Trimble's support for modernized datums in Africa

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

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.

The purpose of this paper is to review how Trimble intends to support modernized geodetic datums in Africa. As examples, we will focus on three countries that have modernized datums supported in Trimble Geodetic Library (TGL): Ivory Coast, Tanzania and South Africa. The Ivory Coast's datum is RGCI 2022, equivalent to ITRF2014 at epoch 2010.0. Since Ivory Coast lies on the stable Nubia plate, we used the ITRF2014 Nubia pole as the deformation model. In Tanzania, TAREF11, which is equivalent to ITRF2014 @ 2011.0, is the official datum. Since Tanzania lies over the East African Rift system, we implemented a velocity grid to correct coordinates to transform RTX coordinates from eom to epoch 2011.0. In South Africa, the TRIGNET VRS gives coordinates in ITRF2014@2018.18. However, the official coordinate system for South Africa is the Hartebeesthoek94 or Hart94 system. Therefore, there are two transformations that TGL has to support. Since South Africa is affected by the Nubia Somalia plate boundary, we implemented a velocity model to transform RTX coordinates from eom to epoch 2018.18 and then we apply a datum grid to transform coordinates from ITRF2014 epoch 2018.18 to Hart94.

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. Le but de cet article est d'examiner comment Trimble entend prendre en charge les référentiels géodésiques modernisés en Afrique. À titre d'exemples, nous nous concentrerons sur trois pays dont les référentiels modernisés sont déjà pris en charge par la librairie géodésique de Trimble: la Côte d'Ivoire, la Tanzanie et l'Afrique du Sud. Le système de référence de la Côte d'Ivoire est le RGCI 2022, équivalent à l'ITRF2014 à l'époque 2010.0. La Côte d'Ivoire étant située sur la plaque Nubienne stable, nous avons utilisé la vitesse de rotation ITRF2014 de la plaque Nubienne, autour de son pôle d'Euler, comme modèle de déformation. En Tanzanie, TAREF11, qui équivaut à ITRF2014 @ 2011.0, est le référentiel officiel. Étant donné que la Tanzanie se situe au-dessus du système du Rift est-africain, nous avons mis en œuvre une grille de vitesse pour corriger les coordonnées. Nous utilisons cette grille de vitesse pour transformer les coordonnées RTX de l'époque de la mesure à l'époque de référence 2011.0. En Afrique du Sud le TRIGNET VRS donne les coordonnées ITRF2014 à l 'époque 2018.18. Cependant, le système de coordonnées officiel de l'Afrique du Sud est le système Hartebeesthoek94 ou Hart94. Notre librairie doit donc prendre en charge deux transformations. Étant donné que l'Afrique du Sud est affectée par la frontière entre les plaques Nubienne et Somalienne, nous avons mis en œuvre un modèle de vitesse pour transformer les coordonnées RTX de l'époque de la mesure à l'époque 2018.18. Ensuite nous utilisons une grille d'offsets pour transformer les coordonnées ITRF2014 à l'époque 2018.18 en coordonnées Hart94.

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Support for dynamic datums in Trimble software

Christopher PEARSON, USA and Sebastien VIELLIARD, France

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 Africa. As examples, we will focus on three countries that have modernized datums supported in TGL: Ivory Coast, Tanzania and South Africa.
The Ivory Coast's datum is RGCI 2022, equivalent to ITRF2014 at epoch 2010.0. Since Ivory Coast lies on the stable Nubia plate, we used the ITRF2014 Nubia pole as the deformation model. In South Africa, the TRIGNET VRS gives coordinates in ITRF2014@2018.18. However, the official coordinate system for South Africa is the Hartebeesthoek94 or Hart94 system. Therefore, there are two transformations that TGL has to support. Since South Africa is affected by the Nubia Somalia plate boundary, we implemented a velocity model to transform RTX coordinates from eom to epoch 2018.18 and then we apply a datum grid to transform coordinates from ITRF2014 epoch 2018.18 to Hart94. In Tanzania, TAREF11 is the official datum. It is equivalent to ITRF2014 @ 2011.0. While TGL already supports ITRF2014, supporting the datum transformation is quite easy but we need displacement model to transform RTX coordinates from eom to epoch 2011.0. Since Tanzania is located on a part of the Nubia Somalia plate boundary that is complicated by several microplates, we implemented a velocity grid as a deformation model.

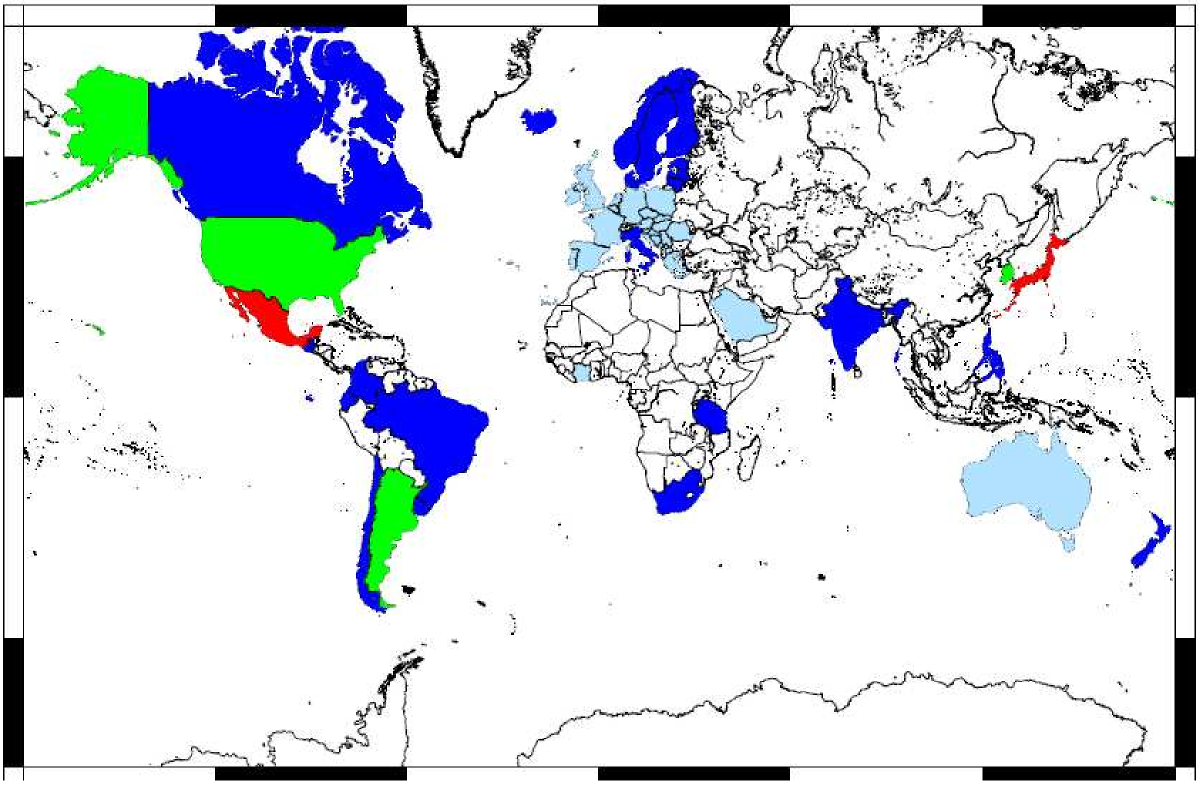

Figure 1 Map showing countries with Dynamic Datums. Countries in light blue model crustal motion using an Euler Pole. Countries in dark blue have a velocity grid. Countries in green use a full displacement model including a velocity model and earthquake grids and countries in red provide an online calculator, 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 et 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 be given either 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.

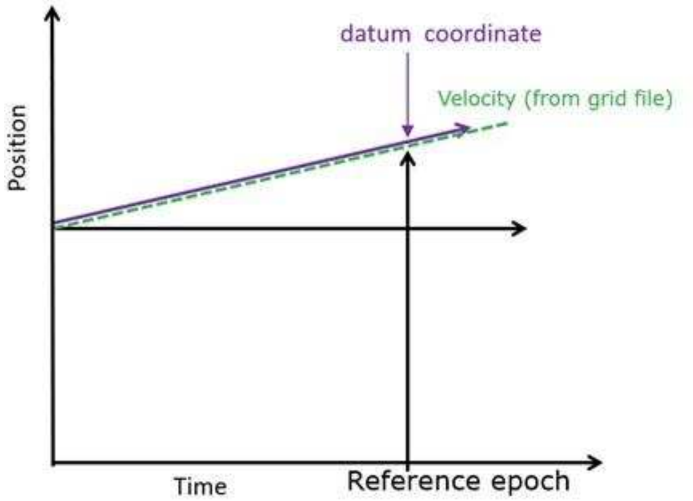

Figure 2 Displacement model with only a constant velocity

- 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.

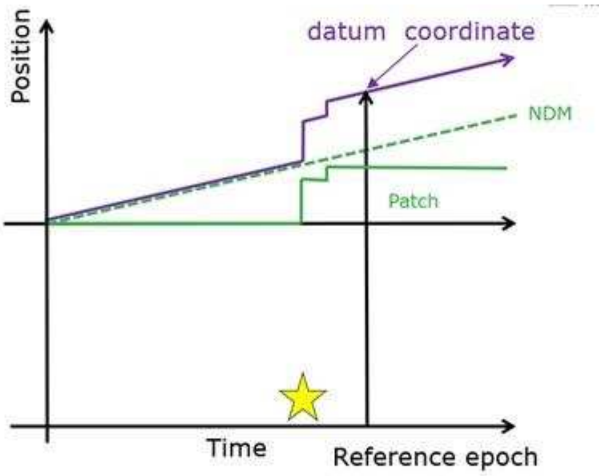

Figure 3 Schematic diagram of a dynamic datum. Dashed green line shows the secular velocity solid green line shows the co-seismic contribution to the displacement mode. The solid purple line shows the displacement model with both contributions combined.

- 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. 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.

3. Tectonic environment of Africa

The Trimble Geodetic Library (TGL) supports four types of deformation models. However, for nearly all of Africa, only three are relevant to our customers.

1. For countries that are located in one stable tectonic plate, the horizontal velocity is determined by applying the absolute Euler Pole for the plate in question. This is used in areas overlying the stable Nubia and Somalia plates. The Nubia plate includes all of the countries of the Eastern Africa region plus the Central African Republic, Democratic Republic of the Congo, Republic of the Congo, Gabon, Angola, Namibia, Botswana, Algeria, Morocco and Egypt. The stable Somalia Plate includes Somalia and most of Kenya.
2. For countries in west Africa effected by the Nubia/Somalia plate boundary not effected by earthquakes the velocity is interpolated from a velocity grid.
3. For countries in northern Africa containing the intracontinental Atlas Mountains fold and thrust belt which have been affected significant earthquakes a velocity grid augmented with patches representing co-seismic displacement may be appropriate. This may be applicable to regions that have had large earthquakes and distributed deformation, particularly northern Morocco and Algeria.

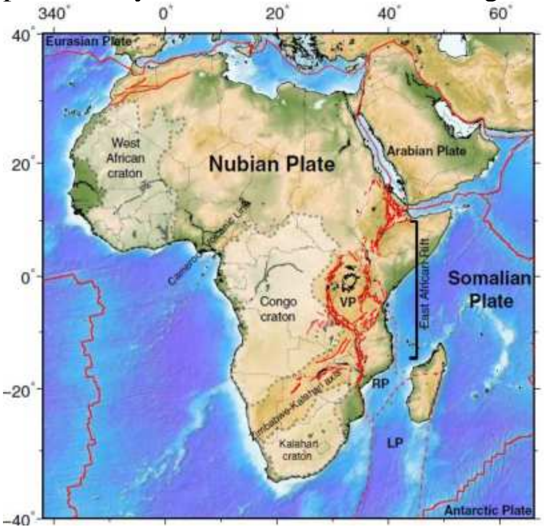

Figure 4 Tectonic environment of Africa from Saria et al (2013) VP refers to the Victoria micro plate and RP referes to the Rovuma micro plate.

4. EXAMPLE RGCI 2022 for Ivory Coast

The national datum for the Ivory Coast is RGCI 2022, which is equivalent to ITRF2014 at epoch 2010.0. In order to implement the datum, we need a method to project coordinates to epoch 2010. However, the Ivory Coast is located in the stable part of the Nubia plate, which

means that obvious way to support time projection requirement is to use the ITRF2014 Numbia pole.
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.

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.

5. EXAMPLE ITRF2014 and HART94 in South Africa

In South Africa the TRIGNET VRS gives coordinates in ITRF2014@2018.18. However, the official coordinate system for South Africa is the Hartebeesthoek94 or Hart94 system. Therefore, there are two transformations required to support South Africa in TGL. First, we transform coordinates from ITRF2014 epoch of measurement (eom) to ITRF2014@2018.18 and then we apply a datum grid to transform coordinates from ITRF2014 epoch 2018.18 to Hart94.

1. **Transformation from epoch of measurement to 2018.18**

Since South Africa is affected by the Nubia Somalia plate boundary, we implemented a velocity model to transform RTX coordinates from eom to epoch 2018.18. For this transformation, we decided to use a velocity grid as the deformation model. South Africa is relatively stable tectonically with most of the country lying on the Kalahari Craton, however the East African rift system extends near the eastern boundary of South Africa. In addition, Malservisi et al (2013) shows evidence of significant tectonic strain in both eastern and western South Africa. Fortunately, Malservisi et al (2013) includes velocities for 45 Trignet stations, which are evenly distributed over the country, which provide a good basis to develop a velocity model. We developed a velocity grid from these using the GMT utility with a grid spacing of 4 points/degree (Figure 6).

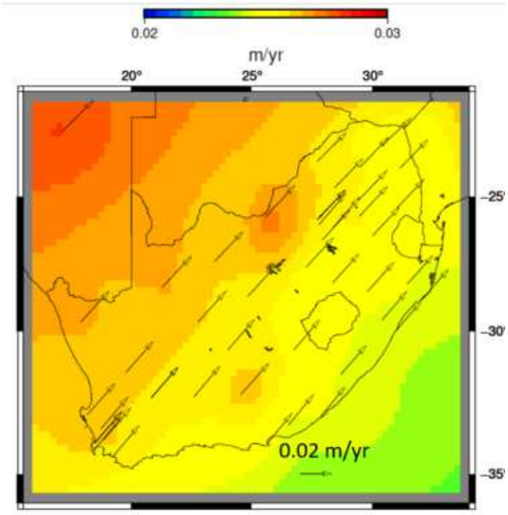

Figure 6 Velocity grid for South Africa. Colors show the magintude of the combined e n and u velocities in m. Areas outside the grid extents are shaded in grey. Velocity measurements used to constrain the grid are shown as vectors.

Since velocities are aligned to the ITRF2005 reference frame and the RTX coordinates are in ITRF2014, coordinates must be transformed to ITRF2005 before the eom to epoch 2018.18 correction can be applied and then transformed to ITRF2014@2018.18. We tested this transformation using twelve Trignet stations as test points. For each test point downloaded a 24 hr RINEX file, all for 1 Jan 2023. Each of these was sent to RTX_PP at https://www.trimblertx.com/ to generate epoch of measurement coordinates. The test point locations are shown in Figure 5. The coordinates were then converted to 2018.18 using the Malservisi et al 2013 velocity model. I then compared these to the official coordinates from the National Geo-spatial Information of South Africa. These are available on ftp.trignet.co.za /Station Information/ /Station Information/ITRF 2014 Epoch 2018.18. The comparison between the calculated and official coordinates are summarized in Table 2.

Table 2 residual between the ITRF2014 coordinate @ epoch 2018.18 derived from the SA velocity model and the truth coordinate from the TRIGNET website

	e m	n m	u m
RMS	0.0045	0.0049	0.014
Max	0.0139	0.0027	0.021
Min	-0.0033	-0.0074	-0.006
average	0.0019	-0.0040	0.0116

Figure 7Map showing TRIGNET stations used to determine both the velocity and datum grids. Red dots were used as test points.while both the blue and red dots were used to constrain the grids.

2. **ITRF2014@2018.18_2_Hart94**

Hart94 is the official datum for South Africa. In order to allow TrigNet and VRS users to develop accurate Hart94 coordinates we need a method to transform from ITRF2014 epoch 2018.18 to Hart94. There are two methods for transforming ITRF2014 epoch 2018.18 to Hart94. The first is based on the definition of Hart94 as coincident with ITRF91 at 1994.0 (https://ngi.dalrrd.gov.za/index.php/technical-information/geodesy-and-gps/datum-s-and-coordinate-systems). We tested this transformation using the 12 test points shown in Figure 7. The results indicate that the transformation is accurate to about a decimeter.
The size of the residuals is not unexpected given the age of the Hart94 datum and the fact that the datum has a physical origin at the Hartebeesthoek Radio Astronomy Observatory Telescope. Indeed, Parker (2011) shows that the standard deviations in north and east are of

6cm and 7cm in good agreement with our results. We were able to develop a datum grid for this transformation by differencing the ITRF2014 epoch 2018.18 and Hart94 coordinates for the same TRIGNET stations used in the velocity study and then gridding them using the same 4 point per degree spacing used above. A test of the transformation using the datum grid using the 12 test points shown in Figure 7 is summarized in Table 3. Clearly, the result is a much more accurate (mm-level) transformation.

Table 3 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

6. Tanzania

We are currently finalizing support for the TAREF11 datum in TGL. Since TAREF11 is equivalent to ITRF2014 @ 2011.0 this will require a displacement model to correct coordinates from eom to epoch 2011.0. However, Tanzania lies in a complex plate boundary zone between the Nubia and Somalia plates. As shown in Figure 4, the plate boundary, which follows the east Africa rift is complex and involves two microplates; the Victoria Plate and the Rovuma Plates. Because of this complexity, the displacement model for Tanzania requires velocity grid rather than a simple Euler Pole.

We developed the velocity grid for Tanzania by combining measured velocities from Sara et al (2013) and Morgan et al (2018). Generally, the measured velocities cover the territory of Tanzania reasonably well, however a small data gap is apparent in western Tanzania southeast of Burundi and southern Tanzania on the Mozambique border. We filled these in using velocities estimated using Euler poles for the Victoria Plate and the Rovuma Plate. We also included three velocities estimated using the Nubian plate in western Congo and four points in the Indian Ocean estimated using the Somalia plate. We used the Euler poles from Sara et al (2013) for all these calculations. We used an identical gridding program as with the South Africa case. The vectors and velocity grid is shown in Figure 8 .

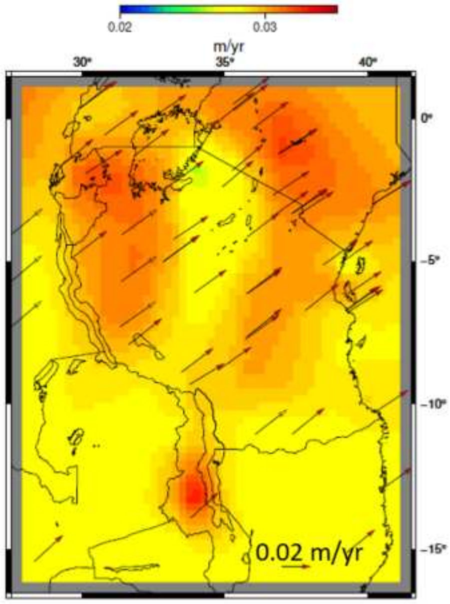

Figure 8 Figure 6 Velocity grid for Tanzania. Colors show the magintude of the combined e n and u velocities in m. Areas outside the grid extents are shaded in grey. Velocity measurements are shown as vectors with red arrowheads and vectors calculated from Euler Poles have transperant arrowheads.

7. 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 three in Africa. 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 Africa, because of the tectonic environment, most countries will be able to use a simple deformation model based on the Euler Pole for the Nubia plate however those located on the Nubia-Somalia plate boundary or regions that have had large earthquakes and distributed deformation, particularly northern Morocco and Algeria, more complex models may be required.

Also, because of the prevalence of classical datums from the 1950-1990's in Africa, the use of modern GNSS based technology will depend on the development of datum grids to transform ITRF eom coordinates into the appropriate national system. In the case of South Africa, we were able to develop a datum grid that seems to transformations at the cm level but this may be difficult in other countries, particularly where the national datum dates from the 1950-1970 era. For this reason, we recommend modern ITRF based datums supported by a national CORS network.

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`

8. FUTURE PLANS

In future, we hope to expand the number of national datums that TGL supports with a special emphasis on Africa and the developing world. 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. We also plan to integrate Trimble Geodetic Libraries in Trimble VRS.

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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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