 10 year period, because of the ~5 mm/yr velocity difference between ITRF96 and ITRF2000 in the New Zealand region. Our estimate of this velocity difference is 4.8 mm/yr at azimuth -101° in the southwest of the country, rising to 5.4 mm/yr at azimuth -111° in the northeast (westward velocities are faster in ITRF2000 than in ITRF96). Because the differences are quite uniform across the country, the absolute position accuracy of the datum is compromised; however, the relative accuracy between marks is maintained.

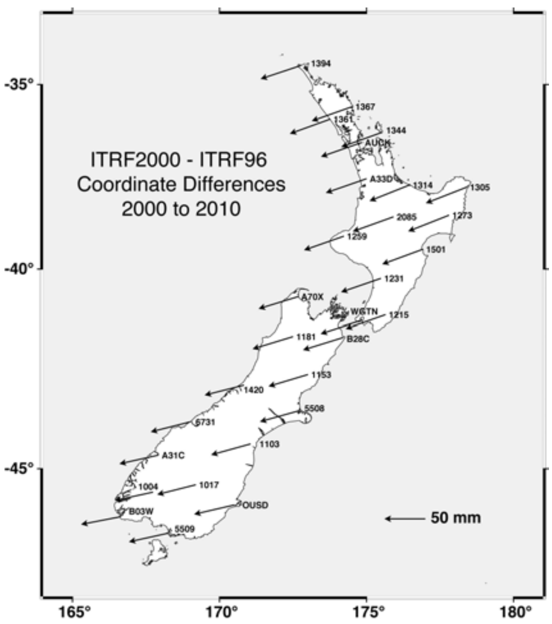

Fig 3. Horizontal coordinate differences between ITRF96 and ITRF2000 from epoch 2000.0 to epoch 2010.0.

While the change from ITRF96 to ITRF2000 velocities can be managed by a standard 7-parameter transformation, the difference of ~5 mm/yr is quite significant; after 10 years it exceeds the NZGD2000 horizontal accuracy criterion cited earlier. We expect that the changes from ITRF2000 to any future realisation of ITRF will be much smaller than this, so that it will be worthwhile aligning any update of NZGD2000 to ITRF2000 (or whatever ITRF realisation is current at the time of the update), rather than retaining ITRF96.

4 Deformation Model Distortions

There are two types of potential distortion in the velocity model itself, even assuming that all points move linearly in time (i.e., with constant velocity). The first is that the velocity estimated at an individual site from 1992-1998 data is likely to be improved by the inclusion of additional (later) data collected from the same site (i.e., more time). The second is that the interpolation of the velocity field between those points where the velocity was actually measured is likely to be improved by the inclusion of velocities from additional spatially distributed points (i.e., more sites). At the time of computation of the NZGD2000 deformation model 371 points were used. There are significant regions where the data were geographically relatively sparse, and the interpolation relied heavily on the minimum strain-rate constraint and the plate-boundary velocity conditions applied at the margins of the model. More than 800 points are now available where velocity estimates can be made and which could be included in a recalculation of the velocity model. These new data have largely been collected in GPS surveys carried out for scientific purposes associated with plate tectonic and earthquake hazard research.

We can test the two types of distortion by comparing the NZGD2000 velocity model with (1) observed velocities at points used in the velocity model where additional data have been collected since 1998, and (2) observed velocities at points not used in the velocity model where at least two well-separated epochs of data have been collected since 1998. In these comparisons, we use a version of the NZGD2000 velocity model that has been transformed from ITRF96 to ITRF2000 as explained in Section 3. We compare this model with observed velocities that we estimate in ITRF2000 by including a set of regional IGS stations in the GPS data analysis and aligning the daily solutions with the ITRF2000 coordinates of these stations. This means we are testing the velocity model itself, with minimal effect from differences in the datum on which it is based.

There are a large number of points that fulfill one or other of the above criteria, but for this study we consider a limited number of points with rather stronger criteria. In the first category (points updated from the NZGD2000 deformation model), we use the 20 1st order points where additional data have been collected since 1998 (Table 1). These were the points that had the best history of occupation in NZGD2000, with at least four epochs of observation between 1993 and 1998. In general either one or two additional epochs of data have been obtained since 1998. In the second category (new points since 1998) we take velocities from 24 continuous GPS stations with at least 2 years of available data. We use these, rather than campaign stations, because the extra data from continuous stations are likely to provide more accurate velocity estimates than we could obtain from the two (or at most three) available campaign occupations.

5 Comparison at updated points

Figure 4 and Table 1 show the velocity differences and estimated uncertainties for the first category of points, whose velocities have been updated since 1998 by the collection of additional data. Since the new velocities use the 1992-1998 data as well as the new data, the uncertainties between the two estimates are not independent.

The uncertainties we plot are from the deformation model (which are larger than those from individual site velocity estimates). Only a few of the differences (3 out of 40; shown in bold type in Table 1) fall significantly outside 3 standard deviations. This suggests that the individual site velocites used in the construction of NZGD2000 were quite reliable, at least for the frequently-measured 1st order sites.

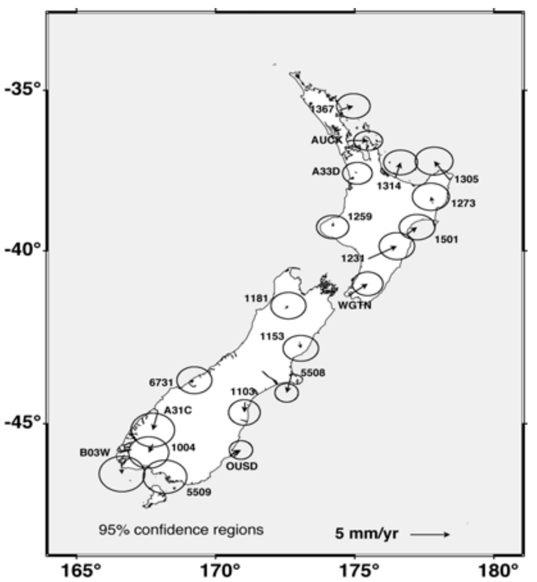

Fig 4. Velocity differences and 95% confidence regions for points used in NZGD2000 whose velocities have been updated with 1 to 3 epochs of new data since 1998.

Table 1. Tabulated velocity differences and 1σ uncertainties shown in Figure 4.

Site	$\delta(v_e)$	$\delta(v_n)$	$\sigma(v_e)$	$\sigma(v_n)$	Yrs[a]	N[b]
1004	-0.50	-1.16	1.03	0.88	7.9	1
1103	-0.08	-1.41	0.81	0.71	11.0	2
1153	0.18	-0.87	0.91	0.72	10.9	1
1181	0.41	0.46	0.90	0.74	10.0	2
1231	**3.59**	1.74	0.91	0.75	11.0	3
1259	-0.07	-0.66	0.83	0.65	10.0	2
1273	-0.24	0.98	0.95	0.76	11.0	2
1305	-1.94	**2.54**	0.97	0.78	11.0	1
1314	0.64	2.06	0.87	0.69	11.0	2
1367	1.53	0.48	0.86	0.69	11.0	2
1501	1.14	0.88	0.92	0.71	11.0	2
5508	-0.67	**-2.69**	0.60	0.52	10.9	2
5509	-0.26	0.41	1.12	0.93	11.0	2
6731	0.82	0.38	0.90	0.75	7.9	1
A31C	-0.64	-2.47	1.12	0.94	5.9	1
A33D	0.34	-0.17	0.76	0.61	10.0	2
AUCK	2.27	-0.02	0.74	0.54	12.3	
B03W	0.09	-1.12	1.17	0.99	7.9	2
OUSD	1.40	0.72	0.60	0.52	10.3	
WGTN	2.30	1.56	0.79	0.66	8.3	

1σ uncertainties are from the deformation model. East-north correlations are ~0. Velocities and uncertainties are in mm/yr. Differences greater than 3σ are shown in bold type.
[a]Total duration of data series in years.
[b]Number of additional epochs of data at campaign sites.

6 Comparison at new points

Figure 5 and Table 2 show the velocity differences and estimated uncertainties for the second category of points, those newly observed since the NZGD2000 calculations. In this case the uncertainties in the model and those in the site velocity estimates are independent, so we combine them by summing variances. A substantially larger fraction of the differences (7 out of 48; shown in bold type in Table 2) fall significantly outside 3 standard deviations in this case. Also, the absolute values of the differences are considerably larger, exceeding ~5 mm/yr at five stations and 7 mm/yr at two of these. This indicates either that the velocity model is not performing particularly well, or that the new velocity estimates are inaccurate in some way. Differences of this size indicate that distortions in the current velocity model may, in some regions, exceed the NZGD2000 50 mm horizontal accuracy criterion in less than 10 years.

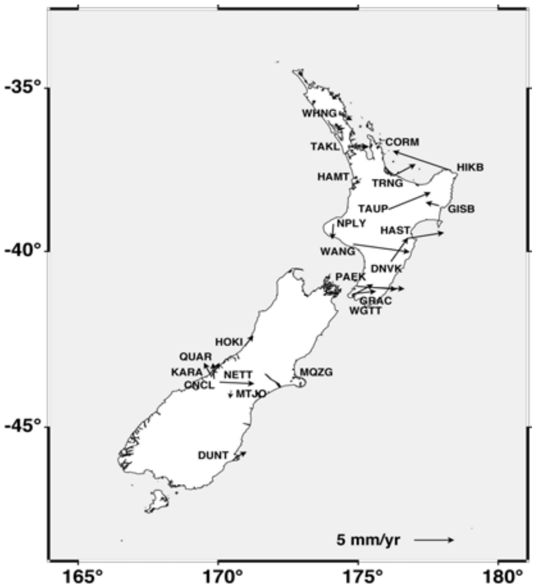

Fig 5. Differences between velocities predicted by the deformation model and velocities observed at continuous sites established since the model was computed, and having > 2 years data. Uncertainties not shown (see Table 2).

Table 2. Tabulated velocity differences shown in Figure 5.

Site	$\delta(v_e)$	$\delta(v_n)$	$\sigma(v_e)$	$\sigma(v_n)$	Years[a]
CNCL	-0.15	2.14	0.99	0.86	5.1
CORM	-0.38	0.20	1.49	1.81	2.2
DNVK	2.12	3.21	1.93	1.85	2.7
DUNT	1.35	0.72	0.54	0.51	5.6
GISB	-1.68	0.45	1.14	1.01	3.0
GRAC	2.54	0.31	0.82	0.72	6.5
HAMT	-0.73	-0.78	1.20	1.11	2.2
HAST	**4.70**	0.80	1.40	1.50	2.8
HIKB	**-7.24**	2.63	2.12	2.44	2.1
HOKI	0.95	1.27	1.05	0.92	6.7
KARA	-0.96	1.90	0.95	0.81	5.1
MAST	3.77	-0.17	1.23	1.21	2.5
MQZG	-0.32	-0.26	0.85	0.76	5.2
MTJO	-0.17	-1.08	0.75	0.74	4.6
NETT	**4.33**	-0.21	1.05	0.95	5.1
NPLY	-0.14	-2.06	0.98	0.93	2.3
PAEK	**5.00**	-0.39	0.91	0.79	5.2
QUAR	0.80	1.54	0.96	0.84	5.1
TAKL	2.16	0.08	0.85	0.78	3.7
TAUP	**5.27**	2.29	1.08	1.01	3.3
TRNG	2.78	1.59	1.36	1.15	2.4
WANG	**7.09**	-1.05	1.81	1.92	2.2
WGTT	**2.63**	1.50	0.79	0.70	5.1
WHNG	1.66	-0.87	1.02	0.83	2.2

Uncertainties are combined from deformation model and site velocity estimates. Other details as in Table 1.

7 Vertical motion

Vertical velocities were also computed for continuous sites with a >4 year data span. The computed velocities all fall between -1.6 mm/yr and +4.3 mm/yr. The largest rates are within the Southern Alps where a more rigorous analysis by Beavan et al. (2004) has shown sites to be rising at 3-5 mm/yr relative to sites on the east coast of the South Island. The definition of vertical rates is subject to some fundamental questions (e.g., Blewitt, 2003), and there are probably regional slopes within the ITRF vertical motion field which affect our estimated velocities. The vertical rates are everywhere small enough that they do not need to be considered in NZGD2000, given the vertical accuracy criterion detailed above.

8 Discussion

It is interesting to explore the reasons for the large horizontal velocity differences between the deformation model and several of the new sites (Table 2). A majority of the large differences are at sites where we have observed non-linear site velocities since the establishment of continuous GPS stations (eg HAST, WANG, DNVK and PAEK). We believe this non-linear deformation is caused by slip episodes lasting from days to months on the deeper part of the subduction interface where the Pacific Plate descends beneath the North Island (Douglas et al., 2005; Beavan et al., 2006). These events are often known as slow slip events or slow earthquakes; the adjective “slow” refers to their rate of slip compared to the several km per second slip rate in normal earthquakes.

Another site with a large velocity discrepancy is HIKB. Though this has shown a fairly steady velocity since the continuous station was installed, it is in a region where slow earthquakes appear to be common. It is possible that the data from this region used in the construction of the NZGD2000 deformation model had been affected by slow earthquakes that were unrecognised in the campaign GPS data available at the time. The widespread occurrence of slow slip events, at least in the North Island, has implications for the NZGD2000 deformation model. So far, the largest event we have observed (in 3 years) has had a magnitude of ~30 mm at the Earth’s surface. This is within the NZGD2000 horizontal accuracy specification, so it is possible that such events can be ignored at the NZGD2000 accuracy level. However, to achieve this it is important that the velocities in the NZGD2000 deformation model are estimated using long enough spans of data that an average velocity is obtained. In the Gisborne region we have evidence that such events recur as often as two-yearly, implying that it should be easy to obtain an average velocity here, the small residual at GISB in Figure 5 indicates we may have achieved this.

Though we have noted that steady vertical velocities may be neglected in respect of the NZGD2000 deformation model, it is still important to estimate these velocities accurately when constructing the datum. This is particularly the case when positions need to be extrapolated to the reference time of the datum. An example is the 2000.0 reference epoch of NZGD2000, for which the data defining the datum were collected between 1992 and 1998. We know of at least one case where the vertical velocity estimated from 1992-98 data was significantly in error. This meant that the height coordinate for that point extrapolated to 2000.0 was in error (though not by more than the NZGD2000 vertical criterion). To mitigate this problem it is desirable to estimate velocities using long data spans, and to set the reference epoch within the available data span.

9 Conclusions

Our tests indicate that the ITRF96 datum drifts at about 5 mm/yr relative to ITRF2000 in the New Zealand region and the NZGD2000 deformation model probably has errors >5 mm/yr in some regions, implying that the NZGD2000 horizontal accuracy criterion will be exceeded within the next few years. Some NZGD2000 stations have larger than desirable vertical position errors because of poor vertical velocity estimates and extrapolation to the 2000.0 reference epoch. There are now >800 sites in New Zealand with GPS velocity estimates, whereas there were <400 when the NZGD2000 deformation model was constructed in 1998. For these reasons it is desirable to construct a new model based on ITRF2000 (or the most current ITRF realisation) within the next few years.

Given the NZGD2000 vertical accuracy requirements, it is not necessary to include a vertical deformation model in the NZGD2000 or successor datums (though it is necessary to use vertical velocities when constructing the datum).

Non-linear site velocities, particularly those related to slow slip events on the North Island subduction zone, have been observed at continuous GPS stations. These events may not be a problem at the specified 50 mm horizontal accuracy level of NZGD2000, provided their future amplitudes do not substantially exceed the 30 mm observed to date (from 3 years of data).

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