DEVELOPMENT OF ORNITHOLOGICAL RADAR AS A TOOL TO INCREASE THE ACCURACY AND EFFICIENCY OF INLAND SURVEYS FOR MARBLED MURRELETS

DRAFT INTERIM REPORT

Submitted to:

Olympic Natural Resources Center
P.O. Box 1628
Forks, WA 98331

by:

ABR, Inc.
P. O. Box 249
Forest Grove, OR 97116-0249

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Brian A. Cooper and Richard J. Blaha

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EXECUTIVE SUMMARY

- This report summarizes the results of the first year of a two-year study to test and develop ornithological radar as a technique to improve the efficiency and accuracy of the inland audio-visual survey method for Marbled Murrelets (*Brachyramphus marmoratus*). We also continued to evaluate the Inland Forest Survey Protocol (IFSP) for the Marbled Murrelet by using the combined results from this study and a study conducted during 1997 and 1998. We made concurrent radar and audio-visual observations that followed the current Pacific Seabird Group (PSG) protocol on 38 mornings in summer 1997, 44 mornings in summer 1998, and 43 mornings in summer 1999 during the murrelets' dawn activity period (i.e., ~105 min before sunrise to ~75 min after sunrise).
- The goal of this research was to test and develop a radar-based method to increase both the efficiency and the accuracy of inland audio-visual surveys for Marbled Murrelets. The specific objectives of the study were to:

  --describe the physiographic attributes (e.g., local topography, vegetation height, access) of the stands where it is possible to use ornithological radar to survey for Marbled Murrelets;

  --estimate the percentage of forest stands on the northwestern Olympic Peninsula where it would be possible to conduct radar-based observations;

  --develop techniques for increasing the percentage of stands where it is possible to use ornithological radar;

  --determine and compare the number of days required by ornithological radar vs. audio-visual observers to determine the "presence" of murrelets at low-use and moderate-use stands (i.e., test H_o: There is no difference between radar methods and standard audio-visual methods in the number of days needed to detect the presence of murrelets in a stand); and

  --continue to use ornithological radar to evaluate the current audio-visual survey protocol for Marbled Murrelets, following Cooper and Blaha (1998).
- Of the 50 randomly chosen stands that we assessed with our lift-equipped radar lab, 23 (56%) were suitable for radar-based observations, 20 (40%) were unsuitable, and 7

(14%) were of unknown or marginal suitability. The 10.5-m radar lift enhanced radar performance at 17 (73.9%) of the 23 suitable sites, compared with a radar mounted 4 m above ground level (e.g., in a fixed position on top of a pickup camper). Further, radar observations would not even have been possible at 8 (34.8%) of the 23 suitable sites without the lift.

- Of all of the physiographic characteristics considered, aspect clearly had the strongest ability to predict radar site suitability (96%) and unsuitability (70%). Adding relative altitude of the radar location to aspect slightly increased the predictive ability of this model. Overall, flat areas lying at the same elevation as the radar station were the most suitable sites for radar sampling.
- Radar-based observations indicated that ~20% of all Marbled Murrelets were seen near occupied stands of trees before the official starting time for audio-visual IFSP surveys, which begin 45 min before sunrise. In contrast, only 6% of the audio-visual observations occurred before the official IFSP survey starting time, suggesting that most of the birds that were detected on radar before the official survey time began were silent as they approached the occupied stands of trees.
- For both radar and audio-visual detections, the timing of flight activity was 10-20 min later on overcast days than on clear days.
- Our limited data suggest that ceiling height and percent cloud cover did not affect the number or proportion of Marbled Murrelets that were detected.
- The number of audio-visual detections of Marbled Murrelets dropped with horizontal distance from an observer. The steep, steady drop in the number of targets and detection rates that we observed for targets beyond 100 m suggests that the current IFSP survey radius of 200 m is larger than the effective audio-visual range of an observer (even without accounting for the fact that survey area increased with distance from observer).
- Concurrent radar and audio-visual observations indicate that ≥2% of the Marbled Murrelets detected by audio-visual observers during IFSP surveys were double-counted and that 11% of the murrelets detected during IFSP surveys actually were using a stand other than the one that was being surveyed.
- Audio-visual observers detected an average of 7–15% (depending on the estimation

method) of all Marbled Murrelets within 200 m of the observer at “occupied” forest stands during IFSP surveys.

- There was substantial among-site and among-day variation in the proportion of Marbled Murrelets that audio-visual observers detected during IFSP surveys. Further, the relationship between radar counts and numbers of audio-visual detections at a site was weak. Because we did not find factors that consistently influenced the among-site or among-day variation in the detectability of murrelets, we can not recommend a way of minimizing that variation by adjusting for season, weather, or among-observer variation. Further, our data suggest that it would not be appropriate to use a mean of our proportions of birds detected as a correction factor for audio-visual counts, because the proportion of murrelets that were detected audio-visually varied so greatly among sites and days.
- Our previous study (Cooper and Blaha 1998) focused on the numerical relationship between the number of Marbled Murrelets observed on radar and the number of them that were detected audio-visually, whereas this study compared the ability of the two techniques to determine the presence of murrelets. It is important to make these comparisons because, when actual IFSP surveys are conducted, it takes only one survey on which ≥1 bird was seen or heard to classify the site as having murrelets "present. " In 1999, we detected birds 100% of the days with radar; thus, the mean number of days required to determine "presence" with radar was 1.0. The number of days required to determine "presence" with the audio-visual technique was significantly higher, ranging from 1 to 5+ days, with a mean >2.3 days. Thus, our preliminary results indicate that a lift-assisted radar is a powerful tool for more quickly determining the "presence" of murrelets at a stand than the standard audio-visual technique.

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ACKNOWLEDGMENTS

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INTRODUCTION

The current ground-based Inland Forest Survey Protocol (IFSP) for Marbled Murrelets (*Brachyramphus marmoratus*) depends on the use of audio-visual cues to detect birds in flight. Collecting biological information on murrelets this way is difficult, because of the low light conditions during their dawn and dusk peaks in inland activity and their small size, cryptic coloration, rapid flight speed, and habitat preference for old-growth, closed canopy forests (Hamer *et al.* 1995). Further, because 85% of the murrelet detections are auditory (Paton *et al.* 1990), it is difficult to determine with accuracy the number of birds that actually are flying over a particular area. Ornithological radar, which does not have this auditory bias, has been used successfully to study Marbled Murrelets in both the Pacific Northwest and Alaska (Cooper 1993; Hamer *et al.* 1995; Burger 1997; Cooper and Blaha 1998; Cooper *et al.* 1997, 1998, 1999a, 1999b, 1999c; Lougheed 1998, Singer and Hamer 1999). Radar also has been used to study other avian species for nearly five decades (Eastwood 1967).

The Washington Forest Practices Board ruling for Marbled Murrelets requires that landowners conduct Marbled Murrelet surveys in all suitable murrelet habitat when proposing a forest practice. These surveys are costly, both in terms of the effort required to conduct them and because of their two-year time frame. Further, a large proportion of murrelets are missed on these surveys, and some murrelet detections simply are of birds passing over that stand of trees on their way to another area (Cooper and Blaha 1998).

Although ornithological radar will not work at all stands because certain terrain types preclude its use, results of our previous work (Cooper and Blaha 1998) suggested that, at least in some areas, radar could be used as a “coarse filter” to determine quickly and accurately whether murrelets were present in a forested stand. Accuracy would be improved because radar tends to detect murrelets at low-use sites, where they often are missed completely by audio-visual observers (Cooper and Blaha 1998). Efficiency also would be improved because radar samples a much larger area (up to a 1400-m radius) than audio-visual observers (up to a 200-m radius). It is possible that radar could reliably determine presence (or absence of birds) in a single year. If the "presence" of murrelets was detected by radar, audio-visual surveys still would be necessary to determine if the stand was "occupied" by nesting murrelets. The current protocol (Ralph *et al*. 1994) recommends that four surveys be conducted per year for two consecutive years to determine whether murrelets are "present" in a stand and that five surveys be conducted per year for two consecutive years to determine whether a stand is "occupied" by murrelets.

This report summarizes the results of the first year of a two-year study to test and develop ornithological radar as a technique to improve the efficiency and accuracy of the inland audio-visual survey method for Marbled Murrelets.

BACKGROUND

The Marbled Murrelet is a small, cryptic seabird that nests solitarily in large trees in old growth, coastal forests throughout most of its range in North America (Nelson 1997). Marbled Murrelets fly at high speeds, visit their nests primarily during periods of low light, and nest up to ~80 km inland. Because of their secretive behavior, the fact that they do not nest in colonies, and the difficulty of locating their nests in large trees, only limited information is available on their nesting behavior, habitat associations, population size in specific areas, and demography. The Washington, Oregon, and California population of the Marbled Murrelet was federally listed as a Threatened Species in 1992 because of a high rate of loss and fragmentation of nesting habitat and mortality associated with oil spills and gill-net fishing (USFWS 1992,1997). The species also is listed as endangered at the state level in California and is classified as threatened at the state level in Washington and Oregon. In addition, the species is listed as threatened in Canada. Comparison of historical and current data suggests that Marbled Murrelets have disappeared or become rare over much of their range south of Alaska and that current population trends of the species in the Pacific Northwest are unknown (Nelson 1997). Population trends projected from demographic analysis suggest that the population in the Pacific Northwest is declining by 4–6% per year (Beissinger 1995).

The Inland Forest Survey Protocol (IFSP) for Marbled Murrelets was designed to determine probable presence or absence of murrelets in a specific stand (i.e., presence occurs when a murrelet is detected in the vicinity of a stand, but when flight altitudes or behaviors indicative of nesting are not observed); to help determine whether a stand is occupied (i.e., probable nesting in the stand); and to monitor murrelet activity levels at specific stands (for pre-harvest inspection) (Ralph *et al*. 1994). The current IFSP recommends four survey visits per year for two consecutive and "normal" years to determine whether murrelets are present at a site and a total of 10 survey visits over a two-year period to determine occupancy with a 95% certainty. Each survey visit entails having a single observer make audio and visual scans for murrelets during the breeding season at a set station from 45 min before sunrise to 75 min after sunrise. Each station provides coverage of up to a 200-m radius from the observer. For a more detailed description of the IFSP, see Ralph *et al.* (1994).

OBJECTIVES

The goal of this research was to test and develop a radar-based method to increase both the efficiency and the accuracy of inland audio-visual surveys for Marbled Murrelets. The specific objectives of the study were to:

- describe the physiographic attributes (e.g., local topography, vegetation height, access) of the stands where it is possible to use ornithological radar to survey for Marbled Murrelets;
- estimate the percentage of forest stands on the northwestern Olympic Peninsula where it would be possible to conduct radar-based observations;
- develop techniques for increasing the percentage of stands where it is possible to use ornithological radar;
- determine and compare the number of days required by ornithological radar vs. audio-visual observers to determine the "presence" of murrelets at low-use and moderate-use stands (i.e., test H_o: There is no difference between radar methods and standard audio-visual methods in the number of days needed to detect the presence of murrelets in a stand); and
- continue to use ornithological radar to evaluate the current audio-visual survey protocol for Marbled Murrelets, following Cooper and Blaha (1998).

STUDY AREA

We examined 50 of the Washington State Department of Natural Resources (DNR) murrelet survey stands in the northwestern Olympic Peninsula, to assess their suitability for radar-based observations (Appendix 1). We then used 14 of these sites for radar sampling (Table 1). Most of the sites consisted of an isolated old-growth stand that was surrounded by a clearcut or by young trees.

METHODS

SITE CHARACTERIZATION

To quantify those physical characteristics that make a site suitable for radar-based sampling, we randomly chose 50 stands from the subset previously surveyed Washington State Department of Natural Resources (DNR) stands in the northwestern Olympic Peninsula (Appendix 1). All of the stands chosen had previously been classified as having murrelets "present" or "occupied. " There were 12 townships in the region with a significant number of stands, and 5 stands from each were chosen with a random number generator. The 10 extra stands that resulted from this process were used to allow for closed roads or other difficulties with access. Stands that did not have road access were dropped, and, if the township had less than 4 locations already, a new one was randomly chosen.

The stands were then visited, and the best possible radar site to view the stand was chosen. For each location, we recorded the following data: location (Township/Range/Section), UTM & latitude/longitude coordinates(measured with a hand-held GPS unit), DNR designation (Township, Range, and stand number; e.g., 271346 is stand 46 in T27R13), road access (defined as number of kilometers of accessible road within 600 m of the stand, measured from an orthophotograph), slope (visually estimated, in degrees), aspect of stand (direction it was facing, in °), direction to the stand from the radar site (in °), stand type (valley/mountain slope, ridge, canyon bottom, plain, rolling [i.e., hilly], estuary, undulating plain), canopy height between the radar site and the stand (in m), relative altitude of the sampling site with respect to the stand (below the bottom of the stand, at the bottom of the stand, at the same level as the stand, at the top of the stand, above the top of the stand), distance from the site to the stand (minimal and maximal, in m), and optimal lift height for radar-based observations (as determined by amount and location of ground clutter and radar shadow zones). We also determined whether the site was suitable for radar-based observations and whether the lift helped overall radar performance.

To assess the radar's effectiveness at each site, we placed acetate overlays on the radar screen, drew in the stand's boundaries, traced the amount of ground clutter, and estimated the amount and locations of radar shadows (i.e., airspace behind an obstruction like a hill, where the radar could not pick up targets). We considered any portion of shadowed airspace deeper than approximately one canopy height (i.e., ~50–75 m) to be in the shadow zone. This delineation of clutter and shadow zones was done for both the standard radar height (4 m) and for what we determined to be the optimal height of the antenna. Then, we visually estimated the following values from the tracings, for both the 4 m and optimal heights: percent ground clutter over the stand, percent ground clutter within 400 m of the stand, percent shadow zone over the stand, and percent shadow zone within 400 m of the stand.

RADAR AND AUDIO-VISUAL SAMPLING

We made radar-based observations at 14 sites in the northwestern Olympic Peninsula during 1999 (Table 1). These sites were selected from the subset of suitable radar sites of the 50 sites that we used for site characterization. We attempted to select randomly at least one site from each of the 12 townships that we examined, but two of the townships did not have any suitable radar sites, so we randomly selected more than one site in two of the other townships. We attempted 43 sampling mornings between 9 May and 31 July 1999 (Table 2, Appendix 2). Sampling was completely cancelled on 6 of those days because of rain, wind, or other factors, and sampling was partially cancelled by rain interference with the radar on several additional days (see below).

In addition, on 5 July, we only have information on total numbers of radar and audio-visual observations and no detailed information on each target, because that portion of our electronic data file was lost. Sampling was conducted at each site for 4–5 days (depending on the size of the stand) or until the presence of murrelets was detected by both radar and audio-visual observers, whichever happened first.

Table 1. Location of all radar-based and audio-visual sampling sites used to evaluate the Marbled Murrelet Inland Forest Survey Protocol in the Olympic Peninsula, Washington, during summer 1999.

	Location		
Site	Legal	UTM	Descriptive
Goodman	T27R13S5	10395415E 5302492N	S of stand in small spur off G2000
North Goodman	T28R13S29	10394165E 5306576N	End of 3rd spur on right past junction of G2600 & G2000
Ozette	T28R15S3	10378366E 5313377N	On D5517, 250 m S of stand, at abandoned T intersection
Hoh	T26R11S3	10416407E 5293059N	First E spur after junction of H1040 & H1043
Clearwater	T24R12S1	10411232E 5273343N	On Q3130, in pullout 150 m from Q3100
Tacoma Creek	T24R11S8	10413861E 5273230N	N spur off Q3300, parallel to W edge of stand
Cedarpile	T24R12S11	10409298E 5272042N	S spur off Q3120, near midpoint of stand
Nolan	T26R12S21	10406191E 5288960N	On RY15Y, 250 m W of stand at pullout
Sand Creek	T25R13S2	10399614E 5283685N	Off N1166, 2nd spur on left, 50 m from road
Blowdown	T25R12S35	10409350E 5274948N	Spur E of SE corner of stand, 100 m N of Q3100
Brush Hog	T25R11S33	10414556E 5275167N	At end of W spur past junction of C1290 & Q3000
McKinnon Creek	T24R12S13	10410907E 5271212N	On spur off SW corner of stand, 200 m S
Lower Tacoma	T24R11S8	10413547E 5272392N	Spur to south off Q3300, 1.25 mi past Q3330
South Clearwater	T24R12S1	10411422E 5273833N	Q3130, at T 400 m from Q3100

Table 2. Sampling dates and sampling effort for radar-based and audio-visual observations at study sites in the Olympic Peninsula, Washington, during summer 1999.

Date	Site (station)	Period of radar sampling	Period of audio-visual sampling
9 May	Goodman (1.2)	0400-0700*	0500-0700
10 May	North Goodman (2.1)	0358-0658	0458-0658
18 May	Ozette (3.3)	0352-0652*	0452-0652
19 May	Hoh (4.2)	0351-0651	0451-0651
20 May	Clearwater (5.3)	0348-0648	0448-0648
25 May	Tacoma Creek (6.1)	0343-0643	0443-0643
25 May	Cedar Pile (7.3)	0343-0521**	0443-0643
26 May	Sand Creek (9.1)	0502-0642**	0442-0642
26 May	Nolan (8.1)	0342-0642	0442-0642
27 May	Blowdown (10.1)	0341-0641	0441-0641
27 May	Brush Hog (11.4)	0351-0641	0441-0641
28 May	Hoh (4.1)	0340-0640	0440-0640
28 May	North Goodman (2.2)	0340-0640	0440-0640
29 May	Clearwater (5.1)	0339-0639	0439-0639
30 May	Tacoma Creek (6.2)	0337-0637	0437-0637
31 May	Cedar Pile (7.4)	0337-0637*	0437-0637
01 June	Cedar Pile (7.4)	Rained out	Rained out
01 June	Blowdown (10.2)	Rained out	Rained out
10 June	North Goodman (2.3)	0333-0633	0433-0633
11 June	Blowdown (10.2)	0333-0633	0433-0633
12 June	McKinnon Creek. (12.1)	0333-0633	0433-0633
19 June	McKinnon Creek (12.3)	0332-0632	0432-0632
20 June	Cedar Pile (7.4)	0332-0632*	0432-0632
21 June	Hoh (4.4)	0332-0632*	0432-0632
01 July	Clearwater (5.2)	Rained out	Rained out
01 July	South Clearwater (14.5)	Rained out	Rained out
02 July	Clearwater (5.2)	0338-0638*	0438-0638
02 July	South Clearwater (14.5)	0338-0638*	0438-0638
03 July	McKinnon Creek (12.2)	Rained out	Rained out
03 July	Lower Tacoma (13.3)	Rained out	Rained out
04 July	McKinnon Creek (12.2)	0339-0639	0439-0639
05 July	Lower Tacoma (13.3)***	0345-0640***	0440-0640***
24 July	Lower Tacoma (13.1)	0358-0708*	0503-0708
24 July	Tacoma (6.4)	0358-0713*	0520-0713
25 July	Blowdown (10.3)	0359-0659	0459-0659
25 July	Cedarpile (7.1)	0359-0659	0459-0659

Table 2. Sampling dates and sampling effort for radar-based and audio-visual observations at study sites in the Olympic Peninsula, Washington, during summer 1999 (Continued).

Date	Site (station)	Period of radar sampling	Period of audio-visual sampling
26 July	Clearwater (5.5)	0401-0701	0501-0701
26 July	South Clearwater (14.4)	0401-0701	0501-0701
27 July	McKinnon Creek (12.1)	0402-0702*	0502-0702
28 July	Blowdown (10.5)	0403-0703	0503-0703
29 July	South Clearwater (14.1)	0404-0719	0504-0704
30 July	Clearwater (5.4)	0406-0706	0506-0706
31 July	Cedarpile (7.2)	0407-0707	0507-0707

* Sampling precluded by weather conditions for part of the sampling period.

** Sampling period shortened because of equipment-related/logistical difficulties.

*** Have total audio-visual counts but no radar data from that day.

Our sampling design consisted of conducting concurrent radar-based and standard audio-visual Marbled Murrelet surveys that followed the current Inland Forest Survey

Protocol for Marbled Murrelets (Ralph *et al.* 1994, 1998). We made audio-visual observations during the morning activity period for Marbled Murrelets, from 45 min before sunrise to 75 min after sunrise (or until 15 minutes after the last murrelet was detected audio-visually, whichever was longer). Audio-visual surveys occurred at all designated DNR survey stations within the stand, unless we detected murrelets by both radar and audio-visual observers before all of those stations had been surveyed. We made radar-based observations from 105 min before sunrise to 75 min after sunrise (or until 15 minutes after the last murrelet was detected audio-visually, whichever was longer), which is the period that encompasses the known peak of daily murrelet activity (Burger 1997; Cooper and Blaha 1998; Cooper *et al.* 1999a, 1999c). During surveys, we videotaped the radar monitor to measure movements and numbers of murrelets in the vicinity of the stand of interest while an observer conducted audio-visual surveys in the stand following the standard IFSP (Figure 1). During sampling, we transmitted each audio-visual observation by radio directly to the videotape as it occurred. The audio-visual observers described locations and flight directions of murrelets seen or heard in precise detail, so that we could determine later whether those birds also were seen on radar. We then compared these audio-visual data collected following the official survey protocol with the data from the videotape of the radar observations. We also used audio-visual data to verify species identifications on the radar.

For each radar target, we collected information on date, time, flight direction (to the nearest 1°), flight behavior (straight-line into stand, straight-line out of stand, straight-line heading elsewhere, straight line over stand with final destination unknown, straight-line through stand [i.e., continuing past the stand to another location], circling over stand, circling elsewhere, erratic movement into stand, erratic movement out of stand, erratic movement elsewhere, erratic movement over stand, erratic movement through stand), closest horizontal distance of radar target to audio-visual observer, observation overlap category (recorded only on radar, recorded only by audio-visual observer, recorded by both radar and audio-visual observer), species (if known), number of birds represented by that radar echo (if known), flight altitude (if known), and audio-visual detection category

Figure 1. Schematic view showing the typical position and maximal sampling area of the radar laboratory and the audio-visual observer in relation to the location of a Marbled Murrelet stand.

(not detected by audio-visual observer, heard only, seen only, both heard and seen).

We also collected the following weather information at the beginning of each session or when conditions changed during a session: wind direction (none, N, NE, E, SE, S, SW, W, NW, variable), average wind speed at ground level (none, 1–5 mi/h, 6–10 mi/h, 11–15 mi/h, 16–20 mi/h, etc.), estimated cloud cover (%; to the nearest 5%), average ceiling height (in m) above ground level at the radar sampling site, precipitation (none, fog, drizzle, light rain, heavy rain, scattered showers), and air temperature (to the nearest 1ºC). The audio-visual observer's data were transcribed according to PSG protocol. The audio-visual observer also recorded the following data on other rapidly flying species of birds (i.e., all cormorants, waterfowl, raptors, shorebirds, gulls, doves, Band-tailed Pigeons [*Columba fasciata*], and Common Ravens [*Corvus corax*]): time, species, number of birds, direction from the radar laboratory when first observed, flight altitude, and direction of flight.

RADAR EQUIPMENT AND OPERATION

Our mobile radar laboratory consisted of a marine radar mounted on a lift-equipped van. The hydraulic lift allowed us to position the radar antenna vertically between ground level and 10.5 m above ground level. This surveillance radar scanned the entire area around the lab at a range setting of 1.4 km and was used to obtain information on flight paths, movement rates, and ground speeds of murrelets. A similar radar laboratory (except for the lift apparatus) is described in Gauthreaux (1985a, 1985b) and Cooper *et al*. (1991). The lab was powered by two 12-V batteries that were linked in series.

The surveillance radar (Furuno Model FCR-1411; Furuno Electric Company, Nishinomiya, Japan) is a standard marine radar transmitting at 9,410 MHz (i.e., X-band) through a slotted wave guide (i.e., antenna) 2 m long with a peak power output of 10 kW. This radar can be operated at a variety of ranges from 0.5 km to 133 km. Pulse length can be set at 0.08, 0.6, or 1.0 µsec, depending on the range-setting used. At shorter pulse lengths, echo definition is improved (giving more accurate information on target location and, hence, distance), whereas, at longer pulse lengths, echo detection is improved (increasing the probability of detecting a target). (An echo is a picture of a target on the radar display screen; a target is one or more birds that are flying so closely that the radar displays them as one echo on the display screen.) This radar has a digital, color display with several scientifically useful features, including color-coded echoes (to differentiate the strength of return signals), on-screen plotting of a sequence of echoes (to depict flight paths), and True North correction for the display screen (to determine exact flight directions easily). A plotting function plots the location of a target at selected time intervals (0.25, 0.5, 1, 3, or 6 min). Because time intervals are fixed, ground speed is directly proportional to the distance between consecutive echoes and can be measured with a hand-held scale.

Whenever energy is reflected from the ground, surrounding vegetation, and other objects that surround the radar unit, a ground-clutter echo appears on the display screen. Because ground clutter can obscure bird targets, we attempted to minimize it by elevating the forward edge of the antenna and by using a ground-clutter reduction screen (described in Cooper *et al*. 1991). Whenever possible, we also reduced ground clutter by parking the radar laboratory in locations that were surrounded fairly closely by trees or low hills. These objects acted as a radar fence that shielded the radar from low-lying objects farther away from the lab and that produced only a small amount of ground clutter in the center of the display screen. For further discussion of radar fences, see Eastwood (1967), Williams *et al*. (1972), and Skolnik (1980).

Maximal distances of detection of birds by this surveillance radar depends on body size of the birds, flock size, flight profile of the birds, distance between flying birds, atmospheric conditions, and, to some extent, the amount and location of ground clutter. Marbled Murrelets usually are detectable to ~1.3 km, whereas single, small passerines are detectable to ~1 km (Cooper *et al*. 1991, Hamer *et al.* 1995, Cooper *et al.* 1999b).

We could not collect data during periods of rain, because the electronic filtering required to remove the echoes of the precipitation from the display screen also removed bird-caused echoes. Six (13.9%) of the 43 sampling sessions in 1999 were entirely canceled because of rain, and another 12 (27.9%) days included short periods in which we were unable to sample because of rain (Table 2).

DATA ANALYSIS

Assessment of the Suitability of Sites for Radar Surveys

We used logistic regression to determine the probability of correctly classifying a stand as suitable or unsuitable for radar observations, based on several landscape variables (maximal slope of stand, maximal distance from radar site to stand, aspect of stand relative to radar site, terrain type, altitude of stand relative to radar site). We examined each variable individually and in combination (by using variables selected by the forward likelihood-ratio method, [P in = 0.05, P out = 0.10]) to assess this relationship. During our site assessment, radar sites were classified as suitable or unsuitable based on the proportion of the total airspace over/near a stand that was occupied by ground clutter and shadow zones (i.e., areas where radar can not detect a bird) and the overall ability of radar to detect a moving target through the zone of interest. To be a suitable, a site had to have enough clutter- and shadow-free space over or around the stand to have a good chance of detecting murrelets on their way into or over the stand. "Maximal slope" is the maximal slope of hillsides within a stand, and "maximal distance" is the maximal distance from the radar to the farthest edge of a stand (up to ~ 1.7 km—the limit of radar sampling at this range setting). Aspect had four categories: slope facing toward, away, or perpendicular to the radar site, or flat (no slope). Another categorical variable, terrain, was created based on stand type. Terrain had values ranging from one to four: (1) ridge or sloping area; (2) rolling (hilly) area or canyon bottom/sloping area combination; (3) gently undulating plain or canyon bottom; and (4) plain. Altitude was separated into five categories, with the radar site (1) below, (2) at bottom edge of, (3) equal to elevation within, (4) at top edge of, or (5) above top edge of stand. We examined collinearity of all independent landscape variables with Spearman's rank correlation coefficients. All statistical analyses were conducted with SPSS 9.0 software (SPSS 1999).

Analysis of Radar and Audio-visual Data

Because analyses of flight speed have determined that a 64-km/h cutoff minimizes the number of non-murrelet targets in the murrelet data set yet eliminates only a low percentage of targets that actually were those of murrelets (Cooper and Blaha 1998;

Cooper *et al.* 1999b, 1999c), we considered only radar targets with a flight speed >64 km/h (>40 mi/h) in this study to be those of Marbled Murrelets. Similar to Cooper and Blaha (1998), we also limited the data set to those targets recorded when average wind speed was <25 km/h, so that slowly flying birds and insects with tailwinds would not exceed the 64-km/h threshold and be counted as murrelet targets. No sampling days were lost because of high wind speeds, however (Table 1).

We used different subsets of data for different types of analyses and, whenever possible, pooled our 1999 data with data collected in 1997 and 1998 (see Cooper and Blaha 1998). For example, all analyses that dealt with the timing of movements or with the proportion of movements that occurred before the official audio-visual survey starting time were restricted to those days during 1997–1999 with complete sampling sessions that were uninterrupted by rain (Table 1, also see Cooper and Blaha 1998). In addition, these data were restricted to radar targets that were headed into, out of, and over murrelet occupied stands, to eliminate observations of birds that may have been associated with other stands farther inland.

For comparisons between the number of radar targets and the number of birds detected concurrent audio-visually, we wanted to partition the data into all observations within 200 m and within 400 m of the audio-visual observers. This partitioning was problematic, however, because information on the distance of birds from the observers was unavailable for most of the audio-visual detections. Therefore, we corrected the total number of audio-visual detections by the percentage of audio-visual detections concurrently observed on radar that occurred within 200 m (63.8% of detections) and within 400 m (91.6%) of the observers (Appendices 3 and 4).

Cloud cover and ceiling height are two weather variables that commonly have been reported to affect the number of murrelets detected during morning surveys. We present results of the effects of these two weather variables on (1) the total number of radar targets, (2) the total number of audio-visual detections, and (3) the percentage of murrelets detected (i.e., the number of audio-visual observations within 200 m horizontal distance of observers × 100/the number of concurrent radar and audio-visual observations within 200 m horizontal distance of observers). We compared counts and proportions between days when ceiling height was ≤200 m versus > 200 m and between days when cloud cover was ≤20% versus ≥80%. For audio-visual counts, we compared counts within both sites and stations because, unlike the radar, an audio-visual observer could not concurrently observe all stations within a site. We used a Wilcoxon matched-pairs signed-ranks test to compare both radar and audio-visual counts under the different ceiling and cloud cover conditions and used a Mann-Whitney test to compare the percent of murrelets detected by audio-visual observers under various weather conditions because, unlike count data, the percentages could be compared across sites.

RESULTS

SUITABILITY OF SITES FOR RADAR SURVEYS

Of the 50 randomly chosen stands that we assessed with our lift-equipped radar lab, 23 (56%) were suitable for radar-based observations, 20 (40%) were unsuitable, and 7 (14%) were of unknown or marginal suitability (i.e., dependent on what the flight paths of birds were in the vicinity of the stand; Appendix 1). The 10.5-m radar lift enhanced radar performance at 17 (73.9%) of the 23 suitable sites, compared with a radar mounted 4 m above ground level (e.g., in a fixed position on top of a pickup camper). Further, radar observations would not even have been possible at 8 (34.8%) of the 23 suitable sites without the lift. An even taller lift would have been even more effective at permitting radar observation, for 7 (35%) of the 20 unsuitable radar sites were surrounded by older trees that were taller than the 10.5-m lift. At suitable sites, mean (± SE) optimal lift height was 6.6 ± 0.6 m agl (range = 3–10.3 m agl).

PHYSIOGRAPHIC ATTRIBUTES OF SUITABLE RADAR SITES

We used logistic regression to determine the physiographic attributes that made a site suitable for radar observation. This was done by determining the probability of correctly classifying a stand as suitable or unsuitable for radar observations, based on several landscape variables (maximal slope of stand [maxslope], maximal distance from radar site to stand [maxdist], aspect of stand relative to radar site [newasp], terrain [newterr], and altitude of stand relative to radar site [alt]). We examined each variable individually and in combination [using variables selected by forward likelihood ratio method], to assess the strengths and biases of the various landscape features in classifying suitability of sites for radar observation. In the logistic regressions, aspect alone correctly classified 96% of suitable sites and 70% of unsuitable sites. That is, aspect underestimated site suitability by incorrectly classifying 4% of suitable sites as unsuitable and overestimated site suitability by incorrectly classifying 30% of unsuitable sites as suitable sites. To compare the overall ability of landscape features to classify radar site suitability, however, it was necessary to examine *overall site suitability*, the overall probability of correctly classifying a radar site as suitable or unsuitable (Table 3).

When each individual variable was forced into the model, all variables except maximal distance were significant ($P < 0.05$) and had varying abilities to classify correctly a radar site as suitable or unsuitable (Table 3). Aspect clearly had the strongest ability to predict radar site suitability (96%), unsuitability (70%), and overall suitability (84%), whereas adding altitude to aspect slightly increased the predictive ability of this model (Table 3). Note that we also examined the correlation of all landscape features with Spearman's rank correlation coefficients (Table 4). Although some of the variables are highly collinear (e.g., maximal slope and terrain, maximal slope and aspect), the two variables eventually selected in the model (i.e., altitude and aspect) were poorly correlated (Table 4).

Overall, flat stands with no slope (i.e., aspect = 4) and lying at the same elevation as the radar station (altitude = 3) were the most suitable sites for radar sampling (Fig. 2). Sites containing ridges or slopes (terrain = 1) were the least suitable, whereas sites with plains (terrain = 4) were the most suitable (Fig. 2). Relationships of the remaining variables were less clear, especially for maximal distance of a stand to the radar site (Fig. 3).

DAILY TIMING OF MOVEMENTS

PATTERN OF TIMING

By standardizing times of observations in terms of number of minutes before or after sunrise, we were able to pool the radar data from all sites and dates (Fig. 4). We partitioned the radar data into targets that flew into, out of, or over a stand of trees (i.e.,

Table 3. Variables used in logistic regression models, χ^2 values of respective models, and their probability of correctly classifying the suitability of radar sites.

				Percent of sites classified correctly		
Model variable	χ^2	df	P-value	Suitable	Unsuitable	Overall
Distmax	3.536	1	0.0601	78	50	65
Maxslope	10.731	1	0.0011	87	60	74
Newterr	12.562	3	0.0057	65	85	74
Alt	18.687	4	0.0009	70	90	79
Newasp	25.036	7	0.0007	96	70	84
Newasp + alt	35.892	11	0.0002	96	80	88

Table 4. Spearman rank correlation coefficients among variables used in logistic regression analysis.

	Distmax	Maxslope	Newterr	Alt	Newasp
Distmax	1.000	0.356[a]	-0.200	0.173	-0.230
Maxslope		1.000	-0.805[a]	0.306[a]	-0.775[a]
Newterr			1.000	-0.211	0.651[a]
Alt				1.000	–0.020
Newasp					1.000

[a] Significant difference ($P \leq 0.05$). All other tests were not significant ($P > 0.05$).

Figure 2. Percent of suitable and unsuitable radar sites (n = 50 sites) in each category of relative aspect, relative altitude, and terrain type in the Olympic Peninsula, Washington, summer 1999.

Figure 3. Percent of suitable and unsuitable radar sites (n = 50 sites) by maximal slope and by maximal distance in the Olympic Peninsula, Washington, summer 1999.

Figure 4. Total numbers of radar targets headed into, out of, and over occupied murrelet stands relative to the timing of sunrise for all days with complete radar sampling sessions, summer 1997–1999.

targets that were above the stand, but it was not known whether they were flying into, out of, or simply crossing the stand). There was wide overlap in timing among the three groups, with most movements occurring from just before first light (i.e., 65 min before sunrise) until 45 min after sunrise (Fig. 4). There was a slight tendency for movements into stands to be earlier than movements out of stands, however.

A substantial portion (mean = 19.0%) of the radar observations into, out of, and over stands in 1999 occurred before the official starting time (45 min before sunrise) for IFSP surveys (Fig. 4, Table 5). This proportion varied little between years, with 18.4% and 22.1% of movements occurring before the official starting time in 1997 and 1998, respectively. The overall mean proportion of bird movement that occurred before official survey start time in 1997–1999 was 20.4% (n = 85 days; range = 0–50%).

EFFECT OF WEATHER ON TIMING

For both radar targets and audio-visual detections, the timing of morning activity was later on overcast days (≥80% cloud cover) than on clear days (≤20% cloud cover; Fig. 5). For radar targets, the pattern on overcast days was nearly identical to that on clear days but was shifted ~10 min later in the day. For audio-visual detections, the pattern also was similar, except that the pattern for overcast days was shifted 10–20 min later in the day.

AUDIO-VISUAL DETECTION DISTANCES

We were able to determine the horizontal distance between murrelet targets and audio-visual observers for the 92 observations of Marbled Murrelets that were detected concurrently by radar and audio-visual observers during 1997–1999. Of these targets, 36 (39.1%) occurred ≤100 m from the observers, 22 (23.9%) occurred 101–200 m from the observers, 16 (17.4%) occurred 201–300 m from the observers, 10 (10.9%) occurred 301–400 m from the observers, 3 (3.2%) occurred 401–500 m from the observers, and 5 (5.4%) occurred >500 m from the observers. Of the 5 birds occurring >500 m from the observers, 1 was at 550 m, 1 was at 600 m, 2 were at 650 m, and 1 was at 700 m.

Table 5. Total number of radar targets occurring before (>45 min before sunrise) and during official Marbled Murrelet survey protocol times, by site, summer 1999. Data are restricted to days with complete sampling sessions.

	Radar targets		
Site	Before (%)	During(%)	n (days)
North Goodman	2 (20)	8 (80)	3
Hoh	0 (0)	3 (100)	1
Clearwater	4 (22)	14 (78)	4
Tacoma Creek	0 (0)	2 (100)	1
Cedarpile	2 (25)	6 (75)	2
Nolan	1 (33)	2 (67)	1
Sand Creek	0 (0)	5 (100)	1
Blowdown	4 (21)	15 (79)	4
Brushhog	0 (0)	2 (100)	1
McKinnon Creek	13 (38)	21 (62)	3
South Clearwater	2 (50)	2 (50)	2
Mean	28 (19.0)	80 (81.0)	23

Figure 5. Timing of occurrence of radar targets (1997–1999) and audio-visual detections (1997–1998) relative to the timing of sunrise on overcast (≥80% cloud cover) and clear (≤20% cloud cover) days in the Olympic Peninsula, Washington.

PROPORTION OF DETECTIONS THAT WERE DOUBLE-COUNTED

We used data from targets observed concurrently by radar and audio-visual observers to calculate the minimal proportion of detections that were double-counted by audio-visual observers during IFSP surveys. Of the 92 murrelets that were observed both by radar and audio-visual observers, 2 (2.2%) were known to be double-counted by the audio-visual observers. We are certain that the actual proportion is higher than 2%, because radar targets rarely could be followed long enough to determine whether they eventually were double-counted at some point in time.

FLIGHT BEHAVIOR AND PROPORTION OF MURRELETS ACTUALLY USING OTHER STANDS

The majority of radar targets were flying straight into, out of, or over the stand of interest (Table 6). The radar sampled a large area around the survey stand, so we also observed a large proportion (44.0%) of radar targets using other stands. Of the 70 targets concurrently detected by audio-visual observers, only 8 (11.4%) were using other stands (Table 6). This lower proportion occurred because radar generally sampled a much larger area around the occupied stand than the audio-visual observers did and, thus, was able to observe more areas beyond the stand of interest. Five of the eight audio-visual detections that were using other stands were heard only, but the three others were seen flying in a straight direction over, or adjacent to, the stand at a height just over (~1.25 times) canopy height.

PROPORTION OF RADAR OBSERVATIONS ALSO DETECTED BY AUDIO-VISUAL OBSERVERS

We used two techniques to estimate the proportion of Marbled Murrelets that were detected by audio-visual observers on IFSP surveys. The first technique was to compute the mean proportion of radar targets that the audio-visual observer concurrently detected at each site. This technique suggested that audio-visual observers missed a large proportion of murrelets during IFSP surveys: during 1997, 1998, and 1999 combined, they detected only 3.4 ± 7.0% of all radar targets (Table 7, Appendices 4 and 5). The audio-visual observers detected 7.4 ± 16.5% of all radar targets when analyses were

Table 6. Number and percent of all radar observations and all overlapping audio-visual and radar observations by flight behavior category for all sites combined, summer 1997–1999. Data from the Nemah site were excluded because the radar could not sample a substantial proportion of the area in the vicinity of the stand.

			Flight behavior									
			Straight					Circling		Erra		
Sampling type	Year	No. /%	Into stand	Out from stand	Over stand	Through stand	Outside of stand	Over stand	Outside of stand	Into stand	Out from stand	Over stan
Radar	97	No.	273	170	226	–[a]	365	90	16	4	6	5
		%	23.4	14.6	19.4	–[a]	31.3	7.7	1.4	0.3	0.5	0.4
	98	No.	133	150	74	12	297	19	9	2	3	0
		%	18.9	21.3	10.5	1.7	42.2	2.7	1.3	0.3	0.4	0
	99	No.	64	63	22	47	271	4	1	0	3	0
		%	13.4	13.2	4.7	9.8	56.8	0.8	0.2	0	0.6	0
	Total	No.	470	383	322	59	933	113	26	6	12	5
		%	20.0	16.3	13.7	2.5	39.8	4.8	1.1	0.2	0.3	0.2
Audio-visual	97	No.	10	7	16	–[a]	3	7	0	0	0	0
		%	23.3	16.3	37.2	–[a]	7.0	16.3	0	0	0	0
	98	No.	5	5	1	1	0	2	0	0	0	0
		%	35.7	35.7	7.1	7.1	0	14.3	0	0	0	0
	99	No.	2	4	1	2	2	2	0	0	0	0
		%	15.4	30.8	6.7	15.4	15.4	15.4	0	0	0	0
	Total	No.	17	16	18	3	5	11	0	0	0	0
		%	24.3	22.9	25.7	4.3	7.1	15.7	0	0	0	0

[a] We did not have “straight through stand” or “erratically through stand” categories in 1997.

Table 7. Six measures of daily percentage of Marbled Murrelets recorded on radar that were detected by audio-visual observers during periods of concurrent radar and audio-visual observations, summer 1999.

		Percent of radar targets detected by audio-visual observers			Total audio-visual detections/total radar + a.vis. targets (%)		
Site	Station	All distances	≤400 m	≤200 m	All distances	≤400 m	≤200 m
Goodman	2	25.0	50.0	100.0	25.0	45.7	63.0
North Goodman	1	0.0	0.0	0.0	0.0	0.0	0.0
	2	0.0	**	**	0.0	**	**
	3	25.0	40.0	40.0	12.5	18.3	12.6
Ozette	3	0.0	0.0	0.0	20.0	31.3	38.7
Hoh	1	0.0	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0	0.0	0.0
	4	33.3	100	**	33.3	100	**
Clearwater	1	0.0	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	**	0.0	0.0	**
	3	0.0	0.0	**	0.0	0.0	**
	4	0.0	0.0	0.0	0.0	0.0	0.0
	5	0.0	0.0	0.0	0.0	0.0	0.0
Tacoma Creek	1	**	**	**	**	**	**
	2	0.0	0.0	0.0	0.0	0.0	0.0
	4	20.0	20.0	20.0	50.0	46.3	38.7
Cedar Pile	1	0.0	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	**	0.0	0.0	**
	3	0.0	**	**	0.0	**	**
	4*	0.0*	**	**	0.0*	**	**
Nolan	1	0.0	0.0	0.0	83.3	82.0	75.9
Sand Creek	1	5.3	33.3	0.0	5.3	30.4	63.0
Blowdown	1	0.0	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0	0.0	0.0
	5	14.3	20.0	0.0	36.8	66.8	71.7
Brush Hog	4	12.5	33.3	50.0	12.5	30.4	31.5
McKinnon Creek	1*	7.2*	12.5*	0.0*	7.2*	11.4*	10.5*
	2	0.0	0.0	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0	0.0	0.0
Lower Tacoma	1	11.1	25.0	33.3	20.0	37.2	34.7
South Clearwater	1	0.0	0.0	0.0	50.0	0.0	0.0
	4	0.0	0.0	**	0.0	0.0	**
	5	0.0	0.0	**	0.0	0.0	**
1999 MEAN ± SD		4.7±9.0	11.1±22.1	10.1±23.9	10.3±18.8	20.0±31.1	22.3±30.9
1998 MEAN ± SD		2.5±3.9	4.7±6.7	6.3±9.3	6.5±8.1	10.2±11.7	12.0±14.0
1997 MEAN ± SD		1.5±2.5	2.5±3.8	2.5±4.5	3.6±6.8	4.9±8.4	6.3±9.9
1997–1999 MEAN ± SD		3.4±7.0	7.4±16.5	7.1±17.1	7.8±14.6	13.9±24.0	14.9±23.4

*Mean of two sampling sessions.

**No birds or targets observed by radar or audio-visual observer in that distance category.

restricted to all targets within 400 m of the observers and improved to 7.1 ± 17.1% of all targets when analyses were restricted to all targets within 200 m of the observers.

The second technique that we used to estimate the proportion of birds that were detected by audio-visual observers on IFSP surveys was to compare the total number of audio-visual detections with the total number of radar targets and audio-visual targets not seen on radar (i.e., total number of birds) for each day. The data also should be examined this way because the first technique depended totally on the proportion of radar targets that were observed concurrently by audio-visual observers and did not include the large number of audio-visual detections that the radar either missed or detected at a different time than the observer. (Only 24.7% of all audio-visual detections were observed concurrently on radar. Many of the non-concurrent detections probably occurred when birds flew below the forest canopy or over areas of ground clutter over the stand, where the radar was unable to sample.) This comparison also suggested that audio-visual observers missed a large proportion of the murrelets during IFSP surveys in 1997–1999: for all distances, the percentage of murrelets that audio-visual observers detected was 7.8 ± 14.6% (Table 7, Appendix 5). The percentage of birds that audio-visual observers detected rose to 13.9± 24.0% and 14.9 ± 23.4% when analyses were limited to birds within 400 m and 200 m of the audio-visual observer, respectively.

Mean proportion of birds detected was roughly twice as high in 1999, as in 1998 or 1997 (Table 7). This probably is an artifact of our sampling schedule in 1999, when we did not conduct concurrent audio-visual counts from 2.25 h before sunrise to 1.25 h before sunrise. We did make concurrent observations for that first hour in 1997 and 1998, and because it was dark and murrelets tended to not to call during that period, few audio-visual detections occurred.

The variation in the ratio of audio-visual detections to radar targets was large both among sites and among days within a station (Table 7, Appendix 5). The large standard deviations resulting from this estimation technique indicate that variation in the proportion of murrelets that audio-visual observers detected also was substantial, no matter which method was used to compute the proportion (Table 7, Appendix 5). In fact, the standard deviation was greater than the mean for most cases, which would result in Coefficients of Variation exceeding 100%.

Given the large among-site and among-day variation in the proportion of birds detected on IFSP surveys, it was not surprising that the relationship between the total number of targets observed on radar and the number of detections ≤200 m from audio-visual observers was extremely weak (Spearman's rank correlation; $r = 0.598$, $P < 0.001$, $n = 104$). The correlation coefficient for targets and detections within 400 m of audio-visual observers was even weaker ($r = 0.500$, $P < 0.001$, $n = 104$ days), and the correlation coefficient for all distances was weaker yet ($r = 0.406$, $P < 0.001$, $n = 104$ days).

EFFECT OF WEATHER ON COUNTS AND ON THE PROPORTION OF BIRDS DETECTED

The mean number of targets recorded on radar during 1997–1999 did not differ between ceiling heights of ≤200 m and >200 m (Wilcoxon matched-pairs signed-ranks test; $Z = -1.492$, $P = 0.136$, $n = 17$ sites). Mean radar counts also did not differ between cloud covers of ≤20% and ≥80% ($Z = -0.841$, $P = 0.400$, $n = 6$ sites). In addition, the proportion of murrelets detected did not differ between ceiling heights of ≤200 m and >200 m (Mann-Whitney test, $U = 754.5$, $P = 0.225$, $n = 89$ days) and between cloud covers of ≤20% and ≥80% ($U = 221.0$, $P = 0.757$, $n = 51$ days).

NUMBER OF DAYS TO DETECT PRESENCE

We also compared the number of days required for radar to determine whether Marbled Murrelets were present in a stand with the number of days for standard audio-visual survey techniques to determine presence (Table 8, Appendix 3). We detected birds on 100% of the days with radar; thus, the mean (± SE) number of days to determine presence with radar was 1.0 ± 0.0 days (n = 14 sites). The number of days required to determine "presence" with the audio-visual technique ranged from 1 to 5+ days, with a mean = >2.3 ± 0.4 days (n = 12 sites; calculation of the mean excluded the 2 sites where no birds ever were detected audio-visually). Obviously, the true mean number of days would be higher than 2.3, with the increase dependent upon how many additional days are required to determine presence at the 2 sites where no audio-visual detections

Table 8. Total number of days required to determine presence at each site with radar and standard audio-visual techniques, Olympic Peninsula, Washington, during summer 1999.

	Number of days to determine presence		
Site	Radar	Audio-visual	n (days)
Goodman	1	1	1
North Goodman	1	3	3
Ozette	1	1	1
Hoh	1	3	3
Clearwater	1	>5	5
Tacoma Creek	1	3	3
Cedarpile	1	>5	5
Nolan	1	1	1
Sand Creek	1	1	1
Blowdown	1	4	4
Brush Hog	1	1	1
McKinnon Creek	1	5	5
Lower Tacoma	1	1	1
South Clearwater	1	3	3
Mean ± SE	1.0 ± 0.0	>2.3 ± 0.4*	

* Calculation of mean excludes the two sites with undetermined number of days (i.e., >5 days).

occurred in 1999. (Sampling will continue at those sites in 2000.) The number of days to detect presence was significantly higher for audio-visual observers than for the radar (Wilcoxon signed ranks test, $Z = -2.565$, $P = 0.010$, $n = 14$ sites).

DISCUSSION

TIMING OF MOVEMENTS

The near-dawn movement pattern of Marbled Murrelets we recorded was consistent with what is known about this aspect of the breeding biology of this species. The incubation period for Marbled Murrelets in Washington ranges from 26 April to 30 July, the nestling period ranges from 26 May to 27 August, and the fledging period ranges from 22 June to 27 August (Hamer and Nelson 1995, Nelson 1997). Thus, most of the murrelets that we observed probably were in the incubation stage during our May and June sampling. In July, some breeding murrelets still were incubating eggs, but most probably were in the chick-rearing stage. In addition, an unknown proportion of failed breeders and non-breeders prospecting for nests probably would have been flying over the forest in July (Nelson 1997). By August, only a small proportion of breeders still were in the chick-rearing stage, and many chicks already had fledged.

Taking into account travel time, the near-dawn movements of landward- and seaward-flying targets observed on radar coincided well with the period when incubation exchanges and feeding of chicks are known to occur. The time for incubation exchanges in Oregon has ranged from 31 min before to 1 min after sunrise (Nelson and Peck 1995, Nelson and Hamer 1995a); no data on this topic are available for Washington, but we assume that they are similar to those for Oregon. Adults overlap an average of only 26 sec at the nest during incubation exchanges. During chick-rearing, adults return to feed the young up to 8 times/day, but the first near-dawn feedings occur from ~37 min before to ~65 min after sunrise, with adults spending an average of 12.6 min at the nest during the feeding of young (Nelson and Hamer 1995a).

The near-dawn movement pattern that we observed also was similar to, but occurred 10–20 min later than, the pattern observed in radar studies on Vancouver Island (Burger 1997) and in Oregon and Washington (Cooper *et al.* 1999b, 1999c). These other studies made observations at locations between the ocean and nesting stands, rather than at nesting stands themselves, however. The timing of movements of Marbled Murrelets on radar at occupied stands in California (B. A. Cooper and T. E. Hamer, unpubl. data) was similar to this study, suggesting that the differences in timing among studies are related primarily to the extra travel time needed to get to nesting areas from the coast. This extra travel time also probably explains why the timing of movements was latest at our two sites that occurred the farthest inland (i.e., Wolflaw and Birdwatch; Cooper and Blaha 1998).

RELATIONSHIP BETWEEN TIMING OF MOVEMENT AND AMBIENT LIGHT

It appears that Marbled Murrelets time their morning flights to arrive at the nest around the time when the first significant light appears in the eastern sky. The radar observations indicated that a peak in arrivals of murrelets at occupied stands occurred immediately after overall ambient light levels first exceeded 0 lux. This coincidental timing may be the result of a compromise between the need to arrive when there is enough light for navigational purposes and the need to maximize predator avoidance by arriving at nesting stands when it is too dark for predators to spot them or at a time before the predators become active. Higher nest-visitation rates during lower light conditions has been suggested as an anti-predation adaptation for several nocturnal or crepuscular species, including Marbled Murrelets (Rodway et al. 1993a), Ancient Murrelets (*Synthliboramphus antiquus*; Jones et al. 1990), and Leach's Storm-Petrels (*Oceanodroma leucorhoa*; Watanuki 1986).

EFFECT OF WEATHER ON TIMING

We found that radar audio-visual detections began later and lasted longer on foggy or overcast days than on clear days. Other studies also have documented this relationship (Rodway *et al*. 1993a, Naslund and O'Donnell 1995, Nelson 1997). The timing of movement on radar also was slightly later on foggy and/or overcast days, indicating that movements actually occur later during those conditions and are not simply an artifact of the audio-visual observers' being less effective during the period near first light on overcast and foggy days. Thus, the later timing that we observed probably occurs because incubation exchanges and chick feeding in Marbled Murrelets occur later on foggy, overcast, and/or rainy days than on clear days (Nelson 1997). Further, it is possible that later exchanges and chick feeding occurs because of the delay in first light on days with inclement weather.

EFFECT OF WEATHER ON COUNTS

Our limited data suggest that there was not a consistent relationship between ceiling height or cloud cover and the number or proportion of Marbled Murrelets detected. In contrast, Kuletz (1994, *in* Naslund and O'Donnell 1995) found that numbers of detections of Marbled Murrelets in Alaska were higher during days with low ceilings. On the other hand, Rodway *et al.* (1993a) and Naslund and O'Donnell (1995) found that numbers of audio-visual detections were higher on overcast days than on clear days, whereas others (e.g., Nelson 1989, Hamer and Cummins 1990) found the reverse. These contrasting results match our results of no consistent patterns.

The use of audio-visual data, which are heavily biased by calling rates of birds, could lead to erroneous conclusions about the actual effect of weather on the abundance of Marbled Murrelets if vocalization rates were affected by weather. Our radar data, which are unbiased by vocalization rates, indicated that there was not a consistent relationship between ceiling height or cloud cover and the abundance of murrelets at a site. Further, the weather variables that we examined did not appear to be related to the proportion of murrelets detected, suggesting that the probability of detecting a murrelet was no different on a clear versus overcast, or low-ceiling versus high-ceiling, day.

EVALUATION OF THE INLAND FOREST SURVEY PROTOCOL

PROPORTION MISSED BEFORE OFFICIAL STARTING TIME

Radar-based observations indicated that 20% of all murrelet movements at stands occurred before the IFSP starting time for audio-visual surveys (which, by protocol, begin 45 min before sunrise). This proportion varied only slightly among 1997–1999. The proportion occurring before the official starting time probably is smaller at those sites that are located farther inland, judging by the difference in timing of activity that we observed between our inland Oregon sites and the Washington sites, which were closer to the coast (Cooper and Blaha 1998; also see above).

A significantly smaller proportion (6.1%) of audio-visual observations occurred before the IFSP survey starting time, suggesting that most of the birds that we detected on radar before official surveys began were silent (Cooper and Blaha 1998). Because there is little or no light in the sky prior to the IFSP survey starting time, the fact that the birds are silent indicates that little would be gained by starting the audio-visual surveys earlier: at that time, it is too dark for observers to detect flying murrelets visually.

Peak murrelet activity at nesting stands in July may include breeding and nonbreeding adults, subadults, and adults that have completed breeding at other sites (Nelson 1997). Could those murrelets that fly into a nesting stand before audio-visual detections begin be the birds of primary interest (i.e., breeding birds)? Given the high incidence of nest predation in some locations (Nelson and Hamer 1995b; J. Marzluff, University of Washington, Seattle, WA, pers. comm.), it would be advantageous for nesting birds to arrive under low light conditions, when they would be harder to see and before some of the nest predators (e.g., corvids) are active. Observations at nest sites suggest that most breeding adults visit the nest for incubation exchanges and chick feeding later in the morning than our first radar targets were recorded, during the period in which the IFSP surveys actually occur (Nelson and Hamer 1995a, Nelson 1997). It is likely, however, that many early-morning observations of returning breeders were missed, because most of the studies that provided these data were limited to daylight hours. For example, Nelson and Peck (1995) were unable to make visual observations prior to 45 before sunrise but occasionally did hear wingbeats of arriving birds before there was enough light to see birds (K. Nelson, Oregon State University, Corvallis, OR, pers. comm.). Thus, we believe that at least some of the early-morning flights that we observed were of breeding birds. At this time, we cannot even speculate on what time of day non-breeders visit nesting stands or on how many non-breeders occur at a stand.

PROPORTION OF DETECTIONS THAT WERE DOUBLE-COUNTED

Our data indicate that >2.2% of detections were double-counted by audio-visual observers during IFSP surveys. We consider this a minimal proportion because radar targets rarely could be followed long enough to determine whether they were double-counted at some point. One example of this type of target that was seen twice but was not known to be double-counted are those adults that were observed on their way into and, later, out of a stand during feeding visits; the 13-minute period spent at the nest would make it impossible for even the radar-based observers to determine whether two targets were the same bird. It is likely that the 2% value more closely represents the proportion of audio-visual detections that were counted once, then were not seen or heard for at least 5 sec but were counted again within a few seconds. This sort of double-counting is not unexpected, given the "5-second" rule for IFSP surveys (Ralph *et al.* 1994) that states that, when birds are not seen or heard calling for more than 5 sec but then start to call or are seen in a different area, they are counted as two detections.

PROPORTION OF BIRDS NOT USING THE SURVEY STAND

In contrast to the above findings, our data also suggest that there is a small probability that a stand could be considered to have birds "present" according to IFSP survey guidelines, when it actually did not have birds present. An average of 11.4% of the murrelets detected on surveys were not using the actual forest stand that was being surveyed. This proportion, however, probably varies widely among sites (e.g., sites along a valley movement corridor versus those at the upper end of the drainage) and, hence, could be higher at some sites. We did not find evidence that a stand could erroneously be considered to be "occupied" according to survey guidelines, when it actually was not occupied. None of the birds that we detected at one stand that actually were flying toward another stand exhibited any behavior associated with "occupied" nesting stands. Under the current IFSP survey protocol, "occupied" stands occur when birds are observed flying at, or below, canopy height, or are circling at low levels.

Our observations also demonstrated how birds using one stand of trees could be detected at another stand. For example, our radar observations showed that birds often made wide circles (up to ~1 km in radius) from the stand with which they appeared to be associated. Further, although birds generally are quiet when flying between the ocean and nesting areas, they occasionally will call at locations far from nesting stands (Cooper *et al.* 1999b, 1999c) and, thus, could be counted as a detection in areas far from the nesting stand.

EFFECTIVE IFSP SURVEY RADIUS

According to the IFSP, the average radius that can be surveyed adequately from a single sampling station is 200 m in a horizontal direction (Ralph *et al*. 1994). Similar to Hamer *et al.* (1995), we found that audio-visual observers were capable of detecting targets up to 700 m at some sites. The steep, steady drop in number of targets and detection rates that we observed for targets beyond 100 m, however, suggests that detectability does drop significantly beyond 100 m, even without accounting for the increasing sampling area with increasing radius. This drop in detectability probably varies widely among sites and weather conditions (e.g., with wind speed and direction, direction of calling bird with respect to wind direction and direction from observer, background noise). Our results indicate that the current IFSP survey radius of 200 m is larger than the effective audio-visual range of most observers under most field conditions.

PROPORTION OF BIRDS DETECTED BY AUDIO-VISUAL OBSERVERS

Our highest estimates of the proportion of Marbled Murrelets that are detected by audio-visual observers during IFSP surveys (i.e., the proportion detected ≤200 m horizontal distance from observers) indicate that audio-visual observers detect an average of only 7–15% of the Marbled Murrelets that are visiting an occupied stand. Because the detectability of murrelets declined rapidly with distance, calculations based on a 200-m sampling radius probably are our best measure of the proportion of birds detected by audio-visual observers. Further, calculating the proportion beyond 200 m does not provide meaningful information on the proportion of birds that are detected on the IFSP surveys currently being conducted in the Pacific Northwest, because 200 m is the maximal survey radius under the current survey protocol.

We are unsure at this time which of the two types of estimates (i.e., the one based on the mean proportion of radar targets within 200 m that the audio-visual observer concurrently detected at each site [7%] or the one based on of the proportion of total audio-visual detections divided by total numbers of radar targets plus any audio-visual targets that were not observed on radar [15%]) is the best estimate of the actual detection rate. The 5% estimate depends entirely on the proportion of radar targets observed concurrently by audio-visual observers and does not include the large number of audio-visual detections that the radar missed or detected at a different time. Altogether, only 25% of the audio-visual detections also were observed simultaneously on radar. Many of the non-concurrent detections probably occurred when birds flew below the forest canopy or over areas of ground clutter over the stand, where the radar was unable to sample. In conclusion, it is likely that the true mean rate of detection fell somewhere between these two estimates (i.e., between 7% and 15%).

Audio-visual observers in California detected 67 ± 15% of the birds that radar detected (Hamer *et al.* 1995). Reasons why they obtained a dramatically different percentage include differences in study sites and differences in sampling methodology. For example, in California, they observed large among-site differences in the proportion of murrelets detected. Perhaps the California sites were similar to the Quilcene or Nolan sites, which had high detection rates. In addition to among-site differences, there were differences in methods between the two studies. For example, audio-visual sampling in the Hamer *et al.* study often was conducted several hundred meters from the stand of trees. Finally, because their study was not designed specifically to determine the proportion of murrelets that were observed by audio-visual observers, some of the data were collected at sites that were not as optimal for radar sampling as the ones used in this study. Murrelets easily could be missed by the radar at such sites, thus inflating the estimated proportion detected by audio-visual observer.

DOES NUMBER OF DETECTIONS PROVIDE A MEASURE OF RELATIVE ABUNDANCE?

Our data indicate that the proportion of murrelets detected by audio-visual observers during IFSP surveys was highly variable, both among sites and among days within a site. We did not find any variables that accounted for the among-day or between-site variation in detectability of murrelets. There was no consistent effect of weather or time of year (Cooper and Blaha 1998) on the proportion of murrelets that were detected by audio-visual observers. Further, because one person (R. Blaha) did most of the audio-visual surveys for this study, among-observer variation was minimized.

Rodway *et al.* (1993b) found significant variation among observers in the proportion of murrelets that were visually detected, suggesting that this would be a further source of variation in the proportion of murrelets detected at a site.

Because we have not yet identified factors that consistently influenced among-site or among-day variation in the detectability of Marbled Murrelets on IFSP surveys, we cannot recommend a way of minimizing that variation by adjusting for season, weather, or observers. Further, with such large variation in the proportion of murrelets that were detected, we believe that it would not be appropriate to use those proportions as a correction factor for the audio-visual counts obtained on IFSP surveys.

Because the Inland Forest Survey Protocol for Marbled Murrelets was not designed to allow for calculations of the absolute number of birds at a stand (Paton 1995, Ralph *et al*. 1994), it is not surprising that the number of detections does not provide a useful measure of abundance. Nevertheless, although researchers apparently recognize this problem, the number of detections has been used by many studies as a measure of relative abundance of murrelets for determining habitat associations, seasonal abundance, and daily activity patterns (e.g., Hamer and Cummins 1990; Rodway 1993a, 1993b; Miller and Ralph 1995; Paton 1995).

RADAR AS A SURVEY TOOL

AVAILABILITY AND DESCRIPTION OF RADAR SURVEY SITES

We found that it was possible to use our lift-assisted ornithological radar at 56% of our randomly-chosen murrelet stands. Thus, in terrain similar to the western side of the Olympic Peninsula, one could expect to be able to use radar at approximately half of all sites. This proportion depends upon having good access to the area and upon having the use of a lift to raise the radar above the trees. Without our 10.5-m lift, we would not have been able to make observations at 35% of these otherwise-suitable sites. Obviously, a longer lift would be even more effective at getting the radar into a position above the surrounding vegetation so that it would be possible to observe murrelets at a particular stand of trees. For example, a longer lift would have helped us get the radar above the surrounding vegetation at approximately 35% of our unsuitable sites (i.e., it could have increased the percentage of sites that we would have been able to sample from 56% up to

71% of all sites).

Even if the radar is raised above surrounding vegetation, however, there still are some types of terrain where radar-based sampling is not possible. For example, observations are especially difficult for stands on steep terrain or at sites where the radar station is located above or below the stand of interest. Overall, flat stands with no slope that are at similar elevations as the radar station were the most suitable for radar sampling.

Although we have described some general guidelines as to what types of sites are suitable, it always will be necessary to ground check each site for its ability to detect murrelets before proceeding with radar observations. This check can be accomplished by making a map of the radar screen with location of ground clutter, shadow zones, streams, and stand boundaries. The amount and location of effective sampling area can then be quantified. Preparation of this map involves tracing the radar screen at a site and adding layers delineating ground clutter and delineating shadow zones where low-flying birds would not be detected. The shadow zones are drawn in based on a visual assessment of all clutter-free zones on the screen. Mapping exercises should be completed for each site so that data collected from these sites can be properly interpreted and their accuracy gauged.

DETECTING PRESENCE OF MURRELETS WITH RADAR

Although our previous study (Cooper and Blaha 1998) focused on the numerical relationship between the number of Marbled Murrelets observed on radar and the number of them that were detected audio-visually, this study compared the ability of the two techniques to determine presence of murrelets. It is important to make these comparisons because, when actual IFSP surveys are conducted, it takes only one survey on which ≥1 bird was seen or heard to classify the site as having murrelets "present."

In 1999, birds were detected on 100% of the days using radar. Thus, the mean number of days to determine "presence" for the radar technique was 1.0. The number of days required to determine presence with the audio-visual technique was significantly higher, ranging from 1 to 5+ days, with a mean >2.3 days. During our 2000 field season, we will be able to continue audio-visual observations at the two sites where no birds were detected in five days, then calculate the actual mean number of days and the actual time difference between techniques to determine presence.

Although radar will not work at all stands because certain terrain types preclude its use, our preliminary results suggest that a lift-assisted radar is a powerful tool for quickly determining the "presence" of murrelets at a stand. At a minimum, it appears that the radar technique will enable us to determine presence more quickly than with the audio-visual technique. There are additional advantages to using radar to determine presence. First, survey accuracy would be improved because radar tends to detect murrelets at low-use sites, where they can be missed completely by audio-visual observers (Cooper and Blaha 1998). Further, with radar it often is possible to determine whether murrelets are using the stand of interest or are just flying by on their way to another stand. We found that 11% of the audio-visual detections were of birds using a stand other than the one being surveyed. Finally, efficiency also would be improved because a radar samples a much larger area (up to a 1400-m radius) than audio-visual observers (up to 200 m radius) can.

Even with all of these advantages of radar, audio-visual surveys still will be necessary to determine if the stand is “occupied” by nesting murrelets, however, radar information could even be used to focus audio-visual surveys toward “hotspots” of activity within the stand. In conclusion, preliminary indications are that a combination of radar and audio-visual techniques will enable land managers to assess murrelet presence in a stand more accurately, more quickly, and less expensively than with the audio-visual technique alone.

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Appendix 1. Characteristics of 50 randomly chosen stands and assessments of their suitability for radar observations, Olympic Peninsula, Washington, during summer 1999.

											Pe
Township (T north, R west)	Section	DNR site name	Suitable for radar?[a]	Slope (º)	Aspect	Direction to stand from site	Stand type[b]	Relative altitude[c]	Distance to stand (range, in m)	Does lift enhance radar performance?	With of sta
T28R15	3	2915275	Y		–	330-30	PL	1	250-800	Y	
T29R15	34	2915194	Y		–	70-160	PL	3	130-600	Y	
	27	2915197	Y	0-20	S	270-340	RI-SL	3	200-1000	Y	
	15	2915213	N	0-30	E, S, W	180-225	RI-SL	5	250-800	N	
T28R13	29	28132	Y	0-3	SW	180-280	RP	3	500-1100	N	
	36	2813B	U	0-5	S	270-360	RI	3	300-600	N	
	32	2813C	U	0-10	NE	210-260	RO	3	500-1100	Y	
	22	2813D	N	10-15	S	340-45	SL	1	250-1000	Y	
T27R13	5	271346	Y		–	315-10	RP	3	250-1000	Y	
	5	271349	N		–	320-20	PL	3	200-800	N	
	2	2713A	N	0-20	W	150-180	SL	5	0-1100	N	
	20	2713003	U	10-30	SW	180-270	RI-SL	4	500-900	Y	
T27R11	17	2711A	N		E	45-125	SL	4	400-700	N	
	22	271146	N		S	10-135	SL	3	75-900	N	
	21	2711032	N		S	290-80	SL	1	100-800	Y	
	15	2711016	N		S	190-290	SL	4	200-1300	N	
	14	271135	N		SE	190-225	SL	4	400-1100	N	
	14	271139	N		S	160-200	SL	5	600-1300	N	
T26R12	21	261243	Y	0-2	E	45-110	PL	3	250-600	Y	
	22	261244	Y		–	315-45	PL	2	150-1200	Y	
	22	2612C	Y		–	45-70	PL	2	600-1000	Y	
	14	2612B	U		–	260-315	PL	3	250-600	Y	
T26R11	3	2611-RPM12	Y		–	95-135	PL	3	400-1000	Y	
	17	2611004	N	20-40	W	90-160	CB-SL	1	250-1200	N	
	21	261183	Y		–	240-280	PL	3	250-1000	Y	
	13	2611002	N		N	350-65	SL	5	250-1700	Y	

Appendix 1. Characteristics of 50 randomly chosen stands and assessments of their suitability for radar observations, Olympic Peninsula, Washington, during summer 1999 (continued).

											Pe
Township (T north, R west)	Section	DNR site name	Suitable for radar?[a]	Slope (º)	Aspect	Direction to stand from site	Stand type[b]	Relative altitude[c]	Distance to stand (range, in m)	Does lift enhance radar performance?	With of sta
T26R10	9	2610Y	Y		SE, SW	135-190	SL	5	150-1100	Y	
	9	2610X	Y		SE, SW	170-250	SL	5	175-1000	Y	
	16	2610268	N		SSE	100-190	SL	4	200-1000	Y	
	20	2610265	N	20-50	SE	0-30	SL	1	600-1000	N	
T25R13	2	2513018	Y		WNW	150-270	RO	3	150-900	N	
	14	2513B	Y	0-20	NE	45-170	SL	5	100-700	Y	
	13	2513A	N		NE	45-125	SL	5	600-1200	N	
	23	2513C	N	10-20	SW	230-315	CB	5	300-1100	N	
T25R12	35	251247	Y	5-15	N, S, E	270-360	RO	3	250-1000	N	
	7	2512025	Y	0-45	S, SE, E	110-190	SL	4	300-1300	Y	
	26	2512A	N	0-15	–	10-045	RI	1	300-750	N	
	14	2512066	N	0-20	S, NE	355-070	RI-SL	1	250-1200	Y	
T25R11	33	2511114	Y	0-5	S	100-240	PL	5	100-800	Y	
	34	2511137	U		S	170-250	SL	4	70-650	Y	
	12	2511251	U		NE, NW	10-110	SL	4	200-750	Y	
	17	251178	N		–	110-250	CB	5	150-700	Y	
T24R12	1	241293	Y	0-2	–	220-300	PL	3	200-800	N	
	11	2412111	Y	0-2	–	270-80	RO	3	100-800	N	
	1	241292	Y	0-15	N	120-220	RO	4	350-850	Y	
	13	241298	Y		–	0-90	SL	3	180-800	N	
T24R11	8	2411121	Y		S	80-160	PL	3	125-850	Y	
	3	2411219	N		–	45-170	PL	5	200-1400	Y	
	7	2411128	U		–	110-260	PL	3	50-1100	Y	
	8	2411129	Y		–	190-240	PL	3	350-1100	Y	

[a] U = Unknown.

[b] SL = slope; RI = ridge; CB = canyon bottom; PL = plain; RO = rolling hills; ES = estuary; RP = rolling or undulating plain.

[c] 1 = below stand level; 2 = at bottom edge of stand; 3 = at stand level; 4 = at top edge of stand; 5 = above stand level.

Appendix 2. Total numbers of radar targets, audio-visual detections, and overlapping observations by site and date during summer 1999. Note that sampling times between days were not always equal, because radar observations sometimes were precluded by precipitation.

			Number		
Site	Station	Date	Radar targets	Audio-visual detections	Overlapping observations
Goodman	1.2	9 May	5	1	1
North Goodman	2.1	10 May	9	0	0
	2.2	28 May	10	0	0
	2.3	10 June	12	1	1
Ozette	3.3	18 May	4	1	0
Hoh	4.1	28 May	5	0	0
	4.2	19 May	11	0	0
	4.4	21 June	6	2	2
Clearwater	5.1	29 May	16	0	0
	5.2	2 July	16	0	0
	5.3	20 May	8	0	0
	5.4	30 July	9	0	0
	5.5	26 July	17	0	0
Tacoma Creek	6.1	25 May	11	0	0
	6.2	30 May	4	0	0
	6.4	24 July	16	3	2
Cedar Pile	7.1	25 July	24	0	0
	7.2	31 July	26	0	0
	7.3	25 May	7	0	0
	7.4	31 May	1	0	0
	7.4	20 June	2	0	0
Nolan	8.1	26 May	8	5	0
Sand Creek	9.1	26 May	19	1	1
Blowdown	10.1	27 May	18	0	0
	10.2	11 June	14	0	0
	10.3	25 July	20	0	0
	10.5	28 July	19	7	2
Brushhog	11.4	27 May	12	1	1
McKinnon Creek	12.1	12 June	22	0	0
	12.1	27 July	21	1	1
	12.2	3 July	2	0	0
	12.2	4 July	29	0	0
	12.3	19 June	13	0	0
Lower Tacoma	13.1	24 July	19	2	1
	13.3	5 July	10	0	0
South Clearwater	14.1	29 July	9	1	0
	14.4	26 July	17	0	0
	14.5	2 July	16	0	0

Appendix 3. Numbers of radar targets, audio-visual detections, and overlapping observations during concurrent radar and audio-visual sampling sessions by site and date, summer 1999.

			Number		
Site	Station	Date	Radar targets	Audio-visual detections	Overlapping Observations
Goodman	1.2	9 May	4	1	1
N. Goodman	2.1	10 May	6	0	0
	2.2	28 May	7	0	0
	2.3	10 June	8	1	1
Ozette	3.3	18 May	4	1	0
Hoh	4.1	28 May	5	0	0
	4.2	19 May	10	0	0
	4.4	21 June	6	2	2
Clearwater	5.1	29 May	12	0	0
	5.2	2 July	9	0	0
	5.3	20 May	6	0	0
	5.4	30 July	6	0	0
	5.5	26 July	15	0	0
Tacoma Cr.	6.1	25 May	0	0	0
	6.2	30 May	4	0	0
	6.4	24 July	5	3	2
Cedar Pile	7.1	25 July	19	0	0
	7.2	31 July	19	0	0
	7.3	25 May	2	0	0
	7.4	31 May	1	0	0
	7.4	20 June	0	0	0
Nolan	8.1	26 May	1	5	0
Sand Creek	9.1	26 May	19	1	1
Blowdown	10.1	27 May	11	0	0
	10.2	11 June	9	0	0
	10.3	25 July	16	0	0
	10.5	28 July	14	7	2
Brush Hog	11.4	27 May	8	1	1
McKinnon Cr.	12.1	12 June	11	0	0
	12.1	27 July	7	1	1
	12.2	4 July	16	0	0
	12.3	19 June	9	0	0
Lower Tacoma	13.1	24 July	9	2	1
	13.3	5 July	10	0	0
S. Clearwater	14.1	29 July	2	1	0
	14.4	26 July	15	0	0
	14.5	2 July	9	0	0

Appendix 4. Total numbers of radar targets and audio-visual detections by site, station, and distance over all periods of concurrent observations during summer 1999. Numbers of audio-visual detections were adjusted for distance, based on the total proportion of all detections in each category.

			Number					
			Radar Targets			Audio-visual detections		
Site	Station	Date	Total	≥ 400 m away	≥ 200 m away	Total	Adjusted for 400 m	Adjusted for 200 m
Goodman	1.2	9 May	4.0	2.0	1.0	1.0	0.9	0.6
N. Goodman	2.1	10 May	6.0	3.0	1.0	0.0	0.0	0.0
	2.2	28 May	7.0	0.0	0.0	0.0	0.0	0.0
	2.3	10 June	8.0	5.0	5.0	1.0	0.9	0.6
Ozette	3.3	18 May	4.0	2.0	1.0	1.0	0.9	0.6
Hoh	4.1	28 May	5.0	5.0	2.0	0.0	0.0	0.0
	4.2	19 May	10.0	2.0	1.0	0.0	0.0	0.0
	4.4	21 June	6.0	1.0	0.0	2.0	1.8	1.3
Clearwater	5.1	29 May	12.0	5.0	2.0	0.0	0.0	0.0
	5.2	2 July	9.0	2.0	0.0	0.0	0.0	0.0
	5.3	20 May	6.0	1.0	0.0	0.0	0.0	0.0
	5.4	30 July	6.0	2.0	2.0	0.0	0.0	0.0
	5.5	26 July	15.0	4.0	2.0	0.0	0.0	0.0
Tacoma Cr.	6.1	25 May	0.0	0.0	0.0	0.0	0.0	0.0
	6.2	30 May	4.0	2.0	1.0	0.0	0.0	0.0
	6.4	24 July	5.0	5.0	5.0	3.0	2.7	1.9
Cedar Pile	7.1	25 July	19.0	5.0	3.0	0.0	0.0	0.0
	7.2	31 July	19.0	1.0	0.0	0.0	0.0	0.0
	7.3	25 May	2.0	0.0	0.0	0.0	0.0	0.0
	7.4	31 May	1.0	0.0	0.0	0.0	0.0	0.0
	7.4	20 June	0.0	0.0	0.0	0.0	0.0	0.0
Nolan	8.1	26 May	1.0	1.0	1.0	5.0	4.6	3.2
Sand Creek	9.1	26 May	19.0	3.0	1.0	1.0	0.9	0.6
Blowdown	10.1	27 May	11.0	4.0	3.0	0.0	0.0	0.0
	10.2	11 June	9.0	3.0	3.0	0.0	0.0	0.0
	10.3	25 July	16.0	11.0	5.0	0.0	0.0	0.0
	10.5	28 July	14.0	5.0	3.0	7.0	6.4	4.4
Brush Hog	11.4	27 May	8.0	3.0	2.0	1.0	0.9	0.6
McKinnon Cr.	12.1	12 June	11.0	9.0	3.0	0.0	0.0	0.0
	12.1	27 July	7.0	4.0	3.0	1.0	0.9	0.6
	12.2	4 July	16.0	11.0	5.0	0.0	0.0	0.0
	12.3	19 June	9.0	6.0	4.0	0.0	0.0	0.0
Lower Tacoma	13.1	24 July	9.0	4.0	3.0	2.0	1.8	1.3
	13.3	5 July*	10	ND*	ND*	0	0	0
S. Clearwater	14.1	29 July	2.0	0.0	0.0	1.0	0.9	0.6
	14.4	26 July	15.0	5.0	0.0	0.0	0.0	0.0
	14.5	2 July	9.0	2.0	0.0	0.0	0.0	0.0

*Have total counts, but no detailed radar information from that day.

Appendix 5. Six measures of mean (± SD) percentage of the proportion of Marbled Murrelets recorded on radar that were detected by audio-visual observers during periods of concurrent radar and audio-visual observations, summer 1997–1998. No SD's are given for sites with only one sampling day.

		Percent of radar targets detected by audio-visual observers			Total number of audio-visual detections/total number of radar + a-vis. targets (%)		
Site (Station)	Year	All distances	≤400 m	≤200 m	All distances	≤400 m	≤200 m
Quilcene (1)	97	8.0 ± 5.9	10.9 ± 8.3	14.4 ± 9.4	24.1 ± 20.0	28.1 ± 21.4	31.3 ± 23.2
	98	2.2 ± 3.0	3.1 ± 4.3	4.3 ± 5.4	8.4 ± 9.0	10.8 ± 11.2	10.4 ± 9.7
Quilcene (2)	97	0 ± 0	0 ± 0	0 ± 0	5.6 ± 7.9	5.8 ± 8.2	4.8 ± 6.7
Wolflaw (1)	97	0	–[a]	–[a]	0	–[a]	–[a]
	98	4.2	14.3	25.0	8.0	23.1	27.2
Wolflaw (2)	97	0	0	0	0	0	0
Wolflaw (3)	97	0	0	0	0	0	0
Wolflaw (4)	97	5.6	6.7	8.3	5.3	5.7	5.0
	98	0	0	0	20.8	38.1	45.6
Wolflaw (5)	98	12.5	18.8	23.1	27.6	35.5	31.2
Scotch Broom (1)	97	0.3 ± 0.6	0.7 ± 1.2	0.0 ± 0.0	0.7 ± 1.1	1.2 ± 2.1	4.4 ± 7.6
Scotch Broom (3)	98	5.0 ± 10.0	7.1 ± 14.3	8.3 ± 16.7	5.0 ± 10.0	6.5 ± 13.0	5.3 ± 10.5
Swamp (0)	97	0	0	0	0	0	0
Swamp (1)	97	1.3 ± 1.8	2.6 ± 3.7	6.3 ± 8.8	2.4 ± 3.4	4.6 ± 6.5	7.3 ± 10.3
	98	0.4 ± 1.0	0.6 ± 1.4	1.0 ± 2.6	6.9 ± 7.5	8.4 ± 7.3	12.0 ± 11.5
Swamp (2)	97	4.5 ± 4.6	9.0 ± 11.5	6.5 ± 7.6	13.7 ± 11.6	19.1 ± 10.0	25.0 ± 14.7
Hilltop (0)	97	2.2	4.5	0	2.2	4.2	10.5
Hilltop (1)	97	0	0	0	0	0	0
Hilltop (3)	98	0 ± 0	0 ± 0	0 ± 0	4.0 ± 5.7	4.8 ± 6.9	5.6 ± 7.9
Hilltop (4)	98	6.5 ± 9.2	11.5 ± 16.3	16.7 ± 23.6	11.5 ± 9.9	17.0 ± 14.7	16.6 ± 15.1
Ocean Ridge (0)	97	0	0	0	0	0	0
Ocean Ridge (1)	97	0	0	0	0	0	0
Ocean Ridge (2)	98	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Ocean Ridge (3)	98	0.0	0.0	0.0	0.0	0.0	0.0
Alder Creek (1)	97	0.0	0.0	0.0	0.0	0.0	0.0
	98	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Kunamakst (0)	98	9.0 ± 11.9	14.6 ± 17.2	16.7 ± 25.0	15.3 ± 23.7	19.9 ± 26.8	40.3 ± 35.0
Kalaloch (1)	98	0	0	0	0	0	0
Kalaloch (2)	98	0	-*	-*	0	-*	-*
Cougar Creek (1)	98	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Birdwatch (1)	98	0	0	0	0	0	0
1997 GRAND MEAN		1.5 ± 2.5	2.5 ± 3.8	2.5 ± 4.5	3.6 ± 6.8	4.9 ± 8.4	6.3 ± 9.9
1998 GRAND MEAN		2.5 ± 3.9	4.7 ± 6.7	6.3 ± 9.3	6.5 ± 8.1	10.2 ± 11.7	10.0 ± 12.0

[a] Neither radar target or audio-visual detection was recorded.