IAG/FIG Commission 5/ICG Technical Seminar

Reference Frame in Practice

Rome, Italy 4–5 May 2012

Four Dimensional Deformation Models for Terrestrial Reference Frames

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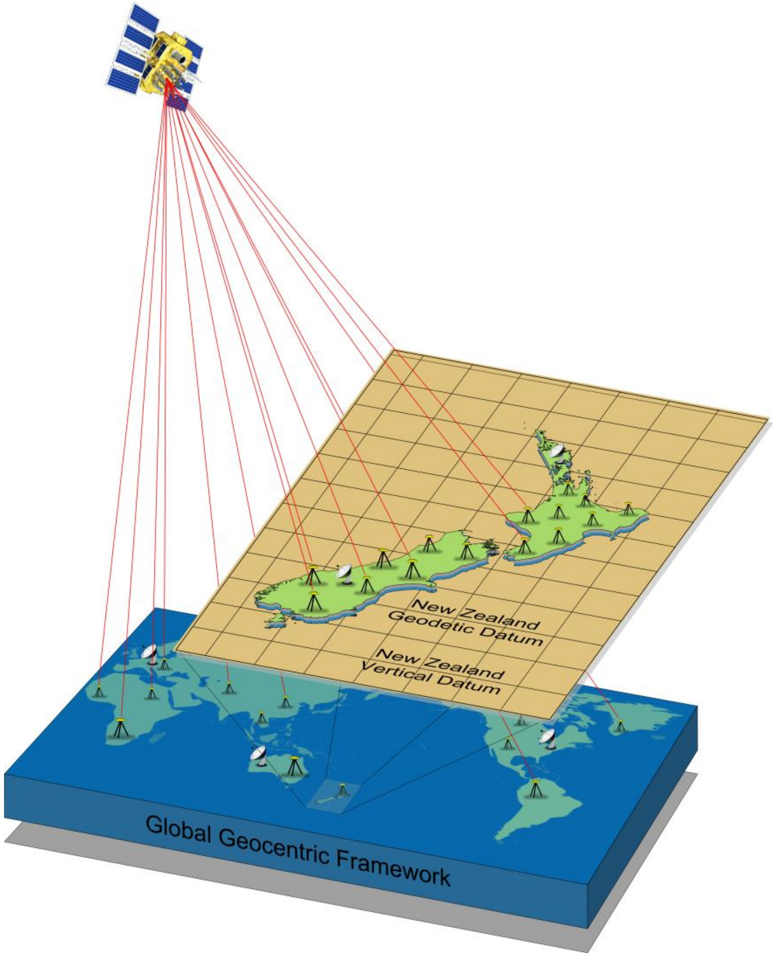
Sponsors:
esri Trimble CIPAG

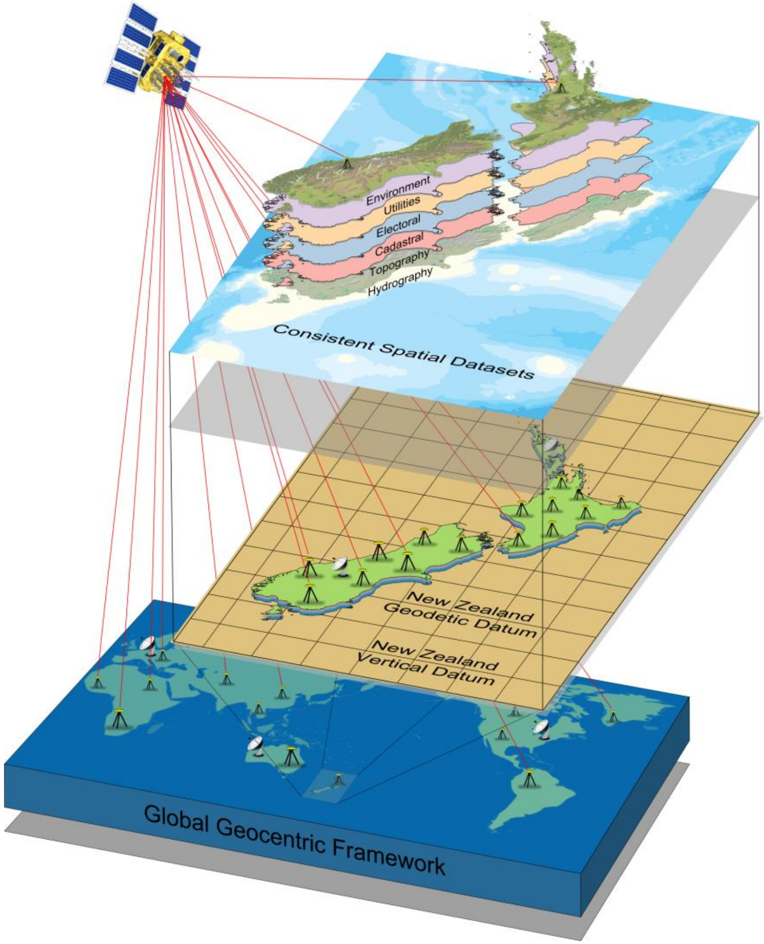
- **Introduction (10min Graeme)**
- **Concepts of 4d datums (10 min Graeme)**
- **The pros and cons of static, semi-dynamic datum and dynamic datums (10 min Grame)**
- **Development of Deformation Models (15min Richard)**
- **Incorporating the effects of events such as earthquakes into the model. (15min Richard)**
- **Case studies,**
  - **Australia (10 min Richard)**
  - **New Zealand, (10 min Graeme)**
- **Questions 10 min**

Introduction

Fundamental Role of Reference Frame



Fundamental Role of Reference Frame

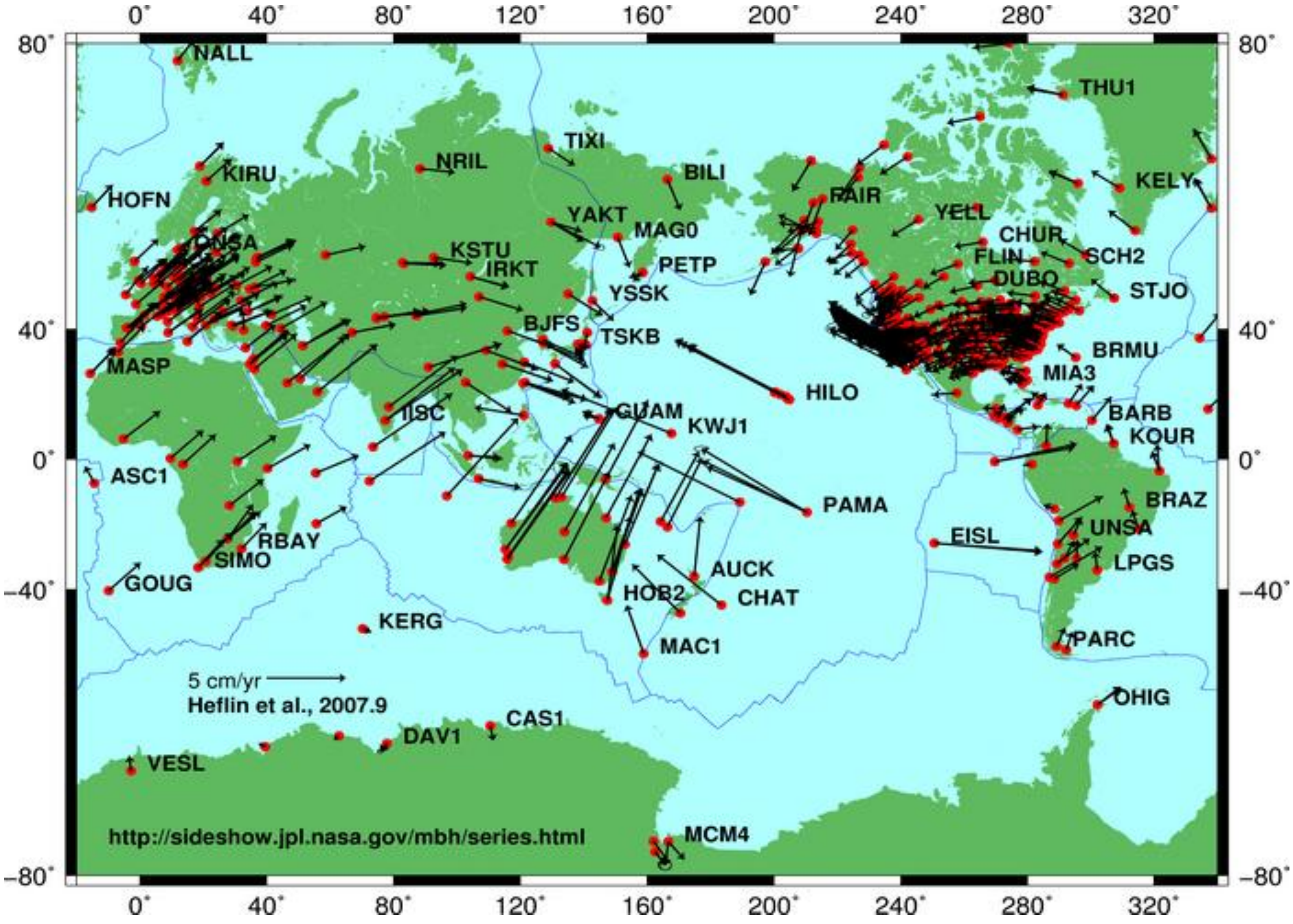


Fundamental Role of Reference Frame

Requirements of a National Reference System

- 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

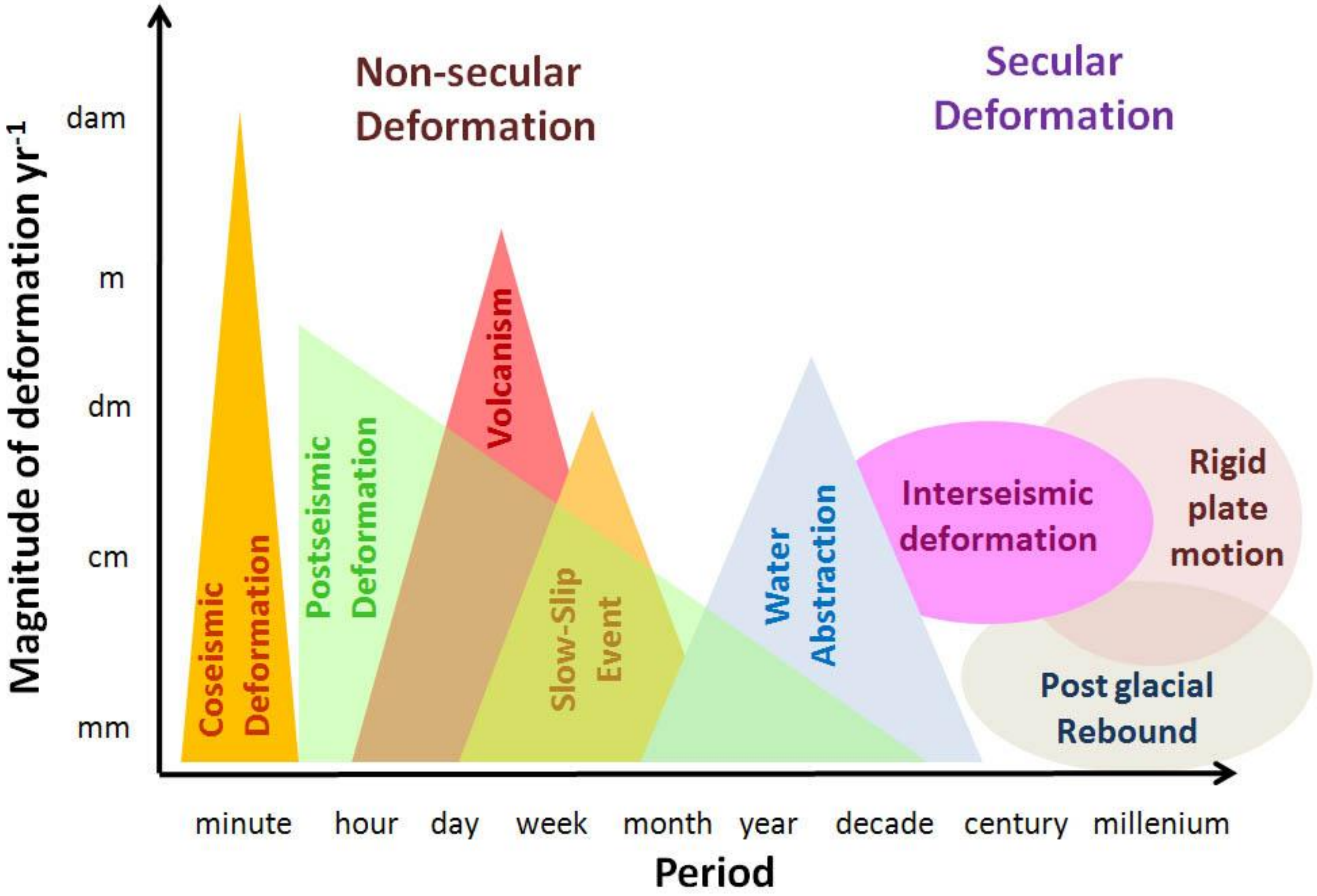
Crustal Dynamics



Heflin et al., 2007.9

http://sideshow.jpl.nasa.gov/mbh/series.html

Temporal and spatial extent of deformation



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- Coordinates slowly go out of date, need to change periodically which is disruptive

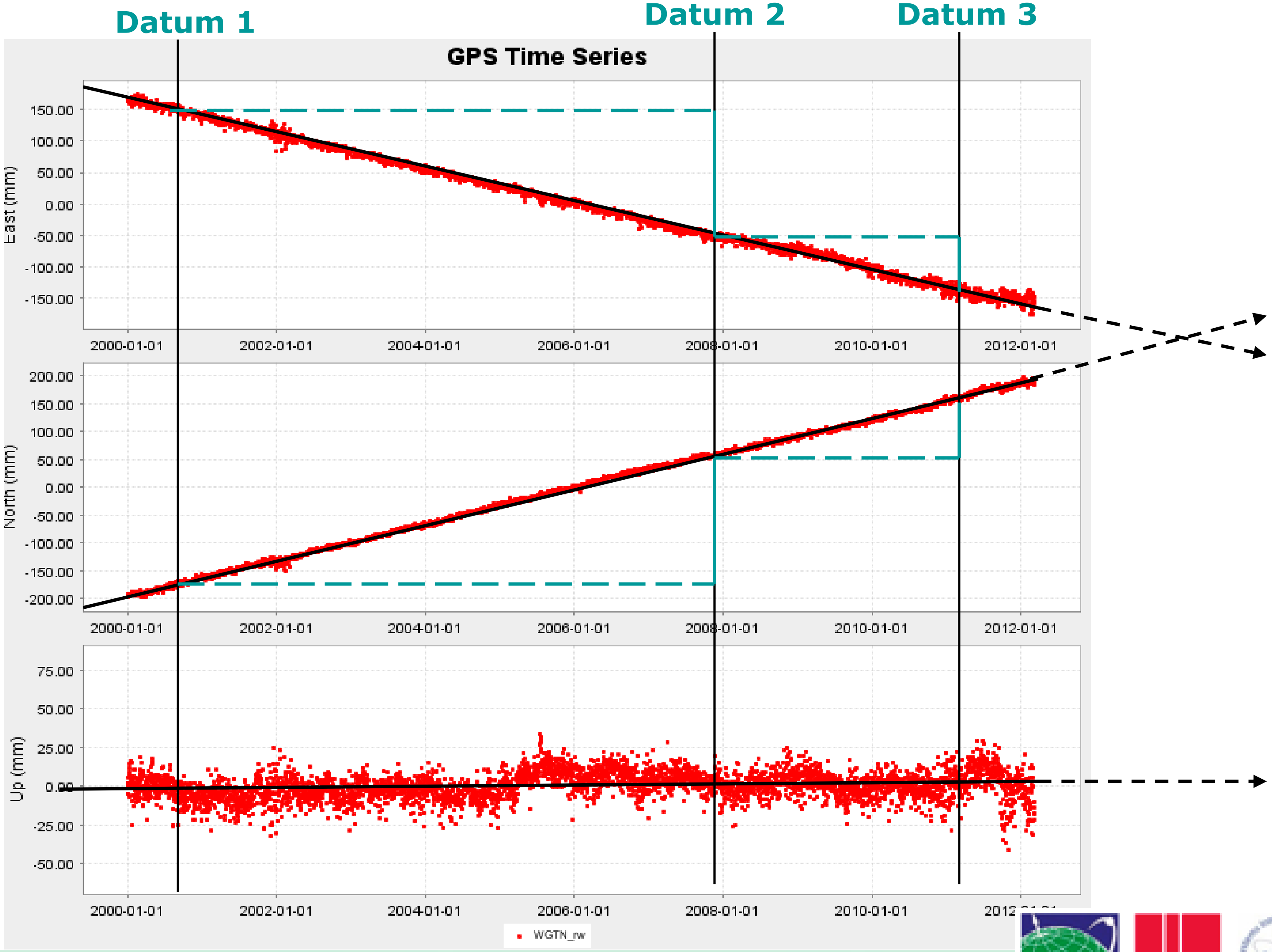
Dynamic datum (4D)

- 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

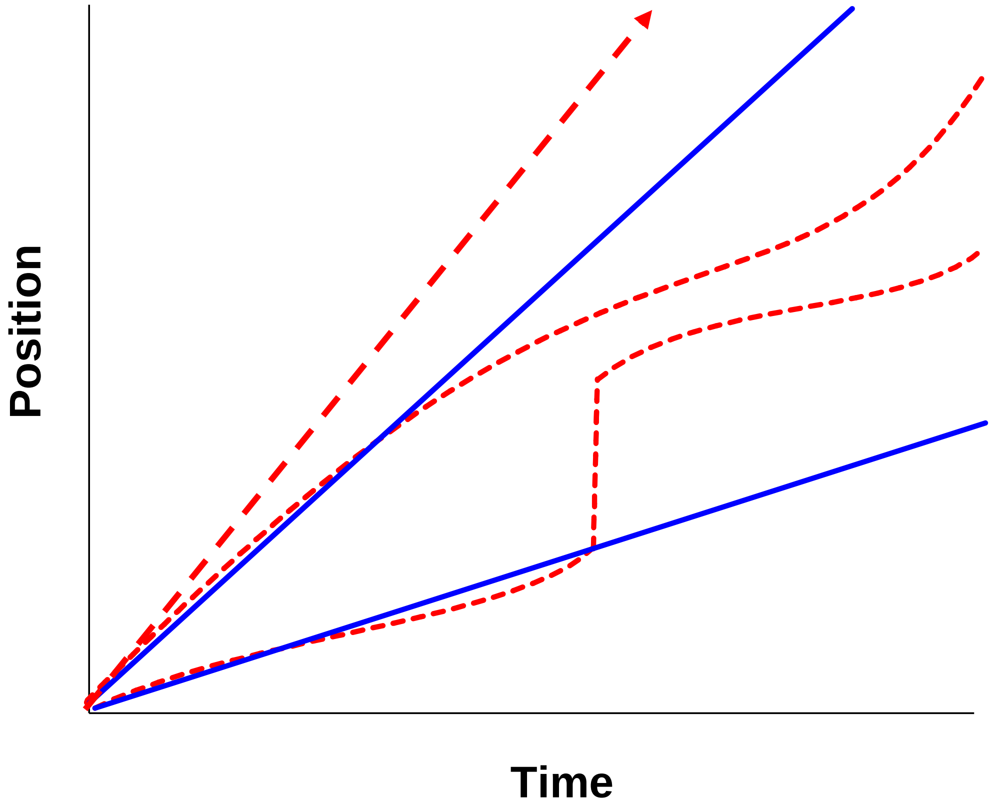


The dynamic world

The ideal world!

Need to accommodate error in model or changes in deformation

Need to accommodate local and spatially complex deformation



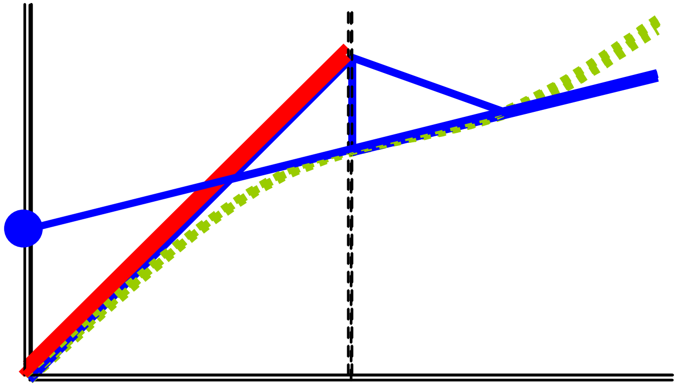
Options - Error in model or changing deformation

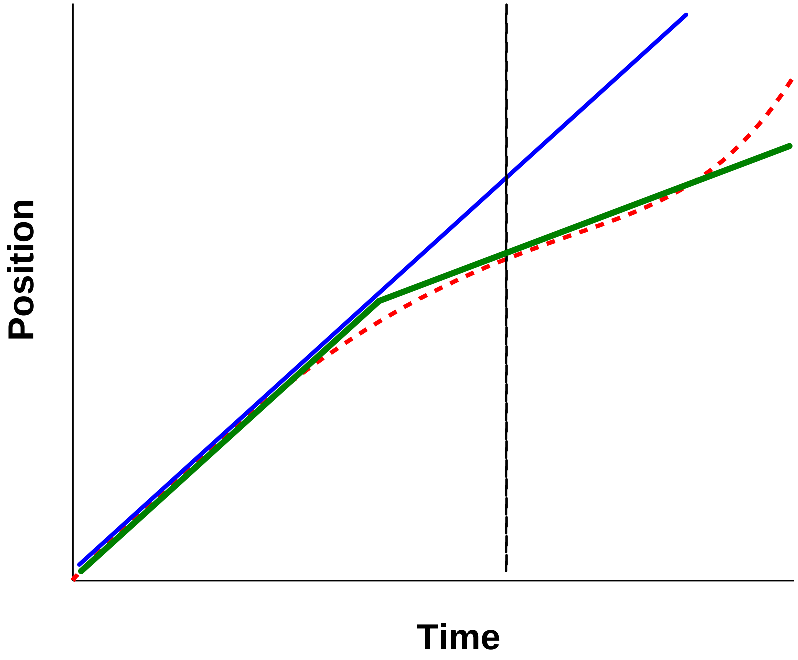
Steer to a new model

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

Options - Spatially complex deformation

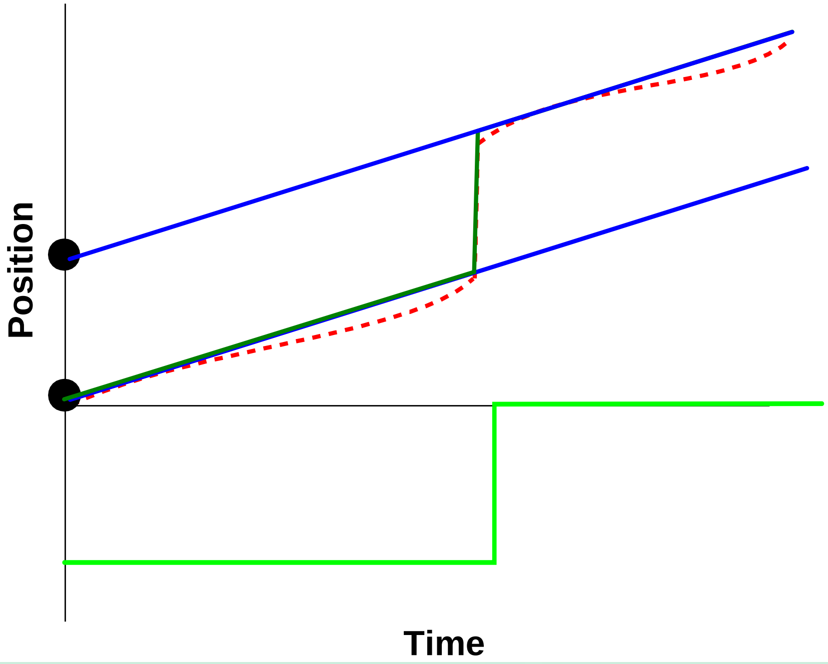
The deformation event is not incorporated into the deformation model (dot is the base epoch coordinate of the mark)

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

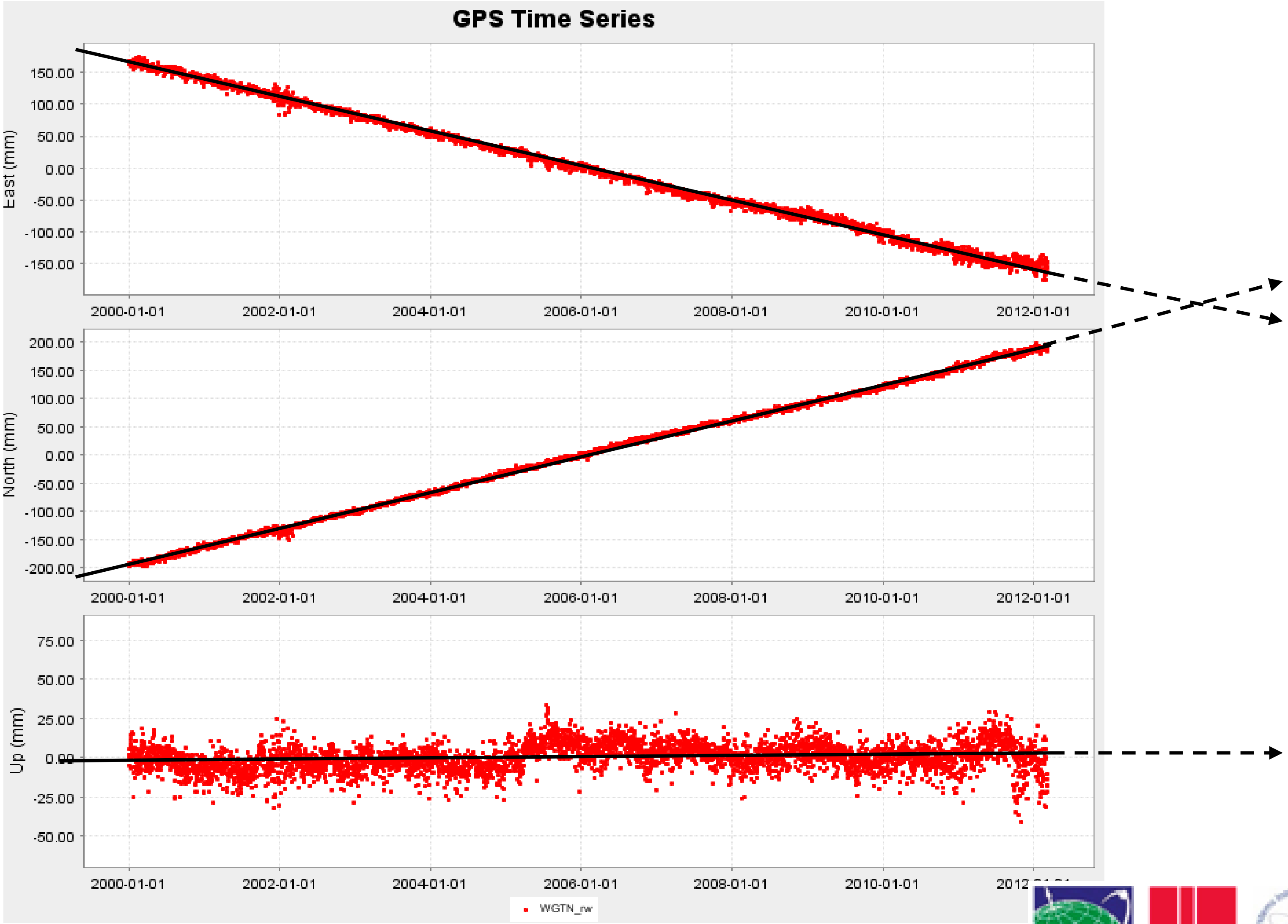
The trajectory of the mark – incorporated the national deformation model and the ‘patch’

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

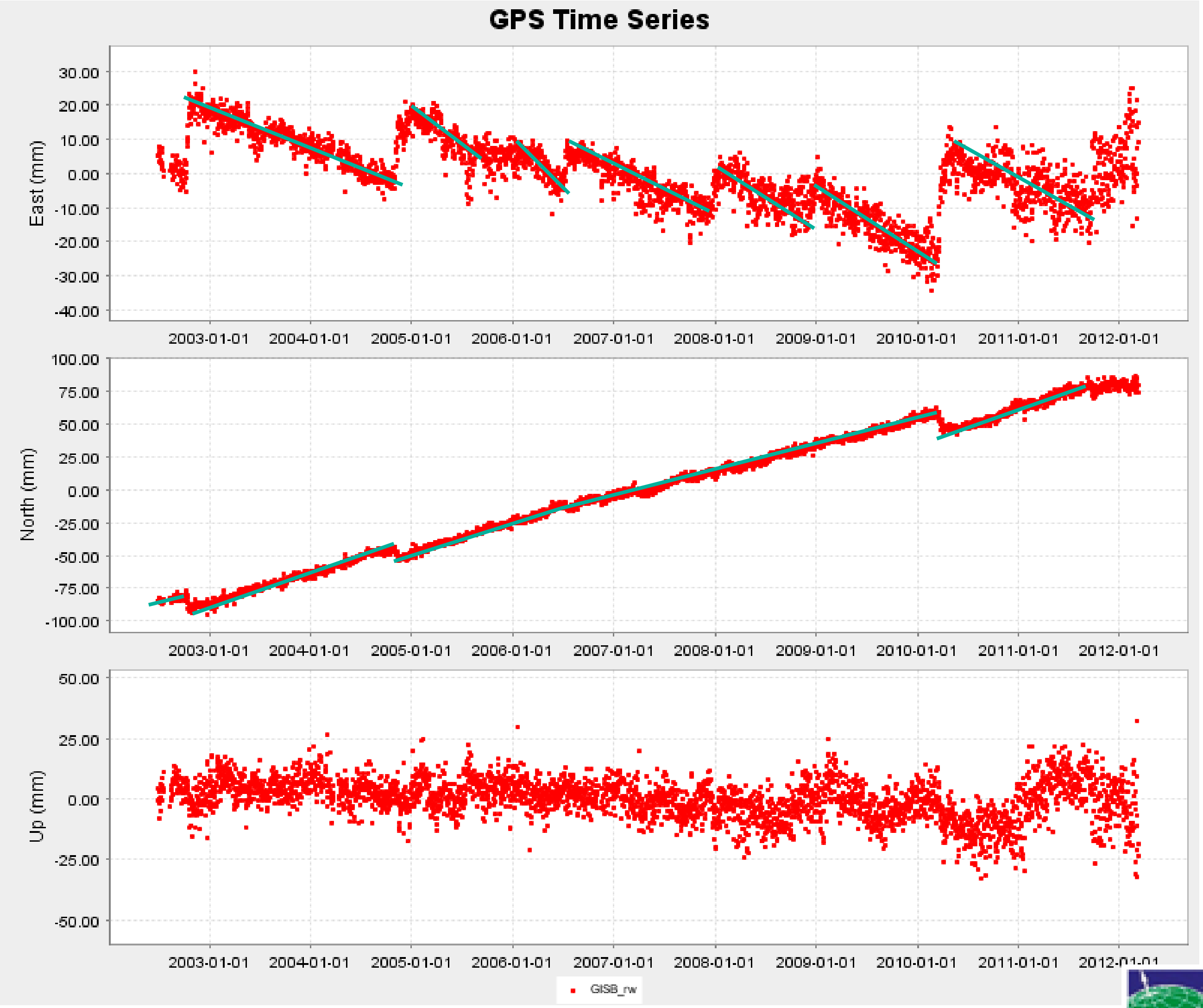
Coordinates for times after the event just use the national deformation model and coordinates before the event include the patch.



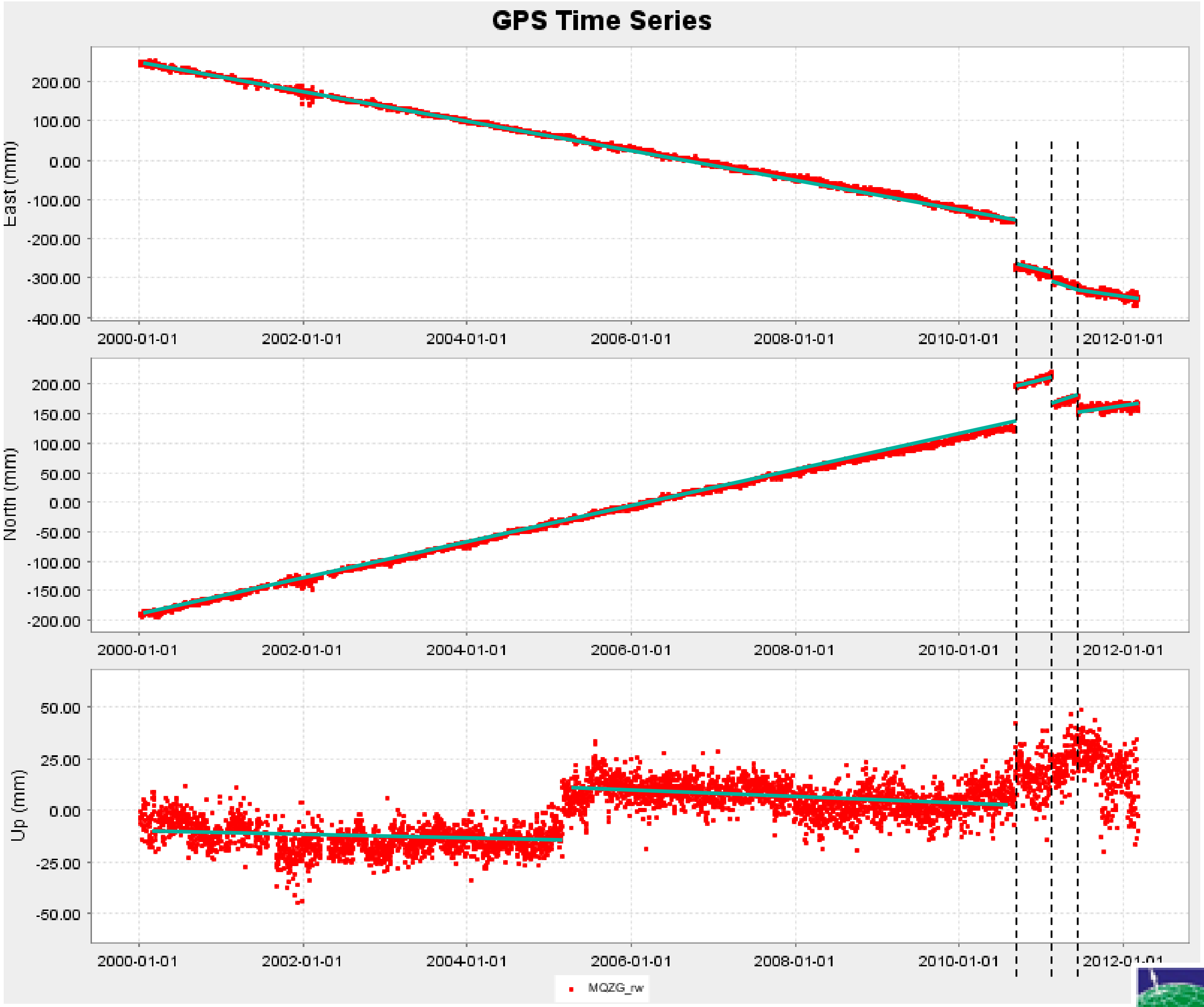
Constant motion through time



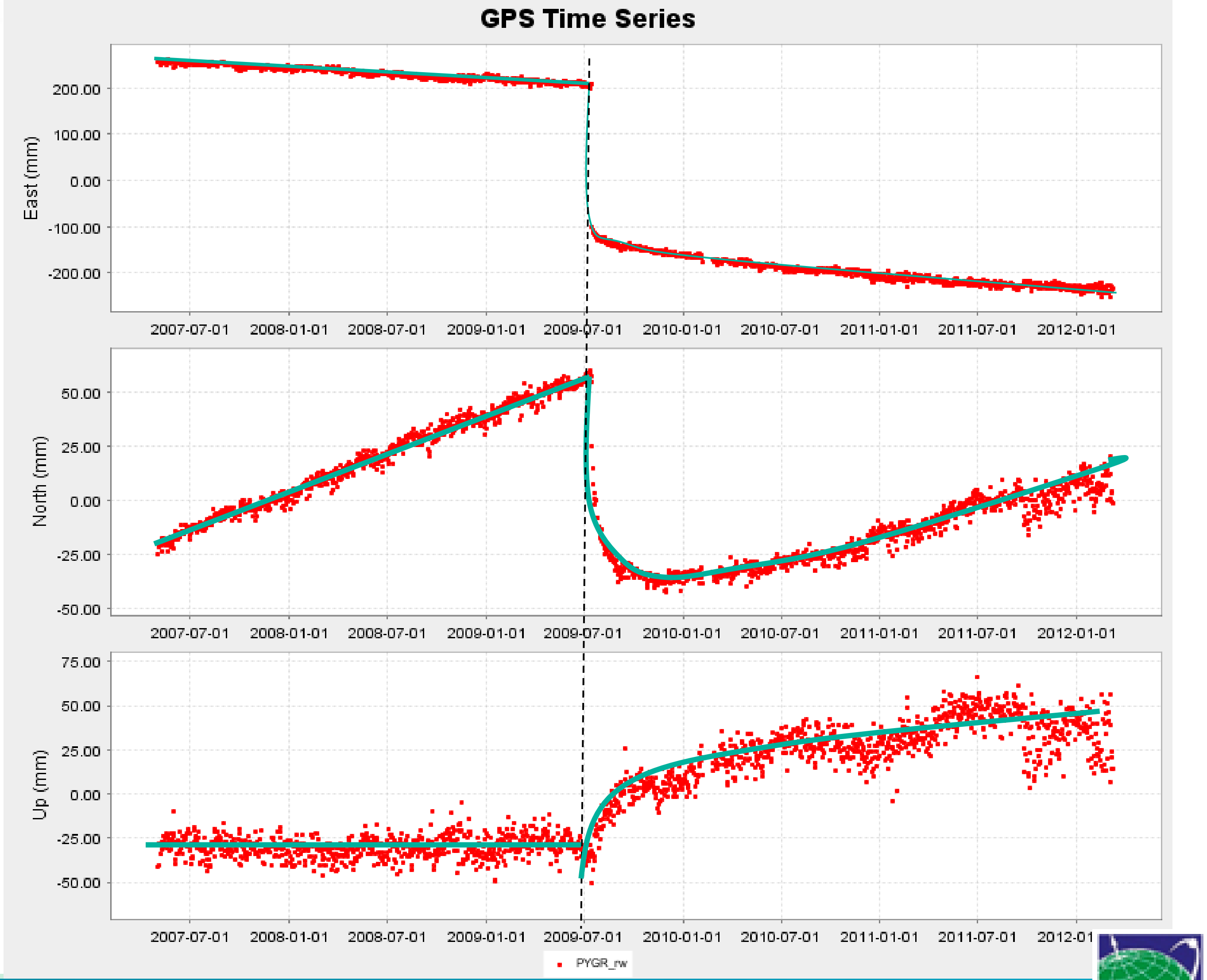
Episodic events



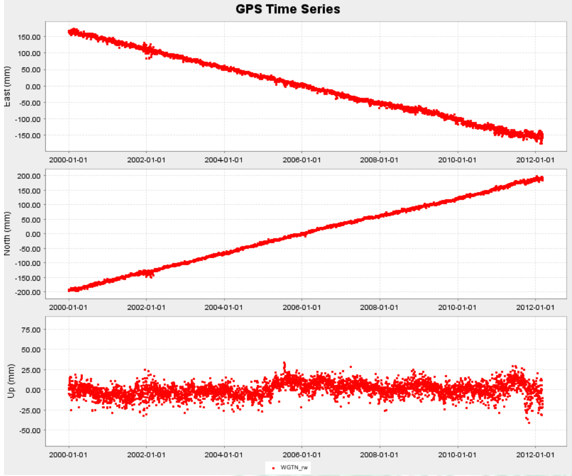
Multiple events



Earthquake and post-seismic deformation



Modelling the deformation

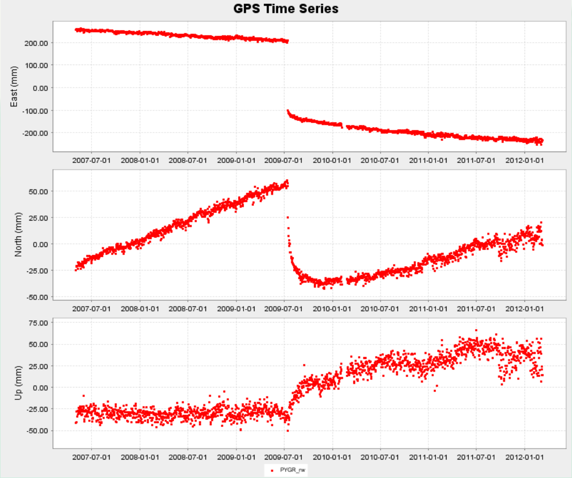


Options – regional deformation

- Simple rectangular grid (simplest method)
- Complex grid (eg 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



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The pros and cons of static, semi-dynamic datum and dynamic datums

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)

Issues to consider

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/datum's

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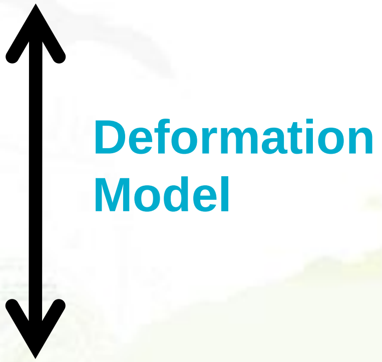
Development of a Deformation Model

Development of a Deformation Model

Aim of a Deformation Model

Dynamic (kinematic) – ITRF



Semi-dynamic (kinematic) datum

Fixed epoch of ITRF

Application:

GNSS data processing & analysis

(e.g. PPP, RTK, NRTK, DGPS, Static post-processing)

Large-scale deformation analysis

GGOS

Application:

All other spatial applications

(e.g. cadastral, engineering, mapping, precision agriculture, mining, LiDar products)

terrestrial surveying

(e.g. TLS, total-station)

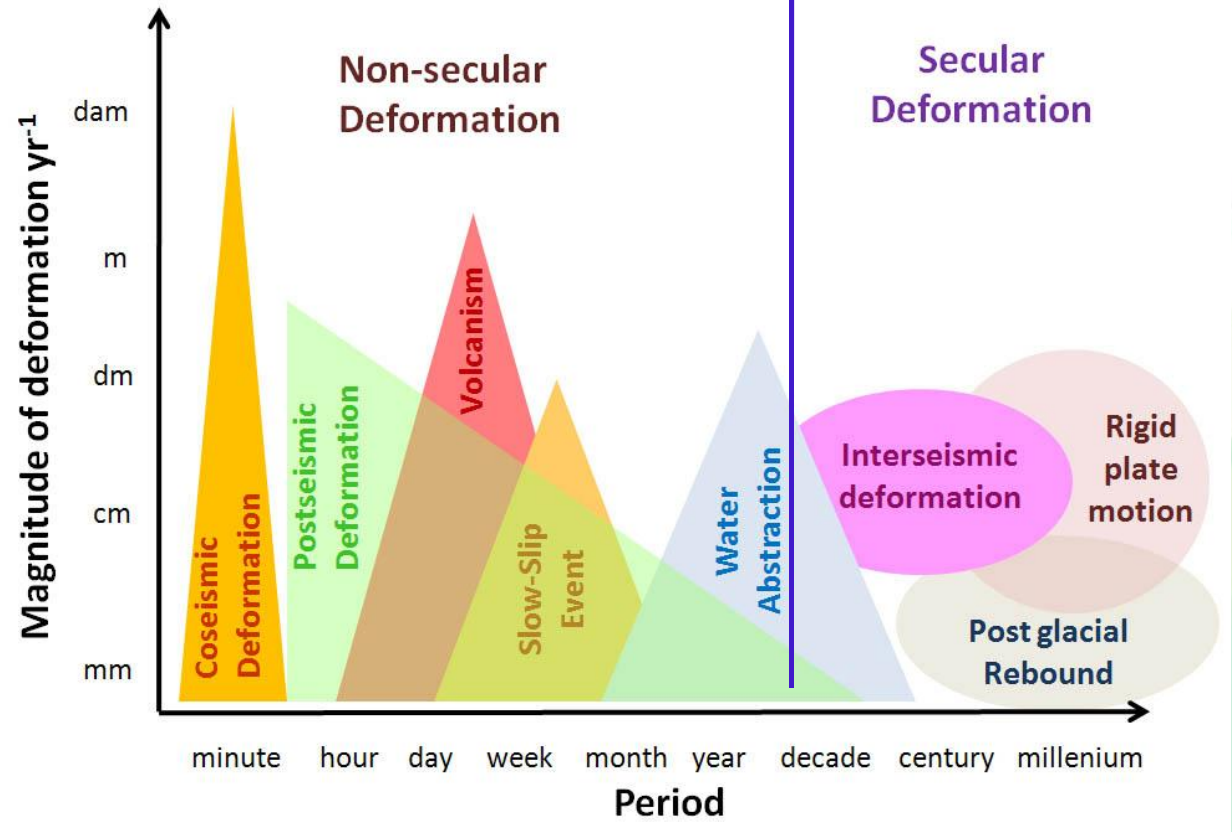
Classification of Deformation

Results in changes in coordinates of working frame

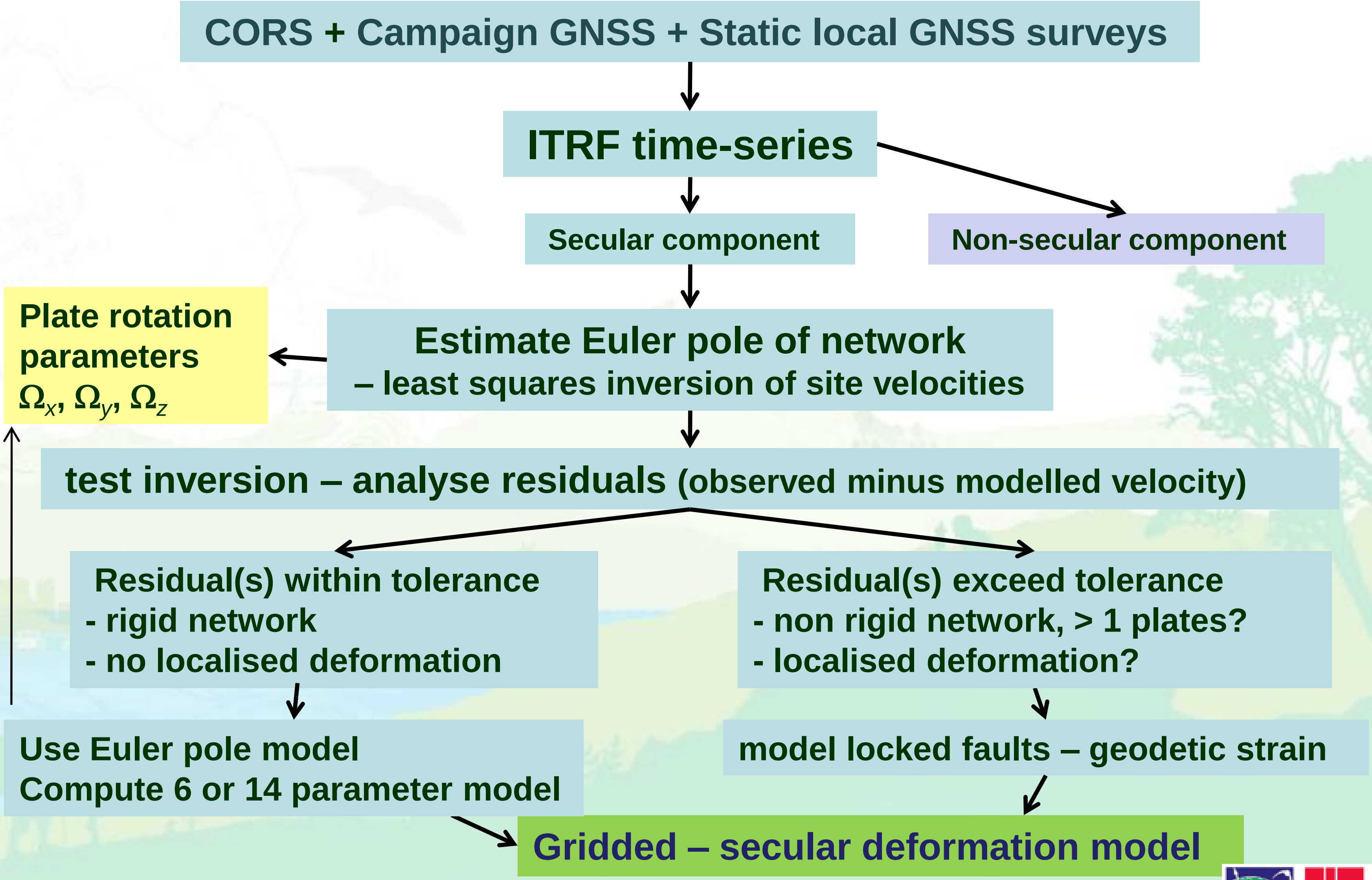
- patch model

Deformation is "invisible" in working frame

- secular model



Developing a Secular Deformation Model



CORS + Campaign GNSS + Static local GNSS surveys

ITRF time-series

Secular component

Non-secular component

Estimate Euler pole of network
– least squares inversion of site velocities

Plate rotation parameters
$\Omega_x, \Omega_y, \Omega_z$

test inversion – analyse residuals (observed minus modelled velocity)

Residual(s) within tolerance
- rigid network
- no localised deformation

Residual(s) exceed tolerance
- non rigid network, > 1 plates?
- localised deformation?

Use Euler pole model
Compute 6 or 14 parameter model

model locked faults – geodetic strain

Gridded – secular deformation model

Secular Model format

aligned with current ITRF

no scale change / rate
no translation / rate
rotation of axes + rate

6 parameter transformation
Rx, Ry, Rz, + rates

or

3 parameter Euler propagation
Ωx, Ω y, Ω z

aligned with earlier ITRF realisation

or non ITRS ellipsoid

scale change / rate
translation / rate
rotation of axes + rate

14 parameter transformation
S, Tx, Ty, Tz, Rx, Ry, Rz, + rates

Gridded secular deformation model
ITRF site velocities on a 1° or 0.1° grid

Site velocity estimated by bilinear interpolation
(as used in geoid or grid distortion modelling)

Kinematic ITRF to Semi-kinematic ITRF by Transformation

14 parameter transformation

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{t_0} = \begin{bmatrix} T_x + \dot{T}_x(t-t_0) \\ T_y + \dot{T}_y(t-t_0) \\ T_z + \dot{T}_z(t-t_0) \end{bmatrix} + \left\{S + \dot{S}(t-t_0)\right\} \begin{bmatrix} 1 & \left\{R_z + \dot{R}_z(t-t_0)\right\} & -\left\{R_y + \dot{R}_y(t-t_0)\right\} \\ -\left\{R_z + \dot{R}_z(t-t_0)\right\} & 1 & \left\{R_x + \dot{R}_x(t-t_0)\right\} \\ \left\{R_y + \dot{R}_y(t-t_0)\right\} & -\left\{R_x + \dot{R}_x(t-t_0)\right\} & 1 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{t}$$

6 parameter transformation (no translation or scale)

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{t_0} = \begin{bmatrix} 1 & \left\{R_z + \dot{R}_z(t-t_0)\right\} & -\left\{R_y + \dot{R}_y(t-t_0)\right\} \\ -\left\{R_z + \dot{R}_z(t-t_0)\right\} & 1 & \left\{R_x + \dot{R}_x(t-t_0)\right\} \\ \left\{R_y + \dot{R}_y(t-t_0)\right\} & -\left\{R_x + \dot{R}_x(t-t_0)\right\} & 1 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{t}$$

t_0	is the reference epoch (years)		
t	is the epoch of measurement (years)		
T_x, T_y, T_z	Translation parameters (m)	$\dot{T}_x \dot{T}_y \dot{T}_z$	rate of change (m/yr)
R_x, R_y, R_z	Rotation parameters (radians)	$\dot{R}_x \dot{R}_y \dot{R}_z$	rate of change (radians/yr)
S	Scale (unitless)	$\dot{S}$	rate of change (per yr)

Kinematic ITRF to Semi-kinematic ITRF by Propagation

Site velocity from Euler pole definition

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} = \begin{bmatrix} \Omega_Y Z - \Omega_Z Y \\ \Omega_Z X - \Omega_X Z \\ \Omega_X Y - \Omega_Y X \end{bmatrix} \cdot 1\text{E-6} \longrightarrow \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{t_0} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{t} + \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} \cdot (t_0 - t)$$

t_0	reference epoch of the semi-kinematic datum (in decimal years)
t	epoch of measurement (in decimal years)
$(\Omega_X, \Omega_Y, \Omega_Z)$	Euler pole (Cartesian rotation format)
$(X, Y, Z)t_0$	semi-kinematic coordinates computed at the reference epoch (m)
$(X, Y, Z)t$	kinematic ITRF coordinates at the measurement epoch (m)
$(\dot{X}, \dot{Y}, \dot{Z})$	ITRF site velocity estimated from the Euler pole definition or interpolated from the secular deformation model (m/yr)

Gridded Deformation Models

Regular grid deformation model

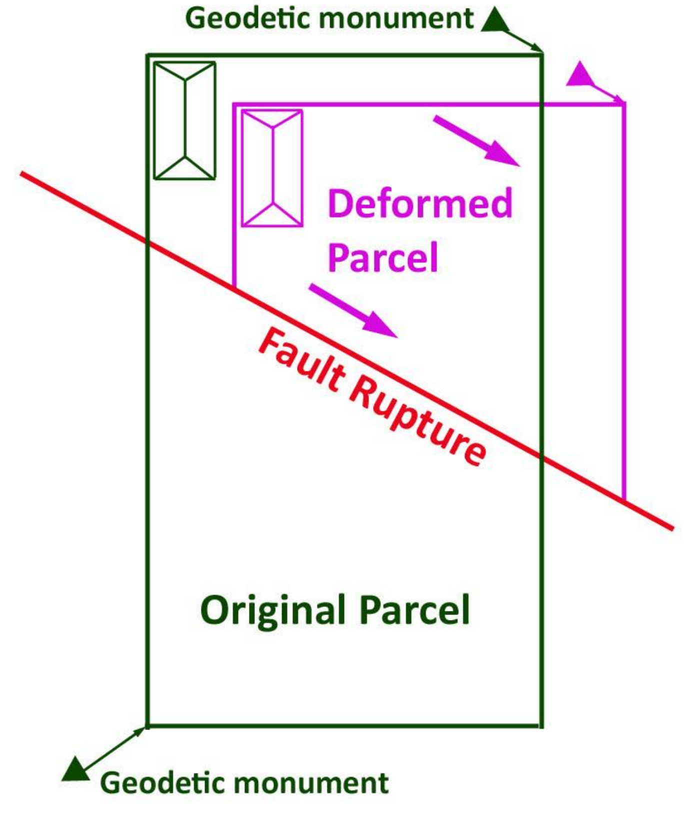
- standard ASCII format
  (latitude, longitude, latitude rate, longitude rate, vertical rate)
- 1°, 0.25° or 0.1° grid size
- bilinear interpolation
- similar format to geoid model
- planar assumption < 0.01 mm/yr error for 1° grid size
- accommodates some localised deformation and strain
  (depending upon grid size)

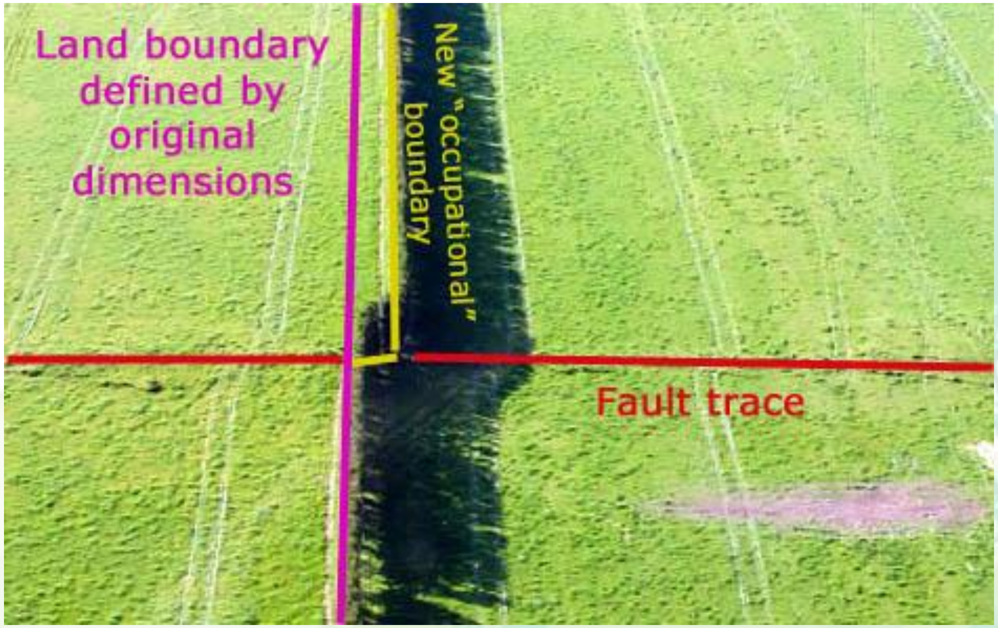
Limitations of rigid plate and 14 parameter models

- localised deformation distributed over model
- does not work where differential geodetic rates occur
- assumes rigid or uniformly deforming tectonic plate

Incorporating Episodic Events (e.g. earthquakes) into a Deformation Model

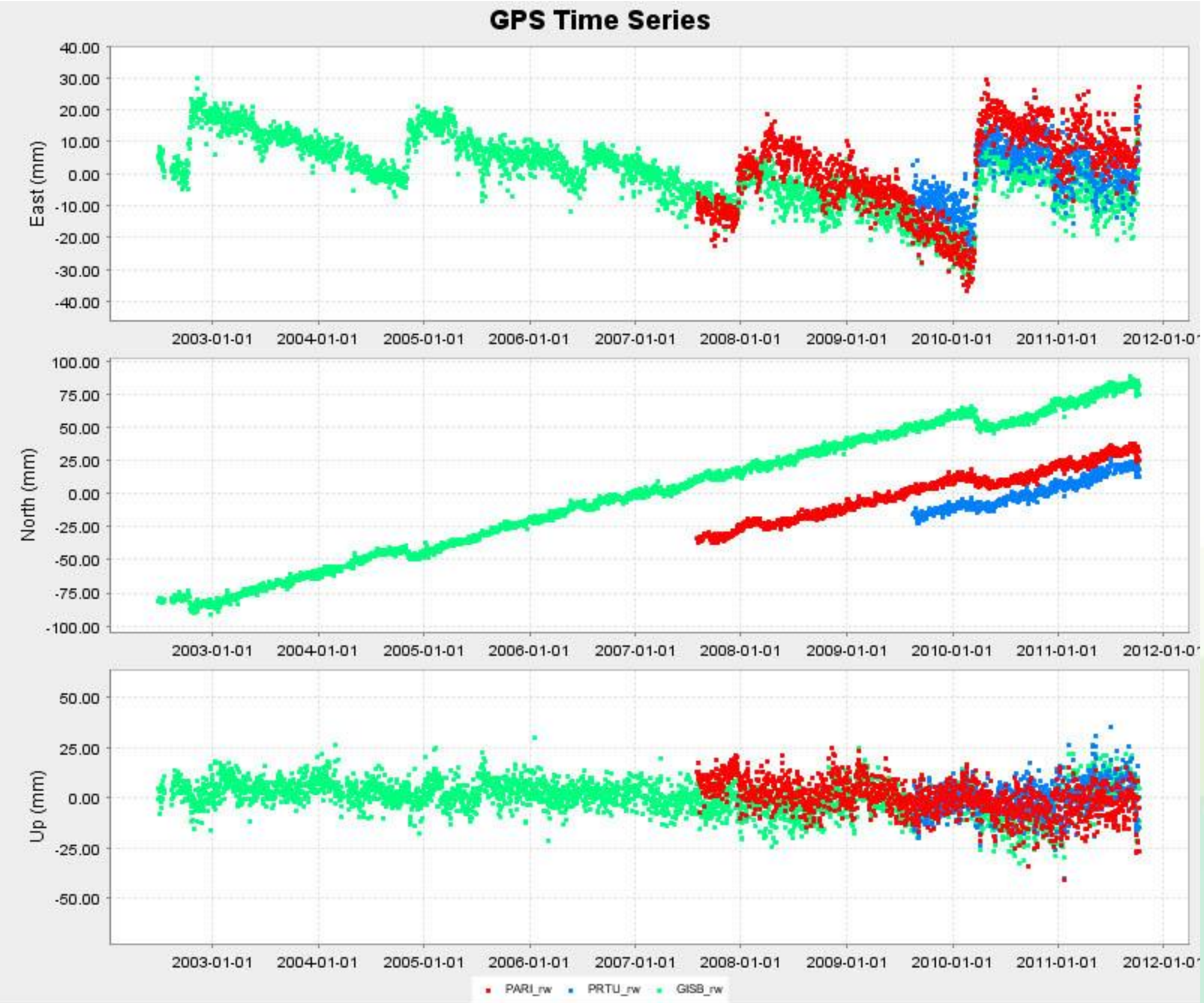
Why episodic events need to be modelled in





Localised deformation should result in coordinate changes to reflect visible reality

Typical time-series in a deforming zone

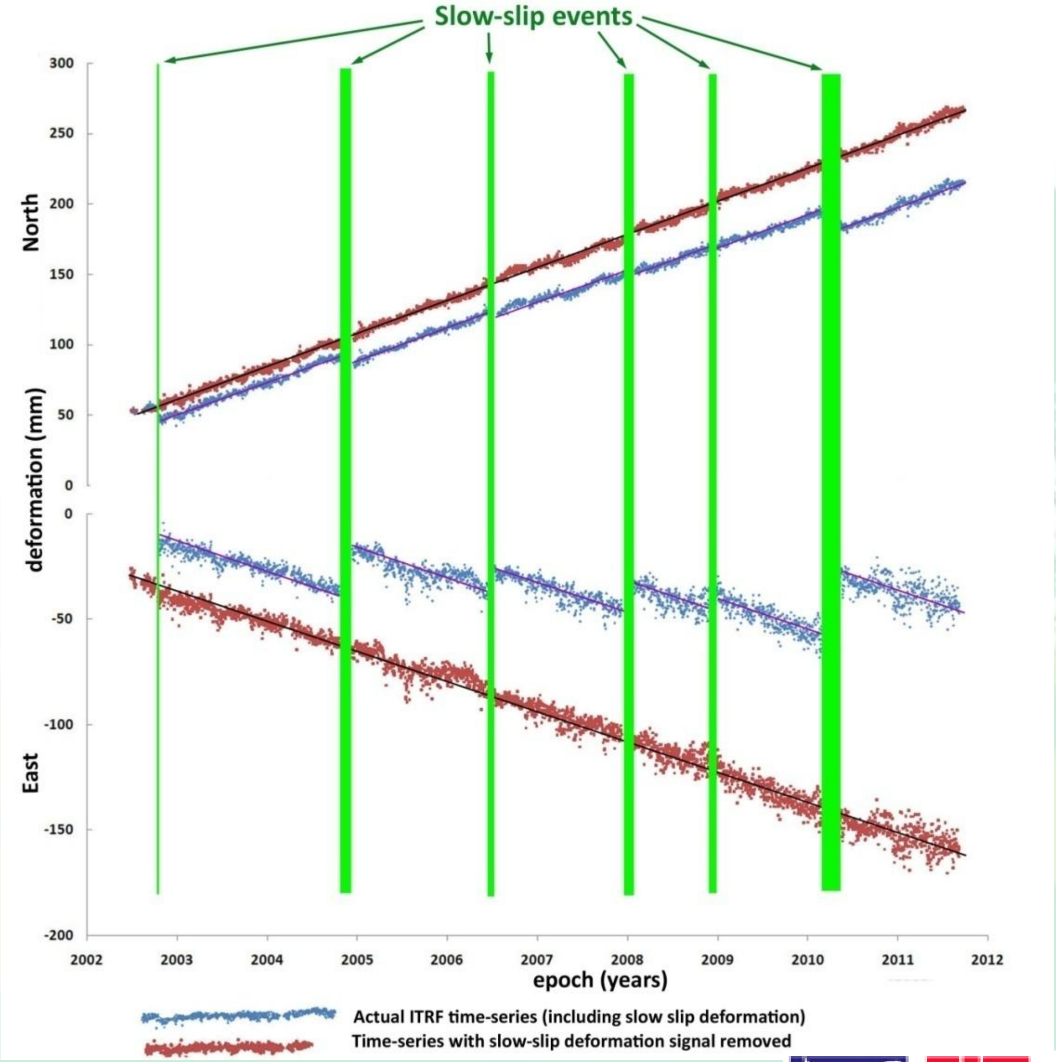


GISB PARI PRTU

Time-series modelling

Separating seismic and secular (interseismic) deformation from time-series

Seismic patch is a sum of all non-secular (episodic) deformation between reference and measurement epoch



Nested model for deformation patch

Model Inputs –

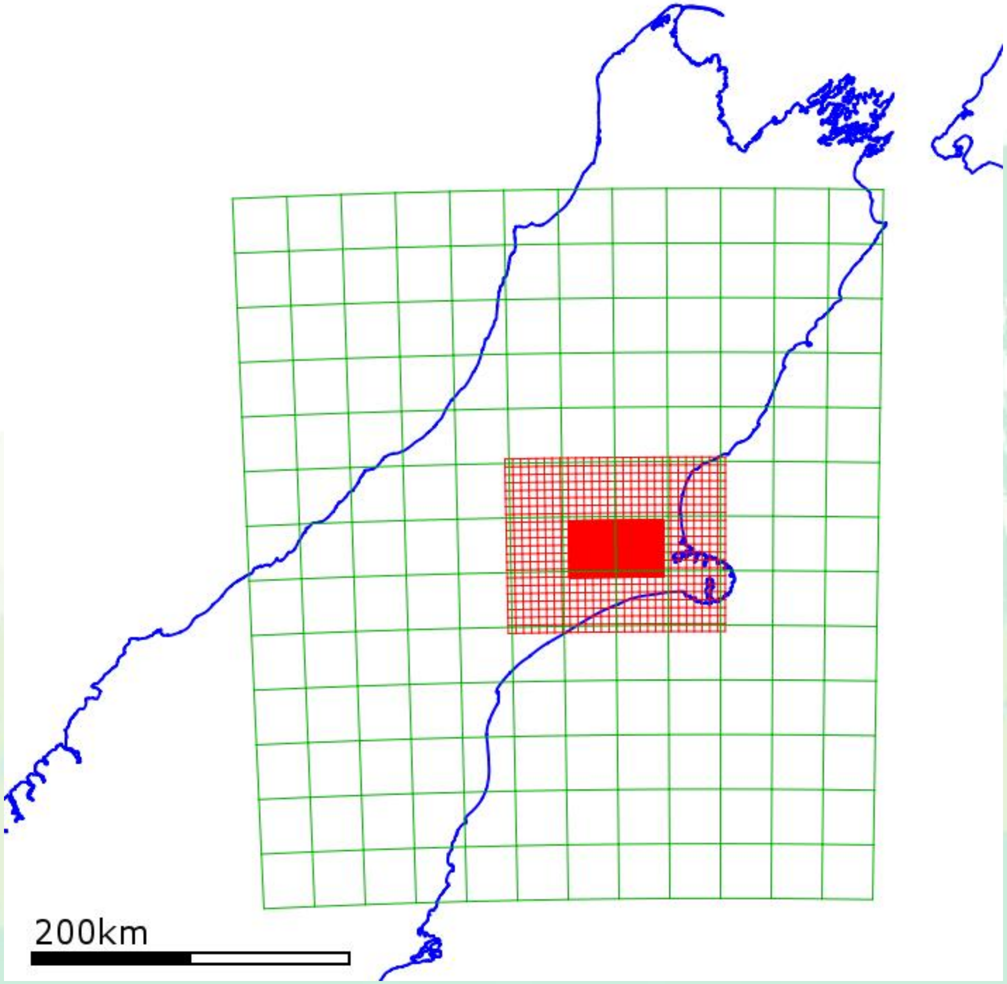
InSAR

LiDar & High-res imagery

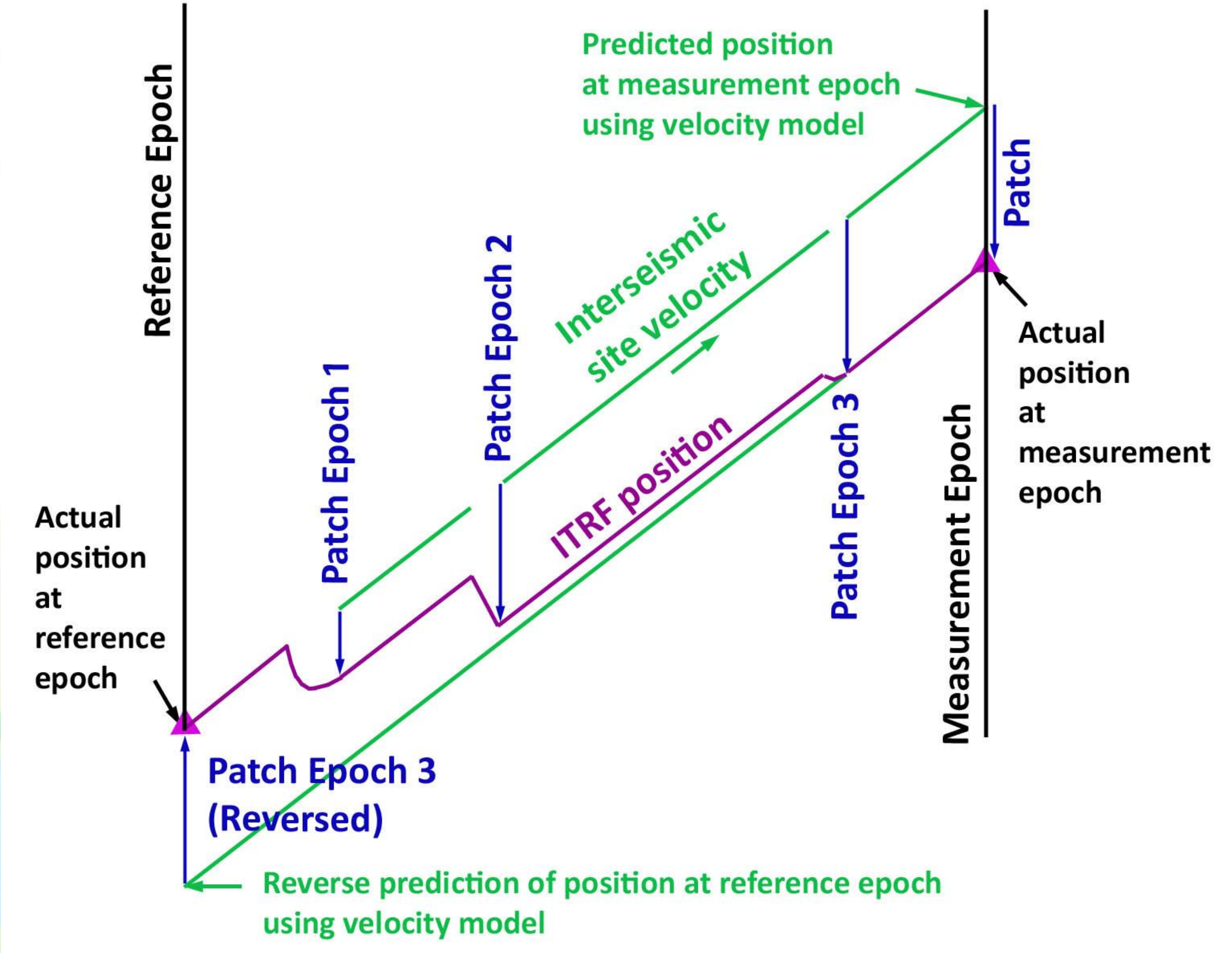
analysis of seismic data

Repeat GNSS
obs of dense passive network
(Strong argument for maintaining passive geodetic infrastructure)

Terrestrial surveys



Two modes of deformation - concept

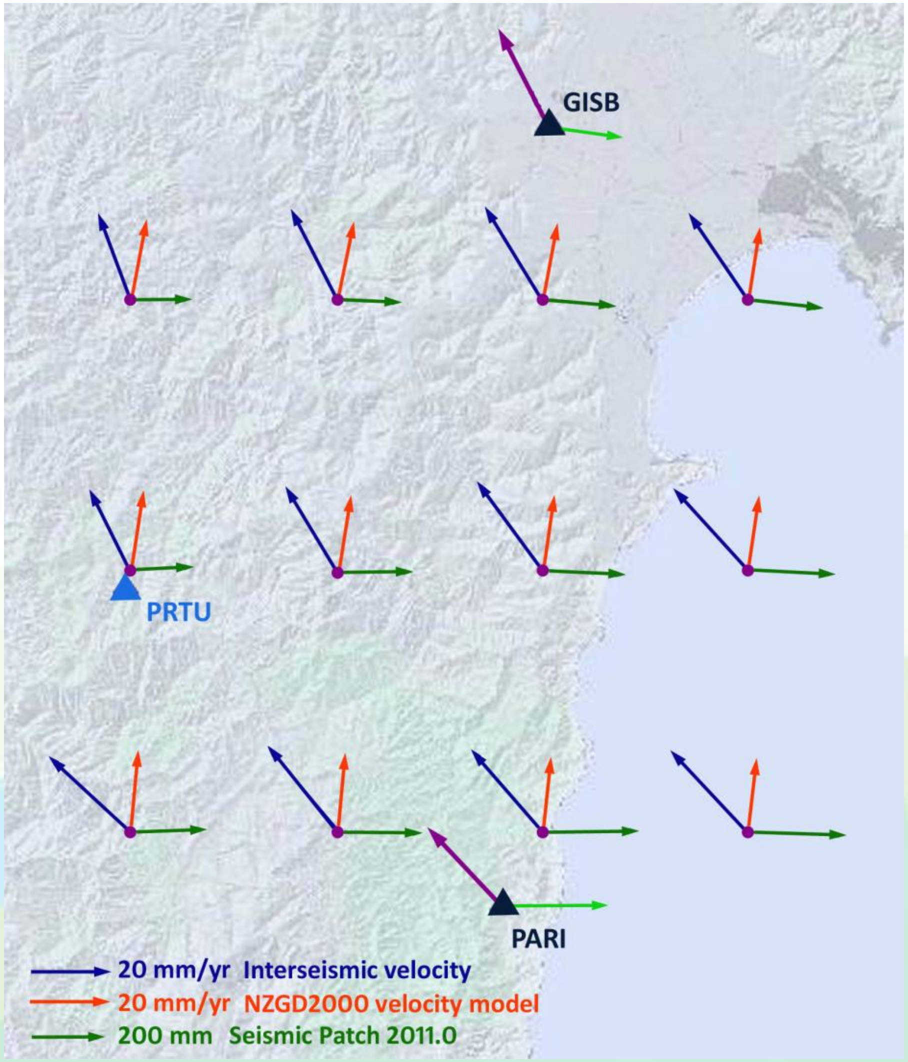


Two modes of deformation in practice

secular model (blue)

patch model (green)

existing model (orange)



Example

Rover (PRTU)		
ITRF2008 Epoch 2011.008	S 38° 48' 51.0946"	E 177° 41' 52.3646"

The ITRF site velocity from interseismic velocity model :

E -0.0108 m/yr N 0.0217 m/yr

The seismic patch model at epoch 2011.0 ΔE 0.183 m ΔN 0.008 m

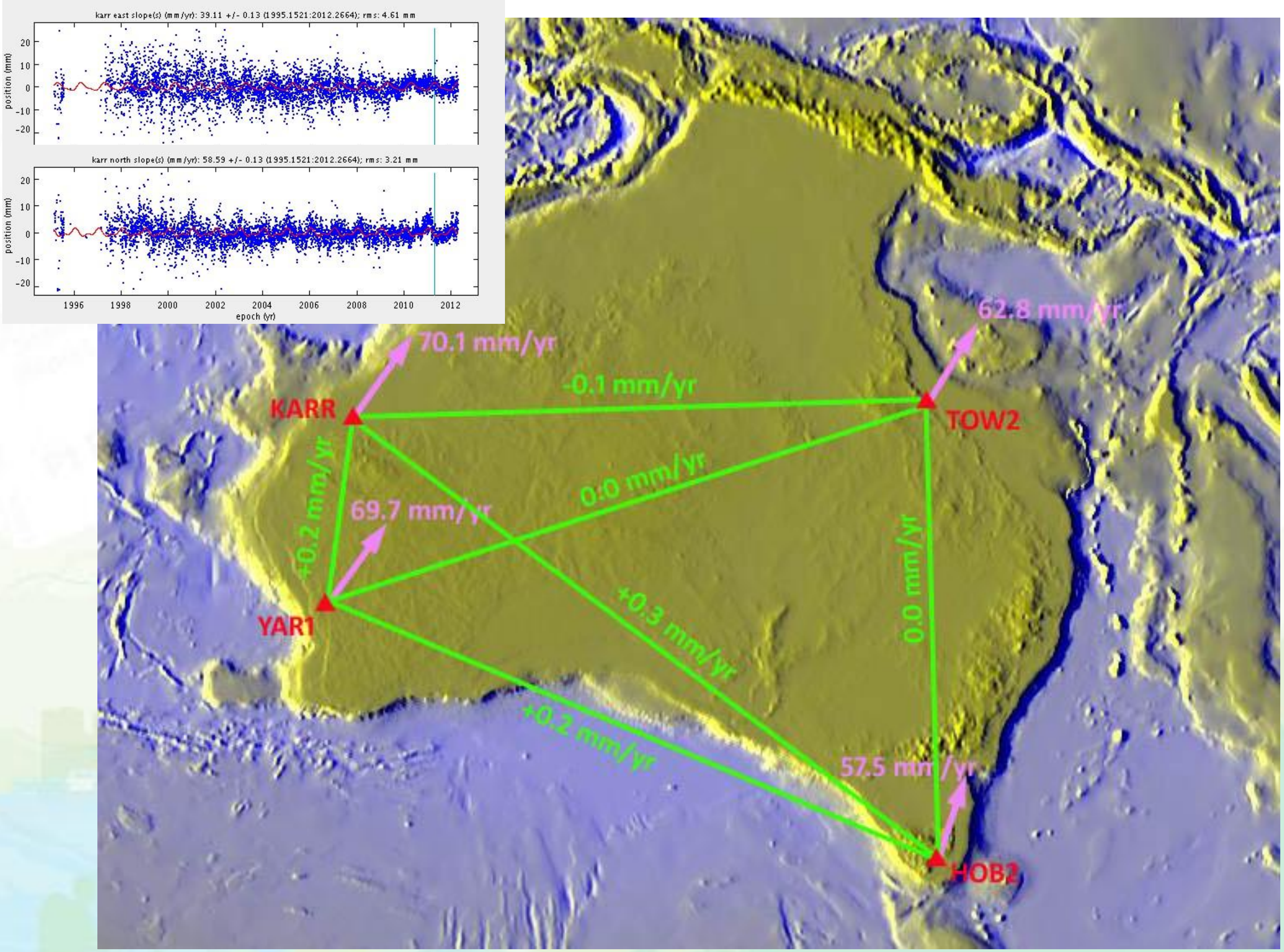
NZGD2000 (estimated from model)	S 38° 48' 51.1026"	E 177° 41' 52.3620"
NZGD2000 (tabulated)	S 38° 48' 51.1021"	E 177° 41' 52.3619"

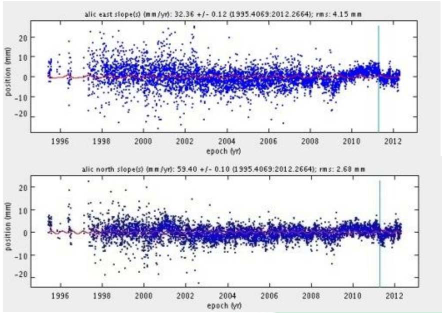
Tabulated – estimated:

ΔE -0.002 m ΔN 0.014 m

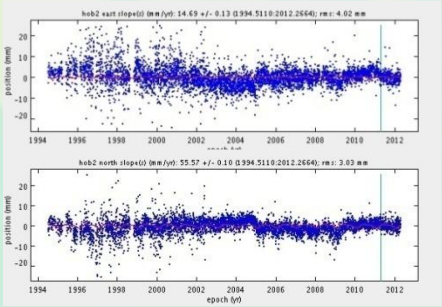
Rigid plate case study (Australia)

Australian Plate Deformation



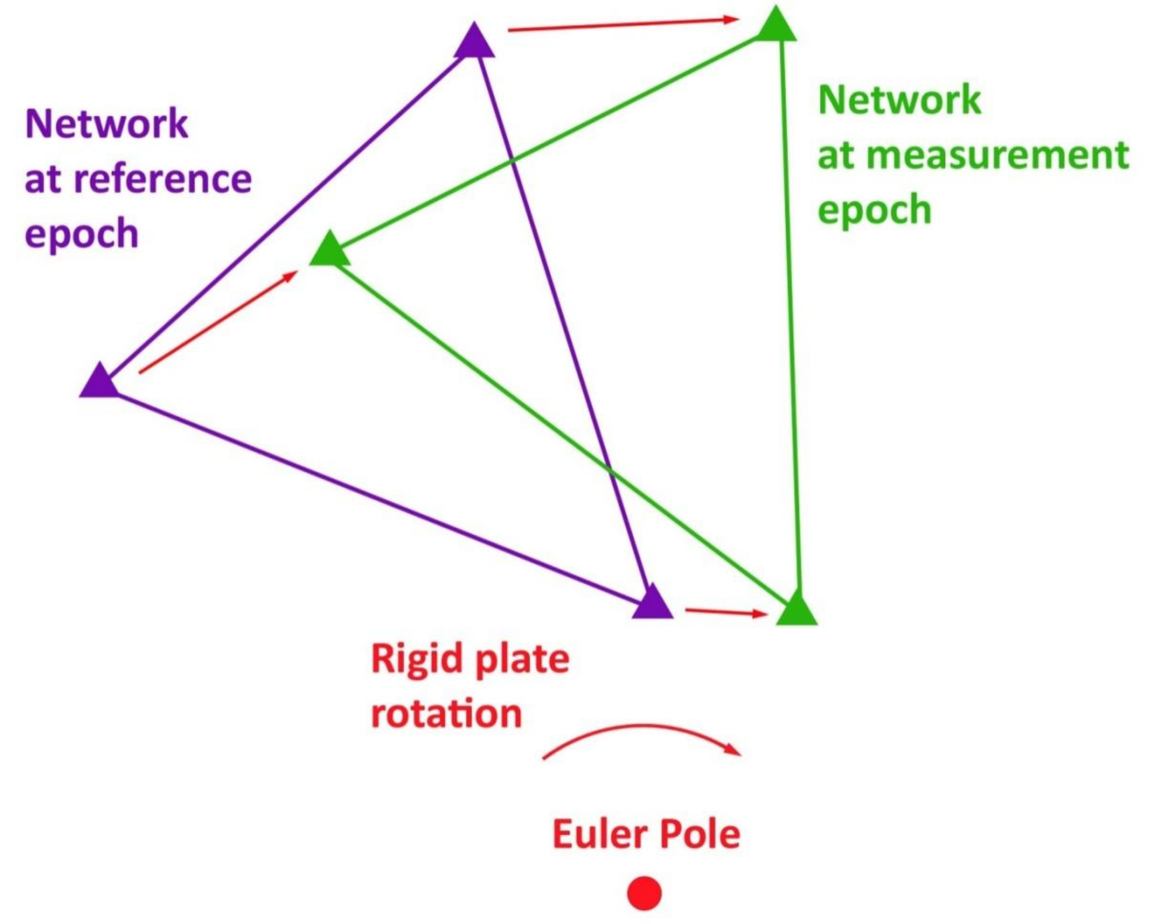


Time-series plots
SCRIPPS, UCSD



purple arrows – tectonic movement, green lines – baseline changes per year

Effect of Rigid plate rotation on GNSS baselines



Australian
Plate rotates at
~0.63° / Ma

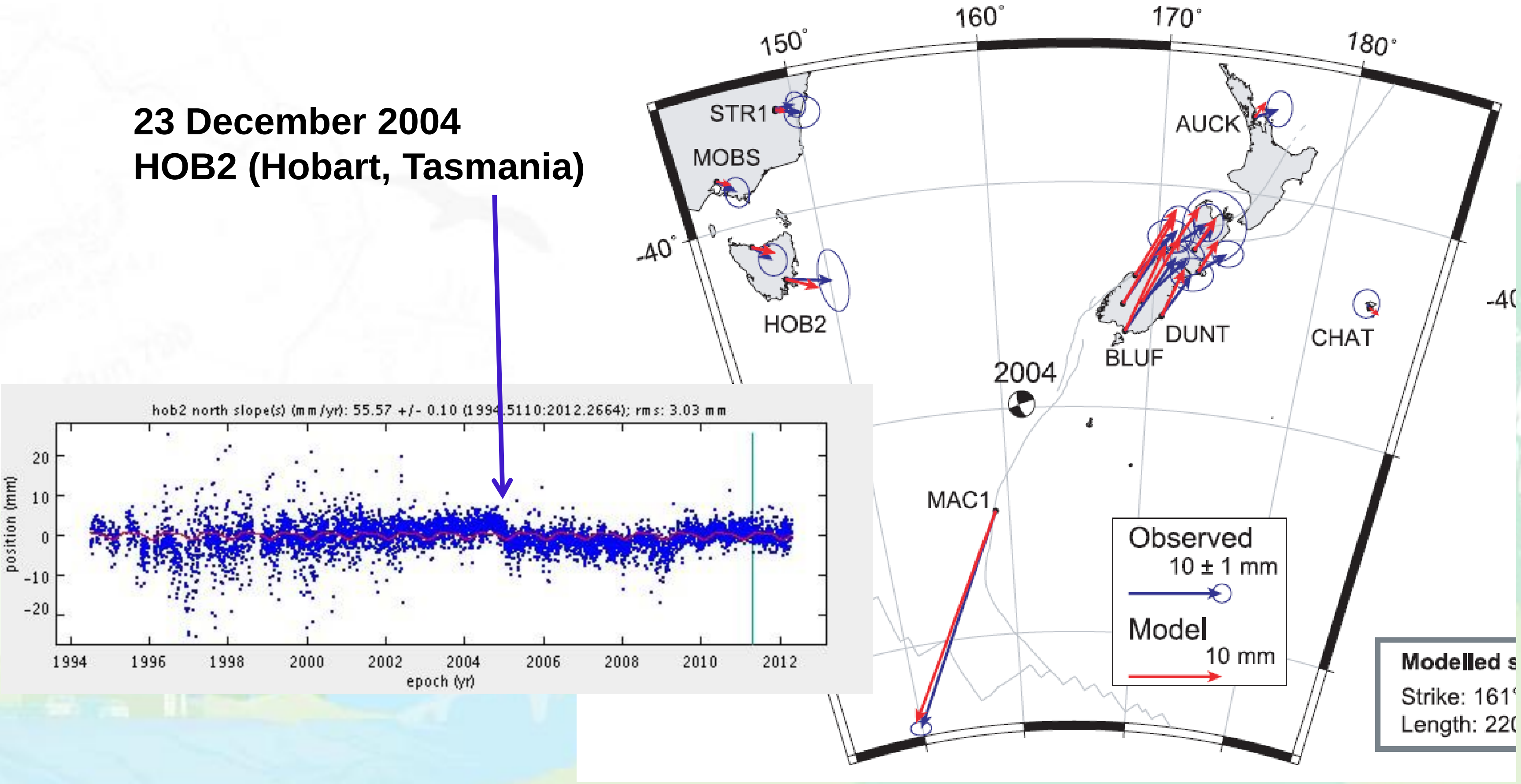
=

5 mm rotation of
a 30 km
GNSS baseline after
only 15 years

e.g. holding rigid plate
coordinates at an early
epoch fixed for
static processing or
RTK at later epochs

Far-field deformation effects on rigid plate

23 December 2004
HOB2 (Hobart, Tasmania)

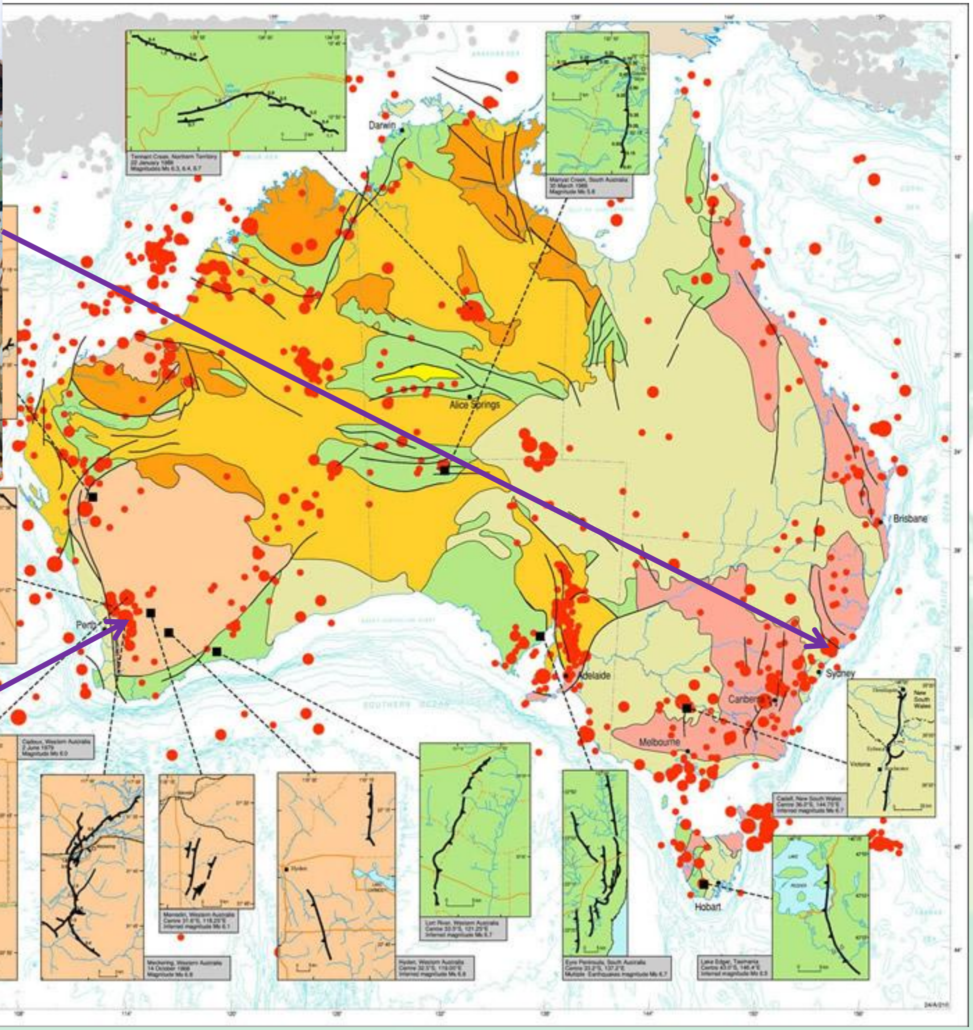


Far-field deformation from great earthquakes around the Australian margin (e.g. Mw8.1 23 December 2004 Macquarie Island, from Watson *et. al*, 2010)

Intraplate deformation

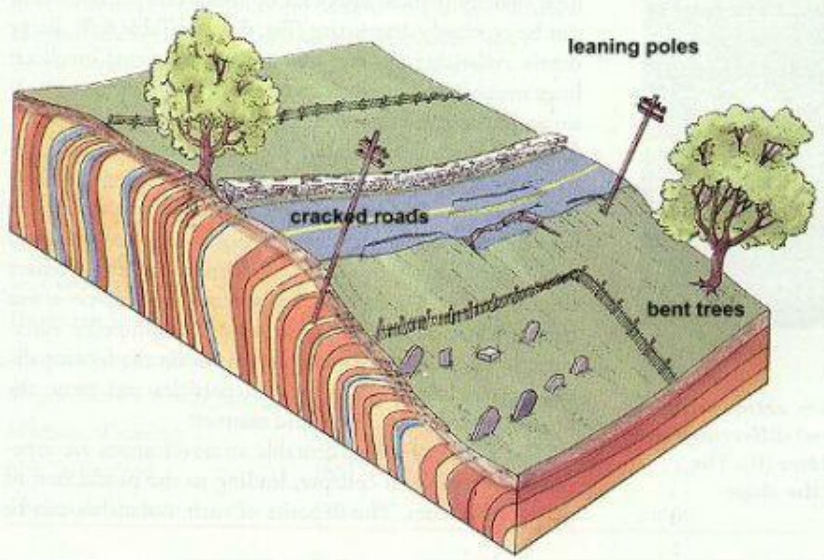
Newcastle, NSW, 1989

Meckering, WA, 1968



Images courtesy Geoscience Australia

Localised deformation



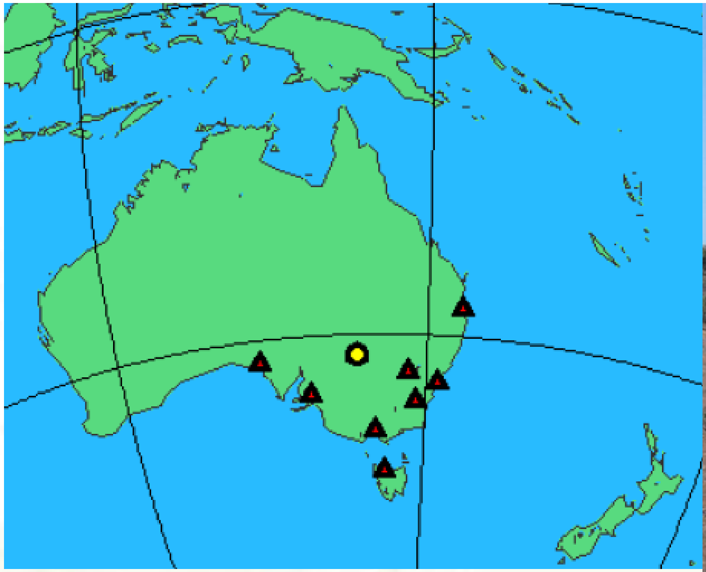
Surface creep

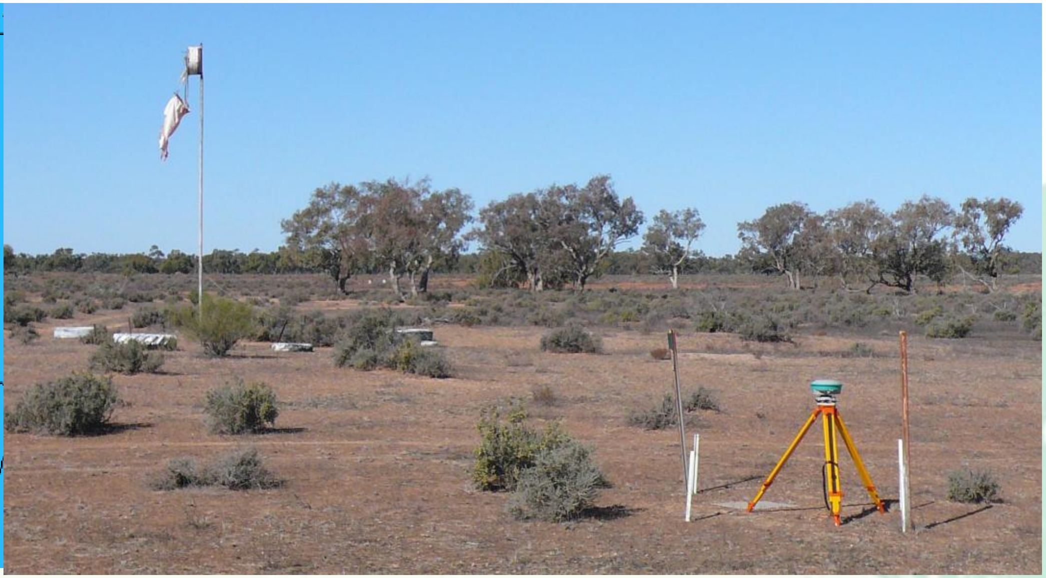
Sedimentary basins and non-bedrock sites can be subject to significant localised deformation

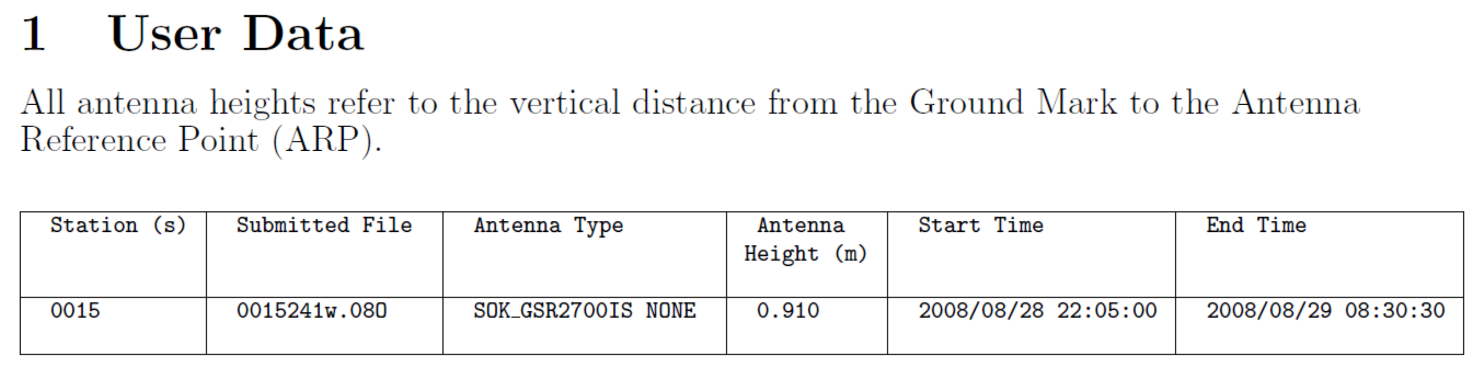
Subsidence

Images from USGS

Australian Example - using AUSPOS





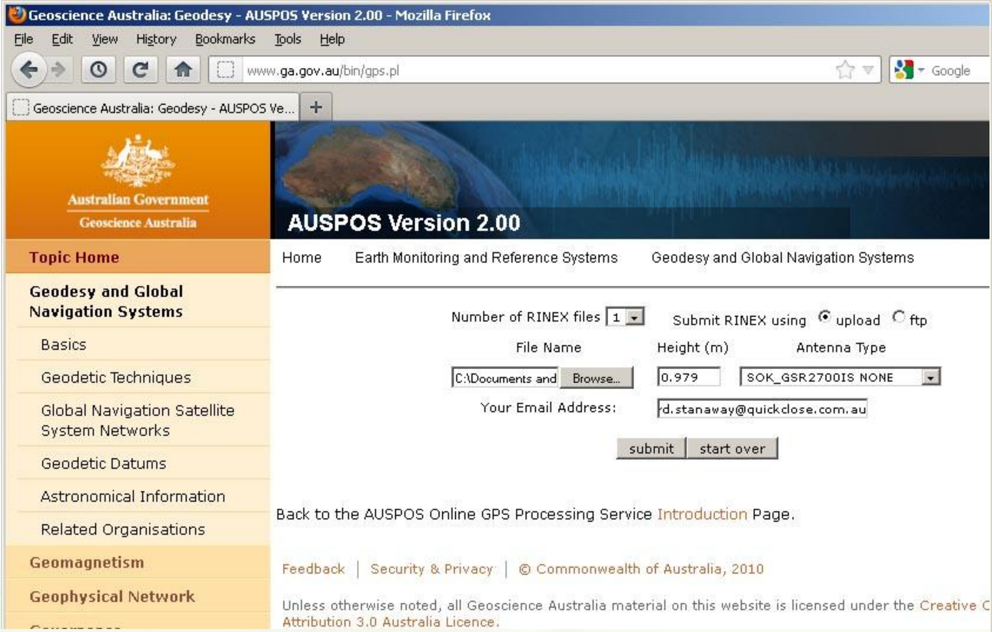


1 User Data

All antenna heights refer to the vertical distance from the Ground Mark to the Antenna Reference Point (ARP).

Station (s)	Submitted File	Antenna Type	Antenna Height (m)	Start Time	End Time
0015	0015241w.08O	SOK_GSR2700IS NONE	0.910	2008/08/28 22:05:00	2008/08/29 08:30:30

Using AUSPOS



Number of RINEX files 1 Submit RINEX using ● upload ○ ftp

File Name	Height (m)	Antenna Type
C:\Documents and	0.979	SOK_GSR2700IS NONE

Your Email Address: d.stanaway@quickclose.com.au

Back to the AUSPOS Online GPS Processing Service Introduction Page.

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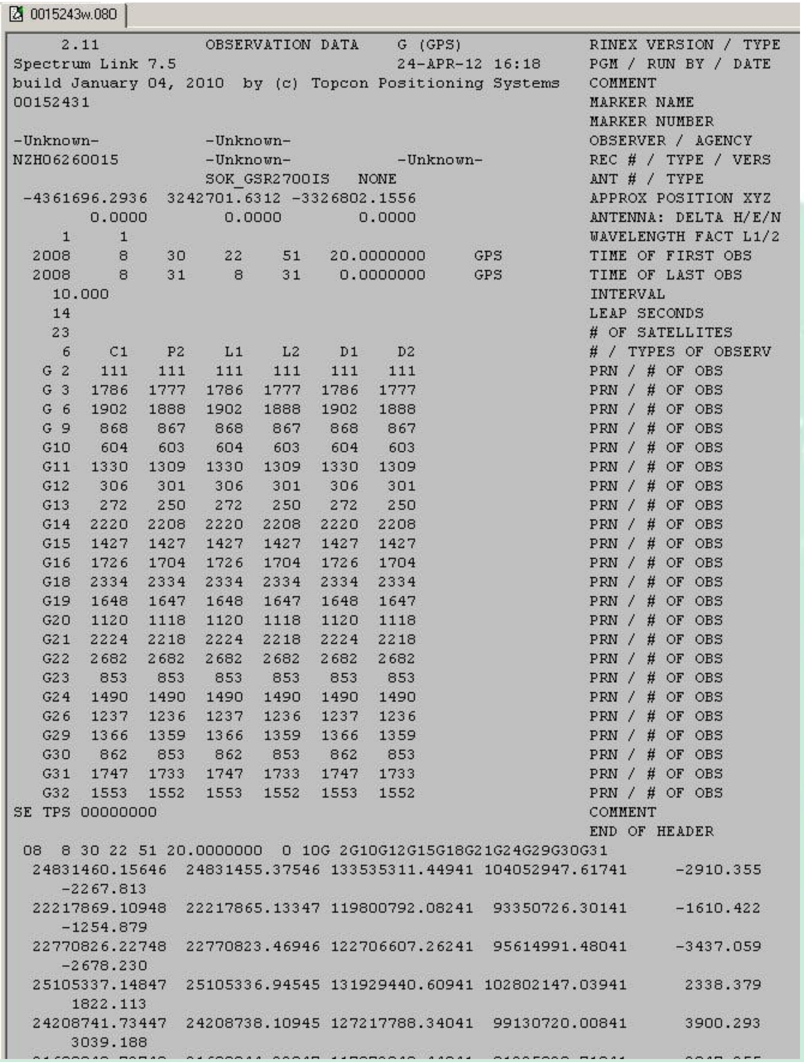
0015243w.080

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     2.11           OBSERVATION DATA    G (GPS)             RINEX VERSION / TYPE
Spectrum Link 7.5                       24-APR-12 16:18     PGM / RUN BY / DATE
build January 04, 2010  by (c) Topcon Positioning Systems   COMMENT
00152431                                                    MARKER NAME
                                                            MARKER NUMBER
-Unknown-           -Unknown-                               OBSERVER / AGENCY
NZH0626OO15         -Unknown-           -Unknown-           REC # / TYPE / VERS
                    SOK_GSR2700IS   NONE                    ANT # / TYPE
 -4361696.2936  3242701.6312 -3326802.1556                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
  2008     8    30    22    51   20.0000000     GPS         TIME OF FIRST OBS
  2008     8    31     8    31    0.0000000     GPS         TIME OF LAST OBS
    10.000                                                  INTERVAL
    14                                                      LEAP SECONDS
    23                                                      # OF SATELLITES
     6    C1    P2    L1    L2    D1    D2                  # / TYPES OF OBSERV
   G 2   111   111   111   111   111   111                  PRN / # OF OBS
   G 3  1786  1777  1786  1777  1786  1777                  PRN / # OF OBS
   G 6  1902  1888  1902  1888  1902  1888                  PRN / # OF OBS
   G 9   868   867   868   867   868   867                  PRN / # OF OBS
   G10   604   603   604   603   604   603                  PRN / # OF OBS
   G11  1330  1309  1330  1309  1330  1309                  PRN / # OF OBS
   G12   306   301   306   301   306   301                  PRN / # OF OBS
   G13   272   250   272   250   272   250                  PRN / # OF OBS
   G14  2220  2208  2220  2208  2220  2208                  PRN / # OF OBS
   G15  1427  1427  1427  1427  1427  1427                  PRN / # OF OBS
   G16  1726  1704  1726  1704  1726  1704                  PRN / # OF OBS
   G18  2334  2334  2334  2334  2334  2334                  PRN / # OF OBS
   G19  1648  1647  1648  1647  1648  1647                  PRN / # OF OBS
   G20  1120  1118  1120  1118  1120  1118                  PRN / # OF OBS
   G21  2224  2218  2224  2218  2224  2218                  PRN / # OF OBS
   G22  2682  2682  2682  2682  2682  2682                  PRN / # OF OBS
   G23   853   853   853   853   853   853                  PRN / # OF OBS
   G24  1490  1490  1490  1490  1490  1490                  PRN / # OF OBS
   G26  1237  1236  1237  1236  1237  1236                  PRN / # OF OBS
   G29  1366  1359  1366  1359  1366  1359                  PRN / # OF OBS
   G30   862   853   862   853   862   853                  PRN / # OF OBS
   G31  1747  1733  1747  1733  1747  1733                  PRN / # OF OBS
   G32  1553  1552  1553  1552  1553  1552                  PRN / # OF OBS
SE TPS 00000000                                             COMMENT
                                                            END OF HEADER
 08  8 30 22 51 20.0000000  0 10G 2G10G12G15G18G21G24G29G30G31
  24831460.15646  24831455.37546 133535311.44941 104052947.61741     -2910.355
     -2267.813
  22217869.10948  22217865.13347 119800792.08241  93350726.30141     -1610.422
     -1254.879
  22770826.22748  22770823.46946 122706607.26241  95614991.48041     -3437.059
     -2678.230
  25105337.14847  25105336.94545 131929440.60941 102802147.03941      2338.379
      1822.113
  24208741.73447  24208738.10945 127217788.34041  99130720.00841      3900.293
      3039.188
```

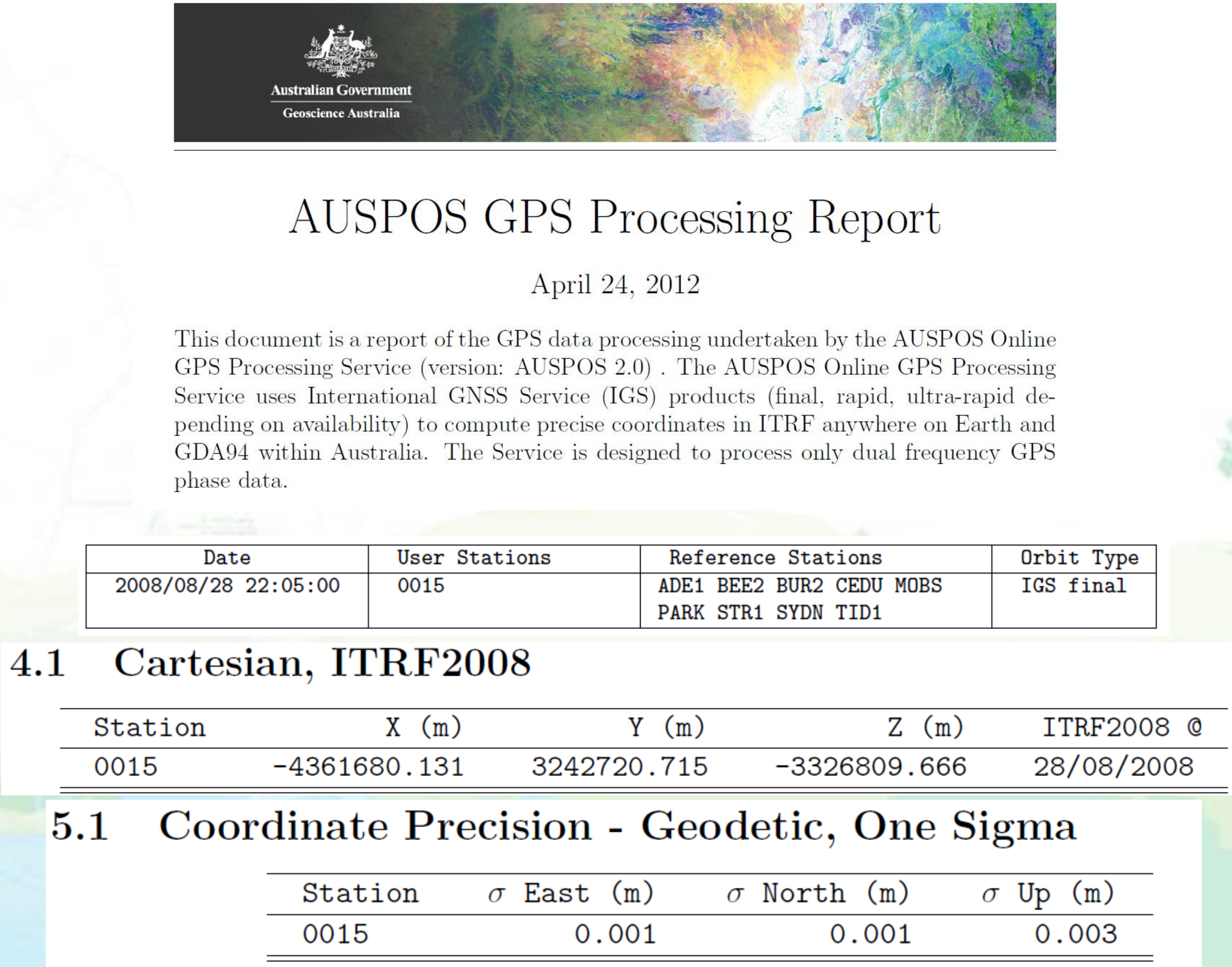
cm precise ITRF coordinates from user-supplied dual-frequency RINEX data for > 8 hour observations

www.ga.gov.au/bin/gps.pl

Wait > 3 days for IGS Rapid Orbit solution or > 14 days for IGS Final Orbit solution

Select correct antenna model and antenna height to ARP

Using AUSPOS



Australian Government
Geoscience Australia

AUSPOS GPS Processing Report

April 24, 2012

This document is a report of the GPS data processing undertaken by the AUSPOS Online GPS Processing Service (version: AUSPOS 2.0) . The AUSPOS Online GPS Processing Service uses International GNSS Service (IGS) products (final, rapid, ultra-rapid depending on availability) to compute precise coordinates in ITRF anywhere on Earth and GDA94 within Australia. The Service is designed to process only dual frequency GPS phase data.

Date	User Stations	Reference Stations	Orbit Type
2008/08/28 22:05:00	0015	ADE1 BEE2 BUR2 CEDU MOBS PARK STR1 SYDN TID1	IGS final

4.1 Cartesian, ITRF2008

Station	X (m)	Y (m)	Z (m)	ITRF2008 @
0015	-4361680.131	3242720.715	-3326809.666	28/08/2008

5.1 Coordinate Precision - Geodetic, One Sigma

Station	σ East (m)	σ North (m)	σ Up (m)
0015	0.001	0.001	0.003

! **Kinematic coordinates at epoch of observation**

Example

3.1 Cartesian, GDA94

Station	X (m)	Y (m)	Z (m)
0015	-4361679.624	3242720.803	-3326810.422

3.2 Geodetic, GRS80 Ellipsoid, GDA94

Station	Latitude (DMS)	Longitude (DMS)	Ellipsoidal Height(m)	Derived AHD (m)
0015	-31 38 33.60805	143 22 14.83619	87.237	73.468

3.3 MGA Grid, GRS80 Ellipsoid, GDA94

Station	East (m)	North (m)	Zone	Ellipsoidal Height (m)	Derived AHD (m)
0015	724826.751	6496729.544	54	87.237	73.468

$$T_x = -0.06386(m)$$
$$T_y = 0.00023(m)$$
$$T_z = 0.04521(m)$$
$$S_c = 1.1308e-08$$
$$R_x = 1.07834e-07(radians)$$
$$R_y = 9.49620e-08(radians)$$
$$R_z = 9.37467e-08(radians)$$

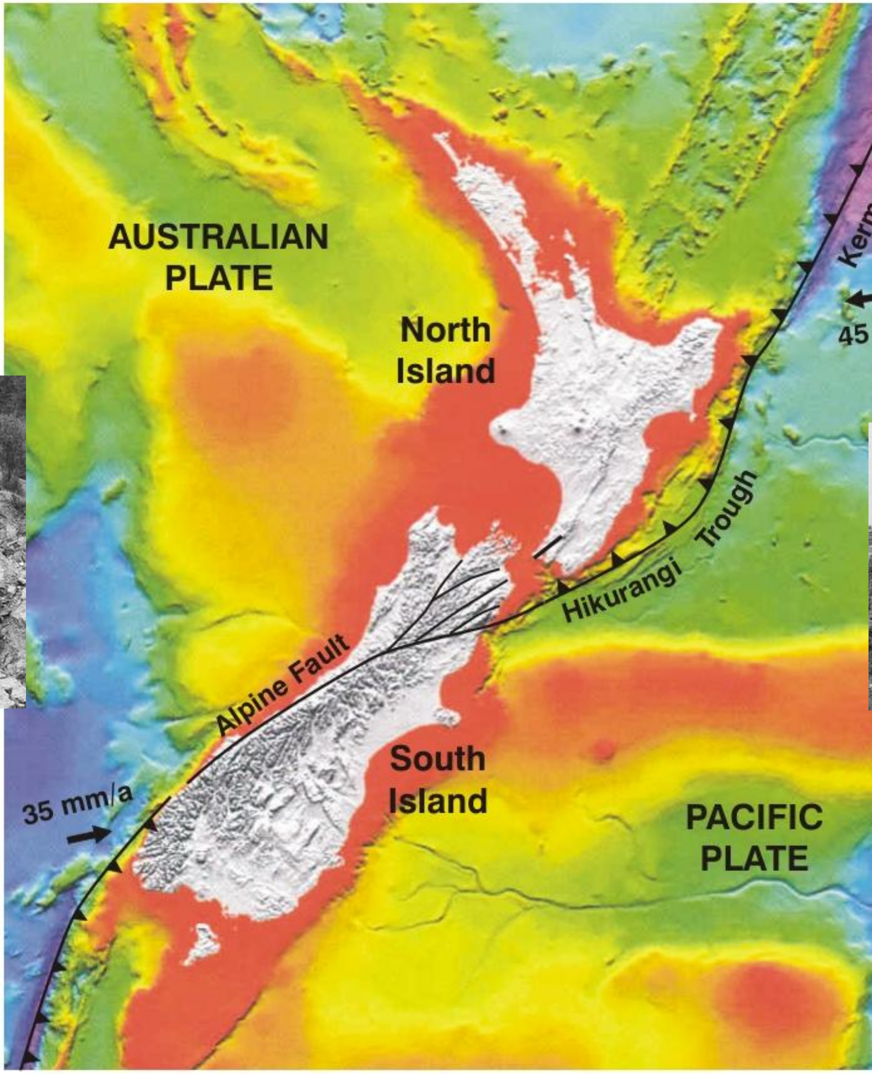
The above transformation parameters are only valid for the epoch 28/08/2008.

After a long day hopping across dry parameter space, a cold beer is near.

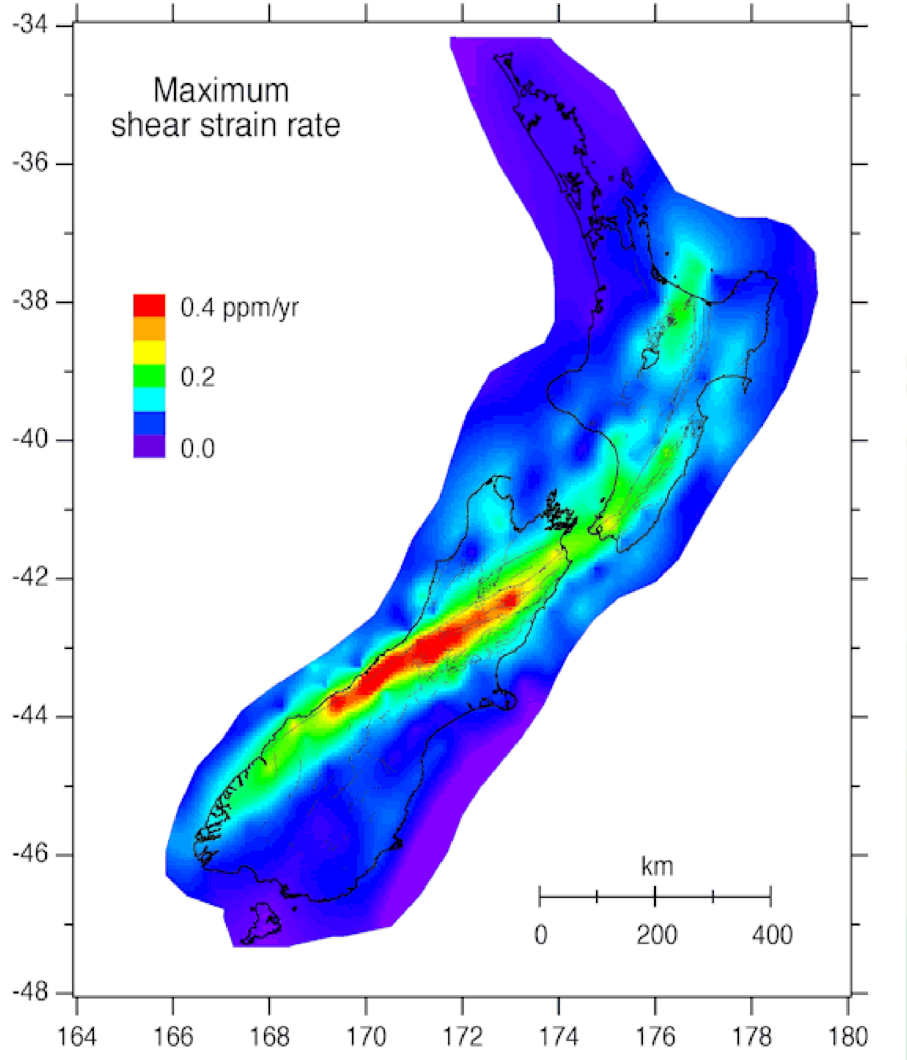
Thank you!

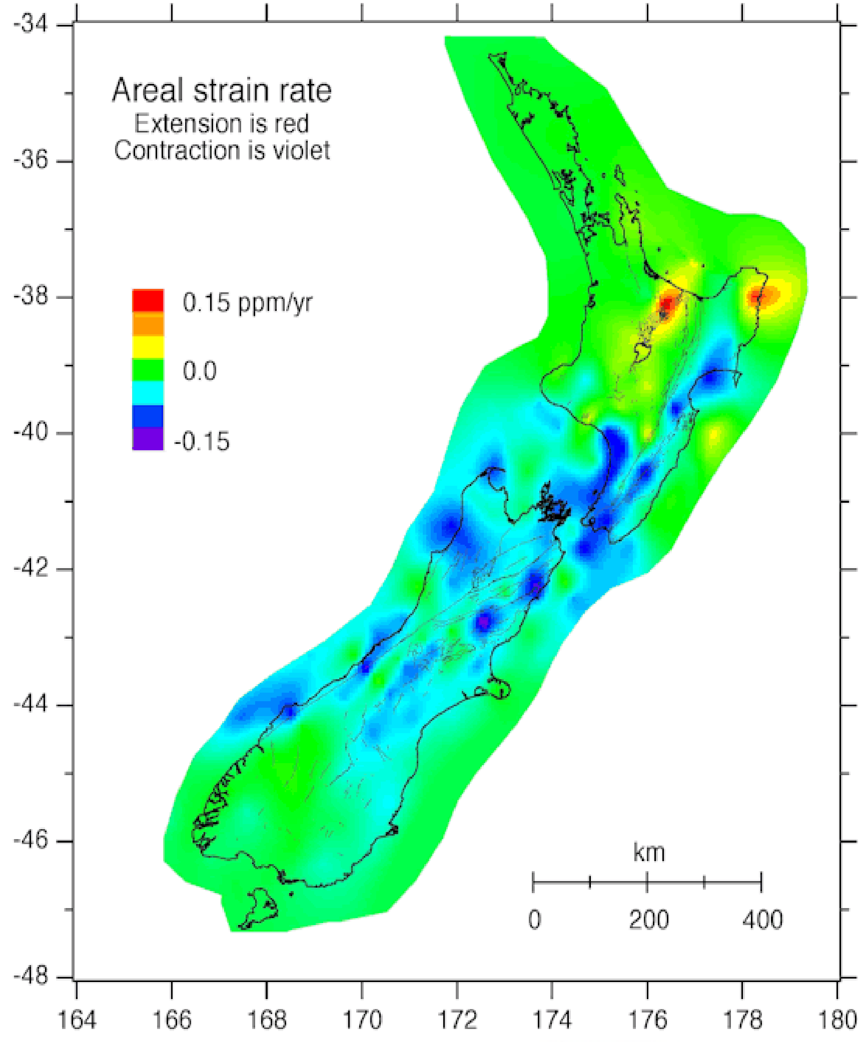
New Zealand Case Study

But we don't live on a stable planet



Measuring deformation - strain





Limitations with NZGD49

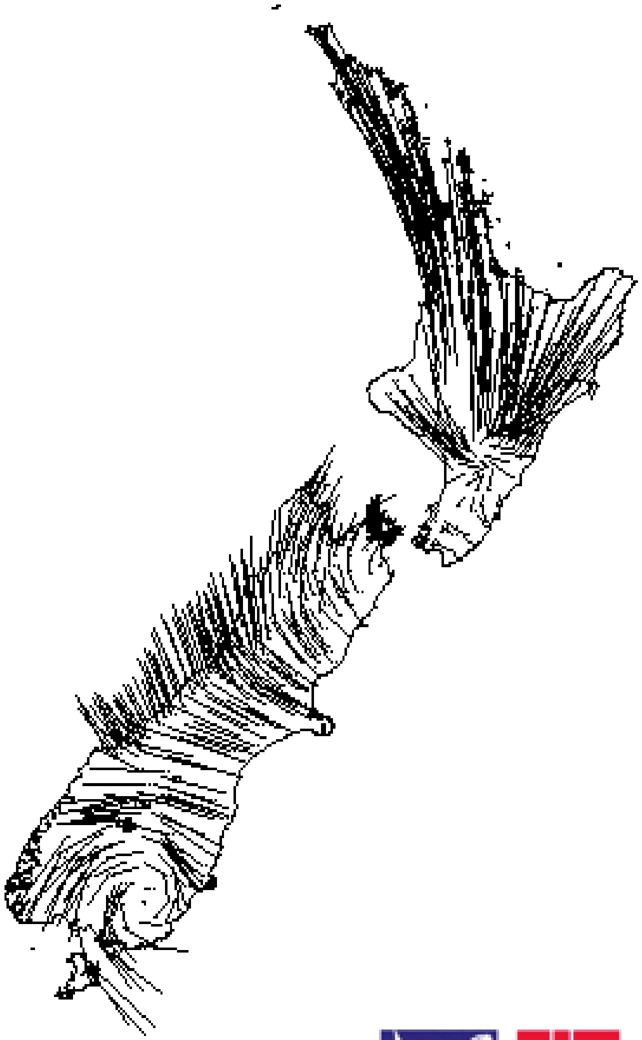
Regional distortions up to 5m present

Built up in a piecemeal fashion

Incompatible with global systems

It is of limited spatial coverage

It is static



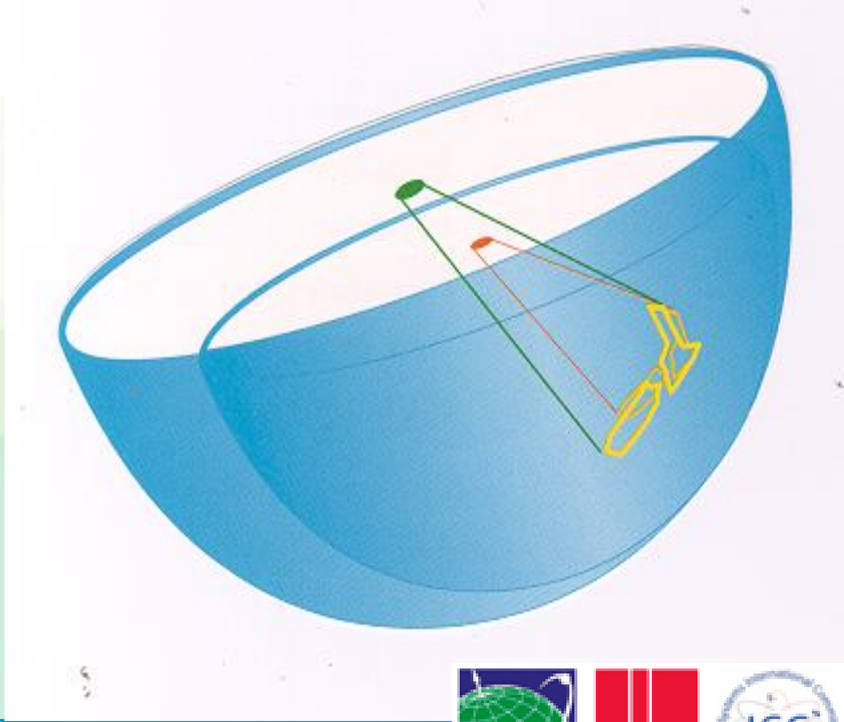
NZGD2000

1998 – NZ introduced NZGD2000 (ref epoch 1 Jan 2000)

- geocentric origin
- aligned with the ITRS
- ITRF96 with epoch 2000.0 coordinates

NZGD2000 - semi-dynamic datum

- generalised motion of points modelled using a deformation model

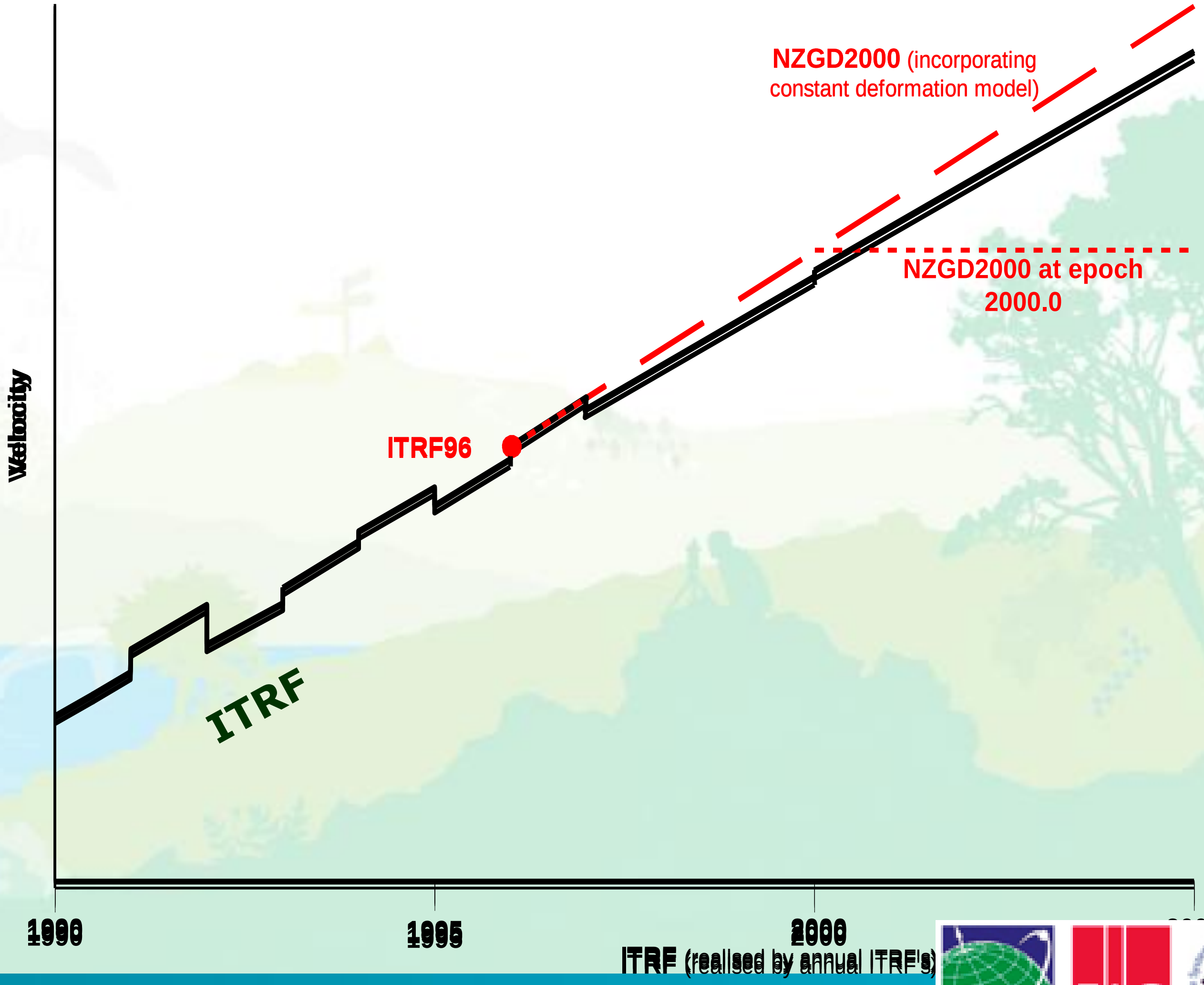


NZGD2000

- **Tied to ITRF96**

- **Generalised motion of points modelled using a constant velocity deformation model**

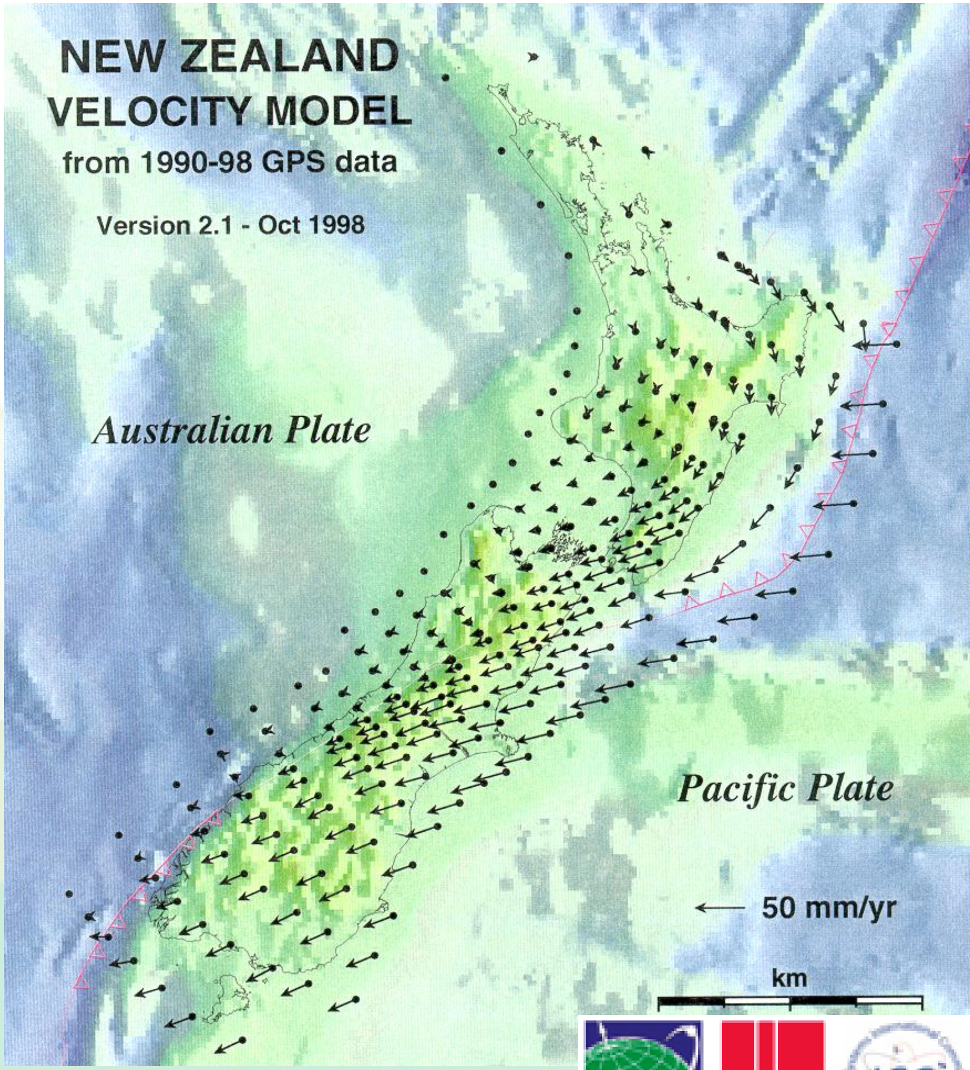
- **Epoch 2000 coordinates generated at 2000.0**



NZGD2000

Semi-dynamic datum

- deformation model – calculated by holding fixed the Aust plate and uses the euler rotation parameters to bring in terms of ITRF96
- velocities provided in a rectangular grid (0.1 degree) for ease of computations
- 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



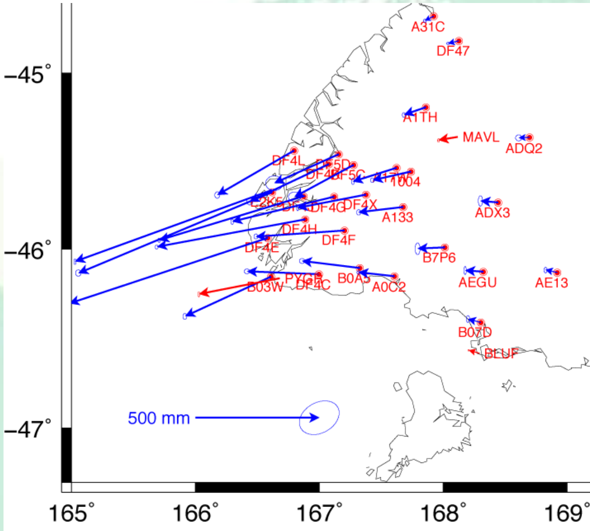
Where are we at

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

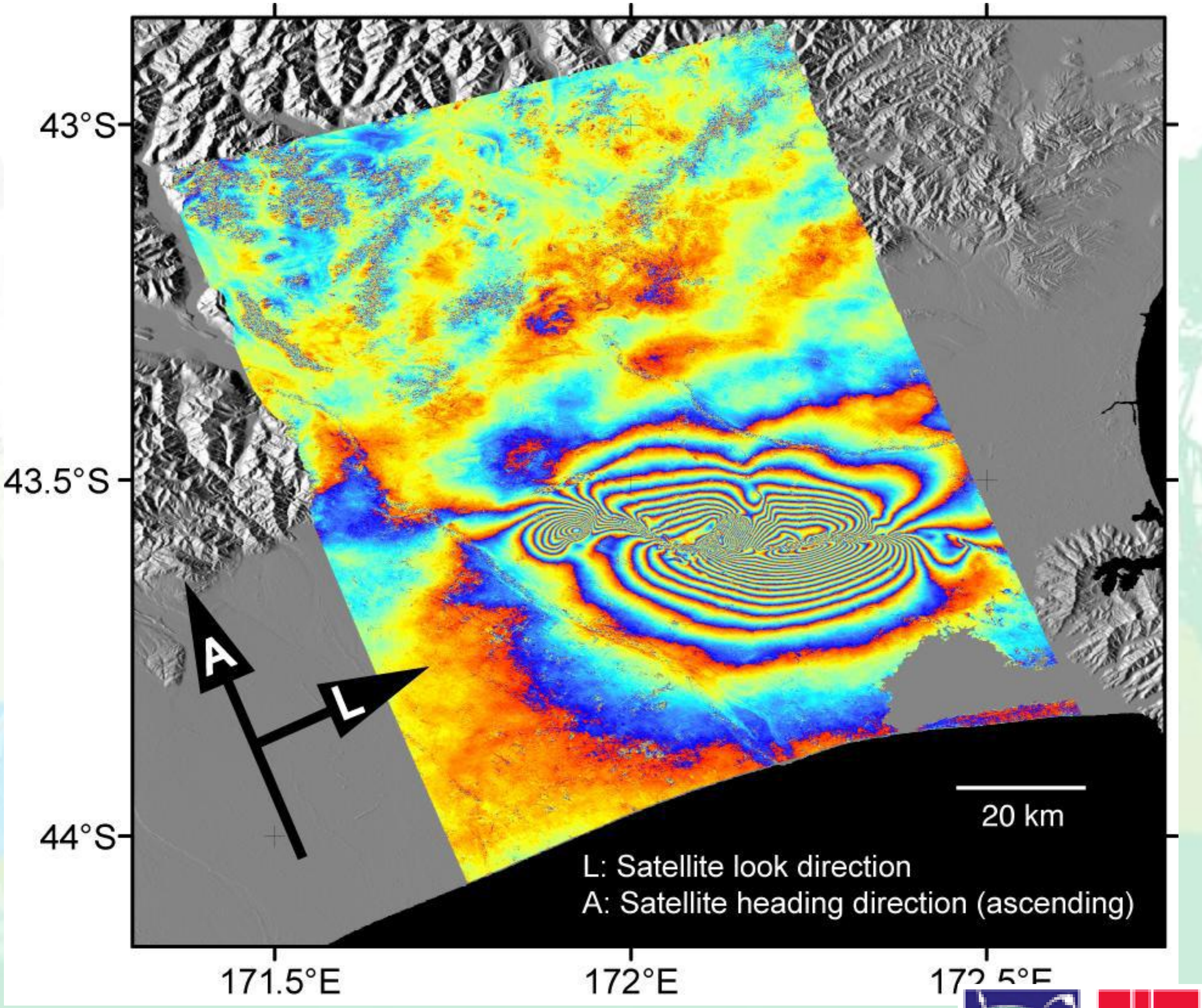
- Updating the Deformation Model
- Vertical Deformation Model
- CORS Real Time – Tools for Managing Coordinates
- Tie to the ITRF - Going Fully Dynamic?

Darfield Earthquake

InSAR interference pattern as a result of the Darfield earthquake

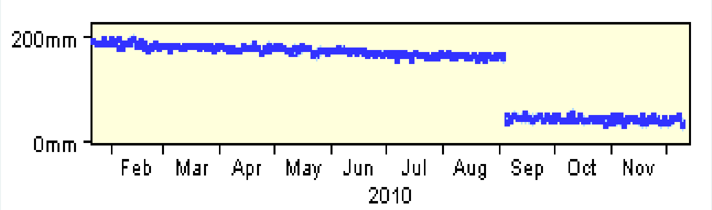
Each coloured fringe represents 1.5 cm of ground displacement in line-of-sight to the satellite

Incoherent regions indicate ground damage

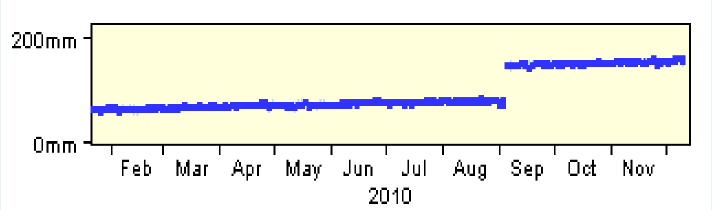


Creating a patch – Canterbury earthquakes

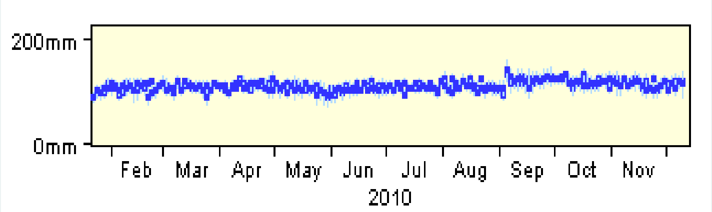
East

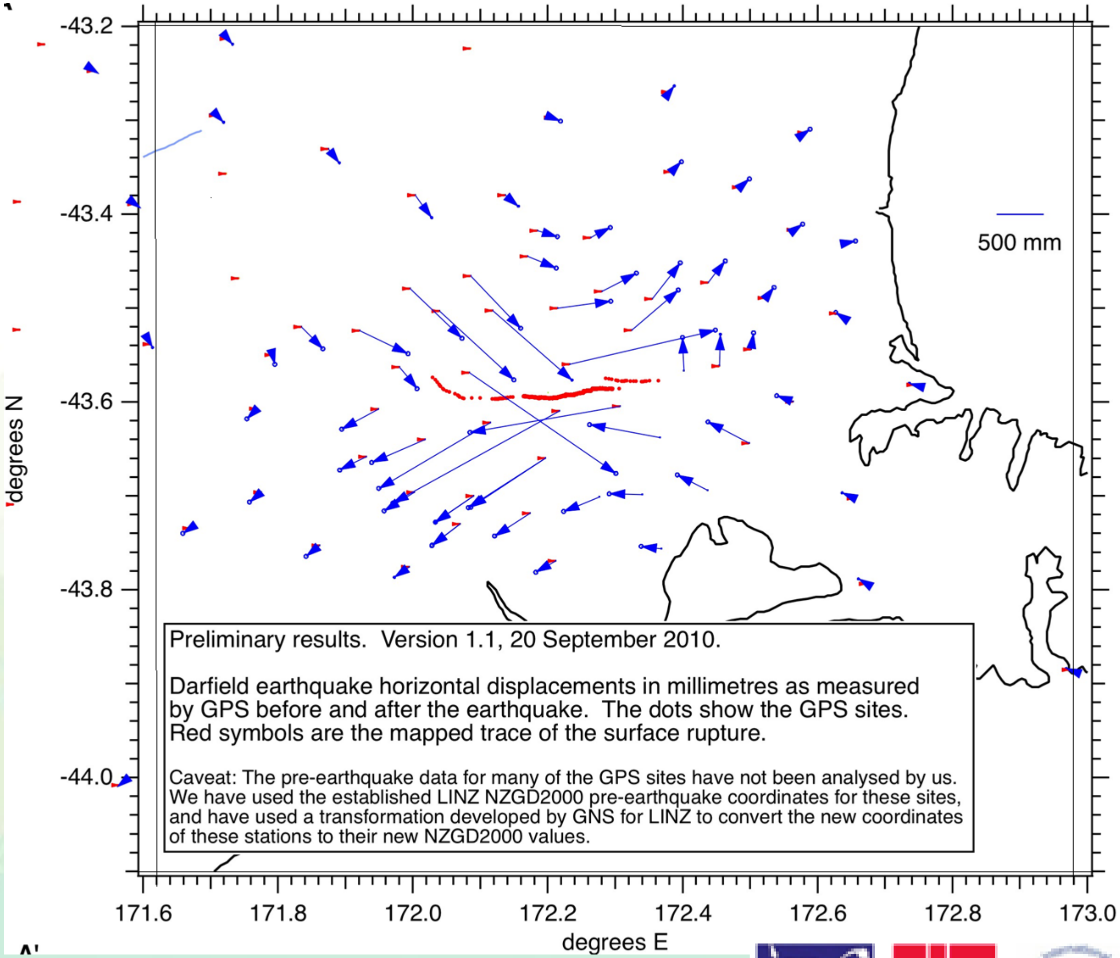


North



Up





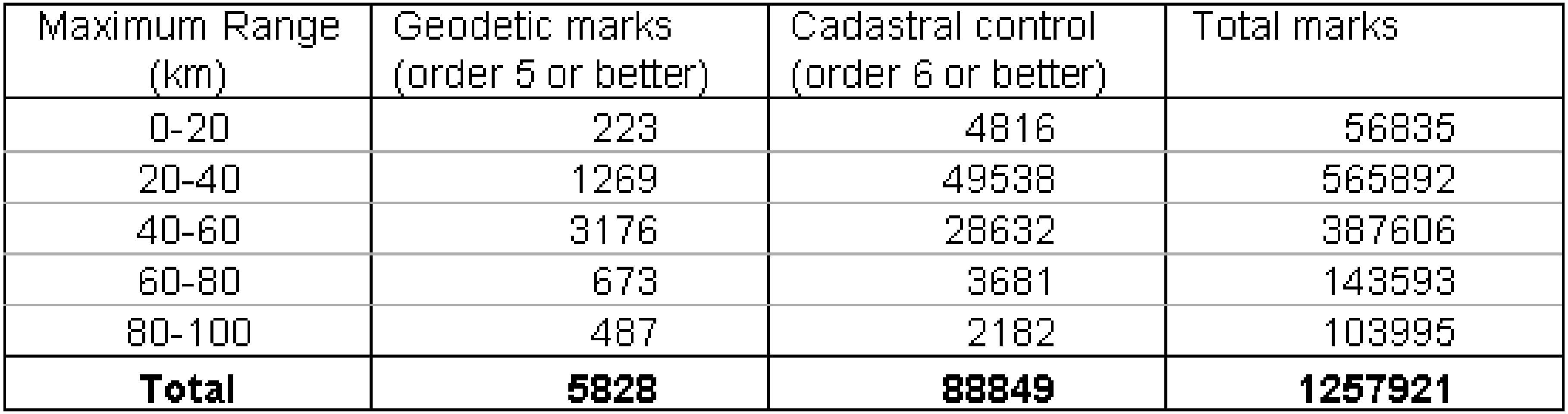
Preliminary results. Version 1.1, 20 September 2010.

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.

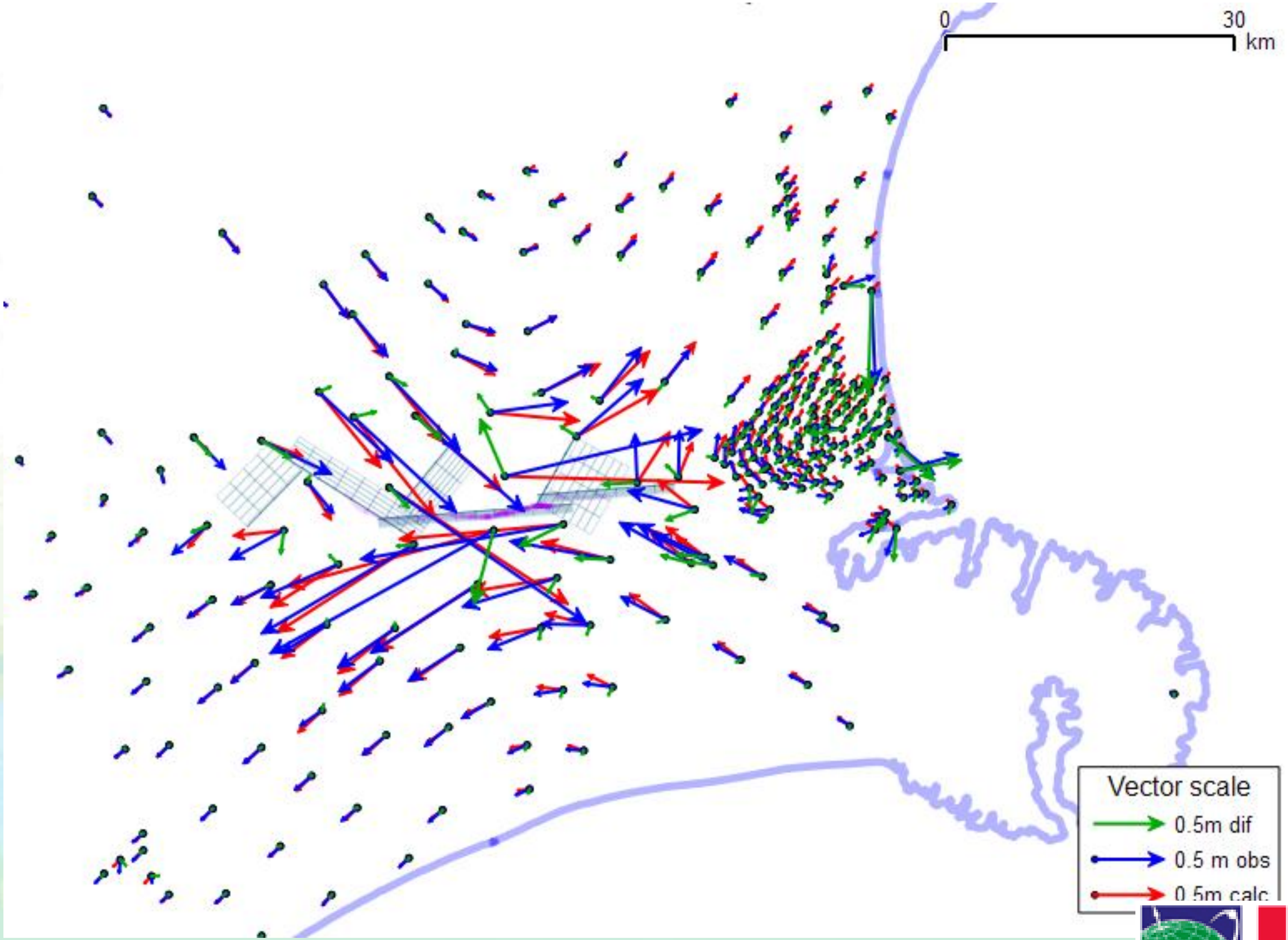
Impact on geodetic control

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

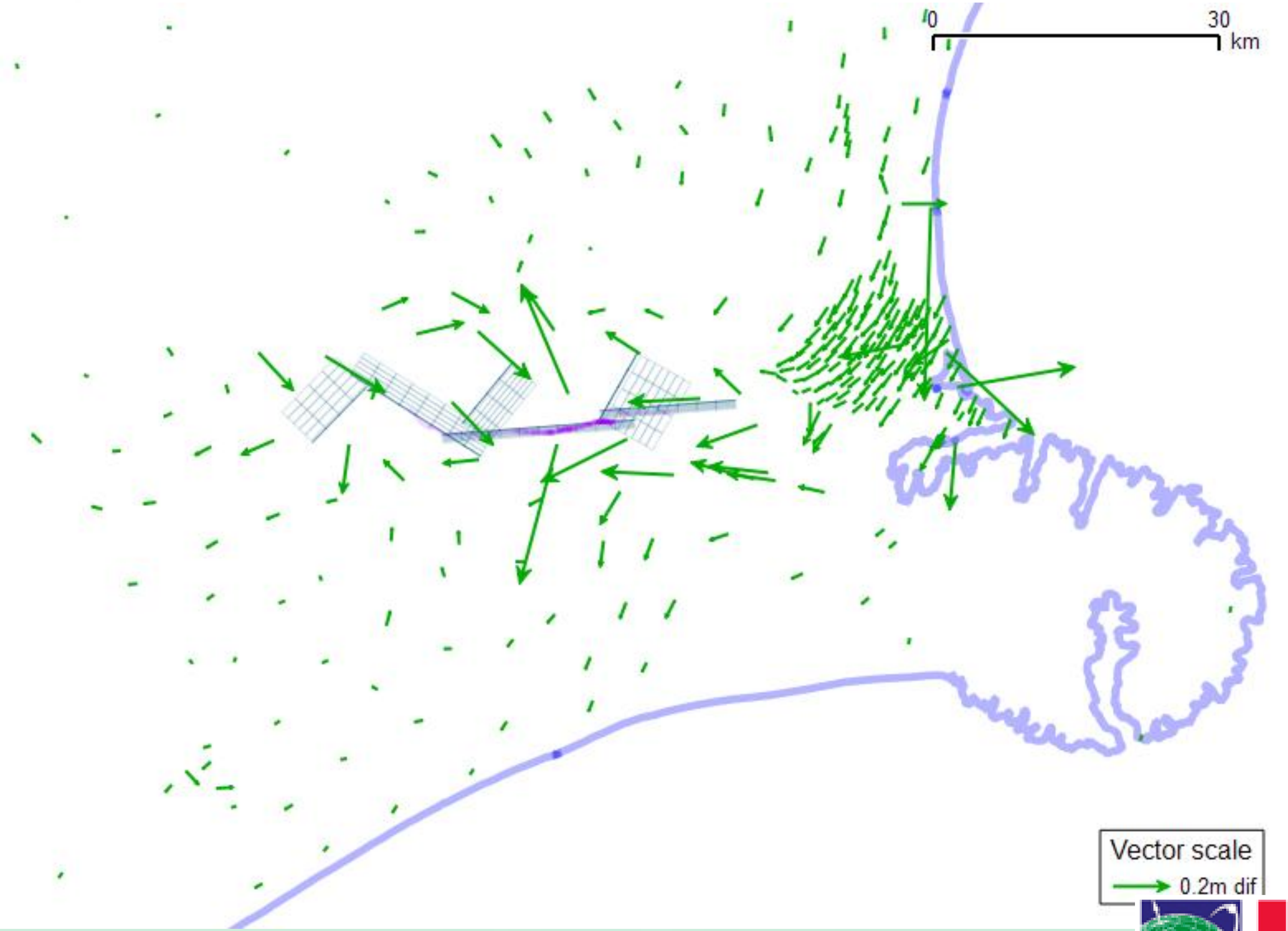


Maximum Range (km)	Geodetic marks (order 5 or better)	Cadastral control (order 6 or better)	Total marks
0-20	223	4816	56835
20-40	1269	49538	565892
40-60	3176	28632	387606
60-80	673	3681	143593
80-100	487	2182	103995
Total	**5828**	**88849**	**1257921**

Model out the effects of the earthquake



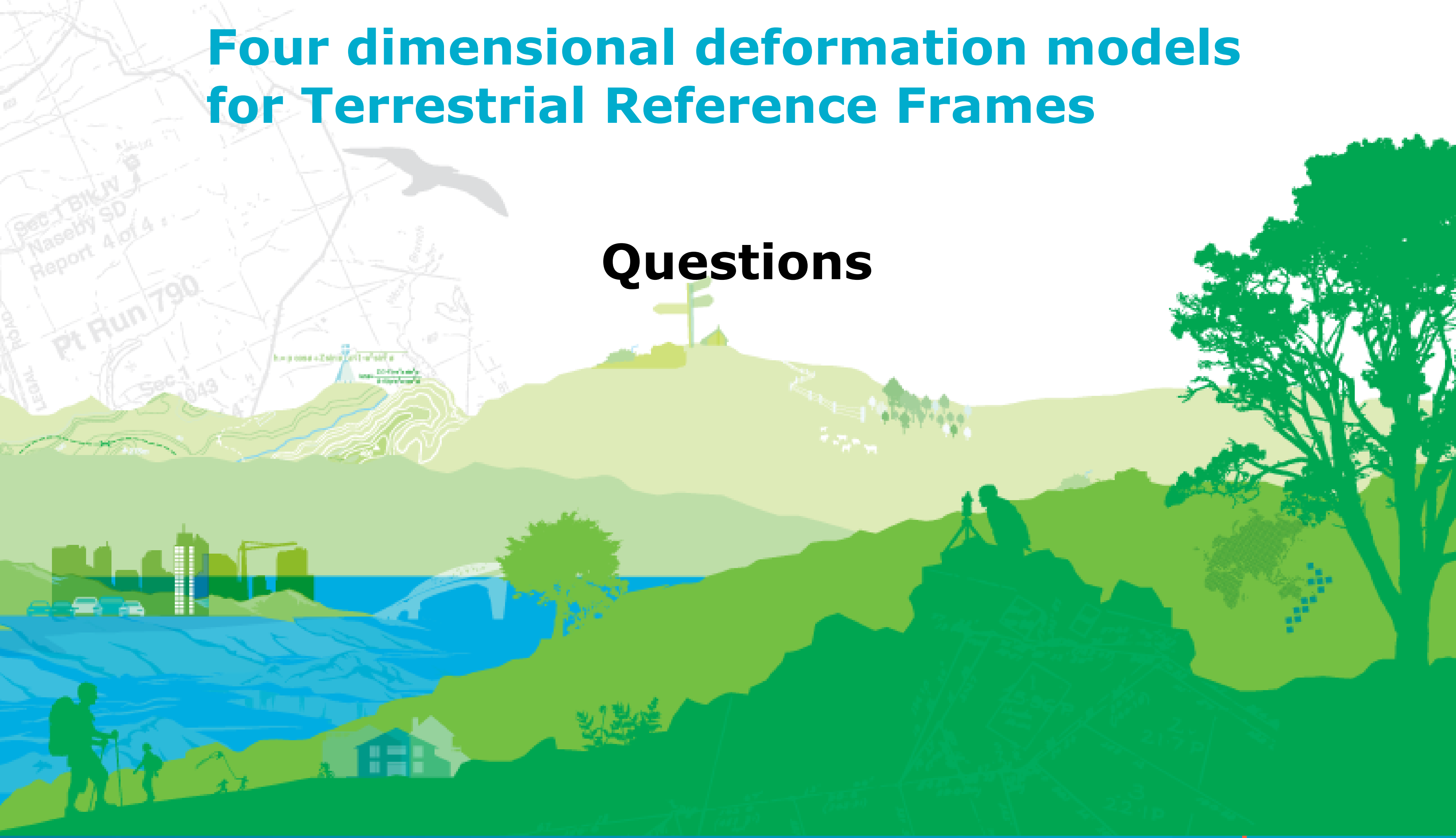
Residuals



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

Four dimensional deformation models for Terrestrial Reference Frames



Questions