Journal of Geospatial Surveying (2022) 2:1
DOI: http://doi.org/10.4038/jgs.v2i1.34

ORIGINAL ARTICLE

Detection of GPS-levelling datum variation using heterogeneous data: A case study in Sri Lanka

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ARTICLE INFO

Article history:
Received 17 February 2022
Received in revised form 17 March 2022
Accepted 21 March 2022
Available online 5 April 2022

Keywords:
Geoid
Tidal analysis
GPS-levelling
MSL

ABSTRACT

Geodetic datum is a fundamental reference surface in positioning, and plays an important role in relation to the survey activities of a country. Sri Lankan horizontal datum was established in 1999 (SLD99) using GPS technology, and the vertical datum was fixed averaging 6 years of tidal observations from 1884 to 1890. This research investigates potential inconsistencies of Sri Lankan GPS-levelling datum. For the analysis, heterogeneous data such as long-term tidal, GPS, levelling, global geoid heights and Mean Dynamic Topography (MDT) around the coastal region were used. Tidal analysis reveals that the tidal MSL around the country is linearly varied with an increasing rate of 3 mm per year. By analysing GPS, levelling, MDT and global geoid heights, it is found that there is around 1.9 m vertical deviation in Sri Lankan GPS datum with respect to the latest realization of ITRF, and the MSL based levelling datum is capable of representing global geoid features.

1 Introduction

Geodetic datum plays an important role in survey activities and serves as a fundamental reference surface in positioning. Traditional static geodetic datums are neither realistic nor do they meet the accuracy of today's demand. In horizontal geodetic datum, points are mapped onto a specified ellipsoid whereas in the vertical datum, points are mapped to the geopotential with a specified geoid. The traditional vertical datum incorporates tidal observations to fix the Mean Sea Level (MSL) by long-time averaging. However, unlike horizontal datums which are geometric, the vertical datums are not globally established and unification of the vertical datum is still under discussion (Prasanna et al., 2021; Sánchez et al., 2021). Although a vertical datum is not necessarily to be a geopotential surface (Featherstone, 1998), many countries have adopted the Earth's equipotential surface which approximately coincides with the MSL, geoid, as the vertical datum. MSL is not a geopotential surface like the geoid since it deviates 1-2 m due to sea surface topography which is globally implemented as the Mean Dynamic Topographic (MDT) heights (Knudsen and Anderson, 2013). Geometric techniques of geoid determination are adopted for regions without dense gravity networks (Prasanna and Chen, 2012), in which known geoid undulations (GPS-levelling) at GPS bench marks are fitted to a surface with the least-squares method with minimum constraints. One of the problems of this GPS-levelling undulation is that it has inherent errors associated with GPS and sprit-levelling observations. Also, GPS-levelling based vertical datum is a geometric surface and does not refer any geopotential value. A precise geoid, even on a global scale, can be used to detect systematic deviations or bias inherent in GPS-levelling datum. In this study, some inconsistencies of Sri Lankan GPS and levelling datums are determined using heterogeneous data.

2 Methodology

In Fig. 1, the methodology of the study is depicted as a flowchart:

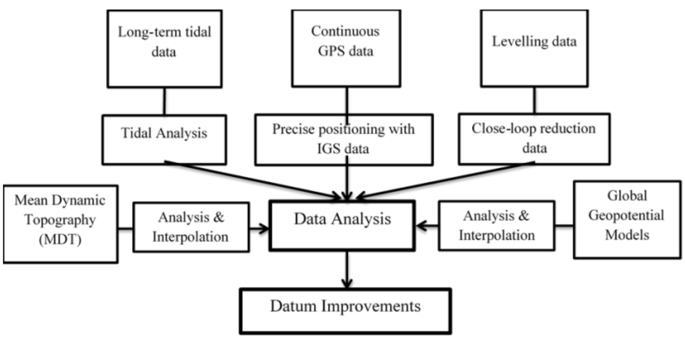

Fig. 1: Methodological flow chart

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To further analyse the mean difference shown in Table 1, the MDT variations around the coastal region of the country was used. The MSL or MSS (mean sea surface) contains the marine geoid plus the sea elevation due to the mean ocean dynamic topography, and MDT is the permanent component of it. The MDT is expressed by (Knudsen and Anderson, 2013): $\varsigma = \bar{h} - \bar{N}$, where $\bar{h}$ is the height of the mean sea surface above the reference ellipsoid and $\bar{N}$ is the geoid height relative to the same reference ellipsoid. For this analysis, DTU12MDT mean dynamic topography model was used (Knudsen and Anderson, 2013). This model used EIGEN-6C global geoid (degree and order 1420) which is associated with GOCE, GRACE and surface gravity based on satellite altimetry data, and DTU10MSS mean sea surface model. The MDT values of six tide gauge stations are shown in Table 2.

Table 2: MDT and EIGEN-6C geoid heights of tide gauge stations

Station	EIGEN-6C (m)	MDT (m)
Colombo	-96.944	0.825
Galle	-97.910	0.839
Hambantota	-96.530	0.845
Trincomalee	-93.827	0.841
Kankasanthurai	-97.037	0.874
Delft	-96.407	0.854

According to the MDT height of the Colombo tide gauge station, i.e. +0.825 m, the MSS is above the EIGEN-6C geoid. Yet, as shown in Table 1, the MSS fixed for Sri Lanka (Sri Lankan MSL) is 1.471 m below the same geoid. This scenario is depicted in Fig. 3.

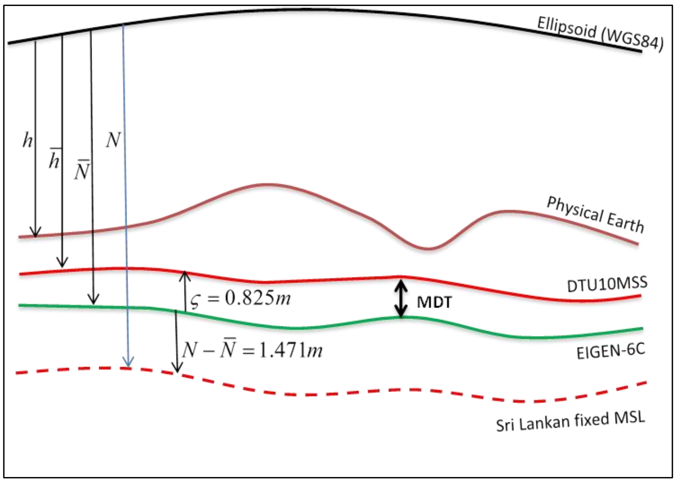

Fig. 3: Different vertical datums, and their variations over the Colombo tide gauge station

The deviation between the fixed MSL based levelling datum of Sri Lanka and the global geoid EIGEN-6C, which is in opposite direction when compared to the MDT around the coastal region, leads to requiring further investigation on the geodetic datums of Sri Lanka. Since the observed geoid height (N) was obtained from sprit-levelling and GPS heights, it contains any errors associated with sprit-levelling and GPS heights. Although the MSL has been fixed 130 years ago, the observed deviation of it with respect to the actual MSL is less than 20 cm (Fig. 2). This deviation is compatible with global sea level rise during the past 100 years, which ranges from 16-21 cm due to global warming (NASA: https://sealevel.nasa.gov/faq/13/how-long-have-sea-levels-been-rising-how-does-recent-sea-level-rise-compare-to-that-over-the-previous/). Therefore, as discussed by Abeyratne et al. (2010) and Prasanna (2014), some peculiarities in the Sri Lankan GPS datum could be the main reason for the dominating negative bias in Table 1.

To detect the potential bias between Sri Lankan GPS datum and International Terrestrial Reference Frame (ITRF) (Altamimi et al., 2011), previously observed and processed 3-days of continuous GPS data (reference epoch 2011.99868) at the base station of the existing GPS network were used. These data had been processed with 37 IGS reference stations in the region (Dow et al., 2009) using Bernese GPS data processing software. Fig. 4 shows the variation of X, Y, Z coordinates of 3-day repeated solution with respect to the day 1 solution of the base station of the network in ITRF2008.

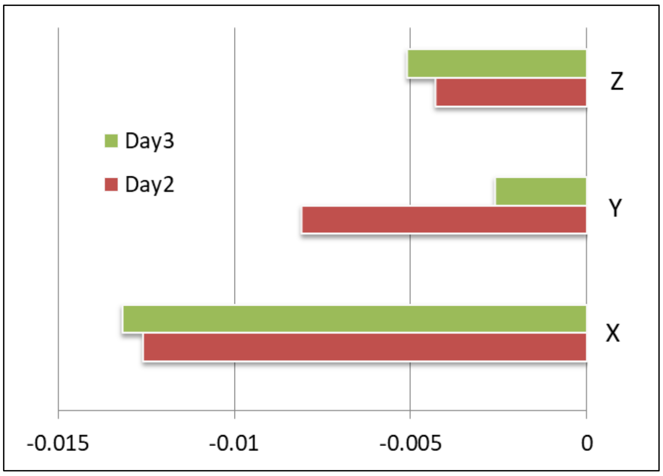

Fig. 4: Variation of X, Y, Z coordinates with respect to the day 1 solution (values in meters).

The *RMS* of the repeatability of each coordinate component was computed by: $RMS = \sqrt{\frac{\sum_{i=1}^{n}(L_i - \bar{L})^2}{n}}$, where L_i is coordinate component, $\bar{L}$ is the mean value and i is number of daily solutions. The RMS repeatability of X, Y, Z coordinates were 2.3 mm, 6.9 mm and 5.2 mm respectively. The adjusted coordinates were obtained by the least squares solution of normal equations, generated by stacking the normal equations of daily (session) solutions. The corresponding solution with respect to the latest realization of ITRF, ITRF2014, was obtained by using the transformation parameters of ITRF2014 for the reference epoch 2011.99868 (https://itrf.ign.fr/). The final results of the 3-day combination solution of the base station of Sri Lanka GPS network are shown in Table 3.

Table 3: Adjusted coordinates of 3-Day Combination Solution in ITRF2014 (Reference Epoch: 2011.99868)

X (m)	995152.6471 ± 0.0004
Y (m)	6255839.0829 ± 0.0014
Z (m)	752227.1526 ± 0.0004
Latitude(DMS)	6 49 2.694429 N ± 0.0003
Longitude (DMS)	80 57 40.900119 E ± 0.0004
Ellipsoidal height (m)	1166.2499 ± 0.0014

The difference between the published (GSU, 2000) and the calculated WGS84 coordinates of the base station are:

ΔN = 0.007269"; ΔE = 0.020119"; Δh = 1.8839 m

From the result, it can be seen that the existing horizontal control network (GPS network) of Sri Lanka has some bias. This bias is more likely in ellipsoidal height, which turns out the possible discrepancy between Sri Lankan GPS datum and ITRF latest realization. Since observed geoid undulations are derived from ellipsoidal and sprit-levelling heights ($h = H + N$), there may be an approximate bias of 1.9 m in the difference between the observed and model geoid undulation shown in Table 1.

This vertical offset was detected by analysing the continuous GPS observations at the base station of the Sri Lankan GPS network. One simple way of correct this bias is to add this vertical difference to all GPS benchmarks in the country. Therefore, this vertical bias (1.884 m) was added to the ellipsoidal height of the Colombo Tide gauge station and the difference between the observed and model geoid undulations was recalculated, and the results are shown in Table 4.

Table 4: Comparison of observed and model geoid undulations after removing the GPS datum bias at Colombo Tide Gauge Station (observed N = -96.531m)

Model	Degree & Order	Model N (m)	Observed N-Model N (m)
EIGEN-6C	1420	-96.944	0.413
EIGEN-6C4	2190	-96.931	0.400
EGM2008	2190	-96.894	0.363
GECO	2190	-96.913	0.382
SGG-UGM-1	2159	-96.954	0.423
Mean			0.396
Standard Deviation			0.024

The corrected deviation of Sri Lankan fixed MSL datum with respect to the EIGEN-6C geoid is shown in Fig. 5.

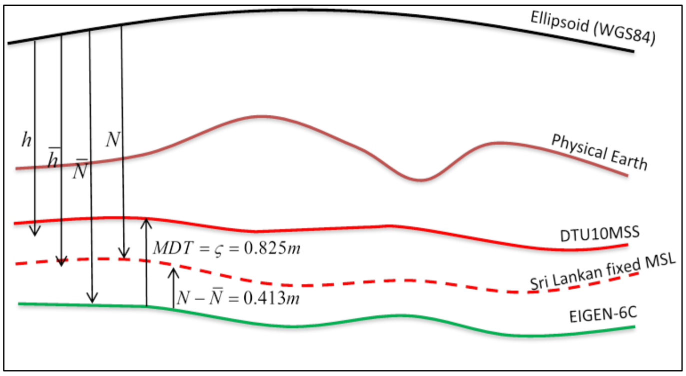

Fig. 5: variations of different vertical datums over Colombo tide gauge station after removing the GPS datum bias

According to the Table 4, the difference between the DTU10MSS mean sea surface and the Sri Lankan fixed MSL surface is 0.412 m. The MSL rise during the past 130 years as shown in Fig. 2 is partly accountable for this difference. The other main cause for this difference could be the unmodelled geoid parts of EIGEN-6C model. The rest could show the omission and commission errors of DTU10MSS model, and its unmodelled sea surface topography (SST) anomalies.

The final analysis of this study was done in order to investigate the performance of Earth gravity models. This study used five gravity models, and among them, EGM2008 is a GRACE based model while the rest contain GOCE (Gravity and Ocean Circulation Experiment) gravity data in addition to the satellite altimetry and ground gravity data. GOCE satellite mission measures the Earth gravity field with exceptional accuracy, leading to significant improvements in the modelling of the ocean circulation and transport. According to Knudsen and Andersen (2013), GOCE gravity models demonstrated the capability in estimating the surface currents compared to pre-GOCE gravity field models, like EGM2008.

In the DTU12MDT model, EIGEN-6C geoid has been used, which is a combination model where GOCE, GRACE and surface gravity based on satellite altimetry have been used. Therefore, the unmodelled parts of the geoid must be smaller. However, it is a low resolution model (degree and order 1420) which introduces comparatively large omission errors. EIGEN-6C4, GECO and SGG-UGM-1 are high resolution gravity models containing GOCE data in addition to the EGM2008 gravity data. In order to compare the performance of gravity models on predicting MDT and geoid heights, the high resolution models were truncated at the degree and order 1420, the same degree and order as EIGEN-6C. The results are shown in Table 5 and their variations are depicted in Fig. 6.

Table 5: Comparison of observed and model geoid undulations of their full spectrum and truncated at the degree and order 1420.

Model	Observed N-Model N (maximum) (m)	Observed N-Model N (1420) (m)	Difference (m)
EIGEN-6C	0.413	0.413	0
EIGEN-6C4	0.4	0.446	-0.046
EGM2008	0.363	0.41	-0.047
GECO	0.382	0.429	-0.047
SGG-UGM-1	0.423	0.468	-0.045
Mean	0.396	0.433	-0.037
Standard Deviation	0.024	0.024	0.021

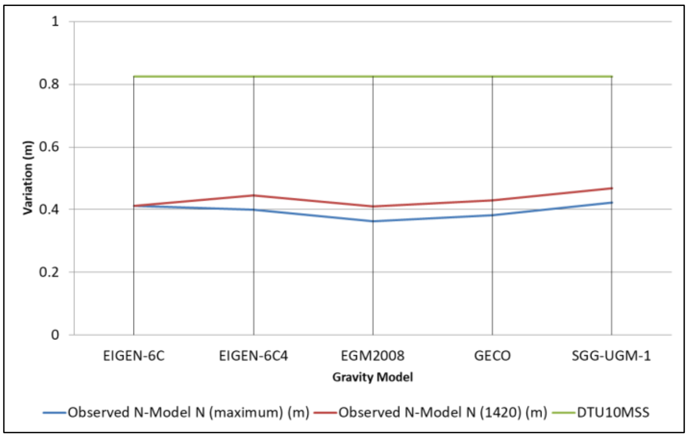

Fig. 6: Variation of observed-Model geoid undulations with respect to the DTU10MSS heights

In predicting MDT values, the SGG-UGM-1 model performs best, and gives the minimum deviation with DTU10MSS model. The main reason could be that it contains newest GOCE gravity data and hence, accurately models the ocean circulation and transport. From Fig. 6, it can be seen that when the full spectrum of gravity models are used, the model geoid undulations are more close to the observed geoid undulations by approximately 4 cm. This is implicitly the validation of Sri Lankan levelling datum, and though there is a bias with respect to the global MSL due to sea level rise, it is capable of representing global geoid features accurately. The minimum difference of 0.363 m given by the EGM2008 model implies that Sri Lankan levelling datum is not capable enough to represent GOCE based geoid parts, even though it performed well against GRACE geoid features embedded in EGM2008. However, finding the best geopotential model that performed well over Sri Lanka is out of the scope of this research, and it needs comprehensive analysis with different gravity field quantities covering the entire country.

4 Conclusions

The main scope of this research is to investigate the potential bias in Sri Lankan GPS-levelling datum using heterogeneous data. For that, long-term tidal data, continuous GPS data, sprit-levelling, geoid heights of GGMs and MDT data were used. The long-term tidal data (37 years) revealed that the tidal MSL around the country varied linearly with an increasing rate of 3 mm per year.

The negative bias between the observed and model geoid heights derived from high resolution GGMs, and positive MDT heights over the coastal region, leads to further analysis of Sri Lankan GPS-levelling datum. Since the MSL variation around the country is less than 20 cm, which is compatible with global MSL rise, the main cause of the negative bias detected as vertical shift of the Sri Lanka GPS datum needs to be studied further. The 3-day continuous GPS data quantified this vertical offset as 1.884 m with respect to the latest realization of ITRF.

The comparison between the bias free GPS-levelling data and global geoid heights shows that the results are compatible with MDT around the country and global MSL rise. Further analysis of the performances of GGMs reveals that the Sri Lankan MSL based levelling datum is capable of representing global geoid features.

Finally, it should be pointed out here that the bias of GPS datum was detected from the continuous GPS data at the base station of the Sri Lankan GPS network. In a simple way, this bias was added assuming that it is a vertical deviation. However, more observation points are needed to investigate whether there are tilt and rotational displacements as well.

Acknowledgement

The abstract of this paper has been published in the 8th International Conference of Sabaragamuwa University of Sri Lanka (ICSUSL-2021), and this is the accompanying full paper. The authors would like to thank the anonymous reviewers for their constructive comments.

Author Contributions

Conceptualization, methodology, analysis, writing original draft, H.M.I.P, and writing, review and editing, M.D.E.K. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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