ACCURACY ASSESSMENT OF GLOBAL TOPOGRAPHIC DATA (SRTM & ASTER GDEM) IN COMPARISON WITH LIDAR FOR TROPICAL MONTANE FOREST

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ABSTRACT: Shuttle Radar Topographic Mission (SRTM) and ASTER Global Digital Elevation Model (GDEM) provide topographic data in a global scale which are freely available for users. The potential use of these datasets for many forestry applications is highly depending on the accuracy of the datasets. In this study, we evaluated the accuracy of SRTM and ASTER GDEM version 2 with high accuracy topographic data of Light Detection and Ranging (LiDAR) acquired using Riegl LMS-Q560 sensor. This study is conducted in tropical montane forest area of approximately 3,600 hectare, Malaysian Borneo. We resampled both the SRTM (90m resolution) and ASTER GDEM (30m resolution) with bilinear interpolation and cubic convolution method to one, two and five meter pixel resolutions. The evaluation was divided into two sites; site 1 (2,100 ha) and site 2 (1,500 ha). The SRTM (SD=9.0m-10.4m; RMSE=9.3m-10.6m) was found to produce better topographic data in comparison with ASTER GDEM (SD=16.9m-18.7m; RMSE=17.0m-19.3m). Our result revealed that resampling using cubic convolution performs only slightly better than bilinear interpolation method (when compared for all SD and RMSE values) for SRTM. Resampling to higher spatial resolution (i.e. 1m) did not influence significantly the performance (when compared for all mean, standard deviation and RMSE values).

1. INTRODUCTION

Topographic maps provide elevation or height information which is useful to many field of applications such as hydrological and geological modelling, planning and construction, land use planning, global change research, telecommunication and natural resource management. In the past, these topographic maps were mainly constructed from aerial photographs or ground survey for small-scale project. The recent technology development of interferometric synthetic aperture radar (InSAR), image matching and light detection and ranging (LiDAR) have provided a milestone in deriving elevation for larger area and/ or with high accuracy depending on several factors especially the sensor type and data acquisition height. Today, there are several freely available global topographic data, namely the Shuttle Radar Topography Mission (SRTM) in 2000, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) in 2009 and GTOPO30 in 1996. In this paper, we only discussed the SRTM and ASTER GDEM2 since GTOPO30 has low spatial resolution (approx. 1km).

Shuttle Radar Topography Mission (SRTM) obtained elevation data on a near-global scale to generate the most complete high resolution digital global topographic database for 80% of the Earth's land surface between 56°S and 60°N with 16m absolute vertical height accuracy (at 90% confidence) and data points located every 1-arc second (approximately 30 meters) on latitude/longitude grid. SRTM is an international project leaded by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). More detailed information of SRTM mission can be found from Farr and Korbick (2000).

ASTER GDEM version 1 was first released in 2009 with joint collaboration between the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). This topographic data was generated using stereo-pair images collected by the ASTER instrument onboard Terra with coverage from 83°N to 83°S latitude, encompassing 99 percent of Earth's terrestrial land with 30 meter spatial resolution. ASTER GDEM version 2 (GDEM2) was released on October 17, 2011 with several improvements (i.e. using additional 260,000 stereo-pairs from 2000 to 2010, improved coverage and reduced occurrence of artifacts, and refined production algorithm). GDEM2 consists a total of 22,702 tiles (each tile is 1 x 1 degree) with DEM output format of GeoTIFF, signed 16 bits and digital number indicates the elevation above the WGS84/EGM96 geoid (Japan Space Systems & METI, 2014). The vertical accuracy was estimated of 17m at 95% confidence interval (Tachikawa et al., 2011).

Recent development of Light Detection and Ranging (LiDAR) mapping system has opened new opportunity for scientist and mapping professionals to investigate both natural and man-made features with several advantages over other techniques especially on the capability of achieving centimeter accuracies and ground detection on vegetated area. This system has offered new prospects to study in forested ecosystem (e.g. Wulder et al., 2013). LiDAR has become a main stream mapping technology alongside with airborne digital imaging (Petrie, 2011). These two complementary airborne technologies are often combined for mapping purpose to produce digital elevation model and ortho-photo for many topographic mapping applications. The general concept of the airborne LiDAR system is that, the sensor's emitting pulses with a combination of GNSS/IMU technology to reference position correction, determine the values (in point clouds) at known position (x, y, and z) creating a profile in cross-track direction. For example, Riegl LMS-Q560 sensor is capable to provide measurement of point cloud with pulse rate up to 240 kHz with accuracy of less than 30 centimeter.

Numerous studies have evaluated the performance of global topographic data either using GPS ground measurement (e.g. Tachikawa et al., 2011) or high quality topographic elevation such as NED (e.g Kenyi et al., 2009) but limited studies using LiDAR (e.g. Sun et al., 2008; Hofton et al., 2006) as reference dataset. The main drawback of using GPS points or topographic elevation map is the limited applicability on vegetated area such as in our study site. LiDAR has enabled the evaluation both using the DEM and DSM on full extent of the study area. Many of the studies kept the original spatial resolution size (e.g. 30m in ASTER GDEM). Thus, it is interesting study to evaluate resampled topographic data to higher spatial resolution which probably could be useful for certain applications.

In this study, we evaluated the performance of resampled SRTM and ASTER GDEM by using different resampling techniques (i.e. bilinear interpolation and cubic convolution) and spatial resolutions (i.e. 1m, 2m and 5m) with LiDAR reference data for rugged terrain in mountainous tropical forest, Malaysian Borneo.

2. MATERIALS

2.1. Study Area

The study area is located in Ulu Padas forest area (approximately 4°26'N, 115°45'E; Figure 1) of Northern Borneo, Malaysia, inside the Heart of Borneo Initiative area which forms part of an important mountain eco-region representation of Borneo together with Pulong Tau National park in Sarawak and Kayan Mentarang National Park in Kalimantan, Indonesia. Ulu Padas forest area is approximately 155,000 hectare in the South-western tip of Sabah which is bordered with North Kalimantan and Sarawak. The area is covered by rugged terrain ranges approximately between 1,000m to almost 2,000m in altitude (i.e. Bukit Rimau at 1,908m) while the vegetation of this region consists of several types (i.e. dominant montane oak/chestnut forest with *Agathis*, hill dipterocarp forest, stunted montane mossy forest and high-level swamp forest; SBCP, 1998). The land use consists of both small and big scale logging activities as well as small-scale farming activities by the local people with some portion remaining as old growth forest. The study area is divided into two sites, site 1 (2,122 hectare) and site 2 (1,509 hectare) based on the coverage of the reference LiDAR dataset. The elevation ranges from 961 meter to 1,895 meter with slope average of 18.6° and 25.1° for site 1 and site 2, respectively. The area is generally covered by vegetation with mean canopy height of 22.5m and 23.9m for both sites.

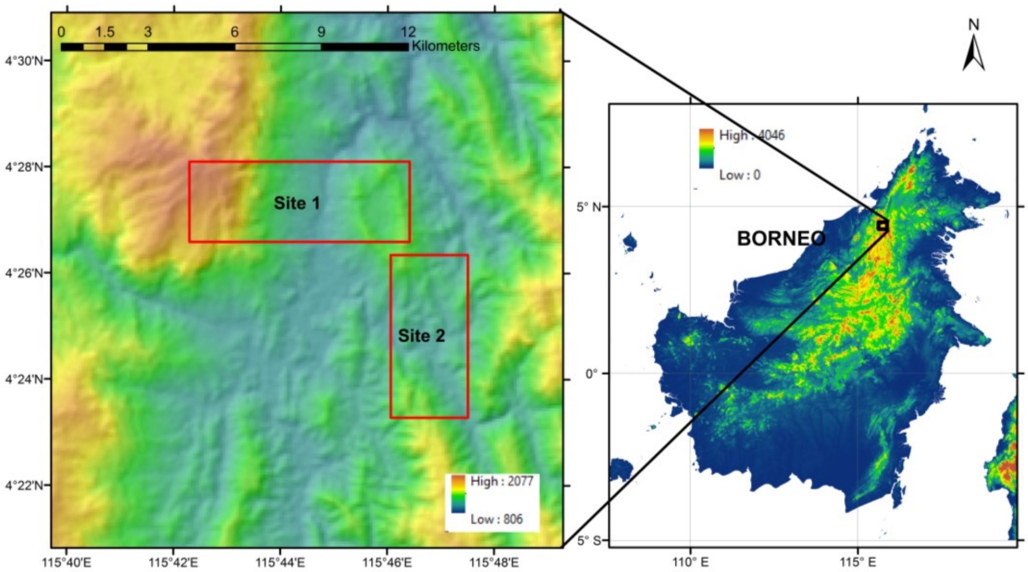

Figure 1: Location of study area. Red polygon represents the study site (source of elevation map: SRTM).

2.2. SRTM & ASTER GDEM2 Data

SRTM consisted of a modified radar system (C-band and X-band) that flew onboard the Space Shuttle Endeavour during an 11-day mission in February 2000.The SRTM measured the elevation by using a technique called radar interferometry (two radar images are taken from slightly different locations and the differences between these images allow for the calculation of surface elevation, or change). The main antenna was located at the shuttle's payload and the secondary (outbound) antenna was attached to the end of the 60m extended mast. The C-band radar antenna could transmit and receive wavelength of 5.6 cm long with 225km swath width and this data was used to produce near-global topographic map of the Earth (USGS, 2014). The SRTM data was processed at the Jet Propulsion Laboratory (JPL) in Pasadena, California and the data was then edited by the NGA to delineate water bodies, define coastlines, remove spikes and wells, and fill small voids (SRTM version 2). Data for regions outside the United States were resampled using a cubic convolution resampling technique to 90 meter from the original 30 meter data for open distribution. The data use geographic coordinate system of WGS84 for horizontal datum and EGM96 for vertical datum. We downloaded the SRTM version 2 data (Figure 2a) in band interleaved by line (BIL) file format via USGS's Earth Explorer website (http://earthexplorer.usgs.gov/).

ASTER instrument was built by METI and launched onboard NASA's Terra spacecraft in 1999. The sensor has an along-track stereoscopic capability using its near infrared spectral band and its nadir-viewing and backward-viewing telescopes to obtain stereo image data with a base-to-height ratio of 0.6. One nadir-looking ASTER VNIR scene consists of 4,100 samples by 4,200 lines, corresponding to about 60km by 60km ground area to produce spatial resolution of 15m in the horizontal plane (Japan Space Systems & METI, 2014). ASTER GDEM version 2 reprocessed 1.5 million scenes including additional 260,000 scenes acquired after the version 1 to improve coverage and data quality by employing a smaller correlation kernel (5 x 5 versus 9 x9 used for GDEM 1) for higher spatial resolution on the order of 75m (135m in GDEM1), and an improved water mask. The GDEM 2 has an overall accuracy of 17m at 95% confidence level (Tachikawa et al., 2011). The data use geographic coordinate system of WGS84 for horizontal datum and EGM96 for vertical datum. ASTER GDEM2 product (Figure 2b) is available at no charge to global users and can be downloaded via the Earth Remote Sensing Data Analysis Center (ERSDAC) of Japan (http://gdem.ersdac.jspacesystems.or.jp/).

2.3. LiDAR Data

The LiDAR data was acquired using Riegl LMS-Q560 sensor (Riegl LMS GmbH, Horn, Austria) on October 5 to 8, 2012 (see also Ioki et al., 2014 for processing information). The sensor was attached to helicopter platform and flew approximately 400 m above ground level with average speed of 62 mph. The system was operated with 45° of field of view and 240 kHz of pulse repetition rate with beam divergence of less than 0.5 mrad. The final point cloud vertical accuracy of RMSE was estimated less than 25cm. The LiDAR was classified into ground and non-ground with average density of 14.9 pulses/m^2 and 16.2 pulses/ m^2 for site 1 and site 2, respectively. The processed data were delivered in the coordinate system of WGS84 UTM Zone 50N for horizontal datum and WGS84 ellipsoid for vertical datum. Figure 2 shows the digital elevation model (Figure 2c) and digital surface model (Figure 2d) derived from the LiDAR data.

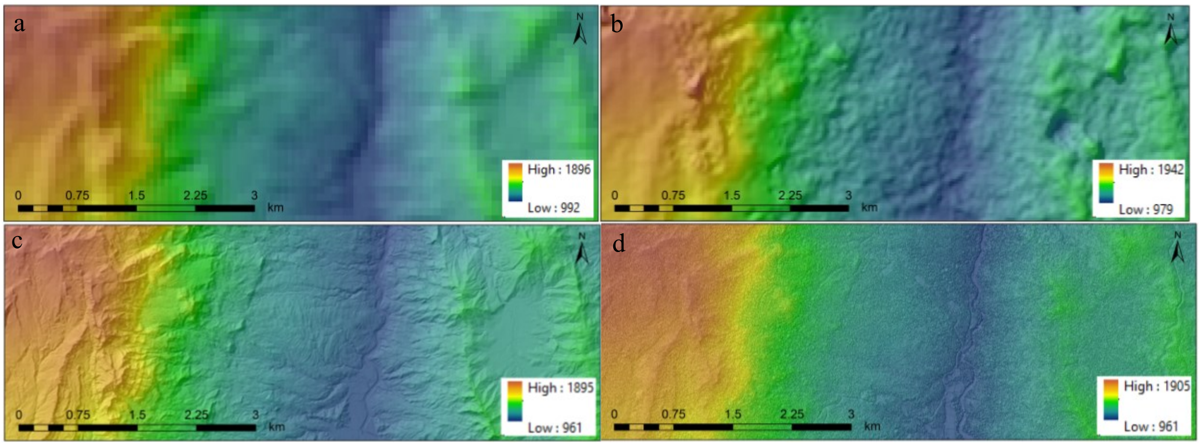

Figure 2: Digital elevation model (DEM) for site 1. (a) SRTM 90m, (b) ASTER GDEM2 30m, (c) LiDAR-DEM 1m, and (d) LiDAR-DSM 1m.

3. METHODS

We generated the digital elevation model (DEM) and digital surface model (DSM) with 1 meter spatial resolution from the LiDAR data by using the LAS tool available in the ArcGIS 10.1 software (ESRI Inc., Redlands, CA, USA). The DEM was generated by using triangulation interpolation method while the DSM by using binning interpolation method with maximum option for biasing the result to higher elevation when generating a DSM. We then transformed the elevation height of WGS84 ellipsoid to ortho-metric height of EGM96 to match the vertical datum of SRTM and ASTER GDEM dataset. The EGM96 geoid height model is available in the ArcGIS 10.1 software. Next, the 1m spatial resolution of DEM and DSM were then resampled to both 2 meter and 5 meter by using nearest neighbor technique.

We resampled the SRTM and ASTER GDEM to three different spatial resolutions (i.e. 1m, 2m and 5m) by using two resampling techniques (i.e. bilinear interpolation and cubic convolution). The output coordinate was set to WGS84 UTM Zone 50N for horizontal datum with no transformation of the vertical datum (EGM96) during the resampling process. Bilinear interpolation technique determines the new cell value based on a weighted distance average of the four nearest input cell centers while cubic convolution is based on a weighted distance average of the 16 nearest input cell centers. In total, we derived twelve newly topographic data with different spatial resolution and resampling technique from SRTM and ASTER GDEM (Figure 3).

Then, we obtained twelve subtracted global topographic data with the reference LiDAR dataset of different resampling technique and spatial resolution. We then calculated the statistic (i.e. mean, standard deviation, minimum, and maximum) and root mean square error (RMSE) of them for two sites (site 1 and site 2).

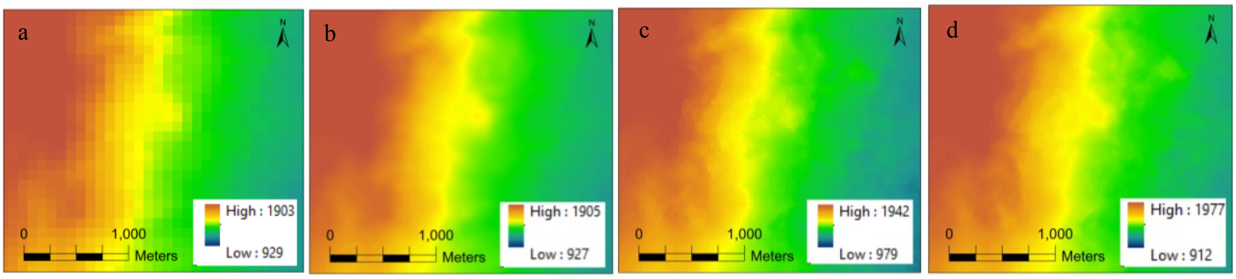

Figure 3: Example of (a) original SRTM 90m version 2, (b) resampled 1m with cubic convolution of SRTM, (c) original ASTER GDEM version 2 30m, (d) resampled 1m with cubic convolution of ASTER GDEM2.

4. RESULTS

4.1. LiDAR vs SRTM

In general, the SRTM height was higher than the LiDAR-DEM by 24.7m to 26.0m and LiDAR-DSM by 2.0m to 2.5m for site 1 and site 2, respectively. RMSEs when compared to LIDAR-DEM and LiDAR-DSM were approximately at 27m and 10m, respectively (Table 1). This result indicated that the SRTM is closer representing the digital surface model or the canopy. The C-band as expected was not capable to penetrate the canopy down to the forest floor. The standard deviation (SD) ranged between 9.0m to 10.4m for all spatial resolutions and resampling techniques. The result revealed that the resampled SRTM with cubic convolution have slightly smaller SD and RMSE value when compared to resampled SRTM with bilinear interpolation. However, the differences of the SD and RMSE values between two resampling techniques did not exceed 0.62m and 0.39m, respectively.

Table 1: Results based on the subtraction of SRTM (Left) and GDEM2 (Right) with LiDAR data.

	Site 1					Site 2						Site 1					Site 2				
	SD	RMSE	Mean	Min	Max	SD	RMSE	Mean	Min	Max		SD	RMSE	Mean	Min	Max	SD	RMSE	Mean	Min	Max
SRTM											**GDEM2**										
compared with LiDAR- DEM											**compared with LiDAR- DEM**										
1m											**1m**										
BL	9.37	26.44	24.73	-15.97	81.02	10.28	28.01	26.06	-10.95	67.68	BL	19.06	33.13	27.10	-155.85	164.95	17.31	30.12	24.65	-69.65	151.37
CC	9.32	26.68	25.00	-12.87	86.31	9.66	27.76	26.02	-10.24	66.96	CC	19.33	33.35	27.18	-156.75	166.92	17.48	30.21	24.65	-70.40	153.22
2m											**2m**										
BL	9.38	26.49	24.77	-15.77	81.12	10.27	28.00	26.05	-10.52	67.19	BL	19.08	33.18	27.15	-155.43	165.03	17.29	30.11	24.65	-69.43	151.22
CC	9.34	26.73	25.05	-12.45	86.31	9.65	27.75	26.02	-10.23	66.39	CC	19.35	33.40	27.23	-156.61	167.25	17.46	30.20	24.64	-70.00	153.22
5m											**5m**										
BL	9.38	26.49	24.77	-15.02	80.65	10.25	27.98	26.03	-10.39	67.19	BL	19.12	33.20	27.14	-154.81	164.59	17.31	30.10	24.63	-68.08	150.23
CC	9.34	26.73	25.05	-12.37	85.65	9.64	27.72	26.00	-9.36	65.30	CC	19.39	33.42	27.22	-155.81	166.59	17.48	30.19	24.62	-69.08	152.05
compared with LiDAR-DSM											**compared with LiDAR-DSM**										
1m											**1m**										
BL	9.09	9.36	2.20	-154.69	76.93	10.39	10.61	2.11	-163.76	64.89	BL	18.39	18.95	4.58	-194.79	157.85	16.96	16.97	0.71	-181.76	148.73
CC	8.98	9.31	2.48	-155.69	81.34	10.00	10.22	2.08	-161.76	63.10	CC	18.65	19.22	4.66	-196.79	160.16	17.15	17.17	0.70	-180.76	150.52
2m											**2m**										
BL	9.10	9.37	2.25	-131.65	76.93	10.39	10.60	2.11	-119.11	64.89	BL	18.40	18.97	4.62	-190.19	157.16	16.94	16.96	0.71	-134.58	148.73
CC	8.99	9.34	2.53	-131.65	78.93	10.00	10.21	2.07	-118.11	62.99	CC	18.66	19.24	4.70	-191.19	160.16	17.14	17.16	0.70	-134.58	150.52
5m											**5m**										
BL	9.09	9.37	2.26	-41.42	66.95	10.38	10.59	2.09	-56.09	63.86	BL	18.45	19.02	4.62	-189.08	150.51	16.97	16.98	0.69	-97.70	134.12
CC	8.99	9.33	2.53	-39.46	72.95	10.00	10.21	2.05	-57.09	61.86	CC	18.71	19.29	4.70	-190.08	152.51	17.17	17.18	0.68	-99.98	139.12

Note: BL denotes bilinear interpolation and CC denotes cubic convolution resampling technique performed on SRTM or GDEM2. All units are in meter (m).

4.2. LiDAR vs GDEM2

In general, the ASTER GDEM2 height was higher than the LiDAR-DEM by 24.6m to 27.2m and LiDAR-DSM by 0.7m to 4.7m for site 1 and site 2, respectively. RMSEs when compared to LIDAR-DEM and LiDAR-DSM had higher value from SRTM evaluation which were approximately 32m and 18m, respectively (Table 1). Similarly to SRTM, the result indicated that the ASTER GDEM2 is also closer representing the canopy. The standard deviation ranged between 16.9m to 19.4m for all spatial resolutions and resampling techniques. The result also revealed that the resampled GDEM2 with bilinear interpolation have slightly smaller standard deviation value when compared to resampled GDEM2 with cubic convolution. However, the differences of the standard deviation value between two resampling techniques were less than the value of 0.27m.

5. DISCUSSION

It is noted from the result that the SRTM is better than ASTER GDEM2 with smaller value of standard deviation (SD_{SRTM}= 9.0m to 10.4m; SD_{GDEM}= 16.9m to 18.7m) and RMSE ($RMSE_{SRTM}$=9.3m to 10.6m; $RMSE_{GDEM}$=17.0 to 19.3m) for the two sites (Table 1). Both SRTM and ASTER GDEM2 overestimated compared to LiDAR-DSM by 2.0m to 2.5m and 0.7m to 4.7m, respectively. It is expected that the SRTM C-band penetrated some portion of the canopy. However, the result showed SRTM is higher than the LiDAR-DSM by the mean value of 2 m. For example, Kenyi et al. (2009) reported that SRTM was found to penetrate into about 44% of the canopy on average for Californian forest while Hofton et al. (2006) also found that SRTM elevations fell on average approximately between 8m to 14m below the LVIS canopy top elevations. Our visual inspection and observation revealed that this overestimate could be caused by the occurrence of the heterogeneous tropical forest canopy height and also land cover change probably by logging or farming activities between the time of SRTM and LiDAR data acquisitions (Figure 4a). Tropical forest is constructed with multiple layers thus it may also reduce the penetration of the C-band wavelength of the SRTM. We also employed resampling technique to higher resolution between 1m to 5m instead of using the original resolution. Our RMSEs was found to be similar with Colosimo et al. (2009) approximately at 10m in forested area when compared to LiDAR-DSM.

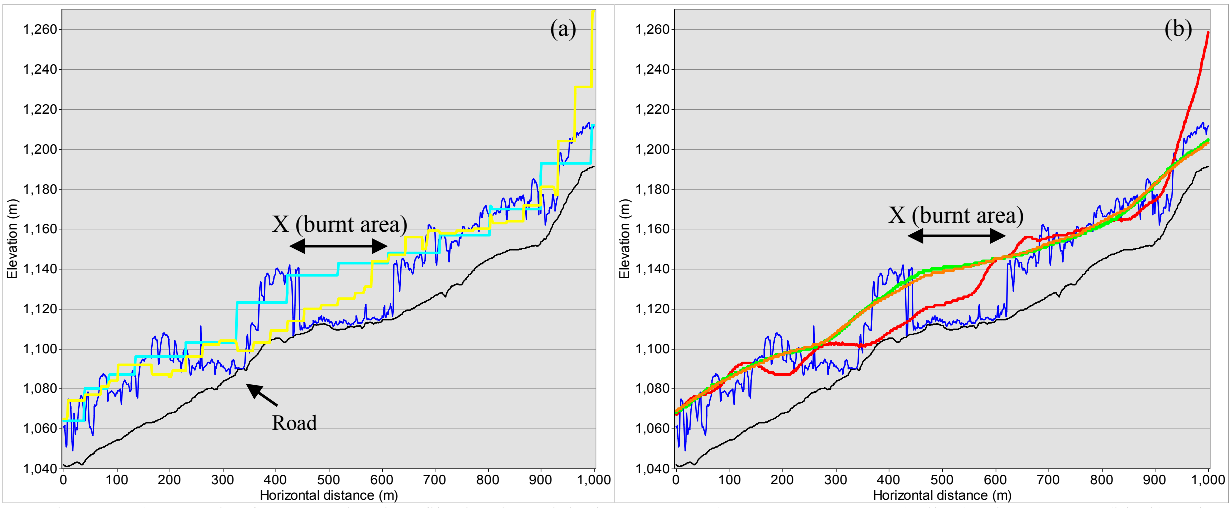

Figure 4: (a) Example of cross-sectional profile showing original SRTM 90m (cyan), GDEM2 30m (yellow), LiDAR-DEM (black) and LiDAR-DSM (blue). SRTM height was found to be highly overestimated over the recent burnt area (X). (b) Example of cross-sectional profile of GDEM2 resampled to 1m by cubic convolution (red), SRTM resampled to 1m by cubic convolution (green) and bilinear interpolation (orange).

Tachikawa et al. (2011) assessed the accuracy of ASTER GDEM2 for vegetated mountainous area in Japan and found out the value offset, SD, and RMSE were +7.4m, 12.7m and 15.1m, respectively, which are slightly lower from our result (offset= +0.7m to +4.7m; SD_{GDEM}= 16.9m to 18.7m; $RMSE_{GDEM}$=17.0m to 19.3m). This probably could be caused by the different type of vegetation and also assessment technique. It is observed that ASTER GDEM2's height is more diverse compared to SRTM (Figure 4a). At some location, GDEM2 is closer to LiDAR-DEM and higher than LiDAR-DSM on another. This could explain the standard deviation and RMSE values for GDEM2 are higher than SRTM between 6.6m to 9.9m for SD and between 6.4m to 10.0m for RMSE.

Many studies are evaluating the performance of SRTM and ASTER GDEM by using national topographic map (e.g. NED) and GPS points. In our study, we used LiDAR data as the reference dataset and this enabled us to perform full extent of 36 million pixel of the study site on 1m spatial resolution in 3,600 hectare mountainous tropical forest. Using LiDAR data as a reference for accuracy assessment has the advantage especially on vegetated area.

Errors of SRTM can be caused by slope, vegetation height and aspect. Su & Guo (2013) found out that the mean difference between SRTM and LiDAR increased with vegetation height, and standard deviation of the difference increased with slope. Meanwhile, Jarvis et al. (2004) found the average error of SRTM about 8m and the some errors was systematically related to aspect by comparing with field-base measurement of GPS points. They found northeastern slopes presented the greatest error where these errors can be attributed to the effect of incidence angle of the original radar images used to produce the SRTM. Greatest errors in the SRTM data were found on ridges and peaks, where they consistently underestimated the elevation which was also found to be similar in our study.

Cubic convolution yielded slight larger variation compare to bilinear interpolation both for the SRTM ($Diff_{SD}$=0.11 to 0.39m; $Diff_{RMSE}$=0.03 to 0.39m; $Diff_{Mean}$=0.03 to 0.28m) and ASTER GDEM2 ($Diff_{SD}$=0.19 to 0.26m $Diff_{RMSE}$=0.20 to 0.27m; $Diff_{Mean}$=0.01 to 0.08m). Bilinear interpolation produced smoother results and cubic convolution have a tendency to sharpen the edges since more cells were involved in the calculation of the output value (Figure 4b). Our result demonstrated that topographic data can be resampled to higher resolution (i.e. 1m). Resampling to higher resolution of 1m might be useful for certain applications especially if correction to ground elevation can be attained.

6. CONCLUSIONS

In this study, we resampled the SRTM and ASTER GDEM2 to higher resolution (i.e. 1m, 2m and 5m) using bilinear interpolation and cubic convolution and then compared the elevation height with high quality reference LiDAR data. Our results reveal that SRTM performed better than ASTER GDEM2. There are only slight variation of the results when the global topographic data were resampled to higher resolution using both bilinear interpolation and cubic convolution. Since errors of SRTM can be caused by slope, vegetation and aspect (e.g. Su & Guo, 2013; Jarvis et al., 2004), it is interesting for further evaluations to be conducted on the resampled global topographic data.

Our study used LiDAR data as the reference in the evaluation, thus enabled us to perform comparison to the ground height (LiDAR-DEM) and surface height (LiDAR-DSM) on full extent of the study site area (3,600 hectare). This is not feasible by using ground-measurement GPS points or topographic map for vegetated area similar to this study site. One of the limitation in this study is the topographic data were taken in different time (i.e. SRTM in 2000, ASTER GDEM2 is based on ASTER archived scenes from 2000 to 2010 and LiDAR data acquired in 2012) and during the time difference, land cover might had changed. We propose that DEM correction (e.g. Liu et al. (2014) and Su & Guo (2014) developed a correction for SRTM DEM for forest in temperate region) for SRTM in tropical forest to be attempted to utilize the resampled SRTM data for certain applications (e.g. deriving canopy height with the combination of digital aerial photogrammetry).

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REFERENCES

Colosimo, G., Crespi, M., Vendictis, L. De, & Jacobsen, K. 2009. Accuracy evaluation of SRTM and ASTER DSMs. 29th Annual EARSeL Symposium, Chania Greece, 15-18 June.

Farr, T. G., & Kobrick, M. 2000. Shuttle radar topography mission produces a wealth of data. Eos, Transactions American Geophysical Union, 81 (48): 583-585.

Hofton, M., Dubayah, R., Blair, J. B., & Rabine, D. 2006. Validation of SRTM elevations over vegetated and non-vegetated terrain using medium footprint lidar. Photogrammetric Engineering & Remote Sensing, 72: 279–285.

Ioki, K., Tsuyuki, S., Hirata, Y., Phua, M.-H., Wong, W. V. C., Ling, Z.-Y., Saito, H., & Takao, G. 2014. Estimating above-ground biomass of tropical rainforest of different degradation levels in Northern Borneo using airborne LiDAR. Forest Ecology and Management, 328: 335–341.

Jarvis, A., Rubiano, J., Nelson, A., Farrow, A. and Mulligan, M, 2004, Practical use of SRTM data in the tropics –Comparisons with digital elevation models generated from cartographic data. Working Document No. 198, p. total 32

Kenyi, L. W., Dubayah, R., Hofton, M., & Schardt, M. 2009. Comparative analysis of SRTM–NED vegetation canopy height to LIDAR-derived vegetation canopy metrics. International Journal of Remote Sensing.

Japan Space Systems and METI, Japan's Ministry of Economy Trade and Industry (2014) - ASTER Global Digital Elevation Model (GDEM). Available at: http://www.jspacesystems.or.jp/ersdac/GDEM/E/4.html (accessed 15.08.2014).

Liu, J., Liu, D., & Alsdorf, D. 2014. Extracting Ground-Level DEM from SRTM DEM in Forest Environments Based on Mathematical Morphology. IEEE Transactions on Geoscience and Remote Sensing, 52(10): 6333–6340.

Petrie, G. 2011. Airborne Topographic Laser Scanners: Current Developments in the Technology. GEOinformatics.

Sabah Biodiversity Conservation Project (SBCP) 1998. Identification of Potential Protected Areas: Ulu Padas Final Report (p. total 123).

Su, Y., & Guo, Q. 2014. A practical method for SRTM DEM correction over vegetated mountain areas. ISPRS Journal of Photogrammetry and Remote Sensing, 87: 216–228.

Sun, G., Ranson, K. J., Kimes, D. S., Blair, J. B., & Kovacs, K. 2008. Forest vertical structure from GLAS: An evaluation using LVIS and SRTM data. Remote Sensing of Environment, 112: 107–117.

Tachikawa, T., Kaku, M., Iwasaki, A., Gesch, D., Oimoen, M., Zhang, Z., Danielson, J., Krieger, T., Curtis, B., Haase, J., Abrams, M., Crippen, R., & Carabajal, C. 2011. ASTER Global Digital Elevation Model Version 2 -Summary of Validation Results (p. total 23).

USGS, 2014. Shuttle Radar Topography Mission: Home, http://www2.jpl.nasa.gov/srtm/ (accessed 15.08.2014).

Wulder, M. A., Coops, N. C., Hudak, A. T., Morsdorf, F., Nelson, R., Newnham, G., & Vastaranta, M. 2014. Status and prospects for LiDAR remote sensing of forested ecosystems. Canadian Journal of Remote Sensing, 39(sup1): S1–S5.