Support for dynamic datums in Trimble software

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SUMMARY

The GNSS satellite orbits are determined in the International Terrestrial Reference Frame (ITRF) at the epoch of measurement (eom) which results in GNSS baselines and precise point positioning coordinates also being in the current ITRF at the eom. However, in national datums, the coordinates reflect the position at a standard reference epoch. Because of the effect of plate tectonic motions, the relationship between these systems change continuously with time. As a result, accurate datum transformations require the application of models to correct tectonic motion. These are implemented in Trimble software using a grid-based algorithm developed by Land Information New Zealand. This algorithm is generally consistent with the standards that are under development by the OGC working group on deformation modelling. Using this algorithm, we are able to support all of the tectonic models currently in use by national governments.

RÉSUMÉ

Les orbites des satellites GNSS sont déterminées dans le repère international de référence terrestre (ITRF) à l'époque de mesure, ce qui fait que les lignes de base GNSS et les coordonnées des points calculés par les logiciels de positionnement précis sont également dans l'ITRF actuel à l'époque de la mesure. Cependant, dans les référentiels nationaux, les coordonnées reflètent la position du point à une époque de référence standard. Du fait du mouvement des plaques tectoniques, la relation entre ces systèmes change continuellement avec le temps. Par conséquent, les transformations de coordonnées précises entre ces systèmes de référence nécessitent l'application de modèles pour corriger les mouvements tectoniques. Ces modèles sont mis en œuvre dans les logiciels Trimble à l'aide d'un algorithme basé sur une grille développée par le Land Information New Zealand. Cet algorithme est généralement conforme aux normes en cours d'élaboration par le groupe de travail de l'OGC sur la modélisation des déformations. Grâce à cet algorithme, nous sommes en mesure de prendre en charge tous les modèles tectoniques actuellement utilisés par les gouvernements nationaux.

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1. INTRODUCTION

Due to the effect of plate tectonic motions, the actual positions of points on the earth change continuously and this is reflected in global datums such as the International Terrestrial Reference Frame (ITRF), where coordinates change continuously with time. However nearly all users find it difficult to deal with continuous coordinate change, so national datums have coordinates that are static. By modeling the motion of the earth's surface, these national datums project each coordinate to its position at a common date called the reference epoch, while still providing a link to the global systems. Accurately transforming coordinates from a global datum to a national datum is a non-trivial task, and Trimble has made significant enhancements to key software packages, automating this task for its users. This is particularly important with the advent of Precise Point Positioning (PPP) services like Trimble RTX®, which provide coordinates in the ITRF at the epoch of measurement.

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The models we support are divided into four broad categories.

1. The crustal motion is determined by applying the absolute Euler Pole for the plate in question.
2. The crustal motion is determined from a model of the velocity field.
3. The crustal motion is determined from a velocity field augmented with grids representing earthquake displacement and sometimes post seismic relaxation.
4. The crustal motion is provided through an online calculator which we have to convert to a distortion grid for integration into our products.

As shown in Figure 1, Trimble currently supports models for New Zealand, the US, Canada, Iceland, India, Japan, South Korea, Chile, Colombia, Brazil, Mexico and the Nordic/Baltic and other European Countries.

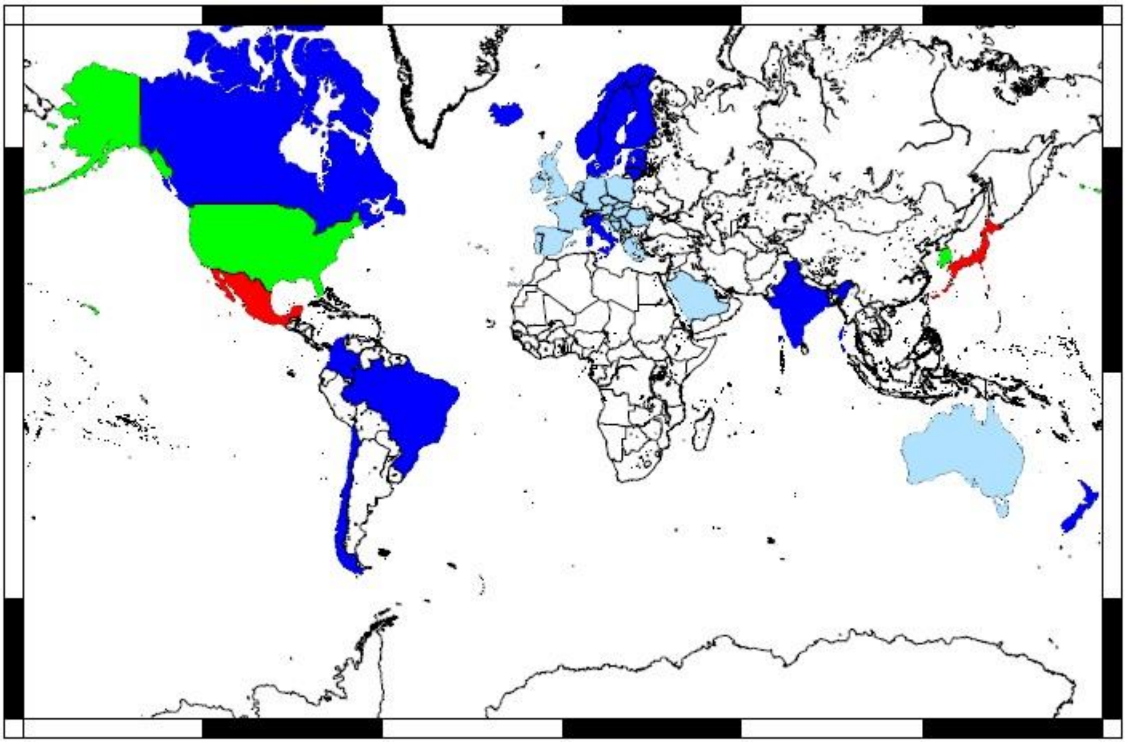

Figure 1 Map showing countries with Dynamic Datums. Countries in light blue model crustal motion using an Euler Pole. Countries in dark blue have a velocity grid. Countries in green use a full displacement mode including a velocity model and earthquake grids and countries in red provide an online calculator, which we implement as a distortion grid.

2. SEMI-DYNAMIC DATUMS

Modern semi-dynamic datums are usually based on a version of the International Terrestrial Reference Frame. Stable coordinates are produced by projecting each coordinate to its position at a common date called the reference epoch (Grant at al 2014). To make this technique work, we need a model of how the earth is moving due to plate tectonics. In stable areas, the effect of earthquakes will be small and the motion of the points will follow the motion of the tectonic plates and can be calculated using Euler Poles. Indeed, in some countries (such as Australia) these are incorporated in 14-parameter datum transformation equations, and no further corrections are necessary to provide stable accurate coordinates. However, for a country like the US where part of the country lies across a plate boundary, a different strategy must be adopted. In this case, an Euler Pole may be adopted to take care of the deformation in the stable part of the country, and a displacement model is used for residual deformation, particularly in the plate boundary zone. Coordinates are propagated to a standard epoch (2010 in the US for example) using a numerical model of deformation across the plate boundary. For this reason, Trimble software will support distinct types of displacement models

- First, for countries that are located in one tectonic plate, the horizontal velocity is determined by applying the absolute Euler Pole for the plate in question. Examples of this include Australia and the ETRS89 based realizations used by most European countries. In this case, the mathematical model is incorporated in the datum transformation parameters, which can be augmented by use of the ITRF2014 plate model in some jurisdictions.

- The second category are velocity models. These are normally characterized by a constant or secular velocity (see Figure 2). The velocity can either be given relative to the absolute or No Net Rotation (NNR) reference frame or relative to a tectonic plate, in which case the velocity field is a correction to the Euler Pole predicted displacement. An example of the velocity field relative to the NNR frame is the VEMOS field used in Chile. An example of the hybrid models involving both a velocity field and a Euler Pole is the NKG velocity field used by the Nordic countries or NAD83 used by Canada and the US.

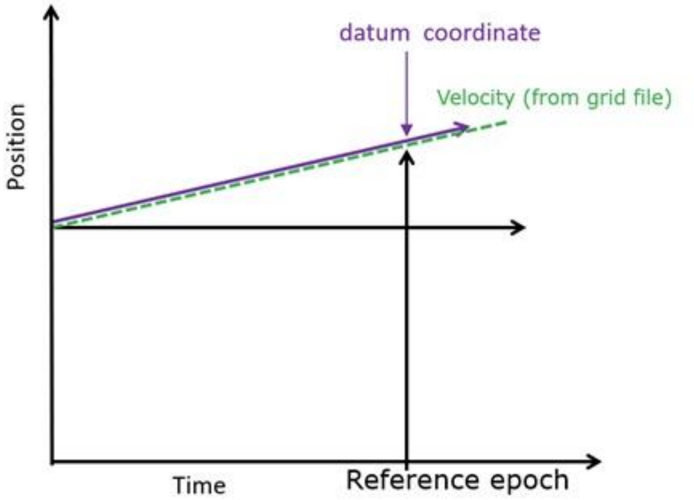

Figure 2 Displacement model with only a constant velocity

- The third type of displacement model incorporates a velocity field augmented with grids representing earthquake displacement and sometimes post-seismic relaxation. These models contain separate models of the secular (continuous) velocity field associated with on-going deep-seated tectonic processes and displacements associated with significant earthquakes. Other (smaller) effects, like post seismic relaxation that sometimes occurs after large earthquakes, are also included in some cases. The models are shown schematically in Figure 3. Note that the effect of earthquakes is an instantaneous offset while the effect of the velocity increases linearly with time. The total motion is just the sum of the earthquake and constant velocity terms.

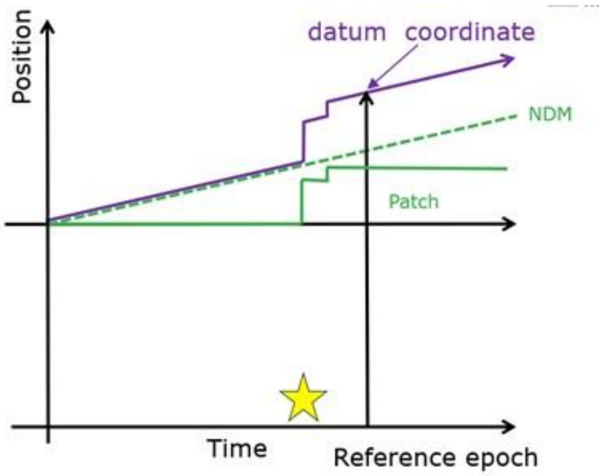

Figure 3 Schematic diagram of a dynamic datum. Dashed green line shows the secular velocity solid green line shows the co-seismic contribution to the displacement mode. The solid purple line shows the displacement model with both contributions combined.

- The fourth type of displacement model supports datums like JGD2011 where semidyna.exe, an online app, provides estimates of the tectonic motion from the reference epoch to the current year. We implement this using a constant displacement grid from which we can interpolate the tectonic motion for any point. Longer term we hope these will be upgraded to displacement models because they are easier for software providers to support and are potentially more accurate. They are also more compatible with emerging standards produced by the OGC working group on deformation models.

3) FUNCTIONAL MODELS

The Trimble Geodetic Library (TGL) underlying many Trimble products has been recently upgraded to support semi-dynamic datums. This requires that TGL support time-dependent datum transformations (introduced with Trimble Access 2020.00 and TBC 5.30) and displacement models (introduced with Trimble Access 2020.20 and TBC 5.40). With these enhancements TGL can support all four types of displacement models discussed above. The correction equation is shown in Equation 1 below:

Equation 1

$$m_k(t,\theta,\varphi) = v(\theta,\varphi)_k t + E(\theta,\varphi)_{ki} H(t-t_i) + P(\theta,\varphi)_{ki} H(t-t_i)\left(1 - e^{-\frac{(t-t_i)}{tc_i}}\right) + d(\theta,\varphi)_k$$

- ν is a constant velocity grid
- E is the earthquake shift (patch)
- P post-seismic decay constant
- H is the step function
- d is a constant displacement grid

In case one, the Euler Pole is applied using the datum transformation parameters and it does not involve Equation 1. In case two only ν() is nonzero. In the case three, ν(), E() and potentially P() are nonzero and in case four, only d() is nonzero.

3. GRIDS

All of the types of displacement models we support except for the Euler Pole (case 1) use grid files and bi-linear interpolation to estimate the parameters for Equation 1. As an example of how grid files are used in Trimble geodetic libraries, consider our model for the contiguous US (CONUS). In this case the model includes 8 grid files, five of which are associated with the velocity model and three are associated with earthquake models. The geographical extents of the areas covered by the grid files are shown in Figure 4.

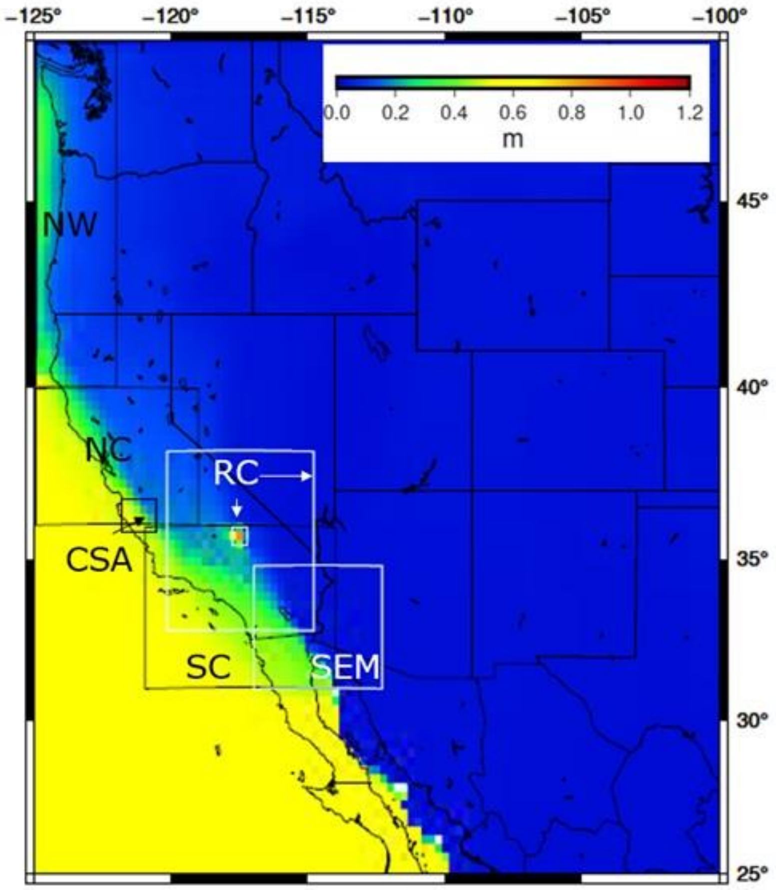

Figure 4 Western part of CONUS. The colors indicate velocity magnitudes from the top-level grid that covers all of CONUS. The geographical extents of all of the other grids in the model are shown as rectangles. Black rectangles show the extents of velocity grids. NW, NC, SC and CSA refer to the Pacific Northwest, Northern California, Southern California and Creeping San Andreas grids respectively. White rectangles show the extents of earthquake grids. SEM stands for the 2010 M 7.2 El Mayor–Cucapah earthquake and the RC stands for the 2019 M 7.1 Ridgecrest, California earthquake. Note that the Ridgecrest model consists of two nested grids.

1.1. Velocity grids

Our velocity model of CONUS consists of five nested grids, a top-level grid covering all of the contiguous US with a grid spacing of 0.25 ° and four sub-grids with a finer grid spacing. The NW, NC and SC grids cover the tectonically active parts of Pacific Northwest and California. They have a grid spacing of 0.0625 ° and the CSD with a grid spacing of .01 ° covers the special case of the creeping section of the San Andreas fault. Our velocity grids are identical to the ones used internally by HTDP (Pearson and Snay 2012 table 3)

1.2. Earthquake grids

When it comes to earthquakes, TGL and HTDP differ in that HTDP uses mathematical models of the earthquake while TGL uses grids. We developed the earthquake grids from HTDP by using the capability of HTDP to transform positions on a regular grid between two dates. For this purpose, we chose the two dates so was one immediately before the earthquake and one immediately after.

We include two earthquakes in our model of CONUS, the 2010 M 7.2 El Mayor–Cucapah earthquake (SEM in Figure 4) and the 2019 M 7.1 Ridgecrest, California earthquake (RC in Figure 4). The SEM model consists of a single grid with a grid spacing of .02°. This is a fairly course grid for an earthquake but the epicenter is well south of the US border so this grid is sufficient to model the deformation in the US portion of the radius of influence for the earthquake.

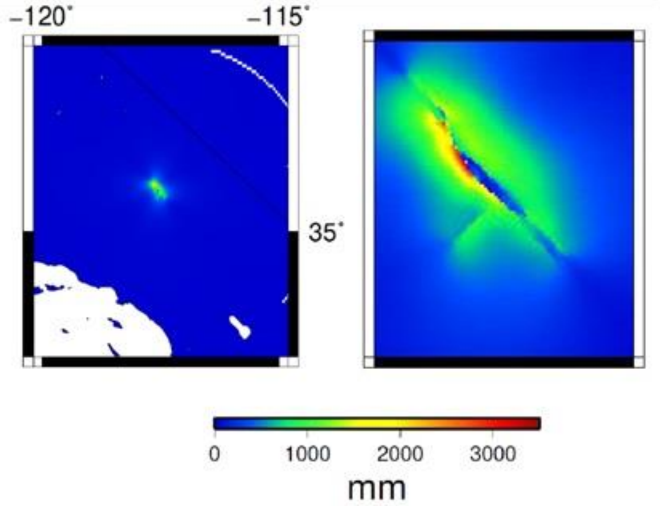

Figure 5 Grids for the Ridgecrest earthquake. The left-hand image shows the full earthquake grid and the right-hand image shows the immediate epicentral region.

The Ridgecrest model consists of two nested grids. The inner grid covers only the immediate epicentral area and has a grid spacing of .005° and the outer grid which covers much of southern California and .05°.   Figure 5 shows both of these grids. Note that deformation in the epicentral region is discontinuous with a 3 m change across the fault. This is a feature of earthquakes where the fault plane breaks the surface. Because of the shallow depth the faults broke the surface producing complex displacements with discontinuities, the modeled displacements from HTDP in the immediate vicinity (say within 1 km or so) of the fault are almost certainly not accurate. This is partly caused by the grid spacing not being fine enough to follow the fault accurately. However, the underlying geophysical model will always be inaccurate here due to the interaction of the propagating fault with the surface of the earth. Consequently, any coordinates that are measured after an earthquake and corrected to a pre-earthquake reference epoch may lose some accuracy and this is particularly true if the measurements are located close to a fault trace. For this reason, Trimble is considering adding functionality to TBC so that users will be aware that positions in this area may be suspect. It is important that geospatial professionals are aware of this problem

4. VALIDATION OF TGL IMPLEMENTATION

As part of the process of developing a new model in TGL we always develop a series of test coordinates. The test points are generated by taking 24 hr RINEX files either from stations in the national CORS network for the country in question or from a VRS network. The RINEX files are then submitted to RTX online post-to develop ITRF2014 coordinates at epoch of measurement (eom). These coordinates are then converted to the appropriate national datum using the transformation parameters and displacement model. We then developed residuals for these points by subtracting our transformed coordinates from the authoritative coordinates from these sites. Figure 6 shows histograms of the residuals for test points for 12 countries (Finland, Denmark, US, Sweden, Chile, Austria, Mexico, Colombia, Italy, Germany, Norway, and the United Kingdom).

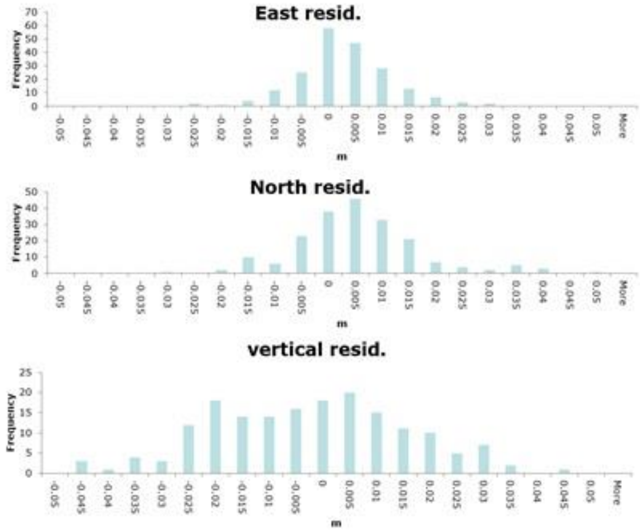

Figure 6 Histograms for combined residuals from 12 countries

In all there are 202 residuals. The statistical summary, (Table 1) shows that our RMS residuals are about 1 cm in the east, north components and a little less than 2 cm in the vertical. These residuals are comparable to the GNSS processing errors we would expect for 24 hr RINEX files which suggests that the transformations in TGL do not add any appreciable error to the coordinates.

Table 1 Statistical summary of residuals. Combined represents the geometrical sum of the East North and vertical components

	e m	n m	u m	Combined
RMS	0.0088	0.0121	0.0178	0.0228
Max	0.0298	0.0469	0.0449	0.0493
Min	-0.0278	-0.0335	-0.0478	0.0001
Ave	0.0006	0.0030	-0.0045	0.0198

5. CONCLUSIONS

Trimble has recently upgraded its geodic transformation libraries to support dynamic datums and displacement modes following a schema developed by Land Information New Zealand. Using these we have been able to support 44 countries. We have found that this upgrade significantly reduces errors particularly in transformations involving ITRF or WGS84 coordinates at the epoch of measurement to national datums with a fixed reference epoch. Because these transformations will become more prevalent given the increasing use of precise point positioning techniques which generate coordinates in the epoch of measurement and improve GNSS processing for long baselines, we recommend that National Agencies worldwide should upgrade their datums to incorporate displacement models to correct for crustal motion. We also support the adoption of appropriate international standards (along the lines of the OGC’s draft standards on GGXF) to ease the integration of future displacement models in vendor’s products`

6. FUTURE PLANS

In future we hope to incorporate estimates of uncertainties into displacement modes where these are available and provide tools for users to visualize velocity and earthquake grids. We also plan to integrate Trimble Geodetic Libraries in Trimble VRS and Pivot

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BIOGRAPHICAL NOTES

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Chris completed a PhD at the University of Otago in 1991. He then worked at Columbia University and the University of Otago as a research fellow specializing in GPS processing and measuring crustal deformation. Between 2001 and 2011 Chris worked for the US National Geodetic Survey where he was geodetic advisor for Illinois and was responsible for maintaining the HTDP program. Between 2011 and 2018 Chris was a lecturer at the University of Otago. Since 2018, Chris has been the geodetic advisor at Trimble.

Sebastien Vielliard, Senior Software Engineer, Trimble
Sebastien obtained a Master's degree in Computer Science in 1993 from Polytech'Nantes, France. Since then, he has worked as a software engineer developing Survey & GIS Office Software for Sercel, Dassault Electronics, Thales Navigation, Magellan, and Ashtech. After Ashtech became a Trimble company in 2011, Sebastien joined the Trimble Business Center team as a senior software engineer, specializing in geodetic libraries and algorithms.

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