Migration Monitoring with Automated Technology[1]

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Abstract

Automated technology can supplement ground-based methods of migration monitoring by providing: (1) unbiased and automated sampling; (2) independent validation of current methods; (3) a larger sample area for landscape-level analysis of habitat selection for stopover, and (4) an opportunity to study flight behavior. In particular, radar-acoustic sensor fusion can provide information on species-specific landing behavior to indicate what portion of the population that pass over a site are available for ground-based monitoring using mist-net capture or census. In this paper, I examine the benefits of radar, infrared and acoustic technologies in the monitoring of bird migration and discuss how automated technology can augment mist-net and census data.

Key words: radar, acoustic, technology, migration, stopover, landbirds, critical habitat, data fusion, infrared.

Introduction

The monitoring of bird populations provides a barometer of environmental health. For species that are sensitive to disturbance or habitat change, a relative change in population trends can indicate a problem in the environment that is not otherwise apparent. Furthermore, population monitoring can provide data indicating the effect, positive or negative, of conservation programs that were undertaken to recover declining populations.

Monitoring during migration is an efficient means of amassing data from large geographic areas and multiple breeding habitats. Landbird migrants travel in multi-species, multi-age groups as evidenced by daily captures in mist-nets. Therefore, migration monitoring provides indices of reproductive success such as the number of young per breeding pair (HY/AHY ratios). In some cases, the recapture rate is high enough to delineate populations and provide survival data.

Automated technology can supplement ground-based methods of migration monitoring by providing unbiased sampling, independent validation of current methods, a larger sample area to follow birds for landscape-level analysis of habitat selection for stopover, and an opportunity to study flight behavior. Automated monitoring technologies provide important tools for use in migration monitoring networks, and they can be easily integrated into networks using global positioning systems and synchronized clocks. With technology-based monitoring systems, information transfer is more efficient, covers a greater distance and can be more accurate.

Automated technology includes radar and other electronic, mechanical and computerized inventions. These inventions have been used to study bird flight since radar was first used in World War II (see Lack and Varley 1945, Eastwood 1967, Williams et. al. 1972, Able 1973, Vaugh 1985). They have provided important information to augment conservation efforts. Some examples are: (a) the delineation of migration routes of endangered birds by satellite tracking (Beekman and Klaasen 2000); (b) long-range movements of night migrants by weather radar (Gauthreaux and Belser 1998, Koistinen 2000); (c) the importance of physiological condition on migration decisions by infrared (Fortin et al. 1999); (d) the influence of weather on timing and direction of flight by surveillance radar (Richardson 1978); and (e) local flight decisions of individual birds by radio-tracking (e.g. Frietag et al. 2001). Orientation and experiments involving migration energetics have been conducted using military tracking and phased array radar (Bruderer and Steidinger 1972, Bruderer et al. 1995, Buurma 1995). However, the high cost of these radar systems is prohibitive to their use in most conservation programs.

A number of challenges remain in the use of automated technology for migration monitoring networks. With infrared sensors, there are limitations in size and range of detection, as well as separation by species. For acoustic-only sampling methods, non-vocal individuals are not detected. For radar-only methods, the challenges include management of the data, species identification, error and worker fatigue associated with manual tracing from the radar screen, and relating data from long-range weather radar to site-selection for stopover. These challenges can be mostly overcome by

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combining technologies and choosing the appropriate technology for the development phase of the network.

This paper includes some background on the use of technology in migration research, proposed benefits of technology for a migration monitoring network, and suggestions for future directions. The focus is on landbirds and therefore, detection and monitoring of night migrants.

Background on the Use of Technology in Migration Research

Not all technologies used to monitor birds are useful for monitoring landbird migration. They must be affordable so enough stations can be set up as an effective network. Five technologies were selected that could augment the information, efficiency and accuracy of mist-net and census-based methods in migration monitoring networks, at a price affordable through cost-sharing or the use of existing data sets (e.g. WSR-88D weather data). The five technologies include long-range radar, short-range radar, acoustic-sensing, acoustic-location and infrared (*table 1*). In each case, the technology can enhance detection of birds in flight well beyond the visibility and audibility of humans (*fig. 1*). The important characteristic of all five is that they are passive, requiring no handling of birds. Radio-tracking is not included as it is not passive, and therefore, does not improve on the risk of handling birds.

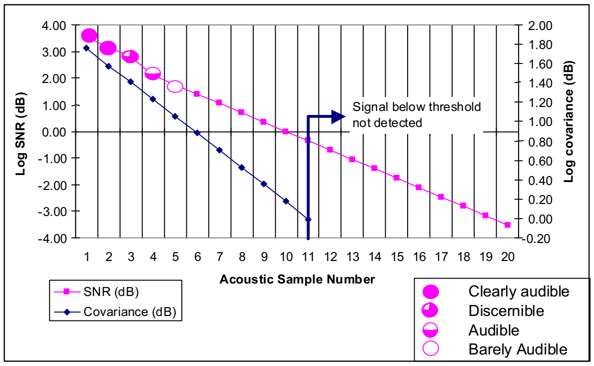


Figure 1—Acoustic detection of bird calls beyond the capability of the human ear. A bird call (signal) was progressively concealed in noise so sample 1 was clearly audible by a human, sample 5 was barely audible and samples 6 to 10 were only detectable using automated acoustic processing.

In this paper, a distinction is made between acoustic-sensing and acoustic-location. Acoustic-sensing provides a traffic rate, measured as the relative number of birds of a species, passing a geographic point (e.g. Birdcast®). By contrast, acoustic-location provides the originating location of each call expressed as the number of each species at particular heights and lateral distributions (e.g. Millikin 2001).

Long-range or weather radar (*fig. 2*) is also distinguished from short-range or surveillance radar (*fig. 3*), in range of detection, resolution, minimum altitude, and portability (Skolnik 1990). Long-range radar is suited to a large area and coarse monitoring (i.e., a range = 230 km and a resolution of flocks, versus 0-5 km and resolution of individual birds for short-range radar). The downside of a long-range radar is that the

Table 1—*Current technologies, their application and limitations to migration monitoring.*

Technology	How applicable[1]	Limitations
Long-range radar e.g. WSR-88D	Long-range movements; General routes; Predict "big days"; Pre-migration flights (Purple Martin); Roosting (Starling)	Birds fall below the beam so cannot be tracked to landing; No species information; No information on individuals
Short-range radar e.g. X-band Surveillance	Traffic rate; Landing habitat; Nesting sites (Marbled Murrelet); Impact assessment (Towers and Wind turbines)	Large-scale movements and routes require multiple units or moving between sites; Data management; 3-D position
Acoustic-sensing e.g. BirdCast®	Traffic rate and species complex	No information on individuals; Some species not known to call
Acoustic-location e.g. Expanding hemispheres™	Landing and nesting sites of priority species; Flight path, spacing, grouping of species	Large-scale movements and routes require multiple units or moving between sites; Some species may not call; Incomplete library of calls; Data management; Rain
Infrared e.g., LORIS, IRTV-445L	Traffic rate, flight path 300-3000 m above ground level (unfocused to 25 m)	Beam 1.45º; Identify to passerine but not species; No height; Data management; Rain and cloud

[1] Purple Martin, *Progne subis*; European Starling, *Sturnus vulgaris.*

increasing distance from the radar increases the minimum detectable altitude for the birds, and therefore, many birds fall below the beam at greater distances. Only within 5.6 km, 2 percent of the range of weather radar, would the image include birds fully within landing heights (i.e., below 100 m). Whereas, depending on interference, short-range radar can detect birds to altitudes below 1 m. With a modification to include height, short-range radar could detect landing heights over the entire range of 5 km. For networks wanting to share the cost of an automated tracking system, short-range radar is portable whereas long-range radar is not.

To develop a migration network that will involve mist-netting for population structure and survival data, the first task is to select the funneling routes of the populations of interest. For example, the three founding stations of the British Columbia (Canada) migration monitoring program were selected in ecoprovinces with the greatest concentration of passerine species (i.e., the Georgia Depression and South Interior, where 91 percent and 80 percent of passerines breed, respectively), and where species were not adequately monitored by Breeding Bird Survey (i.e., the Northern Boreal Mountains). Funneling routes were selected based on topography and convenience to volunteers. In a region with WSR-88D coverage, funneling routes could be confirmed by images of expanding "circles" at dusk and areas of concentration close to the radar, taking care to avoid assuming that birds no longer detectable have landed, because their disappearance may be due to the radar beam projecting out over the curvature of the earth.

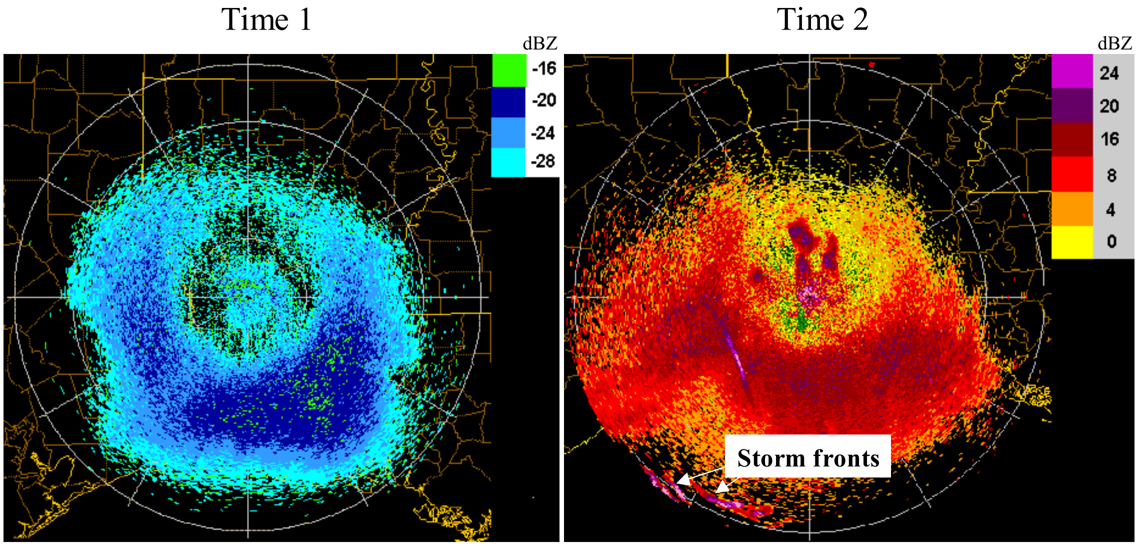
After determining the funneling routes of interest the decision of where to situate the migration station should be based on knowledge of where the birds prefer to land. To track individual birds to landing sites, surveillance radar with the lower minimum altitude and better resolution of individuals is required. Short-range radar has been successfully used to track flights of the Marbled Murrelet (*Brachyramphus marmoratus*), to and from their nests (Hamer et al. 1995), and for impact assessments related to ground objects (Cooper 1995). In cases like the Marbled Murrelet when there are few other species exhibiting similar flight behavior, it is not necessary to know the species. However, with the multi-species flocks of landbirds, the special management of species at risk and the need to correlate with mist-net data, automated species identification is required.

Using automated technology to determine where priority species land, can provide an unbiased selection of sites for the monitoring of population trends and the identification of critical stopover sites to protect. Proper site selection is crucial to the establishment of an effective migration-monitoring network. Given that population trend analysis of migration data can require a ten-year commitment to a site, incorrect site selection can result in a waste of scarce monitoring resources.

An example of radar tracking of stopover behavior is given from the author's work. The surveillance radar was modified to provide height information so birds closer to the ground, either leaving or landing, could be separated from those flying over (*fig. 4*). The length of the vector indicates the bird's altitude. The direction of the vector indicates the direction of flight. The data in *Figure 5* were collected in fall at Prince Edward Point on the north shore of Lake Ontario. At dawn, a larger portion of birds flew in a reversed direction from the main direction of migration (south), to land within 2 km of the radar. This was confirmed with ground-based methods. I propose that by tracking individual birds at close range, the onset and volume of reverse migration can indicate the importance of that site for stopover. A number of sites could then be compared to select the optimum site for the species of interest, before expending resources to prepare the site for the banding station.

Most migration at Prince Edward Point, between 28 August and 19 September 1999 was below 300 m (*fig. 6*). As expected, a larger proportion of birds flew below 300 m at dawn, but many birds were also flying below 200 m at midnight. A bias due to reduced detection at higher altitudes is unlikely since birds were tracked up to altitudes of 790 m above ground. Birds dispersed straight up at dusk to heights (maximum 660 m) above the average height of continued migration at midnight (average 197 ± 11 [95 percent CI]). Many of the low flying birds at midnight were likely landing, based on the reversed flight direction northward of 13 percent of the midnight migrants. The ability to discern a change in height and direction during the night migration will be important for environmental assessment of the risks to bird conservation such as communication towers and city lights.

Radar and infrared alone cannot provide species identification (*table 1*). This can be accomplished by acoustic-sensing or acoustic-location. Acoustic-location has the added potential to augment population trend indices, by providing a measure of the portion of the birds landing at a site that are available for capture in mist-nets. The implication for migration monitoring is the potential to select sites for priority species.


Time 1

Time 2

Figure 2—WSR-88D images depicting the spring migration of birds across the Gulf of Mexico in 1999 (adapted from http://virtual.clemson.edu/groups/birdrad). The images show regions of high base reflectivity (16-20dBZ) representing water particles (e.g. storm fronts) and birds. The series, time 1 to time 2, simulates the start and spread of migration as the bird density increases from an estimated 0 birds/km^3 (-16dBZ) to 227 birds/km^3 (20dbZ). WSR-88D is an example of long-range radar having a range of 230 km, 50-100 times that of short-range radar. Doppler information can be used to show the speed of particles and their direction. The advantages of WSR-88D for migration monitoring are the large geographic coverage and the potential, though not yet realized, for automated analysis. The disadvantages are that it does not differentiate individual birds, it is difficult to calibrate and birds cannot be tracked to landing.

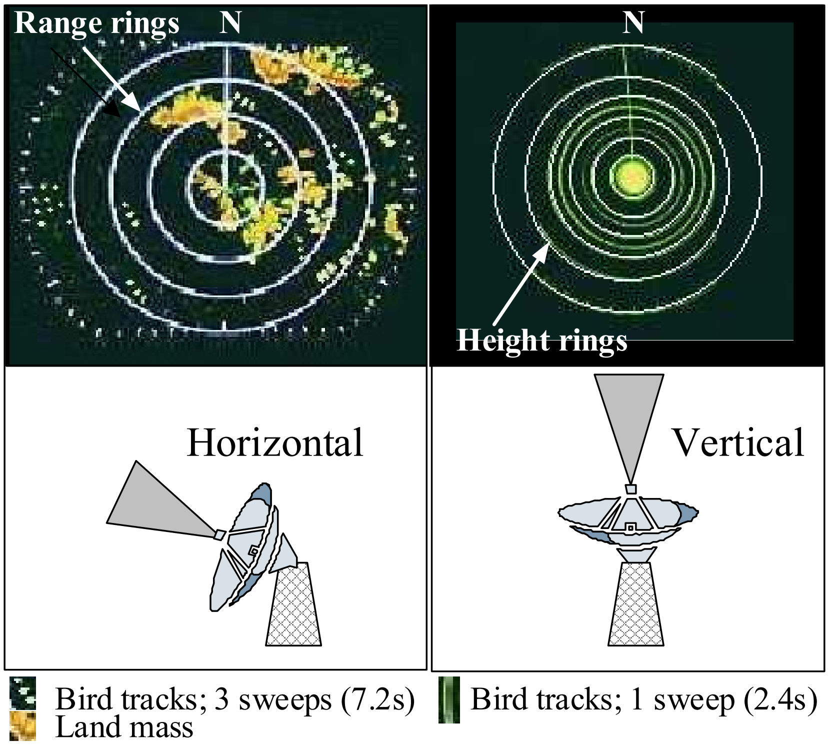


Figure 3—Fall migration across the Juan de Fuca Straight, British Columbia, in 1996, depicted on the planned-position indicator (PPI) of a dual antenna system (Millikin, unpublished). Birds resemble staple-shaped bars that move across the screen when the slotted waveguide antenna is oriented at the horizon (left) and comet-like streaks when a parabolic antenna is oriented straight up (right). Bird speed is calculated as the distance traveled per 2.4s sweep. A composite 3-D image is obtained by combining information from each antenna. The slotted waveguide was 200 cm (25° vertical beam width and 1.2° horizontal beam width), on a 10 kW X-band Furuno FR-810D. The parabolic antenna (2°) was on a 5 kW X-band Furuno FR-805D. A generator powered both units. X-band radar is an example of short-range radar.

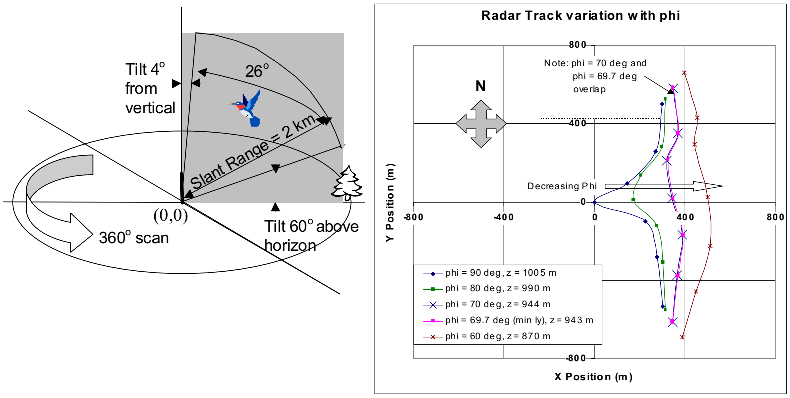


Figure 4—With adaptation to an X-band radar antenna (left) and neutral regression to select the straightest track (right), one antenna can provide the height of individual tracks of birds (patented; Millikin 2001). The radar is located at (0,0) with the antenna tilted 60° above the horizon for a 26° vertical scan of the full 360° coverage out to 2km. The target position in the beam is adjusted (increasing phi) until the track is most straight and this position provides the target height (z).

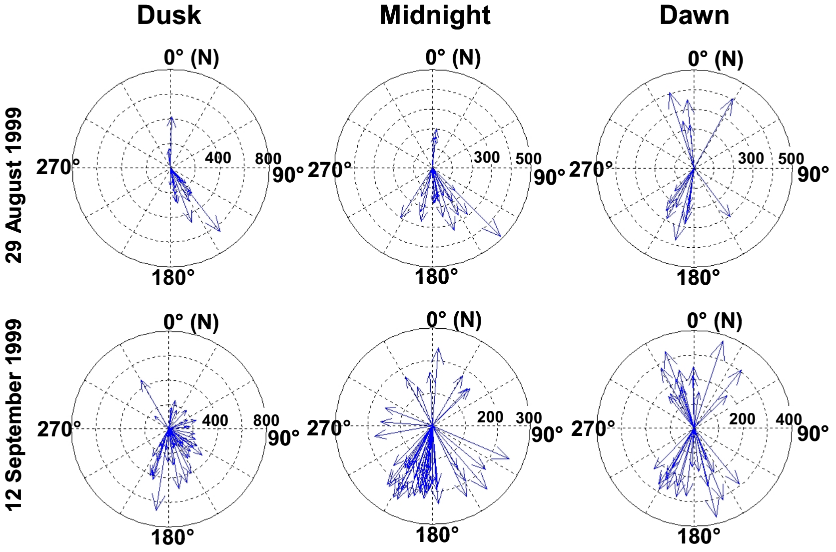


Figure 5—Individual tracks of fall migrants at Prince Edward Point, Ontario, ascertained by the adapted short-range radar (Millikin 2001). The vector length represents the bird's height and the compass direction represents the direction of flight. Note the reversed direction of flight at dawn.

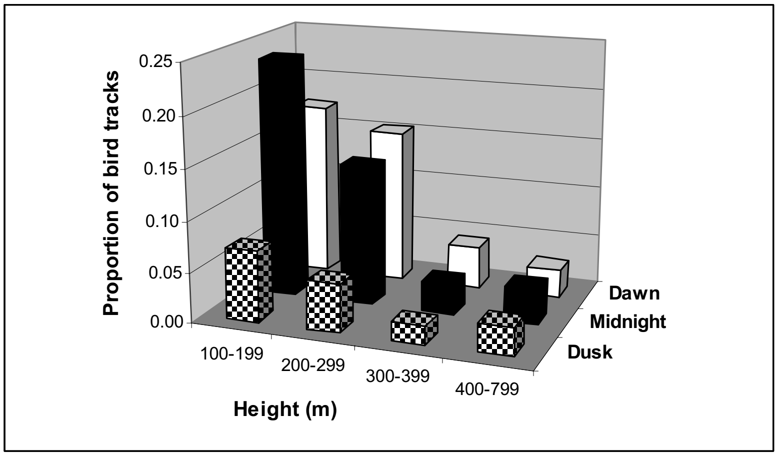


Figure 6—Height distribution of bird tracks at three time periods during the night migration over Prince Edward Point, Ontario, between 28 August to 19 September 1999. Proportions are of all heights and time periods combined, corrected for sample size.

Questions can then be asked of species-specific spacing and flight behavior, then the correlation of traffic rate to mist-net capture and census techniques, for a better understanding of diurnally measured population trends.

Using an example from the author's research, by locating species-specific calls, species can be grouped (*table 2*, Millikin 2001) to determine their spacing, then co-located with radar tracks for further analysis of flight behavior (*fig. 7*, Millikin 2001). By combining the radar track with the acoustic-location, it is apparent that the Swainson's Thrush, *Catharus ustulatus*, experiences Lake Ontario as a barrier and reverses its direction of migration to land at Prince Edward Point. As expected, birds flying together in time (*table 2*, birds less than one second apart), and therefore experiencing the same atmospheric conditions, are more similar in flight behavior with less spread in height and direction between individuals. Birds flying together of the same species were more similar in flight speed with less spread in speed between individuals than pairs of different species (*table 2*). This snapshot of species-specific calls supports the hypothesis that passerines migrate in loosely spaced, multi-species flocks.

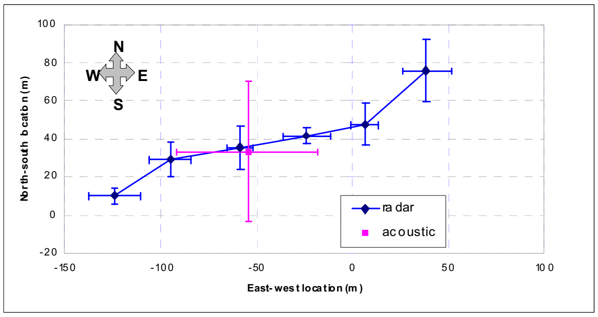


Figure 7—Co-location of a Swainson's Thrush call (acoustic) onto a radar track (radar). The bird was flying SW at a height of 150 m. Of three one-hour dawn samples 12, 18 and 19 September, 28 out of 129 tracks were co-located.

Table 2—*Three minutes of calls ordered by time elapsed between pairs. Birds traveling together experience the same atmospheric conditions such that differences in flight behavior of birds that are paired in time indicate the species' flight behavior.*

	Three minutes on 18 September[1]			**Spread between birds**[5]		
	Time of call[2]	**Elapsed**[3]	**Species**[4]	**Height (m)**	**Speed (m/s)**	**Direction (°)**
<1 second apart	***5:42:35:274***	***0.093***	***swth***	***2***	***7***	***14***
	5:42:35:367		***swth***			
	5:41:37:557	0.344	zeep	2	12	67
	5:41:37:901		swth			
	5:42:26:113	0.469	zeep	9	14	77
	5:42:26:582		swth			
	5:39:51:112	***0.532***	***swth***	***5***	***5***	***13***
	5:39:51:644		***swth***			
>1 second apart	***5:42:24:331***	***1.056***	***zeep***	***104***	***2***	***110***
	5:42:25:387		***zeep***			
	5:42:35:749	1.459	zeep	11	21	97
	5:42:37:208		swth			
	5:39:52:825	2.372	zeep	10	11	150
	5:39:55:197		swth			
	5:41:31:123	3.661	swth	50	5	80
	5:41:34:794		zeep			

[1] calls of birds paired in time that are of the same species are italicized and bold.

[2] presented in hours, minutes, seconds and milliseconds

[3] ordered by the increasing time that elapsed between each pair of birds.

[4] swth = Swainson's' Thrush and zeep = group of eight warblers not easily distinguished.

[5] numbers indicate the spread in height, velocity and azimuth measurements between each pair of birds flying together in time. Birds traveling closer together in time (<1 second apart) have a lower spread or difference in height and direction, but a lower spread in speed is more typical of birds flying together of the same species.

What Technology Can Do for Migration Monitoring

Having discussed the current technology, the specific role of technology in migration monitoring can be explored. The three aspects covered include current problems in migration monitoring with solutions from technology, current unknowns affecting migration monitoring with the potential input from technology, and knowledge gained by technology related to migration monitoring.

Current Problems in Migration Monitoring and Solutions from Technology

Some current problems in migration monitoring are listed in *table 3*, with proposed solutions from technology. The problems include site selection, weather, sampling bias, avian mortality risk, identification of species, and networking of multiple areas.

Site selection: As mist-net sampling requires intense labor to prepare and run the site, it is difficult to monitor a large area. Census can be used to compare sites, habitat or landscapes, but during migration, birds are difficult to detect because they rarely sing. Long-range radar can cover extensive areas, but birds falling below the minimum height of the beam will be missed, giving a misleading picture of the landing sites. Short-range radar can track birds to their landing but to compare sites, multiple units are required or one unit must be moved between sites. Acoustic-location also requires multiple units or moving between sites. Acoustic-sensing has no location information to separate fly-over from landing birds. Infrared cannot identify species and may miss landing birds below 300 m. Therefore, a combination of long-range radar, short-range radar, and acoustic-location, is required for unbiased and landscape-level site selection.

Confounding effects on flight behavior (e.g. weather): Short-range radar can be used in all-weather conditions, day and night, so can provide trend data over all conditions and times. Acoustic-location and infrared cannot be used under certain weather conditions (cloud for infrared; rain for acoustic-location). Even under ideal weather, other confounding effects may be difficult to distinguish with long-range radar and acoustic-sensing, as they do not sample individuals.

Eliminating sampling bias: The greatest advantage of automated technology is to remove problems of sampling bias and avian mortality risk (below). By separating landing birds from fly-over birds, short-range radar can help separate fluctuations in the number of migrants that land due to weather from the changes in population trends that are due to breeding or overwintering success. Long-range radar does not separate landing birds from fly-over birds. Short-range radar should be combined with acoustic sensors to separate weather effects on individual species. Infrared still requires human interpretation and therefore is subject to bias. The automated technologies should be selected for an independent validation of current ground-based methods.

Table 3—*Current problems in migration monitoring with potential solutions from technology. Each technology is ranked as having significant, moderate or no improvement in resolving the problem. Most migration stations currently use census and/or mist-netting.*

Problem	Solution	Census	Mist-netting	Long-range radar	Short-range radar	Acoustic-sensing	Acoustic-location	Radar & acoustic	Infrared
Site selection for observation / sampling	Use a combination of unbiased sensors		–			–		+	
Unrelated flight behavior (weather)	Account for confounding variables in trend data	–	–		+			+	
Sampling bias (human factor)	Automate data collection	–	–	+	+	+	+	+	
Avian mortality risk	Use a passive sensor		–	+	+	+	+	+	+
Identification of species	Direct observation or by call		+	–	–	+	+	+	–
Networking of multiple areas	Sample over a larger area	–		+			+	+	–

+: significant improvement.
-: marginal improvement.
blank: no improvement.
Notes: Improvement is subjectively ranked based on experience and reference materials.

Mortality risk: Mortality risk can be removed by using passive methods. Bruderer et al. (1999) found no change in flight behavior induced by X-band radar. Yet, strong light was found to induce a pronounced shift in flight direction (8-15º over a 10 sec interval), a mean reduction in flight speed of 2-3 m/s (15-30 percent of normal flight speed) and a slight increase in climbing rate.

Identification of species: Mist-netting provides the best detail on species (age, sex, molt, physiology, and parentage), but only for those individuals caught. Acoustic sensors sample all calling species but not all individuals call. Therefore, to relate information obtained from mist-nets to the larger population of landing birds, acoustic sensors should be combined with radar to determine what portion of landing birds call. By tracking landing behavior of a particular species, radar-acoustic sensor fusion provides a measure of the portion of a population available for ground-based monitoring.

Networking: Long-range radar provides route information to link sites. However, short-range radar is a better choice in the mountains (Williams et al. 2001). To follow movements of priority species, acoustic-location can provide landing information important in assessing the potential success of mist-nets. Mist-nets cannot provide sufficient recapture information to link sites.

Summary: The recommended approach to establish a migration monitoring network would be to use automated technology for an unbiased assessment of where to locate the stations. If there is WSR-88D coverage, this can be used to determine the funneling routes of the populations of interest. Then, the preferred landing sites of species at risk can be estimated using short-range radar fused with acoustic-location. The mist-nets and census route should be situated within the range of coverage of the radar-acoustic system to facilitate for a more detailed understanding of flight behavior.

Roughly, the cost of adding automated radar-acoustic data to a migration station would be 1-3 times the cost of a volunteer-based mist-netting program (*Appendix I*). Renting, leasing or sharing the automated equipment could minimize the cost to each monitoring station. The cost would also be offset by the improved data. Sites could be selected more efficiently so more could be monitored immediately. Those selected would be more productive for the species of interest, which would minimize the loss of data when a site is moved because it was not as productive as expected from diurnal observation.

Current Unknowns Affecting Migration Monitoring and Potential Input from Technology

A major concern when establishing a migration monitoring network is whether population trends can be monitored using migration. Mist-netting and census methods monitor population trends based on the portion of birds landed that can be caught or observed. Whereas, long-range radar and acoustic-sensing detect a larger number of birds passing over the site. To separate the population passing over from those coming in to land, a combined system of short-range radar and acoustic-location can be used. Technology can relate the population available for mist-net sampling to the overall migrating traffic.

Traditional migration monitoring capture rates are low, particularly for priority species. To determine if acoustic and radar technology could enhance the population sample, capture rates were compared across methods for a selection of nocturnal migrants that are priority species for Partners in Flight-Canada (*table 4*). The comparisons included the current capture rate over a network of Canadian Migration Monitoring Network (CMMN) stations, capture rate at an individual station (Mackenzie Bird Observatory), acoustic detection by BirdCast® (i.e., available for acoustic-location) and tracked at landing heights by an adapted short-range radar (i.e., available for mist-nets). The average traffic rate was converted from 2/min to a number comparable to mist-net captures (i.e., 12,000 /100 hr). As only 50 percent of tracks are likely to have calls (Millikin 2001), the potential acoustic detection is estimated to be 6,000/100 hr. The Gray-cheeked Thrush (*Catharus minimus;* GCTH), was used as an indicator of catchability, since stations with the priority species, the Bicknell's Thrush (*Catharus bicknelli*), are not yet contributing data to the CMMN. The low mist-net capture rate could be augmented by using short-range radar and acoustic-location to select sites that concentrate these species and/or by simultaneous measurement with independent sampling methods.

Knowledge Gained by Technology Related to Migration Monitoring

As mentioned, significant findings have come out of Europe and North America from the use of technology to understand migration (Eastwood 1967, Williams and Williams 1972, Able 1973, Richardson 1978, Schaefer 1979, Bloch and Bruderer 1982, Clark et al. 1986, Cooper and Ritchie 1995, Hamer et al. 1995, Nisbet et al. 1995, Akesson et al. 1996, Bruderer and Leitchi 1998, Bruderer et al. 1999, Evans and Mellinger 1999, Fortin 1999, Klaassen and Biebach. 2000, Russell and Gauthreaux 1999, Williams et al. 2001, Zehnder et al.

2001). A selection of authors and their contributions is provided in *table 5*. WSR-88D would be an example of pulse Doppler radar. The blank row in *table 5* shows a gap in information that is required to correlate the number of birds landing with population trends.

The examples of contributions below support the further use of automated technology in migration monitoring: (1) Zehnder et al. (2001) using tracking radar, found weather factors explained two-thirds of the variation in intensity of bird migration; (2) Williams et al. (2001) using short-range radar found mountain ridges act as landscape barriers; (3) Fortin et al. (1999) used infrared to show that levels of dehydration and fat affect a bird's decision to stop or go; and (4) Nisbet et al. (1995) showed the bulk of evidence for transoceanic flights of Blackpoll Warbler, *Dendroica striata*, (19 out of 25 papers) came from radar studies.

Table 4—*Comparison of the capture rate by current migration monitoring methods (census and mist-net; CMMN), acoustic sampling (BirdCast®), and radar sampling (Tracked SRR) of selected nocturnal migrants that are priority species of Partners in Flight-Canada.*

Priority species[1]	CMMN No. stations	CMMN No. /100 nhr[2]	BirdCast®	Tracked SRR[3]
Bicknell's Thrush (GCTH)	4/10	0.042	√	√
Blackpoll Warbler	7/10	0.641	√	√
American Tree Sparrow	3/10	0.006	√	√
Clay-colored Sparrow	3/10	0.174	√	√
White-throated Sparrow	9/10	0.184	√	√
Purple Finch	1/10	0.099	√	√

[1] selected from Dunn and others 1999
[2] 1998-2001 average from 17,091.22 hrs, Mackenzie Bird Observatory
[3] SRR = Short-range radar

Notes: Current capture rate was calculated using the rate over a network of Canadian Migration Monitoring (CMMN) stations and at one station, Mackenzie Bird Observatory. BirdCast® results illustrate acoustic sampling capability; a check mark indicates the species could be detected and located. Radar capability was illustrated using short-range radar; a check mark indicates the species could be tracked to landing and thus indicates the capture rate. This does not imply species identification by radar alone. To compare the radar capture rate with netting results, the average migration traffic rate of 2 birds/min translates to 12,000 birds/100hr. Only 50 percent of radar tracks are likely to have calls (Millikin 2001), so the potential calls for species identification were estimated to be 6,000/100hr.

Table 5—*Knowledge gained by six technologies on issues affecting the success of migration monitoring.*

Issue	Short-range radar	Tracking radar	Pulse Doppler radar	Phased-array radar	Acoustic sampling	Infrared	Reference
Correlation between numbers landing and population trends							
Effect of weather	√	√	√			√	Eastwood 1967; Able 1973; Bloch and Bruderer 1982; Richardson 1978; Zehnder and others 2001
Behavior at ecological barriers	√					√	Fortin and others 1998; Klaasen and Biebach 2000
Migration routes	√	√		√		√	Nisbet and others 1995; Bruderer and Leichi 1998; Williams and others 2001
Migration spatial distribution	√	√			√		Williams and Williams 1972; Larkin 1982; Millikin 2001
Threats to survival in migration	√						Cooper and Ritchie 1995; Hamer and others 1995
Use of species-specific night flight calls					√		Evans and Rosenberg 2000

Notes: WSR-88D is an example of pulse Doppler radar.

Summary

In this paper, I discussed how automated radar, infrared, and acoustic technologies can augment mist-net and census data in the monitoring of bird migration. Automated technology can supplement ground-based methods of migration monitoring by providing unbiased and automated sampling, independent validation of current methods, a larger sample area for landscape-level analysis of habitat selection for stopover, and an opportunity to study flight behavior. In particular, radar-acoustic fusion can provide information on species-specific landing behavior to indicate what portion of the population that pass over a site are available for ground-based monitoring using mist-net capture or census.

The recommended approach would be to use long-range radar to suggest funneling routes, then sample within those regions with short-range radar for preferred landing sites. Add acoustic-location to select landing sites that concentrate species of concern. Situate the mist-nets and census route within the range of detection of the radar-acoustic system for a better comparison between sampling methods.

Suggestions for Future Directions

In establishing a network of migration monitoring stations, site selection should be conducted using unbiased observations of landing behavior. Radar-acoustic fusion could be used at a long-term banding site such as Long Point Bird Observatory, to determine under different flight conditions, what portion of the migrant population land to then be available for mist-net and census. Historical data could be reanalyzed with the adjusted population trend indices. By locating individual birds in flight, it is now possible to ask which species do not call and therefore, cannot be monitored using acoustic-sensing or acoustic-location methods. A combination of methods can be used to understand the importance of landscape barriers and the validity of critical habitat for stopover.

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Appendix 1—*Rough cost comparison between the five technologies and the traditional ground-based method of migration monitoring.*

Cost comparison of technology versus traditional migration monitoring methods[1]

	Sampling						
Method	Equipment	Personnel[2]	Analysis	Total cost	Relative cost	Area[3] (ha)	Source
Mist netting and census[4]	15K	10K	2K	27	1	10	Lambie, pers. comm.
Long-range radar[5]	4K	1K	6K	11	0	40	www.intellicast.com
Short-range radar[6]	25K	20K	5K	50	2	10	Cooper 1995
Acoustic-sensing[7]	5K	4K	6K	15	1	8	Personal experience
Acoustic-location[8]	30K	4K	6K	40	1	8	Personal experience
Sensor fusion[9]	75K	4K	6K	85	3	8	Personal experience
Infrared[9]	31K	20K	3K	54	2	1	www.infrared.com

[1] costs estimated from web pages, personal experience and personal communication; K = $1000 CDN.

[2] assuming 0.03K/hr per technology personnel; actual costs for mist netting and census; actual costs for analysis.

[3] estimated ground coverage in hectares (1 hectare = 2.47 acres).

[4] average equipment and expenses for one traditional migration station (MacKenzie Bird Observatory) monitored 6 hr/day for 60 days.

[5] radar images from one WSR-88D (about 40 ha) for 11 hours per day for 60 days.

[6] one non-automated X-band surveillance radar (about 10 ha) for 11 hours per day for 60 days.

[7] one location set of acoustic stations (about 8 ha) for 60 days.

[8] one automated sampling of an 8 ha area of ground for 11 hours per day for 60 days.

[9] one 10-ha migration station for 11 hours per day for 60 days.