Appendix 2

Accuracy of altitude recorded by GPS loggers

INTRODUCTION

The accuracy of altitude recorded by 3D Global Positioning System (GPS) loggers generally varies depending on factors such as the positioning interval, number of satellites used for positioning, and logger model (Bouten *et al*. 2013, Thaxter *et al*. 2015, Poessel *et al*. 2018). We evaluated the accuracy of our data by testing different positioning intervals with the same model of the logger used on the birds, with reference to known altitude.

METHODS

Accuracy tests were conducted in Hakodate City and Nanae Town, Hokkaido, Japan, on November 6, 2019 and December 19, 2019. Both days were cloudy. On each day, we placed ten GPS loggers (CatLog Gen2 Patch Antenna, Perthold Engineering LLC, Germany) and a handheld GPS with a barometric altimeter for actual altitude reference (GPSMAP 64scJ, GARMIN, USA) on the dashboard of a car and traveled for 3–4 hours at a speed of 0–60 km h^{-1} in an area where the altitude was 2–334 m.

To investigate the effects of recording interval, we programmed recording intervals at 10 s, 1 min, 5 min, and 15 min. We programmed the handheld GPS device to record at 1 s intervals. The altitude of the handheld GPS was based on barometric pressure. Before the survey, we calibrated the handheld GPS at a location where the altitude was obtained from a topographic map (Geospatial Information Authority of Japan 2021). During the survey, we further checked the altitude by handheld GPS every 10–60 min at locations with known altitudes (Geospatial Information Authority of Japan 2021). At these points, the difference between the altitude obtained by the handheld GPS and the published altitude was only 1.3 ± 5.8 m (mean ± standard deviation, n = 39). Therefore, we concluded that the altitude recorded by the handheld GPS was sufficiently accurate for our uses.

RESULTS & DISCUSSION

We collected 3,737 points (2,632 for 10 s, 737 for 60 s, 250 for 300 s, 118 for 900 s) using GPS loggers. The difference between the altitudes recorded by the GPS loggers and the handheld GPS showed a normal distribution. When more than six satellites were accessed for positioning and the recording interval was 5 min, the difference was -5.4 ± 34.2 m, -181–100 m (mean ± SD and range) (Fig. S1). The mean was not significantly different from 0 (t_{90} = -1.5175, p = 0.13, One sample t-test); indicating no directional biases. No corrections, therefore, were made. Absolute difference, i.e. error, was smaller when more satellites were captured and when the recording interval was shorter (Fig. S2). The range of the difference (-181–100 m) was similar to the range of altitude recorded by devices on birds (-224–154 m, Fig 4a); suggesting that large errors only arise rarely. Thus, we consider that while errors were substantial, the reliability for the altitude at each point was sufficient for us to know the overall trend of flight altitude through modeling.

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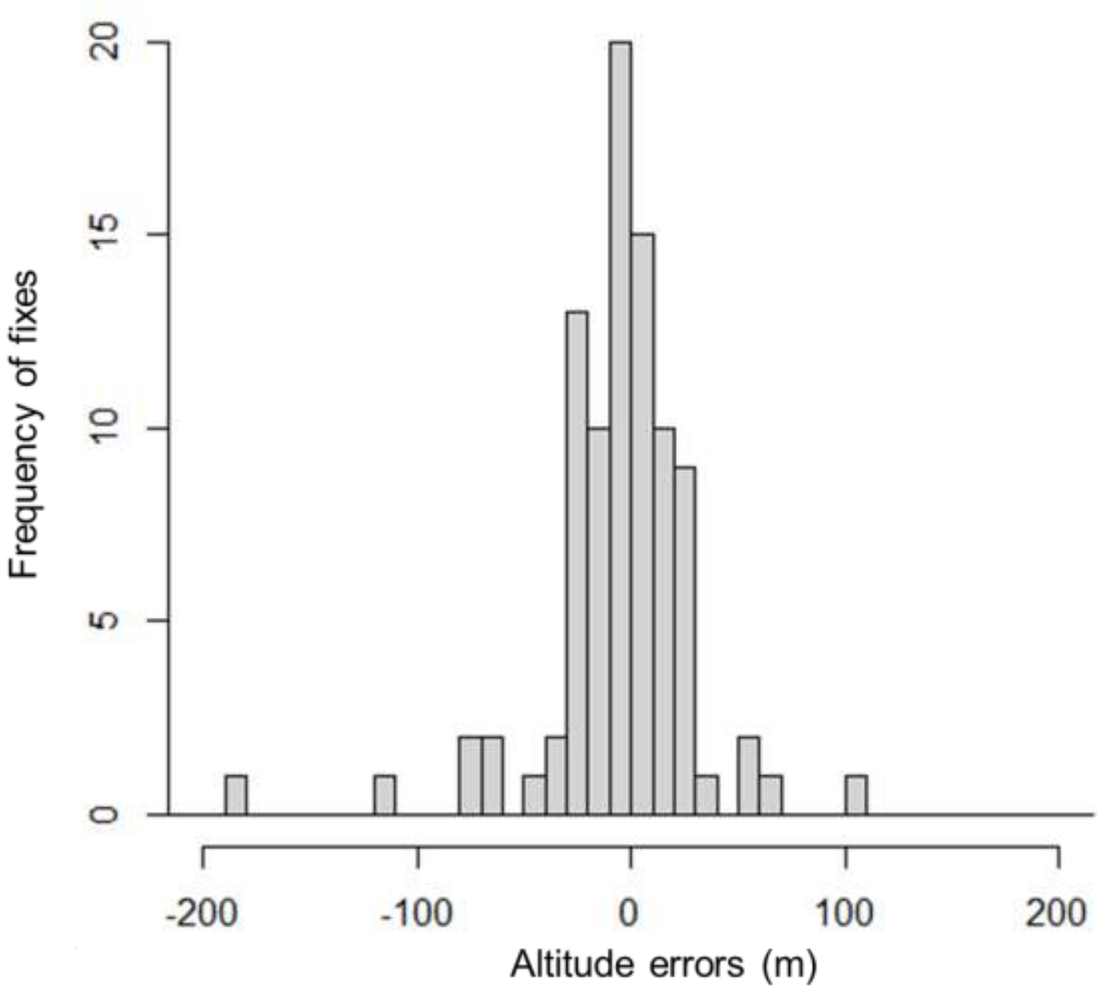

Fig. S1 Accuracy test results for altitude data recorded by GPS loggers (CatLog Gen2, Patch Antenna). This shows the frequency of errors between altitudes recorded by loggers and an accurate altimeter by accessing more than six satellites at 300 s intervals (not absolute value).

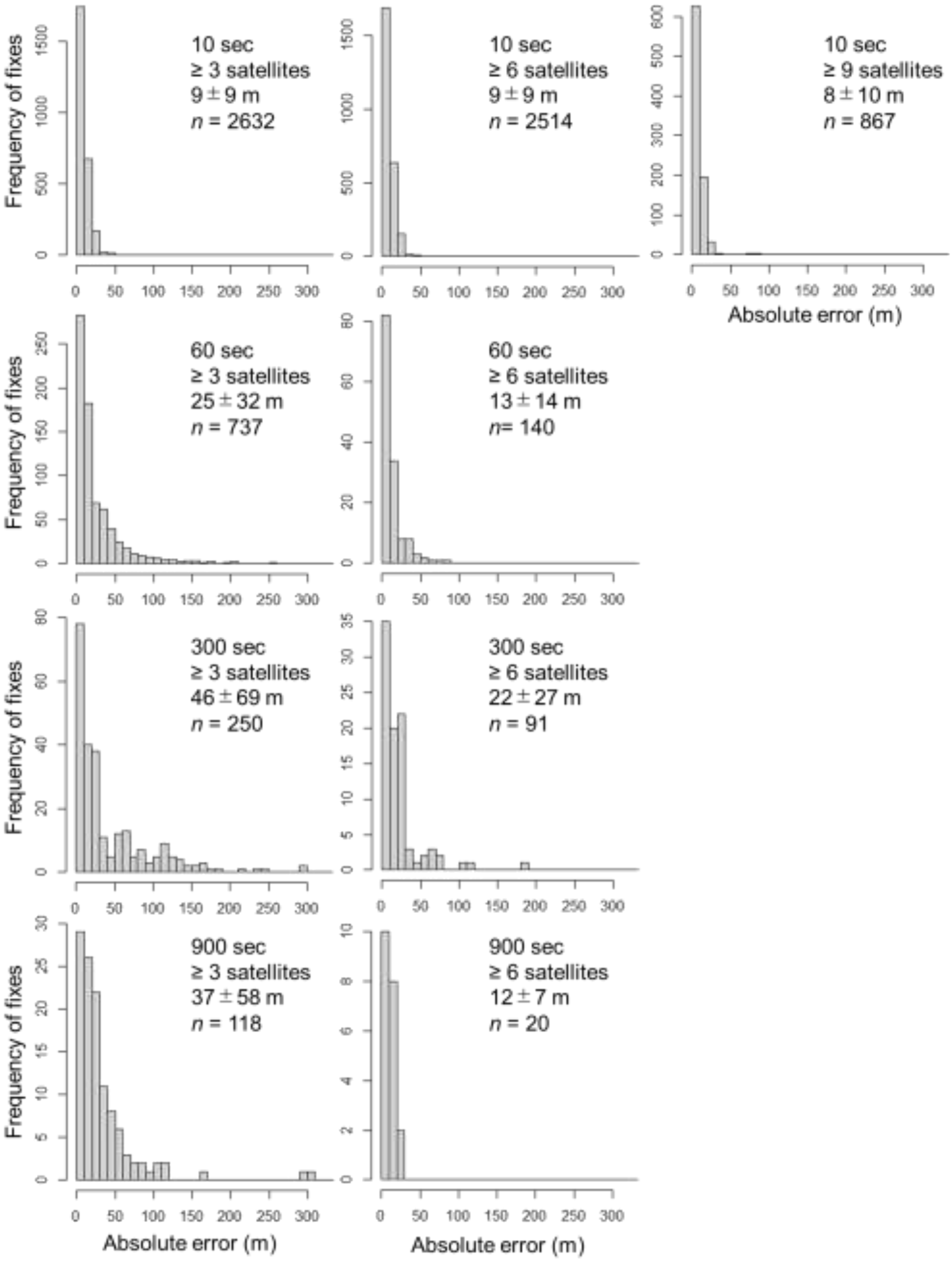

Fig. S2 Accuracy test results for altitude data recorded by GPS loggers (CatLog Gen2, Patch Antenna). The frequency of absolute errors between the altitudes recorded by loggers and an accurate altimeter by positioning intervals (10 s, 60 s, 300 s, and 900 s intervals) and the number of satellites accessed for positioning (≥3, ≥6, and ≥9) are shown. The mean and standard deviation of errors is indicated with the sample size (*n*) in each panel.