The Application of a Localised Deformation Model after an Earthquake

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ABSTRACT

In 1998 Land Information New Zealand (LINZ) introduced the semi-dynamic datum New Zealand Geodetic Datum 2000 (NZGD2000). Official coordinates are fixed to their values as at 1 January 2000 (Epoch 2000.0). Velocities from a national horizontal deformation model (NDM) are used to generate epoch 2000.0 coordinates using observations made at any epoch. The velocities contained in the NDM are based on observed plate tectonic motion and plate boundary deformation.

Away from plate boundaries, such deformation can be modelled sufficiently with a low density network of stations. However, tectonic deformation quickly becomes more complex across plate boundaries and can no longer be represented accurately through regional models. As New Zealand straddles the Pacific/Australian Plate, it is subject to increased national deformation and complex localised deformation events.

The deformation model must be of sufficient accuracy to ensure compliance with the datum accuracy standards. However, the NDM currently provides no allowance for distortions caused by localised deformation such as those caused by earthquakes, landslides or volcanoes. Previous research suggests options on how a dislocation model could be implemented in the NZGD2000 as a patch to the NDM.

On 15 July 2009 a magnitude ~7.7 earthquake struck the south-west area of Fiordland, New Zealand. Significant shifts were detected, indicating substantial failures of the datum absolute accuracy standards. Although the earthquake was centred in an uninhabited national park, its magnitude was sufficient to cause significant movements in populated parts of the country. Therefore a localised deformation model is required to enable new survey observations to be combined with Epoch 2000.0 coordinates

This paper discusses the Fiordland earthquake case study and the process used to generate a localised deformation patch for the NDM. This includes the field work methodology, model creation and the application of the updated NDM within LINZ geodetic processing software.

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1. INTRODUCTION

The advent of Global Navigation Satellite Systems (GNSS) has meant the ability to position points on the surface on the Earth with millimetre accuracy, using post processing techniques. This has also meant that Earth surface deformations have become readily measurable using standard surveying and engineering methods.

A geodetic datum provides a systematic way of expressing points in relation to each other, allowing distances and bearings between marks to be determined. Each country has its own geodetic datum tailored to suit its location and orientation on the globe. Traditionally, geodetic datums have been assumed to be static; once surveyed, reference coordinates were fixed and would remain with the same values until the datum was superseded.

In an era of space-based measurement, these static datums are no longer retaining integrity. Errors that were once too small to measure are now readily exposed. Areas once thought of as stable have been proven to move and deform due to plate tectonic motion, while more significant deformation occurs in countries that lie next to or straddle tectonic plate boundaries.

New Zealand straddles the Pacific/Australian tectonic plate boundaries in a tectonically complex area in which the Pacific plate is subducted in the north and overriding in the south. Most of the country is within 100 km of a major fault line making New Zealand extremely vulnerable to localised deformation events, in addition to the generalised tectonic motion that is moving the country by as much as five centimetres per year. New Zealand is also regularly subjected to localised, non-uniform land deformation such as catastrophic landslips (Abbotsford 1979), earthquakes (Napier 1931), and volcanoes (Ruapehu 1995) and virtually imperceptible slow earthquakes, soil creep and erosion.

In 1998 Land Information New Zealand (LINZ) introduced the semi-dynamic datum New Zealand Geodetic Datum 2000 (NZGD2000). The previous datum, NZGD1949 was a static datum and after almost 50 years the fixed coordinates had been affected by distortions of up to five metres (Bevin and Hall 1995). The semi-dynamic datum defines coordinates in terms of a fixed reference epoch, and defines a deformation model that allows them to be converted from the reference epoch to other times, representing their current location. The deformation model allows the integrity of the datum to be preserved as points are moved by ongoing tectonic deformation, and by specific deformation events, such as earthquakes. The deformation model and the coordinates will be updated periodically to reflect better information from new surveys and to account for the effects of deformation events.

The 2009 Fiordland earthquake generated significant deformation – up to a metre horizontally and similar significant vertical deformation. The following discussion describes the general considerations in accounting for a deformation event in a semi-dynamic datum, and then describes how they apply to this specific deformation event.

2. DEFORMATION IN THE NZGD2000 SEMI-DYNAMIC DATUM

The NZGD2000 deformation model is defined to include a national component, which represents the overall deformation of New Zealand as it straddles the boundary of the Australian and Pacific tectonic plates, and a number of "patches" which represent localized deformation events, such as earthquakes. This model will be updated periodically as required, both to add new patches as deformation events occur, and to update the national model as our understanding of it improves.

The coordinates of a point in the geodetic system are calculated at any specific time by applying an offset calculated from the deformation model to the reference coordinates of the station. In defining the datum we can choose what deformation is represented in the reference coordinates, and what is in the model. Adding an offset to the reference coordinate and subtracting it from the deformation model at that point will leave the coordinate of the point unchanged.

Trading deformation between the reference coordinates and the deformation model gives us several options for implementing a patch to the deformation model. The two basic options discussed in Blick et al (2003) are:

- a "forward" patch – the reference coordinates are unchanged, and the deformation model accounts for the deformation that has occurred for coordinates after the time of the event
- a "reverse" patch – the reference coordinates are changed to reflect the deformation, and the patch defines the "negative deformation" that applies to coordinates before the time of the event to reverse the change.

A third option is a "hybrid" patch, in which some of the deformation is accounted for by changing the coordinates, and the patch defines both deformation after the event, and "negative deformation" before the event

Given that trading deformation between the reference coordinates and the deformation model makes no difference to the actual coordinates of a point at any specific time, why would we care which option we take?

The answer lies in the fact that most users of the geodetic system ignore the deformation model and use only the reference coordinates of geodetic marks. Indeed, to date LINZ has not explicitly published the deformation model, and no one has asked for it. Currently it is used exclusively for geodetic calculations by LINZ.

Users are able to ignore the deformation model because the reference coordinates are sufficiently accurate for their applications. Many, and possibly most, users will naively treat these coordinates as equivalent to true current coordinates of the points they reference.

For most mapping and geospatial analysis applications an accuracy of several decimetres is generally adequate. Although the reference coordinates are typically half a metre from the current true coordinates due to the tectonic deformation since 2000, this has apparently not been an issue for users.

Typically GIS systems do not have a facility for handling time varying coordinates, so much of the geospatial community cannot easily use the deformation model even if they want to. The reference coordinates provide a spatial framework used by this community to define and relate spatial data sets. Typically data sets from different times are combined without considering deformation that may have occurred.

Another large user group, cadastral surveyors, are also able to use the reference coordinates. Although they have relatively high accuracy requirements (typically accuracy of a few centimetres), they are only concerned with relative accuracy of points in a local area. The ongoing tectonic deformation does not compromise this – it does not introduce significant local distortion.

The apportioning of deformation between the reference coordinates and the deformation model can be guided by the needs of the users of the reference coordinates. Their requirements can be summarised as:

- “reasonable” absolute accuracy in relation to true current position – what is “reasonable” will depend upon the application, but it seems that a sub metre level of accuracy meets most requirements
- good local relative accuracy
- coordinates that do not change to provide a consistent reference for spatial data sets.

Clearly the third requirement is in conflict the first two – as the country is deformed, either the reference coordinates must change, or the accuracy in terms of current position must degrade. The relative importance of these needs will vary across the user community.

Typically an earthquake will affect a large area. There will be a relatively small area near the epicentre over which there may be intense deformation and significant distortion – possibly even surface fault rupture. Around this will be a very much larger area over which the deformation is not significant, but is large enough to compromise the accuracy of the geodetic system. For a large earthquake this could encompass a significant percentage of the land area of New Zealand.

Most users of reference coordinates will intuitively expect coordinates to change near the earthquake epicentre.

On the other hand, maintainers of geospatial data sets may not expect to have to update coordinates over the huge area within which the coordinate change is small (less than a few decimetres), but where it is still significant in terms of the accuracy requirements of the geodetic system.

In this scenario the ideal model may be a hybrid patch, changing the reference coordinates and using a reverse patch in the vicinity of the earthquake to model the local distortion, and using a forward patch to model the deformation for the large area over which the deformation and distortion are small, but still large enough to compromise the accuracy of the geodetic system.

Guidance on how much deformation to include in each component comes from work LINZ has recently done in establishing new accuracy standards for the geodetic network (LINZ 2009) This has identified roles for geodetic marks and coordinates for each of which an accuracy standard applies. The horizontal accuracy standards are summarised as follows:

Role	Network accuracy	Local accuracy
National reference frame	0.05m	0.003m $\pm$ 3 x 10^{-8}
Deformation modelling – national	0.05m	0.003m $\pm$ 1 x 10^{-7}
Deformation modelling - regional	0.10m	0.003m $\pm$ 1 x 10^{-6}
Deformation modelling – local	0.15m	0.01m $\pm$ 1 x 10^{-6}
Cadastral network	0.15m	0.01m $\pm$ 5 x 10^{-5}
Basic geospatial network	0.15m	0.01m $\pm$ 5 x 10^{-5}

In this table the network accuracy is the absolute accuracy of a coordinate in terms of the NZGD2000 datum, and the local accuracy defines the relative accuracy of coordinates of any two marks. The relative accuracy is defined by a constant component in metres, and a distance dependent component expressed as a fraction of the distance between the two marks. The accuracies are all expressed as 95% confidence limits. The standards also define vertical accuracy standards.

How does this relate to the accuracy of requirements of a patch to the deformation model?

The national reference frame has little bearing on the deformation model. It defines the national datum in terms of international datums. It is defined by relatively few continuously operating GNSS stations and as such is largely independent of the deformation model.

The deformation modelling networks are used to monitor deformation and maintain the datum. These define the best accuracy that the patch deformation is likely to achieve, since these will provide the input to the model (though other scientific survey networks and other types of information may also contribute to calculating a patch). The most accurate information on a large earthquake will probably come from the regional deformation monitoring network – the national deformation monitoring network is too sparse to provide detailed information. None the less, to preserve the accuracy of the national deformation monitoring network the patch will have to strive to achieve this accuracy standard, at least at the points of that network.

The cadastral and basic geospatial networks are provided principally for the users of the geodetic system. It is the accuracy standards of these networks that reflect most users' requirements, and that we will strive to retain in the reference coordinates of points.

In fact the reference coordinates are already not meeting this accuracy –nationally we have already accumulated about 0.5m of deformation since the datum was defined in 2000. However we can ensure that the local accuracy requirements are maintained.

Typically an earthquake results in both co-seismic and post-seismic deformation. The post-seismic deformation may account for a significant proportion of the total deformation, and may continue for months, or even years, after the event. Incorporating this into the datum deformation model may require several patch models. The decision as to when to release a patch and whether to use several patches will be based on the amount of survey activity in the area during the period of post earthquake deformation.

A final consideration in implementing a patch deformation is a practical one. The LINZ software for using patch deformations allows them to be expressed as a set of points at which the deformation is defined. These points can either be on a regular latitude/longitude grid, in which case the deformation is interpolated between them using bilinear interpolation, or they can be on a triangulated network, in which case they are interpolated by linear interpolation on each triangle.

This implementation will introduce some errors into the deformation model. These will come from the use of linear interpolation, which is an approximation to the actual deformation, and from the finite extent of the model. There may be deformation beyond the extents of the patch that will be ignored.

Both of these errors are controllable – the interpolation errors can be reduced by making the grid or triangulation finer, and the boundary errors can be reduced by making the patch more extensive. However this comes at a practical cost – calculating the deformation becomes more computationally intensive.

Ideally the patch will be constructed to be as small as possible (that is, as few points as possible), while not introducing a significant error to the coordinates of points generated from it.

In summary then, the considerations that will apply in defining patches in the deformation model are:

- how much deformation to apply to the reference coordinates and a reverse patch, and how much to put in a "forward" patch.

- when and how often to generate patches to account for post-seismic deformation
- how to construct a patch, whether to use a grid or a triangulated model, what density of points to use, and over what extents.

Until now the question of how to implement a patch has been academic. Since the datum was defined the earthquakes that have occurred have been an expression of the ongoing national deformation, and have not resulted in a significant, identifiable perturbation of the national model. The magnitude 7.7 Dusky Sound 2009 earthquake has changed that.

3. FIORDLAND EARTHQUAKE

The magnitude ~7.7 earthquake struck the south-west area of Dusky Sound, Fiordland on 15 July 2009. The event was caused by oblique subduction of the Australian tectonic plate under the Pacific tectonic plate. This was the largest earthquake to strike New Zealand since the Napier Earthquake of 1931 and the most significant localised deformation event to occur since the realisation of the NZGD2000 datum. Aftershocks continued in Fiordland for months following the main event.

The fact that the area of the earthquake is sparsely populated meant that damage from the event was relatively light; however, it caused measurable displacement over much of the southern South Island. The effect of the earthquake was recorded at a number of the LINZ PositioNZ continuously operating GNSS stations (CORS), as seen in Figure 1 below. Significant shifts were detected at Puysegur Point (300 mm), Mavora Lakes (60 mm), Bluff (30 mm), Alexandra (20 mm) and Dunedin (10 mm).

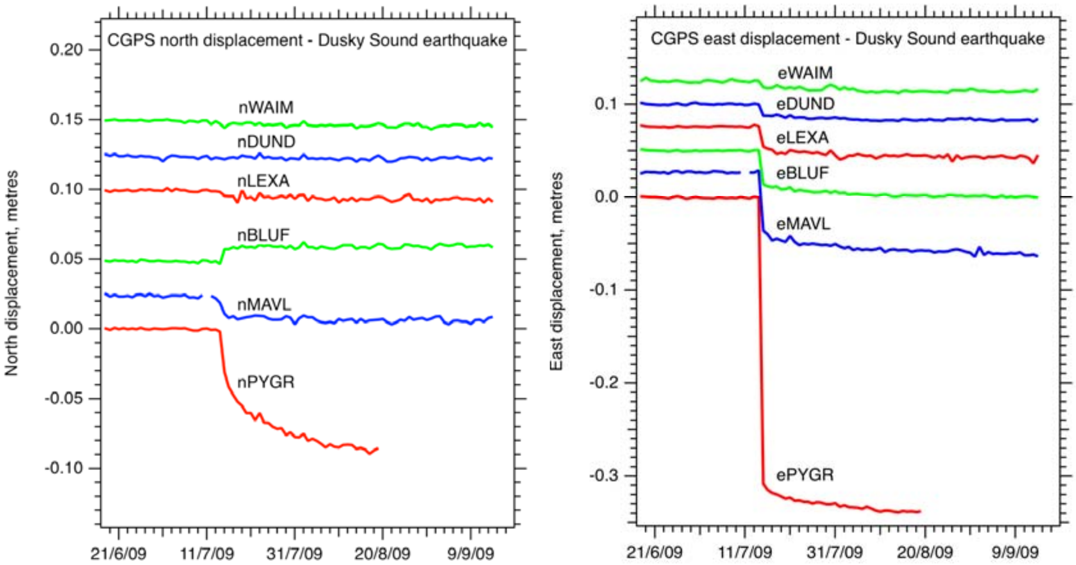

Figure 1: Displacement at CGPS stations (Bevan et al. 2009)

3.1 Data Modelling

A preliminary dislocation model, displayed Figure 2, for the earthquake was determined by GNS Science several days after the earthquake event. This model uses information from New Zealand's PositioNZ stations along with global seismic information.

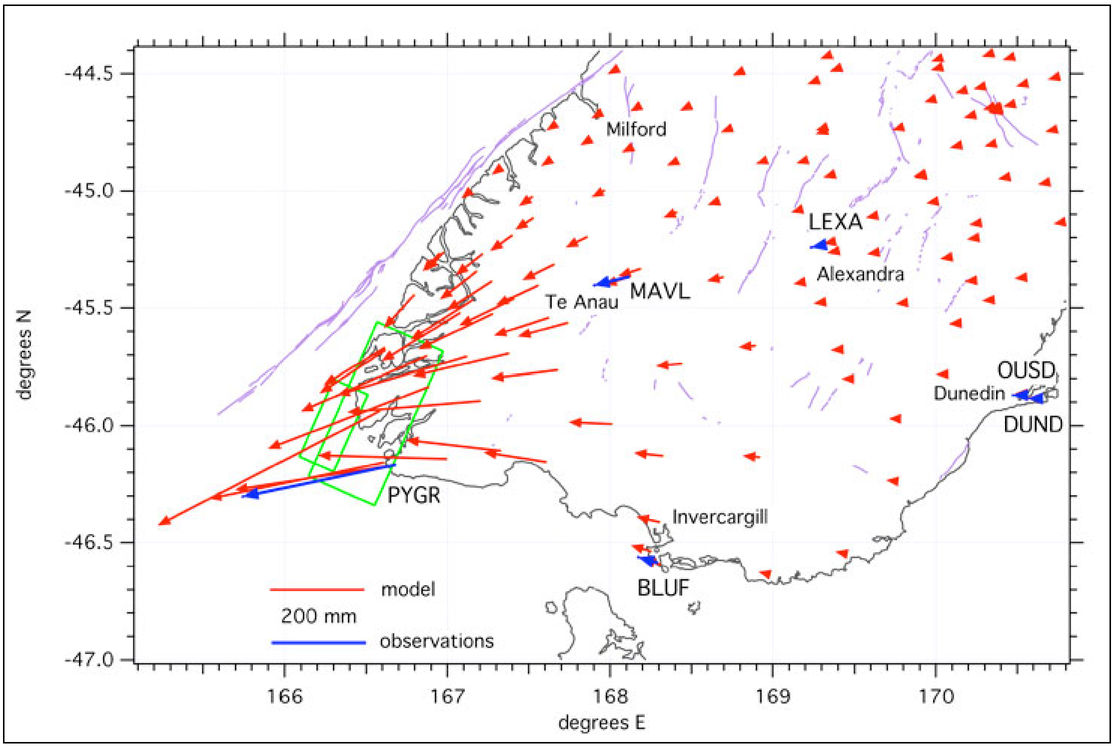

Figure 2: Preliminary Dislocation model (Supplied by GNS Scince)

Once the deformation area had stabilised and winter weather conditions cleared, the resurvey of selected marks in the Fiordland area began. In a joint venture between GNS Science and LINZ, GPS data were collected from 27 sites in west Southland. Data were collected using campaign GPS observation techniques; sites were observed simultaneously with static GPS for approximately 48 hours.

The observed displacements from the campaign GPS survey showed significant differences from the preliminary model, especially close to and north of the earthquake source (where constraints from continuously-operating PositioNZ stations were absent). From this additional GPS data and L-band InSAR data, the original dislocation model was revised.

Currently the best estimate of the deformation model has slip occurring on a fault plane from 5-50km depth, with the most significant deformation between about 10 and 30km depth. Using this model GNS Science have predicted the surface deformation over the southern portion of the South Island of New Zealand on a grid of data points. It is this data that will be used to plan the implementation of the earthquake deformation into the NZGD2000 datum.

4. IMPLEMENTATION OF A PATCH FOR THE FIORDLAND EARTHQUAKE

The preliminary model of surface deformation from the Fiordland earthquake provides a good basis for assessing how to implement a patch for the deformation model. Though it may be revised with further analysis, and the patch will ultimately need to also include the post-seismic deformation, it is unlikely to change substantially. In the following discussion we will focus only on the horizontal component of deformation. This analysis can equally be applied to the vertical component. As generally the vertical accuracy requirements are less stringent than the horizontal accuracy requirements, and the on-land vertical deformation is of a lower magnitude than the horizontal, it is likely that a patch meeting the horizontal accuracy requirements will also meet the vertical requirements.

Recalling the discussion above, we need to decide:

- how much deformation to apply to the reference coordinates and a reverse patch, and how much to put in a "forward" patch.
- when and how often to generate patches to account for post-seismic deformation
- how to construct a patch, whether to use a grid or a triangulated model, what density of points to use, and over what spatial extents.

Of these the second question, how to deal with post-seismic deformation, is in this case the simplest. As the earthquake has occurred in a remote area it will suffice to wait till the post-seismic deformation has substantially stopped, and base a deformation model on the total displacement.

4.1 Apportioning deformation between reference coordinates and the deformation model

In order to assess how much of the deformation should be applied to the reference coordinates we will look at the impact of the earthquake deformation in terms of the two measures of accuracy used in the datum – network accuracy and relative local accuracy.

The impact of the earthquake on the horizontal network accuracy can be quantified as the length of the horizontal component of the deformation vector. This is illustrated in Figure 3.

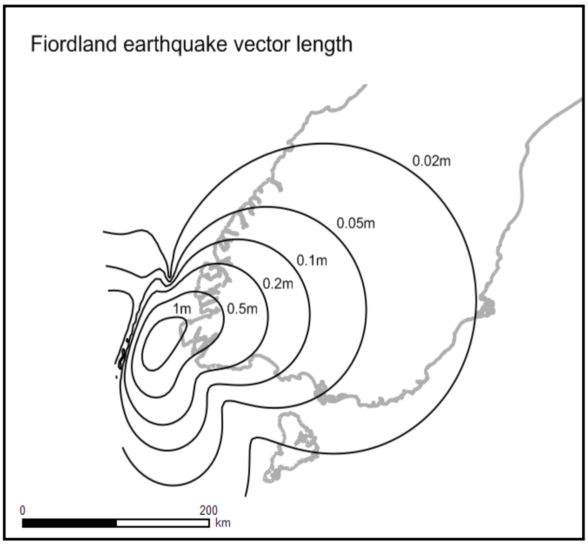

Figure 3: Fiordland Earthquake Vector Length

Deformation approaches a metre in SW Fiordland, well in excess of the 0.15 metres 95% accuracy requirement of the Cadastral and Basic Geospatial networks. The maximum deformation is in the same direction as the ongoing national deformation, so that the total deformation in this area since the datum was defined is about 1 metre.

The impact of the earthquake on the local accuracy can be assessed in terms of the differential of the deformation vector with respect to position. At a given point the effect of deformation on a short vector (x,y) can be expressed as

$$\begin{pmatrix} x_d \\ y_d \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} \delta_{xx} & \delta_{xy} \\ \delta_{yx} & \delta_{yy} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

where (x_d,y_d) is the vector after deformation. The matrix holds the differentials of the deformation field, so δ_{xx} is the differential of the x component of the vector with respect to the x coordinate, and so on.

The local accuracy is concerned with the vector error on a line between two points. In particular we are concerned with the vector error compared with the length of the line, or equivalently, the effect on unit vector. This will clearly vary according to the bearing of the unit vector. We are concerned with the maximum value of this error at the point. This is expressed in terms of the differential components as:

$$d = \left(\left(\frac{A+B}{2} \right) + \left(\left(\frac{A-B}{2} \right)^2 + C^2 \right)^{1/2} \right)^{1/2}$$

where

$$A = \delta_{xx}.\delta_{xx} + \delta_{yx}.\delta_{yx}$$
$$B = \delta_{xy}.\delta_{xy} + \delta_{yy}.\delta_{yy}$$
$$C = \delta_{xx}.\delta_{xy} + \delta_{yx}.\delta_{yy}$$

The differential terms can be derived numerically from the gridded deformation model. The resulting distortion d is shown in Figure 4, expressed in parts per 10^8.

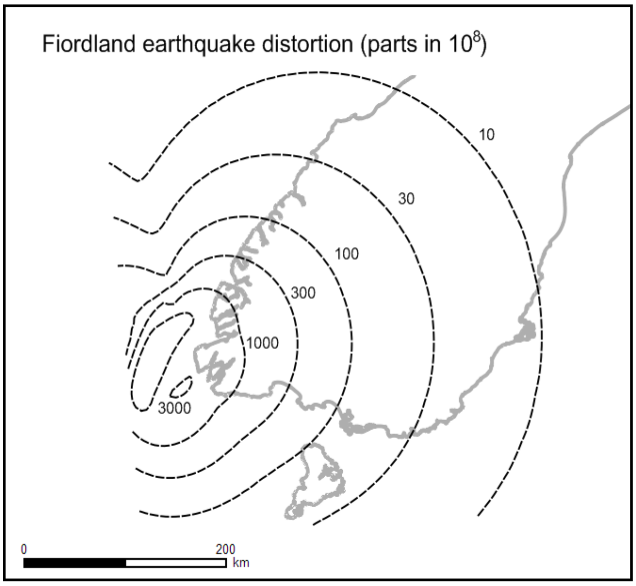

Figure 4: Fiordland Earthquake Distortion

The local accuracy requirement for the cadastral and basic geospatial networks is 5000 parts in 10^8 (ignoring the distance independent component). This earthquake has not generated distortions this large anywhere on the surface. This is because the top of the model fault plane is 5 km deep, and also because the most intense deformation is offshore, where these accuracy requirements do not sensibly apply.

This earthquake has not significantly compromised user's local accuracy requirements anywhere.

This means that in this case the deformation can be completely accounted for in a "forward" patch. There is no advantage to users in changing the reference coordinates.

4.2 Extents of a patch

The patch deformation model must try to meet the accuracy requirements of the deformation modelling network, essentially a network accuracy of 0.05m, and a local relative accuracy of 10 parts in 10^8.

The patch model must extend over at least the areas in which the deformation exceeds these requirements. In fact it should extend further, since the coordinates of geodetic points may already include errors of close to this magnitude from their original definition.

How much deformation can a coordinate tolerate without compromising its accuracy requirements? This will depend on how much better than the specifications its actual error is. The impact of the deformation on the accuracy of the coordinate is defined by the non-central χ^2 distribution.

This is illustrated in Figure 5, which shows how much deformation a coordinate can tolerate without compromising its specified 95% confidence limit as a function of the actual 95% confidence limit of the coordinates from its original definition. Both the actual confidence limit and the allowable deformation are expressed as multiples of the specification.

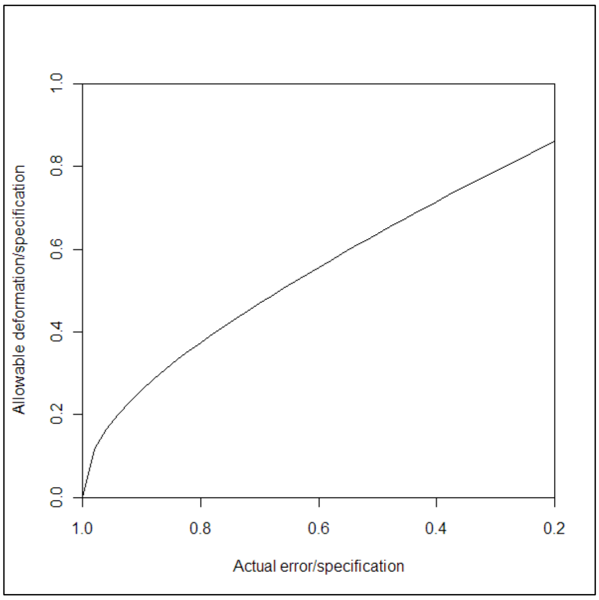

Figure 5: Tolerable Deformation of a coordinate

As an example, a point in the regional deformation monitoring network has a network accuracy specification of 0.1 m at the 95% confidence level. If it was originally surveyed with an accuracy of 0.08 m (95% confidence), then the point can be shifted by up to 0.37 times the tolerance (0.037 m) and we will still be 95% confident that the point lies within 0.1 m of the unadjusted coordinate.

Adjusting the survey data for the southern half of the South Island finds all the stations of the national monitoring network achieving a 95% confidence limit on coordinates of better than 0.015 m, which is 0.3 times the 0.050 m specified for these points.

While this may be optimistic, it seems reasonable to expect that most coordinates at least achieve a tolerance 0.8 times better than the specification. This gives an allowable deformation of 40% of the specification for the national deformation modelling network. The required model accuracy is therefore 0.02 m and 4 parts in 10^8. Of these the local relative accuracy requirement is more demanding, requiring that the deformation patch extends to 450 km from the epicentre of the earthquake and covers half of the South Island of New Zealand.

4.3 Resolution of the patch model

The patch deformation is defined by the deformation at a set of control points between which the deformation is calculated by linear interpolation. Because we are using linear interpolation, the potential error in the approximation is controlled by the second differential of the deformation with respect to distance.

We can estimate the resolution needed to represent the deformation at a point in the preliminary deformation grid by considering the points around it. Figure 6 shows a point $p_{1,1}$ at which the resolution is being calculated. The deformation at this point is compared with that interpolated using bilinear interpolation based on the grid points of the square around it, ($p_{0,0}$, $p_{0,2}$, $p_{2,0}$, $p_{2,2}$). Because it is in the centre of this square, its interpolated value is simply the average of the values at the corners. From this we can calculate δ, the vector difference between the actual and interpolated deformation at $p_{1,1}$.

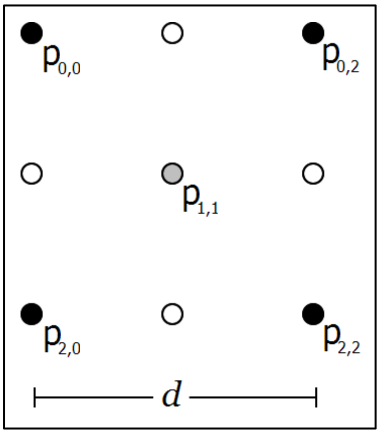

Figure 6: Deformation Grid

If δ is greater than the accuracy we are trying to achieve t, then we need to reduce the grid size, d, to attain the required accuracy. Because the error δ depends on the second differential with respect to distance, the grid size required to achieve the accuracy is calculated as

$$d_{acc} = (t/\delta)^{1/2} \,.\, d$$

The accuracy we are wanting is the same as that used to determine the extents of the patch, that is 0.02 m and 4 parts in $10^{8.}$

Applying this calculation to the preliminary deformation grid we find that the finest resolution of grid required to represent the data has a 170 m spacing. However this is located at sea. Over the land area of New Zealand the finest spacing required is about 300 m.

The extents the grid is required to cover is about 480 km by 480 km, so expressing the patch as a regular grid will require about 2,500,000 data points.

We can estimate the number of points a triangulated patch would require to achieve this accuracy. The point $p_{1,1}$ represents an area of the grid of $d^2/4$. In this area the triangulation will have a spacing of d_{acc}, so each point in the triangle will command an area of $0.75.d_{acc}^2$.

Dividing the area of the grid square by the area covered by a triangulation point gives the approximate number of triangulation points in the square as $d^2/(3.\ d_{acc}^2)$. This can be summed for each of the grid squares in the area of the patch, ignoring the points that are not over land. This gives a total of about 47000 triangulation points.

An alternative to using a triangulation is to build up the patch using several grids of different resolutions, with a fine resolution near the epicentre and coarser resolution for the far field deformation. For example we could use grid of resolution 300 m, 1 km, 5 km, and 10 km. These grids would require about 92000, 50000, 5000, and 2000 points respectively, a total of 150,000 grid points.

Using a multiple grid patch model may be preferable to using a triangulation model even though it has about three times as many points. There are two reasons for this. Firstly, grids are computationally much more efficient, and can be stored more compactly. Secondly, calculations that do not involve points close to the epicentre will not need to use the large 300 m and 1 km grids at all, so for these points the grid model will be much more efficient.

5. CONCLUSION

The 2009 Fiordland earthquake has resulted in significant deformation which must be taken into account to retain the integrity of the NZGD2000 datum.

Although there is quite significant deformation generated by the earthquake, this has not compromised the local accuracy requirements for most users of the geodetic system. This is for two reasons. Firstly, the fault plane is at a depth of 5 km, with most of the fault slip at greater depths, and secondly, the most intense deformation is offshore.

The network accuracy requirements defined by the standards for the cadastral and basic geospatial networks are compromised. Points have moved up to about 1m on the land area of New Zealand. However this is not much greater than the errors in the reference coordinates which the user community already tolerates arising from the ongoing national deformation.

Based on these observations the datum can be patched with a “forward” deformation patch – the earthquake deformation will be entirely represented by a deformation model, and the “epoch 2000” reference coordinates of geodetic marks will not be changed. This means that GIS data sets will not require coordinate updates.

Nonetheless, it may not be long before the total deformation accumulated nationally since 2000.0 exceeds the tolerance of sections of the geospatial community, and a large scale update of coordinates becomes desirable. At that time the accumulation of the national deformation as well as the effects of this, and potentially other, deformation events will be applied to the reference coordinates.

To preserve the accuracy of the datum the patch model will be quite extensive, covering about half of the South Island. At this stage it is proposed that it is represented by a set of grid deformation models, using a fine grid near the epicentre, where there is intense deformation, and a series of coarser grids to represent the deformation at greater distance from the epicentre. This provides a good compromise between accuracy, size of the model, and efficiency of computation of the deformation in geodetic calculations.

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