Going Geocentric - Deformation models for Dynamic (and semi-dynamic) Datums

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• Introduction
• Concepts of 4d datums
• The pros and cons of static, semi-dynamic datum and dynamic datums

Development of Deformation Models
• Incorporating the effects of events such as earthquakes into the model
• New Zealand Case Study (Datum Realisation and Maintenance)
• New Zealand Case Study (Transforming from latest ITRF to national datum)
Introduction
Fundamental Role of Reference Frame
Fundamental Role of Reference Frame

FIG/IAG/UNOOSA Reference Frame in Practice Technical Seminar Rome
– 4-5 May 2012
Requirements of a National Datum

• A coordinate framework that is **accurate, stable, reliable and accessible**

• Direct linkage to International Reference Frames

• **Simple** for users to connect to and use

• Physical infrastructure may include GNSS CORS and traditional geodetic survey marks

• Systems and tools to allow connection to the coordinate reference system and **transformation** of legacy data to the current reference system
Benefits of Going Geocentric

- Compatibility with GPS/GNSS for positioning
- Compatibility with global change monitoring system
- Move towards absolute positioning – measuring position directly in terms of the centre of the Earth
- Well-understood, globally recognised transformation parameters between realisations, or at least common transformation methods
- Any future changes are likely to be small (millimetre to decimetre in absolute terms)
- Can leverage a global community of geodetic expertise
Crustal Dynamics
Temporal and spatial extent of deformation

- Coseismic Deformation
- Postseismic Deformation
- Volcanism
- Slow-Slip Event
- Water Abstraction
- Interseismic deformation
- Post glacial Rebound
- Rigid plate motion
Concepts of a 4D Datum
Datum Types

Static Datum (2D and 3D)
- Coordinates are fixed at a reference epoch
- Does not incorporate the effects of plate tectonics and deformation events
- Coordinates slowly go out of date, need to change periodically which is disruptive

Dynamic datum (4D)
- Incorporates a deformation model to manage changes (plate tectonics and deformation events)
- Coordinates change continuously
- Can be confusing and difficult to manage

Semi - dynamic datum
- Incorporates a deformation model to manage changes (plate tectonics and deformation events)
- Coordinates fixed at a reference epoch
- Change to coordinates is minimised
Constant motion through time

Datum 1

GPS Time Series

Datum 2

Datum 3

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</table>
The dynamic world

The ideal world!
Need to accommodate error in model or changes in deformation
Need to accommodate local and spatially complex deformation
Options - Error in model or changing deformation

Steer to a new model
Jump to the new model
Revise the previous model
Ignore the previous model

Solution
Revise the previous model always preserves the best estimate of past and future position and velocity
The deformation event is not incorporated into the deformation model (dot is the base epoch coordinate of the mark)

The ‘patch’ deformation model – in this case a discrete event

The trajectory of the mark – incorporate the national deformation model and the ‘patch’

The base epoch coordinate is changed to incorporate the offset calculated from the patch

Coordinates for times after the event just use the national deformation model and coordinates before the event include the patch – “reverse patch”
Plot of the daily IGS08 time series at CHAT. Solid red line is the predicted value from the new (2013) version of the NZGD2000 deformation model. Dashed red line is the predicted value from the original deformation model. Note that time series are not corrected for non-tectonic effects such as antenna changes.
Episodic events

Plot of the daily IGS08 time series at GISB. Solid red line is the predicted value from the new (2013) version of the NZGD2000 deformation model. Dashed red line is the predicted value from the original deformation model. Note that time series are not corrected for non-tectonic effects such as antenna changes.
Episodic events - Detrended

Plot of the daily IGS08 time series at GISB. Solid red line is the predicted value from the new (2013) version of the NZGD2000 deformation model. Dashed red line is the predicted value from the original deformation model. Note that time series are not corrected for non-tectonic effects such as antenna changes.

The trend has been removed from the observed and calculated values based on a fit through the observed values.
Multiple events

Plot of the daily IGS08 time series at MQZG. Solid red line is the predicted value from the new (2013) version of the NZGD2000 deformation model. Dashed red line is the predicted value from the original deformation model. Note that time series are not corrected for non-tectonic effects such as antenna changes.
Modelling the deformation

Options – regional deformation
– Simple rectangular grid (simplest method)
– Complex grid (e.g., curvilinear grid)

Options – complex deformation
– Densify the national deformation model (model becomes very complex)
– Need a detailed triangulated grid – becomes complex
– Define a local ‘patch’ for the model (covers the area of the event with zero deformation at the boundaries)
– Change coordinates
The pros and cons of static, semi-dynamic and dynamic datums
Datum types

Static Datum
- Coordinates are fixed at a reference epoch
- Does not incorporate the effects of plate tectonics and deformation events
- Coordinates slowly go out of date, need to change periodically which is disruptive

Dynamic datum
- Incorporates a deformation model to manage changes (plate tectonics and deformation events)
- Coordinates change continuously
- Can be confusing and difficult to manage

Semi - dynamic datum (NZGD2000)
- Incorporates a deformation model to manage changes (plate tectonics and deformation events)
- Coordinates fixed at a reference epoch
- Change to coordinates is minimised
Advantages of a Dynamic or Semi-dynamic Datum

Maintains alignment with underlying global reference frames - ITRF
Lengthen the life of the datum
New observations can be integrated with old observations
Spatial accuracy of the geodetic network/datum is maintained or increased
Enables non-expert users to be isolated from the complexities of the dynamics (semi-dynamic datum only)
For practical purposes appears as a static datum (semi dynamic datum only)
Disadvantages of a Dynamic or Semi-dynamic Datum

Limited by the accuracy of the deformation model
Model can become complex over time to incorporate the effects of deformation events (e.g. earthquakes)
Coordinates need to be time tagged – cause confusion (dynamic datum only)
Most users do not know how to use a deformation model which is required to work with a dynamic datum
If using real time systems (CORS networks) need to use the deformation model to manage real time coordinates (semi-dynamic datums only)
Accommodate vertical deformation
– vertical deformation trends may be obscured by much larger localised episodic or cyclic events
– triangulated or other irregular grid probably required

Latency
– may be considerable time between a deformation event and the ‘patch’ being implemented
– for discrete events deformation may continue for some time requiring different versions of the patch

Extension Offshore
– how do you model deformation offshore?
– offshore may need to incorporate global model – express velocities as global rotations

Changing Reference Epoch
– may ultimately need to change the reference epoch once coordinates become inconveniently different from true current positions (semi-dynamic datum only)

Joining adjacent jurisdictions/datums
New Zealand Case Study
We don’t live on a stable planet
Measuring deformation - strain

Maximum shear strain rate

Areal strain rate
Extension is red
Contraction is violet
Regional distortions up to 5m present
Built up in a piecemeal fashion
Incompatible with global systems
It is of limited spatial coverage
It is static
1998 – NZ introduced NZGD2000 (ref epoch 1 Jan 2000)
  – geocentric origin
  – ITRF96 with epoch 2000.0 coordinates

NZGD2000 - semi-dynamic datum
  - generalised motion of points
  modelled using a deformation model
NZGD2000

- Tied to ITRF96
- Generalised motion of points modelled using a constant velocity deformation model
- Epoch 2000 coordinates generated at 2000.0
Semi-dynamic datum
- current deformation model has horizontal constant velocities only
- generated using repeat surveys between 1992 and 1998
- enables propagation of coordinates and observations between reference epoch and observation epoch
- for many uses has the appearance of a static datum
Where are we at?

What has gone well
• User Acceptance
• Implementation of the Deformation Model in LINZ
• Maintaining the Accuracy of Datum

Issues
• Managing the Deformation Model
• Accuracy of Deformation Model Versus CORS Real Time positions
• Managing the Spatial Alignment of the Cadastral System
• Misalignment of Readjusted Historic Geodetic Control with new Surveyed Geodetic Control
Future developments

- Updating the Deformation Model
- Vertical Deformation Model
- CORS Real Time – Tools for Managing Coordinates
- Tie to the ITRF - Going Fully Dynamic?
Canterbury Earthquakes
InSAR interference pattern as a result of the earthquake

Each coloured fringe represents 1.5 cm of ground displacement in line-of-sight to the satellite.

Incoherent regions indicate ground damage.
Creating a patch – Canterbury earthquakes

Darfield earthquake horizontal displacements in millimetres as measured by GPS before and after the earthquake. The dots show the GPS sites. Red symbols are the mapped trace of the surface rupture.

Caveat: The pre-earthquake data for many of the GPS sites have not been analysed by us. We have used the established LINZ NZGD2000 pre-earthquake coordinates for these sites, and have used a transformation developed by GNS for LINZ to convert the new coordinates of these stations to their new NZGD2000 values.
Impact on geodetic control and digital cadastre

Range is based on the distance from the centre of the fault rupture.

<table>
<thead>
<tr>
<th>Maximum Range (km)</th>
<th>Geodetic marks (order 5 or better)</th>
<th>Cadastral control (order 6 or better)</th>
<th>Total marks</th>
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<td>0-20</td>
<td>223</td>
<td>4816</td>
<td>56835</td>
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<td>20-40</td>
<td>1269</td>
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<td><strong>5828</strong></td>
<td><strong>88849</strong></td>
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Model out the effects of the earthquake
Residuals
Extent of update
Summary

• The incorporation of a deformation model in NZGD2000 has enabled
  – the life of the datum to be lengthened
  – new observations to be integrated with old observations
  – the accuracy of the datum to be maintained

• But
  – how complex deformation events will be incorporated in the model have yet to be fully determined and resolved
Determining Coordinates in a National Datum from Absolute ITRF Positions: A New Zealand Case Study
Overview

• Transformation between reference frames using standard transformations
• Transformation between epochs using a velocity model
• Concepts illustrated through a worked example
Key Concepts

• Local, project-specific reference frame realizations can be made by the surveyor

• Incorporating velocities may be new, but the calculations are simple

• It is vital to check the accuracy of your realization

• A concise but clear description of how the coordinates were generated is needed
Why is this important?

• Getting precise coordinates in the latest ITRF realization has been greatly simplified through the provision of online GNSS processing services. These provide ITRF positions
• But most countries do not use the latest version of ITRF as their official datum
• So we need to be able to transform coordinates from ITRF to the national datum
• We could always just make relative connections to control provided by the national geodetic agency, but this is not always the most efficient method
• Both coordinates may be required: ITRF for maximum precision and global consistency and local coordinates to meet regulatory requirements and ensure consistency with local datasets
Scenario

• Client has requested control for a large project in New Zealand
• They are a global company, and hold all of their data in the latest ITRF realization. Therefore need ITRF2008 coordinates
• To meet regulatory requirements, data must also be provided in the official datum. Therefore need NZGD2000 coordinates
• Client also requires a means of transforming between the two sets of coordinates
• Seven control stations (GLDB, NLSN, KAIK, WGTN, MAST, DNVK, WANG)
• Three new stations (CLIM, LEVN, WITH)
Background

- The official datum is New Zealand Geodetic Datum 2000 (NZGD2000)
- Defined as ITRF96 at epoch 2000.0
- New Zealand is at the boundary of the Australian and Pacific plates
- Even over small distances, marks can be moving at different velocities. Cannot assume a static Earth
- Includes a deformation model which can be used to generate coordinates at other epochs
- Official, highly accurate coordinates are published at CORS stations, and other passive marks
Deformation over Project Area

- Our project area is about 300km x 300km
- Station velocities vary significantly over this area
• We do all our processing in the more accurate reference frame, and then transform to any other desired reference frame and epoch
• Generation of high precision ITRF coordinates usually requires scientific GNSS processing software, not used by most surveyors
• Therefore choose to use an online processing service (in this case JPL precise point positioning)
• This will give us ITRF2008 coordinates, in terms of the reference frame used by the IGS orbital products (IGS08).
• Process 24-hour sessions
• We end up with IGS08 coordinates at observation epoch, which is 2012 Julian Day 60 (2012.16)
Transforming Coordinates

• Throughout, we are working in Cartesian (geocentric) coordinates. Any other transformations, such as to a mapping projection, are made at the end

• Step 1: Identify stations at which coordinates are available in both the desired reference frames (ITRF and national datum)

• Step 2: Use velocities at each station to obtain coordinates at a common epoch in the two reference frames

• Step 3: Calculate appropriate transformation parameters, using least squares. This will usually be three translation/rotation parameters, or three translation/rotation parameters plus one scale parameter over small portions of the Earth’s surface

• Step 4: Use the transformation parameters to convert coordinates between reference frames
Bilinear Interpolation

\[ U(v_e) = R(v_e) + \frac{(U(e) - R(e))/(S(e) - R(e))}{S(v_e) - R(v_e)} \]

\[ U(v_n) = R(v_n) + \frac{(U(e) - R(e))/(S(e) - R(e))}{S(v_n) - R(v_n)} \]

\[ W(v_e) = Q(v_e) + \frac{(W(e) - Q(e))/(T(e) - Q(e))}{T(v_e) - Q(v_e)} \]

\[ W(v_n) = Q(v_n) + \frac{(W(e) - Q(e))/(T(e) - Q(e))}{T(v_n) - Q(v_n)} \]

\[ P(v_e) = W(v_e) + \frac{(P(n) - W(n))/(U(n) - W(n))}{U(v_e) - W(v_e)} \]

\[ P(v_n) = W(v_n) + \frac{(P(n) - W(n))/(U(n) - W(n))}{U(v_n) - W(v_n)} \]
Calculating Velocity – Station GLDB

R(172.5, -40.8, -0.0002, 0.0439) → U(172.530, -40.8, v_e, v_n) → S(172.6, -40.8, -0.0011, 0.0443)

P(172.530, -40.827, v_e, v_n)

Q(172.5, -40.9, -0.0011, 0.0440) → W(172.530, -40.9, v_e, v_n) → T(172.6, -40.9, -0.0020, 0.0444)
Calculating Velocity – Station GLDB

\[ U(v_e) = -0.0002 + \left[\frac{(172.530 - 172.5)}{(172.6 - 172.5)}\right](-0.0011 - 0.0002) = -0.0005 \]

\[ U(v_n) = 0.0439 + \left[\frac{(172.530 - 172.5)}{(172.6 - 172.5)}\right](0.0443 - 0.0439) = 0.0440 \]

\[ W(v_e) = -0.0011 + \left[\frac{(172.530 - 172.5)}{(172.6 - 172.5)}\right](-0.0020 - 0.0011) = -0.0013 \]

\[ W(v_n) = 0.0440 + \left[\frac{(172.530 - 172.5)}{(172.6 - 172.5)}\right](0.0444 - 0.0440) = 0.0441 \]

\[ P(v_e) = -0.0013 + \left[\frac{(-40.827 - 40.9)}{(-40.8 - 40.9)}\right](-0.0005 - 0.0013) = -0.0007 \]

\[ P(v_n) = 0.0441 + \left[\frac{(-40.827 - 40.9)}{(-40.8 - 40.9)}\right](0.0440 - 0.0441) = 0.0441 \]
Transforming Velocities to Cartesian Reference Frame

• Recall that we are always working in Cartesian (XYZ) coordinates, so need XYZ velocities. Call this column vector $\mathbf{v}_{XYZ}$
• But the velocity model is topocentric (ENU). Call this column vector $\mathbf{v}_{ENU}$
• We can convert between the two using the geocentric to topocentric rotation matrix, $R_{gt}$, for the point’s latitude ($\phi$) and longitude ($\lambda$)

$$\mathbf{v}_{ENU} = R_{gt} \mathbf{v}_{XYZ}$$

$$\mathbf{v}_{XYZ} = R_{gt}^T \mathbf{v}_{ENU}$$

$$R_{gt} = \begin{bmatrix}
-\sin \lambda & \cos \lambda & 0 \\
-\sin \phi \cos \lambda & -\sin \phi \sin \lambda & \cos \phi \\
\cos \phi \cos \lambda & \cos \phi \sin \lambda & \sin \phi
\end{bmatrix}$$
Transforming Velocities to Cartesian Reference Frame – Station GLDB

\[
\mathbf{v}_{XYZ} = \mathbf{R}^T_{gt} \mathbf{v}_{ENU}
\]

\[
\begin{bmatrix}
\mathbf{v}_x \\
\mathbf{v}_y \\
\mathbf{v}_z
\end{bmatrix} =
\begin{bmatrix}
-0.130 & -0.992 & 0 \\
-0.648 & 0.085 & 0.757 \\
-0.750 & 0.098 & -0.654
\end{bmatrix}^T
\begin{bmatrix}
-0.0007 \\
0.0441 \\
0
\end{bmatrix}
= \begin{bmatrix}
-0.0285 \\
0.0045 \\
0.0333
\end{bmatrix}
\]
Calculating NZGD2000 Epoch 2012.16 Coordinates – Station GLDB

\[ \mathbf{x}_{\text{NZGD Epoch 2012.16}} = \mathbf{x}_{\text{NZGD2000 Epoch 2000.0}} + 12.16 \mathbf{v}_{\text{XYZ}} \]

\[
\begin{bmatrix}
  x \\
  y \\
  z_{201216}
\end{bmatrix}
= \begin{bmatrix}
  -4792405.831 \\
  628416.781 \\
  -4148068.669
\end{bmatrix} + 12.16 \begin{bmatrix}
  -0.0285 \\
  0.0045 \\
  0.0333
\end{bmatrix} = \begin{bmatrix}
  -4792406.177 \\
  628416.835 \\
  -4148068.263
\end{bmatrix}
\]
Calculating Transformation Parameters

• Use least squares to obtain the best solution, as we have more observations than parameters
• Functional model: \( At = b \), where \( A \) is the design matrix, \( b = \) Calculated (IT96) minus observed (IGS08) and \( t \) is the matrix of unknown transformation parameters
• Stochastic model: \( W = I \), in this case we choose to weight all coordinates equally
• So \( t = (A^T A)^{-1} A^T b \), the standard least squares solution
• And \( \text{Cov}(t) = \sigma_0^2 (A^T A)^{-1} \)
• The Aposteriori Standard Error of Unit Weight is \( \sigma_0^2 = (A^T t - b)^T (A^T t - b) / (\text{degrees of freedom}) \)
• This is a linear problem, so no need to iterate
• Note: if you wish to weight your coordinates: \( t = (A^T W A)^{-1} A^T W b \)
\[
A = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1 \\
\end{bmatrix}, \quad \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix}-4792406.177 \\ 628416.835 \\ -4148068.263 \end{bmatrix}, \quad \begin{bmatrix} b \\ \end{bmatrix} = \begin{bmatrix} -4792406.117 \\ 628416.851 \\ -4148068.23 \end{bmatrix}, \quad \begin{bmatrix} \end{bmatrix} \begin{bmatrix} -0.06 \\ -0.016 \\ -0.033 \end{bmatrix}
\]

\[
\text{Cov}(X) = \begin{bmatrix}
3.22 \times 10^{-5} & 0 & 0 \\
0 & 3.22 \times 10^{-5} & 0 \\
0 & 0 & 3.22 \times 10^{-5}
\end{bmatrix}
\]
Three Parameter Transformation Results

• SEUW = 0.015 m
• $t_x = -0.046 \pm 0.006$ m
• $t_y = -0.016 \pm 0.006$ m
• $t_z = -0.039 \pm 0.006$ m
• Note: In this case least squares simply gives us the average of the coordinate differences, so we could have avoided the matrix algebra, but would not get the precision information so easily
Four Parameter Transformation Results

- SEUW = 0.015 m
- $t_x = -0.103 \pm 0.211$ m
- $t_y = -0.011 \pm 0.021$ m
- $t_z = -0.088 \pm 0.183$ m
- $s = -1.19 \times 10^{-8} \pm 4.40 \times 10^{-8}$
- None of the parameters is significant, so this is not the best transformation
Calculate IT96 Epoch 2012.16 for CLIM

\[ \mathbf{x}_{\text{NZGD Epoch 2012.16}} = \mathbf{x}_{\text{IGS08 Epoch 2012.16}} + t \]

\[
\begin{bmatrix}
  x \\
  y \\
  z_{\text{NZGD2000 201216}}
\end{bmatrix} =
\begin{bmatrix}
  -4793404.120 \\
  407108.010 \\
  -4175081.520
\end{bmatrix} +
\begin{bmatrix}
  -0.046 \\
  -0.016 \\
  -0.039
\end{bmatrix} =
\begin{bmatrix}
  -4793404.167 \\
  407107.994 \\
  -4175081.559
\end{bmatrix}
\]
Calculate IT96 Epoch 2000 for CLIM

\[ x_{\text{NZGD Epoch 2000}} = x_{\text{NZGD2000 Epoch 2012.16}} - 12.16 v_{xyz} \]

\[
\begin{bmatrix}
  x \\
  y \\
  z_{\text{NZGD2000}}
\end{bmatrix}
\begin{bmatrix}
  -4793404.167 \\
  407107.994 \\
  -4175081.559
\end{bmatrix}
- 12.16
\begin{bmatrix}
  -0.0196 \\
  0.0277 \\
  0.0250
\end{bmatrix}
= \begin{bmatrix}
  -4793403.928 \\
  407107.657 \\
  -4175081.864
\end{bmatrix}
\]
Calculate IT96 Epoch 2000 for CLIM, LEVN, WITH

<table>
<thead>
<tr>
<th>Station</th>
<th>IGS08 Epoch 2012.16 (XYZ)</th>
<th>Velocity (ENU)</th>
<th>NZGD2000 Epoch 2000.0 (observed)</th>
<th>NZGD2000 Epoch 2000.0 (GDB)</th>
<th>Difference (ENU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLIM</td>
<td>-4793404.120</td>
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Transformed Coordinates:
Horizontal Residuals

Transformed Coordinates:
Vertical Residuals
Summary

• Absolute positioning is readily available, and its use will increase
• These positions are in terms of the satellite orbit reference frame (latest IGS realization of current ITRF)
• Software to convert to a local reference frame (datum) may not exist, or may need to be tested
• This conversion can be done by the surveyor using a spreadsheet and the procedure outlined in this presentation
Questions and References

• [http://apps.gdgps.net/](http://apps.gdgps.net/) (JPL PPP service)

• For any questions please contact:

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