International Global Navigation Satellite Systems Society
IGNSS Symposium 2011

University of New South Wales, Sydney, NSW, Australia
15 – 17 November 2011

ITRF Transformations in Deforming Zones to Support CORS-NRTK Applications

Richard Stanaway
School of Surveying and Spatial Information Systems,
University of New South Wales, Sydney, Australia
ph. +61 3 9486 7845 fax +61 2 9313 7493
email: richard.stanaway@student.unsw.edu.au

Craig Roberts
School of Surveying and Spatial Information Systems,
University of New South Wales, Sydney, Australia
ph. +61 2 9385 4464 fax +61 2 9313 7493
email: c.roberts@unsw.edu.au

ABSTRACT

NRTK requires precise coordinates of the parent CORS network in order to operate effectively. Typically, an ITRF aligned reference frame is used as the datum for a CORS network as this enables IGS orbit products to be used without further transformation. But fixing the coordinates of the CORS network at an arbitrary reference epoch of ITRF is not feasible if the CORS network is deforming as a result of plate tectonics, ground subsidence or uplift. The effect of internal deformation can be overcome by using a fully kinematic ITRF realisation of the network. For most users however, kinematic coordinates present significant practical issues particularly with regard to integration of spatial data collected at different epochs and coordinate repeatability within a localised reference frame.

This paper describes a methodology that can be utilised within deforming zones to enable kinematic ITRF coordinates of a deforming CORS network to be transformed to a fixed reference epoch without significant loss of precision. The methodology can also be applied to rigid networks on rapidly rotating tectonic plates or microplates. Adoption of this strategy allows kinematic ITRF to be used for CORS integrity monitoring whilst users of the system (e.g. surveyors and precision navigation applications such as controlled traffic steering in agriculture and automated mining) are not encumbered with the complexity of a kinematic reference frame.

KEYWORDS: CORS, NRTK, ITRF, Kinematic Datum

1. INTRODUCTION

Network Real-Time Kinematic (NRTK) GNSS is rapidly developing as one of the primary positioning tools using GNSS technology. NRTK comprises a network of continuously operating GNSS reference stations (CORS). Tropospheric and ionospheric biases as well as orbit errors are modelled over the network and transmitted to rover GNSS sensors. A key assumption with NRTK is that the coordinates of each contributing station within the CORS network are fixed with a relative precision of better than 15 mm (Ramm and Hale, 2004). This ensures that biases are correctly modelled and that errors in the CORS locations do not propagate into an NRTK solution for the rover location.

Provided that the network is maintaining conformality (i.e. not deforming internally) and that the fixed coordinates of the CORS are within a few metres of their instantaneous ITRF positions, no deformation modelling is required for centimetre accurate positioning. Errors arising from rigid tectonic plate rotation of a fixed epoch network cell are small in magnitude (typically < 0.5 mm/yr for a 50 km baseline) (Dawson and Woods, 2010) and can be interpolated at the rover location. Internal monitoring of the network stability is performed by integrity monitoring software (e.g. *Trimble Integrity Manager* and *Leica CrossCheck*) which detects any movement of a station or antenna outside defined tolerances.

Where CORS networks do deform in a non-conformal manner, for example in tectonically active regions, fixing the coordinates of the NRTK reference stations can rapidly degrade the quality of NRTK solutions. In these situations fixed coordinates for the CORS stations cannot be used for centimetre precise positioning. This paper describes how the use of kinematic ITRF coordinates of CORS stations in conjunction with deformation models can be used for NRTK positioning in an actively deforming environment. To demonstrate the approach, a CORS network cell between Gisborne and Wairoa in the North Island of New Zealand is used as a case study. This region is located within the Pacific and Australian Plate boundary zone and deformation is complex with frequent slow-slip events (Wallace and Beavan, 2010). Slow-slip events are essentially slow motion earthquakes that take place over a period of days or months.

2. USING KINEMATIC ITRF FOR NRTK

Apart from holding a single reference station’s coordinates fixed, the most obvious strategy for NRTK positioning in a deforming zone is to adopt high precision kinematic (instantaneous or dynamic) ITRF coordinates for each of the reference stations. Provided that deformation is not rapid, ITRF coordinates can be computed for each station (with a latency of 3 days) using a 24 hour PPP or double-differenced solution computed from the parent regional geodetic network using IGS rapid (precise) orbits. Alternatively, the most recent IGS weekly solution can be used. Secular (interseismic) tectonic deformation rarely exceeds 4 mm over a two week period, so any of these approaches will compute coordinates within the tolerances required for NRTK. Where the secular deformation of a CORS is stable (linear) its ITRF site velocity can be used to predict kinematic ITRF coordinates for any given epoch. Rover GNSS sensors using NRTK would then simply deliver kinematic (dynamic) ITRF coordinates for the given location.

There are two limitations with this approach. First, non-secular deformation (e.g. arising from an earthquake, slow-slip event or subsidence) affecting the network may exceed the required precision. Such deformation can usually be detected and quantified with integrity monitoring software or kinematic PPP, and any affected stations can be unconstrained or excluded from network processing while non-secular deformation is occurring.

The second limitation is that use of a kinematic (dynamic) reference frame such as ITRF without further transformation will mean that the coordinates computed for roving GNSS sensors will also be kinematic. Kinematic coordinates often cannot be used in practice as integration or combination of surveys undertaken at different measurement epochs is difficult to achieve (e.g. between setting out construction works and a later as-built survey, merging large 3D laser scans acquired at different epochs, or controlled traffic steering in precision agriculture applications). Also, discrepancies between kinematic and fixed epoch coordinates of passive geodetic control will become noticeable with NRTK.

The challenge is how best to develop NRTK algorithms and deformation models that can deliver "static" coordinates to users in challenging deforming zones often found near tectonic plate boundaries.

3. CHARACTERISATION OF DEFORMATION OF A CORS NETWORK

From an operational NRTK perspective, any deformation of a CORS station contributing to NRTK should be monitored and modelled. Three main deformation components can be identified: (1) interseismic (secular) deformation, which is typically linear and predictable in character, (2) seismic deformation which is episodic and non-predictable, and (3) site specific deformation (e.g. subsidence, surface creep).

Broadly speaking, NRTK acquired positions are required in an internally consistent spatial reference frame defined by the coordinates of CORS stations and passive geodetic monumentation. In reality, all CORS networks deform in some way. Within rigid tectonic plate settings for example, a CORS network will move uniformly with the underlying tectonic plate whose motion can be described by Euler poles of rotation within ITRF (Figure 1).

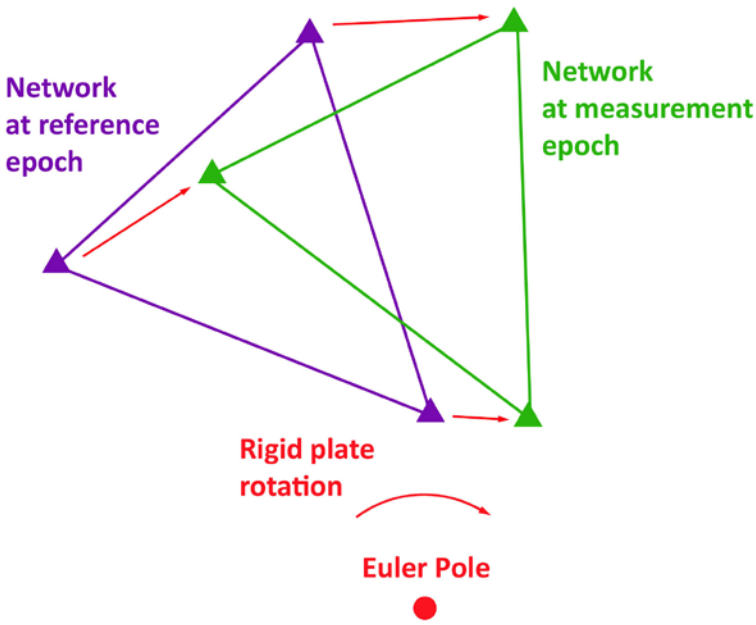

Figure 1. Schematic rigid plate rotation of network about Euler pole

Site velocities for constituent CORS stations on a rigid rotating plate can be estimated precisely using equation (1) (Stanaway and Roberts, 2009) where ($\dot{X}, \dot{Y}, \dot{Z}$ in metres) is the ITRF site velocity in Cartesian format, (X, Y, Z in metres) is a location on a rigid plate defined by a rigid plate rotation model (Ω_X, Ω_Y, Ω_Z in radians per million year):

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} = \begin{bmatrix} \Omega_Y Z - \Omega_Z Y \\ \Omega_Z X - \Omega_X Z \\ \Omega_X Y - \Omega_Y X \end{bmatrix} \bullet 1\text{E-6} \qquad (1)$$

Within plate boundary zones, site motion is characterised by a combination of linear interseismic deformation and episodic displacements resulting from earthquakes. The nature of deformation in the vicinity of plate boundaries differs from those of rigid plate settings in that locked faults induce shear strain deformation at the surface resulting in non-conformal distortion of geodetic networks. Shearing deformation continues until such time as the accumulated strain is released in the form of an earthquake or slow slip event.

Site velocities in plate boundary zones are usually estimated by interpretation of fault locking models such as DEFNODE (McCaffrey, 2011). For operational use, a regular grid of site velocities is generated from these geophysical models and interpolated for any given location e.g. the New Zealand Deformation Model (NZDM) (Beavan and Haines, 2001; Blick *et al.*, 2005). Provided that the model is well constrained by inversion of observed site velocities and other geophysical observations such as earthquake slip-vectors, predicted velocities are usually precise enough for operational NRTK use within the interseismic period. The interseismic velocity model can be regularly updated as time-series of CORS and repeat observations over a network of passive geodetic monuments refine site velocities as a function of time.

Large shallow earthquakes can often result in significant surface rupturing and highly localised and variable deformation. Such deformation can be quantified using a variety of techniques including; slip dislocation modelling, InSAR, analysis of high resolution imagery or LiDar, campaign GNSS/GPS re-observations over a dense geodetic network and terrestrial measurements.

It is reasonable to assume that any seismic deformation should result in a change of coordinates of geodetic infrastructure to reflect reality, especially where fault ruptures displace property boundaries. For example, consider the case where two geodetic monuments reference two adjoining cadastral parcel corners. An earthquake results in a lateral displacement of the boundary between the two corners (Figure 2). A change in coordinates in both the corners and monuments can be expected. To distinguish seismically affected coordinates from those of the original reference epoch a new localised realisation of the datum is usually necessary.

CORS stations undergoing site-related deformation such as localised subsidence or surface creep would need to be unconstrained, as holding coordinates and elevations fixed would propagate positioning errors into NRTK.

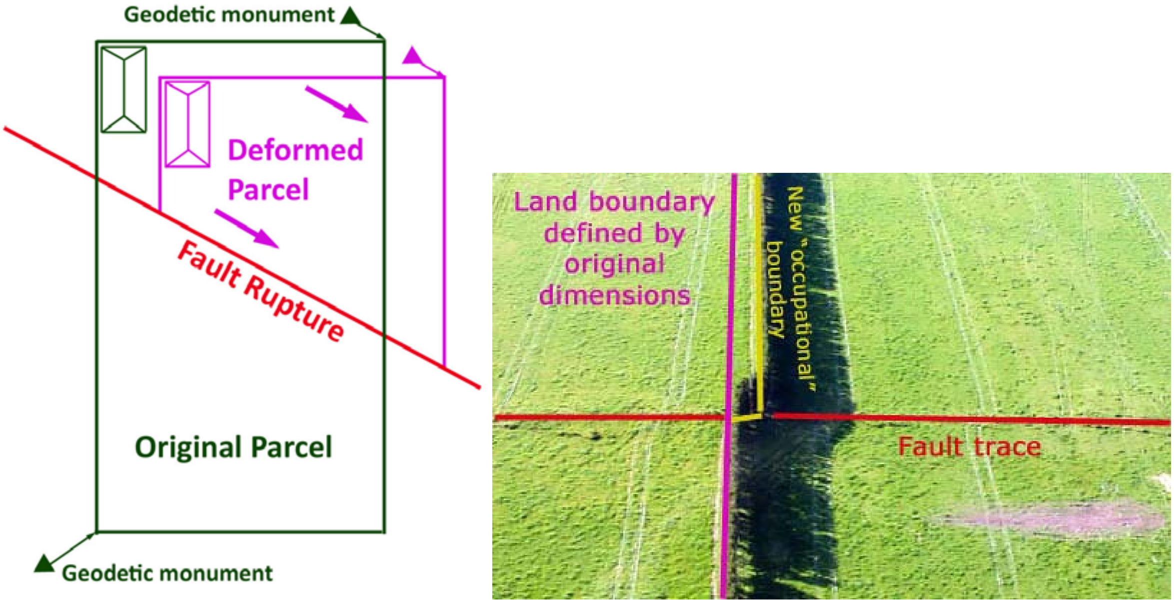

Figure 2. Effect of coseismic deformation on the cadastre and geodetic network.

4. APPLICATION OF DEFORMATION MODELS TO A CORS NETWORK

Deformation models applied for practical purposes such as NRTK should be decomposed into secular (an interseismic velocity model) and episodic (a coseismic and postseismic "patch" model) components. The interseismic velocity model is used to relate instantaneous ITRF coordinates to a specified epoch enabling the coordinates to appear "static" even though they are subject to larger scale deformation. This practice has been adopted in New Zealand with the adoption of a semi-dynamic (semi-kinematic) datum, NZGD2000, which incorporates an interseismic deformation model, NZDM (Blick *et al.*, 2005).

The seismic patch model is a sum of all seismic offsets between the reference and measurement epochs. The patch model is effectively a grid distortion model quantifying what permanent deformation of the original geodetic network has occurred in excess of any interseismic deformation since the reference epoch. In practice the seismic patch can also incorporate other distortions such as small reference frame translations and errors arising from imprecisely estimated interseismic deformation models. Some latency in the release of the patch may be beneficial in the case of large earthquakes and subsequent aftershocks or slow-slip events, to account for any postseismic relaxation which is non-linear in character. The two models are used in conjunction with each other (Figures 3 and 4).

The seismic patch can also incorporate coseismic and postseismic deformation arising from great (> Mw 8.0) regional earthquakes which can result in observable deformation thousands of kilometres from the earthquake epicentre.

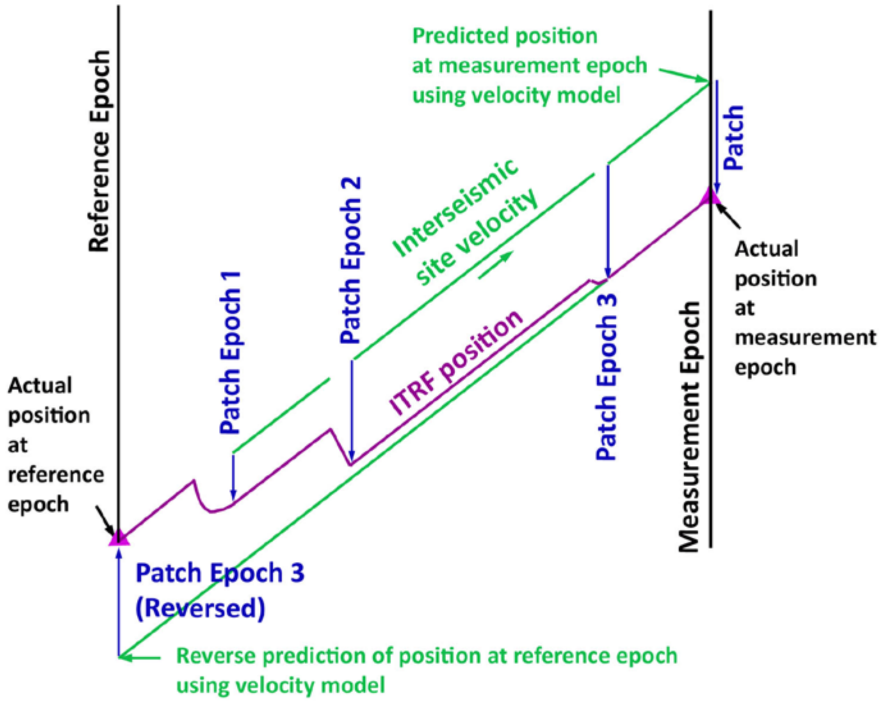

Figure 3. Schematic representation of the application of interseismic velocity models and seismic patches for deforming geodetic networks.

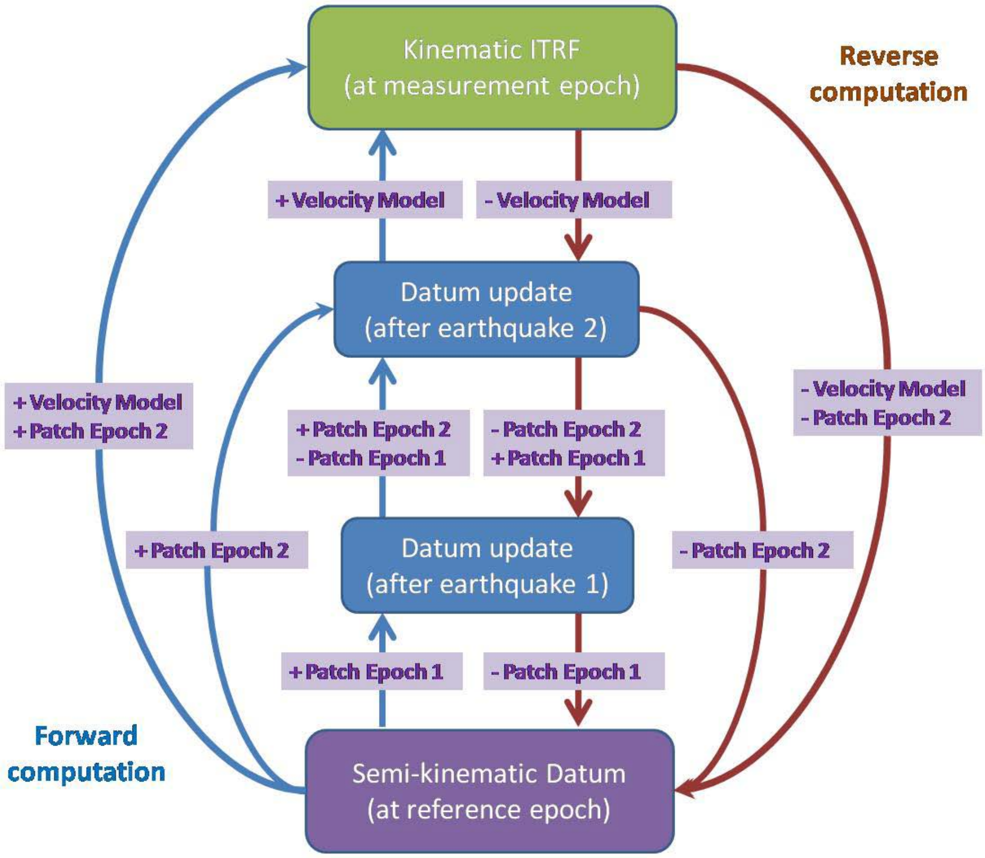

Figure 4. Flowchart showing transformation pathways between a semi-kinematic datum (fixed at the reference epoch) and kinematic ITRF.

For NRTK operations in deforming zones, kinematic ITRF (typically the latest weekly realisation of the IGS reference frame) should be used as the datum for GNSS data processing. Interpolation of the interseismic deformation model enables the reference epoch to be recovered anywhere in the network. A seismic deformation patch at the CORS station accounts for any misalignment of coordinates between the interseismic model and the coordinates of the CORS at the reference epoch. Any further misalignment at the CORS can be attributed to two factors: (1) an imprecise interseismic velocity model, and (2) unmodelled deformation within the patch. These two factors can be isolated and quantified by analysis of the CORS time-series. Analysis of the time-series can identify periods of non-linear deformation (e.g. coseismic, interseismic and slow slip events). These deformations can be summed into a seismic deformation patch which should be updated after each significant seismic event. A significant event is one that results in non-secular deformation in excess of the positioning tolerances required for the datum or NRTK operation.

Vertical deformation of the network should be unconstrained as variations in elevation impact significantly on engineering and hydrology studies. There is also a much higher degree of spatial and temporal variability than is associated with horizontal deformation. The best approach is to use kinematic ITRF ellipsoidal heights for CORS stations in order to maintain network integrity.

Different model structures can be utilised, however a regular grid structure interpolated using the bilinear method is widely used for many practical geodetic applications (e.g. geoid and grid distortion modelling) and the same model structure and software can also be applied for deformation models.

The seismic patch model would have the same data structure and interpolation strategy as the interseismic velocity model, however in areas of highly variable deformation and surface rupturing a higher density model can be applied. In order to optimise model precision whilst minimising the model size, the patch can have a nested structure with very high resolution close to a surface rupture (Figure 5). For example the standard patch model may have a grid size of 0.1 degree. Any 0.1 degree cell with a higher variability of deformation could be represented by a 0.01 degree grid to fit within the 0.1 degree cell. A 0.001 degree grid could be nested in a 0.0001 degree cell and so on.

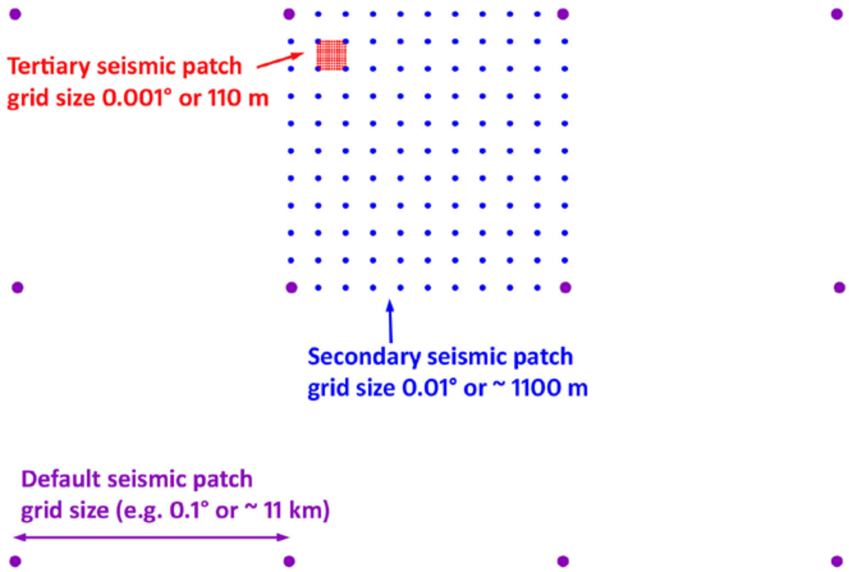

Figure 5. Nested structure of seismic patch grid model to accommodate localised deformation

5. DEFORMATION MODELS IN PRACTICE

NRTK operations are geared towards providing 1-2 cm accurate locations for a roving GNSS sensor within the network. As discussed previously, any NRTK processing should be done within a kinematic reference frame such as ITRF or the IGS reference frame in order to mitigate the effects of unmodelled deformation and rigid plate rotation. Deformation modelling is applied after kinematic ITRF coordinates are estimated for the rover position. The modelling can either be done by the rover controller, or by the NRTK server and the deformation transformation from ITRF to local datum transmitted via RTCM. Where model updates are frequent (e.g. in very seismically active areas) it makes sense for modelling corrections to be computed at the NRTK server. The deformation models within the rover controller may not necessarily be up-to-date and the controller may also not have the software required to perform deformation modelling.

Depending upon the requirements of the user of the rover GNSS, the following transformation equations (2 and 3) can be used to invoke the deformation models (based on flowchart in Figure 4):

Semi-kinematic datum at reference epoch

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{t_0} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{t} + \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} \bullet (t_0 - t) - \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix}_{PATCH} \qquad (2)$$

where,

t_0	is the reference epoch (in decimal years)
t	is the epoch of measurement (in decimal years)
$(X, Y, Z)_{t_0}$	are the coordinates computed at the reference epoch (metres),
$(X, Y, Z)_t$	are the kinematic ITRF coordinates at the measurement epoch (in metres),
$(\dot{X}, \dot{Y}, \dot{Z})$	is the ITRF site velocity interpolated from the interseismic velocity model (m/yr),
$(\Delta X, \Delta Y, \Delta Z)_{PATCH}$	is the accumulated seismic deformation between the reference and measurement epochs interpolated from the most up-to-date seismic patch model (in metres)

Semi-kinematic datum at epoch update (after earthquake)

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{t_{PATCH}} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{t} + \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} \bullet (t_0 - t) \qquad (3)$$

where,

$(X, Y, Z)_{t_{PATCH}}$ are the coordinates computed after the earthquake patch is applied (metres)

Model integrity monitoring

Deformation model integrity can be monitored at each CORS station within the NRTK network. This can be achieved by comparing the reference epoch coordinates computed using equation (2) with the reference epoch coordinates for the station. Whenever the difference between the two exceeds a specified tolerance (e.g. 15 mm) an alert is raised. This would usually happen after an earthquake, or commencement of a slow-slip event. In the absence of any of these episodic events, the inter-seismic velocity model would need to be verified and updated by analysis of the CORS time-series. Repeat observations over a dense network of passive geodetic monuments can also be used to verify and improve the precision of the deformation models in current use.

6. NEW ZEALAND CASE STUDY

The region near Gisborne on the North Island of New Zealand is an ideal location to demonstrate the application of the strategy described in this paper. The region lies within the foreland of the Hikurangi subduction margin on the boundary between the Pacific and Australian Plates (Figure 6). GNS Science of New Zealand has densified the GNSS CORS network (GeoNET) in this region to actively monitor deformation (Figure 7). Deformation is characterised by frequent slow-slip events (SSEs) induced by subduction of the Pacific Plate beneath the Australian plate along the Hikurangi Trough located off the East coast of the North Island.

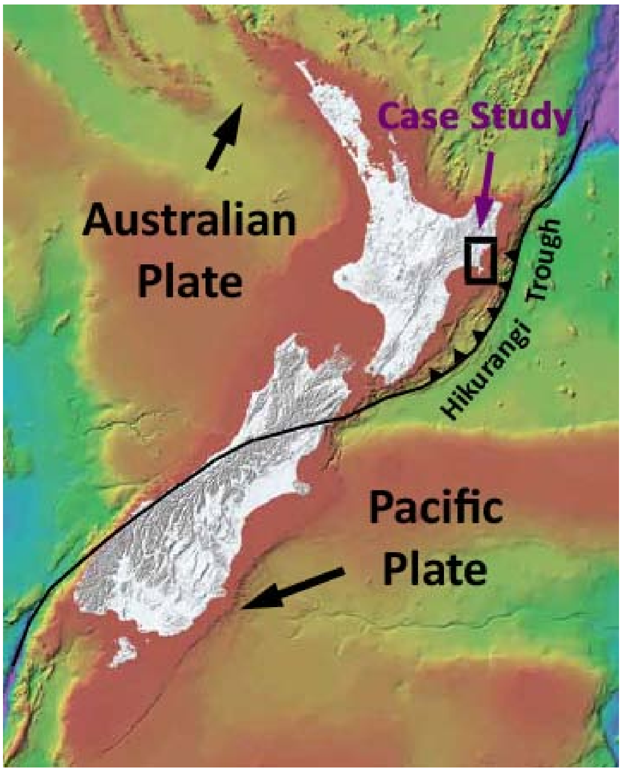

Figure 6. Case study location (background image: www.niwa.co.nz)

Figure 7. GeoNET – CORS stations in case study area

Time-series of GeoNET CORS stations GISB (Gisborne), PARI (Paritu Road) and PRTU (Paparatu) (Figure 8) clearly show episodic deformation arising from earthquakes, slow-slip events as well as the trending interseismic velocity.

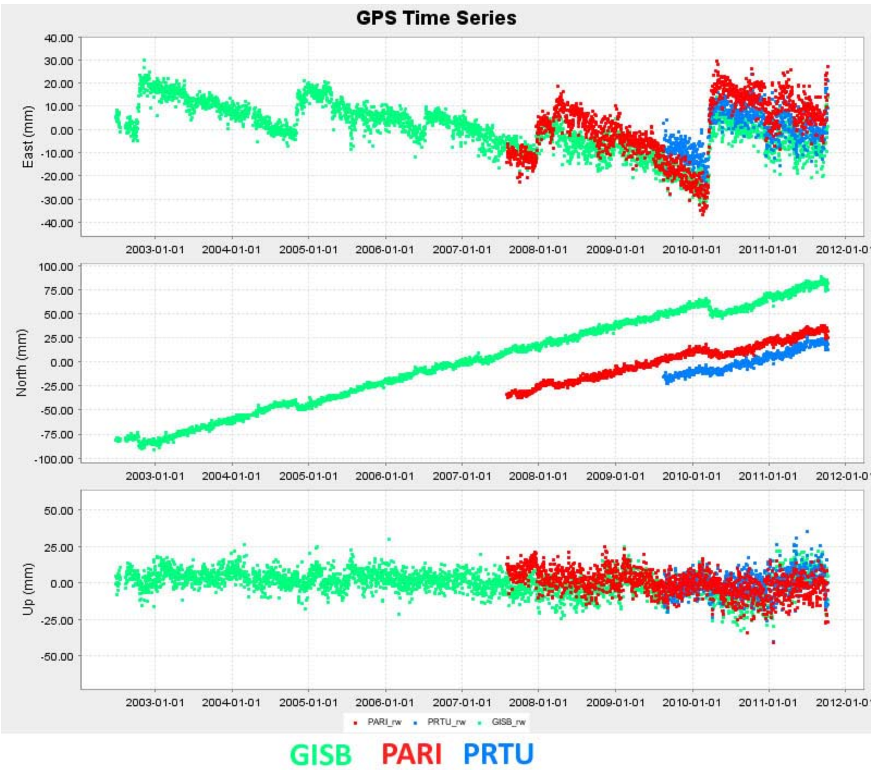

Figure 8. GPS time-series for CORS showing slow-slip events and trending interseismic velocities (GNS GeoNET web-site http://www.geonet.org.nz/resources/gps/)

Time-series for these CORS were analysed by separating the deformation associated with slow-slip events and earthquakes from the interseismic trending velocity. A comparison of the ITRF time-series for GISB showing the effect of removing the seismic signal from the time-series is shown in Figure 9.

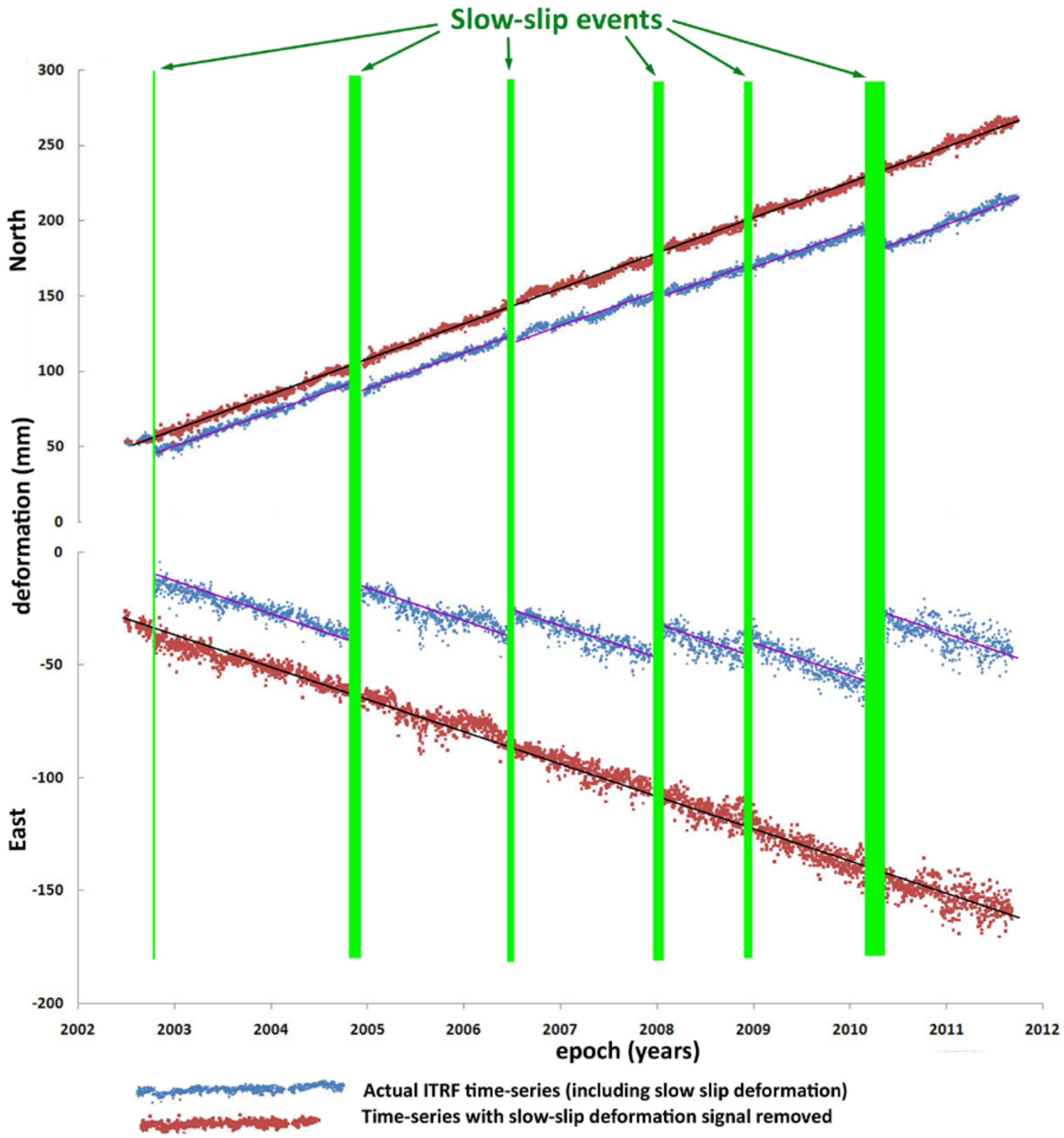

Figure 9. GPS time-series for GISB showing slow-slip events and trending interseismic velocities

Two new deformation models with a grid spacing of 0.1 degree covering the case study area were developed showing both estimated interseismic ITRF velocities and aggregated seismic deformation between 2000 and 2011 in the form of a seismic patch (Figure 10). The velocities and deformations for the 0.1 degree grid were estimated by interpolation of the observed time-series of CORS stations in the region. For comparison, the values from the New Zealand Deformation Model (NZDM) are included in the plot. The NZDM values show that the interseismic and deformation from slow-slip events are conflated.

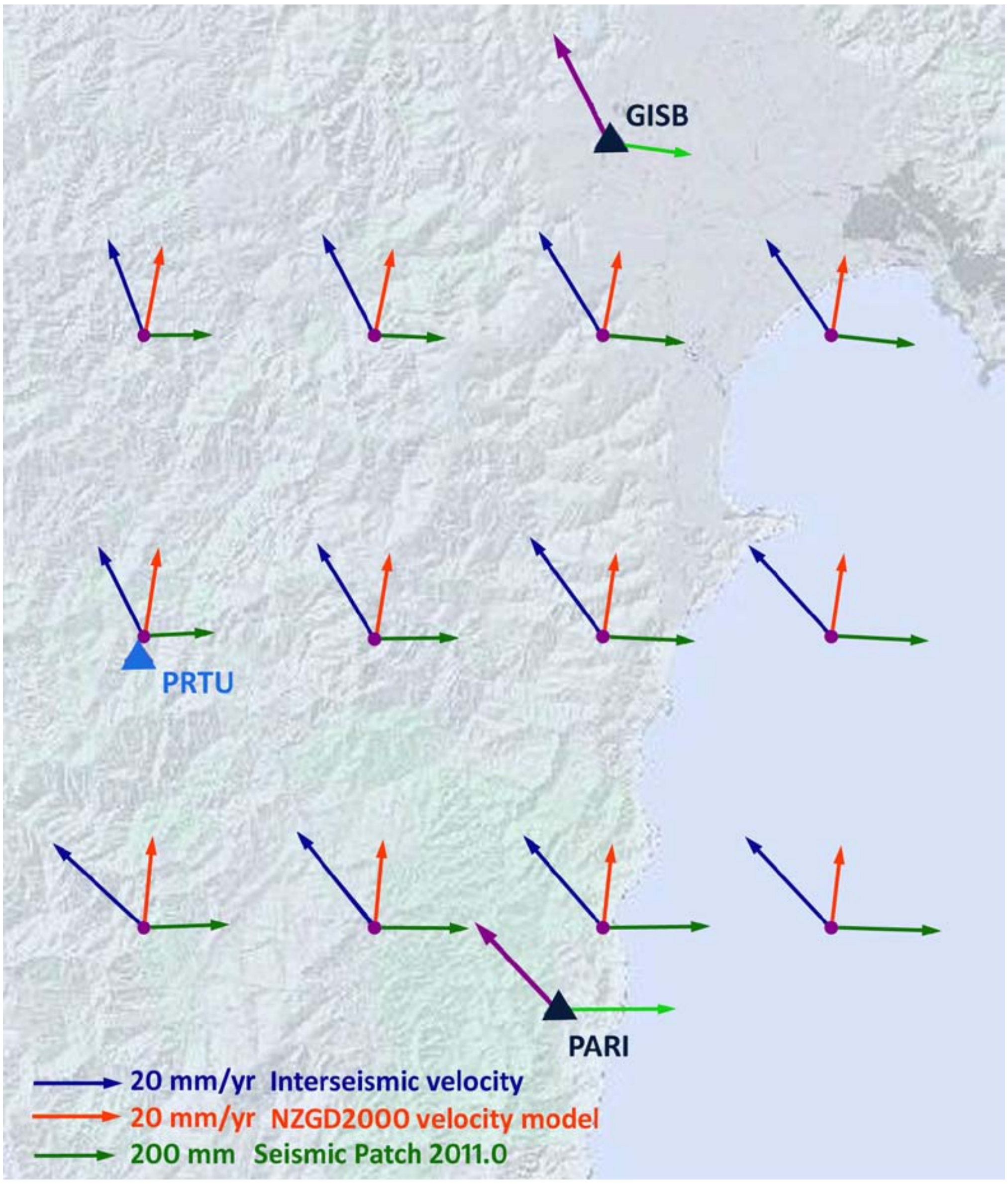

Figure 10. Deformation model for the case study area showing estimated interseismic deformation (blue), accumulated seismic deformation between 2000 and 2011 (green) and the New Zealand Deformation Model (NZDM) velocity estimates. Observed velocities and deformations at PARI and GISB are also shown.

In order to test the application of the strategy and model described in this paper, a hypothetical rover GNSS receiver has ITRF coordinates at epoch 2011.008 (3rd January 2011) computed by NRTK from the regional network. In reality the rover receiver is the GeoNET CORS station at PRTU, and the ITRF2008 epoch 2011.008 coordinates were computed by meaning 5 x 24 hour AUSPOS solutions between DOY 1 and 5 of 2011.

Rover (PRTU)
ITRF2008 Epoch 2011.008 S 38° 48' 51.0946" E 177° 41' 52.3646"
ITRF2008 Epoch 2011.008 X -4972760.286 Y 199911.062 Z -3976663.582

The ITRF site velocity for the rover station is computed by bilinear interpolation of the interseismic velocity model as follows:

E -0.0108 m/yr N 0.0217 m/yr (X -0.0131 m/yr Y 0.0115 m/yr Z 0.0168 m/yr)

The seismic patch model at epoch 2011.0 is interpolated in order to estimate the net seismic deformation between epochs 2000.0 and 2011.0

ΔE 0.183 m ΔN 0.008 m (ΔX -0.0132 m ΔY -0.1826 m ΔZ 0.0073 m)

Equation 2 is then used to compute the NZGD2000 coordinates of the rover as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{t_0} = \begin{bmatrix} -4972760.286 \\ 199911.062 \\ -3976663.582 \end{bmatrix}_t + \begin{bmatrix} -0.0131 \\ 0.0115 \\ 0.0168 \end{bmatrix} \bullet (2000 - 2011.008) - \begin{bmatrix} -0.0132 \\ -0.1826 \\ 0.0073 \end{bmatrix}_{PATCH}$$

so, the rover coordinates at epoch 2000 are:

NZGD2000(estimated)	X -4972760.129 Y 199911.118 Z -3976663.774
NZGD2000(estimated)	S 38° 48' 51.1026" E 177° 41' 52.3620"

As the rover is in reality a 4th order NZGD2000 geodetic station, the coordinates can be compared with the tabulated values (from http://apps.linz.govt.nz/gdb/) which are as follows:

NZGD2000(tabulated) S 38° 48' 51.1021" E 177° 41' 52.3619"

The difference between the estimated and tabulated values are 2 mm in East and 14 mm in North. The NZGD2000 coordinates for the “rover” location are also computed using the NZDM interpolated site velocity as follows:

NZGD2000(from NZDM) S 38° 48' 51.1020" E 177° 41' 52.3630"

The difference between the estimated and tabulated values are 27 mm in East and 5 mm in North.

The estimates are reasonably close to the reference epoch coordinates, however as the NZDM approach currently combines the slow-slip deformation with the interseismic signal, larger differences can be expected at other times depending upon the magnitude and frequency of slow-slip events. Fortuitously, the difference between ITRF2008 at epoch 2000.0 is within 15 mm of ITRF96 at epoch 2000.0 which defines NZGD2000. This agreement was established by submitting seven days (Days of year 001 to 007 for 2000) of RINEX data from NZGD2000 fiducial stations AUCK, WGTN, CHAT, HOKI and OUSD to AUSPOS Version 2.0 which delivers results in terms of ITRF2008.

6. CONCLUSION

In order for NRTK to function effectively within deforming zones, the motion of each CORS station contributing to NRTK network processing should be monitored and modelled. This can only be achieved by adopting the latest epoch of ITRF coordinates for the CORS stations. Two forms of deformation need to be modelled in order to transform these ITRF coordinates back to a fixed reference epoch. An interseismic velocity model is used to model linear deformation and a seismic patch is used to sum any seismic offsets between the reference and measurement epochs. Seismic offsets which are episodic in nature include cosesimic and postseismic effects as well as slow-slip events. The patch model can also accommodate minor reference frame distortions and to some extent imprecision in velocity modelling. Use of the interseismic model alone does not result in significant changes of coordinates at the reference epoch. Seismic offsets however, are expected to result in permanent deformation and a datum update.

The two forms of deformation model are easiest to apply if they are in a gridded data format. A nested grid structure can be employed to increase the density of the model resolution in areas of higher variability in localised deformation (e.g. near fault ruptures). More reliability can be achieved by computing model corrections at the NRTK server using the most up-to-date interseismic and patch models. The transformation (offset from ITRF to datum) is then transmitted to the rover via RTCM.

The New Zealand case study centred around the Gisborne region shows how this strategy can work in areas of very complex deformation.

ACKNOWLEDGMENTS

Graeme Blick and Chris Crook from Land Information New Zealand (LINZ) have been very supportive of this study and have freely provided information and advice.

REFERENCES

Beavan J, Haines J (2001) Contemporary horizontal velocity and strain rate fields of the Pacific-Australian plate boundary zone through New Zealand, *Journal of Geophysical Research* 106, B1, pp. 741-770, 2001 doi:10.1029/2000JB900302

Blick G, Crook C, Grant D, Beavan J (2005); Implementation of a Semi-Dynamic Datum for New Zealand, *A Window in the Future of Geodesy:* Proceedings of the International Association of Geodesy IAG General Assembly Sapporo, Japan June 30 – July 11, 2003; IAG Symposia Vol. 128, Springer-Verlag

Dawson J, Woods A (2010) ITRF to GDA94 coordinate transformations, *Journal of Applied Geodesy* 4, 189–199, DOI 10.1515/JAG.2010.019

McCaffrey R (2011) DEFNODE (http://web.pdx.edu/~pdx07343/www/defnode/index.html) accessed October 2011

Ramm P, Hale M (2004) Realisation of the Geodetic Datum in Victoria, *Proceedings from the 2004 International Symposium on GNSS/GPS*

Stanaway R, Roberts C (2009) A Simplified Parameter Transformation Model from ITRF2005 to any Static Geocentric Datum (e.g. GDA94), *Proceedings of the International Global Navigation Satellite Systems Society IGNSS Symposium*, Holiday Inn Surfers Paradise, Qld, Australia 1–3 December, 2009

Wallace L, Beavan J (2010) Diverse slow slip behavior at the Hikurangi subduction margin, New Zealand, *Journal of Geophysical Research* 115, B12402, doi:10.1029/2010JB007717