Studies of bird hazards to aircraft

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Birds and aircraft have collided, with damage to both, since the early days of aviation. The first recorded human death resulting from a bird-aircraft collision occurred in 1910. As aircraft became more numerous and their speeds increased, damage became more serious and costly. The first serious turbine engine crash caused by birds occurred in 1960 and took more than 60 human lives. Since then, bird-aircraft collisions in the United States have caused about 100 deaths. In Canada, no lives have been lost, but 10 military aircraft have crashed, and a number of commercial aircraft have been damaged.

In 1963 the National Research Council of Canada, at the request of the Deputy Minister of the Department of Transport, founded the Associate Committee on Bird Hazards to Aircraft. That Committee, on which are represented the National Research Council, the Department of Transport, the Department of National Defence, the Canadian Wildlife Service, the Canadian Airline Pilots' Association, Air Canada, Canadian Pacific Airlines, and the engine manufacturers, has studied the problem and recommended solutions.

While engineering solutions may be possible they will take time. Meanwhile, habitat management at airports has resulted in fewer birds being attracted to those areas. That has reduced the likelihood of bird strikes near airports.

Radar study of bird movements aloft has helped to define the timing, duration, direction, speed, and location of major movements of large birds considered to be a major hazard to aircraft in flight. Relations between major bird movements and weather parameters are being studied.

Since 1965 we have been experimenting with forecasting bird migration movements in relation to weather forecasts. The method is being refined with the hope that bird hazard forecasts for aircraft will eventually be as accurate as present thunderstorm forecasts.

The following papers set out the general nature of the habitat management techniques found useful in reducing bird hazards at airports, the radar technique used to gather data for experiments in forecasting bird hazards aloft, and details of some types of bird movement revealed by radar.

V. E. F. Solman

Perspective

Depuis les premiers jours de l'aviation, les oiseaux et les avions sont entrés en collision et les deux en ont souffert. La première perte de vie humaine due à une collision de cette nature remonte à 1910. Avec l'augmentation du nombre et de la vitesse des avions, les dommages devinrent plus sérieux et plus coûteux. Le premier écrasement d'importance d'un avion turbopropulsé attribuable à une collision avec des oiseaux est arrivé en 1960 et a causé la mort de plus de 60 personnes. Depuis lors, les collisions entre oiseaux et avions ont entraîné une centaine de pertes de vie aux Etats-Unis. Au Canada, on ne rapporte pas de victimes, mais dix avions militaires se sont écrasés et plusieurs avions commerciaux ont été endommagés.

En 1963, le Conseil national de recherches du Canada, à la demande du sous-ministre des Transports, a fondé le Comité mixte sur l'étude des dommages causés aux avions par les oiseaux. Ce comité, au sein duquel sont représentés le Conseil national de recherches, le ministère des Transports, le ministère de la Défense nationale, le Service canadien de la faune, l'Association canadienne des pilotes de lignes, Air Canada, les Lignes aériennes du Canadien Pacifique et des fabricants d'avion, a étudié le problème et recommandé des solutions.

Les solutions d'ordre technique prendront du temps à se réaliser. La conservation des habitats à proximité des aéroports a contribué à diminuer le nombre des oiseaux attirés dans ces secteurs. On a donc réduit le danger des collisions avec ces volatiles près des pistes d'aviation.

L'étude par radar des migrations d'oiseaux nous a aidés à déterminer le temps, la durée, la direction, la vitesse et les endroits des déplacements en groupe des gros oiseaux qui constituent un grave danger pour les avions en vol. Les grandes migrations de ces oiseaux sont étudiées en fonction de paramètres météorologiques.

Depuis 1965, nous avons tenté de prévoir le trajet de migration des oiseaux en nous basant sur les prévisions atmosphériques. Nous essayons de perfectionner nos méthodes, espérant prévenir les dangers que les oiseaux représentent pour les avions en plein vol, en vue d'obtenir une précision semblable à celle des prévisions d'orages.

La documentation suivante dresse un bilan des méthodes de gestion de l'habitat qui ont permis de réduire les dangers auxquels les avions sont exposés à cause des oiseaux, et explique la technique consistant à utiliser le radar pour réunir des données à des fins expérimentales, en vue de prévenir les risques de collisions avec la gent ailée et d'étudier en détail certains genres de migrations d'oiseaux.

V. E. F. Solman

Bird control and air safety*

V. E. F. Solman†

*Based on a paper presented at the 33rd North American Wildlife and Natural Resources Conference, Houston, Texas, March 12, 1968.

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Fatal accidents have been caused by bird-aircraft collisions since 1910. In 1960 a turbine-engined aircraft crashed at Boston, Massachusetts, after a bird strike by starlings. Over 60 lives were lost. That crash, and one in 1962, caused by bird damage to the aircraft structure, which resulted in the loss of 17 lives, helped to accelerate research on ways to reduce the bird hazard to aircraft.

The Canadian Wildlife Service has been providing biological information to airport operators to reduce the attractiveness of airports to birds since the late 1940's. In 1962, at the request of the Department of Transport, the National Research Council of Canada appointed the Associate Committee on Bird Hazards to Aircraft to study the problem and to recommend solutions. On that committee are represented the Department of Transport, which is responsible for most Canadian airports, the Department of National Defence, which has a similar responsibility for military aerodromes, the major airlines, the engine manufacturers, the National Research Council, the Canadian Airline Pilots' Association, and the Canadian Wildlife Service.

The committee's studies outlined the magnitude of the problem and the potential for serious accident and loss of human life. Initially, there was emphasis on the engineering aspects. Consideration was given to designing aircraft and aircraft power plants that could withstand contacts with birds without suffering serious damage. The engineers soon realized that the forces involved in impacts between birds and high-speed aircraft are so large that it is difficult to design mechanical components of reasonable size and weight to withstand them. For example, a 4-pound bird struck at a speed of 300 miles per hour exerts a force of 14 tons, at 600 mph 57 tons. The other approach to the problem, that of trying to keep the birds out of the way of the aircraft, offered more hope of success.

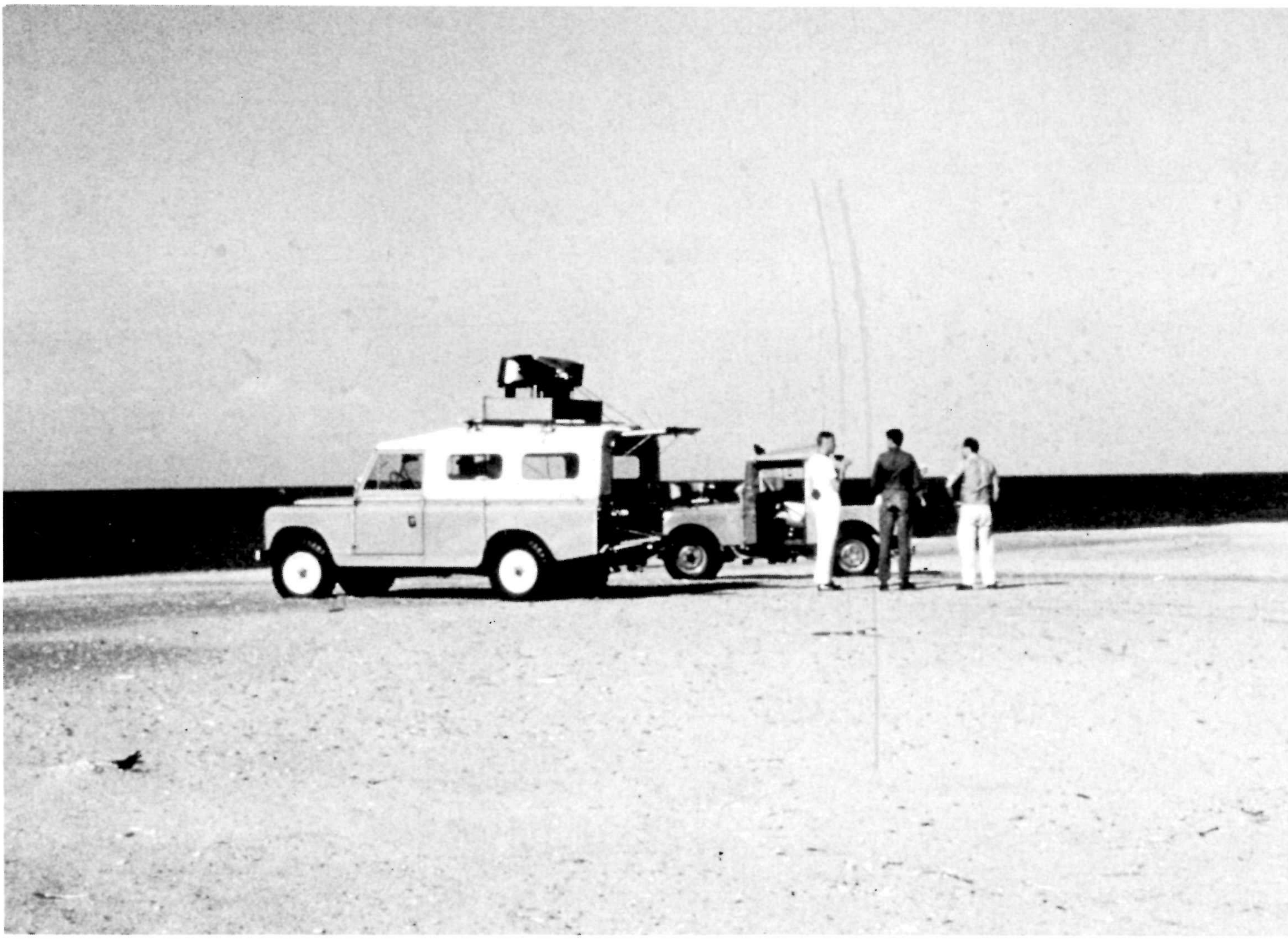
Biological studies at a number of major airports showed that many species of birds used airport areas for feeding, resting, and even nesting. When we examined the problem in detail, we found that airports were attractive to birds for a number of reasons. The first recommendation of the committee was to reduce the attractiveness by altering the ecology of the airport environment. In many cases that was a relatively simple matter. Garbage dumps and other attractive food supplies were moved away from airports. Small bodies of water which attracted aquatic and other birds were drained or filled, or the birds were prevented from using them. Nesting and perching sites could be eliminated or rendered unusable. The pioneering work on improving the airport habitat to reduce bird attraction has been described by Munro and Harris (1963) and Solman (1966).

Birds that persisted in visiting airports after those changes were made could be driven off by patrols armed with pyrotechnic devices, distress call players, or other mechanical means. Considerable testing of pyrotechnic devices has been carried out. There are now available for airports reasonably reliable shot-gun shells that fire a small explosive projectile. There are, also, good tape players, amplifiers and loud speakers that can be used for that type of bird removal. We have encouraged manufacture of effective automatic acetylene exploders designed to our requirements which work well with certain species of birds. In some countries radio-controlled model aircraft are used to harass birds at airports.

Any mechanical method requires decision on the part of the human operator to use the equipment effectively. Human motivation is the *biggest* need in the continuing battle to keep birds out of the way of aircraft.

The committee also investigated the possibilities of using falcons trained to drive birds away from certain airports. Two different falconry techniques were tried. Both gave satisfactory results within the limitations of falcon operation. Those limitations include inability to operate in the

Speaker truck for broadcasting scare calls



hours of darkness and unwillingness to fly in high wind or heavy rain. There are also occasions on which the falcons, which are relatively high-strung animals, simply refuse to work. Falcons are being used at some airports in other countries with good results in clearing single species of birds from aerodromes during hours of daylight. Most civil and military flying is a round-the-clock operation. Simpler and more dependable bird-control methods are preferred by most authorities.

The Canadian program of bird removal from airports has been quite successful. One of our major airlines, which was experiencing increasing numbers of damaging bird strikes up to 1965, reported a 20 per cent drop in the number of strikes in 1966.* Although the number of aircraft and flights has increased since then and the number of bird strikes has risen, there has been a reduction in damage because smaller birds are being struck. The reasons relate to the massive ecological changes which have been brought about by the Department of Transport at a number of major Canadian airports. That work has cost hundreds of thousands of dollars, but in the first test cases resulting from the 1960 Boston crash, caused by birds, when over 60 human lives were lost, the court awarded more than

*Air Canada's cost of repairs due to bird strikes has declined as follows (average per year):

1958–62	$239,000
1963–68	$125,000
1969	less than $50,000.

$100,000 per human life lost. The dollar cost of that one crash would likely exceed the cost of reducing the bird hazard to a very much lower level at several major airports.

While take-off and landing strikes of civil aircraft may not be hazardous to human life, they do result in a variety of expenses to the airline. Consider the case of a DC8 taking off on a long flight with a full fuel load and an acceptable level of passenger seat occupancy. On take-off a bird is struck and catastrophic damage occurs to one engine. The pilot has no problem maintaining flight, even with a full load, but has a problem of immediately returning to base for an engine change and for rerouting of passengers and baggage on another aircraft. Since his take-off weight is greater than his acceptable landing weight, he must jettison fuel before he can land. In addition to the $200,000 cost of an engine replacement, the airline is faced with the problem of jettisoning thousands of gallons of fuel, of making an emergency landing with its attendant hazards, and then of providing alternate means of travel for the hundred passengers and their baggage. The time of the circuit, fuel jettisoning, and emergency landing may exceed an hour. By that time it may not be possible for the passengers to board another aircraft and still reach their destination in time for important commitments. No one has yet worked out what it costs an airline to inconvenience seriously a hundred passengers, nor what it means in terms of reuse of that airline by the passengers in subsequent flights.

One airline has published a figure of a million pounds sterling worth of mechanical damage each year through bird strikes. Another airline published a figure of a loss of two million dollars over a period of 5 years. A third airline reported 75 engine changes due to bird strikes in 2½ years of flying.

Different aircraft-engine types have different bird damage rates and costs, even when flown on the same airline routes at the same times. In aircraft that mount engines in pairs close together, when a bird causes one engine to break up catastrophically, portions of the bird or engine may be projected forward and taken into the adjacent engine with subsequent damage to it also.

In many cases the passengers are not aware of the damage caused by a bird strike. If it is a landing strike and does not interrupt too many schedules, the only cost to the airline is for engine replacement and the time lost while the engine is changed.

Initially, the civil airlines had about three-quarters of their bird strikes at or near airports and the remainder in flight between airports. The military situation is almost exactly the reverse: fewer strikes at airports and more strikes en route. The high rate of strikes away from bases is related to the role of military aircraft, which make many flights at low altitude and high speed.

The CF-104 aircraft has been found to be particularly vulnerable to serious bird damage. Because it is a single-engined aircraft, an engine strike by a bird may easily involve the loss of the aircraft. In 6 years, Canada lost ten CF-104's through bird strikes and two more under conditions strongly suggestive of bird impact damage. The Department of National Defence is much concerned about the loss of aircraft because of the possibility of a pilot being killed and the cost of the aircraft.

Major ecological changes have been made at military airports to reduce the bird problem there. However, because many strikes occur away from airports, the committee has been studying the details of bird movements and migrations which could be encountered by aircraft in flight. To do that, we have used the only tool that is really effective, radar.

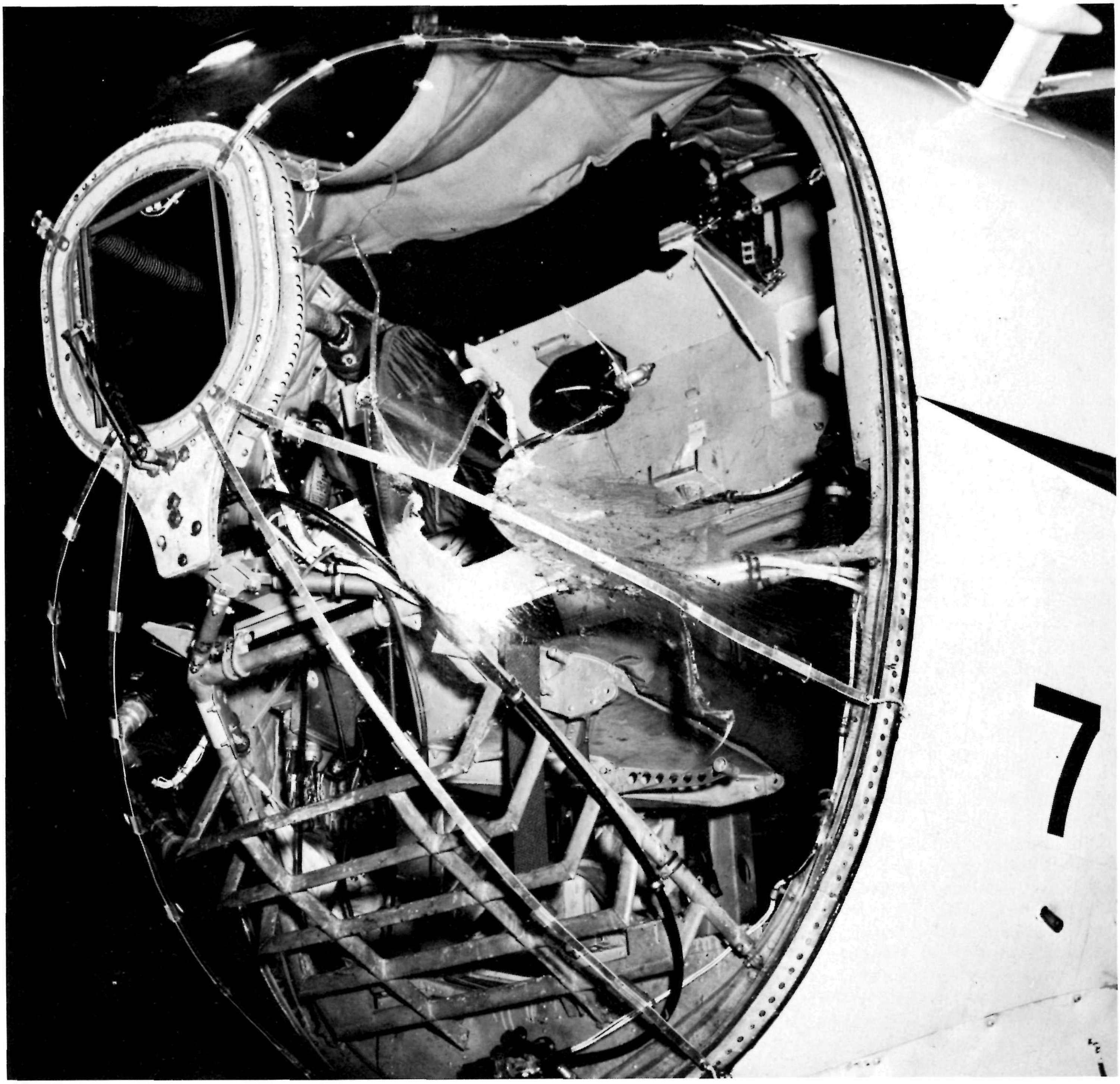
Much of the information about bird migration available in the literature is based on observation, either in daylight or by moon watching. In both cases, the observed birds are those that can be seen from the ground under the prevailing conditions of visibility.

Some of our radar studies have been made on a continent-wide basis using as many as 18 radar stations. We use continuous time-lapse 16-mm motion picture photography of the plan position radar scopes to provide permanent records for study. One frame is exposed for each sweep of the radar antenna (six frames per minute). When projected at normal speed, the films compress the time scale by a factor of 240 times and simplify cataloging of observations.

Examination of the film record has shown that many of the early ideas about bird migration were based on incomplete data, the only kind that could be obtained by visual observation. Our recent experience is similar to that of our colleagues using radar in Europe. There, also, earlier data on bird migration times and patterns have been shown by radar observation to have been less than complete.

During either spring or autumn migration birds generally begin their migratory flight when conditions are favourable. Birds flying north in the spring and entering a southward-moving cold air mass usually stop moving north. If the condition is sufficiently severe, they may reverse their direction. We have radar films from many points in Canada which show that sort of reverse movement in the face of inclement weather. It appears that movement in favourable weather and back-tracking when the situation gets too bad may be the rule for many species in spring northward migration, rather than an exception as we used to consider it.

Our studies of bird migration have shown that the major hazard to aviation caused by mass movements of birds that are gull-sized or larger occurs in rather limited times and locations. We believe that it is possible to forecast when and where those major movements will occur in spring and autumn. After the forecast is made, radar surveillance would permit current reports on the movements. We have already made forecasts and checked their accuracy experimentally for military flying.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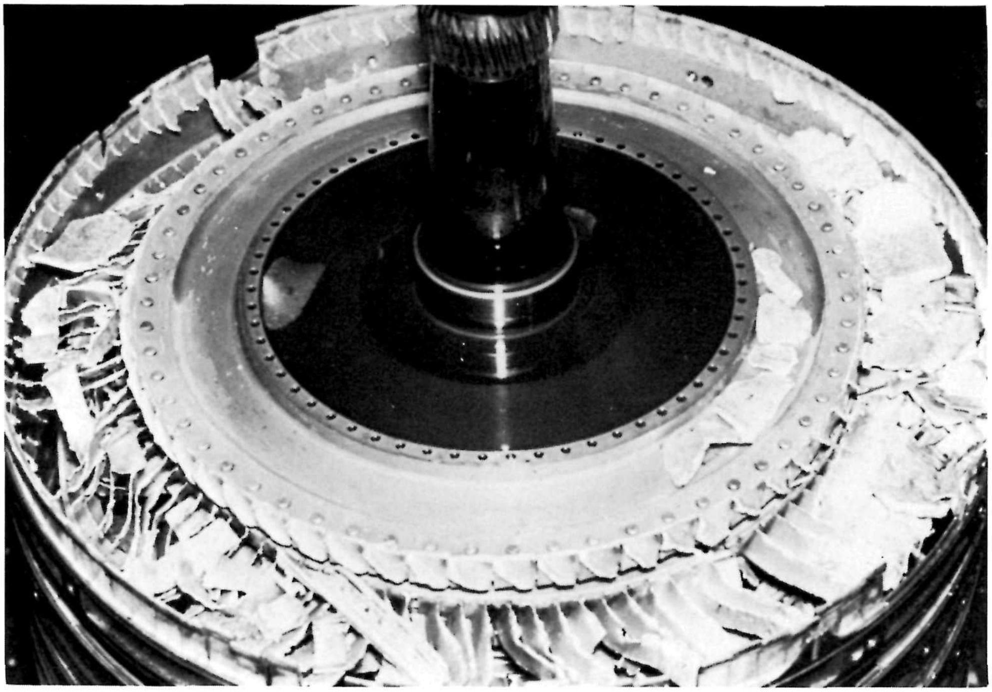

Interior damage to aircraft engine

Much of the bird migration across Canada is in a general north–south direction and much of the airline traffic is east–west. Considering that tens of millions of ducks, about 5,000,000 geese, 300,000 sandhill cranes, 100,000 swans, and millions of smaller birds move across the civil and military air routes twice each year, the possibilities for collision are large during certain short periods and in prescribed locations.

Keeping aircraft away from major bird migrations is not too different from keeping them away from thunderstorms. Thunderstorms are short-duration phenomena associated with severe turbulence and are potentially damaging to aircraft. Much time and effort go into forecasting the time, place, and duration of thunderstorms and into rerouting both civil and military aircraft to avoid them. We believe that as our bird hazard forecast technique improves we can provide bird hazard warnings that will be similar in their value to thunderstorm warnings. The regular traffic control procedures by which civil aircraft and most military aircraft are manipulated in the sky can take account of the bird migration hazard in the same way they now take account of thunderstorms.

We have made experimental forecasts of high bird hazard situations for military purposes. Details of that work were described by Gunn and Solman (1967). Even in this early stage of our studies we can forecast some of the hazard situations with a good degree of accuracy. We do not have enough detailed information about the movements of birds to permit the correlations with weather patterns which will be necessary to make really good forecasts of high utility. We are now comparing months of radar bird observations with the weather data from the same and adjacent areas.

One item on which we need much more information is the triggering mechanism which initiates waves of bird migration. For some species we have clues. We know, for instance, that in James Bay we have in October a build-up of blue and lesser snow geese from nesting grounds farther north. We know that large groups of geese will leave the build-up area during a period of several weeks. Each movement will begin within 24 hours after the passage of a cold front, when there is a strong favourable wind and clear skies.

In other words, we know that two of the four to seven cold fronts that pass through the southern end of James Bay in October of any year will initiate movements of geese. Those geese will constitute a hazard to aircraft at altitudes between six and ten thousand feet over a route of about 1,700 miles from James Bay to the Gulf of Mexico. The moving geese may occupy an area 100 miles long, 30 or 40 miles wide, and 2,000 feet in depth moving in a southerly direction at a speed of 60 or 70 knots, depending on the strength of the tail wind. Our problem is to determine which of the several cold fronts that go through the area during the critical period are the ones which trip the integrating mechanism in the geese and start their movement. We know that for each cold front that passes without a goose movement, the likelihood of movement on the next cold front is increased. We believe further study will help us understand the triggering mechanism so that we can issue a warning before the beginning of movement. Once the geese are in the air we can use radar to monitor their progress to provide warnings along their route about the likelihood of encountering a quarter of a million geese in any given part of the sky.

Through limitations in distribution of radar height-finding equipment our knowledge of the altitudes of migrants is not as complete as we would wish. By using special radar techniques we hope to get information on bird heights to supplement the information we get from pilots.

As our studies continue and our computer correlations work out more of the details of weather effects on bird movement, we believe it will be possible for aircraft to avoid large groups of migrant birds.

Some of the European studies with which we have been involved, including those which we initiated on behalf of the military units in Europe, have suggested that local movements of birds from roosting areas to feeding areas may create a hazard as severe as that caused by major migrations. I refer particularly to mass movements of gulls from large feeding areas such as garbage dumps to resting areas. In one case that kind of movement occurred several times each day and took thousands of gulls across a flight route approaching a major aerodrome. There had been damaging strikes on gulls near that aerodrome which were difficult to understand until radar surveillance showed the type of bird movement and its regularity. Once the timing of bird movement was recognized, it was possible to schedule aircraft landings and take-offs to avoid the major periods of gull traffic. There are North American situations where gulls and even blackbirds pose a similar problem. We believe it would be useful to study local bird movement patterns around airports for the problem may be more widespread than is now realized.

The technique of time-lapse photography of a radar scope is relatively simple and deserves to be more widely used, not only for bird surveillance but also for recording aircraft traffic patterns. It would not be difficult to construct a unit to produce time-lapse photographic records of radar-scope traces for use by a dispatcher. Quickly processed time-lapse movie records of what had happened within range of his radar during the preceding 10 or 15 minutes would permit a check of the validity of forecasts of bird movement. That would permit minute adjustments of aircraft traffic patterns to make use of the safe portions of the sky and to avoid those which were heavily cluttered with birds.

By using modern techniques we can carry heavy civilian and military air traffic through the same skies travelled by millions of birds with fewer damaging impacts than have caused loss of life and high costs in past years. For less than the multi-million dollar expenditure which is now required to repair aircraft damage, we can modify the use of presently available radar to save dollars and human life.

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A bird-warning system for aircraft in flight*

W. W. H. Gunn† and V. E. F. Solman‡

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Gulls at garbage dump

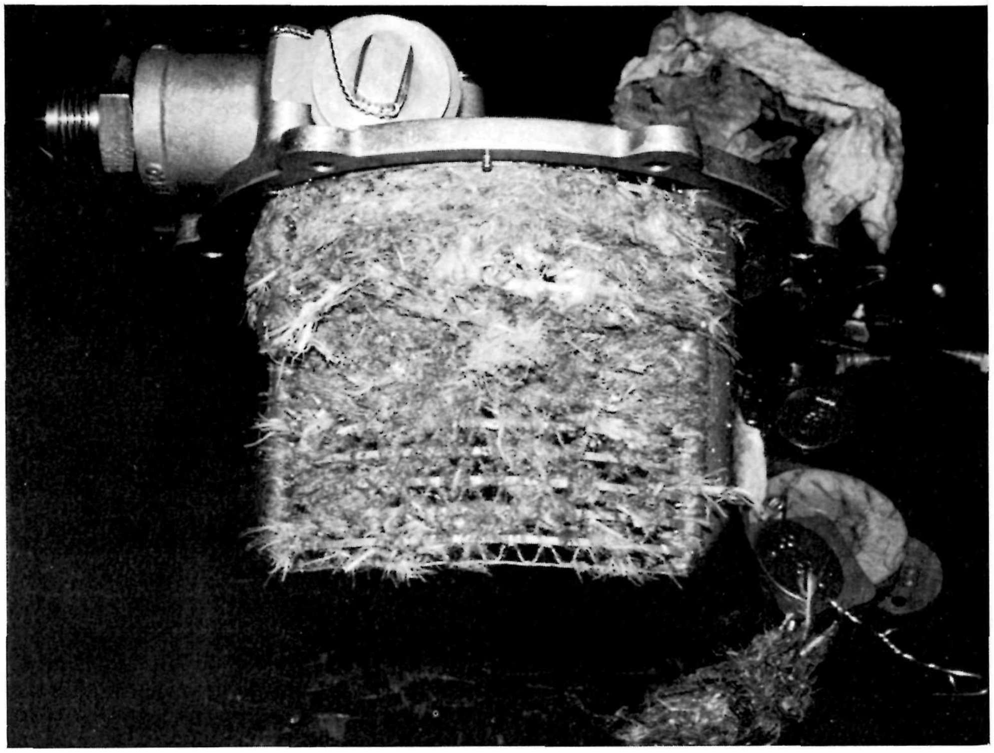
The theme of this paper is that radar can readily detect flights of birds and that this information can be used effectively in flight planning and in air traffic control to reduce significantly the number of bird strikes.

Since military aircraft are expected to carry out training flights and missions at all seasons and all times of day or night, it has been argued that losses of aircraft and even crew owing to bird strikes have to be accepted as one of many operational hazards. The vast complex of national and international air traffic control is said to be an operation requiring split-second timing and having no leeway for diversionary tactics to avoid birds. It has also been argued that the problems of air traffic control are mounting so rapidly because of other factors that birds are becoming a relatively minor problem, scarcely worth consideration. We do not believe these, viewpoints are valid.

Let us look at the commercial operation first. While the chance of an unforeseeable, random bird strike in flight will always exist, it is nevertheless possible to define the high-risk conditions within fairly narrow limits. In the first place, most commercial aircraft cruise at altitudes far higher than those used by the vast majority of birds, so the danger of a strike in the cruise phase is very slight, and comes close to being negligible above, say, 12,000 feet. Secondly, the multi-engines of commercial aircraft mean that loss of power caused by damage to one engine may be expensive but not catastrophic. Thirdly, experience has shown that at present-day cruising speeds wind screens and the rest of the airframe will withstand the impact from one or even a few *small* birds without serious damage. The high-risk conditions are therefore narrowed down to those in which a multiple strike may damage more than one engine and those in which the bird struck is large enough to do serious damage to such vital parts of the airframe as the wind screens and stabilizer. Moreover, as the risk in cruise is small, we can concentrate on other phases of flight — take-off and climb-out, and approach and landing.

The type of risk differs to some extent with the particular flight regime. In take-off and climb-out, the time elapsed is relatively brief, but it is also the time when most power is required: engine damage is the most critical risk here. In the approach phase, the time period is considerably longer and the speed still high, but power is relatively less important, so here we are probably more concerned with structural damage to the airframe. Finally, at landing, the speed is relatively low and the time is quite short, so the risk of a serious strike is less and probably inconsequential, unless the birds are of gull size or larger.

Gull feathers inside aircraft engine



In sum, then, for commercial operators, we are concerned mainly with the take-off, climb-out, approach and landing regimes, and with small birds in dense flocks, medium-sized birds (e.g. gulls) in relatively dense flocks, or large birds (geese, swans, cranes, or vultures, for example) flying individually or in flocks. Moreover, since the risk in the cruise regime is relatively low (above 12,000 feet), we are concerned primarily with airport surroundings outward to a radius of 50–75 miles.

Assume now, for the sake of argument, that we had precise and specific information at hand about bird movements of the type mentioned. What alterations to normal operational routine would federal regulatory bodies or commercial aircraft operators be prepared to make to reduce the bird-strike hazard? The first reaction to this question is likely to be "very little or none". But *suppose we consider the problem in relation* to what is being done today about another aspect of air safety, the thunderstorm. Thunderstorms are seasonal in their frequency, local and short-lived in their occurrence, difficult to track with precision, and harder still to predict with accuracy. Yet the high degree of turbulence lurking in their centres may represent a very real hazard to aircraft. Pilots in training are warned to treat them with respect, and not to fly casually through them. Meteorological services go to considerable trouble to provide pre-flight and in-flight advisory information about their occurrence. Air traffic controllers in airport towers and radar centres may change runways or approach routes or altitudes to help aircraft avoid nearby thunderstorms. When there are severe thunderstorm conditions in the immediate vicinity of an airport, pilots may delay their take-off briefly and landings may be delayed or even diverted until conditions become less hazardous.

If all this can be done for thunderstorms, it can also be done for flights of birds following patterns known to be hazardous — *provided* that the warnings are at least as accurate and precise as they are for thunderstorms. This, I think, is a fair enough challenge, and all the flexibility of operational procedure that need be asked for, to reduce bird-strike hazards. But is the comparison of hazard between thunderstorms and bird-strikes a valid one? Squadron Leader G. W. Ovans, formerly of the Directorate of Flight Safety, Canadian Forces Headquarters, said: "We have an elaborate warning system that allows us to take appropriate precautionary measures when dealing with thunderstorms. At least in part because of those precautions, we very seldom lose planes or have them seriously damaged by thunderstorms. Yet we do lose planes and have many others extensively damaged by bird-strikes. So far, we have not developed any functional warning system against bird-strikes, but if it can be done successfully for the one, it should be possible and worthwhile to do it for the other."

Turning to the military side of the bird-strike problem, we can assume first of all that military transport aircraft encounter roughly the same types of hazards as comparable commercial aircraft. In Canada, we do not as yet have large pure jet transports in military service, and this reduces the size of our bird problems. What we do have, however, is the F-104 or Starfighter aircraft, used by our squadrons serving with NATO, and in Canada chiefly at the training centre at Cold Lake, Alberta. As you know, that is a single-engined jet aircraft flown at very low levels and very high speeds. From our point of view, this is a particularly bad combination, since the F-104 cruises at altitudes where birds are frequently very numerous (250–500 feet), and at speeds which usually preclude either the pilot or birds from taking avoidance action if collision seems imminent. The wind screens seem able to withstand most bird impacts at high speed, and the remainder of the air frame is practically invulnerable to serious damage from bird strikes, but not so the engine. The ingestion of even a small bird can result in serious damage which may lead to loss of power, which in turn means almost inevitably that the aircraft will crash. Fortunately, the Canadian design of ejection seat is extremely efficient, and no pilots have been lost owing to known bird strikes, but there have been nine definite and two possible losses of F-104 aircraft from bird-strikes. At roughly 1.5 million dollars per aircraft, we have felt it worthwhile to do a considerable amount of research on the problem.

With the Canadian military forces, then, the problem lies largely with engine ingestion of birds in a particular type of aircraft, the F-104, where a strike by even a small bird may be catastrophic. A strike is more likely to occur in cruise than during the other phases of the flight regime, because most of the cruising time is spent at low altitudes. Compared with commercial operations, the problem is more specific with regard to aircraft, but considerably less so with regard to the types of bird involved and the distance from the airport.

In military flying, the margin for change in flight plans can be extremely small when, for example, operational exercises are taking place. On the other hand, flexibility may be considerably greater than with commercial operations for much of the time, particularly for training programs. In planning training programs over a 2- or 3-year period, for example, it may be possible to arrange schedules so that the peaks in flying periods do not coincide with seasonal peaks in bird migration. Even during seasonal peaks of bird activity, it may still be possible to minimize flying time during hours of the day or night when bird activity is greatest. If there is some leeway in the number of days to be flown per month, an efficient bird-forecast and warning system should be able to select days and nights within a given period when the bird hazard is relatively high or low, and recommend altitudes and flight routes with the lowest degree of hazard. It would then be up to the operations group to set a threshold for the degree of hazard which would require the altering or postponing of scheduled training flights. The threshold could be adjusted up or down according to the urgency or type of flight programmed.

It was, in fact, with something like that approach in mind that we in Canada made our first efforts to operate a bird-activity forecast program that might be used for operational purposes. This was done at the Canadian Forces Base at Cold Lake, Alberta, from May 1 to June 15 and again from August 21 to October 31, 1966. We were at that time already taking time-lapse motion pictures of a plan-position radar display at Cold Lake for long-term analysis of the relationship between bird movements and weather conditions. For the above periods, we extended our photographic coverage to include a series of still photographs of a similar Plan Position Indicator (PPI) display. One photograph was taken each hour around the clock. Each film was exposed for 10 minutes, followed by a 2-minute pause, then re-exposed for a final minute. The result was a streak of light representing each substantial bird echo (probably indicating a flock of birds), with a break in the track at one end to indicate the direction of movement. Both Polaroid and ordinary negative film were used in about equal quantities. The Polaroid film was quicker and easier to handle but lacked depth. The ordinary negative film, with a two-speed emulsion, provided better contrast and detail, and therefore seemed better for making careful assessments of bird activity, especially in high-density situations. The two kinds of film were often used alternately for 1-hour periods.

The hourly series of photographs was delivered to the duty forecaster at about 9 a.m. and 4 p.m. These were rated according to an arbitrary 8-point scale set up from a selection of photographs covering the whole range of migratory intensities. They provided evidence of bird movements up to 1 or 2 hours before forecast time, which was regularly at 10 a.m. and less regularly at 4 p.m. The forecaster endeavoured to forecast the probable density of bird movement for each hour of the next 24-hour period, basing his decisions on the hourly intensity pattern for the previous 24 hours; the hourly patterns for the past several days, which indicated the seasonal trend; the weather forecast for the next 24-hour period; and a rudimentary idea of what effect this weather might have on bird movements. During the spring of 1966, the project was carried out purely as a "dry run", with no influence on operations; in the autumn of 1966, some limited operational use was made of the forecasts.

An over-all assessment of forecast accuracy was made from verification of 2,068 hourly forecasts. Taking errors of plus or minus one in the rating scale as being insignificant, it can be said in summary that 77 per cent of the forecasts were accurate, 11 per cent under-rated, and 12 per cent over-rated — on the face of it a very acceptable rate of forecast for a first attempt. However, further examination showed that much of the accuracy was obtained by forecasting a continuation of the prevailing state. The level of accuracy was much lower if only those hours of greatest bird-flight intensity are considered. Of the 119 hours when the intensity was rated at 5, 6, 7, or 8, only 50 per cent of these were correctly forecast in spring and 35 per cent in autumn. These presumably high-risk situations amount to only 6 per cent of the total number of hours forecast, so that if this relatively small number could be forecast accurately, the practical value of the forecast system would be greatly enhanced.

A review of the results of the project brought forward three main points. First, a 24-hour forecast with a 12-hour updating provided much more lead time than was normally required. A 6-hour forecast with a 3-hour updating, the standard procedure for meteorological forecasts, would have provided sufficient lead time and allowed greater accuracy in forecasting. Second, there were inherent difficulties in the quality of the radar information. The radar was being operated for purposes other than bird detection, and frequent changes in settings of gain, polarization, beam elevation, Moving Target Indicator (MTI), and range led to difficulty in standardizing measurements of intensity of bird movement. Third, and most important, the input of ornithological data was far too inadequate and vague to enable the forecaster to interpret with any confidence the probable intensity of bird activity in relation to the weather forecast. Not only was very little precise information supplied about the bird/weather relationship, but there was also a lack of precise information as to the kinds and numbers of birds represented by the echoes on the radar scope. The general working hypothesis for the weather was that headwinds from the presumed direction of migration would be unfavourable for intensive bird migration and that opposing winds would be favourable. It followed that, in autumn, the east side of a high-pressure system (following the passage of a cold front) was considered favourable for migration activity and, similarly, in spring, the west side of a high-pressure system or a warm sector following the passage of a warm front was considered favourable. It was also assumed that the primary direction of migration was northward in spring and southward in autumn. Subsequent study of the time-lapse motion-picture films has shown this to be an inaccurate assumption, as the primary direction has proved to be northwest in spring and southeast in autumn — a change that would make quite a difference in the assessment of the influence of the forecast weather on bird migration.

The bird intensity forecasting project at Cold Lake functioned very well at the mechanical level, but showed serious deficiencies in input at the theoretical level. Since then, we have undertaken a program to make good those deficiencies by learning more about the bird/weather relationship at Cold Lake and about the relationship between the echoes displayed on radar and the numbers and kinds of birds they represent. We have run a computer program to make a multivariate analysis of bird movement data assessed from Cold Lake radar film over a period of 17 months in relation to weather data for the same station and period of time. Since in that operation we deal with bird data and meteorological data from one geographical point only, we did not expect to arrive at any conclusive correlations, but hoped to obtain leads that would help in the next step — an analysis of similar bird and meteorological data for the same period from six locations in Alberta and Saskatchewan. That should have illuminating results if we do not become swamped by computer output along the way.

Our second step was to establish an experienced biologist at Cold Lake in 1967 with instructions to obtain quantitative information about radar echoes by relating them to visually verified numbers and species. He is also attempting to quantify our 8-point scale of density and investigate local movements of birds that show up repetitively on the radar display. As our ornithological knowledge of the region is extended, we are preparing a manual for the guidance of biologists and others at Cold Lake participating in the bird warning forecast scheme.

Meanwhile, a good deal of progress has been made in some parts of Europe toward a workable bird-warning system. In the Netherlands, the RNAF has set up a bird-warning system based on time-exposure still photography of a radar scope at Den Helder. When bird flight intensities rise above a certain level on an 8-point scale, nearby military airports are warned by telephone and a graduated scale of precautions is put into effect. This system is simple, since it is a direct warning based on the latest photograph and avoids the uncertainties of a forecast, but it has the drawback that it has no lead time at all and a serious time-lag may develop if there is any delay in the transmission of information to operations control. In West Germany, special efforts are made to monitor and issue warnings about the spring and autumn migrations of cranes across the country, since these are high-risk birds that cross many airport approaches. The program has worked out well, with enthusiastic support from many field observers. Holland, Belgium, France, and Germany now exchange bird warnings through a rapid communications network. In France a number of stations pass on to pilots reports of current radar observations of bird movements.

In France, radar films taken at Aix-en-Provence in the spring of 1967 showed dramatically how local movements of birds may be an even greater hazard than migratory flights. Each morning and evening, gulls made flights between a major food source at a garbage dump northwest of Marseilles and a roosting area at the edge of a lake. The flight traversed the northern approach to the main runway at the military base at Istres, at a critical height, some 5 miles north of the field. That runway, the longest in Europe, is used in the testing of late-model jet aircraft. No one who has seen the films is surprised that serious and expensive strikes have occurred there. It is worth noting that while the motion-picture films pinpoint with clarity and precision this daily local movement, still pictures fail to do the job, because of intermittent coverage and lack of motion. Still pictures are very effective in portraying bird migration taking place on a broad front over a matter of hours, but they are usually ineffective in showing up short-term local movements occurring in only a small portion of the display. The experience at Aix-en-Provence points up the need to give more attention to local bird movements detected by radar, since they may well involve birds in the high-risk category, and quite specific warnings can be made as to when and where they present a danger.

We learned our lesson in this regard one day in October 1966 at Cold Lake, when we lost an F-104 after an encounter with some snow geese. The bird movement intensity forecast for that particular hour of that day called for a low intensity of bird activity. From a quantitative viewpoint this was quite correct. What the forecaster failed to say and did not know was that although the number of birds in flight would be low, Gulls at Long Point, Ontario

a fair proportion of them would be geese that had recently arrived from the Arctic Coast a thousand miles to the north, and were moving about during the day to visit local feeding areas.

We would like to close by outlining what might be a workable basis for an effective bird warning system based in large part on radar-derived information. It should work as well or better in Europe as in North America, because of the closer grouping of airfields and the greater number of weather (and bird) reporting stations.

The bird movement forecast would be prepared every 6 hours to cover the next 6 hours. In migration periods it would be updated every 3 hours, and every hour at times of high risk. It would be issued for a given region covering a number of airfields and would be as specific as possible. Preparation of the forecast would be the responsibility of a roster of biologists, organized in the same manner as duty meteorological forecasters, but covering a much larger area, so that the total number of biologists required would not be impossibly large. The duty biologist would be closely dependent on the current meteorological forecast and would have to be familiar with the synoptic situation on which it is based. It would be his responsibility to interpret the weather forecast in terms of how it was likely to affect bird movements. He will need to have support: the experience gained from detailed studies of radar films and comparable weather data; information on known seasonal trends in bird movements in the region; reports of visual observations made in support of the operation; visual verification made of local movements that appear repeatedly on radar; and a backlog of general information drawn from the literature on the migratory behaviour of birds. This last must be weighed carefully since it may be based largely on visual observations that, by themselves, can often give a very misleading idea of what is actually happening.

The forecasts should be handled in the same general manner as local or special weather advisories. They should be made available with the shortest possible delay to the pilot briefing room for reference and possible action by pilots. On the same basis they should reach airfield controllers in towers and air traffic controllers in radar centres. It might be feasible or desirable to issue bird movement forecasts only when a designated degree of hazard is reached or predicted.

Forecasts for military airports should be prepared on a somewhat modified basis, in line with the differing requirements for military flights, as indicated earlier in this paper.

The outlined scheme needs to be strong enough to do the job but not so complex to become burdensome. Since it would probably take several years to set up such a scheme on a broad scale, it is appropriate to ask whether new generations of aircraft will continue to be vulnerable to bird-strikes, or whether aircraft design can overcome the problem. It seems evident that in the more immediate future aircraft are likely to become more, rather than less, vulnerable to severe damage from bird-strikes. Larger engine intakes will accommodate larger birds. Larger aircraft carrying many more passengers will make plane loss more catastrophic. Increased speeds, such as are forecast for the take-off and climb-out of the supersonic transports, will greatly intensify the force of impact and give birds even less opportunity to evade. There is a possibility that an effective guard or bird disposal unit can be designed to protect future jet engines. Some research has begun in the United States on this aspect of air safety. It may lead to an effective design that would greatly reduce the overall bird hazard. However, such a device would not prevent strikes on the airframe from large birds. It is our belief that the bird-strike problem will not dwindle to an acceptable risk until vertical take-off and landing aircraft are in common use. Meanwhile, in our opinion, any airport that operates without a proper bird-warning system extending outward 50 miles or so just is not trying hard enough for air safety.

A Canada goose migration through the southern interior of British Columbia

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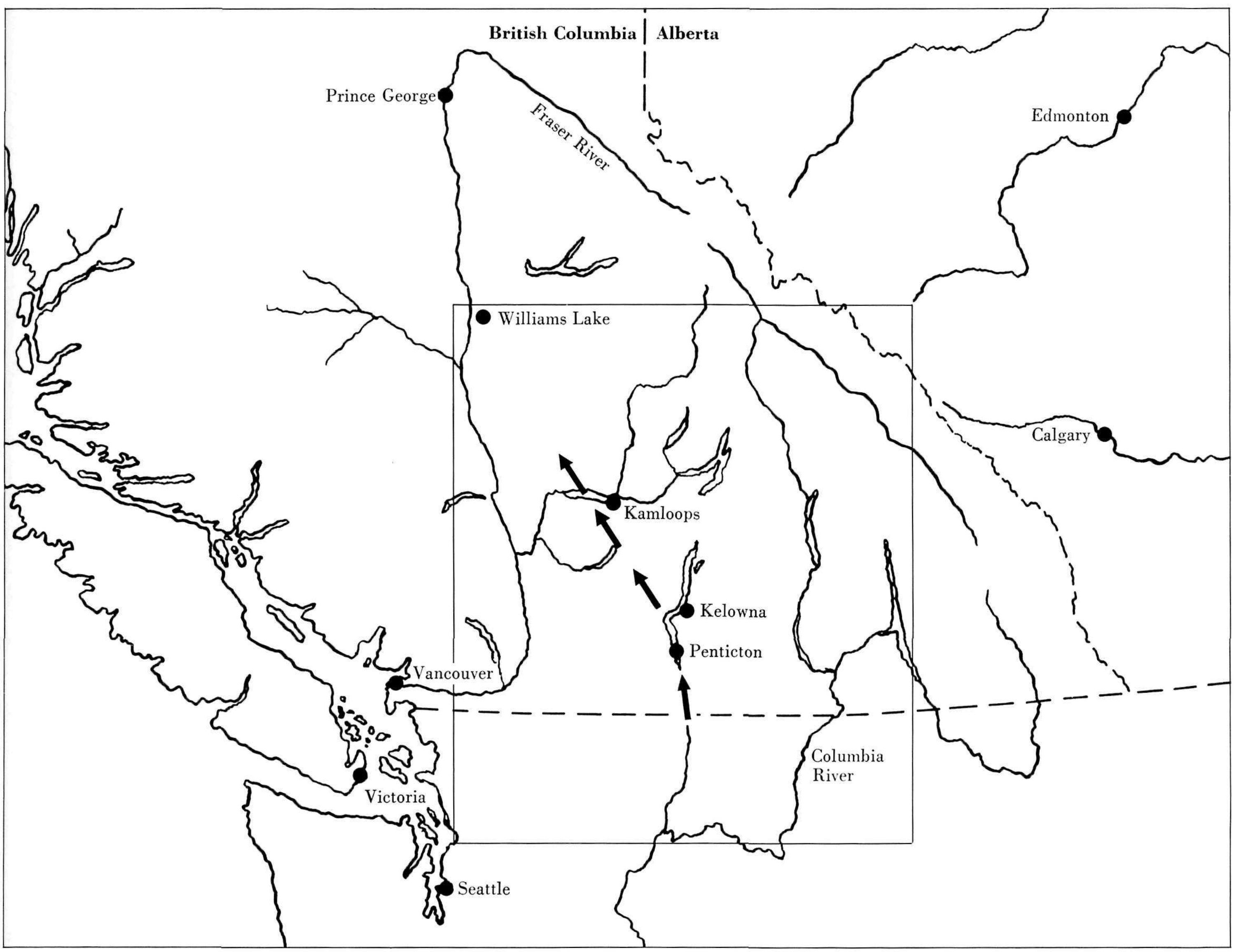
Introduction

Figure 1. Southern British Columbia. The region outlined by a square is shown in more detail in Figure 2. The arrows show the path of a Canada goose migration through the interior of the province in the spring.

During the spring of 1965, from March 22 to June 10, 16-mm movie films were taken of a radar display at a 23-cm (L-band) radar station in British Columbia. Impressive, broad-front migratory movements of birds across the area were recorded during this period. One movement detected by the radar was, however, quite distinct from the rest. Its characteristics were that (i) it was diurnal, (ii) it crossed the display on a narrow front along a route which was the same each day that it occurred, and (iii) it took place only during the 12-day period from April 17 to 28. The analysis of the radar films was carried out, and the paper drafted, by Myres.

It has subsequently been possible, on the basis of visual observations made by Cannings in April of 1968 and 1969, to ascertain with reasonable certainty that the species responsible for this movement was the Canada goose, *Branta canadensis*.

Figure 1



Description

The radar echoes caused by the flocks of birds taking part in this migratory movement were first detected close to the Canada–United States boundary. They were moving northwards in a very narrow flight path which corresponded with the position of the southern portion of the Okanagan Valley of British Columbia (Fig. 1).

The radar echoes (which were round in shape) were regularly of medium or large size, strong in intensity, and crowded closely upon each other. They were evidently caused by large birds, or perhaps large flocks of medium-sized birds. The line of radar echoes followed the course of the valley from south of Penticton to near Peachland, where Okanagan Lake curves northeastwards (Fig. 2). The direction of movement above the southern Okanagan Valley was most frequently 340–350° (NNW) along the line of the valley (Table 1).

Near Peachland the line of echoes always left the Okanagan Valley and, crossing the mountains to the west of the valley, proceeded NNW across the Nicola Lake country along a course that took them approximately over Savona at the west end of Kamloops Lake (Fig. 2), in the direction of 100 Mile House in the Cariboo District, where they disappeared from radar view. After leaving the Okanagan Valley the echoes fanned out somewhat, so that the variation in directions of movement sometimes became as much as 60° (from WNW to N) and the flight path broadened.

This was a strictly diurnal movement, and nothing equivalent was detected at night. It was usually first detected over the southern Okanagan Valley in the mornings between 0600 and 0900 hours Pacific Standard Time (PST), though once it did not appear until 1300 hours.

The mountains along the west side of the Okanagan Valley reach heights of a little over 6,000 feet. Technical considerations (including the distance at which the echoes were detected) permit us to deduce that the birds involved in this movement must have been flying at considerably greater heights than this, and that the echoes on the radar display were probably being caused by flocks of birds that were flying at altitudes between 8,000 and 15,000 feet.

The density of a movement of this kind cannot be strictly compared with densities of broad-front bird movements reported elsewhere; instead, relative densities ("very light", "light", "medium", and "heavy" movements) are provided in Table 1. The total number of echoes counted each day, and the relative rate of passage (echoes per hour) were the basis for assessment (Table 1). The movement continued all day until between 1800 and 1930 PST in the evening,

Figure 2

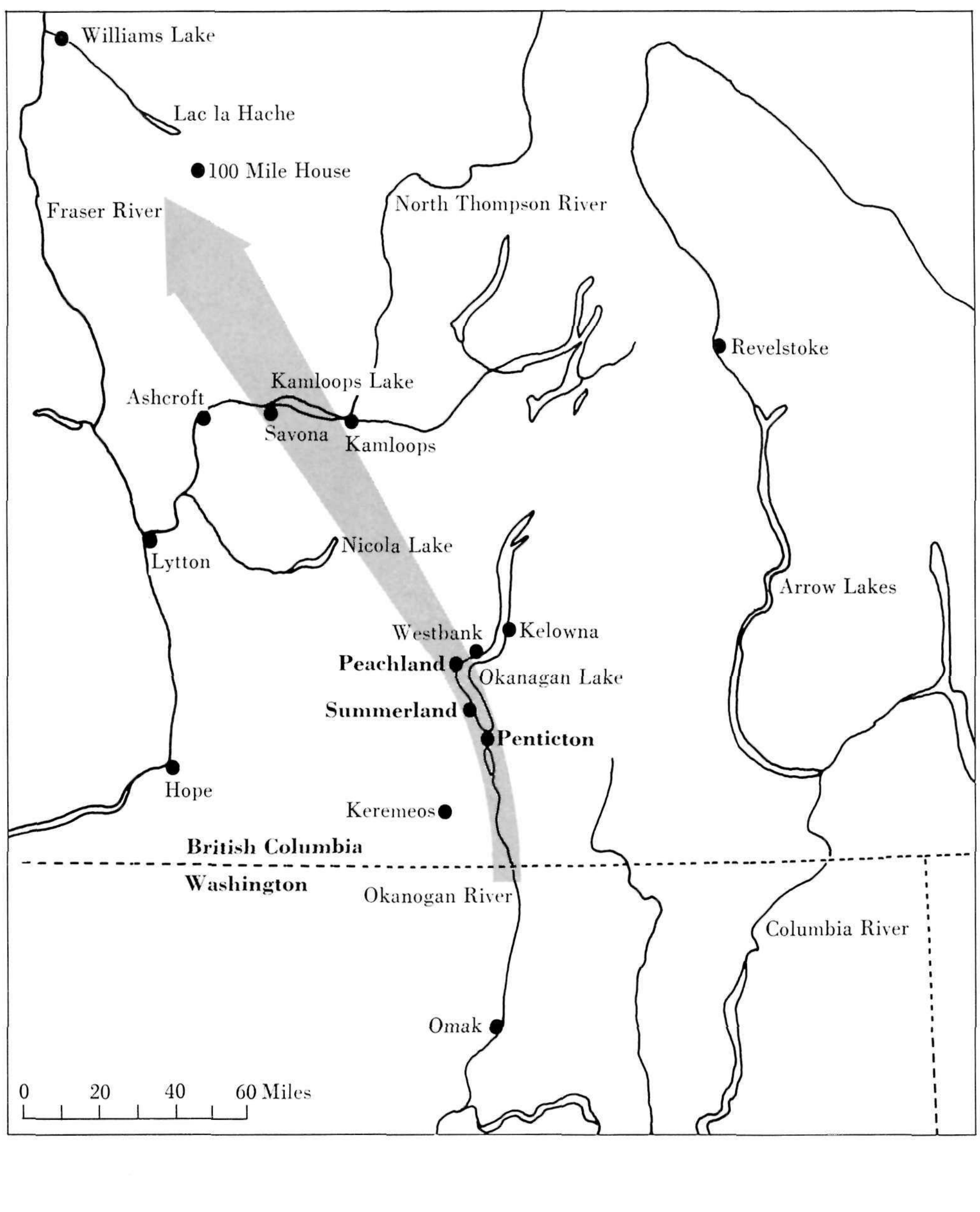


Figure 2. Southern British Columbia. The arrow indicates the track of a Canada goose migration along the southern Okanagan Valley, then across mountains and the Nicola Lake country to Kamloops Lake, then across the latter towards Williams Lake in the Cariboo District.

Table 1
Movements of radar echoes in a line up the southern Okanagan Valley towards the Cariboo in April 1965

Date, April	Period of movement, PST	Relative density	Total no. of echoes during period	Echoes per hour	Direction in Okanagan Valley, °	Weather[a]	Remarks
17	0730–(1915)[b]	Heavy	60	5.1	340–350	H	"Very light" density until 1015 but became "medium" after that; echoes somewhat pulsating; by 1115 the head of the line of echoes had crossed the Thompson River, but echoes were still appearing over the southern Okanagan; the density became "heavy" in the southern Okanagan at 1345.
18	0800–?[c]	Medium	17	4.3	330–350	T	Movement not dense, but prominent.
20[d,e]	0910–1390[b]	Light	19	1.9	340–350	F	"Very light" density after 1700 PST.
21	0730–1000 & 1300–1900[b]	Heavy	46	5.9	340–350	T–H	
22	0600–?[f]	Heavy	62	6.4	330–350	H	At 0600 the density was "very light", but by 1000 it was "heavy".
24	0645–(1900)[b]	Light	>26	>2.4	320–340	F	Density was "very light" before 1415; then a line of about half a dozen echoes moved across the southern Okanagan.
26	1300–1800	Light	17	3.4	340	H	
28	(before 1235)–1800	Medium	22	4.0	340–350	F	A line of bright echoes in the southern Okanagan; from 1415 they were visible moving 300–320° over the southern Cariboo.

[a]H=high pressure system; T=transitional; F=frontal (or low pressure system). April 19–F; April 23–H; April 25–H; April 27–H.

[b]Obscured by the development of a northwestward broad-front movement, probably of shorebirds.

[c]No radar record after 1200 PST.

[d]On April 19 echoes were not seen over the Okanagan Valley, but a few were moving 340–350° north of Kamloops Lake during the morning.

[e]On April 20 the radar shows *simultaneous* movement of bird echoes from the southern Okanagan Valley towards the Cariboo District and movement northeastwards of widespread high-level broken cloud; probably because of the bad weather, some flocks may not have been flying as high as usual, so that the relative density of the echoes recorded by radar is artificially low (echoes/hr).

[f]No radar record after 1545 PST.

and on several occasions there developed in the evening broad-front NW movements (probably caused by shorebirds) which seemed to swamp or replace the linear movements as they declined around sunset (Table 1).

Since the movement continued each day for about 12 hours, with a stream of echoes arriving in the southern Okanagan Valley from the south for the greater part of the day, it is clear that a large number of birds was involved in the movements when the density was high, and some estimates of the probable numbers are made later in the paper.

These movements were observed each day from April 17 to 22 (inclusive) and on April 24, 26, and 28, 1965. Details are given in Table 1. On April 19 the movement was not of significant proportions.

On April 21 the movement was on a broader front than usual in the morning (before 1300 PST), with widely spaced echoes east of the southern Okanagan Valley, which later crossed the northern Okanagan Valley as they moved northwestwards. After 1300, however, the usual line was visible in the southern Okanagan Valley itself. On April 22 the movement formed a swath 30 miles wide, from about Kelowna–Penticton northwest to Savona–Ashcroft, with dense clusters of echoes within these limits.

That the line of echoes first appeared each morning at the southern end of the Okanagan Valley of British Columbia suggests the birds had spent the previous nights on the floor of the valley, probably not far south of the international boundary, in Washington State; but whether the flocks all originate from one (or a few) sites and set off throughout the day, or all set off in the early morning from the whole length of the Okanogan River Valley and Columbia River Valley is not known. It is certain that no echoes first appeared in the mornings north of Peachland (between Okanagan Lake and the Thompson River; evidently the birds which left the valley to the south each day continued on into the Cariboo District, out of radar view, *without* settling in the Nicola–Savona region.

The weather conditions under which these movements occurred are described in a later section.

As this was a diurnal movement, and because it took a linear form (originating from a recognizable valley), it was natural to suspect that the species of bird producing these distinctive radar movements might be diurnal birds of prey, cranes, or geese. Indeed, in 1965, Cannings had noted flocks of 42 and 140 Canada geese at Summerland on April 21, and some sandhill cranes, *Grus canadensis*, flying over Penticton at 1900 PST on April 26. As will be shown from observations made by Cannings in 1968 and 1969 at Myres' request, it is virtually certain that Canada geese were responsible for the movements observed with radar.

In the spring of 1968, Cannings made a special watch for diurnal migration during April in the southern Okanagan Valley. A considerable movement of Canada geese along the valley was observed on 5 days: April 9, 18, and 20–22, 1968 (Table 2). The peak passage occurred on the morning of April 18, when 4,250 Canada geese were recorded in only 1 hour from 0810 to 0912 PST (Table 3); the flocks were spaced about 2 minutes apart in a following wind, a rate of passage that was greatly in excess (about 4×) of that seeming to be detected with radar (Table 1) in 1965. However, this was probably an exceptional occurrence; the seven flocks (1,200 geese) recorded in another 1-hour count later the same morning (Table 3) are more nearly comparable with the findings of radar.

The direction of movement of the geese was always NW over Penticton and Summerland. The altitude of flight of the geese observed varied, being low over Okanagan Lake on one occasion, but on April 18 most of the flocks were seen flying at about 2,000 feet a.g.l. (= about 3,100 feet a.s.l.).

In April 1969 Cannings repeated the watch. Migrating Canada geese were observed on April 14, 16, 17, 19, 20, 22, 23, and 26 (Table 4). The directions of movement and the altitudes of flight were similar to those observed in 1968.

The 1969 passage of Canada geese was 4–5 days later than in 1968, and the dates

Table 2
Visual observations of migrating Canada geese, April 1968

Date, April[a]	Time, PST	Number of birds	Weather[b]	Remarks[c]
9	0815	24	H	NW over Summerland
18[d]	0810–0912	4,250	H–T	In 1 hour (Table 3)
	1030–1130	1,200		In 1 hour (Table 3)
	1200–1300	0		No migrating geese
20	0608	200	H	NW over Penticton; wind NW at 5,000 ft
	1010	70		NW over Penticton
	1850	200		NW over Penticton
	?	4 large flocks		North over Keremeos
	?	2 flocks (300 birds)		N or NE over Westbank
	?	several flocks		Over Wilson's Landing
21	All a.m.	0	H	No migrating geese, Vaseux Lake
	1730	50		NW low over Okanagan Lake
22	0900	>200	H	NW over Summerland; wind from the north
	1100	>100		NW over Summerland; wind from south

[a]On April 14, 17, 19, 23, and 24 *no* migrating geese were seen, although a watch was maintained each day.
[b]Weather symbols as in Table 1. April 19–T.
[c]On April 19 the wind was from the north, and on April 23 there was a strong wind from the south.
[d]On this day Omak recorded 9/10ths cloud cover, the only 1 of the 5 days when cloud cover was extensive. A cold front approaching from the north was almost over the area (Fig. 4b). These conditions may have contributed to the visibility of the migrating geese on this occasion.

Table 5
Visual observations of migrating sandhill cranes, April 1968 and April 1969

	Date, April	Time, PST	Number of flocks or birds	Remarks
1968				
	18	?	One flock	
	21	1600	Two flocks (50 + 50)	NW over Darke Lake, 10 miles NW of Summerland
	23	1600	Three flocks	Circling over Summerland, heading NW
		1800	Three flocks (ca. 600)	North over Summerland
1969				
	13	Ca. 1200	One flock (ca. 20)	Flying north over Penticton
	17	0930	Small flock	Near Summerland
		1000	One flock	Circling over Summerland
	23	0900	One flock (100)	Over Penticton
		1320	130 at 4,000 ft above valley	West of Summerland
	24	1900	Two flocks of ca. 40 each	West of Penticton
	25	1845	25 cranes	Quite low over Summerland
	28	1600	Ca. 20 cranes	Over Summerland
		1820	300–400 cranes	Over Summerland

Table 3
Flocks of Canada geese flying northwest over Summerland, B.C., on April 18, 1968[a]

Time, PST	Number in flock
0810	300+40
0812	50
0815	10
0817	200
0818	300+50
0822	30
0824	200+40
0825	300
0828	200
0833	200
0840	40
0842	40+300
0845	200
0846–0848	800
0852	100
0854	50
0903	200+300
0906	100
0912	200
Total, 1 hour:	4,250
1037	200
1040	200
1046	100
1102	300
1105	100
1114	100
1125	200
Total, 1 hour:	1,200

[a]Observations made by S. R. Cannings. Some flocks were over Okanagan Lake, some over the Canada Department of Agriculture Research Station on the west shore of the lake. Most flocks were flying NW at about 3,000 feet (2,000 feet above Okanagan Lake). The wind was from the south. During a third hour of observation, between 1200 and 1300 hours PST, no geese were seen or heard.

Table 4
Visual observations of migrating Canada geese, April 1969

Date, April[a]	Time, PST	Number of birds	Weather[b]	Remarks
14	0930	Ca. 50	H	Over Penticton
	1930	Ca. 100		Over Penticton
16	0930–1030	Ca. 400 (4 flocks)	H–T	Over Penticton
	1930	Ca. 100		Ca. 4,000 ft above valley floor at Penticton
17	1730	?	T	Flock heard above clouds, Penticton
19	0930	Ca. 100	F	NNW along Okanagan Lake; wind from south at ground level, but changed to north at 1100 PST; at higher levels from west throughout
19–20	?	Ca. 12 flocks		NNW west of Summerland, towards Brenda Mines
20	0820	>100	H	North high over mountains west of Penticton; wind from south at surface, upper wind from west
	1030	100		Ca. 5,000 ft over the centre of the valley at Penticton
	1900	Ca. 200		Over centre of valley at Summerland
	All p.m.	0		No migrating geese seen from a mountain west of Peachland
22	0815	200	F	Over Penticton
	0900	140		Over mountains west of Penticton
	1030	150+200		Over Penticton
23	0745–0800	3 flocks	F	Heard above clouds, Summerland
	0940–0950	300–400 (3 flocks)		North over Summerland at 2,000 ft above valley floor; wind from south
	1015	150		NNW over Summerland at 3,000 ft above valley
	1030	>200		Over Summerland
26	1200	150	T–F	Over Penticton

[a]On April 18 *no* migrating geese were seen, although a watch was maintained.

[b]Weather symbols as in Table 1. April 15–H; April 18–F; April 21–T; April 24–T; April 25–T.

(April 14 to 26) were closer to the dates of the movements recorded with radar in 1965 (April 17 to 28) than to the dates of goose passage in 1968 (April 9 to 22). Also, although the passage extended over an equivalent period of time (12 to 14 days) in each of the 3 years, migration was actually recorded on 8 days in 1965 and 1969 but on only 5 days in 1968. As a corollary, there was in 1969 no day with a passage as heavy as the one that occurred on April 18, 1968. This may perhaps be explained by the difference in the weather in the 2 years (discussed later).

Sandhill cranes were recorded in much smaller numbers (Table 5) than Canada geese. In 1968 flocks were seen on only 3 days: April 18, 21, and 23. Canada geese were also migrating on the first two of these days. The only day a large number of cranes was seen was April 23, when six flocks were observed in the late afternoon. In 1969 flocks of cranes were seen on twice as many days as in 1968: April 13, 17, 23–25, and 28. However, Canada geese were recorded migrating on proportionately fewer of the same days than in 1968 (only one-third: April 17 and 23). The largest number of cranes seen at one time was nearly 400 on April 28 and, as in 1968, this occurred in the late afternoon.

Not only were Canada geese seen on more days than cranes, but also the number of flocks of geese seen each day was greater. Canada geese are, therefore, more likely to have been responsible for the stream of echoes observed with radar for many hours each day in 1965.

Weather

Figure 3. Weather conditions in 1965. Weather maps for 4 of the 8 days in 1965 when movements of radar echoes took place, including three of the five "heavy"- or "medium"-density movements. On April 17, the first day movement was noted, there was high pressure over Washington State (Fig. 3a). On April 22 there was a ridge between high pressure systems to the SW and NE (Fig. 3b). On both days movements of radar echoes were "heavy".

Figures 3c and 3d show the extreme frontal conditions described in the text for April 20 and 28, 1965; movements of radar echoes were seen on both days that were of relatively "light" and "medium" density respectively. Compare Figure 3c with Figure 5c, and Figure 3d with Figures 5a and 5b.

Cross-hatching indicates areas of precipitation. H=high pressure area; L=low pressure area.

1965

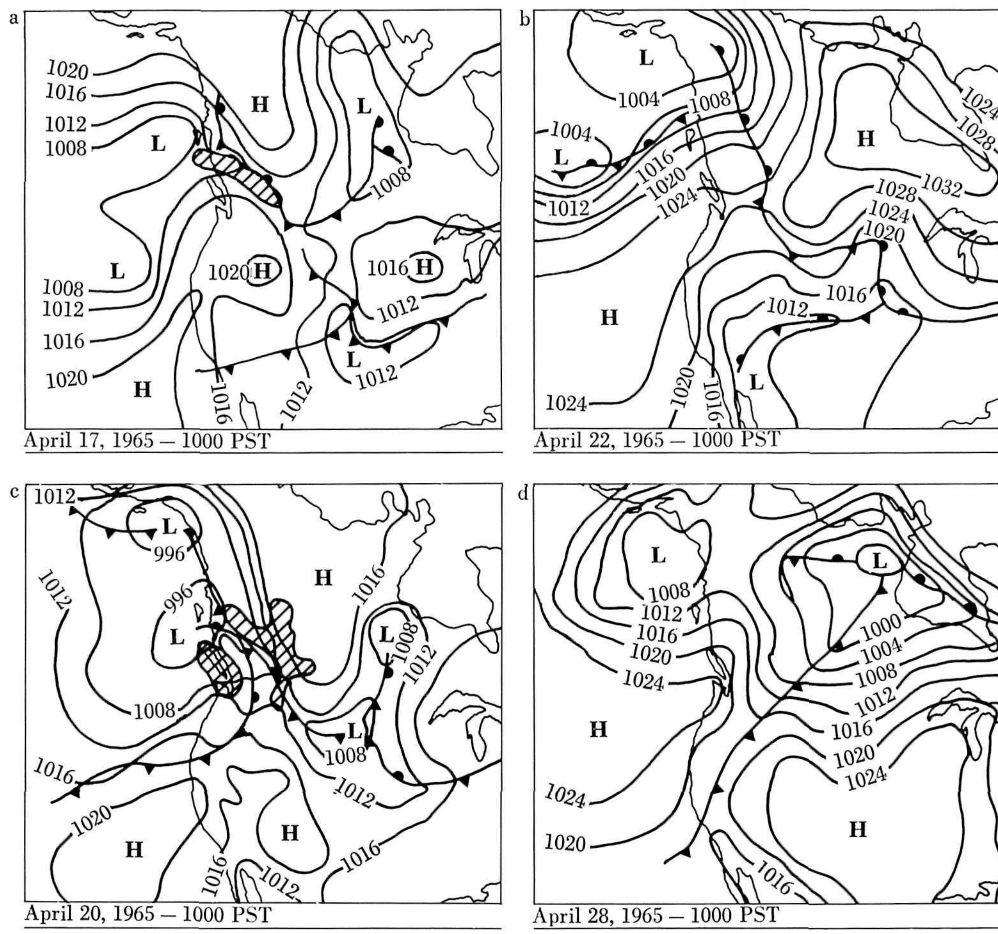
In 1965, according to the U.S. Weather Bureau's *Daily Weather Maps,* the period of movement of the radar echoes was characterized by varied weather. It was preceded by frontal conditions from April 14 to 16. Although the area was under the influence of a high pressure system on April 17 (Fig. 3a), when the first movement was recorded by radar, frontal or transitional weather again predominated from April 18 to 21. The region was again under the influence of a ridge of high pressure on April 22, 23, and from April 25 to 27, interrupted by frontal conditions on April 24 and 28.

The densest movements of radar echoes, those of April 17, 21, and 22 (Table 1), took place when the area was under the influence of high pressure systems (Fig. 3a and 3b), though on April 21 this followed immediately after a low pressure system.

In spite of the varied weather situation just described for April 1965, the surface wind at Omak, Washington, in the Okanogan River Valley south of the international boundary (Fig. 2), was no stronger than 12 knots at 2200 PST on any of the nights preceding days when movements of Canada geese were observed with radar. Likewise, the surface wind at Penticton was not greater than 9 knots at 0400 PST on any of the mornings when movements occurred. Unfortunately, aerological records of the strength of upper level winds are not available for these stations.

Cloud from frontal systems (Fig. 3c and 3d) is to be seen on the radar films themselves on two occasions: (i) from 2030 PST on April 19 until the early morning of April 21, cloud can be seen moving NE across the area, and (ii) from 0630 on April 27 until the afternoon of April 28, cloud can be seen moving slowly first ESE, then E, and finally NE. In both cases this cloud was, undoubtedly, accompanied by rain. It is, therefore, noteworthy that there was a "light" movement of radar echoes on April 20 and a "medium"-density movement on April 28. The cloud conditions recorded at Omak confirm that the weather was variable in

Figure 3



April 1965: there was total overcast on 5, and clear (or almost clear) skies on 7, of the 12 nights from April 16/17 to 27/28.

The more broad-front movements described earlier for April 21 and 22, 1965, may have been caused by eastward displacement of geese by the SW airstream around a low pressure system off the British Columbia coast on April 20, and the fronts associated with it that crossed the states of Oregon and Washington on that day (Fig. 3c).

It would seem, therefore, that (i) the bird movements observed with radar occurred with calm or only very light surface winds; (ii) while light winds might occur when the region was under the influence of high pressure systems, they did not occur exclusively then; (iii) while the densest movements recorded with radar occurred when the region was under the influence of high pressure or transitional systems; (iv) movements were also detected in frontal conditions. The clearest example of movement under frontal conditions occurred on April 20 (Fig. 3c), when extensive high-level broken cloud was seen on the radar display moving NE *simultaneously* with a line of bird echoes moving from the Okanagan Valley towards the Cariboo District (see also footnote *e* of Table 1).

It is not clear why movements were not also detected with radar on April 23, 25, or 27, 1965 (when the area was dominated by high pressure), but it is likely that the peak of the migration was by then over and, perhaps, the movements on each of the preceding days had temporarily depleted the area from which the birds originated.

1968

In April 1968 the weather was more settled than in April 1965, particularly during the main period of the movements by Canada geese. South of the international boundary there were high pressure conditions, with calm, on April 9, the day the first geese were seen (Fig. 4a), although a cold front was approaching from the NW. Conditions were unsettled as low pressure systems and fronts crossed the region April 10 to 16, and no geese were observed. From April 17 to 28 there were high pressure conditions almost continuously (Fig. 4b and 4c), and movements of geese took place on 4 of the first 6 days in this period, after which the migration seems to have been completed.

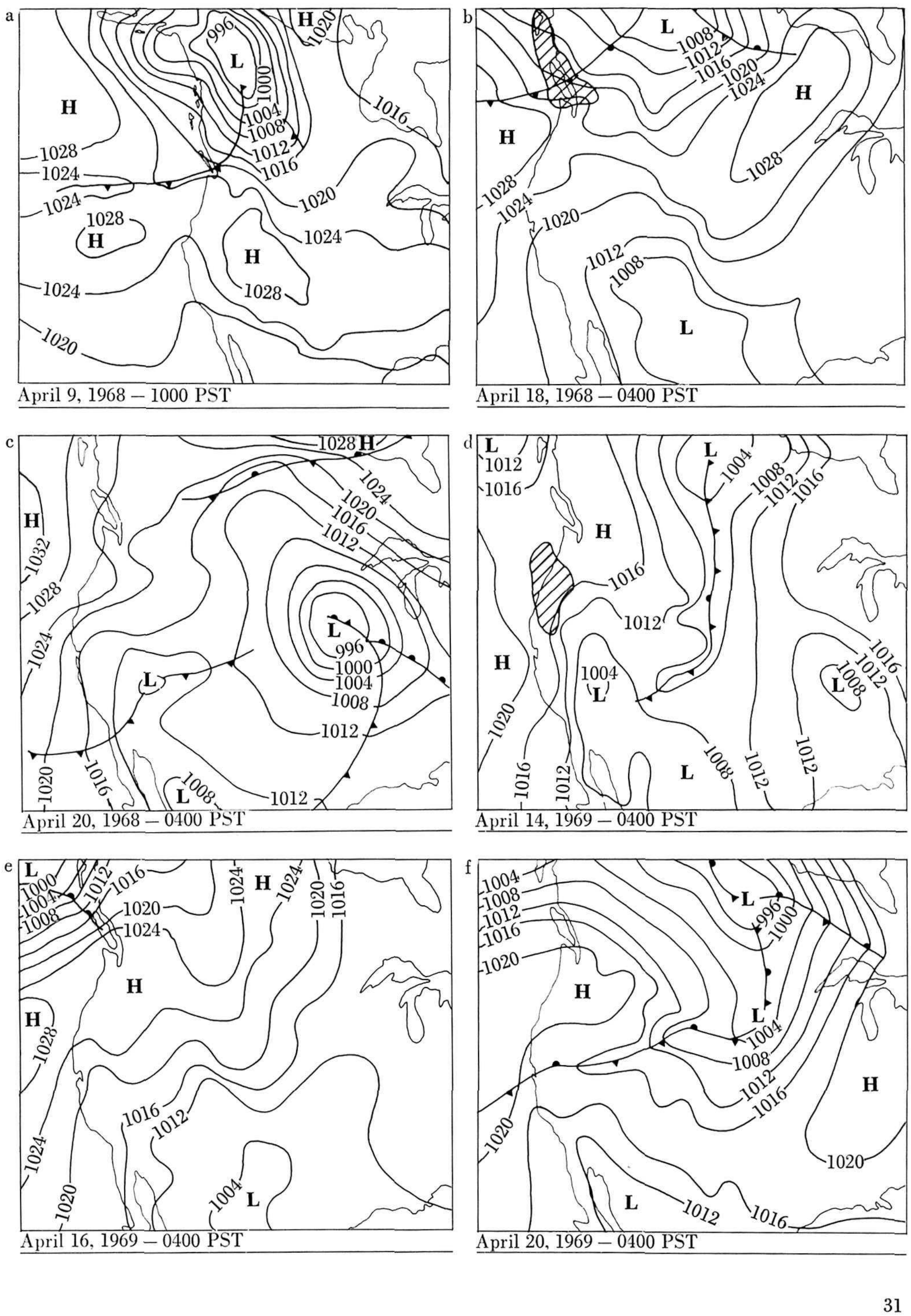
The surface wind conditions associated with the goose movements in 1968 were similar to those associated with the movements observed on radar in 1965. Thus, the surface wind at Omak at 2200 PST during the nights preceding days when movements occurred was calm on 4 of the 5 nights in 1968, and no more than 6 knots on the fifth night. Similar, calm conditions were recorded at Penticton at 0400 PST on the mornings of the movements. Cannings noticed that sometimes the upper level winds were southerly, sometimes northerly (Table 2).

In 1968 (unlike 1965 or 1969), the mean minimum temperature at Omak for the 5 nights preceding movements fell to just below the freezing point, but this evidently did not inhibit the migrating geese.

1969

In April 1969 the weather was more variable than in 1968 (Table 4), and quite similar to that of 1965. High pressure conditions from April 14 to 16, and again on

Figure 4



a: April 9, 1968 – 1000 PST; b: April 18, 1968 – 0400 PST; c: April 20, 1968 – 0400 PST; d: April 14, 1969 – 0400 PST; e: April 16, 1969 – 0400 PST; f: April 20, 1969 – 0400 PST

Figure 4. High pressure conditions associated with Canada goose movements in 1968 and 1969. Figures 4a–c show weather maps for 3 of the 5 days *in 1968 when Canada goose migration* was seen. Figures 4d–f do the same for 3 of the 8 days in 1969.

On April 9, the first day migration was noted in 1968 (Fig. 4a), there was high pressure over Washington State, but an intense low lay to the N and a cold front was approaching from the NW. No more migration was seen until April 18 (Fig. 4b), when similar conditions prevailed (see footnote *d* of Table 2 and compare with Fig. 5a).

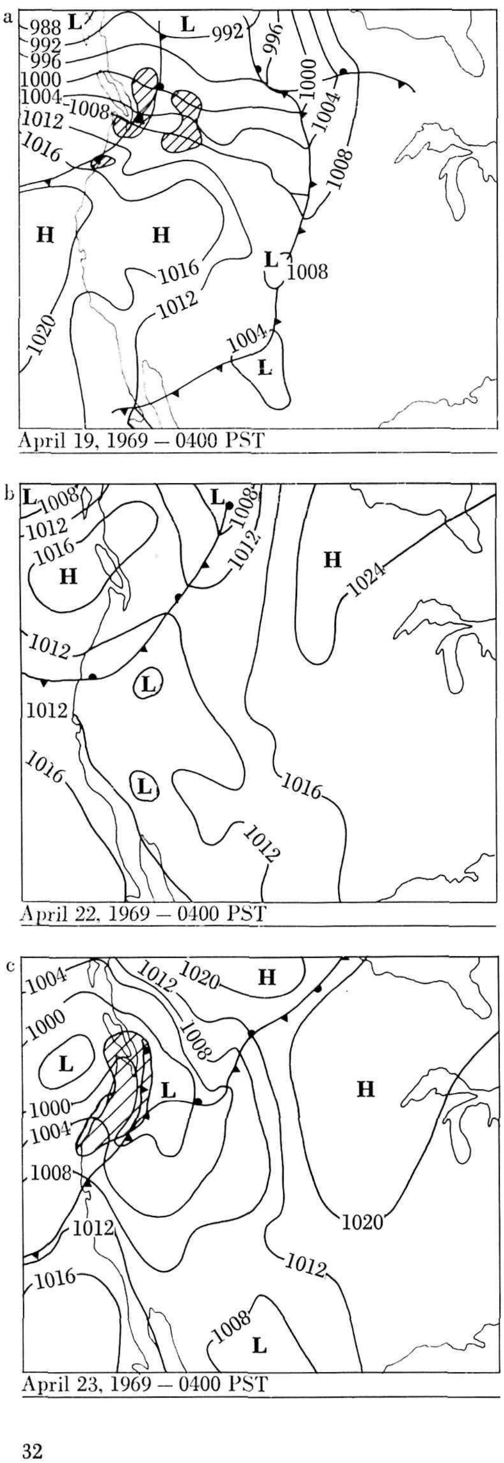
April 14 and 16 (Fig. 4d and 4e) were the *first 2 days that migration was noted in 1969.*

In all six maps Washington State was either in an elongated ridge between high pressure areas over the Pacific to the SW and over the continental landmass to the NE or E or, less frequently, had part of a high pressure area actually centred over it. Winds were usually light, but of variable direction. H = high pressure area; L = low pressure area.

Figure 5. Frontal conditions associated with Canada goose movements in 1969. Weather maps for 3 of the 8 days in 1969 when Canada goose migration was seen. On April 19 the winds were strong. The position of highs and lows is quite different in each map, although in each case a low in, or moving east from, the Gulf of Alaska is responsible for the front extending into high pressure areas. Figures 5a and 5b resemble Figure 3d in this respect. Figure 5c resembles Figure 3c.

Cross hatching indicates areas of precipitation. H=high pressure area; L=low pressure area.

Figure 5



April 20, were followed by frontal conditions on April 18, 19, 22, and 23.

The Canada goose movements of April 14, 16, and 20 (Fig. 4d, 4e, and 4f) occurred in high pressure conditions. Surface winds at 0400 PST were light or calm at Omak and Penticton on at least 6 of the 8 days when movements were observed (thus repeating the situation in 1965 and 1968).

However, the goose movements of April 19, 22, and 23 occurred in quite pronounced frontal weather (Fig. 5a, 5b, and 5c), and on April 19, in particular, the wind was nearly 25 knots in strength both at Omak and at Penticton (for the wind directions, see Table 4). The cloud conditions recorded at Omak confirm the evidence of the weather maps (Fig. 5): in 1969 there was 7/10ths cloud cover or greater at 0400 PST on 4 of the 8 days that Canada goose migration was observed.

The weather conditions associated with the 1969 visual observations therefore correlate rather better with the weather conditions concurrent with the 1965 radar observations than with the weather associated with the visual observations made in 1968, and so lend support to the view that the echoes on the radar films were produced by Canada geese.

Earlier, it was concluded that the movements of radar echoes in 1965 occurred with frontal as well as high pressure conditions. The 1969 observations show that the Canada goose movements through the southern interior of British Columbia are also not by any means restricted to periods of high pressure, or even transitional conditions, but may also occur in frontal and even low pressure conditions.

It should be pointed out that low pressure systems which come from the Pacific Coast are generally weakened during their passage across the coastal mountains, so that the inhibiting effect of eastward-moving low pressure systems upon birds migrating through the mountainous southern interior of British Columbia in April is probably sometimes less than weather maps might suggest.

Discussion and conclusions

The number of echoes that were detected by radar passing across an imaginary line at right angles to the southern Okanagan Valley on each day that movement was recorded in 1965 is shown in Table 1. The largest number of echoes detected on any one day was 62 during a period of 9¾ hours on April 22, 1965. Calculated on an hourly basis, the mean number of echoes passing over a point in the valley on that day was 6.4 per hour, which is also the highest *rate* recorded. On days with "heavy" movements of echoes, the mean hourly rate of passage varied from 5.1 to 6.4, while on days with "light" movements the comparable mean hourly rate of passage recorded by radar varied from 1.9 to 3.4 flocks per hour.

The flocks of migrating Canada geese observed by Cannings in 1968 and 1969 ranged in size from 10 to 300 birds. On the day on which the heaviest movement of Canada geese was recorded in 1968 (Table 3) the mean number of birds per flock was 175, but for the other occasions the mean flock size was 125 birds.

Taking a figure of 150 geese per flock as an average, and each radar echo as representing one such flock of geese, the largest number of geese detected by the radar on a single day in 1965 as they migrated up the line of the southern Okanagan Valley was 9,300. However, because the echoes detected by the radar were at altitudes above the elevations of the mountains surrounding the Okanagan Valley (i.e. above 6,000 feet), allowance must be made for flocks (such as those seen by Cannings in 1968 and 1969) which were flying within the valley itself. It is probably reasonable to conclude that a "heavy" movement would involve between 10,000 and 15,000 geese flying across the region in a day.

On the previous basis (a total of 269 detected echoes and 150 geese per radar echo) the total population of Canada geese detected by radar making this migratory movement between April 17 and 28, 1965, would appear to have been around 40,350. Allowing for flocks *not* detected by the radar, the population of Canada geese migrating along the southern Okanagan Valley appears to number between 50,000 and 75,000 birds.

Because of its short duration and narrow flight path, and the large number of birds migrating together, the movement of Canada geese (as observed with radar) is most unlikely to have involved Canada geese that breed in southern British Columbia itself. Rather, these characteristics suggest that the birds were headed for a destination far to the northwest. The race of *Branta canadensis* that breeds in the interior of the Yukon and in central Alaska is the lesser Canada goose (now known as *B.c. parvipes*) and this race winters in the interior valleys of the western United States, preponderantly in the states of Washington and Oregon. It is considered to migrate through the interior valleys of the western states and British Columbia. It is thought that a part of the population of one other race, *B.c. taverneri*, which breeds in west central and northern Alaska, also migrates through the interior. Therefore, it is reasonable to consider that the movements of Canada geese described in this paper can be referred to *B.c. parvipes* with, perhaps, some of *B.c. taverneri* travelling with them. It is interesting to note, therefore, that the 12-year average for the mid-winter inventory of lesser Canada geese in the Pacific Flyway is 102,000 birds, and that in the winter of 1964/65 the number is reported to have been 92,000 (*Pacific Waterfowl Flyway Report* No. 55, May 1966), a figure that is not markedly dissimilar to the upper estimate in this paper for the number of geese that migrated up the southern Okanagan Valley of British Columbia in April 1965 (75,000 birds).

Only once in either 1968 or 1969 (April 19, 1969) were Canada geese observed migrating by a ground observer at a time when the recorded surface wind was strong. All other movements were observed when there was calm at ground level, or surface winds were light. That, with the one exception, geese were not seen on migration when the surface wind was strong, or even moderately strong, suggests that none were air-borne under such conditions, and that almost all of the movements probably occurred when the *upper* winds were also light to moderate, but not strong. This would permit the birds to fly high, so that this radar station probably seldom fails to detect movements of this population of geese. The density of radar echoes was, however, almost always lower when the weather was frontal, compared with occasions when there were high pressure conditions (Table 1), and this could be due to fewer geese moving under frontal conditions. Alternately, migration may not be much hindered, but more flocks may fly within the valley out of radar view – behaviour which may explain why echoes were detected by radar only over the southern Cariboo on April 19, 1965, when conditions were frontal (see footnote *d* of Table 1), and why the heaviest of all the goose movements seen by Cannings occurred on April 18, 1968, when conditions were deteriorating (see footnote *d* of Table 2 and Fig. 4b).

The valleys of the southern interior of British Columbia are deeply cut into the surrounding mountains. In the winter months, particularly, cold air can stagnate in these sheltered valleys, while warmer winds cross the region above them. The recording of calm conditions on the valley floor may not then provide any indication of the strength of the upper winds. In the early spring it would be possible for geese to be misled by these conditions and to start migrating when the upper winds are nevertheless quite strong. It may be necessary partly to explain in this way the extremely close correlation of the occurrence of goose movements in April 1968 and April 1969 with calm ground conditions or only light surface winds, although the Okanagan Valley warms up rapidly in the second half of April so that mixing of valley and upper airmasses is more complete.

The light winds recorded at Omak and Penticton appear to be a true reflection of fairly wide spacing of the isobars, over the southern British Columbia–Washington–Oregon region as a whole, on many of the weather maps for the periods under consideration (Fig. 3a, 4c, 4d, and 4e), which is indicative that the winds were light over a wide area, not only in the floor of the Okanagan Valley. So, the main conclusions reached earlier about the weather conditions associated with these movements of Canada geese are probably valid.

It would appear that the Canada geese making the movements described from the radar films form a considerable hazard to aircraft flying below 15,000 feet in southern British Columbia during the second half of April in the daytime, particularly over the line of the Okanagan Valley as far north as Westbank, and along the line across the Nicola Lake country from Peachland towards Savona. An equivalent risk probably exists in the Okanogan River Valley south of the international boundary in Washington State. Aircraft travelling between Vancouver and towns in the Okanagan Valley, the Kootenays, and Kamloops, run a risk when crossing the southern Okanagan Valley, particularly if they stop at Penticton airport.

Because of its form and timing, the hazard created by these Canada geese is distinguishable from that due to other large birds migrating on a broad front in that it is highly predictable: it occurs in daylight only, in a narrow specified locality, for only 2 weeks in the spring of the year, and can be observed with radar. Consequently it is possible to take steps to minimize the hazard this movement presents. In particular, it might be wise to divert to Kelowna during this period those planes which are normally scheduled to land at Penticton or have Penticton as their destination. Also, it should be possible to provide private and commercial pilots with advance warning of the risks created by this particular migratory movement of many thousands of Canada geese.

Summary

1. Distinctive movements of medium-large, bright, echoes were detected with radar moving NNW up the southern Okanagan Valley of British Columbia on a narrow front in daylight hours between April 17 and 28, 1965. Where the lake curves to the NE near Peachland, the line of echoes crossed the mountains bordering the lake and fanned out across the Nicola Lake country WNW–N towards the Cariboo District. The birds involved were evidently flying at elevations above 6,000 feet and probably between 8,000 and 15,000 feet.

2. Observations made in the southern Okanagan Valley during the same period of the spring migration in April 1968 and April 1969 have identified the species responsible for the movement, with reasonable certainty, as the Canada goose, *Branta canadensis*, probably mainly of the race *parvipes*.

3. It is estimated that between 10,000 and 15,000 Canada geese may be involved on a day with "heavy" movement, and that between 50,000 and 75,000 geese may migrate up the southern Okanagan Valley during the 12-day period in the second half of April.

4. The Canada goose movements in 1965, 1968, and 1969 occurred when surface winds were light, or there was calm. Although this condition was met most frequently when there were high pressure conditions, the movements also occurred when frontal conditions extended across the region.

5. The radar observations suggest that during long-distance flights Canada geese fly over the mountains of southern British Columbia at a considerable altitude. Though flocks of geese flying below the level of the mountain ridges would not have been detectable, the radar station concerned probably detects all of the separate long-haul movements of this population of geese across the region in the spring. The hazard presented to aircraft by these goose movements is discussed.

Acknowledgements

The radar films were taken for the Associate Committee on Bird Hazards to Aircraft of the National Research Council of Canada by the personnel of the radar station, and the films are deposited at N.R.C. in Ottawa. Mr. M. S. Kuhring, Chairman of the Associate Committee, kindly allowed the senior author to carry out a study of the films. The Canadian Wildlife Service supplied substantial financial support during this study of the films, and this is gratefully acknowledged also. Dr. W. W. H. Gunn made a number of suggestions which led to several improvements in the paper. We also thank those Okanagan Valley naturalists who assisted in the collecting of visual observations of migration in 1968 and 1969.

Radar observations of bird movements in east-central Alberta

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Introduction

Since the discovery that modern surveillance radar routinely detects bird movements (Harper, 1957; Sutter, 1957; Houghton and Coultas, 1958; Tedd and Lack, 1958), there have been many radar studies of migration in Europe and North America (see Myres, 1964b, and Eastwood, 1967, for bibliographies). These studies have provided much new information about migration routes, the height of migration, the relationships between visible and actual migration, and correlations between the amount of migration and weather. Radar has also provided information of relevance to theories of migrational orientation (reviewed by Eastwood, 1967; also Bellrose, 1967; Evans, 1968a,b; Graber, 1968; Steidinger, 1968; Lack, 1969; Parslow, 1969). In spite of the extensive use of radar by ornithologists in the last decade, the major published studies of migration in North America are confined to coastal New England (Drury and Keith, 1962; Nisbet, 1963a,b; Drury and Nisbet, 1964; Nisbet and Drury, 1967a,b, 1968) and the northern Mississippi Basin (Bellrose and Graber, 1963; Hassler *et al.*, 1963; Bellrose, 1964, 1966, 1967; Graber, 1968).

In 1963 a radar study of bird movements was begun by the Canadian Wildlife Service in association with the National Research Council's Associate Committee on Bird Hazards to Aircraft. Since then, time-lapse films have been taken at various times of 24 different radar displays in eight provinces of Canada, at two radar sites in France, and at seven sites in the United States. The major purpose of this study has been to find means of reducing the number of bird-aircraft strikes (Gunn and Solman, 1968; Blokpoel, 1970); hence the methods of recording and analysing data have not always been those most suitable for some ornithological purposes, especially studies of orientational ability. However, many data of scientific interest have been accumulated. Reports on a number of radar studies of specialized types of bird activity are currently in preparation or in press. However, this is the first paper dealing with migration in general and based on our standard film-assessment procedures. We will describe the radar view of migration from one site in east-central Alberta and include an analysis of correlations between migration volume and weather and the effects of wind direction on migration direction.

Methods

Radar and filming

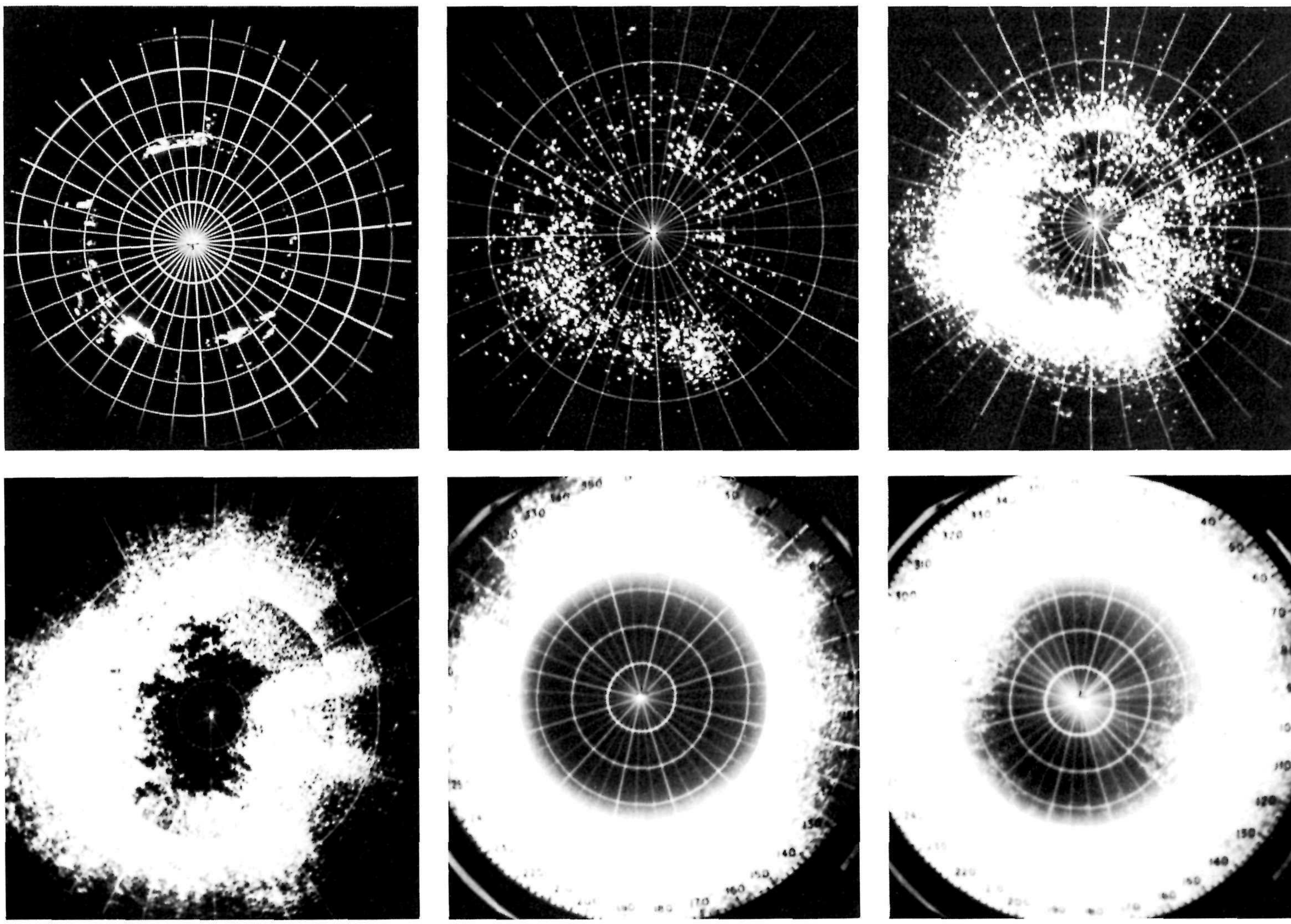
This paper is based on time-lapse filming of a radar display at Cold Lake, Alberta (54°24′N; 110°17′W) from April 1 to June 10, 1965, and from September 10, 1965, to November 30, 1966. Film was available for 11,077 of a possible 12,216 hours (90.7 per cent) in these periods. The radar was a high-powered L-band surveillance installation with a Plan Position Indicator (PPI) display showing an area with 70 nautical miles radius. Moving Target Indicator (MTI) circuitry was always used in the central part of the display (out to about 30 miles range). Beyond that range normal video was used.

Radar adjustments sometimes made very few birds visible in the central MTI area of the display (e.g., in Fig. 1, intensity levels 7 and 8). Also, an irregularly shaped area containing few bird echoes is visible near the centre of intensity levels 2, 4 and 6 in Figure 1. This occurred because the echoes from some of the birds flying above areas of intense ground clutter tend to be suppressed with the ground clutter by MTI systems. We have observed this phenomenon on a number of different types of radar. Besides the suppression of some echoes near the centre of the display by various radar adjustments and over areas of ground clutter, echoes from most birds within a few miles of the radar site were suppressed by Sensitivity Time Control (STC) circuitry.

The radar operated at five sweeps per minute. Initially, five frames of 16-mm film were exposed per minute, with one frame per sweep. Later, five frames were exposed every 2 minutes, with successive sweeps being recorded and skipped in sequence. A clock and a date card situated beside the PPI were included in every frame.

Some directional data from radars at Edmonton and Calgary, Alberta, Regina and Yorkton, Saskatchewan, and Beausejour, Manitoba, are presented for comparison. The last two sites (numbered 47 and 6 respectively on Fig. 7) had radars comparable to that at Cold Lake. The first

Figure 1. Intensity scale used to record the amount of migration at Cold Lake, Alberta. Reading from left to right and top to bottom, intensity levels 0, 2, 4, 6, 7, and 8 are shown. Range rings are at 10-n.m. intervals. Birds are not seen near the centre of the display because of performance characteristics of the radar.



three sites (numbered 18, 103, and 29 in Fig. 7) had 550-kw, 23-cm Air Traffic Control radars similar to those described by Richardson and Haight (1970).

Data recorded

In order to analyse the large amount of filmed radar data obtained at Cold Lake and at the many other sites studied, we had to develop a standard numerical recording system. We recorded bird activity visible with radar in terms of units which we called events. An event consists of a continuous flow of bird-echoes showing similar characteristics and behaviour over a period of time. Events may range from a few echoes making a local movement a few miles long to thousands of echoes in broad-front migration across the whole radar coverage area. Gradual changes over time in the intensity, direction, and echo size of a flight were not considered grounds for dividing the activity into separate events, but discontinuous changes in these parameters (indicating separate types of birds or types of movements) caused us to divide the flight into separate events. While there was unavoidably some degree of arbitrariness in this procedure, most activity fell naturally into separate events. Occasional arbitrary decisions about how to divide the activity into events had no resultant effect on the analysis of weather correlations with migration volume, because this analysis was based on the total amount of activity each night rather than on events (see below). The terms "event" and "movement" have equivalent meaning in this paper.

For each event, a wide variety of information was abstracted from the time-lapse film. General data included the date, the start, peak (greatest intensity), and end times, and indications of how precisely the start and end times could be determined. At each of the start, peak, and end times, the following were recorded: (i) the three most common echo sizes (measured on a more or less arbitrarily defined 7-grade ordinal scale), (ii) the position of the event on the radar display (either in certain octants or over the whole display), (iii) the proportion of the display containing bird echoes, and (iv) the type of movement, e.g. a local flight (defined here as beginning and ending on the display); a flight beginning on the display and moving out of range; a flight entering one side of the display and leaving the other; a roosting flight; a disoriented flight. Two other parameters, the mean direction of flight (estimated by eye to the nearest 10°) and the intensity of flight (see below), were recorded every hour throughout the duration of the event. All these data were placed on punch cards for machine analysis.

The intensity of each event was estimated each hour by eye in terms of the 9-level arbitrarily defined ordinal scale illustrated in Figure 1. The scale is based on the number of echoes per unit area at various distances from the centre of the display. At low intensities, the scale takes into account the progressive "thinning" phenomenon (Nisbet, 1963a) and the suppression by the radar of echoes close to the antenna. ("Thinning" is the progressive decline in number of echoes per unit area on the display as one moves from the centre to the periphery.) At moderate and high intensities, the display is saturated (completely covered with bird echoes) out to some distance from the centre. Hence, this distance is the basic density criterion for moderate and heavy movement. A slightly changed intensity scale was in use when the October and November 1966 films were assessed. These data have been omitted from the analysis whenever this change would require a different interpretation of the results. We are aware of the difficulties involved in obtaining quantitative radar observations (Nisbet, 1963a). We claim only that our data provide a rough estimate of migration volume measured on an ordinal scale. The accuracy of our density estimates is considered in the Discussion.

Data analysed

The Cold Lake radar data were subjected to various types of analysis using computers whenever appropriate. While all types of movements detected by the radar were recorded, the analyses considered here deal only with long-distance "migratory" movements, which were defined as those events that either entered the radar coverage area from out of range, or moved out of range, or both. Unless otherwise stated, we did not consider local movements (defined above). Totals of 873 long-distance and 309 local movements were recorded (exclusive of local roosting flights similar to those described by Eastwood *et al.*, 1962).

Basic data units

We used different basic units for different parts of the analysis.

(i) The description of migration is based on events.

(ii) The analysis of correlations between volume of nocturnal migration and weather is based on the total amount of activity each night rather than on individual events. To determine this total, all the migratory events (usually none, or one, but occasionally two) occurring on a given night within a given 90°-wide range of directions were allocated a single number representing the peak intensity of movement in that range of directions during the night. On those few occasions when there was more than one movement during one night in a single range of directions, the following procedure was used. When the events were of unequal intensity, the overall peak intensity was taken as that of the peak intensity of the strongest event. This procedure was followed because the relation of the lower intensity levels is such that, for example, simultaneous intensity-2 and intensity-3 events looked at together do not appear to show as many birds as a single intensity-4 movement. On nights when two movements did occur in the same direction range, both movements were usually of low intensity. When there were two events with the same peak intensity, the total intensity was taken as the peak intensity of each single event plus one (i.e. two intensity-3 events in a single directional category were assigned an overall intensity of 4). This reflects the general appearance of the display when two events of equal intensity occur simultaneously. On most nights there was no more than one movement in each of the direction ranges, and hence this summation procedure was not needed.

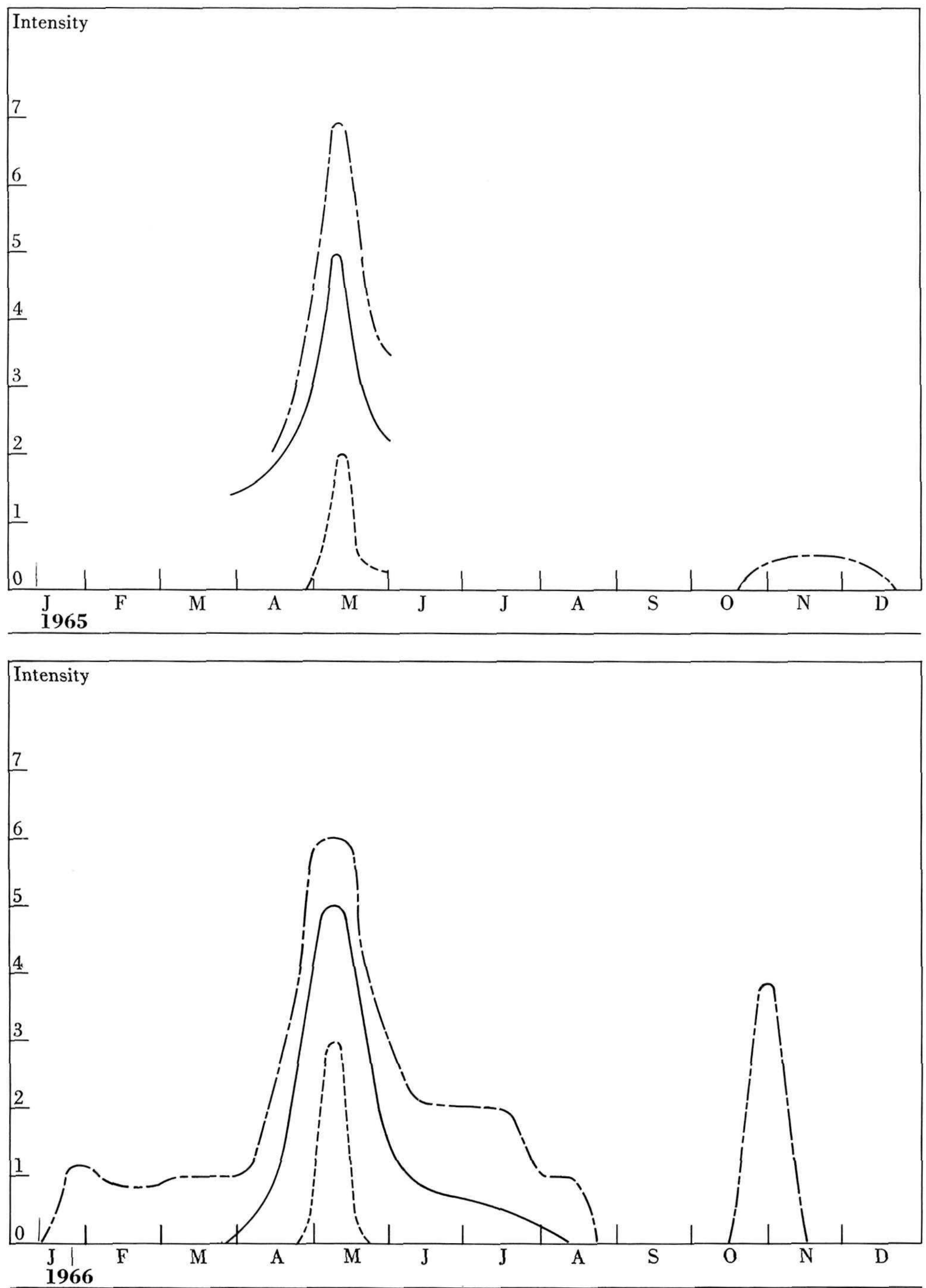
(iii) The analysis of the effects of wind direction on direction of nocturnal migration is based on "event-nights". An event-night is that portion of any migratory event occurring between sunset and sunrise. While an event reaching its peak intensity at night forms an event-night, the few events lasting more than 24 hours may include two event-nights.

Methods of analysing relationships between migration volume and weather

The statistical analyses of correlations between intensity and various weather parameters are based on the peak intensity of movement in the normal and the reverse directions of flight each night. Since we have not yet accurately determined the number of birds represented by each of the values in our intensity scale, procedures based on interval scales of measurement (such as calculating mean intensities or using multiple regression techniques) could not be used. Furthermore, because the normal intensity of nocturnal movement changes from one part of a migration season to another and from year to year, we considered it advisable to develop a modified intensity scale wherein each night's

Figure 2. Peak nocturnal intensities of NW (range W to N) migratory movement. The curves are smoothed 15-day moving quartiles representing the intensities reached on 25 (—-), 50 (——), and 75 (- - -) per cent of the nights. (See Methods section.)

Figure 2



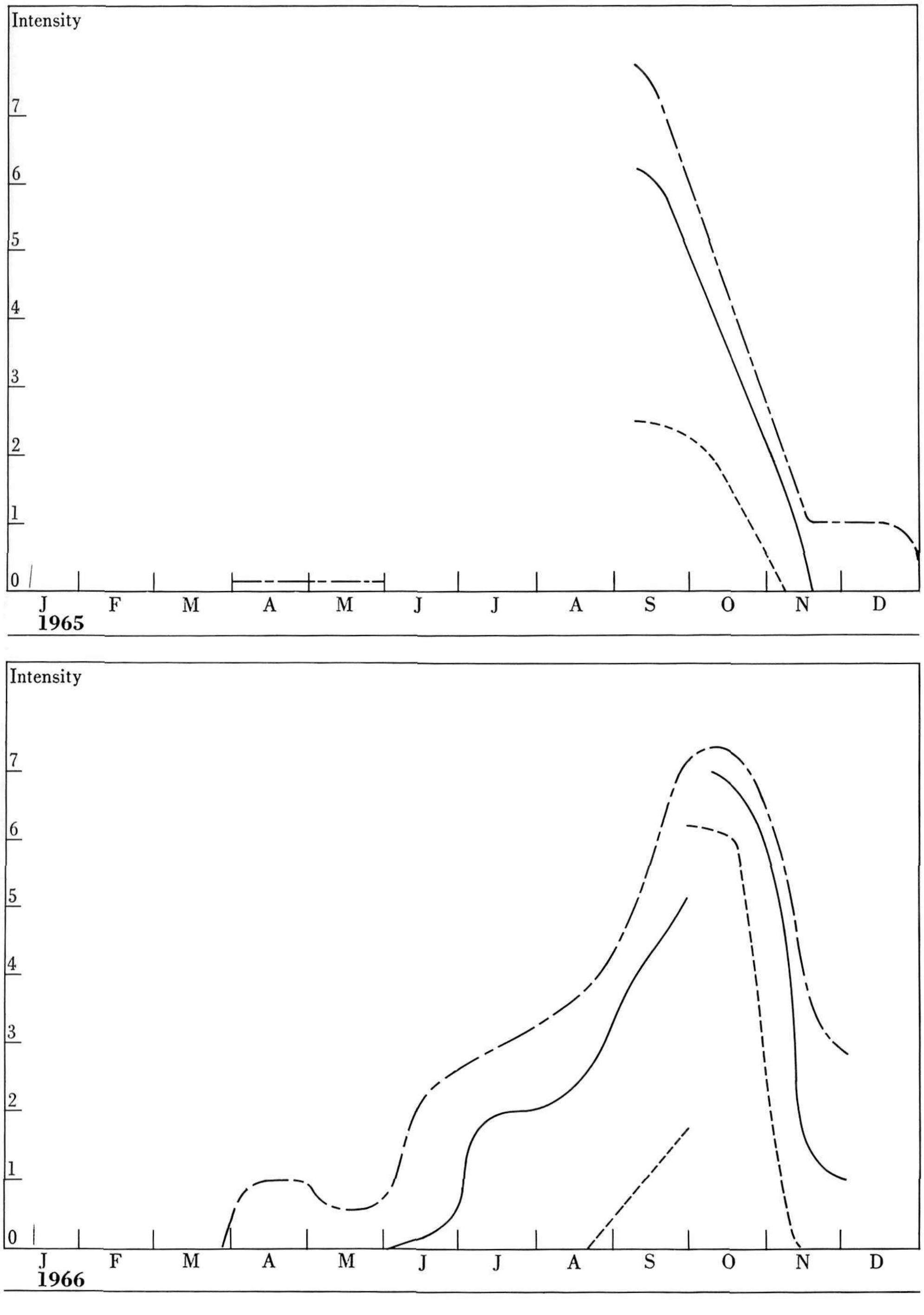
intensity was compared to the normal intensity at that time of year. The computer determined the intensity levels reached or exceeded on 25, 50, and 75 per cent of the nights in 15-day periods centred on each day. This was done separately for NW (range W to N) and SE (range S to E) movements. We drew smoothed "15-day moving quartile" curves through these values (Fig. 2 and 3) and recorded the intensities of NW and SE movement each night as being in the first, second, third, or fourth quartile. Our "moving quartiles" are analogous to a moving average, but are appropriate to an ordinal scale. Thus, a night whose intensity was in the first quartile had very little migration relative to the normal for that time of year, while a night in the fourth quartile had an intensity reached on less than one-quarter of the nights at that time of year. Points lying on a quartile curve were alternately (by date) assigned the quartile intensity values above and below the curve.

The analysis procedures applied to the normal migration situations (W to N movement in spring and E to S in autumn) differed from those applied to reverse migration (SE in spring and NW in autumn) and to winter movements. In the normal situations there were relatively few nights with no movement in the relevant direction and there were large shifts over a period of weeks in the normal intensity (Fig. 2 and 3). Hence the modified 4-level (quartile) scale was used, and the distributions of weather parameters at each of these 4 levels of migration were compared by nonparametric procedures (Siegel, 1956). In the reverse migration and winter situations, only a few nights had any movement. Hence the fourth quartile was usually the only one containing nights of non-zero intensity. Rather than use the quartile scale for these types of movement, we compared the distributions of weather parameters on nights having no movement with those on nights having some movement using the Mann and Whitney U-test (Siegel, 1956).

Relationships between intensity and the synoptic weather situation were examined

Figure 3. Peak nocturnal intensities of SE (range E to S) migratory movement. The curves are smoothed 15-day moving quartiles representing the intensities reached on 25 (—-), 50 (——), and 75 (- - -) per cent of the nights. The sudden increase in the apparent intensities at October 1, 1966, is an artifact of a changed intensity scale. (See Methods section.)

Figure 3



using the U.S. Weather Bureau Daily Weather Maps. In the analyses of correlations between intensity and individual weather parameters we used punch-card records of hourly observations of surface weather at CFB Cold Lake. Figure 10 indicates that most nocturnal movements began near sunset. Hence we chose weather conditions at sunset for use in the analysis. A preliminary examination of the data revealed that sunset temperature relative to normal and relative to that 24 hours earlier was better correlated with intensity than maximum or minimum temperatures relative to their respective normal values for the date in question. Hence the first two temperature parameters were used in the main analysis. The weather data were examined relative to nocturnal intensity of NW (range W to N) and SE (range E to S) movement in spring (April 15 to June 15), autumn (August 1 to October 31), and winter (December 1 to March 15).

Results

Figure 4. Mean directions of nocturnal long-distance movements through the year. Events with their hour of highest intensity during the night are included; the mean direction of each of these at the hour of peak intensity is presented. The left and right diagrams of each pair indicate low-intensity (1–4) and high-intensity (5–8) events, respectively. The relative lengths of lines show the number of movements in each direction proportional to the number in the most-used direction. The total number of events included is given below and to the right of each diagram.

General description of activity

The Cold Lake radar detects bird activity routinely out to 50 nautical miles from the antenna site and occasionally 70 n.m. away. This activity consists of local (beginning and ending within radar range) and long-distance (appearing from out of range, moving out of range, or both) movements. Both local and long-distance movements occurred throughout the year, although with varying frequency and intensity. Local movements were more common by day than by night in all seasons except winter (181 with hour of highest intensity by day vs 75 by night in spring, summer, and autumn; 14 by day vs 35 by night in winter). Long-distance movements were roughly as common by day as by night except in fall, when they were more common at night. However, the peak intensity of long-distance movements was on average higher at night than in the day except in winter, when they were nearly equal. This paper deals only with long-distance movements unless otherwise noted.

Virtually all long-distance movements visible on the Cold Lake radar are "broad-front movements". While there are several lakes in the area, the terrain is relatively flat and is devoid of pronounced valleys or rows of hills that might concentrate the birds. Although the predominant flight direction by both day and night is SE in fall and NW in spring, low-intensity movements in other directions are common in both seasons. In winter and summer both NW and SE movement occurs. Because there is long-distance movement throughout the year, migration seasons are hard to define. Figures 2 and 3 indicate the peak migration periods.

Direction of flight

Distributions of mean directions of long-distance nocturnal and diurnal movements at various times of the year are shown in Figures 4 and 5 respectively. In January and February the low-intensity movements (peak intensity 1 to 4) usually moved either north or south. Northward movements were more common than southward ones,

Figure 4

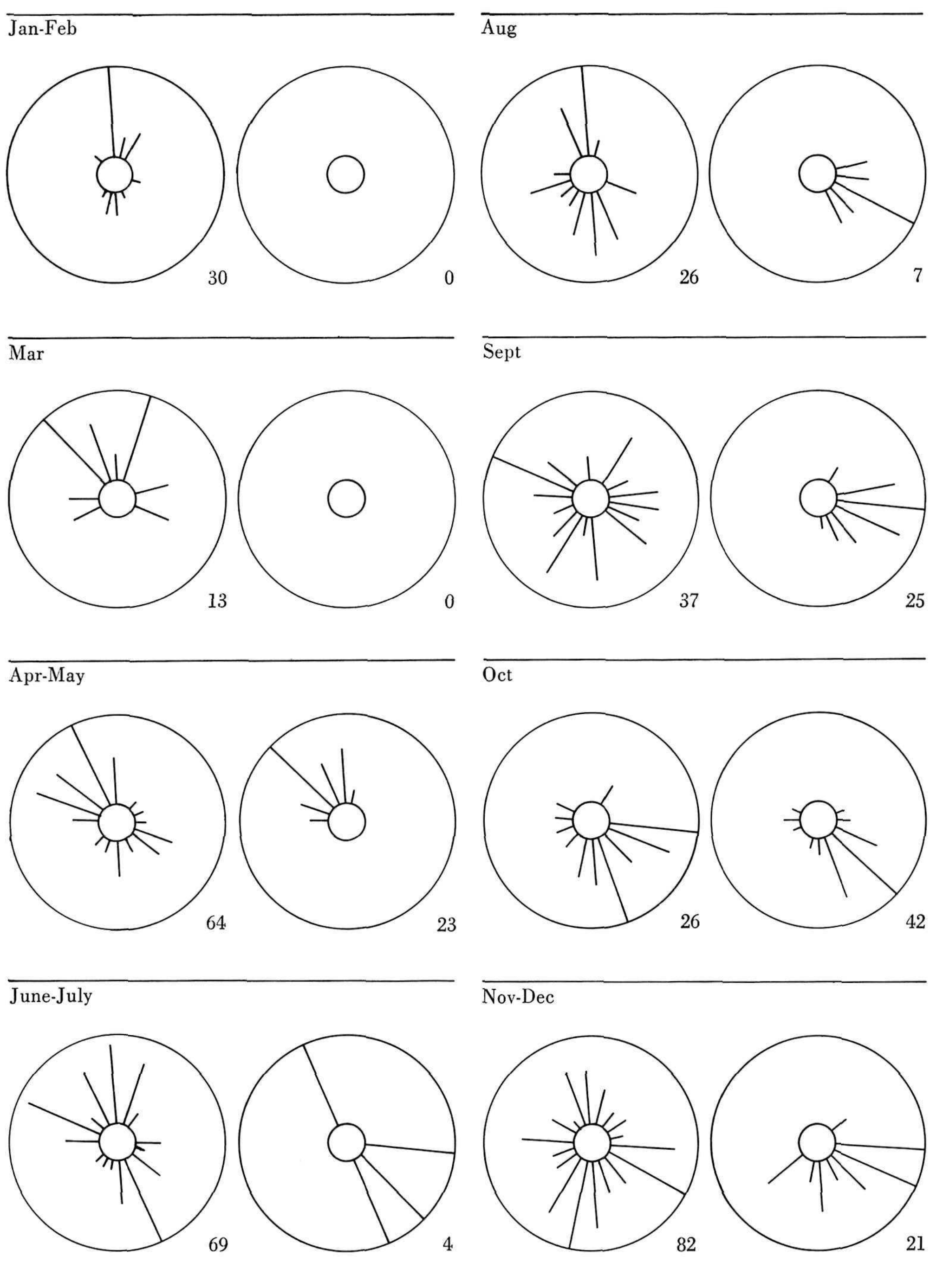
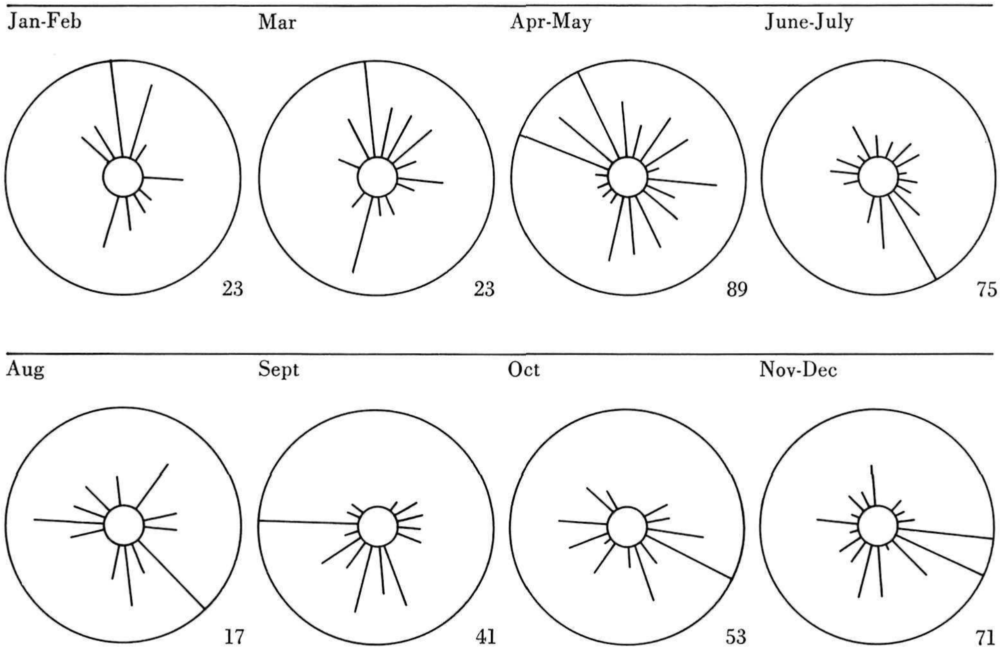


Figure 5. Mean directions of diurnal long-distance movements through the year. Events with their hour of highest intensity during the day are included. Before October and November 1966 (when the intensity scale was modified), 98 per cent of the events were of intensity less than 5. Hence, low- and high-intensity events are not distinguished. The relative lengths of lines show the number of movements in each direction proportional to the number in the most-used direction. The total number of events included is given below and to the right of each diagram.

Figure 5



especially at night. In March most (69 per cent) of the nocturnal movements were in the range of directions WNW–NNE, while the diurnal events were scattered over a wide range of directions. In April and May, many (66 per cent) of the low-intensity and virtually all (96 per cent) of the high-intensity (5 to 8) nocturnal events were in the range west to north; most of the remainder (70 per cent) were in the range east to south. The diurnal events were again more scattered. In particular, there was considerable movement in the NE as well as the NW and SE directions. In June and July, most of the movements were directed in either the range west to north or the range east to south. While diurnal activity was predominantly to the SSE, nocturnal activity was roughly equally split between NW and SE.

By August, the predominant direction was clearly SE. Although many low-intensity nocturnal events moved NNW, most of the high-density and about half of the low-intensity nocturnal events were in the autumn E to SSW range of directions. The low-intensity movements tended to go SSE, while the stronger events went E and ESE. A similar situation occurred in September. In October both low- and high-intensity nocturnal events usually went SE. The E and ESE to SE shift in the predominant direction of high-intensity events from August and September to October occurred in both 1965 and 1966 and was statistically significant ($P<.01$ for the hypothesis that the distributions are the same; Kolmogorov-Smirnov test modified for circular distributions — Batschelet, 1965). Diurnal events from August to October had a wide scatter of mean directions. In November and December there was a wide range of directions by both day and night, but movements in the range east to south were especially common.

Figures 6 and 7 show the mean directions of long-distance nocturnally peaking high-

Figure 6. Distributions of mean directions of high-intensity (5–8), nocturnally peaking, long-distance movements in spring (April–June) at five prairie radar sites. The relative lengths of lines show the number of movements in each direction proportional to the number in the most-used direction. The total number of events included is given on the figure.

Figure 7. Distributions of mean directions of high-intensity (5–8), nocturnally peaking, long-distance movements in autumn (August–October) at six prairie radar sites. The relative lengths of lines show the number of movements in each direction proportional to the number in the most-used direction. The total number of events included is given on the figure.

Figure 6

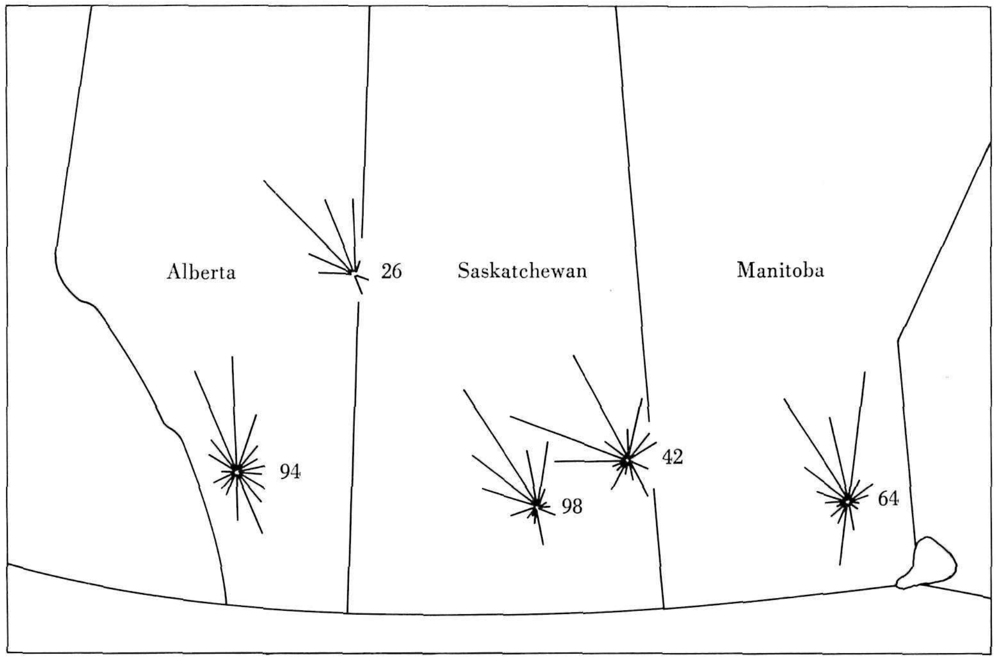


Figure 7

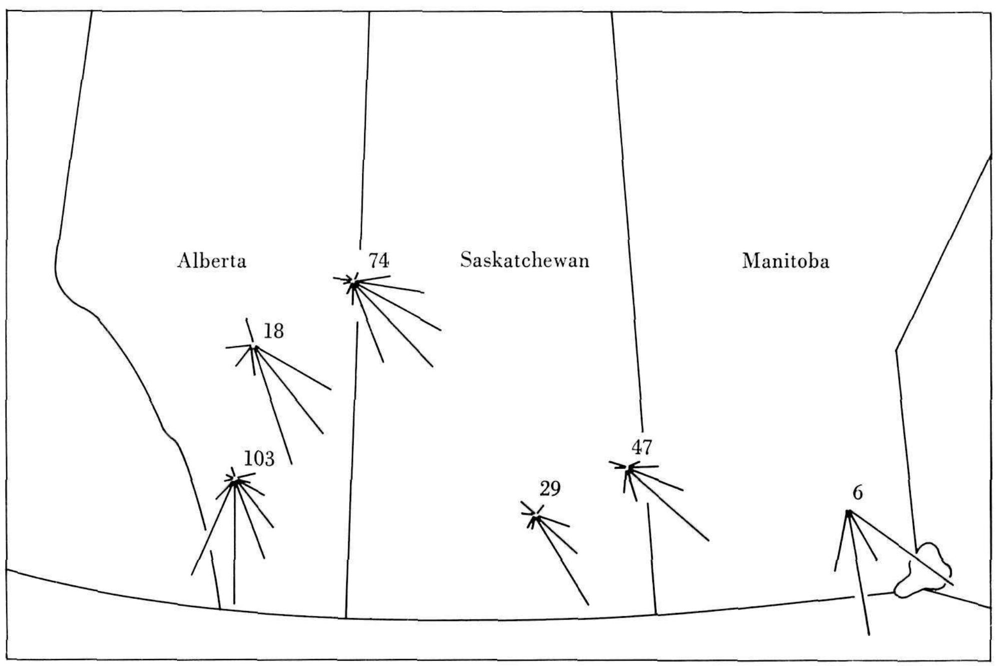
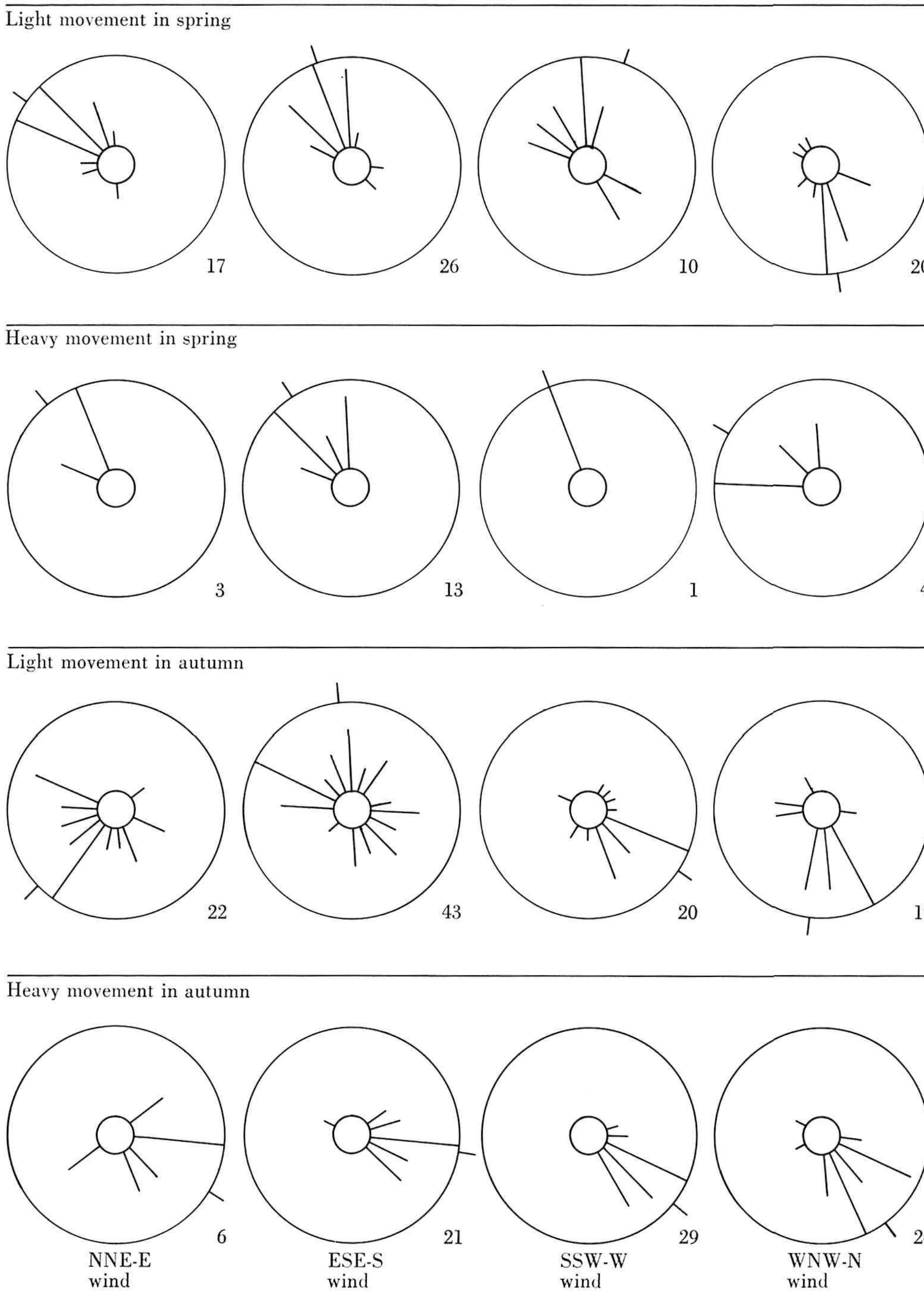


Figure 8. Mean directions at hour of peak intensity of nocturnal light (1–4) and heavy (5–8) long-distance movements in spring (April 1 to June 15) and autumn (July 16 to October 31) with various wind directions. The radial line outside each circle indicates the overall vector mean direction. The relative lengths of lines show the number of movements in each direction proportional to the number in the most-used direction. The total number of events included is given below and to the right of each diagram.

intensity events at Cold Lake and several other prairie sites in spring and autumn respectively. It is apparent that the NW–SE axis of migration observed at Cold Lake is typical of sites in central Alberta and in Saskatchewan. In SE Manitoba, spring migration is more typically to the N than the NW. Data are too sparse to show whether autumn migration in SE Manitoba is more to the south than at sites farther west. At Calgary, Alberta, 300 miles SW of Cold Lake, migration seems to be predominantly on a N–S axis.

Figure 8 and Table 1 show the influence of wind direction on the direction of nocturnal migration by seasons. *Low-intensity movements* tended to be directed downwind. In autumn, small movements with NW winds were nearly always downwind (expected direction), while with SE winds both forward and reverse movements occurred. *High-intensity movements,* on the contrary, were nearly always NW in spring and SE in autumn. Hence, the direction and the amount of variability in direction were less dependent on wind direction in high-intensity movements than in low-intensity movements. There was, nevertheless, some indication that wind direction affected the direction of autumn high-intensity movements. The vector mean direction of the 14 autumn movements occurring with winds in the range NNW to NE was 159°, while that of the 17 movements with SSE to SW winds was 114°. However, there was wide variability among the mean flight directions and among directions of individual echoes within movements.

Figure 8



Changes in direction during a movement

The data presented above refer to the direction of each event at its hour of greatest intensity. However, there are often shifts in mean direction from the start to the end of a movement. Figure 9 shows that by both day and night and throughout the year, the direction of an event rarely shifted by more than 30°. Examination of Figure 9 suggests that with the possible exception of autumn

Table 1
Directions of nocturnal long-distance movements in spring and autumn

Wind direction	Time*	Spring						Autumn					
		Intensity 1–4			Intensity 5–8			Intensity 1–4			Intensity 5–8		
		Mean, °	AD, °	N	Mean, °	AD, °	N	Mean, °	AD, °	N	Mean, °	AD, °	N
NNE to E	1	300	41	18	325	16	4	223	51	21	143	50	4
	2	306	34	17	322	18	3	228	55	22	120	51	6
	3	324	23	7	327	20	5	199	58	17	115	—	1
ESE to S	1	339	35	26	323	23	12	358	71	46	97	46	19
	2	337	35	26	327	56	13	353	72	43	100	34	21
	3	334	34	18	337	20	10	31	66	23	104	33	20
SSW to W	1	20	61	8	335	—	1	136	44	19	126	21	29
	2	21	64	10	335	—	1	126	45	20	128	20	29
	3	97	69	12	345	—	2	131	44	18	137	23	29
WNW to N	1	170	56	21	307	29	5	176	51	22	142	41	28
	2	169	50	20	304	32	4	189	49	19	142	37	24
	3	179	69	17	255	—	2	156	40	13	145	40	15

Wind directions are surface wind direction at CFB Cold Lake at the time of the start, peak, and end of the event night.
Spring and autumn are April 1 to June 15 and July 16 to October 31.
Mean is the vector mean of the movement means.
AD is the mean angular deviation ($=\sqrt{2(1\text{-r})}$, where r is the ratio of the mean vector length to the maximum possible mean vector length—Batschelet, 1965). This measure is comparable to the standard deviation of a normal distribution, e.g. the mean ± 1 AD includes about 67 per cent of the values.
N is number of event-nights.

*Time:
1 Starting time of event-night or sunset, whichever was later. Events beginning after midnight were not included.
2 Peak intensity hour.
3 Ending time of event-night or sunrise, whichever was earlier. Events ending before midnight were not included.

Table 2
Change in mean direction between start and end of nocturnal long-distance migration-season events

Season	Intensity	Shift (Mean ± St. Dev.)*	N	Significance†
April–May	1–4	+17.1 ± 24.6°	55	$P<.001$
	5–8	+30.0 ± 31.6	9	$P\simeq.02$
August–November	1–4	+9.0 ± 22.7	67	$P\simeq.002$
	5–8	+16.2 ± 35.4	39	$P<.01$

*Positive shifts clockwise; negative counter-clockwise.

†Testing hypothesis that mean shift is zero using 2-tailed t-test.

nocturnal events, shifts clockwise are more frequent and larger than shifts counter-clockwise. This possibility was clearly confirmed (in autumn also) by the analysis of migration season events presented in Table 2. The table indicates that for both low- and high-intensity events in both spring and fall, the mean shift between starting and ending times is significantly different from zero and in the clockwise direction. Because high-intensity movements tended to last longer than those of low intensity (see below), one might expect greater directional shifts on the average with high-intensity events. This appears to be the case in both spring and autumn, but only the autumn difference is significant ($P\simeq.8$ and $P<.01$ respectively for hypothesis that the shifts are equal; Kolmogorov-Smirnov 2-sample 1-tail tests — Siegel, 1956).

The data in Table 1 permit us to examine the mean directions of movements early and late in the night when only those occasions within certain wind-direction ranges are considered. With various combinations of season, surface wind direction, and intensity of migration, both clockwise and counter-clockwise shifts are seen. Heavy spring movements with SE (following) winds show a clear clockwise shift from early to late in the night, but heavy autumn movements with NW wind do not. Of the eight situations with side winds (NNE to E and SSW to W) relative to the normal NW–SE axis of movement, three show some degree of shift of their direction of movement *into* the wind. These three cases are light spring movement with NNE to E winds and heavy autumn movement with both NE and SW winds. The other five cases show no change, have very few data, or are not directed on the NW–SE axis of movement and so are not being subjected to side winds. While the three cases of shift in mean direction into the wind might be taken as evidence of overcompensation for lateral wind drift, the shifts are small and inconsistent. Furthermore, differences between wind direction at the surface and at the level of flight are frequent enough that serious biases may result from the use of surface data. Unfortunately, upper wind data were not available at frequent inter-

Figure 9. Distributions of change in direction from first to last hour of long-distance movements, plotted as number of events with a given change in direction relative to number of events with no change. Movements with diurnal and nocturnal peak intensity hours plotted with broken and solid lines, respectively.

Figure 9

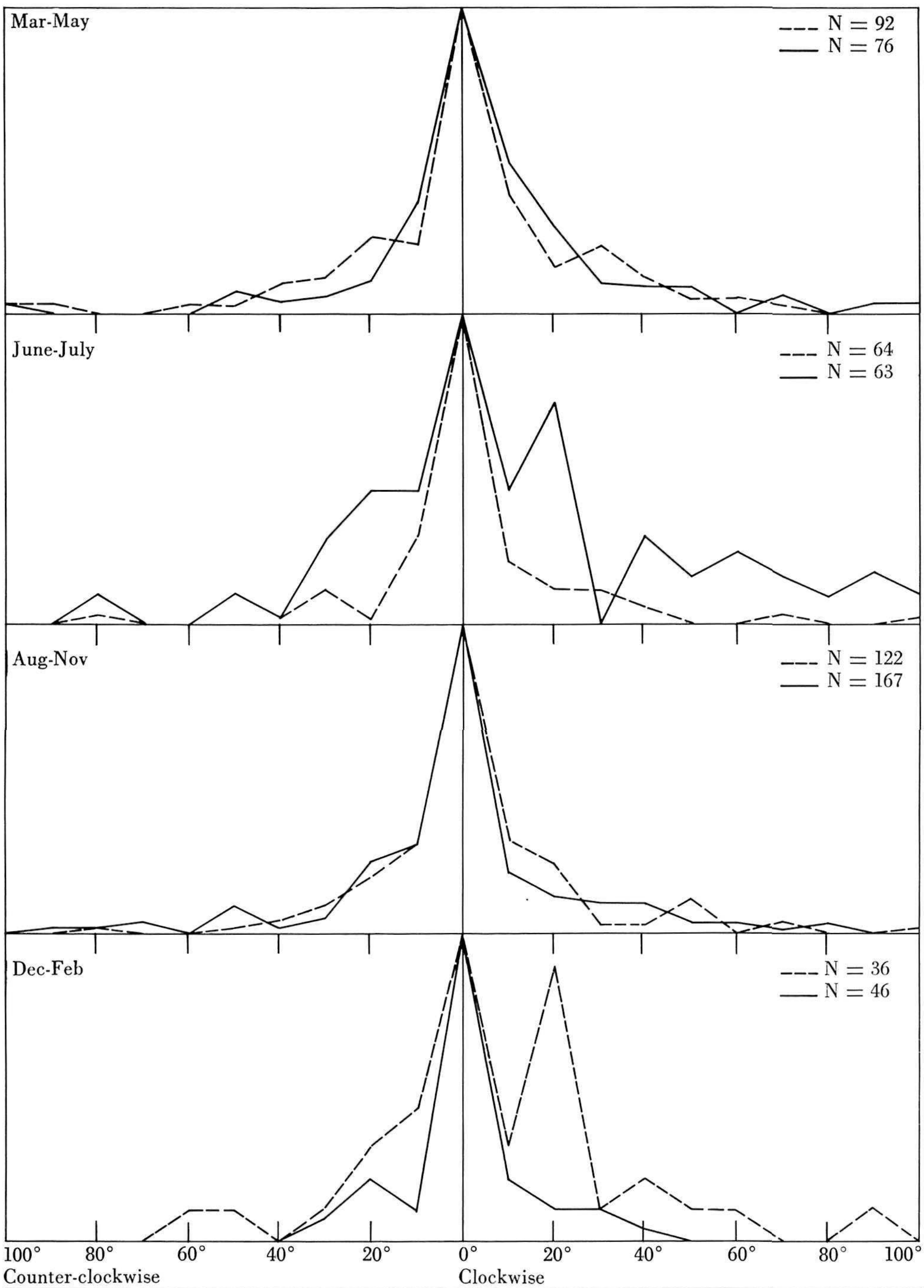
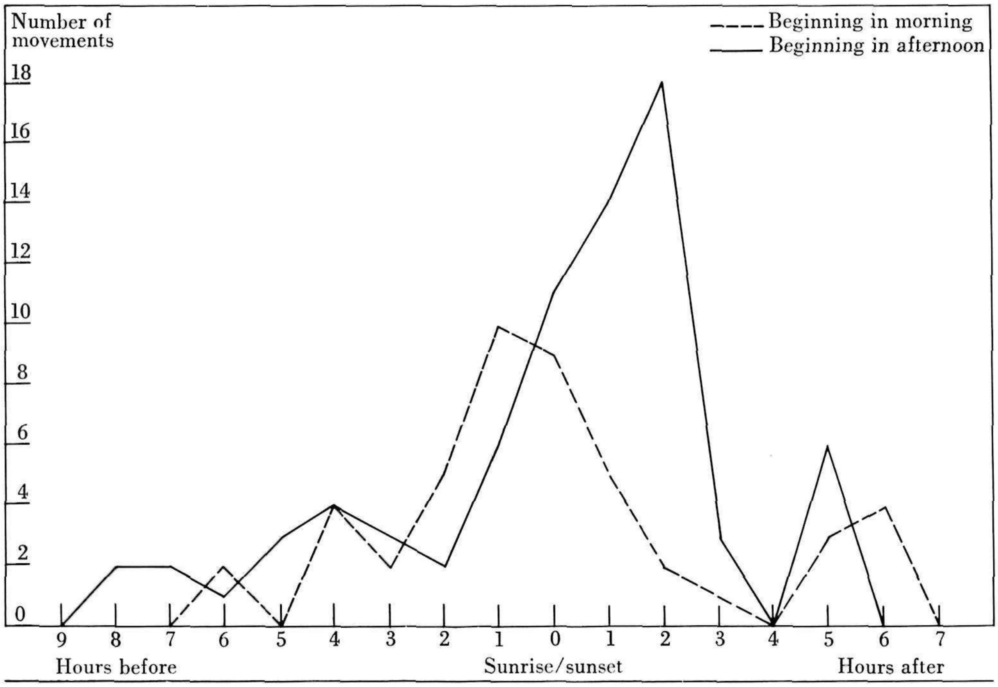


Figure 10. Distributions of starting times of migratory movements in April to November beginning within radar range. Starting times of movements beginning in the morning and afternoon are plotted relative to sunrise and sunset, respectively.

Figure 10



vals, and so could not be used to evaluate the effects of wind shifts during the course of bird movements.

Intensity of long-distance movements

The amount of diurnal migratory activity at Cold Lake was usually low, and it varied much less through the year than did the amount of nocturnal movement (Richardson, 1970). Excluding the data for October and November 1966 (when the interpretation of the intensity scale was changed), 73 per cent of the 330 diurnally peaking events had a peak intensity of 1 and only 1.5 per cent had a peak intensity above 4. In contrast, 42 per cent of the 388 nocturnally peaking events had a peak intensity of 1 while 19 per cent had a peak intensity above 4. The amount of nocturnal activity varied markedly through the year. From November to April, the median intensity of nocturnal events was little or no greater than that of diurnal events. In June, July, and November the median nocturnal event was only slightly stronger than the median diurnal one. However, in May and in August through October, the median intensity of nocturnal events was much greater than that of diurnal events. The heaviest migration of the year occurred in September, followed by May, October, and August in that order.

Figures 2 and 3 indicate the yearly variation in peak nightly intensities in the two main directions of movement. The prevalence of NW over SE movement in winter is obvious. A progressive decline in the amount of NW movement from May to October contrasts with a progressive increase in the amount of SE movement from March to September. The frequency of moderate-intensity movement in both directions during the summer is noteworthy.

During the migration seasons, the intensity of movement was usually relatively low in the early afternoon. It increased sharply from just before sunset until about 2 or 3 hours after sunset and then more gradually to reach a peak usually before or near midnight. There was a parallel seasonal variation in sunset time and peak time. On the average (but not on all nights), the intensity was maintained at or near its peak until well after midnight, especially in autumn. A gradual decline in intensity until dawn then occurred. During the migration seasons, little or no increase in the typical intensity was apparent at dawn.

During the winter and to a lesser extent during the summer, an increase in intensity on the average did occur at dawn. This was followed by a gradual decline through the day. Particularly in summer but also in winter, an increase in intensity occurred again at sunset.

Further details of hour-to-hour changes in intensity are given in Richardson, 1970.

Timing of long-distance movements

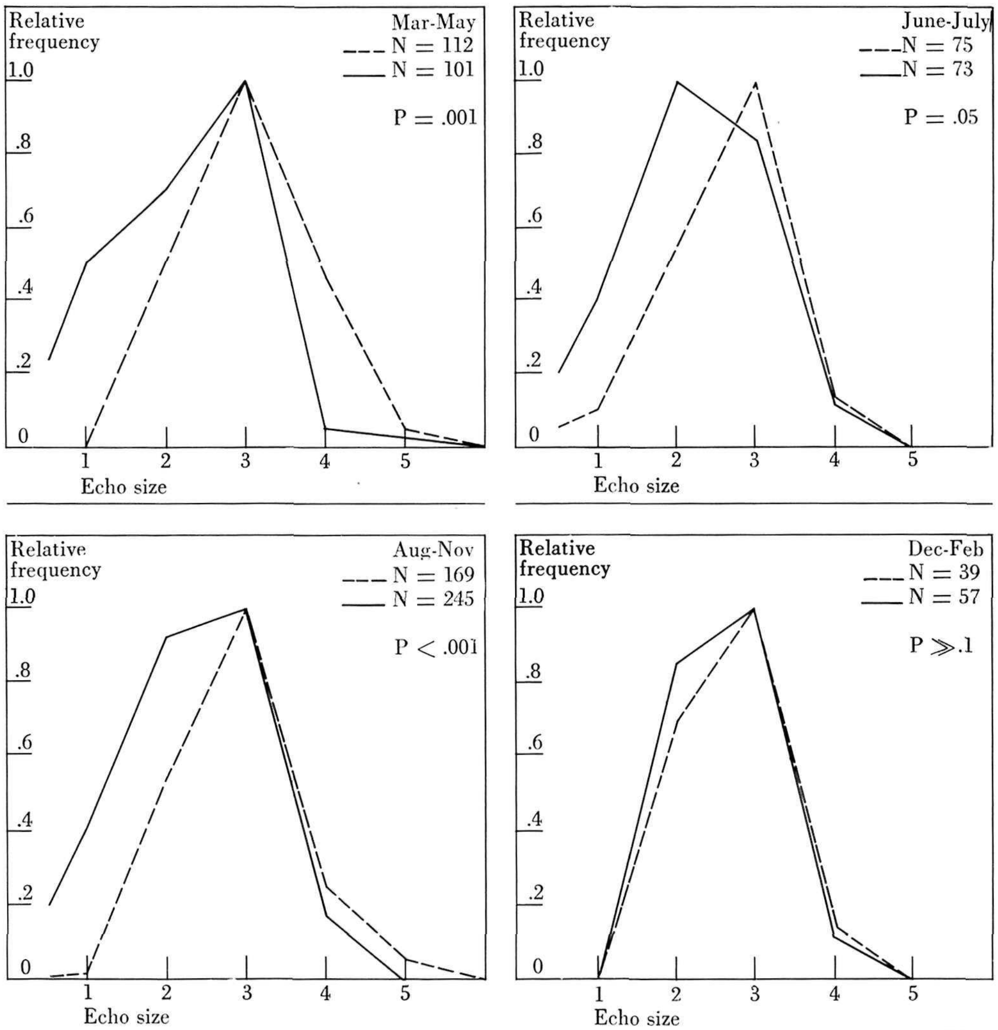
Most events which reached their peak intensity during the day began within a few hours of sunrise, but some began in the afternoon. In contrast, nocturnally peaking events usually began between 4 hours before sunset and 2 hours after sunset. Most heavy (intensity 5–8) nocturnally peaking events began before sunset (42 of 59); 11 began between sunset and midnight; and only 6 began between midnight and sunrise.

The above analysis of *starting times* is based on all long-distance events; that is, it includes those which entered the radar coverage area from out of range as well as those movements which began within range. When only the latter are examined, the close relation of the starting times of diurnal and nocturnal movements to sunrise and sunset respectively can more clearly be seen (Fig. 10). These nocturnal movements tended to begin at or after sunset while diurnal ones usually began at or before sunrise.

Almost all (73 of 78) the heavy-intensity (5–8) events peaked at night. Most peaked between 1 hour after sunset and 3 hours before sunrise. Low-intensity (1–4) events reached their peak intensities at all hours, but with concentration at and just after sunrise and sunset.

Figure 11. Proportion of the diurnally (- - -) and nocturnally (——) peaking migratory events having each echo size as the most frequent size. The number of events having a given echo size as the most frequent size is plotted relative to the number of events recorded with the seasonally most common size. Total number of movements and the probability that the diurnal and nocturnal distributions are identical (2-tailed Kolmogorov-Smirnov test) are given.

Figure 11

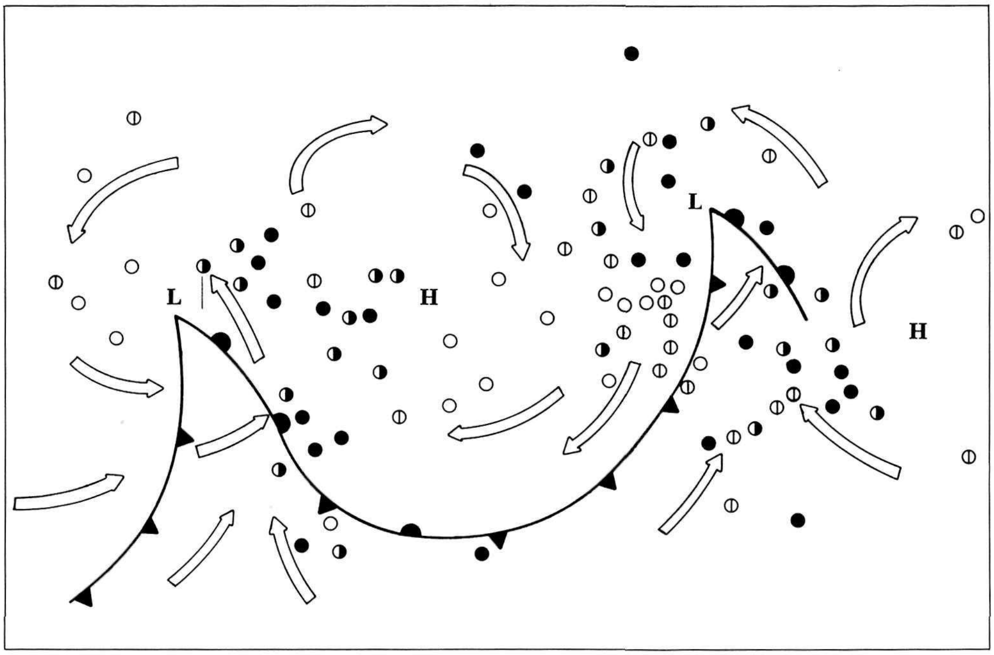


Nearly all (96 per cent) diurnally peaking events ended by 3 hours after sunset. Most (76 per cent) of the low-intensity events peaking at night ended by sunrise. High-intensity nocturnally peaking events almost never ended before midnight (1 of 47 compared to 86 of 276 low-intensity nocturnal events), and most ended near sunrise or during the day. Thus, heavy nocturnal events tended to end later than smaller ones.

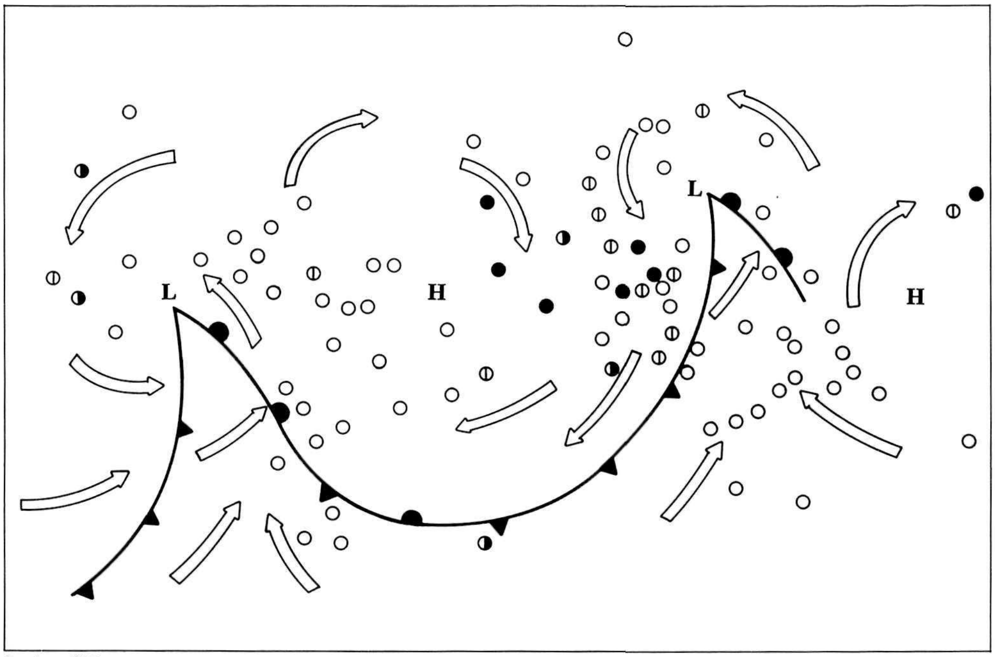
In all months, high-intensity events had longer intervals between their start and their peak times and had longer durations than low-intensity movements ($P \ll .001$ in each case for hypothesis that interval was independent of intensity; Kolmogorov-Smirnov 2-tail tests on intensity 1–4 vs 5–8 events). Median intervals from start to peak for low- and high-intensity events were 2 and 5 hours respectively; median intervals from start to end were 5 and 18 hours. Winter events reached their peaks

Figure 12. Intensity of nocturnal movement in spring (April 15 to June 15) at Cold Lake, Alberta, with different synoptic weather situations. Each circle represents the peak intensity of movement on one night. The circles are plotted on a generalized weather map in the position most representative of the radar site relative to the prevailing synoptic situation on that night (see text). Low and high pressure systems, warm (semicircles) and cold (triangles) fronts, and wind direction are indicated. Intensity of migration is indicated on a 4-level scale by increasing darkness of the circles. For forward movement, the quartile scale is used; for reverse movement, the original 0 to 8 scale with intensities 3 to 8 combined is used.

Figure 12



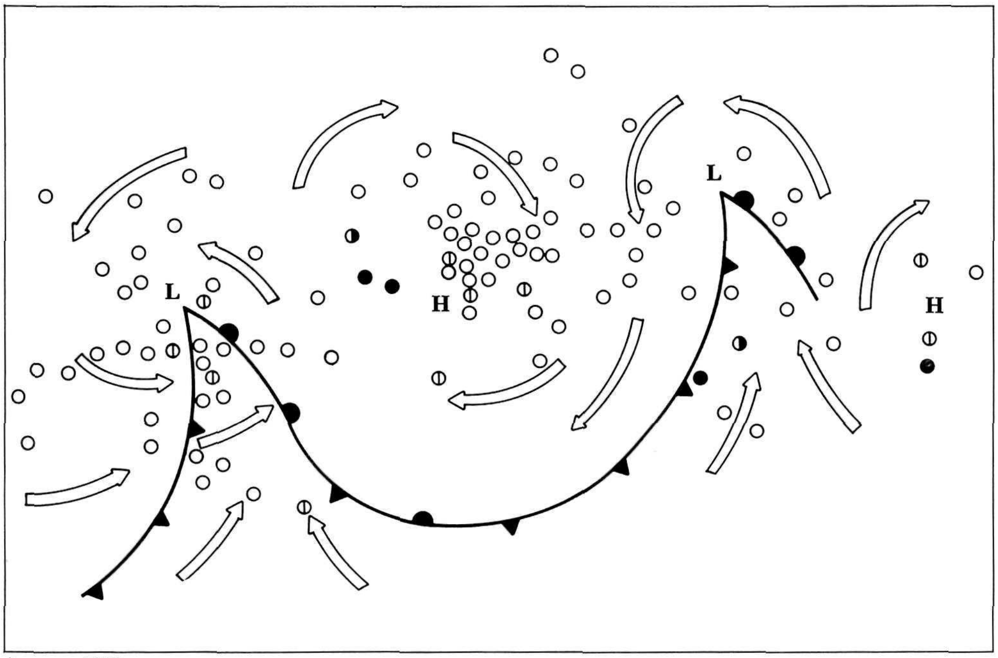
Spring NW movement



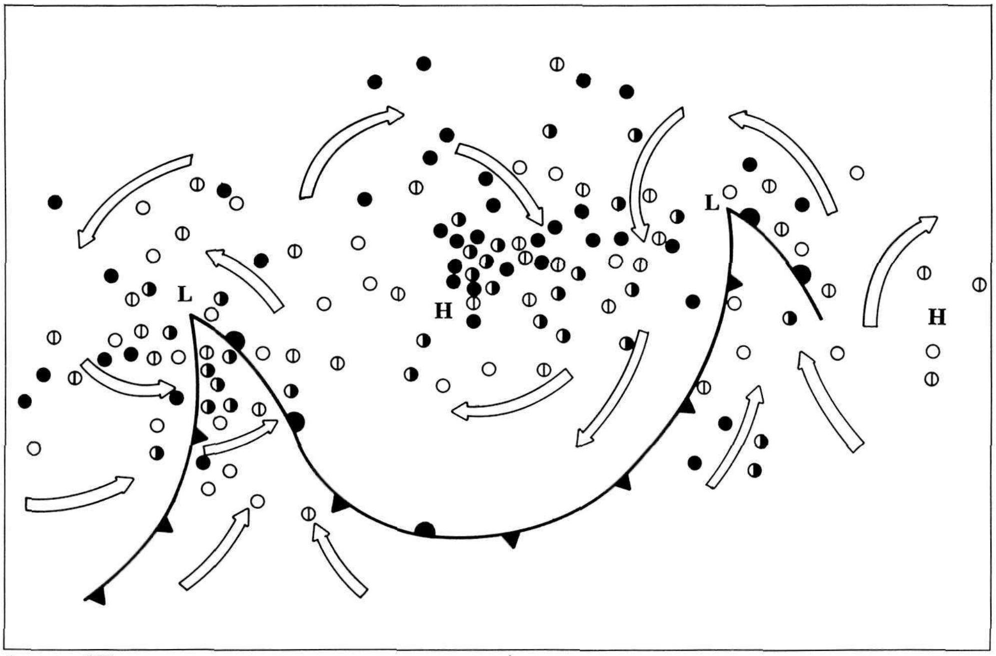
Spring SE movement

Figure 13. Intensity of nocturnal movement in autumn (August 1 to October 31) at Cold Lake, Alberta, with different synoptic weather situations. Symbols as in Figure 12. Four nights were excluded because their synoptic situation could not be classified into any situation found on the generalized map. Data for October 1966 were not used on the NW direction figure because of the change in intensity scale mentioned in the text.

Figure 13



Autumn NW movement



Autumn SE movement

sooner and had shorter durations than low-intensity events in other seasons ($P<.025$ and $P<.001$ respectively).

Temporal changes in intensity within long-distance movements

The intensity of a movement usually (84 per cent of 718 events) rose gradually from zero to a single peak and then decreased again to zero. On rare occasions the rise was very sharp (when many echoes appeared simultaneously on the radar screen). Sometimes a prolonged period of peak intensity (11 per cent of the events) or a bimodal intensity curve (5 per cent) was found. The latter was particularly common in movements which continued through a day and a night. Since high-intensity movements usually lasted longer than low-intensity ones, it is not surprising that high-intensity nocturnal events had flat or bimodal peaks more frequently than low-intensity nocturnal events ($P<.001$; χ^2 test).

Echo sizes

Figure 11 shows that, except in winter, the most prevalent size of echo in diurnal movements was on the average larger than that in nocturnal movements. The second-most frequent echo size was also notably larger by day than by night in the migration seasons. The day–night difference is readily apparent from an examination of the time-lapse films of migration in any area of Canada that we have studied. Echo sizes become notably smaller as the activity increases near sunset and notably larger as diurnal movements begin near sunrise. While there are many difficulties in interpreting the relationship between bird and flock size and sizes of individual radar echoes (Nisbet, 1963a; Eastwood, 1967; Schaefer, 1968), our results indicate that, on the average, diurnal echoes come from more birds per "flock", larger birds, or both, than do nocturnal echoes. This is not surprising in view of the evidence that most types of birds fly either individually or in very loose flocks at night (Lowery, 1951; Nisbet, 1963a; Eastwood and Rider, 1966).

Radars have signal amplitude limiters that would tend to prevent spot size from increasing with target echoing area. The fact that many bird echoes are barely visible and hence below the limiting amplitude probably causes the variability in spot size. Lunar observations of migration at Cold Lake by Mr. Hans Blokpoel have verified that tight flocks are very rare there at night. Of 609 birds seen on 6 nights in September 1967, all except nine pairs and one flock of about 10 waterfowl passed the moon individually (Blokpoel, 1971b).

In late autumn one would expect a larger proportion of the migratory flow to be comprised of waterfowl than in early autumn. Since waterfowl probably fly in flocks at night as well as by day, one would therefore expect that the difference in echo sizes between day and night would be larger and more significant early than late in the autumn. This was indeed the case. The maximum difference between the cumulative distribution of echo sizes by day and that by night (D_{max} in the Kolmogorov-Smirnov test procedure) was 0.401 in August and September but only 0.162 in October and November. These values correspond to respective 1-tailed significance levels of $P \ll .001$ and $.05 > P > .02$ for the hypothesis that day and night sizes are identical.

General relationship between migration intensity and weather

We examined the relationship between the peak intensity of nocturnal migration and the synoptic weather situation as shown on the 2300 MST U.S. Weather Bureau Daily Weather Map. The data are shown diagrammatically in Figures 12 and 13, which are described below. First, we drew a generalized weather map which shows most of the common relationships among pressure systems, fronts, and wind direction at some point on the map. Next, we examined the actual weather map at 2300 on one night in a migration season and noted the locations of these synoptic features relative to Cold Lake (e.g., a high pressure area to the W, a low to the E, a cold front to the SE, and NW winds). Then, we found the location on our generalized map which had a similar position relative to the synoptic features as Cold Lake had relative to the actual synoptic features. At this location a symbol representing the peak intensity of migration on that night was placed. The procedure was then repeated for each night from which we had radar data. Northwest and southeast movements were treated separately on different generalized maps. On most nights, the appropriate position on the generalized map was obvious. On others no position was completely appropriate, and hence we chose the position most closely approximating the true spatial relationships. On 4 autumn nights, we could not locate even an approximately appropriate position; these nights were not plotted. To minimize bias, the appropriate map location was determined in each case without knowledge of the intensity of migration on that night. When examining the resulting figures, it is important to compare the proportions of low-intensity and high-intensity nights under different synoptic conditions and not to look only for concentrations of points (which indicate those synoptic situations which were most common, not necessarily that migration was intense in those situations).

In spring (Fig. 12), NW migration with intensity above normal was proportionately very common with the SE or S winds on the SW and W sides of highs and the SE, E, and NE sides of lows. Heavy NW migra-

Table 3
Percentage of nights with non-zero intensity of movement

	Winter		Spring		Autumn	
	SE*	NW†	SE*	NW†	SE*	NW†
Following wind‡	23	54	55	91	97	40
Side or opposing wind	11	10	12	54	72	8

*Direction of movement range E to S.
†Direction of movement range W to N.
‡E to S for NW movement; W to N for SE movement.

Table 4
Correlations between intensity of migration and wind direction in 10°F-temperature categories[1]

Temperature at sunset hour, °F		Winter		Spring		Autumn	
		SE	NW	SE	NW	SE	NW
With respect to normal							
–30 to	–21	NS	NS	—	—	—	—
–20	–11	—	—	—	—	—	—
–10	–1	—	—	*	*	***	***
0	9	NS	*	NS	NS	*	**
10	19	—	—	—	—	—	—
20	29	—	—	—	—	—	—
With respect to previous day							
–30 to	–21	—	—	—	—	—	—
–20	–11	—	—	—	—	—	—
–10	–1	—	—	**	**	**	***
0	9	NS	**	NS	*	**	*
10	19	—	—	—	—	—	—
20	29	—	—	—	—	—	—

NS (no significance) $P > .05$. * $.05 \geqslant P > .01$. ** $.01 \geqslant P > .001$. *** $P \leqslant .001$. — Insufficient data for test.

[1]Each test examines the null hypothesis that intensity is greater with following than with opposing winds. The one-tailed Mann and Whitney U-test was used.

Table 5
Correlations between intensity of migration and wind direction in 10 per cent humidity categories[1]

Humidity, %		Winter		Spring		Autumn	
		SE	NW	SE	NW	SE	NW
With respect to normal							
. . . to	–21	—	—	—	—	—	—
–20	–11	—	—	*	NS	NS	NS
–10	–1	NS	**	—	—	NS	*
0	9	NS	*	—	—	**	NS
10	19	—	—	—	—	*	NS
20	. . .	—	—	NS	NS	NS	*
With respect to previous day							
. . . to	–21	—	—	—	—	—	—
–20	–11	—	—	—	—	**	NS
–10	–1	NS	*	NS	*	**	NS
0	9	NS	*	NS	*	NS	NS
10	19	—	—	—	—	*	NS
20	. . .	—	—	—	—	—	—

[1]Legend as in Table 4.

Figure 14. Cumulative frequency distributions of number of nights with each peak intensity under different wind conditions. Southeast movement is shown on the left, and northwest movement on the right. The farther a line is to the right, the higher are the intensities with that wind direction. Probabilities are for hypothesis that distributions under different wind directions are alike.

Figure 14

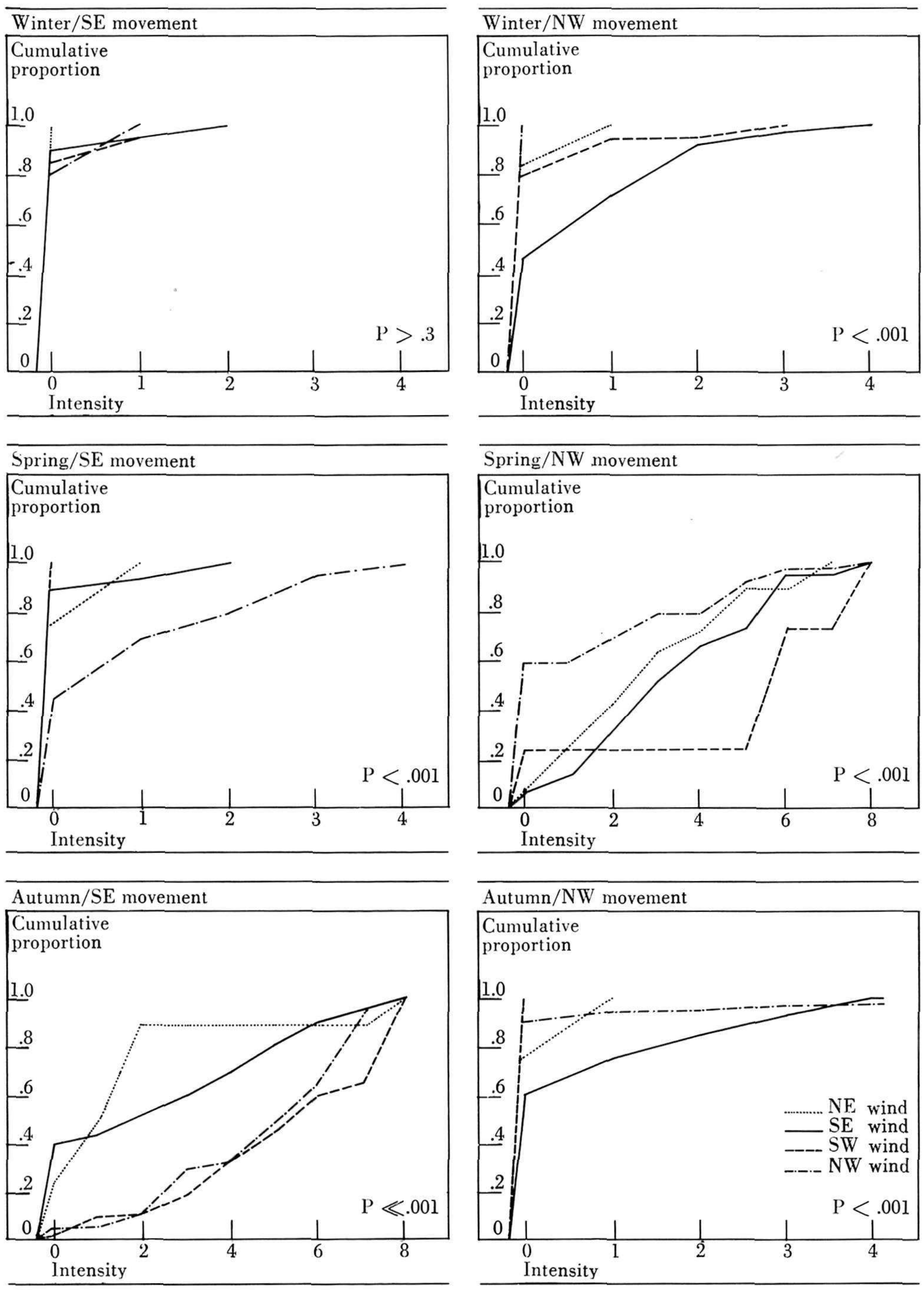


Table 6
Temperature with respect to normal with different combinations of intensity of migration[1] and wind direction

Bird direction	Wind direction	Intensity	Spring Mean	Spring SD	Spring N	Autumn Mean	Autumn SD	Autumn N	Intensity	Winter Mean	Winter SD	Winter N
Forward	All	1	–4.39	12.28	18	–0.79	6.06	29	None	–12.80	15.37	69
		2	–4.67	9.16	24	–0.29	7.76	35	Some	–6.07	14.99	31
		3	0.04	8.15	23	–1.88	10.87	32			*	
		4	0.78	7.39	23	–0.32	9.80	41				
				NS			NS					
Forward	W–N	1	–7.23	12.52	11	–1.00	4.24	4	None			
		2	–6.00	8.69	12	–1.00	8.04	13	Some			
		3 }	–1.00	6.22	10	–4.58	10.49	19				
		4 }				–0.83	10.13	23				
				NS			NS					
Forward	E–S	1 }	–1.55	10.85	11	–1.39	5.87	18	None	–11.50	13.74	20
		2 }				0.46	7.91	13	Some	–7.61	16.07	23
		3	–0.43	8.86	14	1.40	5.13	5			NS	
		4	0.10	8.54	10	–2.00	7.07	9				
				NS			NS					
Reverse	All	None	0.16	8.12	64	–0.04	9.15	111	None	–12.31	15.08	87
		Some	–7.58	10.43	24	–3.92	6.66	26	Some	0.00	14.42	13
				**			(*)				**	
Reverse	W–N	None	–2.80	7.23	15	–1.22	9.23	54	None			
		Some	–6.94	11.18	18	–11.40	8.05	5	Some			
				NS			*					
Reverse	E–S	None				0.26	7.31	27	None			
		Some				–2.06	5.20	18	Some			
							NS					

NS $P > .1$ (*) $.1 \geq P > .05$ * $.05 \geq P > .01$ ** $.01 \geq P > .001$ *** $P \leq .001$

[1]The quartile scale is used for spring NW and autumn SE movement. Weather with some movement is compared to weather with no movement in reverse migration and winter situations. The Kruskal-Wallis test was applied to the spring NW and autumn SE situations while the 2-tailed Mann and Whitney U-test was applied to the reverse and winter movements. The "Forward" bird direction sections refer to movements NW in spring and winter and SE in autumn; the "Reverse" sections refer to movements SE in spring and winter and NW in autumn (NW = W to N; SE = E to S).

tion frequently occurred prior to the passage of a nearby warm front, and it also was not uncommon in the westward airflow N of a low. The intensity of migration was very frequently below normal on the E side of a high and the SW side of a low. Somewhat more nights of high-intensity NW migration occurred on the W side of a low than might have been anticipated.

Reverse migration in spring occurred almost exclusively with more or less NW winds and a high pressure area to the W, a low to the E, or both. It was very infrequent in the synoptic situations which commonly had strong spring NW movement.

The intensity of autumn SE movement (Fig. 13) was related to the synoptic features in a manner similar to that of spring SE movement. Above-normal intensities were especially common with the W, NW, and N winds on the N, NE, and E sides of highs and the NW, W, and SW sides of lows. Heavy SE migration was more common than expected on the S side of lows, including ahead of the cold front and inside a warm sector. However, on these occasions the winds were usually westerly and the birds were not far ahead of the cold front.

Reverse migration in autumn usually occurred in the same conditions as strong

Table 7
Temperature change from previous day with different combinations of intensity[1] of migration and wind direction

Bird direction	Wind direction	Intensity	Spring Mean	Spring SD	Spring N	Autumn Mean	Autumn SD	Autumn N	Winter Intensity	Winter Mean	Winter SD	Winter N
Forward	All	1	-3.06	10.44	17	0.00	7.71	27	None	-1.09	9.12	65
		2	0.71	6.50	24	-1.67	6.51	33	Some	1.27	6.55	30
		3	2.43	7.16	21	-0.16	8.28	31			NS	
		4	0.35	5.75	20	1.33	7.64	40				
				NS			NS					
Forward	W–N	1	-7.40	9.78	10	0.75	5.12	4	None			
		2	1.25	6.66	12	-3.58	5.47	12	Some			
		3 }	0.44	7.75	9	-1.58	6.58	19				
		4 }				-0.39	8.81	23				
				NS			NS					
Forward	E–S	1 }	0.18	7.31	11	0.25	8.90	16	None	3.25	9.32	20
		2 }				1.25	5.80	12	Some	1.70	6.62	23
		3	2.92	6.87	13	2.60	4.16	5			NS	
		4	0.33	5.72	9	1.88	4.36	8				
				NS			NS					
Reverse	All	None	2.10	6.77	58	0.27	7.81	108	None	-0.55	8.38	85
		Some	-4.13	7.77	24	-1.57	6.04	23	Some	1.40	9.12	10
				***			NS				NS	
Reverse	W–N	None	2.39	7.02	13	-0.98	7.15	53	None			
		Some	-4.78	8.82	18	-5.40	7.89	5	Some			
				*			NS					
Reverse	E–S	None				1.54	7.56	26	None			
		Some				-0.07	5.02	15	Some			

[1]Legend as in Table 6.

spring NW migration. It virtually never occurred in the conditions typically associated with autumn SE migration.

It should be emphasized that in Figures 12 and 13, the weather at 2300 MST is considered. While the peak intensity usually occurred about that time, it occasionally was not reached until several hours later. Especially when fronts or lows are nearby, the conditions may change considerably in a few hours.

Winter movements

Both northerly and southerly movements occurred throughout the winter. This might not be expected in an area where in mid-January the normal daily maximum and minimum temperatures are +6° and —12°F. There was movement W, NW, or (most commonly) N on 31 nights between December 1, 1965, and March 15, 1966. Only 9 of these 31 movements occurred on nights when the surface temperature rose above freezing at any time during the two preceding or one following days, and 5 of these 9 nights were in March. During the period January 19 to 28, 1966, the temperature never rose above —12°F, and reached a minimum of —50. Nevertheless, on 4 of these 10 nights small, long-distance movements to the N or NW occurred. The surface wind was easterly on each of these 4 nights. The movements persisted for periods of 3 to 19 hours, although individual birds did not necessarily fly that long.

Nearly all the winter movements were very light. In the Discussion we will indicate that these small movements involve very few birds compared to the large spring and autumn movements. However, on one occasion (January 17/18, 1966) medium-intensity north and later south flights occurred. A movement to the N and NNE began at 1400 (about 2 hours before sunset) and reached its peak intensity around sunset. This flight began with a low pressure area to the west and with southerly geostrophic winds. At sunset the surface wind was SE, the temperature was 25°F (15° above the normal sunset hour value for that date and 12° above the sunset temperature the previous day), the pressure had dropped 7 millibars in the previous 6 hours, and the sky was 9/10 overcast. The low and an associated cold front moved through about 2100, some 5 hours after sunset. At that time, the northerly flight ended and a new southerly flight began. Thereafter the winds were northerly. It is not known whether the same birds were involved in the northerly and southerly flights. The light southerly flight ended at 0100, but began again at 0600, reached medium intensity briefly at 0800, and continued at low intensity until sunset. At sunset on the 18th, the wind was NNW at 16 mph, the temperature was —8°F, and the pressure had risen 3.5 millibars in the preceding 6 hours as the low moved away to the east. This sequence of movements, the heaviest of the winter, thus occurred in the typical conditions for north and south migration-season flights.

Correlations between wind direction and intensity of migration

Intensity of nocturnal flights was strongly correlated with wind direction in five of the six types of movement examined (NW in spring, autumn, and winter; SE in spring and autumn but apparently not winter). In each of these five types of movement, the intensity distributions with NE, SE, SW, and NW winds differed significantly ($P<.001$ in each case; Kruskal-Wallis tests), and in each case the intensities with following winds were markedly higher than the intensities with opposing winds (Fig. 14). With side winds, the intensity distributions were lower than with following winds for reverse and winter movements, but not always for migration in the

Table 8
Barometric pressure change from 6 hours before sunset to sunset with different combinations of intensity[1] of migration and wind direction

Bird direction	Wind direction	Intensity	Spring Mean	Spring SD	Spring N	Autumn Mean	Autumn SD	Autumn N	Intensity	Winter Mean	Winter SD	Winter N
Forward	All	1	10.61	29.62	18	-21.31	26.35	29	None	-1.64	32.38	69
		2	-6.04	26.00	24	-6.94	31.64	35	Some	-21.74	25.46	31
		3	-8.74	24.72	23	1.56	30.88	32			**	
		4	-7.39	21.38	23	-4.73	27.13	41				
				NS			**					
Forward	W–N	1	23.00	27.50	11	11.00	22.32	4	None			
		2	2.00	27.69	12	16.39	30.08	13	Some			
		3 }	13.20	20.29	10	16.58	21.99	19				
		4 }				10.48	24.15	23				
				NS			NS					
Forward	E–S	1 }	-17.73	19.64	11	-30.28	20.53	18	None	-20.20	27.17	20
		2 }				-30.15	24.63	13	Some	-30.91	20.85	23
		3	-15.50	26.38	14	-36.80	36.78	5			NS	
		4	-10.60	21.65	10	-30.89	20.53	9				
				NS			NS					
Reverse	All	None	-10.72	24.57	64	-4.45	29.19	111	None	-9.23	28.64	87
		Some	15.04	19.87	24	-19.65	29.90	26	Some	1.23	47.97	13
				***			*				NS	
Reverse	W–N	None	5.40	32.76	15	13.72	25.26	54	None			
		Some	18.22	18.57	18	14.40	12.12	5	Some			
				(*)			NS					
Reverse	E–S	None				-29.63	22.34	27	None			
		Some				-33.28	24.61	18	Some			
							NS					

[1]Legend as in Table 6. Pressure change is measured in tenths of millibars.

normal direction. While intensities of spring NW movement appeared to be higher with SW side winds than with SE following winds, SW winds occurred on only 4 days and hence the difference is not statistically significant. Figure 14 and Table 3 indicate that reverse and winter movements occurred on only about 10 per cent of the nights without following winds, while the forward-direction spring and autumn movements occurred with any but directly opposing winds (although little autumn SE movement occurred with NE side winds). While the analysis summarized in Figure 14 showed no significant relationship, Table 3 shows that SE movement in winter was twice as frequent with following wind as without. The absence of significant correlation using the Kruskal-Wallis test resulted from the small range of intensities which occurred in this type of activity.

The above analysis is based on the original 0 to 8 intensity scale. When the intensity distributions based on quartile curves were examined with the four different wind directions, we again found a significant effect of wind on intensity ($P < .02$ for spring NW movement and $P \ll .001$ for autumn SE movement; Kruskal-Wallis tests). As before, intensities were markedly higher with following than with opposing winds and intensities with side winds were similar to those with following winds.

Because (i) there are previous reports that both temperature and wind direction are correlated with intensity, (ii) temperature and wind direction are strongly interrelated, and (iii) there is inconclusive and conflicting evidence about the relative magnitude of the partial correlations of intensity with wind direction and temperature

Table 9
Wind speed with different combinations of intensity[1] of migration and wind direction

Bird direction	Wind direction	Intensity	Spring Mean	Spring SD	Spring N	Autumn Mean	Autumn SD	Autumn N	Winter Intensity	Winter Mean	Winter SD	Winter N
Forward	All	1	10.67	6.21	18	8.45	4.41	29	None	9.41	5.21	69
		2	9.13	4.43	24	9.89	7.55	35	Some	8.26	5.73	31
		3	8.74	5.54	23	7.94	5.11	32			NS	
		4	8.74	4.94	23	9.63	4.18	41				
				NS			NS					
Forward	W–N	1	12.91	5.38	11	11.00	6.48	4	None			
		2	12.00	3.79	12	14.46	10.24	13	Some			
		3 }	10.30	5.38	10	9.42	5.19	19				
		4 }				10.74	4.38	23				
				NS			NS					
Forward	E–S	1 }	8.64	3.59	11	9.00	2.95	18	None	8.55	3.40	20
		2 }				7.92	3.69	13	Some	9.30	5.31	23
		3	10.00	5.86	14	8.00	3.24	5			NS	
		4	10.00	3.94	10	9.78	4.30	9				
				NS			NS					
Reverse	All	None	8.64	5.17	64	9.11	5.83	111	None	8.83	5.33	87
		Some	10.83	5.10	24	8.81	3.69	26	Some	10.54	5.64	13
				(*)			NS				NS	
Reverse	W–N	None	10.93	5.11	15	11.44	6.66	54	None			
		Some	12.50	4.59	18	8.00	4.80	5	Some			
				NS			NS					
Reverse	E–S	None				8.04	3.67	27	None			
		Some				9.78	2.86	18	Some			
							(*)					

[1]Legend as in Table 6. Wind speed measured in miles per hour.

(Richardson, 1966; Nisbet and Drury, 1968; Richardson and Haight, 1970), we looked for relationships between intensity of migration and wind direction when only days with temperatures in various 10°F-ranges were considered. The temperature at sunset relative to normal and relative to the previous day were both used (Table 4).

Considering *temperature relative to normal*, 12 combinations of movement type (e.g., NW in spring) and temperature category (e.g., 0 to 9°F above normal) had sufficient data to be used. Here, sufficient data means 5 or more nights with each of following and opposing wind. Of the 12 situations with sufficient data, 7 showed significantly ($P<.05$) greater intensity with following than with opposing winds. If there is no actual correlation within 10°-temperature ranges, the probability of obtaining significant differences in 7 of 12 tests (using the $P=.05$ criterion of significance in each test) is less than 0.0001. Hence, we conclude that the intensity of migration is correlated with wind direction within 10°-ranges of temperature relative to normal.

Considering *temperature change* from the previous day, of 10 situations with sufficient data, 8 showed significantly ($P<.05$) greater intensity with following than with opposing winds. The probability of obtaining 8 or more significant ($P<.05$) differences in 10 tests if there is no actual relationship is again less than 0.0001, so we conclude that intensity is also correlated with wind direction within 10°-ranges of temperature change.

In contrast to the results of our Ontario radar study (Richardson and Haight, 1970), humidity is here at least as strongly correlated with intensity as is temperature. Hence we examined the data to see if the correlation between wind direction and intensity was also maintained when only days within certain ranges of humidity were considered. In examining the relationship between intensity and wind direction within 10 per cent ranges of *humidity relative to normal*, we found 18 situations with sufficient data (Table 5). Of these, 7 showed significantly ($P<.05$) greater intensity with following than with opposing winds. Also, 7 of 16 situations had significantly more migration with following than with opposing winds within 10 per cent *humidity change* categories. The probabilities of obtaining at least 7 of 18 and 7 of 16 significant differences if there are no actual correlations are both less than 0.0001. Hence, we conclude that intensity is correlated with wind direction within 10 per cent ranges of humidity relative to normal or relative to the previous day.

Correlation between temperature and intensity of migration

It was expected that temperature would be high and/or increasing with NW movements and low and/or decreasing with SE movements, since temperatures are correlated with wind direction and wind direction is correlated with intensity of migration. Spring NW movement showed the expected direction of correlation with temperature both relative to normal and relative to the previous day (low and decreasing mean temperature with little movement; higher and relatively stable mean temperature with stronger movement). However, these differences were not statistically significant (Tables 6 and 7). Autumn SE movement showed no evidence of correlation with temperature. Spring SE reverse movement was significantly correlated with low and decreasing temperature as expected. The correlation with decreasing temperature remained significant when only days with following winds were considered; that with low temperature dropped below the significance level. Autumn NW reverse movement was almost significantly correlated with low (but not decreasing) temperature when all days were considered. This is the opposite direction to that expected. In winter there were no obvious correlations with temperature change, but the mean temperature was significantly higher with both NW and SE movement than without such movement. This is the expected direction of correlation for NW but not for SE movement.

When examining the results of many statistical tests, one must remember that using $P = .05$ as a significance criterion, a Type I error (Johnson and Leone, 1964:197) will be made on the average in 5 per cent of the tests. There is only a small (0.004) probability of obtaining 4 significant ($P < .05$) correlations out of 14 tests purely on the basis of Type I errors, suggesting a genuine correlation between temperature relative to normal and intensity. However, this is not the case for the temperature change situation (Table 7), where only 2 of 14 differences are significant (and these are not independent).

Correlation between barometric pressure trend and intensity

In view of the relationships between pressure pattern positions and direction and intensity of wind (Fig. 12 and 13), one would expect days with strong SE and NW movement to have higher and lower pressure trends respectively than days with little SE or NW movement. Table 8 shows this to be the case, although the differences were not all significant. When only days with following or opposing winds were considered, none of the differences was significant at the $P = .05$ level.

Wind speed and cloud extent vs intensity

No clear differences in wind speed or cloud extent were found when the values of these parameters on days with much migration were compared with those on days with little movement (Tables 9 and 10). From the results of others (e.g., Lack, 1963 a,b; Parslow, 1969) and from energetic considerations, we expected the mean wind speed to be lower with strong than with light migration when only days with opposing winds were considered. This was not the case.

If view of the sky is necessary for orientation, one might expect the mean cloud extent would be less with strong than with light migration. Except with strong autumn migration against opposing wind, there was little indication of such an effect (Table 10). Cloud extent refers here to the fraction of the sky over Cold Lake covered by cloud of any type at sunset. Because cloud conditions frequently vary considerably over short intervals of space or time, this is probably not a very good measure of the ability of the birds to see the sky.

Correlations between humidity and intensity

Because strong spring NW migration tends to occur in the west sides of high pressure areas (Fig. 12), lower humidity was expected with strong than with light NW movement. This was the case (Table 11). The direction of this correlation persisted when only days with following wind were considered, but it was no longer significant. Table 12 suggests that humidity tended to be relatively stable as well as low when strong NW movement occurred, while it tended to be rising with light movement. However this difference was not significant. Intensity of autumn SE movement was significantly correlated with humidity, but not in a linear fashion. The correlation of high mean humidity with slightly above-normal intensity persisted when days with either following wind or opposing wind were considered. Spring SE reverse movement tended to occur with higher humidity than when no SE movement was occurring, but this

Table 10
Cloud extent with different combinations of intensity[1] of migration and wind direction

Bird direction	Wind direction	Intensity	Spring Mean	Spring SD	Spring N	Autumn Mean	Autumn SD	Autumn N	Winter Intensity	Winter Mean	Winter SD	Winter N
Forward	All	1	7.17	3.09	18	6.03	3.45	29	None	6.31	3.46	69
		2	6.50	3.40	24	6.63	2.83	35	Some	6.48	4.02	31
		3	6.22	3.57	23	6.66	3.32	32			NS	
		4	5.48	3.09	23	5.56	3.41	41				
				NS			NS					
Forward	W–N	1	7.09	2.59	11	5.25	3.59	4	None			
		2	6.58	3.53	12	7.00	2.58	13	Some			
		3 }	6.80	2.04	10	5.79	3.87	19				
		4 }				6.30	3.20	23				
				NS			NS					
Forward	E–S	1 }	6.91	3.70	11	6.28	3.71	18	None	7.70	2.36	20
		2 }				6.23	3.11	13	Some	7.48	3.57	23
		3	5.71	3.87	14	8.00	1.87	5			NS	
		4	4.90	3.78	10	3.67	4.09	9				
				NS			NS					
Reverse	All	None	5.95	3.42	64	6.27	3.25	111	None	6.39	3.62	87
		Some	7.21	2.83	24	5.85	3.33	26	Some	6.23	3.79	13
				(*)			NS				NS	
Reverse	W–N	None	6.47	2.83	15	6.28	3.29	54	None			
		Some	7.11	2.74	18	5.60	3.58	5	Some			
				NS			NS					
Reverse	E–S	None				6.04	3.71	27	None			
		Some				5.78	3.52	18	Some			
							NS					

[1]Legend as in Table 6. Cloud extent in tenths of the sky covered.

Table 11
Relative humidity with respect to normal with different combinations of intensity[1] of migration and wind direction

Bird	Wind		Spring			Autumn				Winter		
direction	direction	Intensity	Mean	SD	N	Mean	SD	N	Intensity	Mean	SD	N
Forward	All	1	9.56	19.14	18	1.48	12.30	29	None	3.32	8.90	69
		2	13.00	19.12	24	1.29	14.66	35	Some	1.61	10.49	31
		3	1.70	16.62	23	9.69	17.03	32			NS	
		4	-3.00	13.65	23	1.15	13.19	41				
				*			*					
Forward	W–N	1	9.82	18.84	11	1.00	10.23	4	None			
		2	15.42	20.00	12	-0.08	17.69	13	Some			
		3 }	5.70	16.53	10	9.63	15.81	19				
		4 }				3.26	13.13	23				
				NS			NS					
Forward	E–S	1 }	8.55	17.27	11	4.44	12.35	18	None	6.05	9.18	20
		2 }				1.69	11.38	13	Some	2.87	10.98	23
		3	2.14	16.63	14	12.60	18.69	5			*	
		4	-5.50	10.90	10	-4.22	15.03	9				
				NS			NS					
Reverse	All	None	2.25	17.42	64	2.49	14.64	111	None	2.01	9.30	87
		Some	12.92	17.86	24	6.50	14.56	26	Some	8.00	8.65	13
				*			NS				*	
Reverse	W–N	None	9.53	18.94	15	4.00	15.18	54	None			
		Some	11.50	18.60	18	9.00	14.98	5	Some			
				NS			NS					
Reverse	E–S	None				0.78	12.14	27	None			
		Some				5.89	15.77	18	Some			
							NS					

[1]Legend as in Table 6. Relative humidity in per cent relative to normal.

difference disappeared when only nights with following winds were considered. Autumn NW movement showed no obvious correlation with humidity. Winter days with SE movement had higher humidity than those without SE movement, while winter days with NW movement tended to have lower humidity than those without NW movement, at least when only following wind situations were considered.

We were interested in the possibility that the correlation of spring NW intensity with humidity might be the result of autocorrelation of humidity with other weather parameters to which the birds might be responding. A rigorous analysis was not possible because of the ordinal nature of the data (see Discussion). However, application of the non-parametric Kendall partial rank correlation procedure (Siegel, 1956) to various pairings of likely parameters suggested that autocorrelation neither of humidity and temperature nor of humidity and pressure gradient was responsible for the apparent intensity–humidity correlation (Table 13). This result might have been anticipated from the absence of strong temperature or pressure correlation with intensity of spring NW movement on days with SE winds.

The situations under which the various types of movement usually occurred will be summarized and discussed below.

Table 12
Relative humidity change from the previous day with different combinations of intensity[1] of migration and wind direction

Bird direction	Wind direction	Intensity	Spring Mean	Spring SD	Spring N	Autumn Mean	Autumn SD	Autumn N	Winter Intensity	Winter Mean	Winter SD	Winter N
Forward	All	1	4.94	26.97	17	–1.82	11.23	27	None	1.11	11.58	65
		2	3.50	19.97	24	–0.12	16.83	33	Some	0.00	10.97	30
		3	–1.57	13.27	21	4.03	20.01	31			NS	
		4	–2.85	12.31	20	–2.70	17.33	40				
				NS			NS					
Forward	W–N	1	10.40	27.10	10	1.00	5.72	4	None			
		2	3.67	17.69	12	–0.42	16.40	12	Some			
		3 }	1.11	13.15	9	1.26	21.59	19				
		4 }				–4.61	21.14	23				
				NS			NS					
Forward	E–S	1 }	8.64	17.04	11	–0.06	10.00	16	None	1.20	10.78	20
		2 }				–5.67	17.94	12	Some	1.35	10.12	23
		3	1.15	11.93	13	9.40	14.52	5			NS	
		4	-1.56	6.97	9	0.00	8.19	8				
				NS			NS					
Reverse	All	None	–1.48	16.51	58	–0.38	17.36	108	None	0.59	11.51	85
		Some	6.83	22.21	24	0.22	14.63	23	Some	2.20	10.19	10
				NS			NS				NS	
Reverse	W–N	None	0.39	11.15	13	0.98	19.60	53	None			
		Some	8.50	24.13	18	–6.20	19.97	5	Some			
				NS			NS					
Reverse	E–S	None				–1.81	13.42	26	None			
		Some				1.67	13.49	15	Some			
							NS					

[1]Legend as in Table 6. Relative humidity change in per cent.

Table 13
Correlation of intensity of spring northwest movement with weather* on days with following winds†

Factors examined for correlation	Factor whose effect held constant	Kendall correlation coefficient
Intensity and humidity	—	–.35‡
	Temperature	–.35
	Pressure	–.36
Intensity and temperature	—	.06
	Humidity	–.09
	Pressure	.07
Intensity and pressure	—	.08
	Temperature	.09
	Humidity	.13

*Humidity and temperature are humidity and temperature relative to normal for that day and hour and are measured at sunset. Pressure is pressure trend from 6 hours before sunset to sunset.

†Winds in the range E to S were considered to be following.

‡This coefficient is significantly different from zero ($P<.01$) while the comparable test in Table 11 showed only marginal significance. The difference results from either the differing properties of the two tests, the fact that quartile intensities were used in Table 11 and actual intensities here, or both.

Discussion

Direction of movement in different parts of North America

We have found that the heavier movements in Alberta and Saskatchewan tend to go NW in spring and SE in autumn. In SE Manitoba, they more commonly go N than NW in spring. The results of other workers, moving from east to west across the continent, are as follows: Lowery (1951:455) showed that in the E and SE United States, spring migration is more to the NE than to the N. Moon-watching studies in southern Ontario (Richardson, unpubl.) reveal that this is also the case there. The predominant directions of migration in E Massachusetts and in Nova Scotia and New Brunswick are NE or ENE in spring and SW in autumn (Drury and Nisbet, 1964; Nisbet and Drury, 1967a; Richardson, unpubl.). In central Illinois, the mean directions of the general flow of migrants are slightly E of N in spring (but not NE) and slightly E of S in autumn (Bellrose and Graber, 1963). At Havana, Illinois, and at St. Louis, Missouri, the mean directions of autumn duck migration are SSW and S respectively, while farther west at Des Moines, Iowa, and Kansas City they are both SSE (Bellrose, 1964). Mallard ducks (*Anas platyrhynchos*) banded in Illinois are recovered to the NW rather than to the N (Bellrose, 1966). The mean directions of spring migration in 1948 at Stillwater, Oklahoma, Columbia, Missouri, and Ottumwa, Iowa, were all approximately NNW, although that at Lawrence, Kansas, was slightly E of N (Lowery, 1951). The Ottumwa results are based on 10 nights of observations; only 3 or 4 nights of data are available from each of the other three sites.

In summary, the above results suggest a gradual shift in the predominant axis of migration from NE–SW in the east through N–S in the eastern plains area to NW–SE in the central and western plains of the United States and Canada. This is doubtless in large part explained by the geography of North America: the distance between the mountains to the west and the ocean to the east progressively increases as one moves north from the Gulf of Mexico to Canada. In Alberta, the NW–SE migration axis is parallel to the eastern edge of the mountains, which are only about 300 miles SW of Cold Lake and much closer to the Edmonton and (especially) Calgary radar sites. The apparent exception to the general pattern found at Calgary may reflect the proximity of that site to the mountains. The wintering areas of most Anseriform, Charadriiform, and passerine species migrating through Alberta are largely east of the longitude of Cold Lake.

Changes in direction over the course of a movement

When all spring or autumn small or large long-distance nocturnal events are examined as groups, slight but statistically significant clockwise shifts in direction from early to late in the night are apparent (Table 2; Fig. 9). Clockwise shifts during the night have also been found by Drury and Nisbet (1964), Nisbet and Drury (1967a), Graber (1968), and Steidinger (1968). Gehring (1963) found a clockwise shift during the day in Switzerland. While it is possible that birds passing early in the day or night have different "preferred" directions from those passing later, especially in coastal New England, it is also possible that individual birds characteristically change their direction to the right while in flight. If the latter possibility actually occurs and if the birds start to fly each night in the direction they were flying at the end of the last flight, the elliptical migration routes discussed by Bellrose and Graber (1963:383), Evans (1966a:352), Graber (1968:63), and Parslow (1969:67) would result. Such routes may have evolved to take advantage of prevailing wind directions. Gehring (1963), Graber (1968), and Steidinger (1968) all found that the clockwise shift could not be explained by wind change. Likewise, the clockwise shift at Cold Lake is still seen in heavy spring nocturnal movements when only nights with surface winds in the range east to south are considered (Table 1). However, the shift in heavy autumn movements disappears when only nights with west to north winds are considered.

Variations in direction between movements

Smaller movements were found to occur in virtually all directions at all times of the year; generally they were directed downwind. In contrast, high-intensity movements were nearly always directed NW in spring and SE in autumn regardless of wind direction, but most frequently occurred with following winds. These results seem reasonable if one accepts the postulate that it is energetically advantageous for birds to fly with following winds. Presumably (i) certain proportions of the migratory birds in the Alberta area possess orientation systems directing them in each of several different ranges of direction, (ii) a larger proportion of these birds are oriented along the NW–SE axis than in other directions, (iii) each of these birds has a mechanism determining whether or not to fly at a given time, (iv) one of the inputs to the timing mechanism is wind direction or related factors, and (v) following wind situations (relative to the "preferred" direction for that bird) are more likely to result in migration than opposing wind situations. Such a system has been proposed by Evans (1966a) and Nisbet and Drury (1967a). This system would result in predominantly downwind flight each day, with the largest flights always directed NW in spring and SE in autumn and occurring with following winds.

The possible occurrence of lateral drift caused by the wind has been extensively debated because of its importance to theories of orientation (see Nisbet and Drury, 1967a for references; also Bellrose, 1967; Evans, 1968a,b; Steidinger, 1968; Lack, 1969; Parslow, 1969). We have found that the wind direction on a given day has a pronounced effect on the direction of any small movements which may occur on that day and, at least in autumn, a smaller effect on strong movements. Much of this effect is probably explained by the selection of following wind situations for migration as discussed above. Whether or not there is any residual lateral drift cannot be determined from our data.

Reverse movements

It is difficult to believe that the normal migration direction of many birds past Cold Lake is NW in autumn or SE in spring. Nevertheless, considerable numbers of movements are so directed (Fig. 4–8). This suggests that in at least some birds, the orientation systems referred to above direct individual birds in different directions at different times within the same season. Possible reasons for these changes in direction have been suggested for specific cases: (i) following of "diversion lines" along the edge of geographic or habitat barriers (e.g., Wallraff and Kiepenheuer, 1962; Bergman and Donner, 1964; Mueller and Berger, 1967), (ii) adaptive response to being over water at dawn (Baird and Nisbet, 1960; Myres, 1964a), (iii) confusion of a celestial orientation system (Lee, 1963), (iv) inaccuracy in the mechanism of the orientational system (Gehring, 1963; Steidinger, 1968), (v) overshooting of the goal area (Bellrose, 1966; Mueller and Berger, 1969), and (vi) "redetermined" orientation after lateral drift caused by the wind (e.g., Evans, 1968b). With the possible exception of overshooting, it is unlikely that these suggested reasons apply to the "reverse" flights in Alberta. Possibilities iii, iv, and vi may occasionally occur, but these would probably produce shifted but not totally reversed directions.

Reverse migration seems to occur in more restricted synoptic weather situations than forward migration (Fig. 12 and 13; Richardson and Haight, 1970). Southward flight in spring in response to a return of cold weather would seem to have some selective advantage, but northward autumn flights cannot be explained in this manner. For some reason, a few NW autumn movements began with the opposing winds found with a high pressure area close to the west (see Fig. 13 and below). The significance of reverse movements to theories of orientation has yet to be explored.

Most radar and moon-watching studies, including this one, have found that reverse migration is frequent, but usually involves smaller movements than the large forward-direction flights (e.g., Lowery, 1951; Lowery and Newman, 1955, 1966; Drury and Keith, 1962; Gehring, 1963; Lack, 1963a,b; Lee, 1963; Drury and Nisbet, 1964; Parslow, 1969). Richardson and Haight (1970) found that reverse starling migration in Ontario is not only rather common but also frequently quite intense. In contrast to these studies, Hassler *et al.* (1963:70) found that reverse autumn migration is very uncommon in Illinois. Furthermore, moon-watching in Ontario for a total of 164 hours on 31 spring and 24 autumn nights has shown that only about 5 per cent of the migrants are directed towards the southern half of the compass in spring and the northern half in autumn (Richardson, unpubl.). Nevertheless, reverse movements are frequently seen on radar. This apparent contradiction results from the different techniques employed. Moon-watching and the narrow-beam short-range radar used by Hassler *et al.* (1963) can detect individual birds and so give a fair indication of the actual number of birds moving in each direction. Moderate and high-power surveillance radars with PPI displays (used in all the radar studies mentioned above except that of Hassler *et al.*) have lower resolution and, to oversimplify, indicate whether or not there is a threshold amount of echoing-area in a given volume of space. Whether there is 5 or 50 times the threshold echoing-area per pulse volume has little effect on the appearance of the display in that area. Hence, high-power radars tend to underemphasize the volume of large movements and overemphasize small reverse flights, unless detailed analyses (involving echo counts and examination of "thinning") are made. Furthermore, moon-watching and narrow-beam radars sample a larger volume of space at high than at low altitude. If reverse migrants tend to fly lower than forward migrants, a smaller proportion of the reverse than of the forward migrants might be detected with these techniques. However, we have evidence that the high-power surveillance radars we use are quite capable of detecting very low-flying migrants.

While we therefore conclude that reverse migration constitutes only a small proportion of the total migration past a given area during a season and that reverse movements usually involve comparatively few birds, both moon-watching and radar indicate that at many times more birds are involved in reverse than in forward movement. The phenomenon is certainly worth further study.

Intensity of movement

As noted above, there are many difficulties in estimating numbers of birds from radar displays. These problems are of two types.

(i) The amount of echo on the screen is not necessarily linearly related to the number of birds or groups of birds in the air. We are just now developing the capability of calibrating the surveillance radar using moon-watching and a narrow-beam radar (Blokpoel, 1971a,b). In the meantime, we have had to use an arbitrary ordinal intensity scale and statistical methods appropriate to ordinal data rather than a more desirable interval scale and parametric statistical procedures.

(ii) There are various possible sources of error in the application of the ordinal intensity scale to the data. In the first place, adjustments of the radar over which we had no control may change the apparent intensity. Secondly, the presence of anomalous propagation (AP — described by Eastwood, 1967:51) occasionally makes assessment of the film especially difficult. Although AP and bird echoes can almost always be distinguished on the time-lapse film, AP sometimes tends to obscure bird echoes at long range and at other times increases the range to which birds are visible. The use of the quartile scale for NW spring and SE autumn movements and of the "some vs none" analysis for reverse and winter flights minimized these two sources of error. A third possible problem is that birds flying high are more likely to be detected by radar than those flying low, especially at greater distances from the antenna. Wilcock (1964) has found that large low-altitude visible movements may not be detected by radar, and Evans (1966b) has presented evidence that visible (i.e., low-altitude diurnal) migration may constitute a significant fraction of the total migration in some areas. We must therefore qualify all our results by stating that they may be biased in favour of birds flying at medium and high altitudes. However, we believe that most birds are flying high enough to be detected, since (i) the modal height of those migrating birds flying above 1200 feet a.g.l. at Cold Lake is usually well above 1200 feet (Blokpoel, 1971b), (ii) we have detected low-altitude starling roosting and gull flights in Ontario using surveillance radars with much lower power (550 kw) than the Cold Lake radar, and (iii) we have used a height finder radar to measure the heights of many bird echoes visible on a high-power surveillance radar PPI and have found that very low migrants are visible on the PPI. A fourth source of error is the assigning of intensity values by eye rather than by any procedure involving echo counts. This source of error is minimal — repeated assessment of the same film gives very similar results (within 1 intensity scale value in nearly all cases). A fifth possible source of error is that, on the average, birds flying upwind will have lower groundspeeds than those flying downwind (although Bellrose, 1967, has provided evidence that the difference may not be as great as expected). The MTI system will therefore reduce the signal strength of echoes moving upwind more than it does of echoes moving downwind. This in turn will reduce the maximum detectable range of birds moving upwind, and so on the average will lead to a reduced apparent density at each distance from the centre of the display compared to what would be seen if the same birds were flying downwind. This source of error is minimized in our case because Normal Video rather than MTI was used beyond about 30 n.m. range.

Considering all these possible sources of error, one might suspect that our estimates of migration density are so crude as to be useless for analyses of the effects of weather on migration. Fortunately, this does not seem to be the case. Preliminary results suggest that errors of more than 1 or at most 2 scale values (on our 0 to 8 scale) are unusual (Blokpoel, 1971b). However, many more data will be needed to confirm this. The reason for the apparent relative accuracy of our estimates in spite of the many possible sources of error is probably that migration density frequently varies by two and occasionally by three orders of magnitude from night to night (Newman and Lowery, 1964; Nisbet and Drury, 1968:502; Blokpoel, 1971b; Richardson, unpubl.). In contrast, most of the sources of error are by factors considerably less than ten.

Weather and migration

Many authors have looked for correlations between weather and day-to-day variations in the volume of bird migration (see Lack, 1960 for review). More recent papers are cited by Nisbet and Drury (1968). It has been believed for many years that "waves" of spring migrants in eastern North America most commonly move north with falling pressure and a southerly flow of warm air associated with a high pressure area moving away to the east, a low approaching from the west, or both (e.g., Bagg *et al.*, 1950). This was confirmed statistically by Richardson (1966). Curtis (1969) has recently published an analysis of the relative amounts of departure and arrival in spring with various synoptic situations. It is believed that heavy autumn migration occurs with rising pressure and a northerly flow of cold air as a low pressure area moves away to the east, a high approaches from the west, or both (e.g., Bennett, 1952; Mueller and Berger, 1961). Recent studies have attempted to determine (i) whether conclusions based on radar and moon-watching data are similar to the original conclusions based on diurnal visual observations, (ii) how well these generalizations apply to different species and different geographic areas, and (iii) what specific proximate factors are involved in determining whether or not a bird will migrate at a given time (Richardson and Haight, 1970). We shall discuss each of these questions in the light of the Alberta data.

(i) Direct observations of migration vs ground censuses

In general, the Alberta data support the original ideas about relationships between pressure patterns and intensity of migration (Fig. 12 and 13). However, strong migration did not occur on all the nights with supposedly favourable conditions. More surprisingly, considerable migration occurred on some nights with supposedly unfavourable conditions. Lowery and Newman (1966) obtained similar results by examining different sites on the same nights rather than the same site on different nights. The pressure trend was indeed more negative in spring and more positive in autumn with heavy than with light migration, but only the autumn difference was significant (Table 8). Also as expected, spring intensities were greatest with S winds and autumn intensities with NW winds (Fig. 14). On the other hand, there was little difference in temperature and temperature change between days with high- and low-intensity migration.

(ii) Differences in the responses to weather

Different birds in different areas sometimes migrate with different weather conditions. For example, Nisbet and Drury (1968:520) found more NE migration in spring when they were near the centre of a high pressure area, than a day or two later when they were in the warm sector of an approaching low. They believed that earlier authors had reported more migration in the warm sector because "most of the previous studies were of grounded or diurnal migrants, and were biased by the fact that such birds tend to be concentrated or forced down by the disturbed weather associated with troughs". However, Richardson and Haight (1970) have found that starlings, which also migrate NE in spring, depart proportionately more frequently in the warm sectors of lows than near the centres of highs. That study was based on direct radar observations of starling migration departures, and so was not biased, although the migration was diurnal.

Spring and autumn forward and reverse starling migration appeared to be more closely related to a NW–SE than to a W–E pressure gradient; this is perpendicular to their NE–SW axis of flight. In contrast, Figures 12 and 13 suggest that migration in Alberta is strongest with a NE–SW pressure gradient (perpendicular to the predominant NW–SE axis of migration). This difference is especially apparent if these figures are compared with the corresponding ones for starling migration (Richardson and Haight, 1970: Fig. 3 and 4). Heavy autumn SE migration in Alberta is proportionately most frequent on the NE or even N sides of highs and the W and SW sides of lows; autumn SW (and spring SW reverse) starling migration in Ontario is most frequent on the E and SE sides of highs and the NW and W sides of lows. Heavy spring NW migration in Alberta is most frequent on the SW and W sides of highs and SE, E, NE, and even N of lows; spring NE starling migration is most frequent SE or S of lows. When these pressure-gradient directions are combined with the data on pressure-trend correlations (Table 8), one finds that both forward and reverse movements in both spring and autumn of both starlings in Ontario and all birds in Alberta are all strongest and most frequent when the pressure gradient is falling from the birds' right to their left. Such situations give following geostrophic winds.

However, as noted above, Nisbet and Drury (1968) found more NE migration along the East Coast with SE winds and near the centre of a high than with SW winds in the warm sector of a low. Perhaps it is adaptively more advantageous for birds along the coast to select conditions with onshore SE side winds and little chance of a rapid change to offshore winds than to select conditions with following SW winds but an appreciable chance of a shift to offshore winds should the cold front behind the warm sector suddenly arrive.

(iii) Responses to individual weather parameters

Many authors have attempted to determine which individual weather parameters are used in the mechanism determining whether or not a bird will fly at a given time. Some studies have examined only the simple correlations between intensity and various parameters one at a time. Since different weather variables are highly interrelated, this method is of little assistance in determining causal relationships. However, it is useful in providing a description of the conditions under which much and little migration occur. Other studies, notably Lack (1963a,b), Gruys-Casimir (1965), and Nisbet and Drury (1968), have applied multiple linear regression procedures to study the amount of correlation between each weather variable and intensity, other parameters being equal. This method could not be used here because our intensity scale is ordinal rather than interval. Other difficulties with the multiple regression model are discussed by Richardson and Haight (1970). A third approach, that used here, is to examine the relationship between migration volume and one weather variable at a time when only those days with one or more other variables in certain restricted ranges of values are considered.

Regrettably, none of the above methods allows us to determine conclusively which parameters the birds respond to and which they ignore. Nevertheless, some indications have been obtained.

(i) There is an obvious simple correlation between intensity and *wind direction* for NW spring, SE autumn, and most other types of movement (Fig. 14). More importantly, this correlation persisted in 10°F-temperature categories and in 10 per cent humidity ranges. Wind direction has been considered by most North American authors to show the strongest simple correlation of any parameter with the volume of migration. Of the several parameters which have been found by various authors to be correlated with migration volume, only wind direction and rain show the same direction of correlation for all types of broad-front movement. That is, migration is almost always heavier with following than with opposing winds regardless of season or direction of movement, whereas at different times and places intensity may be positively or negatively correlated (or uncorrelated) with temperature, humidity, pressure change, wind speed, cloud extent, and atmospheric stability.

(ii) *Pressure trend* shows clear simple correlation with intensity, but at least in autumn this trend disappears when only nights with following (or opposing) wind are considered (Table 8). If birds were reacting to pressure changes *per se*, one would expect the correlation to persist, since not all nights with following (or opposing) winds have similar pressure trends.

(iii) Intensity of normal direction migration was not obviously related to *temperature* (Tables 6 and 7). This was unexpected, in view of the correlation between intense migration and S winds in spring and NW winds in autumn (Fig. 14). Several previous studies of migration in North America have found correlations between intensity and temperature (e.g., Mueller and Berger, 1961; Richardson, 1966; Nisbet and Drury, 1968; Richardson and Haight, 1970), but some have not (e.g., Raynor, 1956; Hassler *et al.*, 1963). In contrast to the situation with normal migration, we did find relationships between intensity of reverse migration and temperature in both spring and autumn. The unexpected direction of the autumn correlation was the result of very low temperature on the few nights having reverse migration with opposing winds (Table 6).

(iv) *Wind speed* and *cloud extent* show no obvious simple correlation with intensity nor any correlation when only nights with following winds were considered. Again, if the birds were strongly influenced by either of these factors, correlation on nights with following wind would be expected.

(v) In spring, the relationship between high intensity of NW movement and low *humidity* persisted when only nights with SE wind were considered (Table 13). The correlation was also not the result of autocorrelation of humidity and temperature or pressure trend (Table 13). This indicates that these birds may be using low humidity as an indicator of the preferred time for NW migration. Nisbet and Drury (1968) found a negative partial correlation between intensity and humidity using the multiple regression method. Richardson (1966) found that, on the average, spring "waves" of migrants in Ontario occurred with rising but near-normal humidity. How humidity might be measured by the birds is not clear.

The above results suggest but do not prove that birds flying over Cold Lake respond to wind direction and (at least for spring NW movement) humidity. They also suggest that pressure trend, temperature, wind speed, and cloud extent are not major cues used in the system which determines whether or not to fly on a given night. However, the absence of any apparent correlation with one factor may mean only that birds respond to that parameter and also to another correlated with the first in an opposing manner. We suspect that at least some of the last four parameters listed above may have modifying influences on the responses to other factors by the Alberta birds and that they may be more important in some birds than others.

In general, we believe that birds have evolved short-term migration timing mechanisms placing different weights on the separate weather parameters depending upon season and species. More specifically, the particular pattern of weights would depend primarily upon the "preferred" direction. The pattern would serve to initiate migration in synoptic situations optimal for survival. Since most birds in most situations seem more likely to fly with following than with opposing winds, and since there are obvious energetic reasons for flying with tail winds, we believe that wind direction is a key factor in the timing mechanisms of most birds. The other factors involved are less clear and vary from situation to situation. At present, it is probably safest to describe the typical values of all weather parameters when heavy migration of a given type occurs rather than to attempt to single out individual factors besides wind direction. We agree with Curtis (1969:244) that "the effects of specific weather components on migration should be examined in relation to the general weather situation rather than independently". Thus we find the following:

(i) *Heavy SE autumn migration in Alberta* usually occurs with a high to the W, SW, or S and/or a low to the E or NE. The wind is from the NW and the pressure is higher than the previous day. The temperature is relatively stable and not different from that on days of little movement. The humidity situation is unclear (Table 11). These conditions are somewhat different from those prevailing when there is SE reverse movement in spring (see below). It is not obvious why temperature should not be lower with heavy than with light migration in view of the strong correlation between heavy migration and NW wind.

(ii) *Heavy SW autumn starling migration in Ontario* usually occurs on days with geostrophic winds between N and E (surface winds between NW and E) on the E, SE, or S sides of highs or on the NW or W sides of lows. The temperature is both low and lower than the previous day; the humidity is near normal.

(iii) *SE spring reverse migration in Alberta* almost never occurs unless there in a high to the W or SW and/or a low to the NE or E. The winds are from the NW, the temperature is low and falling, and the pressure is rising. The humidity is high and it is on the average cloudier than when no reverse movement occurs. These humidity, temperature, and cloud correlations were not found with autumn SE migration, probably because spring reverse SE movement tends to occur closer to the low than heavy autumn SE migration (Fig. 12 and 13).

(iv) *Winter NW and SE movements in Alberta* occur in similar conditions to reverse autumn and spring migration respectively, except for temperature relationships. Both winter and reverse movements rarely occur without following winds while forward migration in spring and autumn is frequent with side as well as following winds (Table 3). Lack (1963b) also found that winter movements are very closely correlated with wind direction. While he believed that lapwings *(Vanellus vanellus)* undertake northward flights to Britain in winter to take advantage of unfrozen areas farther north, this is obviously not the case at Cold Lake in midwinter.

(v) *Heavy NW spring migration in Alberta* typically occurs with SE winds on the W or SW side of a high or the SE, E, NE, or N side of a low. The temperature is moderate and not increasing much more than when little movement occurs; the pressure is falling. The humidity is typically lower than when little migration occurs and perhaps slightly lower than the previous day. The intensity is greater on the average on days with SE wind and low humidity than on days with SE wind and higher humidity.

(vi) *Heavy NE spring starling migration in Ontario* typically occurs with SW winds SE or S of a low. On these days the temperature is high and rising (compared to low and falling on days without movement), but the humidity is not obviously different from days with no movement (Richardson and Haight, 1970). The temperature averages higher relative to normal here than with heavy Alberta NW movement because heavy starling flights occur later in the transition from high to low pressure than NW flights at Cold Lake, probably because the wind shifts from SE to SW as a high moves away and a low approaches. Also, increases in temperature with southerly airflows are likely to be greater in southern Ontario than in Alberta, since flows of maritime tropical air from the Gulf of Mexico frequently reach Ontario but do not reach Cold Lake. For the same reasons, the Alberta movements probably have lower humidity relative to days with no movement than the movements of Ontario starlings.

(vii) *NW autumn reverse migration in Alberta* occurs near the centres of highs and in the area of S flow and falling pressure when there is a high to the E and/or a low to the W or NW. Most flights have the near-normal and stable temperature and humidity found on the west side of a high. However, the few flights occurring with NW winds just before the high passed by had low temperatures. The usual conditions when NW autumn reverse migration occurred more closely resemble the typical conditions when spring NW movement occurred in Alberta than the situation when NE starling migration occurred in Ontario.

By the hypothesis proposed earlier involving selection of conditions with falling pressure gradient from right to left and following winds, heavy NE spring migration in Massachusetts would be expected to occur in the same conditions as NE starling migration in Ontario. However, it apparently occurs in conditions intermediate between those of heavy Alberta NW and Ontario NE migration (Nisbet and Drury, 1968). As in Alberta, it is associated with SE winds and low humidity. However, it is also associated with rising humidity and high temperature, which are to be expected later in the transition from high to low pressure than is typical of heavy NW migration at Cold Lake. As noted earlier, perhaps it is more advantageous to avoid the warm sectors and the possibility of encountering a cold front while in flight near the coast than it is disadvantageous to fly with a side rather than a following wind.

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Numbers, speeds, and directions of migrating geese from analysis of a radar display at Fort William, Ontario

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Introduction

Various methods have been used to obtain information on the flight speed of birds. Waterfowl have frequently been studied. Clayton (1897:26) and an assistant, each with a theodolite at the ends of a 8496-foot baseline, calculated the height, angular velocity, and speed of a flock of ducks. Meinertzhagen (1921), Aymar (1936), and Cooke (1937) each summarized the available methods and data. Using a stop watch, another observer, and telescopic communication, Speirs (1945:135) timed the speed of several flocks of oldsquaws through the cut between Toronto Bay and Lake Ontario. Speedometers in automobiles have frequently been used to obtain ground speeds of birds, and air-speed indicators in aircraft have been used to obtain air speeds of various birds.

Radar has presented a new opportunity to obtain ground speeds of birds. Using a Doppler radar, Schnell (1965) measured the speeds attained by 1627 birds of 17 species. This method has been restricted to birds flying within 20 to 50 yards of the portable unit or to birds released in the beam.

In the present study, we analysed a 16-mm time-lapse film of the radar display at the Fort William, Ontario, airport on October 3, 1965. The film shows a magnificent display of echoes crossing the field from north to south from 0300 to 1700 hours. These echoes are considered to be flocks of geese. The purpose of the analysis was to obtain quantitative expressions for the numbers, speeds, and directions of the flocks.

Methods

The 16-mm film was projected at a distance of 30 feet on sheets of graph paper about 2 feet square, attached to a vertical blackboard with Scotch tape. The display filled the sheets of paper at this distance.

The vertical lines of the graph paper were oriented so that they paralleled the north–south direction of the radar display. Individual echoes were traced across the paper with a pencil, and their flight directions measured with a protractor. The film in the projector could be stopped, reversed, and reprojected to check the accuracy of the measurements.

Flight speeds were determined by noting the time taken for a target to traverse a given length of path (generally about 20 nautical miles). Times to traverse this distance were read from the sweep-second hand of the clock which had been photographed with the radar display. One operator called out the beginning and end of the flight path while the other operator noted the elapsed time.

Numbers of echoes were determined by counting the numbers crossing an east–west line (about 41 miles wide) about 35 miles north of the centre of the radar display at 10-minute intervals. Knowing the speed of the targets, we then calculated the number of flocks in a square 100 miles by 100 miles (roughly the area of the radar display). The echoes were distributed over the whole screen, not concentrated into paths.

These measurements and observations were made by the junior authors under supervision of the senior author.

Discussion

Identification of the echoes

The echoes were large and bright, almost as conspicuous as those produced by aircraft. They could frequently be picked up at distances of 50 to 60 n.m. from the display centre. Only very large flocks can produce such echoes: geese, ducks, gulls, shorebirds, and blackbirds seem the only possibilities. Dr. W. W. H. Gunn believes that icterids can be eliminated as they generally produce more diffuse echoes. Most ducks passing over Fort William are en route from the Prairie Provinces and Northwest Territories and move from northwest to southeast, rather than from north to south. Geese are known to produce echoes similar to those made by aircraft.

Canada geese are known to breed along the Hudson Bay lowland near Fort Severn, Ontario, and to migrate to Wisconsin and Illinois. If projected backward, the flight paths of the echoes in question suggest an origin near Fort Severn; if projected forward, they suggest a destination in Wisconsin or Illinois. Dr. F. Graham Cooch (pers. comm.) stated that reports from Winisk and Severn, Ontario, suggest a major migration of blues, snows, and Canadas left October 2 and 3, 1965. An article in the *Ontario Logger* for March 1966, page 2, confirms that hunting for geese in the Hudson Bay area ceased shortly after the big flight was recorded on film at Fort William. Dr. Harold Hanson reported (pers. comm.) seeing geese over Sioux Lookout, Ontario, at about the time of this radar display at Fort William. Keith Denis (pers. comm.) reported hearing one flock of "honkers" over Port Arthur, Ontario, on October 3. The late Dr. A. E. Allin, hunting in the Sturgeon Bay and South Gillies area southwest of Fort William, recorded in his diary 40 blue and snow geese flying southwest at 5:15 p.m., October 3. Richard A. Hunt, biologist at Horicon Marsh, Wisconsin, (pers. comm.) wrote that there was a heavy influx of Canada geese along the east side of Horicon Marsh and along the Lake Michigan shore on October 3, with over 120,000 geese on the refuge by October 5, 1965. There can be no doubt then that a major flight of geese probably involving three species was in progress at the time the radar display showed the big flight of echoes, and there is no doubt in our minds that the echoes were in fact geese.

The fact that they were picked up by the radar at 60 n.m. indicates they were flying quite high and might easily have been missed by ground observers. The minimum height above ground, under normal conditions of refraction, at which the Fort William radar could detect objects at 60 n.m. is about 5500 feet, although some intermittent echoes might be expected from objects down to 4000 feet. At a range of 45 n.m., by which time most of the echoes noted on the October 3 display were strong and steady, the minimum height would be 4000 feet.

Flight directions

The flight directions (see Table 1) were remarkably consistent, deviating on the average less than 10° from due south. The directions tended to be slightly east of south in the morning and slightly west of south in the afternoon. To achieve these directions with a strong northwest wind (from 330°), the actual *headings* of the geese must have been strongly southwesterly, i.e., the geese must have compensated for the wind to a considerable extent, not merely flying downwind nor heading due south. The actual headings are calculated in Table 2 for a height of 4000 feet using the upper wind data provided by the Department of Transport (Table 3). Some wind drift (under-compensation) is suggested however by the gradual change from slightly east of south in the morning to slightly west of south in the afternoon as the wind velocity slackened in the afternoon.

Table 1
Radar directions of 928 flocks of geese passing over the Fort William, Ontario, region on October 3, 1965

Hour, EST	Number measured	Average direction, azimuth degrees	Standard deviation	Range, degrees
0300–0400	33	174.0	12.6	130–200
0400–0500	43	172.7	10.5	135–195
0500–0600	54	173.5	10.5	135–205
0600–0700	64	170.5	9.6	145–195
0700–0800	71	172.7	13.1	145–205
0800–0900	72	179.9	11.8	150–210
0900–1000	84	181.7	10.7	150–205
1000–1100	71	184.9	9.8	170–210
1100–1200	75	184.5	12.6	145–210
1200–1300	70	188.4	12.1	155–210
1300–1400	71	190.4	11.8	160–220
1400–1500	75	195.2	14.2	155–220
1500–1600	74	186.5	13.0	145–210
1600–1700	71	188.8	9.9	165–215

Table 2
Estimated headings and air speeds of goose flocks over Port Arthur, Ontario, on October 3, 1965, corrected for wind speed and direction at 4000 feet

Hour, EST	Headings, azimuth degrees	Air speeds, knots
0300–0400	210	27
0400–0500	205	30
0500–0600	205	30
0600–0700	200	24
0700–0800	205	29
0800–0900	220	28
0900–1000	220	28
1000–1100	210	35
1100–1200	210	35
1200–1300	220	33
1300–1400	220	32
1400–1500	220	36
1500–1600	210	35
1600–1700	215	34

Table 3
Winds aloft at Fort William, October 3, 1965

Altitude, feet	Wind direction, azimuth degrees	Wind speed, knots: 0000 to 0800	Wind speed, knots: 1200 to 1800
1000	330	25	12
2000	330	25	14
3000	330	30	15
4000	330	34	20
5000	330	40	27

Speed of flight

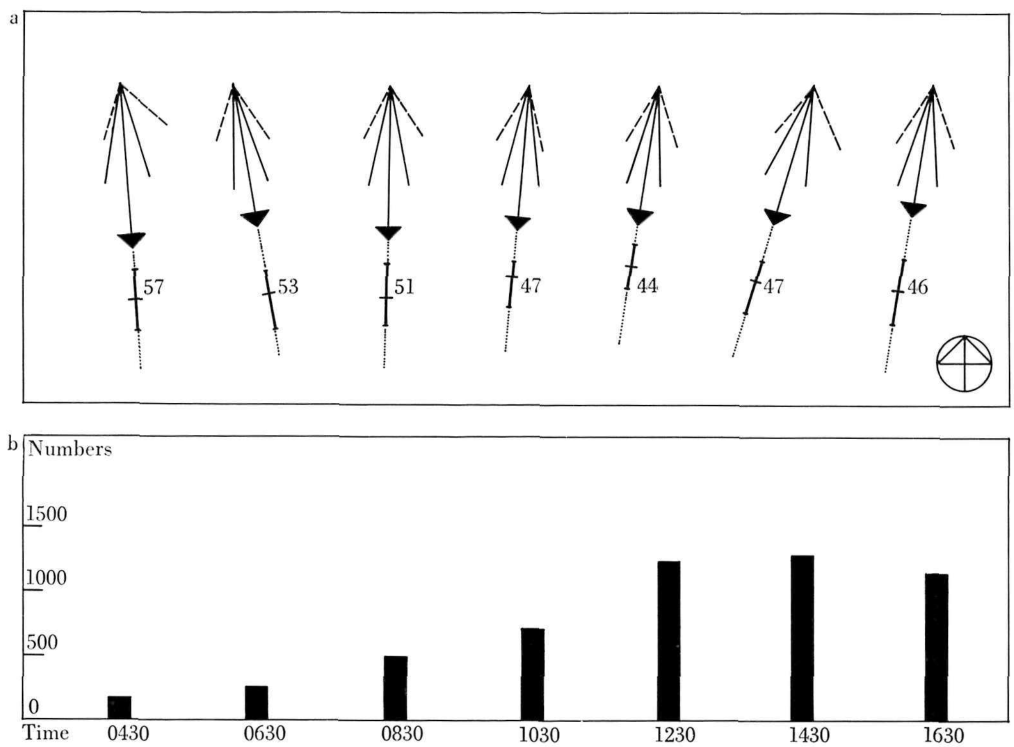
Figure 1a. Direction and ground speed in knots of Canada goose flocks crossing Fort William radar display October 3, 1965. The extremes of direction are indicated by the dashed lines, the mean direction is indicated by the solid lines, and the standard deviations from the means by the shorter solid lines on each side of the mean direction. Speeds are proportional to the lengths of the mean direction lines. Again, the dotted portions indicate the range of speeds, the solid lines the standard deviations from the mean, and the cross lines through the solid lines the average speeds at the given times. The data are presented in Tables 1, 3, and 4.
Figure 1b. Number of flocks per 100 x 100 square miles at 2-hour intervals from 0430 to 1630 on October 3, 1965.

Table 4 and Figure 1a show that the average *ground* speed of the geese was about 50 knots. At this rate these flocks could have left the Hudson Bay lowlands about dawn on October 3 and some could reach Wisconsin before dark on the same day. The *air speeds* (see Table 2) correspond with the calculation of Canada goose migration rates made by Hanson and Smith (1950:112) from Jack Miner's data, i.e., 35 to 40 miles per hour (30 to 40 knots). Based on data from Cooke (1937:6), Kortright (1942:42–43) gives Canada goose speeds of 60 miles per hour (chased) and 44.3 miles per hour by theodolite. Aymar (1936:138) gives 42 to 55 miles per hour for the flight speed of geese. Rathbun (1934:23) tried to keep up to a flock of cackling geese with a model T Ford but gave up the chase at 58 mph. (Those geese had a light favouring wind.)

Table 4
Ground speeds of 651 flocks of geese over the Fort William, Ontario, region on October 3, 1965

Hour, EST	Number measured	Average speed, knots	Standard deviation	Range, knots
0300–0400	20	53	7.0	40–68
0400–0500	15	57	9.2	43–77
0500–0600	24	57	10.3	38–78
0600–0700	42	53.4	7.3	37–67
0700–0800	50	54.5	7.9	41–78
0800–0900	50	51.2	7.3	39–69
0900–1000	50	50.6	6.8	36–69
1000–1100	50	47.5	6.1	35–66
1100–1200	50	47.9	4.8	40–63
1200–1300	50	44.5	4.6	36–58
1300–1400	50	42.6	7.3	33–80
1400–1500	50	47.2	6.3	34–63
1500–1600	50	49.0	7.4	34–69
1600–1700	50	45.7	7.4	33–67
1700–1800	50	41.4	6.9	29–63

Figure 1



Numbers

Table 5 and Figure 1b show that the peak of the flight over Fort William was in the early afternoon (1200–1600), when more than 1000 flocks were in the 10,000-square-mile area covered by the radar display at any one time. Approximately 5000 flocks crossed through this 10,000-square-mile area between 0300 and 1700 on October 3, 1965. If we allow 100 geese to a flock this would give an estimate of half a million geese. If we allow only 10 geese to a flock there would still be 50,000 geese. The truth is probably between these estimates. In my experience, 50 geese is about the usual flock size.

Table 5
Estimated number of goose flocks on the Fort William, Ontario, radar display (covering about 10,000 square miles) on October 3, 1965

Time, EST	Number of flocks
0330	149
0430	127
0530	251
0630	271
0730	464
0830	398
0930	586
1030	698
1130	1122
1230	1100
1330	1308
1430	1466
1530	1359
1630	961

Hazard to aircraft

The chance of a collision between an aircraft and flocks of migrating birds appears to depend on two factors: the target density (i.e., number of flocks per unit of volume) and the effective volume swept out by the aircraft crossing the zone containing these targets. The speeds of the aircraft and of the geese do not enter into the calculations, although these would no doubt affect the chances of either taking effective evasive action.

Gunn and Cockshutt (1966) have provided data on the effective area swept out by various types of aircraft in relation to bird flocks of various kinds, including geese. They have also provided data on the normal rate of climb of aircraft on take-off. To get the effective area swept out by the aircraft they have added to the actual width of the aircraft the effective diameter of the bird flock, and to its average height they have added the effective height of the bird flock. For the case of a DC-8 (say, 140 feet wide) intercepting a flock of geese (say, 220 feet in diameter), the effective area would be of the order of 10^{-4} square nautical miles $\frac{(140 + 220)\ (4 + 6)}{6000 \times 6000}$.

If the rate of climb is 1:10 then the aircraft would climb through approximately 10 n.m. before emerging above the zone containing goose flocks. We are assuming that the geese are confined to a zone 1 n.m. in vertical range and that the aircraft fly above this zone after take-off. The effective volume swept out in take-off would then be of the order of 10^{-3} cubic n.m. Our maximum target density was of the order of 1500 flocks per 100 x 100 square n.m. If we assume that they were confined to a vertical dimension of 1 n.m. this gives us a target density of 1500 per 10,000 cubic n.m.

The chance of a collision then works out to be of the order of $\frac{10^{-3} \times 1500}{10{,}000}$ or 1.5×10^{-4} or about 1 in 6500 take-offs. Note that in a *vertical* take-off this would reduce to 1 in 65,000, while in *horizontal* cruising through 100 n.m. of the zone containing geese it would become 1 in 650 (if we assume that the geese were evenly distributed vertically over the 6000 feet that we have assumed to contain all the goose flocks). If in fact the geese were all cruising at about the same level, say within a vertical range of 600 feet, the probability of a collision in level flight within this zone would increase to 1 in 65!

The hazard of geese to aircraft is greatest during fall migration, which takes place in late September or early October, usually when there is a strong northerly flow of air from the Hudson Bay area down to the midwestern states. This condition follows a cold front and precedes a ridge of high pressure with freezing temperatures in the Hudson Bay area. The hazard is probably greatest at elevations between 4000 and 6000 feet. It may be reduced somewhat by increasing the rate of ascent or descent through the hazardous zone, and level flight in this zone should obviously be avoided.

Acknowledgements

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The M33C track radar (3-cm) as a tool to study height and density of bird migration

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Introduction

Radar used for bird studies at
Canadian Forces Base, Cold Lake, Alberta

Operation Bird Track, initiated and sponsored by the Associate Committee on Bird Hazards to Aircraft of the National Research Council of Canada, is a project to develop a system of forecasting the intensity of bird migration, based on data obtained by time-lapse photography of displays on 23-cm radar screens.

From these data an intensity scale of bird movements, ranging from 0 through 8, was developed by arbitrarily selecting photographs to represent successive units

in the scale. Thus, intensity 0 corresponds with situations where there are no or very few bird echoes visible and intensity 8 with the greatest coverage of the radar screen by bird echoes. This scale was used to express the hourly intensity of bird movements at Canadian Forces Base Cold Lake, Alberta (Fryers, 1966). It became evident that the practical value of the migration forecasts would be materially increased if one could (a) obtain an idea of the height distribution of nocturnally migrating birds, and (b) establish the numerical relationship between each unit of the 0–8 intensity scale.

The purpose of this paper is to report on a trial of M33C (3-cm) track radar as a means of determining height distribution of night migrants and of estimating their numbers.

Radar studies on the height of migration have been carried out in Switzerland by Sutter (1957) and Gehring (1963), in England by Harper (1958), Lack (1960), and Eastwood and Rider (1965, 1966), and in the United States by Nisbet (1963a) and Bellrose and Graber (1963). This work has been reviewed by Eastwood (1967) in his book *Radar Ornithology*.

To determine the numerical relationships between the units of the intensity scale one has to compare the hourly intensities with counts or estimates of the migrating birds.

The density of nocturnal migration has been calculated by Lowery (1951), who introduced the moon-watch technique. Density is expressed as the number of birds per mile of front per hour, mentioned in later work (Lowery and Newman, 1966) as the migration traffic rate. Nisbet (1963b) used moon-watch data to develop a system to calculate bird densities from radar data.

The migration traffic rate was calculated from radar data by Graber and Hassler (1962) in the United States and by Eastwood and Rider (1966) in England.

Brief description of M33C track radar

The M33C radar is an anti-aircraft radar consisting of a 10-cm search and 3-cm track radar. Targets observed on the Plan Position Indicator (PPI) screen of the search can be followed with the track radar either manually or automatically. Height and track of the target can also be plotted automatically. The RCAF provided a complete M33C radar set for Operation Bird Track.

The PPI of the search radar did not show bird echoes. The Moving Target Indicator (MTI) circuit, designed to reduce ground clutter, did not work effectively. Radar technicians told me that this is common with the M33C search radar.

The track radar worked well and, according to the technicians, tends to break down less frequently than the search radar.

The antenna of the track radar is mounted on the roof of the Operations Van (Fig. 1). All other components are housed in the Operations Van, with the exception of the Auxiliary Power Unit.

The frequency varies between 8,500 and 9,600 MHz; the wave length is about 3 cm. The peak power is 250 kw for a pulse width of 0.25 μsec (peak power measured in the field was 180 kw). Pulse repetition frequency is 1,000 pulses per second.

The antenna is of the phase advance type and steerable in azimuth and elevation. The beam has a width of 22 mils ($= 1.2°$; 17.78 mils $= 1°$) in both the horizontal and vertical plane. This is the angle between the half-power points, where the energy is half as much as at the axis of the beam. By rotating the feedhorn of the radar, a wider beam is obtained. This method, called conical scan, enables automatic tracking of a target. The radiation pattern is shown in Figure 2. The width of the conical-scan beam is 40 mils (2.2°) between the half-power points. At these points the energy is more than half that at the beam's centre (or lens axis).

The radar echoes are represented as "pips" or "spikes" on three A-scopes (one each for azimuth, elevation, and range). By switching on range markers one can

Figure 1. Operations van of M33C radar, with the antenna of the track radar mounted on the roof (from U.S. Dept. of the Army, 1956).

Figure 2. Radiation pattern of M33C track radar, using conical scan. The width of this conical-scan beam is 40 mils (2.2°) between the half-power points. (Redrawn from U.S. Dept. of the Army, 1956).

Figure 1

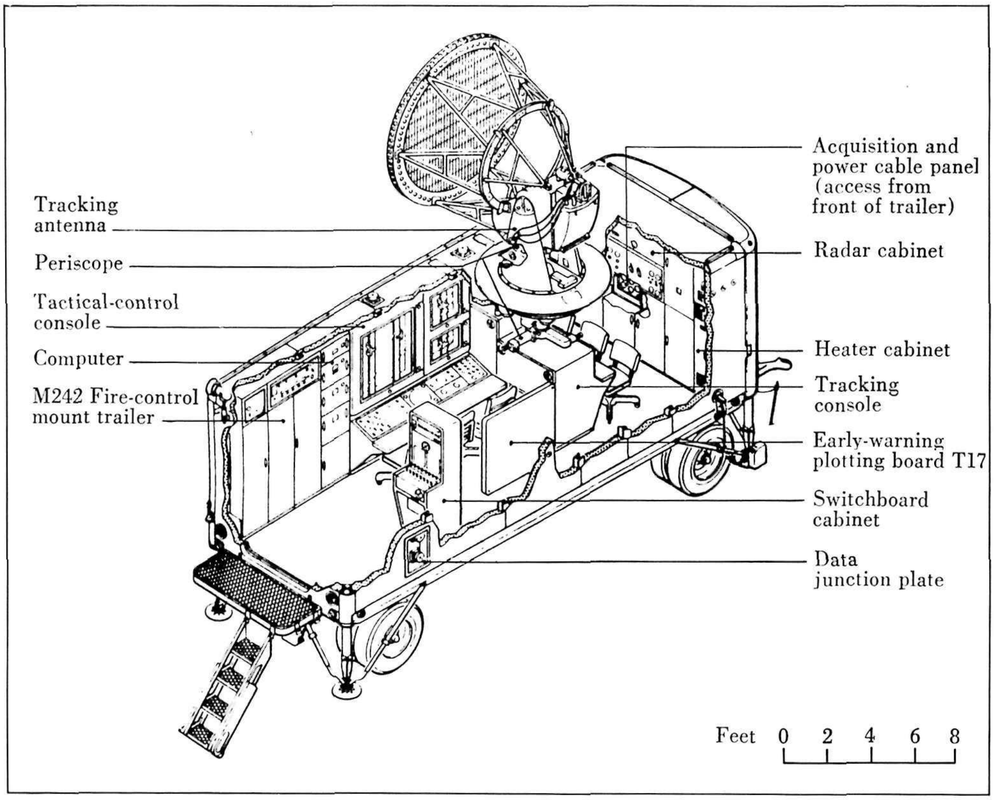
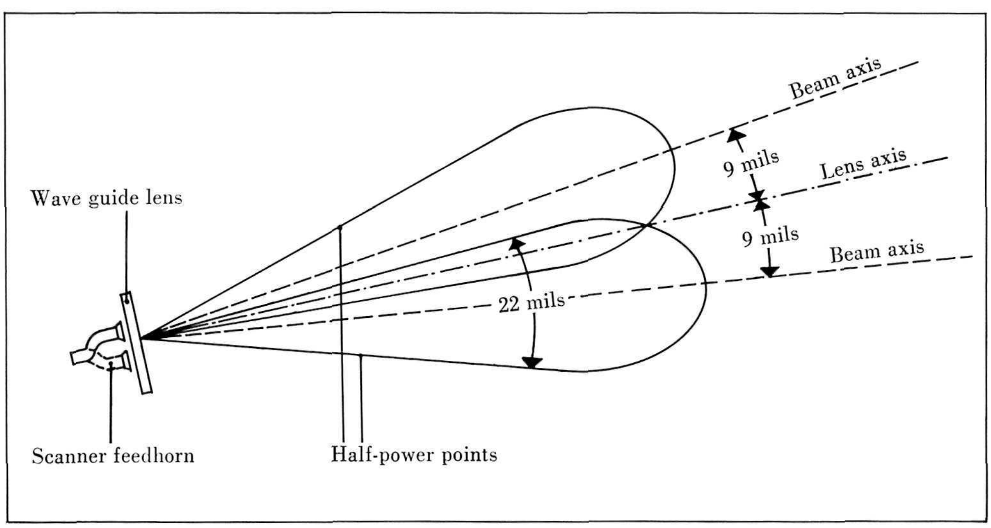


Figure 2



estimate the slant range of the target. Azimuth and elevation can be read from dials. Height can be found from slant range and elevation angle.

The periscope system of the radar is particularly helpful for bird studies. This 8x-power periscope is mounted in the centre of the antenna and moves with it. It has three oculars inside the radar van. To study the echo of a known bird target, one man kept the bird at the intersection of the cross-hairs of the periscope (and thus in the centre of the radar beam) while another man observed the height of the spike of the bird and its range while it moved through the air.

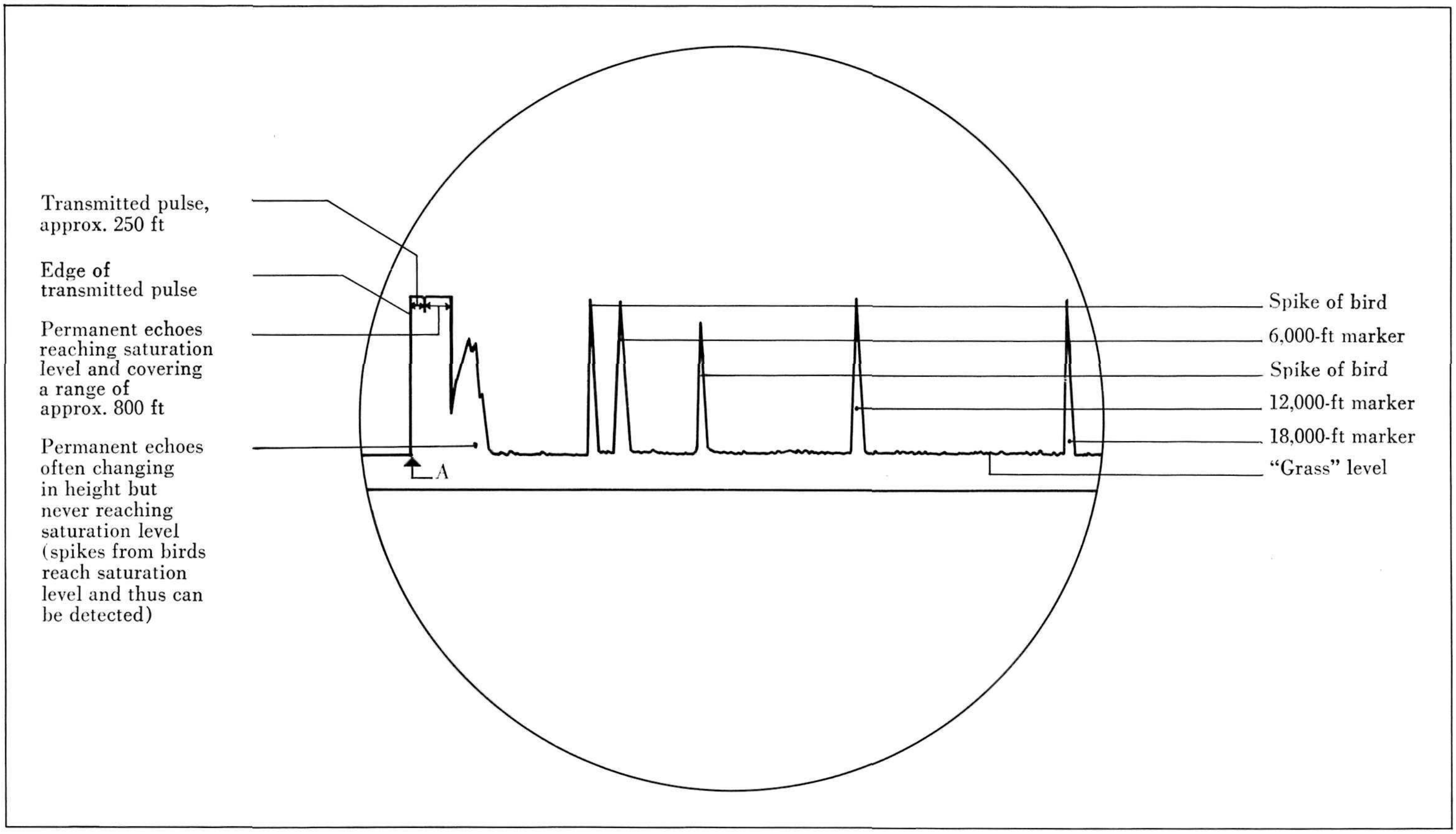
Detailed information on this radar equipment can be found in military handbooks (U.S. Dept. of the Army, 1956).

The M33C radar was built shortly after World War II. For many military purposes the M33C is now becoming obsolete and thus easily accessible for non-military organizations. Maintenance is increasingly difficult since many parts are no longer manufactured. Cannibalization is often helpful. In the United States the M33C search radar is used for weather studies (Davis, 1963).

Method of operation

Figure 3. Presentation of A-scope of vertically aimed M33C track radar, during a night of migration in fall 1968, Primrose Lake, Alberta. Point A, at the bottom of the edge of the transmitted pulse, is the 0-foot marker.

Figure 3



The M33C radar set was installed at the Primrose Lake Evaluation Range, 54°49′N latitude and 110°02′W longitude. The site was on the southwest shore of the panhandle of Primrose Lake, Alberta, at an elevation of about 55 feet above lake level and 2,020 feet above sea level.

Conical scan was used during both routine operations and experiments. (When using the term beam width, I from now on refer to the width of the conical-scan beam.) The track radar was kept at an elevation of 1,560 mils (or 87.7°). When aimed completely vertically, the antenna hits a switch that makes the antenna turn down again. When making calculations, the antenna was considered to be aimed at 90° elevation.

The azimuth was kept at 3,200 mils (or due south) after we had found that this setting coincided with the smallest amount of permanent echoes.

The range setting of one of the A-scopes was adjusted so that a range of just more than 18,000 feet filled the scope. This scope was filmed with a modified N9 camera (16 mm). The exposure time per frame was 6 seconds.

Since the range markers (6,000, 12,000, and 18,000 feet) could easily conceal a bird spike, they were switched on only for a few frames every half hour.

Figure 3 is a typical example of the scope's presentation during a night of migration. When the scope's image was properly focused, as in Figure 3, there was an ineffective range from 0 to approximately 1,050 feet. To increase the brightness of the presentation, the image was usually slightly off-focus. Then the lines of the image were thicker, resulting in an ineffective range from 0 to 1,200 feet.

The radar films were assessed by projecting the film frame by frame on a screen that was fitted with a numbered scale. By placing the projector at a fixed distance from the screen, each number of the scale corresponded to a certain range (in our case altitude), providing that point A (see Fig. 3) of the projected frame coincided with the beginning of the scale. Thus it was possible to divide the 18,000-foot range into portions of 200 feet each and to count the bird spikes in each height band.

Effectiveness of M33C track radar in detecting birds

For a quantitative evaluation of the data obtained with the vertically aimed track radar one has to know how many birds are missed because the birds are flying too low, or too high, or too close to the edge of the beam. Birds may also pass unnoticed due to meteorological conditions.

Birds missed because they fly too low

The radar had an ineffective range from 0 to 1,200 feet. One night, October 5/6, 1968, a nearly full moon and clear sky permitted an experiment to find how many birds at low altitude were picked up by the moon-watch technique (Lowery, 1951) but not by the radar. The ground wind that night fluctuated between 0 and 4 miles per hour. The surface temperature reached a low of 30°F at 0400 hours Mountain Standard Time (MST) on October 6 (data for CFB Cold Lake). The PPI of a search radar near Cold Lake, approximately 30 miles from Primrose Lake, showed migration of medium density (intensity 4) in an easterly direction.

The moon was followed simultaneously by telescope (20x Bushnell) and by radar. The moon was kept at the intersection of the cross-hairs of the radar's periscope by continuous adjustment of the azimuth and elevation of the antenna.

The telescope observations were made outside the van, on the ground just below the antenna, the distance between the telescope and the antenna being about 18 feet.

The radar screen was watched continuously for bird spikes. The screen-watcher and moon-watcher (who used a walkie-talkie) informed the recorder as soon as they saw a bird spike or bird, respectively. I assumed that observations made at exactly the same time were of the same bird. The results are shown in Table 1.

Table 1 shows that only 36 of the 44 birds seen by the moon-watcher were observed by the radar. This would seem to indicate that eight birds were missed by the radar because they flew too low.

This is, however, not the case. The moon-watcher estimated the range of every bird he saw. The radar range on the screen was divided with grease pencil in six segments, each 3,000 feet. By comparing the estimates of the moon-watcher with the actual range shown on the radar screen, it appeared that the estimates were rough but reasonably reliable.

Table 1
Periods that moon-watch observations were made simultaneously by radar and telescope. Numbers observed by each method. October 5/6, 1968, Primrose Lake, Alberta

Period of observation (MST)	No. of bird spikes on radar screen	No. of birds seen by moon-watcher	No. of birds observed by radar and moon-watcher at same time	No. of birds seen by moon-watcher, but not by screen-watcher
2057–2147	113	15	12	3
2305–2353	101	7	4	3
0153–0243	113	17	16	1
0249–0309	38	5	4	1
Totals	365	44	36	8

Table 2
Moon-watcher's estimates of size, speed, and range of birds missed by radar, October 5/6, 1968, Primrose Lake, Alberta

Time (MST)	Estimated by moon-watcher: Size	Speed	Range
2059	Medium		Medium (6,000–9,000 ft)
2105	Very small	Slow	Very far out (beyond 10,000 ft)
2125	Small	Fast	About 7,500 ft
2313	Very small	Medium	Very far out (beyond 10,000 ft)
2316	Medium	Medium	About 10,000 ft
2321	Medium	Fast	Under 6,000 ft
0211	Large	Slow	About 6,000 ft
0301	Medium	Fast	About 6,000 ft

Seven of the eight birds missed by the radar had estimated ranges of "medium" to "very far out" (see Table 2). The eighth was "under 6,000 feet" but not "close by".

Apparently there were no birds flying at low altitude during that night, or at least so few that none were observed by the moon-watcher. During nights with low-altitude migration the radar would miss an unknown portion of the birds.

It still has to be explained why the radar missed eight birds. One reason might be that the distance between telescope and radar antenna is so great birds flying through the "inverted cone of moonlight" need not necessarily fly through the "inverted cone of radar energy". This is in all likelihood not the case. Rense (1946) describes a method to calculate the height of migrants from simultaneous observations of two moon-watchers. He advises a distance of 5 to 8 feet for optimal results. In our case the centres of the antenna and the telescope were about 18 feet apart, but instead of having two cones of moonlight, each with an apex-angle of 0.5°, we had one cone of moonlight with an apex-angle of 0.5° and one cone of radar energy with an apex-angle of 2.3° (i.e., the "effective beam width" which will be discussed later). Calculations, given in Appendix 1, show that

Table 3
Results of tests with birds carried aloft by balloons and followed with the M33C track radar, Primrose Lake, Alberta. Test (a) was carried out on November 1, 1968, tests (b) and (c) on November 15, 1968

	(a) One snow bunting		(b) Two redpolls		(c) One redpoll	
Slant range of birds (feet)	Estimated average height of bird spike (as percentage of maximal height)	Angular distance between bird and balloons (in mils)	Estimated average height of bird spike (as percentage of maximal height)	Angular distance between bird and balloons (in mils)	Estimated average height of bird spike (as percentage of maximal height)	Angular distance between birds and balloons (in mils)
4,800	100	> 50				
8,700	100					
9,000±	95		100	> 50		
9,600	70	35				
10,200	60					
10,500			90	> 50		
11,400	35	27	70	> 50		
12,000	30				60	35
12,300			50–60	> 50		
12,600					50	33
12,900	25	22				
13,500			50–60	> 50	20	30
15,000	15	20				
15,600			40–50	50	15	28
17,400			30	45		
18,000			30	40	Spike barely noticeable	26
21,000			15–20	27		
24,000			Spike barely noticeable			

the radar and moonlight cones, with apices 18 feet apart, start to overlap each other at shorter range than two moonlight cones with apices 8 feet apart.

Another reason might be that birds seen with the telescope at very great range are missed by the radar. This is not the case as is shown in the second part of Appendix 2. The fact that eight birds seen by the moon-watcher were not recorded by the screen-watcher seems most likely to be due to inattentiveness of the screen-watcher.

Birds missed because they fly too high
The maximum range at which the M33C track radar can detect birds was determined by manually tracking birds that were carried aloft by balloons. The balloons were released close to the van, so that we could "lock on" the bird, using the periscope, at its point of take-off. As the balloons drifted away, the range of the bird increased and the average height of its spike on the screen slowly decreased. We used red, hydrogen-inflated balloons, about 2 feet in diameter.

Since one balloon gave detectable radar echoes at ranges of about 10,500 feet, long string was used to separate birds and balloons.

Both cross-hairs of the periscope were provided with scales in mils (17.78 mils

= 1°). The angle of vision of the periscope was 100 mils, there being 50 mils from the centre to the edge. The width of the radar beam was 40 mils at the half-power points (see Fig. 2).

Just after release, only the bird showed in the periscope's field of vision. After a few minutes the balloons could usually be seen at the edge of the field of vision. The calibrated cross-hairs enabled us to tell at what range the balloons were entering the beam, i.e., were coming within 20 mils of the centre. This information was important since we wanted to study the spike of the bird and not that of the combination of bird and balloons.

The following tests gave conclusive results:

(a) On November 1, 1968, a pair of balloons carried aloft one live snow bunting *(Plectrophenax nivalis)* at the end of about 300 feet of 2-mm cotton twine. The balloons were 4 feet apart. Up to a range of 8,700 feet the height of the bird spike was maximal. At greater range the height began to fluctuate and the average height gradually decreased. The results are given in Table 3. The radar technicians were able to follow the balloon-bird combination out to 24,000 feet, but I considered 15,000 feet the maximum range at which a free-flying bunting-sized bird crossing the centre of the beam would give a bird spike that is still just detectable.

(b) On November 15, 1968, a pair of balloons carried aloft two dead common redpolls (*Acanthis flammea*) at the end of about 600 feet of 1.5-mm nylon string. The balloons were 4 feet apart, the redpolls about 15 cm. The results are given in Table 3.

When the birds were at a range of 12,000 feet we briefly raised the elevation of the antenna to pick up the balloons. They gave a spike that was barely noticeable. The string itself did not give a detectable echo.

(c) A test similar to (b) but with one instead of two dead redpolls yielded the results given in Table 3. This test was also carried out on November 15, 1968. No data were obtained for short ranges since the radar operator had difficulty picking up the bird immediately after take-off.

Table 3 shows that on November 1 a snow bunting at 12,000 feet produced a bird spike with an average height of only 30 per cent of maximal, whereas on November 15 a common redpoll (which is smaller than a snow bunting) at 12,000 feet produced a bird spike with an average height of 60 per cent of maximal. The radar's superior performance on November 15 was probably due to the fact that the crystals of the receiver had been replaced.

These tests indicate that sparrow-sized birds can be detected at altitudes up to about 15,000 feet, provided the birds fly through the centre of the beam. This height is much greater than that at which most migration is reported to occur. Nisbet (1963a) found that during nocturnal migration over Cape Cod, Massachusetts, an average of 90 per cent of the birds flew below 5,000 feet, the most frequent height usually being 1,500 to 2,500 feet. It is, therefore, unlikely that migrants that cross the beam close to its centre will pass undetected because they fly too high.

Birds missed because they fly at the edge of the beam

During moon-watch observations the inverted "cone of moonlight" forms a well-defined observation area. Birds passing beside the moon are not counted.

In the case of a vertically aimed beam of radar energy the observation area is not exactly defined, since the radar energy drops from the centre to the sides. Beam width is usually given as the angle between half-power points, i.e., points with half the energy of that at the centre. This angle is 40 mils for the M33C track radar, when using conical scan.

A tight flock of birds may produce a bird echo when flying outside the 40-mil beam, while a single, small bird flying inside the 40-mil beam may be detected only when it actually crosses the centre of the beam. Thus, there is no such thing as "the" beam width of the radar. Yet one needs a well-defined beam width (sample area) to calculate height distribution and density of the migrants.

It was possible to determine what I call the "effective beam width" from the results of the moon-watch experiment already mentioned. In this calculation the number of birds observed through the telescope and its known observation area were compared with the number of birds detected by the radar and its unknown observation area. In this way the "effective beam width" was calculated as 2°19′ or 41.25 mils. The calculation and the assumptions made are given in Appendix 2.

The meaning of the "effective beam width" is not that the radar detects all birds that are inside and none that are outside the beam. It means that the radar, though missing a few small birds that cross the beam at the edge but picking up a few big ones, or flocks, that pass outside the beam, will give an estimate of the numbers flying through the effective beam. No attempts were made to determine the accuracy of the calculated effective beam width, since only few data were available and many assumptions had to be made.

Since the effective beam is applicable to altitudes of up to 9,600 feet (see Appendix 2), it can be used to deal quantitatively with the bulk of the radar data. As mentioned before, 90 per cent of the nocturnal migration over Cape Cod occurred below 5,000 feet (Nisbet, 1963a).

Birds missed because of weather conditions

The vertically aimed track radar detects clouds and birds flying below them. An unknown proportion of the birds flying above or in the clouds will pass undetected. It is, therefore, necessary to record clouds and precipitation overhead during the observation periods and to take these factors into account when assessing radar films.

Determination of height distribution

In Figure 4 a schematic view is given of the effective radar beam, aimed vertically. This figure shows that the sample area increases with height and that correction factors are to be used to make the data comparable for different height bands. Assuming an even vertical bird distribution, the numbers of birds per height band, intercepted by the vertical radar beam, relate as the surfaces of the bottom triangle and the trapezoids (1:3:5:7 etc.) as is explained in the first part of Appendix 2. The 2,400- to 3,600-foot band was chosen as the standard height band, since it is often the altitude of densest migration.

The correction factor for each height band is given in the right column of Figure 4. Since the effective beam width holds for only the first 9,600 feet (see Appendix 2), the correction factor for higher altitudes is considered the same as that for the 9,000- to 9,600-foot band.

The corrected numbers per height band give a fair idea of the height distribution above the 1,200-foot altitude.

As an example of the height distribution, the results for the night of September 27/28, 1968, are given in Table 4. During this night the sky was clear. Ground winds were southerly and light. After 2300 hours it was calm at ground level. At 2300 hours the wind at 3,000 feet above ground level was west-southwest at 15 mph, at 5,000 feet it was west at 13 mph (data for CFB Cold Lake). On the PPI of the search radar near Cold Lake a heavy southeasterly migration was recorded.

Table 4 shows that 90.4 per cent of the birds above 1,200 feet flew below 6,000 feet and that there was no preferred height band between 1,800 and 5,400 feet. The height distribution between 1,200 and 5,400 feet suggests that the number of birds flying below 1,200 feet might have been small.

The height distributions per observation period are plotted in Figure 5. There is a tendency for the birds to fly higher in the latter part of the night.

The results of a single night are not a good comparison with the results of most

Figure 4

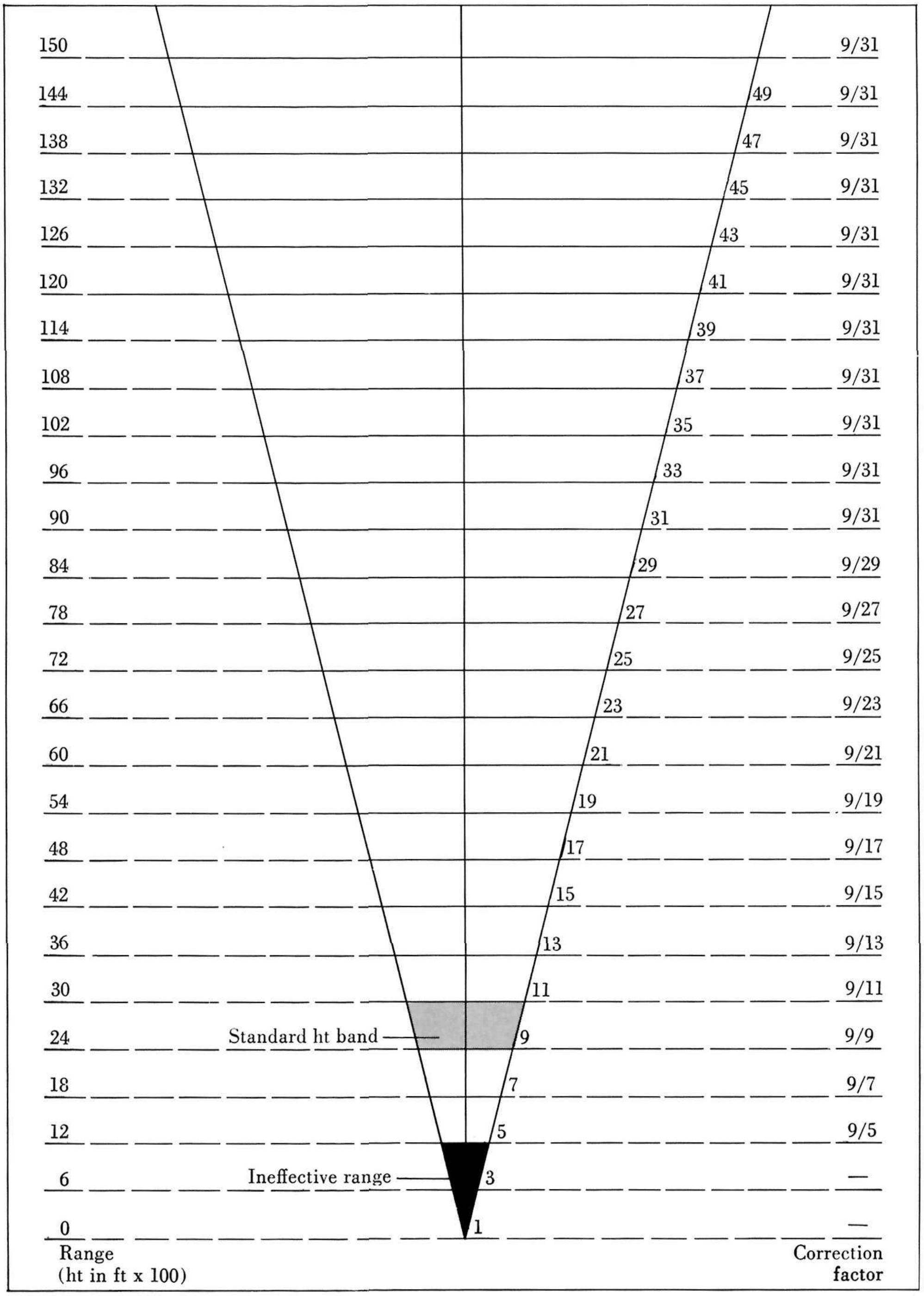


Figure 4. Schematic view of the "effective radar beam". The surfaces of the bottom triangle and the trapezoids relate as 1:3:5:7, etc. The left column shows the height bands, the right one the correction factor for each height band.

Figure 5

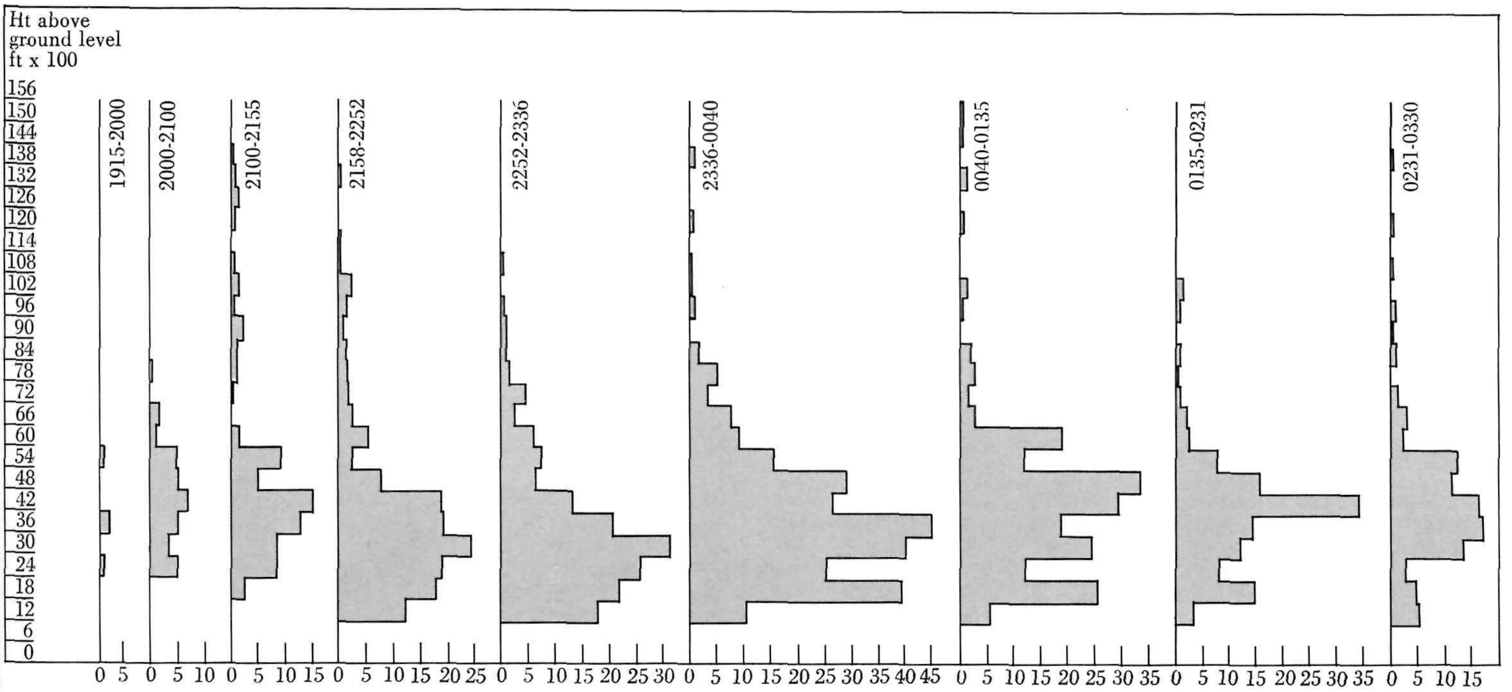


Figure 5. Height distribution of migrants above 1,200 feet, September 27/28, 1968, Primrose Lake, Alberta. Periods of observation, in MST, are indicated in upper part of the figure.

other workers. Graber and Hassler (1962), however, gave the height distribution of fall migrants over Illinois throughout one September night with heavy migration, using two methods which gave rather different height distributions. Yet their data show that there was no preferred height band and suggest that few birds were flying below 1,000 feet.

Table 4
Height distribution of migrants flying above 1,200 feet, during the night September 27/28, 1968, Primrose Lake, Alberta. Total number of bird spikes was 1,665

Height above ground (feet)	Per cent of total of corrected numbers of birds	Height above ground (feet)	Per cent of total of corrected numbers of birds
1,200–1,800	5.1	7,800–8,400	1.2
1,800–2,400	12.6	8,400–9,000	.7
2,400–3,000	9.7	9,000–9,600	.3
3,000–3,600	16.7	9,600–10,200	.3
3,600–4,200	13.4	10,200–10,800	.5
4,200–4,800	15.9	10,800–11,400	.2
4,800–5,400	11.2	11,400–12,000	*T
5,400–6,000	5.8	12,000–12,600	T
6,000–6,600	3.1	12,600–13,200	T
6,600–7,200	1.9	13,200–13,800	T
7,200–7,800	1.1	13,800–14,400	T

*T = trace (< 0.2 per cent).

Determination of density

The effective beam width is 2°19′; the diameter of this beam at a range of 2,700 feet, the middle of the standard height band (2,400–3,000 feet), is 117 feet. The data for all other height bands have been corrected so as to be directly comparable with this standard.

By adding up all the adjusted numbers one obtains the number of birds passing per 117 feet of front.

Multiplication by 45 gives the number of birds per mile of front of all migration above 1,200 feet altitude. The migration traffic rate is the number of birds per mile of front per hour.

As an example of the density of migration, the results for the night September 27/28, 1968, are shown in Table 5. Density of migration peaked around midnight. This is in accordance with findings of Graber and Hassler (1962), who studied nocturnal fall migration over Illinois. They reported that the night of September 28/29, 1960, brought one of the heaviest flights of migrants through the Champaign region of Illinois recorded in that year. The estimated peak flight density on that night was 1,970 birds per mile of front per hour. The night of September 27/28, 1968, was one of the five nights during that month that had heavy migration over the Cold Lake area and the estimated peak density during that night was 10,930 birds per mile of front per hour. These figures cannot be compared very well, because of differences in equipment, location, and species involved.

Table 5
Periods of observations with vertically aimed track radar at Primrose Lake, Alberta, on September 27/28, 1968, and the numbers of birds per mile of front per hour (migration traffic rate)

Period of observation (MST)	Duration of observation period (minutes)	Number of birds per mile of front during observation period (above 1,200 feet)	Migration traffic rate (above 1,200 feet)
1915–1945	30	166.5	333
1945–2045	60	1,759.5	1,760
2045–2152	67	4,081.5	3,655
2158–2252	54	6,399.0	7,110
2252–2336	44	7,294.5	9,947
2336–0040	64	11,659.5	10,930
0041–0135	54	9,405.0	10,450
0135–0231	56	5,508.0	5,901
0231–0331	60	4,113.0	4,113

Discussion

Drawbacks and advantages of the method used

The main drawback of the vertically aimed track radar is that it is ineffective at close range (0–1,200 feet); this is probably due to echoes from ground objects caused by side and back lobes. La Grone *et al.* (1964) had a similar problem with their vertically aimed M33C track radar. They reduced their ineffective range from 5,900 to 2,000 feet by moving the radar van into a deep, narrow gravel pit to screen off side and back lobes. The relatively short ineffective range (1,200 feet) of our radar at Primrose Lake can perhaps be further decreased by building a fence of material that absorbs radar energy (pers. comm., Dr. F. R. Hunt, National Research Council).

Another disadvantage of the technique is the small sample size. Bellrose and Graber (1963) rotated the pencil beam of their 3-cm radar in azimuth under an elevation angle of 30° to detect more birds. We did not use this method since the ineffective range increases considerably at azimuths other than the one we used for routine observations. We also would have lost an unknown portion of high-flying birds. The vertical beam method provides a good idea of the bird movements overhead, but these are not necessarily an accurate representation of the migration over a wider area.

The main advantage of M33C X-band radar, with its peak power of 180 kw, is its capability to detect single, small birds that fly through the centre of the beam at ranges up to 15,000 feet. The X-band radar used by Bellrose and Graber *(op. cit.)* had a peak power of 45–52 kw, and the range above which the effectiveness in detecting birds was reduced was about 6,400 feet.

The effective beam width is useful when dealing quantitatively with the radar data. However, it is applicable only to altitudes up to 9,600 feet (see Appendix 2), and its accuracy was not determined because of the scarcity of the data. Given that (a) the intensity of bird echoes usually fluctuates strongly, (b) the beam width between the half-power points is 40 mils, and (c) single

Table 6
Number of birds detected by radar, by radar and telescope at the same time, and their relation, October 5/6, 1968, Primrose Lake, Alberta

Range band (feet)		Birds detected by radar (a) and in parentheses those observed by telescope at the same time (b)					
		2057–2147	2305–2352	0153–0243	0249–0309	Totals	a:b
I	0– 3,000	2 (1)	9 (1)	9 (1)	2 (0)	22 (3)	7.3:1
II	3,000– 6,000	28 (4)	24 (1)	39 (9)	8 (3)	99 (17)	5.8:1
III	6,000– 9,000	59 (5)	36 (1)	28 (4)	12 (1)	135 (11)	12.2:1
IV	9,000–12,000	21 (2)	32 (1)	33 (1)	14 (0)	100 (4)	25.0:1
V	12,000–15,000	2 (0)		4 (1)*	2 (0)	8 (1)*	8.0:1
VI	15,000–18,000	1 (0)				1 (0)	

*Doubtful. Another bird spike was simultaneously seen on the radar screen at the 3,000- to 6,000-foot range. The moon-watcher's estimate was "very high".

Table 7
Results of χ^2 tests, applied to the difference between the values for a:b, given in Table 6.
S = significant difference, NS = non-significant difference

a:b (Range-band I)	and a:b (Range-band II)	NS	$P > 0.05$
a:b (Range-band II)	and a:b (Range-band III)	S	$0.025 < P < 0.05$
a:b (Range-band III)	and a:b (Range-band IV)	NS	$P > 0.05$
a:b (Range-band I and II)	and a:b (Range-band III, IV, V, VI)	S	$P < 0.005$
a:b (Range-band, I, II, III)	and a:b (Range-band IV, V, VI)	S	$0.025 < P < 0.05$

birds produced detectable echoes at ranges up to 15,000 feet, one would have expected the effective beam width to be in the same order of magnitude as that between the half-power points. As the effective beam width is dependent on the species composition of the migrants and their flocking patterns, it might vary during the migration season, and even between height bands during one night. These variations would probably be small, particularly during nights of heavy migration, when both small and big birds are on the wing.

Mr. A. E. Krause, University of Saskatchewan, mentioned to me that birds might be detected not only by the main beam but by the minor lobes of the beam as well. However, Capt. P. L. Burcombe, the military expert on the M33C radar, wrote me that the antenna of the M33C track radar is specially designed to produce only one thin pencil beam and that "unless the antenna is damaged or incorrectly installed, minor lobes if any, are a negligible factor". Since our antenna was undamaged and properly installed by experienced technicians, there were probably no minor lobes biasing the results. When continuing the M33C observation program, calibration tests should be carried out to check this assumption.

The film exposure time was 6 seconds per frame. Thus two birds flying through the beam at the same height will show up as one bird spike on the film, even though they might have been flying in different directions and up to 5 seconds apart.

Having no accurate data in this regard, I would guess that the number of birds that passed undetected because their spike was concealed by another bird spike would be less than 5 per cent of the total. It seems worthwhile to reduce the exposure time to eliminate this source of error.

Comparison of the method used with those of other workers

A. Height

3-cm radar. Compared with the APS radar used by Graber and Hassler (1962) and Bellrose and Graber (1963), the M33C track radar has the advantage of a greater range (15,000 ft). At close range with the APS radar no data could be obtained for the 0- to 1,000-foot height band. For the M33C track radar this ineffective range extended from 0 to 1,200 feet.

Eastwood and Rider (1966) used a vertically aimed, high resolution, 3-cm radar. Eastwood (1967) explained that the transmitter of this radar supplied pulse lengths of 1 μs or 0.3μs which corresponded to minimum altitudes of 491 and 147 feet, respectively, or range intervals for measurements of 600–8,000 feet and 300–2,000 feet, respectively. The M33C detected birds from 1,200 feet to 14,400 feet.

Because of the low elevation angle of his 3-cm radar, Sutter (1957) could study only a height range of 165 of 3,000 feet. This height range was even further reduced when later a rain filter was built in (Gehring, 1963).

10-cm radar. Nisbet (1963a), who used 10-cm radar, says that "for practical reasons, the quantitative study was restricted to heights above 600 feet" since it was usually impossible to observe birds below 600 feet. He also pointed out that quantitative observations in his paper "refer to the height distribution of flocks, which is not necessarily the same as that of birds". The moon-watch experiment showed that the M33C track radar probably detected individual birds rather than flocks. Harper (1958) and Lack (1960), who both used 10-cm radar, did not give details of the bird-detecting capabilities of their height-finding equipment.

23-cm radar. Interesting results were obtained by Eastwood and Rider (1965), who used a 23-cm radar tracker which "was equipped with the M.T.I. facility, i.e. moving target indicator, so that bird targets well below 1,000 feet, which are normally obscured by the ground clutter, could also be observed and their altitudes measured". Their height distributions show in many cases a considerable number of bird echoes below 1,000 feet. This shows that attempts to reduce the ineffective range of the M33C track radar are well worth considering.

B. Migration Traffic Rate

Compared with the moon-watch technique of Lowery (1951), the radar has the advantages of a larger sample area, better detection of birds at ranges greater than 6,000 feet (Appendix 2, Table 6), ability to measure and compensate for height distribution, and simpler calculations (since the beam is vertical). Radar can be used every night, even when there is a high layer of clouds. Filming of the scope provides a permanent record.

Disadvantages of the radar are the efforts required to keep it running and it ineffective range, 0–1,200 feet. In comparison, we tested the ineffective range of a 20x Bushnell telescope focused on the moon by moving a cardboard cut-out of a 20-cm-long bird with half-extended wings across the moon's surface. The cut-out was attached to a long stick. We are unable to give the cut-out a speed of migrating birds. At the low speeds that we used, the cut-out appeared as an unrecognizable blur for a range of 0–100 feet.

The moon-watcher has a well-defined sample area but this is partially undone by the fact that some birds at the edge of the moon are missed (Nisbet, 1963b).

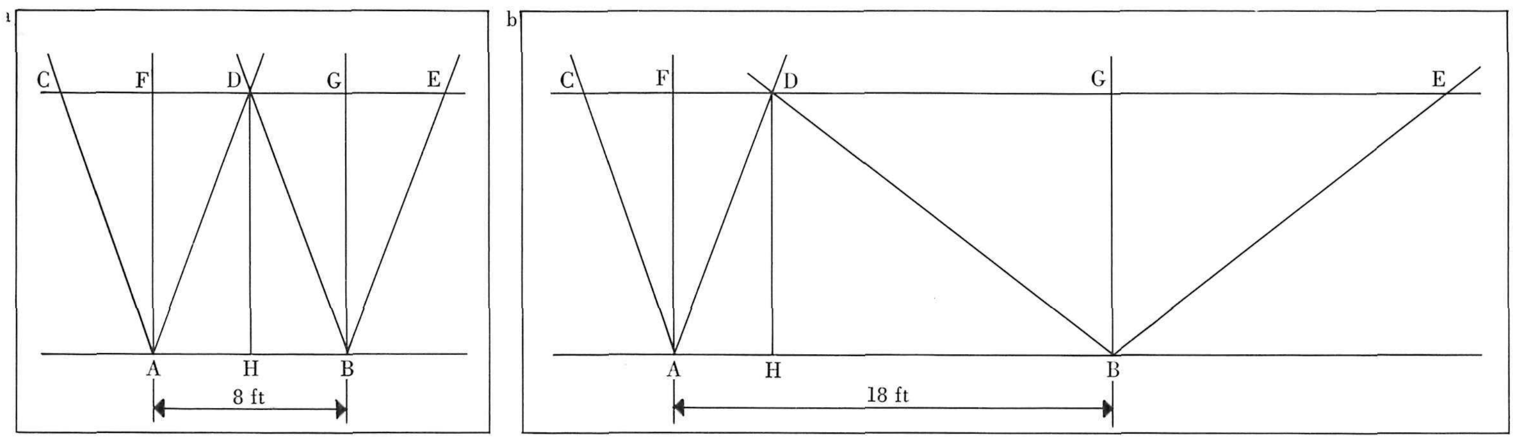
The vertically aimed track radar provides data on both height and intensity of migration over a very small area. Thus one runs the risk of studying a local phenomenon rather than a sample of large-scale migration. Nisbet (1963b) used moon-watch data to develop a system to calculate the migration traffic rate from the number of bird echoes on the scope of a search radar. His results, covering an area with a radius of 70 nautical miles, are free of possible local bias.

Whereas Nisbet used a mixed moon-watch and radar technique, Eastwood and Rider (1966) used a combination of a 23-cm search radar to "map the general progress of angel activity across a front" (of migration) and a 3-cm radar, directed vertically upwards as "undoubtedly the most accurate way of counting the passage of migrant birds by night". In combination, the radars can give an estimate of numbers of birds migrating over a large area. In Alberta we had a similar arrangement, i.e, a powerful search radar at Cold Lake and a vertically aimed M33C track radar at Primrose Lake, which, at about 30 miles distance, is covered by the search radar.

Figure 6 a. A and B are the apexes of two cones of moonlight. $\angle CAD = \angle DBE = 0.5°$.

Figure 6 b. A is the apex of the cone of moonlight. B is the apex of the "effective radar beam". $\angle DBG = \angle GBE = 1°14'30''$.

Figure 6



Appendix 1

1a Calculation of the distance at which the two cones of moonlight start to overlap (see Fig. 6a). The axes of the cones (AF and BG) can be considered to be parallel. $DH = FA = \dfrac{FD}{\tan 15'} =$ 917 feet = distance where overlap begins.

1b Calculation of the distance at which the cone of moonlight and the cone of radar energy start to overlap (see Fig. 6b).

$FD = X$

$AF = BG \qquad DG = 18 \text{ feet} - X$

$$\tan 1°14'30'' = \frac{DG}{GB} \longrightarrow DG = GB \tan 1°14'30''$$

$$\tan 15' = \frac{FD}{AF} \longrightarrow FD = AF \tan 15' = GB \tan 15'$$

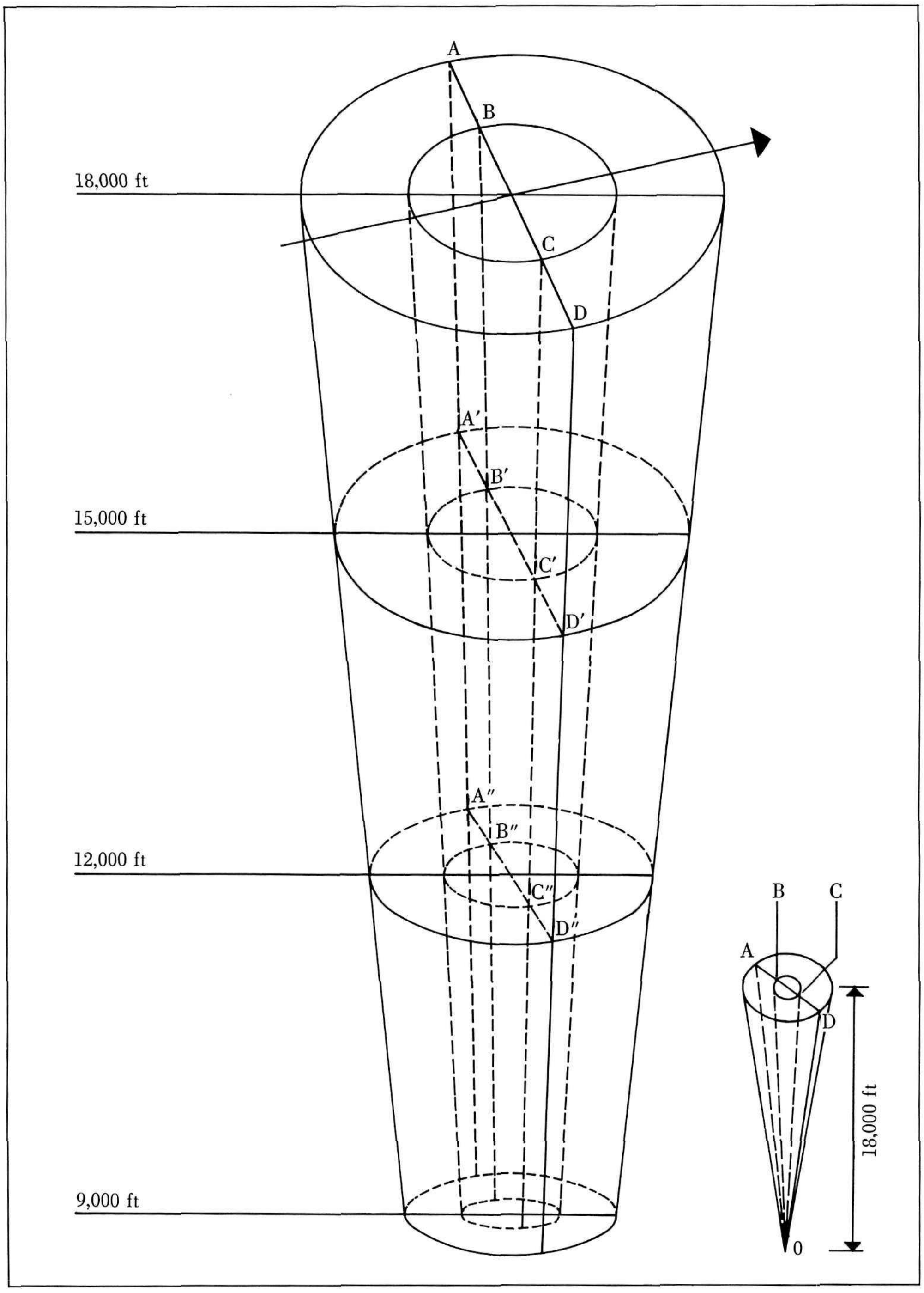
$$\frac{DG}{FD} = \frac{18 \text{ feet} - X}{X} = \frac{GB \tan 1°14'30''}{GB \tan 15'} \longrightarrow X = FD = 3 \text{ feet}$$

$$\frac{AH}{HD} = \frac{FD}{HD} = \tan 15' \longrightarrow HD = \frac{FD}{\tan 15'} = 688 \text{ feet} = \text{distance}$$

where overlap begins.

Figure 7. Schematic view of "beams" of telescope and radar, aimed at an overhead moon. O, the place of observation, is the apex of the cone of moonlight and the cone of radar energy.

Figure 7



Appendix 2
Calculation of "effective beam width"

Part 1. In the moon-watch experiment, telescope and antenna were trained at the moon and the birds detected by each method were counted.

Assuming that radar and telescope detected all the birds flying through their "beams", the relation between the number of birds detected by radar and those observed by the moon-watcher should be the same for all height bands, whether the height distribution is even or not. This can be shown as follows. In Figure 7, the small cone is the observation area of the telescope, the big one that of the radar. For the sake of convenience the moon is assumed to be straight overhead. The dark arrow on the big cone indicates the general direction of migration. The plane through A, O, and D is perpendicular to this flight direction.

Migrating birds are observed by radar only if they cross plane AOD; by telescope if they cross plane BOC.

Thus the number observed by radar in the 15,000- to 18,000-foot band and the number by telescope in this band relate as the surfaces of the trapezoids AA′D′D and BB′C′C. This relation holds for all height bands since: Surf. AA′D′D: Surf. BB′C′C = Surf. A′A″D″D′: Surf. B′B″C″C. When the moon is not overhead but at its usual elevations, the changes in this relationship are so small that they can be neglected.

Part 2. When making moon-watch observations one normally can estimate the range of the observed birds only from their size and speed.
In our case the range of those birds that were detected by telescope and radar at exactly the same time was obtained from the radar screen. The results, given in Table 6, show that the relationship between birds observed by radar and birds simultaneously observed by the moon-watcher varies considerably per range band.

Table 7 shows that the radar detects, in a statistically significant way, relatively more birds at greater range than the moon-watcher. The assumption that the moon-watcher detects all birds flying across the moon is not correct since he misses birds that are far away. This, of course, does not imply that the radar does detect all birds at greater range.

Yet I think it is safe to assume that all birds at a range of 3,000–6,000 feet that cross the moon close to its centre are detected by the moon-watch technique.

Tests carried out by Newman (1962) and Nisbet (1963b) showed that a mounted parula warbler was clearly visible against blue sky at a distance of a mile through a 20x telescope. Against the background of a full moon it should be visible at much greater range.

But even at the 3,000- to 6,000-foot range, birds can easily be missed when they cross the edge of the moon. Nisbet (1963b) calculated the edge loss to be 25 per cent of the total number of observed birds, and I used this number to correct my data.

Only 36 of the 44 birds seen by the moon-watcher were observed as bird spikes by the screen-watcher (Table 1). I argued that the radar did not miss these birds but that the screen-watcher missed their spikes. So, 8 out of 44, or 18 per cent of the birds seen through the telescope passed unnoticed as bird spikes on the screen. Because of this inattentiveness of the screen-watcher, I assume that 18 per cent of all birds detected by the radar also passed unnoticed as bird spikes on the screen.

To obtain the actual number of bird spikes, the observed number therefore has to be multipled by $\frac{100}{122}$.

The total number of birds detected by the radar at the 3,000- to 6,000-foot range was $\frac{122}{100} \times 99 = 120.78$ birds. The total number of birds flying through the cone of moonlight at the range of 3,000 to 6,000 feet was $\frac{122}{100} \times \frac{125}{100} \times 17 = 25.93$.

Thus at a range of 3,000 to 6,000 feet the radar detected 4.65 as many birds as the moon-watcher $\left(\frac{120.78}{25.93}\right)$.

Using a value of 0.50° for the angle of the telescope's cone of moonlight, the width of the "effective beam" of the radar is 2°19′ or 41.25 mils, at least for the range 3,000 to 6,000 feet and thus also for 0 to 3,000 feet. (The data for the 0- to 3,000-foot band could not be used, since the ineffective ranges of radar and telescope are not the same.)

Effective beam width and half-power point beam width are virtually the same. The tests with the birds carried aloft by balloons showed that a snow bunting gave a maximum spike up to ranges of 8,700 feet, and spikes with an average height of about 70 per cent of maximal at 9,600 feet. This means that this bird might well have produced a clearly visible bird spike, although of very short duration, at the half-power points at both these ranges. Thus the effective beam width can probably be applied to the 6,000- to 9,600-foot range as well. Normally only a very small fraction of the migration takes place above 6,000 feet and possible errors due to the application of the effective beam width on the 6,000- to 9,600-foot range will thus be very small as well.

Summary

1. A brief description is given of the M33C track radar.
2. The vertically aimed radar had an ineffective range of 0–1,200 feet. Single sparrow-sized birds, carried aloft by balloons, produced detectable echoes up to a range of 15,000 feet.
3. Since a beam of radar energy is not a well-defined sample area, the "effective beam width" of the vertically aimed M33C track radar was calculated. The effective beam width is an estimate of the size of the sample area of the radar. It was calculated from results of an experiment in which the moon was followed simultaneously by telescope and radar. The "effective beam width" can be used for altitudes of up to 9,600 feet.
4. A method to determine the height of distribution above 1,200 feet is described and the results for one night are given as an example.
5. A method to determine the migration traffic rate (the number of birds per mile of front per hour) above 1,200 feet is described and the results for one night are given as an example.
6. The methods and their results are compared with those of other workers.

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A preliminary study on height and density of nocturnal fall migration

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Introduction

This paper presents the preliminary results of studies conducted as part of Operation Bird Track, a project to develop a method of forecasting the intensity of bird migration. This project, initiated and supervised by Dr. W. W. H. Gunn, is carried out on behalf of the Associate Committee on Bird Hazards to Aircraft of the National Research Council of Canada.

Forecasts of the intensity of migration over the area around Canadian Forces Base (CFB) Cold Lake in east-central Alberta have been made by Fryers (1966) and Blokpoel (1969). They rated the intensity as 0 through 8 according to an arbitrary intensity scale, described by Fryers (*op. cit.*).

To increase the value of the migration forecasts, I attempted to discover (a) the height distribution of nocturnal migrants, (b) the influence of weather on the height distribution, and (c) the numerical relationship between the steps of the arbitrary intensity scale.

Methods and materials

An M33C radar was used to study the height distribution and Migration Traffic Rate of all migrants flying higher than 1,200 feet above ground level. The Migration Traffic Rate is the number of birds per mile of front per hour, where the front is a line perpendicular to the direction of migration (Lowery and Newman, 1966).

The M33C track radar is a 3-cm anti-aircraft radar with a peak power of 250 kw. The radar was located at the southwest shore of the panhandle of Primrose Lake (54°49′N, 110°02′W), Alberta, at an elevation of 2,020 feet above sea level and about 55 feet above lake level. The pencil beam (2.2°) was aimed vertically, and one of the A-scopes, with its range adjusted to 18,000 feet, was filmed. The radar was ineffective through the first 1,200 feet, but was able to detect single small passerines flying across the centre of the beam at altitudes up to 15,000 feet. Since the diameter of the radar beam increases with height, the number of bird echoes per height band must be corrected to be comparable. From these corrected numbers of bird echoes, the height distribution and density of migrants above 1,200 feet can be calculated (Blokpoel, 1971). I assumed bird echoes represented single birds rather than flocks.

Clouds and precipitation are also detected by the M33C radar. A small amount of clouds shows on the scope as a concentration of small "spikes", slowly changing in size and shape, and always staying well below maximum height. Bird spikes usually do reach maximum height and can thus easily be told from such clouds. Heavy clouds and precipitation, however, show on the scope as one solid echo ranging from 1,200 to several thousand feet and having maximum height.

Weather information was obtained from CFB Cold Lake (54°24′N, 110°17′W), located about 30 miles south of the M33C radar. To provide more detailed information, a radiosonde balloon was released one night at Primrose Lake, 4 miles from the radar site.

All times in this paper are Mountain Standard Time.

Results

Radar films were made in the period September 25 to October 31, 1968. This paper deals with the data obtained during 15 nights, or parts thereof, that were either completely clear or had clouds only above approximately 12,000 feet. A total of 6,615 bird echoes was counted on these nights (corrected number 5,316).

A. Height distribution

The height distributions of migrants flying above 1,200 feet on the 15 nights used for quantitative analysis are given in Table 1. The table shows that both the 50 and 90 per cent levels vary from night to night, and that there generally is no obvious preference for any particular height band. The 50 and 90 per cent levels are in general not close together.

There is no consistent maximum altitude of flight. For each night the number of birds gradually decreased with height. The highest bird echoes were recorded between 13,800 and 14,400 feet on September 25/26 and 27/28. Some were recorded above 14,200 feet (16,200 ft a.s.l.).

Although the nights with heavy migration have more high-altitude stragglers than other nights, there is no indication that the 50 and 90 per cent levels are higher on those nights than on nights with light migration. On September 26/27, both the 50 and 90 per cent levels are much higher than on any other night. On October 4, the 90 per cent level and, even more, the 50 per cent level are unusually low.

To determine whether the height distribution shifts during the night, the distribution for each observation period during the 6 heavy-migration nights was plotted in Table 2. These 6 nights had a total of 6,209 bird echoes (corrected number 4,972), compared to a total of 6,615 bird echoes (corrected to 5,316) during all 15 nights. Lack of data prevented analysis of the light-migration nights.

Table 2 shows there was no consistent shift in the height distribution from night to night. The nights of September 27/28 and 28/29 are best compared since the radar observations cover similar, 8-hour periods. Both nights show small fluctuations for the 50 and 90 per cent levels, but on September 27/28 the 50 per cent level tended to be higher during the latter part of the night, whereas the distribution did not change on September 28/29, apart from a rise of the 50 per cent level from 2200 to 2400 hours. (The corrected number of bird echoes from 1930 to 2000 hours on September 28/29 was only 25).

On September 26/27 there were minor fluctuations but no consistent shift in height distribution. On September 25/26 both the 50 and 90 per cent levels were much higher during the last than the first observation period. No shifts could be determined for September 30 and October 4, because too few observations were made.

B. Influence of weather on height distribution

On September 25/26 a radiosonde was released at Primrose Lake at 2247 hours, while a high-intensity migration was being recorded by a surveillance radar near CFB Cold Lake. The direction of migration during the period 2000–0100 hours was 140° (i.e., from 320°). Figure 1 gives weather data obtained with the radiosonde for the 2247- to 2302-hour period, and the direction and height distribution of birds above 1,200 feet for the 2205- to 2307-hour period.

Figure 1 shows there was no pronounced preference for any height band, and that almost all birds were flying below 6,600 feet. Yet, the pressure gradually decreased from 912 millibars at 1,000 feet to 620 millibars at 11,000 feet, the temperature dropped from 10°C at 1,000 feet to -10°C at 8,200 feet, and the relative humidity and wind speed varied considerably with height. The wind direction hardly changed with height. The birds had an almost perfect tail wind at altitudes up to 7,000 feet. The data show that, for this particular night, the birds did not have a preference for a particular pressure, temperature, or relative humidity.

Table 1
Percentage height distribution of birds flying above 1,200 feet in fall 1968 at Primrose Lake, Alberta

Height above radar site (x 100 feet)	Date and observation period MST														
	Heavy migration						Light migration								
	Sept. 25/26 2000–0007	Sept. 26/27 1825–0110	Sept. 27/28 1915–0330	Sept. 28/29 1930–0252	Sept. 30 2130/2350	Oct. 4 2000–2325	Sept. 29 1900–2345	Oct. 2 1910–2230	Oct. 3/4 1855–0023	Oct. 16 1915–2042	Oct. 17 1745–2247	Oct. 24 1755–2205	Oct. 26 1715–2229	Oct. 27 1730–2336	Oct. 28 1738–2331
138–144	T	—	T	—	—	—	—	—	—	—	—	—	—	—	—
132–130	T	—	T	T	—	—	—	—	—	—	—	—	—	—	—
126–132	T	—	T	T	—	—	—	—	—	—	—	—	—	—	—
120–126	T	T	T	T	—	—	—	—	—	—	—	—	—	—	—
114–120	—	T	T	T	—	—	—	—	—	—	—	—	—	—	—
108–114	T	T	T	T	—	—	—	—	—	—	—	—	—	—	—
102–108	—	T	T	T	—	—	—	—	—	—	—	—	—	—	—
96–102	T	1	T	T	—	—	—	—	—	—	—	—	—	—	—
90–96	T	T	T	T	—	—	—	—	—	—	—	—	—	—	—
84–90	T	T	T	T	—	—	T	T	—	T	—	—	—	—	—
78–84	T	2	T	T	T	—	—	—	—	—	—	—	—	—	—
72–78	T	*5*	1	T	—	—	T	—	—	T	—	—	—	—	—
66–72	1	4	2	1	—	T	2	T	—	2	—	1	4	—	—
60–66	6	13	3	2	1	T	T	1	—	5	—	1	—	—	—
54–60	*4*	14	*6*	2	T	T	1	1	—	*4*	*26*	—	—	—	8
48–54	6	**13**	11	4	3	3	4	*7*	—	T	—	*8*	*10*	—	*8*
42–48	5	13	16	*7*	3	4	*6*	20	*12*	3	**32**	22	5	—	9
36–42	7	9	**13**	9	*10*	*6*	4	16	—	8	—	15	29	—	**64**
30–36	11	5	17	13	17	11	15	**19**	**47**	22	42	**21**	**22**	—	12
24–30	**17**	7	10	**15**	**20**	18	**32**	11	—	**9**	—	18	5	—	—
18–24	23	6	13	35	23	**35**	24	13	41	21	—	—	17	—	—
12–18	20	4	5	11	22	21	11	10	—	23	—	13	8	—	—
Corrected number of bird echoes	1150	385	1119	1638	205	475	138	88	5	55	2	27	22	0	7

Note: Boldface and italic type indicate the height bands containing the heights below which 50 and 90 per cent of the birds flew respectively. T=less than 1 per cent.

*On nights with "heavy migration" more than 4,000 birds passed per mile of front per hour (Table 4); on nights with "light migration" fewer than 4,000.

Wind direction and speed for the other 5 nights with heavy migration were obtained with pilot balloons (pibals), released at CFB Cold Lake at 2215 hours. Mr. C. R. Finlay, Base Meteorological Officer, kindly estimated the freezing level for these nights for the 2200- to 2300-hour period, from the original weather maps drawn at his office and from radiosonde data from Edmonton (160 miles WSW of the air base) for 1700 and 0500 hours.

Weather data, direction of migration, and height distribution of migrants for the 2200- to 2300-hour period for the 6 nights with heavy migration are given in Table 3. The 3 nights with overcast had different amounts and types of clouds; the winds were northwesterly and hardly changed

Table 2
Percentage height distribution of birds flying above 1,200 feet for 6 nights with heavy migration during fall 1968 at Primrose Lake, Alberta

Date and observation period MST

Height above radar site (x 100 feet)	Sept. 25/26					Sept. 26/27							Sept. 27/28									Sept. 28/29								Sept. 30/Oct. 1			Oct. 4			
	2000–2051	2051–2142	2142–2205	2205–2307	2307–0007	1825–1900	1900–2000	2000–2113	2115–2200	2200–2300	2300–2400	0000–0110	1915–1945	1945–2045	2045–2152	2158–2252	2252–2336	2336–0040	0041–0135	0135–0231	0231–0331	1930–2000	2000–2100	2100–2200	2200–2300	2300–2400	2400–0100	0100–0200	0200–0252	2130–2200	2200–2300	2300–2350	2200–2100	2105–2200	2200–2300	2300–2325
138–144	—	—	—	T	T	—	—	—	—	—	—	—	—	—	—	—	—	T	—	T	T	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
132–138	—	—	—	T	T	—	—	—	—	—	—	—	—	—	—	T	—	—	T	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
126–132	—	—	—	T	—	—	—	T	—	—	—	—	—	T	—	—	—	—	—	—	—	—	—	—	T	—	T	T	T	—	—	—	—	—	—	—
120–126	—	T	—	—	T	—	—	T	—	—	—	—	—	—	—	—	—	T	T	—	—	—	—	T	—	T	T	T	T	—	—	—	—	—	—	—
114–120	—	—	—	—	—	—	—	T	—	—	—	—	—	—	—	T	—	—	—	—	—	—	—	—	T	—	T	T	—	—	—	—	—	—	—	—
108–114	—	—	—	—	T	—	—	T	—	—	—	1	—	—	T	T	T	T	T	T	—	—	—	T	—	—	—	—	T	—	—	—	—	—	—	—
102–108	—	—	—	—	—	—	—	2	—	—	2	3	—	—	2	1	—	T	—	T	T	—	—	T	—	T	—	—	T	—	—	—	—	—	—	—
96–102	—	T	—	—	—	—	T	4	—	T	T	—	—	—	T	1	T	T	T	—	T	—	T	T	—	T	T	—	T	—	—	—	—	—	—	—
90–96	—	—	—	T	T	—	2	2	—	T	T	T	—	T	—	T	T	—	T	—	T	1	—	T	—	T	T	—	—	—	—	—	—	—	—	—
84–90	—	—	—	—	T	—	—	*2*	2	T	—	—	—	—	T	—	T	T	T	T	T	—	T	—	T	T	—	—	—	—	—	—	—	—	—	—
78–84	—	T	—	—	T	—	4	6	1	1	2	—	—	—	1	1	T	2	2	T	1	2	T	T	—	T	T	T	—	1	T	—	—	—	—	—
72–78	T	T	—	—	T	—	*12*	7	4	5	2	2	—	—	1	1	3	1	T	T	—	4	1	T	T	T	T	T	—	—	—	—	—	—	—	—
66–72	1	T	T	T	3	—	8	5	3	*5*	3	3	—	—	2	2	1	3	T	2	2	—	T	T	1	2	T	T	T	—	—	—	—	—	T	T
60–66	T	T	T	*10*	*12*	—	5	8	*10*	16	*10*	*26*	—	—	*T*	*4*	4	*3*	4	1	4	*12*	1	T	1	2	2	3	T	—	T	2	—	—	1	T
54–60	1	1	T	5	9	—	15	17	13	10	18	14	—	1	T	2	*4*	6	*9*	8	*10*	11	4	3	2	1	3	2	T	—	T	1	T	1	T	T
48–54	*2*	1	5	6	16	*22*	**14**	**16**	12	**15**	**13**	**6**	—	5	23	*6*	4	*11*	12	10	23	8	*4*	5	*7*	*4*	*4*	2	3	5	3	1	T	3	3	4
42–48	4	4	*7*	7	5	—	2	8	**13**	12	21	22	*16*	*12*	14	14	9	10	**22**	**36**	**11**	7	8	*9*	9	2	5	*8*	*9*	—	4	2	*13*	4	2	1
36–42	*4*	*6*	6	9	**8**	—	6	8	7	6	10	16	—	18	**11**	14	13	**17**	12	8	14	**8**	2	5	24	11	4	6	7	*21*	*8*	*9*	8	*7*	*7*	3
30–36	15	11	9	13	5	**35**	5	2	2	7	7	7	22	**25**	23	**17**	**20**	15	12	11	22	13	11	7	**16**	17	15	11	10	19	20	12	12	13	12	*5*
24–30	17	20	8	**20**	15	43	18	12	10	4	1	—	**27**	10	8	14	16	10	7	8	3	20	14	18	7	**25**	11	13	15	**23**	**19**	20	**21**	**33**	7	20
18–24	**30**	**35**	**29**	12	12	—	4	—	16	12	5	—	35	17	10	13	14	15	13	12	4	5	**37**	**42**	28	26	**42**	**34**	**37**	26	19	**27**	24	19	**43**	**46**
12–18	24	20	33	18	12	—	5	—	7	6	5	—	—	9	—	9	11	4	4	1	2	7	17	9	3	8	12	18	17	6	25	25	20	19	24	20
Corrected number of bird echoes	217	286	98	274	275	2	34	78	49	94	80	48	4	39	91	142	162	259	209	122	91	25	118	268	229	292	265	221	220	30	95	80	53	122	199	101

Note: Boldface and italic type indicate the height bands containing the height below which 50 and 90 per cent of the birds flew respectively.
T = less than 1 per cent.

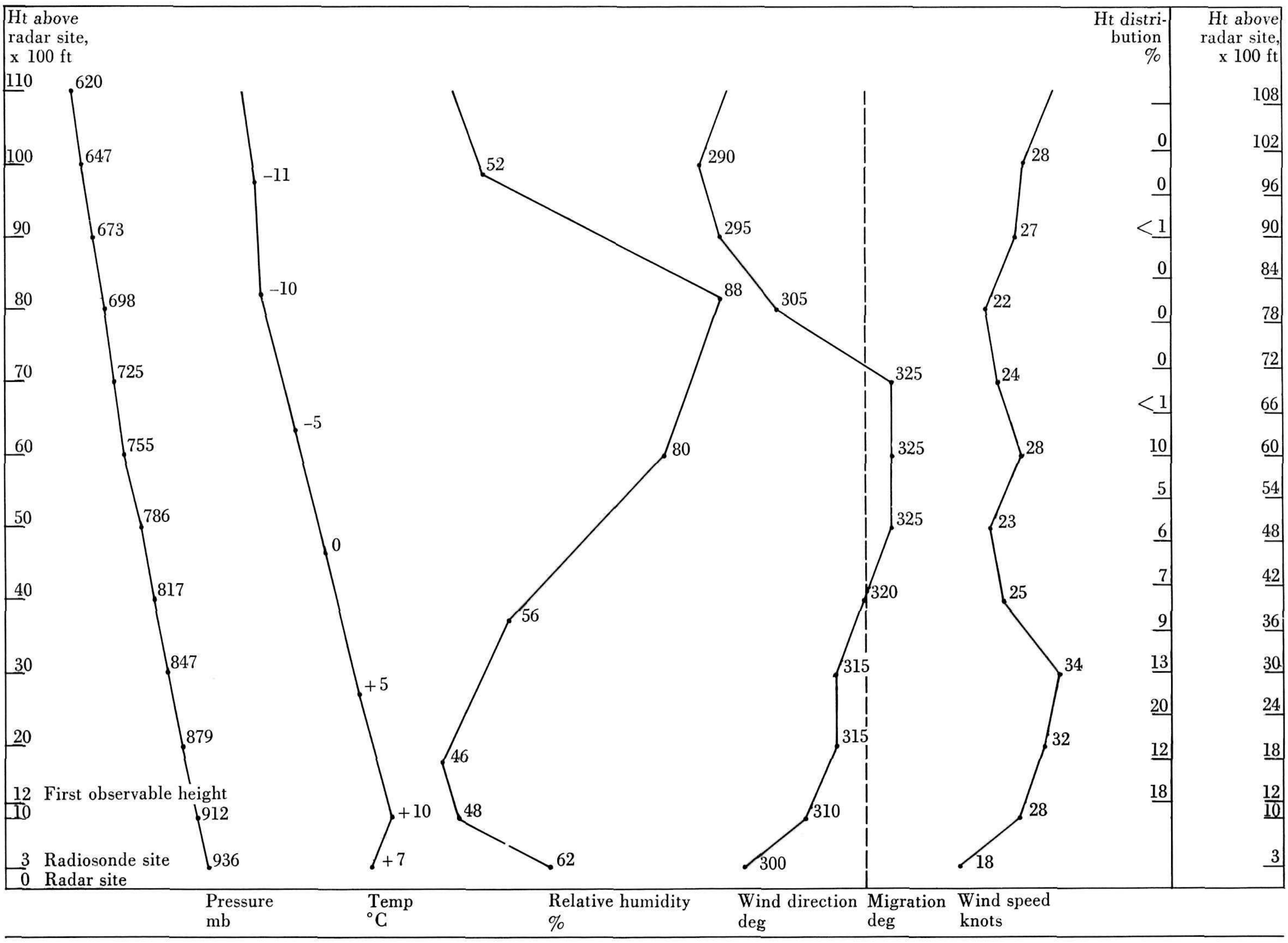
with height. The birds flew lower under a combination of altocumulus and cirrostratus (October 4) than under thin cirrus (September 28).

On the 3 clear nights, wind direction changed with height by 15° on September 25, by 175° on September 26, and by 70° on September 27. On September 26, birds had to climb considerably to avoid the head winds at low levels and even higher to use the favourable winds at about 6,500 feet and up. The data show that at least part of the migrants did fly at high altitudes, causing unusually high 50 and 90 per cent levels that night.

The wind speed changed very little with height, except on September 26 and 27. On September 26 the increase in wind speed (and in numbers of birds) from 4,000 to about 6,500 feet coincided with a shift in wind direction from 205° to about 275°. The increase in numbers of migrants most likely reflects a preference for wind direction rather than for wind speed. The change in wind speed on September 27 occurred at too high an altitude to have any demonstrable effect.

Figure 1. Height distribution of migrants above 1,200 feet, direction of migration, and upper-air weather data for 2205 to 2307 hours MST on September 25, 1968, at Primrose Lake, Alberta.

Figure 1



Of the migrants above 1,200 feet, on September 25 more than 20 per cent flew above freezing level. On September 30 the estimated freezing level was 3,800 ±400 feet. About 8 and 20 per cent flew above 4,200 and 3,400 feet, respectively.

The data for the 6 heavy-migration nights suggest that cloud cover and wind direction were the main factors that influenced the height of migration during those nights.

C. The numerical relationship between the steps of the 0–8 intensity scale

Lowery and Newman (1966), who used the moon-watch technique to study migration, introduced the term "Migration Traffic Rate" (MTR) to express the density of bird migration. A method for calculating the MTR's of birds above 1,200 feet from M33C radar data was described by Blokpoel (1971). The MTR's of migrants above 1,200 feet for the 15 nights are given in Table 4.

In many instances the observation period for which the MTR was calculated did not last exactly 60 min. or did not run from the full hour to the full hour as shown in Table 4. In these cases the MTR was plotted for the full hour that comprised the larger part of the observation period (e.g., the MTR for

Table 3
Height distribution (up to 9,000 feet) of migrants above 1,200 feet, direction of migration, and selected weather data for 6 heavy-migration nights during fall of 1968 at Primrose Lake, Alberta

	Date and observation period MST																	
	Sept. 25, 2205–2307			Sept. 26, 2200–2300			Sept. 27, 2158–2252			Sept. 28, 2200–2300			Sept. 30, 2200–2300			Oct. 4, 2200–2300		
Sky, Primrose Lake	Clear			Clear			Clear			Overcast			Overcast			Overcast		
Sky, Cold Lake	Clear TO = 1			Scattered cirrus at 28,000 ft TO = 1			Clear TO = 1			Overcast cirrus at 24,000 ft TO = 6			Overcast cirrostratus at 25,000 ft TO = 10			Scattered altocumulus at 12,000 ft broken cirrostratus at 23,000 ft TO = 6		
Direction of migration,°	140			130			120			120			140			150		
Corrected number of bird echoes	274			94			142			229			95			199		
Height above radar site (x 100 feet)	Wind direction,°	Wind speed, knots	No. of birds, %	Wind direction,°	Wind speed, knots	No. of birds, %	Wind direction,°	Wind speed, knots	No. of birds, %	Wind direction,°	Wind speed, knots	No. of birds, %	Wind direction,°	Wind speed, knots	No. of birds, %	Wind direction,°	Wind speed, knots	No. of birds, %
90 –																		
						T			1*			T						
84 –																		
	305	22		300	14	1*	290	15	1			*	270	32	T	310	28	
78 –																		
			T			5			1			T						
72 –																		
	325	24	T	295	15	*5*	285	11	2			1	270	28		315	30	T
66 –																		
			10			16			*4*			1			T			1
60 –	325	28		255	15		270	9					265	21		310	36	
			5			10			2			2			T			T
54 –																		
	325	23	6	250	10	**15**	270	13	6			*7*	270	25	3	305	40	*3
48 –																		
			7*			12			14			9			4			2
42 –																		
	320	25	9	205	5	6	255	15	14	275	38	24	270	25	*8**	305	39	7
36 –																		
			13			7			**17**			**16**			20			12
30 –	315	34		165	10		250	15		270	40		275	30		300	42	
			20			4			14			7			**19**			7
24 –																		
	315	32	12	150	11	12	235	15	13	270	45	28	265	29	19	295	43	**43**
18 –																		
			18			6			9			3			25			24
12 –																		
	310	28		125	13		220	21		270	45		250	28		295	39	
6 –																		
0 –																		

Note: Boldface and italic type indicate the height bands containing the heights below which 50 and 90 per cent of the birds flew, respectively. Asterisks indicate estimated freezing level.

TO = Total Opacity. T = less than 1 per cent.

Table 4
Migration Traffic Rates of migrants flying above
1,200 feet during fall of 1968 at Primrose Lake, Alberta

Hour of observation, MST	Sept. 25	Sept. 26/27	Sept. 27/28	Sept. 28/29	Sept. 29	Sept. 30	Oct. 2	Oct. 3	Oct. 4	Oct. 16/17	Oct. 17	Oct. 24	Oct. 26	Oct. 27	Oct. 28
1700–1800	—	—	—	—	—	—	—	—	—	—	0*	—	42	0	*0
1800–1900	—	177	—	—	—	—	—	—	—	—	0	249	252	0	86
1900–2000	—	2,040	333	2,250	1,556	—	1,091	54	—	1,350	0	270	81	0	27
2000–2100	11,494	2,866	1,760	5,297	927	—	959	36	2,376	2,070	23	396	347	0	32
2100–2200	15,157	2,958	3,655	12,060	1,602	2,727	2,005	0	5,994	—	36	274	194	0	86
2200–2300	11,941	4,226	7,110	10,287	1,130	4,280	666	95	8,952	—	35	—	168*	0	68
2300–2400	12,389	3,600	9,947	13,154	1,248	4,331	—	63	10,919*	—	—	—	—	0	0
2400–0100	—	1,821	10,930	11,930	—	—	—	0*	—	—	—	—	—	—	—
0100–0200	—	—	10,450	9,963	—	—	—	—	—	—	—	—	—	—	—
0200–0300	—	—	5,901	11,433	—	—	—	—	—	—	—	—	—	—	—
0300–0400	—	—	4,113	—	—	—	—	—	—	—	—	—	—	—	—

*Observation period lasted between 13 and 30 minutes.

the 2051- to 2141-hour period is shown as 2100–2200 hours). There were 82 observation periods in total: 52 lasted from 60 to 74 min., 15 from 45 to 59 min., 10 from 30 to 44 min., and 5 from 13 to 29 min.

Migration Traffic Rates varied from 15,157 to 0. Most nights began with small MTR's. On some nights (e.g., October 17) the MTR remained small; on other nights it rose to medium (September 26) or to large (September 28) numbers.

On September 26/27 and 27/28, numbers decreased during the latter part of the night. On September 28/29, however, the MTR was still large during the 0200- to 0300-hour period.

Of the 3 clear nights with heavy migration (see Table 3), the night of September 25, with strong tail winds at all levels, had the largest MTR. On September 26/27, the birds had to fly high to get favourable winds. Apparently this situation was not favourable for migration, since the MTR barely exceeded 4,000. On September 27/28, the winds were not as favourable and the MTR not as large as on September 25.

Data on MTR's were available for 15 nights, but reliable intensities from films of the scope of the surveillance radar were obtained for only four of these nights. The few results show a clear correlation between intensity and averaged MTR (Table 5). The correlation is very crude, however, since intensity 5 corresponded with MTR's varying from 4,113 to 10,930 birds per mile of front.

Table 5
Intensity* of bird migration shown by surveillance radar near CFB Cold Lake, Alberta, and Migration Traffic Rate of birds above 1,200 feet obtained with the M33C radar at Primrose Lake, Alberta, for the same periods in the fall of 1968

	Migration Traffic Rate				
Intensity	Sept. 25	Sept. 27/28	Oct. 3/4	Oct. 4	Average
8					
7	15,157 11,941				13,549
6	11,494 12,389			8,952	10,945
5		7,101 9,947 10,930 10,450 5,901 4,113		5,994	7,777
4		3,655			3,655
3		1,760		2,376	2,068
2		333	95 63		164
1			0 36		18
0			0 54		27

*Intensity scale from Fryers, 1966.

Discussion

Method

Nisbet (1963a) combined radar and moon-watch techniques to study nocturnal migration over Cape Cod, Massachusetts. He concluded that many species of passerine night migrants fly in loose groups, extending over an area 100 to 200 feet across. These groups consist of 2 to 12 (average 6) widely separated birds.

Eastwood and Rider (1966) studied spring night migrants at the coast of Essex, England. They used a 23-cm surveillance radar and a vertically aimed 3-cm radar (beamwidth 0.7°) which detected single birds (Eastwood, 1967). Their results suggested that "while some of the nocturnal angels which give good echoes at long range are probably true groups of birds analogous to those observed by day, others, and perhaps the majority, are pseudo-groups which result from the pulse-volume effect".

I assumed that the vertically aimed M33C 3-cm track radar (beamwidth 2.2°) detected single birds. Moon-watch data (angle of vision 0.5°) obtained at Cold Lake, Alberta, during September 1967 support this assumption. Of a total of 609 birds, only 9 "pairs" and one flock of about ten birds (waterfowl) were observed. If the M33C detected many flocks or groups rather than single birds the MTR's are minimum estimates; the height distributions are correct assuming that the flocking and grouping birds had the same height preferences as single birds.

Both moon-watch (James, 1955) and radar studies (Drury and Keith, 1962) showed that passerine night migrants are not guided by topographical features. Thus the bird movements studied at the shore of Primrose Lake represent migration at large rather than a local phenomenon.

No confidence limits for height distributions and MTR's could be given since the method used was based on few data (Blokpoel, 1971).

Height distribution

Nisbet (1963b), Bellrose and Graber (1963), and Eastwood and Rider (1965) made radar studies of the height of bird migration. Nisbet's equipment permitted a study of flocks higher than 600 feet; Bellrose and Graber studied birds higher than 1,500 feet; and the radar used in the present study detected single birds above 1,200 feet. The radar of Eastwood and Rider was equipped with a Moving Target Indicator which permitted a study of birds well below 1,000 feet. Height distributions obtained with these different equipments cannot be strictly compared. Yet my results are in good general agreement with Nisbet's results at Cape Cod, Massachusetts (based on 22,000 echoes during 37 nights in spring and fall). He found that "on average, 90 per cent of the birds were below 5,000 feet and over 99 per cent below 10,000 feet". Of the birds flying above 1,200 feet over Primrose Lake, 50 per cent were, on average, below about 3,500 feet, 90 per cent below about 5,000 feet, and 99 per cent below about 10,000 feet. The results of Bellrose and Graber are not suitable for comparison with mine, since their radar started to miss birds beyond a range of 6,400 feet.

Eastwood and Rider found that about 80 per cent of 346 echoes during 4 nights in September 1962 were below 1,500 feet and about 37 per cent of 2,210 echoes during 14 nights in October and November 1962 were below 1,500 feet. Nisbet *(op. cit.)* believed that, on average, only 10–20 per cent of the echoes were below 600 feet, and that many of these were of non-migrating birds (e.g., gulls, shorebirds, ducks, geese, and other sea birds). The height distributions obtained in this study suggest that on some nights (e.g., September 26/27, 27/28, and 29) few birds were flying below 1,200 feet. On other nights (e.g., September 25 and October 16), there may have been relatively many birds below 1,200 feet. The results of Eastwood and Rider clearly show the advantages of the MTI.

Influence of weather on height distribution

Eastwood and Rider (1965) described a day-time situation in March which suggested that the freezing level operated as a ceiling for the birds. The results of this study show that birds do fly above the freezing level in considerable numbers at night in the fall. Those authors also suggested that "it is hardly reasonable to expect altitude adjustment by migrant birds in response to the variations in wind speed and direction encountered during an extended flight". My results for one hour on September 26 suggest that some birds avoided unfavourable lower winds by flying higher than usual. This would indicate that birds, once in the air, are able to detect variations in wind direction on a clear night.

Relationship between the steps of the 0–8 intensity scale

Since the surveillance radar picked up birds below 1,200 feet whereas the M33C did not, a comparison of results obtained with these radars has limited value. The few results suggest that the relation between all intensities of the 0–8 scale and the corresponding MTR's may not be a simple one, but the relation between the higher intensities (4–7) and the corresponding MTR's may be linear. Many more data are needed to solve this problem.

Summary

The height and density of nocturnal migration during the fall of 1968 over the area around Canadian Forces Base Cold Lake, Alberta, were recorded by filming an A-scope of a vertically aimed M33C track radar. The radar was located at the southwest shore of Primrose Lake (54°49'N latitude, 110°02'W longitude) about 30 miles north of CFB Cold Lake. The radar detected single birds flying above 1,200 feet. The paper deals with the results for 15 nights which were either completely clear or clear up to 12,000 feet.

Of the birds flying over 1,200 feet, 50 per cent were on the average below about 3,500 feet, 90 per cent below about 5,000 feet, and 99 per cent below about 10,000 feet. The highest bird echoes were recorded at 14,200 to 14,400 feet. The 6 nights with heavy migration showed no consistent shift in the height distribution during the course of the night.

Cloud cover and wind direction were probably the main factors that influenced the height distribution during the 6 nights with heavy migration.

The Migration Traffic Rates (i.e., the numbers of birds per mile of front per hour), obtained from M33C data, showed a crude but clear correlation with the densities of migration obtained from films of a scope of a surveillance radar, located near CFB Cold Lake.

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