Initial implementation of Chile's REDGEOMIN datum in Trimble Geodetic Library

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Key words: Deformation measurement, Reference frames, semi-dynamic datums

SUMMARY

Since 2020, Trimble Geodetic Libraries (TGL) have supported deformation models to correct coordinates from the epoch of measurement (eom) to the reference epoch of national datums. This step is critical to allow coordinates from Trimble's RTX system to be accurately transformed into the reference epoch of the national datum. Currently TGL supports 63 dynamic datums including NZGD2000, GDA2020 and a beta version of PGD2020 which allows NAMRIA to use Trimble products to complete their work on this datum.
However, maintaining accurate geodetic coordinates in Chile is a significant challenge to geodesists because of the combination of a very active plate boundary, co-seismic deformation from a series of great earthquakes and complex time varying post seismic deformation field. The ADELA (Analysis of DEformation beyond Los Andes) project from the University of Santiago Chile (USACH) has developed a novel approach based on analysis of the time series from continuous GNSS from Chile and adjacent parts of South America. However, this approach is challenging to implement in TGL which is based on the application of a functional model of deformation where the values for geophysical parameters (crustal velocities, earthquake shifts and post seismic decay constants) as a function of latitude and longitude are determined from the interpolation of grids. Implementing this in TGL requires that a new paradigm be introduced. In this paper, we describe how we have developed a hybrid approach where the individual network solutions based on USACH's Bernese processing of a network of over 250 GNSS stations are used to develop a series of distortion grids by differencing the Bernese CRD files. These grids together can be used to approximate the time dependent motion of Chile. This approach has two advantages compared to the geophysical based models we have used in other areas. First, the process of developing distortion grids can be automated which substantially reduces latency. In addition, we do not have to wait for new geophysical models to be developed which gives us substantially greater flexibility in modeling deformation.

RÉSUMÉ

Depuis 2020, la Librairie Géodésique de Trimble (en anglais TGL) prend en charge les modèles de déformation pour corriger les coordonnées entre l'époque de mesure (en anglais eom) et l'époque de référence des systèmes de référence nationaux. Cette étape est cruciale pour permettre aux coordonnées du système RTX de Trimble d'être transformées avec

précision à l'époque de référence du système de référence national. Actuellement, TGL prend en charge 63 systèmes de référence dynamiques, y compris NZGD2000, GDA2020 et une version bêta de PGD2020 qui permet à NAMRIA d'utiliser les produits Trimble pour compléter leur travail sur ce système de référence.

Cependant, maintenir des coordonnées géodésiques précises au Chili est un défi important pour les géodésistes en raison de la combinaison d'une frontière de plaque très active, de la déformation co-sismique d'une série de grands tremblements de terre et d'un champ de déformation post-sismique complexe et variable dans le temps. Le projet ADELA (Analyse de la DEformation au-delà de Los Andes) de l'Université de Santiago du Chili (USACH) a développé une approche novatrice basée sur l'analyse des séries temporelles des stations GNSS du Chili et des parties adjacentes de l'Amérique du Sud. Cependant, cette approche est difficile à mettre en œuvre dans TGL, qui est basé sur l'application d'un modèle fonctionnel de déformation où les valeurs des paramètres géophysiques (vitesses crustales, déplacements sismiques et constantes de décroissance post-sismique) en fonction de la latitude et de la longitude sont déterminées à partir de l'interpolation de grilles. La mise en œuvre de cela dans TGL nécessite l'introduction d'un nouveau paradigme. Dans cet article, nous décrivons comment nous avons développé une approche hybride où les solutions de réseau individuelles basées sur le traitement Bernese de l'USACH d'un réseau de plus de 250 stations GNSS sont utilisées pour développer une série de grilles de distorsion en différenciant les fichiers CRD de Bernese. Ces grilles peuvent être utilisées ensemble pour approximer le mouvement dépendant du temps du Chili. Cette approche présente deux avantages par rapport aux modèles basés sur la géophysique que nous avons utilisés dans d'autres régions. Premièrement, le processus de développement des grilles de distorsion peut être automatisé, ce qui réduit considérablement la latence. De plus, nous n'avons pas à attendre le développement de nouveaux modèles géophysiques, ce qui nous donne une flexibilité beaucoup plus grande dans la modélisation de la déformation.

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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.

The purpose of this paper is to review how Trimble intends to support modernized geodetic datums in complex tectonic environments using the REDGEOMIN datum from Chile as an example. Because Chile is narrow strip of land along the Pacific coast of South America paralleling the Peru-Chile trench which marks the Nazca and South America plate boundary accurately correcting for tectonic motion is challenging here. Ongoing subduction of the Nazca under South America produces a complex velocity field combined by repeated great earthquakes and associated post seismic deformation which cause significant challenges in maintaining accurate coordinates in this region. TGL already supports the current national datum for Chile (SIRGAS Chile 2021). However, because of the importance of the mining industry in Chile, the University of Santiago of Chile (USACH) have developed a regional kinematic reference frames for Chile called (REDGEOMIN) that allows survey measurements to be corrected for inter-seismic, co-seismic, and post-seismic deformation.

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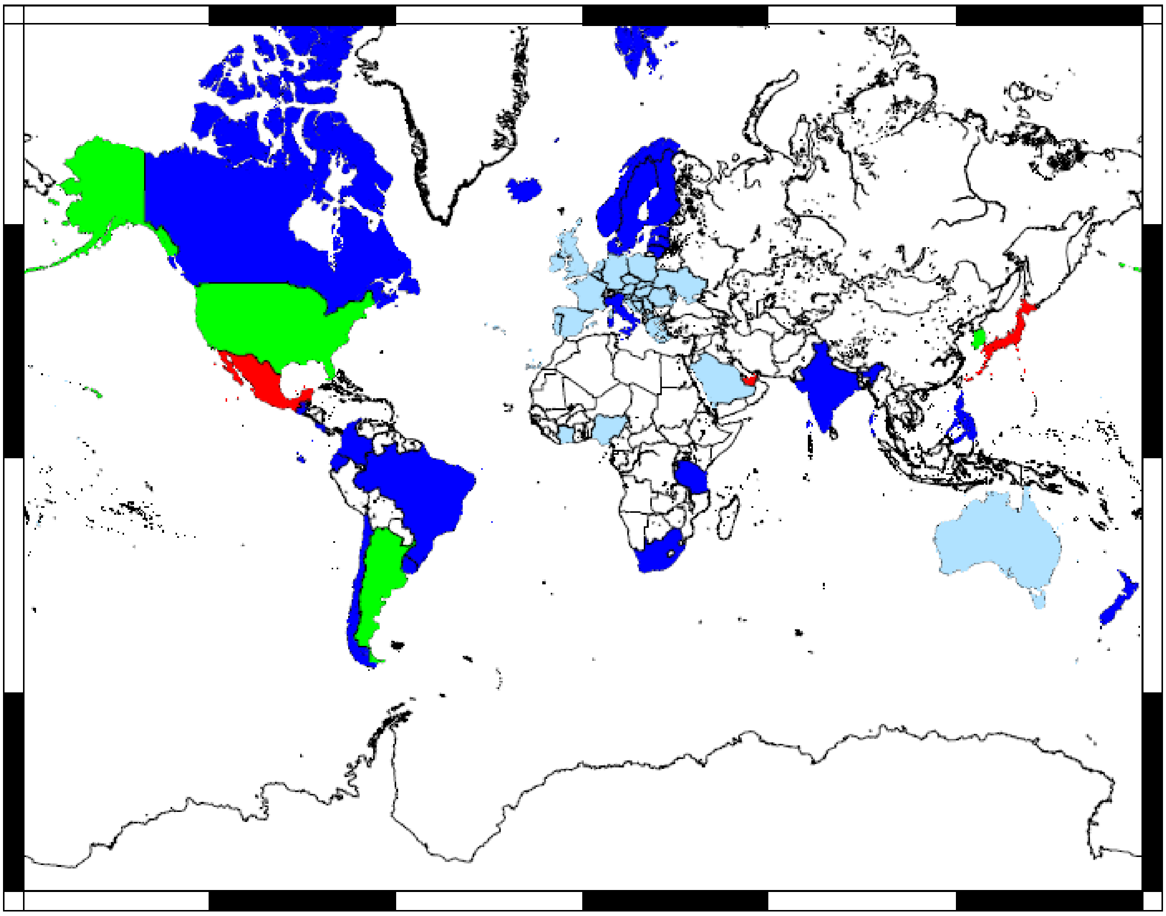

Figure 1 Map showing countries with Dynamic Datums. Countries in light blue model crustal motion using an Euler Pole. Countries in dark blue have a velocity grid. Countries in green use a full displacement mode including a velocity model and earthquake grids and countries in red provide an online calculator, 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, in cases where part of the country lies across a plate boundary, a different strategy must be adopted. In this case coordinates are propagated from the epoch of measurement (eom) to a standard epoch 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.

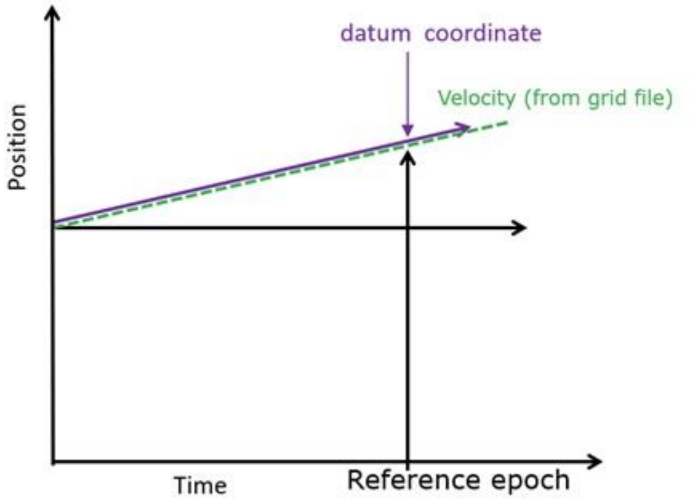

Figure 2 Displacement model with only a constant velocity

- 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.

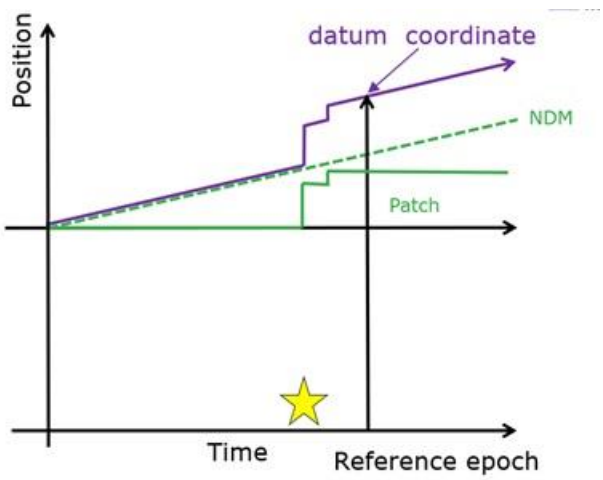

Figure 3 Schematic diagram of a dynamic datum. Dashed green line shows the secular velocity solid green line shows the co-seismic contribution to the displacement mode. The solid purple line shows the displacement model with both contributions combined.

- 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.

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. 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.

4. The REDGEOMIN deformation model

The REDGEOMIN deformation model (Tarrío et al 2024) involves modeling time series for 22 CORS (Continuously Operating Reference Stations) in Chile (Figure 4) supplemented by available campaign measurements. However, the paradigm used by REDGEOMIN project requires that the modeled the time series for the nearest CORS to the point in question be interpolated before the deformation can be estimated, and time series estimation is not supported by TGL.

Because, as described in section 3 above, TGL requires that all parameters in Equation 1 are spatial grids not time series as assumed REDGEOMIN so implementing this in TGL requires that a new paradigm be introduced.

We have developed a hybrid approach where the individual network solutions based on USACH’s Bernese processing of a network are used to develop a series of distortion grids. By differencing the solution for the most recent epoch with the one for the reference epoch, we can easily generate a datum grid of coordinate changes for the coordinate changes between the solutions. We implement this using a constant displacement grid from which we can interpolate the tectonic motion for any point, and then gridding the coordinate differences using the GMT software (Wesel 2019). Displacement between the epoch of the datum grid and the actual epoch of measurement can be corrected by extrapolating the correction to cover the extra displacement. These grids together can be used to approximate the time dependent motion of Chile.

This approach has two advantages compared to the geophysical based models we have used in other areas. First, the process of developing distortion grids can be automated which substantially reduces latency. Also, in the case of earthquakes, we do not have to wait for new geophysical models to be developed which gives us substantially greater flexibility in modeling deformation.

Figure 4 CORS in Chile which were included in the REDGEMIN project, dots show the locations of the CORS.. Blue dots are points with residual less than 1 cm and orange shows the one point with a residual greater than 1 cm.

5. Statistical analysis

Using the REDGEOMIN2024.0 coordinate which I transformed from the ITRF2020 epoch 2024.5 coordinate in Trimble Access using the XML and CMG files in the shared drive to test the transformation. By comparing the REDGEOMIN2024.0 coordinate derived in this way with the value from the USC22957_2024_00.CRD which we have treated as truth I could estimate a residual for each of the 21 test points. The results are summarized in Table 1 below.

Table 1 XYZ residuals for the 21 test points

# pts = 21	X m	Y m	Z m
RMS	0.0044	0.0030	0.0045
Max	0.0045	0.0025	0.0074
Min	-0.0160	-0.0075	-0.0035
average	-0.0021	-0.0014	0.0036

. The enu residuals for the same test points used in Table 1 are shown in Table 2 below.

Table 2 enu residuals for the same 21 test points.

	e m	n m	u m
RMS	0.0046	0.0034	0.0040
Max	0.0042	0.0055	0.0042
Min	-0.0175	-0.0011	-0.0077
average	-0.0024	0.0032	-0.0015

With the exception of one point, all of the residuals are in the mm range and our maximum residual is 1.75 cm, for B914 which is well below our normal cutoff of 5 cm. This is the only residual over 1 cm.

6. CONCLUSIONS

Trimble has recently upgraded its geodic transformation libraries to support dynamic datums and displacement models following a schema developed by Land Information New Zealand. Using these we have been able to support 44 countries including Australia, New Zealand and The Philippines. 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. We anticipate that dynamic datums 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. In some cases where non traditional datums are being used datum grids can provide an accurate transformation as long as the grid is updated regularly.

We also support the adoption of appropriate international standards (along the lines of the OGC’s standard on Deformation Models and GGXF) to ease the integration of future displacement models in vendor’s products`

7. FUTURE PLANS

In future we hope to expand the number of national datums that TGL supports with a special emphasis on the developing world, particularly the Asia Pacific region. We also plan to incorporate estimates of uncertainties into displacement models where these are available and provide tools for users to visualize velocity and earthquake grids.

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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.

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Ariel obtained a Master’s degree in Geomatics from University of Santiago de Chile in 2012. He has worked at Geocom for 15 years spreading geospatial innovations and is currently the Engineering Manager.

Sebastien Vielliard, Distinguished Engineer at Trimble
Sebastien obtained a Master’s degree in Computer Science in 1993 from Polytech Nantes, France. He has worked as a software engineer developing Survey & GIS Office Software for Sercel, Dassault Electronics, Thales Navigation, Magellan, Ashtech & Trimble during the last 30 years. Sebastien has been leading Trimble Geodetic Library development and integration into Trimble Business Center since 2014. Sebastien is member of the Coordinate Transformation Working Group at RTCM SC104.

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