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Assessing Global Geodetic Datum between International Terrestrial Reference Frame 2014 and World Geodetic System 1984 using GPS Observation

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Abstract - Nowadays, the countries develop their national modern geocentric datum based on International Terrestrial Reference Frame (ITRF) by tying the Continuous Operating Reference System (CORS) stations to ITRF. At the same time, WGS84 is widely used for positioning and data processing-related applications. It has been assumed that the WGS84 new realisation coincides with ITRF at the 10-centimetre level; thus, the transformation parameters between ITRF and WGS84 are not considered. The reference epoch of WGS84 is often not mentioned in most studies, and this issue is claimed to be insignificant. Thus, this study aims to assess the global geodetic datum - International Terrestrial Reference Frame 2014 (ITRF2014) and World Geodetic System 1984 (G1762) using GPS observation in Peninsular Malaysia. Firstly, the horizontal and vertical components at collocated stations of IGS that give ITRF2014 and WGS84 (G1762) were obtained and compared. Secondly, the daily solution data was checked, followed by Root Mean Square Daily Repeatability checking. Finally, the final coordinate solution evaluated the positional difference at selected MyRTKnet station coordinates between ITRF2014 and WGS84 (G1762) in Peninsular Malaysia. The positional discrepancy for the horizontal component (northing and easting) is at -15.71 and 48.66 centimetres, respectively, while the vertical component (ellipsoidal height) is at 3.88 centimetres level. Overall, this study can provide an insight to the users about the global geodetic datum and eventually a more transparent and improved accuracy on the datum transformation module for geodetic-related applications.

Keywords - Geodetic Datum, Reference Frame, Accuracy, Positional Discrepancy

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1. Introduction

Geocentric datum is formed with the ellipsoid best fit to the world where its origin and orientation are based on the Earth-centred Earth-fixed (ECEF) coordinate system (Yazid et al., 2019). Another prerequisite to clearly defining a datum is the specification of the datum epoch for different realisations (Qinsy, 2020). To date, the world's two most renowned and widely used reference frames are International Geodetic Reference Frame (ITRF) and World Geodetic System 1984 (WGS84). The most significant difference is selecting fixed stations to adjust the framework (ICSM, 2020). Figures 1 and 2 show the distribution of their respective monitoring stations worldwide. The reference frame is utilised at global, regional, and national levels (Blick et al., 2014).

Figure 1. Distribution of IGS stations based on GPS Constellation, which has the ITRF2014 coordinates (IGS, 2020)

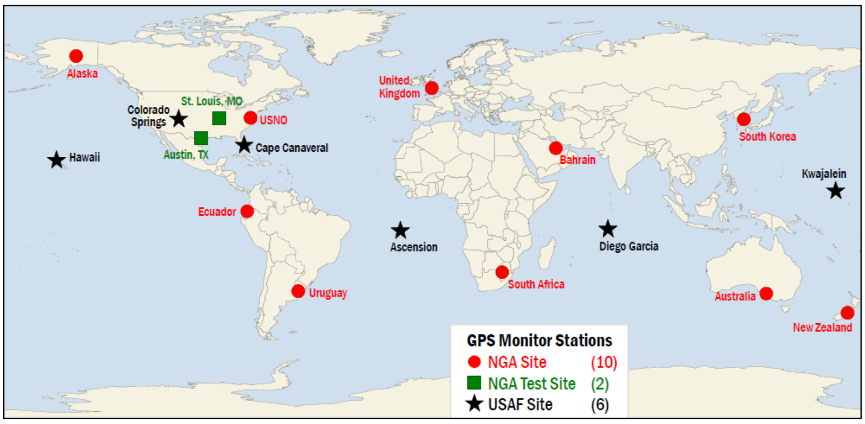


Figure 2. The NGA GPS Monitoring Stations (IGS collocated stations) for WGS84 Network (Malys, 2018)

1.1 International Terrestrial Reference Frame (ITRF)

With the emergence and integration of space geodesy instruments such as Global Positioning System (GPS), Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) (Altamimi et al., 2016), it has allowed the constant improvement of a seamless global spatial reference frame when all these four main geodetic techniques are adopted to compare different observation from different locations compared (IVS, 2020).

The International Terrestrial Reference Frame (ITRF) coordinates are observed at the IGS stations set up in the respective countries (Fazilova, 2017). Most countries develop their national geodetic datum based on ITRF (Kadir et al., 2003; Hadi et al., 2019; Pham Thi et al., 2019; Yazid et al., 2019). For example, in Malaysia, the national Continuously Operating Reference System (CORS), known as Malaysia Real-Time Kinematic GNSS Network (MyRTKnet) stations, are used to establish an active GNSS network which operates continuously nationwide at well-monumented stations based on ITRF (Shariff et al., 2017). Figure 3 shows the distribution of MyRTKnet stations in Peninsular Malaysia.

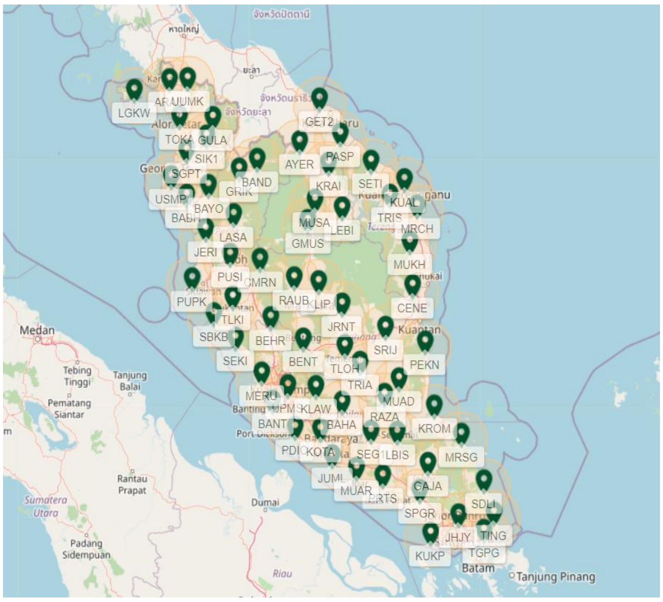


Figure 3. Distribution of MyRTKnet stations at Peninsular Malaysia

(Extracted from JUPEM, 2021)

1.2 World Geodetic System 1984 (WGS84)

Generally, WGS84, developed and maintained by the United States Department of Defense (DoD), has also benefitted global users (NGA, 2014). NGA, the agency responsible for maintaining the station network, has provided the IGS with its GPS tracking data daily since 2015. The NGA has established several co-located stations within the IGS network. Only about ten NGA co-located sites give precise GPS coordinates based on the WGS84 datum, as shown in Figure 2.

During field observation, GPS is widely used to acquire coordinates for points of interest through a direct observation approach (Gill et al., 2016). Although other countries have also adopted WGS84 as their national geodetic datum (Mohammed & Mohammed, 2013; Bosy, 2014; Dawod & Alnaggar, 2014; Novikova et al., 2018), it has come to the attention that WGS84 has its limitations that many countries had questioned the practicality of using WGS84 as their national geodetic datum (Land Information New Zealand, 2016; Geoscience Australia, 2020).

1.3 Limitation of WGS84

It is claimed that WGS84 does not meet the accuracy requirement or "does not have a recognised-value standard for measurement of position" (Geoscience Australia, 2020). Furthermore, since WGS84 is a global datum with a dynamic reference frame, the coordinates of the limited number of monitoring stations, as shown in Figure 2, will be updated annually (NGA, 2014). Their coordinates also vary over time for the objects fixed on the ground due to tectonic plate motion (Blick et al., 2014; Lu et al., 2014; Ronen & Even-Tzur, 2017; Zulkifli et al., 2019). The coordinates are adjusted for tectonic plate motion to an epoch where the WGS84 coordinates obtained via GPS observation by the users move over time. The tectonic plate movement is at a centimetre level per year, for example, 3cm per year in Uzbekistan, 5cm per year in New Zealand, and 7cm per year for Australia, disregarding any major earthquake events (Yazid et al., 2019).

The limitation of WGS84 as a datum is shown as there is no traceability because the WGS84 coordinates are updated annually. Still, users are unaware of these changes, thus quoting only the data used as WGS84 without stating any reference epoch (ICSM, 2020). Legal traceability should prove the users a sense of certainty on the measurement, which should be represented accurately. Furthermore, it means the users should be able to get repeatable results with minimum uncertainty over time with the condition that the traceability documentation is provided according to the International Standard (SI) standard via calibrations (Gill et al., 2016). Hence, it is noted that the absence of proper, official, and standardised transformation parameters of WGS84 causes the users to face confusion (Fazilova, 2017; Geoscience Australia, 2020) during the data processing and map production process. Therefore, the respective countries develop their national geodetic datum tied to ITRF to enable the traceability of the datum (Kadir et al., 2003; Hadi et al., 2019; Pham Thi et al., 2019; Yazid et al., 2019), including Malaysia.

1.4 Relationship Between ITRF and WGS84

ITRF is a global spatial reference frame that aims to provide the highest possible accuracy coordinates to compensate for the movements of the tectonic plates. The ITRF coordinates are monitored and derived by four geodetic-space observations as International GNSS Service (IGS), Satellite Laser Ranging (SLR), and Very Long Baseline Interferometry (VLBI) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). On the other hand, the WGS84 coordinates computed from the GPS receivers are maintained by NGA and are a datum used for GPS positioning and navigation. ITRF and WGS84 are global geocentric datum and aim to cover the local, national and regional needs (Blick et al., 2014).

In most of the studies and publication works (Kadir et al., 2003; IHO, 2008; Rabah et al., 2016; Hassan et al., 2020), it is assumed that the new realisation of WGS84 is aligned with ITRF coordinates at 10cm level (Li, 2014; Qinsy, 2020). Nonetheless, some claimed that the recent realisation of WGS84 shows an overall RMS difference of one centimetre (NGA, 2014; Malys, 2018), while some even suggested that ITRF and WGS84 coordinates are considered to be identical (IHO, 2008). However, two questions are worth to be answered based on the limitation of WGS84, which are (i) "Does WGS84 (G1762) align with ITRF2014 at centimetre level?" and (ii) "Is WGS84 reliable enough to be a geodetic datum in terms of its traceability?"

In this study, only the first question will be answered based on the assessment of the positional difference between the ITRF2014 and WGS84 (G1762) at selected MyRTKnet stations in Peninsular Malaysia to observe whether the level of discrepancy is at the centimetre level and whether this difference is negligibly tiny to be ignored for regional or geodetic transformation, particularly for the region of Peninsular Malaysia.

2. Data and Methods

2.1 Research Area Identification

The study area selected in this study is Peninsular Malaysia at selected MyRTKnet stations (See Figure 3). These stations are used to compare and thus evaluate the geodetic datum of ITRF2014 and WGS84 (G1762). Based on the 'whole-to-part' concept in establishing a control network (JUPEM, 2002; Fazilova, 2017), the selection of the joint or co-located stations of IGS stations that possess both ITRF2014 and WGS84 (G1762) coordinates is mandatory to enable us to evaluate the accuracy of these two geodetic datums (See Figure 4). Therefore, in this study, a total of 25 IGS stations in ITRF2014, 8 IGS co-located stations in WGS84 (G1762), and 37 Selected MyRTKnet stations in GDM2000 are selected. The data input epoch applied is 1 December 2020, with the duration of a one-month processing period.

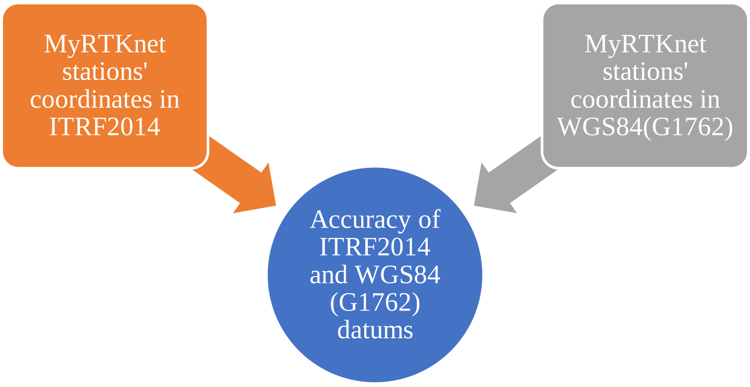


Figure 4. Relationship between ITRF2014 and WGS84(G1762) for the comparison approach

2.2 Data Preparation

The data sources from the IGS website and SpiderWeb for MyRTKnet stations were downloaded and managed using the MATLAB extraction program; GPS tools. The GNSS data processing for ITRF2014 and WGS84 (G1762) was conducted using Bernese GNSS Software version 5.2. The ITRF2014 and WGS84(G1762) coordinates were prepared alongside the site velocities in both reference frames. Besides, there are other input files to be acquired from Crustal Dynamics Data Information System (CDDIS) at https://cddis.nasa.gov/archive/gnss/data/daily/ for raw daily RINEX observation files and https://cddis.nasa.gov/archive/gnss/products/ for products such as the IGS final precise satellite ephemeris, Earth rotation parameters, precise orbit parameters and clock files (Hu, 2019). The atmosphere files like the daily global ionosphere model and monthly differential code biases for satellites and receivers can be obtained at http://ftp.aiub.unibe.ch/CODE/. The GPS raw data in RINEX format is extracted using GPS tools in MATLAB. With this toolbox, the data is extracted and rearranged accordingly, which become the prerequisite input files ready for pre-processing later in Bernese 5.2 software. There were nine other station files prepared for each case of processing, as shown in Table 1.

Table 1. The station input files are needed for processing in Bernese 5.2 software (Dach et al., 2015)

Station files	File extension name
Stations Coordinates	.CRD
Stations Plate Tectonics	.PLD
Stations Velocities	.VEL
Stations Character Abbreviation	.ABB
Fixed Stations	.FIX
Stations Information	.STA
Stations Cluster Number	.CLU
Stations Atmospheric Tidal Loading Correction	.ATL
Stations Ocean Tide Loading Correction	.BLQ

2.3 Processing Strategy

During the pre-processing stage, Bernese 5.2 undergo further checking and preparation of the data process. They further detect the potential errors and outliers of data in RINEX observation files. There are different approaches to pre-process the observation files, depending on the types of files. The aim is to smooth RINEX files after screening residuals as the noise from many stations eliminates the significant outliers (Dach et al., 2015).

After the data cleaning in the pre-processing stage, data processing emphasises error modelling and filtering (Bahadur and Nohutcu, 2018). Data processing starts with the global solution where the satellite data extracted, managed and pre-processed earlier was first processed in the global reference frames, ITRF2014 and WGS84 (G1762). Depending on the fixed stations for each processing case, the processing on MyRTKnet stations was done in two different campaigns.

Double-difference network processing (RNX2SNX) was used in the regional network's automated BPE processing in Bernese 5.2. This technique reduces the system error associated with the measurements through strategies like ambiguity resolution, precise orbits, clock corrections and atmospheric modelling (Gill et al., 2016). The overview of processing strategies is summarised in Figure 5.

Figure 5. Overview of processing strategies in Bernese software version 5.2

2.4 Data Evaluation

For the data evaluation, the following elements are to be calculated and computed according to Malys et al. (2016), which are the displacement indicated by the magnitude of station coordinates in terms of local North, East, Up angle components (Δ NEU), Root Mean Square Error (RMSE) of daily repeatability and the positional or coordinate difference in final coordinate solution. Firstly, the data evaluation and analysis will be done between ITRF2014 and WGS84 (G1762) at IGS stations, followed by ITRF2014 at selected MyRTKnet stations and lastly, WGS84 (G1762) at selected MyRTKnet stations.

To obtain the positional difference in the magnitude of North, East, and Up components between ITRF2014 and WGS84 (G1762) at IGS stations, the three-dimensional Cartesian coordinates (X, Y, Z) components will first be converted to three-dimensional geographical coordinates for each co-located station. Subsequently, the selected map projection method, Universal Transverse Mercator (UTM) Projection, was done based on the respective stations' zone. After obtaining the North and East components, the horizontal components' differences can be compared. At the same time, the ellipsoidal height in geographical coordinate can be used as a vertical component to compare the vertical coordinate difference. Figure 6 shows the simplified flowchart of how this part is to be implemented.

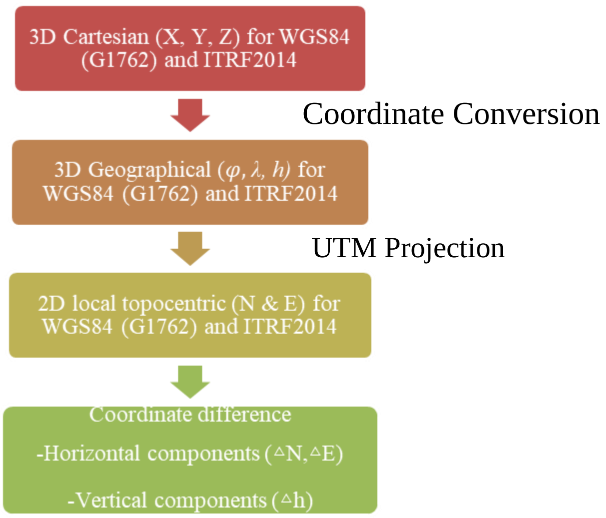


Figure 6. Flowchart of the implementation of and map projection to find a coordinate difference at IGS stations

3. Results and Discussion

3.1 Input Solution Datasets

There was a total of twenty-five (25) IGS stations which comprised 17 IGS stations that gave only ITRF2014 coordinates, and 8 IGS co-located stations gave coordinates in both WGS84 (G1762) and ITRF2014 (See Table 2). In assessing the two geodetic datums, the data from the respective networks of monitoring stations were collected. All the stations selected were evenly distributed worldwide to ensure a suitable network geometry (See Figure 7) and used as fixed stations to execute the 'whole-to-part' concept. Furthermore, the IGS stations were carefully selected based on the horizontal and vertical differences and data availability from 1st to 31st December 2020 (See Table 3). On the other hand, a total of thirty-seven (37) MyRTKnet stations were selected in Peninsular Malaysia (See Figure 3).

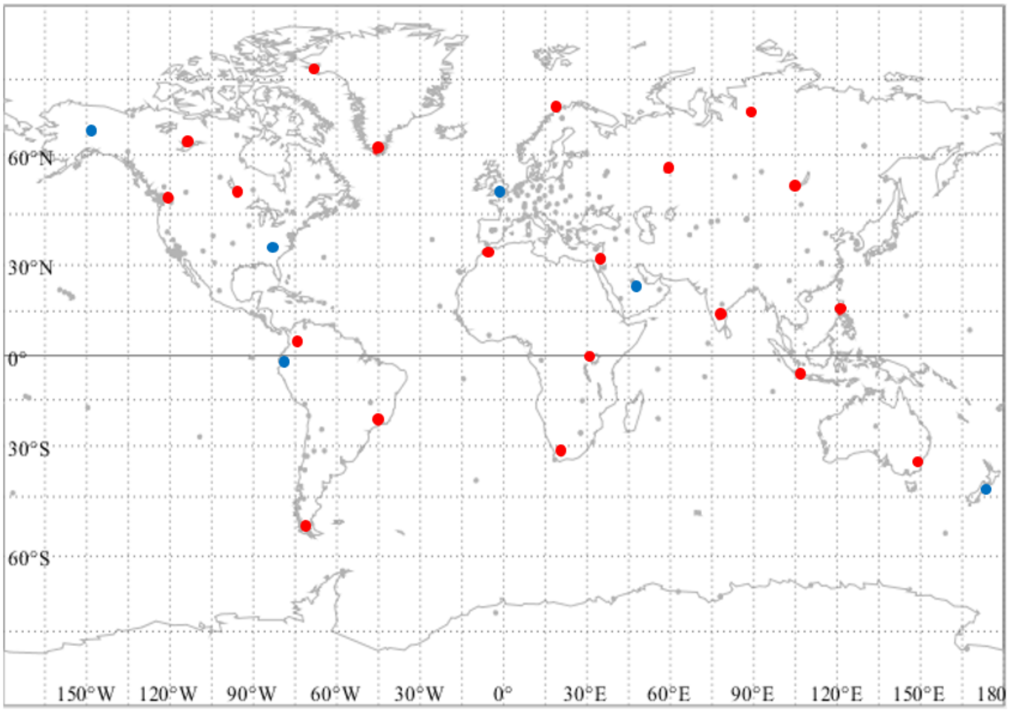


Figure 7. Evenly distributed of 25 selected IGS stations worldwide

Table 2. 3D Cartesian coordinates of selected IGS stations (NGA, 2014; IGS, 2020)

Site	IGS Stations	WGS84 (G1762) (Epoch 2005.0)			ITRF2014 (Epoch 2010.0)		
	Co-located Stations	**X(m)**	**Y(m)**	**Z(m)**	**X(m)**	**Y(m)**	**Z(m)**
Alaska	EIL300USA EIL400USA	-2296304.083	-1484805.898	5743078.376	-2296304.083	-1484805.898	5743078.376
England	OAK100GBR OAK200GBR	4011440.890	-63375.739	4941877.084	4011440.890	-63375.739	4941877.084
Bahrain	BHR300BHR BHR400BHR	3633910.105	4425277.147	2799862.517	3633910.660	4425277.759	2799862.907
Ecuador	QUI300ECU QUI400ECU	1272867.304	-6252772.044	-23801.759	1272867.304	-6252772.044	-23801.759
United State	WDC500USA WDC600USA	1112158.852	-4842855.557	3985497.029	1112158.868	-4842855.614	3985496.946
New Zealand	MRL100NZL MRL200NZL	-4749991.001	520984.518	-4210604.147	-4749991.001	520984.518	-4210604.147
South Africa	PRE300ZAF PRE400ZAF	5066232.068	2719227.028	-2754392.632	5066223.489	2719222.966	-2754406.543
South Korea	OSN300KOR OSN400KOR	-3067863.250	4067640.938	3824295.770	-3068340.810	4066863.981	3824757.006

Table 3. Difference between local topocentric coordinates of ITRF2014 and WGS84 (G1762)

Country/Site	IGS Collocated Station	△North (m)	△East (m)	△ell. ht (m)
Alaska	EIL300USA EIL400USA	0.000	0.000	0.000
England	OAK100GBR OAK200GBR	0.000	0.000	0.000
Bahrain	BHR300BHR BHR400BHR	0.100	0.000	-0.913
Ecuador	QUI300ECU QUI400ECU	0.000	0.000	-0.004
US Naval Observatory	WDC500USA WDC600USA	0.010	0.110	0.006
New Zealand	MRL100NZL MRL200NZL	0.000	0.000	0.000
South Africa	PRE300ZAF PRE400ZAF	-0.340	16.730	2.496
South Korea	OSN300KOR OSN400KOR	-860.680	-550.800	-12.688

Initially, there were altogether 16 co-located stations found in WGS84 (G1762) and ITRF2014, as illustrated in Table 2 (NGA, 2014; IGS, 2020) at epochs 2005.0 and 2010.0, respectively. The 3D Cartesian coordinates are converted to 3D Geographical coordinates followed by UTM projection. The results in Table 3 showed that the horizontal difference (Northing, Easting) and vertical difference of ellipsoidal height are generally genuine for all stations except for monitoring stations in South Africa (PRE300ZAF & PRE400ZAF) and South Korea (OSN300KOR & OSN400KOR). Therefore, they are excluded from the list of fiducial stations. The significant difference indicates that there may be site relocation, antenna movement or changes in methodology (NGA, 2014). It should be noted that there are no solutions for the following stations due to data quality issues: BHR4 (Bahrain), MRL2 (New Zealand), QUI3 and QUI4 (Ecuador) hence leaving only a total of 8 co-located stations to be used in processing.

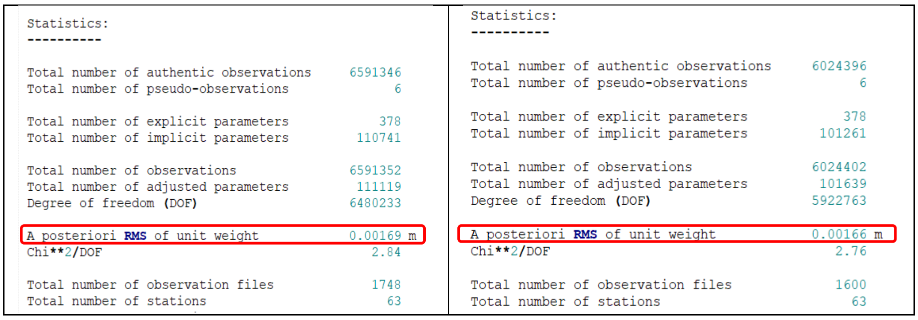
3.2 Quality Checking for Daily Solution

Before combining the coordinates to obtain the average coordinate set, the quality of the daily solution was examined first (Hu, 2019). According to Dach et al. (2015), to check if the network designed for the fiducial stations was well-distributed, the consistency of the network solution is checked. Then, the fiducial station coordinates are checked during Helmert translation to see if the residuals fall below 1 centimetre. The baselines formed between fixed and rover stations are also checked through ambiguity resolution to see the percentage of ambiguity resolved. The daily repeatability of the coordinate solution is also checked in terms of horizontal and vertical for root mean square value.

3.2.1 Consistency of Network Solution

The consistency of the network solution was examined concerning the fiducial stations for datum definition. In addition, the data quality concerning the quality of receivers was checked. As a result, the a-posteriori root mean square of unit weight should fall between 1 to 2 millimetres for elevation-dependent weighting and 2 to 3 millimetres without elevation-dependent weighting case. According to Dach et al. (2015), the orbit and Earth Orientation Parameters (EOP) consistency can be guaranteed by involving the nearby reference sites of the global IGS network. Besides, the geodetic datum of the network was also defined based on these reference sites. The method used to constrain the network was a minimum constraint solution to ensure that the errors in the reference stations, to a certain extent, do not distort the network geometry, which might degrade the datum definition.

Figure 8 shows that the network solutions consistency for having ITRF2014 as a reference frame is 1.69 millimetres and 1.66 millimetres for WGS84(G1762). Thus, both networks show high consistency of network solution, which has proven that the stations chosen are well-distributed, which shows suitable network geometry.



```
Statistics:
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Total number of authentic observations     6591346
Total number of pseudo-observations              6

Total number of explicit parameters            378
Total number of implicit parameters         110741

Total number of observations               6591352
Total number of adjusted parameters         111119
Degree of freedom (DOF)                    6480233

A posteriori RMS of unit weight          0.00169 m
Chi**2/DOF                                    2.84

Total number of observation files             1748
Total number of stations                        63
```

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Statistics:
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Total number of authentic observations     6024396
Total number of pseudo-observations              6

Total number of explicit parameters            378
Total number of implicit parameters         101261

Total number of observations               6024402
Total number of adjusted parameters         101639
Degree of freedom (DOF)                    5922763

A posteriori RMS of unit weight          0.00166 m
Chi**2/DOF                                    2.76

Total number of observation files             1600
Total number of stations                        63
```

Figure 8. Network solution consistency for ITRF2014 (left) and WGS84 (G1762) (right)

3.2.2 Fiducial Station Coordinates

Fiducial stations are used for datum definition, which determines the mean orientation of the network. Thus, it was essential to check on the fiducial stations' quality and were diagnosed to see if they were problematic stations. It was done by verifying the estimated coordinates of all the referenced stations, including the three translation parameters, during the Helmert transformation. The range biases (RGBs) were estimated to detect discrepancies and outliers. The problematic fiducial stations detected as outliers were excluded from processing to sustain the network and baseline quality.

The results were checked daily to see if each fiducial station selected fulfils the conditions where the horizontal component should have the root mean square value of fewer than 10 millimetres and 30 millimetres for vertical components. Figure 9 shows the root mean square error sample in the fiducial station coordinates and its Helmert translation parameters. Fiducial stations that exceed this threshold probably have weak estimated coordinates due to wrong ambiguities, lousy data quality, or even pre-processing issues (Dach et al., 2015).

```
|   63 | USMP                 | R A |     -436.50     -33.81     204.33 | M |
|   64 | UUMK                 | R A |     -431.12     -10.91     208.63 | M |
|   65 | WDC5 40451S010       | R A |     -230.73    -108.50      -7.48 | M |
|   66 | WDC6 40451S010       | R A |     -230.73    -108.51      -7.45 | M |
|   67 | YELL 40127M003       | I W |       -1.32      -1.87      -3.37 |   |
|      |                      |     |                                   |   |
---------------------------------------------------------------------------
|      | RMS / COMPONENT      |     |        4.70       3.58      10.15 |   |
|      | MEAN                 |     |        0.00       0.00       0.00 |   |
|      | MIN                  |     |       -8.28      -5.09     -16.83 |   |
|      | MAX                  |     |        5.07       7.35      16.38 |   |
---------------------------------------------------------------------------


NUMBER OF PARAMETERS  :     3
NUMBER OF COORDINATES :    30
RMS OF TRANSFORMATION :    6.78 MM

BARYCENTER COORDINATES:

LATITUDE              :    84 39 58.42
LONGITUDE             :    23 26 23.30
HEIGHT                :       -1491.139 KM


PARAMETERS:

TRANSLATION IN  N     :           0.00     +-  2.14     MM
TRANSLATION IN  E     :           0.00     +-  2.14     MM
TRANSLATION IN  U     :           0.00     +-  2.14     MM
```

Figure 9. Result of root mean square error in the fiducial station coordinates and its Helmert translation parameters (Sample taken from daily solution day 336)

3.2.3 Ambiguity Resolution

The ambiguity parameters were first estimated as parameters with actual values that were then resolved to their integer values to determine the ambiguities. Ambiguities' resolution reduces unknowns, providing a more stable solution (Dach et al., 2015). Bernese 5.2 software has a powerful function that resolves the ambiguities using different strategies according to the length of baselines, as summarised in Table 4. While Figure 10 shows the example for wide-lane ambiguity resolution.

Table 4. The summary of ambiguity resolution strategies depends on the baseline length (Dach et al., 2015)

Ambiguity resolution strategy	***Length of Baselines***
Code-Based Widelane (WL)	<6000 km
Code-Based Narrowlane (NL)	<6000 km
Phase-Based Widelane (L5)	<200 km
Phase-Based Narrowlane (L3)	<200 km
Quasi-Ionosphere-Free (QIF)	<2000 km
Direct L1/L2	<20 km

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================================================================================
 Code-Based Widelane (WL) Ambiguity Resolution (<6000 km)
================================================================================

 File      Sta1 Sta2    Length     Before     After    Res  Sys  Max/RMS L5      Receiver 1            Receiver 2
                         (km)    #Amb (mm)  #Amb (mm)  (%)       (L5 Cycles)
 ---------------------------------------------------------------------------------------------------------------------
 AUT13400 ARTU TRO1   2403.535    63  0.0    22  0.2  65.1 G    0.150  0.070  JAVAD TRE_G3TH DELTA TRIMBLE NETR9
 BKGJ3400 BAKO GAJA   1024.638    63  0.1    27  0.2  57.1 G    0.129  0.059  LEICA GR50           TRIMBLE NETR5
 CHPR3400 CHPI PARC   3961.403    47  0.0     2  0.4  95.7 G    0.150  0.088  SEPT POLARX5         TRIMBLE ALLOY
 DUSA3400 DUBO SASK    765.433    61  0.0    22  0.1  63.9 G    0.115  0.046  SEPT POLARX5         JAVAD TRE_G3TH DELTA
 GJTL3400 GAJA TLOH    184.337    44  0.0     2  0.3  95.5 G    0.148  0.060  TRIMBLE NETR5        TRIMBLE NETR5
 IISG3400 IISC SGPT   2625.652    45  0.1     3  0.4  93.3 G    0.141  0.075  SEPT POLARX5         TRIMBLE NETR5
 IRNR3400 IRKJ NRIL   2074.113    55  0.0     2  0.4  96.4 G    0.168  0.077  JPS LEGACY           ASHTECH UZ-12
 IRSG3400 IRKJ SGPT   5033.855    43  0.0     2  0.3  95.3 G    0.145  0.081  JPS LEGACY           TRIMBLE NETR5
 NRT13400 NRIL TRO1   2550.040    68  0.0     3  0.3  95.6 G    0.144  0.083  ASHTECH UZ-12        TRIMBLE NETR9
 PMTL3400 PIMO TLOH   2378.418    45  0.0    27  0.2  40.0 G    0.147  0.088  JAVAD TRE_G3TH DELTA TRIMBLE NETR5
 QQT23400 QAQ1 THU2   1954.837    70  0.0     0  0.2 100.0 G    0.120  0.050  SEPT POLARX5         SEPT POLARX5
 RTT13400 RABT TRO1   4193.827    64  0.0    23  0.2  64.1 G    0.150  0.071  JAVAD TRE_3 DELTA    TRIMBLE NETR9
 SAYL3400 SASK YELL   1240.343    61  0.0    20  0.2  67.2 G    0.149  0.087  JAVAD TRE_G3TH DELTA JAVAD TRE_3N DELTA
 SGTL3400 SGPT TLOH    323.666    41  0.0     2  0.2  95.1 G    0.141  0.050  TRIMBLE NETR5        TRIMBLE NETR5
 T2T13400 THU2 TRO1   2636.935    69  0.0     4  0.3  94.2 G    0.144  0.079  SEPT POLARX5         TRIMBLE NETR9
 T2YL3400 THU2 YELL   2257.539    72  0.0    21  0.1  70.8 G    0.161  0.069  SEPT POLARX5         JAVAD TRE_3N DELTA
 ---------------------------------------------------------------------------------------------------------------------
 Tot:  16             2225.536   911  0.0   182  0.3  80.0 G    0.168  0.072
```

Figure 10. Sample of code-based wide-lane ambiguity resolution for baselines with length less than 6000 kilometres in percentage

Overall, the resolved ambiguity solution percentage in this study for 31 days of GPS data is higher than 70%, depending on the suitability of the ambiguity resolution strategy. For example, Figure 10 indicates a good sample of code-based wide-lane ambiguity resolution for baselines with less than 6000 kilometres with 80% percentage ambiguity resolved. Although all daily solutions in this study show the ambiguity solution percentage for higher than 70%, supposedly, the percentage should be higher than 75% to prove that the GPS data are of good quality (Md Din et al., 2015).

3.2.4 Root Mean Square Daily Repeatability

Root Mean Square (RMS) values of daily repeatability are an indicator of the quality of the data solution, which eventually helps this study access the final epoch solution's internal precision or accuracy (Hu, 2019). In a more general context, the RMS value of each session was first compared before the combination to ensure that the problems encountered at orbit and cleaning level have been resolved. Then, the internal precision is determined by studying the coordinate differences values between each session.

RMS results for each daily solution were checked one by one before 'stacking' the solutions to get the average RMS values through mean calculation. Figure 11 indicates the RMS of day-to-day repeatability for day 336 for MyRTKnet stations where IGS stations were fixed in the ITRF2014 reference frame, while Figure 12 shows the RMS of daily repeatability for day 336 for MyRTKnet stations where IGS stations were fixed in WGS84(G1762) reference frame. Once the internal precision is determined, the final coordinates can be exhibited confidently with transparent accuracy and information evaluated. The combined RMS difference of both datums is illustrated in Figure 13.

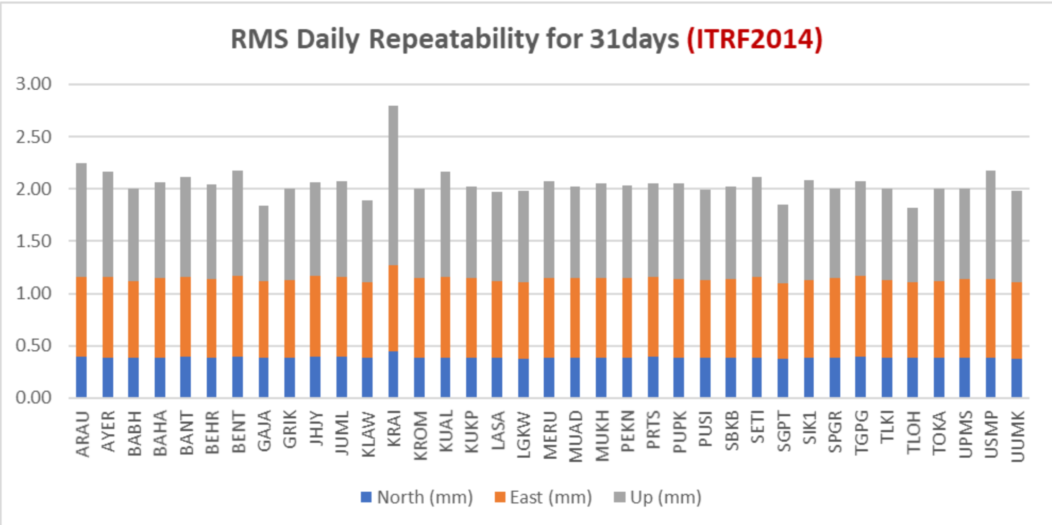

Figure 11. RMS of daily repeatability solution for 31 days for the selected MyRTKnet stations where IGS stations are fixed in ITRF2014

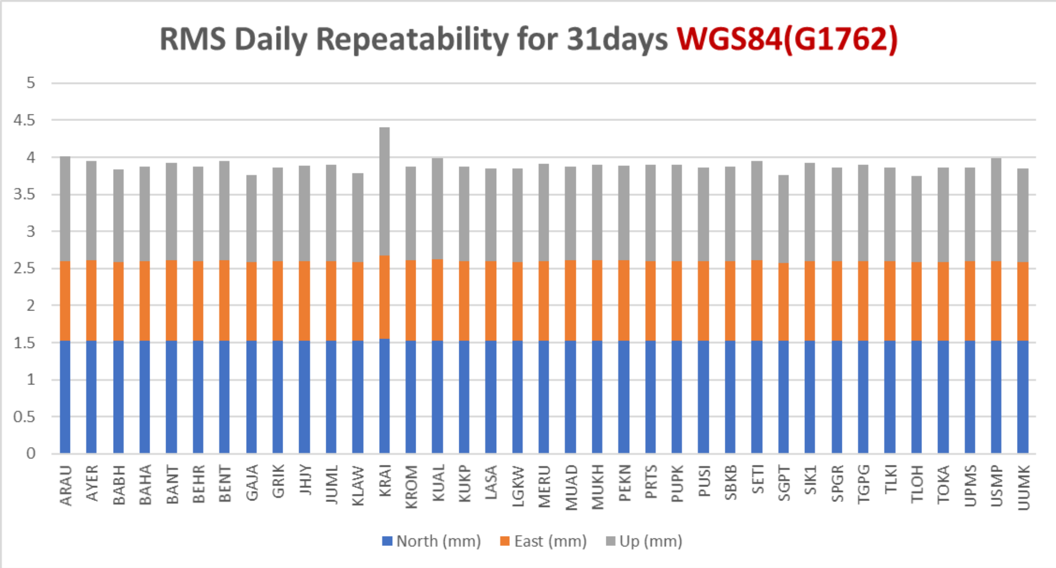

Figure 12. RMS of daily repeatability solution for 31 days for the selected MyRTKnet stations where IGS stations are fixed in WGS84 (G1762)

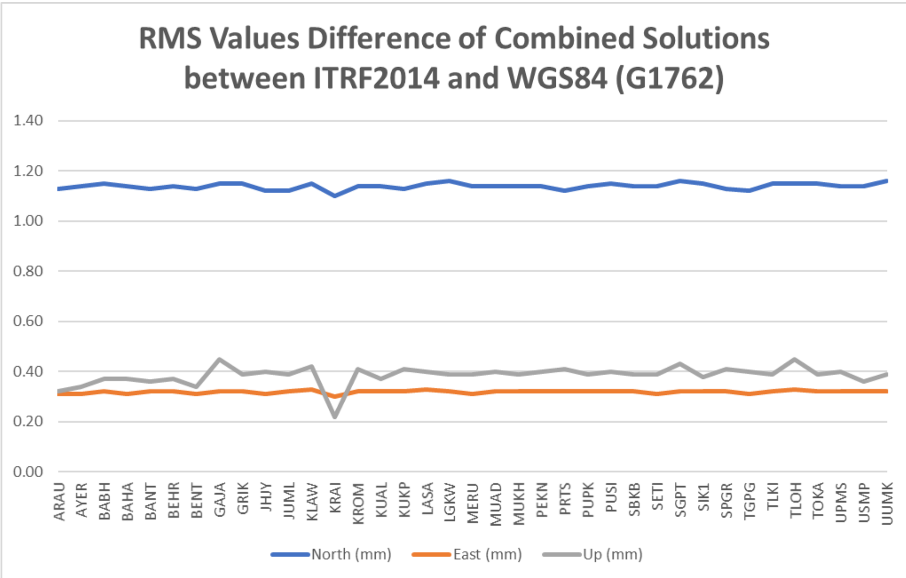

Figure 13: RMS Values Difference of Combined Solutions between ITRF2014 and WGS84 (G1762)

Figures 11 and 12 show that the RMS daily repeatability for 31 days of the selected MyRTKnet stations processed with IGS stations fixed in WGS84 (G1762) is higher than that of ITRF2014. Thus, the combined RMS values of ITRF2014 portray that the GPS data is of superb quality compared to WGS84 (G1762). It is apparent that the average values of the RMS daily repeatability for the North component for ITRF2014 is only 0.39mm [1.53mm for WGS84(G1762)], 0.76mm for the East component [1.07mm for WGS84(G1762)], and

0.91mm for Up component [1.29mm for WGS84(G1762)]. Overall, combined RMS values show the average value of 1.14mm for the North component, 0.32mm for the East component and 0.39mm for the Up component (See Figure 13). Subsequently, the most significant RMS repeatability values for all three components in ITRF2014 and WGS84 (G1762) are smaller than 2mm.

Therefore, it can be claimed that the GPS data's quality is good without fear of contradiction since the RMS values of the single difference baseline for all selected MyRTKnet stations are lesser than 2mm. However, on the other hand, the RMS values of the vertical component are usually three times worse than compared of the horizontal components (Md Din et al., 2015). Surprisingly, although ITRF2014's RMS values follow this trend, WGS84(G1762), on the other hand, indicates that the North component of RMS values is the highest among all. The possible reason for this is the smaller number of fiducial stations used in establishing the WGS84(G1762) network, where only eight IGS collocated stations were available to be used in the data processing. Conversely, twenty-five (25) IGS fixed stations were used in the ITRF2014 datum definition. Thus, the parameters or the unknowns in the WGS84(G1762) network could not be efficiently resolved compared to the ITRF2014 network.

3.4 Final Coordinate Solution

The function of 'Parameter Stacking' in Bernese 5.2 software allows the stacking of daily coordinate solutions where the normal equations files of each station coordinate to be combined into one set of parameters. The output obtained was 3D Cartesian coordinates; hence, the two dataset solutions were compared only after map projection, as shown in Figure 6. In this study, the positional discrepancy is assessed by comparing the final coordinate solutions of ITRF2014 and WGS84(G1762). Subsequently, the 3D geographical coordinates in Table 5 were projected to UTM projected coordinates in Table 6 before evaluating the final coordinate solution difference in Figure 14.

Table 5. Final Solution of three-dimensional (3D) geographical coordinates of selected MyRTKnet stations

3D Geo-graphical	ITRF2014 (Ellipsoid: GRS80)							WGS84 (G1762) (Ellipsoid: WGS84)						
	Latitude			Longitude			Ellipsoidal ht.	Latitude			Longitude			Ellipsoidal ht.
	°	'	"	°	'	"	(m)	°	'	"	°	'	"	(m)
ARAU	6	27	0.56908	100	16	47.04894	18.089	6	27	0.56376	100	16	47.06408	17.982
AYER	5	45	0.88387	101	51	36.52298	67.263	5	45	0.87862	101	51	36.5385	67.225
BABH	5	8	47.97274	100	29	37.17651	9.011	5	8	47.96756	100	29	37.19191	8.949
BAHA	2	48	23.4261	102	22	40.36177	67.385	2	48	23.42084	102	22	40.37759	67.371
BANT	2	49	33.44372	101	32	14.4612	8.800	2	49	33.43868	101	32	14.47736	8.752
BEHR	3	45	55.33374	101	31	1.95926	68.732	3	45	55.32867	101	31	1.97492	68.684
BENT	3	31	36.91163	101	54	25.92328	114.825	3	31	36.90649	101	54	25.93923	114.789
GAJA	2	7	20.24311	103	25	21.75362	60.206	2	7	20.23794	103	25	21.76964	60.175
GRIK	5	26	20.44515	101	7	48.98736	149.19	5	26	20.43993	101	7	49.00287	149.152
JHJY	1	32	12.51818	103	47	47.51143	39.163	1	32	12.5129	103	47	47.52754	39.153
JUML	2	12	42.31682	102	15	21.95123	19.782	2	12	42.31163	102	15	21.96724	19.77
KLAW	2	58	53.4348	102	3	49.19902	168.477	2	58	53.42935	102	3	49.21433	168.439
KRAI	5	30	7.17736	102	13	10.8593	31.707	5	30	7.17214	102	13	10.87544	31.637
KROM	2	45	47.02446	103	29	50.26215	23.577	2	45	47.01913	103	29	50.27821	23.555
KUAL	5	19	8.00237	103	8	20.92401	54.990	5	19	7.99722	103	8	20.93992	54.98
KUKP	1	19	59.79072	103	27	12.35598	15.353	1	19	59.78567	103	27	12.37192	15.322
LASA	4	55	25.81389	101	4	4.94895	61.451	4	55	25.80854	101	4	4.96446	61.396
LGKW	6	19	42.60798	99	51	4.53756	14.509	6	19	42.60258	99	51	4.5525	14.465
MERU	3	8	17.65327	101	24	26.84017	6.410	3	8	17.64832	101	24	26.8556	6.377
MUAD	3	4	18.45578	103	4	27.97186	50.07	3	4	18.45056	103	4	27.98786	50.056
MUKH	4	37	3.49635	103	12	34.01531	54.452	4	37	3.49118	103	12	34.03145	54.428
PEKN	3	29	33.35223	103	23	22.88515	25.999	3	29	33.34699	103	23	22.90121	25.976
PRTS	1	58	53.06876	102	52	23.02103	15.648	1	58	53.06394	102	52	23.03745	15.645
PUPK	4	12	25.17753	100	33	33.27092	13.821	4	12	25.17249	100	33	33.28656	13.794
PUSI	4	28	50.52752	101	1	6.33071	45.303	4	28	50.52233	101	1	6.34634	45.239
SBKB	3	48	45.99481	100	48	59.05763	15.527	3	48	45.98979	100	48	59.07349	15.486
SETI	5	31	56.98491	102	43	57.29129	43.709	5	31	56.97988	102	43	57.30719	43.67
SGPT	5	38	36.87953	100	29	18.14786	10.243	5	38	36.87425	100	29	18.16306	10.204
SIK1	5	48	35.63973	100	43	44.00206	44.340	5	48	35.6343	100	43	44.01762	44.279
SPGR	1	48	38.14373	103	19	15.52265	34.188	1	48	38.13857	103	19	15.53865	34.165
TGPG	1	22	2.67969	104	6	29.73165	18.071	1	22	2.67537	104	6	29.7478	18.064
TLKI	3	59	28.80219	101	3	13.8127	4.063	3	59	28.79735	101	3	13.82888	4.057
TLOH	3	26	58.0223	102	25	9.71285	56.999	3	26	58.01729	102	25	9.72873	56.968
TOKA	6	1	46.5936	100	24	12.84849	-3.322	6	1	46.58831	100	24	12.86364	-3.403
UPMS	2	59	36.22544	101	43	24.6335	100.370	2	59	36.22039	101	43	24.64945	100.346
USMP	5	21	28.03567	100	18	14.52962	19.875	5	21	28.0304	100	18	14.54493	19.798
UUMK	6	27	43.85596	100	30	22.80628	66.163	6	27	43.85064	100	30	22.82136	66.058

Table 6. Final Solution of UTM projected coordinates of selected MyRTKnet stations

	ITRF2014			WGS84 (G1762)		
	N(m)	E(m)	h(m)	N(m)	E(m)	h(m)
ARAU	713144.007	641518.666	18.089	713143.845	641519.132	17.982
AYER	636389.027	816801.557	67.263	636388.868	816802.036	67.225
BABH	569069.425	665559.923	9.011	569069.267	665560.397	8.949
BAHA	310748.516	875643.547	67.385	310748.356	875644.037	67.371
BANT	312663.764	782094.894	8.800	312663.61	782095.393	8.752
BEHR	416596.115	779591.722	68.732	416595.96	779592.206	68.684
BENT	390340.041	823028.577	114.825	390339.885	823029.07	114.789
GAJA	235282.553	992292.573	60.206	235282.395	992293.07	60.175
GRIK	601608.477	736039.795	149.19	601608.318	736040.273	149.152
JHJY	170464.879	1034170.711	39.163	170464.717	1034171.211	39.153
JUML	244864.137	862249.788	19.782	244863.978	862250.284	19.77
KLAW	330023.392	840613.543	168.477	330023.225	840614.017	168.439
KRAI	609116.369	856816.124	31.707	609116.211	856816.622	31.637
KROM	306351.924	1000373.563	23.577	306351.762	1000374.061	23.555
KUAL	589452.992	959008.475	54.99	589452.837	959008.967	54.98
KUKP	147816.378	995924.671	15.353	147816.223	995925.165	15.322
LASA	544600.732	729327.055	61.451	544600.569	729327.533	61.396
LGKW	699595.24	594153.98	14.509	699595.075	594154.44	14.465
MERU	347180.844	767569.278	6.410	347180.693	767569.755	6.377
MUAD	340393.177	953118.131	50.07	340393.018	953118.626	50.056
MUKH	511782.7	967313.927	54.452	511782.544	967314.427	54.428
PEKN	387182.413	988038.781	25.999	387182.254	988039.279	25.976
PRTS	219510.302	931048.632	15.648	219510.155	931049.14	15.645
PUPK	465180.38	673061.477	13.821	465180.226	673061.959	13.794
PUSI	495570.622	723964.39	45.303	495570.464	723964.873	45.239
SBKB	421645.25	701709.73	15.527	421645.097	701710.219	15.486
SETI	612826.66	913710.088	43.709	612826.508	913710.579	43.67
SGPT	624015.7	664839.674	10.243	624015.539	664840.142	10.204
SIK1	642482.995	691429.102	44.34	642482.83	691429.581	44.279
SPGR	200699.805	981036.631	34.188	200699.647	981037.127	34.165
TGPG	151746.833	1069019.078	18.071	151746.701	1069019.58	18.064
TLKI	441454.066	728038.708	4.063	441453.918	728039.207	4.057
TLOH	381955.478	880030.465	56.999	381955.326	880030.956	56.968
TOKA	666677.54	655339.085	-3.322	666677.378	655339.552	-3.403
UPMS	331239.199	802761.834	100.37	331239.045	802762.327	100.346
USMP	592367.377	644489.148	19.875	592367.216	644489.62	19.798
UUMK	714542.124	666578.292	66.163	714541.962	666578.756	66.058

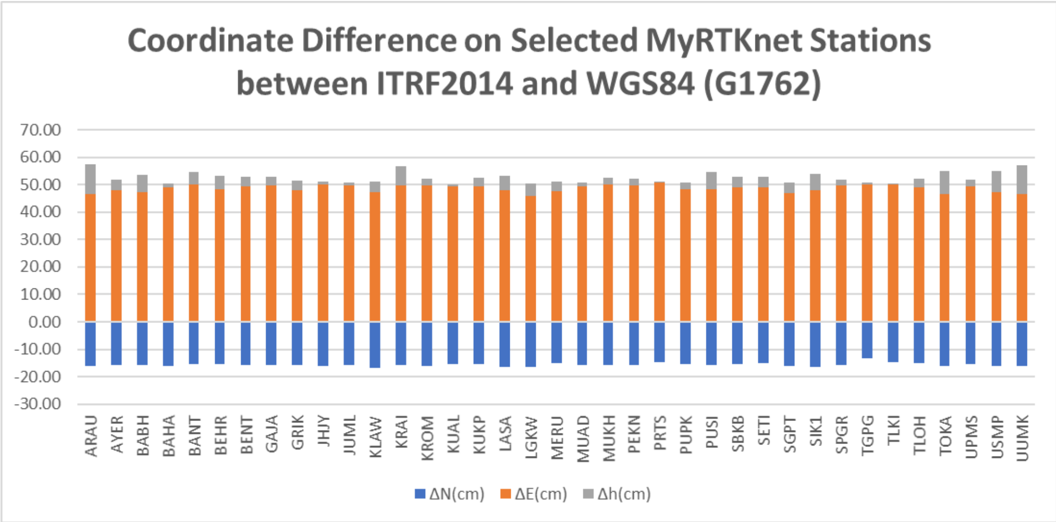

Figure 14. Final coordinate solution difference of ITRF2014 and WGS84 (G1762) in UTM coordinates and ellipsoidal height for MyRTKnet stations

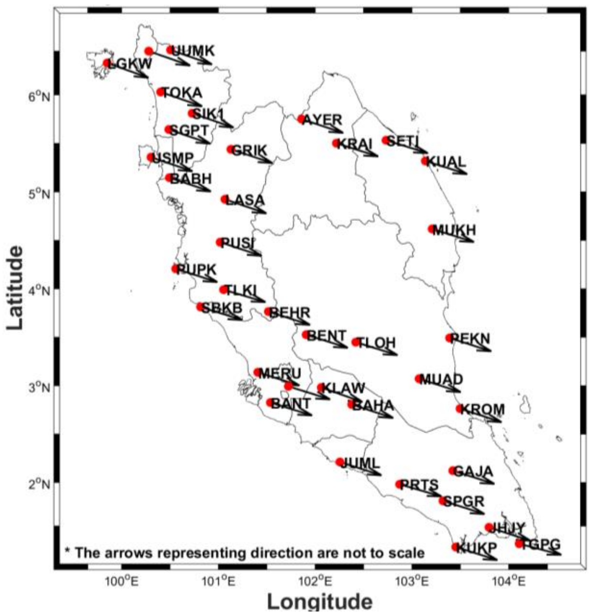

Figure 15. The overview of formal error of selected MyRTKnet stations in terms of their magnitude and azimuth

In computing the coordinates' precision, each station's formal standard error was determined so that the respective stations' magnitude of formal error (horizontal and vertical) and its azimuth could be determined. Figure 15 exhibits the overview of the formal error of selected MyRTKnet stations in their respective magnitude and azimuth. The average magnitude of formal error for the selected MyRTKnet stations for horizontal components (North and East) is 51.14cm and 3.88cm for the vertical component. All the stations are placed in quadrant IV with an average azimuth of 107° 54’ 11”.

The formal error is a method used to represent the semi-major axis or error ellipse which describes the formal positional error of a station (Liu et al., 2018). The vertical component has a higher precision compared to the horizontal components. The magnitude representing the distance of the formal positional error has accumulated both North and East values. Besides, the direction or azimuth tells us which direction the error ellipse is facing. Thus, the formal error helps to determine the precision of the station position difference or discrepancy. All the final coordinate solutions fall within the formal error range, meaning the accuracy is acceptable.

3.5 Comparison between ITRF2014 and WGS84 (G1762) on MyRTKnet stations

The comparison between ITRF2014 and WGS84 (G1762) was made after performing the processing using a double-difference approach between ITRF2014 and WGS84 (G1762) at MyRTKnet stations, respectively (see Figure 5). According to Hu (2019), the final epoch solution's quality and internal precision must be determined by estimating the day-to-day scatter coordinate with the weighted epoch mean. Therefore, the comparison and assessment between ITRF2014 and WGS84 (G1762) were made according to (i) average RMS daily repeatability for internal precision and (ii) accuracy of final coordinate at selected MyRTKnet stations.

3.5.1 Internal Precision of WGS84 (G1762) and ITRF2014

‘Stacking’ the individual time series is the popular technique used (Altamimi et al., 2008, 2016 & Azhari et al., 2020) to estimate the station positions solutions in long-term solutions at specific reference epoch. The values of combined RMS daily repeatability of 31days have significantly improved compared to single individual daily solutions. When the reduced normal equations files are being stacked together, reduced number of unknowns and pre-elimination for data screening and parameters that could not be pre-eliminated constraining to the network ensures the normalisation of normal equations (Dach et al., 2015).

The dataset solution-processed in WGS84 (G1762) has lower internal precision than ITRF2014, with an average combined RMS values difference of 1.140mm for the North component and 0.318mm for the East component 0.386mm for Up components. In addition, due to the number of parameters, or the unknowns in WGS84(G1762), only eight IGS collocated stations could be fixed as fiducial stations in the network solution compared to 25 IGS fixed stations used in the ITRF2014 datum definition.

3.5.2 Accuracy of Station Coordinates in WGS84 (G1762) and ITRF2014

Combining the station positions solutions in long-term solutions at specific reference epochs resulting from stacking gives the long-term coordinate solutions with the local ties in co-location sites (Altamimi et al., 2008, 2016 & Azhari et al., 2020). The final coordinate solutions produced in the report were in 3D Cartesian coordinates; however, the difference of values in 2D Cartesian coordinates, therefore the difference between the two sets of coordinate difference is compared in Northing, Easting and Up components map projection.

The rover stations' coordinates which are the MyRTKnet stations processed between WGS84(G1762) and ITRF2014 show the average values of -15.71 cm for the North component, 48.66 cm for the East component and 3.88 cm for the Up components. Therefore, the assumption made by NGA (2014), Li (2014) and Qinsy (2020) that the WGS84 (G1762) and ITRF2014 coincide at 10 centimetres level is not achievable in this study for North and East components. Still, for the Up component, the assumption stays true.

Besides the input data uncertainty and lower quality of observation (Pham Thi et al., 2019), the difference of epoch adopted for ITRF2014 and WGS84(G1762) was realised at 2010.0 and 2005.0, respectively, have to be taken into consideration as well. According to GEOG (2020), the movement of positions from one epoch to another must be calculated to ensure an optimal accuracy between two datums. Another possible reason for this is the local deformation that takes place at the MyRTKnet stations. Therefore, it is suggested that the transformation positions between WGS84(G1762) and ITRF2014 from one epoch to another be calculated using software like Horizontal Time-Dependent Positioning (HTDP), which also considers the factor of seismic activity (Haider et al., 2020).

4. Conclusion

Overall, this study has successfully addressed the first question, which is "Does WGS84 (G1762) align with ITRF2014 at centimetre level?" through the assessment of the positional discrepancy and accuracy of selected station coordinates in both ITRF2014 and WGS84(G1762) reference frames in Peninsular Malaysia. The results show that the rover stations' coordinates, which are the MyRTKnet stations processed between ITRF2014 and WGS84(G1762), show the average values of -15.71 cm for the North component, 48.66 cm for the East component and 3.88 cm for Up components. Hence, it is concluded that the level of discrepancy in the average magnitude for the horizontal component is 51.14 cm and 3.88 cm for the vertical component for one month of the study period. This difference is considered significant mainly for the region of Peninsular Malaysia; hence it must be deemed to establish a proper datum transformation between ITRF and WGS84 geodetic datums in the future.

Although the second question, "Is WGS84 reliable enough to be a geodetic datum in terms of its traceability?" is not addressed in this study, WGS84 inevitably raised doubts of the users about its reliability when the version or the epoch of WGS84 is often not clarified or justified (ICSM, 2020). Although the difference is relatively insignificant for charting and navigation purposes, this uncertainty will further deteriorate the accuracy of the geodetic datum. Due to its inability to meet the requirement of legal traceability, WGS84 is not traceable and reproducible (Land Information New Zealand, 2016; Geoscience Australia, 2020).

The authors are confident that this study will serve as a base for further studies on the accuracy offered by ITRF and WGS84 at specific epochs. It is hoped that the users will be given insights into a more transparent and known accuracy datum. It is significantly essential that the users be made aware of the accuracy of the desired geodetic datum, especially during the establishment of national or regional datum other than geodetic-related applications, including surveying, mapping and scientific studies. Therefore, it is recommended that a proper datum transformation with known transformation parameters between ITRF2014 and WGS84(G1762) be conducted to evaluate the accuracy between these two models more reliably. Besides, it should be noted that WGS84 can be used for navigation purposes in surveying communities but is not as suitable as a geodetic datum due to its traceability issue. For high accuracy demanding applications like national geodetic datum development, ITRF should be adopted instead of WGS84.

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