Investigation of Large-Scale Navigation Behavior of Echolocating Bats During Natural Foraging, Using GPS and Acoustic-GPS Data-Loggers

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***Abstract*— Large-scale flight paths of echolocating Japanese greater horseshoe bats were measured using GPS and acoustic GPS (A-GPS) data-loggers. The bats flew up to 23.6 km away from their roost at a maximum. The measured flight paths were broadly divided into two patterns; "staying" and "moving". Almost bats spent over 70% of time staying while changing sites, indicating that the bats repeated to stay and to fly, and spent much time staying. Analysis for the environmental preference revealed that the bats selectively move and stay in the forest and tend to move along the artificial road. These findings by the high-resolution GPS bio-logging suggest that the bats repeat to stop the various area for foraging, by following the artificial forest roads. Furthermore, the collected A-GPS logger showed that more pulse emissions were observed during staying than moving, strongly supporting that the bats search prey insects using sonar while perching on the tree at the stay-site. Further investigation by A-GPS bio-logging would provide valuable information on bat's echolocation and flight strategies during natural foraging in the large-scale space.**

Keywords— bio-Sonar, ultrasound, bio-logging, search

I. Introduction

Insectivorous bats capture a lot of small airborne insects a night using sonar. In order to clarify the sophisticated ultrasonic sensing and trajectory planning strategies of bats in the natural environment, various acoustic measurements have been conducted in the field [1, 2]. Meanwhile, bio-logging techniques, which obtains data by directly attaching various measurement devices to an animal, have been highly developed in recent years, and the miniaturization of the device has been advanced. If this technique can be applied to the bat, it becomes possible to understand the whole picture of the foraging flight of the wild bat and it is possible to expect the full elucidation of their rational ultrasonic navigation strategy. In this study, we attached small GPS and acoustic GPS data-loggers to insectivorous echolocating bats, and succeeded in reconstructing flight trajectories when moving in a large-scale space. Then, we examined the large-scale navigation strategy of the bats.

II. Materials and Methods

The target species of this study is *Rhinolophus ferrumequinum nippon*. Body length and body mass of the bat are approximately 6-8 cm and 20-30 g, respectively [3]. They start to forage after sunset and mainly hunt flying moths in flycatcher style using ultrasound sonar [3]. Attachment and collection of the data-loggers for the bats were conducted at their day-roost in Tomakomai, southern Hokkaido, Japan. Two types of the GPS data-loggers were used in this study: PinPoint-50 (Biotrack, UK, 2.2 g, including 0.3 g telemetry unit) and GiPSy-5 (Technosmart, Italy, 2.3 g). PinPoint-50s were set to log every 600 s so that it tracks whole flight paths during a night (actually 9 h). In contrast, logging interval of the GiPSy-5 was set to 2 s (or 3 s), that continuously logging approximately 4 h, in order to measure smooth flight paths of the bats. In addition, custom-made prototype Acoustic-GPS data-loggers (A-GPS loggers, 2.6 g, ArumoTech Corp.) were used to examine the pattern of sonar emissions along the flight path. This type of logger was set to continuously log position every 5 s to simultaneously examine flight path and the timing of sonar emission for 1-2 h. Independently of the GPS-logging, the sonar emission timing can be logged when the voltage of their vocalization exceeds a certain threshold. All types of loggers were set timers to start log positions at 19:00 on that day. One of the loggers of any type was attached to the bats during daytime on totally seven days; June 2, September 3, 2015, June 10, 11 and 12, September 2 and 5, 2016 (Fig. 1A). Total number of bats that we caught and attached loggers was 29 (24 bats for GiPSy-5s, 3 bats for PinPoint-50s and 2 bats for A-GPS loggers).

Prior to the data analysis, we measured the position error of the data-logger (GiPSy-5) by putting different three sites in the forest near the roost of the bats. The measured positions were distributed in Gaussian fashion which have a

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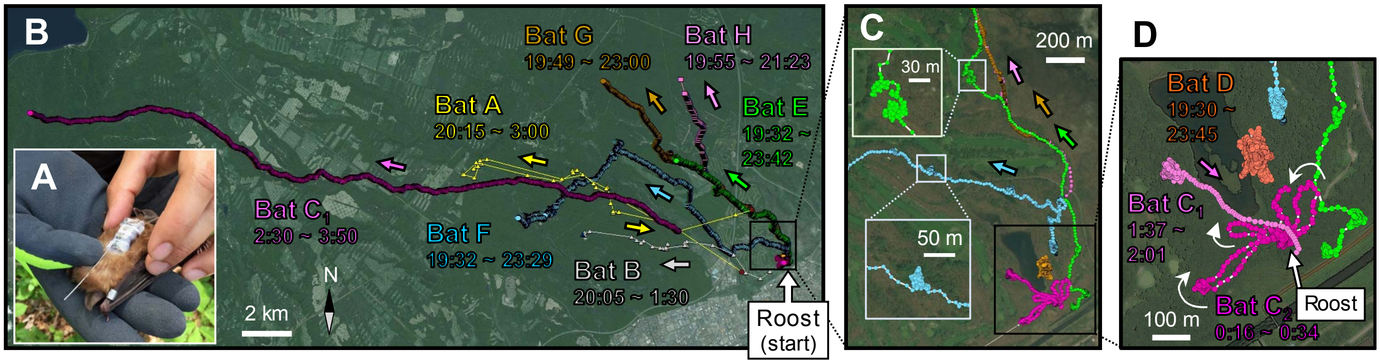

Fig. 1 GPS tracking of the echolocating bats during nightly navigation flight. (**A**) The GPS data-logger which was attached to the back of the bat. (**B-D**) Measured flight trajectories of the bats which were drawn on a satellite photo image; large- (B), middle- (C) and small-scales (D). Arrows represent the flight direction of the bat.

peak at the center of the coordinates in both north-south and east-west axes. Standard deviation σ was ±7-8 m. Consequently, we defined a coordinate of the bat as stay-mode when the maximum distance (max-d_{window}) between two points where logged during 30 s (previous and subsequent 15 s from the current position) less than 50 m (corresponding to approximately ±3σ). When max-d_{window} exceeded 50 m, the bat's coordinate was defined as move-mode. To prevent the false detection due to the positional error, we judge stay or move after smooth processing (moving average algorithm at MATLAB) for the time series of max-d_{window}. We conducted this analysis using a custom-made program in Matlab R2016b (mathworks, USA), and Geographical Information System (GIS) analysis using ArcGIS Desktop 10.4 software (Esri Japan Corporation).

III. Results and Discussion

We successfully collected totally 8 data-loggers; 5 GiPSy-5s, 2 PinPoint-50s and 1 A-GPS logger. Flight paths measured by the collected data-loggers shows that the bats flew towards north-west direction (Fig. 1B). We found stay-mode trajectory pattern (Fig. 1C) in the all of each bat's flight path. Positional distribution of the bats during the detected stay-mode showed Gaussian fashion, whereas the move-mode trajectories indicated smooth flight patterns. All bats except Bat C_1 spent over 70% of time staying while changing sites, indicating that the bats repeated to stay and to fly, and spent much time staying. The bats are suggested to repeat to stay at various area for foraging. In contrast, Bat C_1 flew relatively long distance with little stay (28%), and flew almost directly towards north-west direction with moving distance of 23.6 km, suggesting that this bat on that day may move toward certain goal for something different purpose from the foraging. One bat stayed at a single site for over four hours (bat D), and other one flew away from a stay site and then return back to the same stay-site repeatedly (bat C_2, Fig. 1D), like a "*foray search*" moving pattern, which is known as efficient path to search targets that distributed in biased positions [4].

Next, we examined the environmental preference of the bats to fly and stay (Fig. 2). Natural forests account for the majority of land-use in the direction that the bats flew (Fig. 2A). All of the environments of the stay-site were either natural

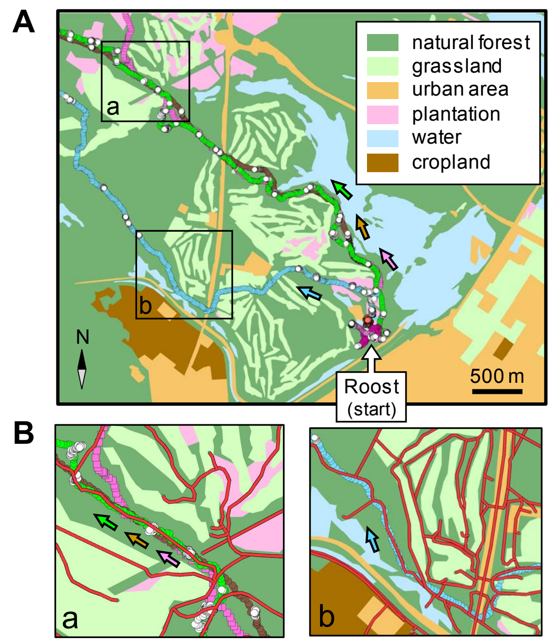

Fig. 2 (**A**) Flight path of the bats on the land-use map around their roost. White circles show locations while stay-mode. (**B**) Enlarged figure of the squared area in the top figure. Red lines show the artificial roads.

forest or conifer plantation. Furthermore, during move-mode, the bats tended to fly inside the natural forest or plantation. Inversely, proportion to move in urban area, grassland and water area was relatively low. These support that forests are preferred as moving and feeding habitats by the bats. Particularly, in the forest, the bats tended to fly along artificial roads (Fig. 2B), suggesting that they conduct route-following navigation [5] by commuting flyways.

From the analysis of the collected A-GPS logger, more pulse emissions were observed during stay-mode than during move-mode (Fig. 3A and 3B). Additionally the shapes of the two distributions of inter-pulse interval were clearly different for each other (Fig. 3C and 3D). These findings strongly suggest that the bats search prey insects using sonar while perching on the tree at the stay-site. A-GPS logger is a powerful tool to understand the states of sonar and flight of the

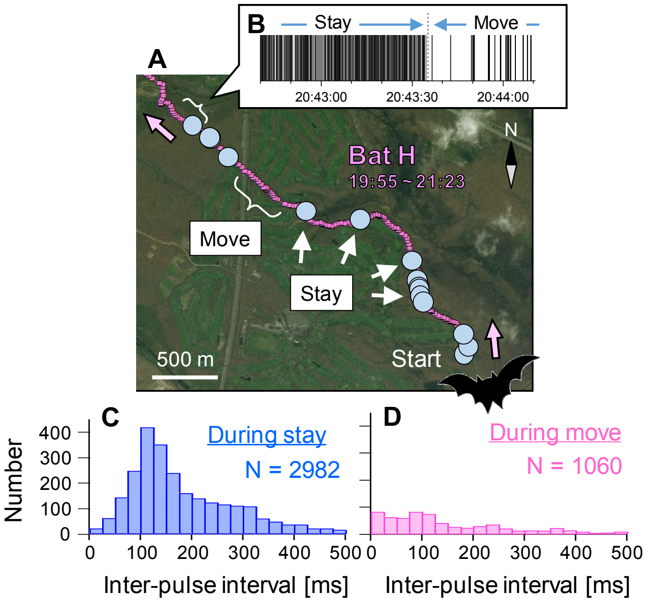

Fig. 3 (**A**) Flight path of bat H while repeating move and stay. (**B**) Time-series of the timing of the detected echolocation pulses. (**C**, **D**) Distribution histogram of Inter-pulse interval during stay-mode (C) and move-mode (D).

echolocating bats. Currently it is difficult to measure raw data of their vocalization with GPS bio-logging because of the weight limitations. In the near future, we would like to analyze the relationship between echolocation and flight during large-scale navigation by improving the logger. Further investigation by the A-GPS bio-logging would provide valuable information on bat's echolocation and flight strategies during natural foraging in the large-scale space.

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