Evaluation of Vertical Accuracy of Digital Elevation Models Generated from Different Sources : Case Study of Ampang and Hulu Langat, Malaysia

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Key words: ASTER, IFSAR, LiDAR, Digital Elevation Model (DEM) and Digital Terrain Model (DTM)

SUMMARY

Digital elevation model (DEM) is a digital representation of ground surface topography and have been used in various applications. The introduction of global coverage DEM available for free or at reasonable cost was a new phenomenon in mapping. The issue is how accurate are these datasets and can it be used for topographic mapping. This paper aims to evaluate the height accuracy of DEMs generated from different sources. Results presented in this paper is part of a study to evaluate the suitable use of different DEMs and high resolution imagery for topographic map updating. For this paper, Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM), Intermap Airborne Interferometric Synthetic Aperture Radar Digital Terrain Model (IFSAR DTM), IFSAR Digital Surface Model (IFSAR DSM), digital topographic map (with a 5m contour interval) and Light Detection and Ranging (LiDAR) datasets are used to generate the contours, height points and height profiles. LiDAR dataset is used as reference DEM to evaluate the accuracy of NEXTMap IFSAR DTM and Digital Terrain Model (DTM) generated from digital topographic maps acquired from the Department of Survey and Mapping Malaysia. The vertical accuracy of ASTER GDEM is obtained by comparing wih the heights of IFSAR DSM. The Root Mean Squares Error (RMSE) of the height points generated from IFSAR DTM and digital topographic map of the non-vegetated areas within the study area are 1.458 m and 2.960 m respectively. For the vegetated area, the RMSE of IFSAR DTM and digital topographic map are 4.736 m and 9.848 m respectively. The accuracy of ASTER GDEM in the vegetated and non-vegetated areas are 8.442 m and 18.900 m respectively. Visual comparison between the contours generated from IFSAR DTM and LiDAR has shown promising result. ASTER GDEM can be used to capture the general characteristic of the terrain. Future work will include the evaluation of factors that contribute to the accuracy of DEMs generated from different sources.

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1. INTRODUCTION

Digital Elevation Model (DEM) can be used in various applications, such as terrain visualization, telecommunication, navigation, disaster management, planning of civil engineering infrastructures and orthorectification of airborne and satellite imagery. The DEM could be acquired through techniques such as stereo photogrammetry from aerial survey, airborne light detection and ranging (LiDAR), interferometric synthetic aperture radar (IFSAR) and land surveying (Li et al. 2005). Other methods of acquiring DEM are real time kinematic Global Positioning System (GPS), block adjustment of optical satellite imagery and existing topographic maps.

ASTER is an international collaboration project between the Ministry of Economy, Trade and Industry of Japan (METI) and the United States National Aeronautics and Space Administration (NASA). The DEM covers 99% of the Earth's Land Mass. Near-infrared stereo imagery is collected simultaneously at both nadir and off nadir angles with along-track alignment. This stereo imagery is then utilized to develop a DEM through stereo correlation technologies (Hirano et al., 2003). As reported in Hirano et al. (2003) vertical accuracy of ASTER DEMs is in the range of 7 to 15 m. Airborne INTERMap IFSAR provides three main products i.e. digital surface models (DSM), digital terrain models (DTM), and orthorectified radar imagey (ORI). The vertical accuracy of 0.5–1.0 m of both the airborne IFSAR DSM and DTM can be achieved by the airborne Intermap mapping system (Wei and Coyne, 2008). LiDAR or airborne laser scanning (ALS) is one of the most accurate and effective methods of terrain data collection. The vertical accuracy of 10–50 cm (at 68% confidence level) can be achieved (ICSM, 2008) while a higher accuracy of 10-15cm can only be achieved under the most ideal circumstances (Hodgson et al., 2004)

The cost of acquiring DEM is largely influenced by the technique and accuracy required. Figure 1 shows the cost (USD/per sq km) of acquiring DEMs using different data acquisition techniques and the expected vertical accuracies. Although Airborne LiDAR is considered as the most expensive technique, it has become preferred technology for digital elevation data acquisition in a wide range of applications (Liu, 2011). Other freely available open source DEM products are Shutter Radar Topography Mission version 3 (STRM3) with 90 m DEM and ASTER GDEM (Farr and Kobrick, 2000; Farr *et al*., 2007) and can be acquired via the United States Geological Survey (USGS) website whilst airborne NEXTMap IFSAR is cost effective DEM for large coverage applications. Another global DEM dataset which combine ASTER GDEM and GTOPO30 datasets is NEXTMap World 30 and can be purchased via NEXTMap web store or from local vendor at a very minimum cost. According to Astrium

Services (2013), WorldDEM, a global digital elevation information which is acquired from German radar satellites TanDEM-X and TerraSAR-X will be made available to the public in 2014.

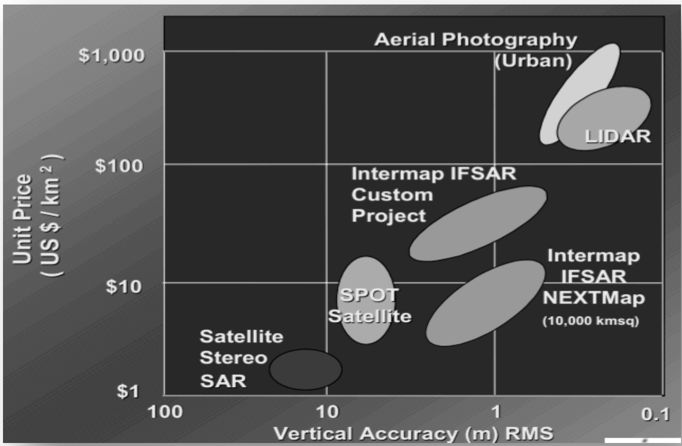


Figure 1: Cost comparison of DEMs verses vertical accuracies
(Source : Mercer, 2004)

Various techniques have been used by different authors to evaluate the accuracy of different DEM data. Zhou et al. (2012), Jarvis et al. (2004), Hall and Tragheim (2010) generate elevation profile to compare the differences between DEMs while Nikolakopoulos et al. (2006) carried out correlation analysis to compare the difference in DEM accuracy. Another method of assessing the DEM accuracy is by comparing the relationship between topographic characteristics such as slope and aspect (Gorokhovich and Voustianiouk, 2006). Yang et al. (2011) used matching contour method to evaluate the accuracy of ASTER GDEM elevation. In a study by Kuuskivi and Li (2006) the accuracy performance of DEM products from airborne and spaceborne IFSAR are compared with high-accuracy ground control points (GCPs) and higher-accuracy DEM.

2. STUDY AREA

The study area covers part of the Federal Territory of Kuala Lumpur (Keramat and Wangsa Maju) and Selangor State (Ampang and Hulu Langat), Malaysia. The coverage for this area is approximately 85 sq km (7.7 x 11.2 km) and rectangular in shape. The area is selected as the study area due to the availability of ASTER GDEM, NEXTMap IFSAR, digital topographic maps, LiDAR data and variable terrain characteristics. The height range of this area is 40 m up to 600 m. The lower part of the study is mainly residential areas while the higher is mainly covered by forest. Figure 2 shows the location of the study area. The perspective view of the study area is shown in Figure 3.

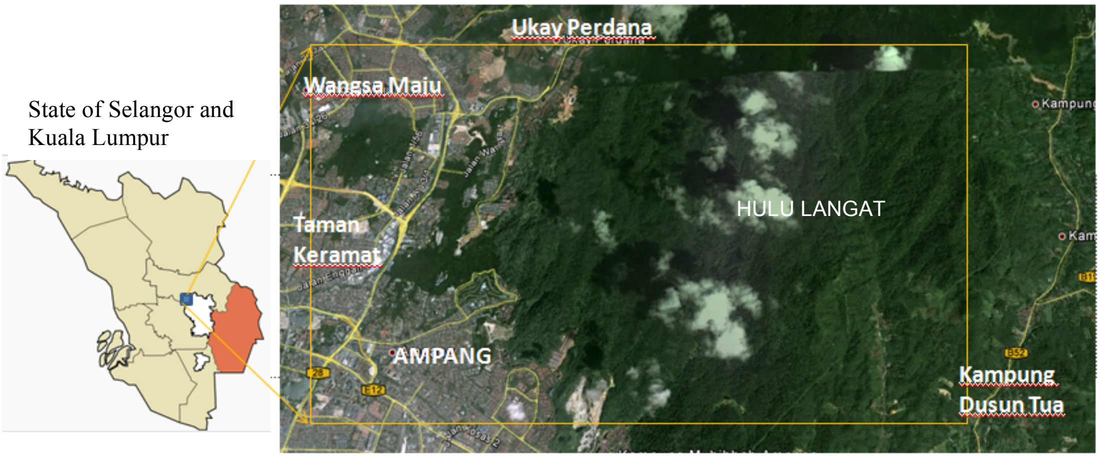


Figure 2: Location of study area
(Adapted from Google Map, 2013)

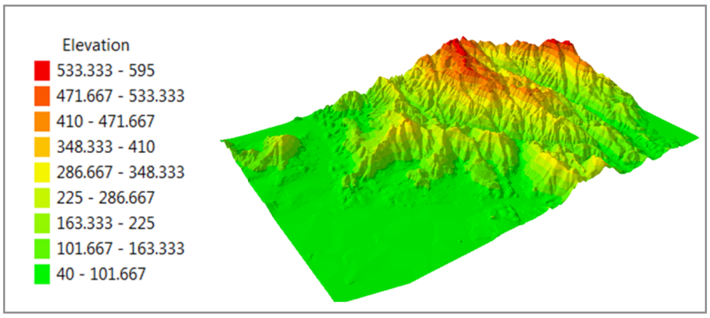


Figure 3: Perspective view of the study area

3. METHODOLOGY

The methodology of this study is organized into three main stages i) data acquisition, ii) data processing and iii) data analysis. Figure 4 shows the flowchart of the methodology adopted for this study.

For this study, open source ASTER GDEM version 2, NEXTMap Airborne IFSAR data, digital topographic maps and LiDAR data are used. ASTER GDEM data is downloaded from the USGS website (earthexplorer.usgs.gov) while the IFSAR datasets are provided by Intermap Technologies Malaysia. The three types of IFSAR data are the DSM, DTM and ORI. The NEXTMap DSM represents the earth's surface and include all features such as buildings and trees on it while DTM is a bare-earth model of the terrain. The digital topographic maps derived from 1:10,000 scale map with 5-m contour interval are acquired from the Department of Survey and Mapping Malaysia (JUPEM).

As the ASTER GDEM data downloaded from the USGS website covers a large area, image subset is carried out to clip data according to the coverage of the LiDAR, IFSAR DTM and IFSAR DSM. All these datasets are later transformed into Malayan Rectified Skew Orthomorphic (MRSO) projection in the ArcGIS software. Contours are extracted from digital topographic maps and later subset according to coverage of LiDAR data. Spatial Analyst tool in the ArcGIS software is used to generate the DEMs. The output of the data processing steps are five different DEMs.

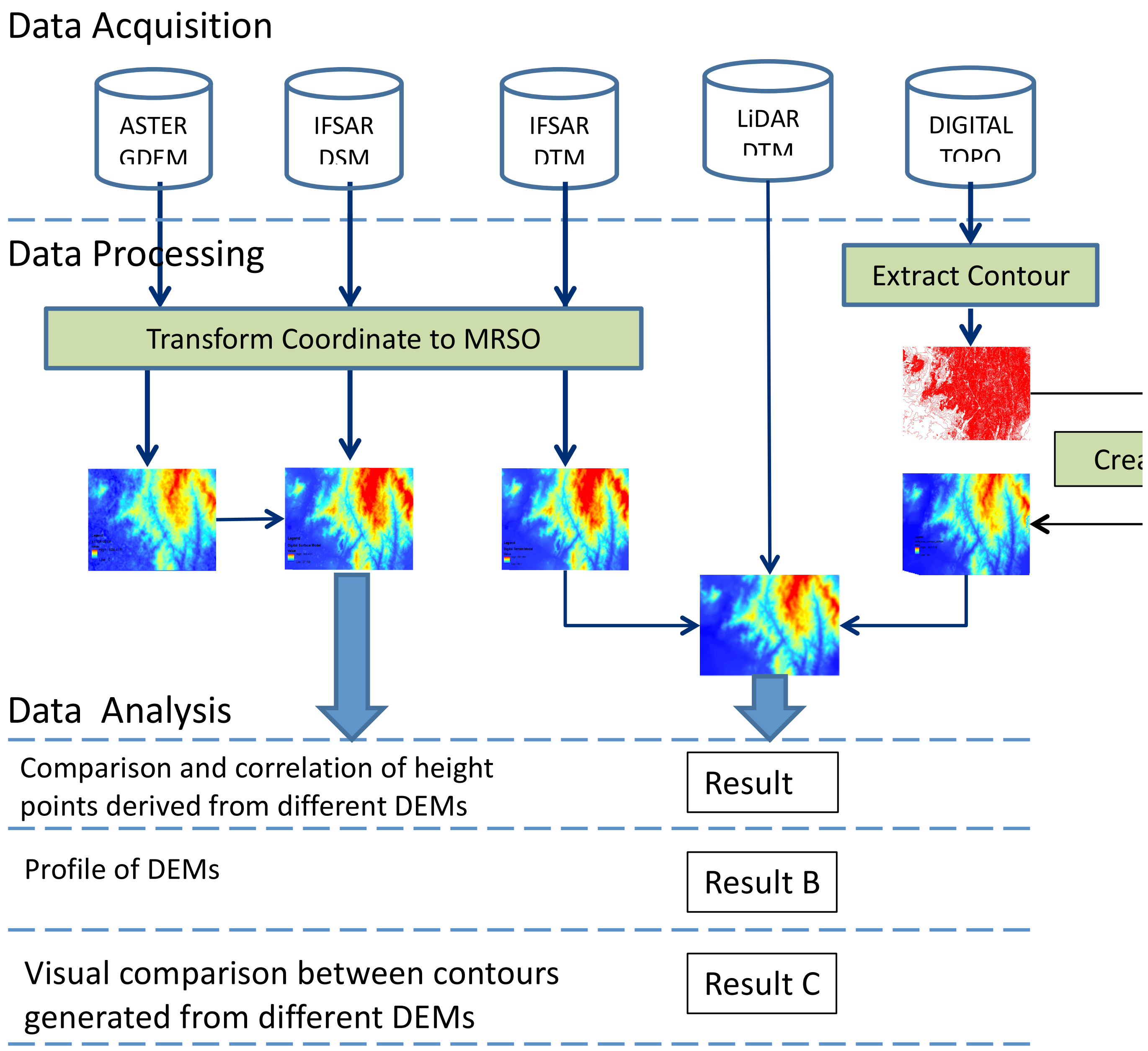


Figure 4: Flowchart of the research methodology

Further processing involved the measuring of selected height points, creating profiles and generating contour maps of selected area based on different DEMs. A total of 50 height points are manually selected and measured within the non-vegetated areas (i.e. open space and residential areas) and the forested section of the study area. Figure 5 shows the distribution of the measured height points (point ID-no from 1 to 25 for non-vegetated area and 26 to 50 for the vegetated/hilly area). Quantitative accuracy assessment of different DEMs is conducted by comparing with the reference DEMs. LiDAR DTM data provided by the Department of Public Works, Malaysia is used as reference DEM to evaluate the accuracy of NEXTMap IFSAR DTM and DTM generated from the digital topographic maps. The accuracy of ASTER GDEM is obtained by comparing with NEXTMap IFSAR DSM elevation data.

To determine the accuracy of different DEMs, the height points measured from these DEMs are compared with reference DEM and RMSE are computed. The minimum and maximum errors are also computed. The minimum error, maximum error and the RMSE are computed based on equations 1, 2 and 3 respectively. In order to determine the degree of relation between the different DEMs and the reference DEMs spatial correlation is computed. Three profiles are generated across the study area and the heights are compared. Locations of the profiles are shown in Figure 5.

$$\text{Minimun error} = \min(|Z_{obs} - Z_{ref}|) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$\text{Maximum error} = \max(|Z_{obs} - Z_{ref}|) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Z_{obs,i} - Z_{ref,i})^2}{n}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where Z_{obs} is the observed heights in different DEMs, Z_{ref} is the observed heights in reference DEM and n is the total number of observation.

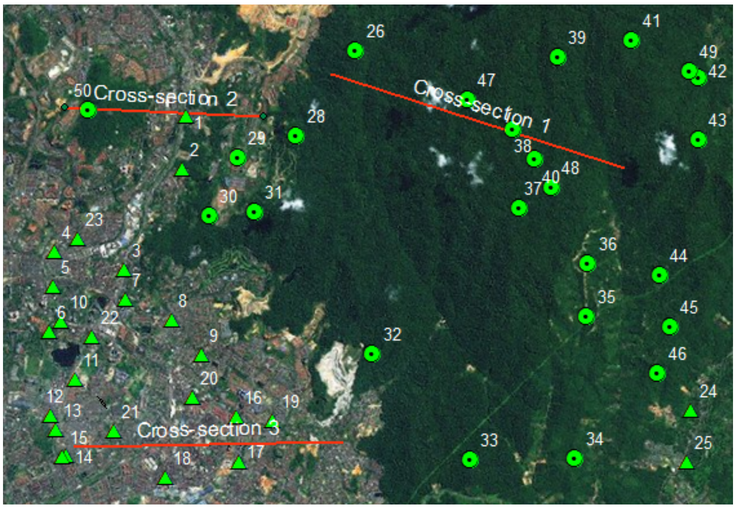


Figure 5: Distribution of manually measured height points and locations of the vertical profiles

4. RESULTS AND ANALYSIS

Figure 6 show DEMs generated from NEXTMap IFSAR, ASTER GDEM, contours extracted from digital topographic maps and LiDAR data. Visual inspection on these figures shows that the generated DEMs are almost similar except for DEM generated from ASTER GDEM (especially in low-lying areas i.e. elevation less than 50 m). This could be due to the courser DEM grid resolution (i.e. 30 m) as compared to the 5-m resolution of the IFSAR data or inaccurate height generated from ASTER GDEM.

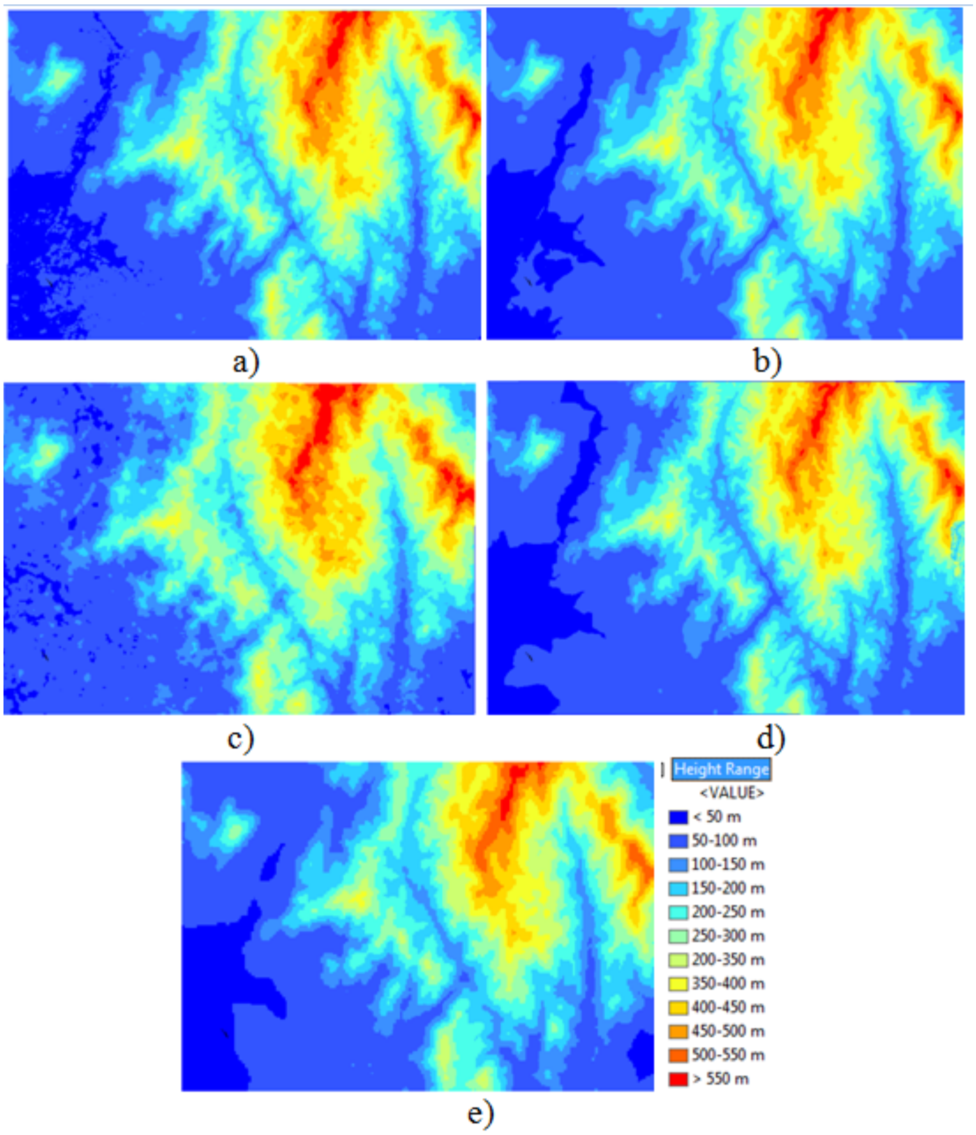


Figure 6: DEMs generated from a) NEXTMap IFSAR DSM, b) NEXTMap IFSAR DTM, c) ASTER GDEM, d) digital topographic maps (TOPO DTM) and e) LiDAR

4.1 Result A - Comparison and correlation of height points derived from different DEMs

Table 1 shows the elevation points manually observed from different DEMs in non-vegetated areas (including open spaces within residential areas) and in the vegetated areas (including forest and hilly areas). The descriptive statistics of the accuracy of DEMs based on the height points measured within the study area is summarized in Table 2

Table 1: Comparison between height points measured in LiDAR, NEXTMap IFSAR DTM, NEXTMap IFSAR DSM, DTM derived from topographic maps (TOPO) and ASTER GDEM for non-vegetated (relatively flat) and vegetated area (hilly)

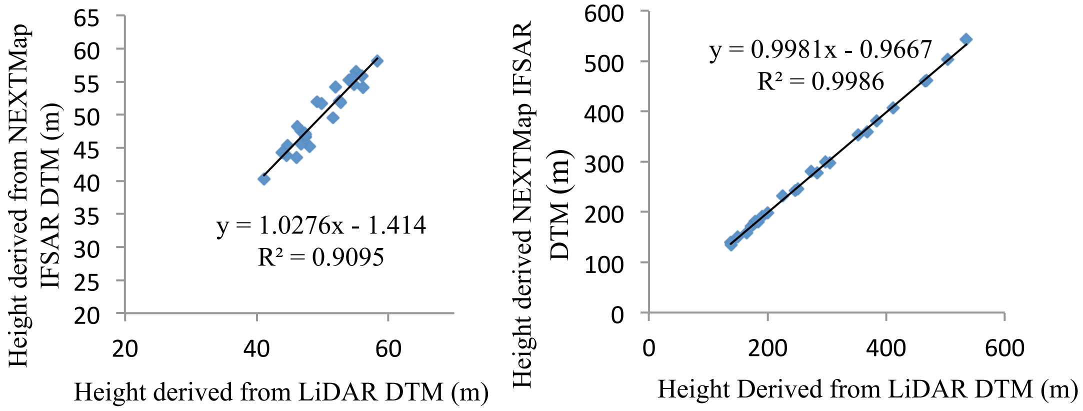
Pt No.	NEXTMap IFSAR DTM (m)	DSM (m)	LiDAR (m)	TOPO (m)	ASTER (m)	Pt No.	NEXTMap IFSAR DTM (m)	DSM (m)	LiDAR (m)	TOPO (m)	ASTER (m)
1	49.16	50.00	51.95	45.00	58	**26**	305.11	320.04	298.04	299.80	304.00
2	52.54	60.00	52.02	51.44	72	**27**	297.54	307.96	299.37	272.49	291.00
3	44.55	42.87	43.84	46.54	49	**28**	247.17	206.00	242.37	242.81	314.00
4	44.72	45.16	45.36	44.23	53	**29**	137.65	150.00	140.02	137.11	189.00
5	41.11	40.00	40.21	40.00	38	**30**	190.68	194.00	191.32	188.32	224.00
6	46.05	50.00	43.54	44.64	48	**31**	178.82	190.00	181.63	184.38	217.00
7	46.79	50.00	47.51	45.00	48	**32**	177.44	180.00	177.48	159.62	214.00
8	49.84	50.00	51.64	50.62	60	**33**	274.05	290.94	280.56	260.81	340.00
9	54.77	58.66	54.62	52.75	63	**34**	139.42	148.40	134.87	143.79	103.00
10	43.81	50.00	44.35	44.41	49	**35**	172.70	180.60	171.26	170.53	211.00
11	47.97	50.00	45.16	50.00	51	**36**	283.62	297.29	278.46	281.11	263.00
12	46.79	50.00	45.61	49.44	44	**37**	383.72	390.00	381.71	371.48	385.00
13	47.44	50.00	46.59	50.00	46	**38**	466.53	476.87	460.10	460.00	470.00
14	47.21	50.00	47.21	48.67	46	**39**	467.90	480.00	461.34	454.73	482.00
15	47.41	50.00	47.03	46.09	48	**40**	504.06	520.00	504.23	492.38	499.00
16	54.07	60.00	55.22	56.43	63	**41**	352.79	358.72	353.42	352.55	313.00
17	58.33	60.00	58.20	59.98	63	**42**	200.35	210.00	198.23	184.57	245.00
18	52.03	60.00	54.23	55.00	70	**43**	535.54	539.68	543.85	529.88	511.00
19	55.12	60.00	56.54	55.00	69	**44**	251.72	260.00	246.57	242.60	269.00
20	52.73	60.00	51.83	55.00	62	**45**	164.72	180.00	158.84	150.00	175.00
21	51.57	54.61	49.50	52.39	60	**46**	184.63	198.27	179.66	186.27	157.00
22	46.15	50.00	48.16	45.00	50	**47**	412.20	420.00	407.32	410.54	462.00
23	54.57	60.00	55.68	55.00	61	**48**	367.32	376.95	359.43	358.11	412.00
24	56.20	60.00	54.14	60.00	69	**49**	225.38	230.32	231.89	230.00	254.00
25	55.97	60.00	55.83	60.97	53	**50**	149.74	154.14	151.23	143.93	215.00

Note : Pt No. 1 – 25 (non-vegetated area) and Pt No. 26 – 50 (vegetated/hilly area)

For the vegetated areas, the RMSEs for NEXTMap IFSAR DTM, DTM generated from contour maps and ASTER GDEM are 4.736, 9.848 and 18.900 m respectively. In the non-vegetated areas, the RMSEs for IFSAR DTM and DTM generated from contour maps are 1.458 and 2.960 m respectively while the accuracy of ASTER GDEM is much lower i.e. 8.442 m. The maximum errors in the non-vegetated and vegetated areas for ASTER GDEM are 19.460 and 49.690 m respectively. In the non-vegetated areas, the minimum and maximum height difference (as compared to LiDAR) for IFSAR DTM are 0.001 and 2.815 m respectively. The maximum error for DTM generated from contours extracted from digital topographic maps is 6.954m. The accuracies for all the DEMs tested are much lower in the vegetated areas as compared to non-vegetated areas of the study area (refer to Table 2). The correlation between the elevations obtained from different DEMs and the reference DEM are graphically shown in figures 7, 8 and 9. Based on these figures and Table 3, it is evident that the correlation between DEMs and reference DEMs is highest in IFSAR DTM (i.e. 90.95% and 99.47% for the non-vegetated and vegetated areas respectively) followed by DTM generated from topographic map (i.e. 73.05% and 99.48% for the non-vegetated and vegetated areas respectively). As shown in Figure 9, strong correlation is also evident in the generated DSMs (i.e. ASTER GDEM verses NEXTMap IFSAR DSM).

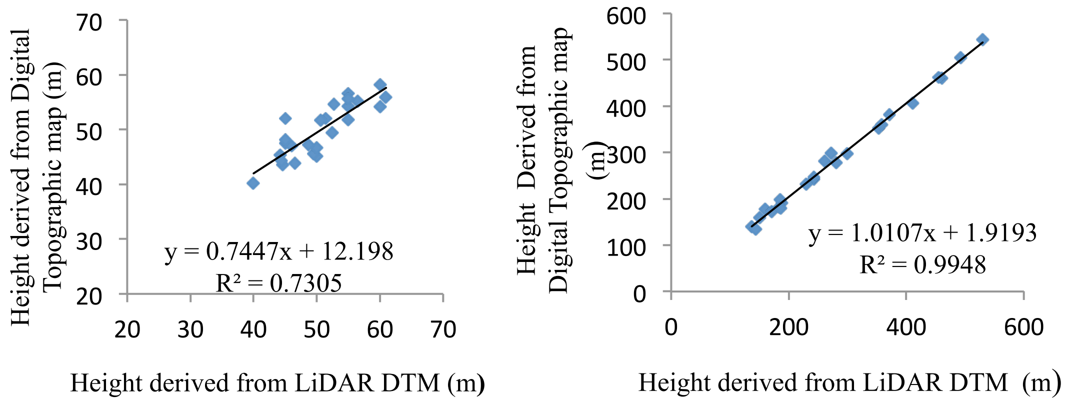
Table 2: Descriptive statistics of the differences between various DEMs and reference DEM of non-vegetated and vegetated areas

	Non-vegetated area			Vegetated area		
	RMSE (m)	Min (m)	Max (m)	RMSE (m)	Min (m)	Max (m)
IFSAR DTM-LiDAR	1.458	0.001	2.815	4.736	0.040	8.306
TOPO-LiDAR	2.960	0.214	6.954	9.848	0.100	26.882
ASTER- IFSAR DSM	8.442	0.059	19.460	18.900	2.400	49.680



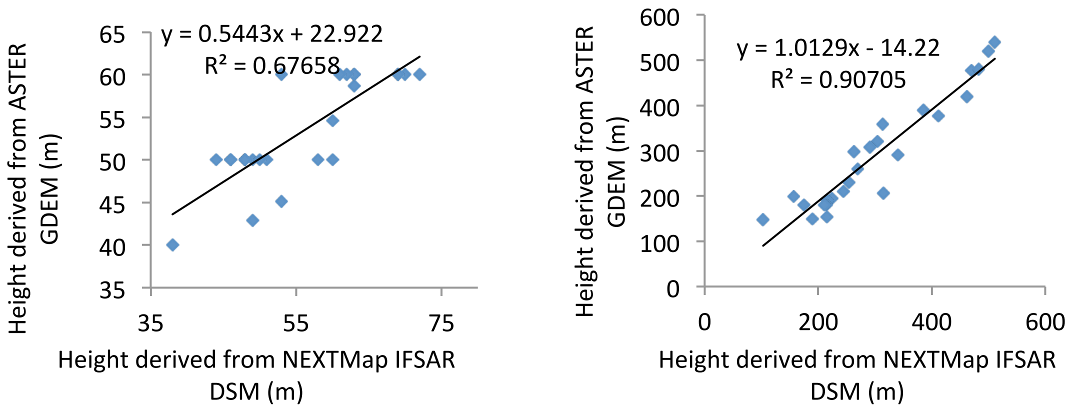
a) b)

Figure 7: Correlation plots of NEXTMap IFSAR DTM verses LiDAR DTM in a) non-vegetated and b) vegetated area



a) b)

Figure 8: Correlation plots of DTM derived from digital topographic map verses LiDAR DTM in a) non-vegetated and b) vegetated area



a) b)

Figure 9: Correlation plots of ASTER GDEM verses NEXTMap IFSAR DSM for a) non-vegetated area and b) vegetated area

Table 3: Correlation and regression coefficients between IFSAR DTM, TOPO DTM, ASTER GDEM with reference DEMs for both the non-vegetated and vegetated areas

	Non-vegetated area			Vegetated Area		
	Correlation Coefficient(R^2)	Gradient (m)	Intercept (c)	Correlation Coefficient(R^2)	Gradient (m)	Intercept (c)
IFSAR DTM – LiDAR	0.9095	1.028	1.414	0.999	0.998	0.967
TOPO - LiDAR	0.7305	0.745	12.198	0.995	1.011	1.919
ASTER – IFSAR DSM	0.6766	0.544	22.922	0.909	1.013	-14.22

4.2 Result B – Terrain Profile derived from different DEMs

Figures 10, 11, 12, 13, 14, and 15 show the profile plots along three cross-sections within the study area. Cross-section 1 run across a vegetated (forest) and hilly area while Cross-section 2 is located in a relatively undulating area. The middle section of Cross-section 2 is a relatively flat area. Cross-section 3 is located within the residential and relatively flat section of the study area. In all the three cross-sections, there is strong agreement between profiles generated from NEXTMap IFSAR DTM, DTM generated from digital topographic maps and LiDAR DTM datasets (refer to figures 10, 12 and 14). Although there is significant variation between heights generated from ASTER GDEM and NEXTMap IFSAR DSM in some areas along cross-sections 1 and 2 (refer to figures 11 and 13), the pattern of height profiles are still quite similar. The largest discrepancies between ASTER GDEM and NEXTMap IFSAR DSM occurred in a relatively flat area (refer to Figure 15).

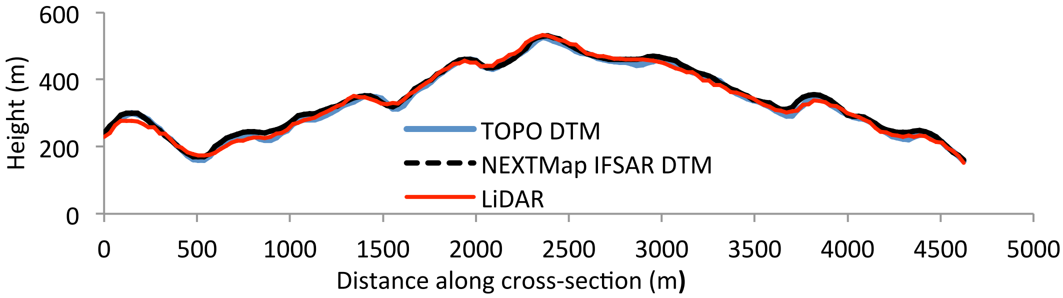


Figure 10: Profile of DTM generated from digital topographic map, IFSAR DTM and LiDAR along Cross-section 1

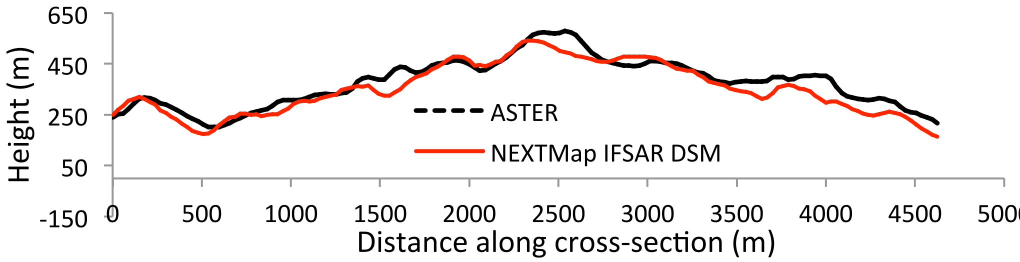


Figure 11: Profile of DSM generated from ASTER GDEM and IFSAR DSM along Cross-section 1

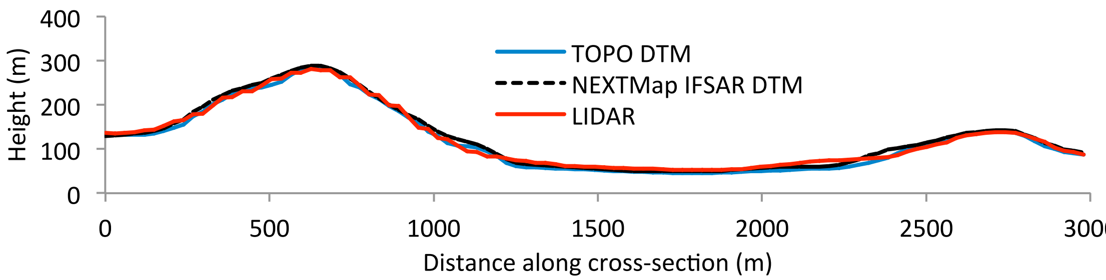


Figure 12: Profile of DTM generated from digital topographic map, IFSAR DTM and LiDAR along Cross-section 2

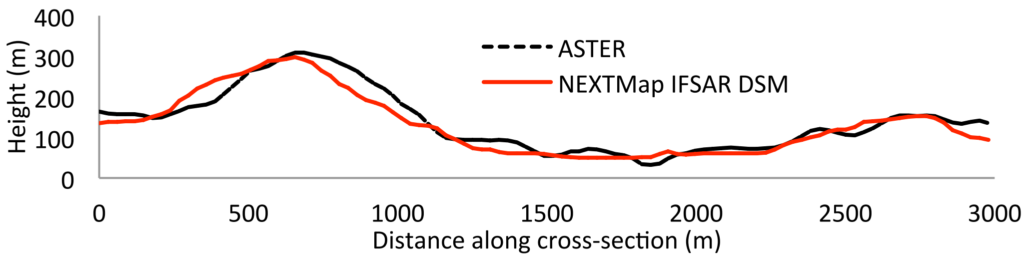


Figure 13: Profile of DSM generated from ASTER GDEM and IFSAR DSM along Cross-section 2

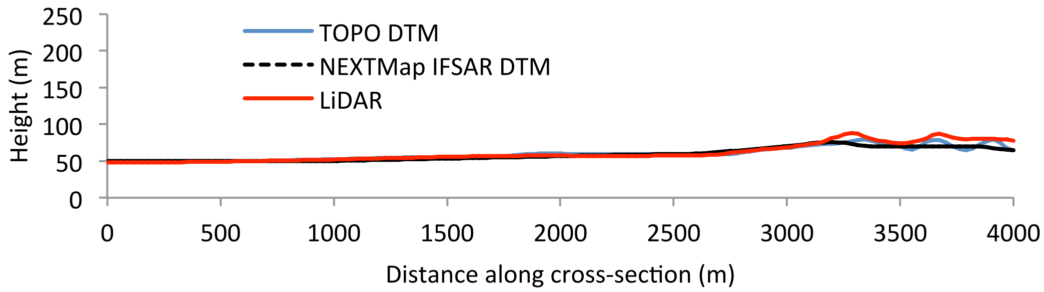


Figure 14: Profile of DTM generated from digital topographic map, IFSAR DTM and LiDAR along Cross-section 3

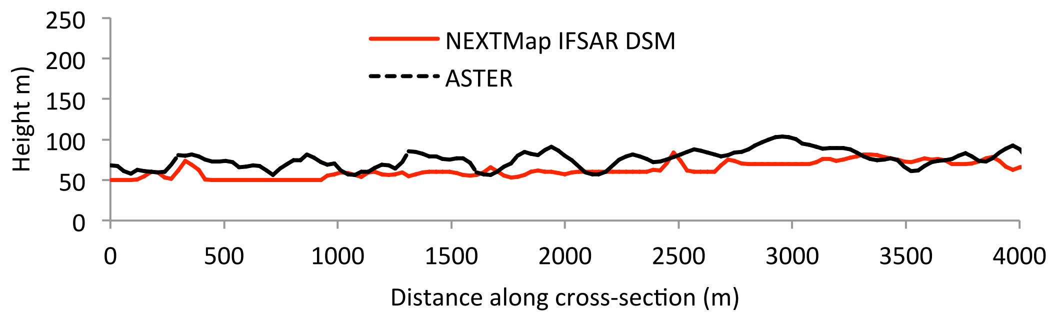


Figure 15: Profile of DSM generated from ASTER GDEM and IFSAR DSM along Cross-section 3

4.3 Result C – Visual comparison of contours generated from different DEMs

Figure 16 compares the contour extracted from digital topographic maps and contour derived from LiDAR DTM. Comparison between contours generated from NEXTMap IFSAR DTM and LiDAR DTM is shown in Figure 17. The contours generated from ASTER GDEM and NEXTMap IFSAR DSM of another section of the study area are shown in Figure 18. Visual inspection clearly shows that there is close agreement between the contours extracted from digital topographic maps, IFSAR DTM and LiDAR DTM data. Although there are some differences in the contours generated from ASTER GDEM and IFSAR DSM, the general pattern can still be seen (refer to Figure 18).

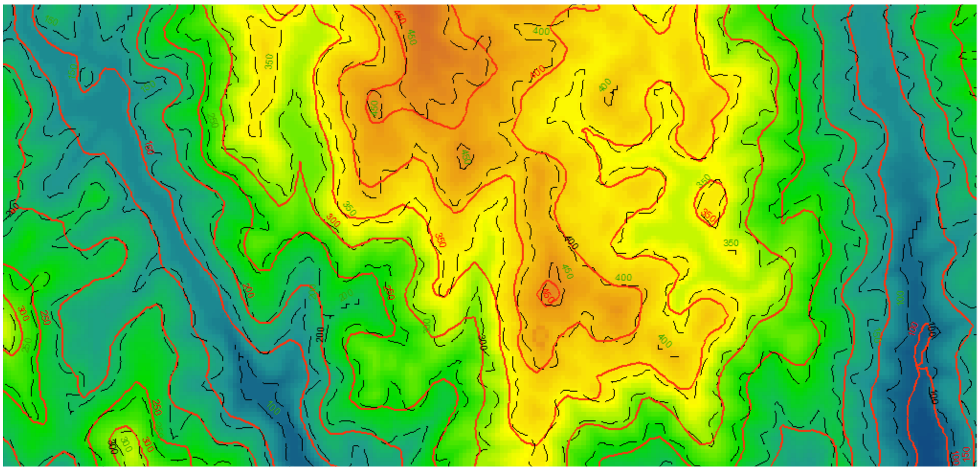


Figure 16: Comparison between contours generated from digital topographic map (dashed line) and LiDAR DTM data (in red colour)

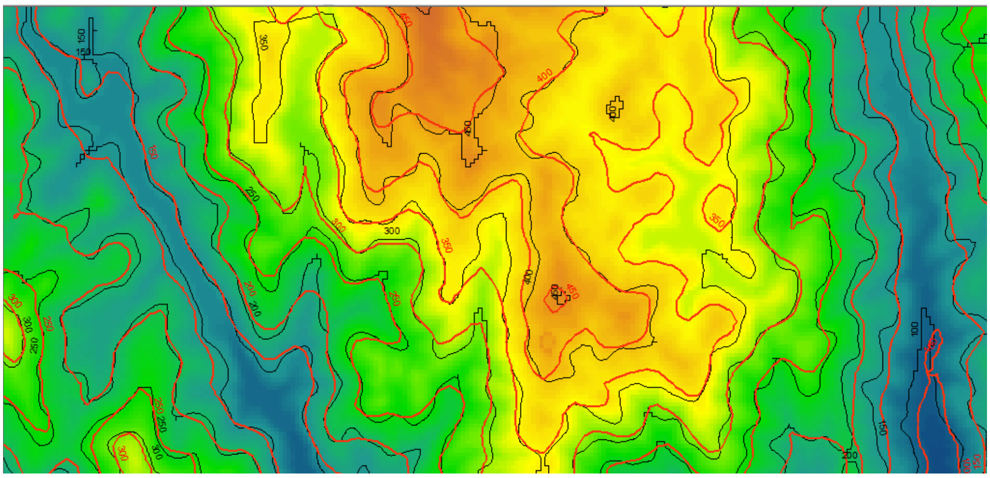


Figure 17: Comparison between contours generated from IFSAR DTM (in black colour) and contour generated from LiDAR DTM data (in red colour)

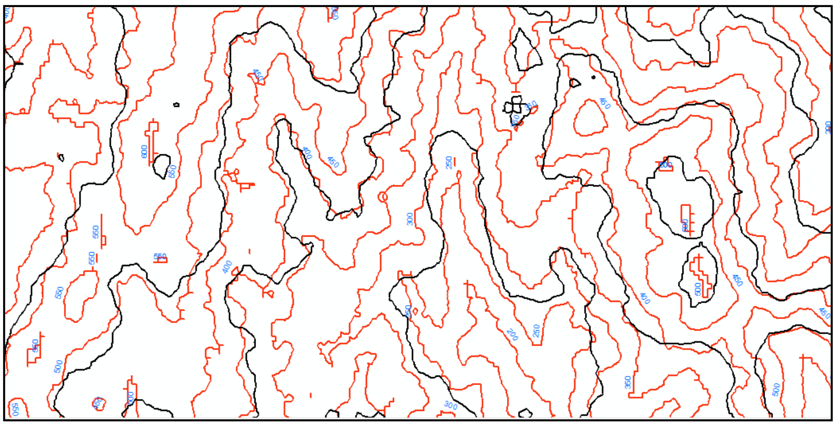


Figure 18: Comparison between contours extracted from ASTER GDEM (in black colour) and contour generated from NEXTMap IFSAR DSM (in red colour)

5. CONCLUSIONS

The vertical accuracy of ASTER GDEM, NEXTMap IFSAR DTM and DTM generated from contours extracted from digital topographic maps are evaluated in the present study. The validation of DTM generated from digital topographic maps and NEXTMAP IFSAR DTM is performed based on LiDAR DTM data. The height accuracy of ASTER GDEM is computed based on NEXTMap IFSAR DSM data. Initial findings have indicated the potential use of IFSAR DTM products for generating accurate contour maps of an area. ASTER GDEM could represent the terrain characteristics of the study area but there are some obvious errors especially in hilly and vegetated areas. Findings from this study have also shown that the accuracy of all DEMs in vegetated and hilly areas are lower than the non-vegetated areas. This could be due to various topographical or terrain factors. Further work is needed to identify factors that contribute to low accuracy of the different types of DEM in certain parts of the study area. As this study is part of a more comprehensive research to evaluate the suitability of using open source or global DEMs for topographic map updating, a detail study on the effects of height accuracy on the orthorectification process of high resolution satellite imagery is needed.

ACKNOWLEDGEMENTS

The authors would like thank the Department of Survey and Mapping Malaysia (JUPEM), Intermap Malaysia Inc., Malaysian Remote Sensing Agency and the Department of Public Works Malaysia, for providing necessary data for this study. Many thanks go to the Board of Surveyors Malaysia for their financial support in completing this study.

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