Incorporating Localised Deformation Events in Dynamic Datums

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SUMMARY

Over the last two decades, with the advent of GNSS, national surveying and mapping systems that support topographical, engineering and cadastral applications have been upgraded from regional to geocentric datums. Although for many countries a static datum is satisfactory, for countries that are close to or cross plate boundaries, the combination of regional deformation and high accuracy (instantaneous) positioning techniques (e.g. PPP) such datums will, in the future, be inadequate.

As New Zealand straddles the Australian-Pacific plate boundary, regional distortions in the geodetic infrastructure caused by earthquakes (both co-seismic, post seismic and slow earthquakes), volcanic activity and more localised deformation e.g. landslides are all too apparent. Such events affect the underlying geodetic framework upon which all surveying and mapping operations are based, and it is a challenge to how best to incorporate deformation events into the geodetic infrastructure.

The secular motion caused by plate tectonics can be adequately modelled using a combination of the ITRF based coordinates and velocities. But for regions that do not lie in the stable portions of tectonic plates, the estimates are of insufficient accuracy due to plate boundary deformation effects.

To overcome this situation Land Information New Zealand (LINZ) in 1999 introduced a semi-dynamic datum (NZGD2000) (Blick *et al.* 2003) based on ITRF96 and a National Velocity Model (NVM) (Beavan and Haines 2001). This system largely models the secular plate tectonic motion at a national level but cannot account for regional and local deformation events.

To account for distortions in the NVM, a National Deformation Model (NDM) has been developed that can incorporate both sudden deformation e.g. co-seismic displacements, catastrophic landslides; and longer term deformation e.g. post-seismic displacements, slow earthquakes and slow and imperceptible land movement (Jordan 2005; Jordan *et al.* 2007). This scenario has been tested in Fiordland where the Secretary Island M_w 7.2 earthquake, which caused horizontal displacements of up to 18cm, has been incorporated into the NDM (Winefield 2006).

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1. NEW ZEALAND TECTONICS

As New Zealand straddles the Australia-Pacific tectonic plate boundary, it is actively deformed through the collision of these two plates. On the broad scale, the tectonic processes causes a secular motion that is easily monitored using global GNSS networks and are relatively straight forward to model. On the edges of the plate boundaries, where there is an increase in the complexity of the deformation, the monitoring and modelling is more difficult. From a geodetic perspective, this gives rise to inconsistencies and distortions of the geodetic framework.

In New Zealand the greatest deformation hazards, such as earthquakes and landslides, occur in a belt extending from Fiordland in the south, up the West Coast of the South Island, the lower North Island to the Taupo Volcanic Zone in the north. This leads to a complex and dynamic environment, made up of numerous active faults and a regular occurrence of medium magnitude ($M_w \geq 4$) earthquakes (Stirling *et al.* 1998). To the north-east of the country, the Pacific plate is subducted under the Australian plate along the Puysegur Trench (Beavan *et al.* 2002), and to the south-west the Pacific plate rides over the Australian plate as part of the Kermadec Trench. In the central South Island there is an oblique collision of the tectonic plates along the Alpine fault, which has resulted in a combination of uplift and strike-slip motion as that the plates slide past each other (Beavan *et al.* 2002).

2. REFERENCE FRAME KINEMATICS

Most geodetic datums ignore the effect of deformation, either the secular tectonic motion or localised effects. Only in the last decade has there been any attempt to incorporate national velocity fields to account for the broad scale motion by modelling the datum kinematics into the geodetic framework. Examples of where this has happened are the USA (Snay 1999; Snay 2003), Japan (Tsuji and Matsuzaka 2004; Tsuji 2005) and New Zealand (Blick *et al.* 2003).

However, as the precision and accuracy of positioning technology improves and as we understand and are able to better determine localised deformation, the inadequacies of the national geodetic infrastructure will become more apparent. Two aspects will be discussed: advanced positioning technologies that are now available and common earth processes that have the potential to cause regional and local deformation.

2.1 Positioning Technology

The positioning technology used today, both GNSS and terrestrial, ignore the effects of earth deformation both at a national level (tectonic processes, earthquakes) and at local levels such as landslides. Most surveying work, either engineering, topographic or engineering projects operate at a local scale where relative movement between control marks is minimal. GNSS technologies are now capable of operating over increasing longer baselines where it may not be possible to ignore the relative motion caused by deformation effects. It is quite possible that the relative motion will become larger than measurement noise.

2.1.1 Network RTK (NRTK)

Differential GNSS using a single base station real-time kinematic RTK is being replaced with network RTK. The spacing between permanent reference stations (CGPS) used in network RTK may be as large as 50-80km. In New Zealand, if the reference stations are close to the plate boundary zone, the differential motion between two sites in a multiple reference station network could be as great as 20mm/yr over a 35km baseline. Although 20mm is close to the positional error of an RTK system, the reference stations used in NRTK solutions typically require coordinate precision better than 10mm.

2.1.2 Precise Point Positioning (PPP)

Although differential GNSS has become a widely used positioning technology, Precise Point Positioning (PPP) is gaining interests within the GNSS community. With continuous improvements in accuracy/availability of precise orbit and clock products and the development of new error mitigation and data processing methodologies, PPP is going to become an efficient alternative to differential technolgies.

One of the key differences between PPP and RTK (or NRTK) is that the coordinates are in terms of the satellite reference frame rather than the geodetic datum adopted by a country or region. The current reference frame used by the International GNSS Service (IGS) is the IGS05 (nominally a subset of ITRF2005) and effectively determines an ”instanteous” position that will be different to the local datum coordinate. The difference will depend upon a number of factors, but will largely be due to the magnitude of tectonic motion and other local deformation effects. In New Zealand, the secular tectonic motion component is generally between 40-50mm/year. A position determined using PPP in 2007 will differ from the national reference frame New Zealand Geodetic Datum 20000 (NZGD2000, reference epoch 1/1/2000) in the order of 0.30-0.35m. Obviously this is not a big problem for most mapping applications but is an issue for projects that require a centimetric level of accuracy.

2.2 Earth Processes

Traditionally, most surveying related activities tend to regard (and would prefer) the geodetic framework to be static, (or nearly static for practical purposes). But the Earths’ surface is in a state of continual change that is driven by tectonic forces, climatic processes and weathering. The processes have the potential to significantly degrade geodetic networks and infrastructure through internal deformation caused by earthquakes, volcanic activity and landslides. The deformation can occur instantaneously and be catastrophic or, occur over long periods of time and be imperceptible. With increased precision, accuracy and range of positioning tools used today, the errors in distorted geodetic networks can easily be detected.

2.2.1 Earthquakes

New Zealand is included in the "Pacific Ring of Fire" located around the edge of the Pacific Plate. This zone, known for its high level of seismic and volcanic activity, contains 75% of the world's active volcanoes and most countries within the zone are prone to the effects of earthquakes. New Zealand has an extensive earthquake history, with the first major recorded event since European occupation occurring in 1848 in Marlborough (M_w 7.5). An event with displacement and magnitude of this size is expected every 10 years (Beavan and Wallace 2004). Since 1848 there have been 16 Earthquakes in New Zealand with a magnitude $M_w > 7$.

In New Zealand, the tectonic processes are dominated by the Alpine fault, which extends along most of the South Island. Yetton (1998) provides geological and other geographical evidence (river terraces, landslides, forest age, tree ring counts) that the Alpine fault has ruptured three times in the last 1000 years. The magnitude of each rupture length is in the order of eight metres (horizontal) giving a total displacement of 24-25m.

Obviously such large events give rise to significant co-seismic deformation that will have a major impact on any geodetic network and would require a large amount of network re-establishment and re-observing. In addition, post seismic deformation may occur over months to years before the Earth's surface returns to a steady state.

2.2.2 Slow Earthquakes

GNSS networks have contributed significantly to the observation and monitoring of slow earthquakes. This phenomena was first observed in North America, but have also been observed in New Zealand and elsewhere (e.g. Brooks *et al.* 2006). They were identified after observing a non-linear motion, which is both more rapid and in a different direction to regular tectonic motion. Typically there is an increase in seismic activity at a level that is not felt by people (but is detected by seismic equipment). A part of the fault system slips at depth, which results is small amounts of earth deformation at the surface, typically of a few centimetres. There is a slow release of built up strain, which takes place over a period of weeks rather than seconds. There is insufficient fault slip for the surface to rupture, but can be detected by CGPS networks as a jump in the position time series.

The first occurrence in New Zealand was in Gisborne (East Coast of the North Island) (Douglas *et al.* 2005), which is thought to be a slow slip event on the northern Hikurangi subduction interface. These events may be quite wide spread with significant displacements that would be catastrophic had they occured as a sudden event. For example, the slow earthquake event that occurred in the Manawatu region of the North Island during 2004-2005 would have resulted in a M_w ~7.0 earthquake had the movement occurred instantaneously (Wallace and Beavan 2006).

In such cases the geodetic infrastructure will be disturbed but the magnitude and extent of the movement may not be obvious. High precision GPS campaign (or epoch) type surveys are unlikely to detect such motion due to the discrete nature and inherent precision of the techniques. The motion can only be detected using CGPS and monitoring sufficient sites.

2.2.3 Landslides

Landslides can be triggered by earthquakes, volcanic activity, high precipitation (*Hilley et al., 2004*) or the gradual effects of gravity overtime. Landslides can result in fast-moving falls, earth slides and rock avalanches; or in the case of slow moving slides, land slumps or lateral spreads. Landslides can dramatically change the topography of an area, creating fissures or displace material down slope (*Keefer, 1999*).

Often people continue to live in areas that are subjected to slumping and non-catastrophic landslide, which can lead to problems in determining the true positions of cadastral boundaries as the boundary markers move with the slip. In turn the immediate control network is distorted and new survey work must extend to regions that have not been subjected to effects of the landslides

2.2.4 Volcanic Activity

Due to their violent nature, volcanoes have the power to radically change the natural environment and cause major distortion of the geodetic networks. Volcanoes are caused by pressure and the stress from the injected of magma and gases, which can also lead to localised earthquakes and landslides.

3. THE NATIONAL DEFORMATION MODEL

Associated with the NZGD2000 is the National Deformation Model (NDM) that accounts for the secular (steady state) motion between the Australian and Pacific tectonic plates. The model has been termed a "deformation" model rather than a "velocity" model as it is required to model the secular velocity as well as localised motion. The goal of the NDM is to be able to combine old and new observational data so that survey mark coordinates can be accurately determined for any epoch in time.

At the present time, the NDM does not account for horizontal deformation associated with localised events such as earthquakes, landslides or volcanic eruptions. A large event will create distortions in the geodetic infrastructure that will downgrade the integrity and accuracy in the affected area.

The possibility of a localised event, sufficiently large to distort the geodetic network in New Zealand is a real possibility. Such events do not occur often, but Land Information New Zealand (LINZ) does need a strategy to deal with these events. The obvious solution is to re-observe the geodetic network as events occur and determine new coordinates for the affected geodetic network marks. This may be feasible when the region of disturbance is small, but becomes a large and expensive exercise when an event is large.

If a magnitude M_w >7 earthquake occurs in an urban or semi-urban region (e.g. lower North Island, New Zealand), with decimetres to metres of surface disturbance, the geodetic network is destroyed. The likely effects are

- surface disturbance extending 10-100's kilometres from the epicentre;
- potentially 100's of high order control marks disturbed;
- potentially 1000's of lower order survey marks disturbed;
- cadastral boundaries disturbed, boundary lines differing from title dimensions;
- post seismic deformation may occur over months to years.

The approach developed by Jordan (2005) is to create a Localised Deformation Model (LDM) that can be integrated into the NDM. The LDM can be considered as another layer (or deformation model) to the NDM that is applied in a specified sequence. By allowing a deformation event to be represented as a sequence of deformation components, variations in deformation over time can be managed. NZGD2000 can then be updated in such away that it retains the network integrity by reflecting the survey marks true positions.

This concept can be illustrated in Figure 1. A particular geodetic mark will have a specified coordinate for a given reference epoch, (t_0). The coordinate at any other epoch, t, is calculated using the site velocity with

$$X(t) = X(t_0) + V(t - t_0) \qquad (1)$$

where X is the position and V is the velocity.

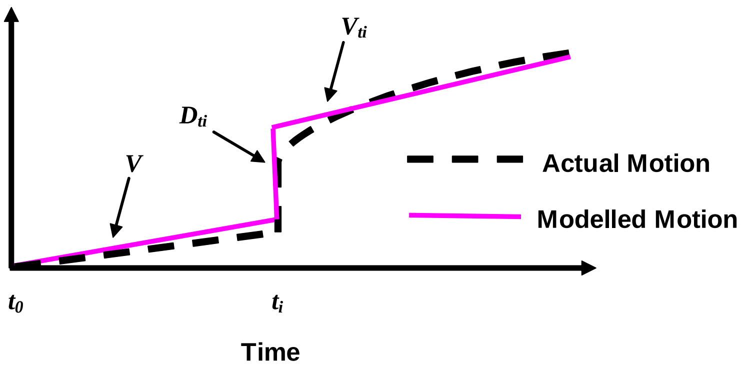

Figure 1: The dashed line represents the true motion and the solid line (pink) represents the modelled motion as described by the NDM. The velocity before and after t_i may not be the same. The event displacement is D_{ti}.

If a deformation event occurs at time, t_i, with an associated displacement, D_{ti}, then the equation for the motion of the site becomes

$$
\begin{array}{ll}
X(t) = X(t_0) + V(t - t_0) & \left| t < t_i \right. \\
X(t) = X(t_0) + V_{ti}(t - t_0) + D_{ti} & \left| t \geq t_i \right.
\end{array} \qquad (2)
$$

where V_{ti} is the site velocity after the event. It may be reasonable to assume that the velocity before and after the event is the same i.e. $V = V_{ti}$. In the case of an earthquake event, it is likely that there will be a period of post-seismic deformation, but eventually the site motion will revert to the pre-seismic velocity.

The value of the co-seismic displacement, D_{ti}, is determined by the LDM. The actual displacement will change spatially and is typically modelled by interpolation of an irregular grid (for more details, see Jordan 2005; Jordan *et al.* 2007).

4. THE FIORDLAND (SECRETARY ISLAND) EARTHQUAKE, AUGUST 2003

In August 2003, a magnitude M_W 7.2 hit Secretary Island, Fiordland, in the south west corner of New Zealand. The majority of the area affected by the earthquake is within a National Park and only a few low population centres felt the earthquake with surface displacements less than 1-2cm.

But the earthquake provided an ideal opportunity to form a strategy for dealing with catastrophic events if (or when) an earthquake occurs in a high population, urban area. The geodetic control in Fiordland is sparse and only used for mapping purposes. However, in 2001 a high precision earth deformation network had been established with the purpose of accurately determining the deformation field within the Australian/Pacific plate boundary.

4.1.1 Observational Data Sets

Since the original 2001 earth deformation survey, there have been six GPS campaigns that have occupied marks in Fiordland (Table 1). In the week following the earthquake (August 2003), a selection of the survey marks surrounding the earthquake epicentre were re-observed in order to compute the co-seismic displacements. To measure the post-seismic motion and further understand the earthquake process, the network has been re-observed at roughly 1 year intervals since 2004.

Table 1: Fiordland earth deformation surveys since 2001.

	Date	**Sites**	
1	February 2001	69	Whole network
2	January 2003	16	
3	August 2003	11	Co-seismic network
4	January 2004	18	Post seismic network
5	January 2005	28	Post seismic network
6	February 2006	84	Whole network
7	December 2006	20	Post seismic network

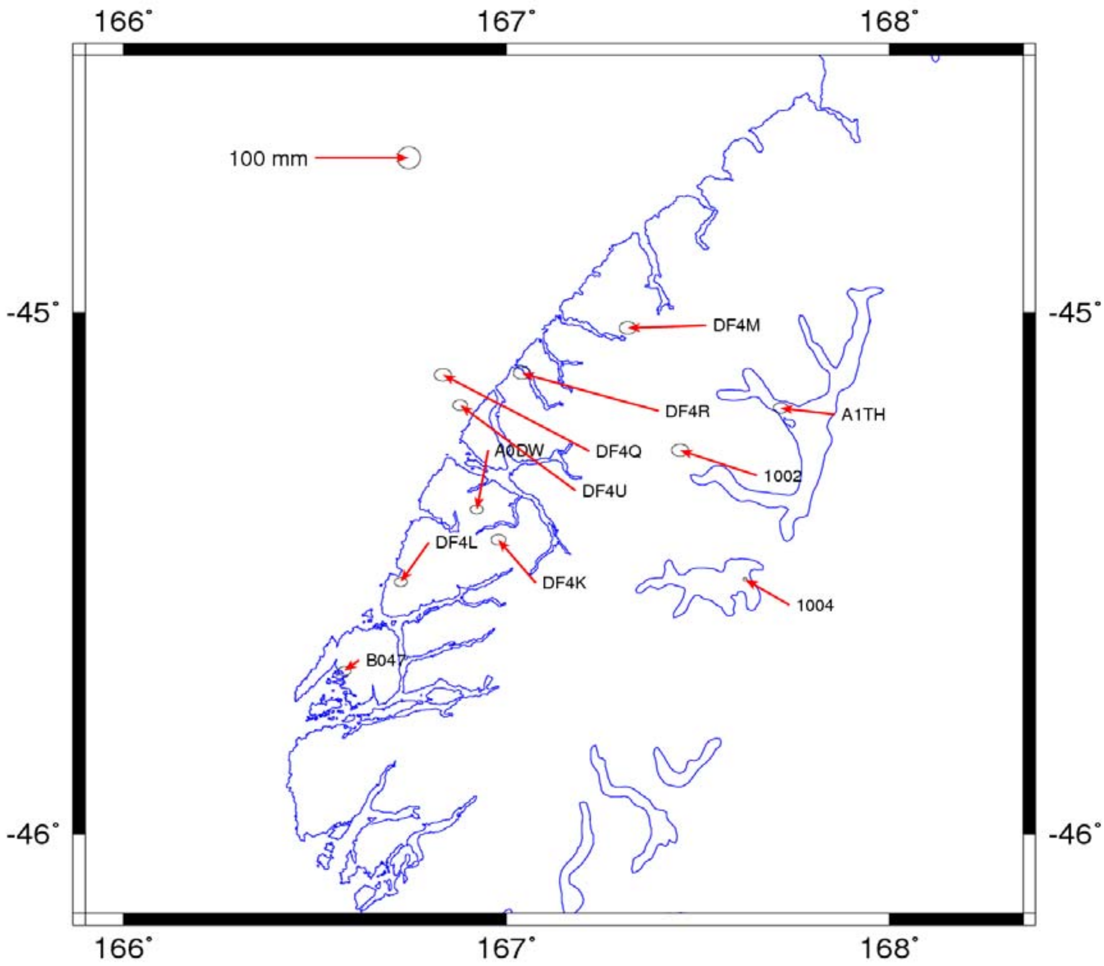

Figure 2: Station displacement caused by the Secretary Island earthquake, 23rd August 2003. Displacement is relative to a fixed Pacific plate. The 95% error ellipses for the displacements are shown.

A summary of the steps taken to include the Fiordland earthquake into the NDM is as follows (see also Jordan 2005):

- Compute co-seismic displacements
- Compute Dislocation Model
- Compute Localised Deformation Model (LDM)
- Combine NDM + LDM

4.1.2 Co-seismic Displacements

Following the August 2003 earthquake, the eleven sites were occupied with GPS. The estimated co-seismic displacements have been estimated by Beavan and Wallace (2004) and Jordan (2005) (**Figure 2**). The largest movement was calculated to be at DF4Q as -0.162m and +0.076m east and north respectively. The smallest movement was calculated at B047 as -

0.015 and -0.0009 m east and north respectively. (Significant vertical displacements were also observed, with a maximum of 13cm subsidence at DF4Q.)

Most stations moved in a WNW direction (the largest movements were at DF4Q, DF4R, DF4U), but the three most westerly sites (A0DW, B047 and DF4L) moved in a SW direction. This demonstrated that the deformation was not consistent in either magnitude or direction over the deformation zone, but also highlights the importance of good spatial distribution of the survey marks in order to accurately measure the full deformation effects of the earthquake.

4.1.3 Dislocation Model

Based on the observed displacements shown in **Figure 2**, a dislocation model was computed using the dislocation equations of Okada (1985). This resulted in a model in which the fault slipped over a length of 35km parallel and immediately below the coast line at a depth between 13-23km (black rectangle, Figure 3). The total fault slippage is estimated to be 2.3m.

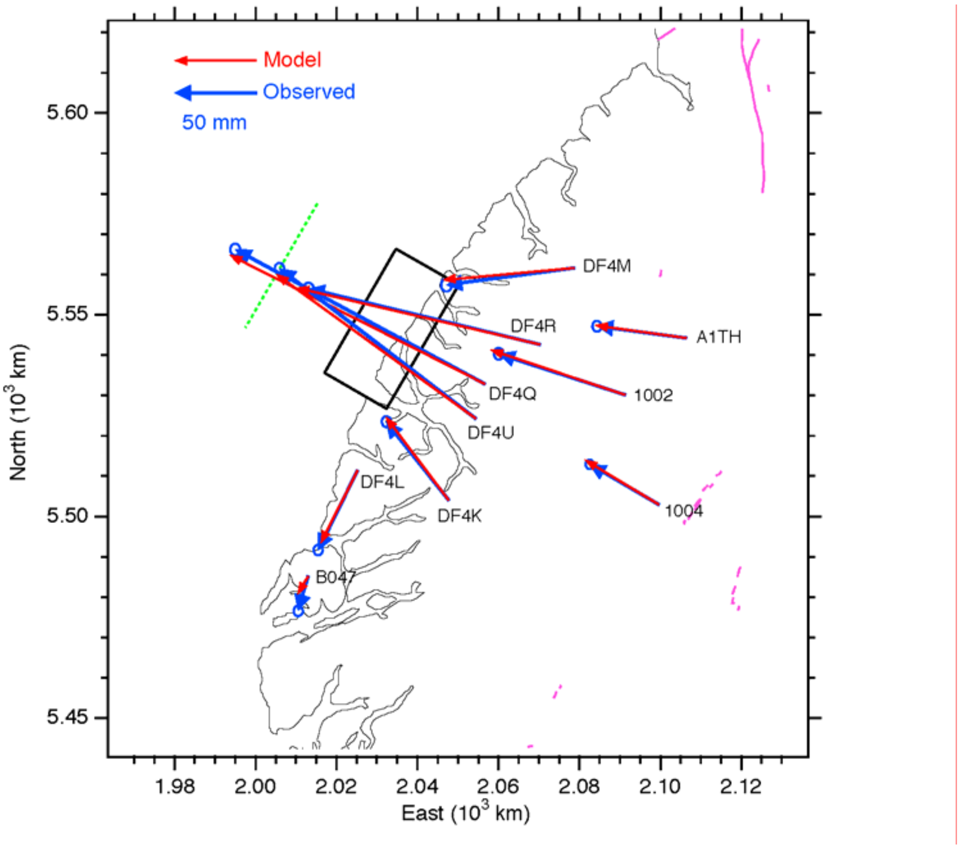

Figure 3: A comparison of the predicted displacements (red arrows)computed using the dislocation model (Beavan and Wallace 2004); and the observed displacements (blue arrows) based on the GPS calculated displacements. The projected fault is represented by the green dashed line and the slip surface is represented by the solid black rectangle.

In general, the agreement between the observed and calculated displacements is good. The RMS values are 0.003m and 0.004m east and north respectively.

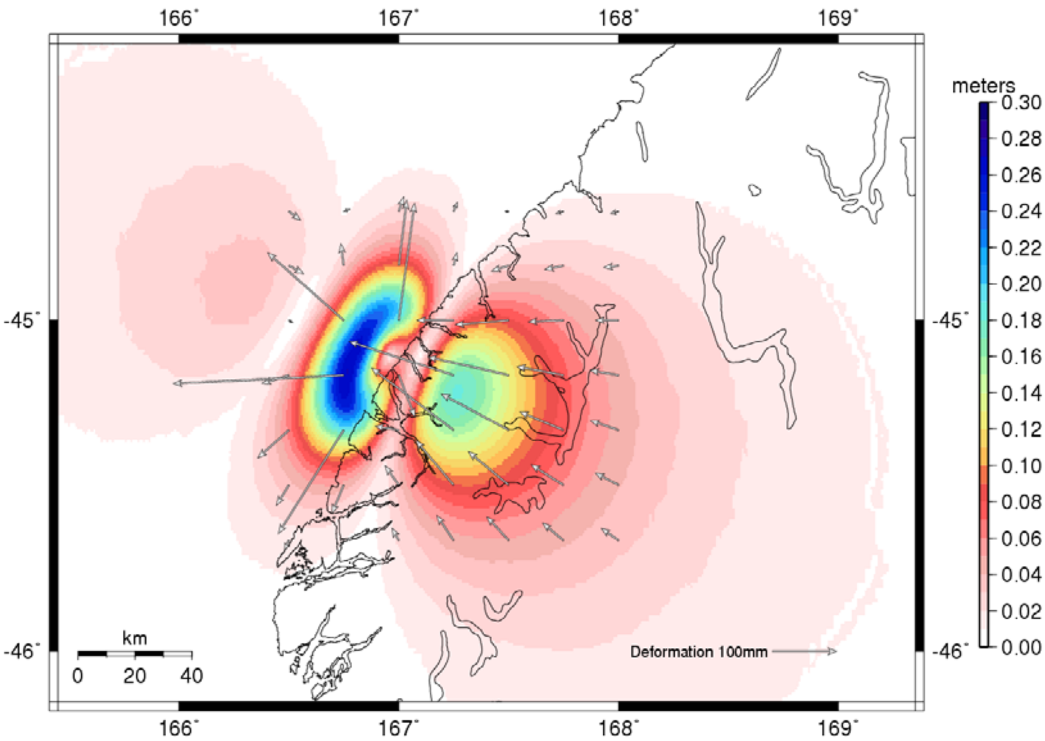

Figure 4: Contour and direction plot of the Fiordland deformation model. Contours are spaced at 0.01m intervals. The scale bar indicates the magnitude of the deformation represented by each colour.

4.1.4 Localised Deformation Model (LDM)

The localised Deformation Model (LDM) for the Fiordland earthquake was generated from an optimised triangular grid (irregular) based on 14,000 displacement nodes that covered a 56,000km^2 area (Jordan 2005). It was assumed that the perimeter nodes had zero deformation. Linear interpolation was used to evaluate the grid for each point and resulted in predicted spatial distribution of the surface deformation shown in Figure 4.

On land, the maximum displacement is in the order of 0.18m (similar to the observed displacement at DF4Q) and decreases to less than 0.05m some 80km to the SE of the maximum displacement. Along the coast there is a region of no displacement while maximum displacements of up to 0.3m are 10-20km offshore. (Obviously the offshore deformation can not be confirmed using GNSS positioning.)

Comparing the displacements as evaluated by the LDM at the 11 station shown in **Figure 2**, results in RMS values of 8mm and 12mm east and north respectively. This is within the accuracy LINZ accuracy standards for 6th order marks (constant portion ±2cm) and is therefore considered of sufficient accuracy for most survey applications.

4.1.5 Combined National and Local Deformation Model

The NDM and LDM can be combined to accurately represent the 2003 Fiordland earthquake. When the NDM is evaluated after 22nd August 2003, the displacements as predicted by the LDM, are applied to all affected sites. Figure 5 shows the predicted motion (pink circles) at a selection of sites.. For comparison purposes, the predicted motion of each site with no modelling of the earthquakes is show as blue circles. After six years (February 2001-December 2006), there is a significant difference between the actual position (green diamonds) and modelled position.

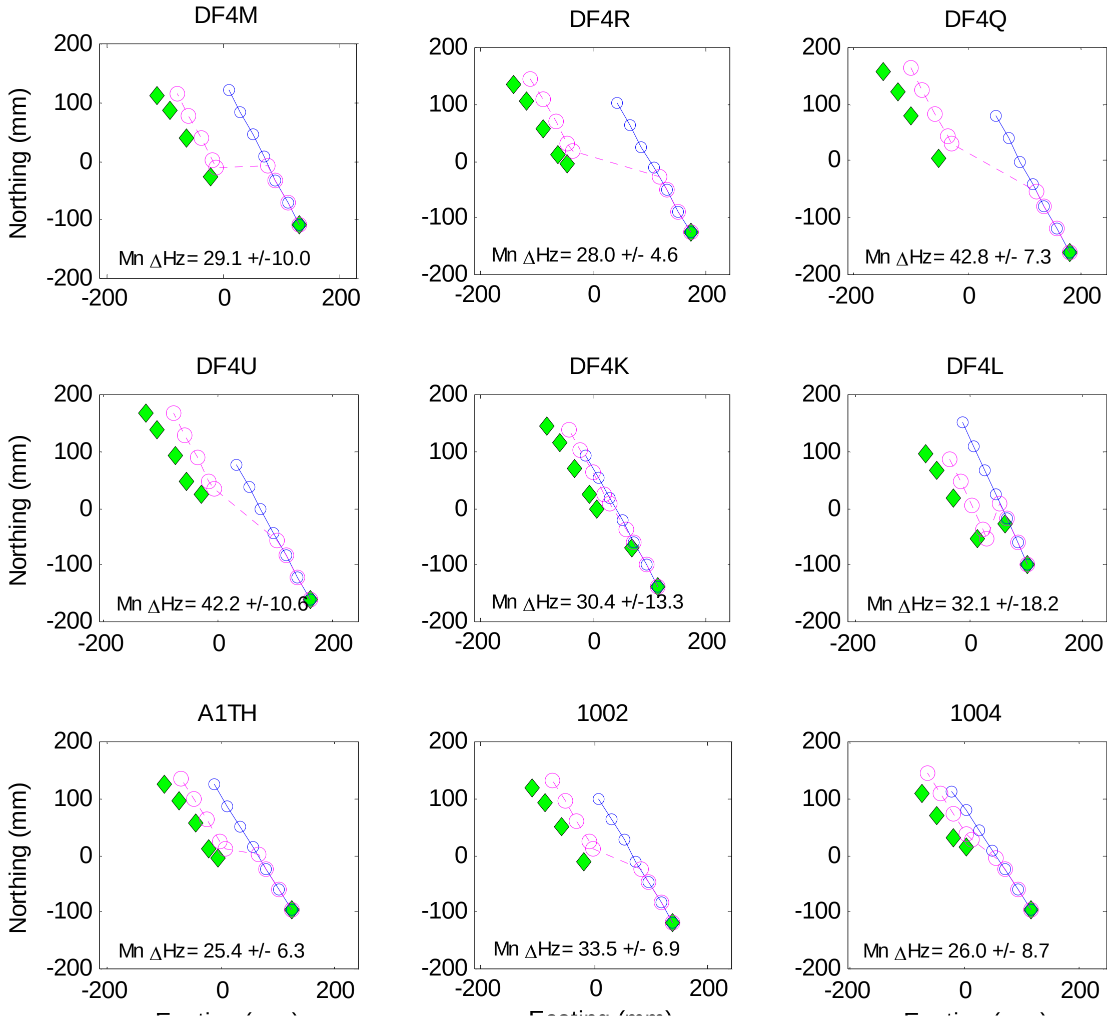

Figure 5: Horzintal plots of the observed and modelled motion. Observed position (green diamonds) from February 2001 (lower right) to December 2006 (upper right). The LINZ NDM positions without the Fiordland deformation model (blue circles). The LINZ NDM poisiton with the Fiordland deformation model applied (pink circles). The text within each site graph is the mean (horizontal) difference between the observed and modelled position for each site. The number of times each mark has been occupied since 2001 can be different as not all marks were pick up during each of the seven campaigns.

The combined NDM and LDM predicts the deformation caused by the earthquake reasonably well. The modelled and observed position post earthquake generally runs in parallel. The average horizontal difference between the modelled and observed positions is 29±8mm (mean of 29 sites surrounding the earthquake epicentre). The difference is caused by a combination of the errors in the modelling of the co-seismic deformation and the error in the assumed station velocity as predicted by the NDM.

The initial NDM velocities for the Fiordland region are not well determined and were largely based on GPS campaigns from outside the region plus a few sites that had been occupied within Fiordland. This deficiency is recognised (see Beavan and Blick 2007) and improved velocities are being computed.

An earthquake's (instantaneous) co-seismic displacement is the biggest effect to model. Since the Fiordland Earthquake, four campaigns have been carried out at roughly one year intervals in an attempt to determine the post seismic motion of the marks. Three of these campaigns have been of selected marks surrounding the Secretary Island epi-centre, while the fourth was a full campaign of the whole of the lower South Island. Although there is some post-seismic deformation, it is small compared to the co-seismic deformation (Figure 5).

5. SUMMARY

New Zealand, located on the Australian-Pacific plate boundary in the SW pacific, is continually being deformed due to the tectonic and related earth processes. Both catastrophic and imperceptible deformation events result in distortions in the geodetic infrastructure that now have to be integrated into the geodetic datum. In addition, contemporary positioning techniques such as network RTK (NRTK) and Precise Point Positioning (PPP) result in centimetric positioning over regions where the relative deformation between survey marks needs to be accounted for. This has implications for the management and maintenance of the geodetic datum, and hence the cadastral, engineering and topographic surveys that are based on the geodetic framework.

A localised deformation model (LDM) that modelled the co-seismic deformation of the Fiordland 2003 earthquake was developed and implemented as a component of the National Deformation Model (NDM). The scenario demonstrated the feasibility of being able to model a large earthquake based on a dislocation model. In this example, the major limitation was the accuracy of the underlying secular velocity.

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