Investigations in support of PositioNZonLine

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19 September 2013

Introduction

With the planned release of the PositioNZ-PP on-line GPS procession tool, LINZ requires updated models to predict forward the position of each of the continuous GPS reference stations of the PositioNZ network and transformation parameters between NZGD2000 and the current GNSS reference frame. This report summarizes the results of Otago University School work in these two areas.

The letter of engagement had two clauses. The first was to analyze 13 years of data from all of the PositioNZ cGPS stations in New Zealand in order to update models that can be used to predict the position of the station with time. Along with the station model files, this part of the project produced average station velocities and two independent sets of station coordinates at epoch 2000.0. The second clause was to analyze the relationship between ITRF08 and NZGD2000 (ITRF96 epoch 2000). During the course of this phase of the program LINZ requested that we evaluate existing global transformations between ITRF2008 and ITRF96 rather than focusing on developing a relationship optimized for the New Zealand region.

The first phase of the project is summarized in section 1 and 2 of the report. The major deliverable for this phase the project were files containing parameters listing all equipment offsets and annual terms and tectonic processes that effect the time series of each station. They are developed from fits to the daily coordinate time series. These files were transferred in two stages. The first which were given to LINZ on the 26 of June included 26th June 2013 were calculated using software developed by GNS science (Beavan 2008). Subsequently LINZ developed improved software and asked us to use the new software to revise our models. This resulted in a second set of models that were transferred to LINZ on August 1 2013.

The second phase of the project is summarized in section 3 and 4 of the report however our preliminary recommendations were subject of preliminary reports on the 24th of June and 22 of August.

1 Coordinate estimation in ITRF2008 for PositioNZ stations.

As the first step in our investigation of the datum transformation parameters between NZGD2000 and ITRF08 we developed new estimates of the ITRF2008 epoch 2000.0 coordinates for all PositioNZ stations. We were given a series of daily network solution processed using Bernese 5.0 by GNS science in the ITRF2008 datum. The epoch 2000.0 coordinates were developed by analysing the time series of daily coordinate and files which were given us LINZ using OUSD's in-house MatLab scripts. This software applies corrections for the tectonic velocity and seasonal terms along with all known equipment offsets, earthquake offsets, post seismic effects and slow slip events. As a first step the time of all tectonic and equipment offsets are identified. The software then estimates the level of the offsets. Post seismic relaxation is modelled using either exponential or logarithmic decay functions. For the 2009 Dusky Sound Earthquake we used a logarithmic decay functions with a time constant of 100 days which was applied to all stations in the southern South Island south of LEXA. Slow Slip events are treated as step velocity changes that extend for the duration of the slip episode.

As discussed below, similar coordinates can be derived from the station predictive model (SPM), however our values represent an independent estimate using a completely separate set of parameters from this used by the SPM model. For this reason they provided a valuable check on the SPM and were useful in identifying gross errors and were also used to test various possible transformations between ITRF2008 and NZGD2000. Unfortunately the stacking was done using only the Bernese coordinate files since the corresponding covariance files were not available. For this reason it was not possible to develop uncertainties for the coordinates. Coordinates derived in this phase of the project are listed in Appendix 1 and velocities are listed in appendix 2.

2 Update of the Station Model Parameters

The station predictive model is a part of the PositioNZ-PP package that estimates accurate coordinates for the PositioNZ stations that are selected as reference stations for the GPS processing. At the start of this project the model parameters for the Station Predictive Model had not been updated since 27 June 2008 and thus did not include models for the 2009 Dusky Sound earthquake or any of the Christchurch earthquakes. As it happened, this phase of the project was conducted as a two stage process. The first step was to update the parameter files developed by Beavan 2008 using the fit_model program developed by IGNS and used in the 2008 study. These were transferred to LINZ on 26 June 2013. Once that had been completed, the Chris Crook developed a new python script (spm_editor.py) and the models from fit_model were used as starting models. Both of these programs had the capability to model equipment and earthquake offsets, post seismic relaxation (modelled by exponential decay function), slow slip events (SSE), and velocity changes along with periodic seasonal variations and constant velocity. The fit_model software was designed to be used with display software that GNS science developed using Igor scripts (Beavan 2008). However this software was not available so we developed perl scripts to graphically display the residuals and the model and input time series. However process lacked of a graphical interface with real time capability to edit the model parameters making the process of optimizing the models tedious. Because of the superior editing capabilities and the graphical interface built into spm_editor.py we were able to develop a much better fit using the new software. Indeed, the median mse improved by over 40% between the results of the fit_model inversion and our best spm_editor models. Several versions of the SPM editor were used in this work. Most of this work was done with the version released on July 19^{th}.

While developing the best spm_editor model, we tried to remove any discrepancies between the SPM epoch 2000 coordinates and the results of coordinate stacking by Otago University and tidy up confusion associated with multiple overlapping slow slip events which importing the fit_model parameters into spm_editor.py seemed to create. Figure 1a shows a map of the 47 stations for which improved station models were calculated as part of this project. Table 2.1 gives a statistical summary of the final models for each of these stations and figure 2 shows histograms of the results. While many of the stations model quite complex geophysical phenomenon, there does not seem to be any clear relationship between the complexity of the model and the mse of the model. The six stations with the highest combined e and n mse are CLIM AVLN MAVL TORY HAAS and LEXA but these stations do not presents particularly complex problems in the time series model. CLIM AVLN and TORY have a single SSE and MAVL HAAS and LEXA are affected by the Dusky Sound earthquake. If the model was the limiting factor then stations like MQGZ (which are affected by multiple earthquakes) or GISB (which is affected by seven SSEs) would have the largest misfits. For these reasons the misfit in the station predictive model is probably related to the day to day scatter in the GPS time series rather than uncertainty in the model. The median mse values are all 47 stations are 1.7 mm for the nth 1.3 mm for the east and 4.5 mm for the up. The largest u mse is 5.69 mm at NPLY while the largest e mse is 2.35 and the largest n mse is 2.10 at HAAS. These residuals are comparable to those shown in Beavan (2008) table 13 .

Table 2.1
Summary of the fit achieved for the modelled stations. The e n and u components list the mse values from spm_editor.py. The days column (also from the summary table produced by spm_editor.py) is the number of days for which data is available.

	days	e mm	n mm	u mm
AUCK	4893	1.45	1.09	3.97
AVLN	2697	2.12	1.86	4.69
BLUF	3390	1.58	1.07	4.18
CHAT	4390	1.49	1.23	4.08
CHTI	2008	1.43	1.26	4.25
CLIM	2816	2.1	1.93	5.35
CMBL	3438	1.9	1.39	4.56
CORM	3698	1.74	1.14	4.4
DNVK	3894	1.99	1.41	4.68
DUND	2869	1.48	1.17	4.27
DURV	3046	2.18	1.29	4.6
GISB	3971	1.81	1.28	4.32
GLDB	3389	1.92	1.51	4.82
HAAS	3289	1.7	2.1	4.64
HAMT	3684	1.74	1.18	4.62
HAST	3877	1.67	1.15	4.2
HIKB	3706	1.77	1.38	4.71
HOKI	4739	1.44	1.2	4.17
KAIK	3429	1.59	1.37	4.7
KAPT	3310	1.85	1.71	4.25
KTIA	2092	1.54	1.08	3.95
LEXA	3294	2.21	1.37	5.28
LKTA	3429	1.71	1.83	5.29
MAHO	3373	1.85	1.18	4.99
MAST	3798	1.55	1.26	4.98
MAVL	3345	2.35	1.47	5.67
METH	1039	1.37	1.38	4.82
MQZG	4784	1.49	1.36	4.11
MTJO	4669	1.62	1.3	4.86
NLSN	3435	1.57	1.2	4.24
NPLY	3711	1.82	1.42	5.69
OUSD	4195	1.72	1.51	4.67
PYGR	2218	1.56	1.78	3.87
TAUP	4106	1.7	1.22	4.2

TORY	2966	1.89	1.97	4.68
TRAV	2942	1.49	1.19	4.37
TRNG	3784	1.58	1.1	4.26
VGMT	3082	1.53	1.32	4.53
WAIM	3112	1.64	1.04	4.34
WANG	3728	1.61	1.1	4.11
WARK	1608	1.4	1.18	4.4
WEST	3209	1.51	1.12	4.12
WGTN	4923	1.97	1.43	4.77
WGTT	4720	1.93	1.69	5.21
WHKT	1567	1.92	1.19	4.13
WHNG	3715	1.48	1.07	4.14

I extracted three parameters from each of the model files, the average velocity after correcting for offsets, tectonic processes and seasonal terms, and the extrapolated XYZ coordinate at epoch 2000.0. These parameters are important in developing a datum transformation between ITRF2008 and NZGD2000, which is discussed in section 3.

The SPM models contain models for the average inter-seismic velocities for each station which is derived from the time series after correction for seismic and equipment offsets, slow slip events and post seismic relaxation. These ITRF08 velocity vectors seem to define a reasonably homogeneous velocity field and are similar to the vectors shown in figures 5 and 6 of Beavan 2008 with the exception of the region extending from Hawks Bay and the southern Raukumara Peninsula. Here the GISB and HAST velocities derived from the SPM models have a greater east component than shown for 1501 and 1273 in figures 5 of Beavan 2008. Since the GISB to 1501 and HAST to 1273 distances are only about 10km and 20km respectively this difference probably represents a true discrepancy between the two velocity fields. The most likely cause of the discrepancy is the fact that the SPM velocities are estimated after the effect of the Slow Slip events have been explicitly corrected for while the velocities from Beavan 2008 do not make an explicate correction for them so the contribution of the SSE's are included in the average velocities. Appendix 2 lists velocity estimates for the PositioNZ stations calculated by both the OU MatLab script and SPM_editor.py. The differences between the two estimates are minimal. The mean value of the difference between the two estimates is not significantly different from 0 in any of the three components which indicates there is no relative bias between the two techniques. The standard deviation is less than 0.5 for the e and n components and less than 1 mm for the vertical.

The SPM models contain an XYZ coordinate and an offset as the first and second parameters in the model XML file. After consultation with Chris Crook, we converted the XYZ coordinates to ITRF2008 velocities at epoch 2000.0 by extracting the XYZ coordinate from the SPM models and applying the offset values. No attempt was made to apply the seasonal terms. These values could then be compared with the ITRF 2008 epoch 2000.0 coordinates that were independently derived by stacking using the OU MatLab script as discussed in section 1. Appendix 1 contains a list coordinates developed from both procedures and a table of coordinate differences. The comparison of the two sets of coordinates is shown graphically in figure 1b.

The two sets of coordinates agree to within about 1 cm for all stations with the exception of the east component of PYGR which is an outlier. Since the Dusky Sound earthquake caused a large offset in the east component of PYGR a little over 2 years after the station was established, it is not surprising that two independent methods of analyzing the time series might give different results when the coordinates are extrapolated over 7 years to epoch 2000.0. The mean value of the coordinate differences are -5 mm in the east and 2 mm in the n and u components (see statistical summary on the bottom of appendix 1). All of these are significant at the 95% level of confidence. While these differences may indicate a small bias between the two techniques the fact that it is only a few mm indicates it is probably not of any concern.

3 Options for the ITRF2008-NZGD2000 datum transformation

In this study we consider four candidates for the ITRF2008 to NZGD2000 datum transformation. Two of these are these global transformations adopted by internationally while the other two are local transformations that apply only two the New Zealand region. There are advantages to both types of transformations. A local transformation will produce the best fit between the transformed ITRF08 coordinates and the official NZGD2000 coordinates while use of the internationally accepted transformation maintains a clear link between ITRF96 and NZGD2000.

3.1 Deriving the transformation parameters between ITRF2008-ITRF1996 for epoch 2000.0

Establishing the transformation between ITRF2008 and NZGD2000 reference frames requires that the conventional 14-parameter Helmert transformations be defined although some of the terms can be zero. The parameters are the 3 translations, 3 rotations and scale parameters shown in eq1, along with their time derivatives. Transformations generally fall into two categories; global transformations where all 14 parameters are defined and local transformations where generally about half of the parameters have non-zero values. Previous studies have normally focused on developing a local transformation for the New Zealand region (Beavan 1998, 2008, 2012). In this study we consider four candidates for the ITRF2008 to NZGD2000 datum transformation. First we develop a local transformation and compare it to the transformation developed by Beavan (2008). However, NZGD2000 is defined relative to ITRF96 (Office of the Surveyor General 2007) and it is important that this link is maintained. For these reason we broadened the study to include global transformations adopted by internationally and based on the IERS and IGS parameters.

There are two sources for authoritative transformations between ITRFs. Both the IERS (which has the overall responsibility for defining the ITRF reference frame) and the IGS (which has the primary responsibility for defining the GPS reference frame) each independently estimate transformation parameters each time a new ITRF is introduced. Normally these estimates do not differ significantly in a statistical sense; however, in the case of the ITRF97-ITRF96 transformation the IGS and ITRF parameters were significantly different. As shown in table 3.1 the IERS ITRF97-ITRF96 transformation parameters are all zero while the IGS version has large and statistically significant translations and rotations.

The transformation from ITRF2008 to ITRF96, denoted (ITRF2008→ITRF96), can be defined in terms of the composition of four distinct transformations, applied sequentially. First, positional coordinates are transformed from ITRF2008 to ITRF2005, then from ITRF2005 to ITRF2000, then from ITRF2000 to ITRF97, then from ITRF97 to ITRF96. This composition may be symbolically expressed via the following equation:

$$\begin{aligned}(\mathrm{ITRF2008} \to \mathrm{ITRF96}) \;&=\; (\mathrm{ITRF2008} \to \mathrm{ITRF2005}) \\ &+ (\mathrm{ITRF2005} \to \mathrm{ITRF2000}) + (\mathrm{ITRF2000} \to \mathrm{ITRF97}) \\ &+ (\mathrm{ITRF97} \to \mathrm{ITRF96}) \qquad (1)\end{aligned}$$

Before this equation can be used however the seven transformation parameters governing the datum transformation for each of the four steps valid at epoch 2000.0 must be derived. These were calculated by projecting the seven parameters in the 2nd through 5th rows of table 7 of Pearson and Snay (2012) forward 3 years (from epoch 1997 to 2000) using the time derivatives listed in last 7 rows of that table. The resulting transformation parameters are listed in table 3.1. The combined transformation from ITRF2000 to ITRF96 is listed in Table 3.2

Table 3.1. Transformation parameters between the sequential ITRF's from IERS and IGS

Parameter	Units	(ITRF2008→ITRF2005) t_0 = 2000.00	(ITRF2005→ITRF2000) t_0 = 2000.00	(ITRF2000→ITRF97) t_0 = 2000.00	(ITRF97→ITRF96) t_0 = 2000.00	(ITRF97→ITRF96) t_0=2000.00
Source		Computed from Pearson and Snay 2012 Table 7	Computed from Pearson and Snay 2012 Table 7	Computed from Pearson and Snay 2012 Table 7	IERS	Computed from Pearson and Snay 2012 Table 7 based on IGS mail msg0032 (1999)
$T_x(t_0)$	meters	-0.002 ± 0.001	1E-04 ± 0.0003	0.0067 ± 0.0009	0	0.00000 ± 0.002
$T_y(t_0)$	meters	-0.0009 ± 0.001	-0.0008 ± 0.0003	0.0043 ± 0.0009	0	-0.00051 ± 0.002
$T_z(t_0)$	meters	-0.0047 ± 0.001	-0.0058 ± 0.0003	-0.0227 ± 0.0009	0	0.01553 ± 0.002
$\varepsilon_x(t_0)$	mas	0 ± 0.0408	0 ± 0.01	0 ± 0.0379	0	0.16508 ± 0.090
$\varepsilon_y(t_0)$	mas	0 ± 0.0408	0 ± 0.01	0 ± 0.0379	0	-0.26897 ± 0.098
$\varepsilon_z(t_0)$	mas	0 ± 0.0408	0 ± 0.01	0.06 ± 0.0443	0	-0.05984 ± 0.088
$s(t_0)$	ppb	0.94 ± 0.1530	0.4 ± 0.05	1.58 ± 0.1581	0	-1.51099 ± 0.311
$\dot{T}_x$	m/yr	0.0003 ± 0.0002	-0.0002 ± 0.0003	0 ± 0.0003	0	0.00069 ± 0.000
$\dot{T}_y$	m/yr	0 ± 0.0002	0.0001 ± 0.0003	-0.0006 ± 0.0003	0	-0.00010 ± 0.000

$\dot{T}_z$	m/yr	0 ± 0.0002	-0.0018 ± 0.0003	-0.0014 ± 0.0003	0	0.00186 ± 0.000
$\dot{\varepsilon}_x$	mas/yr	0 ± 0.008	0 ± 0.01	0 ± 0.012	0	0.01347 ± 0.011
$\dot{\varepsilon}_y$	mas/yr	0 ± 0.008	0 ± 0.01	0 ± 0.012	0	-0.01514 ± 0.012
$\dot{\varepsilon}_z$	mas/yr	0 ± 0.008	0 ± 0.01	0.02 ± 0.014	0	0.00027 ± 0.011
$\dot{s}$	ppb/yr	0 ± 0.03	0.08 ± 0.05	0.01 ± 0.05	0	-0.19201 ± 0.043

NOTES for Table 3.1

The uncertainties (1 sigma) are from:

ITRF2008→ITRF2005 http://itrf.ensg.ign.fr/ITRF_solutions/2008/tp_08-05.php

ITRF2005→ITRF2000 Altamimi et al 2007

ITRF2000→ITRF97 Altamimi et al 2002

ITRF97→ITRF96 http://igscb.jpl.nasa.gov/mail/igsmail/1999/msg00323.html

Counterclockwise rotations of axes are positive;

ITRF08 coordinates are related to their corresponding XYZ coordinates by a Helmert transformation that is approximated by the following equation:

$$\begin{pmatrix} X_{ITRF96} \\ Y_{TRF96} \\ Z_{TRF96} \end{pmatrix} = \begin{pmatrix} T_X \\ T_Y \\ T_Z \end{pmatrix} + \begin{pmatrix} s & \varepsilon_Z & -\varepsilon_Y \\ -\varepsilon_Z & s & \varepsilon_X \\ \varepsilon_Y & -\varepsilon_X & s \end{pmatrix} \begin{pmatrix} X_{TRF08} \\ Y_{TRF08} \\ Z_{TRF08} \end{pmatrix} \quad 2)$$

Where T_x etc. represents the translations, ε_x etc. represents the rotations and s is the scale.

3.1.1 Internationally adopted transformation between ITRF96 and ITRF2008

Because of the increasing importance of GPS, the two largest countries whose national datums are defined relative ITRF96 (Canada and the US) have adopted the IGS ITRF96-97 transformation while using the IERS value for all of the other transformations between sequential ITRFs (Craymer et al 2000, Solar and Snay 2004, Pearson and Snay 2012). The IGN transformation however uses IERS for each of the steps between ITRF's. We will distinguish the two transformations by the source of the parameters in the ITRF96-97 step. The ITRF2008-ITRF96 adopted by the US and Canada and used in Central America and certain Pacific Island states uses the IERS transformation for everything except for the ITRF97-ITRF96 step where it uses the IGS value while the IGN ITRF96 and ITRF2008 transformation uses IERS values consistently. This IERS only transformation is used by the IGN and distributed on their website (http://itrf.ensg.ign.fr/doc_ITRF/Transfo-ITRF2008_ITRFs.txt). These values make a significant difference as they are responsible for all of the X and Y axis rotations in the ITRF08-ITRF96 transformation in column 5. During the discussion that follows, we will refer to the IERS only transformation as the IERS transformation and the transformation used by the US and Canada involving IERS and IGS parameters as the IERS/IGS transformation.

3.1.2 Best fitting local transformation between NZGD2000 and ITRF2008

Because previous transformations between the ITRF and NZGD2000 have been based on a local transformation using high order geodetic control in New Zealand (Beavan 1998, 2008, 2012), we started by deriving a best fitting local transformation between NZGD2000 and ITRF2008. Deriving transformations between reference frames requires that we have coordinate and velocity sets in both frames. For the ITRF coordinates we used the coordinates and velocities from the SPM model however, as discussed in section 2, for the velocity estimation step, the model was first edited to remove SSE's and velocity changes because these will not be reflected in the NDM velocities. For the NZGD2K coordinates we used official coordinates from LINZ. For the NZGD2K velocities we used velocities calculated from version 20130801 of CalcDeformation.py which were transformed from the topocentric to geocentric frame to geocentric Cartesian. Note that the LINZ velocity model currently does not include vertical velocities and this may introduce some biases into time dependent transformation . In any event, the time dependent terms are not necessary to estimate the epoch 2000.0 transformation since both sets of coordinates are valid for this epoch date. Following Beavan 2008, our transformation includes only the T_x, T_y and T_z terms and their time derivatives. We considered using more complex 7 and 4 parameter transformations and 3 parameter model using rotations instead of shifts but this model gave the lowest RMS and the best standard deviation for the parameters. We refer to this transformation as "best local". The other a local transformation that we evaluate is the transformation from ITRF2005 to NZGD2000 from Table 11 of Beavan 2008 updated to ITRF2008 which we refer to as PONL08. We updated the transformation to ITRF 2008 by adding the ITRF2008 → ITRF2005 transformation from column 1 of table 3.1. The transformation parameters for the two models cannot be directly compared because the Beavan 2008 transformation has a significant scale change (which is inherited from the ITRF2008 → ITRF2005 transformation) while our local ITRF2008 → NZGD2000 transformation does not.

The transformation parameters for these four transformations are summarized in table 3.2. Uncertainties in table 3.2 are at the 1 sigma level of confidence. Each of the transformations were checked against both the ITRF coordinates developed from Otago University scripts and those from the SPM editor however, for consistency, we present only the results from the SPM editor. The results of our evaluations of various datums are not very sensitive to which of the two sets of test coordinates are used.

3.3 Transformation parameters for candidate transformations

The transformation parameters for the IERS, IERS/IGS, "best local" and PONL08 transformations are listed in table 3.2 below. The IERS only transformation can be derived by adding the first four columns of table 3.1 and the IERS/IGS transformation is the sum of the first three columns plus the 5^{th}. The IERS/IGS transformation is listed in the first column of table 3.2 while the IERS transformation is listed in the second column. Uncertainties and transformation parameters for

PONL2008 are derived from values in Table 11 of Beavan 2008 updated to ITRF2008 using parameters and uncertainties in column 1 of table 3.1.

The IERS/IGS transformation is the one coded into the US National Geodetic Survey's code HTDP. In order to test were in fact the transformation in equation 1 is in fact the one used by HTDP, we manually converted the ITRF08 coordinate at epoch 2000.0 for three PositioNZ points (AUCK, WGTN and PYGR) using the transformation parameters in table 3.2 column 1 and compared the coordinates with the results of a similar transformation (ITRF08 to ITRF96 epoch 2000.0) done using HTDP. The results were identical. Appendix 3 shows sample transformations using the IERS/IGS transformation.

Table 3.2. Transformation from ITRF2008 to ITRF96

Parameter	**Units**	**(ITRF2008→ITRF96)t_0=2000.00 (IERS/IGS)**	**(ITRF2008→ITRF96) t_0=2000.00 (IERS)**	**(ITRF2008→ITRF96) t_0=2000.00 (best local)**	**(ITRF2008→ITRF96) t_0=2000.00 POLN08**
Source		Sum first three columns in table 3.1 plus column 5	Using IERS transformation	Best fitting local transformation this study	Beavan PONL2008 transformation ITRF2005 →NZGD2000 + ITRF08 → 05 from column 1
$T_x(t_0)$	meters	0.0048 ± 0.003	0.0048 ± 0.0014	-0.020 ± 0.003	-0.0173 ± 0.002
$T_y(t_0)$	meters	0.00209 ± 0.003	0.0026 ± 0.0014	-0.011 ± 0.003	-0.0105 ± 0.002
$T_z(t_0)$	meters	-0.01767 ± 0.003	-0.0332 ± 0.0014	-0.023 ± 0.003	-0.0119 ± 0.002
$\varepsilon_x(t_0)$	mas	0.16508 ± 0.106	0 ± 0.0566	0 ± 0	0 ± 0.041
$\varepsilon_y(t_0)$	mas	-0.26897 ± 0.113	0 ± 0.0566	0 ± 0	0 ± 0.041
$\varepsilon_z(t_0)$	mas	0.00016 ± 0.107	0.06 ± 0.0610	0 ± 0	0 ± 0.041
$s(t_0)$	ppb	1.40901 ± 0.384	2.92 ± 0.2256	0 ± 0	0.94 ± 0.15
$\dot{T}_x$	m/yr	0.00079 ± 0.001	0.0001 ± 0.0005	-0.00049 ± 0.0002	-0.00128 ± 0.0004
$\dot{T}_y$	m/yr	-0.0006 ± 0.001	-0.0005 ± 0.0005	-0.0012 ± 0.0002	-0.00119 ± 0.0004
$\dot{T}_z$	m/yr	-0.00134 ± 0.001	-0.0032 ± 0.0005	-0.0002 ± 0.0002	-0.0009 ± 0.0004
$\dot{\varepsilon}_x$	mas/yr	0.01347 ± 0.021	0 ± 0.0175	0 ± 0	0 ± 0.0080

$\dot{\varepsilon}_y$	mas/yr	-0.01514 ± 0.021	0 ± 0.0175	0 ± 0	0 ± 0.0080
$\dot{\varepsilon}_z$	mas/yr	0.02027 ± 0.022	0.02 ± 0.0190	0 ± 0	0 ± 0.0080
$\dot{s}$	ppb/yr	-0.10201 ± 0.088	0.09 ± 0.0768	0 ± 0	0 ± 0.0300

Uncertainties at the 1 SE level of confidence

3.2 Test of datum transformations between ITRF08 and ITRF96 for New Zealand

In this section we show how the four datum transformations discussed in this report (IERS/IGS, IERS, "best local" and PONL2008 transformations replicate the currently accepted NZGD2000 coordinates. In order to conduct these tests the transformations it is necessary to have a set points (preferably distributed over the land mass of New Zealand which have both ITRF2008 and NZGD2000 coordinates. The best set of test data at the current time are the PositioNZ's stations because these are the only points in New Zealand outside of the IGS stations that have well determined ITRF2008 coordinates. For this reason our methodology is different from previous investigations (Beavan 2008, 2012) which used the New Zealand 1st order marks and three CGPS points (AUCK, OUSD and WGTN) to derive local transformations. The coordinate set that we used in the datum transformation tests presented in this section are the ones derived from the station predictive model as discussed in section 2 above.

Table 3.3 shows a statistical summary of residual differences between the ITRF96 and NZGD2000 coordinates derived from the four transformations. This test indicates that the "best local" transformation provides the best fit between the ITRF08 coordinates for the PositioNZ points purpose and the PONL2008 is second. The fact that "best local" produces the best fit is expected as it was optimized for this purpose. Of the international transformations, the IERS/IGS transformation does a better job fitting NZGD2000 coordinates than IERS values alone do, however all of the mse misfits for all four transformations are comparable. The PONL08 IERS and IERS/IGS transformations all show small but significant mean differences which indicate small biases however these are 1 cm or less with the exception of the IERS transformation where they exceed 2 cm in the ΔZ component.

Table 3.3

Statistical summary of residual differences between the ITRF96 and NZGD2000 coordinates derived from the four transformations

	ΔX m		ΔY m		ΔZ m	
	mean m	mse m	mean m	mse m	mean m	mse m
IERS/IGS	-0.010	0.024	-0.006	0.012	-0.003	0.022
IERS	-0.008	0.024	-0.012	0.016	0.025	0.033
Best local	0.000	0.022	0.000	0.010	0.000	0.021
POLN08	0.004	0.022	-0.005	0.010	-0.005	0.022

As expected the mean residual for the best local transformation is zero, however the mean residuals for the PONL2008 and IERS/IGS transformations are also small and the RMS residuals are comparable for all three cases. Only the IERS transformation stands out as having larger biases and higher RMS residuals.

Table 3.4 shows statistical summary of the residuals for the IERS/IGS transformation in a bit more detail than table 3.3. As shown in table 3.4, the X and Y components have mean residuals that are significant at the 2 sigma level of confidence. The maximum residuals in the X and Z components are quite large, however, as discussed below, both of these are associated with one station PYGR.

Figure 4 shows histograms of the corresponding E, N and U residuals. Clearly the residuals preferentially map into the vertical. Indeed the vertical mse is over 30 mm, more than twice the value for e or n components which are 18 mm and 8 mm respectively. The ,e n and u components have a mean values of 8 mm 4 mm and 10 mm. Since all of these are significant at the 95% level of confidence (although only marginally in the n and u components) they indicates small bias between the transformed ITRF96 coordinates using the IERS/IGS transformation and the official NZGD2000 coordinates. Note that the up residual shows two residuals (PYGR and KTIA) that are clearly anomalous. Because the vertical residuals for PYGR and KTIA are so large, we tried to identify the cause of these anomalous values by trying several different combinations of the coordinate source (i.e. OU stacking and SPM) and the datum transformation. These tests show that using the OU stacking for the ITRF08 coordinates reduces the anomaly at both stations by about 2 cm while the choice of datum transformation had a relatively small effect. We found no combination that eliminated the anomalous residuals. Note that the IERS transformation (shown in the second column of figure 4) has larger biases in the e and n direction than the IERS/IGS case.

Figure 3 shows contours of the contours of the e, n and u residuals for both the North and South Islands. Clearly the up trace is dominated by the very large residuals for KTIA and PYGR that we have previously identified but ignoring these two points there seems to be some spatial coherence in the pattern of residuals that there may be some regional biases in the residuals in the 1 to 3 cm level (see the large region of positive residuals in the central NI and northern SI for example). While the east and north residuals do show significant anomalies, these seem to be associated with particular stations that have anomalous values without any evidence of spatial coherence that might indicate a regional bias. A possible exception to this is the region around East Cape in the north component. It is noteworthy that the PYGR and KTIA stations, that dominated the residual maps in the up component do not seem to be particularly anomalous in either of the horizontal components.

Table 3.4

	ΔX m	ΔY m	ΔZ m
mean	-0.010	-0.006	-0.003
st dev mean	0.004	0.002	0.003
MSE	0.024	0.012	0.022
Max	0.076	0.013	0.081
Min	-0.042	-0.025	-0.032

Table 3.5 shows the differences in the predicted coordinates between the IERS/IGS, local and PONL2008 transformations for all of the PositioNZ sites. The table lists the average and maximum and minimum differences in the predicted ITRF96 coordinates for the indicated pairs of transformations. The purpose of this table is to illustrate the gross difference in the transformations without reference to the NZGD2000 coordinates of the test points. As shown in the table, the X coordinate if the IERS/IGS transformation (averaged across the North, South and Chatham Islands) is 14 mm greater than either the PONL2008 or local transformations while the coordinate differences for the Y and Z components is always less than 10 mm. The range in the X coordinate is less than 1 mm across New Zealand as is the range in Y coordinate shifts for the IERS/IGS PONL2008 comparison while the others have values between 2 and 3 mm. Taken as a whole, the coordinate shifts shown in table 3.5 indicate that adopting the IERS/IGS datum transformation will cause fairly small (15 mm max) coordinate shifts over the main islands of New Zealand.

Table 3.5

	IERS/IGS-local				IERS/IGS-PONL2008				local-POLN2008			
	mean	stdev	max	min	mean	st dev	max	min	mean	st dev	max	min
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
X	13.8	0.1	14.2	13.6	14.1	0.3	14.6	13.5	0.3	0.2	0.7	-0.1
Y	2.8	0.4	3.5	1.7	6.7	0.1	6.9	6.3	3.9	0.3	4.6	3.4
Z	5.6	0.9	6.8	4.0	-1.9	0.6	-1.1	-3.1	-7.5	0.3	-7.1	-8.0

3.2.1 Test of datum transformations between ITRF08 and ITRF96 using first order control and ITRF96 coordinates from Table T6: of IERS Technical Note No. 24.

LINZ requested us to check the original ITRF96 coordinates used in establishing NZGD2000 (Phone conservation to Chris Crook 20/09/2013). There are two sources of ITRF96 coordinates that are available for this test. The first are coordinates for IGS control stations in Technical Note No. 24 (http://www.iers.org/nn_11216/IERS/EN/Publications/TechnicalNotes/tn24.html). There are two of the IGS control stations from listed in Technical Note No. 24 (AUCK and CHAT). We transformed these coordinates to ITRF96 epoch 1997.0 using HTDP (using the IERS/IGS transformation parameters). A comparison of the coordinates shows that transformed and official coordinates agree within a little over 10 mm in the E, a few mm in the nth and 20 mm in the u. The fact that much of the discrepancy between the TN24 coordinates and the transformed ITRF2008 coordinates partitions into the vertical probably relates to the vertical accuracies that were achievable in the late 1990's.

As a second test we compared SPM coordinates and velocities with values from Tables 2 and 3 of Pearce (2000). The coordinates in this comparison are in terms of epoch 2000.0. For the velocities the difference is 1.4 mm/yr in or less except for the N component of Chatham. The coordinate comparison shows that the difference between transformed coordinates compared with the values from table 3.6 is less than 10 mm in the north and east components while the ellipsoid heights differ by a maximum of 17 mm. This indicates a 5-10 mm bias in the E and Nth coordinates and about a 2 cm bias in the vertical. As with TN24 there is a clear tendency for the discrepancies between the transformed ITRF2008 coordinates and the ITRF coordinates to partition into the vertical. Some of these differences probably relate the limitations of the GPS technology available at the time.

Table 3.6

Comparison ITRF96 coordinates from TN24 and OSG Technical Report 1

	ΔE mm	ΔN mm	ΔU mm	ΔN mm/yr	ΔE mm/yr
TN24		Epoch	1997		
AUCK	11.7	0.2	18.8		
CHAT	8.7	2.8	14.5		
OSG	Rept. 1	Epoch	2000.0		
CHAT	-5.6	-7.4	-17.0	4.9	0.5
AUCK	-4.6	-9.0	-16.0	0.8	1.3
WGTN	-5.6	-8.6	-17.0	0.6	0.1

4 Test using the velocities from the SPM model

In this section we compare the SPM velocities transformed to ITRF96 to the interpolated velocities from the NDM (version 20130801). This is a test of the time dependant parameters in the datum transformations discussed in section 3.1. The time dependent parameters were not examined in the tests described in section 3 because all of our tests were at the epoch of 2000.0. In order to systematically compare the SPM velocities we developed a new set with all of the SSE's and velocity changes removed from the SPM models since, as discussed in section 1, the these parameters are not included in the NDM. We then transformed the SPM velocities from ITRF2008 to ITRF96 and compared the north and east components with the corresponding values from the NDM values. Histograms of the velocity differences are shown in figure 5 and the velocity vectors are listed in appendix 3. The differences between the SPM velocities are also summarized in table 4.1. The transformations tested were the IERS/IGS transformation, the updated the PONL2008 transformation from Beavan (2008) and the IERS transformation. The east component shows some significant outliers however these are from stations PYGR which is located in a region where the NDM velocity field is poorly known and TAUP where the deformation field had to be modelled with a series of velocity changes. However the largest difference is for the station AVLN. It is not clear why this station should have an anomalous velocity. It was affected by a single large SSE however this was removed from the model parameters before the SPM velocity was calculated.

Table 4.1 shows that the both the IERS and PONL transformations give a much poorer fit between the transformed SPM and NDM velocities than the IERS/IGS transformation. Neither the east or the up component of the residual velocities from the IERS/IGS transformation have a significant mean (at the 95% level of confidence) while both the IERS and PONL08 transformations have mean significant residuals in at least one component. The RMS residuals for the IERS/IGS transformation are also lower than both of the other transformations, particularly in the north component.

Table 4.1 Differences between the horizontal components of the transformed SPM velocities and the corrosponding estimates from the NDM model version 20130801.

	IERS/IGS		IERS		PONL	
	e	n	e	n	e	n
mean mm/yr	0.096	-0.181	0.982	-1.336	0.032	1.183
RMS	1.0	0.7	1.5	1.5	1.1	1.4
St dev mean mm/yr	0.17	0.10	0.17	0.11	0.17	0.11

Conclusion

The updated Station Predictive Model has an RMS has a mean square error in between the SPM model predictions and the measured coordinates of which are better than 2 mm in the east, 2.1 mm in the n and 5.7 in the u. The median mse values are all 47 stations are 1.7 mm for the nth 1.3 mm for the east and 4.5 mm for the up. The mse is a conservative estimate for the accuracy of the SPM models in areas where we have data, however, this will deteriorate when the model is extrapolated past the extent of the time series used to develop it.

We evaluated four candidates for the **ITRF2008→NZGD2000** datum transformation. The four transformations are, the IERS and IERS/IGS transformations between ITRF2008 and ITRF96, a local transformation between ITRF2008 and NZGD2000 developed as part of this study and the PONL2008 transformation of Beavan 2008. While (as expected) both the local transformations developed by PONL2008 and this report produce the best fit between the transformed and official NZGD2000 coordinates of the PositioNZ sites, all four of the transformations have RMS coordinate differences are on the order of a few cm however only two transformations ("best local" and IERS/IGS transformation) produce a satisfactory alignment between the transformed SPM velocities (for models excluding slow slip events) and the most recent version of the NDM. So the choice comes down to using the IERS/IGS global transformation which has been adopted internationally to base the **ITRF2008→NZGD2000** datum transformation or a locally derived transformation. However the NZGD2000 parameters listed in LINZS25000 include "the ITRS and the parameters defining ITRF96, as defined in Boucher et al (1998) following the conventions in McCarthy (1996)" (see section 2.2 b of Office of the Surveyor General 2007). Because NZGD2000 is defined to be aligned relative to ITRF96, this alignment can only be maintained by using an internationally recognized transformation between **ITRF2008→ITRF96** as the basis for the **ITRF2008 → NZGD2000** transformation. Our investigations show that the IERS/IGS transformation (Pearson2012) is a better choice than the IERS transformation because it gives a significantly better fit with the official NZGD2000 coordinates and velocities for the PositioNZ sites. Inevitably using a global transformation will result in a larger bias between the ITRF96 coordinates and the official NZGD2000 coordinates than will a local transformation that is designed to minimize these differences. Our investigations show that, for the IERS/IGS **ITRF2008→NZGD2000** datum transformation, the biases are comparatively small, only 8 mm, 4 mm and 10 mm in the e n and u directions respectively so any adjustments to NZGD2000 coordinates will also be small. We also tested the IERS/IGS transformation against the official NZGD2000 coordinates for two IGS station in the New Zealand region and three stations from OSG1. The differences, mm level in the e and n about 2 cm in the vertical are reasonable given the accuracies for GPS positioning in the late 1990's.

We tested the compatibility of the IERS/IGS ITRF2008 and ITRF96 transformation with the velocity grid in the NDM. While it is not straightforward to develop a set of velocity estimates for the PositioNZ stations that are directly compatible to the ones in the NDM because of differences in way that the stacking procedure and the NDM treats slow slip events we developed a special estimate of velocities that as closely as possible replicated the assumptions used to develop the NDM. Our test revealed no significant bias between this velocity field and estimates from the NDM if the IERS/IGS **ITRF2008→NZGD2000** datum transformation is used to transform the velocities from ITRF2008 to ITRF96.

For these reason we recommend that LINZ adopt the IERS/IGS transformation between ITRF2008-ITRF96 be as the **ITRF2008→NZGD2000** datum transformation.

Recommendations for further work

Our datum investigations have shown that the NZGD2000 coordinates for PYGR and KTIA are anomalous, particularly in the ellipsoidal height. Since these are 0 order points, the reasons for this should be investigated before completing the current readjustment of the New Zealand geodetic network

The alignment of the velocities in the NDM is somewhat uncertain because it was developed in an Australia fixed frame and we understand that the Euler pole necessary to align it to the ITRF frame is not precisely known. Our test indicates that there is no gross problem but the test using the velocities from the PositioNZ stations is not anywhere near definitive. We recommend that a dataset incorporating all well defined ITRF2008 velocity vectors be compiled and used to make a more comprehensive test. If necessary this data can be used to re-determine the velocities in the NDM by realigning the original Australia fixed velocities. Longer term we recommend that the next velocity grid be determined by gridding the current ITRF velocities without first transforming them into another reference frame.

The NDM is deficient in not having an estimate of vertical velocities yet there is considerable evidence that large areas of New Zealand are undergoing significant vertical motion. Ignoring this effect will introduce distortions in the ongoing National readjustment and, longer term, will compromise the integrity of the ellipsoid heights on which the New Zealand Vertical Datum depend. We recommend that the development of a vertical velocity grid be undertaken as a matter of urgency.

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Figures

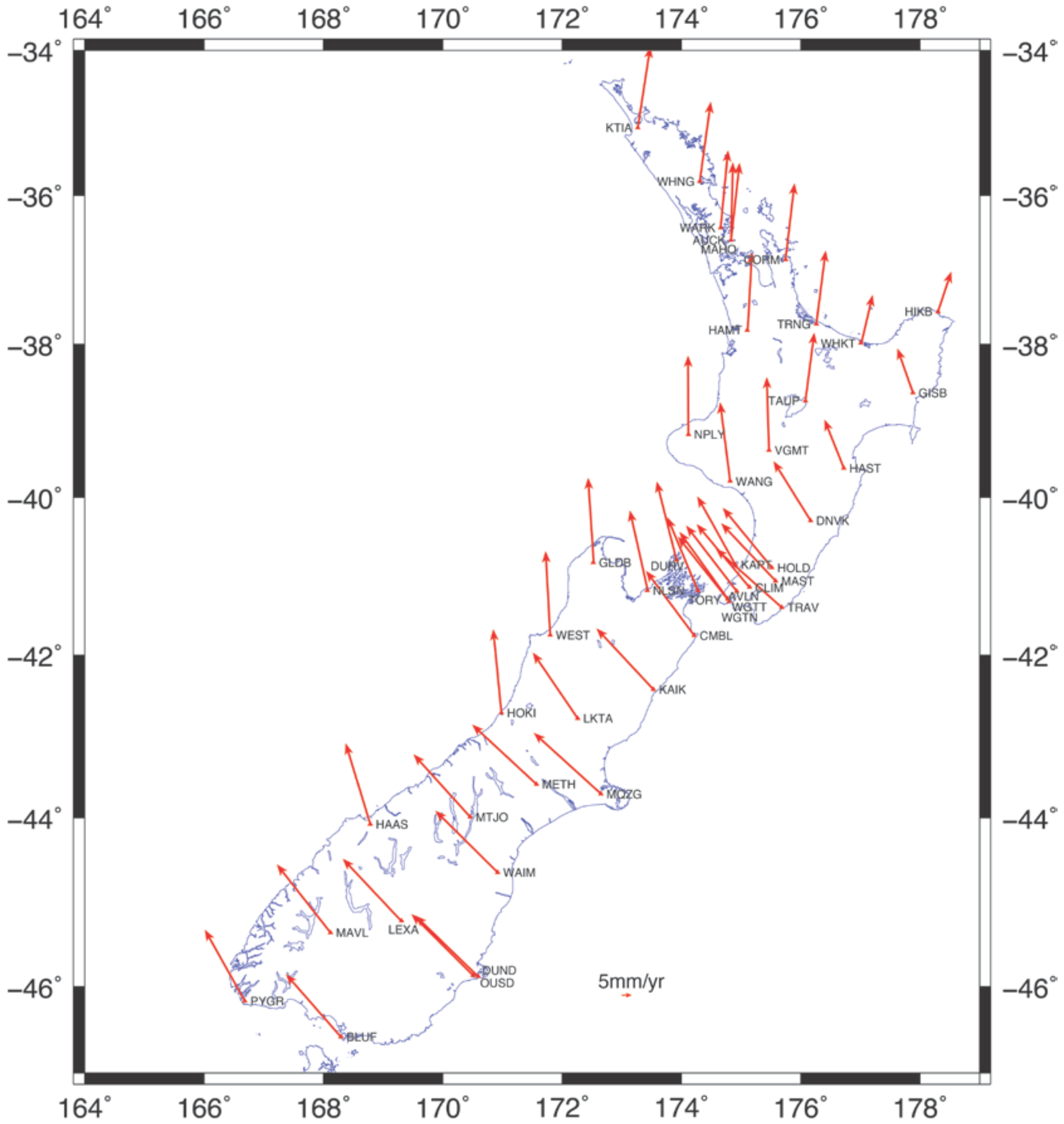


Figure 1a Stations for which we calculated predictive models. Vectors show the ITRF08 velocities from the Station Predictive Model velocity parameter. Figure 1b shows histograms for the east and north components of the velocity differences between the spm and ndm models.

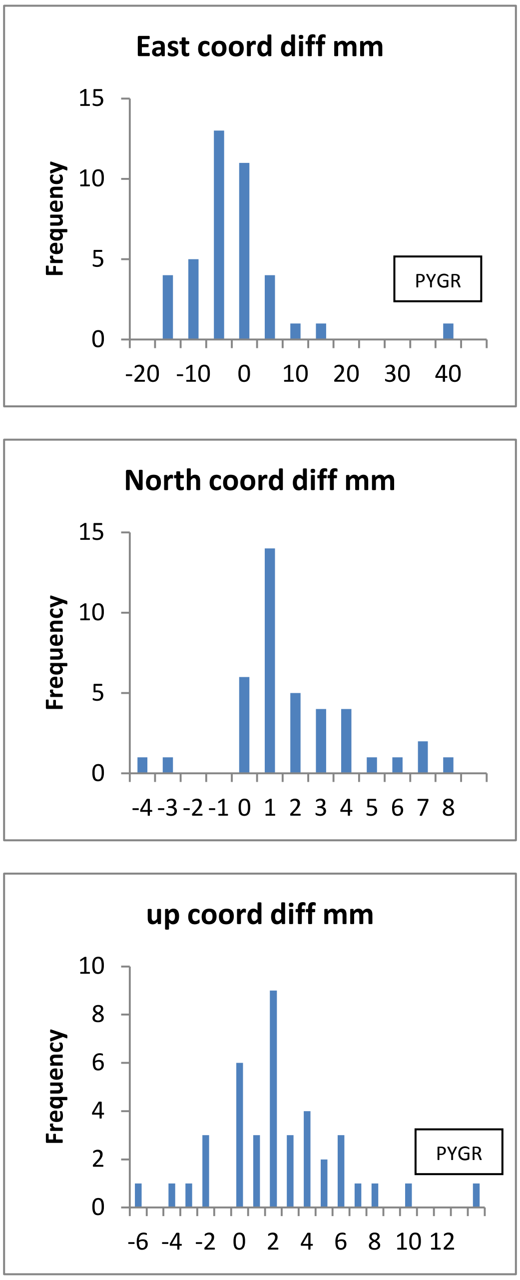


Figure 1b coordinate difference between ITRF 2008 at epoch 2000.0 coordinates from the Station Predictive Model (corrected for offsets) and those derived from stacking using the OU MatLab code. Note that in both the east and up component, PYGR is an outlier.

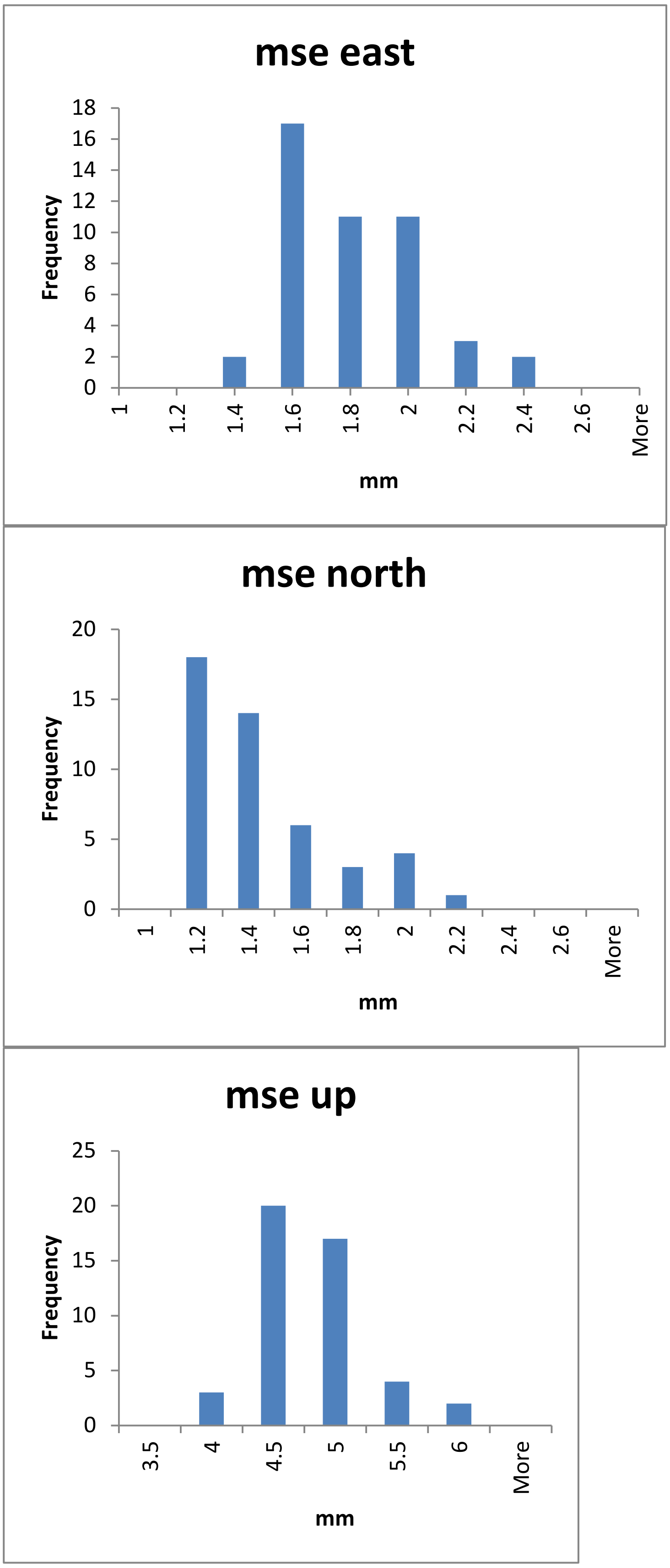
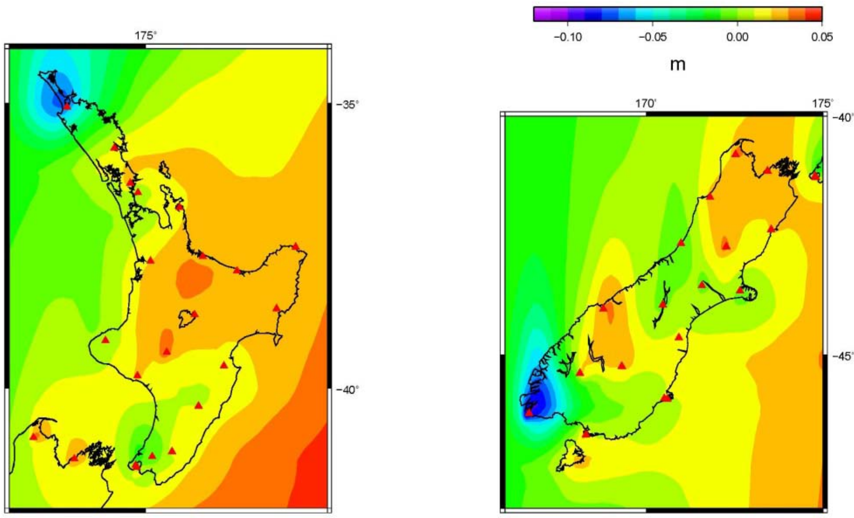
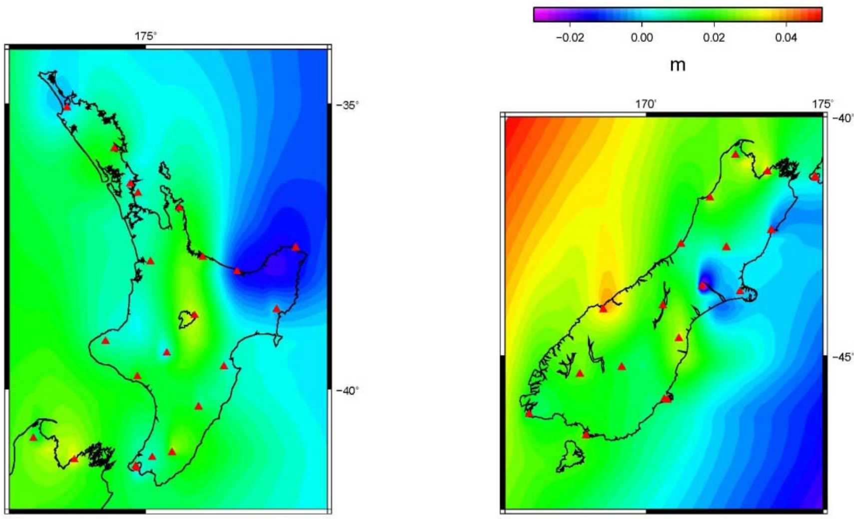


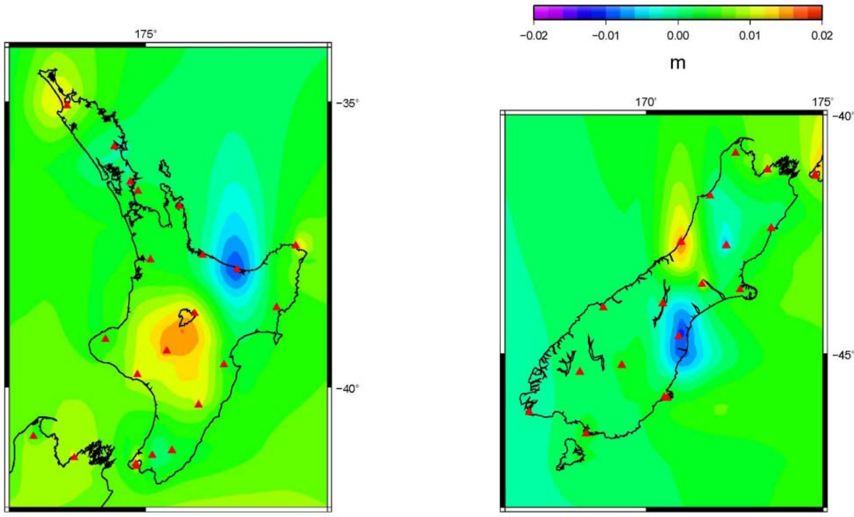
Figure 2 Histograms of mse values from spm_editor.py



Vertical residuals



North residuals



East residual

Figure 3 Stations used in datum investigations indicated by orange triangles. Colors indicate the residuals for the the **ITRF2008→ITRF96** datum from Pearson et al 2012.

IERS/IGS IERS

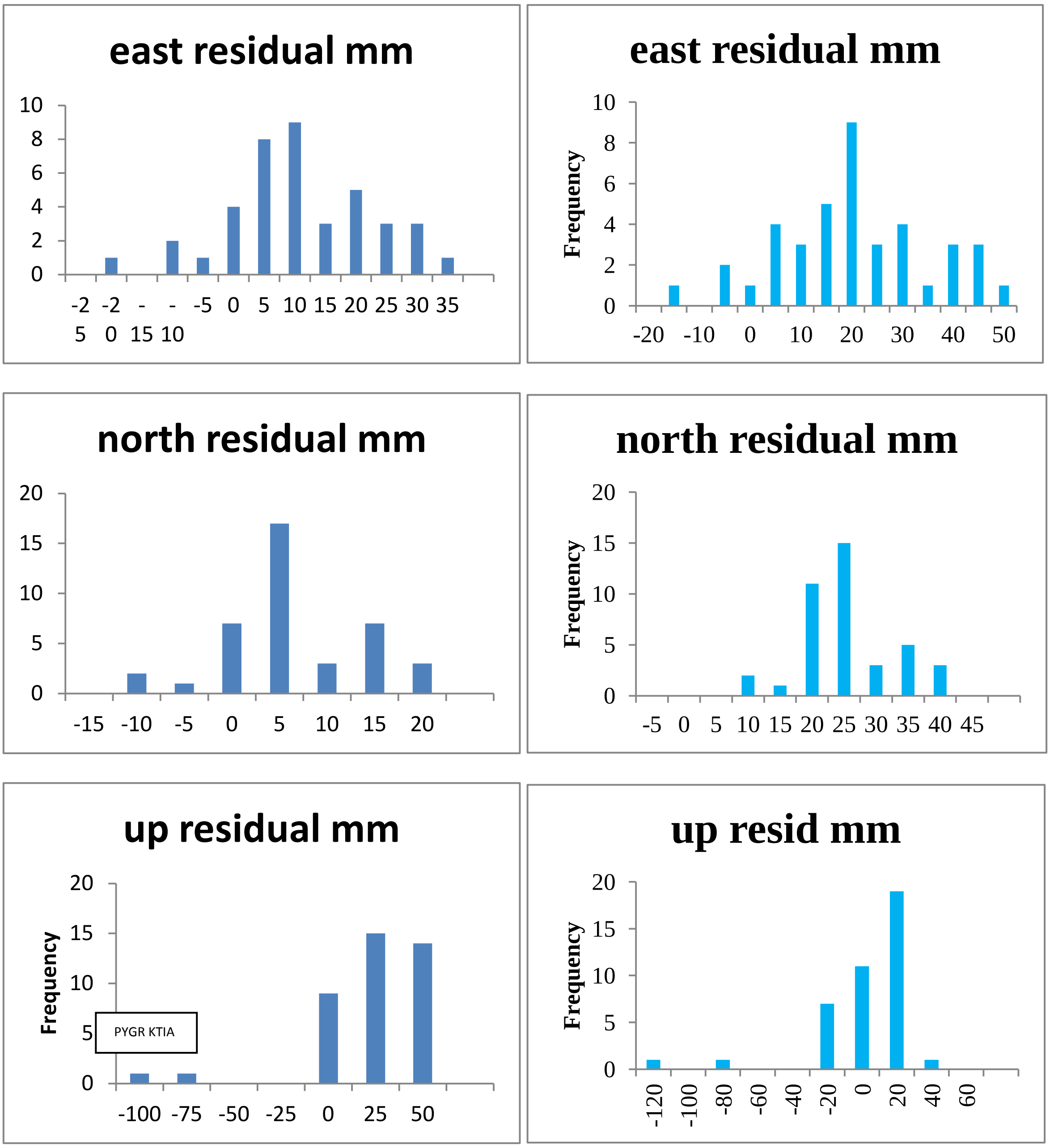


Figure 4 Residuals of coordinate position calculated by subtracting the transformed NZGD2000 coordinates (using the transformation parameters from Pearson et al 2000) from the input NZGD2000 coordinates (from the LINZ website)

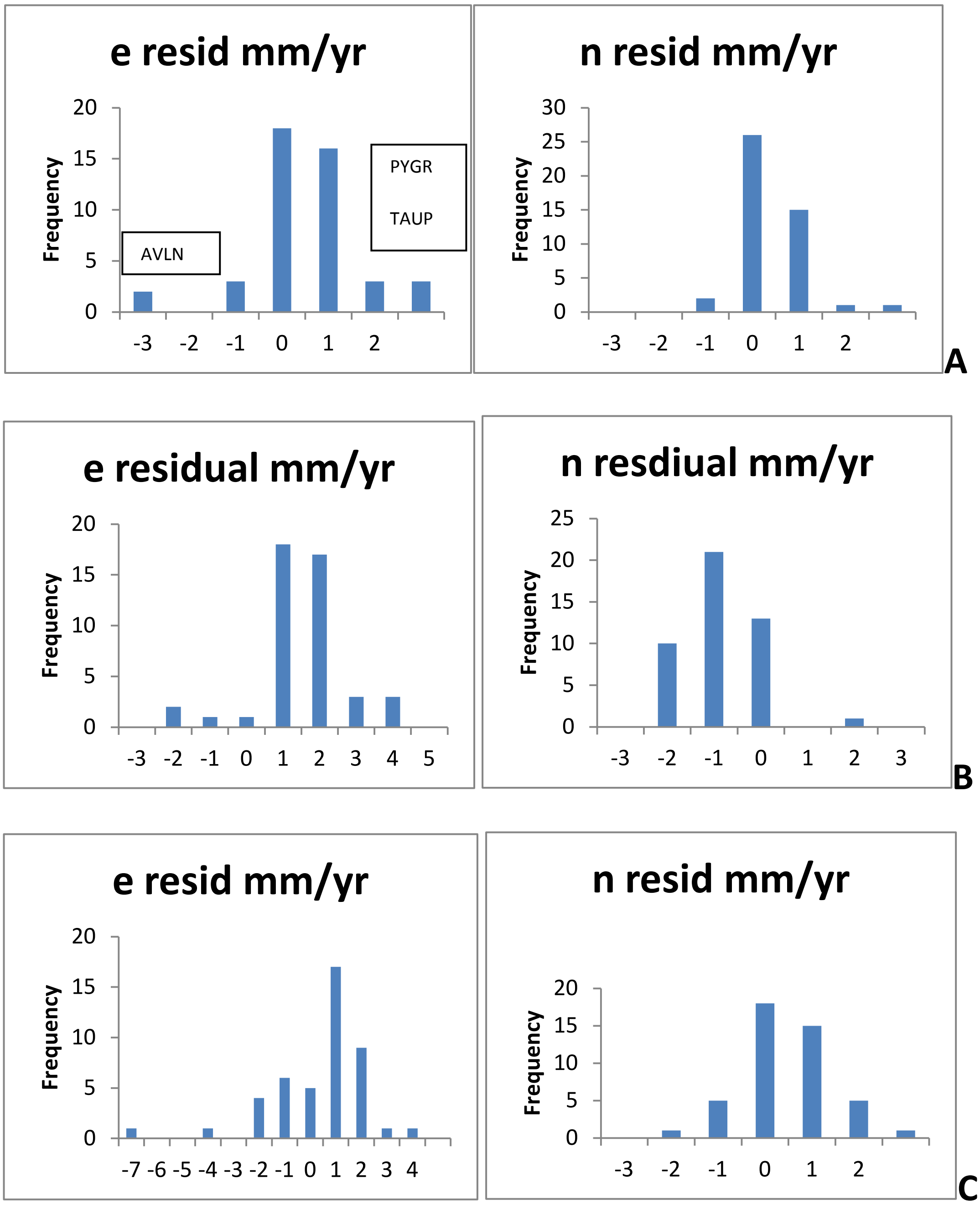


Figure 5 Histograms of differences between the horizontal components of the transformed SPM velocities and the corrosponding estimates from the NDM modelversion 20130801. Line A shows the residuals for the IERS/IGS transformation, Line B shows the IERS transformation and line C shows the PONL08 transformation.

Appendix 1

Coordinates derived from time series developed from Bernese coordinate files derived by John Beavan (pers com to Chris Crook). The OU coordinates are derived from Otago Universities matlab script pts.m The SPM coordinates are derived from the XYZ and offset parameters in the Station Predictive model files.

	ITRF 2008 coordinates from OU MatLab script			ITRF 2008 coordinates from SPM			Differences SPM-OU		
	X m	Y m	Z m	X m	Y m	Z m	e mm	n mm	u mm
AUCK	-5105681.064	461564.044	-3782181.646	-5105681.065	461564.046	-3782181.646	-2	1	1
BLUF	-4300030.476	891112.818	-4610274.861	-4300030.480	891112.832	-4610274.862	-18	4	5
CHAT	-4590670.974	-275482.874	-4404596.693	-4590670.974	-275482.875	-4404596.693	1	0	0
CHTI	-4607855.739	-272376.144	-4386954.665	-4607855.736	-272376.148	-4386954.663	6	-1	-3
CLIM	-4793403.910	407107.674	-4175081.829	-4793403.912	407107.675	-4175081.829	-1	1	1
CORM	-5095050.629	378667.235	-3805558.154	-5095050.630	378667.239	-3805558.154	-4	1	1
DNVK	-4860760.719	325692.555	-4103646.551	-4860760.719	325692.562	-4103646.550	-8	1	0
DUND	-4388120.467	726671.280	-4556533.587	-4388120.468	726671.285	-4556533.586	-7	2	1
GISB	-4985376.118	184022.206	-3960830.178	-4985376.116	184022.211	-3960830.173	-6	2	-4
GLDB	-4792405.795	628416.778	-4148068.630	-4792405.792	628416.787	-4148068.628	-11	0	-3
HAAS	-4502927.274	892783.590	-4414671.978	-4502927.281	892783.605	-4414671.978	-19	7	7
HAMT	-5027289.754	430177.763	-3888562.125	-5027289.755	430177.768	-3888562.125	-5	1	2
HAST	-4912020.483	280940.455	-4045418.507	-4912020.485	280940.455	-4045418.508	1	1	2
HIKB	-5060143.306	149885.214	-3867002.132	-5060143.305	149885.216	-3867002.132	-3	-1	-1
HOKI	-4635697.016	735523.194	-4304158.627	-4635697.019	735523.199	-4304158.628	-7	2	4
KAIK	-4685479.262	531054.859	-4280819.298	-4685479.261	531054.864	-4280819.298	-7	0	0
KTIA	-5190163.081	612173.651	-3644201.943	-5190163.083	612173.639	-3644201.943	15	0	0
LEXA	-4421518.043	834795.138	-4505701.514	-4421518.045	834795.149	-4505701.514	-14	3	3
LKTA	-4646207.396	630972.106	-4310354.697	-4646207.397	630972.115	-4310354.698	-11	0	2
MAHO	-4977264.945	448229.519	-3950347.802	-4977264.946	448229.524	-3950347.802	-7	1	2
MAST	-4801933.709	370788.883	-4167752.551	-4801933.711	370788.885	-4167752.550	-3	2	1
MAVL	-4392931.002	924277.200	-4516480.349	-4392931.009	924277.211	-4516480.349	-13	6	6
MQZG	-4580569.536	590465.440	-4384380.121	-4580569.537	590465.441	-4384380.121	-1	1	1
NLSN	-4775888.091	549740.069	-4177981.444	-4775888.096	549740.076	-4177981.443	-9	5	4
NPLY	-4924806.517	507350.487	-4008310.514	-4924806.518	507350.493	-4008310.513	-2	1	1
OUSD	-4387888.574	733420.988	-4555178.482	-4387888.574	733421.002	-4555178.479	-19	4	0
PYGR	-4306159.009	1019461.372	-4578241.818	-4306159.028	1019461.349	-4578241.824	39	5	14
TAUP	-4969936.375	340472.556	-3970347.252	-4969936.379	340472.563	-3970347.255	-8	0	5
TRNG	-5040272.153	329395.943	-3881773.364	-5040272.152	329395.948	-3881773.361	-7	2	-3
VGMT	-4921573.754	389889.421	-4025938.467	-4921573.748	389889.433	-4025938.463	-16	0	-7
WAIM	-4488353.622	717286.628	-4460947.059	-4488353.631	717286.631	-4460947.058	-3	7	6
WEST	-4717762.102	679316.885	-4224935.610	-4717762.111	679316.895	-4224935.614	-11	4	10
WGTN	-4777269.397	434270.067	-4189484.548	-4777269.396	434270.071	-4189484.547	-5	0	-1

WHKT	-5027028.231	262234.435	-3903984.586		-5027028.229	262234.436	-3903984.584		-2	1	-2
WHNG	-5153430.411	513057.545	-3710656.165		-5153430.414	513057.550	-3710656.165		-6	2	2
METH	-4577296.515	677932.504	-4375630.725		-4577296.515	677932.502	-4375630.731		2	-5	5
MTJO	-4533815.691	761552.574	-4407673.773		-4533815.696	761552.575	-4407673.773		-1	4	4
WANG	-4888073.191	443004.718	-4060015.663		-4888073.189	443004.724	-4060015.667		-8	-4	2
WARK	-5115333.006	477886.917	-3767147.758		-5115333.008	477886.923	-3767147.760		-8	0	4
WGTT	-4779507.965	436517.325	-4186741.182		-4779507.968	436517.325	-4186741.182		0	2	2
							Max		39	7	14
							Min		-19	-5	-7
							Mean		-5	2	2
							St Dev		10	2	4

Appendix 2 Comparison of velocities estimated using OU and SPM codes. Note all velocities are in mm/yr

STN	OU Script						SPM Full model			Diff OU-SPM		
	Ve	Vn	Vu	Se	Sn	Su	Ve	Vn	Vu	Ve	Vn	Vu
AUCK	4.46	39.43	0.01	0.02	0.02	0.07	4.34	39.34	0.01	0.12	0.09	0.00
AVLN	-25.92	33.61	-2.59	0.08	0.07	0.19	-25.92	33.61	-2.59	0.00	0.00	0.00
BLUF	-27.81	31.94	1.04	0.06	0.05	0.19	-28.13	32.07	0.56	0.32	-0.13	0.48
CHAT	-40.80	33.16	0.30	0.01	0.01	0.03	-40.73	33.20	0.30	-0.07	-0.05	0.00
CHTI	-40.84	32.69	-1.15	0.05	0.05	0.16	-41.07	32.74	-0.88	0.23	-0.05	-0.27
CLIM	-26.96	32.30	-2.87	0.06	0.05	0.14	-26.98	32.32	-2.95	0.02	-0.02	0.08
CMBL	-25.23	33.28	1.56	0.07	0.05	0.18	-24.68	33.02	1.83	-0.55	0.26	-0.27
CORM	4.72	39.08	0.21	0.02	0.01	0.05	4.62	38.99	0.20	0.10	0.09	0.01
DNVK	-20.25	30.49	-5.71	0.06	0.04	0.14	-19.00	30.43	-5.55	-1.25	0.06	-0.16
DUND	-31.93	31.16	-1.90	0.04	0.04	0.14	-32.14	31.18	-1.82	0.21	-0.02	-0.08
DURV	-10.24	40.24	1.40	0.08	0.06	0.19	-10.18	40.29	0.42	-0.06	-0.05	0.98
GISB	-8.86	23.29	0.88	0.09	0.07	0.25	-7.96	22.58	1.09	-0.90	0.71	-0.21
GLDB	-2.52	42.95	0.20	0.06	0.05	0.16	-2.89	43.11	1.35	0.37	-0.16	-1.15
HAAS	-12.49	41.04	1.33	0.04	0.05	0.11	-12.53	41.09	1.39	0.04	-0.05	-0.06
HAMT	2.43	39.65	0.29	0.02	0.01	0.05	2.19	39.53	0.28	0.24	0.12	0.01
HAST	-9.25	24.73	-5.36	0.08	0.05	0.19	-9.84	24.65	-6.09	0.59	0.08	0.73
HIKB	6.79	20.38	0.30	0.03	0.02	0.08	6.79	20.41	0.65	0.00	-0.03	-0.35
HOKI	-3.73	43.04	0.70	0.03	0.02	0.07	-4.19	42.54	-0.19	0.46	0.50	0.89
HOLD	-25.07	30.20	-3.40	0.07	0.04	0.21	-25.00	30.45	-3.84	-0.07	-0.25	0.44
KAIK	-28.95	31.51	-0.02	0.03	0.03	0.09	-29.05	31.07	-0.78	0.10	0.44	0.76
KAPT	-18.99	34.96	-4.18	0.05	0.04	0.09	-19.37	34.79	-4.17	0.38	0.17	-0.01
KTIA	6.43	41.16	-0.69	0.06	0.04	0.16	6.39	41.27	-0.57	0.04	-0.11	-0.12
LEXA	-29.57	31.99	0.77	0.08	0.06	0.22	-30.02	31.90	0.47	0.45	0.09	0.30
LKTA	-22.90	33.19	1.96	0.04	0.05	0.12	-22.86	33.52	2.41	-0.04	-0.33	-0.45
MAST	-27.09	29.35	-3.47	0.03	0.02	0.08	-27.77	29.34	-2.65	0.68	0.01	-0.82
MAVL	-26.65	34.84	0.61	0.09	0.06	0.25	-27.30	34.72	0.33	0.65	0.12	0.28
METH	-32.64	30.08	-2.72	0.31	0.25	1.08	-32.85	30.44	-3.79	0.21	-0.36	1.07
MQZG	-34.23	31.14	-0.67	0.03	0.03	0.09	-34.28	31.07	-0.62	0.05	0.07	-0.05
MTJO	-28.82	31.95	-0.76	0.03	0.02	0.09	-28.87	31.88	-0.86	0.05	0.07	0.10
NLSN	-8.70	40.98	1.00	0.05	0.04	0.15	-9.13	40.75	0.91	0.43	0.23	0.09
NPLY	-0.21	40.26	-0.78	0.03	0.02	0.09	-0.19	40.26	-0.04	-0.02	0.00	-0.74
OUSD	-32.37	31.72	-0.87	0.02	0.02	0.07	-31.48	31.28	0.18	-0.89	0.44	-1.05
PYGR	-21.01	35.80	-3.49	0.15	0.16	0.42	-20.43	36.38	-4.30	-0.58	-0.58	0.81
TAUP	4.07	33.34	4.04	0.07	0.05	0.17	4.56	34.84	-0.03	-0.49	-1.50	4.07
TRAV	-33.66	29.89	-4.34	0.02	0.01	0.05	-33.66	29.89	-4.34	0.00	0.00	0.00
TRNG	4.33	37.44	0.56	0.03	0.02	0.07	4.78	37.39	2.10	-0.45	0.05	-1.54
VGMT	-1.89	37.26	1.29	0.07	0.06	0.19	-1.15	37.24	2.90	-0.74	0.02	-1.61
WAIM	-31.66	31.54	-0.66	0.04	0.03	0.11	-31.80	31.47	-0.62	0.14	0.07	-0.04
WANG	-5.15	39.64	0.35	0.03	0.02	0.08	-5.10	40.37	0.22	-0.05	-0.73	0.13
WARK	3.70	39.39	-0.22	0.10	0.08	0.31	3.78	39.46	-0.47	-0.08	-0.07	0.25

WEST	-2.35	42.65	-1.07	0.04	0.03	0.10	-2.34	42.66	-0.67	-0.01	-0.01	-0.40
WGTN	-26.21	33.11	-3.61	0.04	0.03	0.09	-26.24	32.99	-3.19	0.04	0.12	-0.42
WGTT	-23.88	34.37	-3.25	0.02	0.02	0.05	-24.56	34.05	-3.48	0.68	0.32	0.23
WHKT	6.11	24.92	0.21	0.10	0.08	0.26	5.86	24.79	0.35	0.25	0.13	-0.14
WHNG	5.58	40.38	-0.17	0.03	0.03	0.10	5.57	40.41	0.23	0.01	-0.03	-0.40
								Max		0.68	0.71	4.07
								Min		-1.25	-1.50	-1.61
								Mean		0.00	0.00	0.03
								St Dv		0.45	0.36	0.91

Appendix 3 Comparison of measured and predicted velocities, ITRF2008 reference frame. The SPM coordinates were transformed between ITRF2008 and ITRF2006 using the IERS/IGS transformation parameters.

	NDM		SPM no SSE		Diff SPM-NDM	
Station	Ve	Vn	Ve	Vn	Ve	Vn
AUCK	5.8	38.9	5.6	38.2	-0.2	-0.7
AVLN	-21.4	32.3	-24.6	32.5	-3.2	0.2
BLUF	-27.4	30.5	-26.9	30.9	0.5	0.4
CLIM	-23.2	30.2	-23.6	30.3	-0.4	0.1
CMBL	-23.0	32.7	-23.4	31.9	-0.4	-0.8
CORM	6.6	36.6	5.9	37.9	-0.7	1.3
DNVK	-14.8	27.8	-14.1	27.0	0.7	-0.8
DUND	-30.9	29.4	-30.9	30.0	0.0	0.6
DURV	-6.3	38.8	-5.8	38.8	0.5	0.0
GISB	1.2	19.3	1.4	18.5	0.2	-0.8
GLDB	-1.1	41.2	-0.9	41.5	0.2	0.3
HAAS	-10.8	39.0	-11.3	39.9	-0.5	0.9
HAMT	3.7	38.3	3.5	38.4	-0.2	0.1
HAST	-3.6	24.3	-4.2	23.9	-0.6	-0.4
HIKB	8.3	18.8	8.1	19.3	-0.2	0.5
HOKI	-2.9	41.7	-3.0	41.4	-0.1	-0.3
HOLD	-21.5	29.0	-22.5	29.3	-0.9	0.3
KAIK	-27.6	30.6	-27.8	29.9	-0.2	-0.7
KAPT	-14.6	35.1	-13.8	34.7	0.8	-0.4
KTIA	7.4	40.9	7.7	40.1	0.3	-0.8
LEXA	-28.6	30.9	-28.8	30.7	-0.2	-0.2
LKTA	-21.8	33.0	-21.6	32.4	0.2	-0.6
MAHO	5.8	38.9	2.5	38.5	-3.3	-0.4
MAST	-26.1	27.9	-26.1	28.2	0.1	0.3
MAVL	-27.0	34.2	-26.1	33.5	0.9	-0.7
METH	-30.0	29.8	-31.6	29.3	-1.6	-0.5
MQZG	-33.1	29.8	-33.0	29.9	0.1	0.1
MTJO	-27.1	31.0	-27.6	30.7	-0.5	-0.3
NLSN	-5.9	39.6	-5.4	39.6	0.5	0.0

NPLY	1.3	38.8	1.1	39.1	-0.2	0.3
OUSD	-30.5	29.6	-30.2	30.1	0.3	0.5
PYGR	-21.6	35.5	-19.2	35.2	2.4	-0.4
TAUP	4.8	32.6	7.6	31.7	2.8	-0.9
TORY	-12.5	36.2	-11.4	38.5	1.2	2.3
TRAV	-32.1	28.8	-32.4	28.8	-0.3	0.0
TRNG	4.0	36.3	6.1	36.3	2.1	0.0
VGMT	-0.4	36.4	0.8	36.1	1.2	-0.3
WAIM	-31.1	31.0	-30.6	30.3	0.5	-0.7
WANG	-3.0	37.4	-1.6	36.8	1.4	-0.6
WARK	6.1	39.4	5.1	38.3	-1.0	-1.1
WEST	-1.8	41.9	-1.1	41.5	0.7	-0.4
WGTN	-22.9	31.9	-23.8	31.3	-0.9	-0.6
WGTT	-21.0	32.6	-22.2	32.2	-1.2	-0.4
WHKT	7.2	25.3	7.2	23.7	0.0	-1.7
WHNG	6.8	40.2	6.9	39.3	0.0	-0.9
			Max		2.79	2.32
			Min		-3.28	-1.65
			Mean		0.02	-0.18
			St Dv		1.13	0.68

Appendix 3 Sample datum transformations

HTDP (version 3.2) OUTPUT

TRANSFORMING POSITIONS FROM ITRF96 (EPOCH = 01-01-2012 (2012.000))

TO ITRF2008 or IGS08 (EPOCH = 01-01-2012 (2012.000))

INPUT COORDINATES OUTPUT COORDINATES INPUT VELOCITY

1 LATITUDE 53 00 0.00000 N 53 00 0.00148 N 0.00 mm/yr north LONGITUDE 359 54 0.00000 W 359 54 0.00051 W 0.00 mm/yr east ELLIP. HT. -0.000 0.017 m 0.00 mm/yr up X 3846673.870 3846673.844 m 0.00 mm/yr Y 6713.719 6713.710 m 0.00 mm/yr Z 5070543.503 5070543.544 m 0.00 mm/yr

2 LATITUDE 85 00 0.00000 N 85 00 0.00010 N 0.00 mm/yr north LONGITUDE 260 05 59.99999 W 260 05 59.98979 W 0.00 mm/yr east ELLIP. HT. 0.000 0.033 m 0.00 mm/yr up X -95892.950 -95892.977 m 0.00 mm/yr Y 549441.830 549441.825 m 0.00 mm/yr Z 6332400.864 6332400.897 m 0.00 mm/yr

3 LATITUDE 5 00 0.00000 S 4 59 59.99860 S 0.00 mm/yr north LONGITUDE 265 00 0.00000 W 264 59 59.99995 W 0.00 mm/yr east ELLIP. HT. -0.000 0.002 m 0.00 mm/yr up X -553790.014 -553790.016 m 0.00 mm/yr Y 6329848.826 6329848.832 m 0.00 mm/yr Z -552183.960 -552183.917 m 0.00 mm/yr

4 LATITUDE 5 00 0.00000 N 5 00 0.00076 N 0.00 mm/yr north LONGITUDE 93 00 0.00000 W 93 00 0.00087 W 0.00 mm/yr east ELLIP. HT. -0.000 -0.003 m 0.00 mm/yr up X -332544.122 -332544.148 m 0.00 mm/yr Y -6345319.846 -6345319.840 m 0.00 mm/yr Z 552183.960 552183.983 m 0.00 mm/yr

5 LATITUDE 90 00 0.00000 S 89 59 59.99951 S 0.00 mm/yr north LONGITUDE 0 00 0.00000 W 268 31 17.01165 W 0.00 mm/yr east ELLIP. HT. -0.000 -0.035 m 0.00 mm/yr up X 0.000 -0.000 m 0.00 mm/yr Y 0.000 0.015 m 0.00 mm/yr Z -6356752.314 -6356752.279 m 0.00 mm/yr

6 LATITUDE 3 00 0.00000 S 2 59 59.99930 S 0.00 mm/yr north LONGITUDE 185 00 0.00000 W 185 00 0.00050 W 0.00 mm/yr east ELLIP. HT. -0.000 0.011 m 0.00 mm/yr up X -6345216.684 -6345216.695 m 0.00 mm/yr Y

555134.527 555134.544 m 0.00 mm/yr Z -331574.315 -331574.294 m 0.00 mm/yr

7 LATITUDE 45 00 0.00000 S 44 59 59.99931 S 0.00 mm/yr north LONGITUDE 185 00 0.00000 W 185 00 0.00089 W 0.00 mm/yr east ELLIP. HT. 0.000 -0.014 m 0.00 mm/yr up X -4500400.082 -4500400.085 m 0.00 mm/yr Y 393733.988 393734.008 m 0.00 mm/yr Z -4487348.409 -4487348.384 m 0.00 mm/yr

HTDP (version 3.2) OUTPUT

TRANSFORMING POSITIONS FROM ITRF2008 or IGS08 (EPOCH = 01-01-2000 (2000.000))

TO ITRF96 (EPOCH = 01-01-2000 (2000.000))

INPUT COORDINATES OUTPUT COORDINATES INPUT VELOCITY

1 LATITUDE 53 00 0.00147 N 53 00 0.00073 N 0.00 mm/yr north LONGITUDE 359 54 0.00051 W 359 54 0.00007 W 0.00 mm/yr east ELLIP. HT. 0.017 0.014 m 0.00 mm/yr up X 3846673.844 3846673.861 m 0.00 mm/yr Y 6713.710 6713.718 m 0.00 mm/yr Z 5070543.544 5070543.528 m 0.00 mm/yr

2 LATITUDE 85 00 0.00010 N 84 59 59.99989 N 0.00 mm/yr north LONGITUDE 260 05 59.98981 W 260 05 59.99490 W 0.00 mm/yr east ELLIP. HT. 0.033 0.024 m 0.00 mm/yr up X -95892.977 -95892.965 m 0.00 mm/yr Y 549441.825 549441.833 m 0.00 mm/yr Z 6332400.897 6332400.888 m 0.00 mm/yr

3 LATITUDE 4 59 59.99860 S 4 59 59.99931 S 0.00 mm/yr north LONGITUDE 264 59 59.99995 W 264 59 59.99997 W 0.00 mm/yr east ELLIP. HT. 0.002 0.014 m 0.00 mm/yr up X -553790.016 -553790.016 m 0.00 mm/yr Y 6329848.832 6329848.842 m 0.00 mm/yr Z -552183.917 -552183.940 m 0.00 mm/yr