Deformation Models Progress with development of an OGC Standard

Mw 7.8 earthquake, Kaikoura, New Zealand, 16th November 2016

Photo by Julian Thomson, GNS Science NZ

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Chris Crook, Land Information New Zealand

Kevin Kelly, ESRI

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Open Geospatial Consortium

IAG

IAG Commission 1, REFAG 2022, Thessaloniki, Greece, 17-20 October 2022

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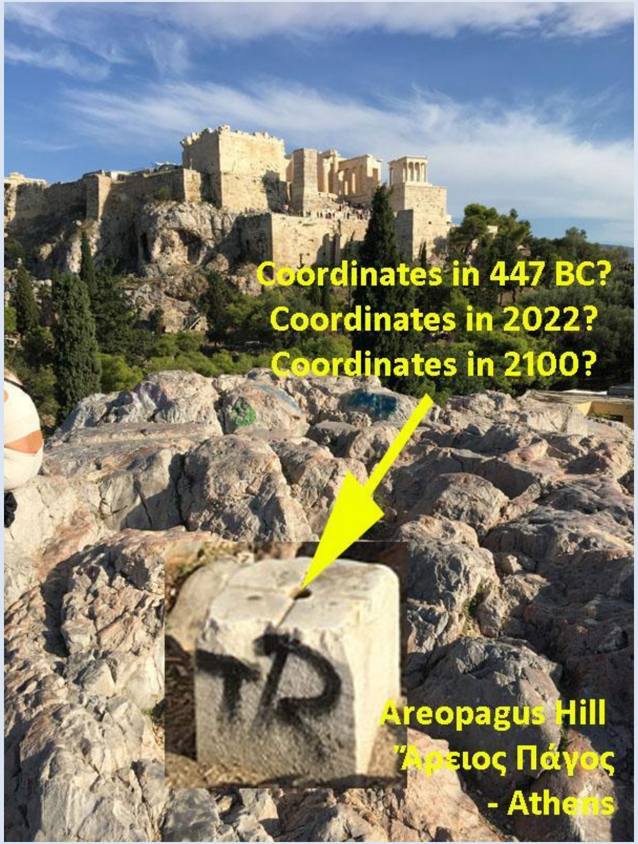
Motivation and purpose



Consistent alignment of geodetic positioning and spatial data at any epoch

Point-motion and time-dependent transformation models used in GNSS positioning need to match those used in GIS and spatial software to ensure consistent alignment over time accounting for geodynamics

"Non-geodetic" user expectation of "ground fixed" RF consistency over time

GNSS Position (any epoch)

Map/data (earlier epoch) ⟷ displacement ⟷ **Map/data (now)**

The GIS problem with kinematic RF

GNSS Precise Point Positioning (PPP) is becoming ubiquitous and ~ 5 mm precision in a global reference frame is now routinely achievable (6+ hours static observations).

Coordinates of "ground fixed" points (survey control, cadastral boundaries, physical infrastructure, assets) are assumed to be stable or consistent in a local context over very long periods of time – This is a GIS user's assumption.

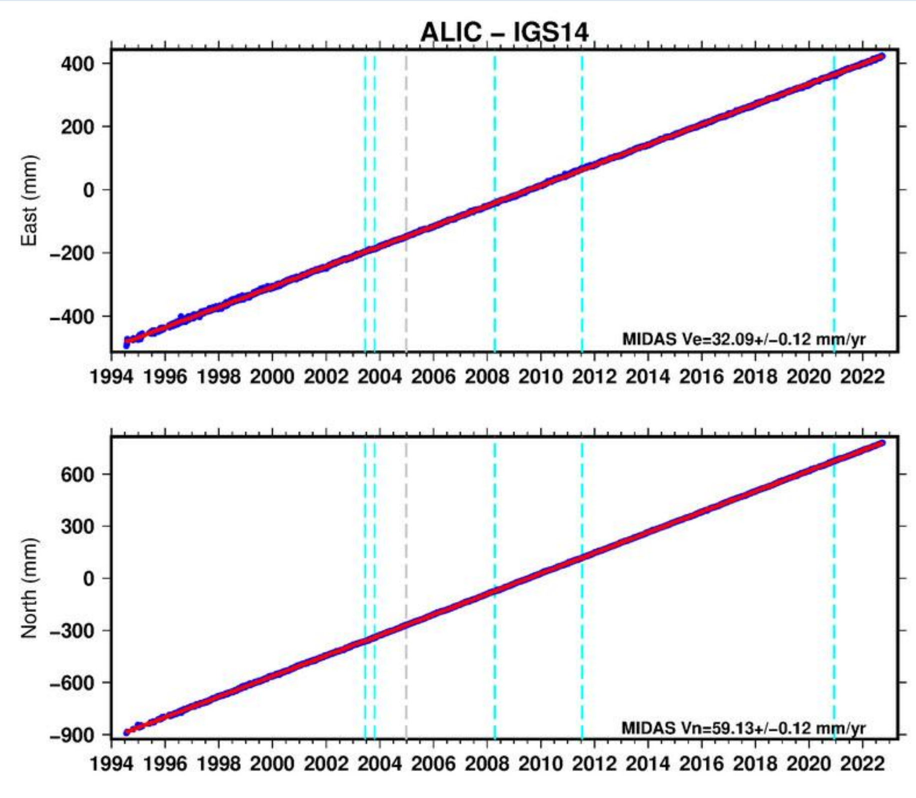
But GNSS coordinates (natively in an ITRF aligned frame) of these "fixed" points change by up to several cm a year due to plate motion and by up to several metres during large earthquakes.

There has been no standardised approach to handle transformation between positioning and spatial data reference frames, especially in deforming zones.

The lack of a standard is a severe impediment to GIS , useable positioning precision and software development (with many agency specific approaches).

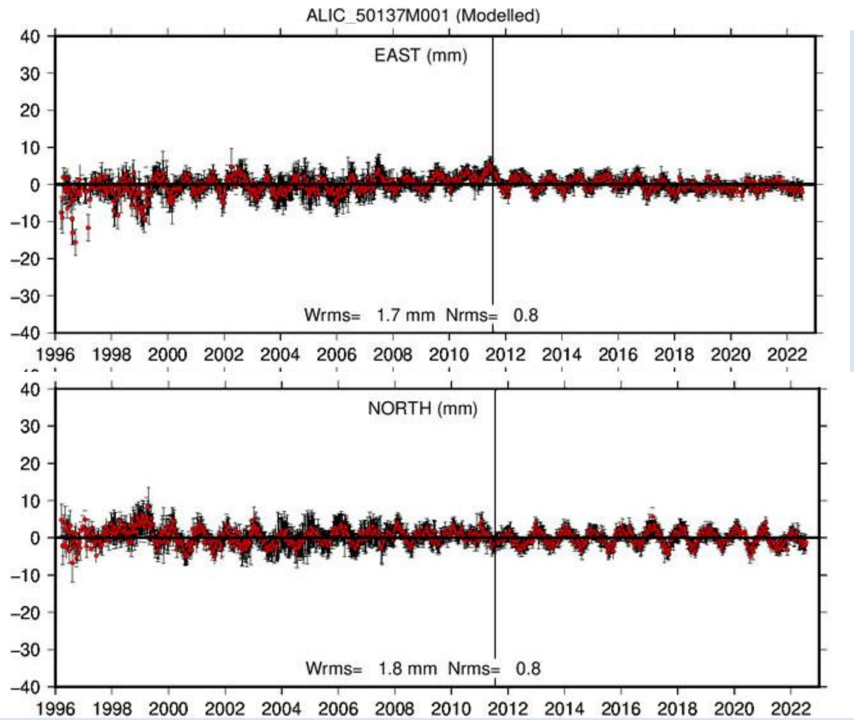
~2 m GIS "errors" due to lack of knowledge of kinematic RF are now very common!

Secular motion of ITRF PPP – Stable plate case



Nevada Geodetic Laboratory, UNR

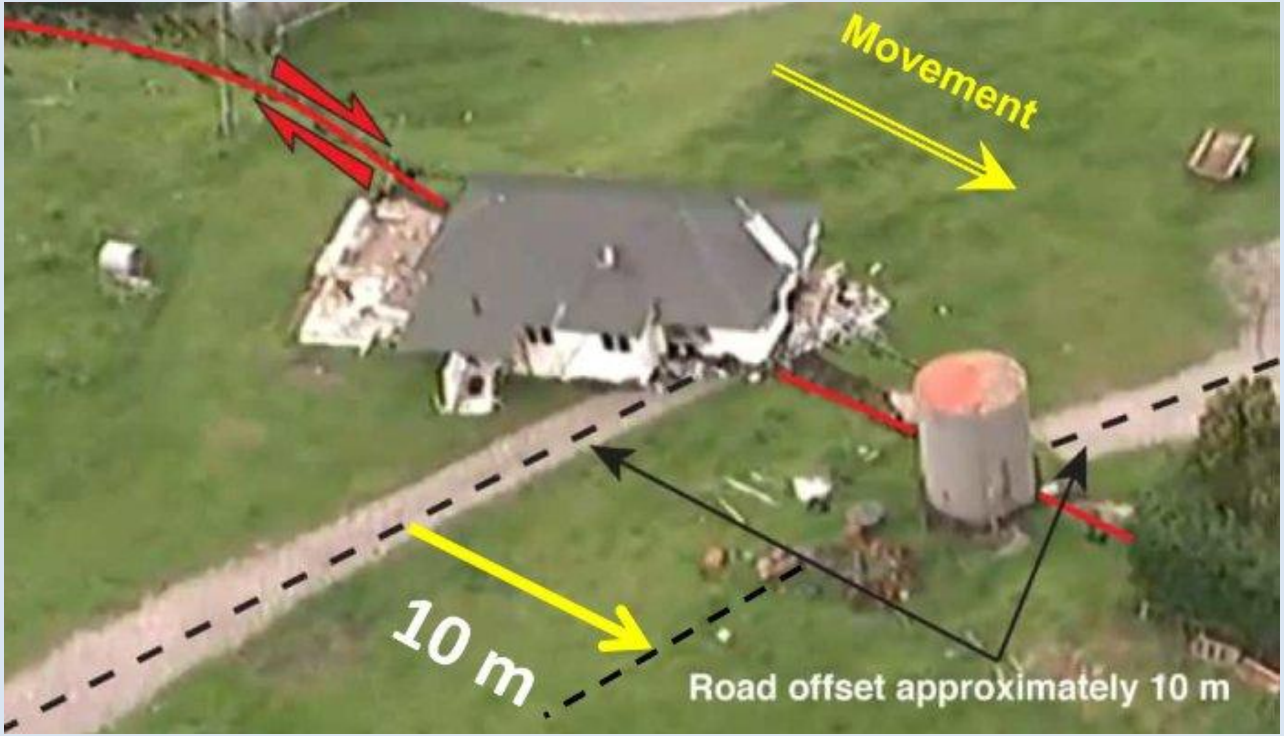
ALIC – ATRF (Australian Terrestrial Reference Frame)



Geoscience Australia

ALIC – Alice Springs, Australia

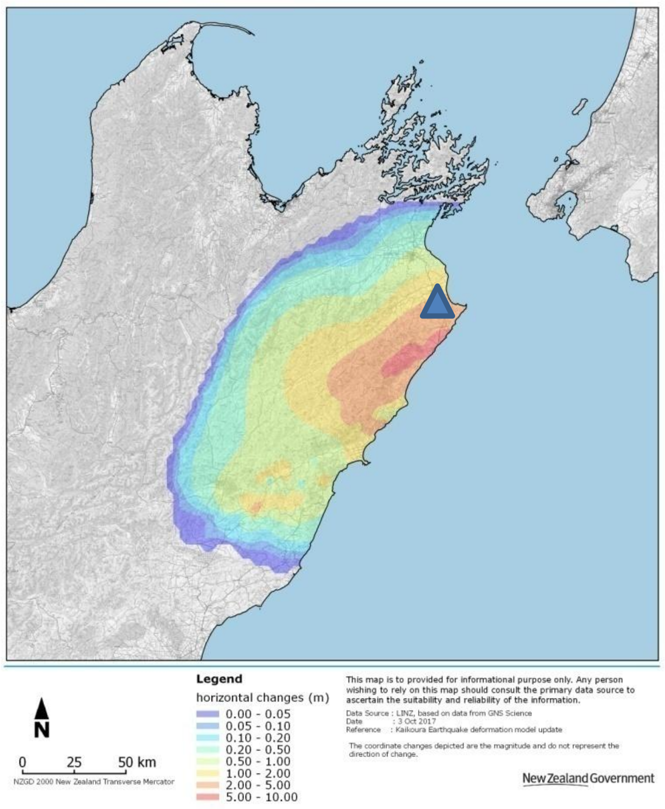
ITRF PPP – plate boundary zone case



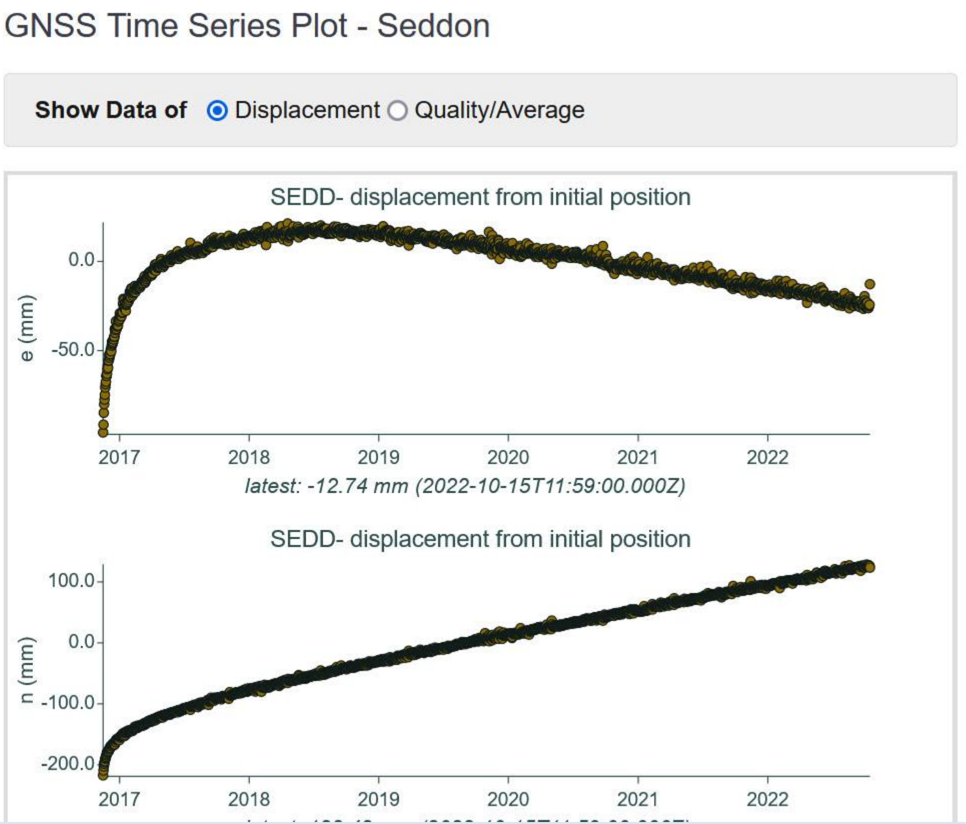
Mw 7.8 Kaikoura, New Zealand, 14th November 2016

Geonet, GNS Science, New Zealand

ITRF PPP – plate boundary zone case (contd.)



Land Information New Zealand



Geonet, GNS Science, New Zealand

SEDD, Seddon, New Zealand

Deformation models in applied geodesy

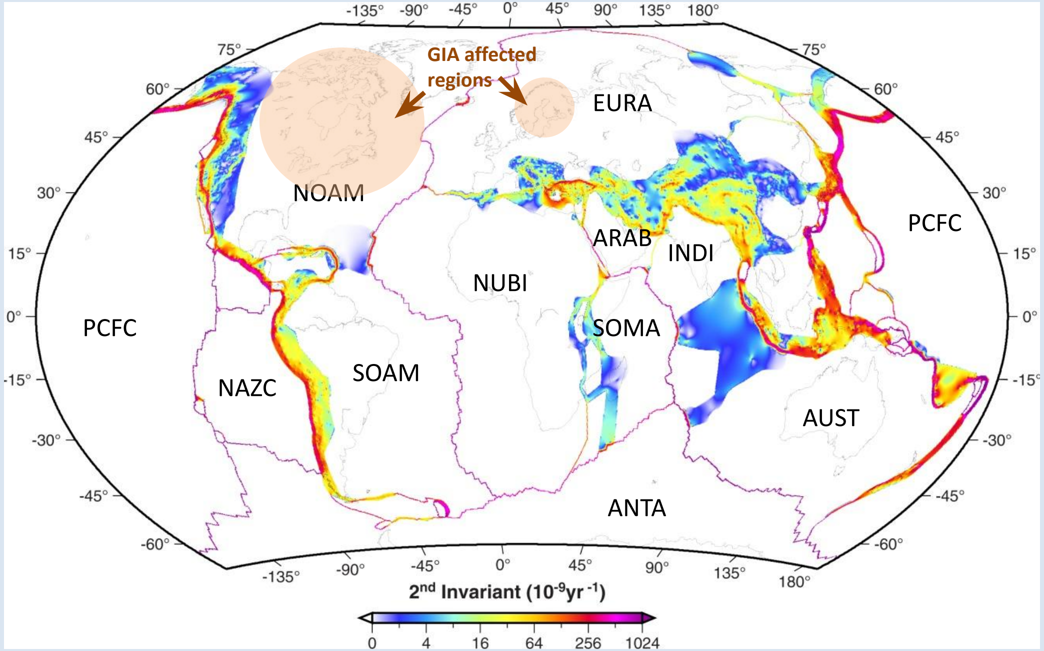
- Geodetic agencies have used tightly integrated custom formats and software for managing crustal deformation effects
  - **Time-dependent transformations were not supported by GIS/coordinate transformation software**
  - **No common format or structure for publishing of deformation models**
- In 2019 Land Information New Zealand (LINZ) commissioned the development of a deformation model transformation capability in PROJ based on a JSON “master file” referencing multiple GeoTIFF gridded data sets
- OGC specification for standardising the description of deformation models with associated Geodetic Grid Exchange Format (GGXF). Collaboration with IAG WG 1.3.1 and bi-weekly web-meetings between June 2020 and early 2022 attended by many from IAG WG.

IAG/OGC – Deformation Model - agency survey (2020)

- Responses from 27 countries on 5 continents
- Mainly from geodetic/mapping agencies – potential producers of deformation models
- 9 have models in use, 10 in development, 4 planned
- 13 are velocity models, but 7 include some coseismic or postseismic models
- Production systems mainly using custom formats and custom software. Recently some models implemented into PROJ coordinate system conversion library

Conformal transformation alone is not adequate

Current parametric conformal geodetic transformation strategies (e.g. 7 parameter, time-dependent 14/15-parameter and plate motion models PMM) are not suitable in deforming zones.

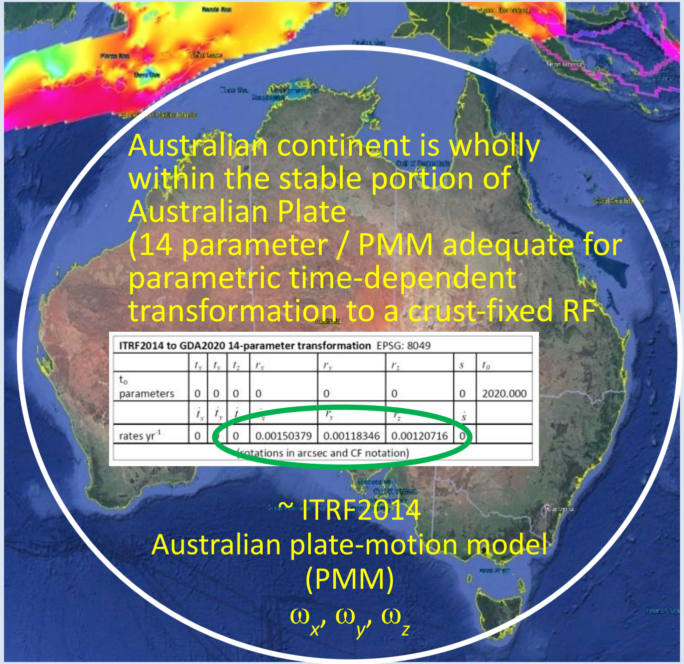


White regions are largely stable plate and a conformal time-dependent transformation approach is adequate for most applications

Coloured regions (plate boundaries and deforming zones) have high strain rates and a conventional parametric model is not adequate for NNR to crust-fixed RF transformations

From (Kreemer, C., Blewitt, G., and Klein, E. C. (2014), A geodetic plate motion and Global Strain Rate Model, *Geochem. Geophys. Geosyst.*, 15, 3849– 3889, doi:10.1002/2014GC005407)
Overlain with ITRF2014 plate definition (Altamimi, A., Métivier, L., Rebischung, P., Rouby, H., Collilieux, X., ITRF2014 plate motion model, *Geophysical Journal International*, Volume 209, Issue 3, June 2017, Pages 1906–1912, https://doi.org/10.1093/gji/ggx136)

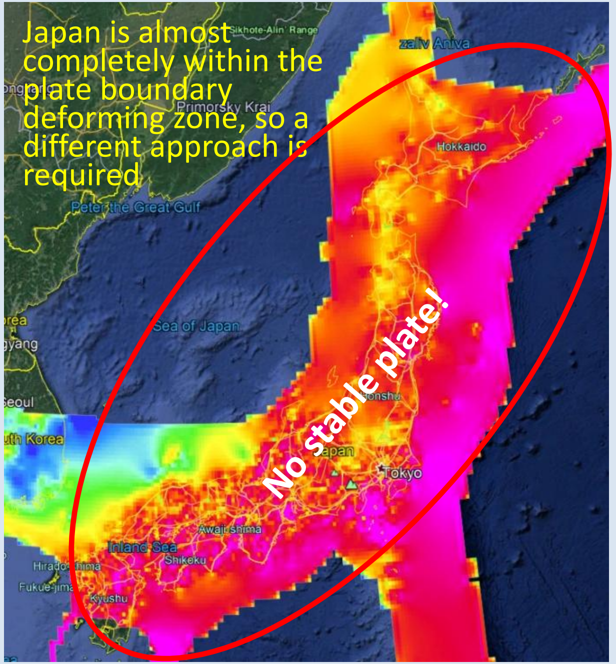
Conformal time-dep. transformation is only suitable in a stable plate interior



ITRF2014 to GDA2020 14-parameter transformation EPSG: 8049

	t_x	t_y	t_z	r_x	r_y	r_z	s	t_0
t_0 parameters	0	0	0	0	0	0	0	2020.000
	$\dot{t}_x$	$\dot{t}_y$	$\dot{t}_z$	$\dot{r}_x$	$\dot{r}_y$	$\dot{r}_z$	$\dot{s}$	
rates yr^{-1}	0	0	0	0.00150379	0.00118346	0.00120716	0	
(rotations in arcsec and CF notation)								

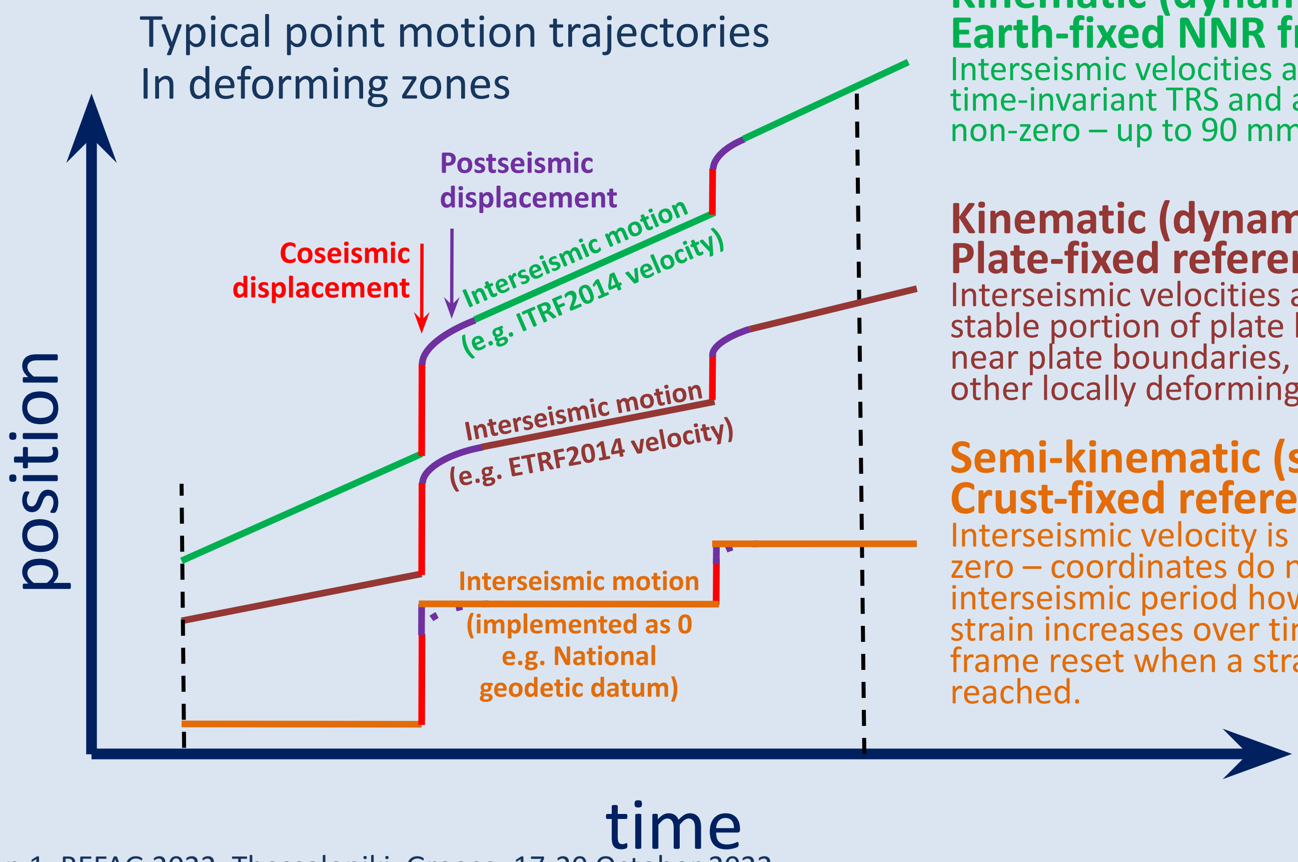
A simple parametric time-dependent (e.g. PMM derived) model is adequate for most applications



From (Corné Kreemer, GSRM visualisation, UNAVCO https://gsrm2.unavco.org/model/model.html)

A gridded or triangulated (e.g. TIN) transformation model is more suitable to capture variability of the deformation field

Time-dependent reference frames



Kinematic (dynamic)
Earth-fixed NNR frame

Interseismic velocities are related to a time-invariant TRS and are usually non-zero – up to 90 $mmyr^{-1}$

Kinematic (dynamic)
Plate-fixed reference frame

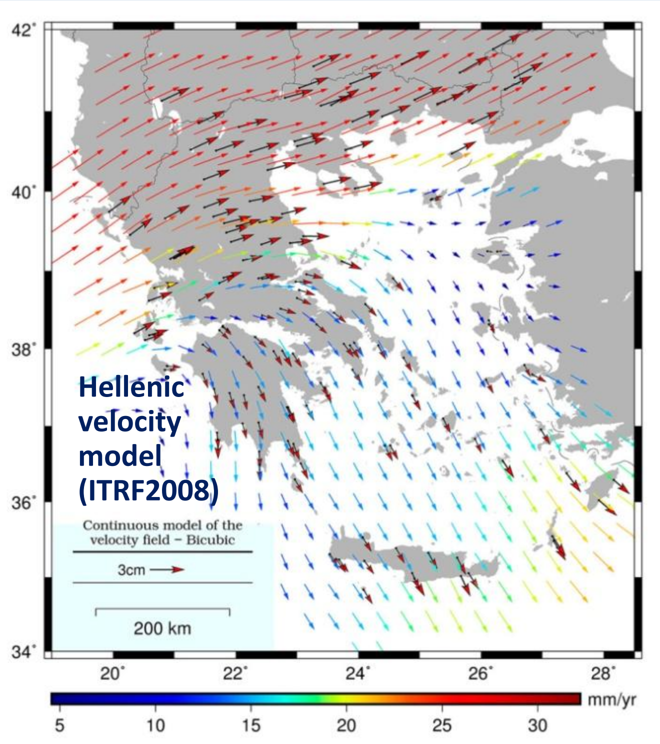
Interseismic velocities are near zero in stable portion of plate but increase near plate boundaries, GIA zones and other locally deforming areas

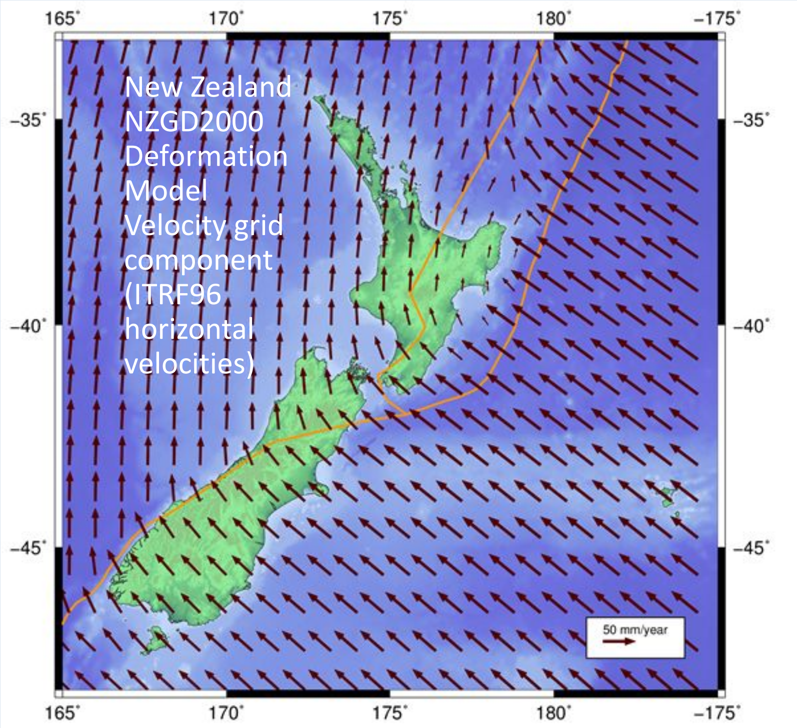
Semi-kinematic (semi-dynamic)
Crust-fixed reference frame

Interseismic velocity is implemented as zero – coordinates do not change during interseismic period however interseismic strain increases over time, requiring a frame reset when a strain tolerance limit is reached.

Velocity grid transformations – ITRF/IGS frame

(Bitharis et al., 2016)

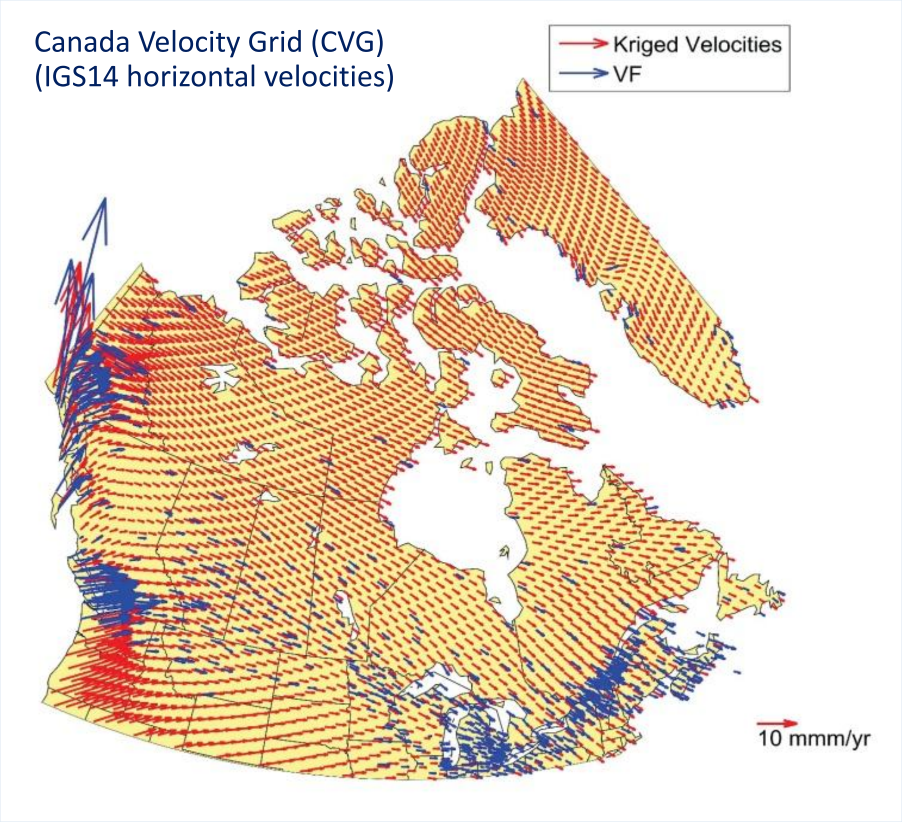




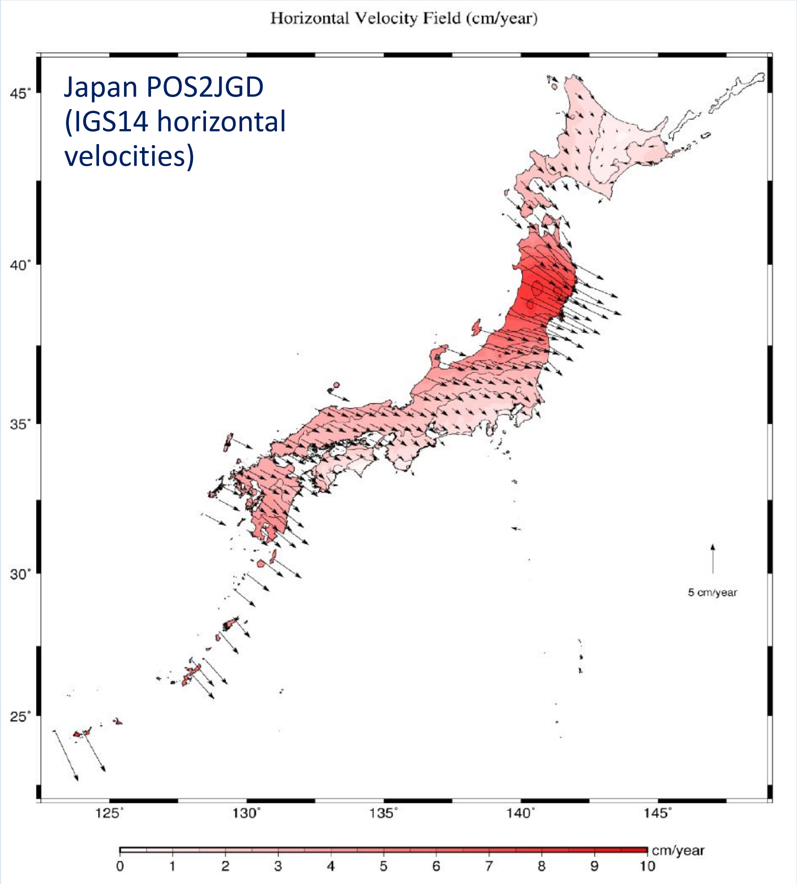
(LINZ, 2021)

Velocity grid models are ideally suited to deforming zones and for GNSS-PPP to local (crust-fixed) reference frame transformations in lieu of a conformal parametric model. **Single-step transformation process.**

Velocity grid transformations – other ITRF/IGS examples

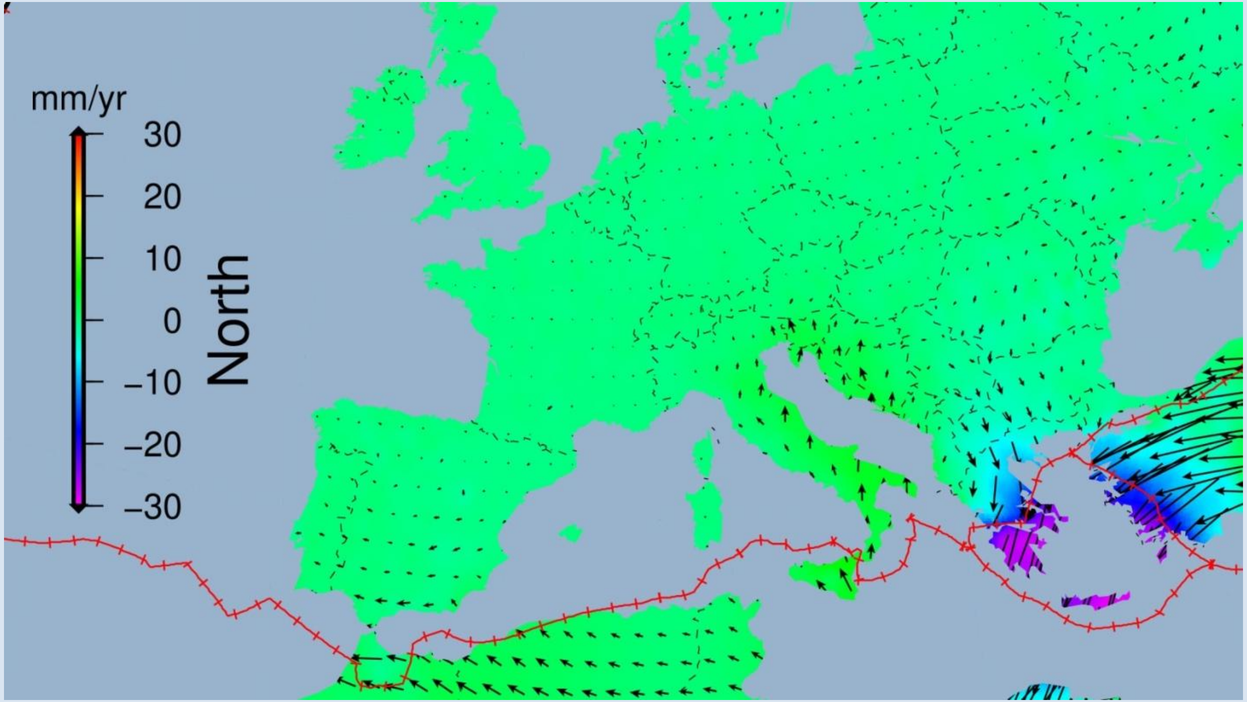


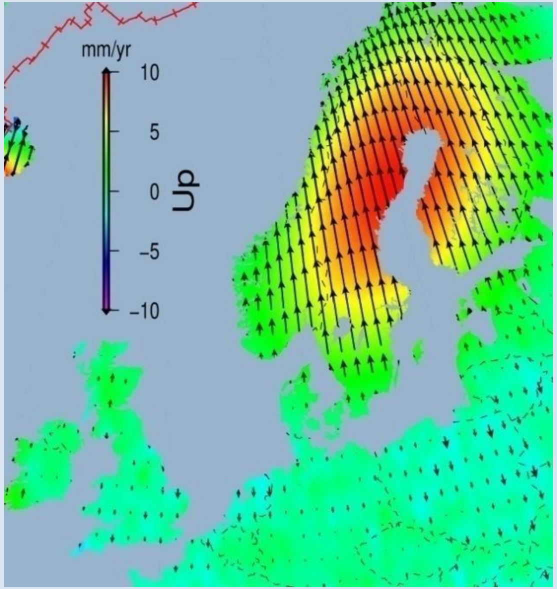
(Robin *et al.*, 2020 – NRCan)



(Yamashita, GSI, 2021)

Velocity grid transformations – Plate fixed RF

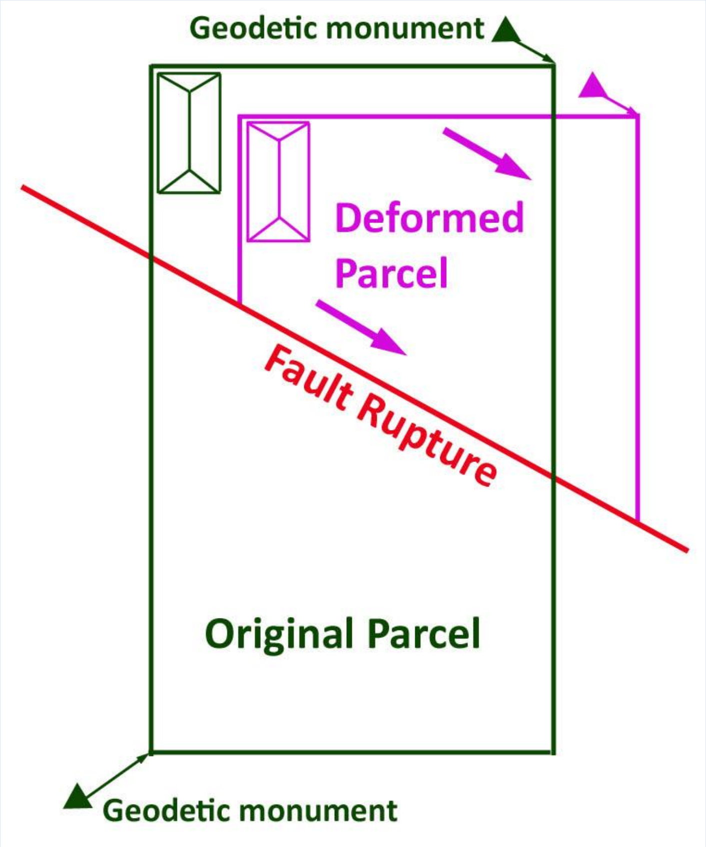




European velocity grid (in Eurasian frame)
Elmar Brockmann, swisstopo, 2022
http://pnac.swisstopo.admin.ch/divers/dens_vel/000.html

Plate-fixed velocities are typically close to zero within the stable plate interior but become non-zero near plate boundaries or GIA regions. Transformation from ITRF/IGS to plate-fixed RF at different epochs becomes a **two step process**

Coseismic displacements



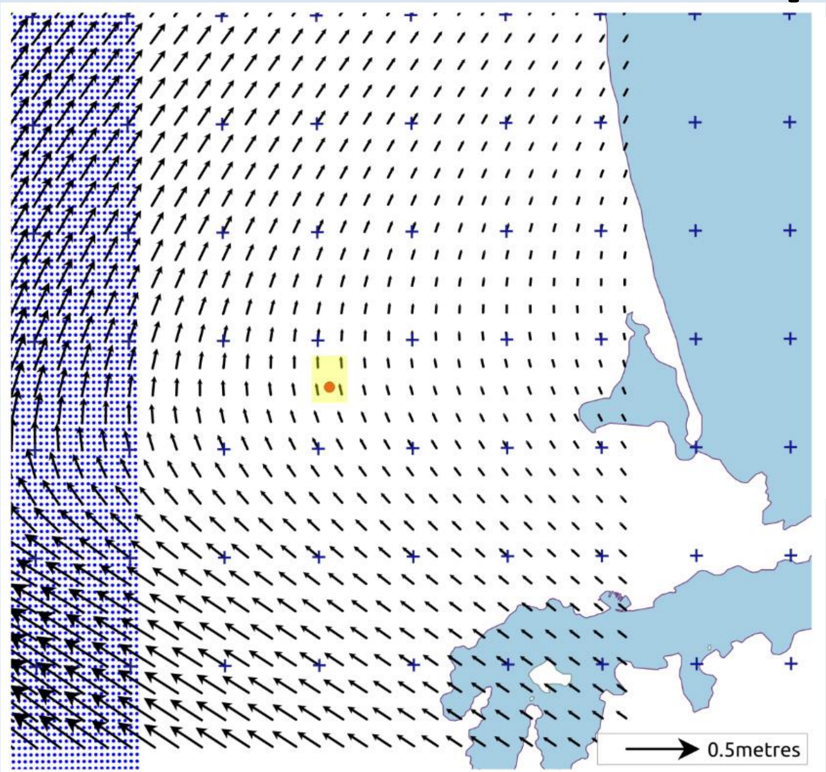
There is an expectation that coordinates of "ground fixed" reference frames **will change** after an earthquake. Especially considering surface fault ruptures and relative coordinate strain. Expectation is less clear in the far field.

A coseismic displacement model is required for each significant displacement event to enable transformation of coordinates across different seismic epochs

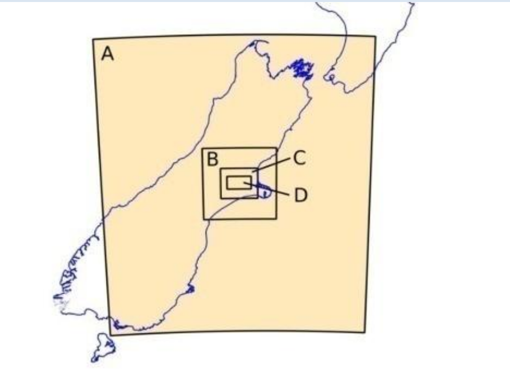
Examples:
Transformation of post-earthquake PPP position to a pre-earthquake frame

Transformation of cadastral or engineering designs in a pre-earthquake frame to a post-earthquake reference frame

Coseismic displacement model



Christchurch, New Zealand. (Crook *et al.,* 2016)



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

NZGD2000v20000101

↓

NZGD2000v20130801

Coseismic displacement model for 2010 and 2011 Christchurch earthquake sequence (and others)

(yyyymmdd)

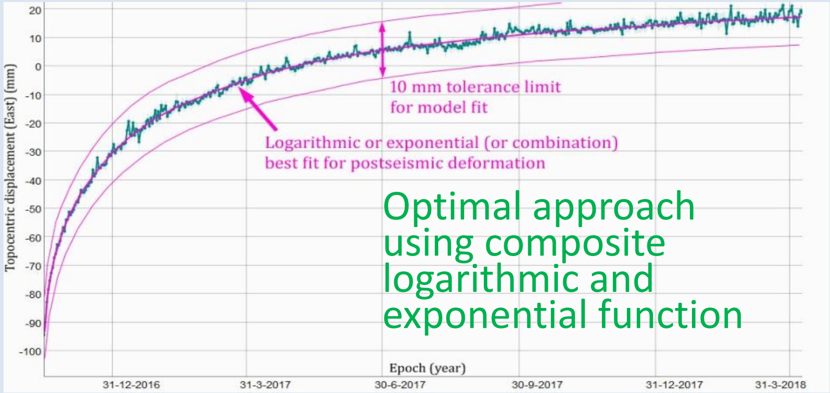
↓

NZGD2000v20180701

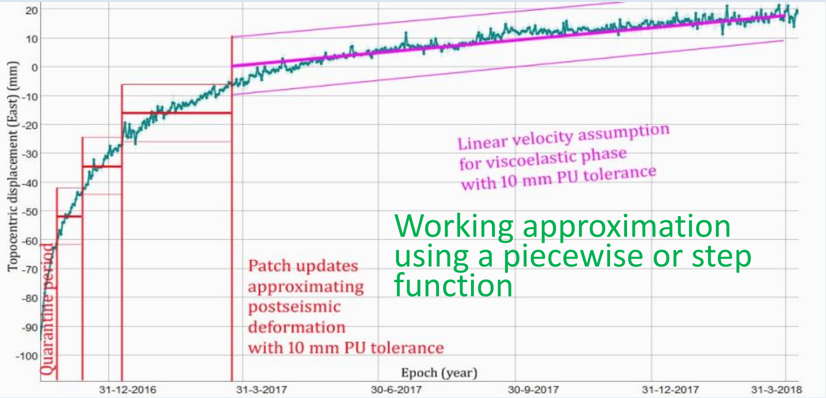
Coseismic displacement model for 2016 Kaikoura earthquake and others.

Transformation between each "version" is a step function using interpolation of a nested coseismic displacement grid (patch). Higher order nesting can be used near surface fault scarps in lieu of a triangulated model.

Postseismic and slow-slip events (SSE)



(Gisborne (GISB) New Zealand, East time-series showing Slow Slip Events, GNS, 2018 and Stanaway, 2020)

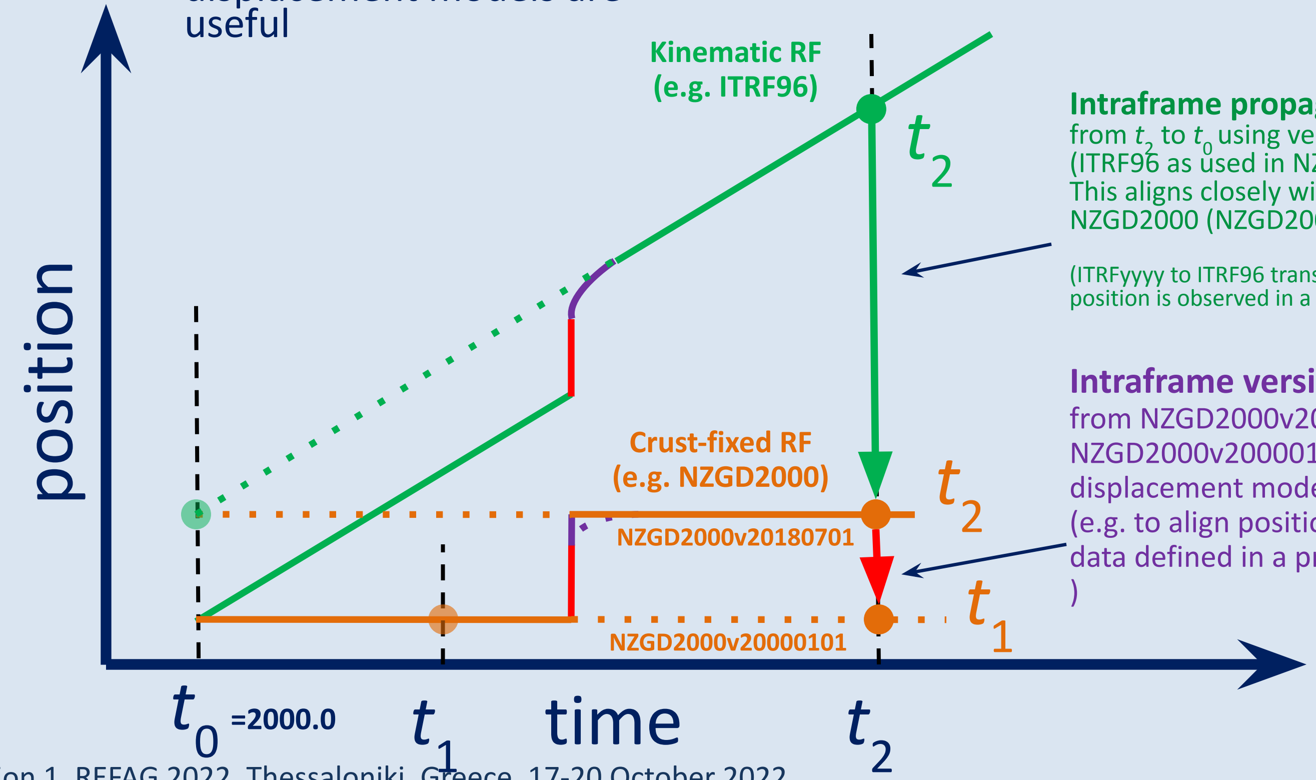


SSE can be modelled as a piecewise function (interseismic + SSE velocity), hyperbolic tangent function or smoothed as an averaged linear velocity if the SSE displacement is within a positioning tolerance threshold.

(Seddon (SEDD) New Zealand, East time-series showing postseismic displacement after Kaikoura earthquake sequence, November 2016,, GNS, 2018 and Stanaway, 2020)

Interframe transformation logic flow

Separate interseismic velocity and coseismic displacement models are useful



Intraframe propagation
from t_2 to t_0 using velocity model (ITRF96 as used in NZ)
This aligns closely with the latest version of NZGD2000 (NZGD2000v20180701)

(ITRFyyyy to ITRF96 transformation also required at t_2 if position is observed in a later realisation of ITRF)

Intraframe version transformation
from NZGD2000v20180701 to NZGD2000v20000101 using coseismic displacement model (subtracted)
(e.g. to align position at t_2 with legacy spatial data defined in a pre-earthquake frame at t_1)

High level structure of deformation model

Timeline

- GGXF (Geodetic gridded data exchange format) and deformation model functional model teams established in June 2020
- GGXF project to determine a common format for geodetic data sets
- Deformation model to determine a common structure for defining deformation models for use in coordinate time-dependent transformation operations
- Teams have been meeting on alternate fortnights – meetings well supported
- Deformation model team working in conjunction with IAG (International Association of Geodesy) WG 1.3.1 on "Time-dependent transformations between reference frames in deforming regions".
- Deformation models are structurally more complex than other gridded geodetic data sets - has dictated scope of GGXF, and depends on GGXF for realization
- Project artefacts in https://github.com/opengeospatial/CRS-Deformation-Models
- 16th June 2022 - Abstract Specification presented at 123rd OGC Member Meeting in Madrid
- August 2022 – progressed to OGC Standards Working Group (SWG)
- ISO Standard development (largely based on OGC Standard) 2023?

Abstract specification exclusions

Does not support other representations of deformation such as:

- Triangulated spatial models (e.g. TINs)
- rigid body transformations between reference frames such as time dependent Helmert or Bursa-Wolf transformations (e.g. 14/15 par.),
- trajectory models for individual stations, such as those described for ITRF geodetic monuments
- Plate motion models (PMMs),
- three dimensional geophysical models of deformation in terms of dislocations on fault planes such as elastic half space (Okada) or finite element models.

Geodetic Grid Exchange Format (GGXF)

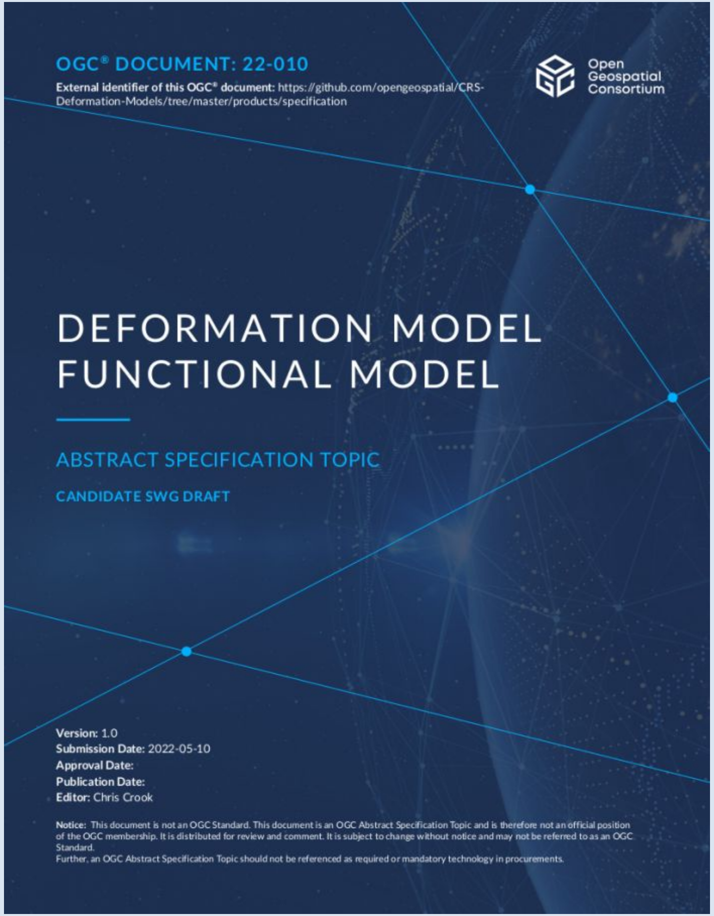
- ✔ Abstract specification of GGXF structure
- ✔ YAML text based format
- ✔ Proof of concept YAML/NetCDF implementation
- ✔ NetCDF agreed binary carrier

NetCDF implementation choices:

- Investigating alignment with CF conventions
- Investigating ACDD NetCDF metadata conventions
- NetCDF structure decided

Next steps:

- Documentation of NetCDF profile
- Update NetCDF proof of concept Github implementation and example data sets
- **https://github.com/opengeospatial/CRS-Gridded-Geodetic-data-eXchange-Format**


OGC® DOCUMENT: 22-010

External identifier of this OGC® document: https://github.com/opengeospatial/CRS-Deformation-Models/tree/master/products/specification

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DEFORMATION MODEL FUNCTIONAL MODEL

ABSTRACT SPECIFICATION TOPIC

CANDIDATE SWG DRAFT

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https://github.com/opengeospatial/CRS-Deformation-Models/blob/master/products/specification/abstract-specification-deformation-model-functional-model.pdf

Ευχαριστώ!