DIGITAL ELEVATION MODEL ALTERNATIVES ASSESSMENT FOR DEFORMATION ANALYSIS PURPOSES USING GNSS AND INSAR

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ABSTRACT

Digital Elevation Model (DEM) is the starting point in the analysis performed to explain the deformation pattern changes from the Earth's surface. The estimated value of deformation based on point-wise GPS and InSAR data with a better spatial resolution must be defined in a reference frame system that reflects the phenomenon of deformation of the real physical world, e.g., orthometric height for the vertical component. Therefore, this study aims to provide alternative DEM models based on a suitable combination between the Global Geopotential Model of Earth Geopotential Model 2008 (EGM2008) and global terrain models, providing position changes with respect to the orthometric height. The alternative DEM models are (i) the global elevation model of ETOPO1 (DEM1), (ii) the modified global elevation model of SRTM30_PLUS (DEM2), and (iii) the regional elevation model of DEMNAS (DEM3). These alternative models comply with each other for the land areas with mean difference values lower than 1 meter. While for the ocean areas, we found that DEM1 and DEM2 have apparent differences due to the different types of data used. However, a similar assessment could not be performed for DEM3 as it only covers the land areas. Additionally, we compared the orthometric height from these terrain models with leveling observations for the coinciding locations. DEM3 achieves the highest accuracy with the estimated standard deviation of 11.2745 meters and is followed by DEM2 and DEM1 with the respective standard deviation of 29.4498 and 37.6872 meters. We found that these models can be used as a starting position determination for horizontal and vertical deformation analysis.

***Keywords**: Digital elevation model, EGM2008, Accuracy assessment, leveling data*

1. Introduction

The traditional geodynamic/deformation analysis is primarily conducted in 1-dimensional analysis, e.g., length changes as measured by Electronic Distance Measurement (EDM) and height changes as measured by leveling. Thanks to the development of Geodetic technology, we can analyze the position changes in 2-dimensional and even 3-dimensional axes. Geodetic technologies currently widely applied in the geodynamic/deformation study are the Global Navigation Satellite System (GNSS) [1], [2] and Interferometric Synthetic Aperture Radar (InSAR) [3]–[6]. GNSS ensures the user obtains an accurate 3-dimensional position of up to a few mm accuracy. Depending on the location and the infrastructure, the GNSS observation can be made episodic or continuous. In contrast, InSAR observation can only be implemented for an episodic case due to the satellite orbit period. However, the estimated coordinates are given for a large area rather than one single point as GNSS does.

Analyzing the position changes or deformation for the mentioned technologies requires a definitive coordinate reference system and frame. GNSS and InSAR typically adopt the Earth-Center Earth-Fix (ECEF) or geodetic coordinate system to represent the position. For 2-dimensional deformation analysis, the problem is not on determining the vertical position. The vertical component becomes crucial if we only analyze the vertical component in 3D deformation analysis. The initial height used as the reference must be clearly defined in the reference datum. At the same time, the changes through time can be determined based on the GNSS and InSAR observation methods in two different epochs. Different types of height determination give different types of Digital Elevation Model (DEM). The selection of the type of height determination depends on the application.

One of the most frequent DEM models used is the Shuttle Radar Topography Mission (STRM), developed by the cooperation between the National Aeronautics and Space Administration (NASA), the National Imagery and Mapping Agency (NIMA), the German Space Agency (DLR), and the Italian Space Agency. SRTM covers nearly the whole of the earth's surface (from 56°S - 60°N) (http://srtm.csi.cgiar.org). SRTM aims to generate the high-resolution digital elevation model after the Advanced Spaceborne

Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) was made in 2009. A radar mapping technique was implemented to derive the elevation model, and the vertical datum was transferred to the EGM96 geoid. Although the radar technique is capable of deriving an accurate elevation model, the choice of vertical datum (EGM96) may reduce the accuracy of the corresponding model. The International Center for Global Earth Models (ICGEM) showed that the global accuracy of EGM96 was calculated to approximately 0.5 meters [7]. Additionally, Üstün et al. [8] reported that the accuracy of EGM96 was estimated to be 3.8 meters for Turkey area. Those results indicate that improvement should be addressed to the SRTM model, e.g., by replacing EGM96 with a better geoid model.

Earth Geopotential Model 2008 (EGM2008) is the recent geoid model published by the National Geospatial-Intelligence Agency (NGA). EGM2008 has a higher resolution compared to the EGM96, with a maximum degree of 2190 and an order of 2160. These degrees and order correspond to about 9 kilometers in the spatial domain. ICGEM reported that the accuracy of EGM2008 reached up to less than 10 centimeters. In Korea, the accuracy of EGM2008 was estimated to be 21.6 centimeters from 1182 GNSS/leveling points [9]. Several studies also indicate that EGM2008 is better than the previous EGM series [10], [11]. Additionally, EGM2008 is considered as the best fit global geoid model compared with other models presently [12] (Figure 1). Therefore, this study aims to propose an alternative DEM model that can be used as a basis for the analysis of deformation using GNSS and InSAR techniques. The methodology includes: (i) the assessment of EGM2008 relative to the previous generation of geoid model of EGM96, (ii) the construction of elevation models based on a suitable combination of EGM2008 with a global/regional digital elevation model, and (iii) accuracy assessment of alternative digital elevation models using leveling observations.

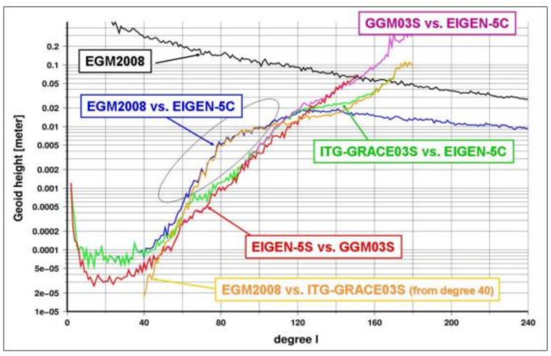

Figure 1. **Comparison of degree variance of EGM2008 in comparison to other geopotential models** [12].

2. Methods

DEM for Deformation Analysis using GNSS and InSAR Data. The basic principle of the DEM is the 3D position of the Earth's surface which states the position of the horizontal and vertical of a point relative to the reference frame system [13]. As previously described, the type of vertical positioning frame or height system will determine the type of the resulting DEM.

In the science of geodesy, four height systems could be adopted, e.g., geodetic height, orthometric height, dynamic height, and normal height systems. The main difference among each other is the adopted reference. The geodetic height uses ellipsoidal as the reference surface, while orthometric, dynamic, and normal height systems are based on a geopotential surface. For Indonesia, the height system commonly used is the orthometric height system referenced to the chosen geoid surface to express natural phenomena related to the equipotential field [14], e.g., the direction of water flow. Thus, the orthometric height system will provide an accurate picture of the elevation for engineering purposes (plumbing water/gas and the bridge construction). However, the geopotential-based height system has drawbacks. They require gravity observations and precise leveling observations at each position. Therefore, the realization of these systems is challenging.

GNSS technology is currently providing alternative solutions of precise-leveling called the GNSS-leveling method. The height system used by the GNSS is the geodetic height system that refers to the ellipsoid reference surface. The relation between geodetic height (h), orthometric height (H), and geoid undulation (N) is shown in Figure 2 and can be defined as:

$$h = H + N \qquad (1)$$

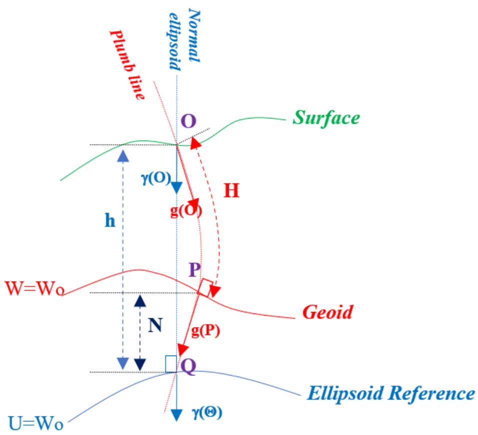

Figure 2. **The relationship between the earth's surface, geoid and reference ellipsoid.**

Position changes is obtained by comparing the observations from two different epochs. It can be stated mathematically as the following equation:

$$\Delta(x,y,z) = (x,y,z)_{t1} - (x,y,z)_{t0} \quad (2)$$

where $\Delta(x,y,z)$ is the position changes in 3-dimensional axis, subscript $t0$ and $t1$ are the initial and end epoch of measurement, respectively. Note that all observations are referred to a reference surface.

The vertical deformation component that refers to the orthometric height system, can be replaced by a geodetic height system as observed by GNSS if the value of geoid undulation has not changed. Let us consider the change in orthometric height and geodetic height as:

$$\Delta H = H_{t1} - H_{t0} \quad (3)$$

$$\Delta h = h_{t1} - h_{t0} \quad (4)$$

where $\Delta h = \Delta H + \Delta N$ and if $\Delta N = 0$, then $\Delta h = \Delta H$.

The same height system is also used to estimate deformation using InSAR technology. The used DEM data must be modeled into the SAR observation data (i.e., defined in the data phase and amplitude) that have the same coordinate system as the coordinate system on the master image. Processing the differential InSAR needs external DEM data (Figure 3). The final quality of the spatial pattern of deformation identified from InSAR depends on the resolution and quality of DEM data. The more rigorous DEM data, the better the ability to detect deformation patterns.

Alternative Elevation Models. Hofmann-Wellenhof and Moritz [15] stated that the Global Geopotential Model (GGM) is the shapes and dimensions representation of the Earth's gravity field. GGM is defined by numbers of spherical harmonic coefficients representing a vast spectrum of the Earth's gravity field. One way to determine the above representation is using potential disturbance (T), the small difference between the actual gravity potential W and the normal gravity potential U (See Eq. (5) and Figure 1).

$$T = W - U \quad (5)$$

Equation (5) can be further expanded in the form of spherical harmonics with a potential value following the reference Geopotential Global Model coefficient as follows:

$$T(r,\theta,\lambda) = \frac{GM}{r}\sum_{n=2}^{\infty}\left(\frac{R}{r}\right)^{n}\sum_{m=0}^{n}(\Delta\bar{C}_{nm}\cos m\lambda + \Delta\bar{S}_{nm}\sin m\lambda)\,\bar{P}_{nm}(\cos\theta) \quad (6)$$

where G is the gravitational constant, M is the mass of the Earth, (λ,θ) is the latitude and longitude observations, ($\Delta\bar{C}_{nm}$ and $\Delta\bar{S}_{nm}$) are the fully normalize geopotential coefficients (with degree n and order m), and $\bar{P}_{nm}$ is the fully normalized associated Legendre function.

$$\bar{P}_{nm}(\cos\theta) = \sqrt{k(2n+1)\frac{(n-m)!}{(n+m)!}}P_{nm}(\cos\theta) \quad \text{with } k = \begin{cases}1 \text{ for } m=0\\ 2 \text{ for } m\neq 0\end{cases} \quad (7)$$

where P_{nm} is the conventional associated Legendre functions (see Torge [16] for detail explanation).

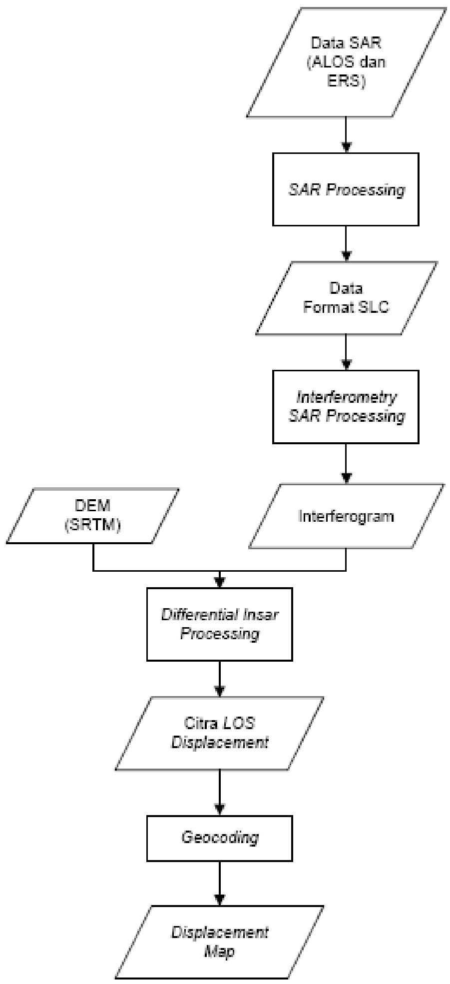

Figure 3. General flowchart of InSAR data processing

The irregularity of the gravity potential can also be seen in the equilibrium figure of seawater or the so-called geoid. The geoid undulation varies from -100 meters to 100 meters globally. It can be calculated according to Brun's formula as follows:

$$N = T/\gamma \quad (8)$$

where γ is the gravity from the normal gravity potential. Similar to the potential disturbance, geoid can be also expressed using spherical harmonics expansion as follows:

$$N(r,\theta,\lambda) = \frac{GM}{\gamma r}\sum_{n=2}^{\infty}\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(\bar{C}_{nm}\cos m\lambda + \bar{S}_{nm}\sin m\lambda)\,\bar{P}_{nm}(\cos\theta) \quad (9)$$

Three alternative elevation models that use orthometric height systems are proposed in this study. The first elevation model is based on the global elevation model of ETOPO1 [17], the second model is adopted from the SRTM30_PLUS global model [18], and Digital Elevation Model Nasional (DEMNAS) [19] developed by Indonesian Geospatial Agency (BIG) is also considered. These models are respectively called DEM-1, DEM-2, and DEM-3. Following are details regarding the respective elevation model:

DEM1/ETOPO1. ETOPO1 is the global elevation model that covers both land topography and ocean bathymetry. As implied from its name, the spatial resolution is set to 1 arc-minute. Specifically, the vertical datum used for ETOPO1 is the sea level, e.g., mean sea level (MSL).

The elevation model is represented as a grid model or in the form of spherical harmonic expansion. The second form is applied for this study:

$$H(\theta,\lambda) = \sum_{n=0}^{N_{max}}\sum_{m=0}^{n}(\bar{C}_{nm}\cos m\lambda + \bar{S}_{nm}\sin m\lambda)\,\bar{P}_{nm}(\cos\theta) \quad (10)$$

DEM2/SRTM30_PLUS. SRTM30_PLUS is created by combining the land data from the SRTM30 gridded DEM data (1-km bins) and GTOPO30 for high latitude areas that are not covered by the SRTM30. At the same time, the ocean data are adopted from the global 1 arc-minute model of Smith and Sandwell. Additionally, higher-resolution data from Lamont-Doherty Earth Observatory (LDEO) Ridge Multibeam Synthesis Project, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) Data Site for Research Cruises, and the National Geophysical Data Center (NGDC) Coastal Relief Model have been introduced to the model. EGM96 is chosen for SRTM30_PLUS. Recalling the relatively poor accuracy of the model, the vertical datum is transformed to EGM2008 using following approach:

$$H(\theta,\lambda) = H(\theta,\lambda)_{SRTM30\_PLUS} + N(r,\theta,\lambda)_{EGM96} - N(r,\theta,\lambda)_{EGM2008} \quad (11)$$

DEM3/DEMNAS. DEMNAS is constructed from several data sources. It includes several Radar data, e.g., the Interferometric Synthetic Aperture Radar (IFSAR), TerraSAR-X, and Advanced Land Observing Satellite Phased Array Type L-band Synthetic Aperture Radar (ALOS PALSAR) data. Additionally, mass point data as derived using the stereo-plotting method from imageries is added to the dataset.

The derivation of final DEMNAS grids includes data assimilation using Generic Mapping Tools (GMT) with surface-tension method [20]. Moreover, to accommodate sharp changes in the surface, breaklines are introduced. The final grids of DEMNAS gave spatial resolutions of 0.27-arcsecond or about 8 meters in the equator and referenced to EGM2008 surface [19]. One can download DEMNAS through their corresponding geospatial portal (https://tanahair.indonesia.go.id/demnas/#/demnas).

3. Result and Discussion

As mentioned previously, DEM2/SRTM30_PLUS uses EGM96 as its vertical datum. Recalling the expected accuracy of EGM96, EGM2008 is used instead. Figures 4 and 5 show the respective geoid undulation for EGM2008 and EGM96, while Table 1 lists these models' statistics. Visually, EGM2008 and EGM96 have a similar pattern. Low geoid undulation lies in the west part of Indonesia and gradually increases to the east part of Indonesia. Some anomalous data, where geoid undulation significantly differs from the vicinity area, occurs in some areas for both models, e.g., along the subduction zones. Statistically, both models also indicate a similar pattern, where their range, mean, and standard deviation are almost similar.

Further, the comparison between EGM2008 and EGM96 reveals significant discrepancies. Figure 6 displays the geoid undulation differences between EGM2008 and EGM96. It varies from about -4 meters to 6 meters. These significant discrepancies mainly occur in mountainous areas. These discrepancies are also possibly caused by the resolution of geoid models used. The maximum degree of EGM2008 spherical harmonic coefficients is 2190, corresponding to approximately 9 kilometers of the spatial domain. In comparison, EGM96's maximum degree is only 360 or about 55 kilometers. Gravity data availability further contributes to the differences between these models. EGM96 uses the final 30 arc-minute, and 1 degree mean gravity anomalies over land areas and altimetry-derived gravity anomalies over ocean areas [21]. In contrast, EGM2008 uses a better coverage and resolution of the 5 arc-minute global merged gravity anomaly data [22]. Note that in-situ gravity observations were not available for all of the regions. Therefore, fill-in data was introduced to the global model computation. The fill-in data were generated using available elevation models. The selection of the elevation model also contributes to errors in geoid determination.

Table 1. Statistic of geoid undulation for EGM2008 and EGM96 (unit in meter)

	EGM2008	EGM96
Minimum	-64.2152	-64.2484
Maximum	86.3989	85.9956
Mean	32.7491	32.7335
Standard deviation	40.5401	40.5543

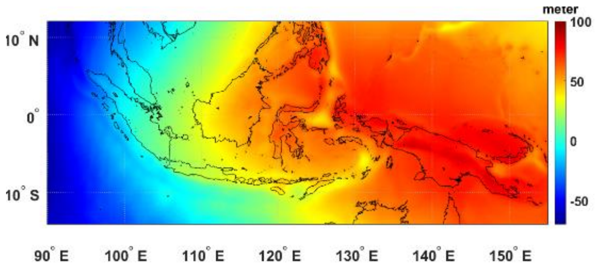

Figure 4. Geoid undulation as calculated using EGM2008.

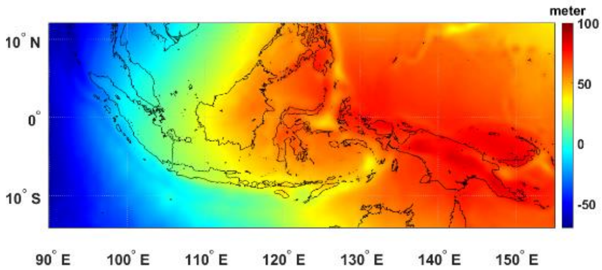

Figure 5. Same as Figure 4, but for EGM96.

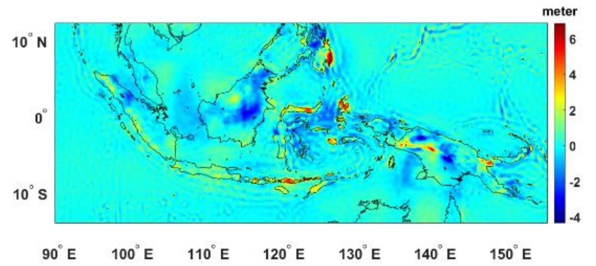

Figure 6. Differences between EGM2008 and EGM96.

Figures 7, 8, and 9 display the corresponding surface elevation model for DEM1, DEM2, and DEM3, and Table 2 lists the statistical components for the mentioned models in the Sulawesi area. Generally, the elevation for DEM1 and DEM2 varies from approximately -6500 to 3200 meters. DEM3 has a higher maximum elevation of up to 3700 meters. However, we cannot evaluate the ocean areas as DEM3 only covers land areas.

In general, the Sulawesi's lowest regions are located in the Gulf of Boni and the northern region of the Sulawesi's arm-shape, part of the Minahasa trench. The highest parts are located on the hilly and mountainous areas of the mainland.

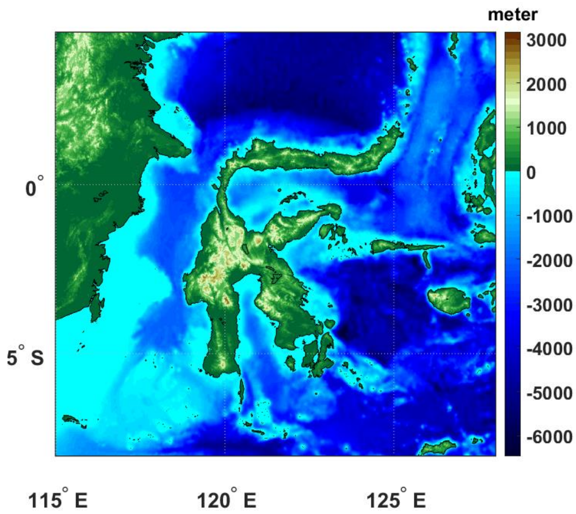

Figure 7. Elevation model for DEM1.

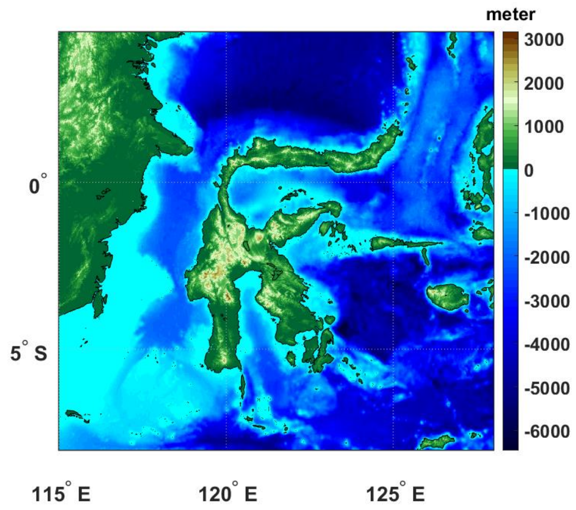

Figure 8. Same as Figure 7, but for DEM2.

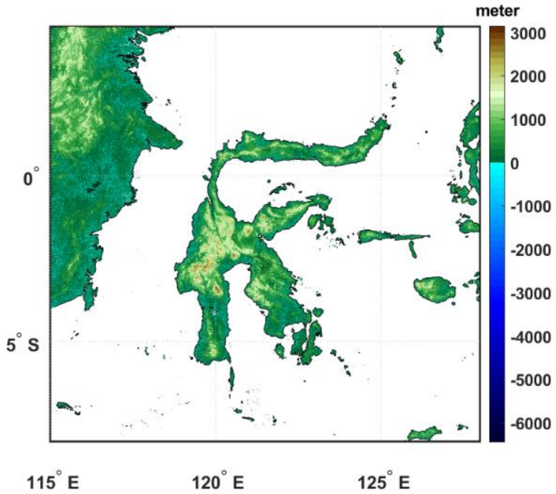

Figure 9. **Same as Figure 7, but for DEM3. Note that there is no data at sea region for DEM3.**

Table 2. Statistic of surface elevation for DEM1 and DEM2 (unit in meter).

	DEM1	DEM2	DEM3
Minimum	-6463	-6461.5205	0
Maximum	3111	3212.7120	3667
Mean	-1613.1604	-1620.1182	408.8875
Standard deviation	1912.3392	1911.9524	449.2351

Further, an assessment was carried out by comparing between elevation models. This was carried out to evaluate whether the models have any systematical errors or not. Figure 10 reveals the differences between DEM1 and DEM2. It varies from -2000 to 1750 meters. Note that these significant discrepancies are mostly located in the ocean areas. Bathymetry data used in DEM1 and DEM2 were compiled from many sources, e.g., sounding observations and satellite-derived bathymetry. However, no sounding data were used in the Indonesia region, particularly for DEM1, which is not the case for DEM2. Only four bathymetric datasets were used in compiling TOPO1/DEM1, i.e., the Japan Oceanographic Data Center (JODC), NGDC, the Caspian Environment Programme (CEP), and the Mediterranean Science Commission [17]. In contrast, SRTM30_PLUS/DEM used IBCAO bathymetry, covering almost all ocean areas in the world [18] (See Figure 11). The availability of bathymetry sounding is possibly the cause of significant discrepancy over sea areas. For the land areas, the mean difference was estimated to be 0.1956 meters and the standard deviation of the differences was calculated to 38.0457 meters.

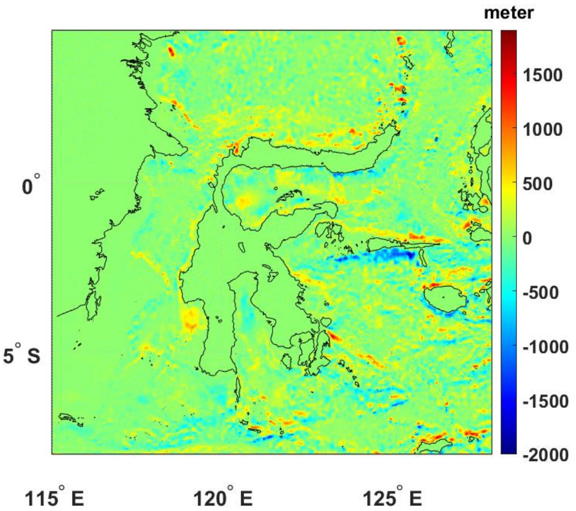

Figure 10. **Differences between DEM1 and DEM2.**

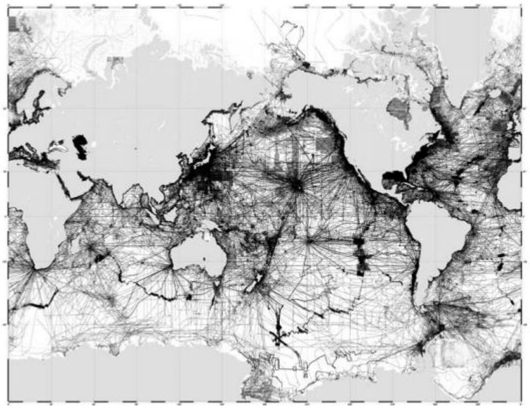

Figure 11. **Ship trajectories of all the soundings used in the SRTM30_PLUS** [18]**.**

Next, we move to the comparison between DEM1 and DEM3. Figure 12 shows the comparison between DEM1 and DEM3. As mentioned earlier, the assessment was performed only for land areas due to the unavailability of DEM3 data at ocean areas. The mean difference was estimated to be a sub-meter level of -0.9390 meters with an estimated standard deviation of 61.4244 meters. Finally, we compared the surface elevation model from DEM2 with DEM3, as shown in Figure 13. The mean and the standard deviation of differences were estimated to be 0.3469 and 33.1962 meters, respectively.

Based on the estimated mean difference values, where they are within the sub-meter level, we note that no apparent bias exists between these models. However, we observe significant discrepancies in cell-by-cell differences between models as indicated by the estimated standard deviation values of differences. Therefore, a further assessment was made by utilizing available leveling data to conclude which model suits most in this region.

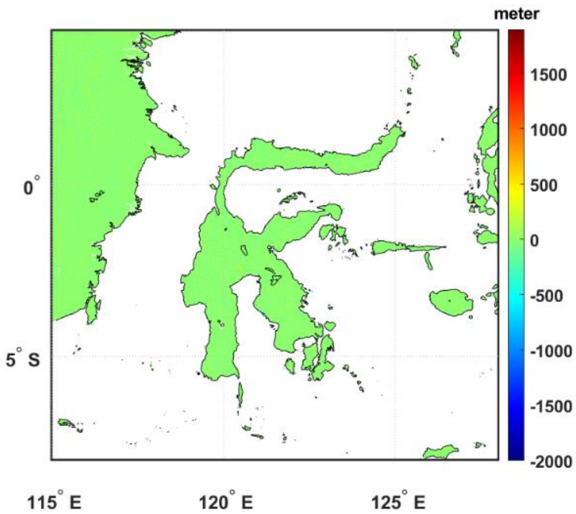

Figure 12. **Same as Figure 10, but for the differences between DEM1 and DEM3.**

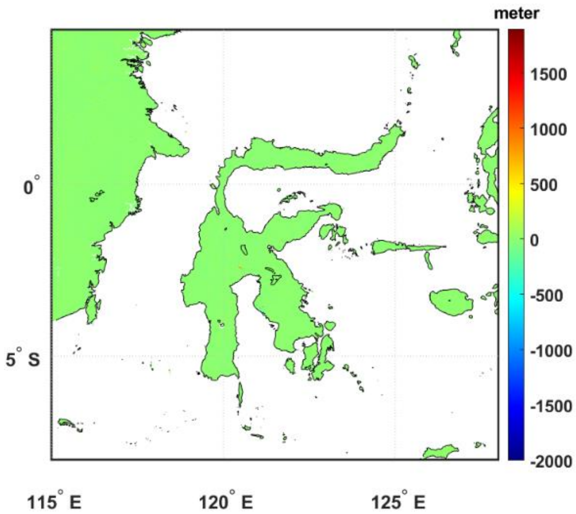

Figure 13. **Same as Figure 10, but for the differences between DEM2 and DEM3.**

Six hundred forty-one leveling data provided by the Geospatial Agency of Indonesia were used in this study. The observations were made in the 1980s to 1990s using precise leveling instruments. All observations were referenced to the mean sea level of the nearby tidal observation stations. It should be noted that we assume no significant geophysical effects exist over the study area, e.g., subsidence and seismic activities. Therefore, we used the estimated orthometric height as it is.

Figure 14 displays the distribution of leveling data used in this assessment. The comparison was made by interpolating the elevation value for DEM1 and DEM2 at the corresponding leveling locations. A simple linear interpolation was used to predict the elevation value. Figures 15, 16, and 17 show the histogram of differences between leveling and models. The accuracy of DEM1 is considerably lower than DEM2, as indicated by the widespread differences. The standard deviation of differences for DEM1 is estimated to be 37.6872 meters. For comparison, the standard deviation of differences for DEM2 is almost 10 meters lower than DEM1, or 29.4498 meters. DEM3, on the other hand, gives the best performing surface elevation model. The standard deviation of differences is calculated to be 11.2745 meters.

However, it should be noted that the discrepancies may arise due to the resolution of the models. The models are provided in 1 arc-minute, 30 arc-second, and 0.27 arc-second bins for DEM1, DEM2 and DEM3, respectively. This implies that the reported elevation of a single cell is averaging from the corresponding resolution. This will cause problems, particularly for rough terrain, e.g., mountainous areas. Further, most of the leveling data are available in coastal areas. Some leveling points were eventually located in the sea areas due to the model resolution.

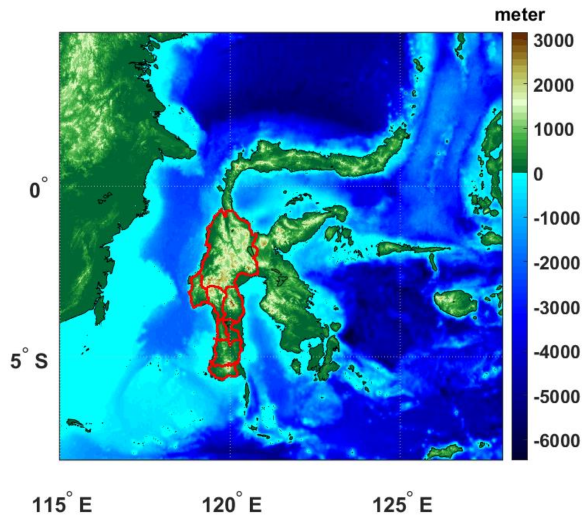

Figure 14. **Distribution of leveling data used in this study (red dots). The background topography is the DEM1.**

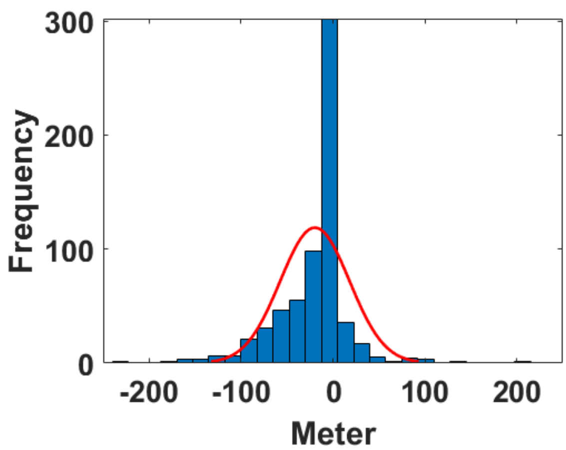

Figure 15. **Histogram of differences between leveling and DEM1.**

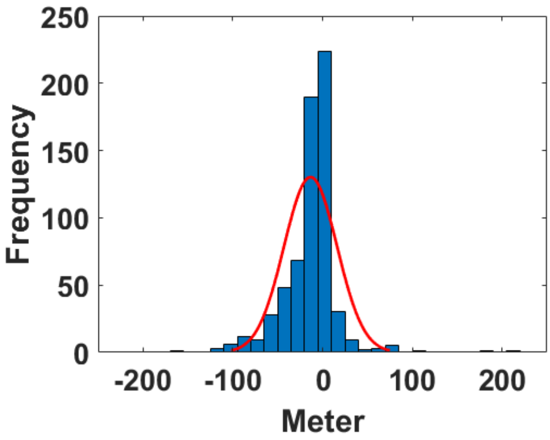

Figure 16. Same as Figure 12, but between leveling and DEM2.

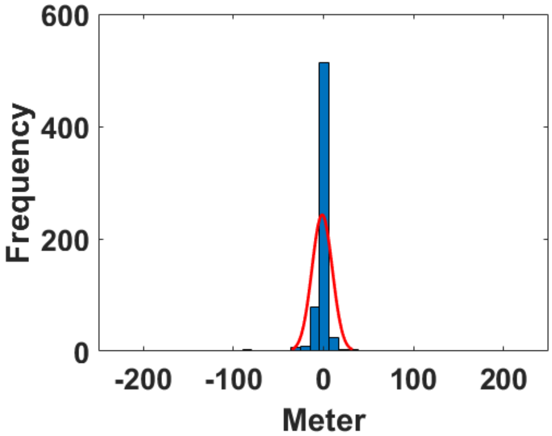

Figure 17. Same as Figure 12, but between leveling and DEM3.

4. Conclusion

Based on the validation conducted on the alternative digital elevation models referenced to the orthometric height system, the estimated accuracy for the respective DEM1, DEM2, and DEM3, are 37.6872, 29.4498, and 11.2745 meters. Further, there is no indication that systematic biases are present in these models. It appears that these models are suitable for starting position determination of both horizontal and vertical deformation analysis. For the analysis of deformation based on GNSS data, DEM data was used for initial orthometric height determination, and the magnitude of deformation can be determined referring to reference ellipsoid, assuming the geoid undulation does not vary in time. For the analysis of 3D deformation using GPS, the selection strategy required interpolation-extrapolation methods that take into consideration the rheological argument. Different from the analysis of deformation using InSAR, DEM data will serve as spatial and does not require interpolation or extrapolation method. However, these DEMs still need to be improved in order to achieve actual representation of the topography-bathymetry.

Acknowledgement

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References

[1] S. Cetin, C. Aydin, and U. Dogan, “Comparing GPS positioning errors derived from GAMIT/GLOBK and Bernese GNSS software Comparing GPS positioning errors derived from GAMIT / GLOBK and Bernese GNSS software packages: A case study in CORS-TR in Turkey,” *Surv. Rev.*, vol. 51, no. 369, 2019, doi: 10.1080/00396265.2018.1505349.

[2] A. Klos, J. Bogusz, M. Figurski, and W. Kosek, “On the Handling of Outliers in the GNSS Time Series by Means of the Noise and Probability Analysis,” in *IAG 150 Years*, C. Rizos and P. Willis, Eds. Springer International Publishing, 2016, pp. 657–664.

[3] F. Cigna and D. Tapete, “Present-day land subsidence rates, surface faulting hazard and risk in Mexico City with 2014–2020 Sentinel-1 IW InSAR,” *Remote Sens. Environ.*, vol. 253, no. 112161, 2021, doi: 10.1016/j.rse.2020.112161.

[4] H. Ren and X. Feng, “Calculating vertical deformation using a single InSAR pair based on singular value decomposition in mining areas,” *Int. J. Appl. Earth Obs.*, vol. 92, no. 102115, 2020, doi: 10.1016/j.jag.2020.102115.

[5] S. Yalvac, “Validating InSAR-SBAS results by means of different GNSS analysis techniques in medium- and high-grade deformation areas,” *Environ. Monit. Assess.*, vol. 192, no. 120, 2020, doi: 10.1007/s10661-019-8009-8.

[6] A. Aobpaet, M. C. Cuenca, and A. Hooper, “InSAR time-series analysis of land subsidence in Bangkok, Thailand,” *Int. J. Remote Sens.*, vol. 34, no. 8, pp. 2969–2982, 2013, doi: 10.1080/01431161.2012.756596.

[7] E. Sinem Ince *et al.*, “ICGEM – 15 years of successful collection and distribution of global gravitational models, associated services, and future plans,” *Earth Syst. Sci. Data*, vol. 11, pp. 647–674, 2019, doi: 10.5194/essd-11-647-2019.

[8] A. Üstün, R. A. Abbak, and E. Zeray Öztürk, “Height biases of SRTM DEM related to EGM96: from a global perspective to regional practice,” *Surv. Rev.*, vol. 50, no. 358, pp. 26–35, Jan. 2018, doi: 10.1080/00396265.2016.1218159.

[9] K. B. Kim, H. S. Yun, and H. J. Choi, “Accuracy Evaluation of Geoid Heights in the National Control Points of South Korea Using High-Degree Geopotential Model,” *Appl. Sci.*, vol. 10, no. 1466, Feb. 2020, doi: 10.3390/app10041466.

[10] N. S. Saray and N. K. Ghazal, “Evaluation of Global Gravitational Models Based on DGPS/leveling Data over Baghdad University (IRAQ),” *J. Phys. Conf. Ser.*, vol. 1804, no. 012044, 2021, doi: 10.1088/1742-6596/1804/1/012044.

[11] C. Hirt, U. Marti, B. Bürki, and W. E. Featherstone, “Assessment of EGM2008 in Europe using accurate astrogeodetic vertical deflections and omission error estimates from SRTM/DTM2006.0 residual terrain model data,” *J. Geophys. Res.*, vol. 115, no. B10404, Oct. 2010, doi: 10.1029/2009JB007057.

[12] C. Förste *et al.*, “Evaluation of EGM2008 by comparison with other recent global gravity field models,” *Newton’s Bull.*, no. 4, pp. 26–37, 2009, [Online]. Available: http://gfzpublic.gfz-potsdam.de/pubman/item/escidoc:239494:1/component/escidoc:239493/13866.pdf.

[13] Z. Li, Q. Zhu, and C. Gold, *Digital terrain modeling: Principles and methodology*. CRC Press, 2005.

[14] A. M. Pahlevi, I. Sofian, D. Pangastuti, and A. B. Wijanarto, “Updating Model Geoid Indonesia,” *Semin. Nas. Geomatika*, vol. 3, p. 761, 2019, doi: 10.24895/sng.2018.3-0.1063.

[15] B. Hofmann-Wellenhof and H. Moritz, *Physical Geodesy*. Vienna: Springer, 2005.

[16] W. Torge, *Geodesy*, 2nd ed. Walter de Gruyter, 1991.

[17] C. Amante and B. W. Eakins, “ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis,” 2009. doi: 10.7289/V5C8276M.

[18] J. J. Becker *et al.*, “Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS,” *Mar. Geod.*, vol. 32, no. 4, pp. 355–371, 2009, doi: 10.1080/01490410903297766.

[19] BIG, “DEMNAS,” 2018. https://tanahair.indonesia.go.id/demnas/#/ (accessed Dec. 19, 2021).

[20] P. Wessel *et al.*, “The Generic Mapping Tools Version 6,” *Geochemistry, Geophys. Geosystems*, vol. 20, pp. 5556–5564, 2019, doi: 10.1029/2019GC008515.

[21] F. G. Lemoine *et al.*, “The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96,” 1997. doi: 10.1007/978-3-662-03482-8_62.

[22] N. K. Pavlis, S. A. Holmes, S. C. Kenyon, and J. K. Factor, “The development and evaluation of the Earth Gravitational Model 2008 (EGM2008),” *J. Geophys. Res.*, vol. 117, no. B04406, pp. 1–38, 2012, doi: 10.1029/2011JB008916.