Radar Monitoring of Marbled Murrelet Populations at Inland Sites on Northern Vancouver Island

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Abstract: Marine surveillance radar was used to inventory marbled murrelet (*Brachyramphus marmoratus*) populations as part of a long-term conservation program for Canadian Forest Products Ltd.'s Tree Farm Licence 37 on Vancouver Island, British Columbia. In 2003, we recorded 4571 radar detections from 32 morning surveys at 19 sites. Most sites were surveyed on consecutive days, and consecutive-day variability ranged from 4 to 61% depending on the site. Average consecutive-day variability was less at coastal sites (20%) compared to inland sites (29%), but was similar for data collected by a tilted radar scanner (26%) and untilted scanner (30%). Minimum flight heights determined for 86 targets based on angles of radar fences ranged from 100 to 730 m (mean = 270 m). The velocity of murrelet targets was measured on the radar screen to the nearest 0.1 mm using precision calipers. The mean estimated velocity of birds flying seaward (101 km/hr) was significantly higher than landward-moving birds (89 km/hr), which was in turn significantly higher than circling birds (82 km/hr). When tilted and untilted radar units were operated simultaneously at the same location, the tilted scanner detected 29– 2925% (mean: 76%) more murrelets than the untilted scanner. We plan to continue long-term population trend monitoring on northern Vancouver Island using tilted scanner radar surveys.

Key Words: marbled murrelet, *Brachyramphus marmoratus,* radar surveys, population monitoring, British Columbia

Introduction

The marbled murrelet (*Brachyramphus marmoratus*) nests in trees in old-growth forests along the west coast of North America, and its populations are believed to be declining in many areas. Threats to the species include the loss of old-growth forest nesting habitat to timber harvesting and impacts associated with oil spills and gill nets (Kaiser et al. 1994; Beissinger 1995; Nelson 1997; Hull 1999; Burger 2002a).

The marbled murrelet is designated as Threatened in Canada (Hull 1999; CWS 2003), and U.S. populations outside of Alaska are designated as Threatened under the U.S. *Endangered Species Act* (USFWS 1992, 2003). The marbled murrelet is red-listed in British Columbia (B.C.) (Fraser et al. 1999), and is included in the list of Species at Risk Schedule 1 under the Identified

Wildlife Management Strategy (IWMS) and the provincial *Forest and Range Practices Act* (Province of British Columbia 2004).

Management of marbled murrelets is a high priority in Canadian Forest Products Ltd.'s (Canfor's) Tree Farm Licence (TFL) 37 on Vancouver Island, B.C., and the company is in the process of implementing a number of conservation initiatives for the species through their Sustainable Forest Management Plan (Deal and Manning 2002). Canfor is currently developing a nesting habitat conservation strategy for the Nimpkish Defined Forest Area (DFA) which protects over 21,000 ha of potential marbled murrelet nesting habitat (Deal and Harper 2005). The strategy is part of a multi-level management program for the Nimpkish DFA which also includes reconnaissance and site-specific habitat assessments, dawn audiovisual surveys, and long-term habitat conservation for the marbled murrelet. The radar component of the management program is designed to monitor long-term population trends at the landscape level as a means of evaluating the effectiveness of the nesting habitat conservation strategy (Deal and Harper 2005).

Study Area

The study area is centered on the Nimpkish DFA, which is located immediately south of Port McNeill on Vancouver Island and encompasses Nimpkish Lake, the Nimpkish River, Woss Lake, Vernon Lake, and the upper reaches of the Tsitika River (Fig. 1). The Nimpkish DFA includes TFL 37 and the associated parks and protected areas in the draft Lower Nimpkish and Upper Nimpkish Landscape Units. Ecologically, the study area is situated in the Northern Island Mountains and Windward Island Mountains ecosections within the Western Vancouver Island ecoregion and the Coast and Mountains ecoprovince (Demarchi 1995). The three biogeoclimatic zones represented are Coastal Western Hemlock (CWH), Mountain Hemlock (MH), and Alpine Tundra (AT) (Green and Klinka 1994).

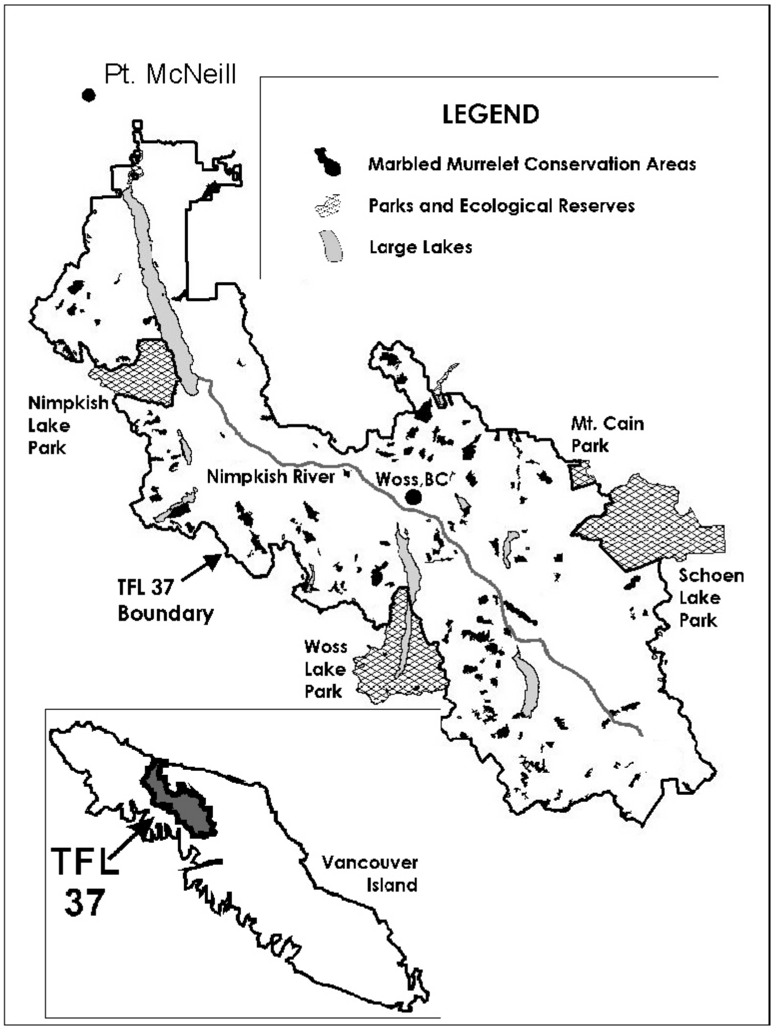

Figure. 1. Location of the Tree Farm Licence (TFL) 37 study area on northern Vancouver Island.

Methods

Marine surveillance radar was used to inventory murrelet populations at both coastal and inland sites on northern Vancouver Island. Methods for conducting radar surveys in the Nimpkish Valley followed the protocol described in *Inventory Methods for Marbled Murrelets in Marine and Terrestrial Habitats*, Version 2.0 (RISC 2001), and closely resembled those used elsewhere in coastal B.C. (e.g., Burger 1997, 2001, 2002b; Schroeder et al. 1999; Manley 2000; Cullen 2002; Steventon and Holmes 2002).

Two mobile marine surveillance radar units were used. A 10-kW Furuno FR-7111 with a 2-m scanner tilted to scan an arc of 25º using 9410 MHz was used at all radar stations, and a 5-kW Furuno FR-805D with a 2-m scanner untilted to scan an arc of 10º using 9410 MHz was used at seven radar stations for comparison purposes. The scanner was generally mounted on the roof of a truck, approximately 2 m above the ground. When two radar scanners were operated simultaneously, the untilted scanner was placed approximately 1 m above the ground to minimize interference. As reported in Hamer et al. (1995), Burger (1997, 2001), and Cooper et al. (1998), we found it relatively easy to distinguish murrelets from other species on the radar screen due to their speed, linear flight path, and size and shape of their radar image.

Radar surveys were conducted at 19 locations throughout northern Vancouver Island between 11 May and 20 July 2003. Eight of the radar stations (RSs) were located on large inland lakes, 2 on small inland lakes, 6 on coastal inlets, 2 on inland cutblocks, and 1 near the end of a small gravel airstrip (Fig. 2). Dawn radar surveys began 2 hours before official sunrise and ended 1 hour after sunrise or 15 minutes after the last murrelet detection (Burger 2001). The time of official sunrise was established each survey day by determining sunrise time at Woss, B.C. (the center of study area) using data from an astrophysical web site (Herzberg Institute of Astrophysics 2003). Concurrent audiovisual surveys were conducted within 50 m of most radar stations.

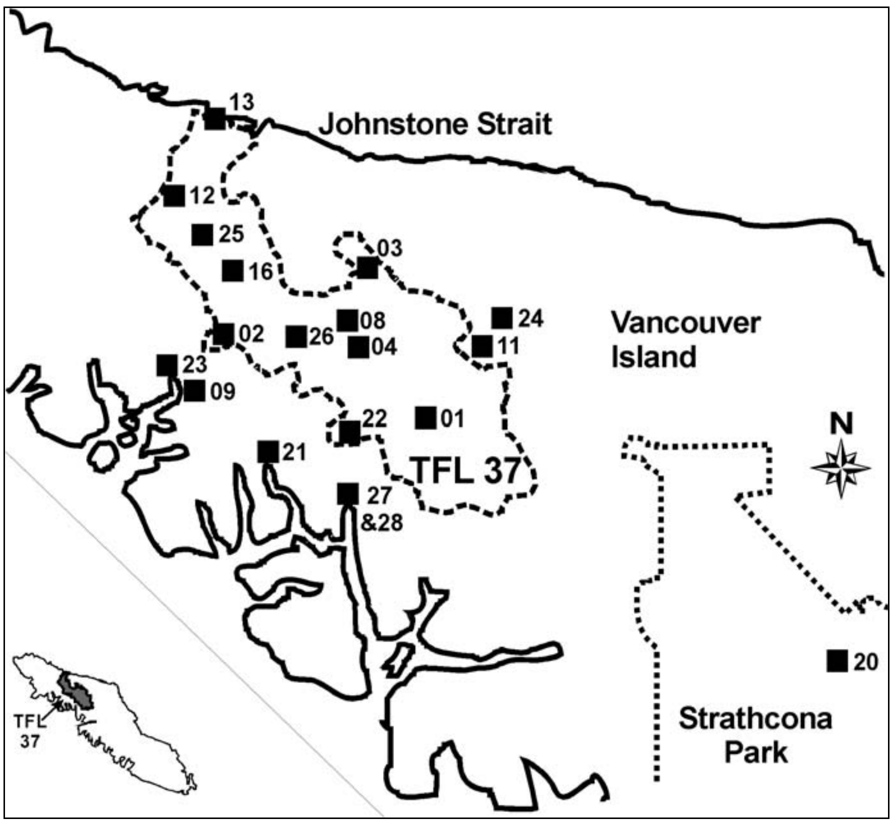

Figure 2. Location of radar stations in and around TFL 37 that were used for monitoring population trends of marbled murrelets in 2003 (numbers next to squares indicate the radar station number).

A transparency was placed over the radar screen and the main murrelet flight corridors were identified by drawing arrows in the direction and along the length of movement areas. Most radar surveys were conducted with the range set at 0.75 nautical miles (1390 m). To gauge the speed of different bird species, the distance between radar echoes was measured on the radar screen to the nearest 0.1 mm with dial and/or digital calipers and was calibrated with the slowest measured rotation rate of 23/min. This ratio was then converted to kilometers per hour (km/hr) to estimate the speed of the bird.

Any weather conditions during the survey period that might have affected murrelet detections (i.e., periods of rain) were noted along with the times that they occurred. Periods of rain that obscured murrelet detections and which lasted > 10 minutes were recorded, and those datasets were excluded from the analysis because the survey protocols regard them as incomplete (RISC 2001; Burger 2001). Caution was used when identifying murrelets during periods when winds were > 20 km/hr as strong tail winds may cause slower flying species to be misidentified as murrelets and murrelets flying against strong headwinds to be misidentified as a slower-flying species (Burger 1997, 2001; RISC 2001; Cooper and Hamer 2003).

For most murrelet detections, the following data were recorded into a tape recorder:

- time of detection
- number of birds
- bearing of the bird's flight path
- flight behavior (circling or direct flight)
- flight direction (i.e., whether the bird was flying in towards the forest or out towards the sea)
- closest distance from the radar unit to the detection
- direction of where the detection was closest to the radar unit
- number of radar echoes associated with each detection
- distance between radar echoes

All field data were transcribed onto forms and then were entered into a computerized spreadsheet for sorting and statistical analysis. Analyse-it + General 1.62 (Analyse-it Software Ltd. 2001) was used to perform parametric tests on normally distributed data and nonparametric tests when normality could not be achieved by transformation. All tests of significance used α = 0.05 as the probability of making a Type I error (i.e., rejecting a true null hypothesis).

Results

Overall, there were 6462 detections of 6951 targets (birds) during 34 morning and 17 evening surveys in 2003, including those surveys when tilted and untilted radar units were run simultaneously. Observers stationed near the radar station at 26 of the 34 morning surveys recorded 180 audiovisual detections compared to 3219 tilted radar detections. On average, 8.5% of the tilted radar detections were of 'flocks' (i.e., single detections consisting of 2, and occasionally 3, separate targets or birds) (Table 1).

Table 1. Number of radar detections and birds (targets) observed with tilted radar during 32 early morning surveys in 2003.

			Radar detections				*Birds (targets)*				
Date	*Station*	*Location*	*inland*	*circle*	*seaward*	*total*	*inland*	*circle*	*seaward*	*total*	*flocks* (%)*
Coastal radar stations											
25-Jun-03	RS09	Artlish River	629	1	248	878	631	1	262	894	2%
26-Jun-03	RS09	Artlish River	321	1	331	653	343	1	417	761	17%
29-May-03	RS13	Nimpkish R Mouth	12	0	63	75	12	0	64	76	1%
05-Jun-03	RS13	Nimpkish R Mouth	32	0	47	79	33	0	49	82	4%
19-Jun-03	RS21	Zeballos Inlet	70	0	41	111	70	0	41	111	0%
20-Jun-03	RS21	Zeballos Inlet	43	0	36	79	43	0	36	79	0%
15-Jul-03	RS23	Tahsish-Kwois	236	0	156	392	257	0	191	448	14%
16-Jul-03	RS23	Tahsish-Kwois	207	0	159	366	211	0	168	379	4%
11-May-03	RS27	Tahsis Park	101	4	39	144	111	6	47	164	14%
12-May-03	RS28	Tahsis Gov't Dock	191	1	85	277	192	1	87	280	1%
Inland radar stations											
27-Jun-03	RS01	Vernon Lake North	16	5	32	53	16	5	33	54	2%
28-Jun-03	RS01	Vernon Lake North	47	6	26	79	47	6	29	82	4%
11-Jun-03	RS02	Atluck Lake West	63	24	105	192	71	32	130	233	21%
09-Jun-03	RS03	Claude Elliott	63	5	48	116	67	4	51	122	5%
10-Jun-03	RS03	Claude Elliott	92	10	72	174	112	12	86	210	21%
08-Jul-03	RS04	Woss Lake North	44	0	13	57	46	0	13	59	4%
09-Jul-03	RS04	Woss Lake North	34	0	16	50	37	0	18	55	10%
21-Jun-03	RS08	Woss Airstrip	25	1	20	46	25	1	21	47	2%
22-Jun-03	RS08	Woss Airstrip	21	1	48	70	21	1	50	72	3%
23-Jun-03	RS11	Schoen Campsite	10	1	2	13	12	1	2	15	15%
24-Jun-03	RS11	Schoen Campsite	1	0	5	6	1	0	5	6	0%

Table 1. Number of radar detections and birds (targets) observed with tilted radar during 32 early morning surveys in 2003 (cont'd).

			Radar detections				*Birds (targets)*				
Date	*Station*	*Location*	*inland*	*circle*	*seaward*	*total*	*inland*	*circle*	*seaward*	*total*	*flocks* (%)*
26-May-03	RS12	Nimpkish Lk North	18	1	35	54	19	1	37	57	6%
27-May-03	RS12	Nimpkish Lk North	44	0	22	66	45	0	24	69	5%
10-Jul-03	RS16	Nimpkish Lk South	20	1	64	85	25	1	70	96	13%
03-Jun-03	RS20	Buttle Lk-Karst Ck	9	0	16	25	9	0	16	25	0%
04-Jun-03	RS20	Buttle Lk-Karst Ck	9	1	12	22	9	1	12	22	0%
12-Jul-03	RS22	Woss Lk South	41	2	43	86	46	2	44	92	7%
17-Jul-03	RS24	Schoen Lake NE	45	16	18	79	57	19	21	97	23%
18-Jul-03	RS24	Schoen Lake NE	29	7	15	51	35	10	17	62	22%
19-Jul-03	RS25	Nimpkish Lk-Kilpala	59	0	50	109	63	0	53	116	6%
20-Jul-03	RS25	Nimpkish Lk-Kilpala	38	0	30	68	43	0	35	78	15%
08-Jun-03	RS26	Kaipit Cutblock	6	0	10	16	7	0	10	17	6%
Total			2576	88	1907	4571	2716	105	2139	4960	8.5%

*'Flocks' are single detections that consist of 2, and occasionally 3, separate targets or birds.

On average, 91% of detections flying inland occurred prior to official sunrise, but this percentage ranged from 40 to 100% among the various survey days and radar stations. Weather conditions were favorable for radar operations on 32 of the 34 survey mornings, but significant amounts and duration of rainfall on 12 June 2003 at RS02 and on 13 July 2003 at RS22 meant that data collected on those days were not used for population monitoring. On 9 days when cloud cover was below the ridges, an average of 86% of detections occurred predawn, which was not significantly different than the 88% of detections that occurred predawn on the 15 days when cloud cover was either above the ridges or was nonexistent (Mann-Whitney U statistic = 64.5, $P = 0.9070$).

Population Monitoring

Using the tilted radar unit, long-term population monitoring data were collected from 32 effective morning surveys at 19 radar stations between 11 May and 19 July 2003 (Table 1). A total of 4571 detections of 4960 murrelet targets were recorded during this period. Twelve surveys at 8 radar stations were categorized as early season surveys (11 May–12 June), 12 surveys at 6 radar stations were categorized as mid-season surveys (13 June–9 July), and 8 surveys at 5 radar stations were categorized as late season surveys (10–20 July). The largest numbers of detections were from RS09, which had a maximum morning count of 878 detections of 894 targets, and RS23, which had a maximum morning count of 392 detections of 448 targets. Other coastal sites also had large daily maximum target counts of murrelets including RS28 (277 detections of 280 targets), RS21 (111 detections of 111 targets), and RS13 (79 detections of 82 targets) (Table 1).

For the most part, inland radar stations had fewer radar detections than coastal stations, but many inland sites also had large daily maximum counts, including RS02 (192 detections of 233 targets), RS03 (174 detections of 210 targets), RS25 (109 detections of 116 targets), RS24 (79 detections of 97 targets), and RS 22 (86 detections of 92 targets). The fewest radar detections occurred at RS11, which had a maximum morning count of 13 detections of 15 targets.

The proportion of detections that consisted of flocks averaged 8.5% for all morning surveys with the tilted scanner but ranged from 0 to 23% for individual survey mornings (Table 1). More details on data collected for population monitoring in TFL 37 are available in Harper and Schroeder (2004).

Most sites were surveyed on consecutive days, and consecutive-day variability (coefficient of variation [CV]) ranged from 4 to 61% depending on the site (Table 2). Average consecutive-day variability was less at coastal sites (20%) compared to inland sites (29%) (Table 2), but was similar for data collected by the tilted scanner (26%) and untilted scanner (30%).

Table 2. Consecutive-day coefficients of variation (CV) for radar surveys for marbled murrelets on northern Vancouver Island from 1999 to 2003.

			Detections		*Birds (targets)*		
First survey	*Second survey*	*Radar station*	*mean*	*CV*	*mean*	*CV*	*Source*
Coastal radar stations							
25-Jun-03	26-Jun-03	RS09	765	21%	829	12%	this study
29-May-03	5-Jun-03	RS13	77	4%	79	5%	this study
4-Jun-99	5-Jun-99	RS21	201	44%	229	50%	Manley 2000
25-May-01	26-May-01	RS21	159	13%	163	13%	Manley, unpublished data
2-Jul-01	3-Jul-01	RS21	197	19%	199	21%	Manley, unpublished data
19-Jun-03	20-Jun-03	RS21	95	24%	95	24%	this study
29-Jun-01	30-Jun-01	RS23	442	15%	454	14%	Manley, unpublished data
15-Jul-03	16-Jul-03	RS23	379	5%	414	12%	this study
4-Jul-01	5-Jul-01	RS28	233	25%	236	26%	Manley, unpublished data
Mean coastal CV				19%		20%	
Inland radar stations							
27-Jun-03	28-Jun-03	RS01	65	30%	68	29%	this study
9-Jun-03	10-Jun-03	RS03	145	27%	165	37%	this study
10-Jun-02	11-Jun-02	RS03	61	32%	66	36%	Harper and Chytyk 2003
8-Jul-03	9-Jul-03	RS04	54	9%	57	5%	this study
21-Jun-03	22-Jun-03	RS08	58	29%	59	31%	this study
24-Jun-02	25-Jun-02	RS11	8	47%	9	42%	Harper and Chytyk 2003
23-Jun-03	24-Jun-03	RS11	10	52%	11	61%	this study
26-May-03	27-May-03	RS12	60	14%	63	13%	this study
3-Jun-03	4-Jun-03	RS20	24	9%	24	9%	this study
17-Jul-03	18-Jul-03	RS24	65	30%	80	31%	this study
19-Jul-03	20-Jul-03	RS25	88	34%	97	29%	this study
Mean inland CV				29%		29%	
Overall mean CV				26%		27%	

Tilted vs. Untilted Radar Scanners

During simultaneous operation, the tilted scanner had 2767 total detections compared to 1575 total detections for the untilted scanner. This amounts to an overall increase of 76% in total radar detections resulting from tilting the waveguide to scan a vertical arc of approximately 25º (Harper et al. 2004) (Table 3); however, there was considerable variation between the seven different radar stations surveyed. At some radar stations, the difference between the tilted and untilted radar was relatively small, on the order of 30% (e.g., RS09 and RS01). At other radar stations, tilting the waveguide increased total detections by several magnitudes (e.g., 2925% at

RS27 and 737% at RS03) (Table 3). The increase in total detections from the tilted scanner was higher at the four inland sites (184%) than at the three coastal sites (60%) (Harper et al. 2004).

Table 3. Effect of tilting the waveguide on total detections of marbled murrelets (after Harper et al. 2004).

Radar station	*Location*	*Total untilted[a] detections*	*Total tilted[b] detections*	*% increase with tilting*
Coastal				
RS09	Tahsish Inlet	1243	1651	33%
RS27	Tahsis Inlet Park	8	242	2925%
RS28	Tahsis Inlet Gov't Dock	128	317	148%
Inland				
RS01	Vernon Lake	102	132	29%
RS03	Claude-Elliott Cutblock	35	293	737%
RS11	Schoen Lake Campsite	6	19	217%
RS16	Nimpkish Lake South	53	113	113%
Total		1575	2767	76%

[a]Furuno FR-805D with a 2-m scanner untilted to scan an arc of 10º using 9410 MHz at 5 kW
[b]Furuno FR-7111 with a 2-m scanner tilted to scan an arc of 25° using 9410 MHz at 10 kW

Movement Patterns

Broad scale movement patterns of marbled murrelets within and adjacent to TFL 37 were determined by plotting the average flight path of birds that were detected near the beginning of surveys. The general pattern of early morning movements (presumably towards nesting areas) suggests that murrelets detected south of the Nimpkish River were mostly associated with the west coast of Vancouver Island, while murrelets detected in the vicinity of Nimpkish Lake were associated with Johnstone Strait (Fig. 3). The western boundary of TFL 37 (see Fig. 3) is formed by the height of land along the rugged spine of Vancouver Island. There is no evidence that this height of land acted as a barrier to murrelet movement. Movement patterns at RS03 and RS08 were the most difficult to interpret since murrelets were observed flying both north and south near the beginning of the morning surveys (Figs. 2 and 3).

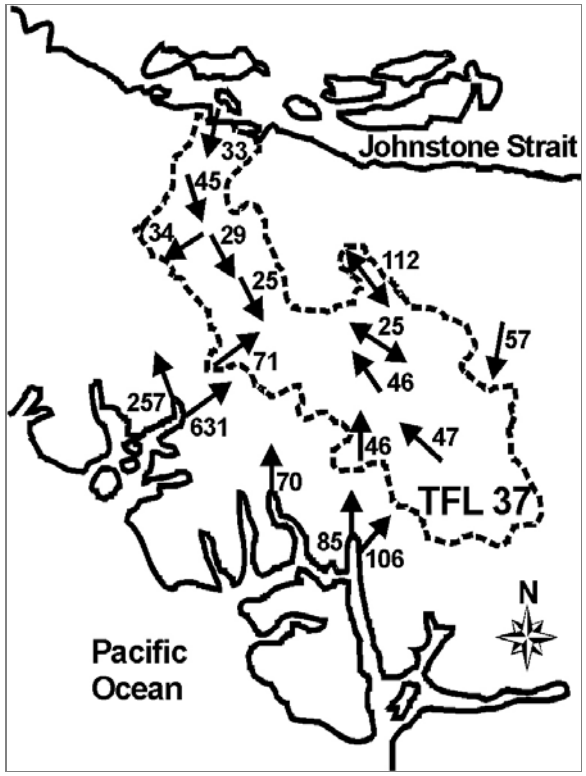

Figure 3. Generalized flight directions (arrows) of early morning 'inland' moving marbled murrelets (numbers next to arrows indicate maximum number of inland moving targets observed in 2003—see Table 1).

Basic trigonometry was applied to data on distance and bearing to targets from acetate overlays and was used to measure angles of radar fences to determine minimum flight heights. When the scanner was closely surrounded by trees, the closest fringe of trees acted as a radar fence, meaning that the remaining forest area was shielded from the radar (Cooper et al. 1991). Minimum flight heights were obtained for 86 targets from 5 radar stations (RS01, RS11, RS16, RS22, and RS24). The highest minimum flight height was estimated at 730 m above ground level at RS11 Schoen Lake Park Campsite. Given the elevation of the radar station, this murrelet was estimated to be flying at a minimum elevation of 1130 m above sea level. Data on minimum flight height could be collected for only a select number of birds that flew behind radar fences of known angular height. These data were not collected on most radar detections due to a lack of radar fences since most detections were obtained over large waterbodies.

The velocity of murrelet targets was measured for 1354 detections. The mean velocities of marbled murrelets flying inland, seaward, or circling were significantly different from one another (Kruskal-Wallis statistic = 111.46, $P < 0.0001$). The fastest moving murrelet targets flew seaward at a mean velocity of 101 km/hr, inland flying birds averaged 89 km/hr, and the slowest moving targets were circling birds, which averaged 82 km/hr. The overall mean velocity of the 1354 detections was 94 km/hr.

Discussion

Consistent with regional, provincial, and national goals for conserving biodiversity, a high priority has been placed on maintaining an effective breeding population of threatened marbled murrelets in British Columbia. Resource managers in both industry and government need specific information on the effectiveness of conservation and management plans if nesting habitat is to be conserved in the face of increasing human activity. The goal of the Marbled Murrelet Recovery Team is to ensure that the species' population decline is no greater than 30% of the 2002 population estimate by 2032 (CMMRT 2003).

Marine surveillance radar monitoring is a proven technique for estimating population numbers of murrelets entering large landscape units (Burger 1997, 2001; Schroeder et al. 1999; Manley 2000; Cooper et al. 2001; RISC 2001; Cooper and Blaha 2002; Raphael et al. 2002; Cooper and Hamer 2003). Radar surveys are better than audiovisual surveys for long-term population monitoring because flight path and flight speed can be determined, observer bias is reduced, birds are more detectable over a larger area, and surveys can be conducted in the dark (Hamer et al. 1995). Although audiovisual surveys are able to detect behaviors associated with breeding occupancy, the high level of within-site variability in detections makes it difficult to design effective monitoring programs using this technique (Jodice et al. 2001; Smith and Harke 2001).

Population Monitoring

Boat surveys were conducted in 1999 and 2001 at a number of inlets on the west coast of Vancouver Island near TFL 37 (Manley 2000). Although the boat survey data can be compared to four shoreline radar stations (RS09, RS21, RS23, and RS28), it is still too soon to detect statistically significant trends in marbled murrelet populations in TFL 37 based on only three to four years of data. Time-series data is even sparser for inland radar stations: radar survey count data are available for only 2002 (Harper and Chytyk 2003) and 2003.

It is important to determine consecutive-day CVs because they can be used to predict how long it will take to detect statistically significant changes in murrelet populations. For the 9 coastal surveys, the mean consecutive-day CVs for detections and targets were very similar—19% and 20%, respectively. For the 11 inland radar surveys, the mean consecutive-day CVs for detections and targets were both somewhat larger at 29%, suggesting it may take longer to detect significant population changes at inland radar stations than at coastal stations. Cooper and Raphael (2004) also found higher levels of within-site variation (55%) at inland sites in Elliott State Forest in Oregon than at coastal sites in Oregon (10%). Overall, consecutive-day CVs were similar for three tilted and three untilted radar surveys—26% and 30%, respectively. Generally, the levels of within-site variation on northern Vancouver Island are comparable to levels determined in large-scale studies on the Olympic Peninsula (28%) (Cooper and Raphael 2004).

Annual variation in counts reflects sampling error, environmental fluctuations, and most importantly, real changes in the population size of marbled murrelets. The time required to determine significant population trends depends on both the level of within-site variation and the rate of change of the population. There are a number of ways to control within-site variation in radar surveys, including the following:

1. The same, or at least very similar, radar units should be used each year. The position of the waveguide has a significant effect on the number of detections, but more subtle difference in horizontal beam width and pulse length can also affect the ability of radar to differentiate between birds flying close together. As well, higher power radar units may have an increased ability to differentiate flocks of two or more birds and to detect birds at greater distances.
2. Data should be reported as number of detections as well as number of birds (targets). A mean of approximately 8% of radar detections in both 2002 and 2003 were of flocks; however, the range between individual surveys was very large—from 0 to 47% in 2002 (Harper and Chytyk 2003) and 0% to 23% in 2003 (Harper and Schroeder 2004). Data reported as detections may have a lower level of variation. Reporting data as the number of detections as well as the number of targets (birds) will minimize this source of variation in survey counts.
3. Correct target identification can be improved by including an audiovisual observer on radar surveys. Also, since tilted radar is less sensitive at picking up birds located close to the ground where many potentially confusing species can be found, tilting the waveguide may reduce the number of targets that are incorrectly identified as murrelets.
4. Sampling for 2–3 days consecutively will reduce within-site variance due to daily fluctuations. By sampling the same site several days in a row, it is possible to obtain both an average count and a maximum count, which may be more useful for monitoring purposes than just a single count.
5. Sampling at approximately the same time each year will reduce within-site variance due to seasonal fluctuations.

Tilted vs. Untilted Radar Units

Although the tilted scanner had an average of 76% more detections than the untilted scanner (Harper et al. 2004), the difference was quite variable between radar stations. At some stations, it was relatively small; at others, tilting the waveguide increased total detections by several magnitudes. The increase in total detections from the tilted scanner was higher at the four inland sites (184%) than at three coastal sites (60%) (Harper et al. 2004).

Harper et al. (2004) compared untilted radar units with different maximum power outputs. Lower power 5- or 6-kW units had more detections than the higher power 12-kW unit, but sample sizes were small. Further investigation is warranted to better determine the relative effects of power output on detectability of murrelets.

Movement Patterns

Marbled murrelet flight is direct and involves rapid, often continuous wing beats. Flight speeds average 73–136 km/hr (45–85 mi/hr) and can reach maximum speeds of 158 km/hr (98 mi/hr) (Hamer et al. 1995; Burger 1997; Cooper and Blaha 2002). In this study, the average speed was estimated at 94 km/hr (n = 1354), and a total of 22 detections were estimated at speeds between 158 and 190 km/hr, which is beyond the reported maximum.

We are not aware of other studies that report flight heights for marbled murrelets using marine surveillance radar. Using minimum radar fence angles, this study estimated that one bird flew a minimum of 730 m above ground level, and many birds flew over 200 m above ground level. This information is consistent with the results of comparisons of tilted and untilted radar units where the untilted radar unit missed hundreds of murrelets that were detected by the tilted radar units, presumably because the birds were flying too high to pass through the radar beam of the untilted unit.

Acknowledgments

Funding was provided by both the Province of British Columbia through the Forest Inventory Investment Account and Canadian Forest Products Ltd. In addition to the authors, Tania Tripp, Jeff Bertoia, Katharine VanSpall, Stephanie Haight, and Nancy Anne-Rose assisted with the collection of field data. Irene Manley, Alan Burger, Sean Cullen, and Bernard Schroeder organized a training session on radar in mid-May 2003 that also collected data for comparing radar units at Tahsis Inlet (RS27 and RS28). Tricia Anvik entered the data into the database for analysis. Trudy Chatwin of the British Columbia Ministry of Water, Land and Air Protection provided the tilted radar unit, and Doug Bertram of the Canadian Wildlife Service provided the untilted radar unit used in this project. As part of a separate but related project, Peter Arcese organized a workshop "Monitoring for trend and cause of population change in marbled murrelets" (Arcese et al. 2005). That workshop and the information it provided were helpful in completing this project.

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