UNIVERSITI PUTRA MALAYSIA

IMPROVEMENT OF VERTICAL HEIGHT ACCURACY USING DATA FUSION TECHNIQUE FOR TERRAIN MAPPING IN OIL PALM PLANTATION

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By

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Digital elevation models (DEMs) play an important role in producing terrain-related applications such as curvature and contour maps for planning and management of oil palm plantation. Compared to Light Detection and Ranging (LiDAR) data, Interferometric Synthetic Aperture Radar (IfSAR) has lower accuracy but the cost is much cheaper. In order to increase the accuracy of IfSAR data, fusion of IfSAR and terrestrial LiDAR (TLS) datasets was proposed in this study.

The TLS data collection was carried out in TH Plantation in Muadzam Shah, Pahang using Faro 3D Laser Scanner. Two different stations were selected with different terrain characteristics. Station 1 was located in a relatively flat area while station 2 was located in a rolling and hilly area. Raw data of TLS were filtered using TerraScan software to extract the ground points from object points.

In this study, the efficiency of filtering technique for TLS data was assessed and determined before being used for data fusion with IfSAR. The performance of data filtering was tested by using double filtering technique. Using this technique, 20,977594 points were correctly identified as object points while 10804 object points were mistakenly classified as ground points. Statistically, 0.05% of type II errors (accept object points as ground points) were obtained in the study area. The result indicates that filtering algorithm in TerraScan was good enough to be used for TLS data in oil palm plantation.

When the filtering was completed, data fusion of TLS and IfSAR-derived DEM was developed to increase the accuracy of IfSAR-derived elevation models and provide high quality data for plantation management especially for slope risk management. This study used fusion by weights based on the spatial errors after

applying regression equation. The results show a significant reduction in RMSEs after fusion. RMSEs of both stations reduced from 1.83 m to 0.35 m and from 3.13 m to 0.41 m for station 1 and station 2 respectively.

In addition, data fusion technique for area with no TLS data that located nearby the station was tested. Data fusion of these areas was carried out by using regression equation of their relative station but the weighted values were computed differently from the previous fusion technique. The weighted value was computed using mean error of the elevation of its relative station, the mean error of the elevation based on classified elevation range and the error pattern based on its relative station. All results proved that the proposed fusion technique could be done in relatively flat area but it could not be used in steep-slope area.

A mobile application was also developed for field data collection and verification. The application has been successfully developed and tested in the field. On the whole, it is concluded that data fusion is a promising technique for increasing the accuracy of IfSAR-derived DEM in oil palm plantation.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENAMBAHANBAIKAN KETEPATAN BAGI KETINGGIAN MENEGAK MENGGUNAKAN TEKNIK FUSION DATA BAGI MENGHASILKAN BENTUK MUKA BUMI DALAM LADANG KELAPA SAWIT

Oleh

NUR 'ATIRAH BINTI MUHADI

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Model ketinggian digital (DEMs) memainkan peranan penting dalam menghasilkan aplikasi yang berkaitan dengan kawasan seperti lengkungan dan peta kontur untuk perancangan dan pengurusan perladangan kelapa sawit. Berbanding dengan *Light Detection and Ranging* (LiDAR), *Interferometric Synthetic Aperture Radar* (IfSAR) mempunyai ketepatan yang lebih rendah tetapi kosnya lebih murah. Untuk meningkatkan ketepatan data IfSAR, gabungan data-data IfSAR dan Terrestrial LiDAR (TLS) diperkenalkan dalam kajian ini.

Pengumpulan data TLS diambil di TH Plantation di Muadzam Shah, Pahang menggunakan Faro 3D Laser Scanner. Dua stesen yang berbeza dipilih dengan ciri-ciri rupa bumi yang berbeza. Stesen 1 terletak di kawasan yang agak rata manakala stesen 2 terletak di kawasan tinggi dan berbukit. Data asal TLS telah ditapis menggunakan perisian TerraScan untuk mengekstrak titik bumi dari titik objek.

Dalam kajian ini, kecekapan teknik penapisan untuk data TLS dinilai dan ditentukan sebelum digunakan untuk gabungan data dengan IfSAR. Prestasi penapisan data diuji dengan menggunakan teknik penapisan berganda. Dengan menggunakan teknik ini, 20,977594 titik dikenalpasti dengan betul sebagai objek objek sementara 10804 titik objek tersilap dikelaskan sebagai titik bumi. Secara statistik, 0.05% ralat jenis II (menerima titik objek sebagai titik bumi) diperolehi di kawasan kajian. Hasilnya menunjukkan bahawa algoritma penapisan di TerraScan cukup baik untuk digunakan untuk data TLS dalam ladang kelapa sawit.

Apabila penapisan selesai, gabungan data TLS dan IfSAR telah dibangunkan untuk meningkatkan ketepatan model ketinggian yang dihasilkan oleh IfSAR dan menyediakan data yang berkualiti tinggi untuk pengurusan ladang terutamanya untuk pengurusan risiko cerun. Kajian ini menggunakan teknik pemberat berdasarkan purata ralat selepas menggunakan persamaan regresi. Keputusan menunjukkan penurunan yang ketara dalam RMSE selepas gabungan. RMSE di kedua-dua stesen dikurangkan dari 1.83 m hingga 0.35 m dan dari 3.13 m hingga 0.41 m untuk stesen 1 dan stesen 2.

Di samping itu, teknik gabungan data untuk kawasan tanpa data TLS yang terletak berhampiran stesen telah diuji. Gabungan data kawasan ini dilakukan dengan menggunakan persamaan regresi dari stesen berhampiran tetapi nilai pemberat dikira dengan cara berbeza dari teknik gabungan yang sebelumnya. Nilai pemberat dikira menggunakan tiga cara iaitu purata ralat ketinggian stesen relatifnya, purata ralat ketinggian berdasarkan julat ketinggian yang telah dikelaskan dan corak ralat berdasarkan stesen relatifnya. Semua keputusan membuktikan bahawa teknik gabungan yang dicadangkan boleh dilakukan di kawasan yang rata tetapi tidak dapat digunakan di kawasan curam.

Aplikasi mudah alih juga dibangunkan untuk pengumpulan dan pengesahan data lapangan. Aplikasi telah berjaya dibangunkan dan diuji di lapangan. Secara keseluruhan, disimpulkan bahawa gabungan data adalah teknik yang mampu meningkatkan ketepatan DEM yang diperolehi dari IfSAR di ladang kelapa sawit.

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CHAPTER 1

INTRODUCTION

1.1 Background Study

Oil palm, or also known as *Elais guineensis* was brought to Malaysia from Africa during the British colonial. It was first introduced as an ornamental plant in the early 1870s. Oil palm tree, a tropical native tree in Africa, can grow well in Malaysia due to its favourable climate. A humid tropical climate with 24°C to 32°C temperature throughout the year with 2000-2500 millimeter (mm) evenly distributed annual rainfall together with an adequate amount of sunshine, are the optimum climate criteria to grow oil palm trees (Corley and Tinker, 2003).

Malaysia was the largest oil palm producer before the title was taken by Indonesia in 2005 (Malaysian Palm Oil Board, 2014). Indonesia decided to expand a thousand hectares of land for a new oil palm plantation each year between 2000 and 2006 (FAOSTAT, 2016). Because of abundant land and cheap labour cost, Indonesia has become the largest and most rapid growing producer. Since then, Malaysia is the second largest palm oil producer in the world (Malaysian Palm Oil Board, 2014).

Nevertheless, oil palm is still the most important commodity crop in Malaysia. In early 1920, Malaysia had only 400 hectares of oil palm plantation (FAOSTAT, 2016). The growth of oil palm plantation experienced a drastic expansion after Malaysia obtained independence from the British colonial in 1957. Statistics on oil palm plantation shows that the hectarage increased from 400 hectares to 54 000 hectares in the 1960s (FAOSTAT, 2016). By December 2014, 5.39 million hectares of land use in Malaysia is under oil palm plantation, producing 19.67 million tonnes of oil palm (Malaysian Palm Oil Board, 2014). Figure 1.1 shows oil palm production in Malaysia from the year 2000 until 2014. It is obvious from the graph that oil palm production has increased over the years.

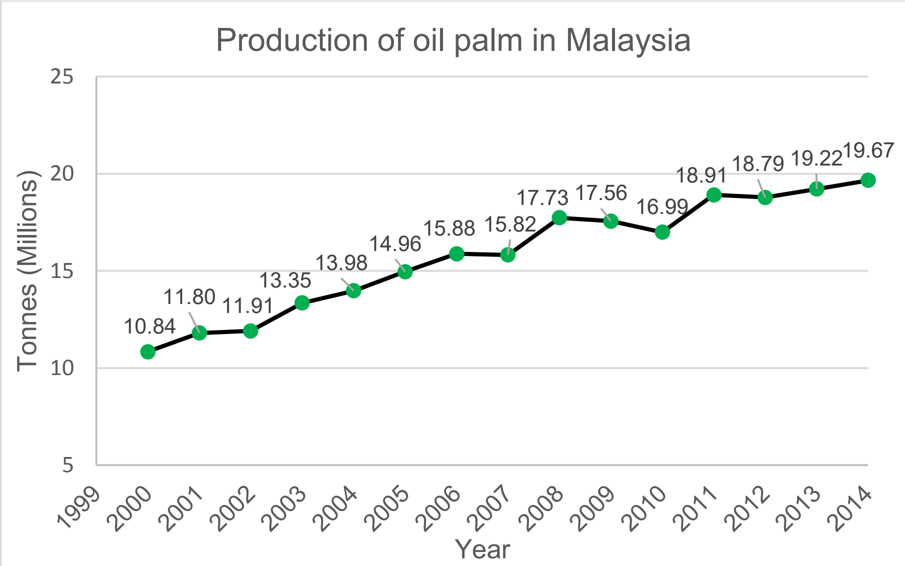

Figure 1.1: Oil palm production in Malaysia (Source: Malaysian Palm Oil Board, 2014; FAOSTAT, 2016)

In order to produce a high oil palm yield productivity, the government and private sectors have allocated a huge amount of money for research and development in oil palm. Various studies on oil palm cultivation were carried out to investigate the best practices for a sustainable oil palm plantation. In oil palm industry, site selection for oil palm planting is critical because it will affect the yield productivity (Corley and Tinker, 2003). If the plantation is placed on a wrong site, it will bring a great loss to the plantation company. The best practices that management has to consider during oil palm cultivation development in terms of land selection was discussed by Paramananthan (2012).

Site characterisation is initially required to determine the slope instability for potential plantation area. It is also periodically required throughout the life of oil palm plantation area because changes in slope stability can occur because of weather and plantation process especially during oil palm replanting stage. Information on the slope and elevation can be extracted from Digital Elevation Models (DEMs). DEM was used for many purposes. The digitised map, such as topographic map and contour map, can be used to collect and analyse information concerning the plantation. In 2012, there was 1:50,000 scale topographic maps available for the whole of Malaysia. Nevertheless, the reliability varies from Peninsular Malaysia and East Borneo Malaysia regions in terms of contour intervals (Paramananthan, 2012). The plantation map could be accurately produced if the DEM data is accurate. Thus, it is important to ensure that the DEM data obtained is as accurate as possible.

DEMs could be used for some analysis, specifically analysis based on elevation. Both elevation and slope are important in land selection and oil palm plantation management. In the plantation, the ideal conditions for oil palm cultivation are found in flat areas with 0-4° slope inclination and could be planted up to 16° (Corley and Tinker, 2003). It is suggested to avoid planting on a steep slope as it requires high planting, maintenance and harvesting cost. In addition, the risk of soil erosion and nutrient losses through runoff increases as slope increases. On the contrary, increase in elevation is strongly correlated with decrease in temperature. Furthermore, elevation is often correlated with slope inclination. It is recommended to avoid planting oil palm on more than 200 meter (m) above mean sea levels (Rhebergen, 2012).

For a new plantation or replanting area, DEM provides information on area topography that requires a study to avoid future problems. Felda and Felda Global Venture (FGV) have practiced oil palm replanting blueprint that involves several activities that require DEM data. DEM data is used in collecting data for planning purposes. Besides, the data is also required during lining and terrace construction. The workflow of replanting scheme used by Felda and FGV is shown in Figure 1.2.

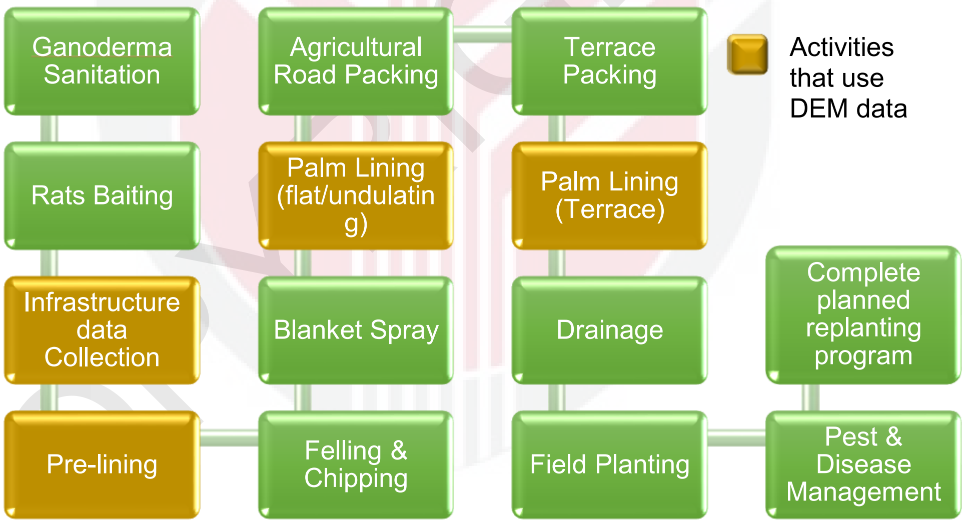

Figure 1.2: Workflow of oil palm replanting implementation

DEM could be generated from many sources, ranging from no cost to high cost data sources depending on its accuracy. Terrestrial laser scanning (TLS) is a ground-based light detection and ranging (LiDAR) that rapidly acquired data using laser technology. The accuracy of TLS is the highest among all sources of DEM data with millimeter accuracy, depending on the parameter used when collecting data.

However, TLS could only cover small-scale area and not suitable for large plantation area. In addition, airborne LiDAR is another source that could provide DEM with centimeter accuracy and cover large-scale area. Nevertheless, the cost of acquiring data is around RM3000 per one square kilometer (sq km), which is very costly for data acquisition in oil palm plantation.

Interferometric Synthetic Aperture Radar (IfSAR) is one of DEM generation methods, which could provide elevation data with accuracy up to 5-meter. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Shuttle Radar Topography Mission (SRTM) are another alternatives that could generate DEM data with accuracy up to 30 meter. Plantation management usually use contour lines produced by JUPEM to generate DEM data. However, the reliability of this source varies in term of location of area of interest and year of map produced.

Therefore, a study on improvement of vertical height accuracy using data fusion technique for terrain mapping in oil palm plantation is carried out to assist oil palm plantation management in planning and decision-making. By having high accuracy information on elevation data, the management can supervise and manage the plantation more systematically especially during replanting stage.

1.2 Problem Statements

Climate, soil type, and slope are the main factors that influence land selection for oil palm cultivation. The slope can be extracted from digital elevation models (DEMs) to describe terrain morphology. Moreover, DEM plays a vital role in producing terrain-related applications such as slope map and curvature map. In oil palm industry, the required vertical accuracy is two feet or around 0.6 meter. Among the DEM generation methods that available, airborne LiDAR and TLS provide the nearest accuracy that is needed by the plantation management application. Airborne LiDAR can provide highly accurate DEM data for large-scale area. However, the cost of acquiring airborne LiDAR is very expensive, which is not cost effective for oil palm plantation management.

On the other hand, TLS produces high accuracy of DEM because the data is acquired from the ground. Nevertheless, it covers small-scale area and only few measurements can be made due to high steep and highly inaccessible of oil palm plantation area. On contrary, IfSAR is could provide 5-meter accuracy DEM source at RM300 per sq km. However, the accuracy of IfSAR does not meet the requirement of vertical accuracy for oil palm sector. To surmount these difficulties, a combination of airborne IfSAR and TLS data is proposed. IfSAR is chosen as a complimentary of TLS because of its reasonable price and large coverage area.

DEM is not the only issue that needs to be faced by the oil palm plantation management. Slow and inaccurate field data collection is also contribute to the non-productive planning and management. The conventional way of field data collection and validation is by using pen and paper. After completing the field data collection, the labours should return to the office and change the hard copy data to soft copy data format to enable further analysis.

This process takes time and it is not cost-effective. Moreover, network connectivity is rarely available when using mobile application in the plantation. Therefore, a mobile application with the ability to collect field data and validate the elevation of study area during online and offline mode is introduced. An accurate DEM data as a base map can help in the process of data collection and validation.

This study is carried out to produce a cheaper data for DEM generation with better accuracy. This work aims to reduce the DEM data cost so that plantation management can afford to purchase the data and thus will result in a wise plantation management and decision-making. In addition, a mobile application is developed to solve network connectivity problem when collecting data in the plantation.

1.3 Objectives of Study

The main goal of this research is to improve IFSAR-derived elevation models accuracy by integrating terrestrial LiDAR and IfSAR datasets. The specific objectives are:

i. To assess the efficiency of filtering process by applying double filtering technique.
ii. To fuse both airborne IfSAR and terrestrial LiDAR to provide high quality DEM data for plantation management
iii. To develop a mobile application for data collection and validation using the improved DEM as a base map.

1.4 Scope and Limitations

This study focuses on DEMs generation for oil palm replanting program in the plantation. Single scan is used to cover the entire scan station using terrestrial laser scanner. Scanning area involved oil palm trees at the age of seven years. Therefore, this study is applicable for trees at the age of seven years and below. Besides, the object points that found in the study area were mostly oil palm trees. Therefore, objects other than trees were not classified. The manual classification of trees was done to determine the filtering algorithm efficiency used in TerraScan software. Assessment of filtering process would focus merely on Type II errors.

When performing data fusion technique, this study assumed that the acceptable errors of elevation were in the range of $-1 < 0 < 1$ because there is no perfect instrument or data that could get zero errors. Besides, the errors were accepted due to the fact that original data errors have errors that are more than those values. In the process of developing the mobile application, the accurateness of field location was out of the scope. From this perspective, this study is only focuses on the recording of field data collection and the ability of the mobile application to operate in an area without network connectivity.

1.5 Thesis Overview

This thesis contains five chapters. Chapter 1 is an introduction to the thesis, providing a background study, problem statements, objectives, and scope and limitation of study. Chapter 2 contains a literature review on several topics that are related to research project. Literature reviews on Light Detection and Ranging (LiDAR), Interferometric Synthetic Aperture Radar (IfSAR), filtering technique, Digital Elevation Model (DEM) generation, data fusion technique, and mobile applications are provided in Chapter 2. Besides, a summary of previously published articles is discussed in Chapter 2. Chapter 3 provides a description of materials and methods used in this study. Study area, data acquisition and data analysis are discussed in this chapter. Chapter 4 contains the results and discussions of the DEM generation and fusion as well as the development of mobile application. The conclusion and recommendation of study are discussed in Chapter 5. Additional figures for this thesis are provided in Appendices.

REFERENCES

ArcGIS. (2017). Retrieved 23 April 2017 from http://www.arcgis.com

Ardiansyah, P. O. D., & Yokoyama, R. (2002). DEM generation method from contour lines based on the steepest slope segment chain and a monotone interpolation function. *ISPRS Journal of Photogrammetry and Remote Sensing*. 57(1–2): 86–101.

Axelsson, P. (1999). Processing of laser scanner data—algorithms and applications. *ISPRS Journal of Photogrammetry and Remote Sensing*. 54: 138–147.

Axelsson, P. (2000). DEM Generation from Laser Scanner Data Using adaptive TIN Models. *International Archives of Photogrammetry and Remote Sensing*, *33*(Part B4), 110–117.

Baker R, Cannon R, Bartlett P, Barker I (2005) Novel strategies for assessing and managing the risks posed by invasive alien species to global crop production and biodiversity. Annals of Applied Biology 146: 177-191.

Baltensweiler, A., Walthert, L., Ginzler, C., Sutter, F., Purves, R. S., & Hanewinkel, M. (2017). Terrestrial laser scanning improves digital elevation models and topsoil pH modelling in regions with complex topography and dense vegetation. *Environmental Modelling and Software. 95*, 13–21.

Barneveld, R. J., Seeger, M., & Maalen-Johansen, I. (2013). Assessment of terrestrial laser scanning technology for obtaining high-resolution DEMs of soils. *Earth Surface Processes and Landforms*. 38(1): 90–94.

Brenner, C. (2005). Building reconstruction from images and laser scanning. *International Journal of Applied Earth Observation and Geoinformation*. 6(3): 187–198.

Brovelli, M. A., Cannata, M., & Longoni, U. M. (2002). Managing and processing LIDAR data within GRASS. In *Proceedings of the GRASS users conference* (Vol. 29).

Chen, C. M., Hepner, G. F., & Forster, R. R. (2003). Fusion of hyperspectral and radar data using the IHS transformation to enhance urban surface features. *ISPRS Journal of Photogrammetry and Remote Sensing*. 58(1–2): 19–30.

Chen, L., Zhao, S., Han, W., & Li, Y. (2012). Building detection in an urban area using lidar data and QuickBird imagery. *International Journal of Remote Sensing*. 33(16): 5135–5148.

Corley, R.H.V. and Tinker, P.B. (2003) Site Selection and Land Preparation. In *The Oil Palm*, *Fifth edition* (pp. 240-274). John Wiley & Sons, Ltd, Chichester, UK.

Culman, M. A., Gomez, J. A., Talavera, J., Quiroz, L. A., Tobon, L. E., Aranda, J. M., ... & Bayona, C. J. (2017, April). A Novel Application for Identification of Nutrient Deficiencies in Oil Palm Using the Internet of Things. In *Mobile Cloud Computing, Services, and Engineering (MobileCloud), 2017 5th IEEE International Conference on* (pp. 169-172). IEEE.

Dalponte, M., Bruzzone, L., & Gianelle, D. (2008). Fusion of hyperspectral and LIDAR remote sensing data for classification of complex forest areas. *Geoscience and Remote Sensing, IEEE Transactions on Geoscience and Remote Sensing*. 46(5): 1416–1427.

Dowman, I. J. (2004). Integration of LIDAR and IFSAR for Mapping. *International Archives of Photogrammetry and Remote Sensing.* 35(B2): 90–100.

Ehlert, D., & Heisig, M. (2013). Sources of angle-dependent errors in terrestrial laser scanner-based crop stand measurement. *Computers and Electronics in Agriculture*. 93: 10–16.

Eitel, J. U. H., Vierling, L. A., & Long, D. S. (2010). Simultaneous measurements of plant structure and chlorophyll content in broadleaf saplings with a terrestrial laser scanner. *Remote Sensing of Environment*. 114(10): 2229–2237.

Elmqvist, M. (2002). Ground surface estimation from airborne laser scanner data using active shape models. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences*, 34(3/A), pp. 114-118.

Elmqvist, M., Jungert, E., Lantz, F., Persson, A., & Soderman, U. (2001). Terrain modelling and analysis using laser scanner data. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences*, *34*(3/W4), pp 219-226.

Erdody, T. L., & Moskal, L. M. (2010). Remote Sensing of Environment Fusion of LiDAR and imagery for estimating forest canopy fuels. *Remote Sensing of Environment*. 114(4): 725–737.

FARO. (2017). Retrieved 23 April 2017 from http://www.faro.com

FAOSTAT, F. (2016). Agriculture Organization of the United Nations Statistics Division. *Economic and Social Development Department, Rome, Italy.*

GeoReposity (2017). Retrieved 3 March 2018 from http://georepository.com

Gruen, A., & Akca, D. (2005). Least squares 3D surface and curve matching. *ISPRS Journal of Photogrammetry and Remote Sensing*, *59*(3), 151–174.

Haala, N., & Brenner, C. (1999). Extraction of buildings and trees in urban environments. *ISPRS Journal of Photogrammetry and Remote Sensing*. 54(2): 130–137.

Heritage, G., & Large, A. (2009). *Laser scanning for the environmental sciences*. John Wiley & Sons.

Hladik, C., & Alber, M. (2012). Accuracy assessment and correction of a LIDAR-derived salt marsh digital elevation model. *Remote Sensing of Environment*. 121: 224–235.

Hodgson, M. E., & Bresnahan, P. (2004). Accuracy of Airborne Lidar-Derived Elevation. *Photogrammetric Engineering & Remote Sensing*. 70(3): 331–339.

Hodgson, M. E., Jensen, J. R., Schmidt, L., Schill, S., & Davis, B. (2003). An evaluation of LIDAR- and IFSAR-derived digital elevation models in leaf-on conditions with USGS Level 1 and Level 2 DEMs. *Remote Sensing of Environment*. 84(2): 295–308.

Holopainen, M., Kankare, V., Vastaranta, M., Liang, X., Lin, Y., Vaaja, M., ... & Kukko, A. (2013). Urban Forestry & Urban Greening Tree mapping using airborne , terrestrial and mobile laser scanning – A case study in a heterogeneous urban forest. *Urban Forestry & Urban Greening*. 12(4): 546–553.

Isenburg, M., Liu, Y., Shewchuk, J., Snoeyink, J., & Thirion, T. (2006). Generating raster DEM from mass points via TIN streaming. *Geographic Information Science*. 186-198.

Jensen, J. R., & Im, J. (2007). Remote Sensing Change Detection in Urban Environments. In R. R. Jensen, J. D. Gatrell, & D. McLean (Eds.), *Geo-Spatial Technologies in Urban Environments: Policy, Practice, and Pixels* (pp. 7–31). Berlin, Heidelberg: Springer Berlin Heidelberg.

Kee, K. K., & Soh, A. C. (2002, July). Management of oil palms on slopelands in Malaysia. In *IOPRI International Palm Oil Conference* (pp. 08-12).

Kraus, K., & Pfeifer, N. (2001). Advanced DTM generation from LIDAR data. *International Archives Of Photogrammetry Remote Sensing And Spatial Information Sciences*, *34*(3/W4), 23-30.

Karkee, M., Steward, B. L., & Aziz, S. A. (2008). Improving quality of public domain digital elevation models through data fusion. *Biosystems Engineering*. 101(3): 293–305.

Koetz, B., Sun, G., Morsdorf, F., Ranson, K. J., Kneubühler, M., Itten, K., & Allgöwer, B. (2007). Fusion of imaging spectrometer and LIDAR data over combined radiative transfer models for forest canopy characterization. *Remote Sensing of Environment*, *106*(4), 449-459.

Korzeniowska, K., & Łącka, M. (2011). Generating DEM from Lidar Data – Comparison of Available Software Tools. *Archiwum Fotogrametrii, Kartografii I Teledetekcji*, *22*, 271–284.

Kuuskivi, T., & Li, X. (2006). Three-dimensional mapping using both airborne and spaceborne IFSAR technologies. In *American society of photogrammetry and remote sensing conference*.

Li, X., Baker, A. B., & Hutt, T. (2002, April). Accuracy of airborne IFSAR mapping. In *Proceedings of FIG XXII International Congress* (pp. 19-26).

Li, Z., Zhu, C., & Gold, C. (2004). *Digital terrain modeling: principles and methodology*. CRC press.

Liu, X. (2008). Airborne LiDAR for DEM generation: some critical issues. *Progress in Physical Geography*, *32*(1), 31-49.

Ma, R. (2005). DEM Generation and Building Detection from Lidar Data. *Photogrammetric Engineering & Remote Sensing*. 71(7): 847–854.

Malaysian Palm Oil Board. (2014). Retrieved 23 April 2017 from http://www.mpob.gov.my/

Martin, Y., Valeo, C., & Tait, M. (2008). Centimetre-scale digital representations of terrain and impacts on depression storage and runoff. *CATENA*, *75*(2), 223–233.

Mercer, B. (2004). DEMs Created from Airborne IFSAR – An Update. *International Archives of Photogrammetry and Remote Sensing, Proceedings of XXth ISPRS Congress*, *35*.

Mercuri, P. a., Engel, B. a., & Johannsen, C. J. (2006). Evaluation and accuracy assessment of high-resolution IFSAR DEMs in low-relief areas. *International Journal of Remote Sensing*, *27*(13), 2767–2786.

Moussa, M., Degré, A., Debouche, C., & Lisein, J. (2014). Geomorphology The evaluation of unmanned aerial system-based photogrammetry and terrestrial laser scanning to generate DEMs of agricultural watersheds. *Geomorphology*. 214: 339–355.

Mrstik, V., Vanblaricum, G., Cardillo, G., & Fennell, M. (1996). Terrain height measurement accuracy of interferometric synthetic aperture radars. *IEEE Transactions on Geoscience and Remote Sensing*. 34(1): 219–228.

Muhadi, N. A., Abdullah, A. F., & Kassim, M. S. M. (2016). Quantification of terrestrial laser scanner (TLS) elevation accuracy in oil palm plantation for IFSAR improvement. In *IOP Conference Series: Earth and Environmental Science* (Vol. 37).

Mutlu, M., Popescu, S. C., Stripling, C., & Spencer, T. (2008). Mapping surface fuel models using lidar and multispectral data fusion for fire behavior. *Remote Sensing of Environment*. 112(1): 274–285.

National Digital Elevation Program. (2004). Guidelines for Digital Elevation Data. *National Digital Elevation Program (NDEP)*, *1*, 1–93.

Nelson, A., Reuter, H. I., & Gessler, P. (2009). Dem Production methods and sources. *Developments in Soil Science*, *33*(C), 65–85.

Papasaika, H., & Baltsavias, E. (2009). Fusion of LIDAR and photogrammetric generated Digital Elevation Models. *In Proceedings of the ISPRS Hannover Workshop on High-Resolution Earth Imaging for Geospatial Information, Hannover, Germany.*

Papasaika, H., Kokiopoulou, E., Baltsavias, E., Schindler, K., & Kressner, D. (2011). Fusion of digital elevation models using sparse representations. In *Photogrammetric Image Analysis* (pp. 171-184). Springer, Berlin, Heidelberg.

Paramananthan, S. (2012). Best Practices for Sustainable Oil Palm Cultivation. *The Planter*, *79*, 27–29.

Podobnikar, T. (2009). Methods for visual quality assessment of a digital terrain model. *Sapiens*. 2(2): 1–10.

Polat, N., Uysal, M., & Toprak, A. S. (2015). An investigation of DEM generation process based on LiDAR data filtering, decimation, and interpolation methods for an urban area. *Measurement*, *75*, 50–56.

Puttonen, E., Krooks, A., Kaartinen, H., & Kaasalainen, S. (2015). Ground level determination in forested environment with utilization of a scanner-centered terrestrial laser scanning configuration. *IEEE Geoscience and Remote Sensing Letters*, *12*(3), 616–620.

Rankine, I. R., & Fairhurst, T. H. (1998). Field handbook. *Oil palm series*, *3*.

Rhebergen, T. (2012). Analysis of Implementation of Best Management Practices in Oil Palm Plantations in Indonesia. *Plant Production Systems. Wageningen University*, *34*.

Roggero, M. (2001). Airborne laser scanning-clustering in raw data. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences*, *34*(3/W4), 227-232.

Sampson, C. C., Fewtrell, T. J., Duncan, A., Shaad, K., Horritt, M. S., & Bates, P. D. (2012). Use of terrestrial laser scanning data to drive decimetric resolution urban inundation models. *Advances in Water Resources.* 41: 1–17.

Schenk, T., & Csathó, B. (2002). Fusion of LIDAR data and aerial imagery for a more complete surface description. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences*, *34*(3/A), 310–317.

Schindler, K., Papasaika-hanusch, H., Schütz, S., & Baltsavias, E. (2011). Improving Wide-Area DEMs Through Data Fusion – Chances and Limits. *Photogrammetric Week '11*, 159–170.

Shi, X., Girod, L., Long, R., DeKett, R., Philippe, J., & Burke, T. (2012). A comparison of LiDAR-based DEMs and USGS-sourced DEMs in terrain analysis for knowledge-based digital soil mapping. *Geoderma*. *170*: 217–226.

Sithole, G. (2001). Filtering of laser altimetry data using a slope adaptive filter. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences, 34(3/W4), 203-210.*

Sithole, G., & Vosselman, G. (2003). Report: ISPRS comparison of filters. *ISPRS commission III, working group*, *3*.

Sithole, G., & Vosselman, G. (2004). Experimental comparison of filter algorithms for bare-Earth extraction from airborne laser scanning point clouds. *ISPRS Journal of Photogrammetry and Remote Sensing*, *59*(1–2), 85–101.

Srinivasan, S., Popescu, S. C., Eriksson, M., Sheridan, R. D., & Ku, N.-W. (2014). Multi-temporal terrestrial laser scanning for modeling tree biomass change. *Forest Ecology and Management*, *318*, 304–317. http://doi.org/10.1016/j.foreco.2014.01.038

Swatantran, A., Dubayah, R., Roberts, D., Hofton, M., & Blair, J. B. (2011). Remote Sensing of Environment Mapping biomass and stress in the Sierra Nevada using lidar and hyperspectral data fusion. *Remote Sensing of Environment*. 115(11): 2917–2930.

Taud, H., Parrot, J. F., & Alvarez, R. (1999). DEM generation by contour line dilation. *Computers and Geosciences*. 25(7): 775–783.

Terrasolid. (2005). TerraScan User's Manual. *Terrasolid: Helsinki, Finland*.

Tran, T. A., Raghavan, V., Masumoto, S., Vinayaraj, P., & Yonezawa, G. (2014). A geomorphology-based approach for digital elevation model fusion - Case study in Danang city, Vietnam. *Earth Surface Dynamics.* 2(2): 403–417.

Tupin, F., & Roux, M. (2003). Detection of building outlines based on the fusion of SAR and optical features. *ISPRS Journal of Photogrammetry and Remote Sensing*, *58*(1–2), 71–82.

Vastaranta, M., Latorre, E. G., Luoma, V., Saarinen, N., Holopainen, M., & Hyyppä, J. (2015). Evaluation of a smartphone app for forest sample plot measurements. *Forests*, *6*(4), 1179-1194.

Vaze, J., Teng, J., & Spencer, G. (2010). Impact of DEM accuracy and resolution on topographic indices. *Environmental Modelling and Software*. 25(10): 1086–1098.

Vosselman, G. (2000). Slope based filtering of laser altimetry data. *International Archives of Photogrammetry and Remote Sensing, 33(B3/2; PART 3), 935-942.*

Vosselman, G. (2002). Fusion of laser scanning data, maps, and aerial photographs for building reconstruction. *IEEE International Geoscience and Remote Sensing Symposium*, *1*.

Vosselman, G. (2003). 3D Reconstruction of Roads and Trees for City Modelling. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences. Dresden, Germany, 34, 3.*

Vosselman, G., & Maas, H. (2001). Adjustment and filtering of raw laser altimetry data. *Proceedings OEEPE Workshop on Airborne Laserscanning and Interferometric SAR for Detailed Digital Elevation Models*, 62–72.

Vozikis, G. (2007). Using Hybrid Surveying Techniques for Documenting the Largest Ancient Theatre in Greece, *XXI International CIPA Symposium*, *01-06 October 2007, Athens, Greece.*

Wang, H., Zhang, Y., Li, P., & Zha, X. (2013). A method of deriving DEM from airborne LiDAR points cloud data. *Joint Urban Remote Sensing Event 2013, JURSE 2013*, *856*, 13–16.

Wang, Y., Mercer, B., Tao, V. C., Sharma, J., & Crawford, S. (2001). Automatic generation of bald earth digital elevation models from digital surface models created using airborne IFSAR. *Proceedings of 2001 ASPRS Annual Conference*, (1999), 23–27.

Warren, S. D., Hohmann, M. G., Auerswald, K., & Mitasova, H. (2004). An evaluation of methods to determine slope using digital elevation data. *Catena*, *58*(3), 215–233.

Weng, Q. (2011). *Advances in environmental remote sensing: sensors, algorithms, and applications*. CRC Press.

White, S. a., & Wang, Y. (2003). Utilizing DEMs derived from LIDAR data to analyze morphologic change in the North Carolina coastline. *Remote Sensing of Environment*. 85(1): 39–47.

Yang, B., Zang, Y., Dong, Z., & Huang, R. (2015). An automated method to register airborne and terrestrial laser scanning point clouds. *ISPRS Journal of Photogrammetry and Remote Sensing*, *109*, 62-76.

Yang, L., Sheng, Y., & Wang, B. (2016). 3D reconstruction of building facade with fused data of terrestrial LiDAR data and optical image. *Optik - International Journal for Light and Electron Optics*. 127(4): 2165–2168.

Zhang, J. (2010). Multi-source remote sensing data fusion: status and trends. *International Journal of Image and Data Fusion*, *1*(1), 5-24.

Zhang, J., & Lin, X. (2013). Filtering airborne LiDAR data by embedding smoothness-constrained segmentation in progressive TIN densification. *ISPRS Journal of Photogrammetry and Remote Sensing*, *81*, 44–59.

Zhang, Y., Tao, C. V., & Mercer, J. B. (2004). An initial study on automatic reconstruction of ground DEMs from airborne IfSAR DSMs. *Photogrammetric Engineering & Remote Sensing*, *70*(4), 427-438.

Zhou, H., Zhang, J., Gong, L., & Shang, X. (2012). Comparison and Validation of Different DEM Data Derived from InSAR. *Procedia Environmental Sciences*, *12*(Icese 2011), 590–597.