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Radar Study of Seabirds and Bats on Windward Hawai'i[1]

MICHELLE H. REYNOLDS,[2] BRIAN A. COOPER,[3] AND ROBERT H. DAY[4]

ABSTRACT: Modified marine surveillance radar was used to study the presence/absence, abundance, and flight activity of four nocturnal species: Hawaiian dark-rumped petrel [*Pterodroma phaeopygia sandwichensis* (Ridgeway)], Newell's shearwater [*Puffinus auricularis newelli* (Henshaw)], Band-rumped storm-petrel [*Oceanodroma castro* (Harcourt)], and Hawaiian hoary bat (*Lasiurus cinereus semotus* Sanborn & Crespo). Hawaiian seabirds were recorded flying to or from inland nesting colonies at seven sampling sites on the windward side of the island of Hawai'i. In total, 527 radar "targets" identified as petrel or shearwater-type on the basis of speed, flight behavior, and radar signal strength were observed during eight nights of sampling. Mean movement rates (targets per minute) for seabird targets were 0.1, 0.1, 0.3, 3.8, 0.9, and 2.2 for surveys at Kahakai, Kapoho, Mauna Loa, Pali Uli, Pu'ulena Crater, and Waipi'o Valley, respectively. Two percent of the petrel and shearwater-type targets detected on radar were confirmed visually or aurally. Flight paths for seabird targets showed strong directionality at six sampling sites. Mean flight speed for seabird targets ($n = 524$) was 61 km/hr for all survey areas. Peak detection times for seabirds were from 0430 to 0530 hours for birds flying to sea and 2000 to 2150 hours for birds returning to colonies. Most inland, low-elevation sampling sites could not be surveyed reliably for seabirds during the evening activity periods because of radar interference from insects and rapidly flying bats. At those inland sites predawn sampling was the best time for using radar to detect Hawaiian seabirds moving seaward. Hawaiian hoary bats were recorded at eight sampling sites. Eighty-six to 89 radar targets that exhibited erratic flight behavior were identified as "batlike" targets; 17% of these batlike radar targets were confirmed visually. Band-rumped storm-petrels were not identified during our surveys.

THREE SPECIES OF SEABIRDS, Hawaiian dark-rumped petrel *(Pterodroma phaeopygia sandwichensis),* Newell's shearwater *(Puffinus auricularis newelli),* Band-rumped storm-petrel *(Oceanodroma castro),* and Hawai'i's only endemic land mammal, the Hawaiian hoary bat *(Lasiurus cinereus semotus),* occur on the island of Hawai'i and appear on the State of Hawai'i Endangered Species List or Federal Endangered Species List (U.S. Fish and Wildlife Service 1992). Factors contributing to the decline of Hawai'i's seabird populations include predation by introduced common barn owls (*Tyto alba*), cats (*Felis catus*), dogs (*Canis familiaris*), rats (*Rattus norvegicus, R. rattus,* and *R. exulans*), and mongooses *(Herpestes auropunctatus)* (Byrd and Moriarty 1981, U.S. Fish and Wildlife Service 1983, Simons 1985, Telfer 1986, Ainley et al. in press); decreased availability of areas suitable for nesting (U.S. Fish and Wildlife Service 1983, Reynolds et al. 1994*b*); and modified landscapes with structures and lighting that can attract birds and lead to collisions. The mortality of Hawaiian seabirds caused by bright lights and collisions with utility wires is well documented (Reed et al. 1985, Telfer et al. 1987, Cooper and Day 1994, Ainley et al. 1995). Threats to the Hawaiian hoary bat are largely unstudied; however, bat populations across the world are threat-

[1] Manuscript accepted 3 April 1996.
[2] USGS/BRD (formerly National Biological Service), Pacific Islands Ecosystem Research Center, Hawai'i Field Station, P.O. Box 44, Hawai'i National Park, Hawai'i 96718.
[3] Alaska Biological Research, Inc., P.O. Box 249, Forest Grove, Oregon 97116-0249.
[4] Alaska Biological Research, Inc., P.O. Box 80410, Fairbanks, Alaska 99708-0410.

ened by habitat loss, pesticides, and disturbance to roosts. Bats suffer additional mortality caused by habitat destruction and reptilian, avian, and mammalian predation (Bat Conservation International 1991).

Conservation efforts for inland nesting Hawaiian seabirds and the Hawaiian hoary bat are currently limited because of the lack of information on their population status, life histories, and habitat use. The Hawaiian dark-rumped petrel and Newell's Manx shearwater recovery plan (U.S. Fish and Wildlife Service 1983) recommended determining population status and distribution, controlling direct mortality, and protecting seabird nesting habitat. Unfortunately, there is a paucity of information on the distribution and population status of these nocturnal species because of the difficulty in detecting them. For most of Hawaii's nocturnal seabirds, locations of important flyways and nesting colonies are not known. Important breeding, roosting, and foraging areas are unknown also for the Hawaiian hoary bat. Currently, no recovery plan exists for this bat, primarily because of limited knowledge of the species' biology (Karen Rosa, U.S. Fish and Wildlife Service, Honolulu, pers. comm., 1995).

We conducted a pilot study in June 1994 using radar and night-vision technology to detect the movements of nocturnally flying species on the island of Hawai'i. Modified marine radar has been used successfully by ornithologists for studies of bird migration (Belrose and Graber 1963, Blokpoel 1970, Gauthreaux 1985, Cooper et al. 1991) and of seabird interactions with powerlines (Cooper and Day 1994). In our study, emphasis was placed on tracking Newell's shearwaters and Hawaiian dark-rumped petrels, but the use of radar and night-vision scopes for surveys of bats and Band-rumped storm-petrels also was explored.

Species Background and Status

NEWELL'S SHEARWATER ('A'O). Newell's shearwater or 'A'o (hereafter 'A'o) is a threatened procellariid that is chiefly oceanic during the nonbreeding season. Today, breeding colonies are known only on the islands of Kaua'i (U.S. Fish and Wildlife Service 1983, Telfer et al. 1987, Harrison 1990, Ainley et al. in press) and Hawai'i (Kepler et al. 1979, Conant 1980, Reynolds and Ritchotte in press), but they have been suspected to breed on the other main Hawaiian Islands (Pratt et al. 1987).

HAWAIIAN DARK-RUMPED PETREL ('UA'U). Hawaiian dark-rumped petrel or 'Ua'u (hereafter 'Ua'u) is an endangered procellariid that is also chiefly oceanic during the nonbreeding season. The largest population studied nests in Haleakalā National Park on Maui (Simons 1985). 'Ua'u also nest in the mountainous central and northwestern regions of Kaua'i (Gon 1988, Telfer 1992) and on the upper slopes of Mauna Loa in Hawai'i Volcanoes National Park (Paul Banko [National Biological Service] and Larry Katahira [National Park Service], Hawai'i Volcanoes National Park, Hawai'i, pers. comm., 1994).

BAND-RUMPED STORM-PETREL ('AKĒ'AKĒ). Band-rumped storm-petrels (hereafter 'Akē'akē [family Oceanitidae]) occur on the northeast rift of Mauna Loa (Banko et al. 1991), on the southwest rift of Mauna Loa, western Kaua'i (Paul Banko, National Biological Service, pers. comm., 1992), and on Haleakalā, Maui (Scott Johnston, U.S. Fish and Wildlife Service, Honolulu, pers. comm., 1995). 'Akē'akē is listed as endangered by the state of Hawai'i (Pratt et al. 1987).

The breeding biology of Hawaiian seabirds was discussed by Harrison (1990) and the at-sea distributions by Spear et al. (1995).

HAWAIIAN HOARY BAT ('ŌPE'APE'A). Hawaiian hoary bats (hereafter 'Ōpe'ape'a) have been recorded on all of the main Hawaiian Islands, with the largest populations occurring on Kaua'i and Hawai'i (Tomich 1986). 'Ōpe'ape'a distributions have been surveyed on those islands (Fullard 1989, Jacobs 1993, Reynolds et al. 1994*a*).

MATERIALS AND METHODS

We surveyed nocturnal seabird and bat populations at 11 sampling sites on windward Hawai'i from 6 to 13 June 1994 (Table 1). Survey sites were chosen based on results of previous surveys (Reynolds and Ritchotte in press) and on knowledge of the species' biology. Sampling periods began at 1900 hours and consisted

TABLE 1

SAMPLING DATES, SITES, AND EFFORT FOR SURVEILLANCE RADAR, NIGHT-VISION SCOPES, AND AUDITORY SURVEY ON HAWAI'I, 1994

DATE	LOCATION	SAMPLING PERIOD (hours)	ELEVATION (m)
6 June	Pohiki Road[a]	1900–0000	25
7 June	Heiheiahulu[a]	1900–0100	326
8 June	Pāhoa[a]	1900–2320	207
	Lelani Road[a]	2000–0000	183
	Pohiki Road[a]	2045–2130	25
	Kapoho	2150–0100	12
9 June	Kahakai	1920–2035	5
	Pahoa[a]	2155–2300	207
	Pu'ulena Crater[a]	2115–2130	183
10 June	Pu'ulena Crater[a]	1900–2300	
11 June	Pu'ulena Crater	0430–0605	
	Waipi'o Valley	1845–2130	366
12 June	Pu'ulena Crater	0400–0540	
	Mauna Loa	1925–2130	2,200
13 June	Kealakomo[a] (Chain of Craters Road)	1900–2020	66
	Pali Uli (Chain of Craters Road)	2105–2140	12

[a] Preliminary sampling showed excessive radar interference caused by rain and insects; therefore, radar data collected at these sites were not used.

of 15- or 20-min radar sampling sessions with 5-min intervals between sessions (Table 1).

At each location, three types of sampling techniques were used: radar, night-vision, and auditory. The mobile radar laboratory consisted of a display screen and a modified marine surveillance radar (Furuno Model FCR-1411, Furuno Electric Company, Nishinomiya, Japan) mounted on a four-wheel-drive truck. The radar obtained information on movement rates (number of targets per minute), flight paths (directions in degrees), and ground speeds (km/hr) of night flyers. The radar transmitted with a frequency of 9410 MHz through a slotted wave guide at peak output of 10 kW. Range settings allowed maximal detection distances of 1.4 km for seabird and bat targets. The radar display was equipped with a digital color display, color coded (radar) echoes, on-screen plotting of true flight paths, and directional corrections for true north (Cooper et al. 1991).

Sampling also was conducted by observers using binoculars (when light levels permitted) and night-vision scopes (5X Noctron-V). The night-vision scopes' performance was enhanced by the use of spotlights (1,250,000 candlepower). Seabirds were also sampled by counting and identifying vocalizations; each call series was counted as a separate detection.

These sampling methods were compared with those used in previous studies (Reynolds and Ritchotte in press), which were only night-vision and auditory sampling. Incidental detections of 'Ōpe'ape'a were recorded, and detection rates were compared with methods employing echolocation and visual survey techniques.

Data Collected

Information recorded on seabird targets detected by the radar included date, session number, time, direction of flight, species (if known), number (if known), flight behavior, velocity (to the nearest 8 km/hr), and target strength. Data collected on batlike targets detected by radar included numbers and times of detections.

Species Identification and Detectability

Displays moving on the radar screen were identified as "targets," but were categorized based on characteristics such as flight speed, flight behavior (directional or erratic), signal strength, and size. To help eliminate species other than A'o, 'Ua'u, and 'Akē'akē from the radar data, we recorded information only on targets that had an airspeed ≥ 50 km/hr. A similar protocol was used by Day and Cooper (1995) to eliminate nontarget species from the radar data collected on Kaua'i. Species identification was more problematic at low-elevation, inland locations on Hawai'i, however, because of the presence of large numbers of fast-flying moth targets and bats. We found that interference from these moth and bat targets could be minimized by sampling only during morning hours (when insect and bat numbers were depressed) or by sampling at locations or times when the predominant flight direction of birds was into the wind, which tended to slow the flying insects down so that they were not confused with seabird-type targets.

Data Analysis

We converted the raw surveillance radar data to movement rates (number of targets per minute) for each sampling session. Circular statistics were used to determine mean flight directions (mean angles and angular deviation) of seabird targets. Rayleigh's test (Zar 1984) was used to test for the significance of flight directions for each sample site and survey date. Significance of flight direction was evaluated at $\alpha = 0.05$. Circular histograms for each survey site are based on flight direction data grouped into 10 or 20° intervals.

Five sites (Pohiki Road, Heiheiahulu, Pāhoa, Pu'ulena Crater evening sessions, Leilani Road, and Kealakomo) were not included in the analyses because of problems in target identification caused by insects and rain. Radar data were analyzed from Pali Uli, Kahakai, Kapoho, Pu'ulena Crater morning sessions, Waipi'o Valley, and Mauna Loa.

RESULTS

Seabird targets were detected on radar at Kapoho, Pu'ulena Crater, Waipi'o Valley, Kahakai, Mauna Loa, and Pali Uli. Petrels or shearwaters were seen at Mauna Loa, Pu'ulena Crater,

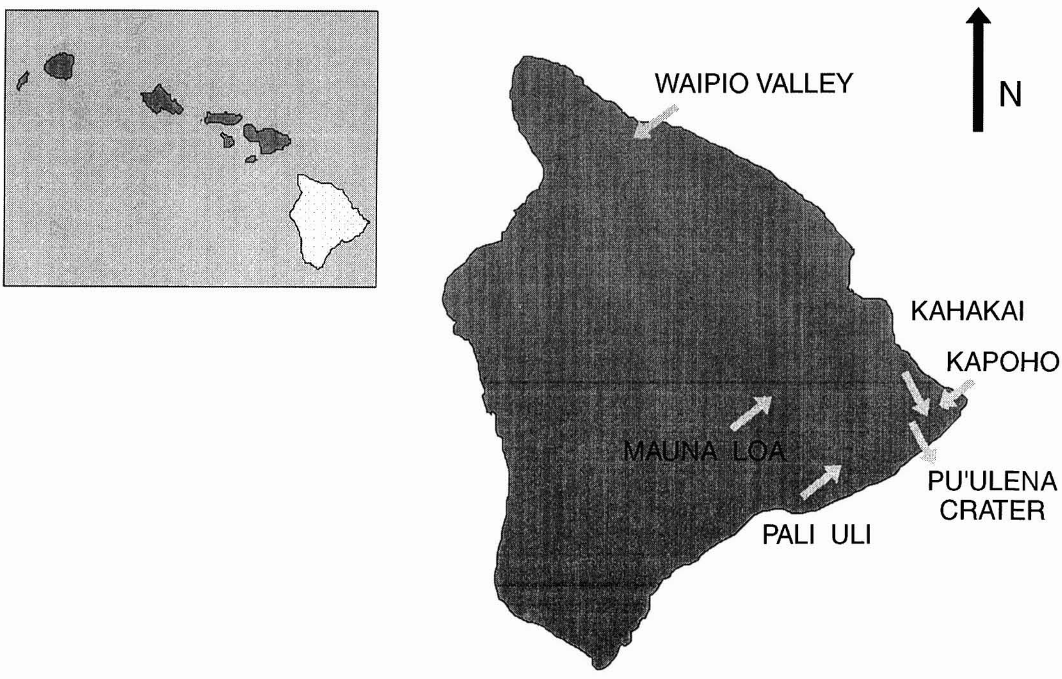

FIGURE 1. Radar survey sites and mean flight directions of seabird targets, Hawai'i, 1994.

and Waipi'o. Surveys using night-vision scopes and/or vocalizations for identification confirmed the presence of the 'A'o at Kapoho, Pu'ulena Crater, Waipi'o Valley, and Heiheiahulu.

'Ōpe'ape'a were observed with night-vision scopes at Pu'ulena Crater, Waipi'o Valley, Heiheiahulu, Pāhoa, Leilani Road, and Kealakomo (Figure 1). Smaller targets exhibiting batlike flight patterns on radar (i.e., nondirectional, erratic, and slower flight than shearwaters or petrels) were observed at Kahakai, Pu'ulena Crater, Mauna Loa, and Waipi'o Valley.

Number of Detections

We detected 527 seabird targets (targets) on radar (Table 2). The mean movement rate for all areas was 0.9 targets per minute. Movement rates were highest at Waipi'o Valley (2.2 targets per minute) and Pali Ulu (3.8 targets per minute).

We also had six visual 'A'o detections at Pu'ulena Crater, five visual 'A'o detections at Waipi'o Valley, and seven auditory 'A'o detections at Pu'ulena Crater. Shearwater or petrels were also observed at Kapoho, Mauna Loa, and Heiheiahulu (Table 2). Auditory and visual detections composed only 2% of the seabird radar detections.

We saw four to six 'Ōpe'ape'a per night at Pu'ulena Crater, three at Waipi'o Valley, and three to four at Kealakomo. In addition, 86–89 batlike targets were detected by radar; ca. 17% of them were confirmed visually.

Timing of Detections

Radar detection showed distinct daily peaks in seabird activity. Most seabirds were detected between 2000 and 2130 hours; morning detections of seabird targets peaked between 0430 and 0530 hours. Bat activity was highest between 1930 and 2100 hours. Two batlike targets were detected on radar in the morning, but only one bat was detected visually in the morning.

Flight Directions and Flight Speeds

Mean flight directions of targets observed after sunset on surveillance radar during June

TABLE 2

SUMMARY OF SEABIRDS AND BATS DETECTED BY RADAR AND OTHER MEANS, HAWAI'I, 1994

LOCATION	DATE	TOTAL RADAR SAMPLING TIME (min)	TOTAL BIRD TARGETS BY RADAR	TARGETS/ MIN	TOTAL VISUAL[a] OR AUDITORY[b] SEABIRD[c] DETECTIONS	BATLIKE TARGETS BY RADAR[d]	TOTAL VISUAL BATS
Heiheiahulu	7 June	—	n/a	—	2 'A'o[a]	n/a	4
Kahakai	9 June	60	6	0.10	0	10	0
Kapoho	8 June	60	7	0.11	1 'A'o[a]	0	0
Kealakomo	13 June	—	n/a	—	0	n/a	0
Mauna Loa	12 June	90	28	0.31	1 Sh/Pe[a]	10–16	0
Lelani Road	8 June	—	n/a	—	0	n/a	1
Pāhoa	8 June	—	n/a	—	0	n/a	2
Pali Uli	13 June	30	115	3.80	0	0	0
Pu'ulena Crater	9 June	15	n/a	—	1 'A'o[a]	4	1
Pu'ulena Crater	10 June	180	n/a	—	3 'A'o[a] 7 'A'o[b]	51	10
Pu'ulena Crater	11 June	75	85	1.13	1 Sh/Pe[a]	0	0
Pu'ulena Crater	12 June	75	51	0.68	1 'A'o[b]	2	1
Waipi'o Valley	11 June	105	235	2.23	4 'A'o[a] 1 Sh/Pe[a]	9–12	3

[a] Visual detection: species determined by field identification cues at dusk or dawn or at night with infrared (night-vision) scopes.
[b] Auditory detection: species identified by vocalization.
[c] Seabird species codes: 'A'o, Newell's shearwater; Sh/Pe, unidentified shearwater or petrel.
[d] Batlike targets identified by nondirectional, erratic flight pattern and slow flight speed.
n/a: not applicable; radar data not used.

were predominantly inland at Kapoho, Kahakai, Mauna Loa, Pali Uli, and Waipi'o Valley (Figure 1). Movements were predominantly seaward before dawn at Pu'ulena Crater, with a mean morning angle of 133° (angular deviation ± 16°; $n = 135$). Flight directions of targets on surveillance radar are shown as circular histograms in Figure 2. Rayleigh's test indicated that flight paths were significantly ($P < 0.05$) directional for all sample sites (Table 3). Mean flight speeds for seabird targets ($n = 524$) were 61 km/hr (SD ± 6 km/hr) for all survey areas combined.

DISCUSSION

This study was designed primarily to evaluate the presence of 'A'o at several sites. At Pu'ulena Crater, 'A'o previously had been confirmed by recording nocturnal calling, but the number of birds visiting the colony and their flyways were impossible to determine at night with existing methods (Reynolds and Richotte in press). Our findings indicate that as many as 85 'A'o occur in the vicinity of this crater during the breeding season, and their flight patterns appear to be highly directional. Preliminary indicators suggest that other areas of windward Hawai'i, such as Waipi'o Valley and Pali Uli, with 235 and 113 seabird targets, respectively, are important flyways and near suspected breeding areas for nocturnal seabirds. Insufficient data were collected for any conclusions about the population status of the species surveyed; however, the size, behavior, temporal patterns, and speed of most targets matched those seen for 'Ua'u and 'A'o on Kaua'i (Cooper and Day, pers. obs.). We believe that most targets detected by radar at Kahakai, Kapoho, Pali Ulu, Pu'ulena Crater, and Waipi'o Valley were 'A'o, and that those detected on Mauna Loa were 'Ua'u. On Kaua'i, 'Ua'u flew inland to colonies under lighter (crepuscular) conditions than 'A'o did, which were essentially nocturnal (Day and Cooper 1995). Visual detections of unidentified shearwater/petrels were made at Mauna Loa Strip Road, Waipi'o Valley, and Pu'ulena Crater. We believe that these crepuscular detections were of 'Ua'u, although positive field marks could not be identified under such distant and low-light conditions.

We were unable to confirm most radar targets visually because of the difficulty of finding flying birds under low light levels, especially at high flight altitudes. Although vertical radar (used to measure flight height) was not used in this survey, studies by Cooper and Day (1994) found that most procellariid species on Kaua'i flew between 26 and 275 m above ground level. Seabird surveys on Kaua'i found lower flight altitudes in the morning than the evening (Day and Cooper 1995), so identification by night-vision scopes may improve during morning sampling periods.

Many factors affect the detectability of nocturnal seabirds surveyed by vocalizations. The frequency of vocalizations of petrels and shearwaters is thought to vary with proximity to the colony, weather, moon phase, breeding phenology, nesting success, sex, number, and age of birds (Brooke 1978, Cruz and Cruz 1990, Podolsky and Kress 1992). Levels of ambient light, flight height, and distance from the observer will affect the detectability of seabirds by night-vision scopes. Factors such as ground clutter (i.e., echoes of surrounding objects such as terrain and vegetation), rain, and insect swarms may limit target detection and identification by radar, as was seen at several of our sampling sites. We found that moth-caused and bat-caused interference with seabird targets was minimized between 0400 and 0630 hours. Conditions for seabird sampling were improved at coastal and high-elevation sites.

Although there are locations and times when radar sampling does not work, we believe that radar provides the most direct method for quantifying nocturnal seabirds on Hawai'i. Extensive radar surveys could be used successfully for estimating the size of local breeding populations. Aural techniques are useful for finding colonies and for species identification, but only 1% of the targets detected on radar were vocalizing during this study. In 1993, seabird surveys were conducted in the Puna District of Hawai'i by using auditory censuses and night-vision goggles (model AN/PVS-5A) techniques (Reynolds and Richotte in press). In that study, 260 vocalization detections were made in 275 survey hours (0.02 birds per minute). In contrast, our

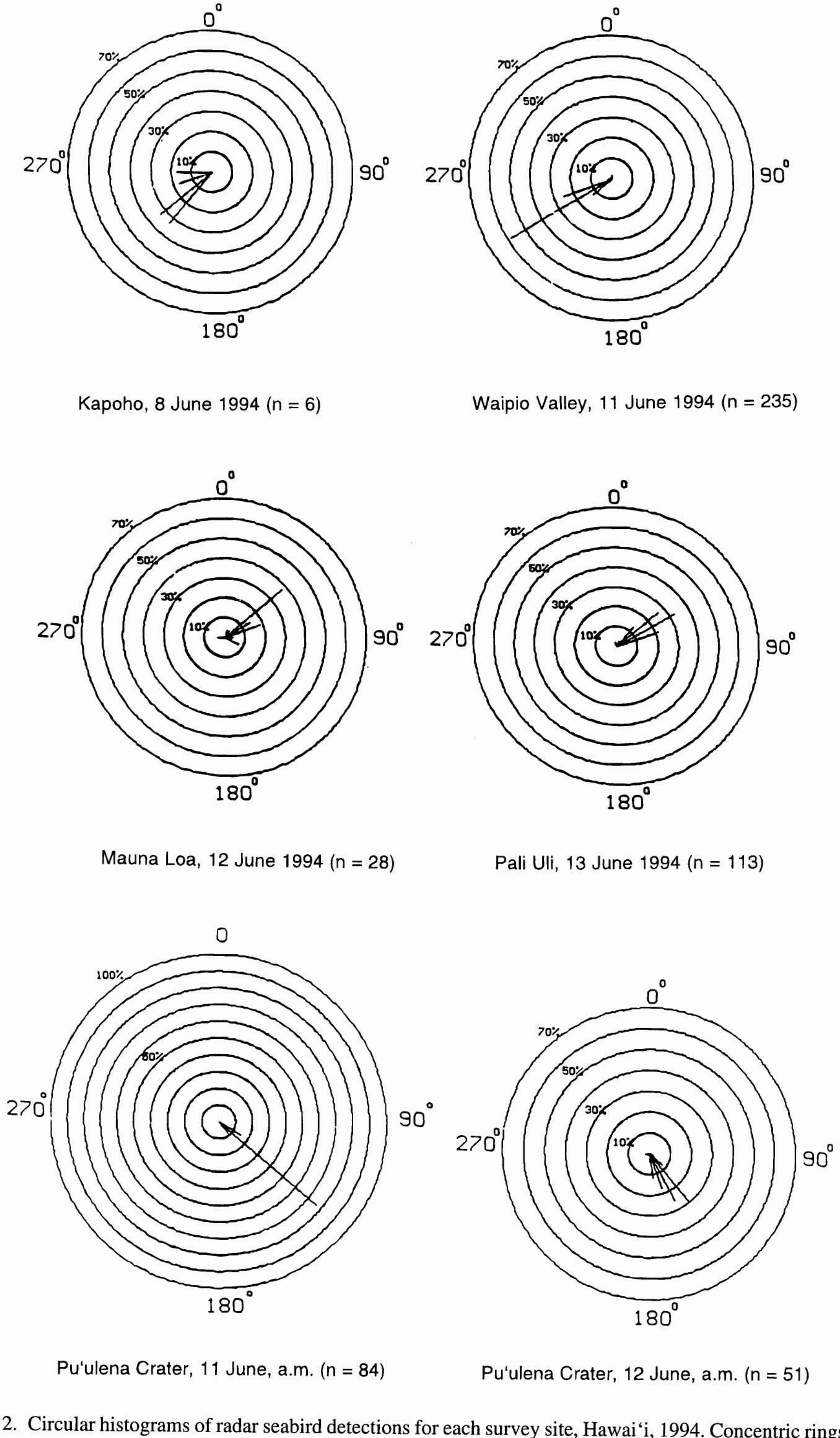

FIGURE 2. Circular histograms of radar seabird detections for each survey site, Hawai'i, 1994. Concentric rings represent relative frequencies of total seabird targets (10% intervals) at each bearing.

TABLE 3

MEAN FLIGHT DIRECTION (DEGREES) OF TARGETS DETECTED ON SURVEILLANCE RADAR AT SAMPLING SITES ON HAWAI'I, 1994

LOCATION	TARGET DIRECTIONS DETECTED (*n*)	MEAN FLIGHT DIRECTION (°)	ANGULAR DEVIATION (°)	*P**
Kahakai	6	148	41	<0.05*
Kapoho	6	234	22	<0.05*
Mauna Loa	28	58	32	<0.05*
Pali Uli	113	51	17	<0.05*
Pu'ulena Crater (11 June[a])	84	124	6	<0.05*
Pu'ulena Crater (12 June)[a]	51	148	18	<0.05*
Waipi'o Valley	235	238	17	<0.05*

* Rayleigh's test is significant at $\alpha = 0.05$. All flight patterns are directional (not random).
[a] Sampling conducted in the morning. All other survey locations were sampled at night.

1994 radar survey detected 527 seabird targets in only 8.25 survey hours (0.93 birds per minute). Both 1993 and 1994 surveys had low sighting rates with night-vision equipment, however: 4% of the seabirds were detected visually in 1993, and 2% were detected during this study.

With radar, we could detect bats at greater distances (1.4 km) than was possible during 1993 bat surveys (Reynolds et al. 1994*a*), which used echolocation detectors (QMC Mini2 Bat Detectors, QMC Instruments Ltd., London, UK). Those detectors, however, had a much smaller range (<100 m) than the radar did.

The use of radar to sample seabird populations enabled us to detect nocturnal procellariids and identify their movement patterns. A combination of survey strategies can be used to answer many of the questions posed for these nocturnal species. The techniques for censusing bats are promising, and a pilot study with emphasis on bats is recommended. We recommend the use of a combination of night-vision techniques, radar, and modified echolocation detectors (i.e., using parabolas and amplification) for bat population surveys. Radar surveys for 'Akē'akē should be tried near suspected breeding areas on Mauna Loa's Southwest Rift Zone, as recommended by Banko et al. (1991).

Information on numbers of birds flying overland and their travel routes will be extremely useful in developing management strategies to protect nesting seabirds and their inland nesting colonies. Data on distribution and flight altitudes can help in the design and placement of utility structures and can reduce the impact of power lines and bright lighting, both of which may cause seabird attraction and collisions.

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