Toitu te
Land whenua
Information
New Zealand

Implementation of a Deformation Model for NZGD2000

OSG Technical Report 20
Office of the Surveyor-General

18 August 2003

Contents

Foreword

Land Information New Zealand (LINZ) (Toitu te Whenua) was established in July 1996. It is a government department with roles and responsibilities in the following key areas:

Regulatory Responsibilities	**LINZ Regulatory Groups**
National spatial reference system and cadastral survey infrastructure	Office of the Surveyor-General
Topographic and hydrographic information	National Topographic/Hydrographic Authority
Land Titles	Office of the Registrar-General of Land
Crown Property and setting rules for rating valuations	Property Regulatory Group

The main role of the department is a regulatory one, to set guidelines and standards and manage contracts for carrying out the day to day business associated with each of the key areas.

LINZ also offers a range of services to customers related to land titles, survey plans and Crown property. Land Titles and Survey services are carried out by the Operations Group based in LINZ processing centres throughout New Zealand.

LINZ overarching objective is to be recognised as a world leader in providing land and seabed information services.

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IMPLEMENTATION OF A NEW ZEALAND DEFORMATION MODEL FOR NZGD2000

1 Introduction

The New Zealand Geodetic Datum 2000 (NZGD2000) is officially defined as a semi-dynamic datum [*Grant et al*, 1999, *Grant and Blick*, 1998, *Office of the Surveyor General*, 2000]. This means that it comprises both a spatial reference frame at a specific time (the reference epoch, ie 1 January 2000 or 2000.0), and a model of how positions change over time. Using this model observations and coordinates observed at other times can be related to the positions of the marks at the reference epoch. Note that while the model has been previously referred to as a velocity model, it is better termed a deformation model because its principal purpose is to predict position, not to predict velocity. For the purposes of this discussion it is referred to as a deformation model.

While the datum is officially defined as semi-dynamic, the deformation model has not yet been published. An initial deformation model that defines a velocity field for New Zealand has been developed by Geological and Nuclear Sciences (GNS) [*Beavan and Haines*, 2001], and is used within LINZ.

This document presents some of the options and issues associated with the implementation of a deformation model, and proposes a more advanced model that can be used.

2 Properties of deformation model

2.1 *Spatial format*

The model spatial definition of deformation must be able to reflect the true deformation field with an adequate resolution. This may include both the long term deformation trend due to plate tectonic movements, and spatially discrete events such as the effect of earthquakes.

The model could be defined to include surface fault ruptures. This would depend upon the extent to which fault movement is reflected by the deformation field, and the extent to which it is represented by changing the official coordinates. This issue is discussed in section 3 below.

To reflect this spatial complexity the deformation model must be defined by dividing the area covered into a number of regions, and defining interpolation functions within each region.

Three possible options for this breakdown are:

Model	Advantage	Disadvantage
Simple rectangular grid	• Very simple and quick to calculate. • Grid interpolation software is simple and widely available.	• Very inefficient for representing discontinuous model, it would require an extremely dense grid.
Complex grid (eg GNS curvilinear grid [*Beavan and Haines*, 2001])	• By structuring a curvilinear grid to reflect the NZ tectonic regime, the model is able to reflect broad scale deformation well with a relatively coarse grid.	• Complex specialist software is required to interpolate. • Relatively slow and expensive to calculate. • Unable to represent spatial discontinuity.
Triangulated or other irregular grid	• Able to represent arbitrary levels of complexity and accommodate variable density of grid points. • Software for interpolating on a triangular grid is available, though it is unclear if any standards relating to this form of model exist.	• Relatively slow and expensive to calculate compared to a rectangular grid.

The simple rectangular grid is the preferred option for the broad scale deformation field, as it is well understood and there are standard formats and implementations of grids. It is also very efficient to calculate deformation at any point on the grid, mainly because it is very simple to identify which grid cell a point lies in.

Note that this model is preferred for publishing the deformation – it is not necessarily the model that will be used to calculate a deformation field. For example the current velocity model has been developed on a complex grid, which has then been interpolated onto a regular grid for use in LINZ software.

2.2 *Temporal format*

The current model defines a constant velocity at each point. This will not remain valid because:

- the model is based on data of limited spatial and temporal extent. Over time the imperfections in the model will become apparent and will require a revised model (though potentially still a constant velocity model);

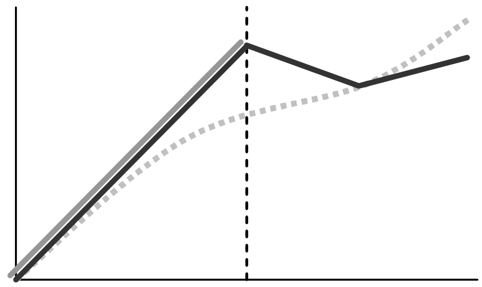
- the velocity field itself may not be constant; and

- there may be discrete deformation events which are not representative of or represented by the long term trends.

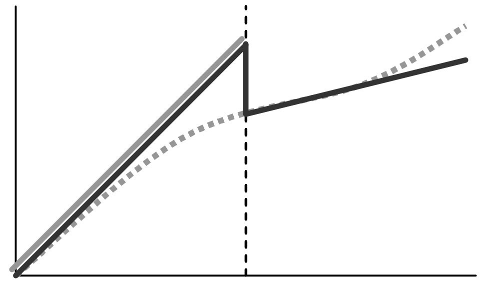
It therefore follows that the model will require periodic updates.

As new information improves our knowledge of the deformation field there are several options as to how this could be implemented. Some options are illustrated in the following table. This shows plots of one-dimensional position on the vertical axis against time on the horizontal axis for each option. The dotted grey line shows the actual movement of the mark. The vertical dashed line indicates the time of an update to the deformation model. The grey solid line is the initial deformation model, and the black solid line is the revised deformation model after the update is applied. These diagrams show just one update – over the course of time more updates will be applied in the same fashion.

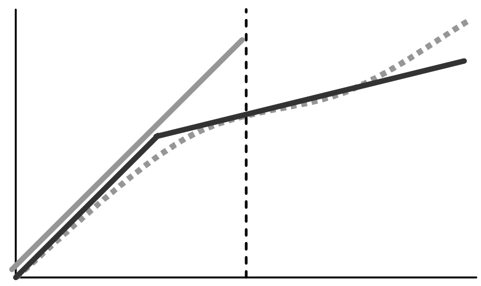
Option 1: Steer to the new model

When new information is available the mark is "steered" back towards its believed position and velocity over an arbitrary period of time. • The original model is preserved • The model is temporally continuous • The model does not always represent our best estimate of the mark position or velocity • The model becomes increasingly complex over time, as it contains more and more sections.	

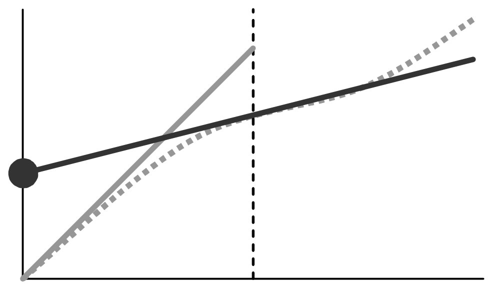
Option 2: Jump to the new model

The original model is preserved. The new deformation model replaces the original for all future times. • The original model is preserved • The model is not temporally continuous • The model always represents the best estimates of current and future position and velocity • The model becomes increasingly complex over time, as it contains more and more sections.	

Option 3: Revise the previous model

The new information is used to revise the previous model. This may involve some complexity of the model (ie a non constant velocity) • The original model is not necessarily retained, though older deformations are unlikely to change, and may be deliberately preserved. • The model is temporally continuous • The model always represents the best estimate of past and future position and velocity • The model becomes increasingly complex over time, as it contains more and more sections.	

Option 4: Ignore the previous model

The new information is used to calculate a new constant velocity model. The old model is discarded. Where necessary the reference epoch coordinates of marks are updated to reflect the backward extrapolation of the new model. • The original model is not retained • The original model is invalidated by the change in reference epoch coordinates • The model is temporally continuous • The model represents the best estimate of current and future position and velocity • The model remains simple, it is always a simple constant velocity model	

Factors that distinguish these models are

- **Temporal continuity**. When we implement a new model, is it necessary that the calculated position of a mark should be temporally continuous. There is a precedent for not requiring this in the spatial domain. When we calculate new coordinates for a mark as a result of new survey data we simply replace the existing coordinate with the new value. There is no requirement to gradually change the coordinate from the old to the new. Old adjustments become invalid, in that if they are to be repeated then they need to use the new values for the coordinates in order to be authoritative. A temporal discontinuity in the deformation model is not a problem for adjustments and observations, since most observations are relative measurements between marks and are considered as being at a single point in time.

- **Preservation of previous versions of the deformation model**. Options 1 and 2 retain the historical model up until the time that the new model is implemented. It is considered authoritative and unalterable for that period. The alternative view is to allow historical models to be replaced with a new authoritative version, as in Options 3 and 4. This may be a better alternative for defining the authoritative four-dimensional path of marks through space and time. This path is changed when the reference epoch coordinate of the mark is updated (for example by a readjustment), so there is little reason for not allowing it to change by updating the deformation model.

- **Validity of observations**. Where and when the deformation model diverges from reality our observations of reality will not fit the model. The model that most closely fits our understanding of reality at the time of the adjustment will obtain the best result from the adjustment. This is option 3.

- **Complexity of the model**. Apart from Option 4 (ignore previous model) these models all become more complex over time as successive updates are added to the model. Option 3 (revise previous model) is potentially more complex than the first two, as it may involve differently timed steps at different locations. This could be resolved by defining a specific set of times at which the deformation is defined (for example defining updates at regular intervals such as once per year).

All of these options define the deformation as a series of periods of constant velocity rather than a (possibly) more realistic model in which the rate of deformation changes gradually. This is considered the best option as we rarely have enough information to define a much more complex model, though this may become possible as the network of continuously tracking GPS receivers grows. It is also very simple and efficient to calculate the deformation at a given time from an offset (at a specified time) and a constant velocity.

The simplest way to represent the deformation is by specifying the deformation at a series of epochs (say 2000, 2001, … or 2000, 2005, …). At each epoch we define the deformation with a spatial model (such as a grid). The deformation at other times, eg 2000.5, is then obtained by interpolating between the two nearest epochs. The complete deformation model must also include velocity models for the periods before the first epoch and after the last epoch.

This is analogous to the international representation of the geomagnetic field, details of which may be found at http://www.ngdc.noaa.gov/IAGA/wg8/igrf2000.html. For example, the International Geomagnetic Reference Field (IGRF) model for 2000 to 2005 comprises at present a set of definitive models for five yearly intervals from 1900 to 1995, a non-definitive model for 2000 and a rate of change model for predicting for the five years 2000 to 2005. In 2005 the definitive model for 2000 will be specified, as will a non-definitive model for 2005 and a velocity model to predict to 2010.

3 Discrete events

The deformation model that is currently used by LINZ cannot depict earthquakes, major landslides, and other discrete deformation events, because it predicts a constant velocity, and is spatially coarse. When a deformation event involves a spatial discontinuity at the surface, such as a fault rupture, it may be difficult to represent with a deformation model at all. If the deformation model fails to match the actual deformation then the survey marks are moved to new locations in terms of the datum – in effect they are new marks. Three potential options for representing deformation events in the datum are:

Option 1: Densify the model

Redefining the national deformation model with a higher density of points, at least in the vicinity of the mark. This is only sensibly possible with the triangulated model, as this model can readily accommodate a locally dense grid.

Option 2: Define a local "patch" for the model

Publish a local perturbation to the deformation model. Although this could reflect the nature of the national model (for example a finer grid model, or a triangulated model), it need not do so. To ensure spatial continuity of the total model (ie national model plus patches) the perturbing model would have zero deformation at its boundaries within the national model. To use the deformation model would require identifying which patches applied in a given area and adding any applicable patch deformations to the deformation of the national model.

Option 3: Change node coordinates

With this option the national model would remain unaltered, but the coordinates of nodes influenced by the local event would be updated. This would ensure that deformation calculations remained simple, but may require some form of versioning of nodes or coordinates

Option 2, the use of a patch, seems most practical. A patch is a localised deformation model defined over the area and time for which the deformation perturbation exists. For example, in the event of an earthquake the patch would include the region around the area in which significant deformation was detected. The patch may define ongoing postseismic deformation for a period after the earthquake in which anomalous deformation is detectable. The patch would also define a permanent final offset resulting from the earthquake, which would apply to all coordinates after the event.

In order to model the complexity of deformation associated with local deformation events the patch would need to use a triangulated or irregular model. Grid type models would not be suitable. An alternative approach would be to use a more specific mathematical model of the process, such as modelling a dislocation on one or more fault planes. However such models often do not reflect the measured offsets accurately, and are generally complex to evaluate. They may be used for extrapolating the measured surface deformation model where observations are not available in order to develop the perturbation model.

If we use patches then the deformation model will be able to reflect discrete events as well as we are able to measure them. The epoch 2000.0 coordinates will not change, and we will be able to combine observations before and after the event in a single adjustment in which the differences due to deformation are fully accounted for by the deformation model.

A difficulty with this approach is that the official coordinates of the datum, in this case the 2000.0 coordinates, will not closely reflect the current relative positions of the marks. For example, adjacent points on opposite sides of a fault line may have moved metres relative to one another during an earthquake. The 2000.0 coordinates without the patch model applied will give relative positions that don't even nearly fit current observations. Users will only find coordinates useful if they have applied the patch to them.

The datum and deformation model will ideally meet two requirements – firstly to model the discrete events well enough that old and new observations can be used together, and secondly to easily provide users with coordinates that are sensible in terms of the current positions of marks in the ground.

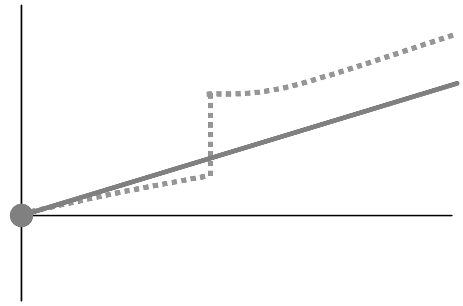
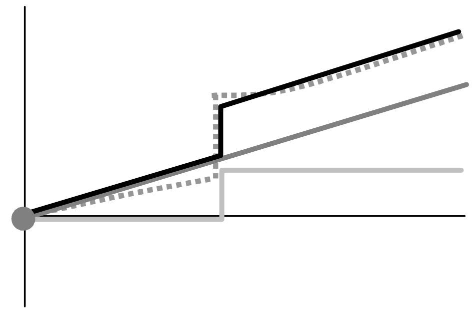
The proposed approach to handling this is to make a paradigm shift. Instead of thinking of NZGD2000 as a set of coordinates of marks defined at 2000.0 and a deformation model for defining coordinates at other times, we think of it as a set of base coordinates and a deformation model that in combination define the positions of marks at any required time. The difference between these two approaches is that the second approach does not require the deformation model to have a zero deformation at the reference epoch of 2000.0, and the base coordinates are not where we believe the marks were at 2000.0.

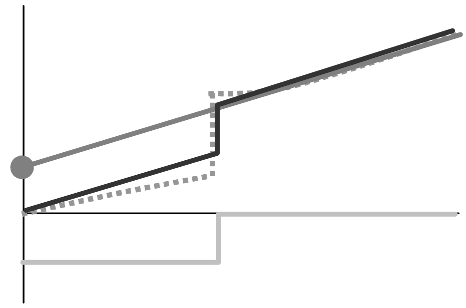
This paradigm shift works very well for patches. The proposed approach is to calculate new base coordinates for the points affected by discrete event, and define a patch deformation model that is used to calculate the coordinates *before* the event – the patch is in effect a negative deformation that applies in the past. Note that the new coordinates are not the current coordinates of the mark, as the national long term deformation model still applies. They are the 2000.0 coordinates with the discrete offset from the event applied to them. It is only points affected by deformation events (and therefore subject to patches) for which the base epoch deformation is non-zero.

The principal advantage of this approach is that calculating current coordinates (the coordinates most often required) does not involve calculating the patch deformation –

it is simply defined in terms of the base epoch coordinate and the national deformation model. This is a significant advantage, as the national model is relatively simple to calculate, whereas the patch deformation may not be.

These two paradigms are illustrated in the following diagrams. Here the dotted grey line is the actual (one-dimensional) position of a mark plotted against time. The mark is affected by a discrete deformation event. The grey dot is the base epoch coordinate for the mark. The dark grey line is the trajectory of the mark defined by the base epoch coordinate and the national deformation model. The light grey line is the patch deformation model, which in this case is simply a fixed offset at about the time of the event. The black line shows the trajectory of the mark as defined by the deformation model including the patch.

Before the event is incorporated into the datum: The datum (base coordinate plus deformation model) does not represent the position of the mark after the event.	
After the event is incorporated into the datum: Patch model. The patch deformation is zero before the event, so that coordinates for times before the event may be simply calculated from the base epoch coordinate and the national deformation model. After the event the patch is non-zero, so calculating coordinates for this period requires evaluating the patch deformation.	

After the event is incorporated into the datum: "Negative" patch model. The base epoch coordinate is changed to include the offset due to the deformation event. The patch deformation model is non-zero at the base epoch, and so the datum trajectory (base epoch coordinate plus total deformation model) is the same as the model above. The patch deformation is zero after the event, so that coordinates for times after the event may be simply calculated from the base epoch coordinate and the national deformation model.	

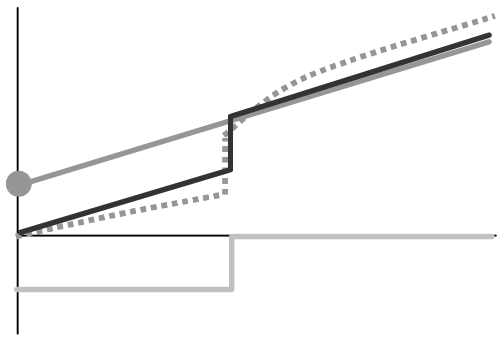
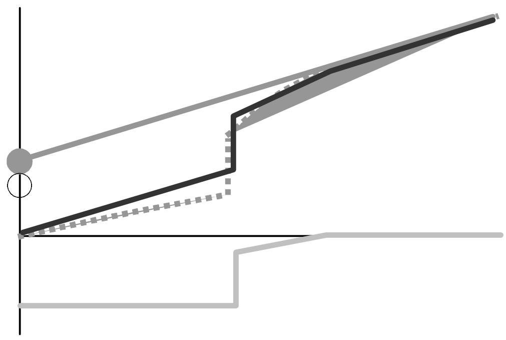
This "negative patch" works well for users of the datum who want static coordinates (such as most users of GIS systems). These users expect positions to be locally accurate – that is they represent the current relative positions of marks well. However they also intuitively expect these coordinates to change following significant discrete deformation events. That is exactly the behaviour of the base epoch coordinates with the "negative patch" paradigm.

This approach also provides benefits for the future. There will come a time when the "2000.0" coordinates become unacceptably different from the current absolute positions of marks for most users. When this happens it could be handled by changing the base epoch of the datum to a new date, say 2010.0, and redefining the national component of the deformation model to have a non-zero offset at 2000. Since the change to the base coordinates is defined by the (simple) national deformation model it is easy to apply to client databases to align them with the new datum "base" coordinates.

Not all discrete events may be able to be represented by an instantaneous offset at a specific time. Earthquakes may be followed by significant post-seismic deformation continuing for months or even years after the event.

Where there is ongoing anomalous deformation it may still be adequate to represent the event with a discrete offset at a specific time. If there are no surveys significantly affected by the ongoing deformation (either because they are before or after the period of deformation, or because they are insensitive to it) then there is no need to model the ongoing deformation. The most that may be required is to revise the patch model and the affected base coordinates if the initially published models do not reflect the total deformation.

If it is necessary to model the ongoing deformation then the patch model will need to include more than one epoch. When each new version of the patch is defined it is likely to redefine the total deformation from the event, which means that there will need to be a corresponding adjustment to the base coordinates. This is illustrated below.

Initial patch model This represents the deformation initially observed, but not the total deformation.	
Second version of the patch model This model is generated after the ongoing deformation has been observed. The new patch model includes an ongoing deformation component. The base coordinate has also been changed to reflect the new estimate of the total deformation from the event.	

4 Proposed deformation model

The proposed implementation of a deformation model for NZGD2000 is as follows:

1. The deformation model will comprise a national ongoing deformation model and zero or more "patches" representing specific deformation events. Both models may predict both horizontal and vertical deformation.

2. The national component will define the deformation at specific epochs (eg 2000, 2005, 2010). The interval between epochs is yet to be decided. Deformation at other times is determined by simple linear interpolation between epochs.

3. The national component will include two velocity models, one for extrapolating times before the first epoch, and one for extrapolating times after the last epoch (including the present).

4. The epoch deformation models and the velocity models will be defined on a regular grid (in terms of latitude and longitude). The deformation will be interpolated within the grid by bilinear interpolation.

5. When a new deformation model is released it may redefine any of the previous epoch deformation models and the velocity models if there is new information to justify doing so.

6. Specific deformation events, such as earthquakes, will be added to the model as "patches", which represent the perturbation to the deformation field due to the event. The patch models will be defined to span the spatial extents of the significant and measurable deformation. The deformation on the boundary of the patch model will be zero where it lies within the national model.

7. The patch model will define the deformation before the event relative to the current position – in effect the patch is a negative deformation event. The base epoch coordinates of all affected marks (ie the official datum coordinates) will be updated to reflect the deformation due to the event. The patch models will be assumed to have zero velocities before and after the event.

8. Where an event includes ongoing anomalous deformation the patch model may include several epochs between which the deformation will be interpolated. The models will always have a final deformation of zero. This may mean that several versions of the patch are published as new information is obtained.

9. When a new patch model is published there will be a corresponding update to the coordinates of affected marks to represent the revised total effect of the deformation event on the coordinates. New models may be published either because there has been a new deformation event, because there has been ongoing deformation from an old event, or because better information has become available about an old event.

10. Each patch model will be based on a triangulated network in order to be able to represent arbitrarily complex deformation (possibly even including discrete fault offsets).

11. For points beyond the NZ deformation model a compatible accepted global model of deformation (such as ITRF2000 or NUVEL1A) will be used. If the global model defines velocities in terms of polar rotations of the tectonic plates then the model will need a mechanism to choose the appropriate plate to use at any given location in order to calculate deformations.

5 Issues

5.1 *Latency*

There may be considerable delay between a deformation event (or a large-scale variation in the deformation field) and it being detected, measured, and implemented in a new deformation model. As the network of continuously operating GPS receivers densifies the latency may decrease, at least in terms of detection of large scale changes in the velocity field. For example the recent "slow earthquake" event near Gisborne was identified by the **PositioNZ** tracking station network. Had these not been in place it would not have been recognised until a high accuracy large scale resurvey of the survey network in the area.

For discrete events the deformation will often be complex, and our initial understanding of it may be incomplete. It is possible that patch models may have several versions as new information becomes available before we are satisfied that the anomalous deformation has stopped and has been adequately defined by the model.

5.2 *Confidence*

The deformation model will have regions and times of differing confidence. For example where we know that there has been a deformation event then our confidence will be less, because we will probably not have sufficient observations to define the deformations accurately for the location and duration of the event. Also our confidence will degrade when predicting for times significantly before or after the period over which the data generating the model was observed.

This uncertainty and other appropriate metadata should be published with the model.

5.3 *Vertical movement*

The current model only defines horizontal velocity. In the future it may be appropriate to include vertical deformation also. Perceived issues with this are:

- in many areas the vertical deformation field is expected to be dominated by local events rather than long term trends; and

- vertical deformation may include significant cyclical seasonal and artificially induced variations in addition to longer term trends.

None the less there are long term broad scale linear trends which are detectable at well founded marks on rocks. These should be incorporated into the deformation model. The continuous GPS receiver network may provide some insight into any such trends, even if the spatial resolution of the network is coarse.

6 References

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Grant, D.B. and G.H. Blick: A new geocentric datum for New Zealand (NZGD2000), *New Zealand Surveyor, No. 288. Pp 40-42*, 1998

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Appendix A: Implementation in Landonline

The coordinate reference system implementation in **Land*online*** (the LINZ computerised survey and title system) does not provide for a dynamic or semi-dynamic datum. The datum definition (for geodetic datums) consists simply of an ellipsoid definition.

The dynamic nature of the datum is incorporated into geodetic adjustments. This is done by specifying a parameter which causes the adjustment to extract a definition of the deformation model from a table of large adjustment coefficients (ie adjustment information that is too complex to be expressed simply as a number or text string). This data is simply input data for the adjustment. It is not explicitly associated with a datum, and there is no status, version, or other metadata associated with it to define its applicability or authority. If a new model is defined then it will be up to the user to ensure those future adjustments include the new deformation model (or indeed any deformation model). The only assurance that this will happen is that the default geodetic adjustment method (upon which geodetic adjustments are generally based) will include the appropriate model. However the user is readily able to change this if they wish.

Currently the geodetic adjustment is only able to use a simple grid based constant velocity deformation model. Obviously this will not be appropriate for long-term use, as it will need to include a definition of the deformation that allows submodels for different time periods, and handles patches for discrete events. To implement this will require defining a format for defining that the complete deformation model and recording the adjustment function to handle the more complex deformation model.

The handling of patches further highlights the limitations of the **Land*online*** model, since the proposed implementation will change the base epoch coordinates for marks affected by the patch. Defining new coordinates is simple enough - they can be added to the coordinate table and authorised, and thereafter effectively replace the previous coordinates. Since many thousands of coordinates (both cadastral and geodetic) will be affected when the patch is applied a new process for bulk updates may be required.

The bigger concern in **Land*online*** is that there is no way of identifying which coordinates are affected by the patch. The patch (or in fact any new deformation model) represents a new version of the datum. To represent this information properly **Land*online*** would allow versioning of datums and should link each coordinate with a datum and version. Ideally the deformation model would be explicitly associated explicitly associated with the datum and version.

One other implication of patch models is that cadastral adjustments will need to take account of the deformation model. Currently this is not done - since cadastral adjustments are of limited extent and relatively low accuracy the effects of the current national velocity model are not significant. The only factor that may need recognition is the rotation defined by the deformation, since that directly (and potentially significantly) affects to cadastral bearing "observations". However patch models may include significant local distortion, and even discontinuities (at fault lines), which would significantly affect cadastral observations (and hence adjustments). Adding deformation to cadastral adjustments is a simple code change to the **Land*online*** adjustment module.