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Terrestrial LiDAR-based automated counting of swiftlet nests in the caves of Gomantong, Sabah, Borneo

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Abstract: High resolution terrestrial laser scanning (TLS) within the *Simud Hitam* Cave, Gomantong, has proven successful at discriminating the nests of black-nest swiftlets from roosting bats in high, inaccessible locations. TLS data were imported into ArcGIS software, allowing for semi-automated counting of nests based on resolved geometry and laser return intensity. Nest resolution and counting accuracy was better than 2%. Spatial analysis of nest locations has established a maximum packing density of 268 nests/m^2 in optimum locations, which correspond to roof slopes of >20 degrees. Co-occurring Rhinolophid bats roost adjacent to, but not within nest locations, preferring roof surfaces close to horizontal.

Keywords: karst; terrestrial laser scanning; geomorphology; bats; swiftlets; Borneo

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INTRODUCTION

One of the more unusual features of the caves of Borneo is their role in the edible bird's nest industry. The nests in question are produced by swiftlets of the genus *Aerodramus*, notably *A. maximus*, the Black-nest swiftlet, and *A. fuciphagus*, the White-nest swiftlet. These birds roost high in the roofs of a relatively small number of large caves, of which the Gomantong caves are amongst the most famous (Burder, 1961; Price, 1996; Lundberg & McFarlane, 2012; Fig. 1). The nests are constructed from a sticky salivary exudate that forms the matrix for the cup-shaped nests. The exudate is a glycoprotein (Kathan & Weeks, 1969) which has been harvested as a delicacy in Chinese cuisine since at least the 16th Century (Lim & Cranbrook, 2002). *A. maximus* earns its vernacular name because its

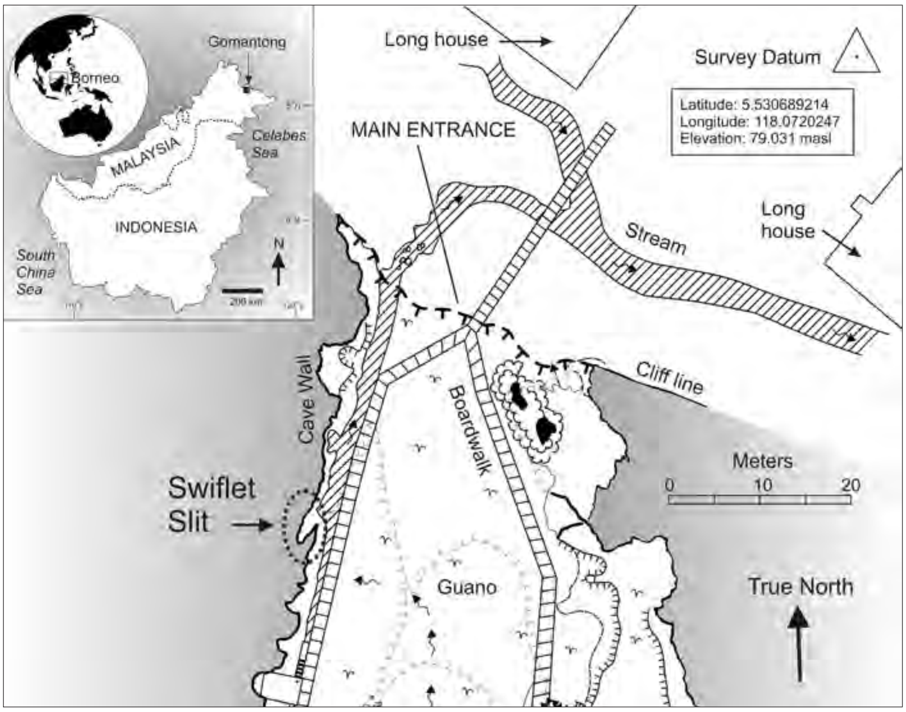

Fig. 1. Plan of the main entrance area of *Simud Hitam*, showing the "Swiftlet Slit" (circled, with arrow).

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nests include a large percentage of feathers and vegetative debris; the nests of *A. fuciphagus* are formed of more-or-less pure salivary exudate, and are therefore the more valuable product. In the late 19th Century, annual nest exports from caves in Sarawak were the 6th largest source of revenue for the Government (Lim & Cranbrook, 2002).

Currently, Sabah harvests nests from 27 different caves or groups of caves, together with a growing infrastructure of artificial "swiftlet barns", and in 2009 exported 8876 kg of nests with a value of ~US$ 4.2 million (Lim et al., 2012). Monitoring and assessment of swiftlet nesting behavior and productivity in these caves is essential to the long-term sustainability of the industry, but is difficult because of the physical inaccessibility of the sites (Francis, 1987). Conventional photography, which images portions of cave roofs from a single angle, has proven impractical for anything other than very localized (~10 m^2) assessment. Here we present a proof-of-concept study that tests the utility of terrestrial LIDAR-based scanning for larger-scale cave swiftlet monitoring through discrimination of nests from roosting bats and small scale rock features.

In recent years, the increasing availability and decreasing size of three-dimensional laser scanners, sometimes called 'terrestrial LiDAR' scanners (TLS), has generated numerous examples of their use underground. Early examples include Marais (2005), Fryer et al. (2005), and Silvestre et al. (2015). Until recently, these projects have been largely of a simple imaging nature. Current trends are towards the use of 3D laser scanning technology to address specific scientific questions, such as passage stability analyses (Lyons-Baral, 2012), and ice volume studies (Petters et al., 2011; Buchroithner et al., 2012; Milius & Petters, 2012; Berenguer Sempere et al., 2014; Burens et al., 2014). There has also been an increase in the scanning of progressively more technically-difficult and complex caves (e.g., Buchroithner & Gaisecker, 2009; Gonzalez et al., 2009; Addison, 2011). The use of TLS as a biological inventory tool is reflected in the work of Azmy et al. (2012), who demonstrated that the technology could be used to precisely count roosting bats in a Malaysian cave, and in some cases, could discriminate between different bat species.

METHODS

In July 2012, *Simud Hitam* (the "Black Cave") was scanned using a FARO Focus 3D instrument (McFarlane et al., 2013), generally at ¼ resolution mode (= 244,000 points/second, yielding an x-y-z point cloud spacing of 12.5 ± 2 mm ranging error, at typical wall/roof distances of 20 m), with additional scans at full resolution (x-y-z point cloud spacing of 3.1 ± 2 mm at 20 m) where required for specific analyses of small targets such as bats and nests. The size and orientation of the nesting/roosting surface (essentially horizontal with respect to the floor) required only a single scan. Data processing was done with FAROSceneLT v. 5.0.1 software (http://www.faro.com/faro-3d-app-center/stand-alone-apps/scene-lt). Here, we present an analysis based on a full-resolution scan of the roof of an 11.04 m^2 roof area (x-y plane), a re-entrant named "Swiftlet Slit" (Lundberg & McFarlane, 2012), in the west wall of *Simud Hitam* (Fig. 2a, b) which hosts both Black nest swiftlets and Rhinolophid bats (*Rhinolophus borneensis/creaghi*). This section of the cave was chosen for proof-of-concept, because its size, orientation and proximity to the cave entrance allowed for conventional photography, and hence the ability to check TLS point cloud data against reliable, visual discrimination of nests and bats.

Feature discrimination was achieved using a combination of geometry and laser return intensity. The spatial (x-y-z) data were read into ArcGIS (v. 9.3), together with the TLS intensity values (a function of target distance, laser incidence angle, and surface reflectivity: González et al., 2010; Balduzzi et al., 2011) for each data point. Intensity values were not distance corrected. We first examined a sub-set of the data, in which bats and nests were clearly identifiable in the spatial data set. ArcGIS Spatial Analyst was used to

Fig. 2. A) Color photograph of the Swiftlet Slit, and B) TLS point cloud depiction of the same area. Note that the point-cloud provides a true planar view, without perspective distortion. View is vertically upwards, northwest at the top of the figure.

determine 'sinks' (i.e., discrete, closed areas of negative topography), which were then "filled" (ArcGIS, Fill tool) to generate polygons, that were then filtered using threshold values of >0.000525 m^2 and <0.02 m^2 (area), determined by trial and error. This model successfully classified 100% of the bats and nests in the test area. Bats were distinguished from nests by filtering for variance in intensity (var_i bats >1500) and variance in z (var_z > 0.003 m); nests were defined as var_i <1500, var_z <0.003 m. The model structure appears in Fig. 3. Ranges and separation of intensity variances appear in Fig. 4. Finally, the model was applied to the whole data set, and nests and bats automatically tallied (Fig. 5). Further, we determined slope of the roosting and nesting areas using the ArcGis/Spatial analyst "Slope" tool.

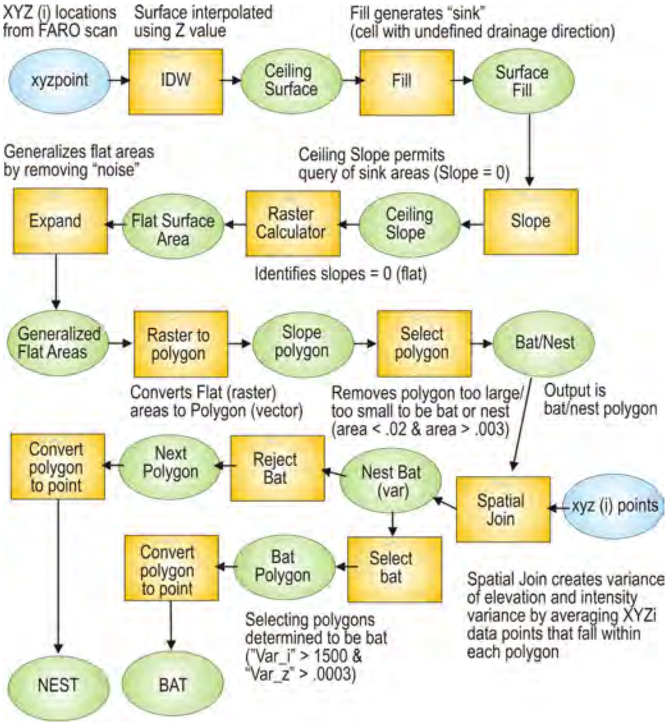

Fig. 3. ArcGIS model structure.

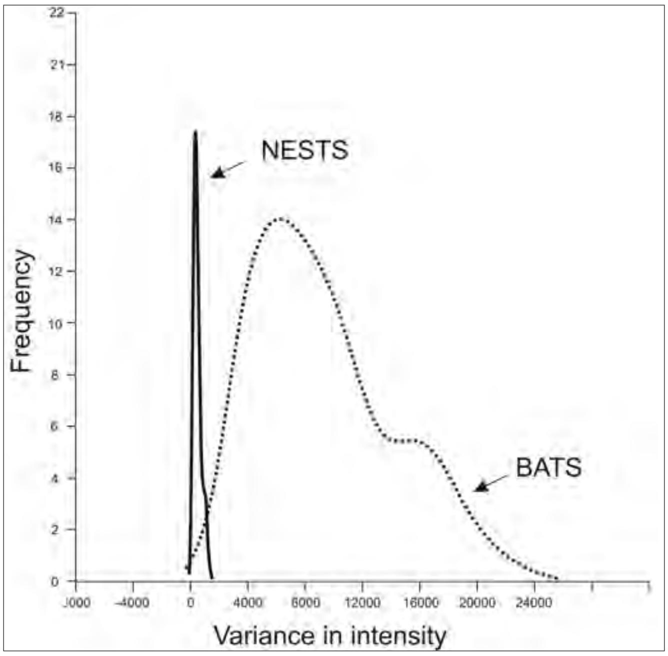

Fig. 4. Frequency plot of laser return intensity variances for bats and nest targets.

RESULTS

The total area (x-y) of the "Swiftlet Slit" roof is 11.04 m^2, the apex of which is a bedding plane oriented approximately horizontal with respect to the floor. The model over-estimated bat numbers by 15.1% relative to the manual count (apparently due to non-discrimination of small rock projections); nests were undercounted by 1.5%, relative to our photographically-based manual counting (Table 1). A total of 526 nests of the Black-nest Swiftlet (*Aerodramus maxima)* were present in July 2012, giving an overall nest density of 47.6 nests/m^2. However, nests are neither randomly distributed, nor clustered in the available roof area. Ripley's K-function analysis demonstrates a statistically significant dispersion at scales greater than ~ 0.6 m ($p < 0.05$). Nearest neighbor analysis shows that the nests tend to be regularly spaced at ~ 6.1 cm inter-nest centroid distance, equivalent to a theoretical maximum density of 268 nests/m^2. Median slope of the nesting surface was 55.5º (minimum slope 20º). In contrast, Rhinolophid bats (N = 152) roost in an over-dispersed pattern with mean nearest-neighbor

Table 1. Effectiveness of manual versus automated counts of bats and swiftlet nests, using TLS imagery.

	Manual count of TLS imagery	**Automated model count**	**Error (%)**
Bats	152	175	15.1%
Nests	526	518	1.52%

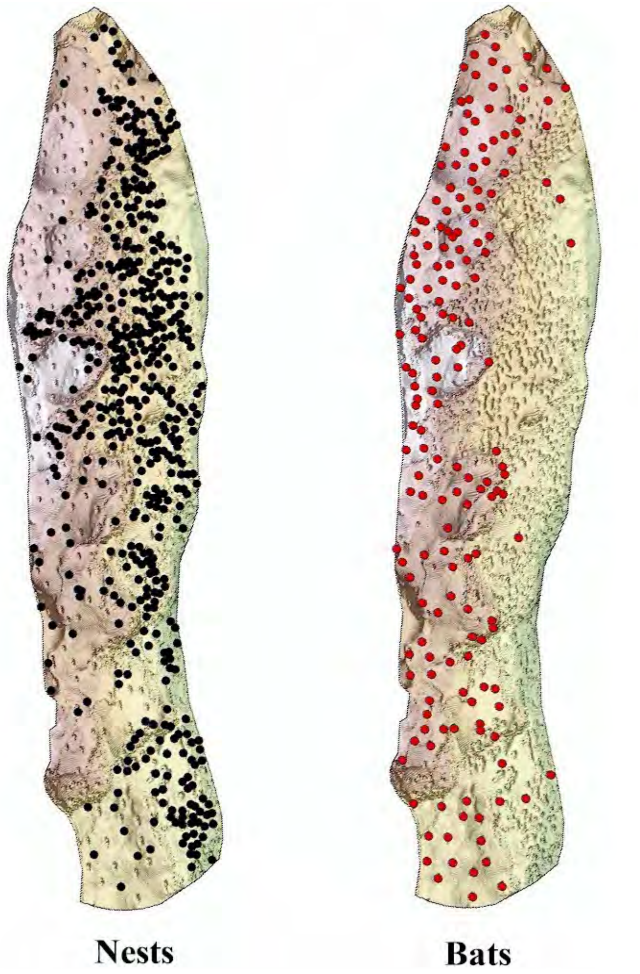

Fig. 5. Model-resolved nests and bats in the "Swiftlet Slit". Orientation as in Fig. 2.

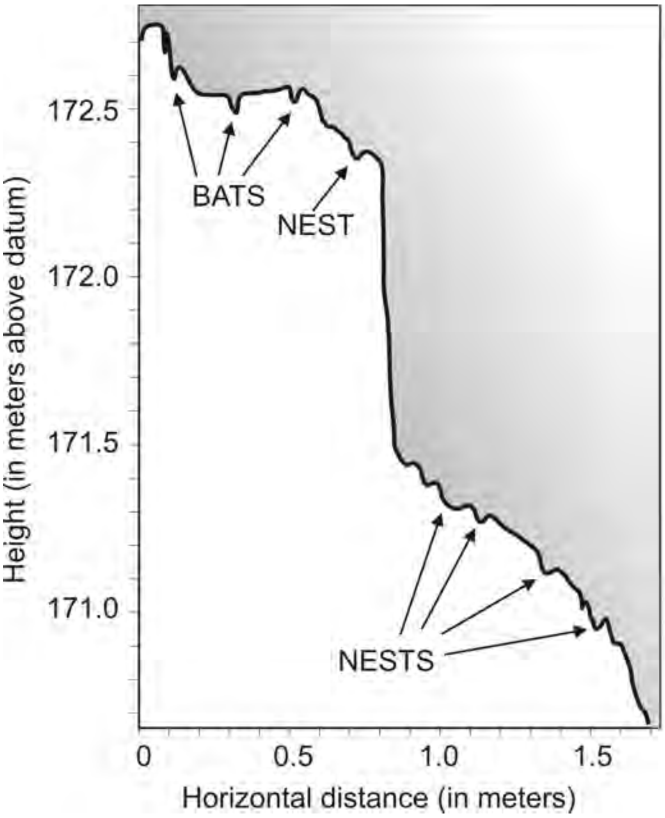

Fig. 6. Profile of the “Swiftlet Slit”, showing the influence of slope on preferred nesting locations of bats and birds.

distances of 13.0 cm. Their preferred roosting surfaces have slopes of median 31.4º (minimum slope 2º): i.e., they are often steep roof surfaces which allow the bats to hang freely. A profile section across the Swiftlet Slit (Fig. 6) shows the differences in slope that define bat roosting versus swiftlet nesting areas.

CONCLUSIONS

Terrestrial laser scanning at Gomantong has now imaged the entire roof (and walls and floor) of *Simud Hitam*. The size of the point-cloud dataset, in excess of 5 billion points, creates significant software processing challenges (e.g., Addison, 2011), but these can be addressed by breaking the whole-cave data set into sections for separate processing in ArcGIS software.

High-resolution terrestrial laser scanning provides a potentially effective tool for assessing swiftlet nest densities on high cave roofs, even in total darkness. TLS data also permits the evaluation of areas of cave roof that are potentially suitable for nests, and therefore facilitates the calculation of upper population size limits. Our demonstration of micro-habitat segregation between rhinolophid bats and black-nest swiftlets, based on roof/wall slope, has not previously been formally described but is a promising avenue for future research. Together with further research to narrow the spatial constraints on swiftlet nesting surfaces, and potentially discriminate between white-nest and black nest swiftlet micro-habitat preferences, TLS techniques may be able to quantify the original pre-harvesting swiftlet population size.

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