Incorporating Episodic Vertical Displacements into Vertical Reference Frames

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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

New Zealand Examples

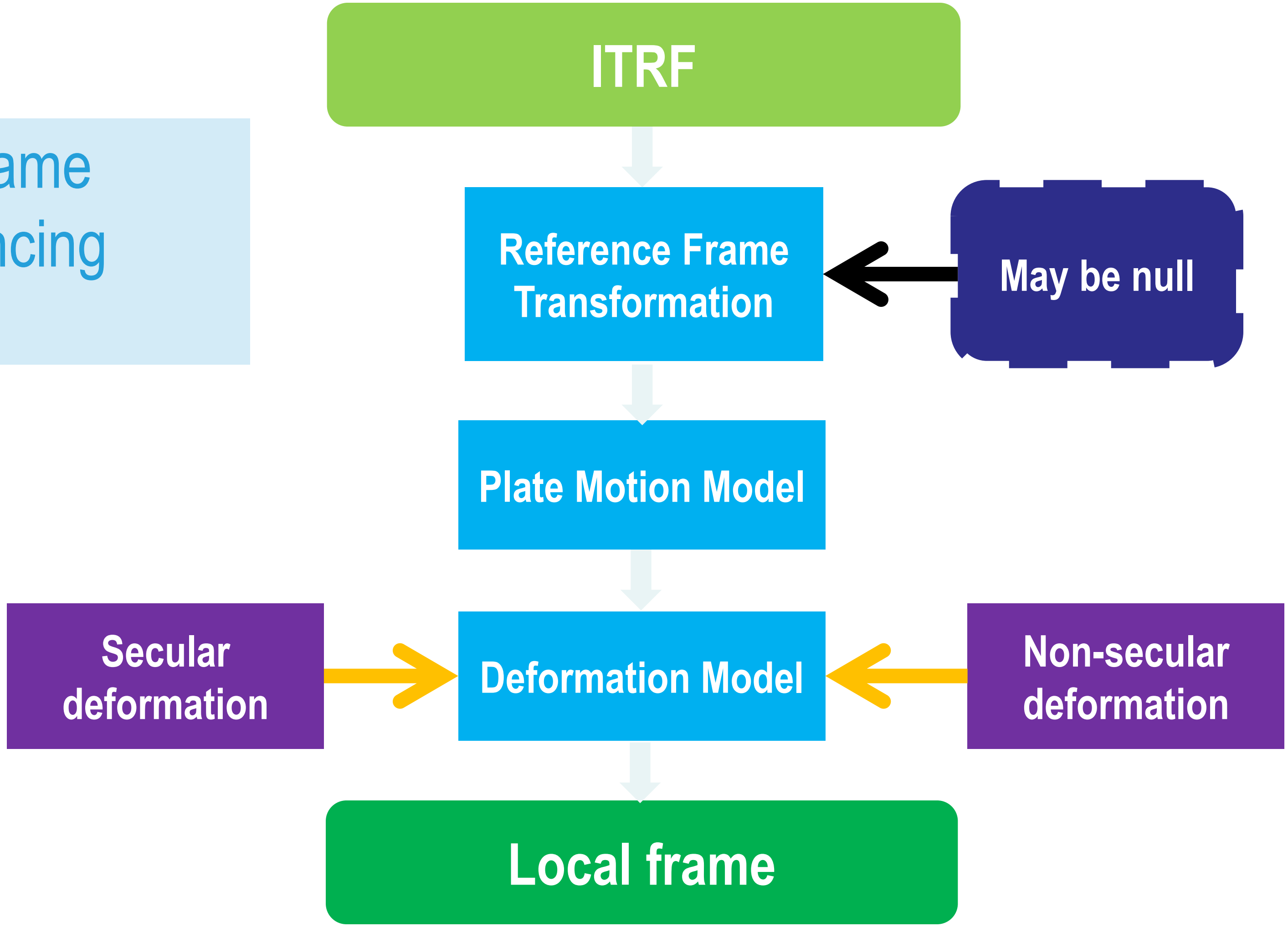
Name	Date	Magnitude	Max Vt (m)
Secretary Island (Fiordland)	22 Aug 2003	7.2	0.72
Macquarie Island	24 Dec 2004	8.1	0.005
George Sound (Fiordland)	16 Oct 2007	6.7	0.27
Dusky Sound	15 Jul 2009	7.8	0.39
Darfield	4 Sep 2010	7.1	1.75
Christchurch	22 Feb 2011	6.3	0.48
Christchurch	13 Jun 2011	6.3	0.13
Christchurch	23 Dec 2011	6.0	0.36
Cook Strait	21 Jul 2013	6.0	0.024
Lake Grassmere	16 Aug 2013	6.6	0.26

2. Impact on Global and Local Vertical Reference Frames

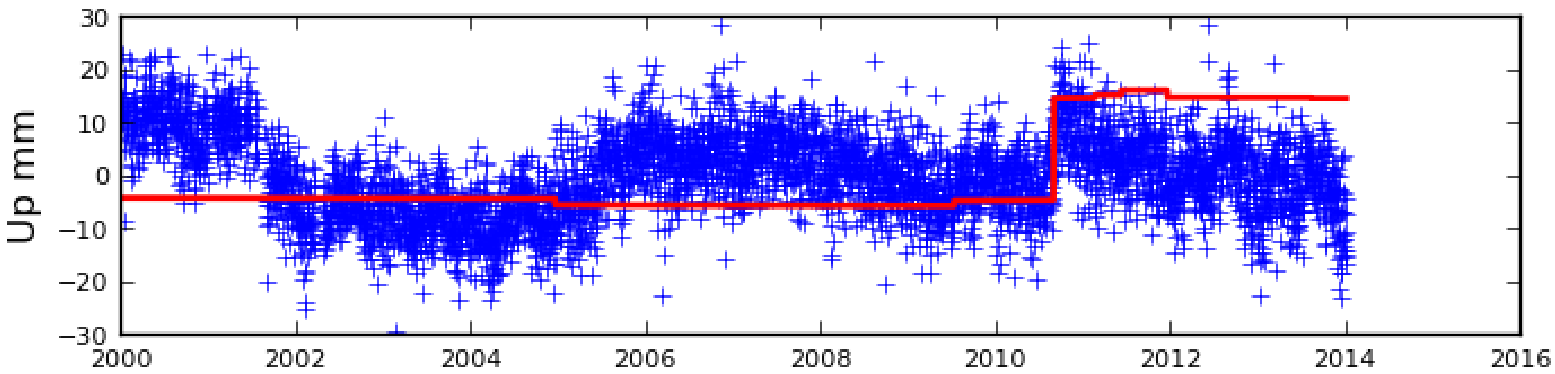
Global vs Local Frame

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

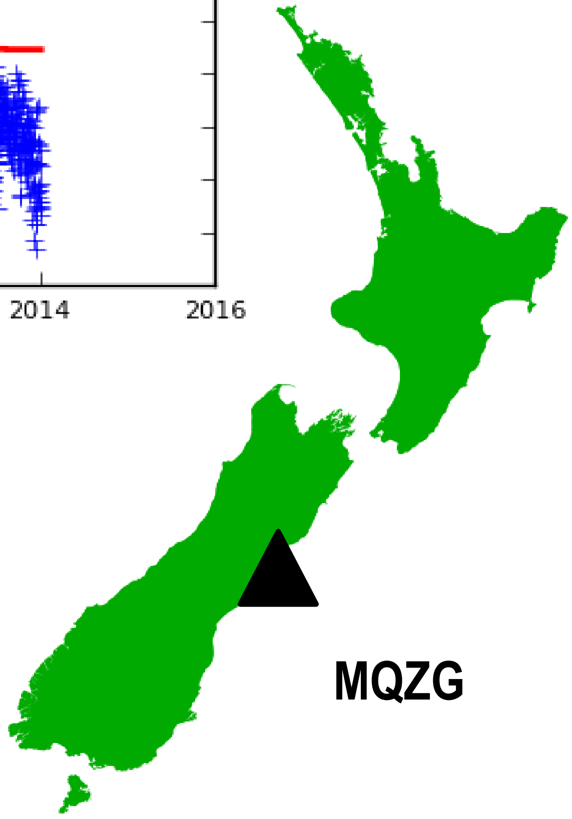
Two-Frame Referencing System



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

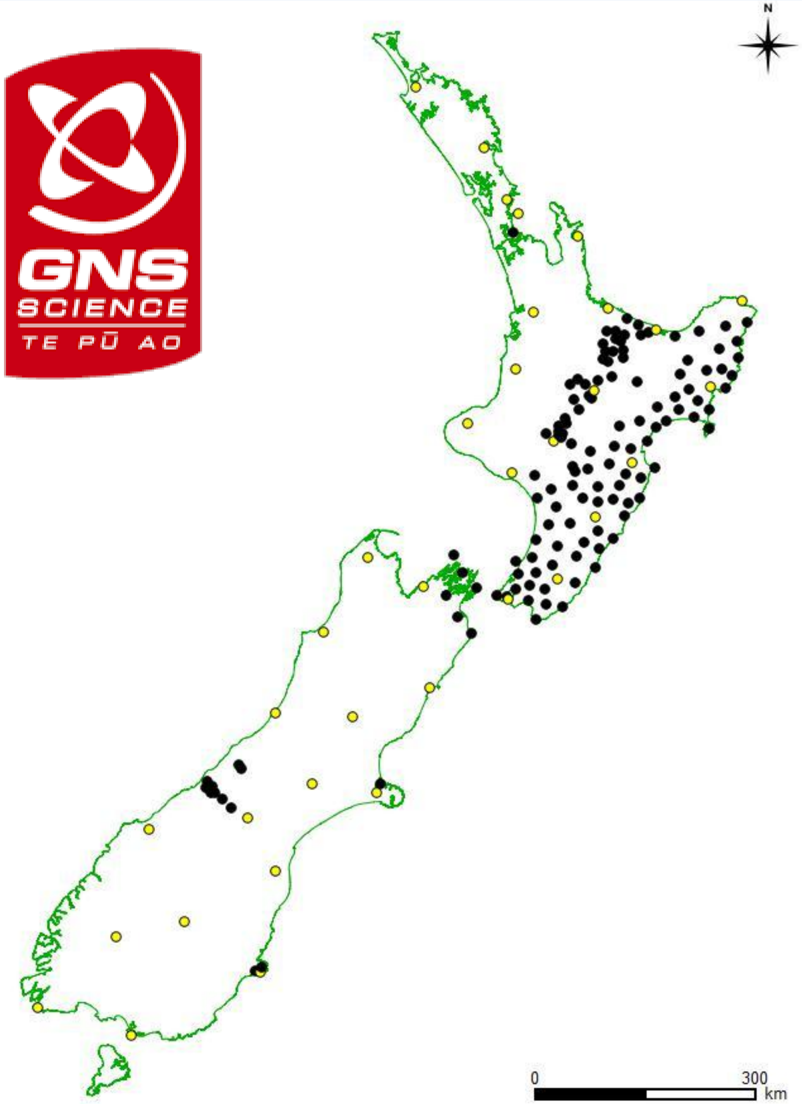
User Requirements for Vertical Deformation Modelling in a Local Frame

- 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

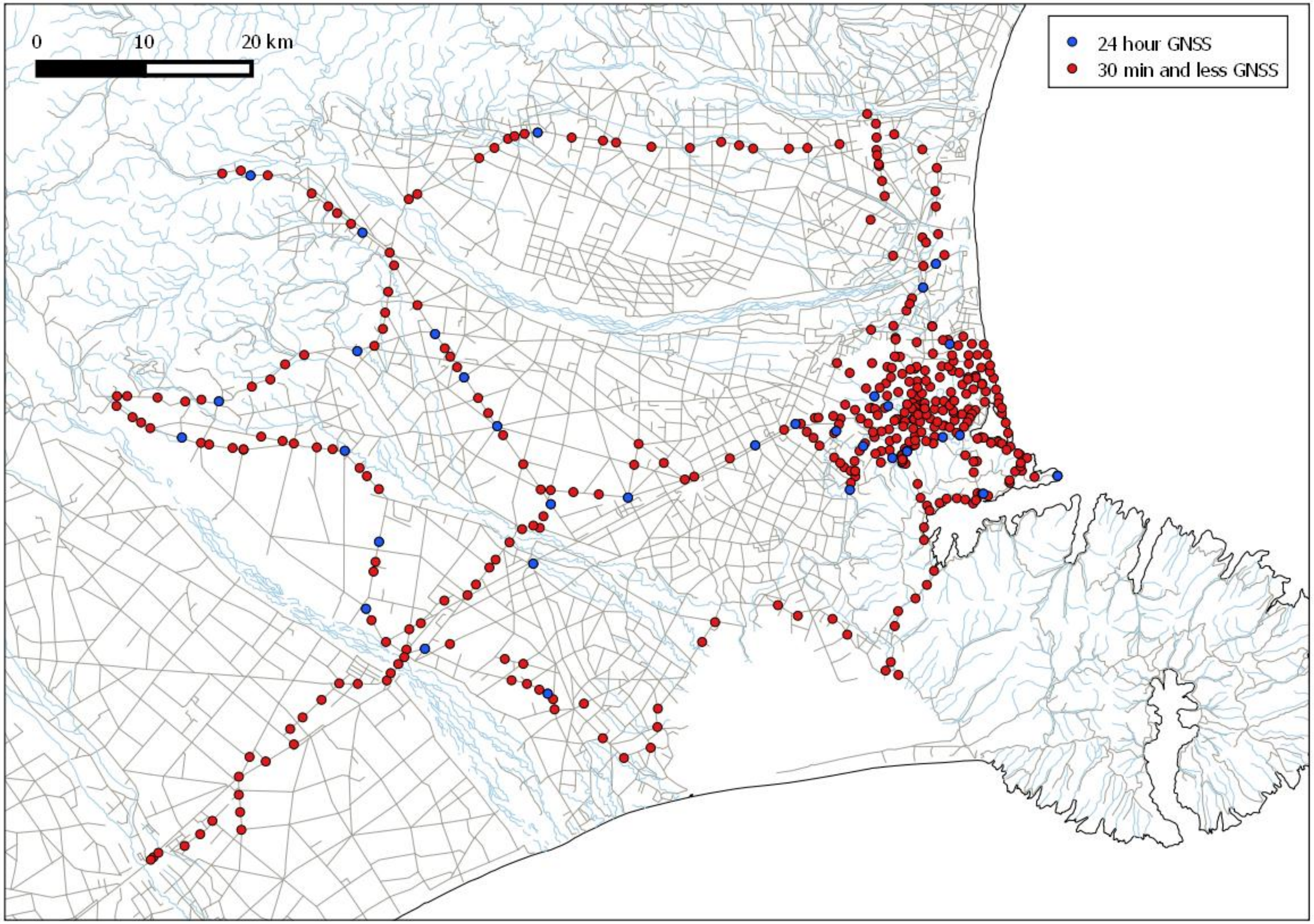
CORS

- Updated heights computed very soon after an event
- Other data uses these updated heights as control

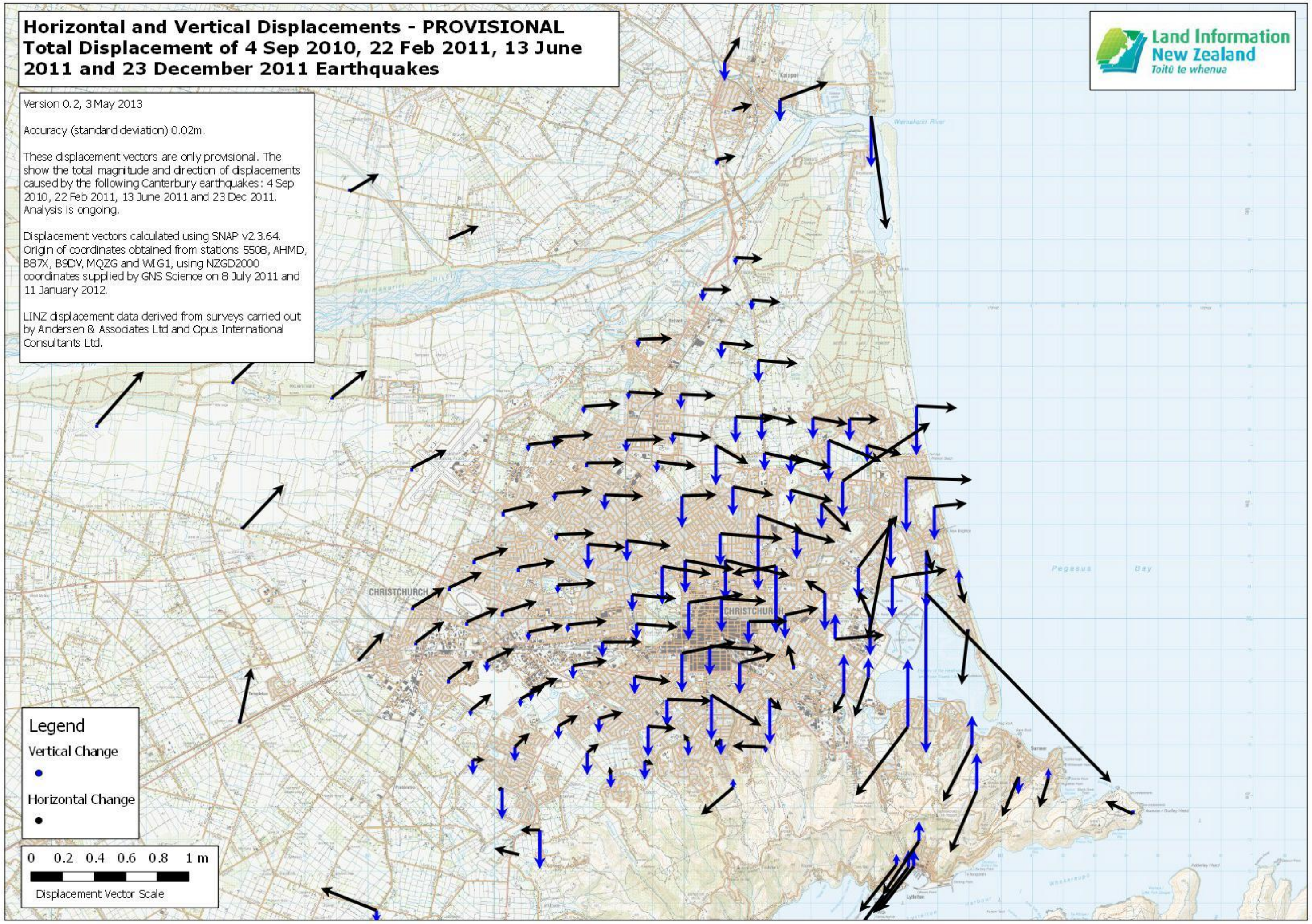


GNSS Campaigns and Levelling

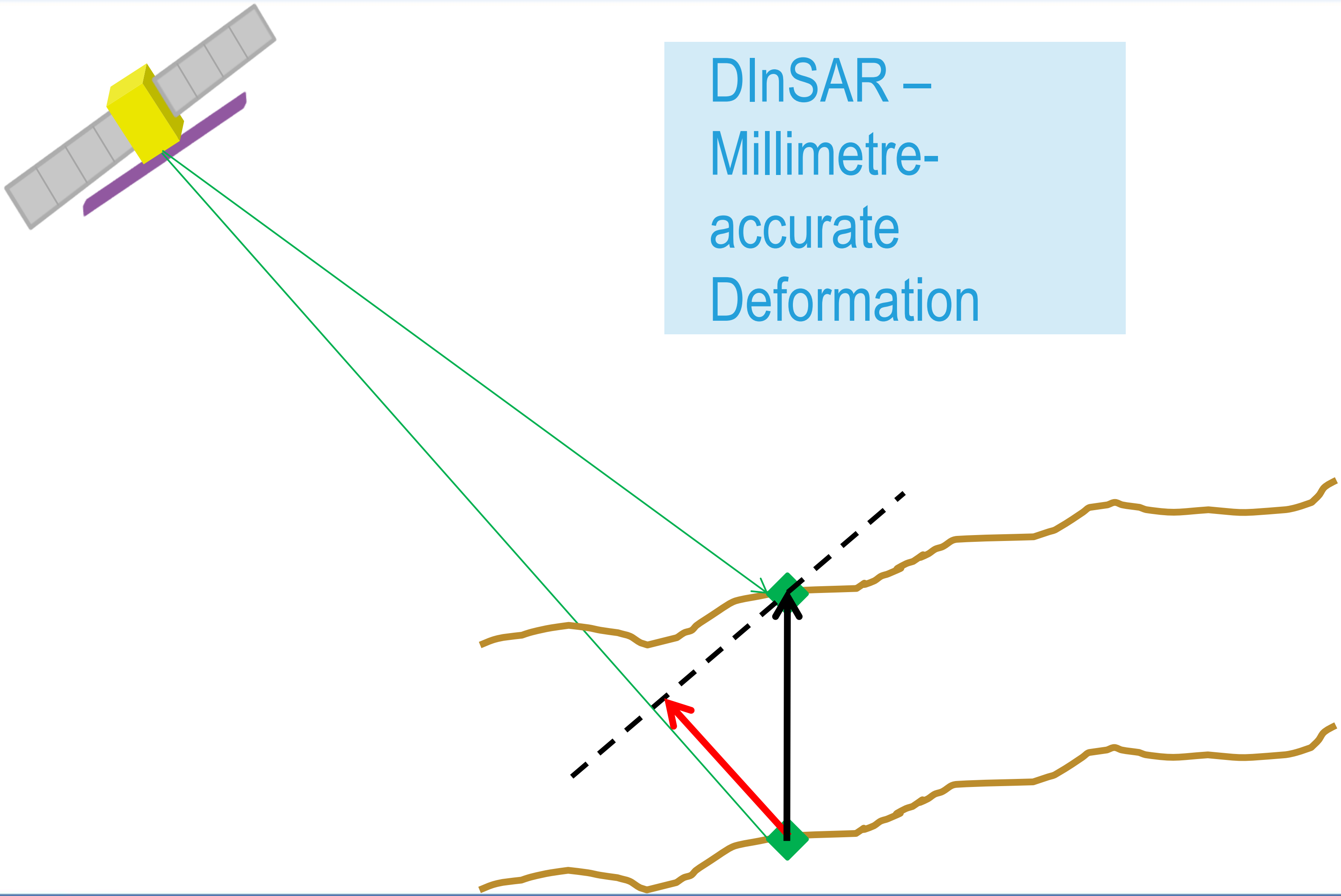
Levelling



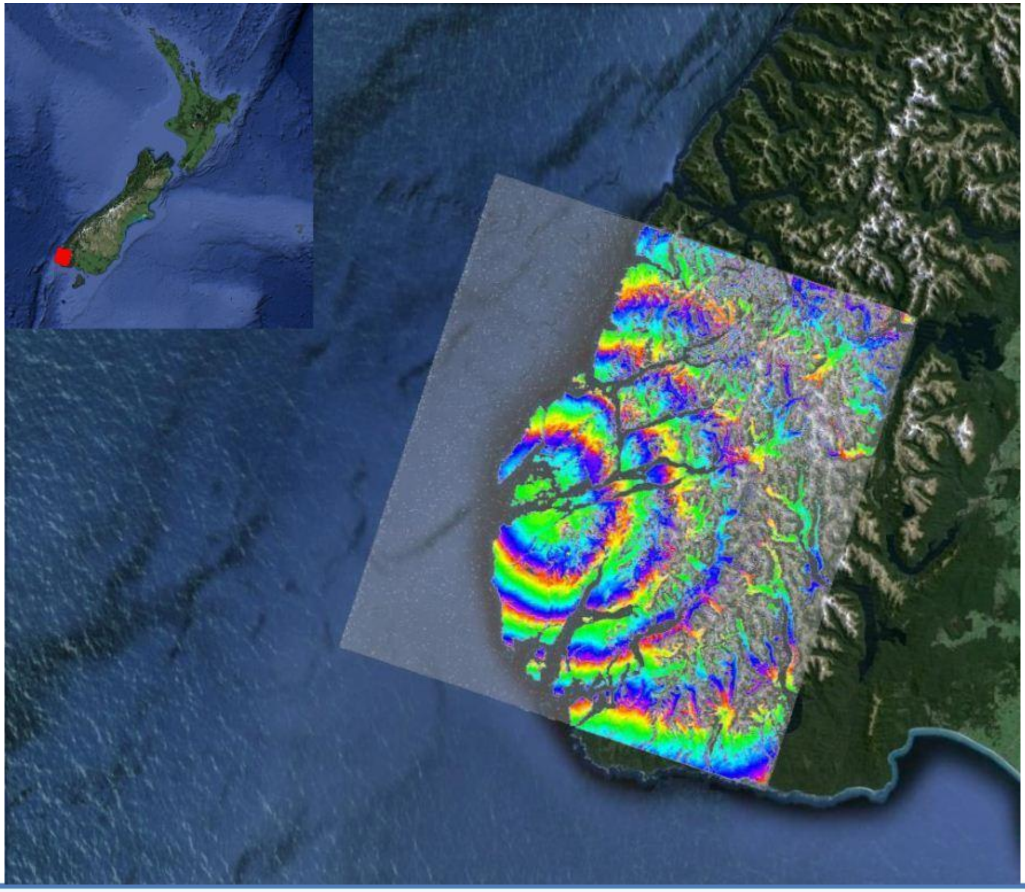
GNSS


Horizontal and Vertical Displacements - PROVISIONAL
Total Displacement of 4 Sep 2010, 22 Feb 2011, 13 June 2011 and 23 December 2011 Earthquakes
Land Information New Zealand
Toitū te whenua
Version 0.2, 3 May 2013
Accuracy (standard deviation) 0.02m.
These displacement vectors are only provisional. The show the total magnitude and direction of displacements caused by the following Canterbury earthquakes: 4 Sep 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 5508, AHMD, B87X, B9DV, MQZG and WIG1, using NZGD2000 coordinates supplied by GNS Science on 8 July 2011 and 11 January 2012.
LINZ displacement data derived from surveys carried out by Andersen & 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
CHRISTCHURCH
Pegasus Bay

DInSAR – Millimetre-accurate Deformation



DInSAR Example



Multiple Measurement Techniques

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

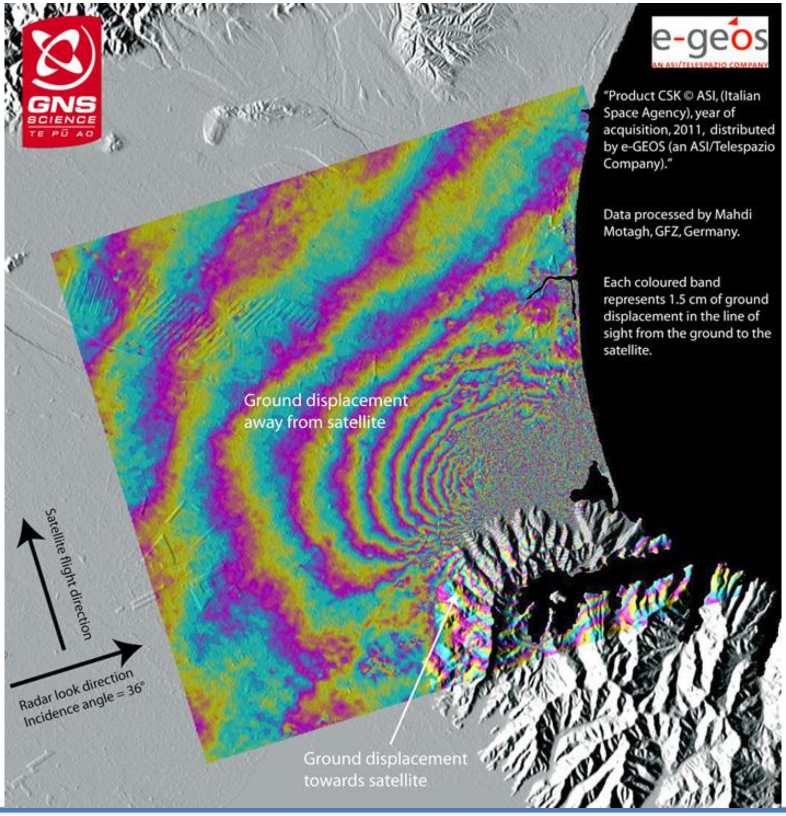
Multiple Measurement Techniques

Technique	Nominal Precision	Contribution to Geodetic System Re-establishment
InSAR	0.010 – 0.050 m relative	Contributes to earthquake deformation model
Airborne LIDAR	0.1 – 0.3 m vertical	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
Precise Leveling	0.001 – 0.010 m vertical	Precise orthometric height control, required for accurate design of gravity-reliant engineering schemes (e.g.,

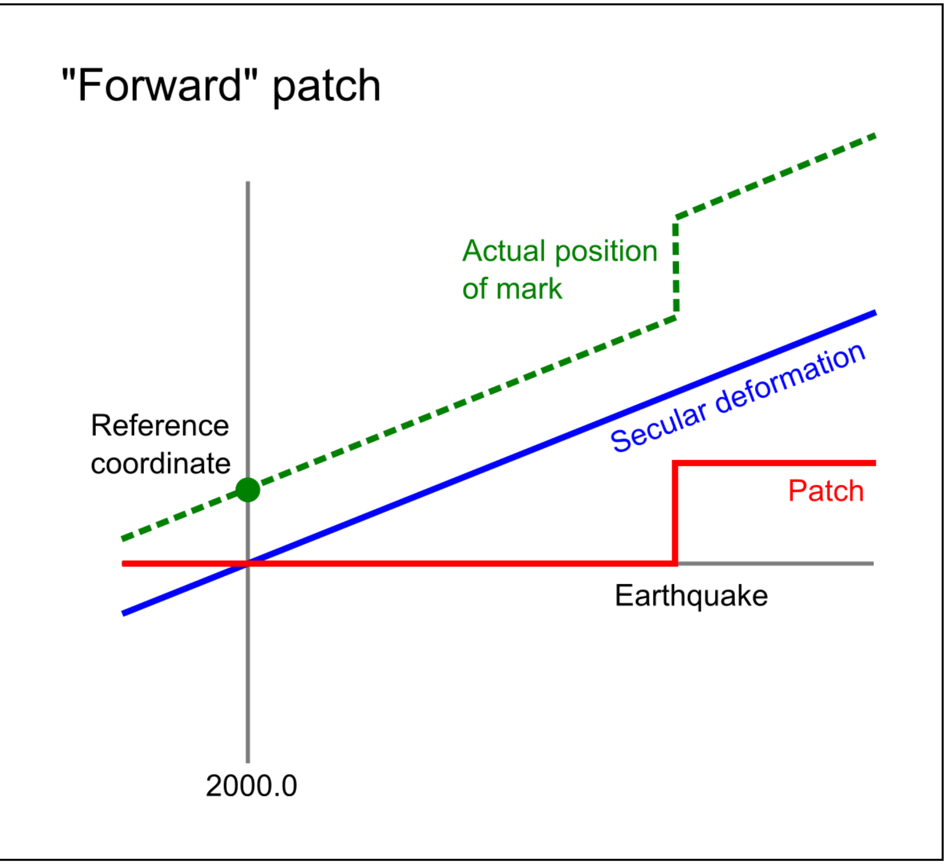
4. Modelling Vertical Deformation

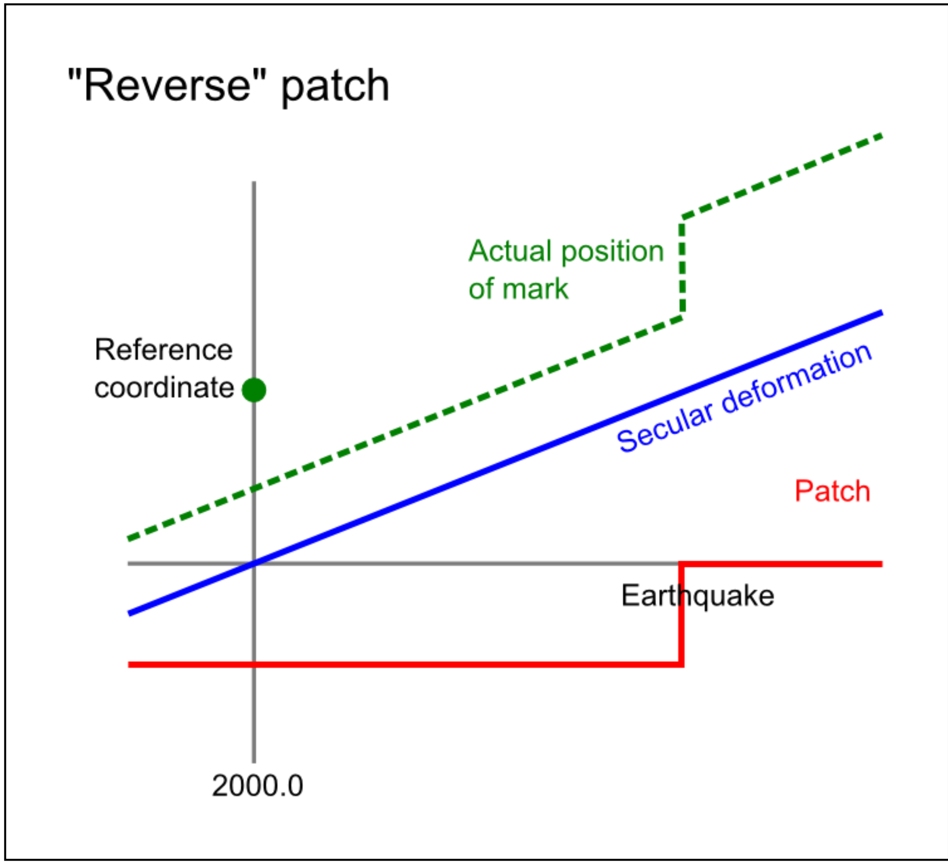
Modelling Deformation

- 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

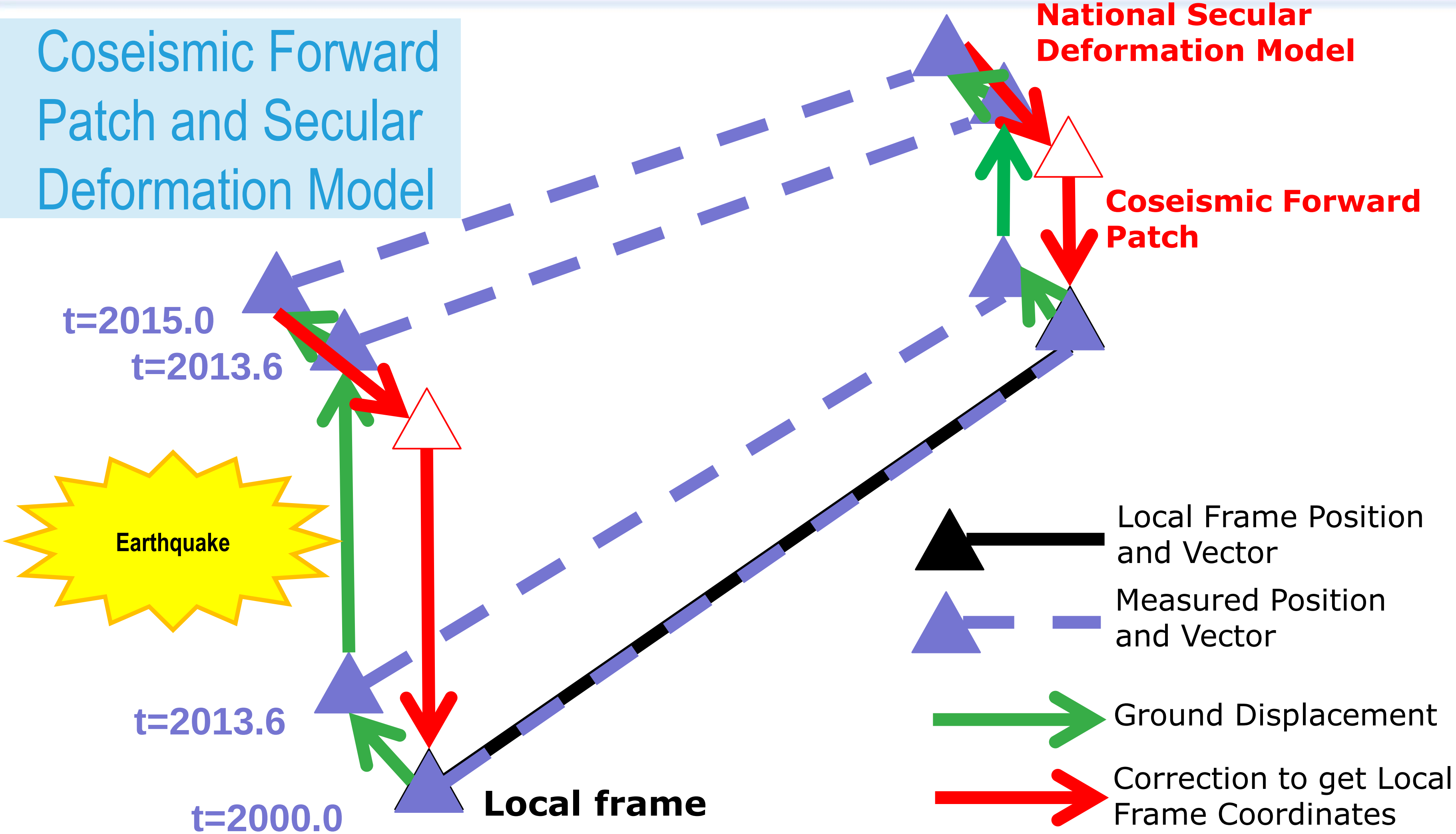


Deformation Model Patches

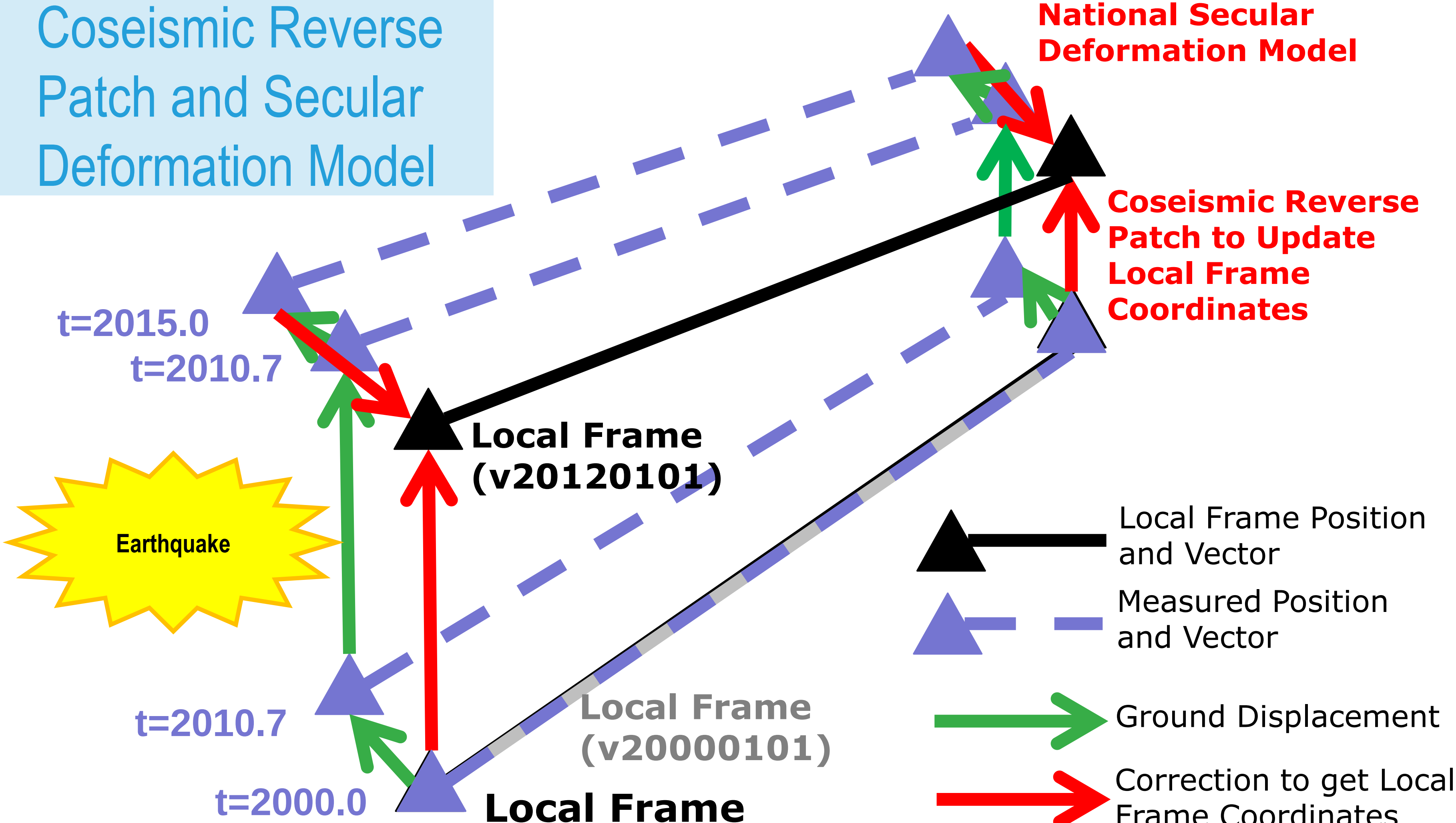




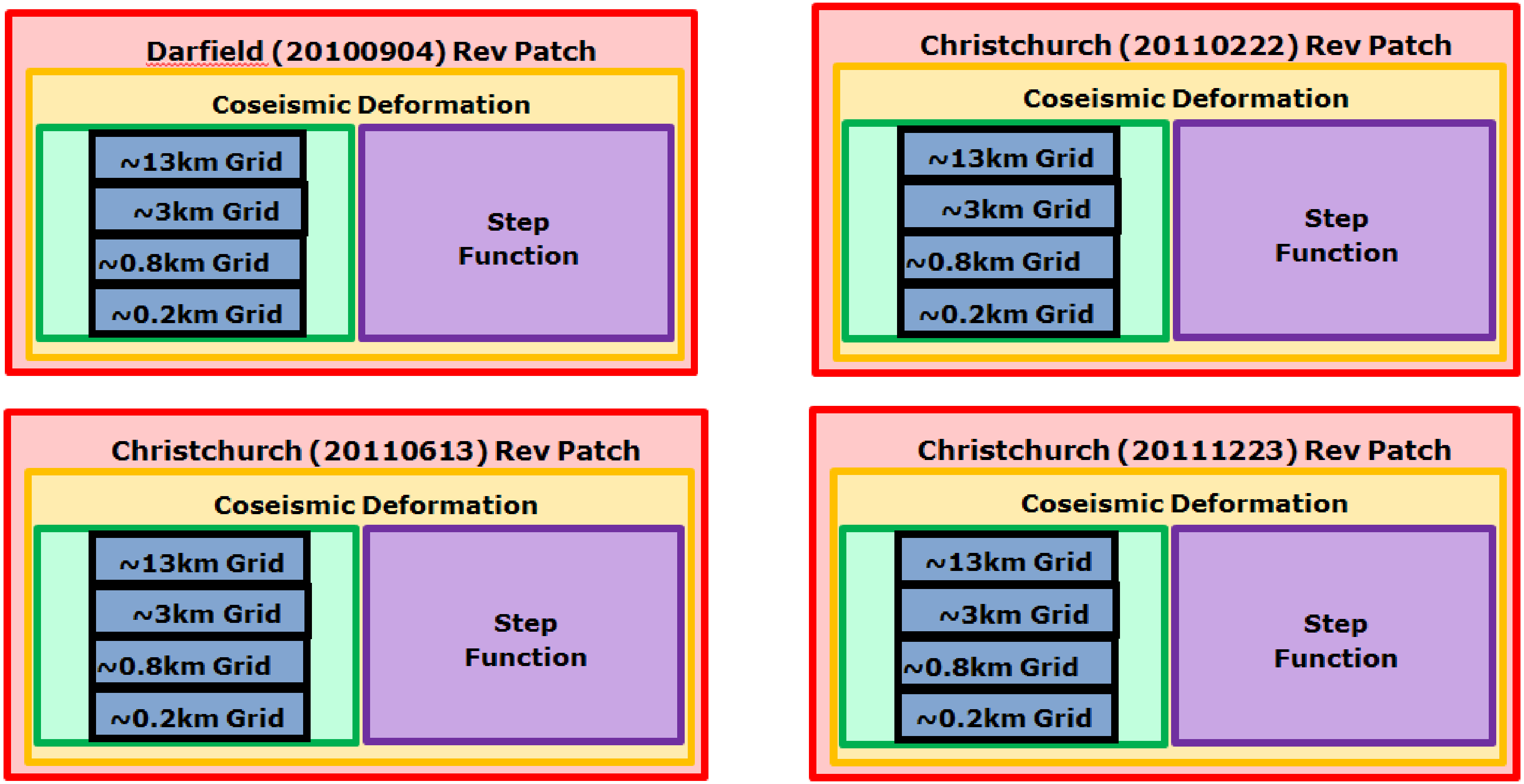
Coseismic Forward Patch and Secular Deformation Model



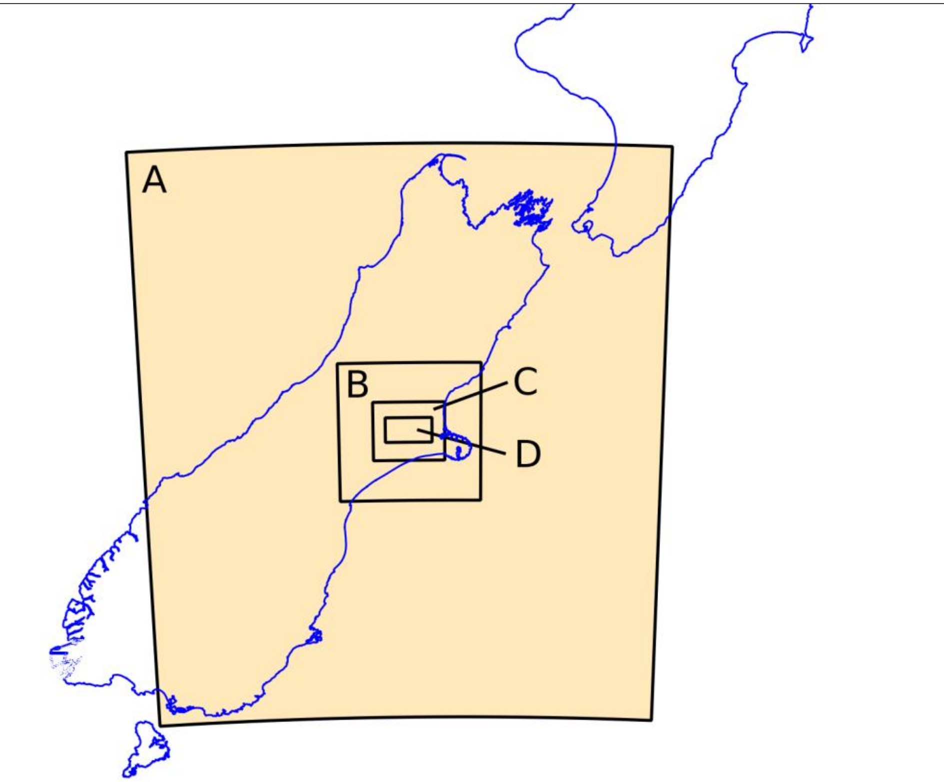
Coseismic Reverse Patch and Secular Deformation Model



Canterbury Earthquakes Submodels



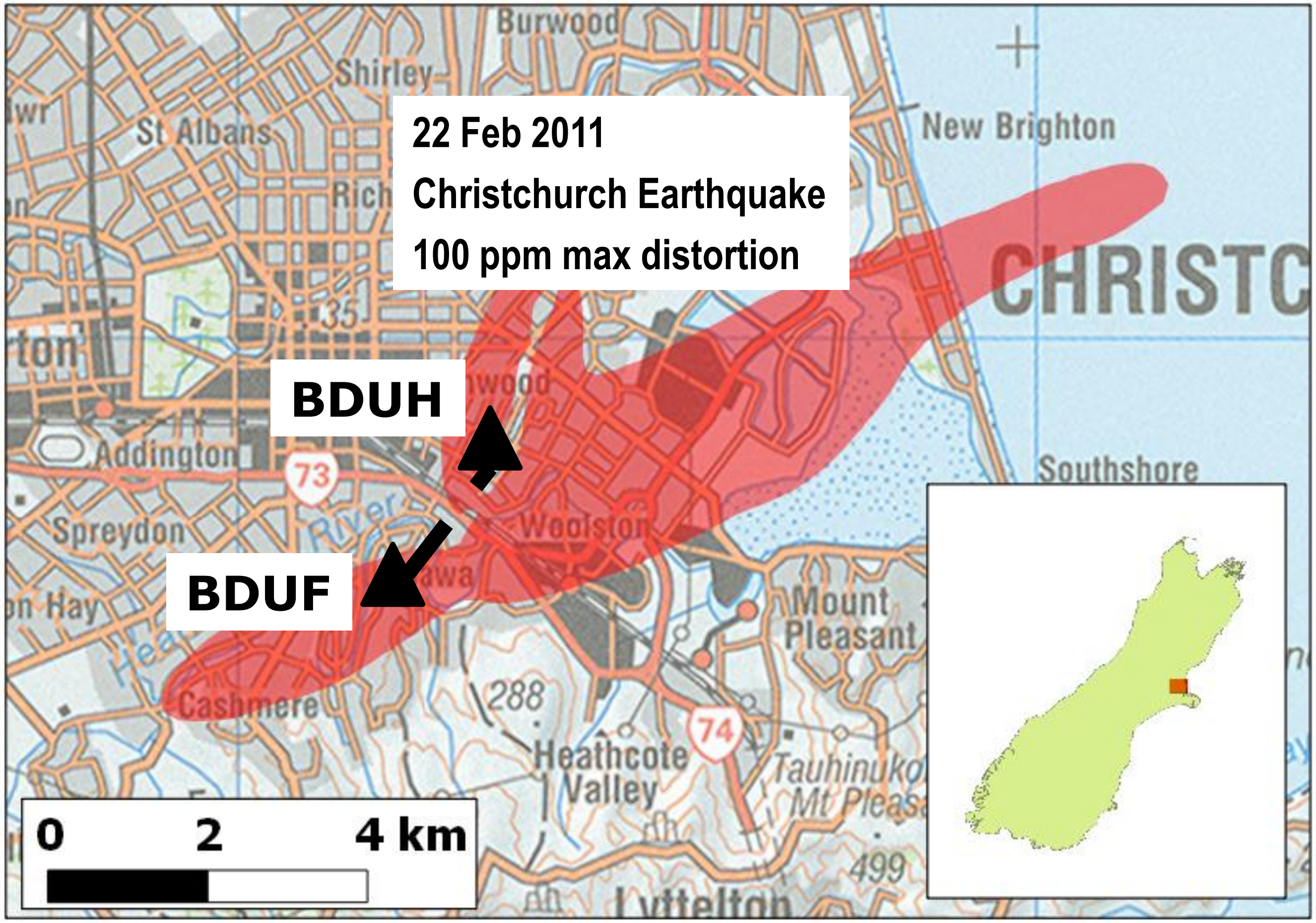
Canterbury Earthquakes Nested Grids



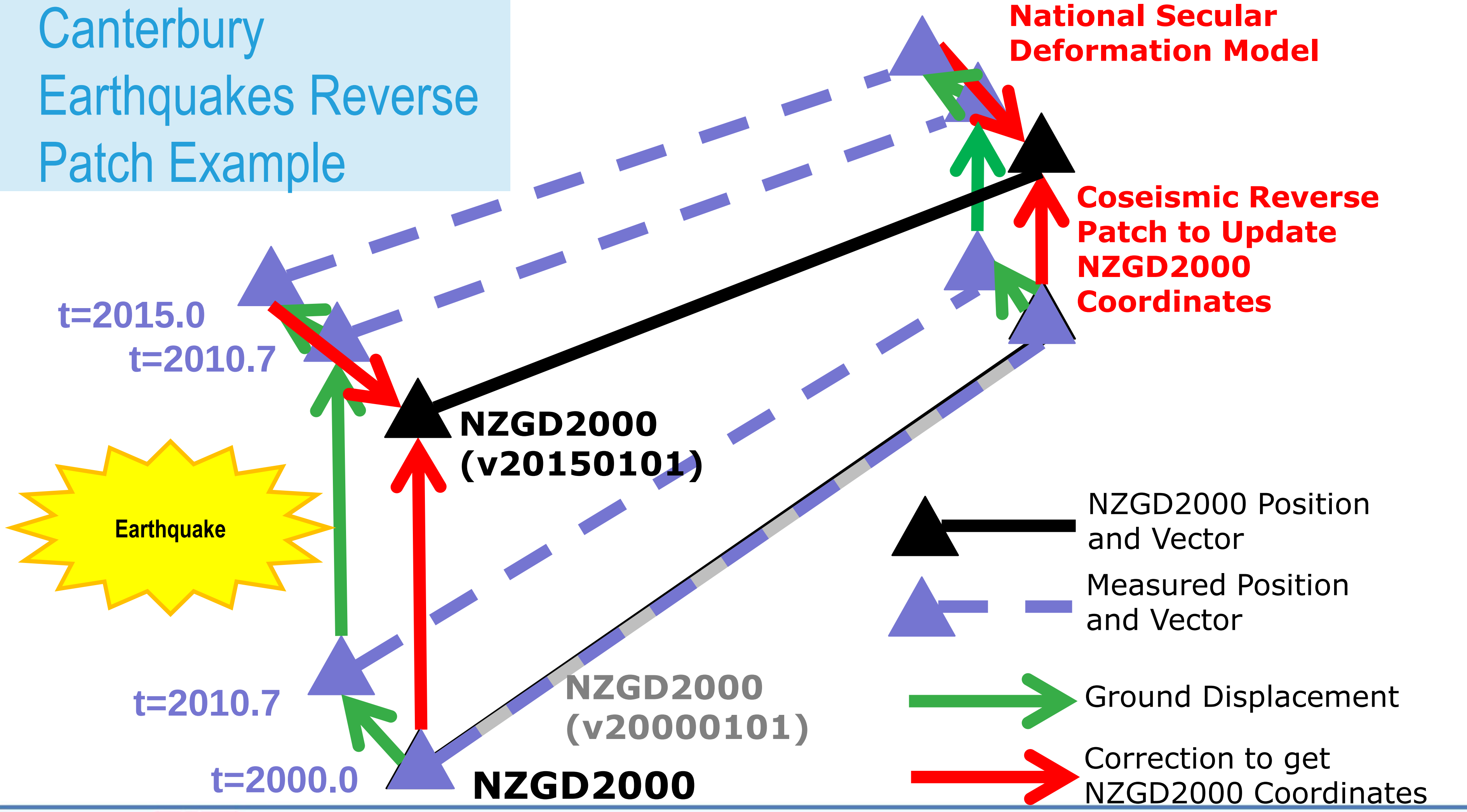
Grid	No Lon	No Lat	Size Lon (deg)	Size Lat (deg)
A	52	54	0.15	0.125
B	50	59	0.075	0.0625
C	84	118	0.0375	0.03125
D	141	306	0.01875	0.015625

5. Using a Vertical Deformation Model Example

Canterbury Earthquakes Reverse Patch Example



Canterbury Earthquakes Reverse Patch Example



Reverse Patch with Post-Earthquake Observations

Deformation Model NOT Used

From	To	Type	Value X,Y,Z	+/-	Calc X,Y,Z	+/-	Res E,N,U
BDUF	BDUH	GB	-806.601	0.016	-806.611	0.000	**0.003**
			-660.795	0.010	-660.791	0.000	**-0.009**
			756.648	0.016	756.650	0.000	**-0.007**
			1288.321		1288.326		**0.011**

Deformation Model Used

From	To	Type	Value X,Y,Z	+/-	Calc X,Y,Z	+/-	Res E,N,U
BDUF	BDUH	GB	-806.601	0.016	-806.611	0.000	**0.003**
			-660.795	0.010	-660.790	0.000	**-0.009**
			756.648	0.016	756.650	0.000	**-0.007**
			1288.321		1288.327		**0.012**

Reverse Patch with Pre-Earthquake Observations

Deformation Model NOT Used

From	To	Type	Value	+/-	Calc	+/-	Res
			X,Y,Z		X,Y,Z		E,N,U
BDUF	BDUH	GB	-806.347	0.016	-806.611	0.000	0.009
			-660.834	0.010	-660.791	0.000	-0.110
			756.753	0.016	756.650	0.000	-0.265
			1288.244		1288.326		0.287

Deformation Model Used

From	To	Type	Value	+/-	Calc	+/-	Res
			X,Y,Z		X,Y,Z		E,N,U
BDUF	BDUH	GB	-806.347	0.016	-806.354	0.000	0.004
			-660.834	0.010	-660.829	0.000	-0.009
			756.753	0.016	756.758	0.000	-0.002
			1288.244		1288.249		0.010

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