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USE OF RADAR FOR MONITORING COLONIAL BURROW-NESTING SEABIRDS

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Abstract.—We used high-frequency surveillance radar as a non-intrusive method to census nocturnal burrow-nesting Cassin's Auklet (*Ptychoramphus aleuticus*) on the world's largest colony, Triangle Island, British Columbia. In the largest subcolony, West Bay, the radar unit was operated 2200–0510 h nightly from 30 Apr.–11 May 1996 during the onset of hatching. Radar images were stored on video cassette for subsequent image analysis. We report total nightly activity based upon cumulative samples from the tapes at 30-s intervals to determine the percent of bird activity within a fixed area. Estimates of the average image size of an individual bird were used to develop conservative counts of birds in the sample area. Activity at the colony began approximately 1.5 h after sunset and ended at least 15 min before sunrise. Activity levels increased over the study period and showed considerably nightly variation. Nightly activity was continuous at low levels through the sampling period from 30 Apr. to 3 May. Late evening peaks of activity around 2300 h were evident and tended to increase in intensity from 3 May onward. Nightly activity at the colony was correlated with the number of chicks hatched the following day. The maximum estimate of individual birds detected was 156,327 on 10 May. Radar has great potential to elucidate patterns of seasonal activity. We contrast and evaluate the use of radar and traditional methods based on burrow counts and identify several major advantages for radar in long-term population monitoring and seabird research programs.

USO DE RADARES PARA MONITOREAR AVES MARINAS COLONIALES QUE ANIDAN EN HUECOS

Sinopsis.—Utilizamos radares de seguimiento de alta frecuencia como un método no intrusivo para censar individuos de *Ptychoramphus aleuticus* anidando en huecos en la colonia más grande del mundo, en la Isla del Triángulo, Columbia Británica. En la subcolonia más grande, West Bay, la unidad de radar se operó de 2200 a 0510 h todas las noches desde abril 30 hasta mayo 11 del 1996 durante el comienzo del empollamiento. Se almacenaron las imágenes de radar en cintas de video para analizarlas luego. Reportamos actividad nocturna total basándonos en muestras acumuladas de las cintas a intérvalos de 30 s para determinar el porcentaje de actividad de las aves dentro de un área fija. Los estimados del tamaño de imagen promedio de un ave individual se usaron para desarrollar conteos conservativos de aves en el área de muestreo. La actividad en la colonia comenzó cerca de 1.5 h después del anochecer y terminaba al menos 15 min antes del amanecer. Los niveles de actividad aumentaron a través del período de estudio y mostraron una variación nocturna considerable. De noche, la actividad fué continua (a bajos niveles) a través del período de muestreo de abril 30 al 3 de mayo. Los picos de actividad tarde en la noche fueron evidentes cerca de las 2300 h y de mayo 3 en adelante hubo la tendencia de aumentar en intensidad. Se correlacionó la actividad nocturna con el número de pichones eclosionados el día después. El estimado máximo de aves individuales detectados fué de 156,327 en mayo 10. El uso de radares tiene un gran potencial para elucidar patrones de actividad estacional. Contrastamos y evaluamos el uso de radares y métodos tradicionales basados en conteos de huecos e identificamos varias ventajas importantes para el uso de radares en programas a largo plazo de monitoreo de poblaciones y de investigación de aves marinas.

Most modern schemes for censusing and monitoring numbers of burrow-nesting seabirds are based upon counts of "apparently occupied burrows" (Anker-Nilssen and Røstad 1993, Walsh et al. 1995) or estimates of occupied burrows (calculated from the product of counts of burrows and the percentage of burrows known to be occupied through physical examination [e.g., Rodway et al. 1988, Bertram 1995]). Counts of apparently occupied burrows, however, are subject to significant observer bias, and the necessity that surveys be conducted prior to the arrival of juvenile prospectors and when vegetation is low and occupancy is most visible (Anker-Nilssen and Røstad 1993). In addition, burrow-based counts underestimate true adult population size (Anker-Nilssen and Røstad 1993). Estimates of "true" burrow occupancy are not suitable for long-term monitoring for some species because physical examination causes frequent desertions and thus lowers the chance that those burrows will be used in subsequent years (Gaston et al. 1988, Rodway et al. 1996). Further drawbacks of this method are reduced repeatability because it is difficult to define objectively what constitutes a burrow; possible bias in estimates of occupancy because nest chambers cannot always be inspected; and intensive labor requirements because, in addition to counts, a subset of the burrows must also be excavated (Gaston et al. 1988). In fragile habitats, methods that require burrow counting (and in particular those requiring excavation) are potentially destructive to colonies thus compromising conservation efforts.

The purpose of this paper is to report the use of radar as an alternative, non-intrusive method for monitoring, censusing, and quantifying colony-attendance behavior of a colonial burrow nesting seabird. Radar has been used in studies of seabird movements (Day and Cooper 1995) and for estimating numbers of the non-colonial Marbled Murrelet (*Brachyramphus marmoratus,* Burger 1997) but had not yet been deployed for census and monitoring studies on a major colony of burrow nesters. We contrast the radar and the burrow count (see above) methods, identify important areas for further research, and highlight the potential utility of radar for long-term monitoring and research programs for seabird populations in general.

METHODS

We studied Cassin's Auklets (*Ptychoramphus aleuticus*) at the world's largest colony on Triangle Island (the Anne Vallée Ecological Reserve, 51°52′N, 129°05′W), in British Columbia, Canada. It is noteworthy that 80% of the world's breeding population of Cassin's Auklet are found along the rugged islands of northern coastal British Columbia (Rodway 1991). Triangle Island is located 46 km northwest of Cape Scott on Vancouver Island (see Vermeer et al. [1979] for a description of the breeding habitat). From 30 Apr.–11 May 1996 we deployed a high-frequency marine surveillance radar unit (Furuno FR810D, 940MHz, 10KW with a 2.0-m antenna) in West Bay (Fig. 1) where the largest burrow densities of breeding Cassin's Auklet were reported. Cassin's Auklet was the only seabird nesting in West Bay in significant numbers (Rodway et al. 1990). The radar unit was positioned above high tide at the base of the edge of a rocky slope behind a large log and wooden fence that reduced the interference caused by wave activity. The radar antenna was 75 cm above the ground and 30 cm below the top of the log. The radar antenna was tilted 15° up from its normal horizontal position and, with an anti-clutter screen mounted on the lower edge (Cooper et al. 1991, Burger 1997), scanned an estimated vertical are of 35° above the horizon. Both the rain and sea-scatter suppressers were turned off to maximize the sensitivity and hence the likelihood of bird detection. The gain was set at 75% of maximum to maximize bird detection and minimize noise. Radial line markers at 240° and 340° were added to the radar screen. The scanning radius was 0.5 km. The time taken for the antenna to make a complete horizontal revolution was 3.02 ± 0.01 s (SD, Burger 1997).

Video images of the radar screen were obtained by installing a video converter (Furuno RP-6065B) between the radar and a VHS video cassette recorder. A time-date stamp was also placed on the recording. The system was operated with a series of 12V batteries. Each night the radar unit was started between 2200–2300 h and stopped at 0300–0510 depending on the available battery power.

The total sample region included the area above the ocean in West Bay and horizontally 100–500 m from the radar unit. The two dimensional sampling area from the radar image was 125,732 m^2 (Fig. 2a). Most birds flew straight in and out of the colony and circling birds were not seen

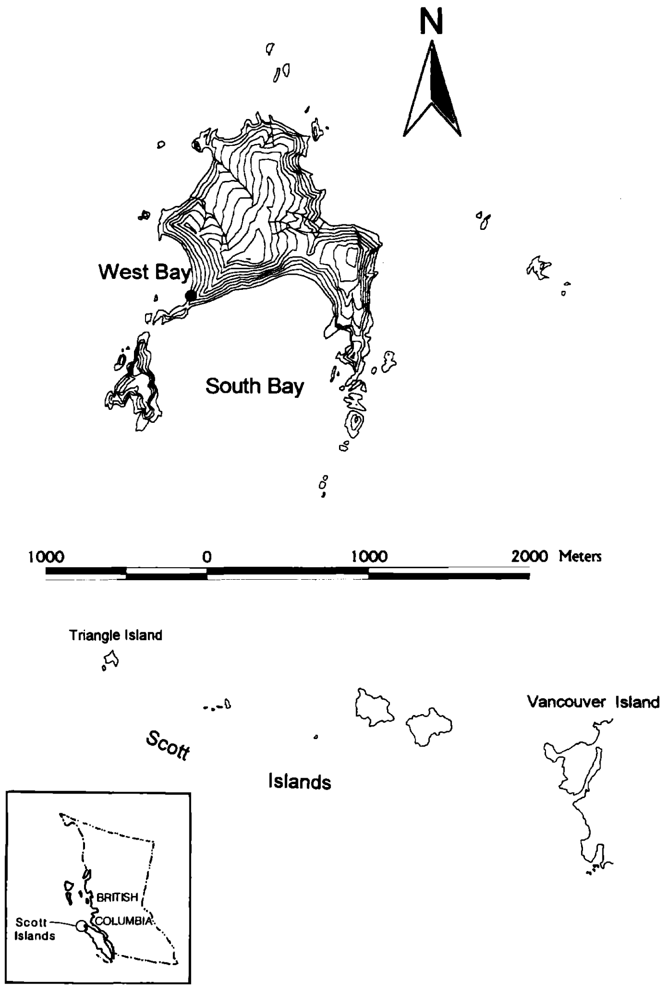

FIGURE 1. Triangle Island, British Columbia showing the location of the radar unit in West Bay in 1996 (●).

on the video tapes. We assumed that birds circling over the colony would stay within 100 m of the radar unit and hence not be counted twice. Seabird activity was sampled from videotapes every 10 min throughout the night and every 2 min near peak activity using an image acquisition device (Play Technologies Snappy Video Snapshot, with the contrast set to the maximum value) on a computer (Nantron Systems, pentium, 120 mhz). We did not sample during periods of rain because bird images were obscured. Birds flying at different heights or distances produced varying amounts of white on the video images thus creating a greyscale. We used

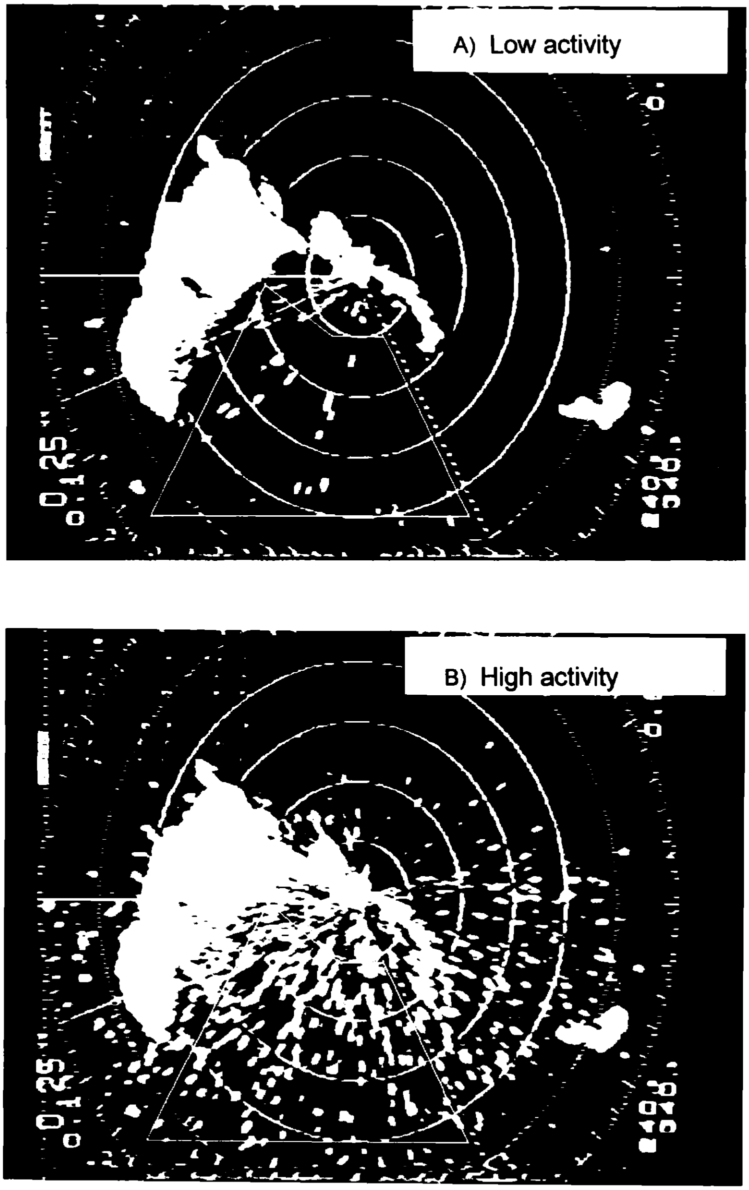

FIGURE 2. The radar images captured from videotape during low activity (A: 1 May, 0020 h) and during high activity (B: 10 May, 2333 h) of Cassin's Auklets in West Bay. The sampling area for activity determination is delineated in both panels. The rings are separated by 100 m and form the boundaries for quadrants 1–4.

the UTHSCSA Image Tool program to create binary images (black and white) by converting all gray pixels to white using the threshold function. For each "captured" image the sampling area in West Bay was selected and a histogram showing the percent white and black was created. Activity was defined as the percent of white pixels due to bird attendance in the scanned area. This was calculated by subtracting the number of white pixels in the images from control images that were taken from the beginning or end of the tapes when no birds were present. Tide heights of the control and sample images were matched as closely as possible, to accommodate changes in shoreline land appearing in the image.

The flight speeds of Cassin's Auklets were estimated from the distance covered between successive images on the radar screen (measured with a ruler with a precision equivalent to 10 m) divided by the time taken for the antenna to make a complete horizontal revolution (3.02 s). To travel the 500 m from the edge of the radar screen to the colony at the minimum speed (60 km/h: max. = 132 km/h, mean = 95.8, SD = 14.8 km/h, $n = 60$) would require approximately 30 s. Sampling every 30 s counted the slowest birds only once and thus produced conservative estimates of nightly activity. To obtain estimates of the number of birds at 30-s intervals we interpolated from the images captured at 2-min or 10-min intervals.

Sampling bouts were not always the same duration, so to compare total nightly activity we interpolated at the beginning and/or the end of tapes. We assumed that the earliest (2200, 2210, or 2225 h) and the latest (0510, 0525, or 0535 h) interpolation times had no bird activity based upon our observations at those times on other nights. Following interpolation, colony activity was gauged for a 7 h 10 min period (861 30-s intervals) each night by the cumulative total of white pixels from all 30-s intervals.

To estimate the number of individual birds in the sampling area we calculated "bird area" estimates based upon echoes of known single birds. We tested for differences in the size of echoes of single birds by sampling 30 individuals in each of four quadrants at distances of 100–200 m, 200–300 m, 300–400 m, and 400–500 m from the radar unit (quadrants 1–4). If differences could not be detected we would use the median value for all quadrants. To calculate a conservative estimate of the number of birds in the radar images we divided the area of activity by the median area of an individual Cassin's Auklet. The cumulative totals of birds observed at 30-s intervals were reported for each night.

In the Farallon Islands, Manuwal and Thorsen (1993) reported that incubating and brooding pairs of Cassin's Auklet alternate duties every 24 h. Brooding lasts for up to 5 d after hatching. Following brooding, both parents can deliver food but single nightly feeds are most common (provisioning rates on Triangle Island vary from 0–2 feeds per night; DFB, unpubl. data). Our estimates of activity and the numbers of individual birds in West Bay assumed that all birds were incubating, brooding, or one parent from each pair was delivering a single meal then brooding. Hence each parent is detected once, either while returning to or departing from the colony.

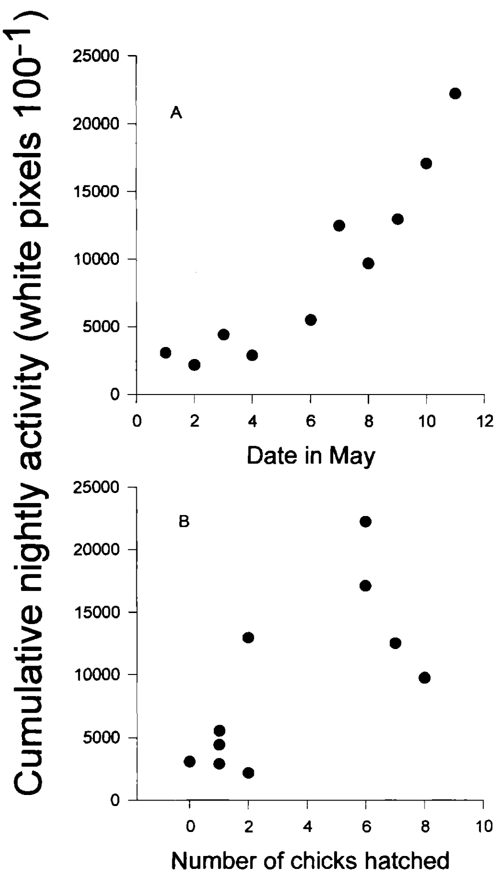

FIGURE 3. Increase in cumulative nightly activity during the study period (A). The relationship between hatch date and cumulative nightly activity levels during the study period on Triangle Island (B).

On four occasions concurrent with radar monitoring we captured Cassin's Auklets as they departed from the colony between 0200–0430 h using a "pheasant net" 15-m long and 3-m high in West Bay. We scored the iris color type as white, offwhite, light brown, or brown, based upon minor modifications of the technique of Manuwal (1978). Eye color is reported to become lighter as the birds age (see also Emslie et al. 1990).

Hatching dates of nestlings in West Bay were estimated by inspection of a sample of burrows at 3-d intervals beginning 30 d after laying.

RESULTS

Activity levels and patterns.—Activity levels increased over the study period (Fig. 3a) and showed considerable nightly variation in pattern (Fig. 4). Activity at the colony began approximately 1.5 h after sunset and end-

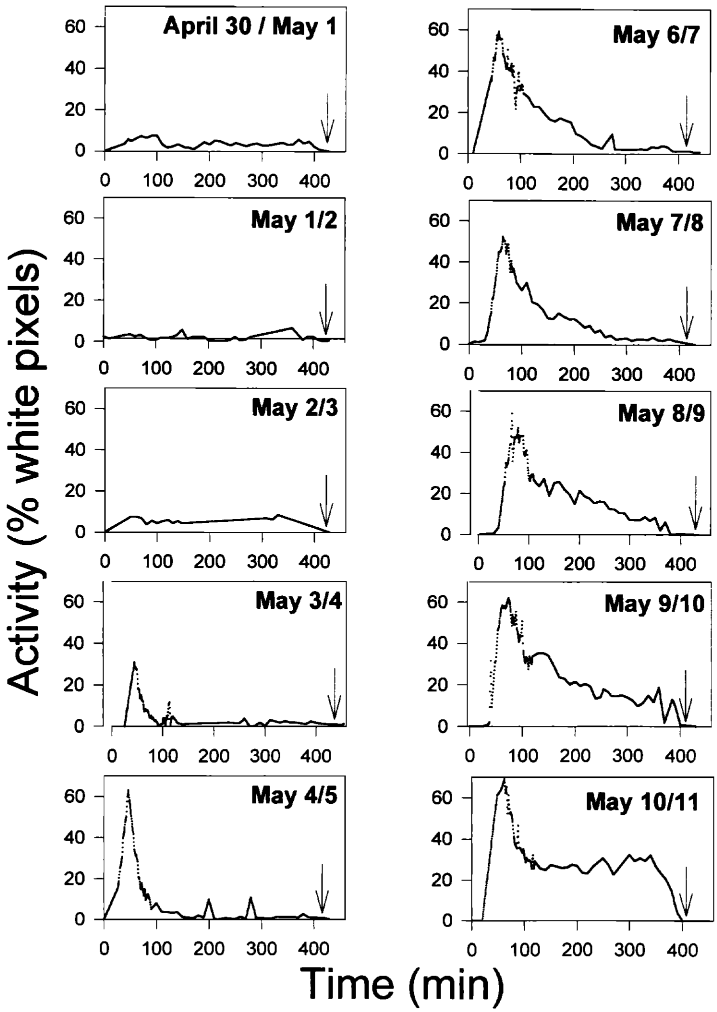

FIGURE 4. Patterns of "nightly" activity (2200–0510 h) from 30 Apr.–11 May 1996 in West Bay, Triangle Island as gauged by radar. Video images were "captured" at 2–10-min intervals and the other values were interpolated. Activity was gauged as the percentage of the sampling area that was occupied by birds. Arrows depict the time of sunrise.

ed at least 15 min before sunrise. Nightly activity was continuous at low levels through the sampling period from 30 Apr.–3 May. Late evening peaks of activity around 2300 h (which lasted approximately 2 h) were evident and tended to increase in intensity from 3 May onward. Activity levels extended progressively into the late night from 7 May onwards until the end of sampling.

Breeding chronology and activity levels.—The first auklet nestling hatched

TABLE 1. Cumulative "nightly" activity, time, and magnitude of maximum activity of Cassin's Auklets as gauged by radar in West Bay of Triangle Island in 1996. Estimates of the cumulative nightly number of birds in West Bay were based upon the median estimates of the area for an individual bird.

Date	Time radar operated	Cumulative activity (white pixels/100)	Maximum activity (%)	Time of maximum activity	Total area of birds (m^2)	Estimated number of birds
30 April	2238–0449	3057.34	7.62	2340	3,844,032	21,475
1 May	2200–0510[a]	2157.57	6.81	0400	2,712,733	15,155
2 May	2250–0330[b]	4410.50	8.52	0330	5,545,369	30,980
3 May	2245–0535[c]	2875.52	30.93	2245	3,615,430	20,198
4 May	2230–0500	5525.16	62.99	2246	6,946,848	38,809
6 May	2245–0445	12,501.89	59.26	2258	15,718,773	87,814
7 May	2210–0430[d]	9715.62	52.36	2304	12,215,567	68,243
8 May	2230–0440	12,955.84	51.92	2318	16,289,530	91,003
9 May	2230–0440[e]	17,112.31	62.22	2314	21,515,509	120,198
10 May	2220–0440[f]	22,255.85	69.01	2302	27,982,542	156,327[g]

[a] Except 0220–0400, 0402–0420 h.
[b] Except 0027–0306 h.
[c] Except 0030–0150 h.
[d] Except 0240–0300 h.
[e] Except 0215–0225, 0410–0425 h.
[f] Except 2225–2310, 0150–0210, 0240–0300 h.
[g] Estimates were 1,974,774, 44,716 and 142,810 using the minimum, maximum and mean values for individual bird area, respectively.

on 2 May in 1996. The median hatch date was 11 May with the latest hatching on 16 June (n = 56). During the radar sampling period the number of chicks hatching generally increased. Nightly activity at the colony was positively correlated with the number of chicks hatched the following day ($r = 0.93$, $n = 10$, $P < 0.001$, Fig. 3b).

Conservative counts of birds in West Bay.—The size of individual bird images did not differ significantly with the distance from the radar unit and therefore samples from all qaudrants were pooled to estimate numbers of birds. The median bird image was 179 m^2 (mean = 196.5, SE = 10.2, n = 124; range = 14.6–661.3).

As expected, the increase in number of birds in early May mirrored the activity results (Table 1). The maximum estimate of individual birds detected was 156,327 on the night of 10–11 May. The minimum was 15,155 on 1–2 May.

At the netting site in West Bay eye color became progressively darker at later capture sessions. No brown-eyed birds (presumed to be immatures) were captured on 5 May (n = 23) and 8 May (n = 31) but they appeared among 6% of captures on 10 May (n = 28) and 11 May (n = 27). The broad category, light brown, increased from approximately 18% on the first two capture bouts to 40% in the last two bouts. Conversely, the incidence of white eyed birds declined 49% to 16% during the same time frame. The number of birds with off-white eye color was similar for all capture sessions (range 25%–43%).

DISCUSSION

Nightly activity levels in West Bay varied seven-fold, with the minimum occurring on 1 May and the maximum on 10 May. Based on the assumptions of 24-h shifts in incubation, and single feeds/night coupled with brooding of young nestlings, the observed increase in activity during hatching was not expected and thus warrants consideration of the validity of the assumptions. For example, the magnitude of shift duration for incubation and brooding may be variable and longer than 24 h. Data on Cassin's Auklets from Frederick Island, British Columbia (1995–1997) do vary (e.g., some 48 h and 72 h incubation shifts), but most nesting pairs (95% or greater) exchange incubation duties every 24 h (A. Harefensit, unpubl. data). Information from another project on Triangle Island in 1998 also suggests 48 h incubation in 5 of 16 burrows examined. Variation in shift duration coupled with more regular visits around hatching could have contributed to the observed increase in activity in our study.

It is also possible that some nestlings may be fed by a single adult and not brooded, resulting in two detections of the same individual when incoming and outgoing. Some of the oldest nestlings may also have been fed by both parents and not brooded in the later part of the study period in which case both parents would be detected twice. Increases in colony activity at hatching have also been reported for Atlantic Puffins (*Fratercula arctica*; Harris 1984). Increased attendance by young, non-breeding birds at the colony during hatching likely contributed to the observed increase in activity during our study. Birds with light brown and brown irises are most likely to be 1–2 yr old and immature, while those with white and off-white irises are most likely to be breeders (Manuwal 1978, Emslie et al. 1990). A larger proportion of dark-eyed birds were captured in the later netting sessions. Harris (1984) also noted that the number of young, non-breeding Atlantic Puffins on the colony increased as the breeding season progressed (Harris 1984).

In British Columbia, a comparison of four survey methods (quadrat, transect, point-center quarter and Batcheler's) identified the quadrat and transect methods as most accurate (Savard and Smith 1985). That finding led to the development of the principal inventory method used for most seabird colonies in the province, including Triangle Island. The census technique (Rodway et al. 1988; Bertram 1995) is based on counts of burrows in plots placed at specific intervals along transects perpendicular to the shore, average burrow density, estimates of colony area, and burrow occupancy estimates. The total estimated nesting population on Triangle Island based on 1989 transect sampling was 547,637 ± 25,748 (SE) pairs (Rodway et al. 1990). In West Bay the breeding population estimates ranged from 96,346 pairs (Rodway et al. 1990) to 130,359 pairs (CWS unpubl. data) depending upon the burrow density estimate used in calculations. This translates to approximately 193,000–261,000 breeding individuals in West Bay in 1989. In the present study, the maximum number of birds detected was 156,327 based on the median size of individuals on the radar screen. This is likely to be a conservative estimate because the sampling interval (30 s) was based on the slowest flight speeds observed, and we could not detect birds that flew into West Bay over land. A further potential source of error, which could produce underestimates, is overlapping and obscured images of birds flying near each other. The relationship between the actual number of Cassin's Auklet and the number detected would be asymptotic if bird overlap and obscured images increased with activity levels. Note, however, that the maximum observed activity never represented more than 70% of the sample area, and that those high levels were short-lived thus reducing the potential for underestimation due to bird overlap. Finally, many departing birds dive steeply from the slopes and often stay close to the water perhaps reducing their chance of detection on radar and thus contributing to the underestimation of individual birds. The similar magnitude of the estimates of numbers based on the 1989 transect survey and the present study suggests that radar can be a useful tool for quantifying population changes. We evaluate and summarize the merits of radar versus monitoring techniques based upon burrow counts below.

Gaston et al. (1988) suggest that a monitoring technique should provide an accurate index of population trends, be fast, have little observer bias and cause minimal disturbance to breeding birds. Our work shows that the radar method has strong potential to provide an accurate index of population trends. Prior to implementation, however, general design principles (e.g., choice of sample unit, when to sample, and statistical power; see Peterman 1990, Thomas 1996) for a radar-based monitoring program will need to be considered to develop the most sensitive index from the least amount of field effort. It is noteworthy that recent analysis of Norwegian long-term data derived from burrow counts (Anker-Nilssen et al. 1996) showed that trends documented for some seabird populations could have been detected with much less field effort (fewer plots and less frequent visits). By contrast, in British Columbia, population trends have been difficult to detect because few colonies have been visited in less than 5-yr intervals, and plots on transect surveys have covered only limited proportions of the colony area. Moreover, on Langara Island, British Columbia, population estimates based on transect surveys did not reflect a decline in Ancient Murrelets despite the fact that colony extent had diminished by half from rat predation (Bertram 1995, Bertram and Nagorsen 1995). The present study was confined to West Bay, but complete colony coverage on Triangle Island could be achieved by sequential sampling in sub colonies with a mobile radar unit. Unlike burrow-based monitoring and census techniques, the radar technique has the potential to be conducted quickly and to be repeated daily. However, the most appropriate time frame for sampling needs to be determined. The large increase in activity levels during our study also underscore the sensitivity of estimates of apparently occupied burrows to sampling date. Radar monitoring should be readily transferable between different observers. This is a major advantage over burrow-based schemes which often require that counts are made by the same person in every year (e.g., Anker-Nilssen and Røstad 1993). Finally, radar is non-intrusive and does not cause the disturbance and possible destruction to breeding habitat which have been identified as significant drawbacks of burrow-based methods (see above).

Our results strongly suggest that radar technology can be a useful tool in seabird population monitoring and research programs. Note that the radar technique could also be applied to monitoring flight activities around large colonies of surface- and cliff-nesting seabirds which are too large for counting individuals. On Triangle Island we will investigate factors which affect colony attendance patterns to develop a population index based on the radar techniques outlined herein. Long-term radar monitoring will thus facilitate the development of a time series data set which will be coupled with traditional demographic studies to evaluate the causes of population changes and to predict future trends. Such time series information will be fundamental for evaluating the effects of large-scale decadal and interdecadal changes in marine ecosystem production on seabird populations.

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