REDUCING BIASES AFFECTING AT-SEA SURVEYS OF SEABIRDS: USE OF MULTIPLE OBSERVER TEAMS

LARRY B. SPEAR,[1] DAVID G. AINLEY,[1] BRITTA DENISE HARDESTY,[2] STEVE N.G. HOWELL,[3] & SOPHIE W. WEBB[4]

[1]*H.T. Harvey and Associates, 3150 Almaden Expwy, Suite 145, San Jose, California 95118, USA*
[2]*Plant Biology Department, University of Georgia, Athens, Georgia 30602, USA*
[3]*Point Reyes Bird Observatory, Stinson Beach, California 94970, USA*
[4]*Oikonos, 400 Farmer Street, Felton, California 95018, USA*
(spearlarry@yahoo.com)

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SUMMARY

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Two survey methods used to estimate seabird density at sea (birds/km^2) were designed to correct for the effect of directional bird movement relative to movement of the survey platform ("bird flux"). Both use strip surveys. One, the "vector" method, requires at least two observers simultaneously on watch to obtain an acceptable detection probability of all birds within the survey strip. The other, the "snapshot" method, is less labor intensive and may be capable of obtaining a high detection probability using a single observer. Only the vector method has been validated to provide accurate estimates of abundance through comparisons with independently derived estimates. We here examine the possibility that the snapshot method, when used by a single observer, also provides accurate estimates. We used both methods during a 24-day cruise from 48°N to 53°S in the eastern Pacific. Two observers on watch together used the vector method; one observer used the snapshot method. Observers using the two methods surveyed a 300 m–wide transect strip to one side of the ship. Vector and snapshot counts were nearly identical for larger, more easily detected species, but snapshot counts were 50%–65% lower for smaller species. A similar pattern was found when comparing count data for single vs. paired vector observers. Thus, the lower snapshot count and the lower count by single vector observers resulted primarily from inadequate detection of smaller species. Our results indicate that the snapshot method can provide accurate abundance estimates, but that, using either method, a single observer cannot adequately detect all birds in a 300 m–wide strip to one side of a vessel. We suggest that use of multiple-observer teams is the best way to avoid detection problems. However, if using multiple observers is not possible, reduction of the strip width is the next best solution. Suggestions also are made about how to prevent other bias, particularly those caused by ship-attracted or -repelled bird movement.

Keywords: Seabirds, at-sea survey methods, abundance estimates, reducing biases, bird movement

INTRODUCTION

Accurate estimates of seabird densities at sea are important for reasons including these:

- Monitoring the significant role of seabirds in energy flux through marine systems (reviewed in Croxall 1987, Hunt *et al.* 1999)
- Detecting and establishing protected areas at sea
- Estimating population sizes, particularly of species difficult to census on the breeding grounds (Clarke *et al.* 2003)

However, a fundamental problem has been the lack of method standardization (see Woehler & Van Franeker 1995) combined with a lack of method validation, which together could ultimately allow results to be grouped across studies to attain a common goal. Lack of standardization reflects the varying approaches among researchers to reduce factors that bias survey counts—primarily the effect of directional bird movement that is random relative to the movement of the survey vessel (reviewed in Tasker *et al.* 1984, van Der Meer & Camphuysen 1996, Clarke *et al.* 2003), although responsive bird movement toward or away from the ship is also a major problem. The most serious problem, random directional movement (as opposed to nonrandom directional movement—e.g. birds that are attracted to the survey vessel; see "Discussion") usually results in density overestimation because most species fly faster than survey vessels move. Densities of birds that fly slower than a survey vessel (e.g. storm-petrels) are often underestimated (Spear *et al.* 1992, Spear & Ainley 1997a; see "Discussion" for an explanation).

Nevertheless, the last two decades have seen much refinement in at-sea survey methods. Currently, two methods that were designed to correct density estimates for the effect of random directional movement (van Franeker 1994) are used. They are the "vector" method (Gaston & Smith 1984, Spear *et al.* 1992) and the "snapshot" method (Tasker *et al.* 1984, van Franeker 1994). Both methods use strip transects and require that

- the designated survey-strip width is accurately maintained, and
- all of the birds within the survey strip are detected. (But see below for qualifications regarding the snapshot.)

TABLE 1
Five physical characteristics of the 28 species of seabirds examined for affect on count differencea between snapshot and vector teams

	Mass (kg)	Flight height (m)	Flight speed (m•s^{-1})	Dorsal color	Ventral color	Count difference		
						All birds[b]	Birds in transit	Birds on water
Black-browed Albatross *Thalassarche melanophris*	3.790	3	11.9	2	3	0.99	1.37	0.85
Salvin's Albatross *Thalassarche salvini*	3.300	3	12.4	2	3	0.94	—	—
Black-footed Albatross *Phoebastria nigripes*	3.980	3	12.5	2	1	0.98	1.13	0.80
White-chinned Petrel *Procellaria aequinoctialis*	1.370	3	12.4	1	1	0.81	0.75	0.98
Antarctic Fulmar *Fulmarus glacialoides*	0.775	3	10.0	3	3	0.83	—	0.81
Cape Petrel *Daption capense*	0.445	2	9.5	3	3	0.69	1.08	0.63
Narrow-billed Prion *Pachyptila belcheri*	0.150	2	8.5	3	3	0.47	0.77	—
Blue Petrel *Halobaena caerulea*	0.200	2	8.5	3	3	0.44	0.56	—
Sooty Shearwater *Puffinus griseus*	0.800	2	11.8	1	1	0.93	—	0.96
Pink-footed Shearwater *P. creatopus*	0.730	2	9.9	1	3	0.09	—	0.00
Wedge-tailed Shearwater *P. pacificus*	0.385	2	10.6	1	3	0.33	0.30	—
Juan Fernandez Petrel *Pterodroma externa*	0.430	3	11.4	3	3	0.63	1.06	0.79
White-headed Petrel *P. lessonii*	0.585	3	11.0	3	3	0.59	0.63	—
Galapagos Petrel *P. phaeopygia*	0.410	3	11.5	2	3	0.91	—	—
Cook's Petrel *P. cookii*	0.180	2	7.3	3	3	0.58	0.48	0.58
de Filippi's Petrel *P. defilippiana*	0.170	2	7.6	3	3	0.45	0.45	—
White-winged Petrel *P. leucoptera*	0.160	2	8.2	3	3	0.52	0.63	0.29
Wilson's Storm-Petrel *Oceanites oceanicus*	0.036	1	7.4	2	1	0.25	0.33	0.00
White-faced Storm-Petrel *Pelagodroma marina*	0.041	1	6.7	3	3	0.22	0.20	—
White-bellied Storm-Petrel *Fregetta grallaria*	0.045	1	8.3	2	3	0.45	0.50	—
Leach's Storm-Petrel *Oceanodroma leucorhoa*	0.041	1	7.1	2	1	0.52	0.53	0.56
Band-rumped Storm-Petrel *O. castro*	0.045	1	7.6	2	1	0.14	0.16	—
Wedge-rumped Storm-Petrel *O. tethys*	0.024	1	7.1	2	1	0.29	0.16	0.75
Markham's Storm-Petrel *O. markhami*	0.055	1	6.7	1	1	0.41	0.42	—
Fork-tailed Storm-Petrel *O. furcata*	0.050	1	7.7	2	2	0.29	—	—
Masked Booby *Sula dactylatra*	1.750	4	13.1	4	3	0.96	—	—
Red-necked Phalarope *Phalaropus lobatus*	0.038	2	9.2	3	3	0.44	—	0.43
Red Phalarope *Phalaropus fulicarius*	0.040	2	11.0	3	3	0.70	—	—

[a] Count difference is the number of birds observed during snapshot counts, divided by corrected number observed during vector counts when both methods are used simultaneously (Table 2). See "Methods" for the scoring of physical variables.
[b] "All birds" is the summed total for all behaviors combined.

Both methods count all birds that are stationary—that is, those sitting on the water, feeding or searching for food in a confined area. The two methods count birds flying in a random, steady direction (transiting) differently. The snapshot method partitions the strip into contiguous segments, each of which is surveyed only once for transiting birds using "instantaneous" counts. In contrast, the vector method counts all transiting birds and subsequently uses the method of Spear *et al.* (1992) to adjust those counts for the effect of movement. The adjustment requires estimation of flight direction to the nearest 10 degrees for each transiting bird (or flock).

Methods may also differ in the number of observers needed to obtain accurate counts. The vector method requires two observers on watch simultaneously (this study). However, van Franeker (1995) suggested that a single observer is adequate when using the snapshot method, because flight direction does not have to be recorded and transiting birds are counted discontinuously.

Indeed, because of the biases encountered during at-sea surveys (see "Discussion"), it has been suggested that accurate survey counts are not possible (Tasker *et al.* 1984, Haney 1985, Wiens 1995). However, Clarke *et al.* (2003) validated the vector method by comparing population estimates of three breeding populations of seabirds obtained using at-sea survey data (in combination with demographic information to compensate for the number of nonbreeders at sea) gathered by us, with estimates obtained independently by three different teams conducting censuses of the same breeding populations at their colonies. Each of the three species has behaviors problematic for obtaining accurate survey counts, including ship avoidance (Waved Albatross *Phoebastria irrorata*), attraction to vessels (Western Gull *Larus occidentalis*), and diving (Common Murre *Uria aalge*). The result was close agreement (<2% difference) between pairs of estimates for the murre and albatross, and less, but still appreciable, agreement (10% difference) for the ship-attracted gull.

Although the snapshot method has not been validated for accuracy, the possibility that only one observer is required would make that method a more cost-efficient means of conducting surveys than the vector-survey method with its required multiple-observer teams. In addition, when berthing space is limited, a method using but one observer is needed. We therefore designed the present study to compare survey results from multiple observers using the favorably validated vector method with results of surveys conducted by a single observer using the snapshot method.

In conducting surveys simultaneously using two teams, our primary objective was to test the snapshot method as a potential means of obtaining accurate density estimates using a single observer. During the present study, observers using the vector method followed exactly the same protocols, including use of the same observers, as did Clarke *et al.* (2003), and we assume that our vector-derived data in the present study has equivalent accuracy.

Two other objectives of our study were to present data gathered earlier concerning the effect on detection rate of differences in the number of vector observers, and to describe methods that we have designed to eliminate other biases encountered during at-sea surveys—particularly responsive bird movement.

METHODS

Survey protocol

During 17 July–10 August 1995, using the snapshot and vector methods simultaneously, we conducted seabird surveys on a cruise spanning 98 degrees of latitude from Seattle, Washington, to Conception, Chile. Ship speed averaged 23.0 km/h (standard deviation: 1.8 km/h) during the 498 0.5-h transects conducted by the vector team. A multiple-observer group conducted the vector surveys, and one observer conducted snapshot surveys. Observers using the two methods counted seabirds seen within a 90-degree quadrant extending 300 m off the side of the ship's bow providing the best observation conditions. All observations were made from one or the other of the bridge wings [10 m above sea level (asl)], with all observers watching from the same side. In this regard, our method (watching a 90-degree segment) differed from that of van Franeker (1994), who also surveyed a 300 m–wide strip, but over a 180-degree segment, including two 150-m segment strips—one on each side of the vessel. Duplication of that configuration was not possible on our vessel because we did not have access to the flying bridge (top of the boat) and because observing from the bow would have placed observers at risk of wave impact during rougher sea conditions. Observers using the two methods recorded birds secretively to avoid cueing the user or users of the alternative method.

With an expansive caliper held at arm's length, we used the method of Heinemann (1981) to maintain the 300-m strip width: Each observer used a derivation of Heinemann's formula to calculate the caliper reading (*C*) required to maintain the strip width:

$$C = (DBH - HBV) / (-DV - H^2),$$

where D is the 300-m strip width, B is the distance from the observer's eye to the jaws of the caliper held at arm's length, H is the height of the observer's eyes above the water and V is the distance from the observer to the visual horizon, calculated using the equation

$$V = 3838 \text{ m } (H^{0.5}),$$

also given in Heinemann (1981). In the present study, B and C were the only variables that varied between observers.

As observers, the four of us had all conducted hundreds of hours of surveys together during previous cruises. Thus, we knew each other's detection abilities, and based on that knowledge, we assigned our two observers with the most acute (but similar) seabird detection abilities to opposite methods (i.e. one used the vector method, and the other used the snapshot method). Our experience with one another indicates that visual acuity differs little among the four of us, however.

Thus, during daylight hours, snapshot surveys were conducted only by DGA for periods lasting 1.5–2 h, followed by a 0.5 h break to avoid fatigue.

Based on previous experience and the results of an experiment presented herein (see "Effect of number of observers on seabird counts" under "Results"), we also knew that, when the vector method is used, at least two observers on watch together are required to detect ≥95% of the birds within the survey area. Our vector surveys were therefore conducted by SNGH, BDH, and SWW, at least two of whom were on watch simultaneously, rotating watch with the third person at 2-h intervals. The third person was off watch for 1 h, although on call in the event of high seabird densities.

Those observers maintained a continuous watch when the ship was underway during daylight. Each had been trained to use the vector method by DGA and LBS. Each had >1000 hours of observation experience and extensive experience with the avifauna encountered. Based on ship speed, snapshots occurred each 41–50 seconds and were timed using a stopwatch with an alarm, with interval adjustment according to the ship's speed.

Because snapshot counts must be "instantaneous," it was not possible to locate each transiting seabird quickly enough to make a snapshot count without prior knowledge of bird location. Therefore, DGA followed van Franeker (*in litt.*) and Tasker (in Gaston *et al.* 1987) and tracked birds within the survey strip so that the presence of all birds was known at the instant of the snapshot count. Each snapshot surveyed a square area, with the shortest boundaries extending directly parallel and perpendicular to the ship's beam, and the most distant point at the corner opposite the observer (Fig. 1). Hence, two of the boundaries of the square area within which birds were counted during each snapshot extended 300 m from the snapshot observer, and the farthest was 425 m from the observer. Thus, each snapshot surveyed an area 21.5% larger than the 300 m–wide radial area being surveyed by vector observers at any given moment.

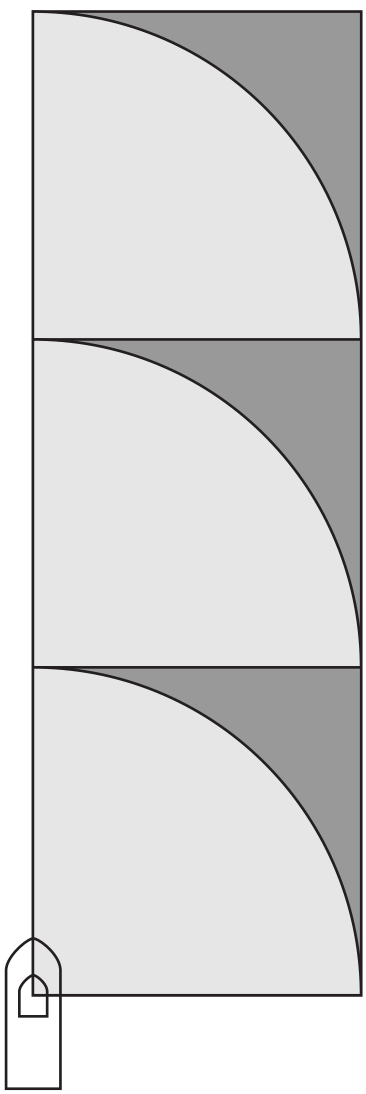

Fig. 1. Segment squares surveyed during three instantaneous counts within a section of survey strip (ship moving from bottom to top) by the snapshot observer, compared with the radial-shaped quadrant (stippled) being surveyed constantly within the same strip section by the vector observers.

Although many birds entering the survey strip were detected with the unaided eye, the vector observers scanned the outer half with binoculars (generally one scan every 30–45 s per observer) to reduce chances of not detecting smaller birds. The snapshot observer also scanned the outer strip, but about 50% as often as the combined scanning by the vector observers.

Data recorded by the vector observers (into a notebook) for each sighting included species, number, behavior, and flight direction of birds in transit. We used coding to record behavior, and flight direction was noted to the nearest 10 degrees. We estimated direction by using the ship's compass to note ship direction and then drawing four-point compass diagrams on the pages of the data books for reference when estimating bird direction.

Birds in transit did not always fly a straight line, but made headway in a given direction. When large multiple-species groups were encountered, species were allocated among observers. In those cases, birds usually were milling or circling and, thus, often did not require notation of direction. In situations in which many birds were in transit, those of a given species were usually flying in the same direction, allowing the recording of many birds in one entry. Except for flight direction, the snapshot observer recorded the same variables as the vector team, also into a notebook.

Birds circling or following the ship were not counted by either method (i.e. consistent with van Franeker 1994); however, birds attracted to the ship ("attractees") were recorded by both methods in our study if they initially approached from the area extending directly beyond the 90-degree survey area. Thus, attractees that approached the ship from the opposite side or from behind were not counted at all [method used to count attractees, whether they circled or followed the vessel or not was not discussed by van Franeker (1994)]. In our study, counts of attractees were not adjusted by either team, although we had adjusted those counts during other studies (details in "Responsive bird movement: attraction" under "Discussion").

Analyses

We followed Spear *et al.* (1992) to adjust vector counts (hereafter termed the "adjusted count") of transiting seabirds for the effect of their movement. Besides comparing adjusted vector counts to snapshot counts, we examined the detection rate of various seabird species by comparing differences between adjusted multiple-observer vector counts and single-observer snapshot counts in relation to bird size (mass), flight height, flight speed, dorsal color, and ventral color of the 28 more abundant species (Table 1). Our rationale for the comparison was that, if both methods recorded all species of birds occurring in the survey strip in similar proportions, no detectability-related differences should exist, and any differences between counts would be method-related only. On the other hand, if the snapshot observer counted some, but not all, species in lower numbers than the vector observers (which was the case—see "Results"), we could then assess the differences relative to factors affecting detection probability of each species.

We used regression analyses to examine the detectability factors and defined the dependent variable, "count difference," as the snapshot count divided by the (adjusted) vector count (Table 1). Independent variables (species mass and mean flight speed) are from Spear & Ainley (1997a, 1997b). Previously, we scored and recorded categories of flight height for all birds in transit during all of our cruises in the Pacific and Southern oceans (1980–1995). Using those data, we calculated mean flight heights of each species using these categories: 1 = <1 m; 2 = 1–3 m; 3 = 3–10 m; and 4 = >10 m. We scored dorsal color using these categories: 1 = dark; 2 = mostly dark, but with some light areas (e.g. Pintado Petrel *Daption capense*) or rump-patch (e.g. storm-petrels, Oceanitidae); 3 = gray or with extensive white (e.g. most gadfly petrels *Pterodroma* spp. and most albatrosses *Diomedea* spp. and *Thalassarche* spp.); and 4 = white (e.g. Masked Booby *Sula dactylatra*). Ventral color was recorded using these categories: 1 = dark; 2 = gray; or 3 = white.

All independent variables were initially entered into the regression model. Insignificant terms were dropped, one at a time, in order of decreasing *P* value. Because many terms were correlated (Table 2), the importance of some were likely masked by others in the initial model. We therefore tested for the effects of eliminated terms by returning them one at a time to the model. The model was complete if no terms could be added or dropped.

In a multiple regression model, any independent variables that test as having a significant relationship with the dependent variable are considered to be true influences. That is, their effects are independent of the effects of other independent terms that also have significant relationships with density, because each term included in the model is evaluated while taking into account (controlling for) the effects of each of the other terms. Frequently, independent terms that are correlated can each have a significant but independent relationship with the dependent variable. The identification of such relationships is one of the benefits provided by multiple regression analysis.

We used chi-square tests to examine proportional relationships and analyzed the numeral data, not percentages. Significance was accepted at $P \le 0.05$.

Effect on detection rate attributable to difference in number of vector observers

On another cruise, three observers simultaneously and independently recorded bird sightings on 28 December 1992 during 27 0.5-h continuous survey transects off the coast of South America, using exactly the same methods as described above for the 1995 cruise. Weather conditions were optimum: wind speed calm to very low and overcast sky (no glare). To facilitate comparisons, observers synchronized their wristwatches, and each recorded sightings by minute. Seabird densities during this exercise were such that we felt justified in assuming that the recording of a bird of a given species by two or all observers within two minutes of one another represented a recording of the same bird by each. We allowed a two-minute interval because of the high density of storm-petrels that sometimes took that long to pass through the survey strip.

RESULTS

Survey effort and total count

The area of ocean surveyed by the snapshot observer during the 1995 cruise was 1226.0 km^2, or 71.7% of the 1709.0 km^2 surveyed by the vector team. The total adjusted number of birds recorded by the vector team (including birds recorded when the snapshot observer was on break) was 2741.7. Hereafter, vector counts refer only to the adjusted count, unless otherwise noted. The number of birds recorded by the snapshot observer was 1296; the number recorded by the vector team when the snapshot observer was on watch was 2172.5 (Table 3).

Thus, the total snapshot count was 47.3% as great as the total vector count during the entire cruise, and 59.7% as great as the vector count during surveys when both methods were being used simultaneously. Both differences were highly significant (χ^2 = 267.48, df = 1, $P < 0.0001$, and χ^2 = 112.67, df = 1, $P < 0.0001$ respectively; tests were of the proportional differences between counts). The differences were strongly affected by the highly abundant and difficult-to-detect storm-petrels (see below). Hereafter, comparisons pertain only to data collected when both methods were used simultaneously.

TABLE 2
Relationship between variables analyzed for effect on species[a] detectability

	Mass (g)[b]	Flight height (m)[b]	Flight speed (m•s^{-1})[b]	Dorsal color[b]
Flight height	0.624[c]	—		
Flight speed	0.692[c]	0.869[c]	—	
Dorsal color	- 0.122	0.283	- 0.035	—
Ventral color	- 0.021	0.387[c]	0.179	0.566[c]

[a] Sample size was 28 species. See Table 3 for values by species.
[b] Values are correlation coefficients (*r*).
[c] Significant correlation.

TABLE 3
Number of birds counted by vector and snapshot teams in route from Seattle, Washington, to Conception, Chile, July–August 1995

	Vector[a]	Snapshot[a]	Percent[b]
All behaviors			
Unadjusted	2421	—	
Adjusted	2174.5	1296	59.6%
Flying in transit	1089.5	622	57.1%
Percent	50.1%	48.0%	
Sitting on water	789	567	71.9%
Percent	36.3%	43.8%	
Foraging/feeding	296	107	36.1%
Percent	13.6%	8.2%	

[a] Counts are given with respect to behaviors (flying in transit, sitting on the water, and foraging/feeding) and include only those birds seen when the two methods were being used simultaneously. "Percent" indicates the extent to which counts for the respective behavior contributed to the total count for a given method.
[b] Calculated by dividing the snapshot count by the vector count, and multiplying by 100.

The relative proportion of seabird counts for three categories of behavior (flying in transit, sitting on the water, and foraging/feeding) differed significantly between the two methods ($\chi^2 = 32.40$, df = 2, $P < 0.0001$; Table 3), mainly because of proportionately higher counts of sitting birds and proportionally lower counts of foraging/feeding birds by the snapshot method.

Effect of vector adjustment compared between seabird species

The effect of vector adjustment changed observed counts among the 11 species groups of seabirds by –61% to +12% for birds in transit, and by –47% to +8% when counts across all behaviors were combined (Table 4, Fig. 2). Compared among species groups, those differences (observed vector counts in proportion to adjusted counts) were significant for both counts ($\chi^2 = 54.16$, df = 10, $P < 0.0001$, and $\chi^2 = 83.26$, df = 10, $P < 0.0001$ respectively). Groups with the largest negative adjustments were albatrosses, large gadfly petrels, alcids, and larids. The only group with a positive adjustment was the storm-petrel group. Species whose overall adjustments did not alter observed counts significantly were shearwaters, Pelecaniformes, and phalaropes, a situation attributable to the high proportion of stationary birds (on water or foraging) compared with birds in transit (Table 4).

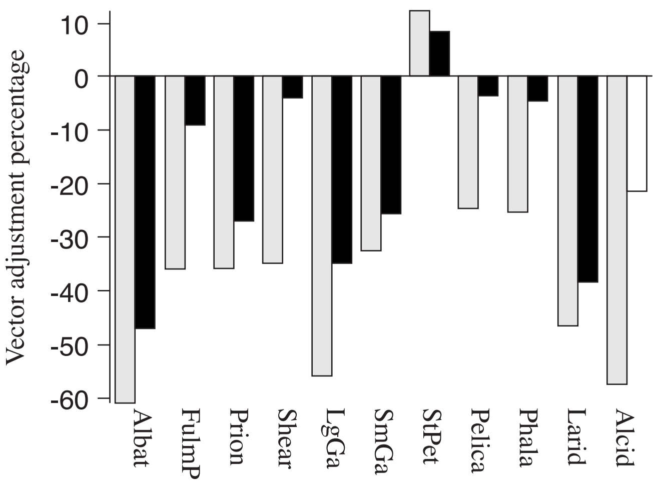

Fig. 2. Adjustment percentage [(vector adjusted count / observed vector count – 1) × 100] for 11 species groups of seabirds. Shown is the vector adjusted percent for transiting birds (light bar) and for all behaviors (sitting on water, feeding, transiting) grouped (dark bar). Albat = albatrosses/giant petrels; FulmP = fulmarine petrels; Prion = prions/Blue Petrels; Shear = shearwaters; LgGa = large gadfly petrels; SmGa = small gadfly petrels; StPet = storm-petrels; Pelica = Pelicaniformes; Phala = phalaropes. See Spear and Ainley (1997a) for species included in each group.

Effect of number of observers on seabird counts

During the 1992 exercise, which was conducted to compare the effect on detection probability of the number of observers on watch together, the three observers recorded 246 individual seabirds. Storm-petrels constituted 59% of the birds observed; large gadfly petrels, 21%; small gadfly petrels, 13%; fulmarine petrels, 3%; tropicbirds and larids, 2% each. However, a single observer recorded 21.5% fewer birds [standard error (SE): 1.1%; n = 27 0.5-h survey segments × 3 observers = 81] than did two persons observing simultaneously. Adding the third observer increased the number of birds detected by 4.8% (SE = 0.7%; n = 81) compared with two persons observing together. Therefore, if we assume that the three observers together detected close to 100% of birds present (as indicated by the relatively small increase in detection rate when using a third observer), single observers missed an average of 26.3% (SE = 1.1%; n = 81) of the birds present.

The total number of birds (summed across groups) recorded by the three two-observer teams was 689 birds (many of which were the same birds recorded separately by each group) as compared with 541 birds recorded by the three observers working alone. As compared with the number of birds detected by paired observers, the proportion not detected by single observers differed significantly among species groups [$\chi^2 = 37.55$, df = 5, $P < 0.0001$; Fig. 3(a)] because of lower counts by single observers of storm-petrels, larids, and small gadfly petrels as compared with large gadfly petrels, fulmarine petrels, and Pelecaniformes.

TABLE 4

Number of birds[a] counted by the vector and snapshot methods while in route from Seattle, Washington, to Conception, Chile, July–August 1995

	All birds			Birds in transit						
	Vector		Snapshot	Vector		Snapshot	Birds on water		Birds foraging	
	Unadj.[b]	Adj.	Total	Unadj.[b]	Adj.	Total	Vector	Snap.	Vector	Snap.
Albatrosses/giant petrels	236	125.3	119	182	71.3	87	37	32	17	0
Fulmarine petrels	341	310.3	241	85	54.3	48	249	193	7	0
Prions/Blue Petrels	132	96.0	45	100	64.0	45	10	0	22	0
Shearwaters	271	260.8	231	29	18.8	14	237	213	5	4
Large gadfly petrels	169	110.5	73	105	46.5	45	51	27	13	1
Small gadfly petrels	205	152.5	80	161	108.5	61	36	18	8	1
Storm-petrels	889	961.6	408	621	693.6	307	91	45	177	56
Tropicbirds/boobies/frigatebirds	59	56.5	54	10	7.5	7	2	2	47	45
Phalaropes	73	69.3	33	14	10.3	6	59	27	0	0
Skuas/gulls/terns	28	17.2	6	23	12.2	2	5	4	0	0
Murres/auklets/murrelets/diving petrels	16	12.5	6	6	2.5	0	10	6	0	0

[a] Bird species are allocated among 11 taxonomic groups based on size and taxonomy (Spear & Ainley 1997a). Counts are divided with respect to behaviors (flying in transit, sitting on the water, and foraging/feeding) and include only those birds seen when the two teams were observing simultaneously.

[b] Refers to the vector count before adjustment for the effect of bird movement.

When considering all birds (i.e. behaviors grouped) recorded during the 1995 exercise when the vector and snapshot teams were observing at the same time, adjusted vector counts were higher for all 11 seabird groups, although the magnitude of the differences between groups was also significant [$\chi^2 = 87.90$, df = 10, $P < 0.0001$; Table 3, Fig. 3(b)]. Groups with the smallest proportional difference [(snapshot count / adjusted vector count – 1) (100) = 0% to 4%], were albatrosses/giant petrels and pelecaniformes. Those with the greatest differences (49%–65%) were prions/Blue Petrels, small gadfly petrels, storm-petrels, phalaropes, larids and alcids.

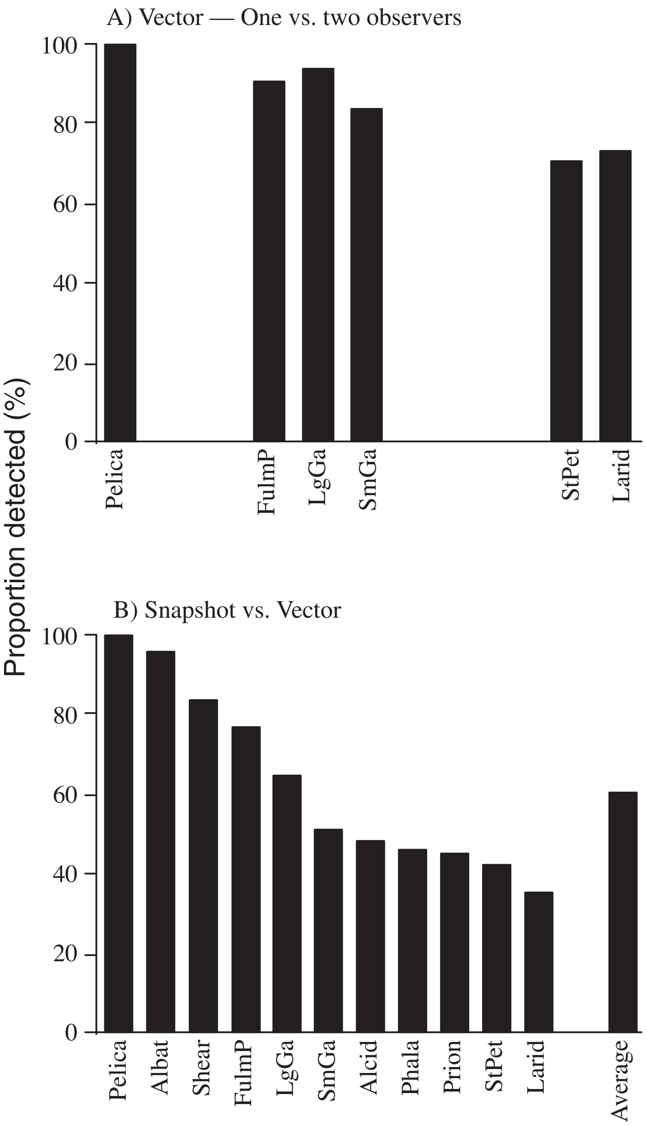

Fig. 3. Proportion of birds detected for 11 major seabird groups compared between one-person and two-person vector teams during the 1992 effort. (A [(Number of birds detected by each of three single vector observers / number detected by each of three paired vector observers) × 100] and proportion detected compared between the snapshot observer and the vector observers in the present study. (B) [(Snapshot observer count / corrected vector count) × 100]. Albat = albatrosses/giant petrels; FulmP = fulmarine petrels; Prion = prions/Blue Petrels; Shear = shearwaters; LgGa = large gadfly petrels; SmGa = small gadfly petrels; StPet = storm-petrels; Pelica = Pelicaniformes; Phala = phalaropes. See Spear and Ainley (1997a) for species included in each group.

Those with intermediate differences (16% to 35%) were shearwaters, large gadfly petrels and fulmarine petrels. Thus, snapshot-count versus vector-count differences, compared among species groups, were similar to the differences seen between the same species groups as recorded by single or paired observers when observing continuously [Fig. 3(a)].

Relationship between morphologic/behavioral features of species and count difference

The count differences among species groups when compared between snapshot and vector teams and between one-observer and two-observer vector teams indicate that some species are easier to detect (Fig. 3). Multiple regression models examining count differences between snapshot and vector teams, as related to the physical characteristics of the 28 more abundant species (Table 5), explained 66.7%–67.6% of the variation in the counts for all behaviors grouped (lower end of the range) and for transiting birds (higher end of the range; Table 5). Species mass and flight height had independent and significant effects when the analysis was controlled for alternate factor. Larger birds that flew highest were detected most consistently. Flight height was the most important variable, having an effect on counts 3.3 times greater than species mass for all behaviors, and 1.5 times greater for birds flying in transit (Table 5; compare *P* values). The flight speed and dorsal and ventral color variables had little effect on the count differences between respective behavior groups. Species mass, dorsal color and ventral color also had little effect on count differences of birds sitting on the water.

TABLE 5
Multiple regression analyses for the relationship between count difference[a] of various species of birds as related to bird mass, mean flying height, mean flight speed, dorsal coloration and ventral coloration

Term	Coefficient sign	*F* value	*P* value
All behaviors combined: model $F[2,25] = 25.08$, $P < 0.0001$, 66.7% of variance explained			
Main effects			
Species mass	(+)	4.68	<0.05
Flight height	(+)	15.37	<0.001
Rejected terms			
Flight speed	NS	3.41	0.07
Dorsal color	NS	0.32	0.6
Ventral color	NS	0.28	0.6
Bird flying in transit: model $F[2,16] = 16.71$, $P < 0.0001$, 67.6% of variance explained			
Main effects			
Species mass	(+)	4.72	<0.05
Flight height	(+)	7.26	<0.02
Rejected terms:			
Flight speed	NS	3.77	0.06
Dorsal color	NS	0.45	0.5
Ventral color	NS	1.10	0.3
Birds sitting on the water: model not significant			
Species mass	NS	2.55	0.2
Dorsal color	NS	0.18	0.7
Ventral color	NS	0.77	0.4

[a] See “Methods” for definition of count difference, and Table 1 for species values of independent terms. All df = 1.
NS = nonsignificant.

DISCUSSION

Effect of survey methods, number of observers, and observer ability

In the present study, ship space (both berthing and on the observation bridge wings) precluded experimentation using a multiple-observer snapshot team alternating with the single snapshot observer, while simultaneously maintaining the vector team effort. We therefore could not directly determine if count differences were attributable to method effects (snapshot vs. vector) or differences in the number of observers. In addition, we did not alternate observers between methods, thus introducing the possibility that between-method count differences could also have reflected differences in observer ability. That is, we attempted to control for possible differences in observer ability only by having our two best observers use opposite methods.

Yet, despite the confounding factors, our results show clear indications regarding the relative effects of differences in survey method, observer number and observer ability. Specifically, snapshot counts of easily detected birds—larger species with higher flight elevation—were nearly identical when compared between the snapshot and vector methods. Assuming that the two vector observers detected at least 95% of the birds (as indicated by Clarke *et al.* 2003), our results show that the snapshot method can provide accurate abundance estimates. However, inability of a single, highly experienced snapshot observer in this study to adequately detect all but the largest seabirds within the 300 m–wide quadrant strip (as was the case for the single observer compared with paired observers in the 1992 exercise) clearly shows that the effect is related to too few observers or to a snapshot observer of lesser ability (or a combination), rather to method per se. Concerning observer ability, however, given that the snapshot observer's ability was similar to that of the best vector observer, but possibly better than that of the other two vector observers (who were on watch without the third vector observer about 33% of the time), we would expect the vector counts to have been lower than the snapshot counts instead of the opposite, if differences in observer ability were responsible for count differences. Thus, the evidence indicates that number of observers, rather than method or observer ability differences, was most responsible. There also is a possibility that the snapshot observer could have become more fatigued, because he had 1 hour of rest during each 4 hours of the survey day, while each vector observer had 1 hour of rest every 3 hours.

Effect of random bird movement

Without vector adjustment, the effect of random bird movement (responsive bird movement is discussed later) would have resulted in density overestimation of up to 47% for the fast-flying albatrosses, but also density underestimation of 8% for the slower-flying storm-petrels. The reason is that, when bird flight speed is slower than movement of the survey vessel, the difference between the ship movement vector and the flight vector of the birds is small, and the correction factor is close to 1. The correction factor will be greater than 1 if the angle between the ship and the bird movement vectors is relatively small. Thus, the slow-moving birds are essentially overtaken and passed while outside of the survey strip by the faster survey vessel, resulting in a negative bias (undercounting) of those birds if counts are not corrected.

The results of vector adjustment in this study are similar to those of Clarke *et al.* (2003), who found that, without the adjustment, true densities would have been overestimated by 20%–37% among the three species examined (albatross, larid, and alcid). The adjustment factors reported herein for various species groups might be applied to strip-survey data in which vector adjustment is not possible (i.e. where flight direction is not recorded); however, such an adjustment would be inappropriate unless ship speed is similar when compared between studies (Spear *et al.* 1992).

Count difference

Overall, the snapshot observer count was 60% as great as the adjusted vector count when both methods were being used simultaneously—a difference attributable to the lower number of detections by the snapshot observer of the more difficult-to-detect species groups: prions, small gadfly petrels, storm-petrels, larids, phalaropes, and alcids. Because storm-petrels were by far the most abundant and among the most difficult-to-detect of seabirds, the total count difference compared between survey methods was largely a result of the lower count by the snapshot observer of those petrels.

Survey configuration

We did not examine the possibility that changing the configuration of the survey area as per van Franeker (1994) would increase the detection rate. Van Franeker scanned two 90-degree arcs, one extending 150 m from either side of the ship, while he observed from the center of the ship's bridge. We agree that reducing the strip width will increase the detection rate per unit area of ocean surveyed and that survey-strip width should not be rigidly fixed (see below). We also believe that surveying from the ship's center could increase the detection rate because that position will result in the attention of observers being focused directly ahead of the vessel instead of at angles up to 90 degrees, as when observing from one side or another. Viewing from the center of the ship would also be likely to facilitate attention to problems caused by bird attraction to, or displacement by, the approaching survey vessel. (See sections on "Responsive bird movement.")

On the other hand, we do not believe that use of dual strips viewed from the ship's center is wise for three reasons:

- Access to the center of the flying bridge frequently is denied because of the presence there of electronic apparatus, particularly radar.
- Observation conditions are frequently very poor on one side as compared with the other because of wind or the sun's glare on the ocean surface.
- When conducting surveys from most vessels (particularly larger ships), it is impossible for one observer to adequately detect birds within a strip of any width when scanning from the center of the ship because views of inner areas of the survey strip are blocked by the mass of the ship's sides. That is, adequate views of the entire double quadrant will require a single observer to move often from one side of the bridge to the other to view survey strip waters closest to the ship.

Although the accuracy obtained when using a dual quadrant observed using multiple observers has not been compared for accuracy with the 90-degree quadrant, we suggest that, until shown otherwise, use of one 90-degree quadrant observed from one side of the vessel is likely to be most effective.

Other biasing factors

Many factors other than observer effort and strip configuration can affect detection probability of seabirds at sea. Those suggested by Tasker *et al.* (1984) and van Der Meer & Camphuysen (1996) include size and color of birds, behavior, weather, observer ability and survey-strip width. (Effect of bird color was insignificant in the present study.) Wiens *et al.* (1978) and Tasker *et al.* (1984) recommended calculation of a "coefficient of detection" for seabird species from analysis of detection rate with distance from the ship, and with further partitioning for weather effects and observer ability. Tasker *et al.* also suggested that examination of the coefficients may allow establishment of "practical transect [strip-] widths," within which adequate detection of a given species can be assumed. Although both authors made the same recommendation for dealing with detection probability biases, the recommendation of Wiens *et al.* applied to all seabirds but that of Tasker *et al.* applied only to "stationary" birds. Additionally, the author explanations of the way in which coefficients of detection might be calculated for birds showing various behaviors, including dealing with several complicating factors, were inadequate.

The detection probability for Marbled Murrelets *Brachyramphus marmoratus* has been examined for various strip widths surveyed from observer platforms of given height asl (Strong *et al.* 1995). Also, the distance sampling methods of Buckland *et al.* (2001) present a means for calculating detection probability that takes into account bird distance from the observer. However, we are unaware of studies that provide a method for calculating, or that have produced, coefficients of detection for seabird species that adjust for all of the important biasing factors simultaneously—possibly because of the complex interaction among them.

Factors affecting detection probability previously not well recognized are the effects caused by differences in observer ability (e.g. van Der Meer & Camphuysen 1996) and difference in number of observers on watch (Verner 1985, Gaston *et al.* 1987), in which the effect of observer differences increases as the number of observers simultaneously on watch decreases. In fact, we believe that the primary factors to be considered for determining strip width are number of observers, observation platform height, weather, and species diversity and density. The last two variables in particular affect the effort required to obtain accurate counts; however, with two or more observers watching together, detection problems caused by those and a host of other factors may mostly be eliminated. Specifically, when using multiple observers, detection adjustments may be reduced to a detection probability curve (Buckland *et al.* 2001) used to calculate the strip-width boundary as a function of platform height, within which each species of seabird is detected with similar frequencies at distances to the strip edge. Adjustments for weather should be ad hoc, but standardized.

An additional benefit from use of multiple observers is that, regardless of the survey method, a single observer obtains fewer data as compared with multiple observers because fatigue does not allow one observer to conduct surveys during all of the available time. For example, the single observer in this study surveyed 71.7% as much ocean surface as the multiple-observer team. This factor justifies consideration in situations in which as many data as possible must be collected—as when studying rarer species or when study duration is short relative to variability in related factors (e.g. oceanographic conditions or breeding chronology).

Strip width

Strict use of a particular strip width (e.g. 300 m) may be impractical (Bartle & Stahl 1995). Even from a platform 10 m asl, larger species (with exception of penguins) are easily detected and identified at distances much greater than 300 m; smaller species are more difficult to identify or detect at 300 m. Use of a 300 m–wide strip can also result in unacceptably low counts of the larger, usually less abundant, species. The resulting problem is obvious, because using many different strip widths simultaneously for different species groups is difficult. Therefore, as suggested by Bartle & Stahl (1995 pers. comm.), researchers might consider using a second strip for albatrosses (and possibly Pelecaniformes), perhaps twice as wide as that used simultaneously for smaller species.

Albatrosses are of special interest because of declining populations (Gales 1998), and numbers of some albatross species counted during even extensive at-sea surveys are inadequate for meaningful analyses unless strip widths are widened (e.g. Spear *et al.* 2003). Use of yet a third, narrower, strip width for the more difficult-to-detect species (storm-petrels, phalaropes, alcids, diving petrels, penguins) might also be possible with practice. Those species are the most difficult to detect at sea, and thus are usually the species that will be undercounted if the strip width being used is a compromise between detection probabilities of larger and smaller species. In addition, with the exception of penguins and phalaropes, most of these species are burrow or crevice nesters that cannot be reliably censused on their breeding grounds. Thus, determination of the appropriate strip width (as a function of the number of observers on watch and the platform height) for these species would be wise. The result is a maximum of three separate strip widths in use simultaneously, depending on avifauna composition. Another bias occurs when observers cannot readily identify all sightings to species level (e.g. phalaropes, storm-petrels, small Pterodroma, small jaegers, small alcids, small terns) and are forced to record them as "Taxon spp." These data have limited use, because they must be deleted when a species-level analysis is to be conducted. As an alternative, we have adjusted "unidentified" sightings by assigning them to species level using the ratio observed among those sightings of the difficult-to-distinguish group of species that were identified to species level (e.g. by using the ratio between identified Red and Red-necked phalaropes to adjust counts recorded as *Phalarope* spp.). This practice is justified only if the majority of individuals of respective species were identified (probably at least 75%) and if identification is not biased toward one of the difficult-to-distinguish species.

Responsive bird movement: attraction

A serious bias faced by marine ornithologists is density overestimation resulting from counting birds attracted to the ship (reviewed in Hyrenbach 2001). This problem has received little attention, and a way to adjust for it has not been developed (but see our later discussion). The primary reasons are lack of information about factors such as the proportion of individuals of each species that are attracted or not attracted after detecting the ship, and the distance from which they respond.

Hence, "abundance estimates" calculated for species represented by a large proportion of individuals recorded as attractees, or as circling the ship, should be used only for within-species comparisons of relative abundance. However, because estimating true abundance for some attracted species is important (e.g. albatrosses), and because the proportion of individuals of some species counted as attractees is small, attempts to estimate abundance of these birds will continue, sometimes justifiably. In these cases, use of a standardized method would facilitate between-study comparisons.

Many methods are used to record attractees. We recorded as attractees only those birds that approached from the direction extending from the 90-degree forequarter being surveyed. Thus, we did not record birds that approached from the other forequarter, aft of the ship's beam on the side we were observing from, or birds that had obviously been attracted because they were circling or following the ship. Birds are deemed attractees if they change their flight direction to inspect the ship; each is given a value (V) of 0.3. This adjustment factor is based on the assumption that, for every bird representing a ship-attracted species that passed within 8 km [the distance at which the ship can be seen by a bird flying 5 m asl (Heinemann 1981)] of the 0.3 km–wide survey strip, 50% responded and 25% of the responders approached from the forequarter extending beyond our survey strip. Hence,

$$V = (0.3 \text{ km} / 8 \text{ km})\ (1 / 0.5)\ (1 / 0.25).$$

We make no further adjustments to those counts. Although that method may at least provide acceptable abundance estimates for large larids (Clarke *et al.* 2003), they are likely to be problematic because of the lack of information on proportion attracted and the likelihood of recording some birds as "not attracted" that were actually attracted (Spear & Ainley 2005).

Using a more sophisticated approach than ours, Hyrenbach (2001) use at-sea surveys of the Black-footed Albatross to develop a method for calculating coefficients of attraction (CA) for ship-attracted species that could be used to correct density estimates for the effect of attraction to a survey vessel. Yet his results are difficult to interpret for several reasons:

- When calculating the CA, Hyrenbach ignored the effect of flux—i.e. bird movement, a factor that also results in density overestimation, particularly among fast fliers such as albatrosses (Spear *et al.* 1992, Spear & Ainley 1997a), causing confounding of two factors (flux and attraction) that both result in positive bias.
- It is unclear how the author recorded and analyzed counts of stationary birds when calculating CA.
- It is unclear why tracking "recognizable" birds that followed the ship after being attracted was important for the calculation of CA.

Several different CAs are reported (1.17, 3.57 and 4).

Despite those discrepancies, Hyrenbach's method (2001) appears promising if certain conditions are met:

- Survey data are recorded in such a way that the bias attributable to bird flux can be eliminated from the data before it is used to calculate CA.
- Standard strip surveys [using either the vector or snapshot methods (this paper)], in which stationary birds and birds in directional flight are both recorded, can be implemented simultaneously with that of the protocol required to calculate CA. The CAs could then be applied to standard strip-survey data of respective species.

Although some marine ornithologists record species and number of birds following and circling the survey vessel, such counts should not be done. Other than the fact that these data are of very limited use, the requirement that the observer track circling/following "individuals" so as to distinguish birds that have just arrived from those that arrived previously and have already been counted (i.e. to obtain accurate counts) is a serious distraction from the more important activity at hand: that of detecting and recording unattracted birds within the survey strip.

Responsive bird movement: displacement

Ships cause three types of potential bias because of displacement of stationary and nonstationary birds (i.e. birds that are sitting on the water, feeding, or flying in transit) positioned ahead of, or to either side of, the vessel. Two of the displacements result in negative bias, and the third can cause positive bias:

- Not counting stationary birds that would have passed within the strip had not the ship caused them to move aside or dive
- Not counting birds that are flying on a directional course that would take them through the survey strip, but that detour around the vessel in an arc beyond the survey strip (e.g. some albatrosses, shearwaters, terns and jaegers)
- Counting birds that would not have been included in the survey strip had they not been displaced (usually positioned on the water on the opposite side of the ship from which surveys are being conducted), but which fly (usually upwind) across the ship's track line and through the strip as they avoid the oncoming vessel

Birds exhibiting the first two behaviors should be counted; those exhibiting the latter behavior should not be counted. Therefore, observers must watch birds well ahead of the ship (and well beyond each of the ship's forequarters) that would or would not pass on the side of the ship being surveyed. Having more than one observer on watch facilitates attention to such situations and to distinguishing birds attracted to the vessel from those not attracted (see earlier discussion).

CONCLUSION

The results of the present study indicate that, regardless of the survey method employed, studies that use a strip ≥ 300 m, and that are designed to obtain accurate estimates of seabird abundance, require multiple observer teams using two or more observers on watch simultaneously. Our comparisons of the vector and snapshot methods also indicate that the snapshot method can provide acceptable estimates of density when a 300 m–wide survey strip is viewed from one of the ship's forequarters. Further studies, with both methods being conducted simultaneously using multiple-observer teams, are required to examine that possibility. In addition, studies are needed to determine the number of observers required to detect at least 95% of the birds of different species groups relative to differences in survey-strip width and configuration. We suggest that another factor fundamental to obtaining accurate counts is the need to use only those observers trained during seabird surveys conducted with an experienced instructor.

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