PERFORMANCE OF BURSA-WOLF MODEL FOR DEFORMING REGION: CASE STUDY IN MALAYSIA

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ABSTRACT

Bursa-Wolf model is a common mathematical approach for coordinate transformation practice between two reference frames. For the case of deforming region, the existing reference frame has been experiencing a non-linear shifting over the time due to co-seismic and post seismic occurrences. Imprecise coordinate in the reference frame definition could degrading critical positioning, surveying, and navigation activities. This require a new realization of reference frame and the coordinate transformation linkage is suggested to be developed in relating the new and existing reference frame. This study provides performance of Bursa-Wolf model as coordinate transformation approach for a deforming region that is experiencing non-linear shifting due to the co-seismic and post-seismic events. TLhe Bursa-Wolf were generated from 32 dependent Global Positioning System (GPS) Continuously Operating Reference Stations (CORS) in Malaysia meanwhile another 20 independent neighbouring stations were utilized for assessment purposes. Seven parameters (7p) of Bursa-Wolf were estimated with RMS at ±4.5mm, ±9.2mm and ±2.1mm respectively. The independent stations were classified as internal and external assessment station and the root mean square (RMS) were found at less than 10mm. The internal station has depicted a better RMS in each component which are ±5.1mm, ±6.5mm and ±1.5mm respectively. Meanwhile for external stations RMS in each component are ±6.1mm, ±8.7mm and ±3.5mm respectively. The result shows that Bursa-Wolf model is sufficient to be used as coordinate transformation approach for deforming region.

1. INTRODUCTION

Cartesian coordinate transformations in three-dimensional (3D) space are commonly used in surveying, photogrammetry and geodesy (Păun et al., 2017; Zeng et al; 2020). They are also called similarity of mathematical relationships between points in two different 3D coordinate systems (Tao et al., 2020). The process involved similarity parameter estimation consists of translation, rotation and scale (Gao et al., 2017; Amiri et al., 2018).

Deforming regions such as Indonesia, New Zealand, and Malaysia, are facing a significant coordinate shifting over the time due to continuous tectonic displacement (Blick et al., 2010; Shariff et al., 2017; Syetiawan et al., 2019). The series of great earthquakes since 2004 have significantly affected the Sundaland plate velocity field (Yong et al., 2017). Hill et al (2015) also found that the *Mw* 8.6 Wharton Basin event caused many different faults ruptured as the static displacement of this event were up to 22cm. This situation causes datum alignment between national and global reference frame thus degrading its compatibility with satellite-based positioning. A new realization of reference frame is necessary, and the coordinate transformation linkage is suggested to be developed to relate the new and existing reference frame for surveying and mapping purposes (Banko et al., 2020).

Malaysia is situated outside the Sunda ring of fire (Mustafar et al., 2017). The region comprises of two (2) mainlands; Peninsular Malaysia and Northern Borneo, both are being affected by major earthquakes in Western belt of Sunda (Tongkul, 2017; Nazaruddin et al., 2021). Aris et al (2016) found that a continuous post-seismic deformation at 39cm/year in Peninsular Malaysia due to 2004 Sumatra Andaman (9.2Mw), 2005 Nias Simeulue (8.5Mw), 2007 Bengkulu (7.9Mw) and 2012 Indian Ocean (8.6Mw). Due to this circumstance, a new realization of reference frame in Malaysia with semi-kinematic datum approach was suggested by considering the secular and non-secular deformation (Azhari et al, 2020). Failing to account for this effect can introduce velocity error up to 0.5mm/yr (Tregoning et al., 2013). Thus, performance of coordinate transformation is necessary to be understood in relating the new and existing reference frame.

Bursa-wolf model is one of practical mathematical approach for coordinate transformation and have been used widely for geodetic reference frame in deforming regions (Syetiawan et al., 2019; Abbey et al., 2020). One important characteristic feature of this model is that the shape of the geodetic network containing the coordinates to be transformed is preserved, hence angles are not altered after transformation, but the coordinate difference between the transformed coordinates and their original positions could be changed (Ziggah et al., 2019). This coordinate difference needs to be understood in order to investigate the performance of Bursa-Wolf model.

This study provides performance of Bursa-Wolf model as coordinate transformation approach for a deforming region. The experimental work utilised geodetic network in Malaysia, a region that is experiencing non-linear shifting due to the co-seismic and post-seismic events (Azhari et al, 2020; Aris et al., 2016). The first reference frame is Geodetic Datum of Malaysia 2000 (GDM2000) which is the standard geodetic datum for the country (Azhari et al, 2020). Meanwhile, the second reference frame is based on self-realization in International Terrestrial Reference Frame 2014 (ITRF2014@2018.0) at similar geodetic framework. It is worth to mention that the results and analysis is mainly for experimental purposes only.

This paper is divided in four (4) sections. Section 2 describes the methodology, mathematical concept as well as assessment approach. Result and analyses are discussed in Section 3. Finally, concluding remarks is drawn in Section 4.

2. METHODOLOGY

Figure 1 shows general flow-chart of the work that comprises of three (3) process which are; coordinate transformation parameter estimations based on Bursa-wolf model, coordinate transformation application, and finally assessment of the coordinate difference. The following sub-sections explain each process in detail.
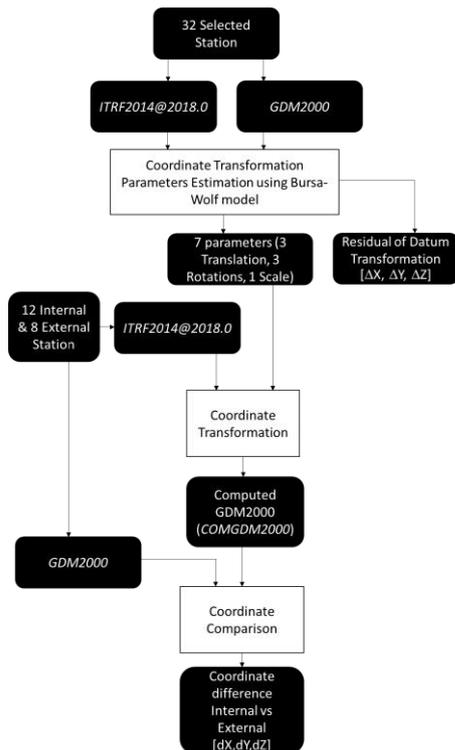

Figure 1. General flow-chart of methodology.

2.1 DISTRIBUTION OF THE GEODETIC NETWORK

This transformation process utilised set of coordinates (GDM2000 and ITRF2014@2018.0) from geodetic network of GPS CORS Malaysia Real-Time Kinematic network (MyRTKnet). Thirty-two (32) of them as shown in Figure 2 were treated as dependent stations. These stations were used for the 7p estimations thus creating a network of Bursa-Wolf model. Meanwhile, another twenty (20) GPS CORS as shown in Figure 3 were treated as independent station for coordinate residual calculation during assessment stage. Noted that these twelve (12) and eight (8) independent stations were situated within internal and external network of the Bursa-Wolf model, respectively.
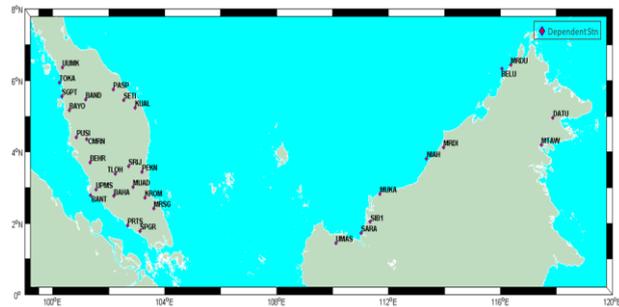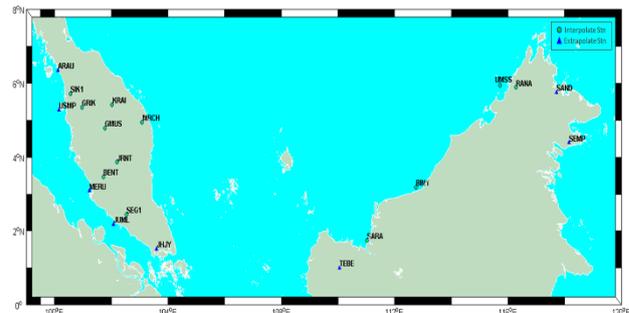

Figure 2. Dependent Stations.

Figure 3. Independent Station.

2.2 COORDINATE TRANSFORMATION PARAMETER ESTIMATIONS BASED ON BURSA-WOLF MODEL

The Bursa-Wolf model provides a mathematical formula for transformation between two reference frames in 3D Cartesian coordinate system by using 7p. The 7p comprise of three datum translations on X-axis, Y-axis and Z-axis (tX, tY, tZ), three rotations (R_X, R_Y, R_Z), and one scale factor ($1 + \Delta s$). Equation (1) shows the Bursa-Wolf model with the 7p as given by Deikan (2006);

$$\begin{bmatrix} X_{GDM2000} \\ Y_{GDM2000} \\ Z_{GDM2000} \end{bmatrix} = \begin{bmatrix} tX \\ tY \\ tZ \end{bmatrix} + \begin{bmatrix} 1+\Delta s & R_z & -R_Y \\ -R_z & 1+\Delta s & R_X \\ R_Y & -R_X & 1+\Delta s \end{bmatrix} \begin{bmatrix} X_{ITRF2014} \\ Y_{ITRF2014} \\ Z_{ITRF2014} \end{bmatrix} \quad (1)$$

Where $X_{GDM2000}, Y_{GDM2000}, Z_{GDm2000}$ is the Cartesian coordinates in *GDM2000* and $X_{ITRF2014}, Y_{ITRF2014}, Z_{ITRF2014}$ is the Cartesian coordinates in *ITRF2014@2018.0*. The 7p in Equation (1) can be estimated by using the inverse transformation approach as in Equation (2).

$$\begin{bmatrix} X_{GDM2000} \\ Y_{GDM2000} \\ Z_{GDM2000} \end{bmatrix} = + \frac{R^{-1}}{(1+S)} \left[\begin{bmatrix} X_{ITRF2014} \\ Y_{ITRF2014} \\ Z_{ITRF2014} \end{bmatrix} - \begin{bmatrix} tX \\ tY \\ tZ \end{bmatrix} \right] \quad (2)$$

The accuracy, S of estimated 7p Bursa-Wolf model in term of Root-Mean-Square-error (RMS), can be computed as shown on Equation (3) and (4).

$$S = (A^T P A)^{-1} . \hat{\sigma} \quad (3)$$
$$\hat{\sigma} = \sum (V^T P V)/r \quad (4)$$

Where $(A^T P A)^{-1}$ is designed matrix from Equation [1], V is coordinate residual at dependent stations, P is weighted matrix and r is number of dependent stations.

2.3 COORDINATE TRANSFORMATION AT INDEPENDENT STATION

Coordinate transformation by using the Bursa-Wolf 7p will be applied at both internal and external independent stations. The equation can be expressed as follow;

$$
\begin{bmatrix} X_{COMGDM2000} \\ Y_{COMGDM2000} \\ Z_{COMGDM2000} \end{bmatrix} = \begin{bmatrix} tX \\ tY \\ tZ \end{bmatrix} +
$$
$$
\begin{bmatrix} 1+\Delta s & R_z & -R_Y \\ -R_z & 1+\Delta s & R_X \\ R_Y & -R_X & 1+\Delta s \end{bmatrix} \begin{bmatrix} X_{GDM2000} \\ Y_{GDM2000} \\ Z_{GDM2000} \end{bmatrix} \quad (5)
$$

Where $X_{COMGDM2000}, Y_{COMGDM2000}, Z_{COMGDM2000}$ is the Cartesian coordinate of computed *GDM2000* after applying 7p and $X_{GDM2000}, Y_{GDM2000}, Z_{GDM2000}$ is the Cartesian coordinates in *GDM2000*.

2.4 COORDINATE DIFFERENCE COMPUTATION

For the validation of the parameter estimation, the two cases by internal and external station were used to be compared with the original coordinate and giving the equation as below:

$$
dX, dY, dZ = [X_{GDM2000}, Y_{GDM2000}, Z_{GDM2000}] -
$$
$$
[X_{COMGDM2000}, Y_{COMGDM2000}, Z_{COMGDM2000}] \quad (6)
$$

Where $X_{COMGDM2000}, Y_{COMGDM2000}, Z_{COMGDM2000}$ is the Cartesian coordinate of computed *GDM2000* after applying 7p and $X_{GDM2000}, Y_{GDM2000}, Z_{GDM2000}$ is the Cartesian coordinates in *GDM2000*.

3. RESULT AND ANALYSIS

This section provides results and analysis; accuracy of Bursa-Wolf 7p estimation, and assessment of Bursa-wolf model in coordinate transformation application.

3.1 Accuracy of Bursa-Wolf 7p estimation

Figure 4 shows residual in Bursa-Wolf 7p estimations in 3D Cartesian coordinate X, Y and Z components illustrated in Figure 4. The RMS value for every components are ±4.5mm, ±9.2mm and ±2.1mm respectively. Small amount of RMS indicates acceptable 7p Bursa-Wolf parameter estimation. Further work was conducted to the see the residual pattern in spatial sense. Thus, the residuals were then converted into horizontal vector as shown in Figures 5. From the figures, uneven direction of residual in horizontal vectors is depicted for all location which varies between -4.5mm and 4.0mm. Large horizontal vector can be seen at northern and southern part of Peninsular Malaysia, and gradually decreasing towards the centre of the region. This could be explained by a driven seismic motion due to on-going post-seismic deformation. Significant horizontal vector also found in the south-eastern of Borneo which can be explained by a slow and continuous local deformation within the area.
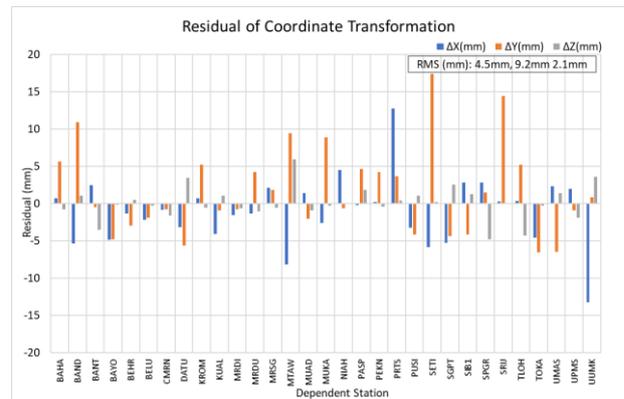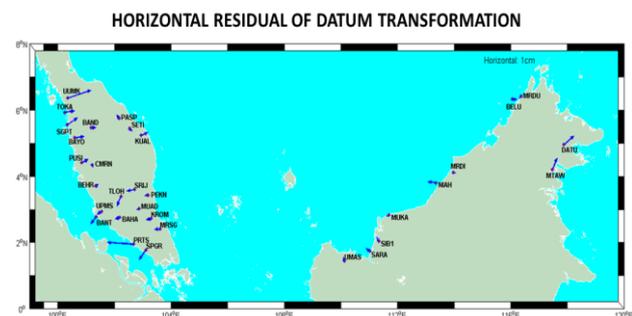

Figure 4. Residual of Coordinate Transformation.

Figure 5. Horizontal residual of Bursa-Wolf in Malaysia.

3.2 Assessment of Coordinate Transformation based on the 7p Bursa-Wolf model

The assessment results from coordinate transformation based on the 7p Bursa-Wolf model is illustrated in Figure 6 and 7. Both figures provide variation of coordinate difference in 3D Cartesian components, X, Y and Z at Independent Station; internal and external, respectively. From the figures, the RMS of coordinate difference at internal station can be achieved at ±5.1mm, ±6.5mm and ±1.5mm for the three components, respectively. The result shows slightly better than RMS of coordinate transformation at external station which are at ±6.1mm, ±8.7mm and ±3.3mm respectively.
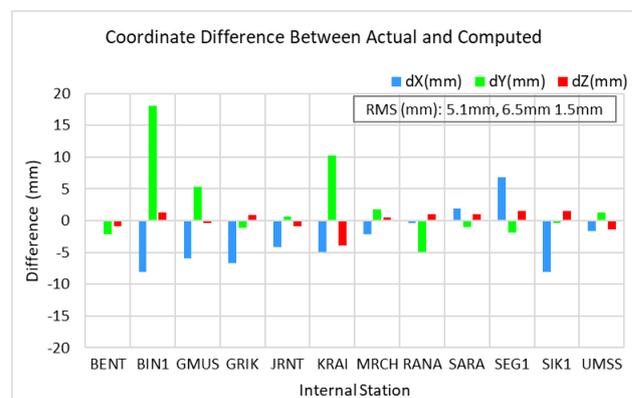

Figure 6. Coordinate difference at Independent Station (internal) after applying the 7p Bursa-Wolf model.
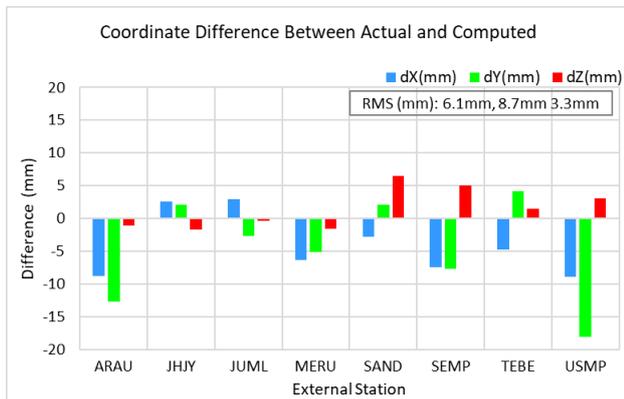
Figure 7. Coordinate difference at Independent Station (external) after applying the 7p Bursa-Wolf model.

Based on Figure 6, internal station BIN1 depicts largest coordinate difference at -8.1mm, 18.1mm and 1.3mm for the northing, easting and up component respectively. This is because the BIN1 has a longest distance at approximately 110km to the nearest dependent station of NIAH. Station BENT situated approximately 57km from nearest dependent station of TLOH and depicts small coordinate difference at 0.1mm, -2.1mm and -0.1mm for the northing, easting and up component respectively. Unlike external stations, uneven coordinate difference is found and with unclear relationship to their distance to the dependent stations. However, this external station still exhibits acceptable coordinate difference and the 7p Bursa-Wolf models is adequate to be used in this region.

4. CONCLUSION AND RECOMMENDATION

This study demonstrated analysis on the performance of Bursa-Wolf model for coordinate transformation approach in deforming region such as Malaysia. The experimental work utilised two reference frames which are GDM2000 and ITRF2014@2018.0 from self-derivation. The accuracy of Bursa-Wolf 7p estimations exhibits acceptable RMS value at ±4.5mm, ±9.2mm and ±2.1mm in 3D Cartesian coordinates respectively. Large horizontal vector was found in the northern and southern part of Peninsular Malaysia as well as south-eastern of Borneo. These can be explained by a slow and continuous post-seismic and local deformation. Comparative analysis of independent stations indicated that internal stations depicted better RMS value as compared to external station. The assessment of the 7p Bursa-Wolf shows RMS of coordinate difference less than ±6.5mm at internal station. The external station shows coordinate difference exceeded up to ±8.7mm. However, this external station still exhibits acceptable coordinate difference and the 7p Bursa-Wolf models is adequate to be used in this region. It is worth to mention that the results and analysis is mainly for experimental purposes only. Further work is recommended to optimize the Bursa-Wolf model for coordinate transformation in the deforming region by applying coordinate correction from the coordinate difference value.

ACKNOWLEDGEMENTS

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