A METHOD FOR CALIBRATING SWIM-SPEED RECORDERS

During the last decade time-depth recorders (TDRs) have been deployed on a majority of pinniped species as a means of studying their diving behavior and foraging ecology (see Boyd and Croxall 1996 for a list of TDR studies). In most of these studies, only the subject's diving depth versus time is recorded, providing a one-dimensional view of movements made in three dimensions. Measurement of swimming speed (Le Boeuf et al. 1992; Castellini et al. 1992; Ponganis et al. 1990, 1993; Boyd et al. 1995) adds a second dimension to dive analysis, as it enables the calculation of horizontal distance covered, helps to interpret individual dive function (i.e., Crocker et al. 1997), and facilitates the study of swimming effort and O$_2$ consumption (Feldkamp 1987). A problem associated with measuring swim speed is calibrating the instrument. Instrument calibration can be affected by variables such as the location and angle of attachment on the animal, the condition of the turbine or paddle-wheel and the subject's size. Consequently, instruments calibrated in the laboratory and then deployed on free-ranging animals often yield unreasonable data, i.e., swim speeds that are lower than the animal's ascent or descent rate (as determined by a pressure transducer). For example, Le Boeuf et al. (1992) measured swim speed in an adult northern elephant seal female using a precalibrated paddle-wheel recorder. In 50% of the dives, the swim speed of the animal could not account for the observed changes in depth. Similarly, Boyd et al. (1995) had to apply an empirical correction factor to swimming speeds collected by a commercially available recorder to match them with swimming speeds of Antarctic fur seals (Arctocephalus gazella) determined in a pool and by attaching the instrument to a dead animal and towing it behind a boat.

Our aim in the present paper is to: (1) present the theoretical framework for a calibration method for flow-driven swim-speed recorders, and (2) render this method easily useable with large TDR data sets by developing an automatic computerized calibration program for general use. The method involves comparing revolutions per minute (rpm) from the turbine of a swim-speed TDR with changes in depth measured by the instrument's calibrated pressure transducer. The subject collects the data for calibrating the instrument it bears, minimizing errors having to do with variation in animal size, shape (i.e., interindividual and interspecific differences) and instrument position.

We used a total of 46 diving records from two species of pinnipeds:

(1) Northern elephant seals, *Mirounga angustirostris*, from Ano Nuevo, California (*n* = 33): three adult males (8-13 yr old), three adult females (3-8 yr old), and 27 juveniles of both sexes (0.8-2.4 yr old), spanning a ten-fold range in size (115 kg to more than 1,200 kg). The animals were all instrumented with custom-made swim-speed TDRs as part of other studies (e.g., Fletcher et al. 1996, Crocker et al. 1997). The swim-speed TDRs (6.5 × 3 × 15 cm,
450 g in air, 100 g in sea water) incorporated a Tattletale Lite datalogger (model L-512psf, Onset Computer Corp., Pocasset, Massachusetts) with either 512 KB or 1 MB of RAM. Diving depth was measured with a Keller pressure transducer (model PA-7–100, KPSI, Oceanside, California) calibrated between 0 and 1,000 m before deployment. The resolution of the depth recording was 0.6 m. Swim speed was obtained by counting and storing in memory the revolutions of a Logtron turbine (Logtron Nautical Instruments, München, Germany). Depth and swim speed were sampled concurrently every 5, 10, or 20 sec.

(2) Hooker sea lions, Phocarctos hookeri, from Enderby Island, New Zealand (n = 13). These animals were all lactating adult females, ranging in size from 83 to 145 kg. They were each instrumented with a Mk6 TDR (Wildlife Computers, Redmond, Washington) as part of other studies. The Mk6 TDR incorporated the same Logtron turbine as the custom-made instruments used on elephant seals. The TDR’s pressure transducer had a resolution of 1 m. Depth and swim speed were sampled concurrently every 5 sec; swim-speed data produced by the Mk6 (in m/sec) was converted into rpm for the calibration, by multiplying it by 600 (according to the manufacturer’s calibration: 600 rpm = 1 m/sec). In both species, the instrument was positioned between the shoulders on the dorsal midline of the animal and was attached to the fur with marine epoxy (Evercoat Ten-Set, Fibre Glass-Evercoat Co., Cincinnati, Ohio; see Le Boeuf et al. 1988).

The calibration program was executed on a Unix workstation. All non-custom software used was obtained via the Internet and included Generic Mapping Tool (Wessel and Smith 1991, 1995a, b), as well as Ghostview and Ghostscript (Free Software Foundation, Cambridge, Massachusetts). Regardless of the original sampling interval, we used depth and rpm data every 20 sec to produce a three-dimensional plot (Fig. 1A) for each diving record. This plot showed (on the x, y, and z axes, respectively): (1) the speed at which the seal was moving vertically through the water column, calculated from the change in depth (m/sec); (2) the rpm of the turbine for the corresponding change in depth; and (3) the frequency of sample intervals, normalized to ensure independence from record length, i.e., the number of data points. Samples in which the rate of depth change was less than the stall speed of the turbine were omitted, as well as samples with an rpm value below 20, which were often collected during periods when the turbine was immobilized, presumably by debris. For any given rate of depth change, the angle of the dive is negatively correlated with rpm values. High rpm values are associated with a more horizontal dive path, low values with a more vertical dive path. From this it follows that the lowest rpm value for any given rate of depth change will be closest to representing vertical ascent or descent, which is when the rate of depth change and true swimming speed are equivalent, and thus, a line along the bottom edge of the raw data plot in Figure 1A represents the swim-speed calibration line.

The rest of the program was designed to extract the calibration line automatically following a low-pass filtration of the data. This filtration was nec-
Figure 1. Swim-speed data from record of 22-mo juvenile northern elephant seal male, displayed in three dimensions. (A) Raw data (B) Gaussian filtered data. Points at base of hill plot (filled circles) used to calculate calibration line (see text).

It is necessary to get a smooth contour (i.e., Fig. 1B) to which a line could be automatically fitted by the software. In addition it reduced the influence of noise, i.e., outlying points that resulted from instances when debris hindered normal function of the rotor. Gaussian filters are particularly well suited for this type of application (Russ 1995). Such a filter was applied to the raw data by replacing each rectangular column in Figure 1A with a discrete Gaussian bump (a three-dimensional normal distribution) of the same volume but having a
Figure 2. Gaussian filtering of column xyz of volume \( v \) (A) produces Gaussian bump of the same volume but with base diameter equal to \( 5x \) (B). Notice that \( z \) scale in (B) is tenth of that in (A).

diameter of five times the \( x \) width of the column (Fig. 2). The calculations associated with this Gaussian filtering are presented in Appendix 1. The sums of the overlapping Gaussian bumps generated the filtered version of the data, which resembles a three-dimensional hill-like surface (Fig. 1B).

The last step involved fitting the calibration line on the bottom edge of the “hill plot.” It was nearly always obvious to a human observer where to place the calibration line, but for the method to remain objective we wanted the program to calculate line location. Because the quantity of noise was extremely variable between records, the software used the following progres-
sion of iterative steps to find the line: (1) A contour was drawn on the hill plot at the "height" \( z = 1.0 \). Because the \( z \)-axis was normalized to ensure independence from the number of data points, this value was arbitrary. It was chosen because it remained above the filtered outlying points (presumably noise), regardless of the record length. On this contour (\( z = 1.0 \)), the \( y \) value was extracted for every rate of depth change (\( x \) value), starting at the stall speed of the instrument (determined experimentally) and ending at the upper limit. The latter was defined as the highest rate of depth change with a frequency \( \geq 4 \), ensuring that only \( x \) values with sufficient data were included in the calibration. (2) A linear regression was computed through the points and its correlation coefficient was calculated. (3) Since the aim was to place the calibration line as close as possible to the base of the hill plot, steps (1) and (2) were repeated for decreasing values of \( z \), from 0.9 to 0.1. Since the turbine's calibration line is affine (according to the manufacturer) in the range of speeds dealt with in this study (i.e., approximately 0.3 to 4 m/sec), the line with the highest \( r \)-value was kept as the final calibration line. Values of \( z \) below 0.1 were not used, to avoid determining the calibration line with artifacts of the Gaussian filtering. The black dots in Figure 1B are the points used for the final calibration in this record, at \( z = 0.6 \). Figure 3 shows the hill plot of a juvenile northern elephant seal with contours drawn at \( z = 1.0 \), 0.6, and 0.1 and the resulting calibration lines. Note that at \( z = 0.1 \) noise gets included in the contour and the calibration line degenerates.

To ensure that the calibration was based on a sufficient number of samples, the whole procedure was repeated on a subset of each record. This subset consisted of every other sample interval from the original file and was therefore half the size of the original file. Mean swim speed was computed for each record with the two calibrations. Sample size was deemed insufficient if either the mean swim speed or the slope of the calibration line differed by more than 6%.

The methodology was applicable to both species and all age groups. Two-dimensional examples of the filtered data with the resulting calibration lines are shown in Fig. 4 for two Hooker sea lions (Figure 4A and 4B) and two northern elephant seals (Fig. 4C, D, E, F). A reasonable calibration line was produced even for extremely noisy records (i.e., 4E and 4F). The correlation coefficients obtained for the regressions were consistently high, \( \bar{x} = 0.988 \pm 0.012 \) (mean \( \pm \) SD) for all northern elephant seals combined and \( \bar{x} = 0.994 \pm 0.005 \) for all Hooker sea lions combined. There was wide variation in the regression slopes, as indicated by a CV of 28.9 for all northern elephant seals combined and 15.9 for all Hooker sea lions combined. In elephant seals, this value was similar when animals of approximately the same size were considered (i.e., for all juveniles, CV = 27.8), and somewhat lower when animals of the same size and carrying the same instrument were taken into account (CV = 19.9 on average for three instruments each deployed respectively six, six, and five times on juveniles). This variation is illustrated by calibration lines obtained from two different instruments deployed on nine northern elephant seals belonging to all age groups (Fig. 5).
According to the manufacturer, the calibration line of the turbine is affine ($y = mx + b$) or linear ($y = mx$) within the range of speeds commonly used by elephant seals, *i.e.*, 0.3–3 m/sec (Le Boeuf et al. 1992). At speeds below 0.3 or 0.4 m/sec, rpm decrease steeply with speed and linearity is not observed. This makes a comparison of intercept values meaningless. Therefore, we calculated the CV of the $y$ values at $x = 1.0$ m/sec, which was 31.0 for all northern elephant seals combined and 9.6 for all Hooker sea lions combined.

Samples sizes, ranging from 918 to 285,160 ($\bar{x} = 33,846 \pm 64,425$) for elephant seals and from 3,048 to 12,052 ($\bar{x} = 9,970 \pm 2,879$) in Hooker sea lions, were sufficient in 42 of 46 records. Running the calibration on half data sets for these records did not result in significant changes in mean swim speed or in calibration line slope. Mean swim speeds differed by only $2.2\% \pm 1.8\%$ (or $0.03 \pm 0.02$ m/sec) in elephant seals and $1.1\% \pm 1.2\%$ (or $0.02 \pm 0.03$ m/sec) in Hooker sea lions. Calibration line slopes differed by $2.5\% \pm 2.4\%$ in elephant seals and $2.4\% \pm 2.5\%$ in Hooker sea lions. As expected, the records with the highest sample size had the least variation. Four out of the five elephant seal records with sample sizes above 50,000 showed less than 1% variation in mean swim speed and less than 1.5% difference in calibration
Figure 4. Two-dimensional views of calibration lines obtained from two adult female Hooker sea lions (A & B) and a juvenile female (C & D) and adult male (E & F) northern elephant seal. Scale same as in Figure 1. Z value leading to highest coefficient of correlation (see text) indicated in upper left corner for each animal. Plots A, B, C, and E show Gaussian filtered data. Plots D and F demonstrate how final calibration line positioned in relation to raw data. Record shown in plots E and F was noisiest of all records analyzed. Ad. = adult, F = female, HSL = Hooker sea lion, Juv. = juvenile, M = male, NES = northern elephant seal.

Increasing the sample size had no effect on the regression r-value (Pearson’s product moment, \( r = -0.16 \), \( P > 0.05 \) for northern elephant seals, \( r = 0.64 \), \( P > 0.05 \) for Hooker sea lions). Three elephant seal records (sample sizes = 100, 583, and 1,476) and one Hooker sea lion record (sample size = 1,016) were excluded from the analysis because of insufficient sample size. In these animals the mean record swim speeds, calculated using calibration lines
from entire records versus a subset of the records, differed by 7%–31% ($\bar{x} = 21 \pm 11\%$) and calibration line slopes differed by 1%–125% ($\bar{x} = 45 \pm 57\%$).

For each animal, the program selected the regression with the highest coefficient of correlation as the final calibration line. For comparison with the line a human observer would pick by inspection, we plotted the calibration lines for each animal and each value of $z$ ($0.1 \leq z \leq 1.0$) onto the raw (unfiltered) data plot (as shown in Fig. 4D, F). One of us, with no knowledge
of the $r$-values, picked the most reasonable line produced by the computer, which we then compared to the software's choice. The $z$ values differed on average by only 0.02 in northern elephant seals and 0.08 in Hooker sea lions, resulting in a difference in mean swim speed of 0.02 m/sec in elephant seals and 0.08 m/sec in Hooker sea lions.

The high coefficients of variation of the slopes and intercepts indicate that calibration lines differ substantially between deployments. We calculated the mean record swim speed for each animal carrying instruments 497 and 495 (Fig. 5A, B) and compared those values to the mean swim speeds obtained using an average calibration line for each instrument, respectively. The mean difference in swim speed was substantial, 21.8% ± 11.0% for 497 ($n = 5$) and 42.5% ± 57.1% for 495 ($n = 4$). When we restricted the analysis to animals of the same age group (juveniles), the mean difference in swim speed was 23.0% ± 12.4% for 497 ($n = 4$), and 1.1% ± 0.1% for 495 ($n = 2$). Such a comparison was not possible with the Hooker sea lion data as all the females carried a different instrument, so we calculated the difference in swim speed resulting from the use of the turbine manufacturer's calibration line ($y = 600x$) instead of the one obtained with the calibration program. The mean difference was 13.2% ± 8.1% (range = 0.5%–24.5%, $n = 12$). These values emphasize the importance of selecting the correct calibration line.

Several factors combined could explain the larger variation in both slope and intercept in the elephant seal data. The custom-made and commercial instruments used in the study both had the same turbine, but their shape was different. The custom-made instruments were larger, had a frontal flat area below the water entrance to the turbine, were slightly variable in shape and were attached to the animals in several different ways. In addition, the elephant seals had a much wider range of sizes than the Hooker sea lions. Our calibration method has the advantage of decreasing errors due to these variations in instrument size, shape, and position on the animal, as well as the subject's size, which determines the thickness of the boundary layer. It takes into account the aging of the rotor (i.e., loss of smoothness in rotation), which could result in the calibration line changing with the age of the instrument. Since it is not possible for a subject to swim slower than its rate of ascent or descent, the method cannot overestimate swimming speed. At worst, it will provide a conservative measurement.

Our calibration method has limitations that could affect the accuracy of the swim-speed measurements. These limitations must be taken into account. The method assumes that the diving animal ascends or descends vertically in the water column at least part of the time. Calibration is possible even if this event is unusual, but its accuracy will increase with the frequency of vertical or near vertical swimming. For example, the steepest angle of ascent or descent for entire dive segments of an adult northern elephant seal female measured by Le Boeuf et al. (1992) was 82°, which would underestimate true swimming speed by less than 1%. A conservative steepest angle of ascent or descent of 55° would lead to a 22% underestimate. Maximum angles of ascent and descent have yet to be determined for most species, but are probably steepest in
deep-diving animals. Interindividual differences in the tendency to swim vertically may be responsible for variation in calibration line slopes. For example, a seal might never exceed a diving angle of 60° when ascending or descending at 1 m/sec. However, in order to obtain a calibration line with an $r$-value close to 1.0 (as seen in both northern elephant seals and Hooker sea lions), the individual in question would never have to exceed this maximum diving angle, regardless of its swimming speed, diving depth, or activity. This seems unlikely, particularly in a foraging animal pursuing prey. Among vertical or near vertical diving events, the ones at high speed are the most unusual. Therefore the calibration line will principally be computed from the lower end of the animal’s swim-speed range and one must assume that the equation is accurate beyond the range of data used to calibrate it. The mean swim speed for the Hooker sea lion female in Figure 4A, for example, is 2.35 m/sec, yet the calibration line is only calculated using vertical speeds up to 2.45 m/sec. Finally, there are circumstances in which an independent calibration will be necessary to avoid circularity, for example, when using speed and depth measurements to examine diving angles.

Because this calibration method relies on depth measurements, the effects of pressure transducer resolution and drift on swim-speed calibration must be considered. The x-axis data are binned into columns of width 0.05 m/sec (visible in Fig. 4D, F), corresponding to a pressure transducer resolution of 1 m ($0.05 \times 20$). Therefore, transducer system resolutions better than 1 m will have little effect on swim-speed calibration. As the instrument’s depth resolution decreases, the x-axis bins will separate from each other, but the Gaussian filtering mitigates this effect up to resolutions of 2.5–3 m. We tested this on the juvenile record shown in Figure 4C, by rounding the depths values to multiples (or a resolution) of 1.2, 1.8, 2.4, and 3.0 m. The calibration line slope and mean record swim speed, respectively, differed from the original values by 0.5% and 0.3% for 1.2 m, 1.0% and 0.7% for 1.8 m, 0.4% and 0.3% for 2.4 m, and 12.5% and 8.1% for 3.0 m. Finally, the effect of temperature-induced drift of the pressure transducer on the swim-speed calibration is probably small, because it is constrained by the amount of change that can take place during one sampling interval of 20 sec. The custom-made instruments had a mean drift of 0.05 m/°C, and a maximum of 0.2 m/°C. Over one sampling interval and with a change in temperature of 2°C, the mean error in the depth measurement was 0.1 m (or 1.4% at speeds of 0.35 m/sec, 0.25% at 2 m/sec), which is significantly less than the resolution of the pressure transducer. Since this error varies as a function of the type of pressure transducer, it is important to calculate it for the model of recorder used.

In summary, the method we have described constitutes a fast and conceptually simple way of calibrating swim-speed recorders that reduces errors due to variation in subject size or position of the instrument on the animal. It has been tested in both phocids and otariids, which have very different swimming modes. When used prudently, this method should facilitate the acquisition of new information on foraging behavior, diving energetics, and the development
of diving, and aid in understanding the increasingly detailed picture of the three-dimensional movements of a number of aquatic vertebrates.

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Literature Cited

**Gaussian Filtering**

Due to the hardware and data compression techniques used in the instruments, we measured the rate of depth change and turbine revolutions to a resolution of 0.05 m/sec and 6 rpm, respectively. Our frequency data is therefore gridded with the above resolutions. A discrete version of the Gaussian bump was calculated as a $5 \times 17$ matrix kernel $M$ (see below). The dimensions $5 \times 17$ give the matrix a width in $x$ of $5 \times 0.05 = 0.25$ m/sec, and a width in $y$ of $17 \times 6 = 102$ rpm. These dimensions were chosen because they make the matrix kernel square in our coordinate system. Next, the 2-dimensional discrete convolution $R$ of the frequency data $F$ with the matrix $M$ was calculated:

$$R_{ij} = \sum_{a=-8}^{8} \sum_{b=-2}^{2} M_{a+9,b+3} F_{i+a,j+b},$$

where $i, j$ vary over the whole data set. Figure 2 shows such a convolution applied to a single column of frequency $z = 1$. The matrix kernel $M$ is given below. Because the matrix is symmetric, only the top left portion is shown. The sum of all components of the matrix is equal to 1 and $i, j$ are the indices of $M$.

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