Incorporating Episodic Vertical Displacements into Vertical Reference Frames

Nic Donnelly | Land Information New Zealand
Contents

• Examples from New Zealand earthquakes throughout
• Types of vertical deformation
• Impact on global and local reference frames
• Measuring vertical deformation
• Modelling vertical deformation
• Using a vertical deformation model
1. Types of Vertical Deformation
Continuous Vertical Deformation

- Until recently, vertical signal often difficult to detect (GNSS noisier in vertical)
- Secular vertical deformation
- Non-secular vertical deformation
  - Post-seismic decay
  - Natural subsidence
  - Human-induced subsidence (resource extraction)
  - Slow landslides
  - Slow earthquakes
Episodic Vertical Deformation

- Earthquakes the major natural cause
- Landslides
- Subsidence
<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>Magnitude</th>
<th>Max Vt (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secretary Island (Fiordland)</td>
<td>22 Aug 2003</td>
<td>7.2</td>
<td>0.72</td>
</tr>
<tr>
<td>Macquarie Island</td>
<td>24 Dec 2004</td>
<td>8.1</td>
<td>0.005</td>
</tr>
<tr>
<td>George Sound (Fiordland)</td>
<td>16 Oct 2007</td>
<td>6.7</td>
<td>0.27</td>
</tr>
<tr>
<td>Dusky Sound</td>
<td>15 Jul 2009</td>
<td>7.8</td>
<td>0.39</td>
</tr>
<tr>
<td>Darfield</td>
<td>4 Sep 2010</td>
<td>7.1</td>
<td>1.75</td>
</tr>
<tr>
<td>Christchurch</td>
<td>22 Feb 2011</td>
<td>6.3</td>
<td>0.48</td>
</tr>
<tr>
<td>Christchurch</td>
<td>13 Jun 2011</td>
<td>6.3</td>
<td>0.13</td>
</tr>
<tr>
<td>Christchurch</td>
<td>23 Dec 2011</td>
<td>6.0</td>
<td>0.36</td>
</tr>
<tr>
<td>Cook Strait</td>
<td>21 Jul 2013</td>
<td>6.0</td>
<td>0.024</td>
</tr>
<tr>
<td>Lake Grassmere</td>
<td>16 Aug 2013</td>
<td>6.6</td>
<td>0.26</td>
</tr>
</tbody>
</table>
2. Impact on Global and Local Vertical Reference Frames
# Global vs Local Frame

<table>
<thead>
<tr>
<th>Global (eg ITRF)</th>
<th>Local (eg NZGD2000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driven by global science</td>
<td>Driven by national spatial</td>
</tr>
<tr>
<td>requirements</td>
<td>community requirements</td>
</tr>
<tr>
<td>Time-varying coordinates for</td>
<td>Time-invariant coordinates for</td>
</tr>
<tr>
<td>ground-fixed marks</td>
<td>ground-fixed marks</td>
</tr>
<tr>
<td>Plate motion and/or deformation</td>
<td>Plate motion and/or deformation</td>
</tr>
<tr>
<td>models to propagate coordinates</td>
<td>models to generate reference</td>
</tr>
<tr>
<td>between epochs</td>
<td>coordinates</td>
</tr>
<tr>
<td>Native system for modern</td>
<td>Modern positioning techniques (GNSS)</td>
</tr>
<tr>
<td>positioning techniques (GNSS)</td>
<td>require transformation to local frame</td>
</tr>
</tbody>
</table>
Two-Frame Referencing System

- ITRF
- Reference Frame Transformation
- Plate Motion Model
- Deformation Model
- Local frame

- Secular deformation
- Non-secular deformation

May be null
Deformation Model for ITRF Coordinate Propagation

- Little overall impact on global frame
  - Requires offset at ITRF station
- ITRF coordinates change due to episodic deformation, but this change is often less significant than a short period of continuous deformation
Impact on Local Reference Frame

- Relative accuracy of local frame is compromised
- Fluids may no longer flow from a greater height to a lesser height
User Requirements for Vertical Deformation Modelling in a Local Frame

• Heights need to reflect fluid flow
• Maintain relative accuracy, especially over short distances
• Often want coordinates to reflect “local” vertical deformation, but the definition of “local” is application-dependent. Models can hide vertical deformation, which can be dangerous. Care is required!
• Generally don’t want coordinates changing for consistent vertical deformation over large areas
3. Measuring Vertical Deformation
CORS

- Updated heights computed very soon after an event
- Other data uses these updated heights as control
GNSS Campaigns and Levelling
Levelling
Horizontal and Vertical Displacements - PROVISIONAL
Total Displacement of 4 Sep 2010, 22 Feb 2011, 13 June 2011 and 23 December 2011 Earthquakes

Version 0.2, 31 May 2013
Accuracy (standard deviation) 0.03m.

These displacement vectors are only provisional. They show the total magnitude and direction of displacements caused by the following Canterbury earthquakes: 4 Sept 2010, 22 Feb 2011, 13 June 2011 and 23 Dec 2011. Analysis is ongoing.

Displacement vectors calculated using SNAP v2.3.64.
Origin of coordinates obtained from stations S509, AHM0, B604, S505, AHM0 and WLL using N02030000 coordinates supplied by GNS Science on 8 July 2011 and 11 January 2012.

LINZ displacement data derived from surveys carried out by Anderson & Associates Ltd and Opus International Consultants Ltd.

Legend
- Vertical Change
- Horizontal Change

0 0.2 0.4 0.6 0.8 1 m
Displacement Vector Scale
DInSAR – Millimetre-accurate Deformation
DInSAR Example
## Multiple Measurement Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Nominal Precision</th>
<th>Contribution to Geodetic System Re-establishment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuously Operating Reference Stations</td>
<td>0.001 – 0.010 m</td>
<td>Immediate indications of co-seismic displacement, monitoring of post-seismic and inter-seismic deformation. Provide the framework for all other GNSS surveys.</td>
</tr>
<tr>
<td>Static GNSS</td>
<td>0.005 – 0.010 m</td>
<td>Contributes to earthquake deformation models. Provides framework for rapid static surveys</td>
</tr>
<tr>
<td>Rapid Static GNSS</td>
<td>0.010 – 0.020 m</td>
<td>Provides the densest level of control to support other surveys. Contributes to earthquake deformation models</td>
</tr>
</tbody>
</table>
Multiple Measurement Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Nominal Precision</th>
<th>Contribution to Geodetic System Re-establishment</th>
</tr>
</thead>
<tbody>
<tr>
<td>InSAR</td>
<td>0.010 – 0.050 m relative</td>
<td>Contributes to earthquake deformation model</td>
</tr>
<tr>
<td>Airborne LIDAR</td>
<td>0.1 – 0.3 m vertical</td>
<td>Detailed model of height changes across the city, to assist flood control; also used to map large horizontal changes due to ground failure, using sub-pixel correlation</td>
</tr>
<tr>
<td>Precise Leveling</td>
<td>0.001 – 0.010 m vertical</td>
<td>Precise orthometric height control, required for accurate design of gravity-reliant engineering schemes (e.g.,</td>
</tr>
</tbody>
</table>
4. Modelling Vertical Deformation
Modelling Deformation

- GNSS data provides three-dimensional displacements at surveyed points.
- InSAR provides displacements in the direction of line of sight between the satellite and ground with a resolution of tens of meters.
- Inversion software is used in a two-step process to estimate parameters for location and geometry of the fault plane(s), and magnitude and direction of slip.
Deformation Model Patches

"Forward" patch

Reference coordinate

Actual position of mark

Secular deformation

Earthquake

2000.0

"Reverse" patch

Reference coordinate

Actual position of mark

Secular deformation

Earthquake

2000.0
Coseismic Forward Patch and Secular Deformation Model

Local frame

National Secular Deformation Model

Coseismic Forward Patch

Local Frame Position and Vector

Measured Position and Vector

Ground Displacement

Correction to get Local Frame Coordinates

t=2000.0

t=2013.6

t=2013.6

t=2015.0

Earthquake
Coseismic Reverse Patch and Secular Deformation Model

Earthquake

Local Frame (v20120101)

Local Frame (v20000101)

National Secular Deformation Model

Coseismic Reverse Patch to Update Local Frame Coordinates

Local Frame Position and Vector

Measured Position and Vector

Ground Displacement

Correction to get Local Frame Coordinates
Canterbury Earthquakes Submodels

Darfield (20100904) Rev Patch

Coseismic Deformation

- ~13km Grid
- ~3km Grid
- ~0.8km Grid
- ~0.2km Grid

Step Function

Christchurch (20110222) Rev Patch

Coseismic Deformation

- ~13km Grid
- ~3km Grid
- ~0.8km Grid
- ~0.2km Grid

Step Function

Christchurch (20110613) Rev Patch

Coseismic Deformation

- ~13km Grid
- ~3km Grid
- ~0.8km Grid
- ~0.2km Grid

Step Function

Christchurch (20111223) Rev Patch

Coseismic Deformation

- ~13km Grid
- ~3km Grid
- ~0.8km Grid
- ~0.2km Grid

Step Function
Canterbury Earthquakes
Nested Grids

<table>
<thead>
<tr>
<th>Grid</th>
<th>No Lon</th>
<th>No Lat</th>
<th>Size Lon (deg)</th>
<th>Size Lat (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>52</td>
<td>54</td>
<td>0.15</td>
<td>0.125</td>
</tr>
<tr>
<td>B</td>
<td>50</td>
<td>59</td>
<td>0.075</td>
<td>0.0625</td>
</tr>
<tr>
<td>C</td>
<td>84</td>
<td>118</td>
<td>0.0375</td>
<td>0.03125</td>
</tr>
<tr>
<td>D</td>
<td>141</td>
<td>306</td>
<td>0.01875</td>
<td>0.015625</td>
</tr>
</tbody>
</table>
5. Using a Vertical Deformation Model Example
Canterbury Earthquakes Reverse Patch Example

22 Feb 2011
Christchurch Earthquake
100 ppm max distortion

BDUH

BDUF

0  2  4 km
Canterbury Earthquakes Reverse Patch Example

Coseismic Reverse Patch to Update NZGD2000 Coordinates

National Secular Deformation Model

Earthquake

NZGD2000 (v20150101)

NZGD2000 (v20000101)

Ground Displacement

Correction to get NZGD2000 Coordinates

NZGD2000 Position and Vector

Measured Position and Vector

t=2010.7

t=2015.0

t=2000.0
### Deformation Model NOT Used

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Type</th>
<th>Value</th>
<th>+/-</th>
<th>Calc</th>
<th>+/-</th>
<th>Res</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDUF</td>
<td>BDUH</td>
<td>GB</td>
<td>-806.601</td>
<td>0.016</td>
<td>-806.611</td>
<td>0.000</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-660.795</td>
<td>0.010</td>
<td>-660.791</td>
<td>0.000</td>
<td>-0.009</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>756.648</td>
<td>0.016</td>
<td>756.650</td>
<td>0.000</td>
<td>-0.007</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1288.321</td>
<td></td>
<td>1288.326</td>
<td></td>
<td>0.011</td>
</tr>
</tbody>
</table>

### Deformation Model Used

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Type</th>
<th>Value</th>
<th>+/-</th>
<th>Calc</th>
<th>+/-</th>
<th>Res</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDUF</td>
<td>BDUH</td>
<td>GB</td>
<td>-806.601</td>
<td>0.016</td>
<td>-806.611</td>
<td>0.000</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-660.795</td>
<td>0.010</td>
<td>-660.790</td>
<td>0.000</td>
<td>-0.009</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>756.648</td>
<td>0.016</td>
<td>756.650</td>
<td>0.000</td>
<td>-0.007</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1288.321</td>
<td></td>
<td>1288.327</td>
<td></td>
<td>0.012</td>
</tr>
</tbody>
</table>

**Reverse Patch with Post-Earthquake Observations**
Deformation Model NOT Used

<table>
<thead>
<tr>
<th>From To</th>
<th>Type</th>
<th>Value</th>
<th>+/-</th>
<th>Calc</th>
<th>+/-</th>
<th>Res</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X,Y,Z</td>
<td></td>
<td>X,Y,Z</td>
<td></td>
<td>E,N,U</td>
</tr>
<tr>
<td>BDUF</td>
<td>BDUH</td>
<td>GB</td>
<td>-806.347</td>
<td>0.016</td>
<td>-806.611</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-660.834</td>
<td>0.010</td>
<td>-660.791</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>756.753</td>
<td>0.016</td>
<td>756.650</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1288.244</td>
<td></td>
<td>1288.326</td>
<td></td>
</tr>
</tbody>
</table>

Deformation Model Used

<table>
<thead>
<tr>
<th>From To</th>
<th>Type</th>
<th>Value</th>
<th>+/-</th>
<th>Calc</th>
<th>+/-</th>
<th>Res</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X,Y,Z</td>
<td></td>
<td>X,Y,Z</td>
<td></td>
<td>E,N,U</td>
</tr>
<tr>
<td>BDUF</td>
<td>BDUH</td>
<td>GB</td>
<td>-806.347</td>
<td>0.016</td>
<td>-806.354</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-660.834</td>
<td>0.010</td>
<td>-660.829</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>756.753</td>
<td>0.016</td>
<td>756.758</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1288.244</td>
<td></td>
<td>1288.249</td>
<td></td>
</tr>
</tbody>
</table>

Reverse Patch with Pre-Earthquake Observations
Key Points

• User requirements for vertical deformation modelling may differ to horizontal requirements
• A range of observation techniques are required to monitor and model vertical deformation: GNSS, precise levelling, InSAR, LiDAR…
• Vertical deformation models can be incorporated into the local reference frame as either forward or reverse patches
• Reverse patches update heights, which ensures heights continue to represent fluid flow