USE OF RADAR TO STUDY THE MOVEMENTS OF MARBLED MURRELETS AT INLAND SITES

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ABSTRACT—A modified vehicle-mounted, X-band marine radar system was used to study the movements of marbled murrelets (*Brachyramphus marmoratus*) at inland and coastal sites in northern California during July. The ability of the radar to discriminate murrelets from other targets, and to estimate abundance was assessed. Murrelets were detected by radar at distances up to 1.3 km. Radar recorded the distance, ground speed, flight direction, and flight behavior (such as circling). The average ground speed of murrelets was 77 km/hr (range = 56–105 km/hr). Ground-based observers recorded an average of 67% of the murrelets within 700 m at inland sites that were recorded by radar. Using ground speed as a identification criterion, radar correctly distinguished murrelets from other bird species 87.8% of the time at coastal sites and 97.8% at inland sites. The only species contributing to identification error at inland sites was the band-tailed pigeon (*Columba fasciata*). Radar has advantages over ground-based observers as it does not rely on murrelets to vocalize for detection and can detect murrelets over a large area, regardless of variability in light conditions, observers' auditory and visual abilities, fog, and background noise. The benefits of using radar to understand the inland flight behavior of murrelets include better interpretations of ground-based observer survey data, better estimates of the number of birds using an area, collection of data that are not biased by murrelet vocalization rates, increased understanding of landscape level flight behaviors and use of flight corridors, 24-hr sampling ability, and a more detailed analysis of seasonal and daily changes in abundance inland sites.

The marbled murrelet (*Brachyramphus marmoratus*) uses old-growth and mature forests as nesting habitat in the Pacific Northwest (Sealy and Carter 1984, Carter and Sealy 1987b, Paton and Ralph 1990, Leschner and Cummins 1992b, Nelson et al. 1992, Hamer and Nelson 1995a). Although most species of the family Alcidae nest colonially and use burrows, cliffs or rock crevices as nesting sites, the marbled murrelet is unusual, at least in the forested portions of its range, in choosing to nest exclusively on large limbs of conifer trees. Old-growth stands used by murrelets have been located 84 km inland in Washington State (Hamer 1995), with rivers and smaller drainages apparently used as flight corridors (Paton and Ralph 1990, Nelson et al. 1992).

Existing inland survey techniques are based on Paton et al. (1990). With this protocol, murrelets can be detected by both sight and sound. However, because 85% of murrelet detections are auditory (Paton et al. 1990) it is not possible to determine the density of birds using an area because the number of individuals in each group detected is unknown (Vermeer et al. 1992). Collecting biological information on this species is extremely difficult because of the low light levels present for observers during its dawn activity period, poor viewing conditions in closed canopy forests, and the species' small size, rapid flight speed, and cryptic plumage. Behavioral observations are limited to glimpses of small segments of much longer flight paths and behaviors. Because of these problems, there is a paucity of information on murrelet flight behavior and activity patterns at inland nesting sites, and little information on how murrelets travel over the landscape to access these sites.

Because of these problems, visual observations by ground-based observers have been slow to yield information on: (1) the number of birds using an area; (2) frequency of use of specific flight corridors by murrelets; (3) the effects of weather on behavior and number of birds flying inland; (4) changes in flight paths and behavior over different habitat types and different topography; (5) seasonal differences in inland behavior and abundance; and (6) evidence of nocturnal activity at inland sites.

To begin to answer some of these questions and determine if radar would be a useful tool to study the movements of marbled murrelets, we used radar to monitor the inland flight activity of this species at a sample of inland and coastal sites. Coastal sites were monitored to determine if it was possible to locate specific flight corridors or foraging areas using radar. Several types of radar have been effective tools for studying bird migration for more than 4 decades (Eastwood 1967). Marine radars designed for use in boats, including small vessels, are easily available, the easiest and least expensive to operate, and have additional benefits such as high resolution, small minimal sampling range, and ease of transport (Sielman et al. 1981, Cooper et al. 1991). This paper describes a pilot project that used a vehicle-mounted, modified marine radar for determining the feasibility of monitoring murrelet flight behavior and abundance at inland and coastal sites.

METHODS

Study Areas

We monitored 8 inland and 5 coastal sites by radar within 19 km of the coast in Del Norte and Humboldt counties of northern California. All sites were in coast redwood (*Sequoia sempervirens*) forests between Crescent City and Rio Dell. Vegetation at the coastal sites typically consisted of sparse, short shrubs, open areas of sand, with the surrounding terrain being level except at sites with coastal bluffs. Inland sites were more mountainous, with steep, v-shaped valleys, and were densely forested.

Periods of Study

Sites were monitored 8–28 July 1993. Morning sampling sessions occurred from 0500 to 0700 and began 45 min before sunrise. Evening sessions were 15 min shorter and occurred from 2000 to 2145, and began 45 min before sunset.

We conducted 70 hr of radar sampling. Inland surveys included 18 morning and 5 evening sessions. In addition, 2 monitoring sessions at Prairie Creek State Park were conducted continuously for 11 hr, from 2000 to 0700. Coastal surveys included 4 morning and 2 evening sessions.

Equipment and Modes of Operation

Information was collected using an X-band marine radar system contained in a 4-wheel-drive pickup truck with a cab-over camper unit with the radar mounted on top. We used a Furuno model FCR-1411 standard marine radar, transmitting on 9410 MHz (X-band) through a 2-m long slotted waveguide to scan in a horizontal (surveillance) direction. Peak power output was 10 kW and the pulse length could be set at 0.08, 0.6 or 1.0 microseconds, depending on the range setting used. The radar had a horizontal beam width of 2° and a vertical beam width of 26°. A complete description of the radar laboratory can be found in Cooper et al. (1991).

We found that a 1.4-km range setting was most appropriate to use for murrelets because they were difficult to detect at greater ranges. The radar completed 1 scan every 2.5 sec with a plotting function set to record the position of targets on the monitor every 15 sec. Because targets were plotted at fixed-time intervals, the ground speed of targets was directly proportional to the distance between plotted points. Therefore, we were able to estimate ground speeds using a hand-held scale.

Whenever a radar transmission is reflected from the ground, surrounding vegetation or other objects that surround the radar unit, ground-clutter echoes appear on the radar display screen. Because ground-clutter can obscure targets, we attempted to minimize it by elevating the forward edge of the antenna, and by using a ground-clutter reduction screen, as described by Cooper et al. (1991). Using these techniques, we placed the lower edge of the radar beam directly on the horizon at the level of the lab. We also reduced ground-clutter by parking the radar truck where it was surrounded closely by trees, buildings or low hills, creating a radar fence that shielded the radar from other nearby low-lying objects (Sielman et al. 1981). This procedure helped limit the ground-clutter to a smaller area around the center of the display screen. For further discussions of radar fences, refer to Eastwood (1967), Williams et al. (1972) and Skolnik (1980).

Even with the use of a radar fence, ground-clutter was still created by surrounding hillsides. A minimum of approximately 300 m of air space free of obstructions was required to detect murrelets crossing a particular location because murrelets flew so quickly that they could pass undetected in narrower areas. Therefore, we chose sites that provided larger areas free of ground-clutter in order to optimize conditions for radar to detect murrelets.

At coastal sites, the radar truck was positioned as close as possible to the open water. At interior sites, the laboratory usually was positioned on a logging road clear of vegetation that provided the best open cross-section of the valley.

Species Identification

We used ground speed as the primary criterion for the identification of murrelet echoes. Any bird flying ≥ 56 km/hr was considered to be a murrelet target. This, and its direct flight patterns when a distance from nest stands, flight directions that were tangential to the coastline, and restricted timing of activity helped ensure identification as marbled murrelets. Murrelet targets not heading at right angles to the coastline usually were following river drainages. Very few other species were active during most of the morning survey period in July. Because of their compact body, we found that the echoes of murrelets also made a comparatively large image on the monitor, compared to many other species. While this helped identify murrelets, target size could not be used as a reliable indicator, because it varied as the flight profile and distance of the target changed.

To judge the ability of the radar to discriminate murrelets from other targets, data collected simultaneously from a ground-based observer and the radar technician were compared. Ground-based observers were trained to identify murrelets visually or by recognizing the unique vocalizations commonly given near nesting habitat. The observer, positioned within 15 m of the radar unit in an opening clear of vegetation, transmitted murrelet detection data to the radar laboratory. Observer data were collected using the 1994 Pacific Seabird Group [PSG] survey protocol (Redwood Sciences Laboratory, 1700 Bayview Drive, Arcata, CA, unpubl. rep.). These observers also recorded as many other species as was possible through visual identification. The observer attempted to track a murrelet and record when vocalizations were no longer audible. At that time, the radar technician then would record the distance to the bird.

The following data were collected for each radar detection: unique record number, time, species identification, ground-based observer species identification, maximal distance from ground observer at which the bird was heard or seen, ground speed, flight direction, flight path, and total time the target was tracked by radar. An overlap code was used to describe whether the bird was detected only by radar, only by the observer, by both radar and the observer, or only > 700 m distant from the radar. Birds > 700 m from the radar were never detected by ground observers. Detections recorded by both radar and the observer were used to compare species identification. Distance of the target from the radar and observer was measured to the nearest 10 m using a plotting function of the radar. Average ground speed was measured to the nearest 8 km/hr, and flight direction was measured to the nearest 1°. Ground speeds were not corrected for wind speeds, because birds often were circling and exposed to a variety of wind directions. In addition, birds tend to adjust air speeds to keep ground speeds similar under a variety of wind conditions (Alerstam 1990). Wind speeds usually were very low at the study sites ($\bar{x}$ = 2.9 km/hr at inland sites and 8.4 km/hr at coastal sites).

During periods of high frequencies of movements by murrelets, it was impossible to record all the data from the radar screen before signal echoes faded. Therefore, each sampling session was recorded with a color video camera mounted on a tripod in front of the monitor. In addition, all detection data recorded by the ground-observer were transmitted directly to this recording. Later, periods with high detection frequencies were replayed and data recorded.

RESULTS

Radar Results

Radar recorded 58 murrelet-type targets at coastal sites, and 1282 murrelet targets at inland sites. Ground-based observers recorded 16 murrelets at coastal sites and 714 at inland sites. For both coastal and inland sites, ground observers detected an average of 55% (SE = 5.5, N = 23 sample mornings) of the murrelets, when compared to sampling by radar. Radar consistently detected more murrelets than ground-based observers at all inland sites. Murrelets consistently were identified by radar up to 1.3 km away at all sites, while ground observers usually were only able to detect birds within a few hundred meters. Morning surveys averaged 19.3 detections/hr, whereas evening sessions averaged 2.2 detections/hr.

Ground Speeds

Ground speeds were recorded for 134 murrelet targets at both coastal and inland sites and 21 of these were confirmed as murrelets by ground observers. At coastal sites, other species such as flocks of small shorebirds (*Calidris spp.*), Caspian terns (*Sterna caspia*), cormorants (*Phalacrocorax spp.*), Canada geese (*Branta canadensis*), and other marine birds, had large

TABLE 1. Ground speeds (km/hr) of bird species recorded on radar at both coastal and inland sites in northern California, 1993. Species are listed by decreasing mean ground speed after marbled murrelets.

Species	Mean	Range	*N*
Marbled Murrelet (*Brachyramphus marmoratus*)	77	56–104	134
Canada Goose (*Branta canadensis*)	80	—	1
Unidentified small shorebird (*Calidris spp.*)	72	61–96	48
Marbled Godwit (*Limosa fedoa*)	72	—	1
Band-tailed Pigeon (*Columba fasciata*)	61	56–64	10
Unidentified cormorants (*Phalacrocorax spp.*)	56	48–72	12
Northern Flicker (*Colaptes auratus*)	48	—	1
Caspian Tern (*Sterna caspia*)	45	32–64	3
Common Raven (*Corvus corax*)	40	32–48	2
Brown Pelican (*Pelecanus occidentalis*)	38	32–48	13
Unidentified gulls (*Larus spp.*)	37	32–48	12
Great Blue Heron (*Ardea herodias*)	37	32–40	3
Osprey (*Pandion haliaetus*)	35	24–48	3
Snowy Egret (*Egretta thula*)	35	16–48	5
Black-Crowned Heron (*Nycticorax nycticorax*)	34	32–40	5
Unidentified Passerine	32	—	1
Tree Swallow (*Iridoprocne bicolor*)	32	32	2
Pine Siskin (*Spinus pinus*)	24	—	1
Vaux's Swift (*Chaetura vauxi*)	24	—	1

overlaps in ground speeds with murrelets (Table 1). At inland sites, murrelet ground speeds were much faster ($\bar{x}$ = 77 km/hr) than almost all inland species except the band-tailed pigeon (*Columba fasciata*), which overlapped slightly at the lower end of the murrelet range (Fig. 1).

Species Identification

Sixty-five targets at coastal sites and 195 targets at inland sites were identified to species or genus by ground observers. At the coastal sites, 2 targets were heard by ground observers and 63 were seen. At inland sites, 141 targets were heard by ground observers, 41 were seen, and 13 were both heard and seen. Using ground speed as the criterion, the radar technician correctly identified 57 targets as murrelets at coastal sites (88%) and 191 targets as murrelets at inland sites (98%).

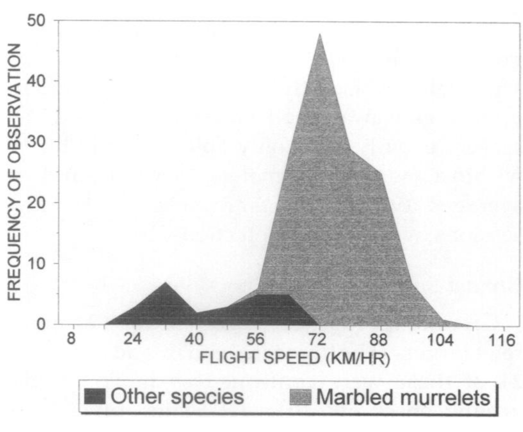

FIGURE 1. Overlap of radar-recorded murrelet ground speeds (km/hr) at inland sites compared with other inland bird species in northern California, 1993.

Maximum Detection Distance

We measured the average and maximum distance at which murrelets were heard by ground observers for 98 of the murrelets identified by both radar and the ground observer. However, in many instances observations < 200 m from ground observers could not be used in these calculations because ground-clutter usually covered this area on the radar monitor. The average distance that observers heard murrelets was 348 m, while the maximum distance was 614 m.

Observers detected 67% (SE = 14.5, *N* = 22 sample mornings) of the birds that radar detected at distances < 700 m. Because ground-clutter within 250 m of the radar routinely made the detection of murrelets by radar difficult at those distances, few close distance measurements from observer to bird were made. The frequency of birds heard in 15-m intervals increased from 200 m to 335 m, but dropped steeply after this distance.

Behavior

Although it was not unusual to have a murrelet target on the monitor for 20–30 sec, murrelets were tracked by radar an average of 15 sec/detection (N = 462 detections), which made the determination of flight direction and flight paths possible. Murrelets flying away from stands that were known to be used for nesting, generally flew straight in and out of the area. Murrelets monitored adjacent to old-growth stands verified as nesting areas, often flew directly toward these stands, circled in the immediate area, or disappeared into the ground-clutter created by the stand.

We identified only 2 murrelet targets during all-night monitoring sessions at Prairie Creek State Park, which typically had 150-200 murrelet detections per morning. On 21 July, 2 murrelet targets were observed flying from west to east. They appeared to enter an old-growth stand at 2314 and 2315 hr, 2.5 hr after sunset. That particular night was darker than usual due to a light drizzle and 100% overcast.

DISCUSSION

Radar Performance

We found that wide drainages with good access for the truck, lower relief, and some open areas free of vegetation were most suitable for radar sampling of marbled murrelet movements and activity. However, many of the inland sites monitored were steep, narrow, v-shaped valleys, that were difficult for the radar to scan fully. Furthermore, on days with dense fog, murrelets often flew in the valley bottoms, sometimes flying below the radar scan. At some sites, areas of extensive ground-clutter on the radar (due to dense forest or mountainous terrain) frequently prevented the detection of murrelets. In addition, the ability of radar to detect more murrelets than ground-based observers varied considerably among the 22 morning sessions compared, as indicated by the standard error in the percentage of murrelets detected by ground observers compared to radar.

Closely spaced murrelets sometimes appeared as only 1 echo on the radar. The technician found that the radar differentiated single murrelets from a larger group if they were at least 30 m apart at distances of 1.4 km or less. Flock size of murrelets at inland sites was generally ≤ 3 birds (Eisenhawer and Reimchen 1990), with single birds and pairs accounting for 40% of the detections at some stands in California (Paton and Ralph 1990).

Maximum Detection Distance

One advantage of radar is its ability to sample birds over a much larger area than can be done by ground observers. Under average conditions, observers can hear murrelets reliably within a 200-m radius of a survey station, and see them within 100 m (1994 PSG survey protocol). Radar, with its ability to detect birds out to at least 1.3 km (discounting ground-clutter), samples an area 42 times larger than a ground observer. The number of birds heard by ground observers and recorded by radar should increase with increasing distance (because the area sampled increases with increasing radius), until the birds become less audible to observers, and the detection rate drops. Our results suggest that this distance is 300–350 m. More radar data using ground-clutter screens are needed, however, to verify how increasing distance reduces the audibility of murrelet calls for ground-based observers.

Species Identification

Because the misidentification of murrelets is higher at coastal sites, due to the fast flight speed of shorebirds and other species in this environment, radar has limited use in these areas. X-band radar is more useful for studying murrelets in areas that are farther from the coast. Only band-tailed pigeons occasionally attained speeds that overlapped with those of murrelets. Other bird species that could be confused with marbled murrelets at inland sites include waterfowl, such as mergansers (*Mergus spp.*) and mallards (*Anas platyrhynchos*). Radar sampling sessions should also be conducted at other times of the year to determine if the presence of nocturnal migrating birds lead to higher rates of misidentification of marbled murrelets.

Behavior

One of the potential benefits of using radar to study murrelets, is the longer tracking time of birds over larger areas, as compared to ground observers, which enables coverage of many different habitat types and topography. This advantage allows a study of flight behavior and how it is influenced by weather, season, habitat availability, time of day, and topography.

Ground observer data may be biased toward those times of the morning and the season when murrelets call more frequently, circle more frequently or spend more time at nest sites. Field biologists have observed birds flying silently into stands during the incubation period (Nelson and Hamer 1995a; Nelson and Peck 1995, Singer et al. 1995), which suggests that low detection rates early in the nesting season may be due to behavioral changes, rather than actual differences in bird numbers. Nesting birds may call less frequently than non-nesting individuals making it difficult to use ground-based data to census the breeding portion of the population. Radar could be used to measure changes in the yearly and seasonal abundance of murrelets, and the timing of inland flights of murrelets with significantly less bias than ground observers.

As radar effectiveness is limited by ground-clutter in areas with steep topography or dense forests, radar could not be used to determine if birds were entering the forest canopy to access nest sites at the majority of stands sampled. If birds disappeared over a stand, radar could not determine if the birds actually flew into the stand or merely flew below the radar field or behind a hillside. However, the use of isolated stands by murrelets could be determined by documenting the behavior of birds using radar, by looking for birds flying directly toward these stands from a distance away and birds either disappearing or circling over the stand, as was documented at known breeding sites. Circling behavior is used in the survey protocol as an indication of occupancy (1994 PSG survey protocol).

Nocturnal sampling with radar provided the first evidence that some marbled murrelets may visit their breeding colonies long after sunset. Many species of alcids are known or suspected to visit their nesting colonies at night (Day et al. 1983, Sealy 1974, 1975b; Gaston 1992). More nocturnal monitoring is needed to verify this behavior and determine its frequency. The few active nests that have been observed at night in Washington and California revealed no nocturnal activity (Naslund et al. 1993; T. E. Hamer, unpubl. data).

We believe that radar could be used to determine the use of inland flight corridors by murrelets, how flight paths change over different habitat types, and how weather influences their flight behavior, abundance, and vocalization frequency. In addition, inland detections of marbled murrelets by ground observers show dramatic increases in mid-July and high daily variability over the breeding season (O'Donnell et al. 1995, Naslund and O'Donnell 1995). It is unknown if these July peaks are caused by non-breeding murrelets visiting the stands, birds circling or vocalizing more frequently, or birds spending longer periods at nesting stands later in the season. Monitoring stands by radar could help provide answers to these questions. Explanations for these trends are necessary to understand the breeding ecology of the marbled murrelet. Radar could also be used as a tool to compare the relative numbers of birds using different river drainages, the use of stands during winter, and it may be the only tool available to study how disturbances from forest management activities affect the abundance and flight behavior of birds at inland sites.

Studies of marbled murrelet behavior using radar will be most efficiently done on landscapes with isolated old-growth stands. Our results indicate that radar is a suitable tool for investigating and answering several crucial questions about the biology and behavior of murrelets, and to analyze the problems and effectiveness of the current ground-based survey protocol. In particular, radar could greatly change how biologists use and interpret survey results if a correction factor for ground-survey data could be developed from the radar that would lead to an estimate of the actual numbers of murrelets using a stand.

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