



Data-processing artefacts in three-dimensional dive path reconstruction from geomagnetic and acceleration data

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ABSTRACT: Tri-axis magnetism and acceleration data loggers have recently been used to obtain time-series headings and, consequently, the 3-dimensional dive paths of aquatic animals. However, problems may arise in the resulting calculation process with multiple parameters. In this study, the dive paths of loggerhead turtles and emperor penguins were reconstructed. For both species, apparently unrealistic movements were found. Time-series heading data of turtles showed small regular fluctuations synchronous with stroking. In the dive paths of penguins, infrequent abrupt changes in heading were observed during stroke cycles. These were unlikely to represent true behaviours according to observations of underwater behaviour and tri-axis magnetism and acceleration data. Based on the relationship between sampling frequency and frequency of body posture change, we suggest that (1) the changes in the animals' posture concurrent with strokes and (2) the mismatched treatment (i.e. filtering and non-filtering) of the acceleration and magnetism data caused the artefacts. These inferences are supported by the results of simulations. For data sets obtained at a given sampling frequency, the error pattern in calculated dive paths is likely to differ depending on the frequency and amplitude of body posture changes and in swim speed. In order to avoid misinterpretation, it is necessary to understand the assumptions and inherent problems of the calculation methods as well as the behavioural characteristics of the study animals.

KEY WORDS: 3D dive path · Low-pass filter · Sampling frequency · Stroke activity · Data logger · Dead-reckoning

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INTRODUCTION

Diving animals move and forage in 3-dimensional (3D) environments, requiring investigations of their movements in 3D to better understand their behavioural ecology and the physiology of diving. Presently, 2 methods are available to estimate 3D dive paths:

acoustic telemetry using ultrasonic transmitters (e.g. Harcourt et al. 2000, Hindell et al. 2002) and dead-reckoning using data loggers (e.g. Mitani et al. 2003, Wilson et al. 2007). In the latter method, locomotion vectors per measurement interval are integrated from the start to the end of a dive to reconstruct paths (Wilson & Wilson 1988). The vectors can be obtained

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with animal-borne recorders, such as gimbaled compass loggers (e.g. Davis et al. 1999) and tri-axis magnetic and acceleration loggers (e.g. Johnson & Tyack 2003, Shiomi et al. 2008)

Although 3D dive paths undoubtedly provide new insights into underwater activities, each method of reconstruction has some weaknesses. For example, application of acoustic telemetry is limited by the range within which receivers can detect signals from transmitters. The dead-reckoning method, on the other hand, does not confine the measurement range, but is based on the assumption that animals are always moving in a direction parallel to their longitudinal body axis. This assumption is not always true, especially for animals in moving fluids. Any movements not meeting this assumption, such as passive transport by water currents, are not included in the calculation and can cause errors in estimated positions (Wilson et al. 1991, Shiomi et al. 2008).

In addition, we suspect that other sources of error arise when the direction of locomotion vectors are obtained using magnetic and acceleration data loggers. In this method, the heading at each measurement interval is not recorded directly, but is calculated indirectly from tri-axis magnetic and acceleration data. The process of the calculations with a combination of multiple parameters can include some factors that cause an error in the estimated paths.

In the present study, we reconstructed 3D dive paths of 2 species, loggerhead turtles *Caretta caretta* and emperor penguins *Aptenodytes forsteri*. Phenomena that looked like artefacts were found in the obtained heading data, specifically during stroke cycles. Possible causes of this are suggested to be associated with data processing in the estimation method.

MATERIALS AND METHODS

Multi-sensor data loggers (W1000L-3MPD3GT, Little Leonardo: 26 mm diameter, 174 mm length, 120 g in air) were used in field studies for both loggerhead turtles and emperor penguins. Each logger recorded depth, ambient temperature, swim speed, tri-axis (longitudinal, lateral, and dorsoventral) magnetism, and tri-axis acceleration. Sampling intervals for all parameters, except for acceleration, were 1 s. Tri-axis acceleration was sampled at 32 Hz for turtles and at 16 or 32 Hz for penguins. Neither magnetometers nor accelerometers had anti-alias filters.

In 2006 and 2007, field experiments for turtles were conducted at Otsuchi Bay, Iwate, Japan (39° 20' N, 141° 56' E). Loggers were deployed on the carapaces of 8 turtles. The data loggers detached automatically using the method invented by Watanabe et al. (2004)

and were retrieved 5 to 17 h after the turtles were released at the centre of Otsuchi Bay (see Narazaki et al. 2009 for details of the experiments). The penguin study was conducted in 2004 in McMurdo Sound, Antarctica (77° 43' S, 166° 07' E). Loggers were attached to the backs of 3 penguins with waterproof tape (Tesa tape 4651, Tesa) and instant glue (Loctite 401, Henkel), following the handling method introduced by Wilson et al. (1997). One to 3 deployments were done for each penguin. The loggers were retrieved 38.0 to 60.4 h after attachment (see Shiomi et al. 2008 for details of the experiments).

To reconstruct the 3D dive paths, first the rotation angles around the lateral and longitudinal axes (pitch and roll, respectively) had to be calculated (Johnson & Tyack 2003). They were estimated using the tri-axis accelerations derived from gravitational acceleration, which change in response to the inclination of the animal's body (hereafter, gravity-based acceleration). In order to estimate gravity-based acceleration, several procedures were followed. We calculated the power spectral density (PSD; Fig. 1) of the entire acceleration data set from each individual by fast Fourier transformation using the function in IGOR Pro version 6.04 (WaveMetrics). Considering the frequency with the peak of the PSD as the dominant stroke frequency of each individual, the low-pass finite impulse response (FIR) filters implemented in IGOR Pro were set to remove the high-frequency components caused by strokes (Sato et al. 2007; Fig. 1). The cut-off values for the filters used for each individual ranged from 0.19 to 0.28 Hz for turtles and from 1.06 to 1.63 Hz for penguins. Under the assumption that the frequencies of changes in the pitch and roll angles are lower than those of accelerations resulting from body motions such as thrust (hereafter, specific acceleration), the extracted low-frequency components of acceleration were used to calculate pitch (p) and roll (r) with equations introduced by Johnson & Tyack (2003):

$$p = -\arcsine(A_{\text{long}}/9.8)$$

$$r = \begin{cases} \text{atan}(A_{\text{lat}}/A_{\text{dv}}) & (A_{\text{dv}} < 0) \\ \text{atan}(A_{\text{lat}}/A_{\text{dv}}) + \pi & (A_{\text{lat}} \leq 0 \text{ and } A_{\text{dv}} > 0) \\ \text{atan}(A_{\text{lat}}/A_{\text{dv}}) - \pi & (A_{\text{lat}} > 0 \text{ and } A_{\text{dv}} > 0) \\ \pi/2 & (A_{\text{lat}} < 0 \text{ and } A_{\text{dv}} = 0) \\ -\pi/2 & (A_{\text{lat}} > 0 \text{ and } A_{\text{dv}} = 0) \end{cases}$$

where A_{long} is longitudinal gravity-based acceleration, A_{lat} lateral gravity-based acceleration, and A_{dv} is dorso-ventral gravity-based acceleration. Magnetism values change depending on angles between the geomagnetic vector and each axis of the loggers. Thus, heading was calculated from pitch, roll, and tri-axis magnetism (Johnson & Tyack 2003). Finally, the 3D paths were estimated using heading, swim speed, and

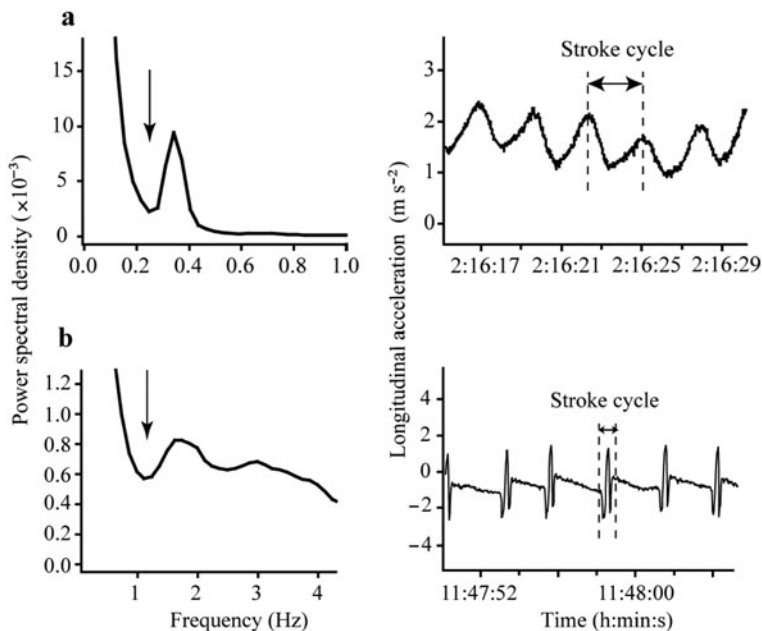


Fig. 1. (a) *Caretta caretta* and (b) *Aptenodytes forsteri*. (left) Power spectral densities of longitudinal acceleration data calculated by fast Fourier transformation. Arrows indicate the troughs providing thresholds of the low-pass filter to extract gravity-based acceleration components (see 'Materials and methods'). (right) Time-series data of longitudinal acceleration. Double-headed arrows show a stroke cycle detected as regular peaks

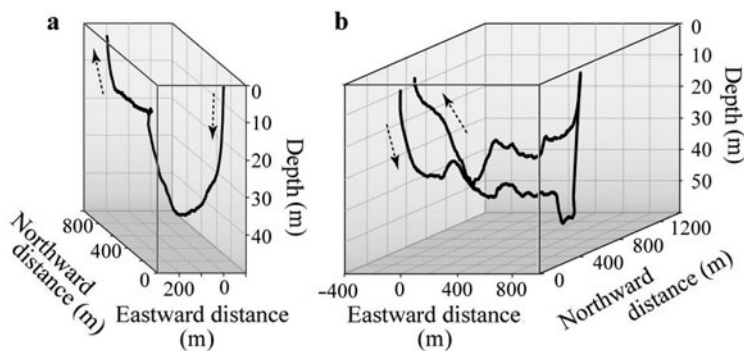


Fig. 2. (a) *Caretta caretta* and (b) *Aptenodytes forsteri*. Examples of reconstructed 3-dimensional dive paths. Dashed arrows indicate the direction of travel

depth by dead-reckoning (Wilson & Wilson 1988, Mitani et al. 2003). The 3D dive paths of the 2 species were calculated from the obtained data set using a customised macro compliant with IGOR Pro. We distribute the macro as freeware at http://bre.soc.i.kyoto-u.ac.jp/bls/index.php?3D_path.

RESULTS AND DISCUSSION

Three-dimensional dive paths were reconstructed for 564 and 723 dives of 8 turtles and 3 penguins, respectively, showing their underwater movements in detail

(Fig. 2). However, apparently unrealistic movements were found on careful examination of the dive paths. In the headings of penguins, infrequent abrupt changes were observed (Fig. 3b). Although no obvious changes in heading were detected in the paths followed by turtles (Fig. 3a), the time-series heading data showed fluctuations (Fig. 4a). These fluctuations seemed to be synchronous with stroking activity identified from longitudinal acceleration data (Fig. 4a). However, such fluctuations in heading were likely to be estimation errors because turtles move lengthwise, but not sideways, when swimming (T. Narazaki pers. obs.). For penguins, abrupt heading changes occurred by several tens of degrees during stroke cycles (Fig. 4b). At the abrupt changes, penguins changed their headings drastically twice within a single stroke (Fig. 4b), which appears to be physically difficult. Considering the mobility of penguins, a sampling frequency of magnetism (1 Hz) might be insufficient to record their movements thoroughly. It is possible that the loggers recorded just one segment of the series of actual movements during the sampling interval of 1 s, and that the incomplete data record due to sampling intervals caused unrealistic changes in the calculated headings. From this perspective, tri-axis accelerations that were sampled at a higher frequency of 16 or 32 Hz were checked visually. If penguins changed their swimming direction so rapidly, then the sharp turns must be detected as acceleration signals, such as prominent peaks on some or all of the 3 axes. However, no specific signals were detected in the vicinity of the abrupt changes of the calculated heading. Therefore, the abrupt heading changes in the penguins' paths also seemed to be artefacts.

The loggers used in the present study provide up to 1 Hz of parameters except for accelerations; consequently, headings were calculated at 1 Hz. Based on sampling theory, the calculated headings allow us to discuss only fluctuations derived from body posture changes at less than 0.5 Hz (Nyquist frequency). Changes at frequencies higher than 0.5 Hz caused aliasing in the data sampled at 1 Hz. When turtles and penguins stroke, their pitch changes slightly in the vertical plane with up- and down-beat motions, respectively (penguins, Clark & Bemis 1979; sea turtles, T. Narazaki pers. obs.). That is, the frequency of changes in gravity-based acceleration and magnetism data during stroke cycles is the same as that of strokes. For turtles, dominant stroke frequencies were less than 0.5 Hz (Fig. 1a); therefore, the pitch

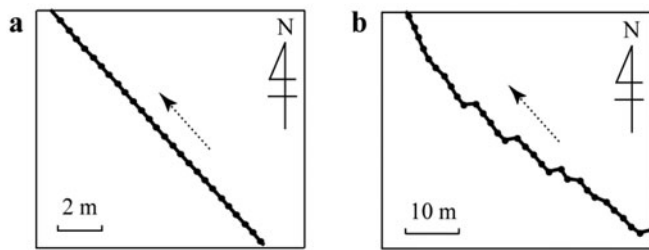


Fig. 3. (a) *Caretta caretta* and (b) *Aptenodytes forsteri*. Enlarged parts of the overhead views of dive paths. Dashed arrows indicate the direction of travel. Note that there are some abrupt heading changes in the path of the emperor penguin, whereas no such change is seen in the path of the loggerhead turtle (see 'Results and Discussion')

changes during stroke cycles did not lead to aliasing in the data (Fig. 4a). However, another problem possibly occurred on combining the magnetism with the low-pass filtered acceleration data. The acceleration sensors in the data loggers record both specific accelerations and gravity-based accelerations, although only the latter, which reflect body posture, are required for heading calculations. Currently, frequency-based filters or running mean procedures are used to separate specific and gravity-based acceleration (e.g. Tanaka et al. 2001, Wilson et al. 2006). The low-frequency components of acceleration and smoothed acceleration obtained using each method are thought to be derived from changes in body posture relative to gravitational acceleration (Tanaka et al. 2001, Wilson et al. 2006). With both methods, however, accurately extracting true gravity-based acceleration is impossible in principle because, as mentioned above, some movements such as strokes can cause concurrent changes in both specific and gravity-based accelerations (Shepard et al. 2008, Shiomi et al. 2008). For our turtle data sets, the PSDs of the acceleration data showing clear peaks indicated that the animals stroked at a particular frequency (Sato et al. 2007; Fig. 1) and that specific acceleration due to the strokes was expected to be filtered out entirely. However, concurrent changes of the gravity-based acceleration are also excluded by the low-pass filters. Therefore, once low-pass filters are applied to acceleration data, magnetism also has to be processed by the same filter to remove high frequency components reflecting body posture changes. Otherwise, the mismatched treatment would cause artefacts in calculated headings.

In the case of penguins, dominant stroke frequencies were larger than 0.5 Hz (Fig. 1b), and pitch could also change at a frequency higher than the Nyquist frequency. While low-pass filters naturally had eliminated high-frequency components of the gravity-based acceleration from such movements, the sampling rate of magnetism (1 Hz) did not allow the application of the same filter. As a result, aliasing was found in the

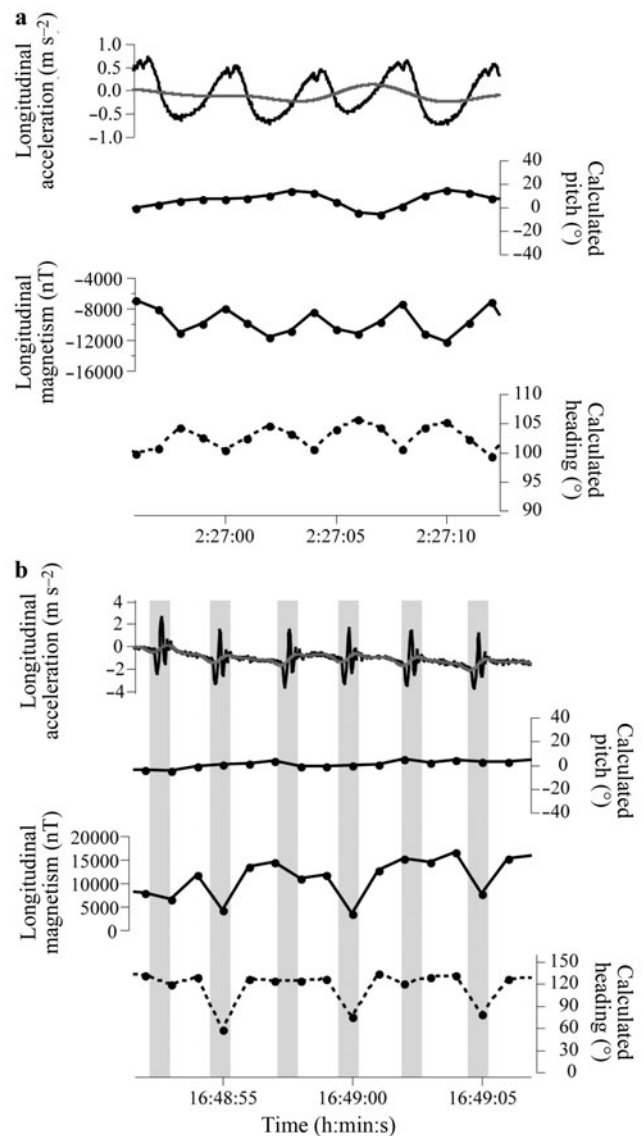


Fig. 4. (a) *Caretta caretta* and (b) *Aptenodytes forsteri*. Time-series data of longitudinal acceleration, calculated pitch, longitudinal magnetism, and calculated heading. Grey lines indicate low-frequency components of longitudinal acceleration. Loggerhead turtles stroked continuously, whereas emperor penguins stroked intermittently. Gray zones indicate stroke cycles of the penguin

magnetism data (Fig. 4b), which seemed to lead to unrealistic changes in the calculated headings.

Simulations with artificial data sets of tri-axis magnetism and gravity-based acceleration at 32 Hz examined the inferences about the source of the artefacts. The simulation data assumed that a turtle and a penguin swim horizontally toward north, east, south, or west within our field experiments sites, at constant speeds of 0.6 and 1.8 m s⁻¹ (the recorded mean swim speed of turtles and penguins in the field experiments, respectively). Pitches and rolls of the animals were set

to 0° except during stroke cycles, when pitches change down (−20°) and up (20°) corresponding with up- and down-beat motions, respectively. Based on the real values recorded in the field experiments, stroke cycle durations and stroke rate were set as 3 s and 0.3 Hz for the turtle simulation and 0.5 s and 0.4 Hz for the penguin simulation. We then estimated headings with the simulated magnetism and gravity-based acceleration data after any one of the 3 patterns of data processing below.

Simulation A: original magnetism and gravity-based acceleration. Magnetism and gravity-based acceleration of 32 Hz were down-sampled to 1 Hz by picking up data points at 1 s intervals. The data were then used for the heading calculation without any filtering.

Simulation B: filtered magnetism and filtered gravity-based acceleration. Magnetism and gravity-based acceleration data were processed by the same low-pass filter. Headings were then estimated with filtered magnetism and filtered acceleration after being down-sampled to 1 Hz.

Simulation C: original magnetism and filtered gravity-based acceleration. Magnetism data were down-sampled to 1 Hz without any filtering. Gravity-based acceleration data were processed by low-pass filters and down-sampled to 1 Hz. Headings were estimated with the magnetism and filtered acceleration. That is, this simulation followed the same data process used for the field experimental data (described in ‘Materials and methods’).

As a result, headings calculated in Simulations A and B were always consistent with the ‘true’ headings (0, 90, 180, or 270°), providing the smooth straight paths (Figs. 5 & 6). On the other hand, minor fluctuations of the headings were found in turtle Simulation C just like in Fig. 4a, which caused small fluctuations in the estimated path (Fig. 5). Although the baselines of the calculated headings in penguin Simulation C showed the ‘true’ values, abrupt changes occurred in calculated headings during stroke cycles. As a consequence, the estimated path was similar to the paths obtained from the real penguin data (Fig. 6). Results of these simulations supported our speculation that unrealistic movements in the estimated paths are attributed mainly to the changes in body postures concurrent with strokes and the combination of filtered acceleration with non-filtered magnetism in the heading

calculation. Because it is practically impossible to obtain true gravity-based acceleration data like in Simulation A, magnetism data should be processed, if possible, by the same filter as applied to the acceleration data, like in Simulation B. It should be noted, however, that both filtered magnetism and filtered acceleration data do not reflect changes in body posture at frequencies higher than the cut-off value of low-pass filters.

In actual dive paths, the effect of the fluctuations in turtles’ headings was not clearly detectable at a 1 m scale (Fig. 3a), suggesting that these errors were negligible. On the other hand, abrupt changes in the heading of penguins appeared in the estimated path at a scale of tens of meters (Fig. 3b). As shown in Fig. 4, the fluctuation in the headings of turtles occurred on less than a 20° scale, whereas the headings of penguins changed by several tens of degrees. One possible explanation for this difference might be that the changes in the body postures of turtles during strokes were smaller than those of penguins, suggesting less discrepancy between the magnetism and filtered acceleration data of turtles. As an additional factor, penguins may have more complicated or variable movement patterns when stroking because the peaks in the PSDs of penguins were more ambiguous than were those of turtles (Fig. 1). This also could promote estimation errors.

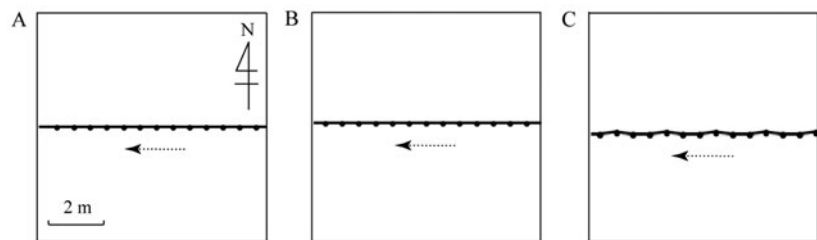


Fig. 5. *Caretta caretta*. Enlarged sections of the overhead views of a loggerhead turtle’s paths obtained by the simulations. In these sections, a turtle was assumed to swim westward with strokes. The paths were calculated (Simulation A) with magnetism and gravity-based acceleration without filtering, (Simulation B) with filtered magnetism and filtered gravity-based acceleration, and (Simulation C) with magnetism without filtering and filtered gravity-based acceleration (see ‘Results and Discussion’ for details). Dashed arrows indicate the simulated direction of travel. Scale size and azimuth direction of graphics are uniform among 3 paths

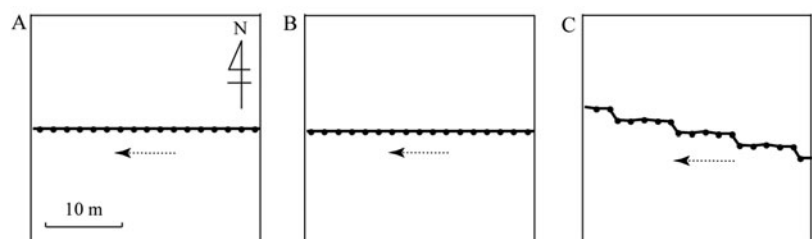


Fig. 6. *Aptenodytes forsteri*. Enlarged sections of the overhead views of an emperor penguin’s paths obtained by the simulations. Other details as in Fig. 5

It should also be noted that differences in the swimming speeds among species would lead to differences in the amplitude of errors in positional data. The mean (\pm SD) swim speeds of turtles and penguins in the present study were 0.6 ± 0.08 and 1.8 ± 0.09 m s⁻¹, respectively. This would cause ~3-fold larger errors in the estimates positions at each interval in the paths of penguins, even if the amplitudes of the heading errors were the same.

The reconstruction of 3D dive paths undoubtedly provides useful information for examining the behavioural, ecological, and physiological significance of underwater activities such as foraging (e.g. Mitani et al. 2004) and orientation (e.g. Davis et al. 2001, Narazaki et al. 2009). User-friendly programs for IGOR and Matlab (MathWorks) provided at http://bre.soc.i.kyoto-u.ac.jp/bls/index.php?3D_path enable one to easily apply the method used in the present study to various diving animals. Unfortunately, however, the 3D dive paths estimated with multiple parameters are susceptible to errors arising during data processing. We presented examples using 2 species that swim differently in terms of stroke frequencies, turning ability, and speed. At a glance, the characteristics of the errors in the heading data during strokes seemed species-specific, but a unified explanation for both phenomena arose by considering the relationship between the sampling frequencies and the frequencies of animal movements. The error patterns in the paths seemed to depend mainly on the frequency and amplitude of body posture change and on swim speeds. In order to avoid misinterpretation of estimated dive paths, it is necessary to understand the behavioural characteristics of study animals as well as the assumptions and inherent problems of the method being used.

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