

# Parameterization of Aerodynamic Roughness Length and Zero Plane Displacement Over Tropical Region Using Airborne LiDAR Data

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## Article history

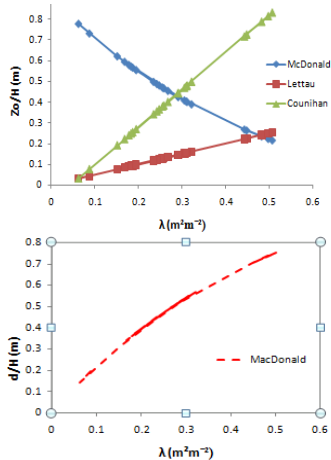
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## Graphical abstract



## Abstract

Airborne LiDAR data has been one of the reliable data for individual tree properties estimation. High density airborne LiDAR data has been used previously for detailed reconstruction of tree geometry. The aim of this study is to estimate aerodynamic roughness over specific height ( $Z_o/H$ ) and zero plane displacement ( $d_o$ ) over forest area using airborne LiDAR data. The results of this study will be very useful as a main guideline for related applications to understand the role of carbon and hydrological cycles, land cover and land use change, habitat fragmentation, and biogeographical modeling. The airborne LiDAR data is first classified into ground and non-ground classes. The ground points are interpolated for digital terrain model (DTM) generation and the non-ground points are used to generate digital surface model (DSM). Canopy height model (CHM) is then generated by subtracting DTM from DSM. Individual tree delineation is carried out on the CHM and individual tree height is used together with allometric equation in estimating height to crown base (HCB) and diameter at breast height (DBH). Tree crown delineation is carried out using the Inverse Watershed segmentation approach. Crown diameter, HCB and DBH are used to estimate individual tree frontal area and the total frontal area over a specific ground surface is further calculated by subtracting the intersected crowns and trunks from the total area of tree crowns and trunks. The considered ground area i.e. plants area determined the final spatial resolution of the  $Z_o/H$  and  $d_o$ . Both parameters are calculated for different wind directions that were assumed to be originated from North/South and East/West. The results show that the estimated  $Z_o/H$  and  $d_o$  have similar pattern and values with previous studies over vegetated area.

**Keywords:** Airborne LiDAR; aerodynamic roughness length; zero plane displacement; forest

## Abstrak

LiDAR bawaan udara data telah menjadi salah satu data yang boleh digunakan untuk anggaran sifat pokok secara individu. Tujuan kajian ini adalah untuk menentukan *aerodynamic roughness* pada ketinggian tertentu ( $Z_o/H$ ) dan *zero plane displacement* ( $d_o$ ) di kawasan hutan menggunakan data LiDAR bawaan udara. Hasil kajian ini amat berguna sebagai panduan utama untuk aplikasi yang berkaitan dengan peranan karbon dan kitaran hidrologi, perlindungan tanah dan perubahan gunatanah, pemecahan habitat, dan pemodelan *biogeographical*. Di peringkat awal data LiDAR bawaan udara yang dikelaskan ke dalam kelas permukaan tanah dan bukan permukaan tanah. Titik laser bagi permukaan tanah digunakan bagi menjana model rupa bumi digital (DTM) dan titik laser bagi bukan permukaan tanah digunakan bagi menghasilkan model permukaan digital (DSM). Model ketinggian kanopi (CHM) kemudiannya dijana dengan menolak DTM dari DSM. Persempadanan pokok secara individu dijalankan pada CHM dan ketinggian pokok digunakan bersama-sama dengan persamaan *allometric* bagi menganggar ketinggian asas rimbus pokok (HCB) dan diameter pada paras dada (DBH). Persempadanan rimbus pokok dijalankan menggunakan pendekatan segmentasi *Inverse Watershed*. Diameter rimbus pokok, HCB dan DBH digunakan untuk menganggar kawasan hadapan pokok individu. Sementara itu jumlah kawasan hadapan pokok di atas permukaan tanah tertentu dikira dengan menolak kawasan persilangan antara rimbus dan batang daripada jumlah keluasan rimbus pokok dan batang. Kawasan tanah ini atau kawasan menentukan resolusi ruang bagi anggaran nilai  $Z_o/H$  dan  $d_o$ . Kedua-dua parameter ini dikira pada andaian arah angin yang berbeza iaitu dari Utara/Selatan dan Timur/Barat. Hasil kajian menunjukkan bahawa anggaran  $Z_o/H$  dan  $d_o$  mempunyai corak yang sama dengan nilai-nilai yang dianggarkan dalam kajian sebelum ini di kawasan tumbuh-tumbuhan.

**Kata kunci:** LiDAR bawaan udara; *aerodynamic roughness length*; *zero plane displacement*; hutan

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1.0 INTRODUCTION

Aerodynamic roughness length ( $z_0$ ) and zero plane displacement parameter ( $d$ ) of land surfaces are among essential variables for investigation of momentum and heat exchanges. The experimental based method (e.g. Micrometeorological profile measurements) and parameterization only valid for local, in which remote sensing technology would be the reliable solution for better estimation of spatially  $z_0$  and  $d$  values. Recently, there have been serious efforts in developing models to estimate the exchange between the land surface and the atmosphere using passive remote sensing. Most of these models require accurate estimation of  $z_0$  and  $d$  if not available. This constraint leads to a simplification in estimating  $z_0$  and  $d$  by using a simple ratio of spectral channel for example the Normalized Difference Vegetation Index (NDVI). It was noted that different methods to estimation  $z_0$  using remote sensing over heterogeneous land surface often leads to significant errors in turbulent flux estimates.

Advances in remote sensing technology, especially Airborne Light Detection and Ranging (LiDAR) technology allowed detailed estimation of structural information of land surface. However, only few studies have utilized airborne LiDAR to parameterize  $z_0$  and  $d$ . There was an early attempt which used LiDAR to estimate  $z_0$  based on the geometrical regularity of vegetation canopies by multiplying the ratio of the standard deviation to vegetation height in segments of a transect by the average height of the vegetation along the transect. This study, they found good agreement between  $z_0$  estimated from airborne LiDAR with the value calculated using the Monin-Obukhov similarity theory applied to measurements of horizontal wind speed profiles. Previous study has been devoted to assess validity of previous models (i.e. by Choudhury and Monteith, Raupach and Schaudt and Ineson) over cool and warm temperate forests in Japan. It was found that the results were not valid for their study area and as a consequence, they introduced a new concept in estimating  $z_0$  and  $d$ . Vries et al. utilized high density LiDAR to estimate  $z_0$  and  $d$  over coppice dunes covered by honey mesquite. The results obtained using LiDAR data have a good agreement with the value measured from a vertical profile of horizontal wind speed measurements. Colin and Faivre estimated  $d$  for a heterogeneous landscape using a combination of LiDAR and computational fluid dynamics models. They discussed the need for footprint definitions and ground measurements to validate their results. Tan et al. used a combination of LiDAR and SPOT spectral data with micrometeorological measurements to test four models to parameterize  $z_0$  over temperate forests in Heihe River basin, China. They showed that the model generated  $z_0$  maps of LiDAR are superior to those from satellite optical remote sensing data and suggested the use of high density LiDAR combined with source areas for eddy covariance (EC) towers to improve their validation.

Previous studies showed that estimation of  $z_0$  and  $d$  basically required detailed structure of individual trees. Airborne LiDAR campaign in temperate region allows good penetration of laser pulses during leaf condition. In this case, vertical individual tree structure can be easily seen and surface model can be used to reconstruct the three dimensional structure of the whole trees. On the other hand, utilization of airborne LiDAR data in tropical region is limited by the fact that high density vegetation canopy will result poor penetration of laser pulses and the point clouds could only represent the top or canopy characteristics of the vegetation. Density of point clouds, its accuracy (horizontal and vertical), and penetration over vegetation canopy can be determined by the LiDAR system position and orientation

system (POS). It can be concluded that the performance of LiDAR and other remotely sensed data of  $z_0$  and  $d$  parameterization in tropical region still require thorough investigation especially on LiDAR system configuration and its relation to extract required parameter over different terrain conditions.

2.0 MATERIALS AND METHOD

The methodology is divided into four main phases which are: 1) Data acquisition, 2) Pre-processing, 3) Estimation of tree attributes, and 4) Validation of results. The first stage focuses on filtering the point clouds to distinguish ground and non-ground laser points, constructing digital terrain model (DTM), digital surface model (DSM) and canopy height model (CHM). The second stage devoted to estimation of individual tree attributes based on the delineated trees. The third stage focuses on estimation of  $z_0$  and  $d$  are based on the structural information of estimated individual tree geometrical properties. Finally the estimated values will be compared with values obtained by previous studies.

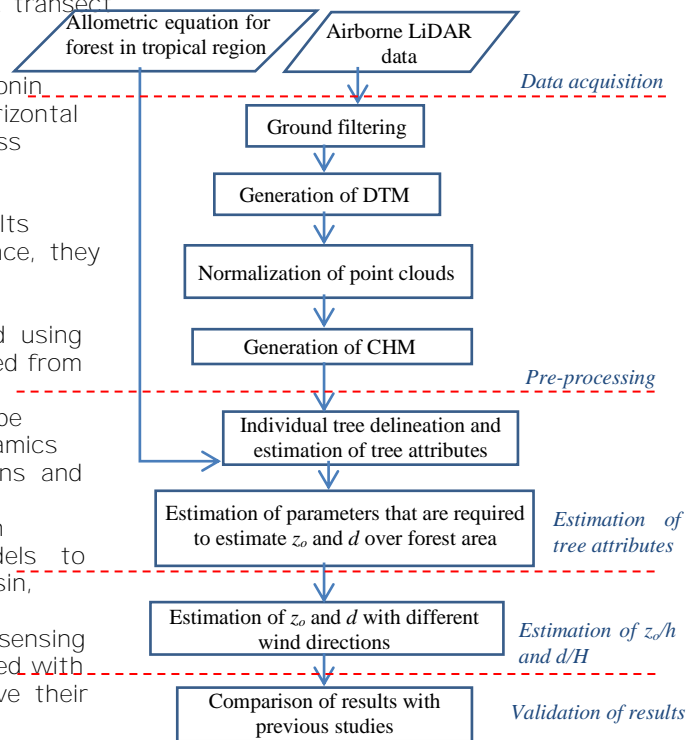


Figure 1 Flow chart of methodology

2.1 Description of data and study area

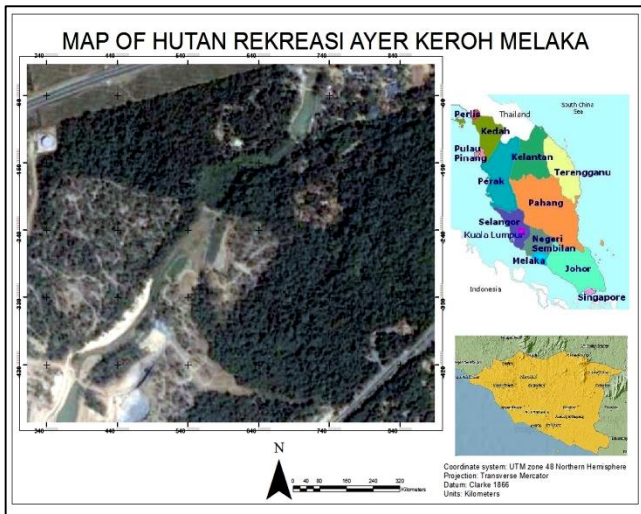
The study area is located at Hutan Rekreasi Melaka, Malaysia (Figure 2). The area has become the recreational park since 17th April 1984. It is 359 hectares in area which consist of tall hardwood tropical trees forest and residential trees. There are nearly 10 species of trees in Air Keroh Recreational Forest. Among them are Karas (*Aquilaria malaccensis*) Kekatong (*Cynometra malaccensis*) Kempas (*Kompassia malaccensis*)

Kedondong Kijai (Triomma malaccensis) Yellow Jackfruit Nyatoh (Pouteria malaccensis) Malacca tree (Phyllanthus embilica) Sesenduk (Endospermum malaccensis) Gwosi (Amoora malaccensis). The trees height is range from 8 meters up to 60 meters.

where  $H_{max}$  is the maximum height of tree with a forest stand and  $H_{asset}$  to 47 m.

**2.4 Estimation of Aerodynamic Roughness Length ( $z_0/h$ ) and Zero Plane Displacement ( $d/h$ )**

Estimation of aerodynamic roughness ( $z_0/h$ ) was carried out using three models i.e. Lettau (Equation 4)<sup>20</sup> Counihan (Equation 5)<sup>21</sup> and McDonald (Equation 6)<sup>22</sup> Zero plane displacement ( $d/h$ ) is calculated using Equation 7



**Figure 2** Hutan Rekreasi Ayer Keroh, Melaka  
The airborne LiDAR data was captured by the Optech ALTM system 2009 with average point spacing of 6m

**2.2 Pre-processing of airborne LiDAR data**

The preprocessing of airborne LiDAR data involves filtering of original point clouds to separate ground and non-ground point clouds, generation of digital terrain model (DTM), classification of point clouds and generation of canopy model (CHM). The filtering process is based on the progressive morphological (PM) approach. The original point clouds were normalized by subtracting the value of corresponding DTM from the elevation value of each point cloud. The normalized point clouds were used to generate CHM with a spatial resolution of 1

**2.3 Estimation of individual tree attributes**

The estimation of individual tree attributes begins with individual tree crown delineation based on the CHM surface. The tree crown delineation process was carried out based on the inverse watershed (IW) segmentation approach. This approach assumes that individual tree crown can be delineated by applying the inverse method of watershed segmentation from the highest point of a tree to the lowest point of a tree crown that marks the edge of the crown. The individual tree crown segments were used together with a specific allometric equation for individual tree attributes estimation i.e. tree height (H), crown width (CW), crown depth (CD) and diameter at breast (DBH).

Individual tree DBH was estimated based on the allometric equation (Equation 1) that relates DBH and maximum tree height.<sup>9</sup> Individual tree crown width is calculated by simplifying crown diameter measurement from tree crown segments (Equation 2).<sup>19</sup> Tree crown depth is calculated using Equation

$$z_0/h = 0.07 \cdot (H_{max} - H_{asset}) \quad (4)$$

$$z_0/h = 0.03 \cdot (H_{max} - H_{asset}) \quad (5)$$

$$z_0/h = 0.01 \cdot (H_{max} - H_{asset}) \quad (6)$$

$$d/h = 0.1 \cdot (H_{max} - H_{asset}) \quad (7)$$

where  $A_f$  is the frontal area,  $\beta$  is coefficient to best fit the relation with experiments,  $C_d$  is the drag coefficient and  $k$  is the Von Karman constant approximately taken as 0.4

The frontal area index for a tree is calculated using Equation 8

$$I_f = \frac{A_f}{A_t} \quad (8)$$

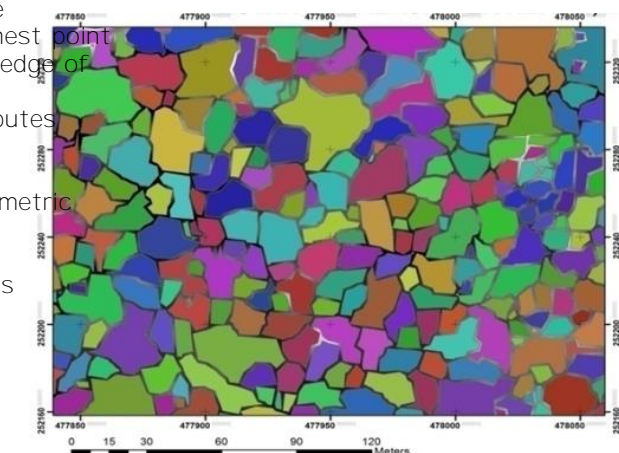
where  $A_f$  is the frontal area and  $A_t$  is the total area covered by roughness elements which determines the spatial resolution of the final map. In this study, the total frontal area over covered by several trees is calculated by combining the estimated crown and trunk area of individual trees (Equation 9)

$$A_f = \sum_{i=1}^n T_i \quad (9)$$

where  $T_i$  is the area of trunk crown ( $H \cdot CD$ ) for  $i$  tree,  $n$  is the total number of tree per unit area,  $C_{int}$  is the crown area,  $T_{int}$  is the intersected area between tree crowns,  $C_{int}$  is the intersected area between tree crowns and  $T_{int}$  is the intersected area between tree crowns and trunks. The  $A_f$  is calculated for two possible wind directions i.e. 0 and 90 degrees from North. Both  $z_0/h$  and  $d/h$  were estimated with 50 and 100 m spatial resolutions.

**3.0 RESULTS AND DISCUSSION**

The individual tree crown delineation process has about 454 individual tree segments which individual tree attributes are estimated as described in section 2.3 (Figure 2.3).



**Figure 3** Individual tree crown marked by different colors of segments

- (1)
- (2)
- (3)

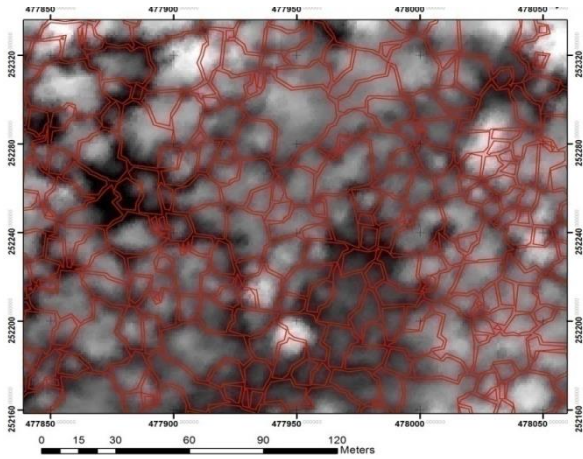


Figure 4 Individual tree crown marked by red segments overlaid on CHM

The estimation of  $z_0/H$  and  $d/H$  as described in section 2.4 were done semi-automatically based on segments available in geographical information system (GIS). Figure 5 shows the example of the two-dimensional sideview of 0° and 90° from the north for 50 and 100 spatial resolution of forest area. In this case we assume that the wind flow direction will hit the front facet of the tree arrays and could not reach the second facets that were blocked by the first frontal facet. Thus, only the air of the first facet will be calculated by excluding the blocking areas.

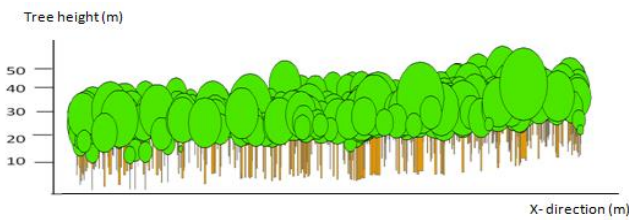


Figure 5 Two-dimensional sideview of individual tree with the assumed wind direction 0° from north (the total area is 50 m)

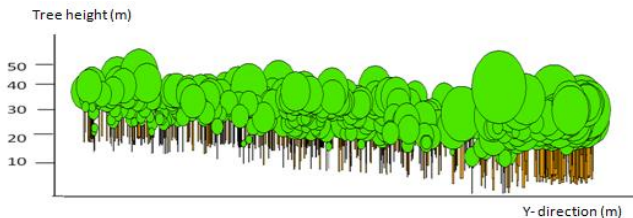


Figure 6 Two-dimensional sideview of individual tree with the assumed wind direction 90° from north (the total area is 50 m)

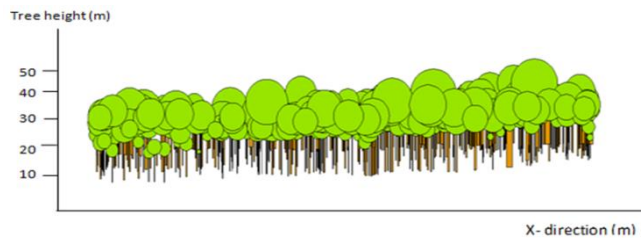


Figure 7 Two-dimensional sideview of individual tree with the assumed wind direction 0° from north (the total area is 100 m)

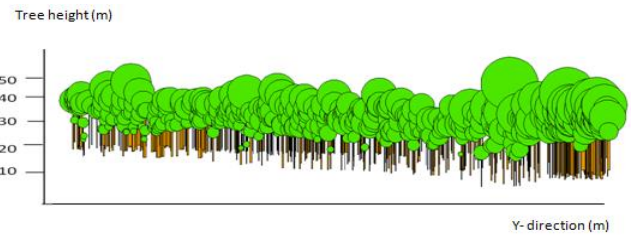


Figure 8 Two-dimensional sideview of individual tree with the assumed wind direction 90° from north (the total area is 100 m)

Lettau  $z_0/H$  values range between 0.03 to 0.30 (Figure 9). This range falls in the terrain category with almost flat terrain to relatively covered by dense vegetation and scattered obstacles as described in Table 1.

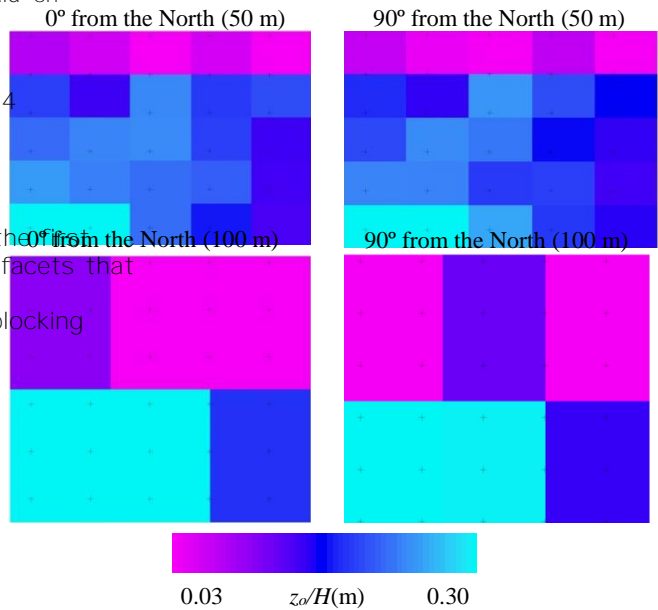


Figure 9 Spatially distributed  $z_0/H$  value with assumed wind direction 0° and 90° from north calculated using the total area's model (50 m and 100 m)

Table 1 Aerodynamic roughness length with its corresponding earth landscape.<sup>23</sup>

Surface	Landscape description	$z_0$ (m)
Sea	Open sea, fetch at least 5km	0.0002
Smooth	Mud flats, snow, little vegetation, no obstacles	0.005
Open	Flat terrain: grass few isolate obstacles	0.03
Roughly Open	Low crops: occasional large obstacles	0.1
Rough	High Crops: scattered obstacles	0.25
Very Rough	Orchards, bushes: numerous obstacle	0.5
Closed	Regular large obstacle coverage (suburban area)	1.0
Chaotic	City centre with high and low rise building	>2

$z_0/H$  values obtained using larger changes in  $z_0/H$  values have of value as compared Lettau's model (Figure 10). The maximum  $z_0/H$  value reaches to the surface category with relatively regular large obstacle roughness effects. Figure 10 shows the  $z_0/H$  values obtained from the MacDonald model that is somehow different in its distribution pattern throughout the study areas compared to Lettau's and Counihan's models. The results show that MacDonald's model is more sensitive to the changes in the spatial resolution. The  $z_0/H$  and  $d/H$  values are compared to the previous findings (Figure 12 to Figure 4). It is shown that the relationship between  $z_0/H$  and  $\lambda$  are consistent with the values obtained by means of wind tunnel experiments and/or turbulence measurements from anemometers on tower

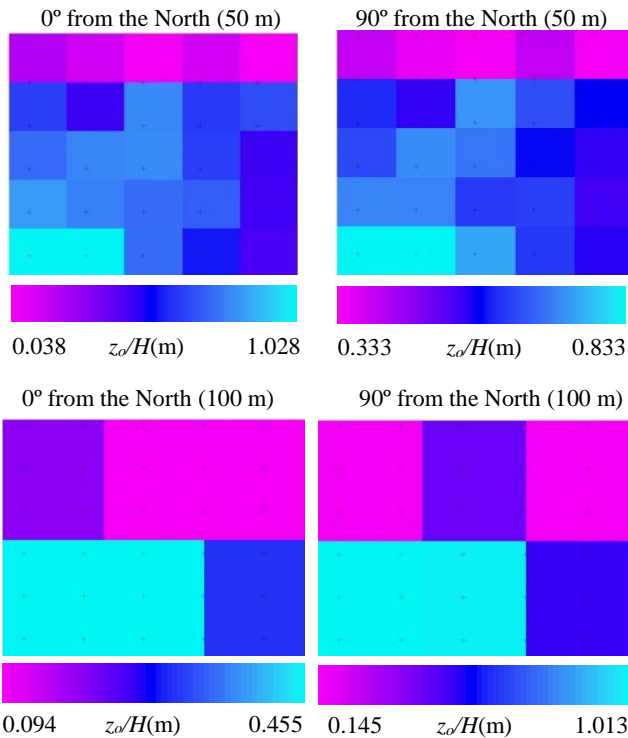


Figure 10 Spatially distributed  $z_0/H$  value with assumed wind directions  $0^\circ$  and  $90^\circ$  from north calculated using i model (the total area,  $A_T$  are 50 m and 100 m)

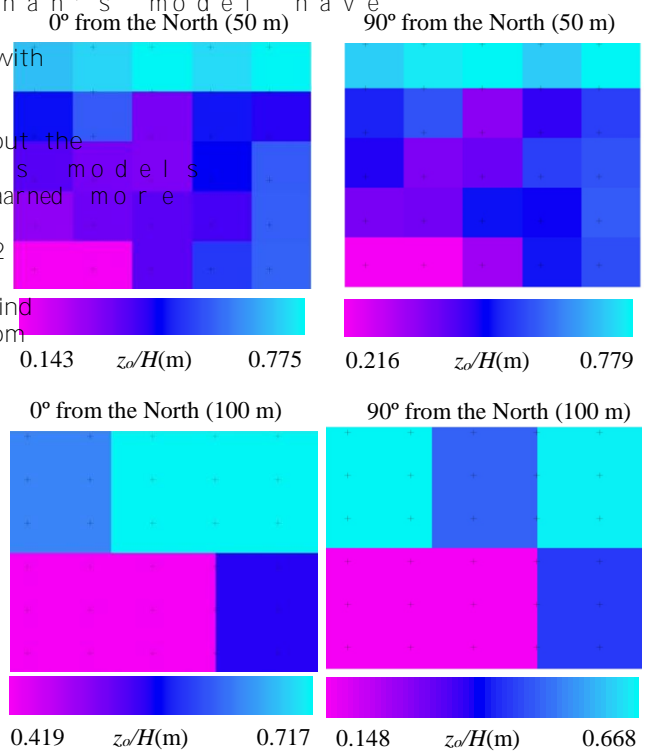


Figure 11 Spatially distributed  $d/H$  value with assumed wind directions  $0^\circ$  and  $90^\circ$  from north calculated using o model (the total area,  $A_T$  are 50 m and 100 m)

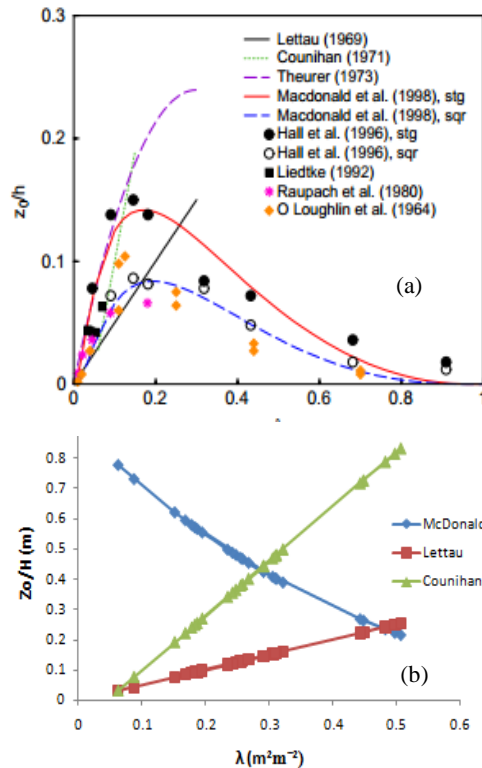
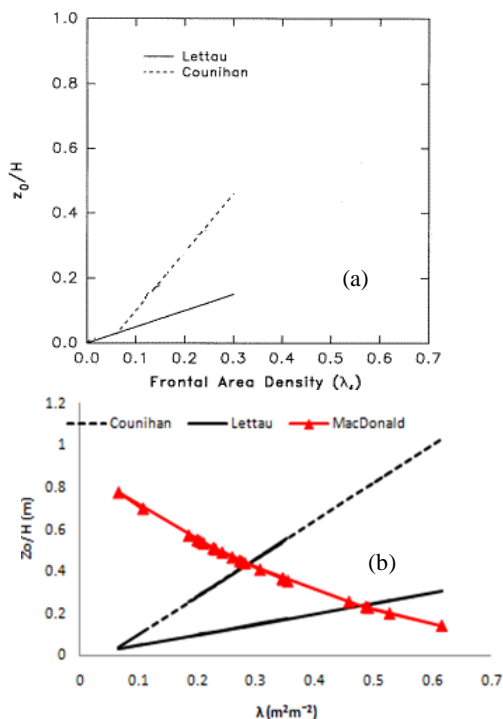
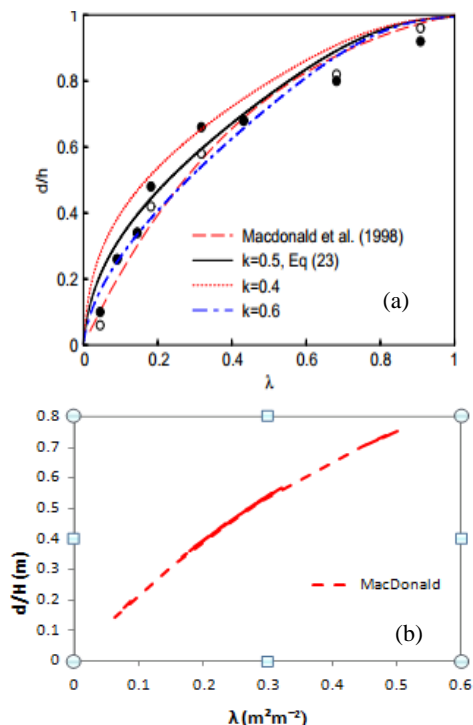


Figure 12 Comparison between  $z_0/H$  values obtained using wind tunnel experiment (a) <sup>24</sup> and values obtained in this study with direction of  $90^\circ$



**Figure 13** Comparison between  $z_0/H$  values obtained using wind or turbulence measurements from anemometers on towers and values obtained in this study with assumed wind direction of  $0^\circ$  (a) and values obtained in this study with assumed wind direction of  $0^\circ$  (b)



**Figure 14** Comparison between  $d/H$  values obtained using wind tunnel experiment (a) and values obtained in this study with assumed wind direction of  $0^\circ$  (b)

**4.0 CONCLUSION**

We have presented a method of  $d/H$  estimation based on individual tree biometrics obtained from airborne LiDAR data. The density of airborne LiDAR data obtained in this study is considerably low, which requires the use allometric equations for individual tree attribute estimation based on delineated tree crowns. The results derived in this study show the values of  $z_0/H$  and  $d/H$  within the recommended ranges obtained by previous studies. Nevertheless, the relationship pattern between  $d/H$  with frontal area density are consistent with the previous findings that were based on wind tunnel experiments and wind/turbulence measurements on towers. We have demonstrated that  $d/H$  values can be estimated with different spatial resolutions and different directions of wind. The results have clearly shown that by employing individual estimation of tree attributes, the  $d/H$  values can be estimated at different assumed wind directions and spatial resolutions depending on the requirement of specific applications. The application of such technology in tropical region is very challenging since the penetration of laser pulse over dense tropical rainforest canopy will lead to underestimation of vegetation height and other individual tree attributes. Individual tree attribute estimations will inevitably lead to the error in the  $z_0/H$  and  $d/H$  estimation.

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