RADAR AS A TOOL FOR MONITORING XANTUS'S MURRELET POPULATIONS

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SUMMARY

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Xantus's Murrelets *Synthliboramphus hypoleucus* are vulnerable to extirpation from breeding islands because of high mortality rates from introduced mammalian predators. Black Rats *Rattus rattus* were eradicated from Anacapa Island in 2001 and 2002 to restore seabird populations. For baseline and subsequent monitoring to assess the results of the rat eradication on Xantus's Murrelet populations, we developed population monitoring methods using a modified marine radar system and conducted nocturnal surveys to count the numbers of birds flying into or out of sample nesting habitats during the 2000 breeding season. High activity periods, activity zones and specific behaviors were examined for their ability to generate reliable data for a long-term population monitoring program. Radar is a useful tool to quantify the level of breeding activity in sample areas at nesting colonies and can be used to monitor population changes, to compare relative sizes of different colonies, to locate new breeding colonies, to confirm the continued existence of known historical colonies and to document use of specific nesting habitats at colonies.

Key words: California Channel Islands, introduced predators, radar, monitoring, rat eradication, *Synthliboramphus hypoleucus,* Xantus's Murrelets

INTRODUCTION

Xantus's Murrelets *Synthliboramphus hypoleucus* nest in loose colonies on the Channel Islands off southern California, USA, and islands off northwestern Baja California, Mexico (Hunt *et al.* 1980, Murray *et al.* 1983, Carter *et al.* 1992, Drost & Lewis 1995). The colonies are vulnerable to extirpation from breeding islands through predation by introduced mammalian predators (Jehl & Bond 1975, McChesney & Tershy 1998). Nest sites of Xantus's Murrelets occur mainly in rock crevices and to a much lesser extent under plants and artificial structures. At many colonies, a large proportion of nests occur in cliffs and steep slopes that are not easily accessible by humans without extensive climbing skill and equipment. Nest sites are visited only at night during the long incubation period (averaging 34 days), parents take long incubation shifts (one to six days), and eggs are periodically neglected (for one to four days). Chicks are precocial upon hatching and at two days old they depart from nest sites, accompanied by adults, for further rearing at sea (Murray *et al.* 1983). The birds' use of largely inaccessible island habitats and of nocturnal and non-daily nest visitations and their foraging far from shore makes it difficult to find colonies, estimate population size and monitor population changes.

In 1998/99, eradication of introduced Black Rats *Rattus rattus* at Anacapa Island in the northern Channel Islands, California, was planned by federal and state trustee agencies with funds obtained from the 1998 litigation settlement for the 1990 *American Trader* oil spill (ATTC 2001). Despite pioneering work to document the continued existence and approximate size of the Anacapa colony during 1994–1997 (McChesney *et al.* 2000; H. Carter, unpubl. data), inadequate baseline data on the murrelet population existed to quantitatively measure changes in the population after rat eradication. During 2000–2003, a team of biologists developed new monitoring techniques and gathered baseline data for a long-term Xantus's Murrelet population monitoring program (ATTC 2001; Hamer *et al.* 2003; Whitworth *et al.* 2003, 2005).

Ornithological surveillance radar techniques were selected for application because they permit examination of bird activity in inaccessible habitats at Anacapa Island and have recently been applied to successfully monitor and study aspects of the biology of other seabirds in relatively inaccessible nesting habitats (Hamer *et al.* 1995, Burger 1997, Cooper & Blaha 1997, Cowen *et al.* 1997, Day & Cooper 1995, Burger *et al.* 2004). In past studies, radar units were mounted either on boats for offshore work or on a camper unit and four-wheel-drive truck for terrestrial work. Several types of radar have been effective tools in ornithological research for more than four decades (Eastwood 1967). Marine radar is probably the easiest and least expensive to operate and has additional benefits of high resolution, small minimal sampling range, high availability and high portability (Cooper *et al.* 1991, Hamer *et al.* 1995).

In this paper, we summarize radar monitoring techniques developed in 2000 to measure changes in the numbers of Xantus's Murrelets attending nest sites in inaccessible habitats in steep slopes and cliffs at Anacapa Island. We also report preliminary work at Santa Barbara and Santa Catalina Islands in 2000, which demonstrated additional uses for radar monitoring.

METHODS

Study area

Anacapa Island falls within Ventura County, California, and lies 15 km off the southern California mainland near Ventura (Fig. 1). Anacapa is the easternmost and smallest of the four northern Channel Islands. The island is composed of three small islets (West, Middle, and East Anacapa) managed by Channel Islands National Park (CINP). Waters extending 9.6 km offshore of Anacapa Island are managed by the Channel Islands National Marine Sanctuary (CINMS) and other agencies. The narrow island chain is approximately 7.5 km long with a 17.5 km perimeter of steep rocky slopes and cliffs, and is topped by flat or more gently sloping plains. The coastline harbors more than 100 sea caves (Bunnell 1993). West Anacapa Island is the largest in area (1.7 km^2) and highest (284 m), followed by Middle Anacapa Island (0.6 km^2, 99 m) and East Anacapa Island (0.5 km^2, 73 m). In April and May 2000, we conducted radar surveys from the CINMS research vessel *Balleña* anchored off the south side of Middle Anacapa Island (34°00.322′N, 119°22.910′W), approximately 300 m off East Fish Camp, a semiprotected anchorage. The location provided approximately 1.5 km of radar coverage of potential coastal nesting habitats (16% of the total shoreline of Middle Anacapa Island and East Anacapa Island combined).

Santa Barbara Island lies 60 km southwest of Los Angeles but still within Santa Barbara County. The island is managed by CINP and the surrounding waters by CINMS and other agencies (Fig. 1). Santa Barbara Island is the smallest (2.5 km^2; elevation: 193 m) of the four southern Channel Islands. The coastline of Santa Barbara Island consists of rugged sheer cliffs and steep rocky slopes topped by a gently sloping plain. We conducted a single radar survey at the island in April 2000 from the vessel *Balleña* anchored off the east side (33°28.983′N, 119°01.522′W), approximately 300 m off Landing Cove, a semiprotected anchorage. This location allowed approximately 1.6 km of radar coverage of potential coastal nesting habitats (12.0% of the total shoreline of Santa Barbara Island).

Santa Catalina Island, managed mainly by the Catalina Conservancy, lies about 30 km southwest of Los Angeles in Los Angeles County. In April 2000, we conducted a single survey aboard the vessel *Balleña* at the northwestern end of Santa Catalina Island, 400 m from Eagle Rock (33°27.892′N; 118°35.856′W) and north of Catalina Harbor. The sampled area has extensive steep slopes and cliffs and is highly exposed to prevailing norhtwest winds, without a protected anchorage (Fig. 1). This location provided approximately 1.6 km of radar coverage of potential coastal nesting habitats (4% of the total shoreline of Santa Catalina Island).

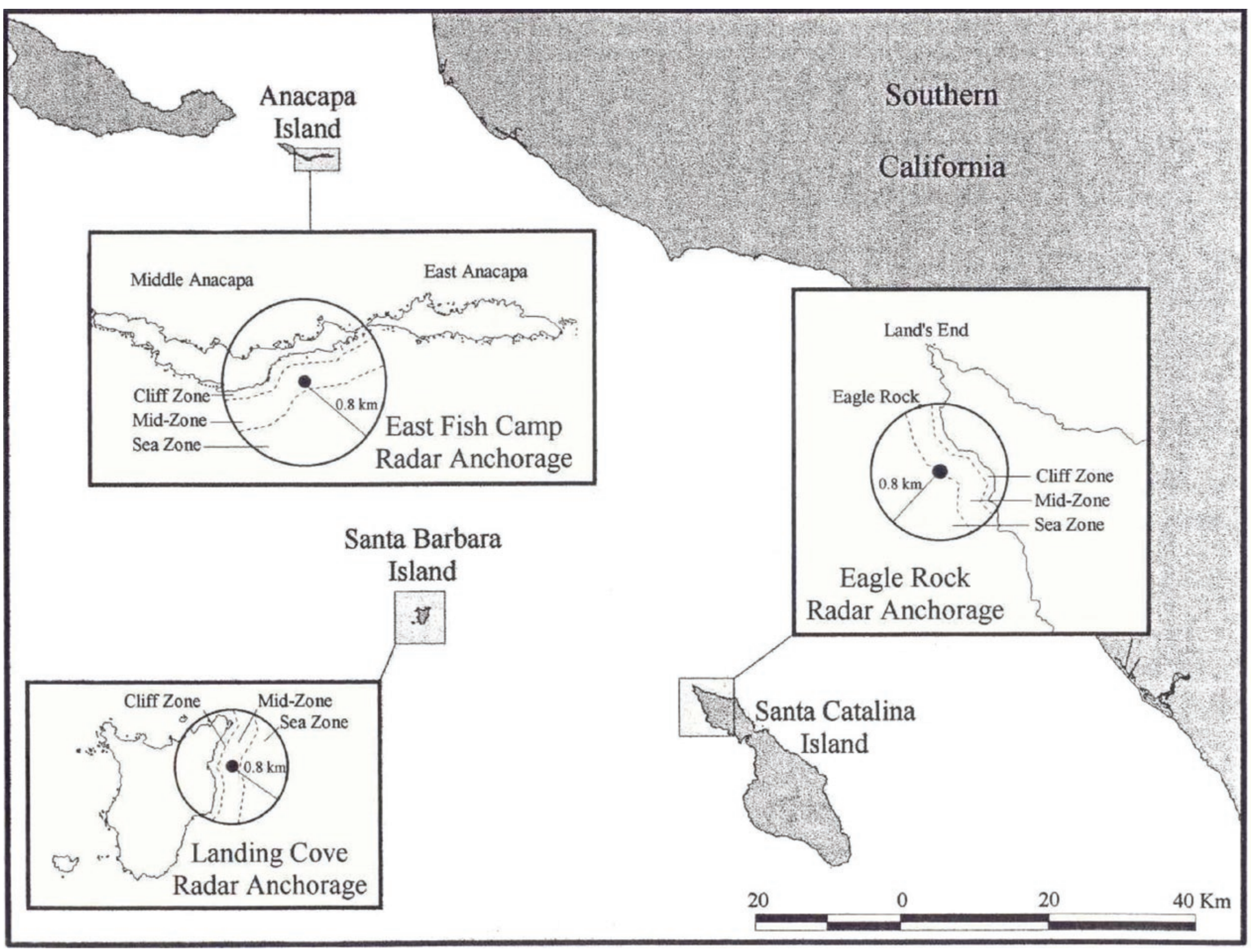

Fig. 1. Radar survey stations at Anacapa, Santa Barbara, and Santa Catalina islands in 2000, and activity zones sampled.

Radar equipment

Radar surveys were conducted using a model FCR-1411, 10-kW, X-band radar unit (Furuno Marine Electronics, Camas, WA, USA), with a flexible two-metre-long slotted waveguide array antenna. Pulse length could be set at 0.08, 0.6, or 1.0 µs, depending on range setting. The radar beam had a vertical span of 25 degrees and a horizontal beam width of two degrees. The radar was mounted directly on the wheelhouse of the *Balleña,* about 4 m above sea level. All data in 2000 were collected under relatively calm sea conditions with a radar vertical tilt of 0–10 degrees. If increasing wave clutter prevented a complete four-hour survey from 23h00 to 03h00 (PDT), the survey was cancelled or the data were not used in analyses. We did not conduct surveys in weather conditions that caused radar clutter along 50% or more of the island coastline, which effectively obscured detections in the survey area. Because of the difficulty of detecting a relatively small murrelet-sized target at great distances with the radar, the 0.5 nm setting (1.1 km radius) was used as the most appropriate scale for monitoring. The radar completed one scan every 2.5 s with a plotting function set to 30 s. Therefore, each radar target would leave an echo trail with each echo retained for 30 s. The echo trail could be subsequently plotted and measured, allowing us to estimate flight speeds by using a handheld scale to measure the distance between three or more echoes.

Data collection

A biologist experienced in interpretation of radar echoes monitored the screen and recorded murrelet detections on a data sheet. Echoes on the radar screen were also recorded for the duration of each survey using a Sony (New York, NY, USA) 8-mm video camera so that biologists could review survey sessions at a later date.

In 2000, we monitored sites during the expected main incubation period in April and May, based on past average timing of breeding at Santa Barbara Island (Murray *et al.* 1983, Drost & Lewis 1995). Radar surveys were conducted throughout the night from 20h00 to 05h00 to document activity patterns. Weather conditions—including sea state, percent cloud cover, horizontal visibility (good, fair, poor), wind speed (km/h), wind direction, precipitation, air temperature (degrees Celsius), sea-surface temperature (degrees Celsius), cloud ceiling height (m) and moon phase (quarterly)—were recorded at the beginning and end of each survey period.

For each radar detection, we recorded identification number, time, activity zone, flight behavior, distance between echoes on the radar screen (mm), flight speed (km/h) and the number of radar echoes. All murrelet detections were segregated into three zones of activity (Fig. 1) when first observed:

- Cliff zone: within 100 m of the coastline
- Middle zone: within 101–400 m of the coastline
- Sea zone: more than 400 m from the coastline.

Large samples of flight paths in the cliff zone were plotted on US Geological Survey 7.5-minute topographic maps, when time allowed. Within the cliff zone, each detection was assigned one of four categories of flight behaviors:

- Inbound: flying towards the island within +45 degrees of a line perpendicular to the coastline
- Outbound: flying away from the island within +45 degrees of a line perpendicular to the coastline
- Circling: circling with a minimum 1/4 arc
- Unknown: flying parallel to coastline, at angles greater than 45 degrees of the coastline axis or without initial or final bearing from the shoreline

Species identification

Flight speed and echo size were used to identify Xantus's Murrelet radar detections. Targets with less than three echoes were not used because accurate flight speeds could not be calculated. When possible, four or more echoes were used to measure and calculate flight speed. To minimize the number of non-murrelet targets recorded, only birds flying 50 km/h or more were recorded as Xantus's Murrelets. The echo size of birds varied with the distance of the target from the radar and the orientation of the bird with respect to the radar. To help distinguish Xantus's Murrelets from other seabirds that frequently occurred in the nearshore region at Anacapa Island, daytime radar surveys in 2000 were conducted concurrently with an outside observer who gathered data on flight speed and echo size of other seabirds, including cormorants *Phalacrocorax* spp., Brown Pelicans *Pelecanus occidentalis* and Western Gulls *Larus occidentalis* (Hamer & Meekins 2002). Other seabird species somewhat similar in body size to the Xantus's Murrelet and known to fly at night included Ashy Storm-Petrels *Oceanodroma homochroa* and Cassin's Auklets *Ptychoramphus aleuticus.* To assist in confirming murrelet echoes, we identified a small sample of murrelet type echoes at night using both radar and simultaneous visual identification by personnel in inflatable boats.

Statistical analyses

We calculated hourly and nightly means, maximums, minimums, standard deviations and coefficients of variation (CVs) for radar detections. For hourly detection rates, we compiled total number of targets and total targets within four behavior categories. We then examined various behavior combinations by one-hour sampling period and presented estimates of the number of targets per hour for each sampling period. We graphically examined CV values for hourly detection rates for all nights combined to identify periods when CVs were lowest. To determine the percentage of the total variance in detection rate that occurred as variation between hours within nights (23h00–03h00) versus variation between nights, we used a nested variance component procedure. To determine if significant differences in mean hourly detections existed, we used ANOVA to test for differences between means. The above analyses were performed using the SPSS 10.0 for Windows statistical software (SPSS 1999) with $\alpha = 0.05$ for all tests. In addition, we tested for differences among islands in total nightly murrelet detections using a *t* statistic (t_s) designed for comparison of a single observation (n = one night each at Santa Barbara Island and Santa Catalina Island) with the mean of a sample (n = six nights at Anacapa Island; Sokal & Rohlf 1995: 227).

RESULTS

Sampling effort

Six nights of radar sampling from 20h00 to 05h00 were conducted at Anacapa Island between 10 April and 4 May 2000 (Table 1). Single nights of radar survey were conducted at Santa Barbara Island on 12 April and at Santa Catalina Island on 27 April (Table 1). A total of 80 hours of nocturnal radar sampling was conducted at colonies with an additional seven hours of diurnal sampling.

Species identification and flight speeds

Xantus's Murrelet average flight speed (all activity zones combined) was faster than other diurnal species examined, averaging 58.4 km/h [n = 1838; range: 45.0–98.2 km/h; standard deviation (SD): 8.4 km/h; Fig. 2]. The wide range of flight speeds probably reflects some birds flying at full speed and others at reduced speeds associated with take-off or landing on the water or at nest sites. All radar echoes (n = 12) recorded as Xantus's Murrelets and simultaneously observed on the water from an inflatable boat at night were confirmed as Xantus's Murrelets. For the 12 confirmed murrelets, the average flight speed was 54.6 km/h (range: 50.0–61.2 km/h). Flight paths of most murrelet targets in the cliff zone at Anacapa Island and Santa Barbara Island were heading directly into or away from (i.e. inbound or outbound) the shoreline of the island. Very few flight paths of birds flying parallel to the shoreline or circling were recorded (5.6% of all detections in 2000). Echo sizes of murrelet targets were relatively small at the 0.5 nm radar scale, varying from 2.0 mm to 2.5 mm in diameter.

Only cormorants (species unknown; three species occurred nearby during daylight hours) overlapped murrelet flight speeds, averaging 54.8 km/h (n = 75; range: 24.1–86.8 km/h; SD: 9.5 km/h; Fig. 2). However, cormorants most often flew parallel to the coastline during the day and were not observed from inflatable boats at night. Western Gull flight speeds averaged 35.6 km/h (n = 73; range: 12.9–49.9 km/h; SD: 5.1 km/h) and rarely attained 50.0 km/h, the lower end of Xantus's Murrelet flight speeds. Gulls also exhibited much larger radar echoes than Xantus's Murrelets. Brown Pelicans also had slower flight speeds than murrelets (average: 35.6 km/h; n = 21; range: 24.1–50.0 km/h; SD: 8.4 km/h; Fig. 2), a much larger radar echo and flight directions that paralleled the shoreline. Erratic and circling flight patterns of Ashy Storm-Petrels were sometimes observed by radar, but those birds had very small echoes on the radar screen (similar to bat echoes), and flight speeds were much slower than those of Xantus's Murrelets. Cassin's Auklets likely have flight speeds and radar echoes that are similar to Xantus's Murrelets, but no auklets were observed at night from inflatable boats and very few breed at Anacapa Island, away from the survey area (Whitworth *et al.* 2005).

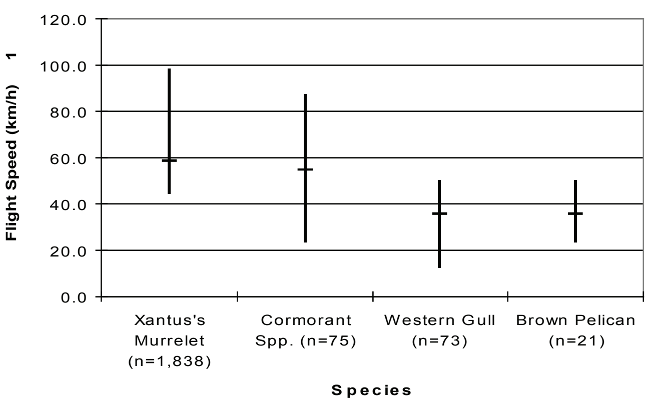

Fig. 2. Flight speeds (mean and range) for seabirds at Anacapa Island in 2000.

Hourly and nightly variation in radar counts

Hourly detection rates within each survey night at Anacapa Island showed similar trends in activity levels (Fig. 3). Birds were not detected until after official sunset (mean sunset time: 19h35), but detections increased rapidly over the next few hours. Over eight days at three colonies, birds were first detected by radar at 20h32, 57 minutes after official sunset on 27 April. For six survey nights at Anacapa Island, the earliest detection occurred at 20h43 on 3 May, 64 minutes after sunset, and the latest detection was at 05h33 (1 May) 48 minutes before official sunrise at 06h21. The mean time of the earliest inbound and outbound detections in the cliff zone occurred at 21h05 and 21h06, respectively (n = six nights). The mean time of latest inbound and outbound detections in the cliff zone occurred at 05h05 and 05h02 respectively (n = five nights).

Except for 13 April, detection rates increased rapidly after 21h00, approximately 90 minutes after sunset, and usually peaked between 24h00 and 01h00. On 13 April, detection rates did not rise

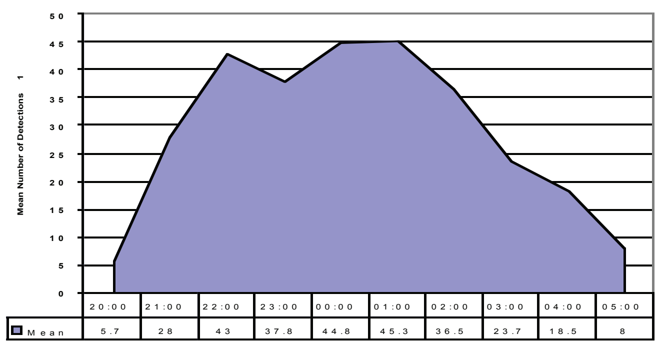

Fig. 3. Mean number of Xantus's Murrelet radar detections per hour (all behavior categories) at Anacapa Island for five nights of sampling in 2000.

TABLE 1
Xantus's Murrelet radar surveys at Anacapa, Santa Barbara and Santa Catalina Islands in 2000

Sampling site	Date	Detections (n)			
		Total, all zones	Cliff inbound	Cliff outbound	Total, cliff
East Fish Camp (Anacapa Island)	10 April	230	136	64	200
	13 April	289	83	117	200
	20 April	327	162	84	246
	1 May	324	88	106	194
	3 May	256	93	62	155
	4 May	305	138	60	198
Eagle Rock (Santa Catalina Island)	27 April	64	19	15	34
Landing Cove (Santa Barbara Island)	12 April	674	390	230	620

significantly until 23h00. Total radar counts were fairly consistent between 21h00 and 01h00. Hourly trends at Santa Barbara Island showed a pattern similar to that at Anacapa Island, with increasing detection rates after 21h00 and highest detection rates between 24h00 and 03h00 (Fig. 4). Most detections at Anacapa Island, Santa Barbara Island, and Santa Catalina Island occurred between 22h00 and 03h00. Detection rates for all nights dropped quickly after 03h00 and stayed relatively low until 05h30. At Anacapa Island, most birds had departed from nesting areas examined by radar and from at-sea congregations by 05h30. Unlike detection rates at Santa Barbara Island and Anacapa Island, the detection rate at Santa Catalina Island peaked between 22h00 and 23h00 (n = 18 detections/hour) and then dropped after 00h00.

Using a nested variance components analysis, variability among nights in detections at Anacapa Island accounted for 15.8% of the total variation; the remaining variation (84.2%) was attributable to variation among the sampling hours (23h00–03h00). Anacapa Island, Santa Catalina Island, and Santa Barbara Island exhibited significant differences in mean hourly detection rates (one-way ANOVA: F = 63.57, df = 2, P < 0.000), with overall means of 72.1, 16.0 and 168.5 detections per hour, respectively. The total detections (inbound and outbound combined; Table 1) on one night at Santa Catalina Island was significantly lower than the mean of nightly detections at Anacapa Island (t_s = 5.28, df = 5, P < 0.01). A similar test confirmed the higher rate of detections for Santa Barbara Island as compared with Anacapa Island (t_s = 13.50, df = 5, P < 0.0001).

The cliff zone exhibited consistent hourly detections through the night. The most consistent nightly counts and lowest CVs were obtained by combining inbound and outbound birds (hereafter "in/outbound") for each hour or each night and by excluding circling or unknown behaviors. Similar consistency of counts between nights and low CVs were observed for total counts for all activity zones and behaviors. CVs were highest when nightly counts of in/outbound behaviors in the cliff zone were examined separately. CVs for in/outbound radar counts at Anacapa Island were lowest between 23h00 and 03h00 (Fig. 5). The mean hourly detection rate, minimum, maximum, SD and CV for in/outbound behaviors in the cliff zone at Anacapa Island were determined (Table 2). For 23h00–03h00, we observed no significant differences between mean hourly detection rates (one-way ANOVA: df = 3, P = 0.661).

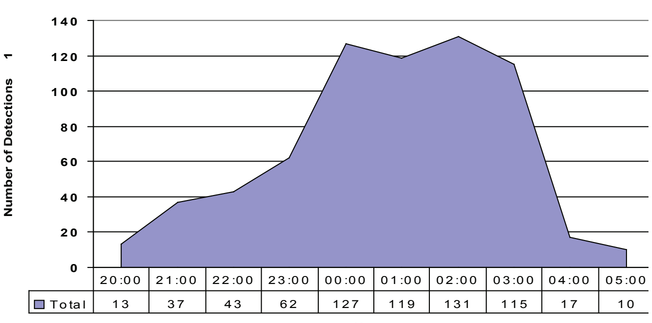

Fig. 4. Total number of Xantus's Murrelet radar detections per hour (all behavior categories) at Santa Barbara Island, 12–13 April 2000.

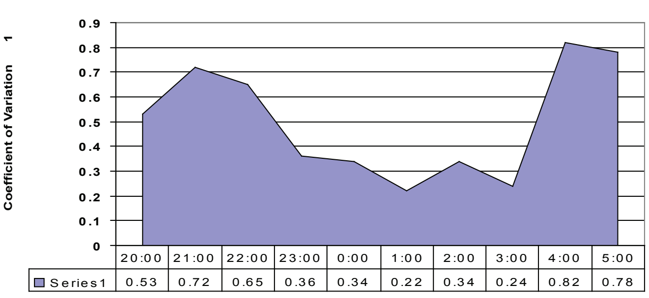

Fig. 5. Mean hourly coefficient of variation in Xantus's Murrelet detections at Anacapa Island for five nights of sampling in 2000.

DISCUSSION

Sampling effort and technique

Radar monitoring was found to be an effective method of gathering quantitative data on the numbers of Xantus's Murrelets flying into and out of sample nesting habitats at Anacapa Island, Santa Barbara Island and Santa Catalina Island. Standardized data for comparisons could best be obtained by limiting radar counts to the more protected near-shore zone where wave clutter is greatly reduced, sampling between 23h00 and 03h00, and using only in/outbound detections. The greatest limitation for conducting radar monitoring at Anacapa Island in 2000 was weather. Rough seas caused wave clutter (i.e. solid echoes from radar reflectance off the waves) on the screen, making it difficult to detect birds. Wind speeds of 24 km/h (13.0 knots) or more sometimes prevented complete surveys. In 2000, we reduced the effects of weather and corresponding wave clutter by selecting radar survey locations that had some protection from predominant northwest winds and by using data only from the more protected cliff zone for monitoring purposes. Subsequently (2001 and 2002), we modified radar deployment by improving vessel stern anchoring, by using a flux-gate compass and by modifying vertical radar tilt to 10 degrees or less (see below). Those improvements served to increase the number of nights of data collection annually (by allowing data collection during marginal conditions) and to improve data quality (by facilitating interpretation of echo trails). Successful survey nights occurred on 46%–67% of 24 potential survey nights in 2001 and 2002 (Hamer *et al.* 2003a).

TABLE 2
Xantus's Murrelet hourly detection rates (n) at Anacapa Island in 2000 for combined inbound and outbound behaviors in the cliff zone for five surveys combined

Time	Mean	Min	Max	SD	CV
20h00–20h59	5.0	3	8	2.65	0.53
21h00–21h59	18.6	3	34	13.46	0.72
22h00–22h59	33.8	8	61	21.90	0.65
23h00–23h59	26.2	17	39	9.44	0.36
00h00–00h59	31.2	17	47	10.78	0.34
01h00–01h59	30.4	21	38	6.58	0.22
02h00–02h59	23.6	13	34	7.96	0.34
03h00–03h59	13.8	8	16	3.27	0.24
04h00–04h59	13.6	1	23	11.10	0.82
05h00–05h59	7.5	1	13	6.24	0.78

SD = standard deviation; CV = coefficient of variation.

Despite various improvements, suitable protected anchorage sites will be the most important factor in the application of the radar monitoring approach to future monitoring at other locations at Anacapa Island and Santa Barbara Island, and at other islands. Long-term monitoring sites need to be somewhat protected from the weather to reduce the effects of wave clutter on the radar screen and shallow enough with suitable substrates to securely anchor. Shore-based radar monitoring could also serve as an alternative radar monitoring approach because it would eliminate problems with the availability of vessels and suitable anchorage sites. However, for some islands with steep rocky shorelines, few suitable sampling locations may exist.

After 2000, we made two modifications to compensate for the boat's movements at sea and to clarify on-screen images. We installed a Furuno model PG-1000 flux-gate compass and used a stern-anchoring system. On nights with high winds or strong currents, the vessel's position often shifted quickly, and sometimes it shifted because of anchor drag. Because of the rapidly changing radar image of the survey area, such movements made it more difficult to interpret and track individual echo trails. In 2001, we installed a PG-1000 flux-gate compass which fixed the image on the radar monitor regardless of the shifting position of the vessel. In 2002, CINP skippers also developed a functioning stern-anchoring system, which greatly reduced swing and anchor drag and helped to stabilize the boat.

In 2002, we also refined our radar-tilting protocol to minimize variation in murrelet detection rates during periods of poor weather. Modifications to our radar system allowed us to use a flexible waveguide to change the vertical angle of the radar antenna. By raising the antenna (in 5-degree increments) off the water, we could minimize wave clutter on the radar monitor. But because echo sizes of targets flying near the surface of the ocean became smaller and harder to detect as the antenna was raised, we established a maximum radar tilt of 10 degrees to minimize variation in radar detections. Through several 2002 trials under varying weather conditions, a tilt of 10 degrees or less was found to reduce wave clutter without reducing detection rates or increasing the difficulty of identifying murrelets. In 2002, to better standardize data collection, we determined that 50% or more of the shoreline must be free of wave clutter for the entire four-hour period to complete an adequate survey.

Species identification and flight speeds

Xantus's Murrelets likely represented almost all, if not all, birds with smaller echoes, high flight speeds and direct in/outbound flight lines detected by radar at night at Anacapa Island and Santa Barbara Island. Based on similar body size and flight speed, the one species most likely to be confused with the Xantus's Murrelets was the Cassin's Auklet; however, few if any auklets occurred in the radar-sampling areas. Nocturnal survey transects of at-sea congregations of Xantus's Murrelets from a small boat also did not detect any Cassin's Auklets or other species on the water that could be confused with Xantus's Murrelets (Whitworth *et al.* 2003).

Hourly and nightly variation in radar count

Counts of birds in the cliff zone best indicated breeding activity because these counts detected birds actually landing at (inbound) or departing from (outbound) nesting areas. Very few circling or unknown behaviors were recorded in the cliff zone because most flying murrelets appeared to be directly approaching or departing from land and were rarely seen sitting on the water in this zone. Birds detected in the middle and sea zones were probably arriving at Anacapa Island or Santa Barbara Island from distant feeding areas, but they first attended at-sea congregations before flying up to nest sites in the cliff zone (Whitworth *et al.* 2003). Similarly, birds departing from nest sites may have attended at-sea congregations before departing from the island. Such behavior could cause double counting of individuals in middle and sea zones and recording of some birds that did not attend nesting areas. The cliff zone also exhibited consistent within-night patterns of hourly detections at Anacapa Island, Santa Barbara Island and Santa Catalina Island. Only in/outbound behaviors in the cliff zone were detected consistently through the night; circling and unknown behaviors were uncommon. These factors may explain why counts combining in/outbound behaviors within the cliff zone had the lowest nightly CVs.

We suggest use of the 23h00–03h00 sampling period for collection and analyses of radar count data for Xantus's Murrelets because highest mean counts were obtained in those hours, with lowest CV between nights. Mean counts with lowest CVs will likely have the greatest power to detect a population trend over time in any monitoring program (Hamer & Schuster 2003b). Therefore, such counts give the most reliable measure of nesting activity at Xantus's Murrelet nesting colonies, provide the best evidence of nesting activity at sites where evidence of nesting is lacking and provide the greatest power to detect population change over time (Hamer & Schuster 2003b). Results of the nested variance components analysis at Anacapa Island indicated that variability in detections between hours (23h00–03h00) far exceeded (*c.* 5:1) the variability in detections between nights. Therefore, radar studies with the objective of monitoring populations over time should attempt to sample all four hours of the peak activity period to control for hourly variation.

Nest monitoring at Anacapa Island in 2000 indicated a mean nest initiation date of 30 March (±11 days; Whitworth *et al.* 2003), while radar surveys at Anacapa Island spanned 10 April to 4 May. Successful breeding adults can be expected to visit nest sites for a minimum of about 39–56 days, given a mean incubation period of 34 days (range: 27–44 days), plus a mean of eight days between laying of two eggs, a mean of two days between clutch completion and start of incubation, and a mean of two days from hatching to nest departure (Murray *et al.* 1983). In 2000, most nest site visitations at Anacapa Island would have been completed by 7–24 May. Therefore, radar surveys in 2000 were conducted during the peak incubation period with highest levels of nest visitations. Future monitoring by radar will have to take into account the differences in the annual timing of breeding of Xantus's Murrelets. Timing of breeding at Anacapa Island has been recently found to differ significantly from year to year, with murrelet nests initiated significantly later in 2004 and 2005 than in 2000–2003 (Whitworth *et al.* 2003, 2005).

The differences between Anacapa Island, Santa Barbara Island and Santa Catalina Island in hourly and nightly rates of murrelet detection by radar survey correspond to major differences in population size as estimated using nest searches and vocal detection surveys (Carter *et al.* 1992, 1997; Burkett *et al.* 2003; Whitworth *et al.* 2003). Using vocal detection surveys, at-sea congregations of murrelets had been previously discovered along the northwest coast of Santa Catalina Island in 1996 (H. Carter, unpubl. data), but no nests have been documented in that area. The description of in/outbound flight paths in 2000 by radar monitoring has provided additional information suggestive of breeding on the northwest side of the island.

Management implications

Our results show that radar is a useful tool for quantifying the relative level of breeding activity at nesting colonies. Using our approach, radar could be used to

- monitor population changes.
- compare relative sizes of various colonies by comparison of breeding activity.
- locate new breeding colonies.
- confirm the continued existence of known historical colonies.
- document portions of cliffs and bluffs being used for nesting at each colony.
- estimate densities of breeding birds for various portions of the coastline within a colony.

No differences in nightly mean count or CV were found among the four hours chosen as the sampling period. Therefore, for studies that do not involve long-term monitoring, we suggest that any of these hours could be used for exploratory work to locate and quantify additional sites at Anacapa Island, Santa Barbara Island or other islands. To survey several sites per night, the vessel could be moved to a new site after an hour of data collecting, and larger portions of an island could be covered in a short period with one radar-equipped vessel. A shorter sampling period would also help deal with rapidly changing weather conditions and perhaps eliminate the need to anchor the vessel, thereby increasing the number of successful survey nights with adequate weather conditions.

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