Support for dynamic datums in Trimble software

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

SUMMARY

Because of the effect of plate tectonic motions, coordinates of points in the International Terrestrial Reference Frame (ITRF) change continuously with time, however, in national datums, the coordinates reflect the position at a standard reference epoch. This mismatch has not been significant for commercial users of high-precision GNSS in the past, since single-base RTK is essentially a differential approach, where the base coordinate can be provided in national coordinates, and network RTK systems typically operate in national coordinate frames. It is becoming important to users with the advent of precise Point Positioning (PPP) services, which develop coordinate in the ITRF at the epoch of measurement. As a result, transforming coordinates to the national datum requires correcting coordinates for tectonic motion.

Countries such as Australia and much of Europe that lie entirely within a tectonic plate are able to incorporate the Euler Pole of the tectonic plate into the transformation equations between the national datum and the ITRF. However, for a country like New Zealand or the west coast of the USA, that lies across a plate boundary a different strategy must be adopted. In this case, the datum may incorporate a national deformation model (NDM) of how the earth is moving and this is used to project coordinates to the reference epoch. These models typically incorporate a velocity field and, where required, earthquake displacements and post-seismic deformation.

Trimble has recently upgraded its geodic transformation libraries to support dynamic datums and deformation models following a schema developed by Land information New Zealand. The model contains one or more sub-models representing different types of deformation. Each sub-model contains a grid file that defines the spatial variation of the model combined with a time function (e.g., velocity, step, ramp, or exponential decay). The secular velocity field uses the velocity time function. Any temporal changes in the velocity field can be accommodated by a ramp time function which is a velocity segment. Earthquakes are modeled using the step time function which is zero before the earthquake origin time, and one afterwards. In this case the grid file represents the earthquake. Post seismic decay is usually modeled using an exponential time function.

Trimble currently supports models for New Zealand, the US, Canada, Iceland, Brazil and the Nordic Countries. We intend to support other models as they are released. In our experience this will significantly increase the accuracy of PPP derived coordinates including RTX.

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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. 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. 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.

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. 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 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 deformation 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. 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 1. 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.

3. SUPPORT FOR DEFORMATION MODELS IN TGL

The Trimble Geodetic Library (TGL) underlying both Trimble Access and Trimble Business Center 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 deformation models (introduced with Trimble Access 2020.20 and TBC 5.40).

- The support for time-dependent datum transformations is an enhancement to allow TGL to transform coordinates more accurately than was possible in the past. It also allows us to support plate-fixed datums like NAD83 and NSRS2022.
- Our support for deformation models allows TGL to develop accurate coordinates in tectonically active areas. In practice both the velocity and earthquake shifts are stored as a series of grid files, which are used to estimate the appropriate values for an arbitrary point by linear interpolation. The basic idea of a National Deformation Model is illustrated in Figure 1, which shows the trajectory of a point affected by a constant velocity and two earthquake shifts which are combined to estimate the total displacement. These are then used to correct the coordinates back to the reference epoch. In addition, the models can also correct for post-seismic deformation.

The correction equation is:

Equation 1

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

- Where *m* is the displacement
- *v* is the velocity (ndm)
- *E* is the earthquake shift (patch)
- *P* post-seismic decay
- H is the step function

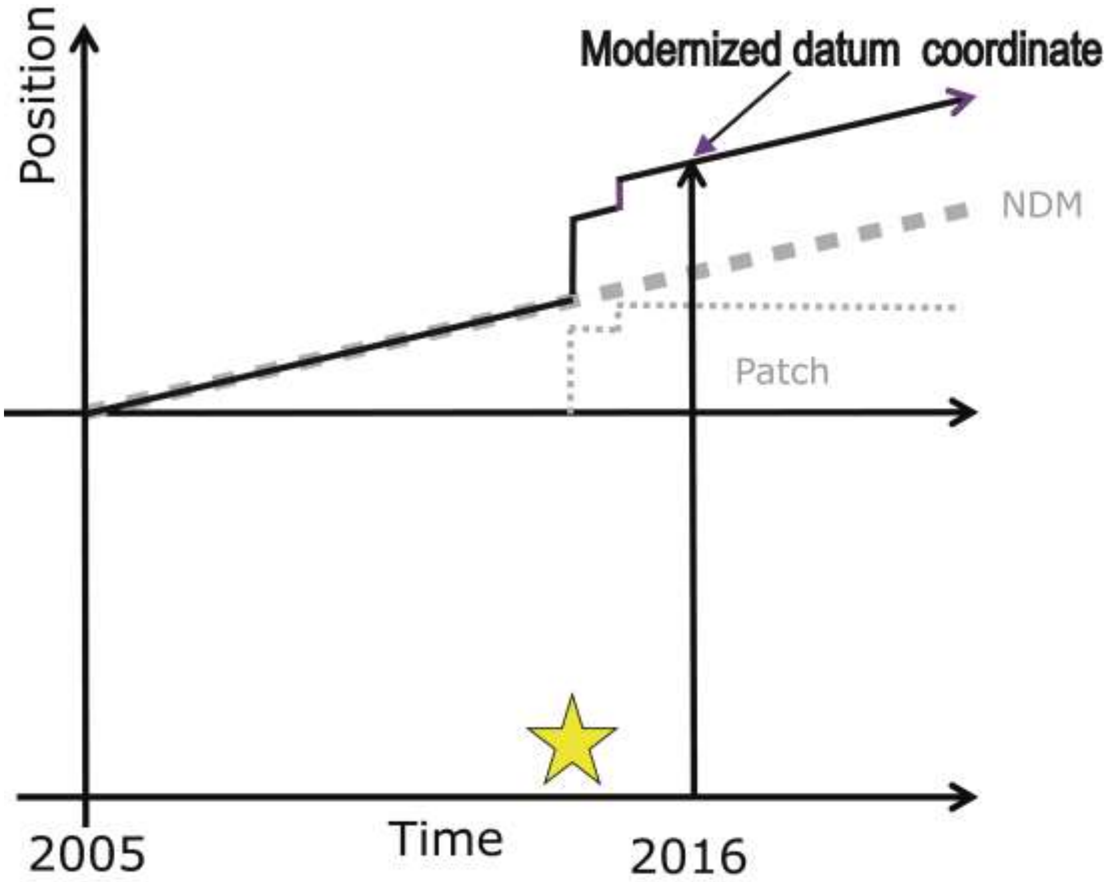

Figure 1 Schematic diagram of a dynamic datum. Heavy dashed gray line shows the secular velocity and thin gray dotted line co-seismic contribution to the deformation model. The solid black line shows the deformation model with both contributions combined.

4. WHERE ARE TRIMBLE OBTAINING THE DEFORMATION MODELS FROM?

4.1 NAD83 deformation models

As an example, consider the North American Datum of 1983 (NAD83). The National Geodetic Survey (NGS) is a federal agency responsible for maintaining NAD83 in the United States. The NGS provides a Horizontal Time-Dependent Positioning (HTDP) utility for transforming coordinates (Pearson and Snay 2013). From December 2020, TGL supports the time transformation functions that HTDP uses to correct positions to 2010 (the reference epoch for NAD83 2011) by supporting the same velocity models and earthquake models that HTDP uses.

4.2 Velocity grids

The extent of the velocity grids for Alaska and CONUS are shown in Figure 2. Note that the grids for Alaska and CONUS do not overlap. For this reason, these models are treated as separate models in TGL. These models only support time corrections to the reference epoch of NAD83(2011) and the observation time has to be after 2010.0.

Figure 2 Grids and sub-grids supporting NAD83. The two large rectangles show the extents of the NAD83_CONUS NAD83_Alaska and NAD83_CSRS models. The post-seismic (Alaska) and earthquake (western CONUS) patches are labeled. The three unlabeled rectangles in western CONUS represent the Pacific NW, N California, S California and creeping SA grids.

Both the Alaska and CONUS models consist of a main velocity grid that covers the full extent of the model, which both have a grid spacing of 0.25° in both latitude and longitude. In addition to the main grid, the CONUS model has four subsidiary grids with a finer grid spacing along the west coast where the tectonic activity is concentrated. These are the Pacific Northwest (PNW), Northern California (NC), and Southern California (SC), which all have a grid spacing of 0.0625°, and the Creeping San Andreas (CSA) with a grid spacing of 0.01°. The CSA grid covers the area where the section of the San Andreas Fault is creeping to the surface and thus produces a very sudden velocity change across the region when the fault is crossed.

4.3 Earthquake Grids

HTDP contains models for 28 earthquakes however only one of these, the 4 April 2010 Sierra El Mayor Earthquake occurred after the 2010 reference epoch of NAD83(CONUS) so this is the only Earthquake patch we have included in our CONUS deformation model. This patch is labelled SEM CS in Figure 2. In addition, the 2002 Denali (M=7.9) earthquake is still producing measurable post-seismic deformation so we have included a post seismic model in the Alaska deformation model.

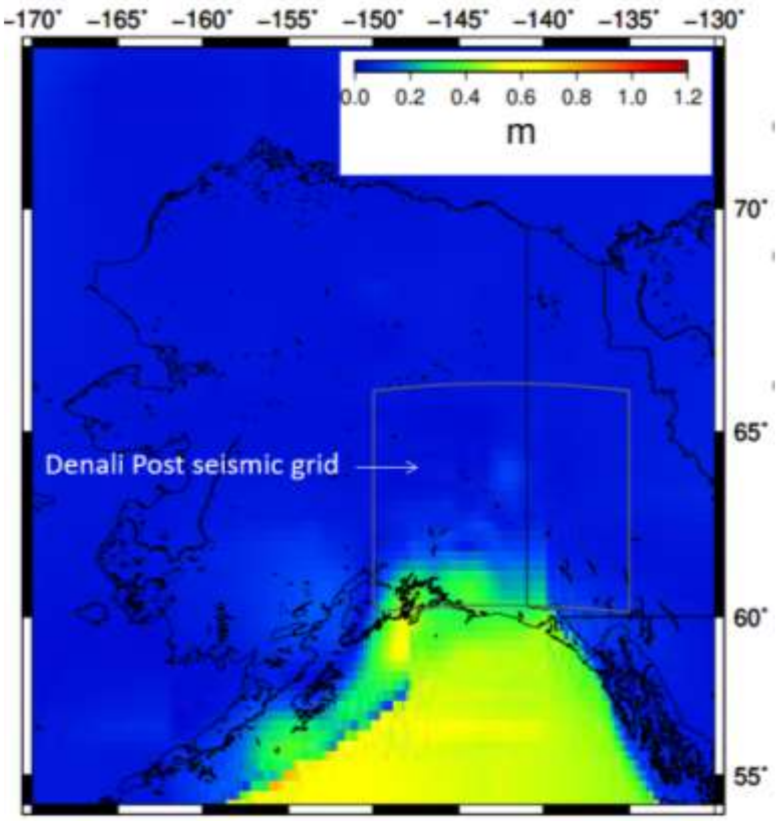

Figure 3 Predicted displacements 2019-2010 for Alaska in the NAD83 datum. The boundary of the Denali post-seismic grid is outlined in grey.

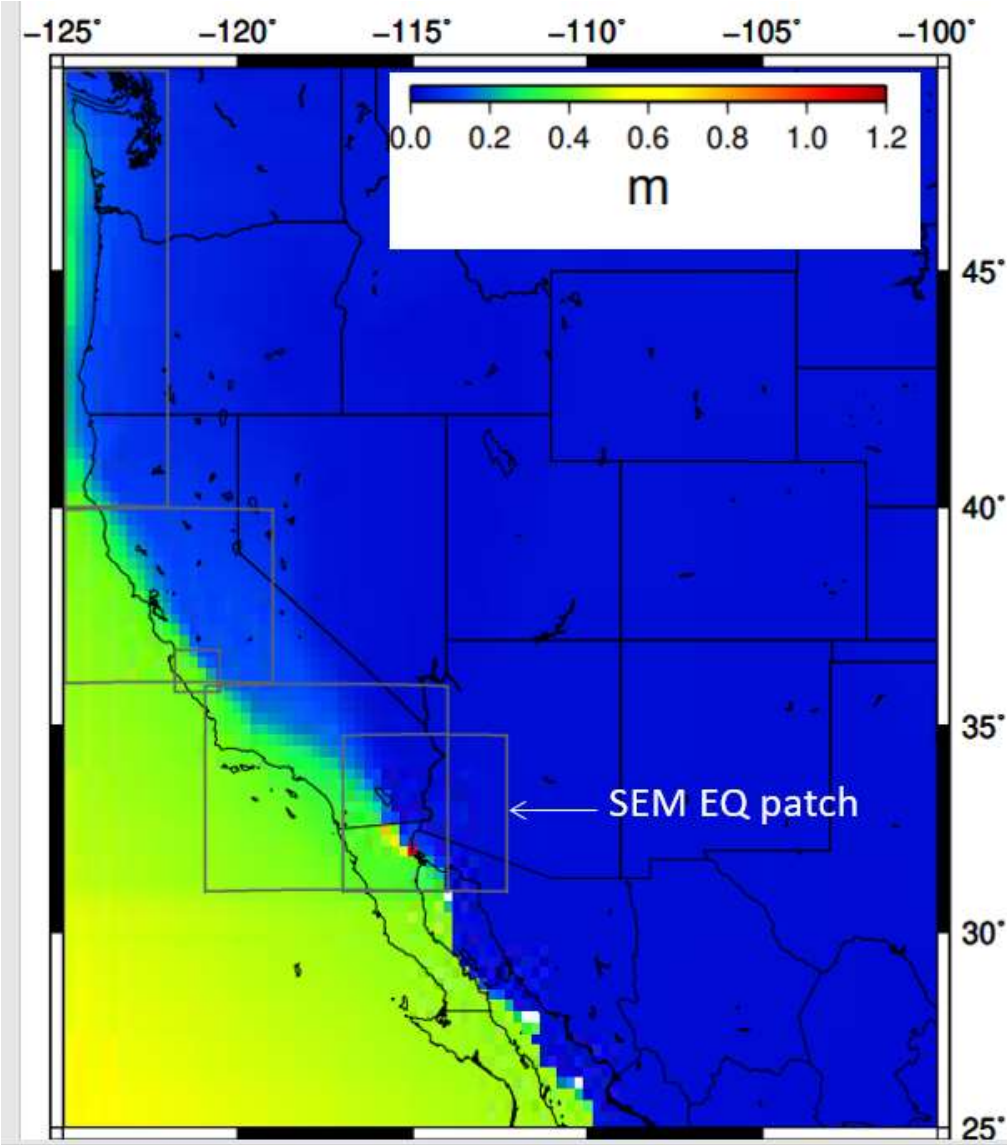

Figure 4 predicted displacements between 2010.0 and 2019.0 relative to NAD83. The boundaries of the velocity sub-grids and the Sierra El Mayor Earthquake patch are outlined in grey.

The figures above show the displacements that deformation models predict between 2010.0 and 2019.0 for Alaska () and CONUS (

). These represent the corrections that the Trimble Geodetic Libraries will apply to RTX coordinates for deformation between the epoch of measurement (2019.0) to the 2010.0 reference epoch of NAD83(2011). Clearly the significant distortions (>0.2m) are restricted to a narrow zone along the coast. In CONUS these are mostly in California and the large distortions of up to 1 m are caused by the 2010 Sierra El Mayor Earthquake.

5. TEST RESULTS OF TGL IMPLEMENTATION

We tested the TGL implementation by taking RINEX files for 68 GNSS stations in CONUS (see Figure 5). We submitted all of these files to OPUS and then extracted ITRF epoch of measurement (eom) and NAD83(2011). The ITRF coordinates were converted to NAD83 using the standard ITRF2014-NAD83 14-parameter transformation, and then corrected back to epoch 2010 using our implementation of the velocity and earthquake models in HTDP to get NAD83(2011) coordinates. We then compared the NAD83 coordinates derived from the ITRF2014 eom coordinates with those from HTDP, which we have treated as truth.

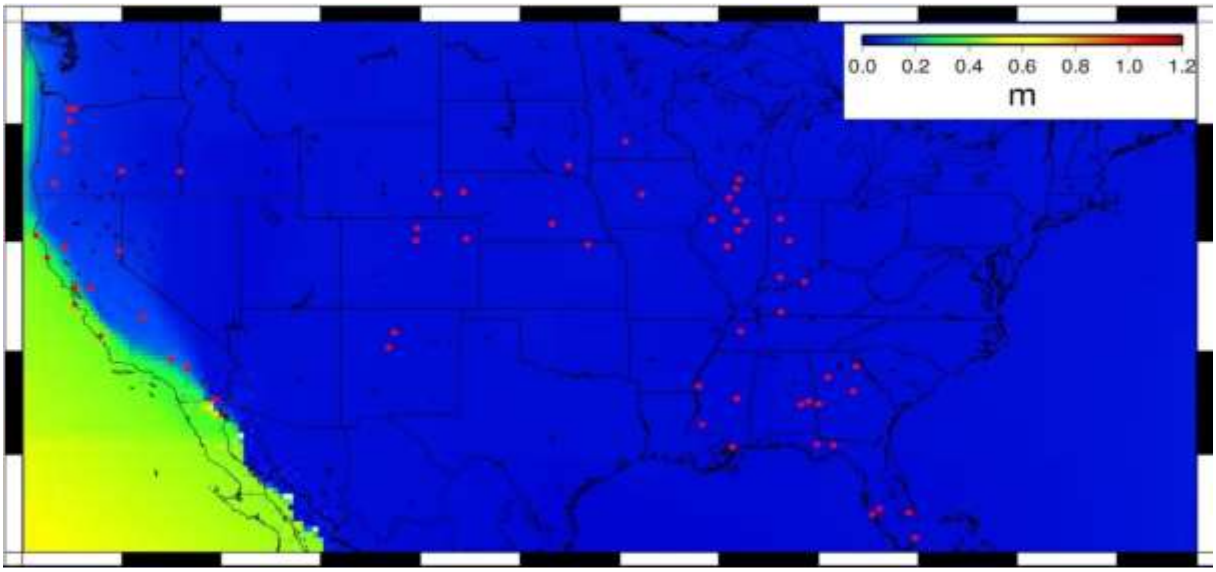

Figure 5 Location of test points shown by red dots. Color scale shows the total between 2010.0 and 2019.0 relative to NAD83.

By comparing our NAD83 coordinates with the NGS derived "truth" values we developed residuals in the e, n and u directions. The residuals are summarized in the following table

Table 1 residuals for test points in Figure 5

	e (m)	n (m)	u (m)
Max	0.0048	0.0015	0.0011
Min	-0.0037	-0.0007	-0.0010
mean	0.0002	0.0002	0.0000
st dev	0.0014	0.0005	0.0005

The implementation of the HTDP deformation models match the NGS values with a standard deviation of less than 1.5 mm in the e, n and up direction with the greatest residuals in the east direction.

Implementation of dynamic datums are critical for determining accurate RTX coordinates in tectonically active areas. As an example, consider EWEE, which is an NGS Continuously Operating Refence Station on Southern California. The table below shows the residuals between the RTX coordinates the EWEE coordinates in NAD83(2011) from the NGS datasheet and the NAD83(2011) coordinates derived from ITRF2014 epoch of measurement coordinates by applying the standard ITRF2014 to NAD83 14 parameter datum transformation. In the top line we have also applied the earthquake and velocity corrections from HTDP while in the second line, no such corrections have been applied. Clearly the application of the earthquake and velocity corrections results over in an order of magnitude improvement in the residuals and is the difference between 1 cm residuals that are adequate for high precision surveying applications and decimetre residuals that are not.

Table 2 residuals between RTX derived NAD83(2011) coordinates and those from the NGS datasheet (truth) showing the effect of applying the deformation model to correct for velocity earthquake shifts.

	e m	n m	u m
With Deformation model	0.011	0.007	0.008
no Deformation model	-0.168	0.218	-0.003

6. SUPPORT FOR DEFORMATIONS IN OTHER COUNTRIES

Deformation models are increasingly incorporated in national datums for countries located on the boundaries of tectonic plates. Currently Trimble supports deformation models for 14 countries:

Table 3

Country	Reference frame	Local displacement model
Brazil	SIRGAS2000	VEMOS2009 (Drewes and Heidbach 2012)
Canada	NAD83(CSRS)v7	CSRS Velocity Grid V7.0 (Craymer et al 2019)
Denmark	EUREF-DK94	NKG-RF03 (Häkli et al 2016)
Estonia	EST97	NKG-RF03 (Häkli et al 2016)
Finland	EUREF-FIN	NKG-RF03 (Häkli et al 2016 (Häkli et al 2016)

Iceland	ISN2016	ISN2016
Japan	JGD2011	JGD2011
South Korea	KGD2002	KGD2002
Latvia	LKS-92	NKG-RF03 (Häkli et al 2016)
Lithuania	EUREF-NKG-2003	NKG-RF03 (Häkli et al 2016)
New Zealand	NZGD2000	NZGD2000 Deformation Model (Crook et al 2016)
Norway	EUREF89	NKG-RF03 (Häkli et al 2016)
Sweden	SWEREF99	NKG-RF03 (Häkli et al 2016)
USA	NAD83(2011)	HTDP V3.2.9 (Snay et an 2013)

For most of these countries the deformation models only include a velocity grid. This includes the NKG-RF03 for the Nordic Countries, ISN2016 for Iceland, the CSRS Velocity Grid V7.0 for Canada and VEMOS2009 for Brazil. Two of the countries listed in Table 2 have deformation models that incorporate earthquakes. In the USA as described above, only one of the earthquakes occurred since 1 Jan 2010 (the reference epoch of NAD83(2011) and that is included as an earthquake patch. For New Zealand, the situation is more complex. New Zealand has had numerous earthquakes since 1 Jan 2000 (the reference epoch of NZGD2000) however the coordinates in NZGD2000 are retrospectively adjusted to correct for the earthquake shifts through a technique of reverse patches (Crook et al 2013), which means we do not need to apply earthquake patches for most of the New Zealand earthquakes in our implementation. As a result, we only have to implement eight grids associated with the post seismic effects of the M7.8 Kaikoura earthquake of 14 November 2016.

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BIOGRAPHICAL NOTES

Chris Pearson is a geodest with Trimble. He is an expert in datum transformations and least square adjustments and works internationally helping countries such as the Philippines. Nepal and Taiwan develop modernized geodetic datums. Prior to this, he worked for the US National geodetic Survey where he was responsible for the HTDP program. Chris is a member IAG WG 1.3.2 and the FIG working group on reference frames in practice. He is an honorary Member IL Prof Land Surveyors association and a member of the New Zealand Institute of Surveyors.

Sebastien Vielliard is a software engineer at Trimble. He 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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