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# Generating an optimal DTM from airborne laser scanning data for landslide mapping in a tropical forest environment

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ABSTRACT

Landslide inventory maps are fundamental for assessing landslide susceptibility, hazard, and risk. In tropical mountainous environments, mapping landslides is difficult as rapid and dense vegetation growth obscures landslides soon after their occurrence. Airborne laser scanning (ALS) data have been used to construct the digital terrain model (DTM) under dense vegetation, but its reliability for landslide recognition in the tropics remains surprisingly unknown. This study evaluates the suitability of ALS for generating an optimal DTM for mapping landslides in the Cameron Highlands, Malaysia. For the bare-earth extraction, we used hierarchical robust filtering algorithm and a parameterization with three sequential filtering steps. After each filtering step, four interpolations techniques were applied, namely: (i) the linear prediction derived from the SCOP++ (SCP), (ii) the inverse distance weighting (IDW), (iii) the natural neighbor (NEN) and (iv) the topo-to-raster (T2R). We assessed the quality of 12 DTMs in two ways: (1) with respect to 448 field-measured terrain heights and (2) based on the interpretability of landslides. The lowest root-mean-square error (*RMSE*) was 0.89 m across the landscape using three filtering steps and linear prediction as interpolation method. However, we found that a less stringent DTM filtering unveiled more diagnostic micro-morphological features, but also retained some of vegetation. Hence, a combination of filtering steps is required for optimal landslide interpretation, especially in forested mountainous areas. IDW was favored as the interpolation technique because it combined computational times more reasonably without adding artifacts to the DTM than T2R and NEN, which performed relatively well in the first and second filtering steps, respectively. The laser point density and the resulting ground point density after filtering are key parameters for producing a DTM applicable to landslide identification. The results showed that the ALS-derived DTMs allowed mapping and classifying landslides beneath equatorial mountainous forests, leading to a better understanding of hazardous geomorphic problems in tropical regions.



## 1. Introduction

Landslides have been recognized as important geomorphic processes which form a major landscape component of the humid tropical mountain environments (Thomas, 1994). In such areas, landslides may damage physical structures and cause loss of lives. In Southeast Asia, landslides occur frequently in areas with steep hillslopes, high rainfall intensities, seasonally dry periods, and unstable soils, which obstruct managing upland forests and agricultural lands (Douglas, 1999; Sidle and Ochiai, 2006).

Landslide inventory mapping is routinely done based on (i) visual monoscopic or stereoscopic aerial or satellite image interpretation, (ii) automated or semi-automated classification of satellite imagery based on spectral and topographic characteristics, (iii) field investigation, (iv) historical records, (v) visual interpretation of shaded relief images derived from airborne laser scanning (ALS) data, and (vi) radar interferometry (Van Westen et al., 2008; Guzzetti et al., 2012). Field mapping yields greater accuracy if aided by GPS and sophisticated instrumentation such as a laser rangefinder binocular (Santangelo et al., 2010), but has limitations in terrain coverage and is time consuming as well as expensive (Haneberg et al., 2009; Santangelo et al., 2010). Image analysis using aerial photographs, optical satellite, and radar images can efficiently cover a large area but results in poor mapping of landslides in rugged forested terrain (Fookes et al., 1991; Wills and McCrink, 2002; Brardinoni et al., 2003; Van Den Eeckhaut et al., 2007; Razak et al., 2011).

In a tropical environment, landslide mapping for large areas is difficult because the landslides are covered by dense multi-storey forest canopies and the weather conditions (cloudy and rainy) are often

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unfavorable for optical remote sensing. Landslides under tropical forests are rapidly covered by vegetation regrowth. Hence, soon after their occurrence the evidences of landslides are obscured in optical images. The lack of reliable landslide inventory maps hampers the assessment of landslide hazard and risk, which may subsequently complicate the implementation of mitigation measures. Therefore, it is essential to test and evaluate new tools for mapping the location and extent of landslides beneath dense vegetation in the tropics.

ALS is one of the most important geospatial data acquisition technologies that have been introduced recently (Petrie and Toth, 2008). ALS has revolutionized the acquisition of terrain data because it can collect explicit topographic data over wide areas at an unprecedented accuracy within a relatively short time. With its ability to penetrate the space between forest foliage to the ground and its independence of solar incidence, ALS is superior over passive optical (e.g. aerial-photograph and satellite images) and active radar sensors (e.g. interferometric synthetic aperture) for generating a high-resolution digital terrain model (DTM) in forested terrain (Kraus and Pfeifer, 1998; Hodgson et al., 2003; Kraus, 2007; Razak et al., 2011).

The essential step towards DTM generation is the classification of ground points and non-ground points (e.g. buildings and trees). It is also known as the filtering process which is important because the extracted point clouds have a direct impact on the quality of the DTM and derived products (Razak et al., 2011). Although humans are cognitively able to identify points representing the ground surface, the manual or semi-automatic filtering is not practically feasible for large point clouds. Despite the availability of automated filtering algorithms, a number of difficult scenarios are reported, such as dense vegetation on slopes, high surface roughness, preservation of sharp ridges, low vegetation, complex objects at convex slopes, and steep forested terrain (Huising and Gomes Pereira, 1998; Sithole and Vosselman, 2004). These cases are predominantly observed for recognizing landslides in tropical environments. Therefore, the selection of an appropriate filtering algorithm and its parameterization is required for such complex landscapes (Sithole and Vosselman, 2004; James et al., 2007). So far, there have been relatively limited studies to properly evaluate the quality of ALS-derived DTMs in the tropics (Blair and Hofton, 1999; Hofton et al., 2002; Clark et al., 2004; Haneberg et al., 2005), particularly for mapping and classifying tropical landslides.

Landslide inventory mapping has made significant steps forward due to the availability of ALS data, because the use of shaded relief images created from ALS-derived DTMs allowed a much better recognition of diagnostic features for landslide interpretation, even under dense forest (Sekiguchi and Sato, 2004; Van Den Eeckhaut et al., 2005, 2007; Ardizzone et al., 2007; Schulz, 2007; Kasai et al., 2009; Razak et al., 2011). However, none of these studies has examined the developed approaches of landslide mapping in tropical environments with a relatively low point density.

The main objective of this study is to evaluate the potential of ALS for generating landslide inventory maps under tropical forests in the Cameron Highlands, Malaysia. We quantitatively and qualitatively assessed DTMs for landslide recognition and classification. We applied three progressively stringent filters to extract ground points, and examined four different surface interpolation methods to create gridded DTMs. The statistical measures of vertical accuracy were computed using field reference data based on GPS (global positioning system) and a TS (total station) for all DTMs with respect to three different land-cover classes. Expert image interpreters created the landslide inventory maps and assessed the interpretability of the different DTMs.

## 2. Study area

The methodology was tested in a 100 km$^2$ study area in the Cameron Highlands, Peninsular Malaysia (Fig. 1) for which ALS data were available. The study area is located in the Indo-Malaysian tropical rainforest zone, largely covered by forests where landslides have been reported, and other areas with agriculture, and tea plantations. Peninsular Malaysia is subdivided in an N–S direction by the Saub-Bentong suture, dividing the East Malaya terrane derived from the Gondwanaland in the Devonian, from the Sibumasu terrane derived from Gondwanaland in the Permian (Metcalfe, 2000). Peninsular Malaysia is in a relatively low seismic hazard zone (Petersen et al., 2004). The current tectonic situation is related to the subduction of the Australian plate under the Sunda plate (with movement of about 34 mm year$^{-1}$), producing large earthquakes along the Sumatran subduction zone and the Sumatran transform fault (Vigny et al., 2005). Also the divergent boundary effect of the Sagaing and Sumatra right-slip faults poses an explicit implication on the seismic situation in Malaysia.

The district of the Cameron Highlands with an area of about 660 km$^2$ is located on an undulating plateau in the central part of the main range of Peninsular Malaysia. The plateau has an average elevation of 1000 m above sea level with peaks reaching up to 2031 m (i.e. Gunung Berincang). Geologically the central mountain range in Peninsular Malaysia is underlain by megacrystic biotite granites (Krahenbuhl, 1991) with some scattered outcrops of meta-sediments which are composed of schists, phyllite, slate, and limestones (Chow and Zakaria, 2003). Weathering profiles in the granites can be very thick, and road-cuts in these weathered materials present many problems related to slope instability (Durgin, 1977; Brand, 1989; Thomas, 1994). The annual rainfall is between 2500 and 3000 mm per year and daily maximum rainfall of approximately 100 mm.

Given relatively high altitudes, the temperatures of the Cameron Highlands are lower than the rest of Malaysia, with an average daily temperature of 23 °C and a night-time average of 10 °C (MMD, 2011). This relatively cool temperature makes the Cameron Highlands a popular tourist destination. The forest types consist of lowland evergreen rainforest (*hill- and upper dipterocarp forest*), lower montane forest (*montane oak forest*), and upper montane forest (*montane ericaceous forest*) (Wyatt-Smith, 1995). The undergrowth consists largely of woody plants – seedlings and sapling trees, shrubs and young woody climbers. The stemmed palms (e.g. *Arenga westerhoutti*), stemless palms (e.g. *Licuala* spp.) and rattans (e.g. *Calamus castaneus*) are dominant undergrowth in the study area. The tropical climate and rich nutrients in granitic soils provide a favorable environment for agricultural activities (e.g. vegetables, floriculture, and tea plantation), and the increasing population pressure has led to the clearing of the original forest for the construction of housing estates, roads and new agricultural areas. One of current practices is to excavate the top of ridges and to create artificial platforms for agriculture terraces and housing. The excavated materials are dumped along the sides of the plateaus, leading to severe erosion and landslides.

Landslides are an increasing problem in the Cameron Highlands, as a result of human interactions such as deforestation, and terrain modification for roads and agriculture (Douglas, 1999; Chow and Zakaria, 2003; Pradhan and Lee, 2010). Mapping and updating landslide data are a difficult task due to the poor accessibility and the rapid revegetation of landslide areas. In the Malaysian National Slope Master Plan 2009–2023, airborne remote sensing is recommended as a tool for collecting landslide information on a national level. Long-term records of landslides are not complete. The first landslide in the records dates back to December 07, 1919 (Jaapar, 2006) and from 1973 to 2007, more than 440 landslides were reported, with about 600 fatalities. However, thousands of minor slope failures were not properly documented (PWD, 2009).

Fig. 2 presents some field photos showing different landscapes, with indications of landslide movements. The forested zone consists of old-growth forests (Fig. 2A–D), with very dense vegetation, and multi-storey canopies, as well as rejuvenated forests in locations which might have been affected by landslides, forest fires, or illegal deforestation activities. The upland agriculture zone (Fig. 2E–H) is sparsely covered by woody vegetation which often indicate the