The Geocentric Datum of Malaysia: Preliminary Assessment and Implications

Noor Suryati Mohd Shariff, Tajul Ariffin Musa, Kamaludin Omar and Rusli Othman

Abstract The reliability of the national geocentric datum must be assessed regularly to maintain high geospatial accuracy in terms of consistency with respect to the global datum, i.e. International Terrestrial Reference Frame (ITRF). This can be accomplished by considering the spatial and temporal variations caused by plate tectonic movements. This study aims to assess the reliability of Geocentric Datum of Malaysia (GDM2000) by analysing the datum shifts via the displacements of the Malaysian Real Time Kinematic Network (MyRTKnet) stations caused by tectonic movements as well as the displacements induced by reference frame effects. A significant land displacement up to 17 and 30 cm in north and east components were found respectively, due to local active fault and the cumulative plate tectonic motion. The implications of a non-geocentric datum are also discussed.

Keywords Geocentric datum · Reference frame · Plate tectonic

1 Introduction

The geocentric datum represents a best-fit ellipsoid where its origin and orientation is with respect to the Earth-centred Earth-fixed (ECEF) coordinate system. Therefore, the geocentric datum has the following descriptions; (1) its origin coincides with the Earth's centre of mass, (2) the orientation of the X-axis is pointing towards the mean Greenwich meridian, (3) the Z-axis is parallel to the rotation axis of the earth, (4) the Y-axis completes the right-handed system, and

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(5) the ellipsoidal axes (a, b) coincides with the X and Z axis, respectively (Leick 2004, Hofmann-Wellenhof et al. 2008).

The realization of a geocentric datum can be classified into three hierarchical levels: global, regional and national. The global realization of a geocentric datum is represented as the foremost datum, followed by the regional and national geocentric datum whereby each realization of the geocentric datum is essentially consistent with the International Terrestrial Reference System (ITRS). The ITRS is realized through the International Terrestrial Reference Frame (ITRF), which represents the best available global geocentric datum. There are several improvements that have been continuously made in the data analysis strategy to achieve the optimal solution for the generation of ITRF (Altamimi et al. 2005). The ITRF takes into account the spatial and temporal variations of its network coordinates and their velocities due to the effects of tectonic plate motion, earth orientation and polar motion (Altamimi et al. 2008, Janssen 2009, Johnston and Morgan 2010). This is achieved by updating and refining its frame regularly. Presently, the version of the ITRF is ITRF2008. Additionally, the ITRF is an indispensable reference that is required to ensure the integrity and inter-operability of Global Satellite Navigation System (GNSS) (Altamimi et al. 2008).

The Geocentric Datum of Malaysia (GDM2000) was adopted by the Department of Survey and Mapping Malaysia (DSMM) to establish a global and homogeneous coordinate system across the country. The realization of the GDM2000 was based on the ITRF2000 at epoch 1st January 2000. However, the GDM2000 remains as a static datum where all site coordinates are fixed or assumed unchanged with time. In fact, the Earth is actually dynamic and experiences numerous deformation events such as plate tectonic motions and earthquakes. The tectonic plates move gradually with the velocity typically varying in many places, up to a few centimetres annually (Anderson 2012). Moreover, a strong earthquake will cause a significant land displacement ranging from decimetre to meters, depending on the site distance from the epicentre.

Malaysia is situated within the Sundaland block. Previously, the Sundaland represents a stable tectonic block, moving approximately east with respect to Eurasia plate at a velocity of 12 ± 3 mm per year (Michel et al. 2001) as shown in Fig. 1. However, since the mega earthquakes in Aceh (2004), Nias (2005) and Bengkulu (2007) the country has experienced significant land displacements (Simons et al. 2007, Chlieh et al. 2007, Socquet et al. 2006, Banerjee et al. 2007). According to Vigny et al. (2005), the 2004 Aceh earthquake had significantly resulted in land displacements up to 10 cm in magnitude for a radius of 400 km away from the earthquake epicentre. Figure 2 shows the post-seismic and co-seismic motions in Peninsular Malaysia from 2004 until 2008 which is the combination of the aforementioned earthquakes and plate tectonic motion (Omar and Mohamed 2010). These studies have indicated that Malaysia is no longer in a stable region.

These earthquakes and plate tectonic motions dislocate the GPS reference stations, thus affecting the geocentric datum causing it to be no longer geocentric (non-geocentric) and does not represent the "true" position of the points. The

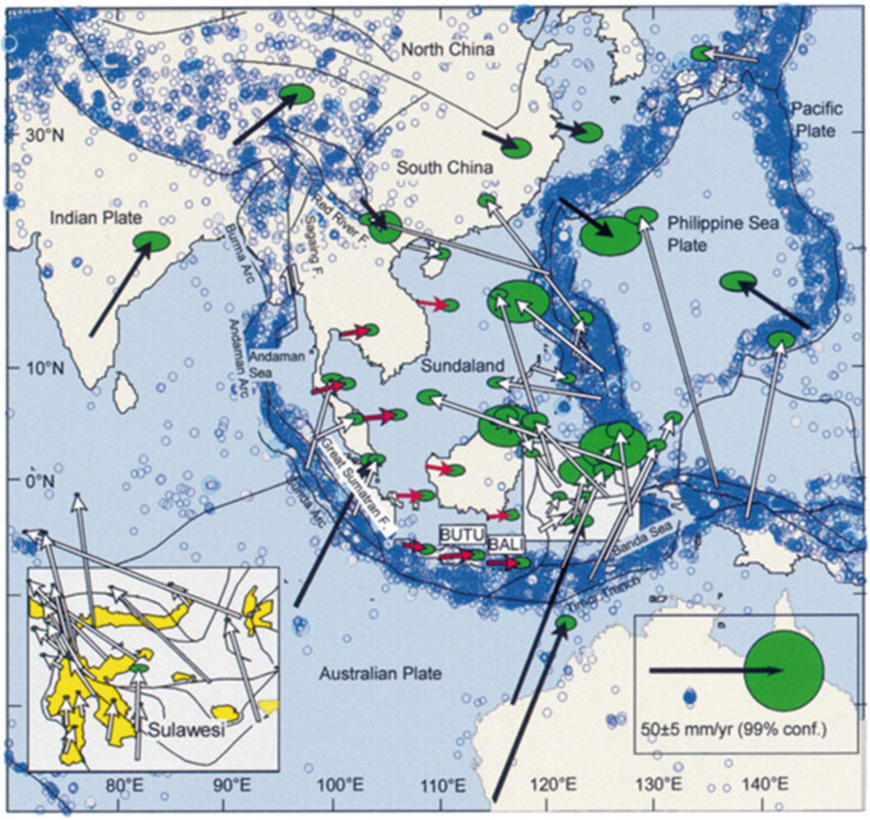

Fig. 1 Map of global positioning system (GPS) velocity vectors from the study by (Michel et al. 2001). *Black arrows* represent GPS velocity vectors of the permanent stations from IGS and AUSLIG; *red* and *white arrows* shows velocities derived in the study where the *red arrows* represent 'stable' Sundaland velocities. *Blue dots* denote epicentres of crustal earthquakes from the U.S. Geological Survey (USGS) catalogue (1973–2001)

consequence is not only seen to affect the activities of survey and mapping, but will also have a big impact on the socio-economic and environment in general. Therefore, a geocentric datum must consider the earth's geodynamic processes (Kelly 2012).

This study firstly addresses the establishment and the current status of the GDM2000. Secondly, tests were conducted to assess the reliability of the MyRTKnet stations' coordinates in GDM2000 by analysing the datum shifts via (1) the displacement of MyRTKnet stations between epoch 2000 and epoch 2011 in ITRF2000, (2) displacement of MyRTKnet stations between epoch 2000 in ITRF2000 and epoch 2011 in ITRF2008. Finally, the implications of a non-geocentric datum are discussed.

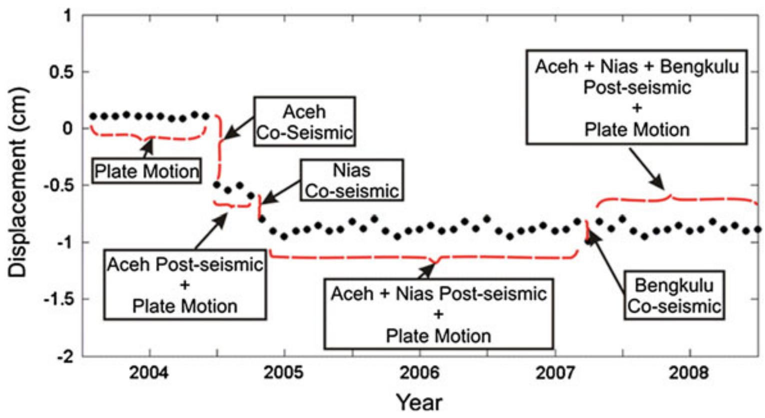

Fig. 2 Post-seismic and co-seismic motions in Peninsular Malaysia (Omar and Mohamed 2010)

2 Status of Geocentric Datum of Malaysia (GDM2000)

Traditionally, there were two existing local geodetic reference systems in Malaysia, namely the Malayan Revised Triangulation 1948 (MRT48) for Peninsular Malaysia and Borneo Triangulation System 1968 (BT68) for Sabah and Sarawak. The reference ellipsoid for the MRT48 and BT68 are Modified Everest (Kertau) and Modified Everest (Timbalai), respectively (Department Survey and Mapping (DSMM) 2009). However, their origins are not explicitly defined and in practice could be many hundreds of metres away from the geocentre (Kadir et al. 2003). On 26 August 2003, the GDM2000 was officially launched nationwide as a national geocentric datum to replace the MRT48 and BT68. It was realized through a set of GPS observations at seventeen (17) Malaysia Active GPS System (MASS) stations and eleven (11) IGS stations, from 1999 to 2002. All the MASS coordinates were defined on the most precise available reference frame at that time i.e. the ITRF2000, based on the Geodetic Reference System (GRS80) ellipsoid.

In 2002, DSMM established a new Continuously Operating Reference Station (CORS) network known as the Malaysian Real-Time Kinematic GNSS Network (MyRTKnet) with 78 reference stations nationwide, to improve the MASS stations and support the generation of network-based positioning solutions. However, on 26 December 2004, these stations underwent land displacements in the range of 1.5–17 cm and orientation predominantly in the south-west direction due to the co-seismic motion from the Aceh earthquake (Department Survey and Mapping (DSMM) 2009). Similarly, the results from Nias and Bengkulu earthquakes indicated land displacements of between 1–6.5 cm and 1–3 cm respectively, also in the south-west direction (Department Survey and Mapping (DSMM) 2009). Therefore, a revision of the GDM2000 was carried out.

Thus far, the revision of GDM2000 had been conducted in epoch 2006 and 2009 which were labelled as GDM2000 (2006) and GDM2000 (2009), respectively. Both of the versions were revised using a similar procedure where the set of new coordinate data were brought to the ITRF2000 at epoch 2000.0, which is the original of GDM2000. In the case of GDM2000 (2009), the reference stations, i.e. the IGS stations, in ITRF2005 at epoch 2007.67 were brought to ITRF2000 at epoch 2000.0 using published velocity models. Based on the Helmert Transformation, root mean square (RMS) fitting for the coordinates of four reference stations (KUCH, BINT, KINA and MIRI) were less than 1 cm in the north, east and height components, respectively (Department Survey and Mapping (DSMM) 2009). Therefore, the coordinates of these four reference stations were fixed, in the final local combined adjustment, with respect to the original GDM2000 (Department Survey and Mapping (DSMM) 2009). However, the set of coordinates of MyRTKnet in GDM2000 (2006) are still being adopted at present. It is due to the discrepancy involved between the new set of coordinates GDM2000 (2009) and the existing database in GDM2000.

3 The Shift of GDM2000

As aforementioned, the GDM2000 has been revised to take into account the co-seismic motions. However, there are no further actions to revise and update the GDM2000, especially with the consideration of post-seismic motion as well at every MyRTKnet station. In order to test the compatibility of GDM2000 with the current position, GPS observation data on Day of Year (DoY) 001 until 023 in year 2011 have been processed by using Bernese GPS processing software. The processing stage involved 63 MyRTKnet stations and 22 IGS stations using the double-difference with Quasi Ionosphere Free (QIF) strategy. The data was processed in ITRF2008 as well as in ITRF2000. The idea was to compare the two set of coordinates in ITRF2000 and ITRF2008 for DoY 001 until 023 with the available set of GDM2000 (2006) coordinates in ITRF2000 epoch 2000.

3.1 Test I: Comparison Between Epoch 2000 and 2011 in the Same Reference Frame ITRF2000

In this test, the set of coordinates at epoch 1st January 2011 was compared to the published set of coordinates of GDM2000 (2006), where both were in ITRF2000. Figure 3 shows the differences of these two set of coordinates in terms of vector displacements. It can be deduced that the position of the sites moved with an average magnitude of 25.5 cm and orientation of 118.8° from epoch 2000 to epoch 2011.

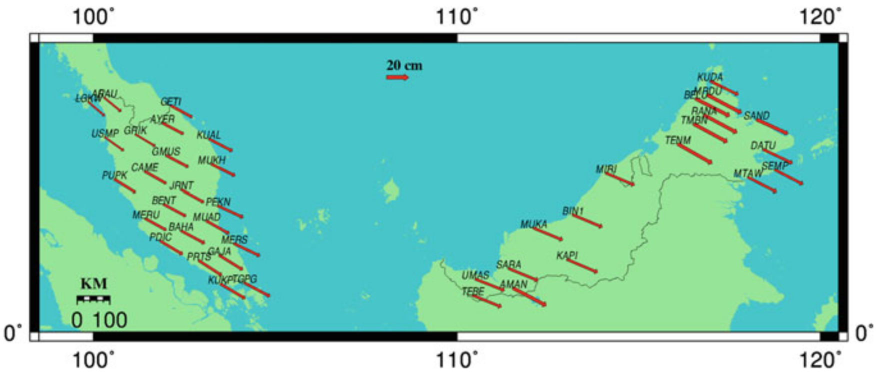

Fig. 3 Comparison between Epoch 2000 and Epoch 2011 in ITRF2000

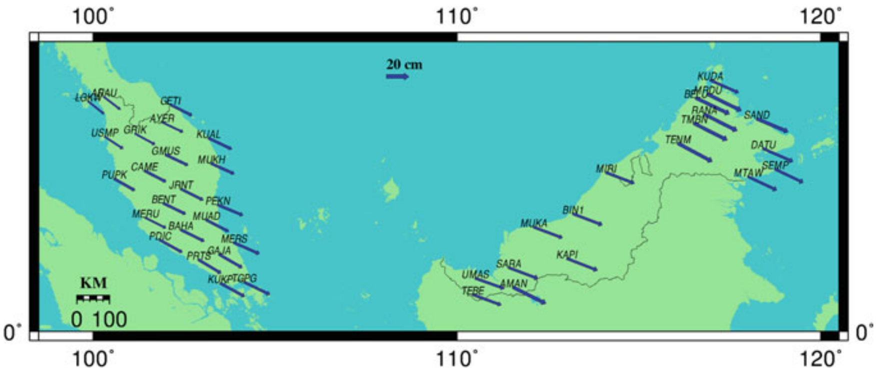

Fig. 4 Comparison between Epoch 2000 in ITRF2000 and Epoch 2011 in ITRF2008

3.2 Test II: Comparison Between Epoch 2000 and 2011 in Different Reference Frames: ITRF2000 and ITRF2008, Respectively

Similar to Test I, one set of coordinates at epoch 1st January 2011 was compared to the published set of coordinates of GDM2000 (2006), but in different reference frames: ITRF2000 and ITRF2008, respectively. Figure 4 illustrates the differences in terms of vector displacements between the two set of coordinates. It can be shown that the position of the sites moved with an average magnitude of 24.7 cm and orientation of 116.7° from epoch 2000, in ITRF2000 to epoch 2011 in ITRF2008.

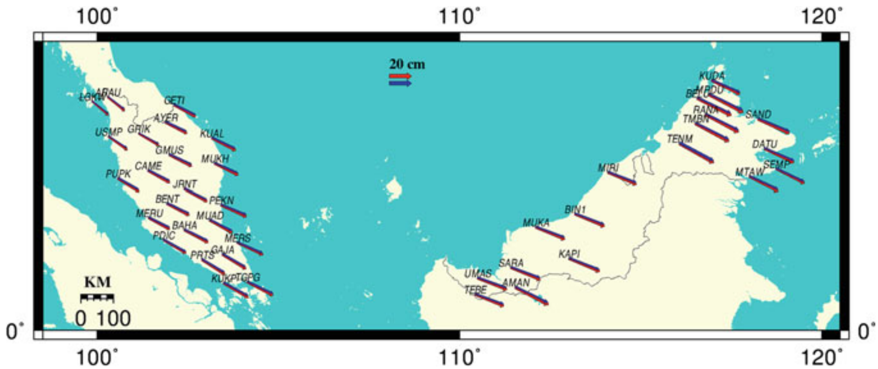

Fig. 5 Comparison between ITRF2000 and ITRF2008 at epoch 2011

3.3 Test III: Comparison Between ITRF2000 and ITRF2008 Reference Frames at Same Epoch 2011

The objective is to show the effect of the set of coordinates in different reference frames, ITRF2000 and ITRF2008, at a single epoch 2011. Figure 5 shows that the vector displacements of epoch 2011 in ITRF2000 (denoted as red arrow) and vector displacements of epoch 2011 in ITRF2008 (denoted as blue arrow). The displacements are almost identical in terms of magnitude and orientation, the difference being about 2 cm in magnitude and about 2° in orientation from the GDM2000 (2006).

3.4 Test IV: Time Series Analysis for Coordinates Difference Between Epoch 2011 in ITRF2000 and the GDM2000 (2006)

The time series of displacements at selected areas is shown in Fig. 6. The selected areas are classified as north (ARAU), south (KUKP) and east (MUKH) of Peninsular Malaysia, as well as Sabah (RANA) and Sarawak (SARA). It was found that the largest horizontal displacement occurred at RANA station up to 17 and 30 cm in the north and east components, respectively. It is due to the fact that the RANA station is located near active fault zone; hence prone to its influences. A study by (Mohamed 2012) shows that the stations coordinates of the Ranau GPS Campaign 2010 underwent displacements of a few mm to 5 cm at stations located in the Mendasan and Lobou-Lobou fault zones. Meanwhile, the smallest displacement occurred at ARAU for the north component and at MUKH for the east component. This is due to the effect of post-seismic motion at the stations.

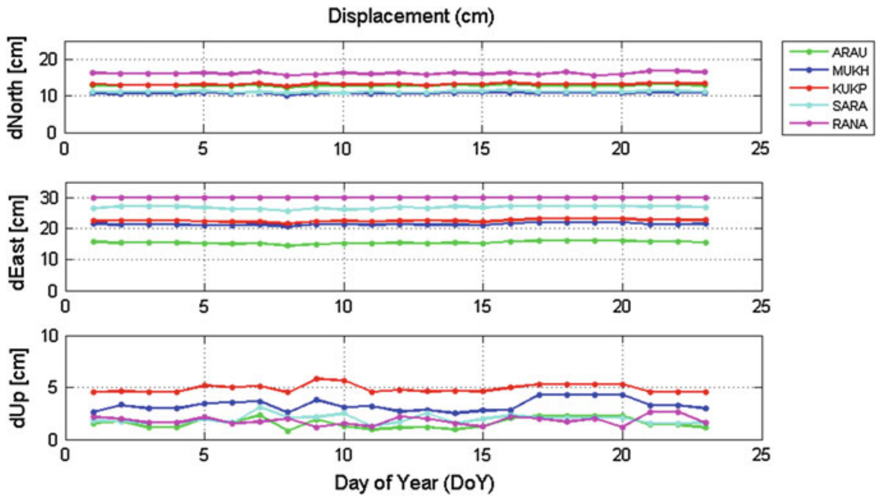

Fig. 6 Time series of displacement at ARAU, KUKP, MUKH, RANA and SARA stations

4 Implication of the Geocentric Datum Shift

The consequences of not updating the geocentric datum to the latest epoch (e.g. 2013), and the present reference frame (ITRF2008) have resulted in a number of implications, which are discussed in the following sub-sections.

4.1 Inconsistent Satellite Orbit and Coordinate Bias

The GNSS reference system for instance, the WGS84 (G1674) for GPS, Parametrop Zemp 1990 (PZ-90) for Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS), China Geodetic Coordinate System 2000 (CGCS2000) for BeiDou, Galileo Terrestrial Reference Frame (GTRF) for Galileo and Japan satellite navigation Geodetic System (JGS) for Quasi-Zenith Satellite System (QZSS) have been designed to be compatible with the global datum, i.e. ITRF. The GNSS reference system is mainly used for satellite orbit determination. Hence, the position of a satellite (ephemeris and especially precise orbit) is corresponding to the ITRF. Therefore, if the national network is contaminated with displacement, the national geocentric datum will no longer be compatible with the ITRF. This can lead to inconsistency in the satellite orbit interpretation. Furthermore, it would introduce coordinate bias, especially in relative positioning, that can be considered in a similar manner as the satellite orbit bias. Figure 7 illustrates the coordinate bias at a reference station; this gives a wrong estimated rover's position in relative positioning.

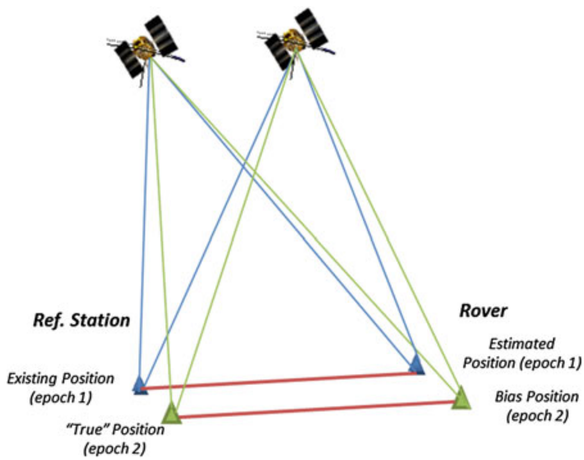

Fig. 7 Coordinate bias in the relative positioning

4.2 Confusion and Mismatch with Base Map

It is recognized that many social and economic activities such as navigation, civil engineering, oil and mineral exploration, agriculture and disaster management, are relying on accurate geocentric datum. Therefore, if the national geocentric datum is not accurate and updated, it will lead to misinterpretation and wrong decision making on land, property and other related matters. For instance, there could be a risk in the cadastral matters that involve dispute in the boundaries, size and shape of land parcels due to land displacement. Furthermore, any coordinate disparity between the "true" and existing geocentric datum will lead to confusion and misinterpretation of the actual position, especially when compared to absolute positioning, e.g. Precise Point Positioning (PPP), results with the existing base map. On the contrary, when using maps in the same reference system with the data, the mismatch can be avoided. However, there are users who do not take notice of the different reference system used in the data and maps or the existence of local deformation, but usually attribute such problems to data processing and positioning technology.

4.3 Decreased Accuracy of Reference Stations Coordinates

The reference stations should be maintained in the order of mm-level accuracy in terms of correspondence with the latest realization of ITRF. Furthermore, the reference station should be compatible with the ITRF because it is essential to avoid transition problems in boundary zones of countries (Pinto 2009). Inaccurate coordinates of the reference stations may also limit scientific research and applications that normally require a reliable coordinate system at the reference stations.

4.4 Managing the Geospatial Database

It is realised that significant earth deformation has occurred with evidences as shown in Sect. 3. The static datum option is not appropriate because it would not effectively consider the significant land displacements. Therefore, one of the options is to regularly update the geocentric datum in order to update the cadastral and mapping database. However, this option raises significant issues especially to a major group of cadastral surveyors and stakeholders due to the assumption of complexity in managing the updated geospatial database. At this stage, it is essential to propose the best mechanism to simplify the management of digital spatial data. With the present computing capability, cartography and Geographical Information System (GIS) technology, it is possible to transform spatial data from one epoch and reference frame to the other seamlessly (Pinto 2009). The important input to allow this transformation is either the velocity or transformation parameters.

5 Concluding Remarks and Future Work

The above review on the status of GDM2000 and several tests about the land displacements have justified that the existing datum is static and does not accommodate the land displacements. This implies that the GDM20000 is non-geocentric, which is only useful for local surveys. In Ranau, for instance, a significant land displacement up to 17 and 30 cm in north and east components respectively occurred mainly due to local active faults and the cumulative plate tectonic motion from 2006 to 2011. The consequences include the following—inconsistent satellite orbit and coordinate bias, confusion and mismatch with the base map, decreased accuracy of reference stations coordinates, and problems in managing cadastral and mapping database.

This study will continue to investigate the variations of land displacement over a longer period of time. It is essential to understand the tectonic setting and local land displacement due to either active faults or the influence from nearby earthquakes. Thus, the trend of the site velocities can be drawn to formulate the deformation model for Malaysia. This is an essential step in order to modernize the existing static datum to a semi-dynamic datum or dynamic datum. These two options further require the best mechanism to handle spatial data, especially for the cadastral and mapping applications to meet user requirements over time.

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Appendix A

Comparison between Reference Frame of ITRF2000 and ITRF2008.

Station	ITRF2000		ITRF2008		Difference	
	Orientation (degree)	Displacement (cm)	Orientation (degree)	Displacement (cm)	Difference (deg)	Difference (cm)
ARAU	129.678	20.126	127.666	19.123	2.012	1.003
AYER	117.725	21.878	115.315	21.062	2.410	0.816
BABH	123.134	20.993	120.835	20.085	2.299	0.908
BAHA	118.319	24.395	116.194	23.571	2.125	0.823
BANT	117.911	24.457	115.803	23.640	2.107	0.817
BENT	118.388	23.028	116.022	22.289	2.367	0.739
CAME	119.819	22.651	117.476	21.890	2.343	0.761
GAJA	121.985	24.897	120.054	24.030	1.931	0.868
GETI	119.067	22.400	116.759	21.562	2.308	0.838
GMUS	117.709	23.063	115.352	22.318	2.358	0.745
GRIK	121.115	21.475	118.801	20.604	2.314	0.871
JHJY	118.400	25.936	116.437	25.126	1.964	0.810
JRNT	118.879	23.573	116.684	22.739	2.195	0.834
JUML	118.040	25.471	116.028	24.657	2.012	0.815
KLAW	115.560	24.953	113.416	24.176	2.144	0.777
KRAI	111.073	24.795	108.751	24.090	2.322	0.705
KUAL	117.723	24.289	115.579	23.456	2.144	0.833
KUKP	120.700	25.981	118.819	25.134	1.881	0.847
LASA	120.986	22.068	118.759	21.182	2.227	0.887
LGKW	131.051	19.391	128.824	18.443	2.227	0.947
MERS	115.873	25.965	113.822	25.192	2.051	0.773
MERU	119.125	21.705	116.642	20.954	2.483	0.751
MUAD	119.512	23.756	117.385	22.922	2.127	0.834
MUKH	116.571	23.909	114.356	23.096	2.215	0.813
PASP	118.857	22.507	116.531	21.669	2.326	0.838
PDIC	121.218	23.806	119.172	22.941	2.046	0.865
PEKN	114.987	25.360	112.763	24.688	2.223	0.672
PRTS	123.194	24.653	121.293	23.765	1.901	0.887
PUPK	121.988	22.578	119.843	21.693	2.145	0.885
PUSI	121.338	22.391	119.143	21.517	2.195	0.874
SEG1	118.084	24.154	115.932	23.337	2.153	0.817
SETI	117.965	22.846	115.608	22.102	2.356	0.744
SGPT	124.503	20.390	122.191	19.461	2.313	0.928
SIK1	122.426	21.484	120.193	20.574	2.233	0.909
SPGR	122.326	24.937	120.415	24.065	1.911	0.872
SRIJ	120.438	25.959	118.503	25.103	1.935	0.857
TERI	118.846	23.363	116.680	22.517	2.166	0.846
TGPG	118.109	26.382	116.171	25.578	1.938	0.804

(continued)

(continued)

Station	ITRF2000		ITRF2008		Difference	
	Orientation (degree)	Displacement (cm)	Orientation (degree)	Displacement (cm)	Difference (deg)	Difference (cm)
TGRH	120.590	24.771	118.467	24.008	2.123	0.763
TLKI	122.765	23.171	120.708	22.277	2.057	0.894
TLOH	115.106	24.376	112.799	23.698	2.307	0.678
TOKA	124.661	20.309	122.396	19.367	2.264	0.941
UPMS	117.243	24.038	115.073	23.233	2.171	0.805
USMP	125.818	20.936	123.483	20.072	2.335	0.864
UUMK	126.185	20.012	123.899	19.058	2.286	0.954
AMAN	118.069	33.744	116.513	32.981	1.556	0.763
BELU	117.318	34.483	115.711	33.687	1.607	0.796
BIN1	112.910	28.865	110.894	28.187	2.017	0.678
DATU	115.681	29.575	113.643	28.956	2.038	0.619
KAPI	113.153	30.034	111.276	29.364	1.877	0.670
KUDA	116.318	28.609	114.206	27.954	2.112	0.655
MIRI	113.111	28.091	111.036	27.413	2.074	0.678
MRDU	117.999	34.732	116.365	33.961	1.634	0.771
MTAW	117.230	29.283	115.290	28.556	1.940	0.727
MUKA	112.625	28.467	110.608	27.793	2.017	0.674
RANA	118.489	33.916	116.834	33.193	1.656	0.723
SAND	114.893	31.131	112.938	30.519	1.955	0.612
SARA	112.650	28.855	110.618	28.269	2.032	0.586
SEMP	117.651	28.811	115.603	28.162	2.048	0.648
TEBE	112.374	28.038	110.360	27.367	2.014	0.672
TENM	119.715	35.596	118.195	34.807	1.520	0.789
TMBN	118.464	34.394	116.884	33.584	1.579	0.810
UMAS	111.726	28.432	109.719	27.770	2.007	0.662
AVERAGE	118.815	25.470	116.726	24.676	2.089	0.794

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