Trimble's Support for Modernized Datums in Africa: Implementation of Semi-Dynamic Reference Frames

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Key words: Deformation measurement, Reference frames, Semi-dynamic datums, GNSS, Geodesy, Africa

SUMMARY

National coordinate reference systems in many African countries are often based on legacy classical datums (1950s–1990s) that contain significant geometric distortions and lack the temporal configuration necessary for modern Global Navigation Satellite System (GNSS) positioning. These datums typically assign static coordinates without providing models to correct for the continuous motion between the epoch of measurement (EOM) from GNSS and the static reference epoch of the datum. This discrepancy necessitates a shift towards semi-dynamic datums based on the International Terrestrial Reference Frame (ITRF), which require robust deformation models to account for crustal motion.

This paper reviews the implementation strategy of modernized African geodetic datums within the Trimble Geodetic Library (TGL). TGL supports four categories of deformation models, with two being most relevant to the African tectonic environment: the use of the absolute Euler Pole for stable tectonic plates (e.g., Nubia) and the implementation of a velocity grid for complex plate boundary zones (e.g., Nubia/Somalia). Case studies focusing on four countries—Ivory Coast (RGCI 2022), Nigeria (NGD2012), Tanzania (TAREF11), and South Africa (Hart94)—demonstrate the methodology. For Ivory Coast and Nigeria, the ITRF2014 Nubia pole was employed for crustal motion correction. For Tanzania, due to its location within the East African Rift System, a velocity grid was developed. The South Africa implementation involves a sequential transformation: a velocity model for EOM to ITRF2014@2018.18 and a subsequent datum grid for transformation to the official Hart94 system. Validation results demonstrate millimeter-level accuracy for the implemented transformations.

RESUME

Les systèmes nationaux de référence de coordonnées dans de nombreux pays africains sont souvent basés sur des systèmes géodésiques anciens (années 1950-1990) qui comportent des distorsions géométriques importantes et ne prennent pas en compte l'aspect temporel nécessaire au positionnement moderne par satellite (GNSS). Ces systèmes géodésiques attribuent généralement des coordonnées statiques sans fournir de modèles pour corriger le mouvement continu entre l'époque de la mesure GNSS et l'époque de référence du système de coordonnées. Cette divergence nécessite une transition vers des systèmes géodésiques semi-dynamiques basés sur le Repère International de Référence Terrestre (ITRF), avec des modèles de déformation robustes pour prendre en compte le mouvement crustal.

Cet article passe en revue les stratégies misent en œuvre pour le support de systèmes géodésiques africains modernisés au sein de la librairie géodésique de Trimble (En anglais TGL). La TGL prend en charge quatre catégories de modèles de déformation, dont deux sont particulièrement pertinentes pour l'environnement tectonique africain : l'utilisation du pôle d'Euler absolu pour les plaques tectoniques stables (par exemple, en Nubie) et la mise en œuvre d'une grille de vitesse pour les zones complexes à la frontière de deux plaques (par exemple, en Nubie/Somalie). Des études de cas axées sur quatre pays — la Côte d'Ivoire (RGCI 2022), le Nigeria (NGD2012), la Tanzanie (TAREF11) et l'Afrique du Sud (Hart94) démontrent cette méthodologie. Pour la Côte d'Ivoire et le Nigeria, le pôle Nubien de l'ITRF2014 a été utilisé pour la correction du mouvement crustal. Pour la Tanzanie, en raison de sa situation au sein du système du Rift Est-Africain, une grille de vitesse a été développée. La mise en œuvre pour l'Afrique du Sud implique une transformation séquentielle : un modèle de vitesse pour passer de l'époque de la mesure à l'époque de référence 2018.18 et une grille de conversion ultérieure pour transformer les coordonnées vers le système officiel Hart94. Les résultats démontrent une précision millimétrique pour les transformations mises en œuvre.

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INTRODUCTION

The International Terrestrial Reference Frame (ITRF) defines the position of points on the Earth's surface in a global system where coordinates are inherently time-dependent due to tectonic plate motions. GNSS satellite orbits, and consequently precise positioning services like Trimble RTX®, deliver point coordinates in the ITRF at the epoch of measurement (EOM). Conversely, many legacy national datums utilize static coordinates that ignore tectonic motion and may be determined using classical survey techniques that include significant distortions. These systems also may lack accurate transformations to the ITRF.

In order to provide static coordinates required by most users while still providing an accurate transformation path to the ITRF at epoch of measurement to support GNSS, modern semi-dynamic datums project each coordinate to its position at a common date called the reference epoch by modeling the displacements of the earth's surface due to tectonic motion. However, accurately modeling tectonic motion is a non-trivial task and failure to implement these models introduces significant errors over time, undermining the precision capabilities of modern GNSS technology. 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.

Trimble has significantly enhanced its geodetic software to automate this correction process through the implementation of support for semi-dynamic datums and displacement models.

Classification of displacement models

Trimble Geodetic Library (TGL) supports four broad categories of **displacement models** for translating coordinates from the EOM to the reference epoch:

1. Euler Pole Model: Crustal motion is derived by applying the absolute Euler Pole parameters for the relevant tectonic plate. This model is computationally simple and suitable for areas within a stable plate interior (e.g., ETRS89, Australia).
2. Velocity Field Model: Crustal motion is determined from a numerical velocity field (grid), allowing velocities to change spatially (secular motion). This is often used for areas affected by plate boundaries.

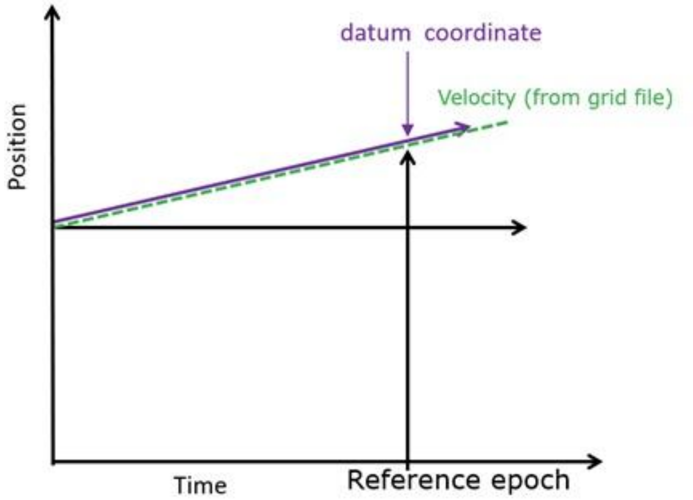

Figure 1 Displacement model with only a constant velocity

3. Full Displacement Model: A velocity field augmented with grids representing instantaneous earthquake displacement (co-seismic) and potentially post-seismic relaxation. This is essential for highly regions affected by earthquakes.

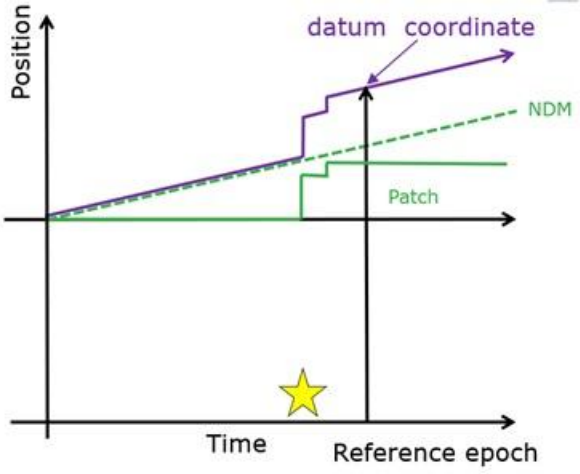

Figure 2 Schematic diagram of a dynamic datum. Dashed green line shows the secular velocity solid green line shows the co-seismic contribution to the displacement mode. The solid purple line shows the displacement model with both contributions combined.

4. Displacement Grid from Online Calculator: A constant displacement grid derived from an external online calculator, used as a temporary measure for systems like JGD2011.

Figure 3 shows the types of displacement models used by countries with semi-dynamic datums in TGL.

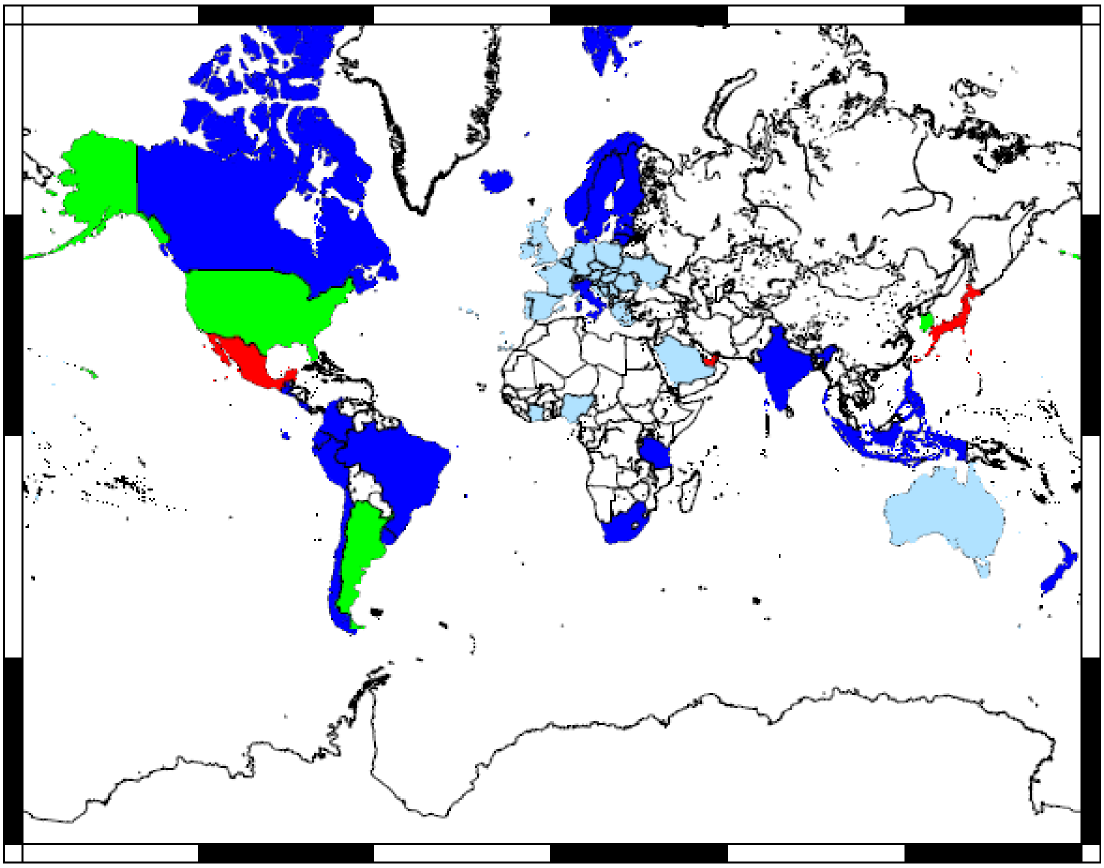

Figure 3 Map showing countries with Dynamic Datums. Countries in light blue model crustal motion using an Euler Pole. Countries in dark blue have a velocity grid. Countries in green use a full displacement model including a velocity model and earthquake grids and countries in red provide an online calculator, which we implement as a distortion grid.

For nearly all of Africa, the Euler Pole Model and the Velocity Field Model (Categories 1 and 2) are the most applicable, based on the continent's tectonic setting. The purpose of this paper is to review the technical strategy and implementation of modernized geodetic datums across Africa within Trimble software. We present case studies for four key countries—Ivory Coast, Nigeria, Tanzania, and South Africa—highlighting the specific deformation models chosen based on their respective tectonic environments.

SEMI-DYNAMIC DATUMS AND FUNCTIONAL MODELS

MODERN semi-dynamic datums provide a stable set of coordinates by projecting the position of a point at the EOM to a common reference epoch (Grant et al., 2014). This projection requires a model of crustal movement as shown in Equation 1.

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

Equation 1The General Displacement Equation to correct coordinates for tectonic motion between EOM and the reference epoch by implementing the functional models discussed above.

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 $\nu(\theta,\phi)$ is nonzero. In the case three, $\nu(\theta,\phi)$, $E(\theta,\phi)$ and potentially $P(\theta,\phi)$ are nonzero and in case four, only $d(\theta,\phi)$ 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.

TECTONIC ENVIRONMENT OF AFRICA

The African continent is dominated by the Nubia and Somalia tectonic plates, separated by the extensive East African Rift System (EARS), a complex divergent boundary that includes microplates like the Victoria and Rovuma plates (Saria et al., 2013). This environment dictates the necessary deformation model:

1. Stable Plate Interiors (Nubia/Somalia): Countries lying on the stable, undeforming parts of these plates (e.g., Ivory Coast, Nigeria, Angola) are best modeled using the absolute Euler Pole for the plate.
2. Plate Boundary Zones: Countries spanning or located near the complex plate boundary between the Nubia and Somalia plates such as Tanzania, require a spatially varying velocity grid.
3. Intracontinental Deformation: Regions affected by historical significant earthquakes such as the Atlas Mountains fold and thrust belt in Northern Morocco and Algeria, may require a velocity grid augmented with co-seismic patches.

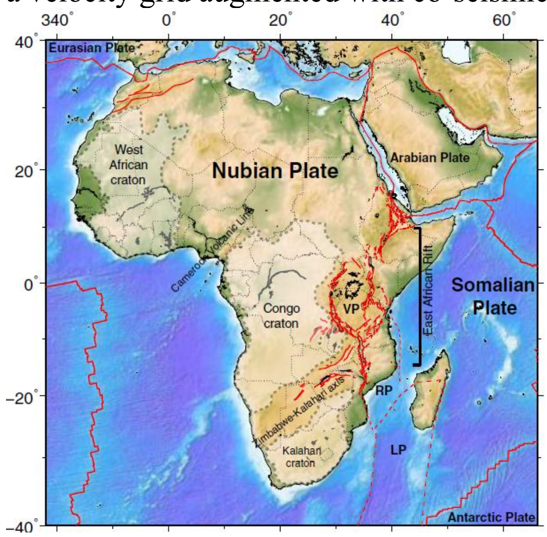

Figure 4 Tectonic environment of Africa from Saria et al (2013) VP referes to the Victoria micro plate and RP referes to the Rovuma micro plate.

CASE STUDIES FROM AFRICA

The following sections detail the TGL implementation for four African datums.

EXAMPLE RGCI 2022 FOR IVORY COAST

- **Datum Definition:** RGCI 2022 is equivalent to ITRF2014 at reference epoch 2010.0.
- **Tectonic Setting:** The Ivory Coast is situated entirely on the stable **Nubia Plate**.
- **Deformation Model:** The crustal motion correction from EOM to 2010.0 is applied using the **Nubia Plate Euler Pole** parameters derived from the ITRF2020 global plate motion model (Altamimi et al., 2023). This is a Category 1 implementation.
- **Validation:** In order to validate the deformation model, we used data from five station VRS network located near Abidjan. For each station, we had the RIGCI 2022 coordinates and a 24 hr data file (Pers. Com. Elias Solomey 2023). The location of the test points is shown in Figure 5 and a comparison of the RTX PPP coordinates transformed to RIGCI 2022 compared with truth coordinates from (Pers. Com. Elias Solomey 2023) is shown in Table 1. A comparison of transformed RTX Precise Point Positioning (PPP) coordinates with coordinates from a five-station VRS network near Abidjan yielded excellent results.

Table 1 summary of residuals for test points

	e m	n m	u m	combined m
RMS	0.0055	0.0081	0.006	0.0114
Max	0.0076	-0.0063	0.004	0.0146
Min	-0.0037	-0.0115	-0.011	0.0073
average	0.0034	-0.0078	-0.0036	0.0111

Figure 5 Location of test points for Ivory Coast.

EXAMPLE NIGERIA: NGD2012

- **Datum Definition:** NGD2012 is a geocentric datum equivalent to ITRF2008 at reference epoch 2012.0. It supersedes the classical Minna datum.
- **Tectonic Setting:** Nigeria is also located on a very stable part of the **Nubia Plate**.
- **Deformation Model:** The **Nubia Plate Euler Pole** (ITRF2020) was used to transform coordinates from EOM to the 2012.0 reference epoch.
- **Validation:** Transformation tests were conducted using four CORS stations. The transformed EOM coordinates (ITRF2020 to ITRF2008@2012.0) were compared to geodetic coordinates from the Nigerian Office of the Survey General (izuegbu pers com 2025) as test-points.

Figure 6 Location of test points for the eom to NGD2012 transformation

The RMS of the combined residual (less than 2 cm in the E, N and Up directions) further validates the use of the simple Euler Pole approach for stable West Africa.

Table 2 residual between the NGD2012 coordinate derived from RTX@eom and the ITRF2020 NU EPP and the truth coordinate

	e m	n m	u m	combined
RMS	0.0118	0.0039	0.0189	0.0226
Max	0.0146	0.0085	0.0355	0.0359
Min	0.0052	-0.0010	-0.0219	0.0140
average	0.0113	0.0019	0.0027	0.0209

EXAMPLE TANZANIA: TAREF11

- Datum Definition: TAREF11 is the official datum, equivalent to ITRF2014 at reference epoch 2011.0.

- Tectonic Setting: Tanzania lies directly within the complex Nubia/Somalia plate boundary zone, which includes the Victoria and Rovuma microplates. This region exhibits significant internal deformation.

- Deformation Model: Due to the complexity, a Velocity Grid was developed (Category 2). The grid was constrained using measured velocities (Saria et al., 2013; Morgan et al., 2018) augmented with Euler Pole estimations for data-sparse areas (Victoria, Rovuma and Nubia plates).

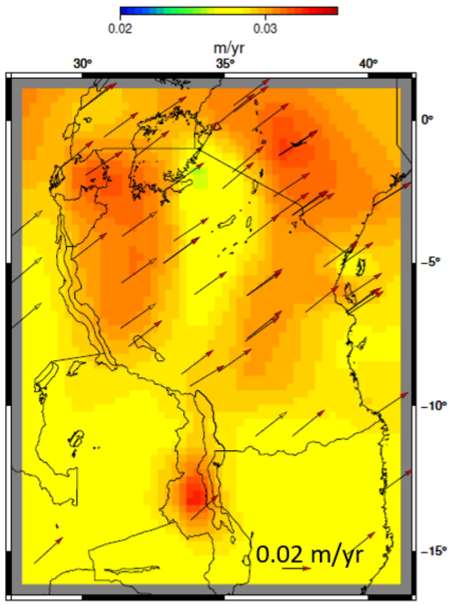

Figure 7 Velocity grid for Tanzania. Colors show the magnitude of the combined e n and u velocities in m. Areas outside the grid extents are shaded in grey. Velocity measurements are shown as vectors with red arrowheads and vectors calculated from Euler Poles have transperent arrowheads.

- Implementation: The velocity grid is used to transform ITRF EOM coordinates to the 2011.0 reference epoch.

- Validation: Authoritative TANZREF11 coordinates for eight test points were available from Morgan et al (2018). The corresponding RINEX files were downloaded from the AFREF Webserver (http://afrefdata.org/).

Table 3 comparison of TANZREF11 coordinates derived by applying the Tanzania velocity model compared to truth coordinates from Morgan et al (2018)

	e m	n m	u m	combined m
RMS	0.0066	0.0077	0.020	0.0226
Max	0.0145	0.0144	0.033	0.0334
Min	0.0000	-0.0088	-0.006	0.0067
average	0.0040	0.0016	0.0131	0.0206

EXAMPLE ITRF2014 and HART94 in South Africa

The South African implementation requires a two-step transformation due to the country's official datum (Hart94) being non-ITRF based, while its modern GNSS infrastructure (TRIGNET VRS) provides ITRF coordinates.

Step 1: EOM to ITRF2014@2018.18 (Time-Dependent Correction)

- **Tectonic Setting:** South Africa is affected by the Nubia-Somalia plate boundary, though it is tectonically more stable than East Africa.
- **Deformation Model:** A **Velocity Grid** was developed (Category 2) based on 45 station velocities from the TrigNet network (Malservisi et al., 2013) to transform RTX EOM coordinates to the standard reference epoch of 2018. (see Figure 8)

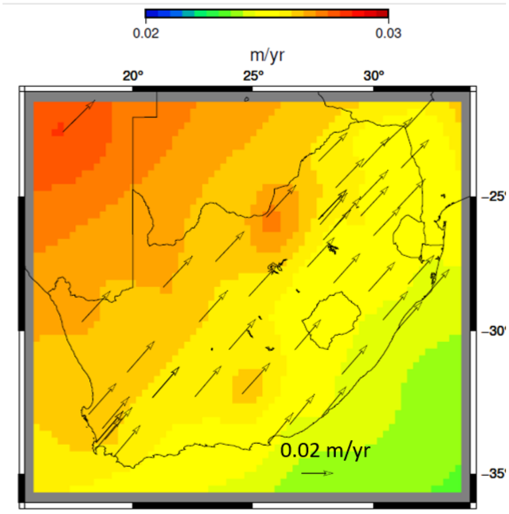

Figure 8 Velocity grid for South Africa. Colors show the magintude of the combined e n and u velocities in m. Areas outside the grid extents are shaded in grey. Velocity measurements used to constrain the grid are shown as vectors.

- **Validation (Step 1):** Comparison of the transformed coordinates with official TRIGNET ITRF2014@2018.18 coordinates showed mm level agreement in the E and Nth components and cm level agreement in the vertical (see Table 4).

Table 4 Comparison of ITRF2018.81 coordinates derived by applying the SA_vel model compared to truth coordinates from National geo-spatial information of South Africa.

10	e m	n m	u m
RMS	0.0047	0.0050	0.0144
Max	0.0139	0.0027	0.0210
Min	-0.0033	-0.0074	-0.0060

average	0.0021	-0.0039	0.0116

Step 2: ITRF2014@2018.18 to Hart94 (Static Datum Transformation)

- **Hart94 Definition:** Hartebeesthoek94 (Hart94) is the official datum, related to the older physical origin at the Hartebeesthoek Radio Astronomy Observatory.
- **Transformation Method:** To achieve the required accuracy, a high-resolution **Datum Grid** was developed by differencing ITRF2014@2018.18 and Hart94 coordinates from the TRIGNET network.
- **Validation (Step 2):** The datum grid transformation was validated, showing a significant improvement over the decimeter-level accuracy of the official definition transformation.
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- *Table 5 residual between the HART94 coordinate derived from the datum grid model and the truth coordinate from the TRIGNET website*

	e m	n m
RMS	0.0053	0.0086
Max	0.0067	0.0069
Min	0.0063	0.0073
average	0.0032	-0.0044

CONCLUSIONS AND RECOMMENDATIONS

The transition to modernized, semi-dynamic datums is critical for leveraging the full accuracy of modern GNSS-based positioning in Africa. Trimble's successful implementation of time-dependent datum transformations and deformation models within the TGL, following standards similar to those developed by Land Information New Zealand, significantly reduces transformation errors from ITRF/WGS84 EOM coordinates to national datums with fixed reference epochs.

Key Findings:

- For the **stable tectonic interiors** of Africa (e.g., Ivory Coast, Nigeria), the simple **Euler Pole** model provides sufficient accuracy for crustal motion correction.
- For countries affected by the **Nubia-Somalia plate boundary** (e.g., Tanzania, South Africa), the implementation of a spatially varying **Velocity Grid** is necessary.

- The implementation for South Africa demonstrates the necessity of a two-stage approach—crustal motion correction followed by a highly accurate **Datum Grid**—to link modern ITRF systems to legacy static datums.

Recommendations:

1. **National Agencies** are strongly encouraged to upgrade their reference systems to modern ITRF-based semi-dynamic datums that explicitly incorporate displacement models to correct for crustal motion, thus supporting the growing use of precise point positioning techniques.
2. The development of accurate **Datum Grids** remains crucial for bridging the gap between modern ITRF coordinates and the prevalent classical datums of the 1950s–1990s era in Africa.
3. We support the adoption of international standards (such as OGC's draft standards on GGXF) to facilitate the seamless integration of future displacement models into vendor software.

FUTURE PLANS

Future work will focus on expanding TGL support for more national datums across Africa and the developing world. We also plan to integrate estimates of uncertainty into displacement models where available and provide advanced tools for users to visualize the velocity and earthquake displacement fields.

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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, Trimble Distinguished Engineer

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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