Consultancy services for coordinates for PositioNZonLine, Phase 2 (PONL-02)

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EXECUTIVE SUMMARY

In support of LINZ's PositioNZonLine automated positioning service we have completed a set of work with three major aims. These were:

(1) the estimation of transformation parameters between the NZGD2000 reference frame and various realisations of the International Terrestrial Reference Frame using all available GPS data since 1995;

(2) the calculation of time series models to predict the future coordinates of PositioNZ stations; and

(3) the updating of the NZGD2000 deformation model to take advantage of the large amount of GPS data collected since the original model was calculated in 1998.

1. INTRODUCTION

Land Information New Zealand (LINZ) requires a way to model and to predict forward the position of each of the continuous GPS reference stations of the PositioNZ network. The model and prediction should be in the current GNSS reference frame. This is so that an on-line processing system can take data collected at an unknown location and generate its coordinates in the current GNSS reference frame by calculating baseline vectors between the unknown station and nearby PositioNZ stations. LINZ further requires a way to transform the calculated position of the station in the current reference frame to its NZGD2000 coordinates.

Earlier work on the PONL contract by the author and discussions between the author and LINZ staff led to the following set of milestones to achieve the objectives outlined above.

Milestone Number	Description of Task
1	Analysis of 2006 1st order data. Reporting.
2	Re-analysis of 1998, 1996 and 1995 1st order data and re-analysis of other days during 1995-2007 on which any of the 1st order stations have been observed. Reporting.
3	Combine NZ solutions with regional and/or global data to define positions and velocities in ITRF96, ITRF2000 and ITRF2005. Reporting.
4	Generate transformation parameters from NZGD2000 to various realisations of the ITRF. Reporting.
5	Improve LINZ deformation model – Stage 1, using existing (Bernese v4) analyses of GPS survey-mode data collected through March 2007. Reporting.
6	Provide a prediction model for PositioNZ stations. See Note 1 below. Reporting.
7	Improve LINZ deformation model – Stage 2, using new (Bernese v5) analyses of all existing GPS survey-mode and continuous data through to March 2008. Reporting.

Note 1: The prediction model for Milestone 6 shall include estimates of velocity, seasonal cycles and offsets at specified times of earthquakes and equipment changes. If feasible, it shall also include velocity changes at specified times, post-seismic signals starting at specified times, and slow-slip events at specified times.

This report describes the achievement of these milestones.

Milestone 1 (Section 2 of report)

We describe the analysis, using Bernese v5.0 software, of the GPS data collected at 1st-order GPS stations and primary tide gauge reference marks (TGRMs) during February-May 2006.

We use LINZ's adjustment software, SNAP v2.15, to test whether the coordinate and covariance results meet the relative accuracy requirements of 1st-order-2000. We show from a minimally-constrained adjustment that the survey results from 1st-order stations meet the

Class B100H horizontal relative accuracy standard and the Class B300V vertical relative accuracy standard on all baselines. All but two of the primary TGRMs fail to meet these standards, in part because of the short (< 30 km) baselines between these sites and nearby 1st-order marks.

We convert the ITRF2000 coordinates to NZGD2000 and compare these with the coordinates in the LINZ geodetic database (GDB). The maximum discrepancies exceed 50 mm at two stations, but these are sites affected by deformation from the 2003 Secretary Island (Fiordland) earthquake and the 2004-05 Manawatu slow-slip event. Excluding these stations, the maximum horizontal discrepancies fall to 25-30 mm, the mean values to a few mm, and the standard deviations to 10-15 mm.

Milestone 2 (Section 3 of report)

We have processed data from 255 days between 15 Jan 1995 and 30 May 2006 on which at least one 1st-order-2000 station was operating for a session approaching 24 hours in length. We have checked the resulting time series of station coordinates and have found no serious outliers.

Milestone 3 (Section 4 of report)

We have taken the daily coordinate and covariance solutions from Milestone 2 and have used a filtering procedure to calculate positions and velocities of 31 zero- and 1st-order stations in the ITRF2000 (IGb00 realisation) and ITRF2005 (IGS05 realisation) reference frames. During the filtering, each daily solution is aligned to the reference frame by using a 7-parameter transformation onto the coordinates of up to eleven regional stations of the International GNSS[1] Service (IGS).

Milestone 4 (Section 5 of report)

We have calculated 14-parameter Helmert transformations (with some of the parameters set to zero) between the IGb00 and IGS05 coordinate and velocity sets from Milestone 3, and have compared the transformations with those derived from global data sets. There are small discrepancies (less than ±2 mm in position and ±1 mm/yr in velocity) between the various transformation parameters, but these variations are within expectations. We have also calculated 14-parameter Helmert transformations (again with some parameters set to zero) between each of the IGb00 and IGS05 coordinate and velocity sets and the NZGD2000 coordinate and velocity set. These provide a way to transform coordinates estimated from modern GNSS data back to NZGD2000. We have compared the new IGb00->NZGD2000 transformation with one determined in PONL Report 2, and find agreement in transformed horizontal coordinates at the ~3 mm level in 2000, and the ~10 mm level in 2010. For transformed vertical coordinates the corresponding values are ~2 mm and ~12 mm. The RMS of the IGb00 to NZGD2000 and IGS05 to NZGD2000 transformations is ~6 mm in 2000, degrading to ~19 mm in 2010.

[1] Global Navigation Satellite System (of which GPS – the Global Positioning System – is one example).

Milestone 5 (Section 7.1 of report)

Following discussions with LINZ in January 2008, it was agreed that this milestone could be adjusted to include data through to March 2005, rather than March 2007. Note that the work and results for this milestone (reported in Section 7.1) are superceded by the work and results for Milestone 7 (Sections 7.2 - 7.4).

The updated continuous horizontal velocity model (or deformation model) was calculated in the same way as the original model (v2.1) (Beavan, 1998), to give velocities that are nominally relative to the Australian Plate. The input data consisted of 863 velocity estimates from 754 distinct GPS stations, which is more than double the number of stations available for the v2.1 calculations. The updated model is called v2.2, and is supplied in exactly the same format as v2.1.

We also provide Euler rotation parameters to convert the "Australia-fixed" horizontal velocities to the IGS05, IGb00 and ITRF96 reference frames. These were calculated by 3-parameter Helmert transformations (3 rotations) between the v2.2 velocity model and the horizontal components of our estimated IGS05 and IGb00 velocities at 29 of the 30 1st-order and continuous stations used in Beavan (1998). (Station WELL is omitted because it was decommissioned in 1997.) For the transformation to ITRF96 we use the ITRF96 velocities of these 29 stations from the LINZ deformation model. These velocities are essentially the same as those calculated by Morgan and Pearse (1999), which were used by Beavan (1998) in transforming the Australia-fixed velocities of the deformation model to ITRF96.

Milestone 6 (Section 6 of report)

We have created model fits to the daily coordinate time series output from GeoNet's standard daily processing of continuous GPS data using data through late June 2008. The prediction model includes estimates of velocity, seasonal cycles, offsets at specified times of earthquakes and equipment changes, velocity changes at specified times, post-seismic signals starting at specified times, and slow-slip events at specified times. The model is fit to the raw coordinates output from the GPS processing, which are aligned to the IGb00 reference frame at the time of writing. To convert the output from the model to the IGS05 reference frame requires the transformation parameters from Milestone 4. The accuracy of the model has been checked at one point in time by comparing its predictions with a 14-day average of daily coordinate solutions from the GPS processing. This comparison has been made in both the IGb00 and IGS05 reference frames. The results suggest that the accuracy of the model is better than 3 mm in the IGb00 reference frame, but only about 6 mm in the IGS05 reference frame. A fortran program and a file of station coordinates have been provided to enable coordinates at a future time to be estimated from the model.

Milestone 7 (Section 7 of report)

We have analysed almost all available GPS campaign data with sessions longer than 6 hours from January 1996 through March 2008, and have included data from selected New Zealand, Australian and Pacific continuous GPS stations. The analysis has been done in a uniform fashion using the Bernese v5.0 GPS software, and the resulting velocities have been transformed to an Australia-fixed reference frame. The resulting data set consists of 770 velocities from 748 distinct GPS stations. These velocities have been modelled using an updated version of GNS's "deformation map" software to produce a continuous horizontal velocity field, relative to Australia, throughout New Zealand (excluding the Chathams and sub-Antarctic islands). We have included corrections for coseismic offsets during the 21 August 2003 Fiordland and 23 December 2004 Macquarie earthquakes. This deformation model is called v3.0, and is supplied in the same format as v2.1. An updated version of the software for reading the model is supplied, the only change to the original being the increase of some array sizes.

We also provide Euler rotation parameters to convert the "Australia-fixed" horizontal velocities to the IGS05, IGb00 and ITRF96 reference frames. These were calculated by 3-parameter Helmert transformations (3 rotations) between the V3.0 velocity model and the horizontal components of our estimated IGS05 and IGb00 velocities at 29 of the 30 1st-order and continuous stations used in Beavan (1998). (Station WELL is omitted because it was decommissioned in 1997.) For the transformation to ITRF96 we use the ITRF96 velocities of these 29 stations as calculated by Morgan and Pearse (1999); this is the same procedure that was adopted by Beavan (1998).

Additional work

During the course of this work, two variations to the contract were executed in order to provide LINZ with updated coordinates and velocities for the purposes of a Network RTK[2] GNSS testing project. The coordinates and velocities were calculated for various GPS stations in the southern North Island and northern South Island. The reports for these two variations are included as Appendix E and Appendix F.

[2] Real-time kinematic

2. ANALYSIS OF 2006 SURVEY OF LINZ'S 1ST-ORDER NETWORK

2.1 GPS data

The collection of the 2006 data (the "FORS" survey) and the quality-checking of the resulting RINEX files are described in GNS Science Consultancy Report 2006/96 by N Palmer, delivered to LINZ in June 2006. The FORS data consist of at least two sessions of at least 23.5 hours each from each 1st-order mark and from primary tide gauge reference marks (TGRMs) at each of New Zealand's standard ports. The session boundaries coincide with the UT day boundary, and the sample interval is 30 seconds. Maps of the stations occupied can be found in Figure 1 here and on pages 7-8 of Palmer (2006), and timelines of station occupations are on pages 9-11 of that report. On each day the survey was active, we also acquired data from 14 regional IGS stations, namely ALIC, CEDU, CHAT, DARW, HOB2, KARR, MAC1, MCM4, NOUM, PERT, THTI, TIDB, TOW2 and YAR2 (see Figure 3). For the purposes of this analysis we are not including PositioNZ stations in the daily solutions, other than stations AUCK and WGTN which were included in earlier 1st-order surveys, and CHAT which we use as a reference station.

Since the previous 1st-order survey in 1998, two of the stations have been modified. Station 1367 was close to a quarry edge and due for destruction in about 2005-06. In 2005, LINZ contracted Beca Carter to perform a high-accuracy tie between this station and nearby station A6RE, with the intention that A6RE would become the new 1st-order mark in this region. Station B28C was replaced in 2004 by a pillar for the PositioNZ station CMBL. Great care was taken to establish CMBL precisely above B28C and the vertical offset was measured accurately (see CMBL on LINZ geodetic database). For the purposes of this analysis we took three days of rinex data from CMBL (days 054-056, 2006), applied the B28C-CMBL vertical offset to the antenna eccentricity, and renamed the resulting CMBL files as B28C.

2.2 Coordinate estimation in ITRF2000

The GPS phase data from each session were processed in a network solution using the high-accuracy Bernese version 5.0 processing package (Dach et al., 2007), to determine daily estimates of relative coordinates and their covariance matrices. The IGS_01 elevation-dependent antenna phase-centre models were used to account for the different antennas used. Zephyr Geodetic antennas were used at all New Zealand sites except CHAT to further minimise any problems associated with antenna mixing.

Ocean loading corrections were not introduced, as testing several years ago indicated that the inclusion of ocean loading made only a minor improvement in daily coordinate repeatability when 24-hour files were processed. This may have been partly because available ocean tide and coastline models were not sufficiently good to generate accurate ocean load predictions at the near-coast stations typical of New Zealand[3]. The use of 24-hour sessions also significantly attenuates the ocean load signal, whose predominant period in New Zealand is semidiurnal (~12 hr 25 min).

[3] We nevertheless recommend that ocean loading is included when analysing spans of data shorter than a day. Tests should be carried out to see how much improvement is gained in coordinate repeatability when ocean loading is included in the processing of short-duration sessions.

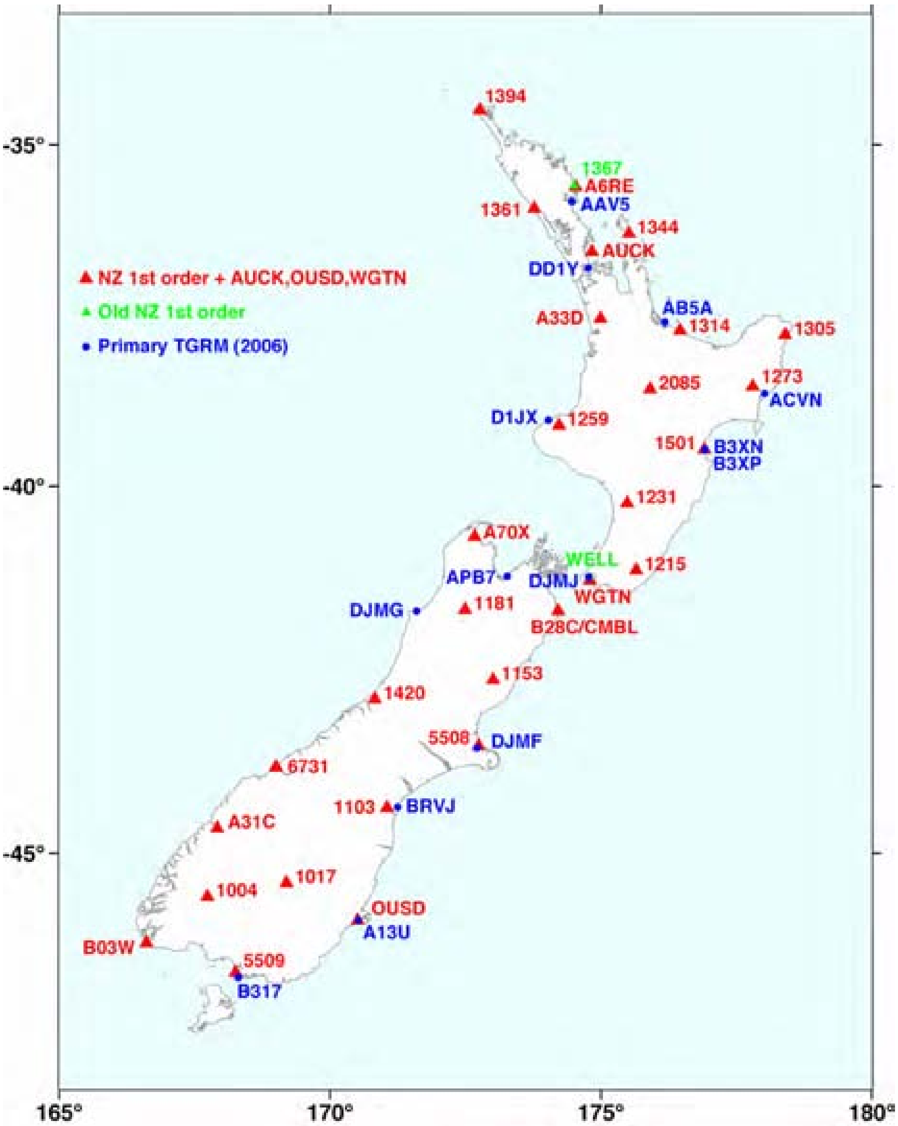

Figure 1 1st order and continuous GPS stations on the New Zealand mainland that were used in the calculation of the NZGD2000 datum and the NZGD2000 deformation model (red and green triangles). Also primary tide gauge reference marks observed in the 2006 First Order Re-Survey (blue circles).

Tropospheric delays were estimated hourly at each station in a piecewise continuous fashion, and the tropospheric gradient was estimated daily in a piecewise continuous fashion. The dry Niell model was used as the a priori model, with the wet Niell mapping function used to map slant-path delays to zenith.

During each day's processing, IGS final orbits and associated polar motion files were held fixed, and a 7-parameter Helmert transformation was applied to the coordinate results so as to best fit the ITRF2000 (IGb00 realisation) coordinates of a set of regional IGS stations at the epoch of observation. The IGS stations used for reference frame realisation were: ALIC, AUCK, CEDU, CHAT, HOB2, KARR, MCM4, NOUM, TIDB, YAR2 (see Figure 3). The daily coordinate results are therefore nominally in the ITRF2000 reference frame (IGb00 realisation) at the epoch of measurement.

All daily coordinate-difference solutions and their covariances were input to the least squares adjustment software ADJCOORD (Crook, 1992; Bibby, 1982) to check for outliers and to obtain the appropriate χ^2 factor for subsequent scaling of the covariance matrix. Station AUCK was held fixed to obtain a minimally-constrained solution. The covariance matrices require scaling because the temporal correlation of the GPS phase data is neglected in the estimation of the formal errors in the Bernese software, so that the formal uncertainties are underestimated compared to the scatter in daily coordinate results. The scaling factor depends on the noise properties of each data set, and also depends on the sample interval of the GPS phase data used to obtain final coordinates. A factor of 5^2 (=25) was determined for the 180-second samples we use in the final stages of our processing (in which 30-second samples are used for data editing and cycle-slip fixing, then the data are decimated to 180 seconds for subsequent processing). This factor is consistent with what we have found for other regional GPS surveys. This procedure ensures that the relative coordinate uncertainties are consistent with the scatter of repeated observations within the survey. Three observations, one each at stations OUSD, A70X and CHAT, were rejected because their standardised residuals exceeded the 95% confidence limit for the maximum variates of a t distribution. Even with these rejections, all three stations have more than two days of data in the resulting solution. The standard error of unit weight of the solution was 1.00.

2.3 Coordinate estimation in NZGD2000

The coordinate files for the daily solutions were each converted to NZGD2000 using the parameters given in PONL draft report 2 (submitted to LINZ in August 2006). These coordinate files and their associated covariance files were combined using the COMPAR program from the Bernese suite to give a combined NZGD2000 coordinate file for the FORS survey. Table 1 gives the NZGD2000 coordinates taken from the LINZ GDB (in which stations A6RE and B3XP are designated as orders 3 and 4). Table 2 gives the FORS coordinates transformed to NZGD2000, and the differences between these coordinates and the GDB values.

Table 2 also gives some statistics on these differences. The mean horizontal differences are only a few mm, with standard deviations of 15-20 mm. The two largest differences of 50-60 mm are at stations 1004 and 1231. These can be attributed to the 2003 Fiordland earthquake and the 2004-05 Manawatu slow-slip event, respectively. With these sites excluded, the maximum horizontal differences fall to 25-30 mm and the standard deviations to 10-15 mm.

2.4 Accuracy testing

We use SNAP (Crook, 2003) to calculate a minimally-constrained solution from the ITRF2000 FORS coordinate and covariance files, with the coordinates of station AUCK fixed to their ITRF2000 (IGb00 realisation) values near the middle of the survey. This solution uses only stations within the region of validity of NZGD2000, so CHAT and the regional IGS stations are not included. The standard error of unit weight of the solution is 0.82, lower than the 1.00 found in Section 2.2. This is probably because of the exclusion of the long baselines to the regional IGS stations.

Table 1 NZGD2000 Coordinates from LINZ Geodetic Database (GDB)

Geodetic Code	Lat	Lon	Ell Hgt	Crd Order
1004	-45.562114202	167.738924057	411.196	1
1017	-45.387644701	169.197702098	1680.809	1
1103	-44.400569527	171.057344596	397.157	1
1153	-42.687417778	173.010278220	405.505	1
1181	-41.729082571	172.499523535	1486.646	1
1215	-41.180141864	175.652164178	590.791	1
1231	-40.240198025	175.488311848	143.609	1
1259	-39.133999595	174.228213410	263.041	1
1273	-38.575152214	177.804852555	323.407	1
1305	-37.824541932	178.407103091	360.454	1
1314	-37.759466453	176.466409162	95.727	1
1344	-36.333055071	175.518603243	438.003	1
1361	-35.962107317	173.769415957	164.970	1
1394	-34.466585968	172.771409170	351.050	1
1420	-42.953246399	170.829658128	919.307	1
1501	-39.478985214	176.917245718	119.271	1
2085	-38.616047237	175.915026922	760.272	1
5508	-43.581503667	172.743045187	335.355	1
5509	-46.536929728	168.253439043	176.343	1
6731	-43.860817407	169.003590817	14.412	1
A13U	-45.862624499	170.523145722	57.243	1
A31C	-44.673506600	167.924065991	9.546	1
A33D	-37.589384029	175.000023214	318.912	1
A6RE	-35.630325580	174.537516523	157.334	3
A70X	-40.713000709	172.672209514	169.539	1
AAV5	-35.851972860	174.469750600	44.299	1
AB5A	-37.633747780	176.183692117	36.566	1
ACVN	-38.675281479	178.025502606	24.780	1
APB7	-41.261823710	173.272632300	19.380	1
AUCK	-36.602844497	174.834385556	132.711	0
B03W	-46.156391318	166.609326421	44.264	1
B28C	-41.749046004	174.213808539	254.535	1
B317	-46.592909909	168.311919726	11.196	1
B3XN	-39.477729194	176.921058353	22.009	1
B3XP	-39.478790193	176.920166665	22.694	4
BRVJ	-44.392936974	171.250297770	27.336	1
D1JX	-39.057618383	174.030661384	28.365	1
DD1Y	-36.841440770	174.770284127	37.509	1
DJMF	-43.603109778	172.718233455	24.827	1
DJMG	-41.745920258	171.599658351	18.385	1
DJMJ	-41.277518035	174.777181636	24.298	1
OUSD	-45.869501593	170.510920749	26.197	1
WGTN	-41.323457079	174.805894058	26.073	0

Table 2 FORS 2006 results converted to NZGD2000, and differences from GDB values[1]

Geodetic Code	Lat	Lon	Ell Heigt	Differences, mm[2] N	E	U
1004	-45.562113911	167.738923402	411.230	32.4	-51.0	34.0
1017	-45.387644673	169.197701751	1680.814	3.1	-27.1	5.0
1103	-44.400569637	171.057344658	397.154	-12.2	4.9	-3.0
1153	-42.687417886	173.010278232	405.521	-12.0	1.0	16.0
1181	-41.729082556	172.499523651	1486.651	1.7	9.6	5.0
1215	-41.180142047	175.652164200	590.775	-20.3	1.8	-16.0
1231	-40.240197835	175.488312548	143.614	21.1	59.4	5.0
1259	-39.133999707	174.228213351	263.055	-12.5	-5.1	14.0
1273	-38.575152187	177.804852432	323.408	3.0	-10.7	1.0
1305	-37.824541789	178.407102734	360.470	15.9	-31.4	16.0
1314	-37.759466272	176.466409142	95.741	20.1	-1.8	14.0
1344	-36.333055157	175.518603246	438.008	-9.6	0.3	5.0
1361	-35.962107400	173.769416064	164.977	-9.2	9.6	7.0
1394	-34.466586121	172.771409228	351.047	-17.0	5.3	-3.0
1420	-42.953246238	170.829658117	919.330	17.9	-0.9	23.0
1501	-39.478985175	176.917245873	119.278	4.3	13.3	7.0
2085	-38.616047057	175.915027131	760.264	20.0	18.2	-8.0
5508	-43.581503921	172.743045072	335.367	-28.2	-9.3	12.0
5509	-46.536929598	168.253439001	176.362	14.5	-3.2	19.0
6731	-43.860817281	169.003590945	14.434	14.0	10.3	22.0
A13U	-45.862624649	170.523145746	57.231	-16.7	1.9	-12.0
A31C	-44.673506764	167.924065743	9.568	-18.2	-19.6	22.0
A33D	-37.589384124	175.000023184	318.928	-10.6	-2.6	16.0
A6RE	-35.630325674	174.537516576	157.395	-10.5	4.8	61.0
A70X	-40.713000847	172.672209611	169.566	-15.3	8.2	27.0
AAV5	-35.851972878	174.469750724	44.309	-2.0	11.2	10.0
AB5A	-37.633747639	176.183692194	36.570	15.7	6.8	4.0
ACVN	-38.675281469	178.025502420	24.817	1.1	-16.1	37.0
APB7	-41.261823683	173.272632541	19.388	3.0	20.1	8.0
AUCK	-36.602844555	174.834385673	132.737	-6.4	10.4	26.0
B03W	-46.156391366	166.609326398	44.275	-5.3	-1.8	11.0
B28C	-41.749045848	174.213808607	254.520	17.3	5.6	-15.0
B317	-46.592909793	168.311919699	11.218	12.9	-2.1	22.0
B3XN	-39.477729212	176.921058501	22.029	-2.0	12.7	20.0
B3XP	-39.478790157	176.920166879	22.713	4.0	18.4	19.0
BRVJ	-44.392937114	171.250297915	27.335	-15.6	11.5	-1.0
D1JX	-39.057618508	174.030661391	28.378	-13.9	0.6	13.0
DD1Y	-36.841440767	174.770284278	37.525	0.3	13.4	16.0
DJMF	-43.603110042	172.718233399	24.830	-29.4	-4.5	3.0
DJMG	-41.745920195	171.599658525	18.346	7.0	14.4	-39.0
DJMJ	-41.277517965	174.777181941	24.288	7.8	25.5	-10.0
OUSD	-45.869501608	170.510920944	26.201	-1.7	15.1	4.0
WGTN	-41.323457027	174.805894227	26.083	5.8	14.1	10.0
			Mean[3]	-0.5	2.9	8.5
			Stdev	14.7	17.2	14.5
			Max +ve[4]	32.4	59.4	37.0
			Max –ve[5]	-29.4	-51.0	-39.0
		Excl. 1004, 1231	Mean	-1.9	2.8	7.9
			Stdev	13.6	12.3	14.3
			Max +ve	20.1	25.5	37.0
			Max -ve	-29.4	-31.4	-39.0

[1]Conversion to NZGD2000 coordinates from ITRF2000 coordinates at epoch of FORS survey uses the parameters from PONL draft report 2 (August 2006).

[2]Differences are in the sense: FORS-GDB.

[3]Statistics (mean, stdev, etc.) omit stations that are not order 0 or 1 in the GDB (i.e., A6RE, B3XP).

[4]Max positive difference is at 1231 and is due to 2004-05 Manawatu slow-slip event.

[5]Max negative difference is at 1004 and is due to 2003 Fiordland earthquake.

We use the relative accuracy specification testing feature of SNAP to test whether the set of stations consisting of the primary TGRMs, the 1st-order stations and the pre-existing zero-order stations (AUCK, WGTN, OUSD) meet the Class B100H horizontal and B300V vertical relative accuracy standards that are required for 1st-order coordinate results (OSG, 2003). The input and output SNAP files are included on the CD accompanying this report, and the summaries of the specification testing are provided in Appendix A.

We find that most tested baselines meet the Class B100H horizontal standard. Twelve baselines fail the test, by a maximum factor of 2.1. The failures are all on short baselines, 0.4 – 30 km, where the B100 test is most stringent, ranging from 3 – 3.6 mm relative accuracy at the 95% confidence level. If we remove all primary TGRMs except APB7 and DJMG from the test, then all baselines pass.

For the vertical component, thirteen baselines fail the B300V vertical relative accuracy test, by up to a factor of 6 on the very short B3XP-B3XN baseline. The failures involve baselines between most of the primary TGRMs and a nearby zero-order or 1st-order station, meaning that the majority of the primary TGRMs fail the test. Again, the failures are all on short baselines, 0.4 – 30 km in length, where the B300 tolerance ranges from 3 – 10 mm relative accuracy at the 95% confidence level. These results reflect the difficulty in achieving such low day-to-day vertical repeatabilities by GPS methods. The situation is probably made worse by the poor environment for GPS surveying at many of the primary TGRM sites (George, 2004; Palmer, 2004). See also our report on TGRM2 processing (Beavan, 2004) for further discussion, as we found similar results when processing that survey. Again, all baselines satisfy the B300V criteria if we remove all primary TGRMs except APB7 and DJMG from the test.

3. REANALYSIS OF ALL HIGH-PRECISION DATA COLLECTED AT 1ST-ORDER STATIONS FROM 1995-2006

We identified all days between 1 January 1995 and 31 May 2006 on which at least 12 hours of data were available in the GNS rinex database from at least one 1st-order station. In general, the data outside the LINZ-supported NZ 1st-order, TGRM, TGRM2 and PONL surveys were collected by GNS in the North Island and by GNS and Otago University School of Surveying (OUSS) in the South Island, under surveys supported by the Foundation for Research, Science and Technology (FRST). Some data were also available from DoSLI 2nd-order-2000 surveys. LINZ also supplied the tie data between stations 1367 and A6RE, which were collected in 2005 due to the imminent destruction of station 1367. Some data collected by DoSLI in 1995 and 1996 were in approximately 8-hour sessions crossing the UT day boundary. These data were rejected by the analysis strategy we used.

Table 3 summarises the 255 days (30 in 2006; 225 earlier) on which we obtained solutions for at least one 1st-order station. In the table, the stations above the horizontal line are the New Zealand first-order stations, plus the three continuous stations – AUCK, OUSD and WGTN – that were used in the development of NZGD2000. The stations below the line are regional stations also included in our analysis. The regional rinex data were sourced from IGS data centres and a set of CDs of early Australian data supplied to GNS several years ago by AUSLIG (Australia Surveying and Land Information Group; now part of Geoscience Australia). Where regional station data are missing in Table 3, this means that the station had not yet started recording or that the data were otherwise unavailable.

Our GPS analysis uses the same strategy as for the 2006 PONL calculations, as described in Section 2.2 above, with two exceptions. (1) We have used a 3-parameter Helmert transformation (3 translations) in the final stages of the Bernese processing (rather than a 7-parameter transformation), as recommended in the Bernese manual for regional networks. (2) We have included estimates of ocean load displacement in the analysis, using the TPX0.7.1 ocean tide model and the on-line ocean loading calculator from Onsala Space Observatory (http://www.oso.chalmers.se/~loading). We use IGS final orbits and the associated IGS polar motion files in our analysis, and do not solve for orbits or polar motion. These orbits were generated in a variety of reference frames, as later realisations of the ITRF were adopted by the IGS. For all orbits prior to the adoption of ITRF2000 we have transformed the orbit and polar motion files to ITRF2000 using the transformation parameters published by the IERS. If there are regional distortions in any of the reference frames, these will not be corrected by this procedure. As discussed in Section 2.2, at the last stage of the Bernese processing we transform (using three translations) each daily solution to best fit the ITRF coordinates (in the IGb00 or IGS05 reference frame realisation) of a set of regional IGS stations. Insofar as any regional distortion can be described by such a transformation, this procedure will tend to correct the distortion. These raw time series, transformed to local (ENU) coordinates and with their mean values subtracted, are plotted in Figure 2 in the ITRF2000 (IGb00) reference frame.

We then analyse the time series of daily coordinate and covariance files using GNS's in-house VELFRAME software. This is a filtering procedure that provides velocity estimates and also detects outliers in the time series, though no significant outliers were found in the present analysis. The VELFRAME processing is discussed more fully in Section 4.

Table 3a Days with processed 1st-order and regional GPS data, 1995-2006

YEAR	1995	1995	1995	1995	1995	1995	1995	1995	1995	1995	1995	1995	1995	1995	1995	1995	1995	1995	1995	1995	1995	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996
DAY	016	018	019	020	022	023	024	025	026	027	028	029	030	066	067	068	102	108	109	110	113	012	013	014	015	016	017	018	019	020	021	022
1004														*	*	*																
1017														*	*	*																
1103														*	*	*		*		*												
1153														*	*	*		*	*	*												
1181														*	*	*		*	*	*												
1215														*	*	*																
1231														*	*	*																
1259														*	*	*																
1273														*	*	*																
1305														*	*	*																
1314														*	*	*																
1344														*	*	*																
1361														*	*	*																
1367														*	*	*																
1394														*	*	*																
1420	*	*	*	*	*	*	*	*	*	*	*	*	*					*	*	*		*	*	*	*	*	*	*	*	*	*	*
1501	*													*	*	*																
2085														*	*	*																
5508	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*		*		*	*	*	*	*	*	*	*		*	*
5509	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*					*											
6731														*	*	*		*	*	*							*					
A31C														*	*	*																
A33D														*	*	*																
A6RE																																
A70X														*	*	*																
AUCK																						*	*	*			*	*	*	*	*	*
B03W														*	*	*																
B28C														*	*	*	*															
OUSD	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*			*	*	*	*	*	*	*	*	*
WELL	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
WGTN																																
ALIC																																
CEDU														*																		
CHAT																						*	*	*	*	*	*	*	*	*	*	*
DARW																																
HOB2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*											
KARR														*			*	*		*	*											
MAC1	*	*	*	*	*	*	*	*	*	*	*	*	*																			
MCM4								*	*	*	*	*	*	*	*	*	*	*	*	*	*					*	*	*	*	*	*	*
NOUM																																
PERT	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*						*	*	*	*	*	*	*	*	*	*	*
THTI																																
TID2																																
TIDB	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
TOW2																				*		*	*	*	*	*	*		*	*	*	*
YAR1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
YAR2																																

Table 3b Days with processed 1st-order and regional GPS data, 1995-2006

YEAR	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1997	1997	1997	1997	1997	1997
DAY	023	024	025	026	027	028	029	030	031	032	033	034	035	036	039	040	041	042	043	044	045	053	065	066	067	284	009	010	011	012	013	014
1004																							*	*	*							
1017																							*	*	*							
1103	*																						*	*	*							
1153																							*	*	*							
1181																							*	*	*							
1215																							*	*	*							
1231																							*	*	*							
1259																							*	*	*							
1273																							*	*	*							
1305																							*	*	*							
1314																							*	*	*							
1344																							*	*	*							
1361																							*	*	*							
1367																							*	*	*							
1394																							*	*	*							
1420	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*			*	*	*	*	*
1501																							*	*	*							
2085																							*	*	*							
5508	*	*	*	*	*	*				*													*	*	*	*	*	*	*	*	*	*
5509																							*	*	*						*	*
6731																							*	*	*							
A31C																							*	*	*							
A33D																							*	*	*							
A6RE																																
A70X																							*	*	*							
AUCK			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
B03W																							*	*	*							
B28C																						*	*	*	*							
OUSD	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
WELL	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
WGTN																											*	*	*	*	*	*
ALIC																																
CEDU																																
CHAT	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
DARW																																
HOB2																*	*	*	*	*		*	*			*						*
KARR																																
MAC1														*									*	*	*		*	*	*	*	*	*
MCM4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
NOUM																																
PERT	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
THTI																																
TID2																																
TIDB	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
TOW2		*		*																			*	*	*							
YAR1	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
YAR2																																

Table 3c Days with processed 1st-order and regional GPS data, 1995-2006

YEAR	1997	1997	1997	1997	1997	1997	1997	1997	1997	1997	1997	1997	1997	1997	1997	1997	1997	1997	1997	1997	1997	1998	1998	1998	1998	1998	1998	1998	1998	1998	1998	1998
DAY	015	016	017	018	019	020	023	037	069	070	071	096	097	098	099	100	107	113	114	119	120	039	040	042	043	044	045	046	047	250	251	257
1004									*	*	*	*	*	*	*	*														*	*	
1017									*						*	*														*	*	
1103									*	*	*				*	*						*	*							*	*	
1153									*	*	*						*													*		*
1181										*	*						*			*	*											*
1215									*	*	*																					*
1231									*	*	*																					*
1259									*	*	*							*	*													*
1273								*	*	*	*																					*
1305									*	*	*																					
1314									*	*	*							*	*													
1344									*	*	*							*														
1361									*	*	*																					
1367									*	*	*							*														
1394									*	*	*																					
1420	*	*	*	*	*	*			*	*	*						*				*				*		*	*	*	*	*	
1501									*	*	*							*	*													*
2085									*		*							*	*													*
5508	*	*					*		*	*	*													*	*	*				*	*	
5509	*	*	*	*	*					*	*				*	*														*	*	
6731									*	*	*				*	*												*		*	*	
A31C									*	*	*				*	*														*	*	
A33D									*	*	*							*	*													
A6RE																																
A70X									*	*	*						*															*
AUCK	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
B03W									*	*	*				*															*	*	
B28C									*	*	*									*												*
OUSD	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
WELL	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*																
WGTN	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
ALIC																		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
CEDU																										*	*	*	*	*	*	*
CHAT	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
DARW																						*	*		*		*		*	*	*	*
HOB2	*	*	*	*	*	*		*		*	*	*		*	*	*						*		*	*	*	*		*	*	*	
KARR																		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
MAC1	*	*			*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*		*		*	*	*	*	*	*	*
MCM4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*									*	*	*
NOUM																								*	*	*	*	*	*		*	*
PERT	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
THTI																																
TID2																						*	*	*	*	*	*	*	*	*	*	*
TIDB	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
TOW2																				*	*					*		*	*	*	*	*
YAR1	*	*	*	*				*	*	*	*	*	*	*	*	*	*	*	*			*	*	*	*	*	*	*	*	*	*	*
YAR2																						*	*	*			*		*	*	*	*

Table 3d Days with processed 1st-order and regional GPS data, 1995-2006

YEAR	1998	1998	1998	1998	1999	1999	1999	1999	1999	1999	1999	1999	1999	1999	1999	1999	1999	1999	1999	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2001	2001	2001
DAY	258	259	264	265	015	016	027	028	029	030	031	035	036	038	039	040	270	271	272	012	013	014	018	019	081	082	087	088	089	008	009	010
1004																																
1017																																
1103																																
1153									•	•																						
1181	•									•	•																					
1215	•	•			•	•																										
1231	•																										•	•	•			
1259			•																						•	•						
1273			•																											•	•	
1305			•	•																												•
1314			•	•																												
1344			•	•																												
1361			•	•																												
1367			•	•																												
1394			•	•																												
1420												•	•										•	•								
1501	•																															
2085			•																													
5508														•	•	•	•	•	•	•	•	•										
5509																																
6731																																
A31C																																
A33D			•	•																												
A6RE																																
A70X	•						•	•																								
AUCK	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
B03W																																
B28C	•											•	•																			
OUSD	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•			•	•	•	•	•	•	•	•	•	•	•
WELL																																
WGTN	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
ALIC	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
CEDU	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
CHAT	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
DARW	•	•	•	•													•			•	•	•	•	•	•	•	•	•	•	•	•	
HOB2	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
KARR	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•						•	•	•	•	•	•	•	•
MAC1	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•									•	•		•	•	•	•	•
MCM4	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•
NOUM			•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
PERT	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•						•	•	•	•	•	•	•	•
THTI																	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
TID2	•	•	•	•													•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
TIDB	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•																
TOW2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
YAR1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
YAR2	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•													

Table 3e Days with processed 1st-order and regional GPS data, 1995-2006

YEAR	2001	2001	2001	2001	2001	2001	2001	2001	2001	2001	2001	2001	2001	2001	2001	2001	2002	2002	2002	2002	2002	2002	2002	2002	2002	2003	2003	2003	2003	2003	2003	2003
DAY	011	034	035	036	038	039	040	041	042	043	044	045	047	048	067	068	022	023	048	049	050	071	072	073	356	016	017	023	034	040	041	042
1004		*	*	*	*	*	*	*	*	*	*																					
1017																																
1103																				*	*											
1153																																
1181																																
1215																						*	*	*								
1231																	*	*												*	*	*
1259																																
1273																																
1305	*																															
1314																													*			
1344																																
1361																																
1367																												*				
1394																																
1420																																
1501															*	*																
2085																																
5508																																
5509																																
6731		*	*										*	*					*	*												
A31C								*	*	*	*	*																				
A33D																									*							
A6RE																																
A70X																																
AUCK	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
B03W						*	*	*																		*	*					
B28C																																
OUSD	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
WELL																																
WGTN	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
ALIC	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
CEDU	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*			*	*	*	*	*	*	*	*	*	*	*	*	*	*
CHAT	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*				*	*	*	*	*	*	*	*	*	*	*
DARW	*	*		*	*		*	*	*	*	*	*			*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*
HOB2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
KARR	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	
MAC1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*			*
MCM4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
NOUM	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*
PERT	*																*	*	*	*	*	*	*	*	*	*	*	*		*	*	*
THTI		*	*	*	*	*	*					*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
TID2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*						*	*	*	*	*	*	*	*	*	*	*
TIDB																	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
TOW2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
YAR1		*	*	*	*	*	*	*				*	*	*	*	*	*	*	*		*	*	*	*								
YAR2																								*	*	*	*	*	*	*	*	*

Table 3f Days with processed 1st-order and regional GPS data, 1995-2006

YEAR	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2003	2004	2004	2004	2004	2004	2004	2004	2004	2004
DAY	043	044	045	046	047	048	108	109	110	111	112	169	170	173	174	177	179	182	184	188	241	242	244	020	021	033	034	036	037	042	044	045
1004																					*	*	*	*	*							
1017							*	*	*	*	*																					
1103																*	*															
1153																														*	*	*
1181																		*	*									*	*			
1215																																
1231	*	*	*	*	*	*										*																
1259			*	*	*	*						*																				
1273													*																			
1305																																
1314																																
1344																																
1361																																
1367																																
1394																																
1420																																
1501															*																	
2085																																
5508														*																		
5509																				*												
6731																																
A31C																																
A33D																																
A6RE																																
A70X																										*	*					
AUCK	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
B03W																																
B28C																																
OUSD	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
WELL																																
WGTN	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
ALIC	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
CEDU	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
CHAT	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
DARW	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*			*	*	*	*	*	*	*	*	*	*
HOB2	*	*	*	*		*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
KARR	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
MAC1	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
MCM4	*	*	*				*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
NOUM	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*		*	*				
PERT	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
THTI	*	*	*	*	*	*	*	*				*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*		*	*
TID2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*				*								
TIDB	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
TOW2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
YAR1																																
YAR2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Table 3g Days with processed 1st-order and regional GPS data, 1995-2006

YEAR	2004	2004	2004	2004	2004	2004	2004	2004	2004	2004	2004	2004	2004	2004	2004	2004	2004	2004	2004	2004	2004	2004	2005	2005	2005	2005	2005	2005	2005	2005	2005	2005
DAY	048	050	051	054	055	056	057	058	059	068	069	070	072	073	074	076	077	078	080	081	082	089	022	023	044	045	059	060	061	062	098	099
1004																							*	*								
1017																											*	*	*	*		
1103										*	*	*																				
1153																																
1181				*	*	*		*	*																							
1215																																
1231										*	*	*																				
1259										*	*	*																				
1273																			*	*	*											
1305																			*	*												
1314																*	*	*							*	*						
1344																																
1361																																
1367					*	*	*	*	*													*									*	*
1394																																
1420																																
1501																*	*	*														
2085																																
5508	*	*	*																													
5509													*	*	*																	
6731																																
A31C																																
A33D					*	*	*	*																								
A6RE																																*
A70X																																
AUCK	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
B03W																																
B28C																																
OUSD	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
WELL																																
WGTN	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
ALIC	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
CEDU	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
CHAT	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
DARW	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
HOB2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
KARR	*	*	*	*	*	*												*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
MAC1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
MCM4	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
NOUM	*	*	*			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
PERT	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
THTI	*	*					*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*				*	*	*
TID2																						*	*	*	*	*	*	*	*	*	*	*
TIDB	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
TOW2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
YAR1																																
YAR2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Table 3h Days with processed 1st-order and regional GPS data, 1995-2006

YEAR	2005	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006
DAY	100	038	039	040	042	043	044	045	046	053	054	055	056	057	058	060	061	062	066	067	086	087	088	089	121	122	123	124	148	149	150
1004							*	*	*																						
1017		*	*	*																											
1103																			*	*											
1153											*	*	*	*																	
1181											*	*	*	*																	
1215																									*	*	*				
1231																									*	*	*	*			
1259																										*	*				
1273																									*	*	*				
1305																									*	*	*	*			
1314																						*	*								
1344																						*	*								
1361																					*	*	*								
1367	*																														
1394																					*	*	*								
1420												*	*	*	*																
1501																										*	*				
2085																						*	*	*							
5508										*	*	*	*	*		*	*	*													
5509		*	*																												
6731		*	*	*																											
A31C		*	*		*	*																									
A33D																					*	*	*	*							
A6RE	*																					*	*								
A70X										*	*	*	*																		
AUCK	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
B03W							*	*																					*	*	*
B28C											*	*	*																		
OUSD	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
WELL																															
WGTN	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
ALIC	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
CEDU	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
CHAT	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
DARW	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
HOB2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
KARR	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*			*	*	*	*	*			*	*	*	*	*	*	*
MAC1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
MCM4	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
NOUM	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
PERT	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
THTI	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*
TID2	*																														
TIDB	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
TOW2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
YAR1																															
YAR2	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*			*	*	*	*	*	*	*	*	*	*	*

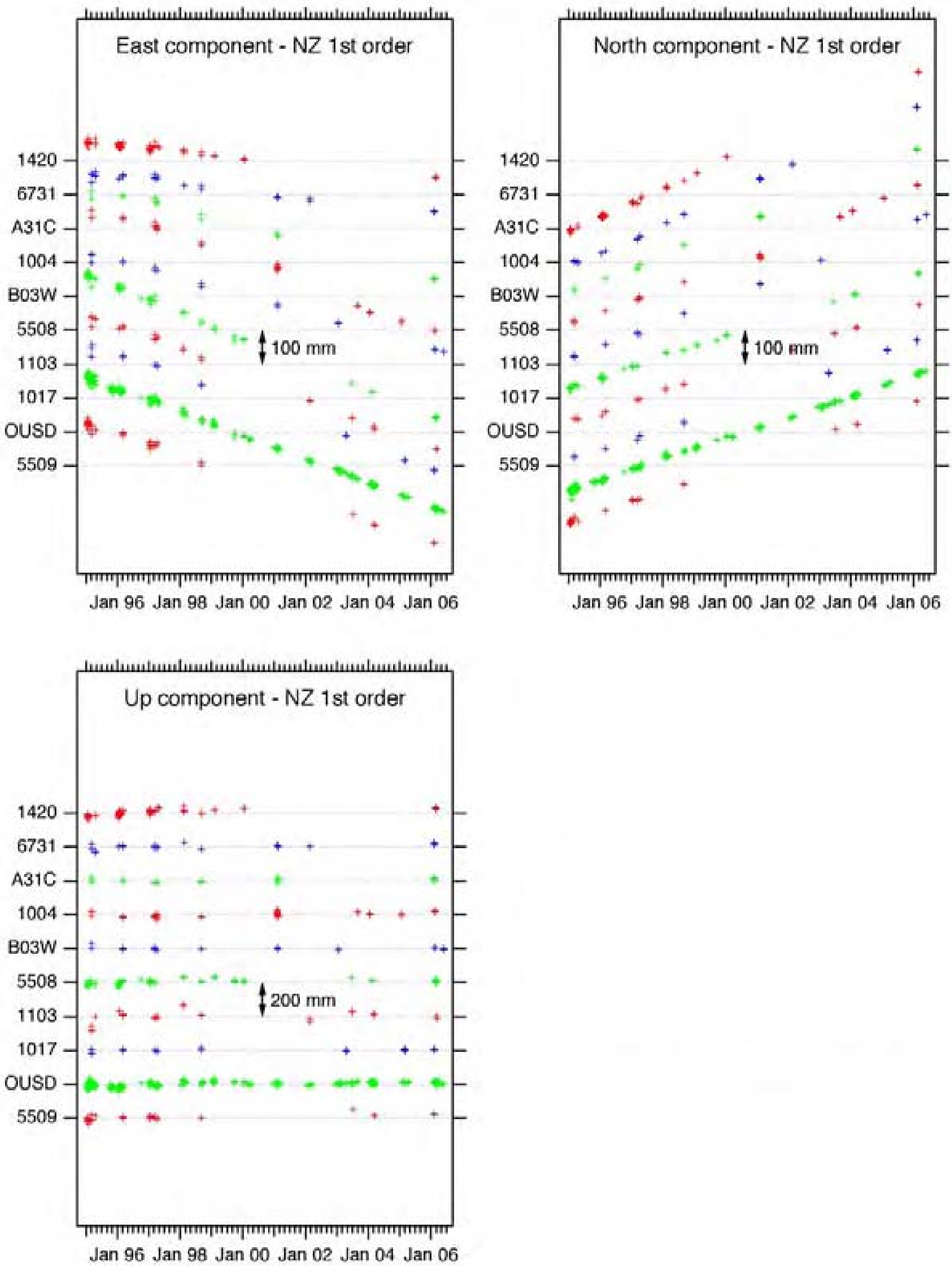

Figure 2a ITRF2000 coordinates taken from Bernese solutions and plotted as “raw” time series for southern New Zealand. The coordinates are plotted in a local (ENU) frame, with their mean value subtracted. The traces are coloured cyclically red, green, blue from the bottom of each plot to help differentiate the stations from each other. LINZ station codes are given on the left axis.

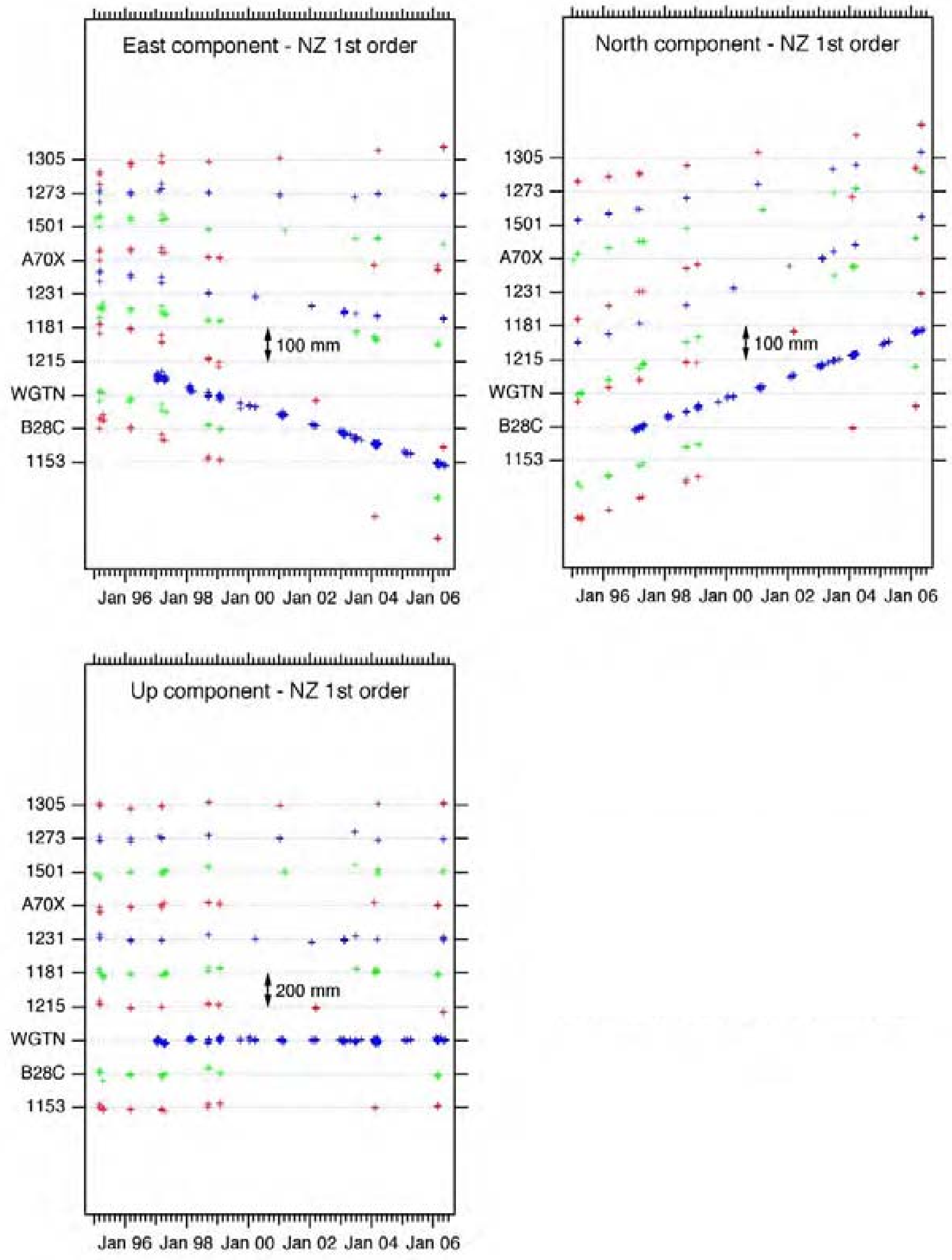

Figure 2b ITRF2000 coordinates taken from Bernese solutions and plotted as "raw" time series for central New Zealand. The coordinates are plotted in a local (ENU) frame, with their mean value subtracted. The traces are coloured cyclically red, green, blue from the bottom of each plot to help differentiate the stations from each other. LINZ station codes are given on the left axis.

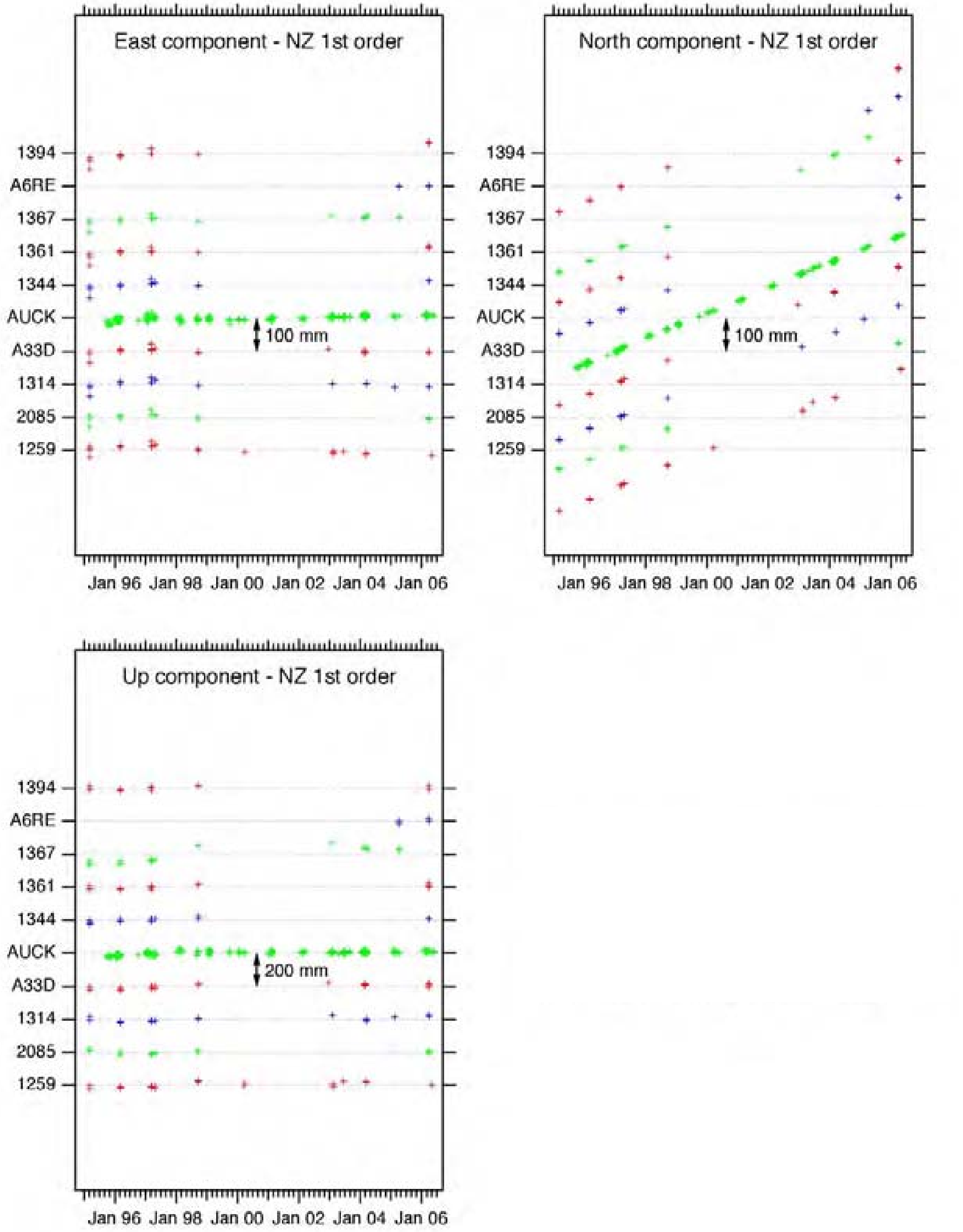

Figure 2c ITRF2000 coordinates taken from Bernese solutions and plotted as "raw" time series for northern New Zealand. The coordinates are plotted in a local (ENU) frame, with their mean value subtracted. The traces are coloured cyclically red, green, blue from the bottom of each plot to help differentiate the stations from each other. LINZ station codes are given on the left axis.

4. ITRF COORDINATES AND VELOCITIES

4.1 Terminology

GNS deformation model. This is the continuous horizontal surface velocity model calculated throughout New Zealand by Beavan and Haines (1997) and Beavan (1998), using all GPS data that were available at the time of the calculation. The velocities are defined in a nominally Australia-fixed reference frame. Version 2.1 of this model was utilised by LINZ in creating NZGD2000.

NZGD2000 deformation model. This is the continuous horizontal surface velocity model adopted for the semi-dynamic NZGD2000 datum. It is the GNS deformation model transformed by an Euler rotation into the ITRF96 reference frame. (The Euler rotation may be thought of as a 3-parameter Helmert, or similarity, transformation, in which only the three rotation terms are retained.) The Euler rotation parameters were determined by calculating a Helmert transformation (rotations only) between the velocities of 30 zero- and 1st-order stations determined by the GNS deformation model, and the velocities of the same 30 stations determined in the ITRF96 reference frame through an analysis of global and New Zealand 1st-order GPS data by Morgan and Pearse (1999).

In LINZ's implementation of the deformation model, the continuous model supplied by GNS has been evaluated at a set of latitude/longitude grid points, and a bilinear interpolation method is used to calculate model velocity values at other points. We use LINZ's velocity values in this report. Comparison of LINZ's values with those given by the GNS deformation model (after transformation to ITRF96) at 28 zero- and 1st-order stations show maximum differences of 0.3 mm/yr, usually much less.

4.2 Coordinate and velocity estimation in the ITRF, and checks on our solutions

Coordinates and velocities for the New Zealand stations are generated by a filtering procedure where the daily coordinate/covariance solutions for the NZ stations and a set of IGS stations are added to the filter one daily solution at a time. The solutions are maintained in the required reference frame by transforming the daily coordinates using a (3- to 7-parameter) transformation that brings the coordinate solutions of a set of IGS stations as close as possible to their "official" ITRF values for that day.

Specifically, we use the IGb00 realisation of ITRF2000, and the IGS05 realisation of ITRF2005 to obtain solutions in those reference frames.

The daily coordinate solutions have already been transformed to a particular ITRF realisation in the Bernese processing, as described in Section 3. VELFRAME nevertheless makes small reference frame adjustments, because: (1) it uses a slightly different set of reference stations; (2) it takes account of the variance/covariance matrix of the reference station positions and velocities (taken from the IGS SINEX files); and (3) we use a 7-parameter Helmert transformation to transform each daily solution. The transformation in Bernese uses an unweighted fit, with rejection of reference stations whose residuals exceed given criteria, and we have used only a 3-parameter translation at that stage of the processing.

We use GNS's in-house software, VELFRAME, to perform the solution, with the reference frame defined by a set of regional Australian, Pacific and Antarctic IGS stations (Table 4). We also attempted to double-check the VELFRAME results by combining the daily Bernese SINEX files with daily global "h-files"[4] (from Scripps Institution of Oceanography) using the GLOBK software suite, and with the reference frame defined by about 50 globally-distributed sites. This comparison was not entirely satisfactory, perhaps because the constraints employed in the Bernese New Zealand solutions were not compatible with those employed by Scripps' GAMIT processing of the global data sets. For IGb00 we did obtain excellent agreement in both horizontal velocity components at all NZ 1st-order stations (better than 0.8 mm/yr on average with a maximum difference of 1.3 mm/yr), but simultaneously found a more-or-less uniform offset of a few mm/yr in vertical velocity. For IGS05 the horizontal velocity agreement was better, 0.5 mm/yr on average with a maximum difference of 1.1 mm/yr, but the vertical velocity agreement was worse. The VELFRAME vertical velocities at IGS sites not included in the reference frame realisation were in reasonable accord with their ITRF values, so we use the VELFRAME solutions.

The reference stations are listed in Table 4. We used these because (1) they are available in both the IGb00 and IGS05 SINEX files, and (2) they were in our daily Bernese solutions.

Table 4 Reference stations, coordinates and velocities

Site	DOMES No.	X, m	Y, m	Z, m	Vx, m/yr	Vy, m/yr	Vz, m/yr
				IGb00 (coordinates at 1998.0)			
ALIC	50137M001	-4052051.8800	4212836.1099	-2545105.7901	-0.0408	-0.0028	0.0510
CEDU	50138M001	-3753472.2849	3912741.0004	-3347960.8212	-0.0429	0.0033	0.0480
CHAT	50207M001	-4590670.9383	-275482.9536	-4404596.7568	-0.0255	0.0402	0.0224
DARW	50134M001	-4091358.8388	4684606.7397	-1408580.4059	-0.0359	-0.0126	0.0539
HOB2	50116M004	-3950071.4009	2522415.1934	-4311638.3228	-0.0415	0.0107	0.0377
KARR	50139M001	-2713832.3061	5303935.0991	-2269514.9621	-0.0452	0.0041	0.0510
MCM4	66001M003	-1311703.2404	310815.0925	-6213255.1247	0.0090	-0.0112	-0.0042
THTI	92201M009	-5246415.2482	-3077260.3896	-1913842.4502	-0.0401	0.0539	0.0308
TIDB	50103M108	-4460996.1663	2682557.0764	-3674443.6501	-0.0386	0.0026	0.0428
TOW2	50140M001	-5054582.7327	3275504.4388	-2091539.6545	-0.0328	-0.0123	0.0498
YAR1/2	50107M004	-2389025.5832	5043316.8807	-3078530.6822	-0.0468	0.0080	0.0486
				IGS05 (coordinates at 2000.0)			
ALIC	50137M001	-4052051.9586	4212836.1050	-2545105.6805	-0.0395	-0.0056	0.0541
CEDU	50138M001	-3753472.3711	3912741.0114	-3347960.7200	-0.0417	0.0007	0.0511
CHAT	50207M001	-4590670.9849	-275482.8716	-4404596.7082	-0.0257	0.0387	0.0244
DARW	50134M001	-4091358.9070	4684606.7121	-1408580.2927	-0.0350	-0.0146	0.0569
HOB2	50116M004	-3950071.4760	2522415.2101	-4311638.2398	-0.0403	0.0087	0.0408
KARR	50139M001	-2713832.3938	5303935.1039	-2269514.8516	-0.0445	0.0014	0.0540
MCM4	66001M003	-1311703.2146	310815.0718	-6213255.1140	0.0090	-0.0129	0.0000
THTI	92201M009	-5246415.3282	-3077260.2834	-1913842.3861	-0.0401	0.0532	0.0338
TIDB	50103M108	-4460996.2402	2682557.0825	-3674443.5584	-0.0371	0.0006	0.0455
TOW2	50140M001	-5054582.7913	3275504.4130	-2091539.5466	-0.0321	-0.0136	0.0522
YAR1/2	50107M004	-2389025.6733	5043316.8902	-3078530.5734	-0.0476	0.0094	0.0499

[4] A gamit h-file is a binary file containing a (usually loosely-constrained) set of parameter estimates and covariances. It contains similar information to a SINEX solution file, or a normal-equation (NEQ) file in Bernese. A set of loosely-constrained parameter estimates from different networks and different days can be combined to give solutions for position and velocity (as well as other parameters if they are present in the h-file) and these can then be placed in a particular reference frame using the programs globk and glorg in the gamit software suite.

We experimented with various choices of reference stations. Excluding the Australian and Antarctic Plate sites one at a time from the reference station set had an insignificant effect. The biggest effect occurred when we excluded both Pacific Plate stations (CHAT and THTI) from the reference station set; this caused changes in northward/eastward velocity of up to 1.1/0.3 mm/yr at the New Zealand sites. We suppose that this occurs because there are small regional distortions in both IGb00 and IGS05. It is certainly true that the Australia-Pacific relative rotation vectors derived from ITRF2000 and ITRF2005 are somewhat inconsistent with values where larger numbers of Pacific Plate sites have been used in the analysis (e.g., Beavan et al., 2002; Prawirodirdjo & Bock, 2004). ITRF2000 (Altamimi et al., 2002) predicts Australia-Pacific relative velocities along the NZ plate boundary that are about 2 mm/yr faster than Beavan et al. or Prawirodirdjo & Bock, while ITRF2005 (Altamimi et al., 2007) predicts relative velocities about 2 mm/yr slower. We have chosen to keep both CHAT and THTI in the reference station set, as our primary aim in this work is to achieve solutions aligned as closely as possible to the ITRF realisations.

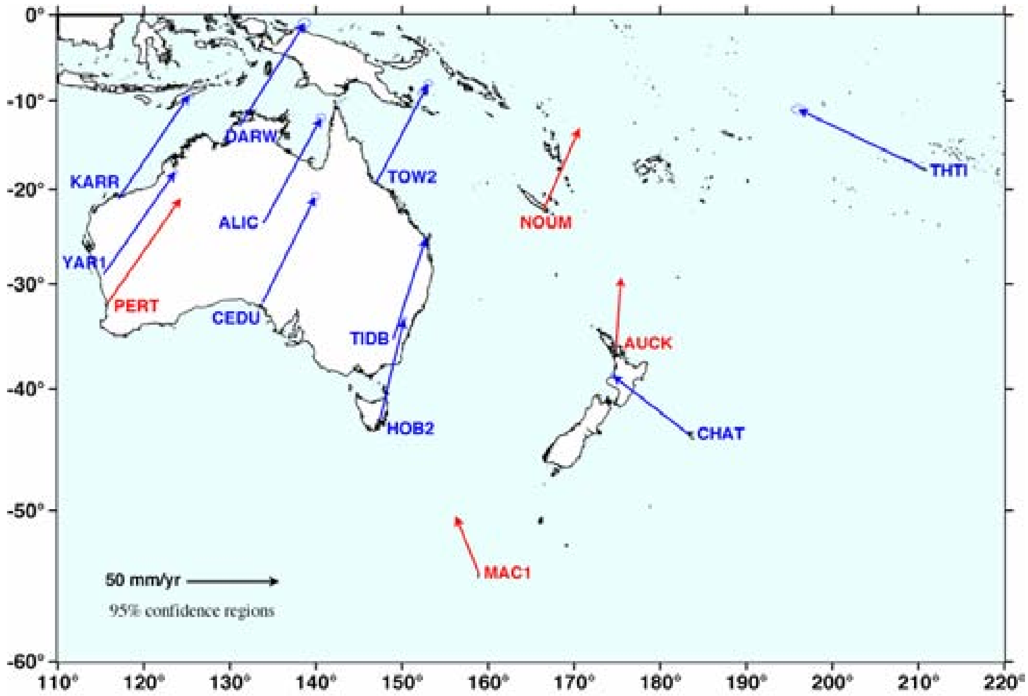

Figure 3 Regional IGS stations processed in our daily Bernese analysis, with their official IGb00 velocities (blue) and IGb00 velocities estimated by GNS (red). Station MCM4 (McMurdo Sound) is also used and would be shown in blue if it were on the map. We treat YAR1 and YAR2, which share an antenna, as the same station, and similarly for TIDB and TID2. Different subsets of these stations are used for reference frame realisation (Sections 2.1; 2.2; 7.3; Table 4). In the VELFRAME analyses, the blue stations are used as reference stations for both the IGb00 and IGS05 realisations.

Our Bernese analysis included two IGS stations (NOUM and PERT) that were not used to set the reference frame in VELFRAME (we do not consider MAC1 because its velocity is non-linear due to the 2004 earthquake). Our horizontal velocities for these stations agree with their IGS velocities within 1 mm/yr (for both IGb00 and IGS05), indicating that we have achieved consistency at this level with these reference frames. The agreement is a factor of three worse for the vertical velocities. The various consistency checks described in Altamimi et al. (2007) indicate that we should not expect agreement at much better than this level.

4.3 VELFRAME analysis

As each day's solution is added to the filter, VELFRAME updates the following parameters:

- 7-parameter transformation between daily solution and predicted position of the sites defining the reference frame
- position of each station
- velocity of each station

Each of these parameters is given an *a-priori* uncertainty, and an *a-posteriori* uncertainty is calculated after each day's processing using Bayesian statistics. The starting uncertainties for position and velocity are made large; the *a-posteriori* uncertainty on position decreases rapidly as data are added to the filter, while the *a-posteriori* velocity uncertainty takes some time to decrease. The GPS data are assumed to follow a white-noise process in this implementation of VELFRAME, so the final *a-posteriori* uncertainties are optimistic because of the neglect of the correlated noise in the GPS time series (e.g., Williams et al. (2004); see Beavan (2005) for New Zealand examples). (The uncertainties can be converted to realistic values using heuristic methods described by Williams (2003), but since our prime interest in this project is in comparing coordinate sets calculated in different reference frames, the values of the uncertainties are of limited importance.)

Where there are known offsets at individual stations (typically from antenna changes or earthquakes), the values of these offsets are provided to VELFRAME, and later data are corrected for the offsets when calculating station positions and velocities. This means that if the actual position of a station is to be calculated from the derived reference position and velocity, then the offsets must be added back at the appropriate times.

VELFRAME does not estimate the offsets; they have to be calculated elsewhere. Typically this is done by an examination of regionally-filtered daily position time series, with offsets detected and estimated either (1) by eye (using graphics software in which the level of the series before and after the offset can be shifted to give a visually-best fit), (2) by averaging short lengths of data either side of the offset, or (3) more rigorously, by using a maximum-likelihood procedure such as the "cats" maximum-likelihood software of Williams et al. (2004).

The offsets used in our processing of the NZ 1st-order data are given in Table 5. We make corrections for both the 21 August 2003 Fiordland earthquake and the 23 December 2004 Macquarie earthquake, using the dislocation models discussed in Section 7.2.1 below.

VELFRAME also includes a "time-constant" parameter that controls how rapidly the velocity of each station may vary as each new data set is added to the filter. This means that the filter is able to keep track of a station whose velocity is slowly changing, rather than insisting on a constant velocity. If a short time-constant is used, the final velocity estimate will be biased towards more recent data at the expense of older data. For the NZ 1st-order processing we have kept the time constant long, 10,000 years, so that all data are weighted essentially equally (though still subject to the data variances).

Table 5 Station offsets used in time series analysis[1]

Year	Month	Day	Station	Up, m	East, m	North, m	Reason
1999	11	10	WGTN	0.0008	0.0027	-0.0007	Radome change
2001	10	28	AUCK	-0.001	0.001	0.001	Antenna change
2001	11	28	CHAT	0	0.004	0.002	Antenna change
2003	8	21	1004	-0.0071	-0.0428	0.03	Fiordland earthquake
2003	8	21	1017	0.0002	-0.0098	0.0026	Fiordland earthquake
2003	8	21	1103	0	-0.0019	0.0001	Fiordland earthquake
2003	8	21	5509	0	-0.0053	0.0057	Fiordland earthquake
2003	8	21	6731	-0.0009	-0.0014	-0.0001	Fiordland earthquake
2003	8	21	A13U	0.0003	-0.0037	0.0014	Fiordland earthquake
2003	8	21	A31C	-0.0049	-0.0127	-0.0026	Fiordland earthquake
2003	8	21	B03W	-0.0029	-0.0016	0.001	Fiordland earthquake
2003	8	21	B317	0	-0.0053	0.0057	Fiordland earthquake
2003	8	21	BRVJ	0	-0.0019	0.0001	Fiordland earthquake
2003	8	21	OUSD	0.0003	-0.0037	0.0014	Fiordland earthquake
2004	12	24	1004	-0.0032	0.0042	0.0083	Macquarie earthquake
2004	12	24	1017	-0.0023	0.0029	0.006	Macquarie earthquake
2004	12	24	1103	-0.0016	0.002	0.0041	Macquarie earthquake
2004	12	24	1420	-0.0016	0.002	0.0038	Macquarie earthquake
2004	12	24	5508	-0.0012	0.0014	0.003	Macquarie earthquake
2004	12	24	5509	-0.0027	0.0034	0.0078	Macquarie earthquake
2004	12	24	6731	-0.0022	0.0028	0.0054	Macquarie earthquake
2004	12	24	A13U	-0.0015	0.0018	0.0047	Macquarie earthquake
2004	12	24	A31C	-0.0029	0.0037	0.0071	Macquarie earthquake
2004	12	24	B03W	-0.0044	0.0058	0.0114	Macquarie earthquake
2004	12	24	B317	-0.0027	0.0034	0.0078	Macquarie earthquake
2004	12	24	BRVJ	-0.0016	0.002	0.0041	Macquarie earthquake
2004	12	24	DJMF	-0.0012	0.0014	0.003	Macquarie earthquake
2004	12	24	DJMG	-0.0014	0.0016	0.003	Macquarie earthquake
2004	12	24	MAC1	-0.0092	-0.0106	-0.0238	Macquarie earthquake
2004	12	24	OUSD	-0.0015	0.0018	0.0047	Macquarie earthquake
2005	3	21	WGTN	0.0115	-0.001	-0.002	Antenna change
2005	11	3	AUCK	0.001	0.001	-0.0044	Antenna change

[1] In this table, we only show those sites where the displacement is greater than 1.5 mm for the 2003 Fiordland earthquake, and 3.0 mm for the 2004 Macquarie earthquake. However, all site displacements are used in the analysis, using the dislocation model parameters given in Table 16.

After each day's coordinate solution has been added to the filter, a chi-squared-per-degree-of-freedom increment ($\Delta\chi^2_n$) is calculated. If this increment is much higher than 1, this is an indication that this day's solution may have problems; perhaps one or more stations should be excluded on this day, or perhaps the whole day should be excluded. We did not find any day where $\Delta\chi^2_n$ exceeded 5 for either the IGb00 or the IGS05 analysis (and on most days it was less than 3 in both cases), so we did not exclude any data from the VELFRAME analysis.

To calculate the best estimates of position residuals the filter is run a second time, but this time the starting values of position and velocity are constrained to their final values from the first run. The residuals for the IGb00 calculation are plotted in Figure 4. Most show fairly random scatter. An interesting exception is the east component of station 1231 (Fig. 4c), which shows a steady negative trend prior to 2004. This site, Mt Stewart, is in the region of the 2004-05 Manawatu slow-slip event (Wallace & Beavan, 2006), which caused a generally eastward shift of the ground surface of up to 36 mm in this region over a 1.5-year period. This means that the average westward velocity of this station for 1995-2006 is substantially slower than the average velocity that would have been calculated using 1995-2004 data.

The velocity solutions in IGb00 and IGS05 are plotted in Figures 5 and 6, and listed in Tables 6 and 7. The formal uncertainties are not given as they are unrealistically low, typically 1-1.5 mm in horizontal position, 3-5 mm in height, 0.2-0.3 mm/yr in horizontal velocity, and 0.4-0.8 mm/yr in vertical velocity. There are larger uncertainties at A6RE, which has only a 2-year data span, and particularly at WELL, where the data series ended in 1997.

Table 6 Estimated coordinates and velocities in IGb00 reference frame

	Coordinates at epoch 2000.0, IGb00			Velocities, IGb00		
Name	**Lon, degrees**	**Lat, degrees**	**Ht, m**	**Ve, m/yr**	**Vn, m/yr**	**Vu, m/yr**
1004	167.738923837	-45.562114277	411.202	-0.0277	0.0330	0.0028
1017	169.197701851	-45.387644767	1680.801	-0.0311	0.0310	0.0001
1103	171.057344446	-44.400569628	397.145	-0.0337	0.0304	0.0012
1153	173.010278080	-42.687417860	405.496	-0.0306	0.0303	0.0020
1181	172.499523432	-41.729082605	1486.644	-0.0080	0.0422	0.0005
1215	175.652164034	-41.180141938	590.782	-0.0320	0.0279	-0.0027
1231	175.488311899	-40.240198029	143.591	-0.0107	0.0338	0.0005
1259	174.228213298	-39.133999653	263.033	-0.0003	0.0385	0.0023
1273	177.804852375	-38.575152230	323.395	0.0009	0.0186	0.0006
1305	178.407102866	-37.824541911	360.443	0.0076	0.0157	0.0023
1314	176.466409086	-37.759466427	95.715	0.0012	0.0369	0.0020
1344	175.518603146	-36.333055137	437.997	0.0035	0.0378	0.0004
1361	173.769415922	-35.962107374	164.961	0.0039	0.0393	0.0008
1367	174.514359108	-35.617244016	174.416	0.0033	0.0405	0.0089
1394	172.771409117	-34.466586044	351.034	0.0060	0.0399	0.0000
1420	170.829657956	-42.953246386	919.303	-0.0075	0.0418	0.0031
1501	176.917245635	-39.478985223	119.259	-0.0054	0.0224	0.0018
2085	175.915026875	-38.616047219	760.253	0.0014	0.0350	-0.0003
5508	172.743044994	-43.581503788	335.349	-0.0362	0.0300	0.0014
5509	168.253438879	-46.536929751	176.342	-0.0302	0.0307	0.0025
6731	169.003590711	-43.860817429	14.413	-0.0087	0.0421	0.0019
A31C	167.924065769	-44.673506710	9.553	-0.0215	0.0378	0.0014
A33D	175.000023124	-37.589384086	318.908	0.0018	0.0382	0.0015
A6RE	174.537516512	-35.630325926	157.373	0.0023	0.0442	0.0018
A70X	172.672209404	-40.713000807	169.549	-0.0032	0.0410	0.0018
AUCK	174.834385470	-36.602844508	132.714	0.0028	0.0382	0.0023
B03W	166.609326216	-46.156391387	44.265	-0.0241	0.0359	0.0003
B28C	174.213808439	-41.749046000	254.514	-0.0270	0.0322	-0.0004
OUSD	170.510920677	-45.869501665	26.179	-0.0329	0.0301	0.0017
WELL	174.782953166	-41.274892339	37.672	-0.0262	0.0317	-0.0028
WGTN	174.805893941	-41.323457111	26.059	-0.0263	0.0319	0.0005

In Figures 5 and 6, the parameters near the lower right of the plot have the following meanings. XSTD = 0.2 m and VSTD = 0.2 m/yr are the a priori position and velocity standard errors of a station before any data have been added to the filter. CORR_TRANS etc. are the a priori standard errors on the 7-parameter transformation of each day's solution to the reference frame realisation. They are each set to be equivalent to 0.01 m at the Earth's surface. SEUW is the factor by which the formal standard errors of the daily GPS solutions are multiplied before the data enter the filter. FLUCSTD = 0.002 m/yr is the standard error on velocity fluctuations, which describes how rapidly the estimated velocity may vary as new data are added. RELAX is the relaxation time in years for velocity correlations. FIXSTD is a standard error that may be added in quadrature to the formal standard errors of the daily GPS solutions, usually if a station has been tightly constrained in prior processing. We set FIXSTD to zero since station positions have been transformed to IGb00 but are not otherwise tightly constrained.

Table 7 Estimated coordinates and velocities in IGS05 reference frame

	Coordinates at epoch 2000.0, IGS05			**Velocities, IGS05**		
Name	**Lon, degrees**	**Lat, degrees**	**Ht, m**	**Ve, m/yr**	**Vn, m/yr**	**Vu, m/yr**
1004	167.738923811	-45.562114266	411.193	-0.0261	0.0342	-0.0002
1017	169.197701838	-45.387644757	1680.793	-0.0295	0.0322	-0.0029
1103	171.057344431	-44.400569616	397.137	-0.0320	0.0317	-0.0018
1153	173.010278067	-42.687417852	405.488	-0.0289	0.0318	-0.0008
1181	172.499523412	-41.729082589	1486.636	-0.0063	0.0437	-0.0023
1215	175.652164028	-41.180141928	590.775	-0.0302	0.0295	-0.0054
1231	175.488311888	-40.240198016	143.583	-0.0090	0.0354	-0.0022
1259	174.228213290	-39.133999642	263.026	0.0014	0.0402	-0.0003
1273	177.804852369	-38.575152215	323.387	0.0027	0.0203	-0.0020
1305	178.407102856	-37.824541901	360.436	0.0094	0.0175	-0.0003
1314	176.466409077	-37.759466411	95.707	0.0030	0.0386	-0.0006
1344	175.518603140	-36.333055119	437.990	0.0052	0.0395	-0.0021
1361	173.769415914	-35.962107357	164.954	0.0056	0.0410	-0.0018
1367	174.514359102	-35.617243995	174.409	0.0050	0.0422	0.0063
1394	172.771409105	-34.466586025	351.027	0.0077	0.0417	-0.0025
1420	170.829657943	-42.953246374	919.294	-0.0058	0.0432	0.0003
1501	176.917245625	-39.478985214	119.250	-0.0037	0.0241	-0.0009
2085	175.915026866	-38.616047204	760.246	0.0031	0.0367	-0.0029
5508	172.743044983	-43.581503778	335.342	-0.0345	0.0314	-0.0013
5509	168.253438861	-46.536929744	176.334	-0.0285	0.0319	-0.0005
6731	169.003590691	-43.860817418	14.405	-0.0070	0.0434	-0.0010
A31C	167.924065750	-44.673506699	9.545	-0.0198	0.0391	-0.0017
A33D	175.000023117	-37.589384070	318.900	0.0036	0.0399	-0.0010
A6RE	174.537516514	-35.630325889	157.358	0.0039	0.0456	0.0005
A70X	172.672209393	-40.713000796	169.542	-0.0015	0.0425	-0.0010
AUCK	174.834385460	-36.602844493	132.707	0.0046	0.0399	0.0001
B03W	166.609326200	-46.156391376	44.256	-0.0225	0.0370	-0.0028
B28C	174.213808426	-41.749045990	254.505	-0.0253	0.0337	-0.0031
OUSD	170.510920660	-45.869501658	26.170	-0.0313	0.0313	-0.0012
WELL	174.782953154	-41.274892331	37.664	-0.0244	0.0332	-0.0056
WGTN	174.805893930	-41.323457104	26.051	-0.0246	0.0334	-0.0023

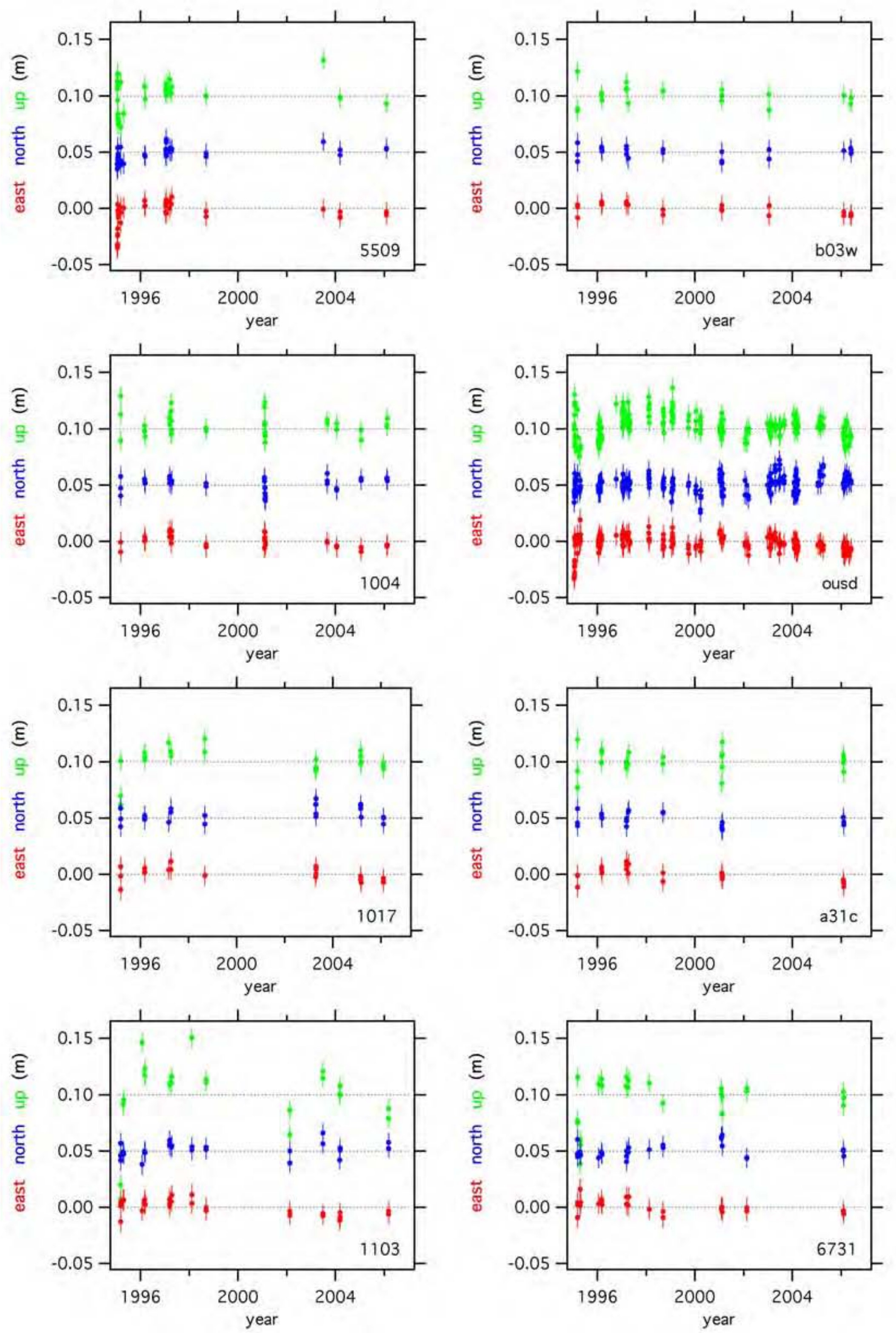

Figure 4a Residuals of the fit of the NZ GPS position data to the IGb00 reference frame. The plots are organised roughly from south to north.

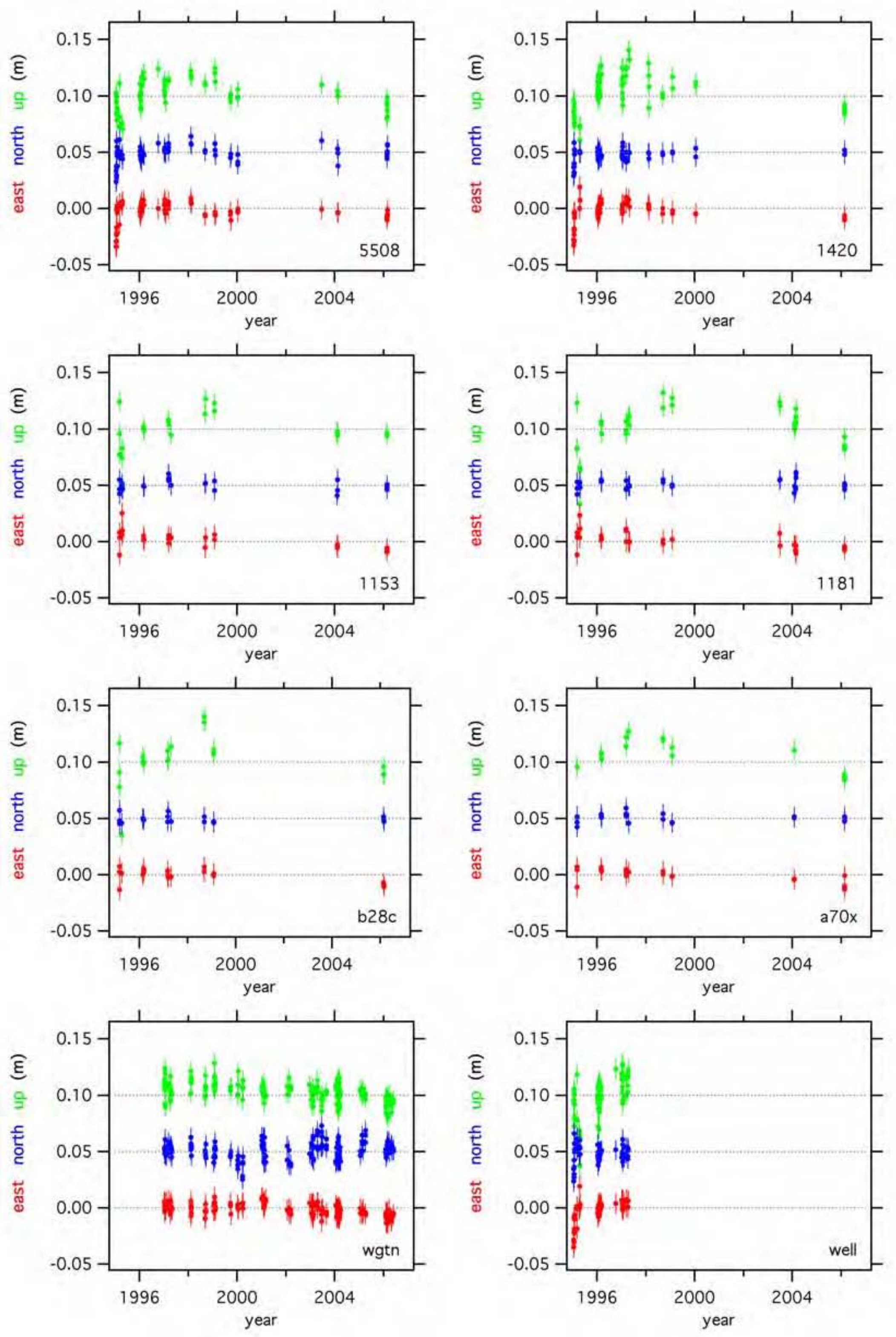

Figure 4b Residuals of the fit of the NZ GPS position data to the IGb00 reference frame. The plots are organised roughly from south to north.

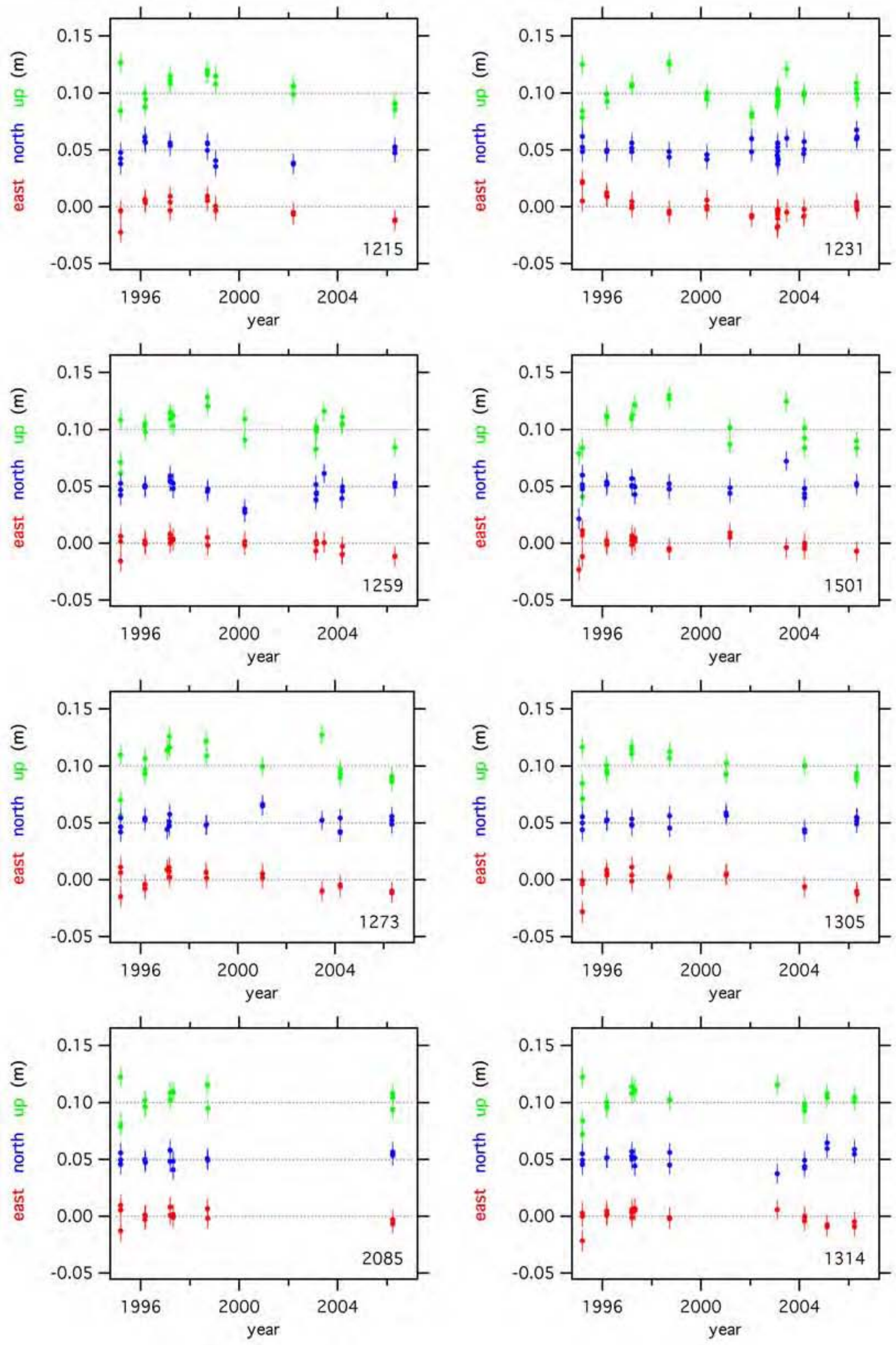

Figure 4c Residuals of the fit of the NZ GPS position data to the IGb00 reference frame. The plots are organised roughly from south to north.

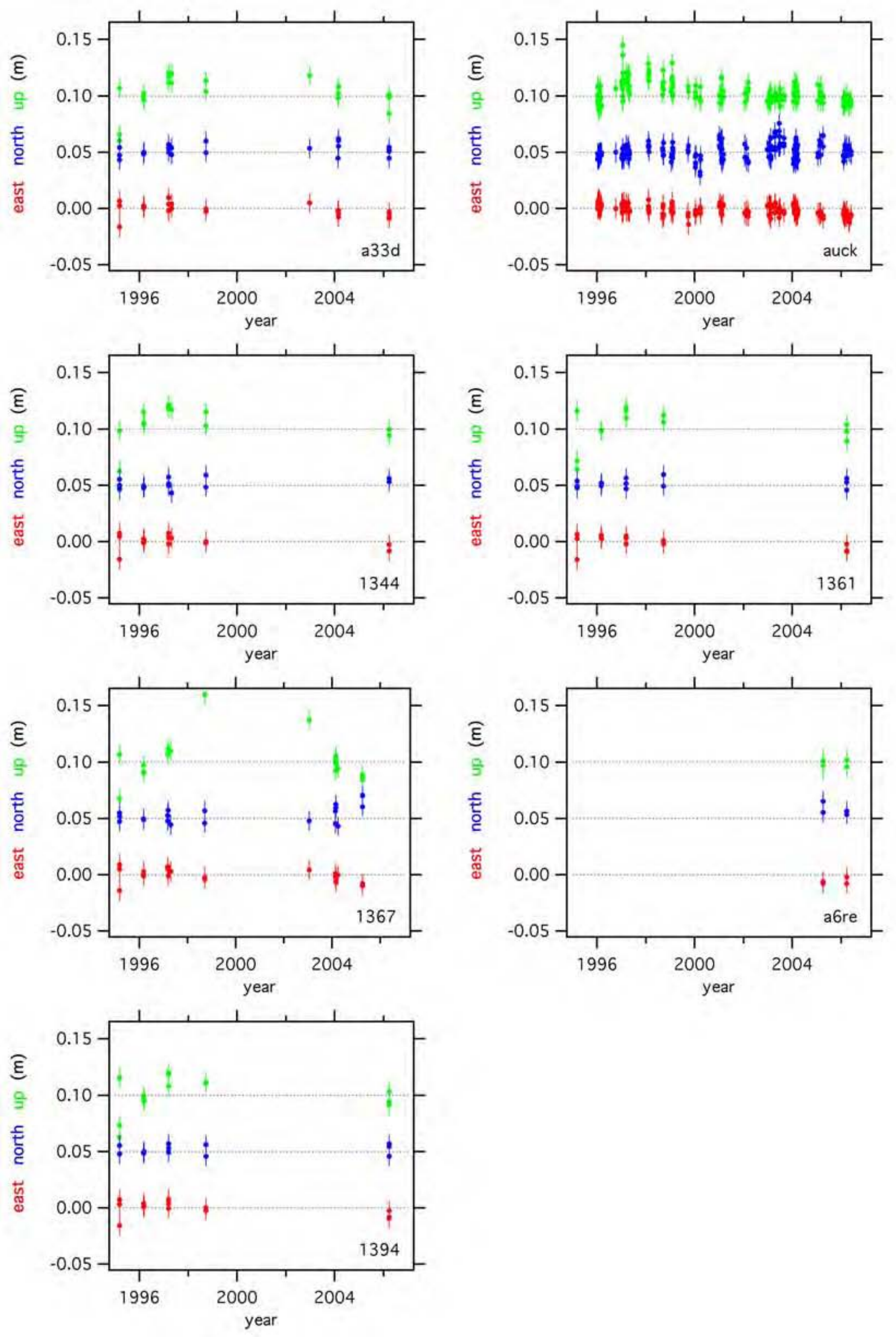

Figure 4d Residuals of the fit of the NZ GPS position data to the IGb00 reference frame. The plots are organised roughly from south to north.

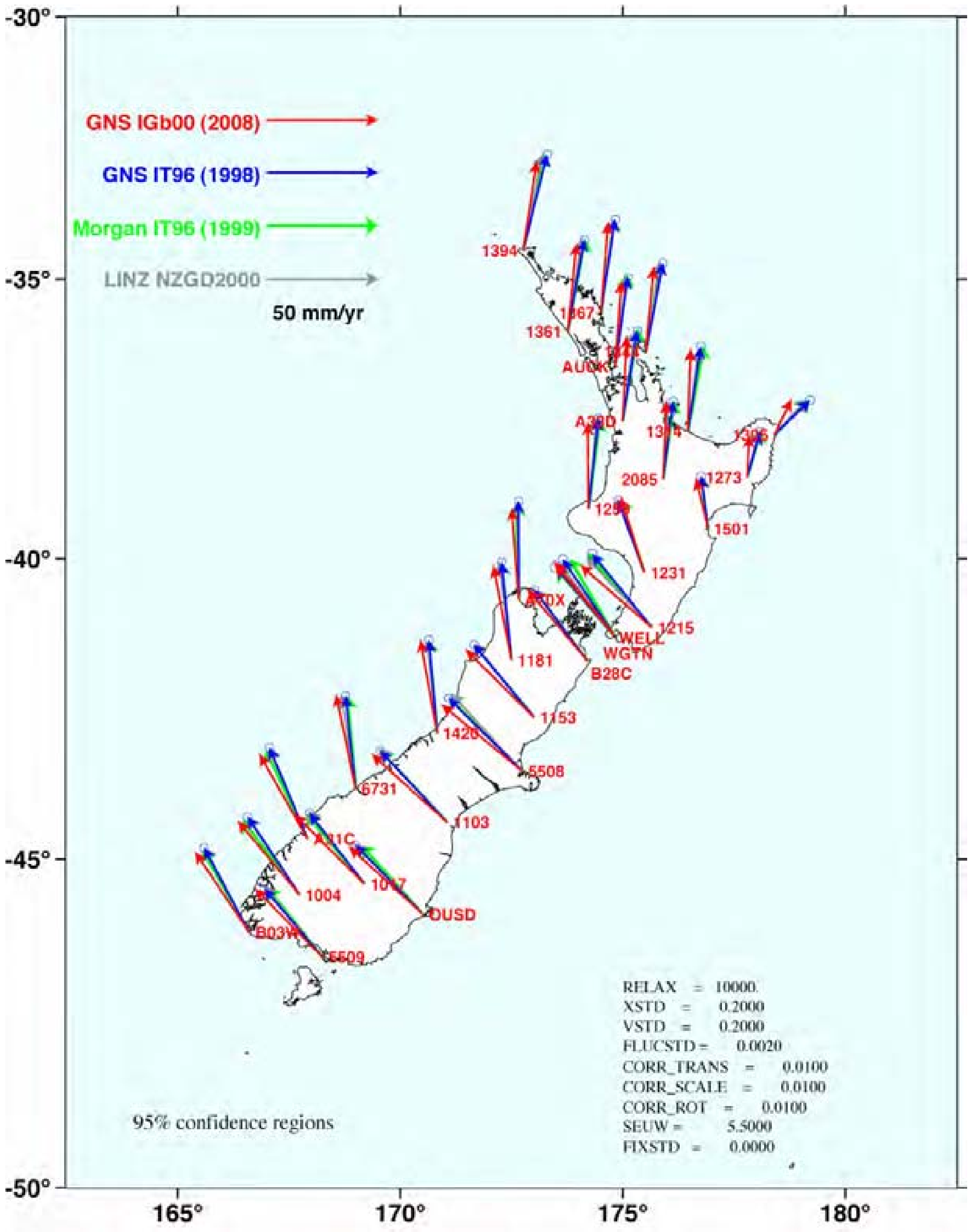

Figure 5 Estimated IGb00 velocity field (red arrows) at NZ zero-order and 1st-order sites. Also shown are the ITRF96 velocities estimated by Beavan (1998) (blue), by Morgan & Pearse (1999) (green), and the velocities used in the NZGD2000 velocity field (or LINZ deformation model) (grey). The latter three sets of velocities are almost indistinguishable, except at WGTN which had a short time series for the NZGD2000 calculations.

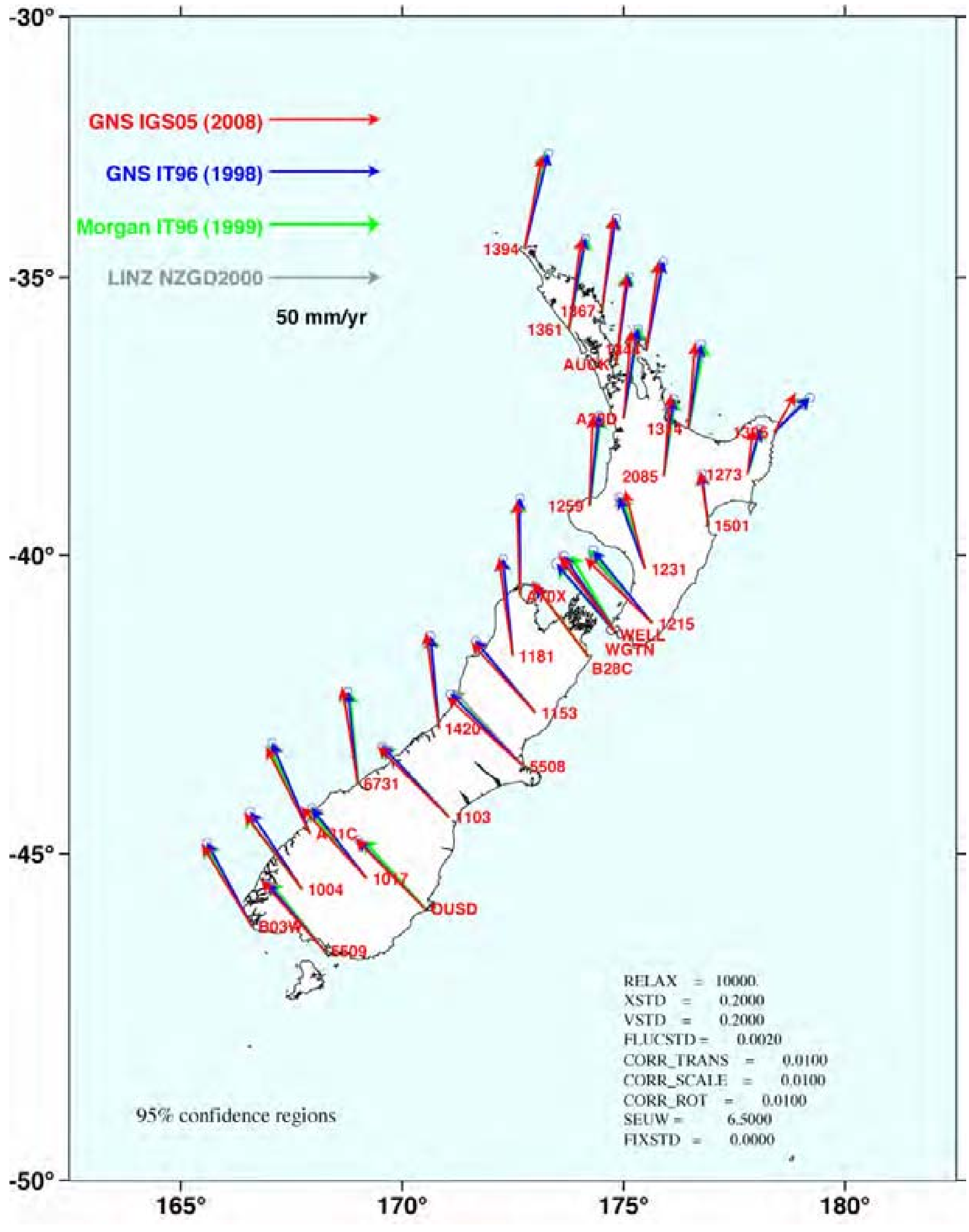

Figure 6 Estimated IGS05 velocity field (red arrows) at NZ zero-order and 1st-order sites. Also shown are the ITRF96 velocities estimated by Beavan (1998) (blue), by Morgan & Pearse (1999) (green), and the velocities used in the NZGD2000 velocity field (or LINZ deformation model) (grey). The latter three sets of velocities are almost indistinguishable, except at WGTN which had a short time series for the NZGD2000 calculations.

5. ITRF - NZGD2000 TRANSFORMATION PARAMETERS

To establish transformations between the ITRF reference frames and NZGD2000 we calculate conventional 14-parameter Helmert transformations (with some parameters set to zero) between the IGb00, IGS05 and NZGD2000 coordinate and velocity sets. We use the ITRF coordinate and velocity sets given in Tables 6 and 7. For NZGD2000, we use the coordinates taken from the LINZ Geodetic Database in October 2007, and the station velocities supplied by LINZ in October 2007 from interpolation of their internal gridded version of the NZGD2000 deformation model. These coordinates and velocities are listed in Table 8. We have compared these velocities with those calculated by GNS's original continuous version of the deformation model, and the difference is usually only 0.1 mm/yr, with a maximum of 0.3 mm/yr. The velocities from the NZGD2000 deformation model are plotted in Figures 5 and 6, where they are compared with our IGb00 and IGS05 horizontal velocities.

Table 8 NZGD2000 coordinates and deformation model

	Coordinates at epoch 2000.0, NZGD2000			NZGD2000 velocities		
Name	**Lon**	**Lat**	**Ht, m**	**Ve, m/yr**	**Vn, m/yr**	**Vu, m/yr**
1004	167.738924057	-45.562114202	411.1960	-0.0229	0.0348	0
1017	169.197702098	-45.387644701	1680.8090	-0.0253	0.0328	0
1103	171.057344596	-44.400569527	397.1570	-0.0307	0.0332	0
1153	173.010278220	-42.687417778	405.5050	-0.0271	0.0333	0
1181	172.499523535	-41.729082571	1486.6460	-0.0054	0.0437	0
1215	175.652164178	-41.180141864	590.7910	-0.0292	0.0314	0
1231	175.488311848	-40.240198025	143.6090	-0.0125	0.0335	0
1259	174.228213410	-39.133999595	263.0410	0.0037	0.0414	0
1273	177.804852555	-38.575152214	323.4070	0.005	0.0199	0
1305	178.407103091	-37.824541932	360.4540	0.0141	0.0157	0
1314	176.466409162	-37.759466453	95.7270	0.0046	0.0364	0
1344	175.518603243	-36.333055071	438.0030	0.0064	0.0403	0
1361	173.769415957	-35.962107317	164.9700	0.0063	0.0417	0
1367	174.514359180	-35.617243980	174.4030	0.0057	0.0418	0
1394	172.771409170	-34.466585968	351.0500	0.0086	0.0431	0
1420	170.829658128	-42.953246399	919.3070	-0.0046	0.0415	0
1501	176.917245718	-39.478985214	119.2710	-0.0032	0.0239	0
2085	175.915026922	-38.616047237	760.2720	0.0025	0.0344	0
5508	172.743045187	-43.581503667	335.3550	-0.0318	0.0348	0
5509	168.253439043	-46.536929728	176.3430	-0.0263	0.0319	0
6731	169.003590817	-43.860817407	14.4120	-0.0063	0.0423	0
A31C	167.924065991	-44.673506600	9.5460	-0.0171	0.0413	0
A33D	175.000023214	-37.589384029	318.9120	0.0055	0.0407	0
A70X	172.672209514	-40.713000709	169.5390	-0.0007	0.0441	0
AUCK	174.834385556	-36.602844497	132.7110	0.0049	0.0404	0
B03W	166.609326421	-46.156391318	44.2640	-0.0201	0.0382	0
B28C	174.213808539	-41.749046004	254.5350	-0.024	0.0324	0
OUSD	170.510920749	-45.869501593	26.1970	-0.0311	0.0317	0
WGTN	174.805894058	-41.323457079	26.0730	-0.0246	0.0328	0

We first evaluate the transformation between IGS05 and IGb00 as derived from our coordinate and velocity results. We expect that this will agree reasonably closely with the ITRF2005 to ITRF2000 transformation given by Altamimi et al. (2007), though any local or regional distortion of the reference frames will mean the agreement will not be exact. We use the same sign convention as Altamimi et al. (2007), as defined in equation (1) (which is written for the particular case of transformation from the "*i05*" reference frame to the "*i00*" frame):

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i00} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i05} + \mathbf{T} + S \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i05} + \mathbf{R} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i05}$$

(1)

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{i00} = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{i05} + \dot{\mathbf{T}} + \dot{S} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i05} + \dot{\mathbf{R}} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i05}$$

$\mathbf{T} = \begin{pmatrix} Tx \\ Ty \\ Tz \end{pmatrix}$ and $\mathbf{R} = \begin{pmatrix} 0 & -Rz & Ry \\ Rz & 0 & -Rx \\ -Ry & Rx & 0 \end{pmatrix}$ are the translation vector and rotation matrix, S is the scale factor, and $\dot{\mathbf{T}}$, $\dot{\mathbf{R}}$ and $\dot{S}$ are their time derivatives.

We find that a scale and three translations in each of position and velocity (final section of Table 9) are sufficient to describe the transformation; adding rotation terms makes no significant improvement in fit. The largest differences between our values and those of Altamimi et al. are in the *x* position translation term, which differs by 4.0 mm, and the y velocity translation term, which differs by 1.7 mm/yr.

Since the GPS solutions are in the IGb00 and IGS05 realisations of ITRF2000 and ITRF2005, we also evaluate the transformation between IGS05 and IGb00 using (1) a global set of 67 stations and (2) a regional set of 12 stations. For these calculations we take the coordinates and velocities from the IGS03P33_RS106.SNX and IGS05.SNX sinex files. We choose stations that are common to both these files and for which the residuals to an unweighted transformation are within certain criteria. The results are given in the second and third sections of Table 9.

There are similarities and differences between these transformations, but we think there is sufficient agreement to provide confidence in our results, given the 2.3 mm RMS in position and 0.7 mm/yr RMS in velocity quoted by Altamimi et al. (2007, p 14). It does appear that there is a small difference between the transformation derived from data in the New Zealand region and that derived from global data.

Table 9 Transformation parameters from ITRF2005 to ITRF2000

	Tx, mm $\dot{Tx}$, mm/yr	Ty, mm $\dot{Ty}$, mm/yr	Tz, mm $\dot{Tz}$, mm/yr	S, ppb $\dot{S}$, ppb/yr	Rx, mas $\dot{Rx}$, mas/yr	Ry, mas $\dot{Ry}$, mas/yr	Rz, mas $\dot{Rz}$, mas/yr
Altamimi et al. (2007) IT05->IT00	0.1±0.3 -0.2±0.3	-0.8±0.3 0.1±0.3	-5.8±0.3 -1.8±0.3	0.40±0.05 0.08±0.05	0.0±0.01 0.0±0.01	0.0±0.01 0.0±0.01	0.0±0.01 0.0±0.01
Global IGS data, this report, IGS05->IGb00	-0.2±0.5 -0.23±0.1	-1.3±0.5 0.79±0.1	-6.6±0.5 -1.12±0.1	0.8±0.1 0.08±0.03	0 0	0 0	0 0
Regional IGS data, this report IGS05->IGb00	-2.3±1.7 -0.02±0.4	-0.9±1.3 1.55±0.3	-5.8±1.5 -2.29±0.3	0.5±0.3 0.18±0.07	0 0	0 0	0 0
NZ data, this report IGS05->IGb00	-3.9±0.7 -0.54±0.1	-0.5±0.1 1.78±0.1	-5.1±0.6 -2.67±0.1	0.3±0.1 0.07±0.02	0 0	0 0	0 0

We next evaluate the transformation from IGb00 to NZGD2000 (Table 10). We use the stations in Table 8, but exclude station 1367 as it has a known height problem (Fig. 3d) and a shorter length than the other time series. We find that three translations in each of position and velocity are sufficient to describe the transformation; adding scale or rotation terms does not significantly improve the fit. The RMS of the fit is 6.1 mm in position (at epoch 2000.0) and 1.4 mm/yr in velocity. The RMS of the fit will therefore degrade as the transformation is extended into the future; Table 12 shows that the RMS of the fit is 18.6 mm at epoch 2010.0.

We can compare this transformation with the IGb00 to NZGD2000 transformation proposed in PONL Report 2 submitted to LINZ on 24 August 2006 (Beavan, 2006). The transformation parameters in that report were presented in an unconventional fashion but are equivalent to the 14-parameter Helmert transformation (with some terms set to zero) given in the first row of Table 10. (The translation terms come from eqn (5) of the earlier report; the rotation terms are from eqn (6) with a sign change; and the rotation rate terms come from just above eqn (1) of the earlier report. The rotation and rotation rate terms have been converted from radians in the earlier report to milli-arc seconds (mas) in this report.) Though the two transformations in Table 10 use different parameters, and therefore look quite different, they are in fact reasonably similar. (Over a limited area such as New Zealand a translation appears similar to a rotation about a distant axis.) The maximum difference in horizontal coordinates between the transformations over the NZ land area is ~3 mm at 2000.0 and ~11 mm at 2010.0; in vertical coordinates the differences are ~2 mm and ~12 mm, respectively. These values are lower than the typical differences between official NZGD2000 coordinates and the FORS (epoch 2006) coordinates converted to NZGD2000, as in Table 2 of this report. This gives confidence that our estimates of the transformation parameters are robust.

We next evaluate the transformation from IGS05 to NZGD2000 (Table 11). We find that three translations in each of position and velocity are sufficient to describe the transformation; adding scale or rotation terms does not significantly improve the fit. The RMS of the fit is 6.1 mm in position (at epoch 2000.0) and 1.4 mm/yr in velocity. The RMS of the fit will therefore degrade as the transformation is extended into the future; Table 12 shows that the RMS of the fit is 18.7 mm at epoch 2010.0.

Table 10 Transformation parameters from IGb00 to NZGD2000

	Tx, mm $\dot{T}x$, mm/yr	Ty, mm $\dot{T}y$, mm/yr	Tz, mm $\dot{T}z$, mm/yr	S, ppb $\dot{S}$, ppb/yr	Rx, mas $\dot{R}x$, mas/yr	Ry, mas $\dot{R}y$, mas/yr	Rz, mas $\dot{R}z$, mas/yr	RMS of fit
PONL	-5.7	-0.9	-6.5	0	-0.220	0.150	0.120	
Report 2	0	0	0	0	0.161	0.078	0.019	
This	-10.2±1.2	-9.2±1.2	-1.0±1.2	0	0	0	0	6.1 mm
report	-0.71±0.3	-3.01±0.3	2.05±0.3	0	0	0	0	1.4 mm/yr

Table 11 Transformation parameters from IGS05 to NZGD2000

	Tx, mm $\dot{T}x$, mm/yr	Ty, mm $\dot{T}y$, mm/yr	Tz, mm $\dot{T}z$, mm/yr	S, ppb $\dot{S}$, ppb/yr	Rx, mas $\dot{R}x$, mas/yr	Ry, mas $\dot{R}y$, mas/yr	Rz, mas $\dot{R}z$, mas/yr	RMS of fit
This	-15.3±1.2	-9.6±1.2	-7.2±1.2	0	0	0	0	6.1 mm
report	-1.58±0.3	-1.19±0.3	-0.91±0.3	0	0	0	0	1.4 mm/yr

Table 12 Translation parameters from IGb00/05 to NZGD2000 at 2010.0

	Tx, mm	Ty, mm	Tz, mm	S, ppb	Rx, mas	Ry, mas	Rz, mas	RMS of fit
IGb00	-16.9±3.5	-39.4±3.5	19.8±3.5	0	0	0	0	18.6 mm
IGS05	-30.7±3.5	-21.6±3.5	-15.9±3.5	0	0	0	0	18.7 mm

It is of interest that the translation between IGS05 and NZGD2000 is slightly larger than that between IGb00 and NZGD2000 at 2000.0 (19 mm vs 14 mm, comparing $\sqrt{T_x^2 + T_y^2 + T_z^2}$ in Tables 11 and 10), but is somewhat smaller by 2010.0 (41 mm vs 47 mm; Table 12). This indicates that the NZGD2000 velocity field is a little closer to IGS05 than to IGb00, as can also be seen by examining Figures 5 and 6.

For the specific case of converting IGxx coordinates evaluated at time t back to NZGD2000 coordinates (at time 2000.0 by definition), equations (1) may be rearranged (neglecting second-order terms) to give (see Appendix B):

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{NZGD} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{IGxx} - t \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix}_{NZGD} + \left(\mathbf{T} + \dot{\mathbf{T}}t\right) + \left(S + \dot{S}t\right) \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{IGxx} + \left(\mathbf{R} + \dot{\mathbf{R}}t\right) \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{IGxx} \tag{2}$$

where the values of $\mathbf{T}$, S and $\mathbf{R}$ and their time derivatives are given in Tables 10 and 11, t is the time in years since 2000.0, and $(v_x, v_y, v_z)_{NZGD}$ is the velocity of the site expressed in Cartesian coordinates from the NZGD2000 deformation model.

6. PREDICTION MODEL FOR POSITIONZ STATIONS

6.1 Creating the model

The final stage in GeoNet's standard daily processing of the PositioNZ GPS data provides "raw" daily coordinate solutions in the ITRF2000 (IGb00) reference frame. This is achieved by a Helmert transformation, using translation parameters only, to the set of regional IGS stations shown in Figure 3. Prior to the Helmert transformation the coordinates are already nominally in the ITRF, using the realisation of the reference frame defined by the IGS precise orbits. Reference stations are rejected if their transformed position differs from the official IGb00 coordinates by more than 15 mm in the horizontal or 40 mm in the vertical, and the Helmert transformation is recalculated with a reduced set of reference stations.

We extract 2000.0 and later coordinate results from the GeoNet solutions, and convert these to (east, north, up) time series. It is these that are posted on GeoNet and LINZ web pages (www.geonet.org.nz/resources/gps/index.html, www.linz.govt.nz/geodetic/positionz/index.aspx).

There is a regional "common-mode" signal in the resulting time series (believed to derive from the satellite orbits, and/or regional-scale to global-scale atmospheric and hydrological mass movements, and/or use of non-optimal models in the processing) that can be attenuated through a regional filtering procedure (e.g., Zhang et al., 1997; Williams et al., 2004; Beavan, 2005). Our modelling procedure works best if this (presumably non-predictable) common-mode signal is first removed from the time series, at least for sites within the New Zealand land mass. However, the common-mode signal should be included in the predicted position of the PositioNZ sites, since the apparent position of the sites in the ITRF includes this signal. There are two possible approaches: (1) estimate and subtract the regional common-mode signal, perform the modelling, then add the common-mode signal back with some form of extrapolation to future time; (2) perform the modelling on the "raw" (east, north, up) time series. We take the second approach for now, even though it means that the fit of the model to the data is less good. In future work the common-mode signal should be examined to see if it has any predictable character that could be included in the time series model for each station.

The raw daily coordinate solutions of PositioNZ stations from 2000.0 onwards are converted to (east, north, up) displacement time series using the following expression:

$$(e(t), n(t), u(t)) = xyz2local((X(t) - X_{NZGD}), (Y(t) - Y_{NZGD}), (Z(t) - Z_{NZGD}), \lambda, \phi) \qquad (3)$$

For each station, (X,Y,Z) are the raw daily coordinate solutions, $(X,Y,Z)_{NZGD}$ are its NZGD2000 coordinates, *xyz2local()* is a function that converts an *(x,y,z)* displacement vector at latitude, longitude (λ,φ) to a displacement vector in local coordinates, and e, n and u are the displacement time series. To ensure that the displacement time series consist of reasonably small numbers, a constant position equal to the approximate position of the station must be subtracted from the daily (X,Y,Z) positions before converting the displacements to the local coordinate system. It does not matter exactly what the constant values are, as the same values are added back to the model at the end of the fitting procedure. For this purpose, we use the NZGD coordinates of the sites as published on the LINZ web site, since there is no published source of coordinates for the PositioNZ sites in any other reference frame.

Each e, n and u time series is then modelled as a sum of the following terms. Only those terms that are appropriate for a particular site are included in the model.

1. constant
2. velocity (or trend, or slope)
3. seasonal (annual and semi-annual) cycles
4. velocity changes at specified times
5. offsets at specified times of equipment changes
6. coseismic offsets at specified times if the site is sufficiently close to the earthquake
7. decaying exponential postseismic signals starting at specified times
8. slow-slip events (amplitude and duration) at specified times

$$\begin{aligned} m(t) = c + vt &+ \sum_{i=1,2}(A_i \cos(2\pi f_i t) + B_i \sin(2\pi f_i t)) + \sum_{j=1,Nv} V_j (t - t_j) H(t - t_j) + \sum_{k=1,Ne} E_k H(t - t_k) \\ &+ \sum_{l=1,Nc} C_l H(t - t_l) + \sum_{m=1,Np} P_m H(t - t_m)(1 - \exp(K_m (t - t_m))) + \sum_{n=1,Ns} 0.5 S_n erf(D_n (t - t_n)) \end{aligned} \quad (4)$$

where m is the model, t is the time in days from 2000.0, and $H(t - t_0)$ is the Heaviside step function that is zero for $t \le t_0$ and 1 for $t > t_0$. Other variables are as follows: c is the constant term and v is the velocity; A_i and B_i are the amplitudes of the in-phase and quadrature seasonal terms, where i=1 for annual and i=2 for semi-annual cycles; V_j and t_j are the magnitudes and times of Nv velocity changes; E_k and t_k are the magnitudes and times of Ne equipment offsets; C_l and t_l are the magnitudes and times of Nc coseismic offsets; P_m, t_m and K_m are the magnitudes, start times and inverse time constants of Np exponentially-decaying postseismic signals; and S_n, t_n and D_n are the magnitudes, centre times and inverse durations of Ns slow slip events. A slow slip event (SSE) is parameterised as an error function, since this functional form is similar to the shapes of SSEs we have observed in New Zealand.

The times of coseismic offsets and equipment offsets are precisely known, so they are specified by the user rather than being variable parameters. The times of a velocity change (t_l) or the mid-point of an SSE (t_m) are harder to specify precisely, so could be included as variables. For this modelling, however, these times are specified by the user.

The model uses a non-linear least squares solution, so starting estimates must be provided for each of the parameters. Our strategy is as follows.

1. Fit a model to the data using just the first three parameter types, with all starting parameters set to zero (this is a linear problem).
2. Examine the solution to see if all parameters are necessary and justified (e.g., the semi-annual terms are rarely necessary, and the annual terms are not desirable if the time series is very short, such as at KTIA).

3. Re-run the model with a reduced parameter set if necessary.
4. Examine each data, model and residual time series by eye, to see whether the residual is sufficiently flat. Many of the time series are fit adequately by this model and there is no need to go to the next step.
5. For time series that are not yet well fit, use the parameters from steps 2 or 3 as the starting parameters for a model run that also includes parameter types 4, 5, 6 and 8 (there are no events of parameter type 7 in the present models).
6. Examine the data, model and residual time series, then add or subtract parameters as necessary to achieve a good fit. Where SSEs or velocity changes are involved, the time of the event may be modified to achieve a better fit. Several iterations may be required in the more complex cases.

Once the fitting and display software had been prepared and tested, we were able to model all 30+ PositioNZ stations (90+ time series) in about a day. The task should be much easier and faster subsequently, as parameters will only rarely need to be added to the model. The fitting software is written in Fortran, and the display software we are using is written as Igor scripts (www.wavemetrics.com). If LINZ wishes to use the display software, a copy of Igor will need to be purchased (it runs on Windows and Macintosh).

The model parameters (as at 25 Jun 2008) are provided in the text file ponl_model_parameters_2008jun25_raw.txt (Appendix 3, electronic-only supplement). Plots of the model fits to the time series are also provided as files accompanying this report. The format of the plots is described in Appendix 3.

In addition to the PositioNZ stations, LINZ requested time series models for several other stations in the southern North Island and northern South Island as variations to this contract. The time series for these stations are also provided in Appendix 3 and the model fits are discussed further in Section 6.3.

6.2 Prediction of future positions using the model

After the model parameters have been evaluated, equation (4) can be used to predict the site displacement, $(e_p(t_f), n_p(t_f), u_p(t_f))$, relative to its NZGD2000 coordinates at any time, t_f, in the future. Here, the subscript p refers to the model prediction from equation (4). To recover the ITRF2000(IGb00) latitude, longitude and ellipsoidal height from the model, equations (3) then need to be applied in reverse:

$$(X_p(t_f), Y_p(t_f), Z_p(t_f)) = (X_{NZGD}, Y_{NZGD}, Z_{NZGD}) + local2xyz(e_p(t_f), n_p(t_f), u_p(t_f), \lambda, \phi) \quad (5)$$

$$(\lambda_p(t_f), \phi_p(t_f), h_p(t_f)) = xyz2geod(X_p(t_f), Y_p(t_f), Z_p(t_f))$$

where *local2xyz()* is a function that reverses the displacement transformation of *xyz2local(), xyz2geod()* is a function that converts *(x,y,z)* coordinates to latitude, longitude and height on the ellipsoid, and the subscript p refers to the model prediction from equation (4).

The daily results from GeoNet processing are presently evaluated in the ITRF2000(IGb00) reference frame, though this will be upgraded to ITRF2005(IGS05) in due course. So to calculate predicted IGS05 coordinates at the PositioNZ stations the results of the model from equation (5) need to be converted from IGb00 to IGS05 using the transformation from Section 5 of this report (final entries in Table 9).

6.3 Individual model solutions

Apart from the offset and average slope, one signal observed at many NZ GPS sites is a coseismic displacement at the time of the 23 December 2004 Macquarie earthquake (time = 1819 days from 1 Jan 2000). We have solved for a horizontal coseismic offset at all stations at the time of this earthquake. In a few cases, the coseismic event occurred close to some other event in the time series, and solving for it caused an obviously incorrect trade-off between the two events; in these cases we switched off the solution for the coseismic event. We did not solve for vertical coseismic offsets as the event was almost pure strike slip and should have caused no appreciable vertical displacement in New Zealand.

We now discuss the model results for each PositioNZ station in turn, highlighting those series that require parameters in addition to intercept, slope, and annual sinusoid (and Macquarie coseismic offset for stations established prior to this earthquake).

AUCK. There are two equipment offsets due to antenna changes on days 667 and 2134. There is a slow signal of unknown origin on the east component centred about day 1210. We have modelled this as a slow slip event, though it presumably does not have this physical origin, in order to get an adequate fit of the model to the time series.

BLUF, LEXA, MAVL. We have modelled the October 2007 Fiordland coseismic offset in these time series. The offset is largest at MAVL, but also noticeable at LEXA and BLUF.

CHAT. There is one equipment offset due to an antenna change on day 698.

CORM, DUND, HAAS, HAMT, HIKB, KAIK, KTIA, LKTA, MAHO, MTJO, NPLY, PYGR, TRNG, WAIM, WEST, WHNG. No additional model parameters required. At KTIA no annual signal was solved for, due to the short length of the time series at present.

GLDB, NLSN. We have modelled the 2007-08 Kapiti Coast slow-slip event, which started in December 2007 and is still ongoing to some extent in June 2008.

DNVK. Two slow-slip events are modelled: the 2004-05 Manawatu event and the August 2006 south-of-Hastings event. To get a good fit to the time series, we also had to model a velocity change in the east component following the south-of-Hastings event. We do not presently understand the origin of this signal.

GISB. Three slow-slip events are modelled, plus an additional two smaller events in the east component. Slope changes in the east component following the second and fourth events were also required for a good fit.

HAST. Four slow-slip events were modelled, some of them as velocity changes rather than an error function. Several other velocity changes were required in the horizontal components to obtain a satisfactory fit.

HOKI. There are two equipment offsets due to antenna changes on days 20 and 1344.

MAST. This required a velocity change of unknown origin at about day 1600.

MQZG. There are two equipment offsets due to antenna changes on days 612 and 1886.

SCTB. We included a semi-annual term as well as an annual term.

TAUP. The time series from TAUP are full of interesting (but fairly small) signals. The source of these signals is presently unknown, but they are likely to be of volcanic or geothermal origin. We have made an approximate model of the series as a set of 7 velocity changes (5 in the case of the vertical signal).

WANG. There is a slow-slip event (the Manawatu event) centred at about day 1860. We turned off the Macquarie coseismic offset in the east component, as it interacted with the Manawatu slow slip in the model solution.

WGTN. There is one equipment offset due to an antenna change on day 1907, and the 2007-08 Kapiti Coast slow-slip event was modelled as a velocity change.

We now discuss the model results for the supplementary stations.

AVLN, CLIM, DURV, HOLD, KAPT, TORY, WGTT. We have modelled the 2007-08 Kapiti Coast slow-slip event. In the case of TORY and WGTT it is presently modelled as a velocity change rather than an error function.

CMBL, OTAK, PALI, PARW, TINT. No additional model parameters required.

PAEK. We have modelled the 2003-04 and 2007-08 Kapiti Coast slow-slip events, and an equipment offset due to an antenna change on day 2445.

6.4 Quality checking of model predictions

We have done some quality checking to ensure that the output from the model agrees with the average of daily solutions at the time of the prediction, in both the IGb00 and IGS05 reference frames.

We generated the model for all PositioNZ stations using data through 25 June 2008. We used the model to predict the positions of all stations on day 150 of 2008 (t = 3072.5 days) in the IGb00 reference frame. We compared this with the average, using Bernese COMPAR, of 14 days of coordinate solutions (days 143-156 of 2008) output from the final Helmert transformation in the daily processing. This comparison is in the IGb00 reference frame and is shown in Table 13. The results show < 3 mm bias between the predicted and actual solutions, and standard errors at the 1-3 mm level.

We also used the model to predict the positions of all stations on day 150 of 2008 in the IGS05 reference frame (using the transformation parameters from the final section of Table 9). We then ran the final stages of the Bernese processing in the IGS05 reference frame for 14 days (days 143-156 of 2008), and took the average, using Bernese COMPAR, of the coordinate solutions output from the final Helmert transformation in the daily processing. Because the coordinates and velocities of the reference sites are in the IGS05 reference frame this coordinate set is also in the IGS05 reference frame. The IGS05 model predictions and the averaged results from the Bernese processing are compared in Table 14, and show differences at a somewhat higher level than for the IGb00 comparison. This indicates that a small additional bias is being introduced, either in the way the coordinates are transformed to the IGS05 frame in the Bernese processing, or in our IGS05-IGb00 transformation.

Table 13 Comparison of estimated and predicted coordinates, IGb00 reference frame

Helmert-transformed raw daily coordinates in IGb00. Days 143-156, 2008, averaged using COMPAR.				PONL-02 IGb00 time series model from raw daily results. Prediction for day 150, 2008.			Differences, mm		
							N	E	U
AUCK	-36.602841644	174.834385614	132.7280	-36.602841634	174.834385648	132.7274	-1.1	-3.0	0.6
BLUF	-46.585062159	168.292084152	124.6670	-46.585062157	168.292084185	124.6647	-0.2	-2.5	2.3
CHAT	-43.955784336	-176.56584428	57.9910	-43.955784313	-176.56584424	58.0038	-2.6	-3.0	-13.
CORM	-36.865430575	175.749557597	170.2780	-36.865430563	175.749557621	170.2820	-1.3	-2.1	-4.0
DNVK	-40.298855496	176.166656224	457.6720	-40.298855490	176.166656252	457.6755	-0.7	-2.4	-3.5
DUND	-45.883663766	170.597166673	386.9660	-45.883663763	170.597166703	386.9628	-0.3	-2.3	3.2
GISB	-38.635335301	177.886034419	87.2240	-38.635335291	177.886034458	87.2250	-1.1	-3.4	-1.0
GLDB	-40.826593592	172.529562291	302.6440	-40.826593572	172.529562330	302.6450	-2.2	-3.3	-1.0
HAAS	-44.073202532	168.785551415	1053.5710	-44.073202502	168.785551425	1053.5736	-3.3	-0.8	-2.6
HAMT	-37.806752423	175.109198198	69.4380	-37.806752412	175.109198214	69.4392	-1.2	-1.4	-1.2
HAST	-39.617031048	176.726563075	152.4040	-39.617031033	176.726563108	152.4069	-1.7	-2.8	-2.9
HIKB	-37.561039922	178.303352757	107.3230	-37.561039922	178.303352785	107.3240	0.0	-2.5	-1.0
HOKI	-42.712904202	170.984314515	53.6940	-42.712904209	170.984314553	53.6945	0.8	-3.1	-0.5
KAIK	-42.425464603	173.533655629	314.8090	-42.425464592	173.533655653	314.8112	-1.2	-2.0	-2.2
KTIA	-35.068929801	173.273110046	127.4850	-35.068929795	173.273110094	127.4822	-0.7	-4.4	2.8
LEXA	-45.231014842	169.308246595	331.8820	-45.231014851	169.308246618	331.8778	1.0	-1.8	4.2
LKTA	-42.783368894	172.266330602	713.0080	-42.783368870	172.266330621	713.0089	-2.7	-1.6	-0.9
MAHO	-38.513006225	174.854087386	302.5370	-38.513006206	174.854087403	302.5381	-2.1	-1.5	-1.1
MAST	-41.061988319	175.584574615	207.2640	-41.061988312	175.584574656	207.2685	-0.8	-3.4	-4.5
MAVL	-45.366515494	168.118212700	592.4870	-45.366515491	168.118212734	592.4860	-0.3	-2.7	1.0
MQZG	-43.702733717	172.654701146	154.6890	-43.702733712	172.654701196	154.6961	-0.6	-4.0	-7.1
MTJO	-43.985703468	170.464939904	1043.6760	-43.985703472	170.464939936	1043.6780	0.4	-2.6	-2.0
NLSN	-41.183505461	173.433729307	302.1960	-41.183505472	173.433729349	302.1973	1.2	-3.5	-1.3
NPLY	-39.182554417	174.118173731	416.9750	-39.182554409	174.118173745	416.9767	-0.9	-1.2	-1.7
PYGR	-46.166172484	166.680737516	253.1950	-46.166172486	166.680737563	253.1930	0.2	-3.6	2.0
SCTB	-77.848985691	166.758018403	-18.9090	-77.848985687	166.758018431	-18.9157	-0.4	-0.7	6.7
TAUP	-38.742714217	176.080994621	427.0550	-38.742714207	176.080994655	427.0554	-1.1	-2.9	-0.4
TRNG	-37.728809353	176.260877218	151.1410	-37.728809341	176.260877243	151.1444	-1.3	-2.2	-3.4
WAIM	-44.655702438	170.920298898	1044.9110	-44.655702425	170.920298925	1044.9106	-1.4	-2.1	0.4
WANG	-39.786878121	174.821446330	289.7190	-39.786878122	174.821446353	289.7179	0.1	-2.0	1.1
WEST	-41.744743525	171.806222275	665.3990	-41.744743517	171.806222282	665.3998	-0.9	-0.6	-0.8
WGTN	-41.323454699	174.805891210	26.0700	-41.323454705	174.805891243	26.0693	0.7	-2.8	0.7
WHNG	-35.803768493	174.314566729	172.8200	-35.803768478	174.314566753	172.8204	-1.7	-2.2	-0.4
						Mean	-0.8	-2.4	-0.9
						Stdev	1.1	0.9	3.4

The significant biases (non-zero means in Tables 13 and 14) are due to the fact that the model is not designed to fit the regional common-mode signal that is present in all the time series. At times when the common-mode signal is non-zero, the coordinates of all series will tend to deviate from the model by this amount. The effect of the common-mode signal can often be seen in the plots provided as part of Appendix 3. For example, most of the residual time series for the north component show a peak at about 2430 days.

We have also generated models using regionally-filtered (rather than raw) time series as input, and the RMS values of the residuals are typically half what they are when the raw data are used in the modelling. We would therefore expect up to a factor of two improvement in prediction accuracy if the regional common-mode signal could be incorporated more correctly in the modelling.

Table 14 Comparison of estimated and predicted coordinates, IGS05 reference frame

Helmert-transformed raw daily coordinates in IGS05. Days 143-156, 2008, averaged using COMPAR.				PONL-02 IGS05 time series model from raw daily results. Prediction for day 150, 2008.			Differences, mm		
							N	E	U
AUCK	-36.602841502	174.834385724	132.6980	-36.602841487	174.834385800	132.6975	-1.7	-6.8	0.5
BLUF	-46.585062071	168.292084262	124.6350	-46.585062060	168.292084348	124.6313	-1.2	-6.6	3.7
CHAT	-43.955784219	-176.56584413	57.9610	-43.955784182	-176.56584406	57.9736	-4.1	-5.8	-13.
CORM	-36.865430433	175.749557711	170.2490	-36.865430415	175.749557776	170.2522	-2.0	-5.8	-3.2
DNVK	-40.298855370	176.166656346	457.6420	-40.298855355	176.166656415	457.6449	-1.7	-5.9	-2.9
DUND	-45.883663674	170.597166786	386.9340	-45.883663659	170.597166869	386.9299	-1.7	-6.4	4.1
GISB	-38.635335166	177.886034541	87.1950	-38.635335147	177.886034621	87.1952	-2.1	-6.9	-0.2
GLDB	-40.826593472	172.529562401	302.6130	-40.826593445	172.529562487	302.6136	-3.0	-7.2	-0.6
HAAS	-44.073202432	168.785551522	1053.5400	-44.073202393	168.785551582	1053.5408	-4.3	-4.8	-0.8
HAMT	-37.806752287	175.109198314	69.4090	-37.806752270	175.109198370	69.4090	-1.9	-4.9	0.0
HAST	-39.617030919	176.726563199	152.3740	-39.617030895	176.726563271	152.3765	-2.7	-6.2	-2.5
HIKB	-37.561039782	178.303352880	107.2940	-37.561039774	178.303352946	107.2945	-0.9	-5.8	-0.5
HOKI	-42.712904093	170.984314623	53.6620	-42.712904092	170.984314711	53.6624	-0.1	-7.2	-0.4
KAIK	-42.425464489	173.533655745	314.7780	-42.425464470	173.533655816	314.7795	-2.1	-5.8	-1.5
KTIA	-35.068929655	173.273110152	127.4560	-35.068929644	173.273110241	127.4525	-1.2	-8.1	3.5
LEXA	-45.231014747	169.308246703	331.8500	-45.231014746	169.308246779	331.8449	-0.1	-6.0	5.1
LKTA	-42.783368785	172.266330717	712.9770	-42.783368751	172.266330782	712.9770	-3.8	-5.3	0.0
MAHO	-38.513006093	174.854087499	302.5060	-38.513006066	174.854087560	302.5076	-3.0	-5.3	-1.6
MAST	-41.061988198	175.584574737	207.2340	-41.061988181	175.584574820	207.2376	-1.9	-7.0	-3.6
MAVL	-45.366515400	168.118212807	592.4550	-45.366515389	168.118212893	592.4529	-1.2	-6.7	2.1
MQZG	-43.702733611	172.654701265	154.6580	-43.702733596	172.654701361	154.6640	-1.7	-7.7	-6.0
MTJO	-43.985703366	170.464940016	1043.6450	-43.985703361	170.464940096	1043.6454	-0.6	-6.4	-0.4
NLSN	-41.183505342	173.433729421	302.1650	-41.183505345	173.433729509	302.1659	0.3	-7.4	-0.9
NPLY	-39.182554289	174.118173847	416.9450	-39.182554273	174.118173901	416.9460	-1.8	-4.7	-1.0
PYGR	-46.166172397	166.680737616	253.1630	-46.166172390	166.680737721	253.1595	-0.8	-8.1	3.5
SCTB	-77.848985768	166.758018748	-18.9420	-77.848985736	166.758018949	-18.9507	-3.6	-4.7	8.7
TAUP	-38.742714085	176.080994740	427.0260	-38.742714066	176.080994814	427.0251	-2.1	-6.4	0.9
TRNG	-37.728809215	176.260877336	151.1120	-37.728809197	176.260877401	151.1145	-2.0	-5.7	-2.5
WAIM	-44.655702340	170.920299015	1044.8800	-44.655702316	170.920299088	1044.8780	-2.7	-5.8	2.0
WANG	-39.786877994	174.821446447	289.6890	-39.786877988	174.821446512	289.6871	-0.7	-5.6	1.9
WEST	-41.744743411	171.806222384	665.3680	-41.744743394	171.806222440	665.3680	-1.9	-4.6	0.0
WGTN	-41.323454579	174.805891328	26.0400	-41.323454576	174.805891406	26.0381	-0.3	-6.5	1.9
WHNG	-35.803768347	174.314566836	172.7910	-35.803768329	174.314566904	172.7906	-2.0	-6.1	0.4
						Mean	-1.8	-6.2	-0.1
						Stdev	1.1	0.9	3.6

7. UPDATED DEFORMATION MODEL

7.1 Deformation model using GPS data through March 2005

We note that the work and results reported in Section 7.1 are superceded by the work and results described in Sections 7.2 - 7.6 below. Section 7.1 is retained for completeness, but the reader may wish to go directly to Section 7.2.

Following discussions with LINZ in January 2008, it was agreed that Milestone 5 could be adjusted to include data through to March 2005, rather than March 2007, in order that LINZ could be supplied by the end of January with an interim new deformation model for PositioNZonLine development purposes. The updated continuous horizontal velocity model (or deformation model) was calculated in the same way as the original model (v2.1) (Beavan, 1998), to give velocities that are nominally relative to the Australian Plate.

The input data consisted of 863 velocity estimates from 754 distinct GPS stations, which is more than double the number of stations available for the v2.1 calculations. The updated model is called v2.2, and is supplied as a "solution.gns" file in the same format as v2.1. For details on the usage of this file, see Section 13 of Beavan (1998). The "solution.gns" file supplied with this report has the name: solution_gns_v22.txt

We have also calculated Euler rotation parameters to convert the "Australia-fixed" horizontal velocities to the IGS05, IGb00 and ITRF96 reference frames. For the first two frames, this is achieved by 3-parameter Helmert transformations (3 rotations) between the v2.2 velocity model and the horizontal components of our estimated IGS05 and IGb00 velocities (taken from earlier versions of Tables 6 and 7 of this report) at 29 of the 30 1st-order and continuous stations used in Beavan (1998). Station WELL is omitted from the calculation because it was decommissioned in 1997 so does not have an up-to-date velocity estimate. For the transformation to ITRF96 we use the ITRF96 velocities of these 29 stations as calculated by Morgan and Pearse (1999); this is the same procedure that was adopted by Beavan (1998). Note that we have used only horizontal velocities in these calculations because vertical velocities are assumed to be zero in NZGD2000. The RMS of the fit of the rotated deformation model velocities to the reference frame velocities is 1.2 mm/yr for ITRF96, 0.8 mm/yr for IGb00, and 0.7 mm/yr for IGS05.

The Euler vectors that rotate the "Australia-fixed" deformation model into each of the three reference frames are given in Table 15.

Table 15 Euler rotation parameters to convert v2.2 deformation model to different reference frames

Reference frame	Latitude (deg)	Longitude (deg)	Rate (rad/10 Myr)
IT96 (Morgan & Pearse, 1999)	-29.47	225.57	0.0993
IGb00 (this report, Table 6)	-30.44	222.26	0.0982
IGS05 (this report, Table 7)	-30.84	224.52	0.0994

7.2 Reprocessing of survey-mode GPS data collected from 1996 to 2008

As part of one of GNS's FRST contracts ("Impacts of Plate Tectonics on New Zealand"), we have undertaken reprocessing of all survey-mode GPS data collected in New Zealand between January 1996 and February 2008. We used the same GPS processing methods described in Section 3 for the 1995-2006 processing of 1st-order stations, with the exception that we allow a minimum session length of 6 hours, rather than 12 hours, because many survey-mode data were collected in 6-8 hour sessions, especially in the earlier years. Some data that were collected across day boundaries in 1996 are still omitted from the processing under this procedure. The reprocessed data are available for use in an updated calculation of the GNS deformation model.

A total of 1089 daily coordinate and covariance solutions were calculated from just over 12 years of data collection. We processed these using the geodetic adjustment software adjcoord (Crook, 1992) to obtain minimally-constrained velocity estimates relative to station AUCK. An advantage of estimating the velocities this way, as opposed to directly estimating them relative to a global or regional reference frame, is that common-mode signals within New Zealand are removed to first order. A disadvantage is that the resulting velocity field has later to be transformed into some conventional reference frame.

7.2.1 Treatment of coseismic displacements from nearby earthquakes

During the processing it became plain that the coseismic displacements due to the 23 December 2004 M_w 8.0 Macquarie earthquake were significantly affecting estimated station positions (and velocities) throughout New Zealand, especially in the southern South Island. Coseismic displacements were as much as 10 mm, leading to errors in the estimated velocities up to about 1 mm/yr. The 21 August 2003 M_w 7.2 Secretary Island earthquake also affected station positions over a more restricted region in Fiordland, Southland and Otago. We therefore undertook some pre-processing steps prior to the adjcoord analysis, as described below.

In order to obtain the best estimates of steady-state (interseismic) velocity we have made a correction to the daily coordinate data at the times of the two earthquakes. We generated a dislocation model of each earthquake assuming a uniform-slip, rectangular fault surface buried in an elastic half-space. The parameters of the two models are given in Table 16.

For the Secretary Island earthquake, the model was obtained by inverting the coseismic displacements obtained from pre-earthquake GPS surveys in 2001 and early 2003 and a post-earthquake survey a few weeks after the earthquake, with a correction made for the steady interseismic displacement between the pre-earthquake surveys and the time of the earthquake. The dislocation model was briefly described in Reyners et al. (2003), and has been refined since. A recent inversion of the data by Rob McCaffrey using independent software gives an almost identical model. The use of a uniform-slip model is appropriate for this case as very few GPS stations are close enough to the earthquake to be sensitive to the slip distribution on the fault plane.

By the time of the Macquarie earthquake, most CGPS stations of the PositioNZ network were operating, as well as a number of GeoNet stations, so that their coseismic displacements could be measured without requiring an interseismic correction. Starting with the seismological location, magnitude and fault plane solution of the earthquake, we ran forward dislocation models varying these parameters in order to obtain a best fit to the coseismic displacements observed at southern NZ CGPS stations and the IGS station MAC1. Survey-mode data collected at Auckland Island and Campbell Island may help to refine the model in future, but the processed data from these islands is not yet available. Uniform slip is again an appropriate assumption for this earthquake, given the distance of New Zealand from the earthquake source. The slip magnitude trades off directly against the fault area (length × width) because there are no near-field observations, so only the product of (slip × area) is constrained (i.e., the earthquake could have been on a shorter fault with a proportionally larger slip). The elastic half-space assumption may not be appropriate for this earthquake because of the large distance (> 1500 km) at which surface displacements were observed. However, we obtain a good fit to the observed displacements at the southern South Island CGPS sites, and even if we mis-model site displacements further north by 30% this will only cause errors on the order of 1 mm.

Table 16 Model parameters for coseismic corrections

	Secy. Is. 2003	**Macquarie 2004**
Lat, º	-45.13	-50.4
Lon, º	166.941	160.9
Depth, km	19	11
Strike, º	30	340
Dip, º	30	90
Rake, º	98	17
Slip, m	4.3	5.1
Length, km	35	300
Width, km	12	20

We correct the daily coordinate-difference data by subtracting the coseismic model prediction for each station in each daily data set following the day of the earthquake. (In fact, because the data are now in the form of coordinate differences, we subtract the difference between the model predictions at the two stations). We do not modify the daily covariance matrices as we consider we are only making a small correction to the coordinate data.

We also make three other amendments to the data prior to the adjcoord processing.

1. For sites close (approx 100 km) to the 2003 earthquake we solve independently for the velocity before and after the earthquake. This is so that the site velocity is not biased by any inaccuracy in our coseismic correction. It also gives us the opportunity to investigate if there is a significant velocity change at the time of the earthquake.

2. We omit the data set collected in the several weeks following the 2003 earthquake. This is because any postseismic deformation due to afterslip is likely to be greatest in the several months following the earthquake. If left in the dataset these data could bias the estimation of the steady velocity.

3. We omit the data set collected about two months after the 15 October 2007 M_w 6.8 Fiordland earthquake because these cannot contribute to a steady velocity solution until a second set of post-earthquake data is collected.

7.2.2 Treatment of slow slip events beneath the North Island

Using these procedures we have corrected for biases in steady velocity estimation that would otherwise result from the occurrence of earthquakes in or near the GPS network. The occurrence of slow slip events (SSEs), or “slow earthquakes” affecting much of the southern and eastern North Island means that similar biases will be present in the calculated velocity field in the North Island. Examination, for example, of the time-series plot of the DNVK east component (Appendix 3) shows that the station velocity between SSEs is several mm/yr different from the velocity that would be obtained by averaging through all the data. This is even more striking for the case of the GISB east component, where the velocity between events is about double the average velocity.

For LINZ’s purposes, the important requirement is that the deformation model should predict the horizontal site position to within 50 mm (and preferably substantially better than that). Concerning SSEs, the two end-member approaches are:

1. Use the average velocity as determined from the occasional survey-mode measurements. So long as the SSE amplitudes at the surface are fairly small (36 mm is the largest we have seen to date), and especially if the SSEs occur quite frequently (as they appear to do along the east coast), this estimated average velocity will give a fairly accurate prediction of future position (within 15-20 mm) even in the presence of SSEs. If some SSE displacements are much larger than 30 mm, or if the repeat interval is on the order of the length of the GPS data set, or longer, then it is possible that velocities estimated from occasional survey-mode data will be substantially in error, thus leading to prediction errors that could exceed 50 mm.

2. Generate an inversion model that uses all continuous and campaign GPS time series to estimate the location, amplitude and duration of every SSE and earthquake as well as the velocity between these events, rather like we have done in Section 6 for the CGPS time series but considerably more sophisticated. This is a more complex prediction tool than a simple position and velocity, and it is also not applicable to data prior to about 2002 when we started to gather information on SSEs.

For this report we will keep to the first approach, but we note that the second approach could be considered by LINZ in the future. As the global earth science community learns more about SSEs over the next few years, the best approach to modelling them should become clearer.

7.3 Transformation of velocity solution into Australia-fixed reference frame

The result of the adjcoord processing is a set of 770 velocities relative to AUCK from 748 sites in New Zealand (Figure 7), plus another 11 site velocities in Australia and the Pacific (22 sites in Fiordland and Southland have two velocity estimates each – one before and one after the 2003 earthquake). We use the horizontal velocities of the Australian sites plus AUCK to transform the velocity solution into a best fit to an Australia-fixed reference frame. We found the fit to be most self-consistent if we used sites in eastern and central Australia for this transformation, namely ALIC, CEDU, TOW2, TIDB, and HOB2, in addition to AUCK.

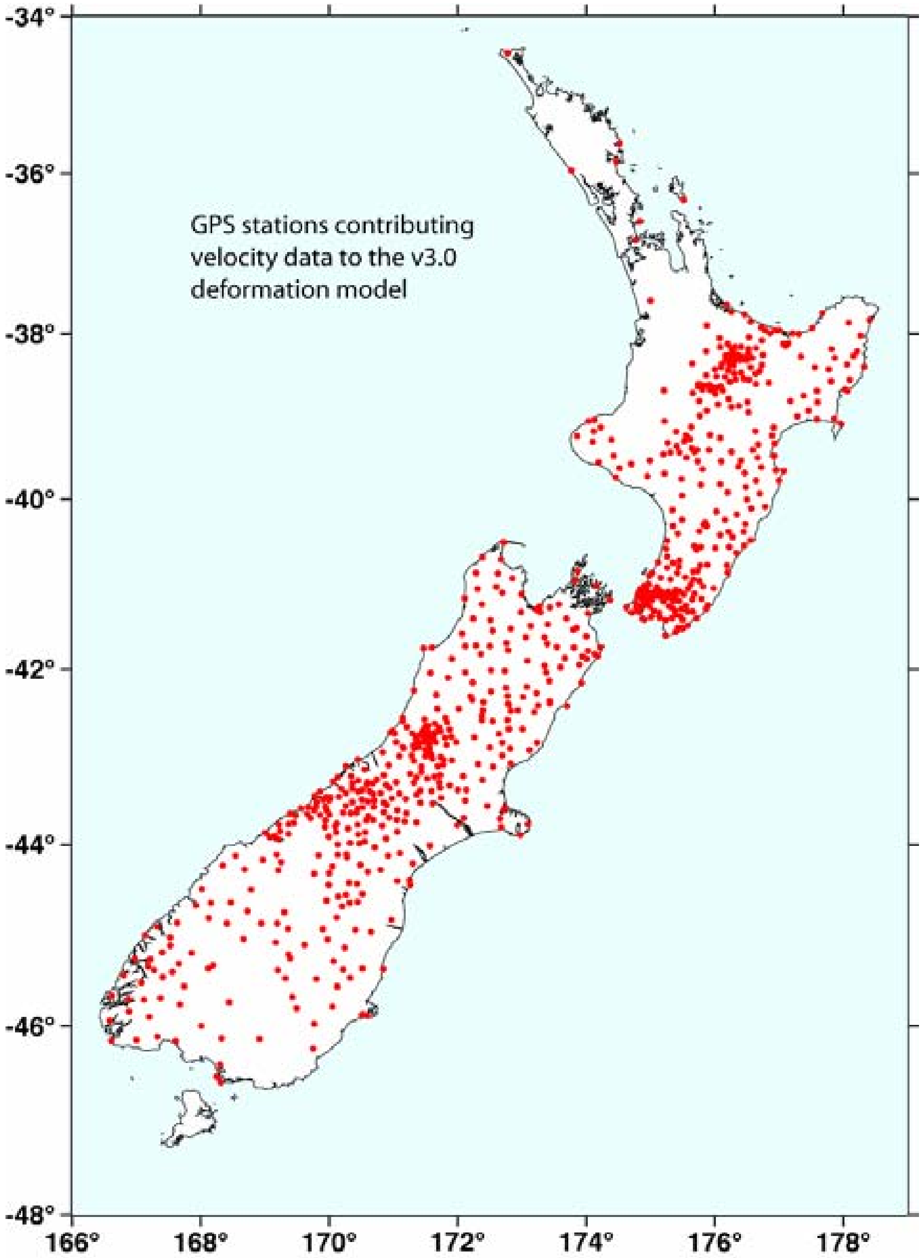

Figure 7 The 748 GPS sites contributing velocity data to the v2.3 and v3.0 deformation models.

7.4 Calculation of continuous horizontal deformation model

We then use these 770 New Zealand site velocities as input to GNS's deformation mapping software in order to produce a continuous horizontal velocity field throughout the New Zealand mainland and near-offshore islands. The new data set of 770 independent velocities is almost double the 391 independent velocities used by Beavan (1998) for the current LINZ deformation model (labelled v2.1 by GNS). The site distribution across the country is also much superior (Figure 7), and the velocity estimates tend to have lower uncertainty due to the longer time interval, the improved quality of more recent data and the more uniform GPS data processing.

We have calculated two continuous velocity fields. One (v2.3) uses the original software and the same grid as was used for the original (v2.1) model. The second (v3.0) uses an updated version of the software and a much finer grid. The grids are compared in Figure 8. The new software uses essentially the same methodology as described in Beavan & Haines (2001). However, it has been reconfigured so that it can efficiently process much larger arrays of grid points in order to be able to solve much larger problems. In the case of New Zealand this means the grid dimensions can be much smaller than previously, allowing the bicubic-spline fitting to more faithfully follow the observed GPS velocities in regions with spatially dense data. A disadvantage of the updated method is that only the standard errors and single-site correlations are carried through the inversion; inter-site correlations are ignored. Additional information on the differences between the original and updated versions of the software can be found in Appendix D.

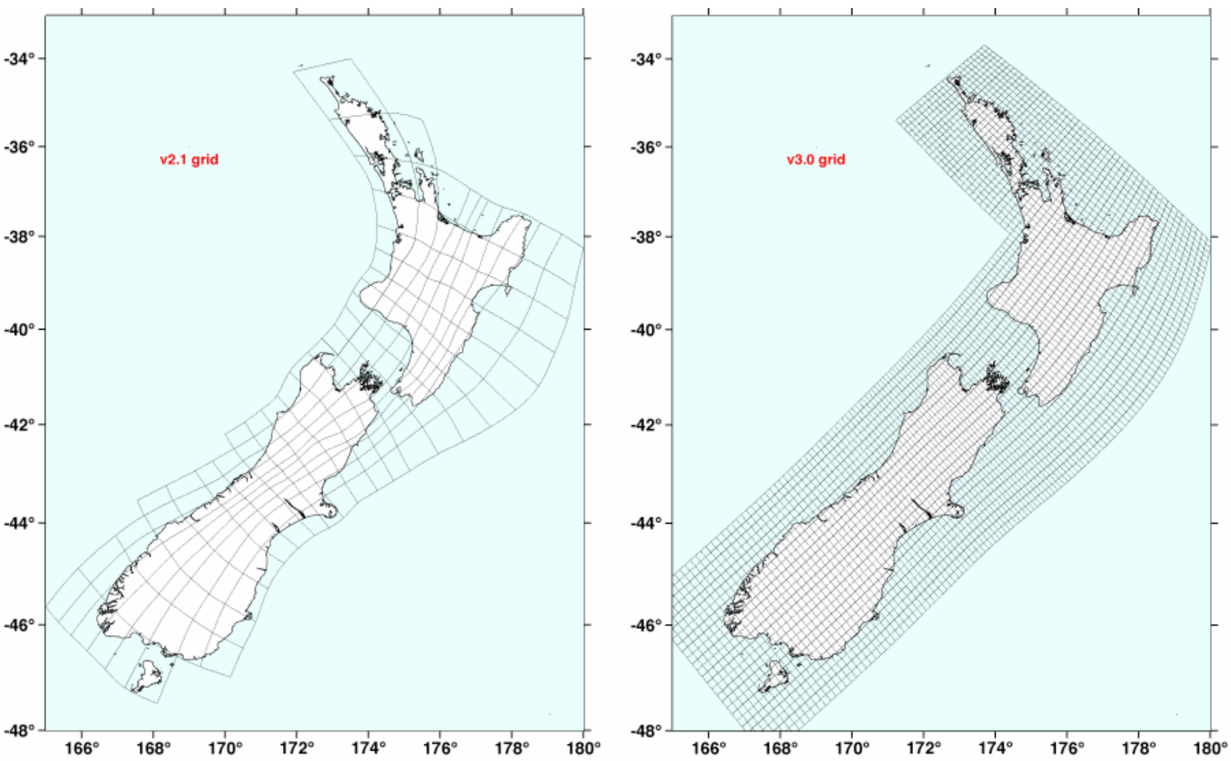

Figure 8 Comparison of grids used in v2.1 (left) and v3.0 (right) deformation models.

7.5 Comparison of v3.0 and v2.1 deformation models

The v3.0 and v2.1 deformation models are compared in two ways in Figures 9 and 10. Figure 9 shows the velocities relative to Australia, while Figure 10 shows them after transformation into the ITRF96 reference frame (using the parameters from Table 17 below for v3.0, and the parameters in Beavan, 1998, p 31 for v2.1). There is an overall translation of about 1.5 mm/yr in a NW direction between the two velocity fields when they are compared at either the 1st-order stations or the set of points plotted in Figure 9. After taking this into account there are RMS differences of about 1.5 mm/yr in both horizontal components, and maximum differences up to 6 mm/yr at individual points.

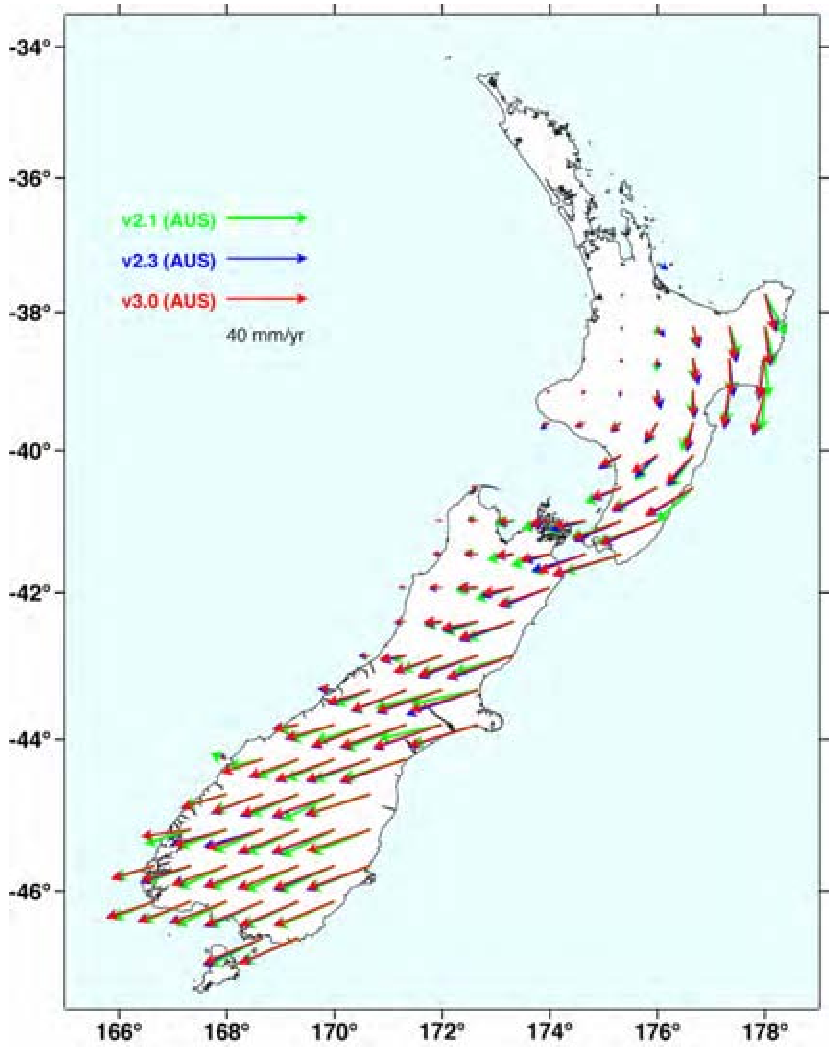

Figure 9 Velocities from the v2.1 (green), v2.3 (blue) and v3.0 (red) deformation models at a set of points at about 50 km spacing throughout New Zealand, evaluated in an Australia-fixed reference frame. The blue and red arrows are generally very similar, showing that the changes to the velocity modelling software do not cause a significant difference in the calculated velocity field.

We have also compared the v2.3 and v3.0 velocity fields. Evaluated at either the NZ 1st-order stations or the set of points in Figure 9, the mean agreement is better than 0.8 mm/yr, with an RMS difference less than 1 mm/yr and a maximum difference of 3 mm/yr. This level of agreement shows that there is no significant difference between the old and new velocity modelling software when the same input data are used. At points between existing GPS stations (i.e., at locations where velocities are interpolated by the model) we assume that the finer grid used by the new software provides more accurate interpolation. We test this assumption and the accuracy of the interpolation in Section 7.7.

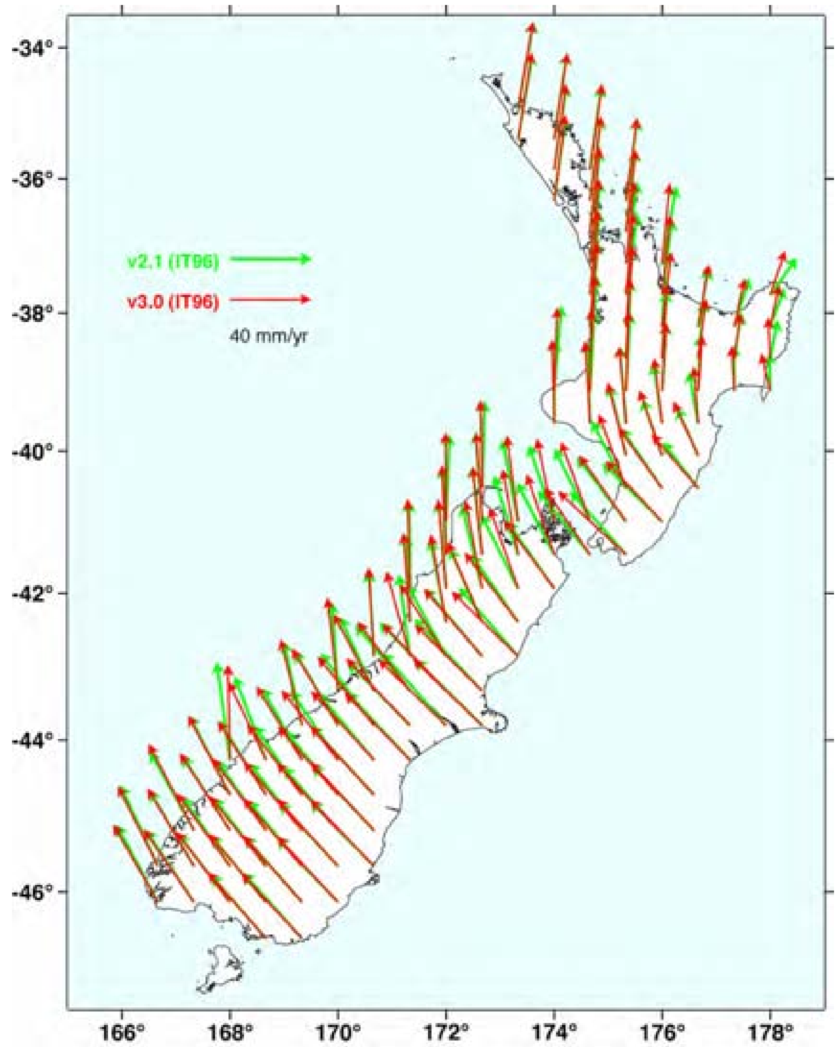

Figure 10 Velocities from the v2.1 and v3.0 deformation models at a set of points at about 50 km spacing throughout New Zealand, with both models transformed to a best fit to the ITRF96 velocity field of Morgan & Pearse (1999). This highlights the differences between the v2.1 and v3.0 velocity fields. These differences are mainly a result of the improved velocity data, rather than the change in velocity modelling software.

7.6 Transformation of deformation model into ITRF reference frames

We determine the transformation parameters between the v3.0 deformation model (nominally in an Australia-fixed reference frame) and the various ITRF reference frames in the same manner as previously. We evaluate the deformation model at the stations listed in Table 6 (excluding A6RE and WELL), then calculate 3-parameter Helmert transformations (3 rotations) between this velocity field and the IGb00 and IGS05 velocity fields given in Tables 6 and 7. We also evaluate the transformation between the v3.0 deformation model and the ITRF96 reference frame used in NZGD2000. The results, in terms of Euler rotations that can be used by the velocity modelling software, are given in Table 17.

Table 17 Euler rotation parameters to convert v3.0 deformation model to different reference frames

Reference frame	Latitude (deg)	Longitude (deg)	Rate (rad/10 Myr)
IT96 (Morgan & Pearse, 1999)	-32.555	224.960	0.09875
IGb00 (this report, Table 6)	-30.243	221.785	0.09735
IGS05 (this report, Table 7)	-31.021	223.828	0.09880

7.7 Comparison of interpolated and measured velocities

In this section we test how well the v3.0 deformation model predicts velocities at sites not included in the model calculations. For this we use PositioNZ and GeoNet cGPS sites whose data were not included in the model. We discount sites that have time series shorter than two years or that are clearly affected by non-linear deformation, leaving a total of 40 sites for comparison (Table 18). The measured velocities are taken from linear fits to the time series of daily coordinates in the IGb00 reference frame after regional filtering (these time series are displayed on the GeoNet web site). The predicted velocities are taken from the v3.0 deformation model with the Euler rotation parameters from the second row of Table 17 applied. The agreement is excellent, with biases of only ~1 mm/yr, and RMS differences of 1.0-1.4 mm/yr in the two horizontal components. We have made the same comparison using the v2.3 deformation model, and find slightly larger RMS differences of 1.1-1.5 mm/yr in this case. This supports our assumption that the v3.0 model (finer grid) does a better job of interpolation that the v2.3 model (coarser grid), but the difference is very minor.

7.8 Use of deformation model software

The velocity model is contained in the file solution.gns. The version number (v3.0), date (24 jun 2008), and standard error of unit weight (1.52) are included in the first line of the file.

The fortran code to generate point velocity estimates from solution.gns is in file gns_velocity.f.

gns_velocity expects a data file named lat_long.dat that contains as its first line the number of points to follow. Succeeding lines contain an index number, latitude and longitude for each point. The latitude (positive north) and longitude (positive east) are entered in decimal degrees. The point must lie within the boundaries of the grid displayed in Figure 8 (right panel). An example lat_long.dat file is:

```
4
1  -42.355   176.398
2  -43.65657 174.5676
3  -41.99827344  173.39387489
4  -44.4     171.45
```

Table 18 Comparison of measured and predicted velocities, IGb00 reference frame

Site	Latitude (deg)	Longitude (deg)	Ell. Ht. (m)	Measured N	Measured E	v3.0 predicted N	v3.0 predicted E	Diff. (mm/yr) N	Diff. (mm/yr) E
AVLN	-41.196439075	174.932858320	39.590	31.9	-25.1	32.3	-24.6	0.4	0.5
BIRF	-40.679766342	176.246106836	308.971	29.5	-29.3	27.4	-27.9	-2.1	1.4
BNET	-43.862486612	170.190142352	757.772	33.2	-27.3	33.0	-27.7	-0.2	-0.4
CAST	-40.909816437	176.201553547	173.614	29.0	-30.7	27.6	-27.9	-1.4	2.8
CLIM	-41.144667708	175.145471052	830.702	30.7	-27.5	30.0	-26.4	-0.7	1.1
CMBL	-41.749044852	174.213807238	256.093	33.2	-27.8	32.5	-27.0	-0.7	0.8
CNCL	-43.666242905	169.855855930	1222.264	38.8	-18.6	36.9	-20.1	-1.9	-1.5
CORM	-36.865432293	175.749557638	170.277	38.6	0.9	37.1	2.7	-1.5	1.8
DUND	-45.883664550	170.597168068	386.952	30.8	-34.8	30.0	-33.2	-0.8	1.6
GLDB	-40.826595228	172.529562651	302.630	42.4	-4.8	41.2	-3.7	-1.2	1.1
HAAS	-44.073203984	168.785552275	1053.564	41.7	-14.6	40.8	-15.8	-0.9	-1.2
HAMT	-37.806754184	175.109198341	69.414	39.2	-1.2	37.8	2.0	-1.4	3.2
HIKB	-37.561040838	178.303352634	107.298	19.6	3.2	17.3	6.9	-2.3	3.7
HOLD	-40.897246153	175.515187643	469.693	29.6	-21.1	28.7	-24.7	-0.9	-3.6
HORN	-43.777329810	170.105511375	960.356	34.7	-25.5	34.6	-25.3	-0.1	0.2
KAIK	-42.425465808	173.533657467	314.805	31.0	-31.7	29.7	-31.2	-1.3	0.5
KARA	-43.608389905	169.775163343	1403.271	41.8	-13.7	40.4	-14.0	-1.4	-0.3
LKTA	-42.783370185	172.266331991	712.977	33.3	-25.5	32.1	-25.9	-1.2	-0.4
MAHO	-38.513007719	174.854087541	302.525	39.2	-1.5	37.9	0.9	-1.3	2.4
MANG	-40.668695886	175.574867791	417.992	32.7	-24.3	30.6	-21.1	-2.1	3.2
MAST	-41.061989672	175.584576644	207.278	29.0	-30.8	27.6	-29.2	-1.4	1.6
MATW	-38.333846202	177.526203424	646.252	22.1	-0.2	19.6	2.6	-2.5	2.8
PALI	-41.569227713	175.254780249	624.151	30.1	-37.4	28.8	-35.3	-1.3	2.1
PARW	-41.381548484	175.426941018	556.883	30.5	-36.1	28.9	-34.9	-1.6	1.2
PTOI	-40.601059767	175.999266968	511.620	30.1	-27.3	27.3	-24.6	-2.8	2.7
QUAR	-43.531680634	169.815819098	58.006	42.1	-10.5	42.1	-10.5	0.0	0.0
RGKA	-38.020069348	176.244053702	497.307	36.7	0.9	33.9	2.3	-2.8	1.4
RGLI	-38.003277555	176.385724035	386.967	33.6	1.1	33.4	2.1	-0.2	1.0
RGMK	-38.138339826	176.467113143	955.534	30.1	0.7	32.5	3.3	2.4	2.6
RGUT	-38.176647204	176.194167348	560.219	35.0	1.4	33.0	3.1	-2.0	1.7
TEMA	-41.106564732	175.890460308	515.203	28.7	-32.5	27.6	-31.3	-1.1	1.2
TGTK	-38.611030663	175.810831686	637.179	39.0	-2.2	35.8	-0.3	-3.2	1.9
TINT	-40.776031949	175.885671618	538.525	30.1	-28.3	28.5	-27.0	-1.6	1.3
TRAV	-41.398003412	175.687906551	365.589	29.8	-36.5	28.5	-35.3	-1.3	1.2
VGOB	-39.199837461	175.542240155	1161.255	37.2	-1.8	35.5	-0.9	-1.7	0.9
WAIM	-44.655703451	170.920300584	1044.902	31.3	-34.4	31.3	-33.9	0.0	0.5
WAKA	-43.584040835	169.885311513	1409.347	42.3	-15.7	39.9	-15.2	-2.4	0.5
WEST	-41.744744993	171.806222623	665.385	42.3	-5.3	41.7	-4.2	-0.6	1.1
WGTT	-41.290440163	174.781596114	43.014	33.8	-25.8	32.8	-24.9	-1.0	0.9
WHNG	-35.803770283	174.314566702	172.812	39.5	2.1	39.9	4.1	0.4	2.0
							Mean	-1.2	1.1
							Stdev	1.0	1.4

gns_velocity issues two prompts. The first states that there are no variances and covariances and asks if you wish to continue; you need to answer “Y”. The second asks for the latitude, longitude and rate for the pole of rotation of the reference frame. Since the velocity solution stored in solution.gns is with respect to an Australia-fixed reference frame, you should reply "0 0 0" if you wish for velocity results with respect to Australia. If you wish for results with respect to another reference frame then you should enter the latitude, longitude and rate of rotation of that frame with respect to Australia. The values should be entered in decimal degrees for the coordinates and in radians per 10 million years for the rate. gns_velocity outputs its results to a file called velocity.out, with the velocities and standard errors in unconventional units of Earth radius/10 Myr. To convert these to mm/yr, you need to multiply by 637.1.

A run of gns_velocity producing velocities relative to Australia would look like:

```
% gns_velocity
   No variances and covariances
Do you want to continue (Y/N)?
Y
 Enter the latitude and longitude (in degrees) of the Euler
  pole for the frame of reference and the rotation rate to
   be removed
0 0 0
%
```

To generate velocity results in IGb00, the run would look like:

```
% gns_velocity
   No variances and covariances
Do you want to continue (Y/N)?
Y
 Enter the latitude and longitude (in degrees) of the Euler
  pole for the frame of reference and the rotation rate to
   be removed
-30.243  221.785  0.09735
%
```

And for velocity results in IGS05, it would look like:

```
% gns_velocity
   No variances and covariances
Do you want to continue (Y/N)?
Y
 Enter the latitude and longitude (in degrees) of the Euler
  pole for the frame of reference and the rotation rate to
   be removed
-31.021  223.828  0.09880
%
```

No standard error or correlation estimates are produced by gns_velocity because there is no uncertainty information in the v3.0 solution.gns file. The standard error of unit weight in the header line is therefore not used.

A spline-fitting and inversion procedure is necessary to locate the requested point within the curvilinear grid and interpolate the gridded velocity to that point. We expect that LINZ will wish to speed up the procedure by using the GNS model to generate the velocity solution on a fine latitude-longitude or NZTM grid that may then be interpolated rapidly, and/or by reformatting the ascii data file in binary. We expect that LINZ may also wish to make changes to gns_velocity.f. In order to maintain compatibility betwen GNS and LINZ software, GNS will supply updates to the velocity model in the format of solution.gns, unless it is mutually agreed by GNS and LINZ that a format change should be made.

8. RECOMMENDED FUTURE WORK

The effect of ocean loading on the estimation of coordinates from GPS data needs to be assessed. Tests undertaken by GNS a few years ago indicated that the improvement in solution repeatability for coordinates calculated from full 24-hour datasets was minor. More recently, we have noted that the daily coordinate solutions for some near-coastal cGPS stations contain a significant fortnightly signal that is markedly reduced when ocean loading is included in the daily analysis. (The signal appears at fortnightly periods due to aliasing; e.g., Penna et al., 2007.) We have therefore used ocean loading for the processing of GPS data in Section 3. However, we have not yet incorporated ocean loading into the GeoNet daily analysis, so the time series used for the prediction models in Section 6 do contain some fornightly noise from unmodelled ocean loading. The GeoNet daily processing will be updated to include ocean loading before the end of 2008.

The effect of ocean loading on the coordinates calculated from short time series - which are a major aim of the PositioNZonLine automated processing system - are likely to be much larger than the effect on daily solutions because the benefit of averaging the tidal cycles over a 24-hour period are lost. Tests could be carried out to see how much improvement is gained in coordinate repeatability when ocean loading is included in the analysis of short-duration sessions. This task could be achieved using the current database of PositioNZ rinex data.

As discussed in Report 2 of the PONL contract, there are at least three methods for providing coordinates for the PositioNZonLine automated processing system. The first two suggested methods were: (1) an average of the previous week's solutions; and (2) a prediction model fitted to the PositioNZ time series. It is the second of these suggestions that has been followed up in the present report. It would be reasonably straightforward, and we think of value, to compare the relative accuracy of these two approaches using "postdiction" on already-recorded PositioNZ data. This has already been done at one epoch, as reported in Tables 13 and 14 and the associated discussion.

Better treatment of the regional common-mode signal is needed in the time series modelling. This signal should be subtracted from the time series prior to the model fitting of equation (4). It should then be modelled and predicted forward in some way and added back to the model prediction. This is an important recommendation for future work, as we believe it could significantly improve the prediction accuracy of the model.

It would enhance the model if the parameters t_m and t_j in equation (4) were solved for rather than being set by the user. It needs to be considered whether this enhancement is worthwhile.

The GeoNet/PositioNZ daily processing will eventually be updated to give results directly in the IGS05 reference frame. At this time the model parameters will all change, and it will no longer be necessary to include the transformation step between IGb00 and IGS05. The introduction into our processing of the uniformly-estimated orbits from the IGS reprocessing effort that is currently underway will also result in small changes to the model parameters. We anticipate that it will be possible to introduce these changes without any significant disruption to the PositioNZonLine service.

The velocity data set used as input to the deformation model in Section 7 uses data from 1996-2008. The velocities estimated for 1^{st} order stations in Sections 3 and 4, and used for calculating transformations between NZGD2000 and various ITRF realisations in Section 5, uses data from 1995-2006. This possibly contributes to minor inconsistencies between the velocities at 1^{st}-order stations in Tables 6 and 7, and the velocities at these stations used as input to the v3.0 deformation model. In future work it would be preferable to use identical data sets for the two calculations.

New velocity modelling software is becoming available that uses a more deterministic approach than the one used in this report. In this approach, the time series of daily coordinates of all available campaign and continuous GPS stations are jointly inverted using a model consisting of a superposition of plate motions, individual tectonic block rotation rates, elastic strains from locked faults along the tectonic block boundaries, and individual earthquake sources, slow-slip sources and volcanic deformation sources. Such an approach allows the construction of a continuous deformation model using a different set of assumptions than is used in the current work. It has the advantage that earthquakes and other rapid deformation sources form an integral part of the model, rather than being corrections applied to the model. We recommend that LINZ consider such modelling during a future phase of development of the New Zealand geodetic system.

9. CONCLUSIONS

The three major aims of the contract have been completed: (1) the estimation of ITRF2000-ITRF2005-NZGD2000 transformation parameters using all available data since 1996; (2) the calculation of time series models to predict the future coordinates of PositioNZ stations; and (3) the updating of the NZGD2000 deformation model to take advantage of the large amount of GPS data collected since the original model was calculated in 1998.

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APPENDICES

APPENDIX A — SUMMARY OF ACCURACY SPECIFICATION TESTS

Tables A1 and A2 on the following two pages show the summaries provided by SNAP for relative accuracy specification tests required to evaluate whether the final coordinate results meet 1st-order-2000 standards. The full SNAP input and output files are included on the CD accompanying this report.

The relative accuracy tests use a minimally-constrained solution with station AUCK held fixed at its ITRF2000 (IGb00) coordinates near the middle of the survey period. The coordinate and covariance files used are those output from the Bernese processing software (after suitable reformatting) in the ITRF2000 reference frame.

The stations tested in the first run (Table A1) are all the 1st-order stations, all the primary TGRMs, and the long-lived continuous stations that were used in the construction of NZGD2000 (AUCK, OUSD and WGTN).

The stations tested in the second run (Table A2) are the same, but all the primary TGRMs except APB7 and DJMG are excluded. This is in order to omit baselines shorter than 30 km from the test, as these short baselines have problems meeting the B100H and B300V relative accuracy specifications.

Table A1 Testing of all 1st-order stations, AUCK, WGTN, and all primary TGRMs

```
================================================================================
NZFOTG06 relative accuracy test in IT00                    11-SEP-2007 10:49:57

                          ACCURACY SPECIFICATION TESTS

================================================================================

Note: 14 rejected stations not used in specification tests

Testing order specifications: ORDER1

Based on 95.00 apriori confidence limits
Horizontal accuracy: (error multiplier:   2.45)
           Absolute:  50.0 mm
           Relative:   3.0 mm    0.100 ppm
Vertical accuracy:   (error multiplier:   1.96)
           Absolute: 150.0 mm
           Relative:   3.0 mm    0.300 ppm

------------------------
Absolute accuracy tests

Horizontal tolerance:
    Stations tested:                      42
    Stations exceeding tolerance:          0
     Largest error/tolerance:           0.13 (A13U)

Vertical tolerance:
    Stations tested:                      42
    Stations exceeding tolerance:          0
     Largest error/tolerance:           0.11 (A13U)

------------------------
Relative accuracy tests

Horizontal tolerance:
    Stations tested:                     42
    Vectors tested:                     903
    Vectors exceeding tolerance:         12
    Largest error/tolerance:           2.08 (A13U to OUSD)

Vertical tolerance:
    Stations tested:                     42
    Vectors tested:                     903
    Vectors exceeding tolerance:         13
    Largest error/tolerance:           6.01 (B3XN to B3XP)
```

Table A2 Testing of all 1st-order stations, AUCK, WGTN, and primary TGRMs APB7 and DJMG

```
================================================================================
NZFOTG06 relative accuracy test in IT00                    11-SEP-2007 15:50:25

                          ACCURACY SPECIFICATION TESTS

================================================================================

Note: 14 rejected stations not used in specification tests

Testing order specifications: ORDER1

Based on 95.00 apriori confidence limits
Horizontal accuracy: (error multiplier:   2.45)
           Absolute:  50.0 mm
           Relative:   3.0 mm    0.100 ppm
Vertical accuracy:   (error multiplier:   1.96)
           Absolute: 150.0 mm
           Relative:   3.0 mm    0.300 ppm

------------------------
Absolute accuracy tests

Horizontal tolerance:
    Stations tested:                      30
    Stations exceeding tolerance:          0
     Largest error/tolerance:           0.08 (DJMG)

Vertical tolerance:
    Stations tested:                      30
    Stations exceeding tolerance:          0
     Largest error/tolerance:           0.08 (DJMG)

------------------------
Relative accuracy tests

Horizontal tolerance:
    Stations tested:                     30
    Vectors tested:                     465
    Vectors exceeding tolerance:          0
    Largest error/tolerance:           0.59 (DJMG to 1181)

Vertical tolerance:
    Stations tested:                     30
    Vectors tested:                     465
    Vectors exceeding tolerance:          0
    Largest error/tolerance:           0.62 (DJMG to 1181)
```

APPENDIX B — DERIVATION OF EQUATION (2) IN SECTION 5

We require an expression for the NZGD2000 coordinates of a survey mark (at epoch 2000.0 by definition) in terms of its ITRF coordinates at epoch *t* (where we measure *t* in years after 2000.0) and the NZGD2000 velocity field.

The site position and site velocity transformation from one frame to another is given in equation (B1) for the particular case of transformation from the "i05" reference frame to the "i00" frame. We use the sign convention of Altamimi et al. (2007), which is slightly different from the LINZ convention. In LINZ's formulation the rotation terms have the opposite sign, and the factor (1+*S*) is applied to the rotation matrix. The first of these differences is important; the second is negligible (sub-atomic) for the small transformation terms we are considering.

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i00} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i05} + \mathbf{T} + S \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i05} + \mathbf{R} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i05}$$

(B1)

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{i00} = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{i05} + \dot{\mathbf{T}} + \dot{S} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i05} + \dot{\mathbf{R}} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i05}$$

$\mathbf{T} = \begin{pmatrix} Tx \\ Ty \\ Tz \end{pmatrix}$ and $\mathbf{R} = \begin{pmatrix} 0 & -Rz & Ry \\ Rz & 0 & -Rx \\ -Ry & Rx & 0 \end{pmatrix}$ are the translation vector and rotation matrix, *S* is the scale factor, and $\dot{\mathbf{T}}$, $\dot{\mathbf{R}}$ and $\dot{S}$ are their time derivatives. **T**, **R**, and *S* are defined at a particular epoch, t_0, and $\dot{\mathbf{T}}$, $\dot{\mathbf{R}}$ and $\dot{S}$ are assumed constant. Thus:

$$S(t) = S(t_0) + \dot{S} \times (t - t_0)$$

and similarly for **T** and **R**.

At epoch 2000.0 (which we take as *t* = 0) and using vector notation, equations (B1) for the ITRF to NZGD2000 transformation are:

$$\mathbf{x}_{NZGD} = \mathbf{x}_{ITRF}(0) + \mathbf{T} + S\,\mathbf{x}_{ITRF}(0) + \mathbf{R}\,\mathbf{x}_{ITRF}(0)$$

(B2)

$$\dot{\mathbf{x}}_{NZGD} = \dot{\mathbf{x}}_{ITRF} + \dot{\mathbf{T}} + \dot{S}\mathbf{x}_{ITRF}(0) + \dot{\mathbf{R}}\mathbf{x}_{ITRF}(0)$$

We require $\mathbf{x}_{NZGD}$ in terms of $\mathbf{x}_{ITRF}(t)$ and $\dot{\mathbf{x}}_{NZGD}$, which are respectively the measured position of a point in a particular ITRF realisation at time *t*, and the known NZGD velocity field (which we can also write as $\mathbf{v}_{NZGD}$).

The ITRF position at time t is:

$$\mathbf{x}_{ITRF}(t) = \mathbf{x}_{ITRF}(0) + \dot{\mathbf{x}}_{ITRF}\, t \qquad \text{(B3)}$$

Using equations (B2) this can be rewritten:

$$\begin{aligned}\mathbf{x}_{ITRF}(t) = {} & \mathbf{x}_{NZGD} - \mathbf{T} - S\mathbf{x}_{ITRF}(0) - \mathbf{R}\mathbf{x}_{ITRF}(0) \\ & +(\dot{\mathbf{x}}_{NZGD} - \dot{\mathbf{T}} - \dot{S}\mathbf{x}_{ITRF}(0) - \dot{\mathbf{R}}\mathbf{x}_{ITRF}(0))t\end{aligned} \qquad \text{(B4)}$$

Rearranging gives:

$$\mathbf{x}_{NZGD} = \mathbf{x}_{ITRF}(t) - \dot{\mathbf{x}}_{NZGD}\, t + (\mathbf{T} + \dot{\mathbf{T}}t) + (S + \dot{S}t)\mathbf{x}_{ITRF}(0) + (\mathbf{R} + \dot{\mathbf{R}}t)\mathbf{x}_{ITRF}(0) \qquad \text{(B5)}$$

Because $\mathbf{T}$, $\mathbf{R}$, S, $\dot{\mathbf{T}}$, $\dot{\mathbf{R}}$ and $\dot{S}$ are all small, we can replace the $\mathbf{x}_{ITRF}(0)$ in equation (B5) with $\mathbf{x}_{ITRF}(t)$. If we also rewrite $\dot{\mathbf{x}}_{NZGD}$ as $\mathbf{v}_{NZGD}$, we have the required relationship:

$$\mathbf{x}_{NZGD} = \mathbf{x}_{ITRF}(t) - \mathbf{v}_{NZGD}\, t + (\mathbf{T} + \dot{\mathbf{T}}t) + (S + \dot{S}t)\mathbf{x}_{ITRF}(t) + (\mathbf{R} + \dot{\mathbf{R}}t)\mathbf{x}_{ITRF}(t) \qquad \text{(B6)}$$

APPENDIX C — MODEL PARAMETERS AND PLOTS FOR POSITIONZ TIME SERIES

The model parameters take up >25 pages of text so are supplied as an electronic-only supplement.

The version attached to this report is: ponl_model_parameters_2008jun25_raw.txt.

A plot is provided for each station, showing the coordinate time series output from the Bernese processing in the IGb00 reference frame (red), the model fit to the data using the parameters in "ponl_model_parameters_2008jun25_raw.txt" (blue), and the residual (grey). The residual is plotted against the right axis, which has a different scale from the left axis. The mean and RMS values of the residual are given in the plot title.

Model parameters and plots are provided for a number of stations in addition to the PositioNZ stations. These are: QUAR because it fills something of a "hole" in the South Island; AVLN, CLIM, CMBL, DURV, HOLD, KAPT, OTAK, PAEK, PALI, PARW, TINT, TORY, WGTT because the coordinates of these sites were required for Network RTK tests run by LINZ during 2008; and TRAV in case it was needed for these tests.

APPENDIX D — NOTES ON UPDATED DEFORMATION MAPPING SOFTWARE

The following notes are written by John Haines, with minor editing by John Beavan.

The original programs use Singular Value Decomposition {SVD} to do the inversion, whereas the new programs use Sparse Matrix Cholesky Decomposition, in order to take advantage of the sparse structure of the matrix to be inverted and make it possible to solve very large (many grid cells) problems. SVD preserves numerical precision much better than Cholesky, but cannot handle the big matrices as it needs to store them in their entirety.

However, a disadvantage of Cholesky is that to solve the least squares problem y=Ax it works with the positive-definite product matrix A{transpose}*A, whereas SVD works with just the matrix A that relates the statistically-normalised “observations” y to the model parameters x. Consequently, working in double precision with Cholesky achieves only effectively the same numerical accuracy in the calculations as working in single precision with SVD for problems where the Singular Values differ by many orders of magnitude.

This presented me with a problem when I made the changeover. Recall that my parameterisation of the velocity field involves 3-component rotation vectors to represent the 2-component horizontal velocities. In the old programs the vertical components of the rotation vectors were associated with very tiny Singular Values. Where these were too small for the inversion to be stable they were simply damped out. Damping according to Singular Value isn't possible with Cholesky, and combined with the effective decrease in numerical precision the tiny Singular Values lead to ghastly numerical instability.

The solution I have implemented is to add an additional constraint to the least squares system. This involves requiring area averages of the vertical component of the rotation vector to match the corresponding area averages of the vertical-component geodetic rotation, with conservative standard errors large enough to allow for the actual differences between these two quantities in deforming regions - the two quantities are identically the same on a rigid plate. The standard errors for the differences in the two vertical rotations are determined from the strain rate input, and these differences are treated within the system in exactly the same way as differences between observed and modelled area averages of strain rate.

There is a slight disadvantage of the new system which is needed to preserve the sparse structure of the matrix A. This is that GPS velocities at different sites are taken to be statistically independent; that is, the correlation matrix relating the velocities at different sites is no longer used. In future, I could relax this a little by allowing sites in the same or adjoining boxes to be correlated. That wouldn't affect the sparsity structure of A, but would make the coding somewhat messier.

John Haines

APPENDIX E — REPORT FOR PONL-02 VARIATION 1

PONL-02 geodetic contract, Variation 1 (January 2008)

Positions and velocities of ten continuous GPS stations in the southern North Island and northern South Island in support of LINZ real time kinematic testing programme

John Beavan, GNS Science
7 February 2008

1. Station positions

The accompanying Excel spreadsheet contains estimated IGb00 and IGS05 positions in late January and early February 2008 for ten cGPS stations (Table 1). The positions are estimated by two methods. The first method averages 14 days of solutions from the Bernese processing, in the IGb00 and IGS05 realisations of the ITRF. Fourteen days was chosen in order to reduce any variation in coordinate solutions as a result of a fortnightly cycle. The second method predicts the position of the station using the time series model developed in the PONL-02 project (Section 6 of PONL-02 draft report), in both the IGb00 and the IGS05 reference frame realisations. The first method uses days 020-033 of 2008 to give an estimated position on day 027. The second method uses the time series model to predict the position on day 040 of 2008. In the comparisons below, it should be noted that the change in coordinates due to this 13-day time difference is no more than ~1 mm.

Table 1. Stations whose coordinates and velocities were requested by LINZ

CMBL	DURV	HOLD	KAPT	MAST
OTAK	PALI	PARW	TORY	WGTN

In the IGb00 reference frame, the two methods give predicted coordinates that differ at the 1-2 mm level (lines 1-40 of spreadsheet), which is very satisfactory. Either set of coordinates could be used to define the locations of the cGPS sites in early February 2008.

In the IGS05 reference frame the differences are at the 3-4 mm level, which is less satisfactory (lines 43-82 of spreadsheet). For defining the locations of the cGPS sites in early February 2008 I recommend using the first set of coordinates (average of Bernese solutions) rather than the second (time series model). This is because the first method is a more direct estimate that doesn't involve transformations extrapolated from earlier data. (The IGS05 time series model has an extra uncertainty compared to the IGb00 model, because the input data for the model are in IGb00, and a Helmert transformation is used to convert the predicted position from IGb00 to IGS05.)

Station velocities

Also in the spreadsheet are the horizontal velocities of the ten stations in IGb00 (lines 85-96 of spreadsheet), IGS05 (lines 98-108) and the Morgan & Pearse (1999) ITRF96 (lines 110-

120) reference frame realisation. These are estimated from the version 2.2 deformation model calculated for the PONL-02 contract (Section 7 of PONL-02 draft report). There are several reasons why I have chosen to provide the deformation model velocities, rather than velocities obtained by fitting a straight line to daily cGPS station coordinates, or velocities from the time series model. For example, some of the stations have quite short duration time series, so do not yet provide a very accurate velocity estimate. Also, some of the stations are affected by slow slip events, leading to difficulties in estimating a single velocity. But most of all, the velocity of each station corresponds to a position change of about 1 mm per 10 days, so the velocity estimate does not need to be particularly accurate in order to provide an adequate extrapolation for several weeks into the future.

Use of NZGD2000 coordinates

If LINZ wishes to experiment with using NZGD2000 coordinates propagated to the current epoch with the version 2.2 deformation model, there are a number of possible approaches.

One would be to use the NZGD2000 coordinates currently in the LINZ GDB (which probably does not include all stations of interest), and to propagate them to the current epoch using the version 2.2 model. There are potential inconsistencies here, as the current NZGD2000 coordinates of these stations have been calculated by propagating the coordinates determined at some epoch back to 2000.0 using the version 2.1 velocity model, together with a Helmert transformation determined prior to the PONL-02 project.

A second approach would be to re-determine the NZGD2000 coordinates of each site using (1) their current IGb00 coordinates from the first section of the accompanying spreadsheet, (2) the IGb00->NZGD2000 Helmert transformation from Table 10 of the PONL-02 draft report, and (3) the ITRF96 velocities from the last section of the accompanying spreadsheet. I'll call these coordinates NZGD2000*. The NZGD2000* coordinates could then be propagated to the current epoch using the version 2.2 deformation model. I do not see that anything will have been achieved, since all we have effectively done is to apply a small Helmert transformation to the current IGb00 coordinates of all ten cGPS stations. The kinematic solutions will be just as good as if we had used the IGb00 coordinates, but with a small uniform shift.

If the purpose of such work is to test the usefulness of the current NZGD2000 coordinates as base station coordinates for the RTK network, then probably the most self-consistent approach would be to propagate the NZGD2000 coordinates of the cGPS stations from 2000.0 to the present using the version 2.1 deformation model. But it would be necessary to restrict the test to only those stations where an NZGD2000 coordinate has been previously calculated.

Table 2. Printed version of spreadsheet supplied to LINZ on 7 February 2008

IG0b coordinates at 2008 day 027, calculated as the mean of the IG0b coordinates output from Bernese processing for days 020-033, 2008.

	X, m	Y, m	Z, m	Lat, deg	Lon, deg	Ell. ht., m
CMBL	-4741514.3324	480471.2086	-4225019.2161	-41.749043632	174.213805735	256.1040
DURV	-4808175.0611	512013.1541	-4146089.5717	-40.801761349	173.921591267	468.4440
HOLD	-4813640.5280	377557.9042	-4154111.9084	-40.897245953	175.515187313	469.6930
KAPT	-4811936.8938	428627.4971	-4150993.0082	-40.860898965	174.909762694	367.6020
MAST	-4801933.8457	370789.1334	-4167752.3942	-41.061988406	175.584574791	207.2650
OTAK	-4816954.4445	406996.2040	-4147186.2208	-40.816543914	175.170411117	245.1410
PALI	-4762965.2136	395371.8100	-4210341.8149	-41.569227485	175.254779760	624.1530
PARW	-4777843.9401	382155.2769	-4194678.4136	-41.381547529	175.426939512	556.8790
TORY	-4783047.7492	479091.3440	-4178785.3164	-41.191574460	174.280078051	499.1000
WGTN	-4777269.5571	434270.3086	-4189484.3705	-41.323454791	174.805891355	26.0650

IG0b coordinates at 2008, day 040, predicted from time series model using data through 2008, day 033

CMBL	-4741514.3393	480471.2130	-4225019.2187	-41.749043605	174.213805691	256.1110
DURV	-4808175.0590	512013.1532	-4146089.5691	-40.801761344	173.921591275	468.4407
HOLD	-4813640.5281	377557.9039	-4154111.9070	-40.897245943	175.515187316	469.6921
KAPT	-4811936.8917	428627.4955	-4150993.0067	-40.860898968	174.909762711	367.5994
MAST	-4801933.8521	370789.1403	-4167752.3963	-41.061988380	175.584574716	207.2721
OTAK	-4816954.4439	406996.2055	-4147186.2204	-40.816543914	175.170411098	245.1405
PALI	-4762965.2137	395371.8132	-4210341.8154	-41.569227486	175.254779722	624.1534
PARW	-4777843.9425	382155.2832	-4194678.4144	-41.381547517	175.426939439	556.8815
TORY	-4783047.7486	479091.3442	-4178785.3155	-41.191574457	174.280078047	499.0992
WGTN	-4777269.5644	434270.3134	-4189484.3743	-41.323454771	174.805891305	26.0734

Differences in mm (Bernese mean coordinates - Time series model)

CMBL	6.9	-4.4	2.6	-3.0	3.7	-7.0
DURV	-2.1	0.9	-2.6	-0.6	-0.7	3.3
HOLD	0.1	0.3	-1.4	-1.1	-0.3	0.9
KAPT	-2.1	1.6	-1.5	0.3	-1.4	2.6
MAST	6.4	-6.9	2.1	-2.9	6.3	-7.1
OTAK	-0.6	-1.5	-0.4	0.0	1.6	0.5
PALI	0.1	-3.2	0.5	0.1	3.2	-0.4
PARW	2.4	-6.3	0.8	-1.3	6.1	-2.5
TORY	-0.6	-0.2	-0.9	-0.3	0.3	0.8
WGTN	7.3	-4.8	3.8	-2.2	4.2	-8.4
Mean	1.8	-2.4	0.3	-1.1	2.3	-1.7
Stdev	3.7	3.1	2.0	1.2	2.8	4.3

IGS05 coordinates at 2008 day 027, calculated as the mean of the IGS05 coordinates output from Bernese
processing for days 020-033, 2008.

	X, m	Y, m	Z, m	Lat, deg	Lon, deg	Ell. ht., m
CMBL	-4741514.3207	480471.1928	-4225019.1900	-41.749043536	174.213805910	256.0770
DURV	-4808175.0494	512013.1384	-4146089.5456	-40.801761249	173.921591437	468.4170
HOLD	-4813640.5163	377557.8885	-4154111.8823	-40.897245851	175.515187487	469.6660
KAPT	-4811936.8821	428627.4814	-4150992.9821	-40.860898864	174.909762867	367.5750
MAST	-4801933.8339	370789.1176	-4167752.3680	-41.061988305	175.584574968	207.2380
OTAK	-4816954.4328	406996.1883	-4147186.1947	-40.816543813	175.170411290	245.1140
PALI	-4762965.2018	395371.7943	-4210341.7888	-41.569227387	175.254779936	624.1260
PARW	-4777843.9283	382155.2612	-4194678.3875	-41.381547431	175.426939688	556.8520

TORY	-4783047.7375	479091.3283	-4178785.2903	-41.191574362	174.280078223	499.0730
WGTN	-4777269.5454	434270.2929	-4189484.3444	-41.323454692	174.805891529	26.0380

IGS05 coordinates at 2008, day 040, predicted from time series model using data through 2008, day 033

CMBL	-4741514.3311	480471.1987	-4225019.1919	-41.749043483	174.213805852	256.0860
DURV	-4808175.0508	512013.1389	-4146089.5424	-40.801761219	173.921591433	468.4159
HOLD	-4813640.5200	377557.8896	-4154111.8802	-40.897245815	175.515187478	469.6676
KAPT	-4811936.8834	428627.4811	-4150992.9800	-40.860898842	174.909762872	367.5747
MAST	-4801933.8440	370789.1260	-4167752.3696	-41.061988253	175.584574878	207.2476
OTAK	-4816954.4357	406996.1913	-4147186.1936	-40.816543787	175.170411258	245.1159
PALI	-4762965.2055	395371.7988	-4210341.7887	-41.569227362	175.254779885	624.1286
PARW	-4777843.9344	382155.2689	-4194678.3877	-41.381547392	175.426939602	556.8569
TORY	-4783047.7404	479091.3299	-4178785.2888	-41.191574333	174.280078207	499.0744
WGTN	-4777269.5561	434270.2991	-4189484.3475	-41.323454647	174.805891467	26.0486

Differences in mm (Bernese mean coordinates - Time series model)

CMBL	10.4	-5.9	1.9	-5.9	4.8	-9.0
DURV	1.4	-0.5	-3.2	-3.3	0.3	1.1
HOLD	3.7	-1.1	-2.1	-4.0	0.8	-1.6
KAPT	1.3	0.3	-2.1	-2.4	-0.4	0.3
MAST	10.1	-8.4	1.6	-5.8	7.5	-9.6
OTAK	2.9	-3.0	-1.1	-2.9	2.7	-1.9
PALI	3.7	-4.5	-0.1	-2.8	4.2	-2.6
PARW	6.1	-7.7	0.2	-4.3	7.2	-4.9
TORY	2.9	-1.6	-1.5	-3.2	1.3	-1.4
WGTN	10.7	-6.2	3.1	-5.0	5.2	-10.6
Mean	5.3	-3.9	-0.3	-4.0	3.4	-4.0
Stdev	3.8	3.1	2.0	1.2	2.8	4.3

Horizontal velocities in IGb00 predicted from the v2.2 New Zealand deformation model

	Ve, m/yr	Vn, m/yr
CMBL	-0.0235	0.0331
DURV	-0.0035	0.0389
HOLD	-0.0223	0.0302
KAPT	-0.0143	0.0349
MAST	-0.0269	0.0290
OTAK	-0.0189	0.0348
PALI	-0.0317	0.0301
PARW	-0.0319	0.0306
TORY	-0.0130	0.0382
WGTN	-0.0232	0.0323

Horizontal velocities in IGS05 predicted from the v2.2 New Zealand deformation model

CMBL	-0.0234	0.0330
DURV	-0.0034	0.0388
HOLD	-0.0223	0.0300
KAPT	-0.0143	0.0348
MAST	-0.0269	0.0288
OTAK	-0.0189	0.0347
PALI	-0.0317	0.0300
PARW	-0.0318	0.0304
TORY	-0.0129	0.0381
WGTN	-0.0231	0.0322

Horizontal velocities in ITRF96 predicted from the v2.2 New Zealand deformation model

CMBL	-0.0242	0.0342
DURV	-0.0042	0.0399
HOLD	-0.0231	0.0312
KAPT	-0.0151	0.0360
MAST	-0.0277	0.0300
OTAK	-0.0197	0.0358
PALI	-0.0325	0.0311
PARW	-0.0326	0.0316
TORY	-0.0137	0.0393
WGTN	-0.0239	0.0333

APPENDIX F — REPORT FOR PONL-02 VARIATION 2

PONL-02 geodetic contract, Variation 2 (June 2008)

Positions and velocities of 16 continuous GPS stations in the southern North Island and northern South Island in support of LINZ real time kinematic testing programme

John Beavan, GNS Science
12 June 2008

1. Station positions

The accompanying Excel spreadsheet contains estimated IGb00 and IGS05 positions on 29 May 2008 for 16 cGPS stations (Table 1) in the southern North Island and northern South Island. The positions are estimated by two methods. The first method averages 14 days of solutions from the Bernese processing, in the IGb00 and IGS05 realisations of the ITRF. Fourteen days was chosen in order to reduce any variation in coordinate solutions as a result of a fortnightly cycle. The second method takes the position of the station from the time series model developed in the PONL-02 project (Section 6 of PONL-02 draft report), in both the IGb00 and the IGS05 reference frame realisations.

In the first method we average solutions from days 143-156 of 2008 to give an estimated position on day 150. (For station KPTG we use days 130-143 as the rinex data were only provided for a limited period.) The second method uses the time series model estimate of the position on day 150 of 2008. (There is no time series model estimate for station KPTG, as the time series is not sufficiently long to fit a model.) The time series estimate is a fitted rather than a predicted position, as the model includes data through day 160.

Table 1. Stations whose coordinates and velocities have been estimated

AVLN	CLIM	CMBL	DURV	HOLD	KAPT
KPTG	MAST	OTAK	PAEK	PALI	PARW
TINT	TORY	WGTT	WGTN		

In the IGb00 reference frame, the two methods give predicted coordinates that differ at the 1-3 mm level on average. I recommend using the averaged coordinates for the June 2008 RTK testing (rows 2-20 and columns E-H of spreadsheet[5]).

In the IGS05 reference frame the differences are at the 3-5 mm level, which is less satisfactory. For defining the locations of the cGPS sites in June 2008 I recommend using the second set of coordinates (average of Bernese solutions; rows 22-40 and columns E-H of spreadsheet) rather than the first (time series model). This is because the second method is a more direct estimate that doesn't involve transformations extrapolated from earlier data. (The IGS05 time series model has an extra uncertainty compared to the IGb00 model, because the

[5] Row and column numbers refer to the spreadsheet supplied to LINZ on 12 June 2008. The spreadsheet formatting has been changed for the table in this appendix.

input data for the model are in IGb00, and a Helmert transformation is used to convert the predicted position from IGb00 to IGS05.)

Station velocities

Also in the spreadsheet are the horizontal velocities of the 16 stations in IGb00 (lines 45-62 of spreadsheet), IGS05 (lines 64-80) and the Morgan & Pearse (1999) ITRF96 (lines 82-98) reference frame realisation. These are estimated from the version 2.2 deformation model calculated for the PONL-02 contract (Section 7 of PONL-02 draft report). I have used this velocity model rather than the new velocity model (milestone 7 of PONL-02 report) because work on the new model is not yet complete.

There are several reasons why I have chosen to provide the deformation model velocities, rather than velocities obtained by fitting a straight line to daily cGPS station coordinates, or velocities from the time series model. For example, some of the stations have quite short duration time series, so do not yet provide a very accurate velocity estimate. Also, some of the stations are affected by slow slip events, leading to difficulties in estimating a single velocity. But most of all, the velocity of each station corresponds to a position change of about 1 mm per 10 days, so the velocity estimate does not need to be particularly accurate in order to provide an adequate extrapolation for several weeks into the future.

Table 2. Printed version of spreadsheet supplied to LINZ on 12 June 2008

PONL-02 contract, Variation 2. Spreadsheet accompanying text report of 12 June 2008.

	Time series model at day 150, 2008			**Bernese, average of days 143-156, 2008**		
	IGb00			**IGb00**		
AVLN	-41.196438440	174.932857590	39.5898	-41.196438451	174.932857565	39.5910
CLIM	-41.144666979	175.145470096	830.7085	-41.144666987	175.145470058	830.7090
CMBL	-41.749043509	174.213805578	256.1095	-41.749043534	174.213805548	256.1050
DURV	-40.801761225	173.921591264	468.4396	-40.801761225	173.921591209	468.4430
HOLD	-40.897245856	175.515187201	469.6890	-40.897245871	175.515187166	469.6900
KAPT	-40.860898819	174.909762701	367.6091	-40.860898804	174.909762651	367.6110
KPTG				-40.785069711	175.092268840	19.9370
MAST	-41.061988312	175.584574651	207.2685	-41.061988319	175.584574615	207.2640
OTAK	-40.816543792	175.170411053	245.1462	-40.816543795	175.170411055	245.1450
PAEK	-41.021763704	174.952078865	443.2663	-41.021763732	174.952078834	443.2680
PALI	-41.569227381	175.254779573	624.1508	-41.569227391	175.254779530	624.1520
PARW	-41.381547428	175.426939300	556.8797	-41.381547451	175.426939283	556.8790
TINT	-40.776031393	175.885670775	538.5244	-40.776031389	175.885670767	538.5210
TORY	-41.191574310	174.280078039	499.1016	-41.191574308	174.280077993	499.1040
WGTN	-41.323454703	174.805891230	26.0680	-41.323454699	174.805891210	26.0700
WGTT	-41.290437043	174.781592990	42.9989	-41.290437040	174.781592964	43.0010
	IGS05			**IGS05**		
AVLN	-41.196438310	174.932857758	39.5644	-41.196438340	174.932857705	39.5620
CLIM	-41.144666848	175.145470264	830.6832	-41.144666872	175.145470196	830.6780
CMBL	-41.749043383	174.213805745	256.0838	-41.749043424	174.213805701	256.0750
DURV	-40.801761095	173.921591429	468.4141	-40.801761115	173.921591348	468.4150
HOLD	-40.897245724	175.515187369	469.6638	-40.897245752	175.515187315	469.6640
KAPT	-40.860898688	174.909762868	367.5838	-40.860898696	174.909762789	367.5800
KPTG				-40.785069588	175.092268963	19.9080
MAST	-41.061988181	175.584574820	207.2433	-41.061988204	175.584574764	207.2350
OTAK	-40.816543661	175.170411220	245.1209	-40.816543678	175.170411192	245.1160
PAEK	-41.021763573	174.952079032	443.2410	-41.021763621	174.952078966	443.2380
PALI	-41.569227253	175.254779742	624.1253	-41.569227278	175.254779686	624.1220
PARW	-41.381547298	175.426939470	556.8544	-41.381547336	175.426939430	556.8510
TINT	-40.776031260	175.885670944	538.4993	-40.776031273	175.885670913	538.4920
TORY	-41.191574182	174.280078205	499.0760	-41.191574212	174.280078131	499.0740
WGTN	-41.323454575	174.805891398	26.0425	-41.323454592	174.805891350	26.0410
WGTT	-41.290436914	174.781593157	42.9735	-41.290436930	174.781593106	42.9720

	IGb00 differences, mm			**IGS05 differences, mm**		
	N	**E**	**U**	**N**	**E**	**U**
AVLN	-1.2	-2.1	1.2	-3.3	-4.4	-2.4
CLIM	-0.9	-3.2	0.5	-2.7	-5.7	-5.2
CMBL	-2.8	-2.5	-4.5	-4.6	-3.7	-8.8
DURV	0.0	-4.6	3.4	-2.2	-6.8	0.9
HOLD	-1.7	-2.9	1.0	-3.1	-4.5	0.2
KAPT	1.7	-4.2	1.9	-0.9	-6.6	-3.8
KPTG						
MAST	-0.8	-3.0	-4.5	-2.6	-4.7	-8.3

OTAK	-0.3	0.2	-1.2	-1.9	-2.4	-4.9
PAEK	-3.1	-2.6	1.7	-5.3	-5.5	-3.0
PALI	-1.1	-3.6	1.2	-2.8	-4.7	-3.3
PARW	-2.6	-1.4	-0.7	-4.2	-3.3	-3.4
TINT	0.4	-0.7	-3.4	-1.4	-2.6	-7.3
TORY	0.2	-3.8	2.4	-3.3	-6.2	-2.0
WGTN	0.4	-1.7	2.0	-1.9	-4.0	-1.5
WGTT	0.3	-2.2	2.1	-1.8	-4.3	-1.5
Mean, mm	-0.8	-2.7	0.5	-2.8	-4.6	-3.4
Stdev, mm	1.4	1.2	2.4	1.2	1.4	2.8

Horizontal velocities in IGb00 predicted from v2.2 New Zealand deformation model (m/yr)

	Ve, m/yr	Vn, m/yr
AVLN	-0.0238	0.0308
CLIM	-0.0256	0.0297
CMBL	-0.0249	0.0313
DURV	-0.0049	0.0370
HOLD	-0.0237	0.0283
KAPT	-0.0157	0.0330
KPTG	-0.0179	0.0328
MAST	-0.0283	0.0271
OTAK	-0.0203	0.0329
PAEK	-0.0199	0.0324
PALI	-0.0331	0.0282
PARW	-0.0333	0.0287
TINT	-0.0272	0.0271
TORY	-0.0144	0.0364
WGTN	-0.0246	0.0304
WGTT	-0.0236	0.0311

Horizontal velocities in IGS05 predicted from v2.2 New Zealand deformation model (m/yr)

AVLN	-0.0224	0.0325
CLIM	-0.0242	0.0314
CMBL	-0.0234	0.0330
DURV	-0.0034	0.0388
HOLD	-0.0223	0.0300
KAPT	-0.0143	0.0348
KPTG	-0.0165	0.0346
MAST	-0.0269	0.0288
OTAK	-0.0189	0.0347
PAEK	-0.0185	0.0341
PALI	-0.0317	0.0300
PARW	-0.0318	0.0304
TINT	-0.0258	0.0289
TORY	-0.0129	0.0381
WGTN	-0.0231	0.0322
WGTT	-0.0221	0.0329

Horizontal velocities in ITRF96 predicted from the v2.2 New Zealand deformation model (m/yr)

AVLN	-0.0232	0.0337
CLIM	-0.0250	0.0326
CMBL	-0.0242	0.0342
DURV	-0.0042	0.0399
HOLD	-0.0231	0.0312
KAPT	-0.0151	0.0360
KPTG	-0.0173	0.0358
MAST	-0.0277	0.0300
OTAK	-0.0197	0.0358
PAEK	-0.0193	0.0353
PALI	-0.0325	0.0311
PARW	-0.0326	0.0316
TINT	-0.0266	0.0301
TORY	-0.0137	0.0393
WGTN	-0.0239	0.0333
WGTT	-0.0229	0.0340

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