The implementation and advancement of a regional geodetic vertical datum

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Abstract. The essential parameter in computing three-dimensional coordinate system is the height or depth of the Earth’s surface. It represents a particular reference surface that recognised as a vertical datum. The vertical datum is alienated into two foremost categories recognised as Mean Sea Level and Lowest Astronomical Tide. Different modifications approach, techniques and software programs are developed to determine vertical datum of a region with respect to geoid surface. This paper presents an effort to review and discuss the implementations and advancement of geodetic vertical datum based on geoid height reference surface. Hence, there are eight countries will be extracted and outlined in this paper consist of the United States of America, Australia, Taiwan, New Zealand, South Korea, Thailand, Philippines and Malaysia. An overview of geodetic vertical datum which implemented in these countries are summarised to support the future development of a regional vertical datum model. Then, the overview will also be utilised and analysed based on the essential elements and parameters for vertical datum model determination which include: data gathering, data input and analysis approach in order to develop a geodetic vertical datum model with good accuracy. These attempt and initiative are vital for the current and future implementation and advancement of geodetic vertical datum in the region of Malaysia across land and marine areas.

Keywords: Height, Vertical Datum, Mean Sea Level, Lowest Astronomical Tide, Geoid Model

Track Name: Coastal Management and Marine Ecosystem

1. Introduction

Vertical coordinates or heights of points are based on a coordinate surface known as vertical datum. The vertical datum of a height network is described as remitting the zero height to the Mean Sea Level.
(MSL) referred to a particular period at a classified tide gauge in the prior 200 years. Traditionally, this reference height surface is implemented in countries to determine a regional vertical datum. Conventional spirit level is used to transfer the determined MSL value of the tide gauge measurement from the benchmark to another point for determining height differences that provides good accuracy [1]. Nevertheless, in a large area practically, it is costly and challenging particularly that require a huge point’s number towards the need of height.

A seamless reference surface represents a continuous and time-invariance surface. Due to the irregular topographic surface of the Earth, the geodetic computations and determinations are difficult to be performed. To clarify this issue, geodesists utilise a flat and even mathematical reference surface to determine the irregular shape of the Earth’s surface, hence, precisely explains as to determine a regional geoid height. [2] defines geoid as an equipotential surface of the Earth’s gravity field closely approximates with mean sea level. Besides, geoid is also defined as the equipotential surface of the Earth’s gravity field that best fits to the mean sea level [3] with a constant value of the gravity potential on the surface.

Global Navigation Satellite System (GNSS) is a revolution in this era of survey and mapping activities, which has turned out to be more necessitating than conventional levelling measurement [4]. The evolution of GNSS in providing a position with good accuracy up to mm level has been verified but there is lack of physical description. Thus, height transformation procedure is needed with the availability of high resolution and precise gravimetric geoid model. The GNSS ellipsoidal height is transformed to orthometric height (H) reference to geoid height by subtracting geoid heights (N) from the GNSS ellipsoidal heights (h).

GNSS levelling plays an important role in providing a good accuracy of geoid model. Currently, the height system has revolutionized by several countries through geoid modelling for determining orthometric height implementing GNSS levelling instead of conventional levelling. The initiation of new gravity from satellite gravity missions which provide an accurate Global Geopotential Model (GGMs) to be combined with the terrestrial gravity data either from land or marine area which the gravity data can also be integrated with several technique that require to be optimised properly with good geoid model accuracy.

Therefore, this paper affords to revise the techniques implemented towards the establishment of geodetic vertical datum implementation for a region. Six (6) countries are elected in this study in order to revise the geodetic vertical datum techniques and methods implements in Malaysia, United States of America, Australia, Taiwan, New Zealand, South Korea, Philippines and Thailand.

2. Geodetic Vertical Datum Implementation

There are numbers of vertical datum implemented for land and marine area in the determination of height or depth. However, the tidal observation is utilised to a reference datum, entirely [5]. Survey and mapping in Peninsular Malaysia is referred to Peninsular Geodetic Vertical Datum (PMGVD) via First Order Precise Levelling Network (FOPLN) as a vertical datum. Nevertheless, for charting activities, local Chart Datum (CD) via Lowest Astronomical Tide (LAT) are utilised. The knowledge about the discrepancy of height or depth at the coastal areas turn out to be crucial due to rapid development in a region [6]. The vertical network establishment in Peninsular Malaysia, Sabah and Sarawak are developed discretely. Besides, the levelling networks in Sabah and Sarawak are disjointed and referred to numbers of vertical datum [7].

Peninsular Malaysia Seamless Geoid Model 2014 (PMSGM2014) by [8] is the initial gravimetric geoid model in Peninsular Malaysia, which is computed using the Least Squares Modification of Stokes with Additive Corrections (LSMSA) or known as KTH approach. Nevertheless, this geoid model is developed by utilising terrestrial land and marine gravity without the utilisation of airborne gravity data. Thus, two types of geoid model is presented known as the gravimetric and hybrid (fitted) geoid models. The verification is performed by implementing GNSS-levelling points with 10 cm accuracy of the geoid model.
Nevertheless, an accuracy of a hybrid geoid model with a mean parametric surface corrector model established by [8] provide high Root Mean Square (RMS) of 7 cm as evaluated to the official geoid model over Peninsular Malaysia, MyGEOID. This is defying as the development of PMSGM2014 model without the utilisation of airborne gravity data with the gravity data problem related to the sparse of terrestrial gravity data that affected an accuracy of a gravimetric geoid model. Next in 2020, [9] has been developed, a latest height reference system modernisation in Peninsular Malaysia using LSMSA technique by integrating the airborne gravity data known as Peninsular Hybrid Geoid 2020 (PMHG2020). The hybrid geoid models were validated with GNSS levelling points and provided the optimum two parameters comprised of 50 km correlation length and 0.03 m with an accuracy, RMSE of 0.04716 m.

In United States of America, American Vertical Datum (GRAV-D) has been proposed by the National Geodetic Survey (NGS) in 2022 to redefine the vertical datum with the integration of airborne gravity, terrestrial gravity, latest satellite gravity and altimetry data from DTU13 known as XGEOID2020 [10]. The aim of this project is to achieve 2 cm accuracy level of the gravity-based vertical datum and comprised in the NGS 10-year plan.

The NGS has a distinctly mentioned mission to delineate, maintain and provide retrieve to the National Spatial Reference System (NSRS). The major fundamental of the NSRS is the height determinations with regard to the ellipsoidal height, orthometric height and dynamic height which any points or locations in the United States or its territories. Besides, NGS play a crucial role in of presenting the basic data and information for federal mapping activities in the nation.

The varies of the ellipsoidal heights over times in the United States have been estimating by NGS with the utilisation of GPS Continuously Operating Reference Stations (CORS). Moreover, the current regional gravity data has been surveyed and measured by NGS, then the gravimetric geoid model is developed. However, these attempts are inadequate at the maximum levels of accuracy, because of tremendously incongruent type of the available data and crustal motion.

The nation requires to handle a gravity survey due to the current regional gravity are insufficient for performing its requirement to the enormous NOAA mission. The high-resolution gravity survey needs to be conducted in recognition of the need to estimate the varies of heights which derived from estimated varies of gravity field information, particularly the geoid. Firstly, the improvement of existing gravity fields with dense spatial distribution, but with a short temporal span based on high resolution snapshot. Next, low-resolution movie to track the temporal changes to the gravity field on a broad scale which a re-occurring survey with very coarse spatial coverage and a long temporal span. Then, a terrestrial collaboration surveys to determine a regional gravity field data to the fine-scale regional determination of heights.

Hence, there are several issues need to be highlighted in a re-survey, for example, the data gaps, aged data, discontinuities, imbalance of spatial coverage, lack of data and knowledge with respect to gravity field varies over time and incompetence to retain the existing vertical datum realization. As a solution in order to establish a regional geoid model with good accuracy and track the varies through time, hence, a supplementary data in addition to the gravity survey will be vital. For example, the digital elevation models (DEM), geoid slopes from co-located (temporally and spatially) levelling and GPS surveys over large regions, rock densities of the largest mountain ranges of the United States, bathymetry of main lakes and near-shore regions of the United States, deflection of the vertical for testing upward continuation algorithms as required, gravity gradiometry and satellite derived gravity models.

Meanwhile, Australia implements a fitting gravimetric geoid or quasi-geoid models to GPS-levelling data and it is crucial in Australia due to distortions in the Australian Height Datum (AHD). Hence, Australia took an alternative to fit the Australian Gravimetric Quasigeoid 2017 (AGGQ 2017) [11] model to a nationwide GPS-levelling dataset [12] to establish a model of the separation between the GDA2020 ellipsoid and the AHD. Hence, a direct transformation between ellipsoidal and AHD heights is permitted. This method is a combined gravimetric-geometric model or known as “hybrid quasigeoid model”.

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According to Kotsakis and Sideris [13], a combined gravimetric-geometric model are affected by errors in GPS ellipsoidal heights, heights estimations, levelling data and systematic errors in the geoid model. Consequently, the geometric component is determined and its complementary grid of improbability values utilising least squares prediction (LSP) [14]. The existing AUSGeoid model known as AUSGeoid2020 is established with respect to a combined gravimetric-geometric model be associated with a 1’ by 1’ grid of ambiguity values propagated from input data into the LSP-gridded surface. Thus, Australian geodetic datum is transformed from GDA94 to GDA2020 and referenced to International Terrestrial Reference Frame 2014 (ITRF2014) [15]. The geometric component of AUSGeoid2020 was established by adopting least squares prediction (LSP) based on 7624 co-located GPS-levelling points across Australia. Hence, 40 points were determined to misfit AUSGeoid2020 by more than five standard deviations from the mean after handling a primary cross-validation test. Then, the points were removed and the geometric component redefined.

By referring to the outputs in [16], AUSGeoid2020 presents an approach to transform between GPS-derived ellipsoidal heights and AHD heights. Next, the differences of AHD height are computed. Pseudo-independent accessing of AUSGeoid 2020 has presented that it is capable to transform from ellipsoidal heights to AHD heights with ±27 mm, an absolute uncertainty. Thus, AUSGeoid 2020 is similar or enhanced as compared to conventional third-order levelling in Australia at distances beyond ~3 km.

The development of a high-resolution geoid model in Taiwan needs a substantial effort in gravity data collection and statistical techniques [17]. Taiwan is bounded by the Pacific Ocean to the east with deep trenches, the South China Sea to the south, the Taiwan Strait to the west and the East China Sea to the north. The topography of Taiwan is mostly rugged (up to 4000 m high), with flat regions only on its coastal plans. Land-based gravity surveys can only be performed along mountains treks and easy access area. Hence, a precise geoid model is required to overcome these issues.

In order to overcome these problems, three-dimensional, real-time cm-level positioning has been performed by utilising a continuous GNSS network. Next, the Kuroshio Current east of Taiwan and the surrounding seas perform large gradients in the dynamic ocean topography over Taiwan that can influence great variances in the vertical datums between Taiwan and its offshore islands. To end, Taiwan’s ellipsoidal heights and most parts of Taiwan’s offshore islands have been measured and surveyed by Light Detection and Ranging (LiDAR). A transformation method from ellipsoidal heights to orthometric heights necessitate a precise geoid model. The accuracy of a geoid model in low-lying areas and foothills play an importance role to weighing flooded zones and geohazards due to high sloping topography.

In geoid modelling, there are three categories of data implemented specified to terrestrial (land and near shore) gravity data such as terrestrial land gravity, airborne gravity and the offshore gravity data and described as follows:

1. Land gravity data
   This data set is classified into two division:
   a) Division 1: gravity data consisted over 1980 until 2003 at Taiwan’s horizontal control points and first-order benchmarks
   b) Division 2: gravity data surveyed over 2004 until 2006 except gravity measurements based on horizontal control points [18].

2. Airborne gravity data
   Over 2004 until 2009, three airborne gravity measurements were accomplished to measure and survey gravity data over Taiwan [19] [20].

3. The offshore gravity data
   The gravity data were surveyed within 50 km to the five tide gauges and over waters 20 km offshore Taiwan. This survey is significance to improve vertical datum linking between Taiwan and islands, besides for the coastal geoid model improvement.
However, in order to fulfil the data gaps in the shipborne gravity data along the coastal area, the altimeter-derived sea surface heights (SSHs) was utilised to fulfil that occupied area. Then, the current approach is used to model a gravimetric geoid model that referred to gravity anomalies on the ground and the implementation of planar terrain corrections. Primarily, the height anomalies are determined resulted by transformation to geoidal heights. Hence, in the determination of a localised gravity fields information, a global geopotential model and a Digital Elevation Model (DEM) were needed. Next, a gravimetric geoid model in Taiwan is established which is implemented in the development of a hybrid geoid model using the computed geoid heights with respect to the remove-compute-restore technique. The details regarding to the procedure and step in the development of a new gravimetric-only and hybrid geoid models has been described in [17]. Based on the findings in [17], the combining of gravimetric geoid with the GPS and tidal records provides the errors identifications of about 40 to 50 cm in the existing geodetic vertical datums.

Next in 2009, New Zealand officially utilised a gravimetric quasi-geoid model as the primary national vertical datum known as NZVD 2009 model [21]. Previously, 13 various local vertical datum were adopted, each of a regional vertical datum were referenced to dissimilar tide-gauge with respect to localised mean sea level. Due to these issues, there were offsets of up to 0.4 m amongst the NZ local vertical datum. The NZGeoid2009 model was merged with the local vertical datum by computing the local offsets from the iteratively computed gravimetric quasigeoid model [22], [23], [24].

The gravity field data was implemented to determine NZGeoid 2009 for quasigeoid modelling. The terrestrial land gravity data largely comprise of ancient measurements with irregular accuracy and sparse distribution, commonly isolated to valley through rough terrain areas. Besides, satellite altimetry data provides large error in coastal areas, and the large survey vessels commonly for shipborne gravimetry surveys unable to navigate near to the coast. Hence, an appropriate set of gravity measurements with a consistent spatial distribution (seamlessly onshore and offshore) and consistent precision is needed in order to provide precise quasi-geoid modelling. Thus, as a solution, airborne gravimetry measurement gives large and good gravity field coverage over challenging areas. It is an appropriate technique for the determination of regional geoid computations; hence, it will enhance the gravimetric quasi-geoid model [25].

The terrestrial, shipborne, altimeter and airborne gravity measurements were reduced to refined Bouguer gravity anomalies and then integrated onto a single grid at the topographic surface using least squares collocation (LSC). The gridded data were then transformed to estimate Molodensky gravity anomalies, by joining the Bouguer plate term. The modified Stokes integration [26] and remove-compute-restore technique was used in the determination of quasigeoid heights that implemented EIGEN-6C4 global gravity model as a reference field. The quasigeoid model was fitted to 1422 independent GPS-levelling-derived quasigeoid heights, consequent to removal of offsets between the dissimilar levelling datums in New Zealand. The outputs represent 4 mm more precise than EIGEN-6C4 and 14 mm more precise than NZGeoid 2009 based on the differences between the gravimetric quasigeoid and the GPS-levelling data. However, the largest-magnitude change in quasigeoid heights with 0.122 m subsequent to the contribution of airborne gravity data. Thus, the evaluation of a regional quasigeoid heights with GPS-levelling data were more precise for each set of integration parameters.

However, in 27 June 2016, New Zealand Vertical Datum 2016 (NZVD2016) substitutes NZVD2009 as the authorised vertical datum for New Zealand. This new vertical datum model is determined by the NZGeoid2016 geoid. The vertical datum values in the local vertical datum correlations grids differ with horizontal position. Where, it is slightly dissimilar from NZVD2009 that represents an average offset for the whole local vertical datum. NZVD2016 is constant with NZGD 2000. Thus, the normal-orthometric NZVD2016 heights can be converted to ellipsoidal NZGD2000 heights, conversely. NZVD2016 model is properly determined in the LINZ standard LINZS25009 (Standard for New Zealand Vertical Datum 2016) [27].
The National Geographic Information Institute (NGII) has established three Korean national geoid (KNGeoid) models recognised as KNGeoid13, KNGeoid14 and KNGeoid18 by utilising the Earth’s gravity field model, satellite-altimetry-derived gravity data, land and ocean gravity data, airborne gravity data and digital elevation model (DEM) data. These geoid models are hybrid geoid models accomplished by NGII to the height measurement accuracy with respect to GNSS measurements.

Primarily, the KNGeoid13 model is developed by NGII for land area which developed based on gravity data from several national control points (unified control point, benchmark and triangulation point), airborne gravity data [28], DTU10 satellite altimetry data, EGM 2008, and 5m gridded topographic data. Then, in 2014, KNGeoid13 model was established by using the equivalent methods by combining the gravity data and shipborne gravity data from Korea Hydrographic and Oceanographic Agency (KHOA) that provides, 3.3 cm of residual’s standard deviation [29]. The final procedure, the KNGeoid18 model was developed by implementing Experimental Gravity Field Model 2016 (XGM2016) with respect to GOCE gravity data [30] as the first sort of Earth Gravitational Model 2020 (EGM2020) with standard deviation of residual about 2.33 cm. Hence, EGM2008, EIGEN-6C4 and GECO model have been implemented as a Global Geopotential Model (GGM) with coefficients up to degree 2190. The accuracy of the geoid heights derived from the latest released Earth gravity model based on gravity data was validated with the geoid heights derived from the Global Navigation Satellite System (GNSS)-levelling, 1182 unified control points (UCPs) developed by the National Geographic Information Institute (NGII) over South Korea.

Hence, by referring to the output provided by [31], the geoid heights derived from the three high-degree global geopotential models (GGMs) and the three Korean National Geoid (KNGeoid) models represented regular distributions ranging from 17 to 33 m around South Korea. Next, the EGM2008 model gave a good residual accuracy with root-mean-square-error (RMSE) that relative to geoid heights accuracy. Thus, the EGM2008 model is suitable model than the GECO and EIGEN-6C4 for a region of South Korea and could be selected as an appropriate GGM for determining a gravimetric geoid model. Lastly, among the three KNGeoid models, the KNGeoid18 model was represented a good gravimetric geoid model accuracy over South Korea rather than the KNGeoid13 and KNGeoid14 models with respect to the GNSS/levelling-derived geoid heights.

Previously in Philippines, the determination of orthometric height and benchmarks was performed using Geodetic levelling, a tiresome procedure that obstruct the densification of benchmarks. 22851 benchmarks are established along major roads nationwide with a maximum divergence of 4.0 mm√K between two level runs (1st order accuracy) during the Philippine Reference System 1992 (PRS92) in 2007. These level networks were linked to the respective reference tidal benchmarks to provide local mean sea level elevation. Hence, the primary step of determining a preliminary gravimetric geoid for the Philippines is through the Natural Resources Management Development Project (NRMDP) in year 1991. Land gravity data and altimetrically-derived anomalies at marine area and a reference global model from OSU89A as a reference model to degree and order 360 were utilised [32].

Then in 2014, a preliminary geoid model known as Philippine Geoid Model 2014 (PGM2014) has been performed with the technical assistance of National Space Institute-Denmark Technical University (DTU-space) and a financing from National Geospatial Intelligence Agency (NGA). The land gravity, airborne gravity, marine satellite altimetry and the latest satellite gravity data from the GOCE mission release 5 are performed with 0.30 m accuracy. The PGM2014 is determined by a set of Fortran routines known as GRAVSOFT system established by DTU-Space and Niels Bohr Institute, University of Copenhagen [33]. It conducts the base of major recent geoid computation projects like the joint Nordic “NKG” geoid models, conducted as joint geoid model computations of the Nordic and Baltic countries [34] under the auspices of the Nordic Commission for Geodesy (NKG), as well as the OSGM02 geoid model of the UK and Ireland [35] and numerous national geoid models performed from airborne surveys in current years such as Malaysia, Mongolia, Indonesia and many more.

Hence, a “remove-restore” technique was performed in determining the geoid with full 3-dimensional modelling going via the quasigeoid to the final geoid, where a spherical harmonic earth geopotential model (EGM/GOCE combination) is utilised as a base. The EGM08 model is
encompassing GRACE satellite data which identifies the error spectrum of the EGM08 up to spherical harmonic degree 80 or so. The terrain part of the computations was referenced to RTM method, where topography is referred to a mean elevation level, and only residuals relative to this level is considered. The gravimetric geoid is determined using spherical FFT method with optimised kernels. This method is an alternative of Stokes integral in which there is an appropriate weighting of the long wavelengths from EGM08 and shorter wavelengths from the regional gravity data.

The gravimetric geoid is determined on a grid of 0.025° x 0.025° resolution covering the Kalayaan Island of West Philippine Sea using least squares collocation and Fast Fourier Transformation methods. Thus, the final input used in PGM 2014 computations are airborne gravity data, land gravity from NAMRIA, DTU10 global gravity anomalies from multi-mission satellite altimetry (the chosen open ocean area, away from the airborne gravity), SRTM 15’’ DEM data for the region and EGM08 and GOCE RL5 satellite data. A series of 190 GPS data in ITRF2005 levelling benchmarks is utilised to verify with the final computed geoid. These GPS data represented high errors relative to the geoid with high outliers in certain regions due to a combination of geodynamic effects, levelling and GPS errors.

For the improvement of a regional geoid model, several recommendations are suggested by [36]. Then, the PGM2014 was re-determined to the current Philippine Geoid Model (PGM2016) with an accuracy of 0.022 m, the accuracy is reduced compared to PGM2014 geoid model. Where, the additional land gravity stations (from 2017 until 2020) are combined with the similar airborne and satellite gravity data in order to re-determine a latest the Philippine geoid model.

The Royal Thai Survey Department (RTSD) collaborated with Chiang Mai University and Chulalongkorn University developed THAI12H regional geoid model [37] utilising 3979 land gravity points with as near to 5 cm accuracy in Bangkok Metropolitan Region. Nevertheless, Chao Phraya basin, the northern part of Thailand and another area represents the larger errors up to 30cm due to low intensity of gravity measurements performed before 1991. Besides, the outdated land relative gravimeters could influence the value of the gravity measurements. The establishment of a current geoid model for Thailand was performed in 2015 to develop a height modernisation system that connected the geoid model to the national real-time kinematic network (RTK GNSS network). This height modernisation system will represent elevation values significance for natural disaster management which spirit levelling unable to perform and other vertical positioning works [38].

TGM2017 was established in 2005 until 2007 [39] over the Short-Term National Water Strategy Plan, then published to public users in 2018. This model was developed based on the current gravity data sets of more than 10 000 terrestrial land and airborne gravity data over Thailand’s territory by RTSD. Hence, TGM2017 model was determined from the airborne and terrestrial gravity data utilising remove-restore technique. Then, EGM2008 and DTU13 were utilised for the marine area and uncovered airborne gravimetric surveys for land area, respectively [40]. The gravimetric data were gridded utilising least-squares collocation within the study area as suggested by [41]. Next, the multi-band spherical Fast Fourier Transform (FFT) approach was utilised for determining and computing TGM2017 geoid model with the spatial resolution of one-arc minute regular grid around 1.8km.

For validating the TGM2017 geoid model, \( N_{TGM} \), 100 GNSS/levelling-derived geoid heights, \( N_{kolak} \) points was utilised using two procedures as elaborated in [38]. The values of geoid heights from the model were compared with those derived by the combination of Kolak-1915 orthometric (or leveled) heights and GNSS-based geodetic (ellipsoidal) heights. The validation of the new gravity measurements over Thailand enhanced the long- and medium-wavelengths of TGM2017 model by comparing with EGM2008 model at 360 and 2190 degree. Nevertheless, TGM2017 model was fitted to Kolak-1915 vertical datum, where EGM2008 was inconsistent. Then, the previous gravimetric geoid model known as THAI17G geoid model was utilised instead, to develop TGM2017 geoid model. Hence, the final validation represented the enhanced of TGM2017 geoid model than other geoid models with standard deviation of 4.9 cm.
3. Results and Discussions

Each country comprised of their own regional geodetic vertical datum developed based on gravity field information. The development of geodetic vertical datum is conducted based on selected and different approach as represented in Table 1. Hence, the geodetic vertical datum of Malaysia is developed by utilising Least Squares Modification of Stokes with additive corrections (LSMSA) approach. However, other countries such as United States of America, New Zealand, Thailand and Philippines adopting Remove-Compute-Restore (RCR) approach in the development of their regional geoid model. Besides, Thailand and Philippines also utilised FFT method in a localised geoid computation. However, Australia represents a new technique called as the combined gravimetric-geometric model also recognised as hybrid quasi-geoid model. The combined gravimetric-geometric models are influenced by errors in GPS ellipsoidal heights, estimations in the determination of heights, errors in the levelling data and systematic errors in the geoid.

Thus, it can be figured out that airborne gravimetry provides a good data coverage especially over inaccessible areas like coastal areas and in rough topography. As discussed in previous section related to the geodetic vertical datum in New Zealand, the terrestrial data largely consist of historical measurements of varying accuracy with sparse distribution, commonly remote to valleys through areas of rough terrain areas. In addition to that, satellite altimetry data are unreliable in coastal areas [42] besides, the large survey vessels typically implemented for shipborne gravimetry also unable to navigate close to the coast. For the development of a precise quasigeoid modelling, the gravity measurements with a consistent spatial distribution (seamlessly onshore and offshore) and precision is needed with an adoption of a suitable gravity data for a regional geoid computation. Due to this reasons, airborne gravimetry appears well suited to account for the shortcomings of the existing gravity data in each country to enhance the gravimetric quasigeoid model [43]. Moreover, Global Geopotential Model (GGM) and marine gravity data from DTU are suggested to be utilised to cover up the lack of terrestrial gravity and airborne gravity data for land and marine area as performed by Thailand.

Table 1. The vertical datum applications in Malaysia, United States of America, Australia, Taiwan, New Zealand, South Korea, Philippines and Thailand.

| Study Area          | Data Gathering                  | Data Input                                      | Analysis Approach                  |
|---------------------|---------------------------------|------------------------------------------------|-----------------------------------|
| Peninsular Malaysia | Terrestrial land gravity data,  | Gravity data, geoid heights, othomeric heights | LSMSA and Fitted geoid            |
|                     | Ship track marine gravity data, | and ellipsoidal heights                         |                                   |
|                     | International Gravimetrics      |                                                |                                   |
|                     | Bureau GGM and Satellite        |                                                |                                   |
|                     | altimetry data from DTU10       |                                                |                                   |
| Peninsular Malaysia | Terrestrial gravity, airborne   | Gravity data, geoid heights, othomeric heights | LSMSA                             |
|                     | gravity, satellite gravity      | and ellipsoidal heights                         | Fitted geoid/hybrid geoid (fitted  |
|                     | data from GGM, shipborne        |                                                | to PMGVD and MSL)                |
|                     | gravity, satellite altimetry    |                                                |                                   |
|                     | from DTU13, GNSS levelling      |                                                |                                   |
| United States of    | Airborne gravity, latest        | Gravity data                                    | R-C-R                            |
| America             | satellite gravity models,       | Timeline: from year 2014 to 2020 (NGS published | Fitted geoid                      |
|                     | Terrestrial gravity             | annual experimental geoid (XGEOID) models.      |                                   |
| Australia           | GPS ellipsoidal height,         | Gravimetric quasi-geoid, ellipsoidal height     | A combined gravimetric geometric  |
|                     | gravimetric quasi-geoid,        |                                                | model known as hybrid quasi-geoid |
|                     | altimeter-derived gravity       |                                                |                                   |
| Country       | Gravity data                                           | Geoid model                  | Processing Method                                      |
|--------------|--------------------------------------------------------|------------------------------|--------------------------------------------------------|
| Taiwan       | Airborne gravity, shipborne gravity, terrestrial gravity and satellite altimetry data, 5 major tide gauges | Gravity data (land and marine), gravimetric geoid | Merging land and marine gravity using Least Squares Collocation (LSC) |
|              |                                                        |                              | Fitted geoid                                           |
| New Zealand  | Land gravity, DEM, GPS levelling, shipborne gravity, satellite altimetry, scalar airborne gravity and GGMs | A one arc-minute resolution gravimetric quasigeoid model, EIGEIN-6C4 | Modified Stokes integration using R-C-R |
| South Korea  | Global Geopotential Models (EIGEN-6C4, EGM2008 and GECO), GNSS levelling, land gravity and DTU10 altimetry data | Gravity data                 | The combinations of gravity data from satellites and land gravity data (blank area of gravity data is filled with DTU10 altimetry data). |
| Philippines  | Terrestrial land gravity, airborne gravity, DTU10 marine satellite altimetry, the newest satellite gravity data from GOCE mission release 5, DTM (15” SRTM) and GNSS levelling | Residual gravity anomalies, geoid residuals, gravity data, ellipsoidal heights, orthometric heights | • FFT to residual gravity anomalies  
    • spherical FFT with optimized kernels (Stokes integral)  
    • LSC  
    • Fitted geoid  
    • GRAVSOFT system  
    • Remove-restore method |
| Thailand     | Airborne gravity (land area and shorelines), terrestrial land gravity, GNSS levelling, DTU13 and EGM2008 marine gravity data | Orthometric heights, geoid heights | Remove-restore technique, LSC, FFT method |

4. Conclusion

In a conclusion, the appropriate technique and approach for merging and integrating land and marine gravity data can be optimized which is crucial for developing the high-resolution gravity potential field especially for Malaysian region. The high-resolution of a regional gravity data is significance for establishing a regional geoid model (geodetic vertical datum) with good accuracy. Hence, multi-mission gravity data from terrestrial gravity data, airborne, shipborne, satellite altimetry and satellite gravity from GGM can be implemented to determine seamless vertical datum for a region. Where, each types of gravity data either land or marine area will provide their own gravity field accuracy depends on the types of measurements.
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