The development and implementation of New Zealand Geodetic Datum 2000

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ABSTRACT

There has been clear evidence in recent years that New Zealand Geodetic Datum 1949 is inadequate for some current and emerging applications. A new geocentric datum, New Zealand Geodetic Datum 2000 (NZGD2000), designed and built during 1998, is realised through ITRF96 and uses the GRS80 ellipsoid. Coordinates for 29 primary 1st Order 2000 network stations, were generated at an epoch of 1996 using data from 5 repeat GPS surveys made between 1992 and 1998. Data from these and other repeat surveys are used to generate a velocity model to account for crustal deformation across New Zealand, primarily due effects of plate tectonics. The velocity model has been used to generate coordinates at epoch 2000.0 (the reference date for the new datum of 1 January 2000) for the 1996 dataset. The velocity model will also be used to ensure that Land Information New Zealand can generate epoch 2000 coordinates from observations made at other times and to allow other specialised users to generate up-to-date coordinates for times other than the reference epoch. As the geodetic network is densified, new marks will be incorporated into the new datum. The new datum will be implemented in conjunction with the implementation of the New Zealand Survey and Title Automation Programme, Land*online*. A description of the new datum, its design, and implementation will be presented.

1. Introduction

A national geodetic datum provides a country with a local implementation of global coordinate systems. It minimises the risk to government and other users of having core spatial datasets defined in terms of different and inconsistent coordinate reference systems. It enables a wide range of spatial applications to be supported in a manner that is consistent with international standards and best practice.

When New Zealand Geodetic Datum 1949 (NZGD49) was established, it complied with the then current recommendations of the International Association of Geodesy (IAG). It used what could be called the global positioning system of the day - geodetic astronomy - to establish the datum origin and orientation. As much as the technology of the day allowed, it was an effective implementation of an internationally accepted terrestrial reference system.

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Although we now know the difference between the centre of the NZGD49 ellipsoid and the centre of mass of the earth, until the advent of satellite geodesy in the 1960's and 1970's, this difference was not really measurable and was therefore of no practical consequence. The same is true of many other national datums around the world that were developed around this time.

It was only in the late 1980's and 1990's that increasing use of a satellite based geodetic measuring system - the Global Positioning System (GPS) - began to impact on the utility of the national datums of many countries including New Zealand. The inconsistency between NZGD49 and international reference systems started to adversely affect navigation, scientific applications and routine spatial data management.

Prior to this, internal distortions of the datum, steadily increasing at the rate of half a metre per decade due to earth deformation, also began to impact on geodetic processing. The introduction of Electronic Distance Measurement (EDM) highlighted variations in the definition of scale and the new observations were inconsistent with the distances derived from coordinates of geodetic stations. GPS, with its potential to efficiently meet existing survey accuracy requirements over very long distances, has significantly increased this problem.

2. Dynamic models

One of the key decisions required for the new datum was the choice of model for managing the actual or apparent motion of geodetic stations - mainly as a result of earth deformation but also coordinate updates resulting from new geodetic surveys and changes to international reference systems.

New Zealand lies across the obliquely convergent boundary of the Pacific and Australian plates. To the north east, the Pacific plate is subducted under the Australian Plate. To the south-west the Australian plate is subducted under the Pacific plate. In central New Zealand, the oblique collision of continental material has resulted in a combination of uplift and strike slip motion. Motion of about 40 to 55 mm per year occurs on the boundary through New Zealand. Modern GPS observation and processing techniques allow accuracies better than 0.1 ppm which, in many parts of New Zealand, is equivalent to a few months' earth deformation.

2.1 Static Datum

The classical long term method of maintaining accurate coordinates in the presence of earth dynamics is to generate static datums which are subsequently replaced by new datums as their errors become unacceptable. A static datum is one in which the datum is effectively defined by the coordinates of key geodetic stations. The coordinates of these stations are held fixed. NZGD49 is an example of a static datum with the 1st Order trig coordinates having being defined in 1949 and subsequently held fixed.

Taking the short term view (which could cover a significant proportion of a surveyor's working life) the issue of dynamics can often be ignored. Datum changes can appear to be isolated events that disturb the status quo of fixed coordinates. If we take a longer term view, we see that the dynamics are being modelled by a step function. The flat parts of the steps are comfortable for users but the jumps from one step to another are traumatic. The dynamics of the datum are modelled in a jerky and unpredictable way.

The timing of a datum change is difficult. Users wanting high accuracy will find that an old datum does not meet their needs. Users that are about to make large investments in spatial data will want the datum to change before they invest rather than just afterwards. On the other hand, users that have already made large investments, or users that have low absolute accuracy needs, will want the old datum preserved as long as possible. If the datum does change, they may refuse to switch over thus increasing confusion in the spatial data marketplace.

2.2 Dynamic Datum

If we take a long term view of the datum and dependent databases, we can see that dynamics must eventually be included in the model. We need to be able to accurately relate observations to coordinates. We need to be able to match coordinate sets based on observations that were made at different times. Changes in survey technology mean that we can no longer assume that coordinate sets are in terms of on the most local geodetic control marks. We need to be able to interpolate the dynamics in space and time.

An alternative to the series of fixed datums is a datum that includes the motion of control stations and coordinate axes in the datum definition. For example, the IERS Terrestrial Reference Frames in which velocities are assigned to station coordinates and transformations to other reference frames allow for the relative rotation of reference frame axes.

Under this option, a national datum can be defined by its relationship to a dynamic global reference system such as the International Terrestrial Reference System (ITRS). Time dependencies are included in the definition such as station velocities, rates of change for transformation parameters, etc. Coordinates, velocities, transformation parameters, etc., change as required to ensure that the datum axes, and thus the coordinates of points, closely maintain their defined relationship to those of the global reference system.

Therefore, a dynamic datum is one where the coordinates of geodetic control stations change in some consistent and organised way as:

1. the control stations move due to earth deformation;
2. spatial accuracy of the geodetic network is increased; and
3 (perhaps but not necessarily) as underlying global reference frames are refined.

Such a datum is four dimensional and the coordinates of a point are not defined correctly without a time tag. Mechanisms for management of the fourth dimension (time) are built into the dynamic datum and must also be built into systems that depend on the datum for high accuracy positioning. This adds to the set-up costs for these systems. However, long term maintenance costs will be reduced because the maintenance of spatial accuracy can be automated.

2.3 Semi-dynamic Datum

Initially at least, many users of the datum will reject the costs involved in making their systems fully four dimensional. Therefore, a variant of the dynamic datum model was proposed as a transitional arrangement to minimise impact on users. This is referred to as a "semi-dynamic datum".

Under this option, the datum is defined by its relationship to a dynamic global reference system at a specified epoch. A velocity model is used to transform coordinates or observations to or from this epoch. Coordinates at the reference epoch may change slightly on acceptance of new survey data in order to reflect the improved determination of their reference epoch position. This will maintain the defined relationship between the datum as a whole and the global reference system. Such changes will primarily be as a result of improved accuracy although larger coordinate jumps may be required as a result of earthquakes or localised mark movement.

Modelling of more uniform time dependencies are applied during calculations in order to remove systematic errors due to earth deformation. This modelling is based on the velocity model which effectively acts as a time-dependent transformation. All results are converted back to the reference epoch and expressed in terms of that epoch. The velocity model itself may be updated periodically which may, in turn, require some change to reference epoch coordinates.

This model allows users - especially those not requiring high accuracy - to maintain a fixed coordinate system in their databases. Over time, users may find that new spatial data entering the database needs to be transformed back to the epoch of database coordinates using the velocity model. In some circumstances where "true-of-date" coordinates are required, database outputs may be transformed to the epoch of date.

The extent to which users will need to apply the velocity model will depend on their accuracy requirements. For 1.0 metre accuracy (assuming no major earthquakes), it may be a decade before station velocities become significant. Similarly, for surveys of limited spatial extent. However, if tools such as GPS are used for engineering or cadastral surveys over tens or hundreds of kilometres (eg, a high precision wide area differential GPS network) use of the velocity model to transform results to the reference epoch will be required as a matter or course.

3. Datum Decisions

Land Information NZ (1998a) outlines the recommendations for development of a new geocentric datum to be known as New Zealand Geodetic Datum 2000 (NZGD2000). It also provides a detailed analysis of the business drivers and user issues that were considered in making the recommendations.

The recommendations, subsequently accepted as Land Information NZ policy by the Office of the Surveyor General, are:

1. The new datum for New Zealand will be know as 'New Zealand Geodetic Datum 2000' (NZGD2000).

2. NZGD2000 will be based on the International Terrestrial Reference System (ITRS). Initial realisation will use the International Terrestrial Reference Frame 1996 (ITRF96) at epoch 1 January 2000 (2000.0) which has a geocentric origin.

3. The ellipsoid associated with the initial realisation of NZGD2000 will be the Geodetic Reference System 1980 (GRS80 ellipsoid).

4. All points coordinated in terms of NZGD2000 will have coordinates defined at epoch 1 January 2000 (2000.0).

5. Generalised motions of points in New Zealand with respect to ITRF96 will be modelled to:

    - ensure that observations made at a date other than the reference epoch (2000.0) can be used to generate epoch 2000.0 coordinates; and

    - allow up-to-date coordinates at a date other than epoch 2000.0 to be generated from epoch 2000.0 coordinates.

6. Coordinates of geodetic marks in terms of NZGD2000 will not be fixed. Coordinates will be updated as required to account for new ITRF's, new observations, earthquakes, or localised mark movement.

The business plan for implementing these decisions is detailed in Land Information NZ (1998b).

4. Connecting New Zealand to the ITRS

4.1 Survey Data

The new geocentric datum for New Zealand been developed using only GPS observations to coordinate the stations. The following sub-sections describe the GPS observation methods and data collected.

4.1.1 Observed First Order Data

During September 1992 Land Information New Zealand's predecessor, the Department of Survey & Land Information (DOSLI) occupied 6 stations as an initial pilot on processing approximately 100 km GPS baselines to provide the assurance that reliable results could be obtained.

In March 1993 a network of 30 stations was observed by DOSLI.

In March 1994 a campaign to observe those stations missed in the 1993 campaign was conducted by DOSLI.

From the experience gained from the collection and processing of the 1992 to 1994 data, a slightly modified network of first order stations was designed. In March of 1995, 1996 and

1997 this new network was observed with all stations being simultaneously occupied. In September of 1998 the network was observed in three stages using a mixture of receivers.

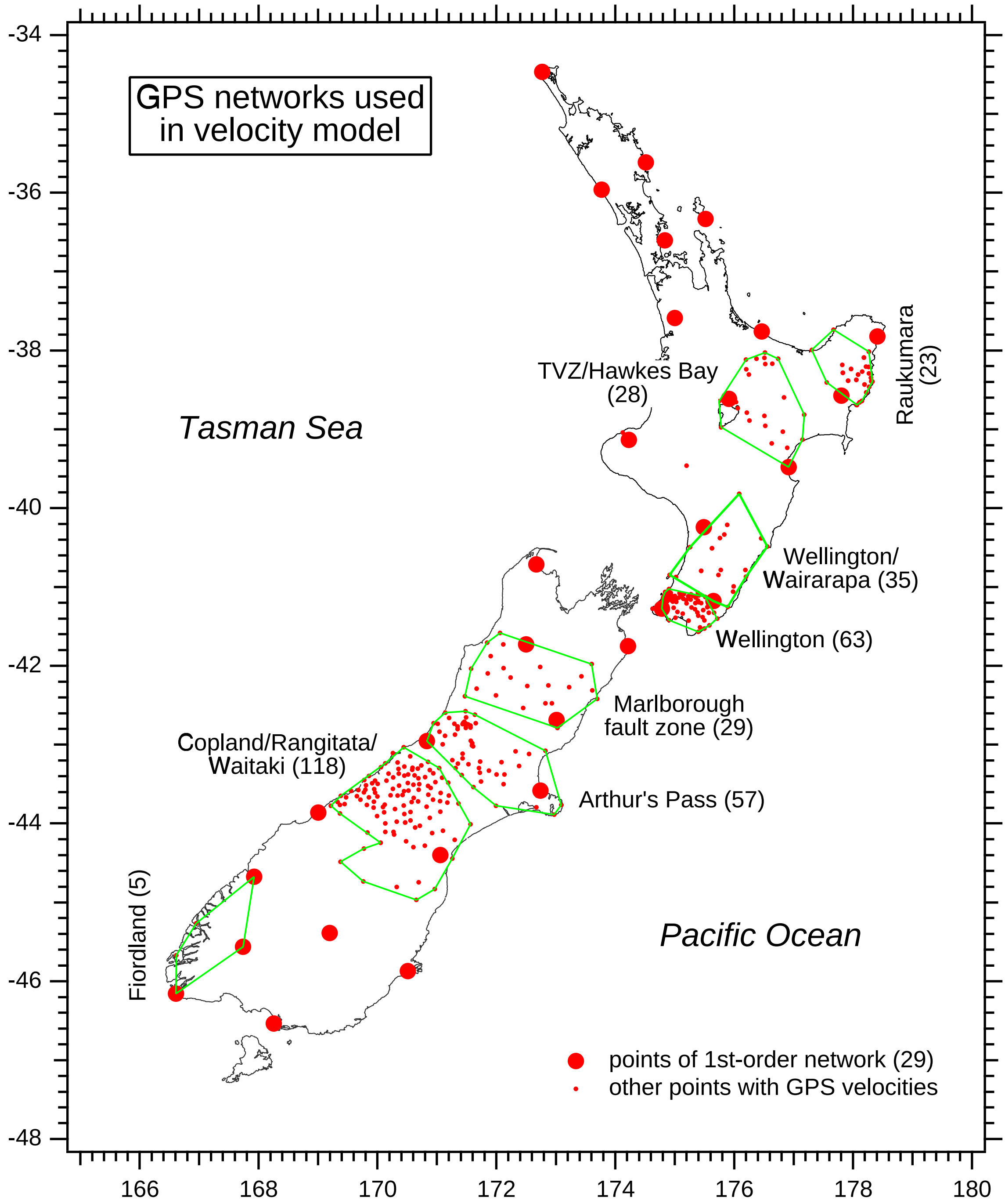

Figure 1 GPS observed marks used to develop the New Zealand Velocity Model

4.1.2 Observed Second Order Data

In 1995 and 1996 the Second order network was designed and surveyed. All 1st Order NZGD49 stations were included in the survey with a significant number being observed to 2nd Order 2000 standard. Other than the reoccupation of the second order stations during the survey of the third and lower Order 2000 stations there has not been a national campaign to the re-observe the entire 2nd Order 2000 network.

4.1.3 Observed Third and Lower Order Data

Since 1995 the break down of the second Order 2000 network has been undertaken in regional campaigns through the third and fourth Order 2000 networks. The South Island is nearing completion with the main focus now on the North Island.

4.2 Processing the GPS data

4.2.1 First Order Data Processing

The processing of the 1992 through 1998 first order data was completed under contract by Dr Peter Morgan at the University of Canberra, Australia. The contract required that the data supplied be processed using the GAMIT/GLOBK suite of software and that the results were to be supplied in terms of ITRF96 at the mid-campaign epoch of 1996.5. Below is a brief summary of the processing methodology taken from the contract report (Morgan and Pearse, 1999).

The data was processed using the fiducial approach, which meant processing the New Zealand data with data from the IGS (International GPS Service for Geodynamics) permanent tracking network. In 1998 a large number of improvements were made to GAMIT/GLOBK suite which warranted the reprocessing of earlier GAMIT/GLOBK solutions. Some of the processing options implemented were:

- Modelling the satellite clocks
- Using the IGS Antenna Phase Model for satellite elevation but the not azimuth terms
- The ambiguities were left as real numbers rather than fixed to integers
- The Whar solid earth tide model with K_1 frequency terms but not Pole or Ocean tide models
- The Satellite Attitude was modelled for all days except when re-positioning or orientation manoeuvres were performed
- Stochastic atmospheres using the Saastamoinen model as the a-priori delay and the Neil mapping function at 2 hourly intervals
- The orbital parameters and modelling used the Berne model with IGS combined solutions orbits as a-priori values
- The Earth Rotation Parameters estimated via the two polar motion components (x and y) and the rotation component (UT_1)

The coordinates for the first order stations had 0.003m maximum uncertainties (1σ) in all 3 components (XYZ) at the epoch of 1996.5 in terms of ITRF96.

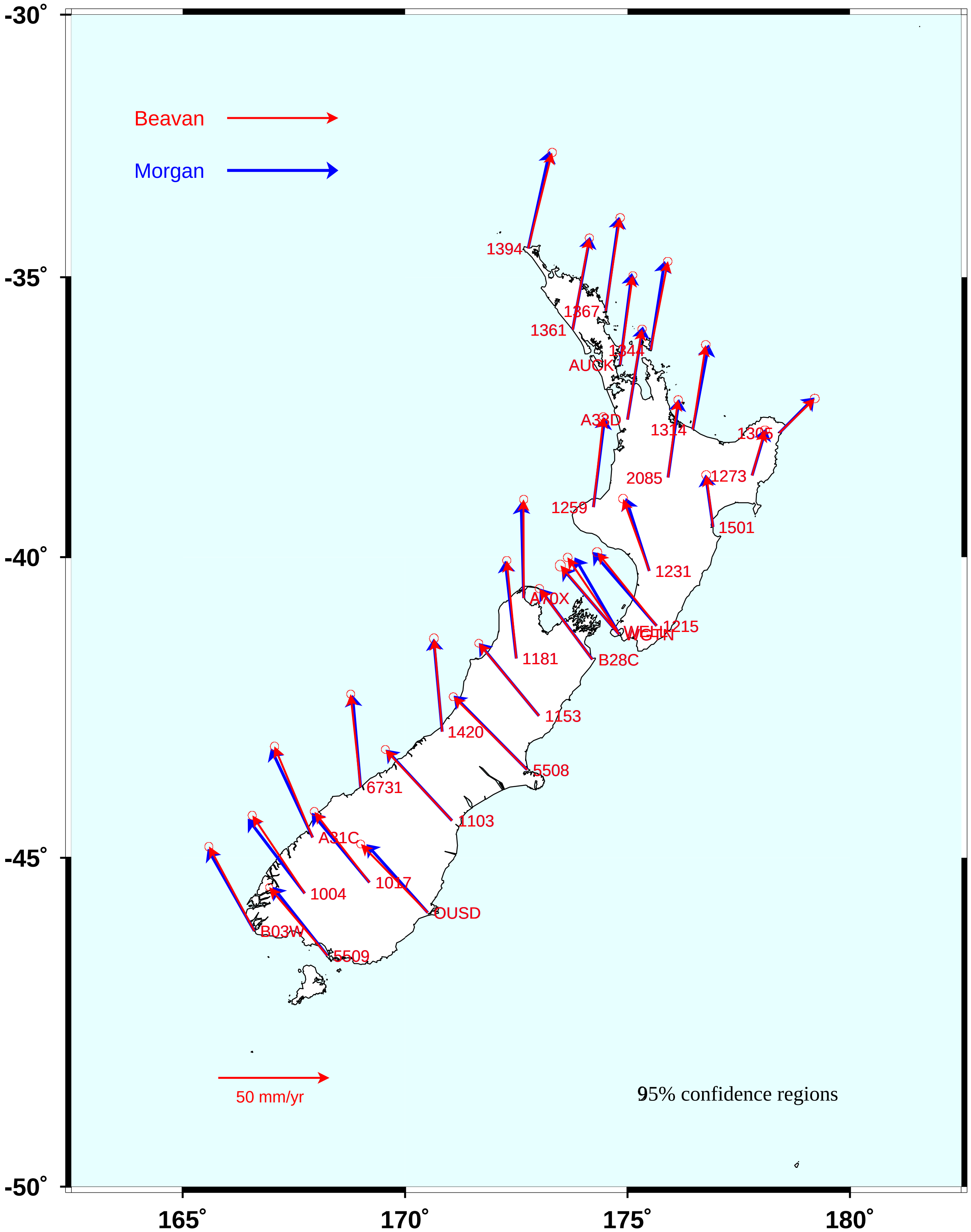

Figure 2 Comparison of Morgan & Beavan velocity estimations

4.2.2 Second and lower Order Data Processing

The data collected for the second Order network was processed in house using the Trimble GPSurvey software. The third and fourth Order networks have been broken into smaller regional networks. The individual contractors who won the Geodetic Control Survey contracts for each of the regional networks processed the data in the proprietary software associated with the geodetic quality receivers they used.

The results for these second, third and fourth Order networks were at the mid-observation epoch of each individual campaign.

4.3 Calculating Station Velocities

4.3.1 Dynamics of the ITRS

For the determination of a station's position in an ITRF, the station is assigned to a specific tectonic plate. New Zealand's ITRF96 station Wellington (WELL) is assigned to the Australian plate (Boucher et al., 1998). The Wellington station, like most of New Zealand, is located within the deforming zone between the Australian and Pacific tectonic plates. Assigning Wellington to either plate is incorrect. Current ITRF's accommodate the horizontal velocity of sites on plate boundaries by assigning a larger a priori standard deviation (10 cm/year) to the site's velocity than for sites located on the rigid part of a tectonic plate (3 mm/year) (Boucher et al., 1994). Therefore to improve the reliability of a New Zealand station with respect to an ITRF solution, a specific plate motion or velocity model for New Zealand needed to be developed.

4.3.2 Velocity Model for New Zealand

A contract was let to Dr John Beavan at the Institute of Geological and Nuclear Sciences (GNS) to compute a velocity model of New Zealand from the 1992 through 1998 first Order network data. The LINZ supplied data was supplemented by additional GNS fault monitoring data. A summary of the results and processing methodology taken from the contract report (Beavan, 1998) are presented in this section.

The GPS data was processed in the Bernese software. Repeated GPS observations from more than 300 sites throughout New Zealand have been combined using sophisticated mathematical techniques to produce velocity and strain maps of the whole country. These techniques employ bi-cubic spline interpolation on a curved surface.

The GNS velocity model only contains horizontal components with zero for the vertical component. This is primarily due to there being insufficient data currently available to reliably model the vertical component.

As part of the contracts with Beavan and Morgan they were required to compare their solutions for the coordinates and velocities at the first order stations. As reported in Beavan (1998) the results at epoch 1996.5 from using different processing software and methodologies had maximum coordinate differences of 3.3, 8.2 and 26 mm (NEU) and maximum velocity differences of 1.5, 3.3 and 13.2 mm/yr (NEU).

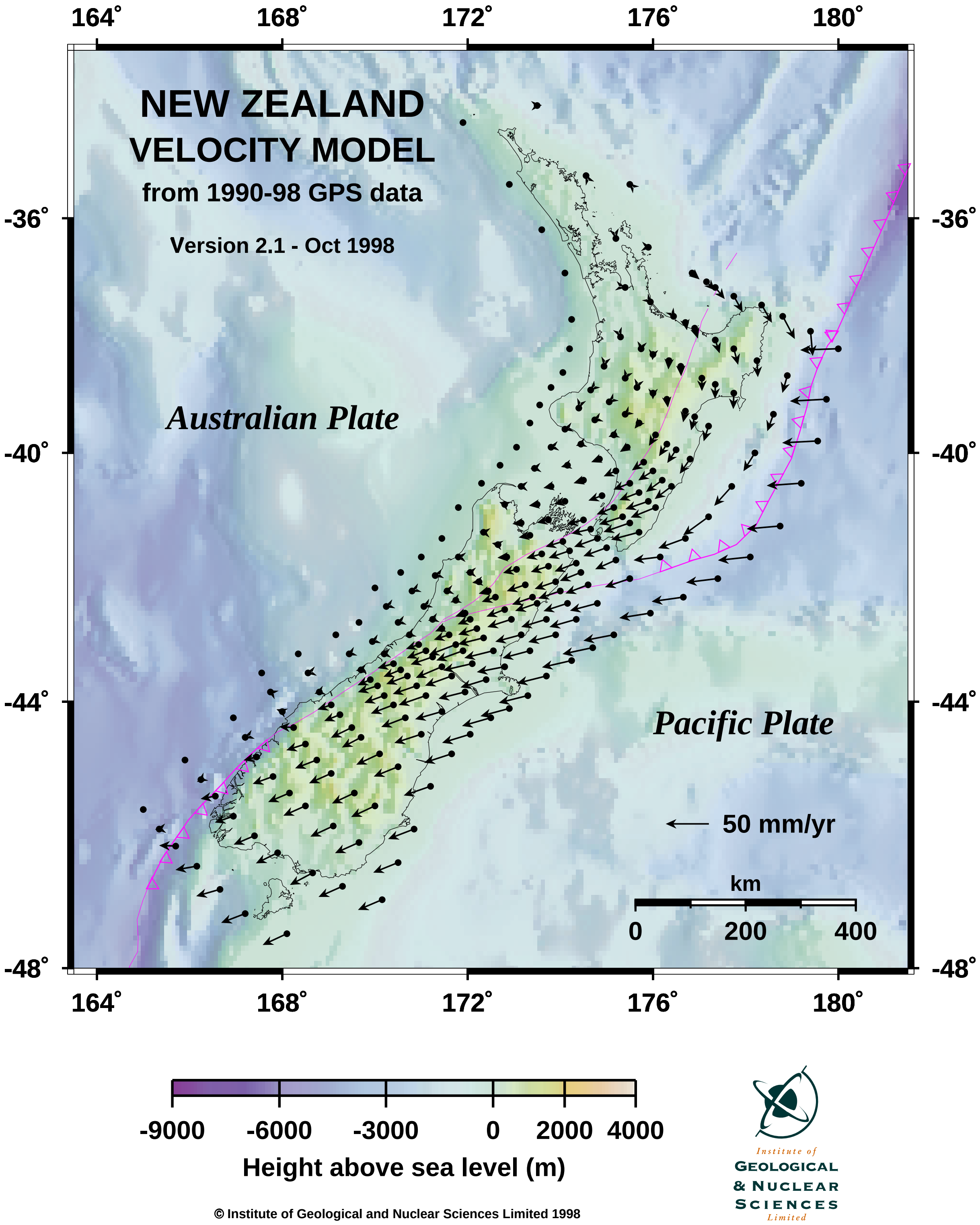

Figure 3 New Zealand Velocity Model

4.4 Computing Epoch 2000.0 Coordinates

4.4.1 First Order Stations

The coordinates as supplied by Morgan were at the mid-observation epoch of 1996.5. These coordinates were then transformed to epoch 2000.0 in terms of ITRF96 using the GNS horizontal velocity model. These epoch 2000.0 coordinates have maximum uncertainties (1σ) of 0.01 m in the XYZ components.

4.4.2 Second and lower Order Stations

The LINZ network adjustment software, SNAP, was used to adjust all the available second, third and fourth order data (baselines) in terms of the first order coordinates at the epoch 2000. Unfortunately the SNAP software does not support Bayesian estimation. Therefore the 1st Order station coordinates were held fixed rather than being weighted by their error estimates.

The second, third and fourth order baselines were transformed from their observation epoch components to their predicted components at the epoch 2000.0 using the GNS velocity model.

A single combined adjustment of all the lower order data was performed to provide a rigorous solution. This adjustment consists of approximately 3100 stations and 78100 baselines.

5. Implementation and Future Goals

5.1 Land*online*

Land Information New Zealand is implementing an integrated automated survey and title system in New Zealand (Dawidowski & Blick, 1998; Winmill, 1998; Haanen & Grant, 1998), called Land*online*. In this system, survey and title transactions will be combined into a single generic land transaction with survey and/or title components.

In this system when fully implemented, cadastral survey data will be submitted in a digital format. The fundamental building block for the survey component of an automated system is a Survey-accurate Digital Cadastre (SDC) with coordinates based on the geodetic network. This will allow efficient electronic validation of new survey data. There is a requirement for a spatial reference system to underpin the integration of all cadastral survey data into a digital database. The development of the Survey-accurate Digital Cadastre will involve the capture and adjustment of parcel dimensions in terms of the new geodetic datum 2000 network. This will enable all boundary points to be assigned geodetic coordinates.

Implementation of Land*online* will commence in March 2000 and will be fully implemented across the country by 2002. The new datum will be implemented as the Land*online* project is rolled out. Cadastral survey data in the new system will be held as longitude and latitude in terms of the new datum.

5.2 National Mapping

A decision is currently being considered on the replacement of the existing national mapping projection. The current projection, New Zealand Map Grid (NZMG) is in terms of NZGD49 and is a unique projection tailored to minimise scale error within the main islands of New Zealand. Options include the development of a new map grid specific to New Zealand in terms of the new datum or adoption of a standard projection such as the Universal Transverse Mercator or Lambert Conformal Conic. A decision on the replacement of NZMG is expected in mid 2000.

5.3 Hydrographic Survey & Charting

New hydrographic charts are in terms of World Geodetic System 1984 (WGS84). For practical charting purposes, this is indistinguishable from NZGD 2000.

New Zealand will submit, by 2006, a claim for its legal continental shelf to the United Nations Commission on the Limits of the Continental Shelf. The Commission acknowledges the rights of states to make submissions in terms of their national geodetic reference systems. However, it also requires coordinates to be supplied in terms of an International Terrestrial Reference System and transformation parameters from any national reference system used to the ITRS. New Zealand's adoption of a new datum based on ITRS will facilitate the preparation of data for its claim.

5.4 New Goals

The New Zealand Geodetic Strategic Business Plan (Land information NZ, 1998b) outlines a 10 year plan for the development of the geodetic system in New Zealand. The first goal of this plan was the development of NZGD2000 - this has now been realised. A number of other key goals, that are dependent on the development of the new datum, are also identified in this plan. These goals include:

- the provision of a cost-effective system that can generate orthometric heights of points in terms of a nationally accepted system to an acceptable and defined accuracy;

- to support multiple projections, and authoritative transformations of coordinates between those projections and the official geometric (three-dimensional) datum, to an acceptable and defined accuracy;

- to enhance the automated cadastral system and extension to include the seabed;

- to consider the implementation of a four-dimensional datum;

- where appropriate, to contribute to and become an integral part of, the global geodetic system;

- to adapt the design and management of the physical network to take greater advantage of the potential efficiencies offered by new technology.

The development and implementation of NZGD2000 is key to the realisation of these goals that will see the implementation and modernisation of the geodetic spatial referencing system in New Zealand over the next 10 years.

6. Maintenance

Because of New Zealand's location across the Pacific/Australian tectonic plate boundary it will be subject to continued crustal deformation across the country of about 5cm/year and the effects of large earthquakes. The development of the New Zealand velocity model will help geodetic management of the effects of ongoing continual crustal deformation of about 5cm/year. However it is expected that this model will not account for all of the deformation, particularly at the detailed level (Blick & Grant, 1997).

In the future a GPS permanent tracking network could control NZGD2000 at the large scale - this option is being considered. Other control points will be required to provide origin for surveys to ensure that unmodelled distortions have not crept into the network. While a surveyor may make GPS observations relative to a base station many tens of kilometres from the site of their survey, they could be required to connect to control in the vicinity of the survey to ensure that the dynamically modelled coordinates in that area reflect the true position of the ground marks. As new survey data comes to hand it is expected that this will be incorporated into the velocity model and the model further refined as required and/or coordinates of datum points at epoch 2000.0 changes to reflect the new data.

The velocity model will not account for the effects of large earthquakes. Following these events, a local re-survey of the geodetic network will be undertaken resulting in changes to the velocity model and epoch 2000.0 coordinates to account for the effects of the earthquake.

In the future it is conceivable that as surveyors make cadastral surveys and submit data in digital format to the Department under the automated system, the observations used to establish and prove the survey origin could also be used to enhance and update the geodetic network. In the future, well defined physical features in the environment (eg corners of building foundations) could possibly be used to densify the control network. In this manner, the effects of crustal deformation over small areas could be monitored and used to improve the velocity model.

Future survey technology (eg, remote sensing) may soon provide the ability to map crustal deformation in detail utilising a few survey marks for calibration and control. The use of Interferometric Synthetic Aperture Radar (InSAR) to interpolate earthquake deformation is an example of what is possible. Utilising such detailed deformation maps along with the enhanced ability to cheaply and precisely fix well defined physical features in the environment could result in reduced need for geodetic control points. These physical features in the environment would thus take over the current function of dense, lower order control marks. Each house corner may essentially become a control point. The potential of this, combined with high resolution remote sensing, could provide an as-built cadastre showing both legal and physical aspects of land ownership.

The future may also see the implementation of a fully dynamic datum, where coordinates change to represent the true positions in the physical world.

7. Conclusions

New Zealand Geodetic Datum 2000 is a significant step forward in meeting New Zealand's future spatial positioning needs. The alignment with the ITRS ensures compliance with international standards. The adoption of a semi-dynamic datum model based on a national velocity model provides for future-proofing of the national datum while minimising the adverse impact on users.

As users increasingly move to digital technology for management of spatial data, the transition to a fully dynamic datum will become more practicable. If international systems such as the ITRS are able in the future to incorporate deformation models at a level more detailed than current plate models, it may be that the concept of national geodetic datums will become redundant. At that stage, the accessibility of international systems and their accuracy and stability at a detailed level, may be such that they can fully meet all national spatial referencing requirements.

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