A METHOD FOR AUTOMATICALLY DETECTING BIRDS ON RADAR

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INTRODUCTION

Radar, since it can have a great range and does not depend on special conditions to be useful, is the most versatile means we have of studying migratory behavior (Alerstam, 1972). Aside from tracking radar, which is presently used to follow individual birds or sometimes compact flocks, other radar types are used to estimate the density of bird migration, provide information on the altitudes of flight, and estimate the direction of flight of bird targets.

In radar studies, birds appear as small dots or bright areas on a display screen. The images on the screen are photographed or visually described by techniques reviewed below, and estimates of the number of dots present are recorded by hand. The written record is necessarily of a statistical nature, being almost always a description of the migration of many species and subject to many uncertainties. Often the investigator turns to the use of digital computers to analyze the written record, transferring it onto punched cards or other computer media. Thus most contemporary techniques start with an electronic signal in the radar representing a bird target or targets and end with an electronic signal in a digital computer, but interpose several tedious and often subjective steps between.

In the present report we describe a way of improving this clearly unsatisfactory state of affairs, a technique that allows echoes from bird targets to be recorded directly by a computer or microprocessor, permitting the biologist to study the spatial and temporal patterns of bird movements with increased accuracy and objectivity. We review present methods of collecting ornithological data from radar displays and discuss some reasons for the unsophisticated nature of the techniques used. Then we list some methods developed by others to process radar signals automatically and describe a device we have built that allows great flexibility of operation at a reasonable cost.

METHODS OF ESTIMATING BIRD DENSITY VISUALLY OR PHOTOGRAPHICALLY

Immense numbers of birds in the sky and our almost universal inability to distinguish with certainty between taxa of birds from their radar echoes make descriptive statistics an important part of radar studies of bird migration. A basic datum in many such studies is the number of birds in a certain altitude stratum, at a certain place, or at a certain time of day or night. Given an accurate representation of the amplitude of the signal present at the receiver of a radar and a knowledge of the calibrated characteristics of the radar, in many cases one should be able to make an accurate estimation of the numbers and size distribution of targets within the space surveyed by the radar. Yet, unless complicated procedures are followed to compare radar and visual methods (Nisbet, 1963; Gauthreaux, 1970), reliable absolute estimates of bird densities are not often obtained using radar alone. As a result, many studies of bird migration report only relative numbers of birds, often on an ordinal scale, or give estimates that are based on unjustified assumptions.

Some causes for this situation are inherent in properties of some types of radar: anomalous propagation (bending of the radar beam), insufficient range resolution, insufficient angular resolution due to the shape of the radar beam, and insufficient sensitivity at the ranges of interest. Other causes, however, are avoidable if quantitative information is available on the intensities of bird echoes and the characteristics of the radar. These include: lack of absolute calibration of the radar on known spherical reflectors, lack of accurate knowledge of the shape of the radar beam or the settings and electronic characteristics of the radar, and lack of sufficient dynamic range in the radar display. We expect that the latter class of avoidable difficulties can be minimized by taking advantage of the numerical techniques afforded by direct computer input of the radar video signal. The device described here can be programmed to aid in calibrating and measuring the performance of a radar as well as in collecting data.

Techniques used to estimate bird densities from radar displays have varied in precision and tediousness of application but are basically visual estimations (Eastwood, 1967). Several studies have used a pencil beam in combination with an A-scope (a radar display of echo intensity as a function of slant range) to count individual echoes (reviewed in Blokpoel, 1969; Bruderer and Steidinger, 1972; Blokpoel and Burton, 1975; Blokpoel, 1976). Other investigators have counted the numbers of individual dots appearing on the PPI display (Plan-Position Indicator, the conventional map-like radar display; Nisbet, 1963) or measured the range at which saturation of the PPI display occurs (Gauthreaux, 1974). Gauthreaux (1970) describes a method of adjusting the gain of a search radar so that the PPI matches a predetermined standard density of bird echoes at a given range. The attenuation necessary to produce a density match is recorded and converted into an estimate of bird density. A similar method is described by Hunt (1973). Less tedious, but also less accurate and less easily calibrated, is the method of establishing a graded ordinal series of dot-densities and matching photographs of the PPI display with one of the members of the series. The resulting dot-density estimate is related to, but not necessarily a simple function of, the bird migration density. The scales used have employed three (Williams et al., 1974), five (Gauthreaux, 1970), six (Alerstam, 1972), or nine (Blokpoel, 1969; Richardson, 1972) categories.

Several reasons are apparent for the present lack of sophistication in radar ornithology: (1) Like weather radar (Smith et al., 1974) radar ornithology has developed as a "spinoff" from military, space, and air-traffic-control applications. Consequently, techniques that are now routine in other radar applications are untried in the study of birds. (2)

Except for a few installations, the radars used by ornithologists are meant to monitor weather systems or aircraft, and are used for ornithology in slack periods or as an ancillary project. In fact, improvements in the design of radars for aircraft detection have often been such as to reduce clutter on the screens suppressing birds along with ground targets and water droplets (Miller, 1975). Someday it may be difficult to observe bird movements on many radars unless the special circuits designed to suppress bird echoes can be bypassed and the "raw radar" (amplified video) signal displayed for the ornithologist (Gauthreaux, 1977). (3) Students of birds are primarily interested in biological questions and have neither the background nor the funds to apply highly sophisticated techniques. (4) Even the conventional techniques allow the investigator to collect an enormous amount of data in a short time. Then the sheer quantity of information filling one's file cabinets discourages one from gathering more detailed data by more sophisticated means. (5) Most importantly, the currently used techniques are useful in that they continue to provide new insights into migration and other high-altitude flights of birds.

METHODS OF DETECTING TARGETS ON RADAR AUTOMATICALLY

Visual displays such as the PPI scope discard much of the information that is available from the radar signal; for example, the amplitude range of a PPI dot is only about 6 dB. Since echoes on radar are electrical signals, it is desirable to substitute a device to process these signals electrically, instead of displaying them visually and recording this visual representation on photographic film.

To our knowledge, other techniques for dealing with the radar video signal have suffered from low resolution, high cost, or both. Many devices generate only target/no target information (discussed in Hansen, 1974). Boardman (1970) and Smith et al. (1974) describe a cloud "profiler" that records echo strengths on computer disk from range bins which are 1,280 m in length. The system, designed to map clouds out to 111 km, uses a fixed bin length and cannot be adapted for high resolution without prohibitive expense. Glover (1972) describes a specially built device that achieves a 75 m range bin length. Hunt (1975, 1977) devised a bird-counting system for aid in prediction of bird-aircraft collisions. It is hardwired and is designed to count numbers of birds in 305-m bins along the radar beam. A new "Moving Target Detector" (ARTS-3) designed for air traffic control expressly suppresses slow-moving targets such as birds, while recording radar echoes to 100 m resolution (Anon., 1975). The Moving Target Detector maintains a "clutter map" similar to the idea described below. Its production cost is about $70,000. Similarly, a number of computer-based target detectors on military equipment are designed to detect large, fast-moving targets at great range, and to reject birds as "clutter."

Two constraints make radar signals of small targets like birds somewhat difficult to capture by conventional means in digital form at a reasonable price. First, the analog-to-digital (A/D) converter that samples the radar signal must be very fast compared to the ones normally available in laboratory computers, and secondly the memory unit that receives the radar data must be equally fast to cope with the output of the A/D converter. As an illustration of the cost of such devices, an A/D converter that can sample 8 bits every 33 nsec currently costs about $6,000 and a transient recorder with computer-compatible output, operating every 50 nsec, costs about $5,600.

THE VIDEO SAMPLING UNIT

By using a sampling procedure instead of a fast conversion, we have constructed a relatively inexpensive device which allows the information contained in the radar video signal to be transferred directly to a computer or microprocessor, permitting accurate, detailed, and quantitative analysis of numbers, size distributions, and spatial distributions of bird echoes. The device, which we have called a Video Sampling Unit (VSU), is simple in principle. It is contained on a single printed circuit board and functions as a peripheral device to a PDP 8/E minicomputer, although it could easily be adapted to work with many types of digital machines including the inexpensive and rapidly developing microprocessors. The prototype was constructed in the Rockefeller University Electronics Laboratory and cost less than $2,000 including installation and modifications, but not including the cost of the minicomputer. (A circuit diagram and other details are available from the authors.)

The VSU can be adapted to any pulsed radar. It has been designed to be used with an AN/MPQ-29 pencil-beam tracker with a 4 kHz nominal pulse repetition frequency (PRF), and 0.25 μsec pulse width (further described in Larkin and Sutherland, 1977).

A simplified block diagram of the VSU is shown in Figure 1. Its operation is similar to sweep sampling units which are sold as accessories to some sophisticated oscilloscope systems (also called "serial sampling"; Findlay and Ornstein, 1975). It converts the radar echo amplitude into a digital form by collecting one sample, at a narrow and specified range, for each pulse transmitted by the radar. The VSU differs from the conventional sweep-sampling device because the range of each sample is determined by the computer program. It can be programmed to sample each range 'bin' in turn, producing the information contained in an A-scope display or, with antenna position information available to the computer, that in a PPI or Range-Height display. Or it can be programmed to sample one or a few range bins, generating data ideal for wingbeat or target "signature" analysis.

The initiation of a sample is preceded by transferring an 8-bit number, corresponding to the complement of a number representing a range of 0–255 units, from the computer to a fast 8-bit counter in the VSU. When the next radar trigger occurs, an enabling flip-flop is set that serves to gate a 20 MHz crystal oscillator into the counter. The counter counts down until it reaches zero at which time three events are

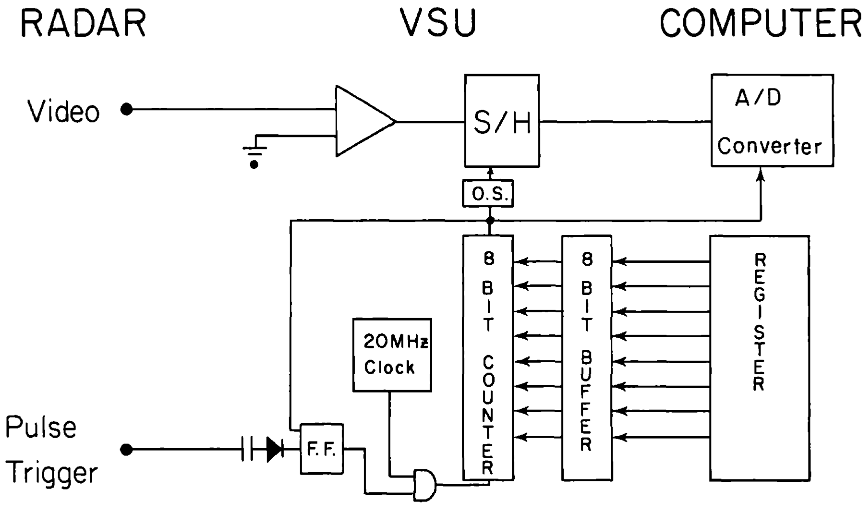

FIGURE 1. A block diagram of the principal elements in the VSU interface. The path along the top (radar video, amplifier, S/H, A/D converter) carries the analog signal, whereas the rest of the circuit is basically digital. Abbreviations: S/H = sample-and-hold, A/D = analog-to-digital, O.S. = one-shot, F.F. = flip-flop.

initiated: (1) the enabling flip-flop is reset stopping the clock entry into the counter; (2) a fast sample and hold unit is triggered and put into a sample mode for a period of 50 nsec (7.5 m) by means of a 50 nsec one-shot; (3) the A/D converter of the computer is also triggered, initiating a conversion and setting the computer interrupt request line when the conversion is complete. As a result, the VSU collects a very fast sample of the radar video signal at a specified time following the radar pulse and presents it to the computer's A/D converter. The A/D converter, which is the standard model sold by the computer manufacturer, takes up to 30 μsec to perform the conversion. The computer can then transfer a new 8-bit value to the VSU, arming it for another conversion at the next radar trigger pulse.

The accuracy and resolution of the VSU were determined more by convenience and economics rather than by what is possible with modern electronics. The 20-MHz clock has a stability of 5×10^{-5} over the range of 0 to 50°C. The 50-nsec interval between counts results in a range uncertainty of ± 7.5 m, plus a negligible uncertainty due to jitter in the radar trigger pulse. The 8-bit counter provides a total range interval of 7.5×256 or 1,920 m, of which the first 180 m is currently useless since it precedes the outgoing radar pulse in time. A complete sequential scan of the 1,920-m range takes 64 msec (256 samples/4,000 PRF). If used with a radar with longer range and longer pulse length, different trade-offs of these parameters might be chosen without an increase in cost. Ten-bit amplitude resolution, determined by the A/D converter, provides a measure of echo strength that is far more accurate than needed.

The temporal resolution of the VSU is also sufficient for studying birds in the radar beam. As mentioned above, the VSU can generate a complete sequential scan each 64 msec. Since the maximum speed of a bird might be about 40 m/sec, the bird would move a maximum of only about 2.6 m or ⅓ of a range bin width, between one sweep and the next. It is only when moving the radar beam at high angular velocities that a complete sequential scan might provide insufficient data rates for detecting and locating bird targets. In this case, programming solutions to concentrate on certain areas of the beam would be easy to implement. Trials using a rotating antenna show that 2–8 recognizable blips, or "hits" are attained on single distant bird targets, even when conducting complete sequential scans while rotating the antenna at 10–20 degrees/sec.

In practice, we have found that the digitized radar signal is nearly as useful as the actual radar video signal even for purposes of visually observing migrating birds on radar. A single complete sequential scan during a night of fall migration is shown in Figure 2. The display is a

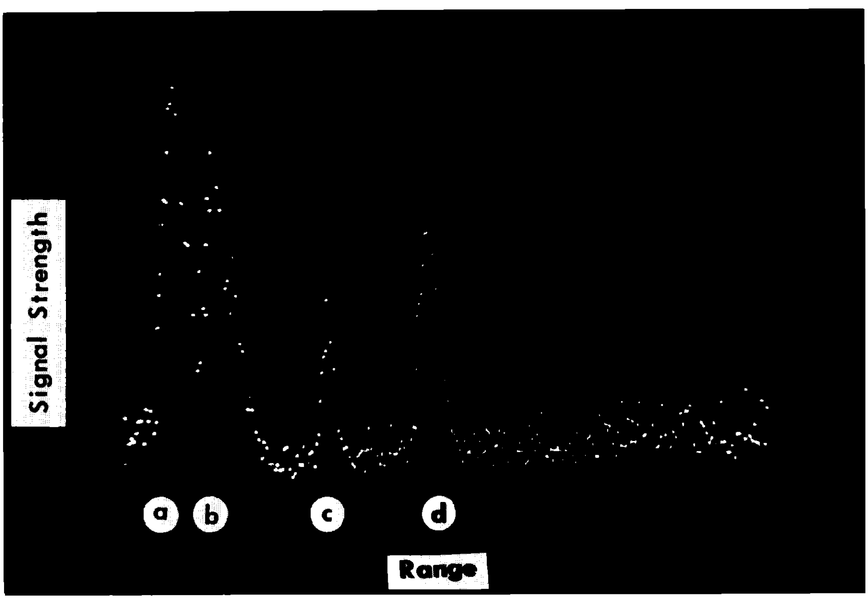

FIGURE 2. A photograph of a digital reconstruction of the A-scope display, stored by a single VSU scan. Each dot represents the signal strength at one 50 nsec interval from the radar pulse trigger corresponding to approximately 7.5 m range. The display is 1,920 m in total range. (a), The outgoing radar pulse, or "main bang," defining range zero. (b), A peak representing ground clutter at short range. (c) and (d), Two bird targets at more distant ranges.

digital version of the conventional A-scope display of echo strength as a function of slant range. Since the trigger precedes the outgoing radar pulse ("main bang") in time, the values at the extreme left contain no echoes. Because adjacent samples are taken only 250 μsec apart, the shape of the bird echoes is not distorted by the sampling technique. The display shown in Figure 2 is generated in real time and the operator can compare it to the A-scope display on the radar to verify that the VSU is operating correctly.

QUANTITATIVE RECORDS OF BIRD MIGRATION

Potentially, all the information available from the conventional radar displays, location of targets in range, target echo strength, range velocity, and echo signature, is available from the video sampling unit as accurate numerical quantities. These data can then be processed immediately by a computer or microprocessor to provide information which is more meaningful than is available from a PPI or A-scope display analyzed by hand.

As an example of what is possible after a modest amount of processing is performed on the raw VSU data, Figure 3 illustrates the passage of two birds through a stationary conical radar beam on a night of heavy fall migration, 11 November 1976. Several simple operations were performed to produce Figure 3. On the day previous, a record of several VSU scans had been taken, averaged, and stored for later use. This stored record provided a sample of the radar noise and clutter at the radar site. Then similar records were taken during the period of nocturnal passerine migration and the noise record was subtracted from each, providing a distribution-free (Vogel et al., 1975) means of identifying the bird targets. The data were then scaled to arbitrary values 0–9 in order to construct the printed image of target height and range as a function of time in Figure 3. (Figure 2 is a record of one scan occurring about second 6 in Figure 3.)

Ground clutter is present at extremely close ranges even after the noise subtraction operation; nearby vegetation probably became more reflective at night because of dew formation. Two birds appear and disappear gradually as they fly through the vertical beam, not changing in range since they are presumably flying nearly level. The closer bird is either a much smaller target than the farther bird or is passing through the edge of the beam rather than its center.

By taking advantage of the flexibility afforded by the computer control over the VSU, it will be possible to gather completely different kinds of data than those illustrated in Figures 2 and 3. For example, the VSU can be used with a tracking radar in a signature analysis mode to gather data on the wingbeats of bird targets and analyze them using frequency-domain techniques, without the phase lags, filtering, and nonlinearities usually inherent in data taken from automatic gain control circuits. In this mode, the computer can conduct a sequential scan of all or part of the beam, locating one or several targets of interest. It can then sample

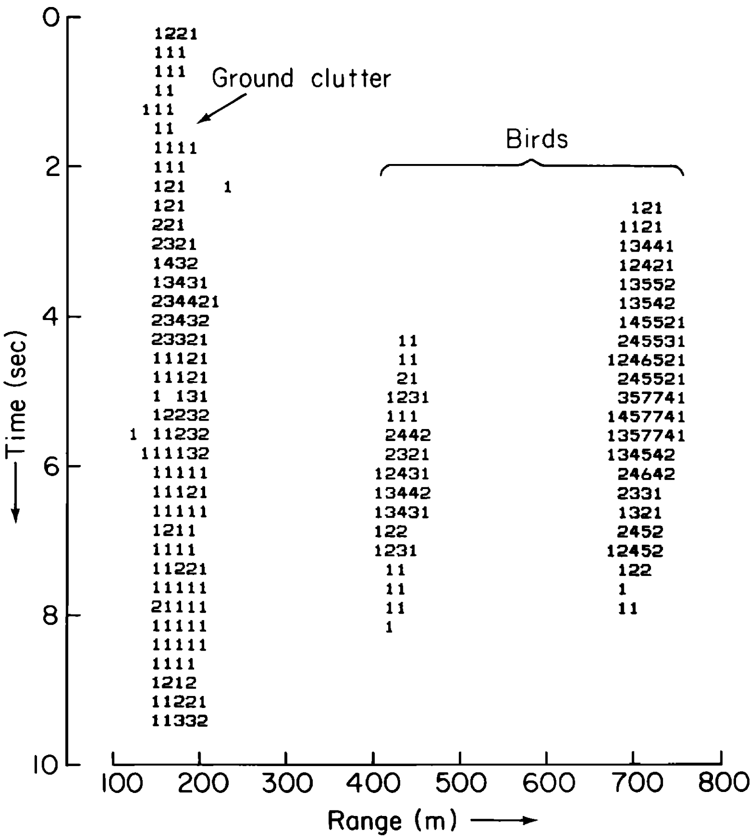

FIGURE 3. A printed record of two birds passing through a stationary radar beam. The VSU, running continuously, obtained a scan approximately every 1/16 sec. Each four consecutive scans were averaged together to generate a line approximately every 1/4 sec, starting at the top of the figure. On the horizontal axis, each two adjacent range bins were averaged together so that a character represents 15 m range. Where the radar video signal was below the average noise (measured previously at each range interval by the VSU), the record is blank. Signals above this threshold are indicated by a number corresponding to the echo height in arbitrary linear units 1–9.

at high rates (up to the PRF) near each target, recording amplitude fluctuations as a function of time. Since the data stored represent absolute echo strengths, the task of correlating target size with wingbeat characteristics would become manageable instead of extremely laborious.

The use of devices such as the VSU will allow significant improvements in radar ornithology. Large amounts of precise data can be gathered and analyzed quickly, instead of requiring months of tedious cataloging and scoring of photographs. In order to gain such improvements, the investigator must invest in some electronic hardware (minicomputer or microcomputer plus VSU) and must further invest time in programming the computer to control the VSU in conjunction with a given radar unit. But the continuing increase in popularity and decrease in price of small computers will make the initial investment easier in the future.

SUMMARY

Most of the presently available methods for taking ornithological data from radar displays are time-consuming and only partly quantitative. A device is described that costs under $2,000 and allows the video signal from any pulsed radar to be transferred directly to a computer or microprocessor. All the information available from conventional radar A-scope displays may be derived from the device, termed a Video Sampling Unit, as accurate numerical quantities. With appropriate programming, distributions of bird altitudes and sizes, wingbeat analysis and other information relevant to bird migration may be obtained.

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LITERATURE CITED

ALERSTAM, T. 1972. Nocturnal bird migration in Skane, Sweden as recorded by radar in autumn 1971. *Ornis Scandinavia*, **3:** 141–151.

ANON. 1975. New target detector sifts out clutter. Aviation Week and Space Technology, 8 Sept., 49–51.

BLOKPOEL, H. 1969. A preliminary study on height and density of nocturnal fall migration. *In* Proceedings of the World Conference on Bird Hazards to Aircraft. (M. S. Kuhring, ed.), Kingston, Ontario, 335–348.

———. 1976. Bird Hazards to Aircraft. Ottawa, Clarke, Irwin, and Company, Ltd.

BLOKPOEL, H., AND J. BURTON. 1975. Weather and height of nocturnal migration in eastcentral Alberta: a radar study. *Bird-Banding*, **46:** 311–328.

BOARDMAN, J. H. 1970. Processing weather radar data with a small computer. DECUS Proceedings, Atlantic City, N.J., 189–201.

BRUDERER, B., AND P. STEIDINGER. 1972. Methods of quantitative and qualitative analysis of bird migration with a tracking radar. *In* Animal Orientation and Navigation (S. J. Galler, K. Schmidt-Koenig, G. J. Jacobs, and R. E. Belleville, eds.), NASA SP-262, U.S. Government Printing Office, Washington, D.C., 151–167.

EASTWOOD, E. 1967. Radar Ornithology. London, Methuen & Co.

FINDLAY, A. M., AND E. ORNSTEIN. 1975. Sampling wideband, non-repetitive radar signals. *In* Report of the IEEE 1975 International Radar Conference (Institute of Electrical and Electronics Engineers, New York), 288–293.

GAUTHREAUX, S. A. 1970. Weather radar quantification of bird migration. *BioScience*, **20:** 17–20.

———. 1974. The detection, quantification, and monitoring of bird movements aloft with airport surveillance radar (ASR). *In* Proceedings of a Conference on the Biological Aspects of the Bird/Aircraft Collision Problem. (S. A. Gauthreaux, Jr., ed.), Clemson, S. C. 5–7 February, 289–307.

———. 1977. The role of radar in the avoidance of bird/aircraft collisions. Bird Hazards to Aircraft Seminar and Workshop (S. A. Gauthreaux, ed.), East Point, Ga., Sept. 8–9 1976, 179–190.

GLOVER, K. M. 1972. A precision digital video integrator. Fifteenth Radar Meteorology Conference, 193–198.

HANSEN, V. G. 1974. Optimization and performance of multilevel quantization in automatic detectors. IEEE Transactions on Aerospace and Electronic Systems, AES-10, 274–280.

HUNT, F. R. 1973. Bird density and the PPI. Associate Committee on Bird Hazards to Aircraft, Field Note No. 63, Ottawa, Canada.

———. 1975. Automatic radar equipment to determine bird-strike probability. Part I. Night-time passerine migration. Field Note No. 69, Associate Committee on Bird Hazards to Aircraft, National Research Council, Ottawa, Canada.

———. 1977. Automatic radar equipment to determine bird-strike probability. Part II. Migrating water-fowl flocks. Field Note No. 75, Associate Committee on Bird Hazards to Aircraft, National Research Council, Ottawa, Canada.

LARKIN, R. P., AND P. J. SUTHERLAND. 1976. Migrating birds react to Project Seafarer's electromagnetic field. *Science*, **195:** 777–779.

MILLER, J. T., JR. 1975. Some sequence length characteristics of dot angles and small aircraft. *In* Record of the IEEE 1975 International Radar Conference (Institute of Electrical and Electronics Engineers, New York), 274–277.

NISBET, I. C. T. 1963. Quantitative study of migration with 23-centimetre radar. *Ibis*, **195:** 435–460.

RICHARDSON, W. J. 1972. Temporal variations in the ability of individual radars in detecting birds. Field Note No. 61, Associate Committee on Bird Hazards to Aircraft, National Research Council, Ottawa, Canada.

SMITH, P. L., K. R. HARDY, AND K. M. GLOVER. 1974. Applications of radar to meteorological operations and research. *Proceedings of the IEEE*, **62:** 724–745.

VOGEL, L. E., W. S. REID, AND P. E. STEICHEN. 1975. An examination of radar signal processing via non-parametric techniques. *In* Record of the IEEE 1975 International Radar Conference, 533–537.

WILLIAMS, J. M., T. C. WILLIAMS, AND L. C. IRELAND. 1974. Bird migration over the North Atlantic. *In* Proceedings of a Conference on the Biological Aspects of the Bird/Aircraft Collision Problem, (S. A. Gauthreaux, ed.), Clemson, S.C., 5–7 Feb., 359–382.

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