Aligning the New Zealand National Datum with the International Terrestrial Reference Frame in the Face of Tectonic Deformation

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Key words: deformation, positioning, reference frames, New Zealand

SUMMARY

The New Zealand National Datum NZGD2000 provides a local reference system for the geospatial information community. To do this it must account for the tectonic deformation occurring in New Zealand. The datum definition is therefore based on a deformation model - a time and position dependent model relating NZGD2000 coordinates to the International Terrestrial Reference Frame (ITRF) in such a way that they are substantially "ground fixed". Monitoring and maintaining this model in the face of ongoing secular deformation as well as episodic events such as earthquakes and slow slip events provides challenges for the national geodetic agency Land Information New Zealand (LINZ). There is a technical challenge in terms of measuring the deformation and maintaining models. There is also a practical challenge to minimize the impact of maintaining the datum on the user community. Key to the datum maintenance is routine analysis of data from the national network of continuously operating GNSS reference stations - the "PositioNZ" network. These are processed to generate time series of daily ITRF coordinates which are compared with the deformation model to identify significant discrepancies. The smoothed time series are also used by the LINZ online RINEX post processing service PositioNZ-PP to provide current local alignment with ITRF. The combination of the accurate ITRF coordinates at the PositioNZ stations and the deformation model allows the datum to provide a framework for high accuracy measurement in terms of ITRF as well as a practical spatial reference frame for the positioning community.

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1. HISTORY OF THE NZGD2000 DATUM

The New Zealand Geodetic Datum 2000 (NZGD2000) was developed between 1998 and 2000 to replace the previous datum New Zealand Geodetic Datum 1949. It is an innovative datum, including a deformation model that effectively provides two coordinate systems – one the geocentric coordinate system on which it is based (International Terrestrial Reference Frame (ITRF) 1996) and one a system within which coordinates of objects fixed on the ground are substantially constant (Donnelly et al., 2015). The latter static coordinate system is what is perceived by most users as the NZGD2000 coordinate system – coordinates in this system are used in geographic information systems and in mapping to identify and locate physical features such as buildings, utilities, etc. Generally the term NZGD2000 coordinates is used to refer to coordinates in this system. It was aligned with ITRF96 at epoch 2000.0 – since then it has diverged from ITRF96 as New Zealand deforms. The deformation model defines the difference between these two coordinate systems as a function of time and location.

This style of datum, integrating a deformation model to account for tectonic movement and distortion over time, was termed a “semi-dynamic” datum at the time it was formulated (Grant et al, 1999). However this term is now deprecated in favour of the less ambiguous term ”plates-fixed” datum (Donnelly et al., 2015).

The NZGD2000 datum is officially defined by the Land Information New Zealand (LINZ) standard 25000 (LINZ 2007) and its development and implementation documented in a series of papers including Grant et al (1999) and Blick (2003). Beavan and Blick (2006) highlighted the shortcomings of the deformation model that became evident from observations made after the model was developed in 1998. However it was not until 2013 that the model was first updated in response to the Canterbury earthquake sequence (Crook et al., 2016). Two further modifications were made after 2013 – firstly to account for the Cook Strait earthquakes of 2013, and secondly to expand the spatial extent of the model to include the extent of New Zealand's Exclusive Economic zone. Earlier models only covered the land extents of the New Zealand North and South Islands.

The deformation model itself includes a secular velocity model defining the ongoing tectonic deformation of New Zealand, as well as a series of ”patches” representing the deformation due to earthquakes. This model is updated periodically – each version is identified by its release date (e.g. 20130801). Technically each release is equivalent to a new datum, but for most users and usages the change has little or no impact. To simplify usage of the datum the sequence of updates are identified collectively as NZGD2000. When the version of the deformation model is significant the datum can be qualified with the version identifier as, for example, NZGD2000(20130801).

Although NZGD2000 is nominally defined in terms of ITRF96 it is now becoming more difficult to directly access that datum. Many of the reference stations defining ITRF96 have been affected by deformation events so that the ITRF96 defined coordinates and velocities are no longer consistent with the actual locations of the marks. Additionally products such as satellite orbit parameters are no longer calculated in terms of ITRF96. Rather than directly measuring ITRF96 coordinates, they are now derived indirectly by transforming from ITRF2008 (Pearson, 2013, Donnelly et al., 2014). The transformation from ITRF2008 to ITRF96 is now treated as definitive so that NZGD2000 coordinates can be derived from ITRF2008 coordinates by applying this transformation and the deformation model. The relationship of these coordinate systems and the deformation model is represented in Figure 1.

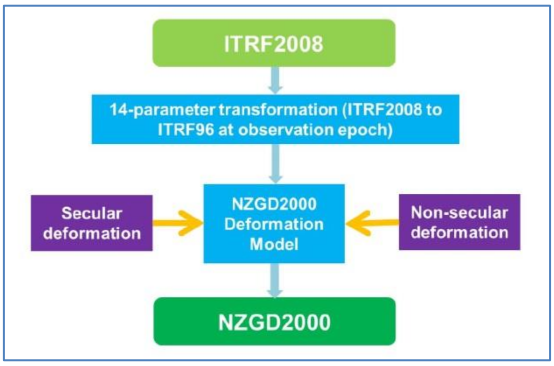

Figure 1: Transformation between ITRF2008 and NZGD2000 coordinates (from Blick and Donnelly, 2016).

The NZGD2000 coordinate system is generally accessed, either directly or indirectly, by the coordinates assigned to the zero order stations which are continuously operating GNSS (Global Navigation Satellite System) receivers (CORS) forming the PositioNZ network (Gentle et al., 2016). Although these stations reflect the realisation of the datum their coordinates are not held fixed. Indeed they need to be periodically updated to maintain this alignment. While their NZGD2000 coordinates are nominally static, in practice the errors in and incompleteness of the deformation model mean that for the CORS ITRF coordinate to remain correct small updates to their NZGD2000 coordinates are required periodically.

One consequence of the using a "plates-fixed" datum in New Zealand is that although NZGD2000 coordinates serve to identify physical features well, the coordinates cannot be used to calculate the relationship between points accurately (Crook et al., 2016). Figure 2 shows the "rate of distortion" of the datum, a measure of the maximum error in an observed vector. This can be up to 0.8 ppm/year. So in 2015 vectors calculated from the NZGD2000

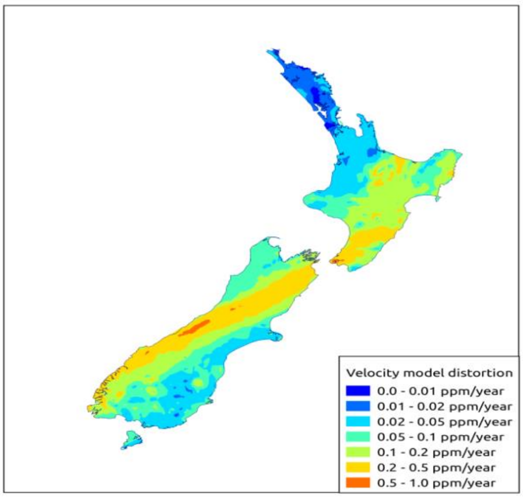

Figure 2: Rate of distortion of NZGD2000 coordinates (from Crook et al., 2016)

coordinates may be differ from the true vector between corresponding points by up to 12ppm (here assuming the deformation model is perfect – there may be an additional difference due to the difference between the modelled and actual deformation).

Because of this LINZ recommends that high accuracy work is done in terms of ITRF coordinates. Alternatively it can be done in NZGD2000, but then calculations must include accounting for deformation, which most survey and engineering software cannot do. For long term large scale projects it is possible that deformation will need to be considered even working in terms of ITRF, as accumulation of deformation during the project may be significant.

Note that in this paper the term ITRF coordinates is used to mean coordinates in terms of an ITRF reference frame (e.g. ITRF2008). Generally the current ITRF will be most appropriate to use. The significant feature of these coordinates is that they are in terms of a global, "earth-fixed" reference frame, rather than a local "plates-fixed" frame.

Most survey work in New Zealand will be either directly or indirectly tied with PositioNZ network and may be using the coordinates assigned to these stations as control. The alignment of the PositioNZ network with ITRF and the accuracy and consistency of coordinates derived from it is the principal subject of this paper.

2. HISTORY OF GNSS DATA PROCESSING

The NZGD2000 datum was originally realized and is maintained using GNSS observations. In practice as of 2015 only data from the GPS satellite constellation have been used, but it is anticipated that the other constellations will be used in the near future.

The development and maintenance of the datum can be categorized into five activities:

- initial realisation of the NZGD2000 coordinates of geodetic marks
- development of the initial deformation model
- updating NZGD2000 coordinates of geodetic marks
- updating the deformation model
- monitoring the integrity of the datum

These activities are strongly correlated. Calculating NZGD2000 coordinates generally involves converting them from the observation reference frame and epoch to the NZGD2000 coordinate system, which requires using the deformation model. Observations which are used to monitor the datum or deformation model will also be used to update coordinates or the deformation model.

The initial realisation of NZGD2000 was based on principally on two analyses as documented in Grant et al (1998).

Beavan (1998) used the Bernese software to process the CORS and campaign data from 1992 to 1998 within a regional network of IGS stations to determine station velocities and from these derive a national velocity model (Beavan and Haines, 2001).

Morgan and Pearse (1999) used GAMIT/GLOBK processed data for zero and first order NZGD2000 stations within a global framework of IGS stations to provide the alignment with ITRF96 and the first order network of stations into which lower order stations could be integrated.

The two analyses provided an independent check on the integrity of the datum. They used different software and processing strategies to calculate coordinates. None the less they achieved good agreement in both coordinates and velocities, with the maximum coordinate differences of 3.3, 8.2 and 26 mm (NEU) and maximum velocity differences of 1.5, 3.3 and 13.2 mm/year (NEU) (Beavan, 1998).

After the initial realisation of NZGD2000 the GNSS processing maintaining the datum definition was carried out by GNS under contract to LINZ. This included both calculating the time series of CORS stations producing daily coordinate solutions and monthly averages, as well as the campaign GNSS data used to recalculate the deformation model. Currently the daily CORS processing is being carried out by LINZ. GNS continue their daily processing in parallel, though they have changed their processing strategies and software.

The LINZ processing strategy currently uses the Bernese 5.2 software to process data within a regional IGS network comprising the stations ALIC, AUCK, CEDU, CHAT, CHTI, DARW, HOB2, KARR, MAC1, MCM4, PERT, THTI, TIDB, TOW2, and YAR2. YAR2 shares an antenna with YAR1, and is treated as equivalent to it. The IGS 2008 absolute antenna phase models are used. The Bernese RNX2SNX (RINEX to SINEX) processing control file (PCF) is currently used for the processing with only minimal modification.

Significant features of the processing are:

- GPS only observations L1/L2 observations are used
- the IGS 2008 absolute antenna phase calibrations are used
- the IGS final orbits and earth rotation parameters are used
- the final solution is based on double differenced L3 ionosphere free linear combination
- the global mapping function (GMF) troposphere model is used
- the troposphere path delay is estimated hourly, and the troposphere horizontal gradient parameter estimated daily at each station
- the FES2004 ocean tide loading model is used
- the final coordinate solution is minimally constrained to the regional IGb08 station coordinates using a no net translation. Rotation and scale of the combined baseline solution are preserved.

The Bernese processing selects a minimal set of baselines to process each day in such a way as to maximize the number of simultaneous observations between paired stations. This strategy favours short baselines as these will observe the same satellites for longer periods of time. A typical set of baselines is shown in Figure 3.

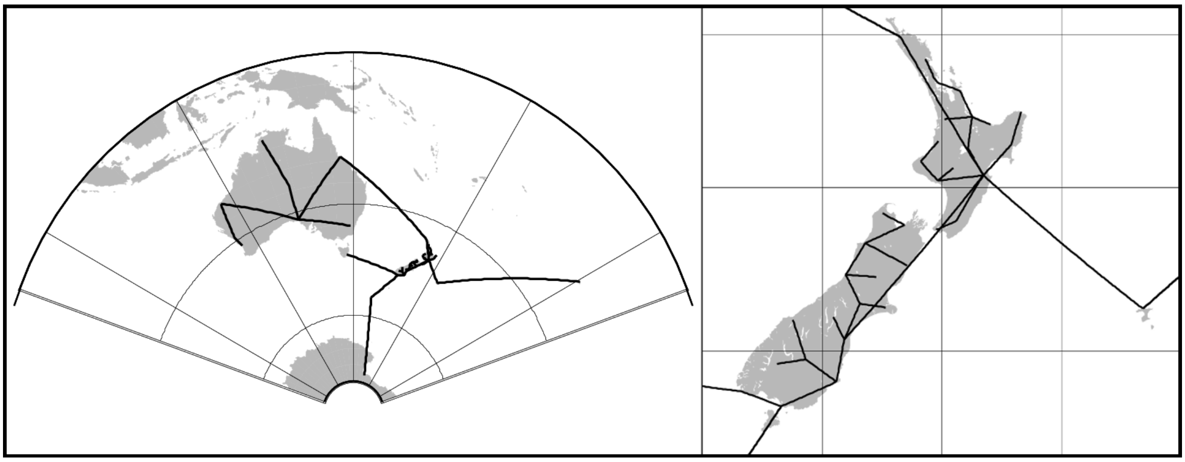

Figure 3: Typical set of baselines processed in the LINZ daily processing of the PositioNZ CORS stations

The following analysis is based on the results of this processing. The earliest data considered is from 1 January 2000 is considered despite some stations have a considerably longer history.

3. REFERENCE STATION TIME SERIES ANALYSIS

Ultimately the quality of the connection between NZGD2000 and ITRF depends on the accuracy of the PositioNZ station coordinates. This can be assessed by considering the time series of daily solutions for the 15 IGb08 reference stations.

The IGb08 solution is a realization of ITRF2008 based on data up to 20 August 2012. For each of the reference stations the IGb08 solution defines a coordinate and velocity plus a set of offsets to the coordinates (Rebishung, 2012). Generally the offsets represent tectonic events. For example the IGb08 solution for MAC1 includes and offset at 25 December 2004 representing the coseismic offset due to the Macquarie earthquake as well as offsets at 26 March 2005, 24 September 2005, and 23 September 2006 which approximate the post-seismic movement at the station.

Each daily solution generates a set of coordinates for these stations, which are then translated to align them with the IGb08 coordinates at the measurement epoch. These coordinates do not exactly fit the IGb08 solution due to the random errors in the daily processing as well ground movement at the reference stations which is not accounted for by the simple velocity and offsets in the IGb08 solution. The misfit between these time series and IGb08 solutions provide a measure of the quality of alignment with IGb08.

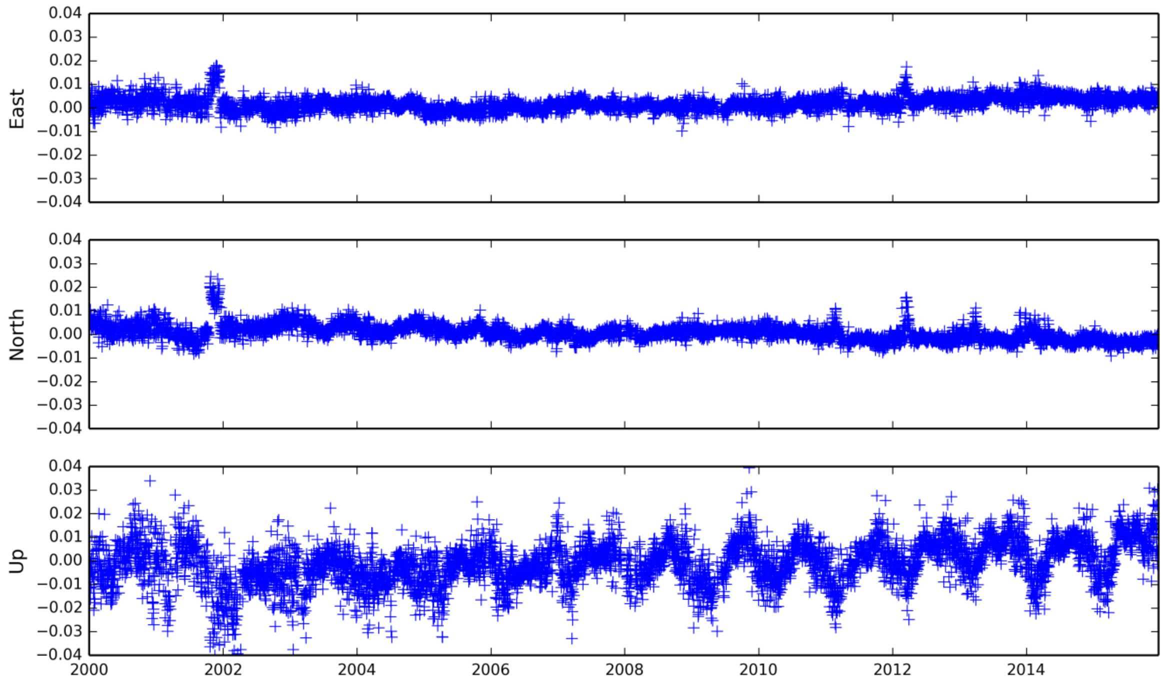

Figure 4: Residual errors of daily coordinate solution at DARW (Darwin) relative to the IGb08 solution

Consider for example the misfit at station DARW (Darwin, Figure 4). The vertical or "Up" component of the misfit at this station shows a clear annual signal of about 4cm amplitude. This is likely to be a combination of cyclic ground movement as well as incompletely modelled seasonal effects in the processing. The annual signal is not accounted for in the IGb08 solution so it shows as a residual.

Some care must be taken in interpreting these residuals, as they are not independent. If the misfit at DARW is due to ground movement, then it will also affect the residuals at other stations to some extent as a result of using a translation to align the daily coordinate solutions with the IGb08 coordinates. The translation will subtract the average of the misfits at each station from each residual time series (at least to a first order approximation – in fact the translation takes account of the variance/covariance of the calculated coordinates so not all stations will affect the calculated translation to the same extent).

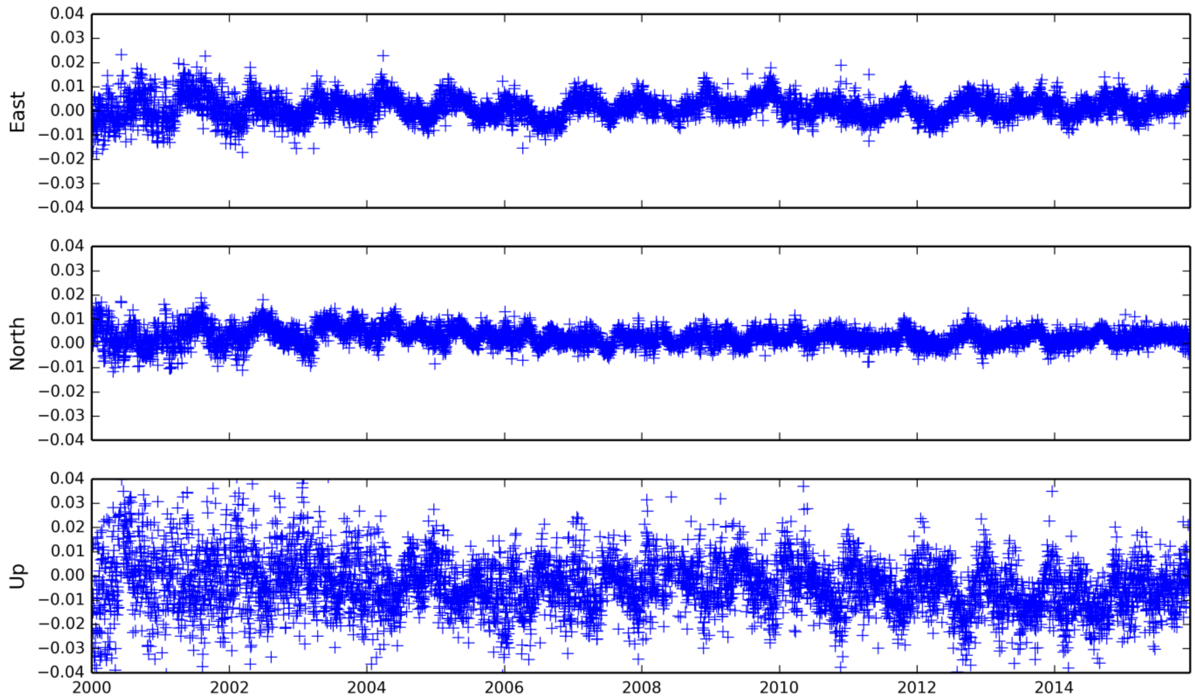

Figure 5: Residual errors of daily coordinate solution at THTI (Tahiti) relative to the IGb08 solution

Evidence of this can be seen in the THTI (Tahiti, Figure 6) residuals. This figure displays a definite annual signal in the East component of the misfit. While this could be due to ground movement, it is quite likely that it is in fact an artefact of the vertical annual signal at DARW (as well as that of other Australian stations), as the vertical direction at DARW is closely aligned with the east direction at THTI.

The residuals are summarized in Figure 8 which shows the mean residual and two measures of the variation of the residual for the east, north, and up components at each station. The first measure of variation is the standard deviation of the residuals about the mean offset for each component. The second measure is an estimate based on the 95 percentile of the coordinate difference between each day and the next. In the context of this paper this will be termed the "robust standard error". The robust standard error is the smaller measure of variance because it eliminates the variation due to longer term systematic effects such as cyclic ground movement and is much closer to a measure of the random measurement error in the residuals. The absolute value of the mean residual of each component is shown in Figure 8 to simplify comparison. In fact some stations will have positive mean residuals and some negative values.

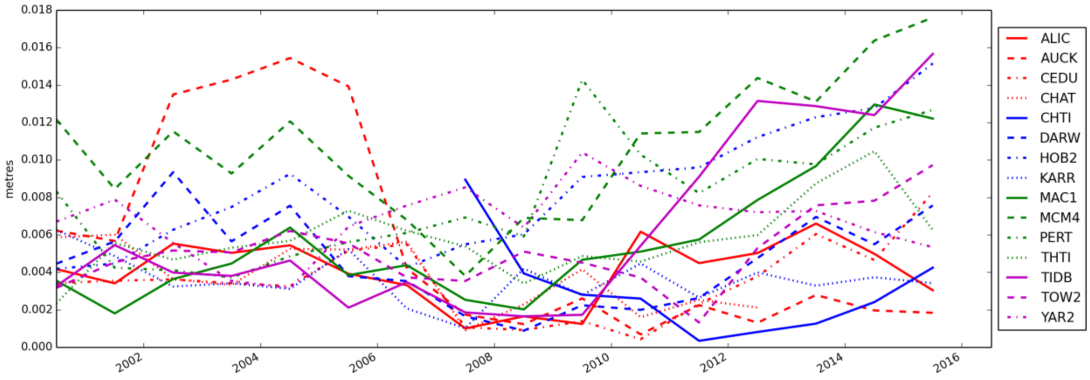

Figure 7: Length of annual mean residual vector for each reference station.

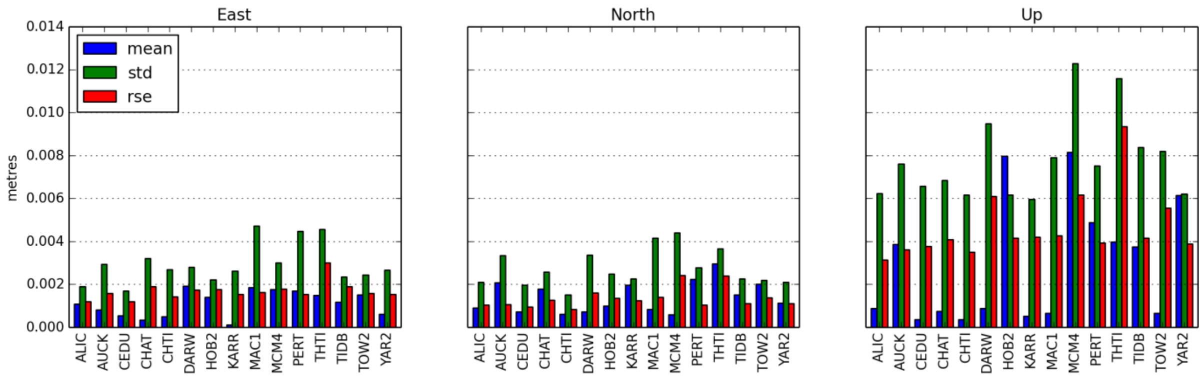

Figure 6: Summary of east, north, and up residuals at each station relative to the IGb08 solution. Each plot shows the absolute value of the mean residual (mean, red), the standard deviation of the residuals around the main (std, green), and a robust estimate of the observation error based on the day to day scatter (rse, red)

Perhaps the most direct measure of the quality of the alignment with IGb08 is the mean residual at each station. The east and north components at each station are almost all less than 2mm. The mean vertical residuals are greater, up to 8mm. This is due to both the greater measurement error in the vertical in GNSS observations, as shown by the larger values for the robust standard error, and due to the larger vertical systematic effects for example ground movements due to changes in hydrostatic ground water.

It is also instructive to assess the change in the quality of alignment over time. This is assessed by considering the magnitude of the average vector residual for each station over a year. Averaging over a year largely eliminates the effects of the annual cyclic signal that is evident in most station time series. The average offsets for the each year from 2000 to 2015 are shown in Figure 7. Note again that the offsets at different stations are not independent – a systematic offset at one station will also cause a smaller negative offset at the others.

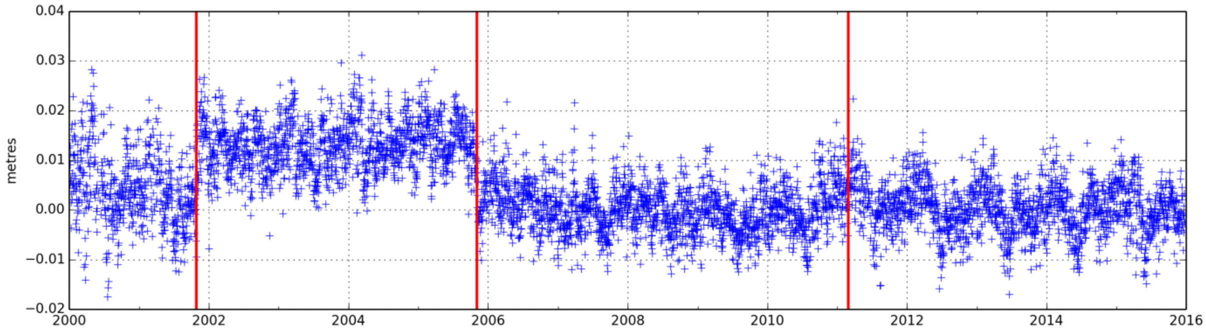

Figure 8: Vertical component of difference between the daily solution for AUCK (Whangaparoa, located near Auckland) and the IGb08 reference coordinates and velocity. The red lines indicated the dates of antenna changes.

Over the time period on which IGb08 is based, that is up to mid 2012, the most significant offset is at AUCK. There is an approximately 15mm offset which is clearly a result of antenna changes. The vertical residuals at AUCK are shown in Figure 5 where the dates of antenna changes are shown by red bars. There is an unambiguous vertical offset at each of the first two antenna changes at 28 October 2001 and 3 November 2005. Interestingly there is no signal from the third antenna change at 28 February 2011. However this change is marked by an offset in the IGb08 solution, which is why it is not manifested in the residuals. The IGb08 offset is about 3mm and predominantly horizontal.

The AUCK data is also processed as part of the Geoscience Australia Asia-Pacific Reference Frame (APREF) solution. Their analysis has identified offsets at all antenna changes.

Apart from the AUCK offset the remaining stations show relatively good agreement with IGb08 before mid 2012 (Figure 7). After that date the agreement steadily degrades so that by 2016 there are errors up to 16mm.

Based on this analysis we can expect that the alignment with ITRF is likely to be good to 2mm horizontally and 8mm vertically, and probably better since it is based on the average of the fit at all the reference stations. Any alignment should ideally be based on fitting over a whole number of years to minimize the impact of cyclic ground movement or other seasonal systematic errors that are not modelled in the IGb08 solution.

The forthcoming ITRF2014 solution (IGN, 2014) does include cyclic terms in its analysis, as well as including data up to 2014. Once this is readily available the data can be reprocessed into this framework to provide a better alignment to ITRF. Also the alignment may be improved by including a larger global network of stations, using more sophisticated tropospheric models such as the Vienna Mapping Function (VMF), and by handling offsets such as the antenna changes at AUCK.

4. POSITIONZ STATIONS ALIGNMENT WITH ITRF2008

Once the daily solutions have been aligned with the IGb08 reference stations then they provide IGb08 coordinates not just for the reference stations, as described in the previous section, but also for the other PositioNZ stations.

However for most users of the datum a daily time series of coordinates is not useful. Generally surveyors do not use global or regional networks to calculate coordinates. More usually they position themselves accurately with respect to the PositioNZ network using techniques such as differential GPS (DGPS). To generate good ITRF coordinates for their own stations they therefore need good ITRF coordinates for the PositioNZ stations. A casual inspection of daily solutions shows a typical error of the order of 0.005m horizontally and 0.01m vertically. If a surveyor were to use the daily coordinate solutions of the PositioNZ stations as control for a survey they could expect variations of over a centimetre from one day to the next from the control. On the other hand because the PositioNZ network is moving and distorting over time with respect to the global ITRF reference frame the ITRF coordinates are not constant. A simple average of the daily solutions is not useful.

To provide a useful framework for surveying in New Zealand LINZ must publish coordinates or coordinate time series for the PositioNZ stations that reflect the real movement of the stations, while reduce the random error in the daily solutions as far as practical.

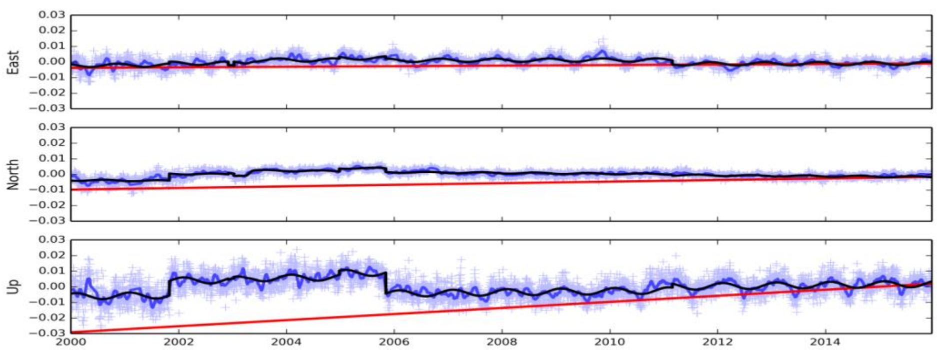

Figure 9: AUCK time series. The red line shows the LINZ geodetic database coordinate converted to ITRF2008 using the deformation model. The blue line shows the monthly solution (calculated each day).

Three different approaches have been used to generate smoothed coordinates ITRF2008 coordinate time series for the stations – combining into monthly solutions, time series modelling, and using NZGD2000 coordinates with the NZGD2000 model. These are described in more detail in the following sections.

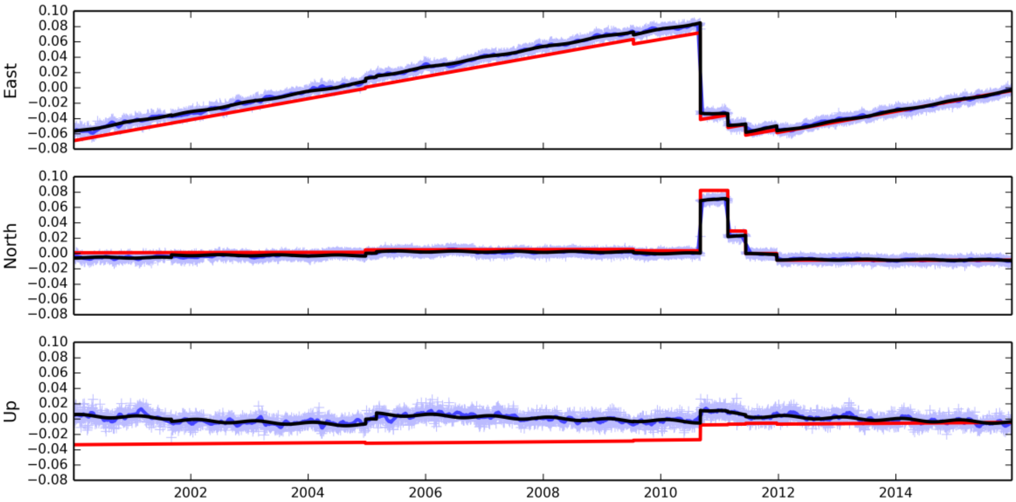

Figure 10: MQZG time series. The red line shows the LINZ geodetic database coordinate converted to ITRF2008 using the deformation model. The blue line shows the monthly solution (calculated each day). The black line is the PositioNZ-PP station coordinate model.

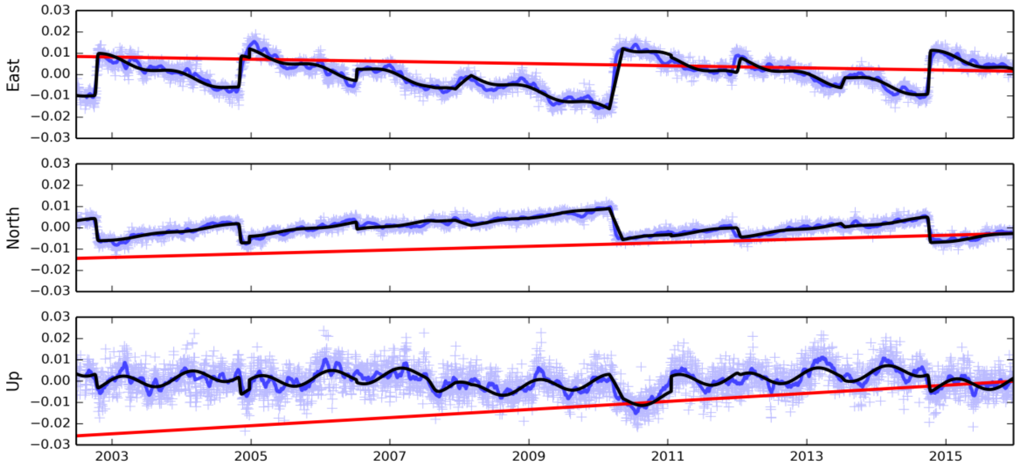

Figure 11: GISB (Gisborne) time series. The red line shows the LINZ geodetic database coordinate converted to ITRF2008 using the deformation model. The blue line shows the monthly solution (calculated each day). The black line is the PositioNZ-PP station coordinate model.

The time series resulting from applying these methods are shown for three stations: AUCK (Figure 9) for which the dominant component of movement is a constant velocity, MQZG (Figure 10) which has significant offsets due to the Canterbury earthquake sequence of 2010-2011, and GISB (Figure 11) which experiences slow slip events every 2 to 5 years (Beavan et al., 2007). Note that these plots are detrended to allow more detail to be seen.

4.1 Monthly solution combination

The daily solutions can be combined using the Bernese COMPAR program (Dach et al., 2015) to generate longer terms solutions. These fully take into account the covariance matrix of the solutions as well as managing constraints such as requiring the troposphere parameters at the end of one day solution to match those at the beginning of the next. This is used to compile monthly (actually 29 day) solutions which are shown by the blue lines on Figure 9 to Figure 11.

It is clear in the AUCK plot (Figure 9) that although much of the daily scatter is removed by combining there is still significant apparently random variation in the solutions of up to about 0.005m horizontally and 0.01m vertically.

One shortcoming of using monthly solutions is that they smooth out sudden events such as earthquake offsets across the 29 day window.

4.2 Time series modelling

Pearson et al. (2015) describe how the PositioNZ station coordinate time series have been modelled by a set of time dependent functions including constant velocity terms, annual and semi-annual cyclic functions, step functions and exponential functions representing either tectonic events or earthquakes, and a gamma function model or ramp model to represent slow slip events (SSE). These components are used to generate a "station coordinate model" for the ITRF2008 coordinate time series at each station.

These models were developed to support the LINZ PositioNZ-PP online post processing service (www.linz.govt.nz/positionzpp). The service processes a user's GPS data (supplied in a RINEX file) with data from nearby stations of the PositioNZ network to calculate a coordinate for the user's station. These models provide the ITRF2008 coordinates for the reference stations.

The models are generated manually for each station time series using the LINZ spm_editor software (https://github.com/linz/python-linz-stationcoordmodel). The process to generate the model typically involves excluding outlier observations and then adding functions to represent offsets or other events observed in the time series. Once the functions are added the parameters of the function (e.g. magnitude of offset, duration of slow slip event) can be recalculated using a non-linear least squares fit to the parameters.

While these models fit the time series well, there are a number of weaknesses in this approach:

- the selection of which functions to include in the model is subjective. For example looking at the time series from GISB (Figure 11) it is very unclear which of the apparent offsets along the time series should be modelled. Although different subjective choices could be made the sum of the components may still fit the time series equally well
- there is a delay in including new events into the model. It may not be immediately apparent when a slow slip event has started and it may be some time after that before there are sufficient data to model its onset well.
- the models are limited to a few functional representations of the time series (such as step functions, ramp functions, exponential functions). These may not represent the actual deformation adequately. In practice this has not been a problem, and in any case other functions can be emulated by combining these components.

The models are maintained manually to ensure that new events are included. This is not an onerous task for the less than 40 stations of the PositioNZ network but it does introduce a delay between events happening and the time series models being updated to include them.

The smoothed coordinates calculated using this approach are shown as black lines on Figure 9 to Figure 11. Not surprisingly these fit the time series from which they are generated well.

4.3 NZGD2000 coordinate with the deformation model.

Each PositioNZ station has a periodically updated official NZGD2000 coordinate defined in the LINZ geodetic database (http://www.linz.govt.nz/gdb). This can be converted to an official ITRF2008 coordinate at any specific time by applying the NZGD2000 deformation model and the 14 parameter Bursa-Wolf transformation from ITRF96 to ITRF2008. The ITRF2008 coordinates calculated in this way are shown as a function of time by the red lines on Figure 9 to Figure 11.

Clearly these do not fit the observed coordinate time series as well as the site specific models. The NZGD2000 deformation model is a much simpler model comprising mainly a horizontal velocity model and with offsets representing earthquake events (as seen in the MQZG time series, Figure 10). Because the deformation model is a representation of deformation across the whole country, rather than at a specific station, the quality of the fit at individual stations is compromised.

One limitation of the current deformation model is that it does not include a vertical velocity component. However some stations do exhibit consistent vertical velocities. This is evident looking at the Up component of the three time series in Figure 9 to Figure 11 where there is a clear trend in the observed coordinates relative to the official coordinates. Based on the time series modelling the velocities are up to 8mm/year at HAST (Hastings), but more typically about 2mm/year.

A second limitation is that the deformation model does not include slow slip events. For example at Gisborne (Figure 11) the east component of the deformation model is an average velocity through the sequence of slow slip events. This leads to errors of up to a few centimetres.

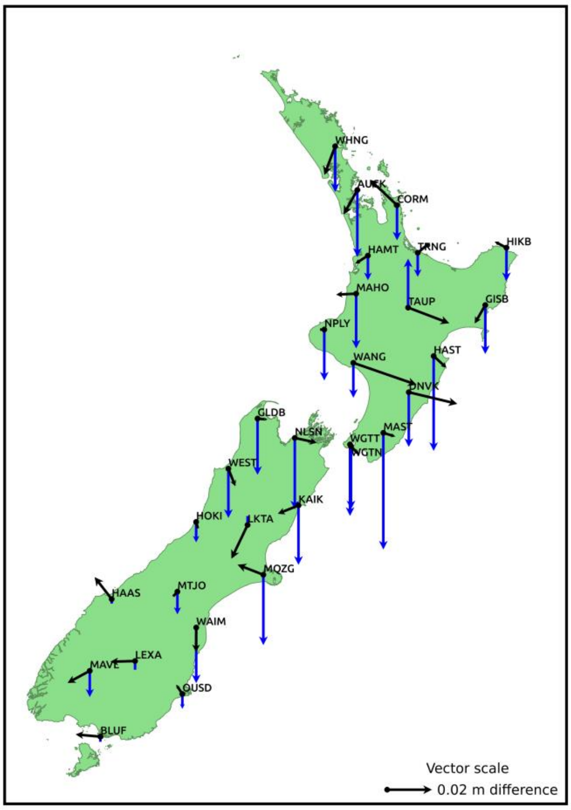

Figure 12: Difference between official NZGD2000 coordinates converted to ITRF2008 and time series models evaluated at 1 Jan 2005. Black vectors are the horizontal difference and blue vectors the vertical difference.

The PositioNZ station coordinates are periodically updated. The process currently used to calculate new coordinates for PositioNZ stations is based on the modelled time series described in the previous section. The cyclic components in the time series model are ignored and the current ITRF2008 coordinates are calculated based on the remaining terms. The most recent modelled position of each mark is used as the official coordinate, as most users of the datum are interested in the current location of features rather than historic locations. These coordinates are transformed to an NZGD2000 coordinate using the deformation model. This provides coordinates that are consistent with ITRF2008 and the deformation model at the time they are calculated.

Typically updates are applied every year or so when the coordinates appear to be in error by more than a few centimetres. Generally the errors are due to accumulated vertical movement, but they may also derive from slow slip events. The official coordinate time series shown by the red lines in Figure 9 to Figure 11 are based on the NZGD2000 coordinates at the time of writing in 2016, which is why they fit the later observations in the time series better than the earlier observations.

5. IMPLICATIONS OF DEFORMATION FOR COORDINATE ACCURACY

At present the only coordinates LINZ publishes for PositioNZ stations are the NZGD2000 coordinates. In addition to the errors in calculating these coordinates there are also errors inherent in the deformation model. As described in section 4.3 the PositioNZ coordinates are maintained to be consistent with ITRF at the time they are calculated.

At 1 January 2016 the maximum error in these coordinates is less than 2mm horizontally and 3mm vertically relative to the modelled time series, which is arguably the best estimate of the actual ITRF2008 coordinate at any given time.

If the official coordinates at 2016 are transformed back to 1 January 2015 using the deformation model and compared with the modelled coordinates time series the difference is much greater. These differences, up to 30mm horizontally and 60mm vertically, are shown in Figure 12. The vertical differences are mainly due to subsidence that is not modelled in the secular component of the deformation model. The horizontal differences are mainly due to the slow slip events, which are averaged by the deformation model, as seen in the East component in Figure 11.

The coordinate differences at older epochs will impact on network adjustments using the deformation model to combine data from different epochs in a single adjustment. For these adjustments the error in the deformation model may be misinterpreted as observational error and may be reflected in coordinate errors. For example the calculated elevation of a station in an area of subsidence which is only fixed by old observations may be a few centimetres too high.

5.1 Implications for the PositioNZ-PP service

The difference between the deformation model and the actual station time series also impacts on the LINZ PositioNZ-PP online GPS post processing service. This service allows users to submit RINEX files of GPS data. Each RINEX file is combined in a GPS adjustment with data from three nearby PositioNZ stations. The resulting mark coordinates are provided back to the user in both ITRF2008 and NZGD2000 coordinate systems.

The service calculates the coordinates in the ITRF2008 system, and uses the station coordinate models to provide the control coordinates for the adjustment. The resulting ITRF2008 coordinate is then converted to NZGD2000 using the deformation model.

This implies that there may be discrepancies between the NZGD2000 coordinates generated by the service and the coordinates of the nearby NZGD2000 PositioNZ reference stations. This is because the modelled ITRF2008 coordinates of the reference stations are slightly different from values calculated from their official NZGD2000 coordinates. One subject for investigation is whether the reference station NZGD2000 coordinate discrepancies could be interpolated to the user's station.

This could allow the service to provide an NZGD2000 coordinate that is more consistent with the other local coordinates even though it would not be consistent with the transformed ITRF2008 coordinate provided to the user.

5.2 Implications for other geodetic marks

As noted above NZGD2000 coordinates of the PositioNZ stations are periodically updated to ensure that their location in ITRF2008 is correct. However this means that their NZGD2000 coordinate may be out of terms with other stations around them. Typically other stations are located by measurements relative to the PositioNZ stations, either directly or indirectly. However these coordinates are not necessarily updated when the PositioNZ coordinates are. For example if a station is positioned relative to a PositioNZ station in 2005 and the PositioNZ station coordinate is updated in 2015, then that update will not be applied to the coordinates of the station.

Generally the changes to coordinates are small, less than 2cm horizontally or vertically, and for most geodetic marks an error of this size is well within their specified coordinate accuracy.

LINZ is currently compiling a “national geodetic adjustment” that will allow the coordinates of all geodetic marks to be recomputed easily. This will make it very easy to assess the coordinates of all geodetic marks after updating the PositioNZ coordinates. The resulting readjusted coordinates can be compared with the official NZGD2000 coordinates to determine which have changed sufficiently to require updating.

6. SUMMARY

The time series of coordinates calculated for the PositioNZ CORS stations provide a strong connection with ITRF2008. From examination of the time series we believe the alignment with ITRF is likely to be good to 2mm horizontally and 8mm vertically.

However, most users in New Zealand want coordinates that represent physical locations, and this requires a coordinate system that takes account of tectonic deformation. The NZGD2000 coordinate system provides this, but it is not directly measurable – instead it is derived by measuring in terms of ITRF and then transforming to NZGD2000. The transformation is dependent on the deformation model, which itself introduces errors to the coordinates. The PositioNZ station coordinate time series provide a direct measure of the errors that are introduced. Typically these are up to 30mm horizontally and 60mm vertically.

In practice most users derive locations by calculating relative to other NZGD2000 coordinates without taking account of the deformation model, and this also introduces errors. For many usages this is adequate, but it may introduce errors of up to 12mm per km in 2015 and this amount of will increase each year.

The main limitations on the accuracy of the deformation model come from the secular vertical movement and from slow slip events, neither of which is modelled.

In the future LINZ is working to improve the quality of the tie to ITRF by including more global reference stations, using more sophisticated atmospheric models, and using other GNSS constellations in the processing. The deformation model can be improved by including vertical deformation in its definition. Additionally with more CORS stations and using other techniques such as INSAR it may be possible to include slow slip events into the model.

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BIOGRAPHICAL NOTES

Chris Crook is a geodetic scientist working in Land Information New Zealand. His work includes maintaining the NZGD2000 deformation model and the LINZ geodetic database. He developed and maintains the survey network adjustment software that is used in LINZ to calculate station coordinates and test geodetic and cadastral observations. He is an honorary member of the New Zealand Institute of Surveyors.

Dionne Hansen is the newest member of the Geodetic Team at Land Information New Zealand joining in February 2016. Previously, she was the British Isles continuous GNSS Facility (BIGF) Product Developer from 2008 - 2016 producing long term position solutions for the UK's network of GNSS stations in a global reference frame using Bernese 5.2 software. She has contributed to international efforts such as the EPN Regional Dense velocity field and the IGS TIGA project. Additionally, she was a member of the COST GNSS4SWEC working group focused on producing high quality water vapour estimates from GNSS data.

Paula Gentle, BSurv (Otago). Paula has worked as a Geodetic Surveyor for LINZ for the last 7 years. Her key areas of focus are the management and development of the PositioNZ network in partnership with GNS Science. Other areas of focus include support for the LINZ Antarctic programme and the New Zealand local tie surveys.

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