Implementation of a Semi-Dynamic Datum for New Zealand

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Abstract. In 1998 New Zealand implemented a new geocentric datum, New Zealand Geodetic Datum 2000 (NZGD2000). NZGD2000 is defined as a 'semi-dynamic' datum, and accounts for the significant ongoing earth deformation in New Zealand. Published coordinates are defined in terms of their values at the reference epoch of 1 January 2000. Deformation is provided for by a deformation model which allows positions at other times to be extrapolated from the reference epoch coordinates. The deformation model currently used was generated from repeated GPS survey observations and assumes a constant velocity through time. As we move further from the reference epoch we need a more complex model in order to predict positions with sufficient accuracy. The proposed model has two components, 1) a national deformation component using a latitude/longitude grid which is spatially and temporally continuous, and 2) a number of 'patches' used to model specific deformation events such as earthquakes. The national model will comprise a series deformation grids at fixed time intervals between which the deformation can be interpolated. The patches are localised triangulation based models of limited extent and time that can represent arbitrarily complex deformation. They will be implemented as 'negative deformation models' – the reference epoch coordinates of marks will be updated to reflect the deformation due to the event, and the patch will be used to calculate coordinates prior to the event. This is seen as meeting both the needs of the geodetic community, who require accurate coordinates at arbitrary times, and the mapping community, who prefer static coordinates, but expect them to reflect major deformation events.

Keywords. Datum, velocity model, deformation, New Zealand

1 Introduction

In 1998 Land Information New Zealand (LINZ) implemented a new geocentric datum for New Zealand, New Zealand Geodetic Datum 2000 (NZGD2000) with a reference epoch of 1 January 2000 (2000.0). A major conceptual departure from the definition of the previous national datum, (New Zealand Geodetic Datum 1949) and other international datums is that NZGD2000 accommodates the effects of crustal deformation. This is achieved by applying a deformation model when generating new coordinates. This use of the deformation model to generate coordinates for points at a specified reference epoch implements what LINZ refers to as a semi-dynamic datum. For many users, it has the appearance of a static datum, which facilitates use of the datum by the GIS and mapping community who do not have the tools to manage constantly changing coordinates. (In the future, a fully dynamic datum will provide for the deformation model to be made generally available to users to generate coordinates at any user-specified epoch).

NZGD2000 is realised in terms of ITRF96 and uses the GRS80 ellipsoid, see Grant and Blick (1998) and Grant et al (1999). Coordinates for 29 primary 1st Order 2000 network stations were generated from 5 repeat GPS surveys made between 1992 and 1998 (Office of the Surveyor-General (2000)). Data from these and other repeat surveys were used to generate a horizontal deformation model by the Institute of Geological and Nuclear Sciences (GNS) (Beavan and Haines (2001)). The deformation model (Figure 1) is used to account for broad scale crustal deformation across New Zealand, primarily due to the effects of plate tectonics.

The current deformation model used for the definition of NZGD2000 assumes a constant deformation velocity through time. The surveys used to determine the deformation model are now five years old. As time passes, errors in the determination of the velocities used in the deformation model will lead to increasing errors in the calculated position of marks in terms of the reference epoch of 2000.0. In effect, the spatial accuracy of the datum is steadily degrading. Additionally, the datum and effectiveness of the deformation model may be degraded by localised and temporally non-linear deformation, eg earthquakes. The following issues are now considered:

- How much error can be tolerated before a new deformation model is required?
- When there is local and spatially complex deformation, how much should be accommodated by the deformation model, and how much should be accommodated by changing the reference epoch (2000.0) coordinates?
- What temporal model should be used to accommodate non-linear changes in deformation?

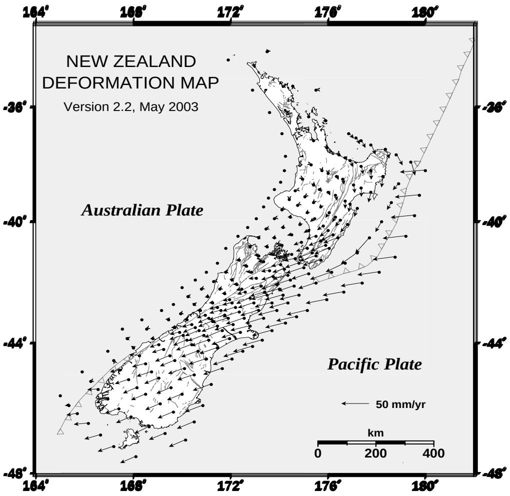

Fig. 1. New Zealand Deformation Model (Beavan and Haines (2001)).

This paper considers these issues and presents New Zealand's option for implementing a semi-dynamic datum. A full description of the various options that were considered is available in Office of the Surveyor-General (2003a).

2 How Much Error can be Tolerated in the Deformation Model?

A general principle in the development of NZGD2000 is that: '*the accuracy of a mark's coordinates relative to adjacent marks of the next highest order shall be dependent on the distance between them and shall not exceed 0.05m horizontally and 0.15m vertically*' (Office of the Surveyor-General (2003b)).

It follows that the coordinate error and deformation model must be of sufficient accuracy to enable these accuracy requirements to continue to be achieved over time. Where the computed positions of marks using the deformation model, differ from the surveyed positions by greater than these limits, consideration will need to be given to refining the deformation model.

3 Spatial Format of Deformation Model

The spatial definition of deformation must be able to reflect the true deformation field with an adequate resolution. A model should include both the long term deformation trends and potentially discrete events such as earthquakes, where the model definition could include surface fault ruptures. This would depend upon the extent to which fault movement should be reflected by the deformation field, and the extent to which it should be represented by changing the coordinates of survey marks.

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 options for this breakdown were considered (Office of the Surveyor-General (2003a)):

- Simple rectangular grid
- Complex grid (eg curvilinear grid)
- Triangulated or other irregular grid

The simple rectangular grid was selected for the national deformation model, 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). However where discrete events such as earthquakes occur, more complex models may be required and a triangulated grid may be more appropriate (see section 5).

4 Temporal Format of Deformation Model

The current deformation model defines a constant velocity at each point. This will not remain valid for long however, as:

- 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 using a constant velocity);
- The deformation field itself may not be constant; and
- There may be discrete deformation events (eg earthquakes) which are not representative of, or represented by, the long-term trends.

It therefore follows that the model will require periodic updates. The following models were considered (Office of the Surveyor-General (2003a)):

Steer to the new model: When new information is available the mark is 'steered' back towards its believed position and velocity over a period of time.

Jump to the new model: The original model is preserved. The new deformation model replaces the original for all future times. A discontinuity is introduced at the time of model update.

Revise the previous model: The new information is used to revise the previous model. The new model may not necessarily have constant velocity.

Ignore previous model: The new information is used to calculate a new constant velocity deformation model. The old model is discarded. Reference epoch coordinates are updated to reflect the backward extrapolation of the new model.

These models differ in the extent to which coordinates and velocities prior to the update are allowed to change. A key consideration for a national geodetic datum is the need to maintain the coherence of coordinates for a range of users over an extended period of time. Therefore, both the spatial and temporal continuity of the model are important.

Of the options considered, the third option, **Revise the previous model**, is adopted (Figure 2).

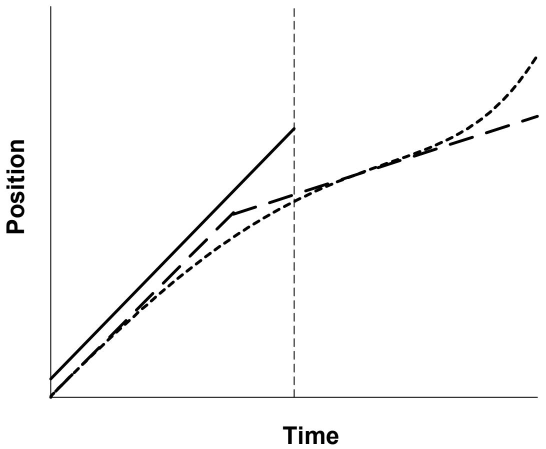

Fig. 2. One dimensional position of a mark against time. Dotted line shows the actual movement of the mark. The solid line is the initial deformation model and the dashed line is the revised deformation model after the time of updating, indicated by the vertical dashed line.

In such a model the original model is not necessarily retained, though older deformations are unlikely to change, and may be deliberately preserved. In this option the most recently published model always represents the best estimate of past and future deformation.

5 Accommodation of Discrete Events

Earthquakes, major landslides, and other discrete deformation events are ignored by the current deformation model. Where the event involves spatial discontinuity, such as a fault rupture, it may be difficult to handle with a deformation model at all. Where and when the deformation model fails to match the actual deformation, the survey marks are effectively moved to new logical locations – in effect the old mark appears in a new position. This complicates management of the survey network.

Three potential options for representing deformation events in the datum were considered (Office of the Surveyor-General (2003a)):

Densify the model: Redefining the national deformation model with a higher density of points, at least in the vicinity of the deformation event. This is only sensibly possible with the triangulated model, which is not the preferred option for the national model.

Define a local 'patch' for the model: Publish a local perturbation to the national deformation model. To ensure spatial continuity of the total model (ie national model plus patches) the perturbing model would have zero deformation at its boundaries (except where it extends to the edge of the national model). To calculate the deformation at a given time and place would require identifying which patches, if any, apply and adding the deformation from them to that from the national model.

Change coordinates: With this option the national model would remain unaltered, but the coordinates of all points influenced by the local event would be updated. This would ensure that deformation calculations remained simple, but may require some form of versioning of marks and coordinates. Where property boundary marks are managed in terms of the geodetic system (as in New Zealand), a very large number of marks may be affected.

Of these options the use of a patch is considered most practical. A patch is essentially a localised deformation model defined over the area and time for which the deformation perturbation exists. For an earthquake, the area of the patch would be the region around the epicentre in which significant coseismic and post-seismic deformation was detectable. The model may define ongoing post-seismic deformation for a period after the earthquake during which, anomalous post-seismic deformation is detectable. The model 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 similar irregular model.

If we use patches then the existing deformation model will be able to reflect discrete events, at least as well as we are able to measure them. The reference epoch coordinates could be retained, 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 marks 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 do not fit current observations. Users will only find coordinates useful if they have applied the patch to derive them. Use of the deformation model and its patches thus becomes virtually essential for all users.

What is required is datum and deformation models that meet two requirements – firstly they model the discrete event well enough that old and new observations can be used together, and secondly that they easily provide users with coordinates that are sensible in terms of the current positions of marks. The proposed approach to handling this is to use patches 'in reverse'. Instead of using patches to correct unchanging base or reference epoch coordinates to their current positions, we will update the reference epoch coordinates to reflect the effects of the perturbing deformation, and use the patch as a 'negative' deformation to determine coordinates for times before the deformation event.

The principal advantage of this approach is that calculating current coordinates (the coordinates most often required by users) does not involve calculating the patch deformation – it is simply defined in terms of the base epoch coordinate and the (relatively simple) national deformation model. However most coordinates remain static, which is a user requirement of most GIS and mapping users. The only coordinates that change are those directly affected by earthquakes and similar events, and most users would intuitively expect these to change.

The implementation of the 'patch' is illustrated in the following two diagrams. In Figure 3 the deformation event is not incorporated into the deformation model. The dotted line is the actual (one dimensional) position of the mark plotted against time and the dot the base epoch coordinate for the mark. The mark is affected by a discrete deformation event. The line is the trajectory of the mark defined by the base epoch coordinate and the national deformation model. The datum (base coordinate plus deformation model) does not represent the position of the mark after the deformation event.

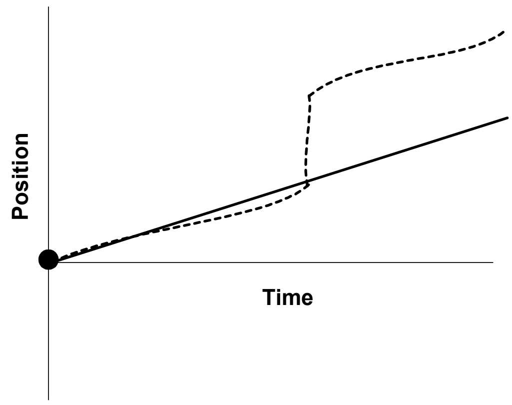

Fig 3. Coordinate of mark defined by deformation model that does not include the deformation event.

In Figure 4 the deformation event is incorporated into the deformation model. The long dashed line is the patch deformation model, which in this case is simply a fixed offset at about the time of the event. The short dashed line shows the trajectory of the mark as defined by the deformation model, which includes the patch. The base epoch coordinate is changed to include the offset calculated from the patch. 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 new base epoch coordinate and the national deformation model.

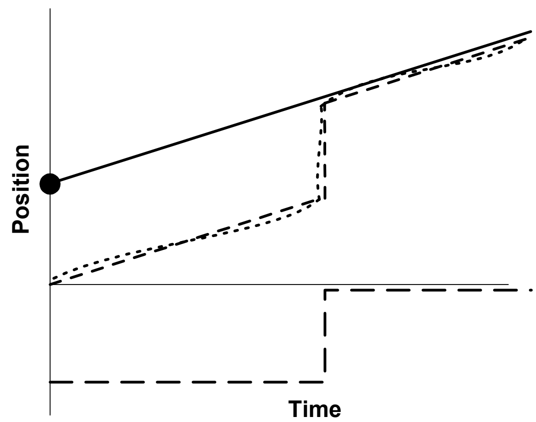

Fig 4. Coordinate of mark defined by deformation model incorporating a patch to model the deformation event.

Not all discrete events will 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 (eg, because all such surveys are either before or after the period of deformation) then there is no need to model that 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.

6 Other Issues to Consider

6.1 Accommodating Vertical Deformation

The current model only defines horizontal deformation. When data from the repeated 1st order surveys and other repeat surveys were used to derive the deformation model any vertical velocities calculated were disregarded and vertical velocities assumed to be zero. However vertical motion, although generally smaller than horizontal motion, is known to exist and this motion must be accommodated in the future.

Unfortunately the national vertical deformation trends are in many places obscured by much larger localised episodic or cyclic events, such as response to geothermal steam extraction, drainage, and so on. This means that in many areas the datum will not be able to reflect the vertical deformation well, and even using a patch type of approach may be too complicated to realise.

Nonetheless the national trends should be discernable by careful selection of the survey marks used to define it. This will be integrated into the national model by simply including vertical as well as horizontal deformation components.

6.2 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 New Zealand's national network of continuously operating GPS receivers densifies, this latency may decrease, at least for the national model.

For discrete events the deformation will often be complex, and our initial understanding of it may be incomplete. Patch models may require several versions as new information becomes available.

6.3 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 not initially have sufficient observations to define the deformations accurately for the location and duration of the event. Also our confidence will reduce when extrapolating well beyond the period over which the data generating the model was observed. This uncertainty and other appropriate metadata should be published with the model.

6.4 Extension Offshore

The current velocity model only provides deformations for the New Zealand land area. If we wish to calculate deformations for offshore locations, the Chatham Islands, etc, we will need to include a definition of a more extensive model (possibly a global model). For a global model it may be preferable to express the velocity as a global rotational velocity rather than east and north components of velocity. For points beyond the NZ (national) deformation model a compatible and accepted global model of deformation will be used.

6.5 Changing the Reference Epoch

Ultimately there will come a time when coordinates referenced to epoch 2000.0 become inconveniently different from the true current positions of coordinates to the extent that the difficulties of managing the differences outweigh the desire of many users for static coordinates. At that time the national deformation model can be used to migrate the coordinates to a new reference epoch – effectively a new datum. It may also be used to transform users GIS databases to the new positions.

7 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 an arbi-

trary number of 'patches' representing specific deformation events.

2) The national component will define the deformation at specific epochs (eg 2000, 2005, 2010). The time between epochs is to be determined. Deformation at other times is determined by linear interpolation between epochs.
3) The national component will include two deformation models, one for extrapolating times before the first epoch, and one for extrapolating times after the last epoch (including the present).
4) The deformation models will be defined on a rectangular 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 published, it may redefine any of the previous epoch deformation 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 (except where it is also the boundary of 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 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 on the coordinates. New models may be published either because there has been a new deformation event, because there has been ongoing deformation of a previous event, or because better information has become available about a previous event.
10) Each patch model will be based on a triangulated network in order to be able to represent arbitrarily complex deformation such as localised deformation across a fault trace.
11) Both the national component and the patches may define horizontal and vertical deformation.

8 Summary

The current deformation model using a constant velocity and implemented in NZGD2000 provides a short term solution to manage the effects of crustal motion on the datum. However as we move further away from the datum's reference epoch, 2000.0, a number of limitations with this simple model will become apparent. A deformation model has been proposed that will overcome these limitations and ensure that NZGD2000 remains a modern accurate geodetic datum that serves New Zealand's spatial needs into the future.

9 References

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