CORRECTING FOR VISIBILITY BIAS IN STRIP TRANSECT AERIAL SURVEYS OF AQUATIC FAUNA

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Abstract: We develop methodology for correcting for visibility bias by calculating and applying survey-specific correction factors in strip transect aerial surveys of aquatic fauna and incorporating their associated errors into the population estimate. The technique is applicable at all densities of the target species. Perception bias (the proportion of groups of the target species that are visible in the transect yet missed by observers) is corrected for using a modified Petersen estimate calculated for each of 2 teams of 2 observers with 1 team on either side of the aircraft. Within a team, each observer reports their uncolluded observations into a separate track of a 2-track tape recorder, so that after the survey, each group can be characterized as being seen by only 1 (specified) or both members of the team. A correction factor is also suggested to standardize for the proportion of animals that are unavailable to observers because of water turbidity.

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Aerial surveys have been used to estimate population sizes of wildlife since the late 1940's (Caughley 1979). The technique has been plagued by visibility bias resulting from animals being missed by observers. Caughley (1977:35) presents data from a range of wildlife surveys illustrating that 50–60% of animals are often missed. There are 2 categories of missed animals: those that are potentially visible to observers but are not seen (perception bias), and those that are not available to observers because they are concealed by other animals, vegetation, or turbid water (availability bias).

Caughley (1979) argued that aerial survey estimates are most useful as indices tracking relative density over time, because the bias becomes irrelevant as long as it is held constant by rigid standardization of transect width, the height and speed of the aircraft, and the repeated use of the same survey crew. It is, however, impossible to standardize many other factors that influence visibility bias. Factors such as variable vegetation density, water turbidity, time of day, weather conditions, group size, behavior, and distribution of the target species have major effects on the number of animals sighted in aerial surveys (Bayliss and Giles 1985, Hill et al. 1985, Packard et al. 1985). As such factors have repeatedly been shown to vary even between repeat surveys of the same area, we believe that it is important to develop survey-specific correction factors to correct for perception and availability biases if absolute population estimates are required, or at least to standardize for these biases if trends in numbers are being monitored.

The Petersen mark-recapture model has been used by Henny et al. (1977), Magnusson et al. (1978), Grier et al. (1981), Caughley and Grice (1982), Bayliss (1986), and Eberhardt and Simmons (1987) to develop a correction factor for visibility bias (sensu perception bias as defined above). In the technique used by Caughley and Grice (1982) and Bayliss (1986), the target species was counted independently by 2 observers seated behind each other on the same side of the aircraft, simultaneously scanning the same strip transect. The first observer saw (marked) a group that then might or might not be seen by the second observer. Hence, the second observer saw groups of animals in 2 categories: those that were "marked" and which he "recaptured" and those that were "unmarked." As detailed in Caughley and Grice (1982), these data were then used in equations derived from the Petersen estimate to estimate the probability of a group being seen (counted) by each observer. These estimates formed the basis of a correction factor that was used to multiply the observed density of groups of the target species and provide an estimate of true group density. Caughley and Grice (1982) suggested that this correction factor could then be applied to counts obtained in subsequent surveys of the same target species on the assumption that the bias did not vary between surveys. This assumption is unwarranted as discussed above.

There are 2 additional problems with the techniques described by Caughley and Grice (1982) (Pollock and Kendall 1987). It assumes that all animals are equally catchable and that there is no difficulty in deciding which animals were seen by both observers. The first assumption is clearly violated. Animals that are unavailable to observers have a zero probability of being caught. Bayliss (1986) dealt with this by limiting counts to groups of dugongs (*Dugong dugon*) on the water surface and assuming that all of these were equally available. Bayliss (1986) used a theoretical correction for submerged dugongs to yield a total population estimate. If the only animals seen on a transect are under the water and therefore not scored, this technique can lead to serious biases in relative and absolute population estimates, and in density distribution maps. This problem is compounded by other sources of sighting heterogeneity such as group size and glare off the surface of the sea.

A more reasonable assumption would be that all available animals are equally catchable. There may be problems with this assumption, however, as the search images of tandem observers are not independent. Because marking and recapturing occur at the same instant, the search image transmitted to both observers would be expected to be nearly identical. If this is so, their specific probabilities of detection, group by group, will have a correlation approaching unity which negatively biases the population estimate (Seber 1982).

The problem of the difficulty in deciding which animals were seen by both observers (especially if the population is dense) means that the technique of Caughley and Grice (1982) and Bayliss (1986) is applicable only at very low densities of the target species. These authors divided each transect into 5-km units, separated by a 7-second pause during which the counts for the last unit were recorded. If both observers recorded a group of animals in the same time slot, it was assumed to be the same group; this procedure is also likely to negatively bias the population estimate.

We develop procedures for using this tandem observer technique to develop survey-specific correction factors for perception bias, even in areas of high animal density. Procedures are also outlined to standardize for availability bias in aerial surveys of large, aquatic animals such as dugongs, and to incorporate the errors in the correction factors into the standard error of the final population estimate.

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SURVEY PROCEDURE

Our procedures were developed for large scale surveys of dugongs in northern Australia. We flew a twin-engine Partenavia 68B at 137 m at 185 km/hour along predetermined transects. The pilot, a front-right survey leader, 2 mid-seat observers, and 2 rear-seat observers comprised the survey team. The middle and rear-seat observers on the same side of the aircraft formed a tandem team searching the same (200-m-wide) strip transect defined by transect markers attached to (artificial) wing struts.

Data were recorded by the survey leader using an Epson HX20 portable computer (Epson, Japan) programmed as a data logger and timer, and equipped with a printer that produced an immediate hard copy of the data. The rear-seat observers reported their sightings to the survey leader via a 2-way intercom system connected to 1 track of a 2-track tape recorder. The mid-seat observers were visually screened from the rear-seat observers with a curtain and acoustically isolated from the other crew (apart from each other). They reported their sightings into the second track of the tape recorder. The arrangement and duties of the crew are summarized in Figure 1.

All reports from observers were in standardized format; e.g., dugongs: group size, number of calves, number at the surface, position of sighting in the transect. The top (furthest from aircraft), middle, and bottom thirds of the transect were color marked on the artificial wing strut. The position of the sighting along the transect was recorded to increase the probability of distinguishing between different sightings reported simultaneously by both members of a tandem team.

Surveys were carried out only in fine conditions and in calm seas (≤Beaufort 3). The surveys were timed to minimize glare off the surface of the water associated with a low or midday sun.

After the survey, the tape record of each transect was used to check and edit the computer records, so that each sighting could be coded as being made by 1 (specified) member or both

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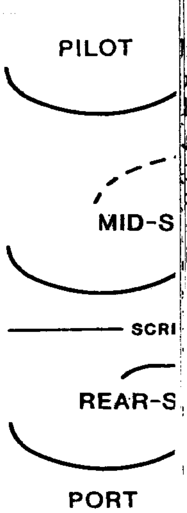

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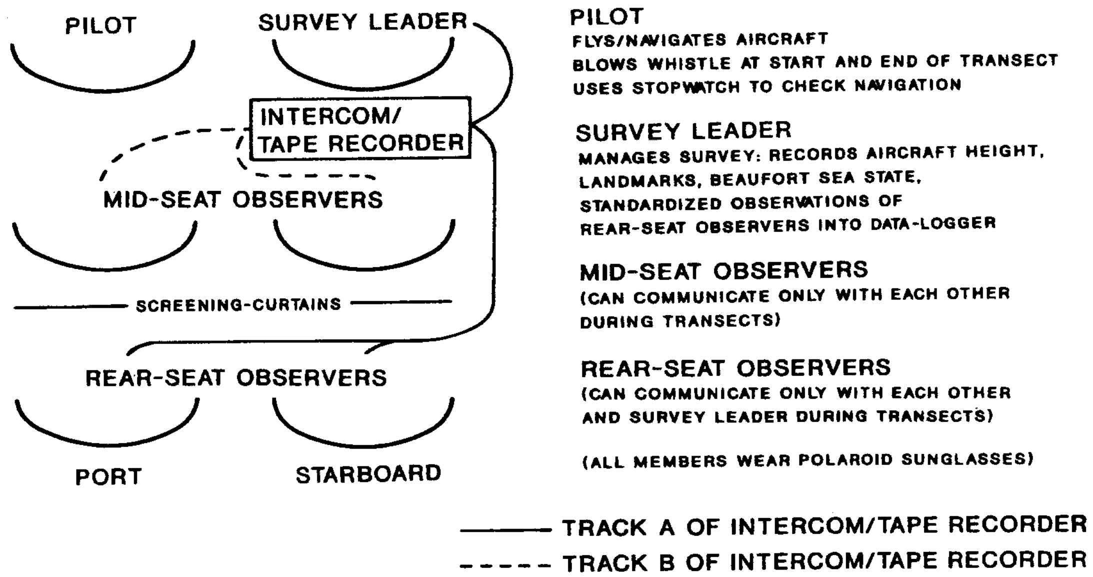

Fig. 1. Diagrammatic representation of the arrangement and duties of the crew used to aerial survey dugongs in Australia.

members of a tandem observing team. The reports of team members were deemed to be different if they were unambiguously distinct (usual situation) or if they were separated by ≥5 seconds. Discrepancies between dual sightings of the same group were also noted.

CORRECTING FOR PERCEPTION BIAS

Let S_m = number of groups seen by the mid-seat observer only,
S_r = number of groups seen by the rear-seat observer only, and
b = number of groups seen by both observers.

This fits into the framework of the Petersen mark-recapture model, in which the $(S_m + b)$ groups seen by the mid-seat observer are "marked," and b of these groups are "recaptured" by the rear-seat observers. The Petersen estimate (Seber 1982) for the total number (N) of groups available to the observers is:

$$\hat{N} = \frac{(S_m + b)(S_r + b)}{b}. \qquad (1)$$

For given observed numbers $(S_m + b)$ and $(S_r + b)$, b has a hypergeometric distribution (Seber 1982) and the estimated variance (var) of $\hat{N}$ is

$$\text{var}(\hat{N}) = \frac{S_m S_r (S_m + b)(S_r + b)}{b^3}. \qquad (2)$$

Chapman (1951) showed that $\hat{N}$ is biased and proposed a modified estimate,

$$\hat{N} = \frac{(S_m + b + 1)(S_r + b + 1)}{b + 1} - 1, \qquad (2)$$

which is unbiased for $(S_m + S_r + 2b) > N$. Seber (1982) estimated the var of this modified $\hat{N}$ as:

$$\frac{S_m S_r (S_m + b + 1)(S_r + b + 1)}{(b + 1)^2 (b + 2)}.$$

This var estimate is also unbiased for $(S_m + S_r + 2b) > N$. The results of all of our dugong surveys (Table 1) satisfy this condition, and the modified $\hat{N}$ has optimal statistical properties as an estimator of the total number of groups available to the observers. Although slightly biased, the estimates of $\hat{N}$ and var($\hat{N}$) in equations (1) and (2) are adequate for our purposes.

The important point to recognize is that $\hat{N}$ is an estimate of the number of groups of animals available to the observers, and not necessarily of the total number of groups in the population. Provided that it is clear which groups are seen by both observers, the main assumption being made is that all available groups of animals are equally catchable.

Our survey results suggest that this assumption is not unrealistic for dugongs. In an experimental evaluation of aerial survey techniques during which 341 groups were sighted, Marsh and Sinclair (1989, table 3) used log-linear models

Table 1. The groups sighted and the perception and availability correction factors developed for various aerial surveys for dugongs in northern Australia. Except where indicated, all counts were made from a survey height of 137 m. The coefficient of variation of the perception correlation factor (eq. 3), is C_p, C_a is the coefficient of variation of the availability correction factor (eq. 4), and C_g is the ratio of the standard error to the mean of the group size.

			No. groups of dugongs counted						
Survey date	Blocks	Side of aircraft	Mid-seat only (S_m)	Rear-seat only (S_r)	Both (b)	$\hat{N}$	Correcton for perception bias (C_p)	Correction for availability bias (C_a)	$\bar{x}$ group size (C_g)
Far Northern Section and northern part of the Cairns Section of the Great Barrier Reef Marine Park									
Apr 1985		S[a]	10	7	12	34.83	1.20 (0.069)	1.95 (0.19)	1.57 (0.07)
Nov 1985	Area 1	P	36	18	58	123.17	1.10 (0.019)	2.62 (0.12)	1.47 (0.04)
		S[b]	16	18	30	73.60	1.15 (0.035)		
	Area 2	P	5	3	12	21.25	1.06 (0.028)	1.44 (0.23)	1.53 (0.09)
		S	2	3	15	20.40	1.02 (0.009)		
Northern half of the Central Section of the Great Barrier Reef Marine Park									
Sep 1986		P	8	6	11	29.36	1.17 (0.065)	3.00 (0.17)	1.29 (0.10)
		S	5	2	7	15.43	1.10 (0.057)		
Mackay/Capricorn Section of the Great Barrier Reef Marine Park									
Nov 1986		P	5	8	16	31.50	1.09 (0.032)	3.08 (0.15)	1.35 (0.13)
		S	5	5	18	29.39	1.05 (0.018)		
Torres Strait									
Nov 1987		P	12	23	65	104.25	1.04 (0.009)	2.72 (0.12)	1.39 (0.05)
		S[b]	18	19	46	90.43	1.09 (0.019)		
Moreton Bay (southeast Queensland)									
Jun 1985		P	17	19	50	92.46	1.08 (0.016)	1.06[c] (0.14)	2.08[c] (0.14)
		S[b]	10	8	28	48.86	1.06 (0.018)		

[a] S = starboard and P = port.

[b] Starboard team not available for entire survey.

[c] Includes counts made from a flying height of 274 m.

to show that the chance of an observer missing a group of >5 dugongs was not significantly different ($P \geq 0.43$) from the chance of missing a smaller group. Three of 4 observers missed a group of ≥10 dugongs (1 occasion each).

The number of groups observed by the tandem team is $(S_m + S_r + b)$. It is convenient to write $\hat{N}$ as:

$$\hat{N} = (S_m + S_r + b)\cdot\frac{(S_m + b)(S_r + b)}{b(S_m + S_r + b)},$$

and regard $\frac{(S_m + b)(S_r + b)}{b(S_m + S_r + b)}$ as the perception correction factor, to be applied to the number of groups observed to estimate the true number of groups available to the observers.

Using the delta method (Seber 1982), the approximate var of the perception correction factor can be shown to be:

$$\frac{S_m S_r (S_m + b)(S_r + b)(S_m + S_r)^2}{b^3 (S_m + S_r + b)^4}.$$

Thus, the approximate coefficient of variation of the perception factor (C_p) is:

$$C_p = \frac{S_m + S_r}{S_m + S_r + b} \cdot \sqrt{\frac{S_m S_r}{b(S_m + b)(S_r + b)}}. \tag{3}$$

Perception correction factors for the port and/or starboard teams on various dugong surveys range from 1.02 to 1.20 (Table 1). The perception correction factors obtained for Moreton Bay (Table 1) were compared empirically with those that would have been obtained using the recording technique of Caughley and Grice (1982) and Bayliss (1986) by dividing each transect a posteriori into a series of 97-second sampling units, each unit representing an area of 2 km² at a survey altitude of 137 m. If each member of a tandem pair recorded a group of dugongs in the same unit, it was assumed to be the same group regardless of the timing of the observations. Use of sampling units rather than the 2-track tape recorder resulted in underestimation of the correction factors for the observation teams by 2.9 and 4.5%. Use of the 2-track tape recorder clearly reduces errors in deciding which groups have been sighted by both observers.

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CORRECTING FOR AVAILABILITY BIAS

The major source of availability bias in aquatic surveys is water turbidity. Conditions can range from extremely turbid so that only animals on the surface are visible to very clear when all animals are potentially visible.

Let $\hat{p}_s$ be the proportion of observed animals at the surface in an aerial survey over clear water and $\hat{p}_u$ the proportion seen at the surface in a second survey over more turbid water. Then assuming that the porportion observed at the surface is independent of the observer (as suggested by our data [Marsh and Sinclair 1989]), and that $\hat{p}_s$ is a valid estimate of the proportion of animals at the surface for all habitats and under all survey conditions, $\hat{p}_u/\hat{p}_s$ would be an index of the availability bias at the time of the second survey that could be used as the availability correction factor.

Using the delta method, the approximate var of $\hat{p}_u/\hat{p}_s$ is given by:

$$\operatorname{var}\frac{\hat{p}_u}{\hat{p}_s} = \frac{1}{\hat{p}_s^2}\cdot\frac{\hat{p}_u(1-\hat{p}_u)}{N_u} + \frac{\hat{p}_u^2}{\hat{p}_s^4}\cdot\frac{\hat{p}_s(1-\hat{p}_s)}{N_s},$$

where N_u and N_s are the sample sizes on which $\hat{p}_u$ and $\hat{p}_s$ are based. The approximate coefficient of variation of the availability correction factor is:

$$C_a = \sqrt{\frac{1-\hat{p}_u}{\hat{p}_u N_u} + \frac{1-\hat{p}_s}{\hat{p}_s N_s}}. \qquad (4)$$

In view of its untested reliability, this correction for availability bias is best considered as a means of standardizing fluctuating availability bias for repeat surveys of the same area under conditions of varying water turbidity.

Most of the dugongs sighted in Marsh and Sinclair's (1989) experimental evaluation of dugong aerial survey techniques in Moreton Bay were in extremely clear, shallow (<5 m) water over white sandbanks covered with sparse seagrass. All animals in this area were potentially available. By comparing the uncolluded observations of tandem observers, Marsh and Sinclair (1989) showed that observers had difficulty recording the position in the water column of dugongs in larger groups. There was, however, very good agreement between observers in their reports of how many dugongs in groups of ≤5 were at the surface. This proportion (80/480 or 16.7%) is not significantly different from that obtained independently from vertical color photographs of dugongs (68/486 or 14%) that have been taken under excellent conditions on the same sandbanks on other occasions.

We tentatively propose 80/480 as an unbiased estimate of the proportion of dugongs at the surface in Moreton Bay at the time of our aerial survey experiment. Further, assuming that this proportion is valid for all habitats and at all times, it can be used as the estimate for $\hat{p}_s$ for surveys of dugongs over shallow waters when the sea is calm. These conditions apply to most dedicated aerial sightings of dugongs in northern Australia.

Availability correction factors for the port and/or starboard team have been calculated for various dugong surveys using 80/480 as the estimate for $\hat{p}_s$. The estimates range from 1.06 to 3.08 (Table 1). These are used to standardize availability bias; population estimates obtained from repeat surveys of the same area under different weather conditions are within 10% of each other (Marsh and Saalfeld 1989). The proportion of dugongs on the surface used as the standard for these estimates of the availability correction factor (16.7%) is greater than the 1.9% obtained from shore-based observations in muddy water by Anderson and Birtles (1978). Hence, it is likely that the population estimates listed in Marsh and Saalfeld (1989) that are based on the correction factors for availability bias in Table 1 are conservative. A more accurate assessment will require more data on dugong diving and surfacing under different environmental conditions.

APPLICATION OF CORRECTION FACTORS

The following steps convert counts of groups of the target species obtained during strip transect aerial surveys to population estimates:

1. Classify each group as being observed by 1 (specified) member or both members of the appropriate tandem team.
2. Calculate the mean group size for the whole survey area at the time of the survey and the standard error of the group sizes.
3. Calculate the survey-specific perception correction factors (1 for each tandem team) and availability correction factor as detailed above.
4. Calculate for each transect the total number

of groups sighted by the members of the port and starboard tandem teams, respectively.

5. Obtain the corrected number of animals/transect as follows. Multiply each of the 2 values in step (4) by:
   - (i) the appropriate perception correction factor to obtain the Petersen estimate for the number of available groups,
   - (ii) the availability correction factor, and
   - (iii) the mean group size of the target species in the survey area;

   then sum the 2 corrected values for each transect.
6. Use the corrected number sighted for each transect and, if necessary, the ratio method (Cochran 1963, Jolly 1969, Norton-Griffiths 1978, Caughley and Grigg 1981), to estimate the population size and its associated sampling var. The ratio method allows for transects of different sizes and is applied as follows. Let T = total number of transects that could be fit into the census zone, t = number of transects sampled, A = area of census zone, a = area of any 1 transect, y = total corrected number of animals counted in that transect, $\hat{Y}$ = estimated size of the population in the census zone, $\hat{R}$ = the ratio of the corrected number of animals counted to the area searched = $\Sigma y / \Sigma a$, S_y^2 = variance between the corrected number of animals counted on all transects

   $$= \frac{1}{t-1} \cdot \left[\Sigma y^2 - \frac{(\Sigma y)^2}{t} \right],$$

   S_a^2 = variance between the areas of all the transects,

   $$= \frac{1}{t-1} \cdot \left[\Sigma a^2 - \frac{(\Sigma a)^2}{t} \right],$$

   S_{ay} = covariance between the corrected number of animals counted on a transect and the area of the transect,

   $$= \frac{1}{t-1} \cdot \left[\Sigma ay - \frac{(\Sigma a)(\Sigma y)}{t} \right],$$

   and S^2 = sampling variance of $\hat{Y}$.
   Then

   $$\hat{Y} = A \cdot \hat{R},$$

   and

   $$S^2 = \frac{T(T-t)}{t} \cdot (S_y^2 - 2\hat{R}S_{ay} + \hat{R}^2 S_a^2).$$
7. Calculate the total var of the density or population estimate by adding the errors from the estimates of mean group size and the correction factors to that due to sampling variability in step 6. Following Jolly and Watson (1979), this gives an approximate var of the total population estimate of:

   $$S^2 + \hat{Y}_p^2(C_g^2 + C_{pp}^2 + C_a^2) + \hat{Y}_s^2(C_g^2 + C_{sp}^2 + C_a^2) \qquad (5)$$

   where S^2 is the sampling var of the corrected population estimates in each transect in step 6; $\hat{Y}_p$ and $\hat{Y}_s$ are the contributions to the corrected population estimate made by the port and starboard observing teams respectively; C_g is the coefficient of variation (SE/$\bar{x}$) of the mean group size; C_{pp} and C_{sp} are the respective coefficients of variation of the perception correction factor for each transect for the port and starboard teams as given by equation (3); and C_a is the coefficient of variation of the availability correction factor, equation (4). The standard error of the population estimate and associated confidence intervals are then readily obtained.

Parallel calculations can be performed to estimate the population density, its standard error, and associated confidence intervals. As Jolly and Watson (1979) stated, implicit in equation (5) is the assumption that the correction factors are mutually independent and also independent of the survey observations. As the correction factors are based on the total counts for an entire survey, they would not be expected to be correlated with the observations from individual transects. Our data indicate that, at least for dugongs, the perception correction factor is not correlated with the availability correction factor ($r = 0.264$, 11 df; $P > 0.20$) or the mean group size ($r = 0.174$, 11 df; $P > 0.50$). However, the availability correction factor is correlated with mean group size ($r = 0.864$, 5 df; $P < 0.01$). It must be remembered that we are dealing with approximations; we are confident that equation (5) provides a more realistic approximation of the estimated variance of the population size than that obtained by ignoring errors in the estimated correction factors (i.e., simply S^2).

ASSESSMENT OF PROCEDURES

The system of using 2 teams of tandem observers, a 2-track tape recorder, and a microcomputer has advantages over previous methodologies. Survey-specific correction factors

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compensate for visibility biases that cannot be eliminated by a rigid standardization of procedures, such as fluctuations in the biases due to sea state, glare, cloud cover, and water turbidity. Survey-specific correction factors also reduce the need to use the same observers for each survey, especially as new observers can be readily trained using the 2-track tape recorder. This recorder also reduces errors in deciding which animals were seen by both members of a tandem team, even when the population is dense. All observations of the target species within the transect by both members of each tandem team are used in the final population estimate and in the calculation of the correction factors. This reduces the biases, especially when the population is sparse.

The system also has some disadvantages. This procedure requires a crew of 6 (Fig. 1). Provided that trained observers are available, this is not a disadvantage in marine surveys where 2-engine aircraft are required for safety reasons. However, it could result in a substantial increase in cost when a twin-engine aircraft is not mandatory. The system can be modified for a 4-seater aircraft with a tandem team on the right side of the aircraft only, along the lines suggested by Caughley and Grice (1982). However, the rear-seat observers should alternate to and from the right side of the aircraft to form a tandem team with the observer in the front right seat, so that the correction factors for perception bias can be calculated separately for each rear-seat observer.

We used a tandem team on 1 side of the aircraft when training a new observer (Marsh and Saalfeld 1989) with 1 trained observer and the trainee on the other. During training, the intercom system was switched so that the trainee could hear the reports of his counterpart on the same side of the aircraft. This system greatly reduced the period required to train reliable observers.

The major disadvantage of using our system in a 4-seater aircraft would be that there would be no room for a survey leader as defined in Figure 1. Many of the survey leader's duties (e.g., checking the position, ht, and speed of the aircraft) would be unnecessary when using a trained pilot (particularly a person with scientific training) in an aircraft equipped with a radar altimeter. It would not be possible, however, to obtain a computer record of the sightings of the rear-seat observers if everyone but the pilot were acting as observers. The computer record is irreplaceable as a back-up in the case of tape recorder failure. Our computer also has a printer that gives an immediate hard copy of all entries, preventing undetected computer malfunction.

Another disadvantage of our system is that all the voice tapes have to be listened to in real time after the survey to record the sightings of the mid-seat observers. These sightings then have to be edited on to the computer files. This involves approximately 2 hours of work for every hour of survey time. The additional cost is minor compared to the cost of the aircraft charter.

This methodology overcomes many of the problems of previous mark-recpature survey methods, especially for surveys of aquatic fauna. The problem of determining whether a group was seen by 1 or both members of a tandem team has been solved by the use of the 2-track tape recorder, and the system of recording the position of groups on the transect. This makes the method useful even when the density of the target species is high. Although the problem of the correlated search image of tandem observers has not been eliminated, its impact is minimized by the steps taken to reduce sighting heterogeneity such as limiting the surveys to days when the sea is calm and the weather fine, and timing them to minimize glare off the surface of the water. Because it is impossible to eliminate all biological and environmental biases, the development of techniques to estimate survey-specific correction factors to compensate for perceptual and availability biases should find application in aerial surveys of other species.

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NESTING
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