Tracking Radar Studies of Bird Migration

TIMOTHY C. WILLIAMS
JANET M. WILLIAMS
The State University of New York at Buffalo

JOHN M. TEAL
JOHN W. KANWISHER
Woods Hole Oceanographic Institution

RADARS HAVE NOW BEEN USED to study bird migration for more than two decades (ref. 1). The majority of these studies have been performed with search radars, designed to detect a maximum number of targets aloft. Tracking radars, on the other hand, are designed to detect and follow a single target and extract the maximum information from this one target. To accomplish this, tracking radar antennas produce a pencil beam of radar energy rather than the fan-shaped beam produced by search radars. Detection of the target to be tracked is usually accomplished by first rotating the antenna in a search mode. When the radar echoes are displayed on a plan position indicator (PPI), an image similar in appearance to that obtained with search radars is produced (see fig. 1).

The interpretation of the PPI is, however, quite different; while search radars are designed to detect all targets regardless of altitude, the PPI produced by a tracking radar will show only those targets that fall within
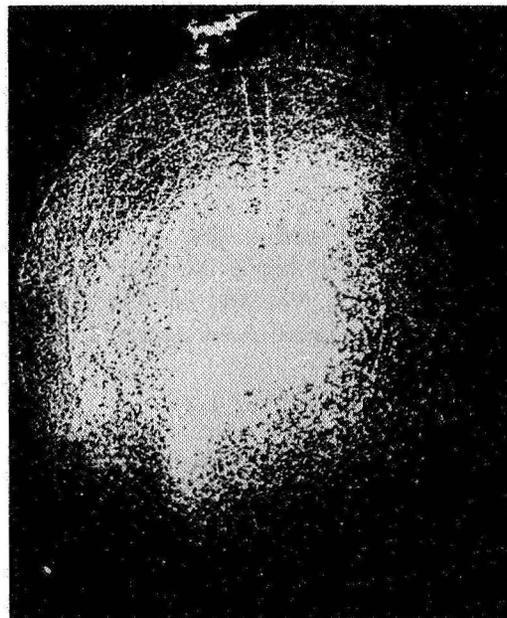
FIGURE 1. PPI presentation of SPANDAR radar, Wallops Island, Va., 1° elevation, 5-mile range marks. North is toward top of figure; coastline is oriented NNE to SSW through center. Major part of migration is over land to west of the radar.

115

its narrow pencil beam. Since this beam is usually directed upward, the altitude of targets will necessarily be a function of range. Bellrose and Graber (ref. 2) utilized this principle in their study of the altitude of nocturnal migrants. A number of other investigators have also used the pencil beam of small tracking radars (refs. 1, 3 and 4). Not until recently, however, has there been an effort to use the second stage of radar tracking, that of actually following a target once it has been detected in the search mode. Such studies have been performed by Gehring (ref. 5), Houghton (ref. 6), and, as is noted by Griffin and by Bruderer and Steidinger (this volume). Once the radar is set in the tracking mode the amplitude and modulations of the radar echo reveal the size of the target and most probably the wingbeat pattern (refs. 5 and 6). We hope that the analysis of such radar signatures will greatly aid in the identification of nocturnal migrants.

TECHNIQUES

The radars used in this study were the SPANDAR (and briefly the Q-6) radar at Wallops Station, Va., and the Q-6 radar at Bermuda. The radar characteristics are given as follows:

SPANDAR
   10 cm (2700–2900 MHz)
   5 Mw, peak power
   18.3-meter (60-ft) parabolic dish antenna
   0.39° beam width (at half power points)

Q-6
   5 cm (5400–5900 MHz)
   3 Mw, peak power
   8.84-meter (29-ft) Cassegrainian parabolic dish antenna
   0.40° beam width (at half power points)
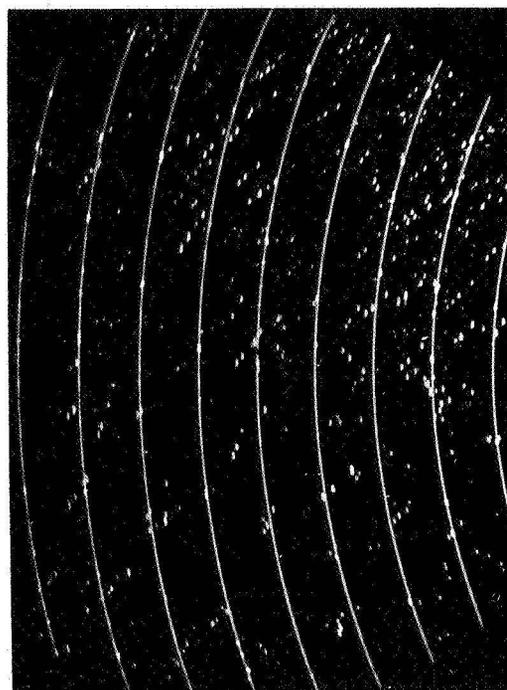
FIGURE 2. Sector scan of small area to west of the radar shown in figure 1 (2-mile range marks, 16- to 36-mile range).

Before tracking we used a polaroid camera to obtain photographs of the PPI display; these enabled us to assess the general patterns of migration and to determine the most profitable areas for tracking. Figure 1 was made during a heavy nocturnal migration over Wallops Island in April 1969; the shore line is oriented through the center of the figure running NNE to SSW. As one may see from figure 1, the major part of the migration at

FIGURE 3. Speed, direction, and present location of moving birds are recorded by timing the camera shutter action while photographing radar display; this technique was used in figures 1 and 2.

this time was over land. During such dense migrations, search radars are often saturated over much of their usable range and, as in the center portion of figure 1, individual targets cannot be distinguished.

Figure 2 demonstrates how the pencil beam of the tracking radar may be used to separate targets during even a heavy migration. The PPI display is off-centered covering the range from 26 to 58 km (16 to 36 mi with 2-mi range marks), the center of the sector scan being due west from the radar. Both figures 1 and 2 were made so that the direction and speed of the targets, as well as their position, could be determined. The radar was rotated twice with the shutter of the polaroid camera held open. The shutter was closed for the third revolution of the radar antenna and opened again for the fourth. All moving targets would thus show as two dots followed (in time) by a third at some distance, as illustrated in figure 3. Although individual targets can be distinguished only at the periphery of figure 1, figure 2 reveals that the migration over the Cheasapeake Bay was strongly oriented toward the NE; 78 targets were flying a course between 000° and 090°, five targets between 090° and 180°, and only four between 180° and 360°. Photographs such as figures 1 and 2 allow us to determine whether the bird tracks we obtain represent the typical flight direction and speed or an unusual type of movement.

The use of the pencil beam also allows one to determine the density of radar targets; the volume swept out by the radar beam in the central sector of figure 2 is about 220 cubic kilometers (54 cubic miles) if we assume the SPANDAR radar detected only targets within its 0.39° beam width. This would give a density of 1.6 targets per cubic mile. (If one wished to be more conservative and count only the largest targets, the density drops to 0.86/cubic mile.)

We used the PPI photos to select the most promising areas to obtain bird targets. This was done by specifying azimuth, elevation, and range, and then having the radar operator search for bird targets in that area. Bird targets were identified on the A scope[1] by their small size (relative to aircraft) and rapidly fluctuating amplitude. During the preliminary phases of our work, there is undoubtedly a bias toward the selection of large bird targets as these would be easier to track. Once an operator had set the radar to automatically track a target, we checked the target speed using an analog plot board; any target moving at more than 160 km/hr (100 mph) was rejected.

After accepting the target as a bird target, range, azimuth, antenna elevation, and average echo amplitide were recorded once a second on magnetic tape for later analysis. The analog plotboard was used for real-time analysis. In addition we maintained a continuous log of A scope observations, such as nearby targets and weather. If it appeared that the radar had swtiched targets during a heavy migration, we considered this to be a new bird track. At the beginning of each track and at 20-min intervals we obtained a 2-min record of the fluctuations in echo strength, and the azimuth and elevation errors of the radar for later identification of the target's radar signature.

After a relatively short period of time the SPANDAR operators became so skilled at tracking birds that we were able to briefly interrupt tracking, obtain weather information with the radar, and then regain the target for further tracking. The weather information consisted of radar images of cloud formations near the bird target. The radar was either moved to the right and left of the target (PPI) to determine the horizontal ex-

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[1] Display of radar echo amplitude vs time.

tent of the clouds, or moved above and below the target to determine the altitude of clouds (RHI: range height indicator). This tech- nique is illustrated in figure 4. This figure also illustrates the manner in which birds may avoid weather. Here, a bird is moving
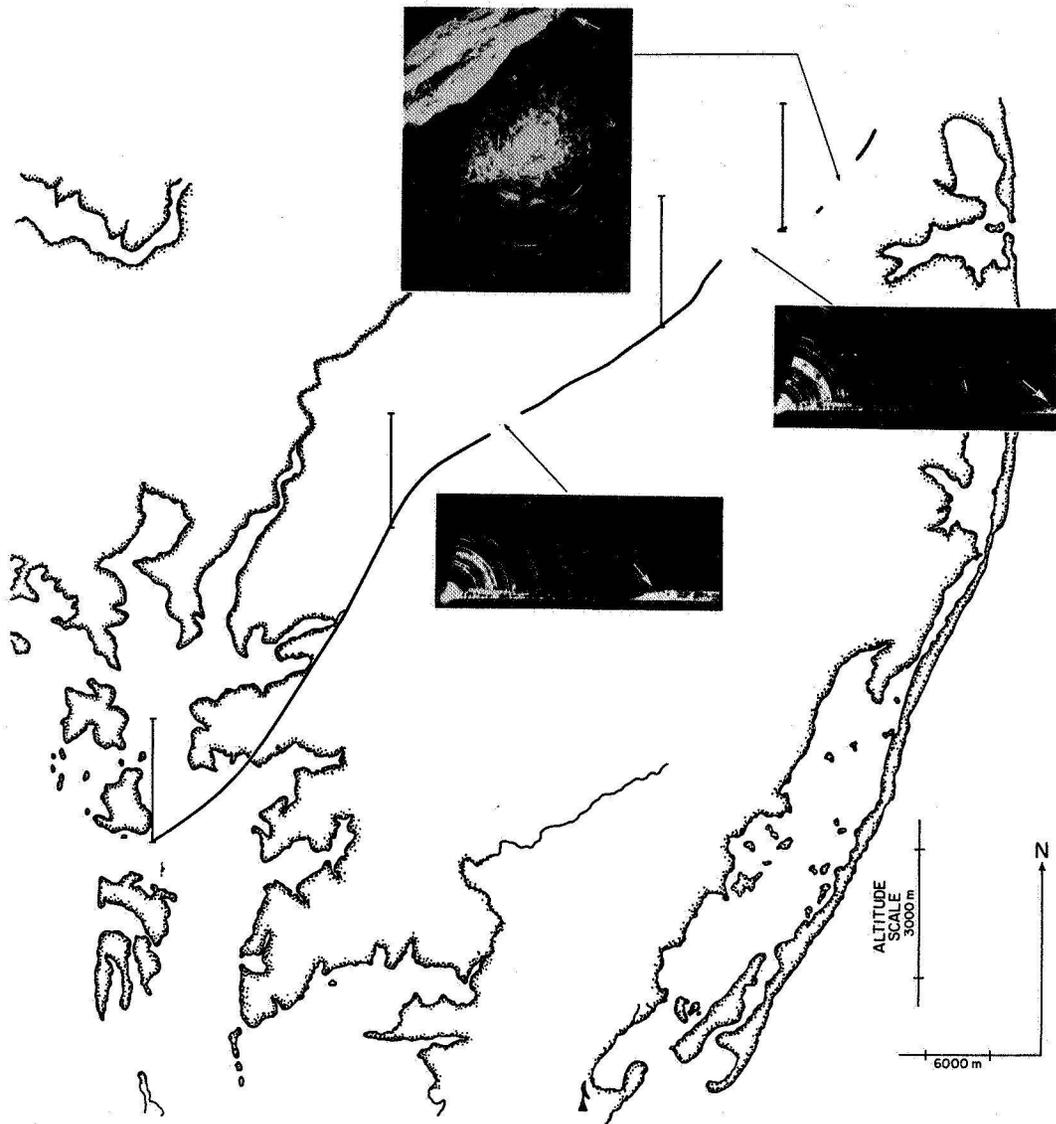
FIGURE 4. Track of bird avoiding heavy weather. Tracked from SPANDAR. Track was interrupted at three points to take PPI and RHI records of weather shown in insets; position of bird indicated by arrow. In some RHI's it was possible to have bird echo show in the weather photograph. Altitude at four points on track shown by bars and also on track 12K–L–M in figure 6. Bird can be seen above cloud front in RHI displays. Shape of track fits the shape of cloud front in PPI display.
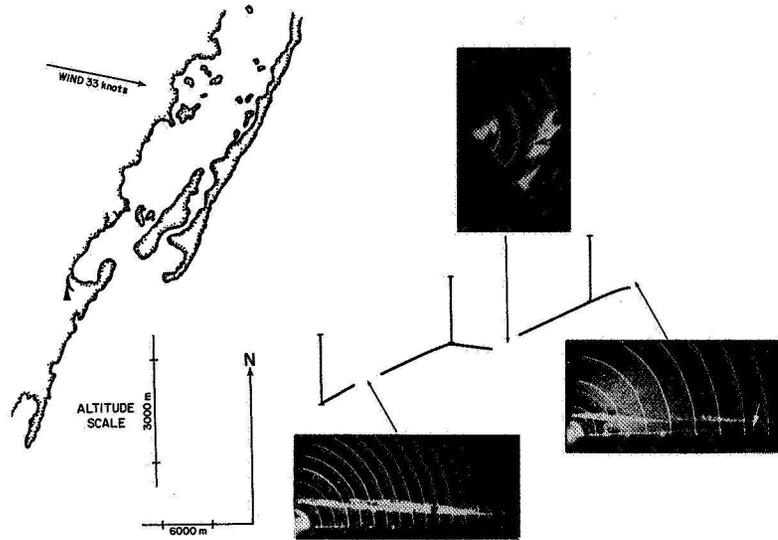
FIGURE 5. Track of bird flying beneath cloud layer over open water (SPANDAR). Track was interrupted at three points to obtain PPI or RHI weather data shown in inset; position of bird is shown by arrow. Pencil beam of this radar only picks up clouds above (beyond) target, although clouds extended on all sides for several miles.

along the edge of an advancing cold front. The two RHI insets, in which altitude is up and range to the right, show the bird just above the edge of the cloud bank. The PPI inset taken just before we lost the target, reveals that the shape of the advancing front closely resembles that of the bird's track.

Figure 5 illustrates another interaction of brids and weather—birds flying under a heavy overcast. In this case the two RHI insets show a dense layer of clouds above the bird; the PPI reveals that the clouds extend several miles on either side of the bird. (Note that the PPI only shows clouds beyond the bird; this is due to the pencil beam of the radar failing to intercept the high clouds at the altitude of the bird.) Tracks of birds on this night will be discussed later.

Analysis of the digital data consisted of a computer printout once every 5 seconds of elapsed time, speed of the bird relative to the ground, direction of flight, altitude of the

bird with corrections for curvature of the Earth, rate of climb or fall, and radar crossection of the target. Plots were made of the x, y coordinates and altitude vs time. The minimum smoothing needed to eliminate errors in the tracking radars was used in these plots. One aim of our research has been to analyze the accuracy of bird navigation under a variety of weather conditions. In order to obtain an estimate of the straightness of the plots, we fitted a linear equation to the plot using the least squares method. The standard error of estimate (based on 500 points at equal time intervals along the track) was then computed for the following variables: East-West range (x) [vs North-South range (y)] and altitude (vs time). The interpretation of these standard errors will be discussed below.

Weather data consisted of surface observations, winds aloft from radiosondes at the Wallops Island and Kindley AFB (Bermuda)

weather stations, and satellite photographs of cloud patterns above the eastern coast of the U.S. and Bermuda.

RESULTS

During the spring of 1969 we were able to observe at the SPANDAR radar from March 24 through April 4 and from April 21 to 25. A second set of observations was made during the fall from October 6 through 17, using both the SPANDAR at Wallops Island and the FPQ-6 at Bermuda. Up to this point our work has been primarily exploratory, as- sessing the capabilities of the radar systems for following bird targets. The use of long-range tracking radars, however, has already added new data to the study of bird migration.

Figure 6 presents all the tracks we obtained at Wallops Island under clear skies (both spring and fall) that were more than 60 km (200 000 ft) long. This figure gives the plots of altitude vs time as well as the vector computation of wind, air, and ground velocities for the targets. Inspection of figure 6 reveals several different types of tracks representing (we believe) different populations of migrating birds.

Tracks such as 9F–G–H–I and 5D during the spring and 15D during the fall correspond to our idea of the typical migratory bird track—a long straight track directed toward the presumed migratory goal. Other tracks such as 28H, 23A, and 30D are also long and straight but appear to be headed into the vastness of the Atlantic Ocean. As yet we cannot determine if a bird's course is appropriate to its destination, only its accuracy in maintaining course. Table 1 presents the standard error of estimate for the deviations of these tracks from a straight line. This is done first for the horizontal plot coordinates and then for the altitude of the bird's flight.
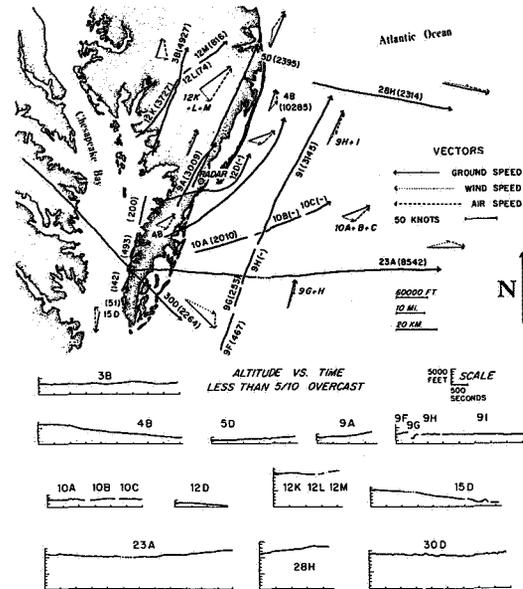
FIGURE 6. Bird tracks longer than 200 000 ft recorded under less than 5/10 overcast. Upper half shows the x-y coordinates of the tracks against local topography. Each track is identified by a number and letter followed by x-y standard error in parenthesis. Code number identifies the day of tracking (3–12, spring 1969; 15–30, fall 1969); letters distinguish tracks made on the same day. At various points along the tracks, vector diagram of wind, ground, and airspeeds is given. Winds were taken at radar site at altitude of the bird. Lower half of figure gives plots of altitude vs time for each bird track shown above. Breaks in the tracks were used to take RHI or PPI data on weather and other targets. Altitude data below 3000 ft may be unreliable due to anomalous propagation of radar beam.

The x,y standard error for most "straight" tracks is about 1 percent (The x,y standard error for all tracks obtained is presented later in this paper as a function of track length). The standard error of altitude reveals that many birds appear able to determine altitude with great accuracy. Track 3B maintained an almost level flight producing a standard error of only 56.7 me-

TABLE 1.—*Standard Errors of Straight Tracks* (*shown in figure 6*)

Track	Length (ft×10³)	x, y error [a]	% of length	Slope	Altitude- time error	% of length
3B	216	4.297	2.2	+0.019	0.186	0.085
5D	290	2.395	0.82	+0.336	0.077	0.026
9F	62	0.467	0.75	+1.452	0.034	0.055
9G	33	0.253	0.78	+7.497	0.190	0.58
9I	320	3.145	0.98	−0.283	0.052	0.016
10A	99	2.010	2.0	....	....	....
23A	590	8.542	1.4	−0.373	0.110	0.019
28H	280	2.314	0.83	+1.223	0.116	0.041
30D	432	2.264	0.52	−0.116	0.281	0.065

[a] A linear equation was fitted to the horizontal track and to plot of altitude vs. time; the standard error of bird tracks with respect to the linear equation indicates the accuracy with which the birds could maintain altitude and course.

ters (186 ft) on a track 66 km (41 miles) long, and track 5D was able to maintain a steady rate of ascent within 10.4 meters over 88.5 km. Track 30D illustrates the track of a bird that was apparently able to maintain course but not altitude. The altitude plot shows periodic fluctuations of about 150 meters (500 ft) which are correlated with changes in forward speed suggesting soaring flight. As may be seen from the triangle of velocities in figure 6, this bird was heading at an angle of about 60° away from its actual track; yet despite this and its undulating flight, the bird produced one of the straightest tracks we have recorded.

Even on clear nights not all bird tracks were straight. At least one of these, 12K–L–M, we know to result from the attempts of the target to avoid an approaching storm (see fig. 4); track 9A may represent a similar circumstance. Some tracks in figure 6 show a constant decrease in altitude (4B, 12D, and 15D). This often occurred when birds were flying against unfavorable winds. The birds apparently descended to seek calmer conditions near the surface. Bird 4B was successful in finding a favorable wind, and

12D and 15D either landed or flew too low to be tracked. The shorter tracks we obtained (not shown) exhibited similar patterns to those shown in figure 6.

On any one night there was a definite tendency (which we have not yet quantified) for all targets tracked to be similar in heading (see discussion under PPI above), altitude, and speed. Our impression is that we were usually dealing with only a few types of bird movements on a given night.

Although dense clouds obliterated the radar echoes from bird targets, we were able to track on several nights when the sky was completely obscured by high cloud layers. Clouds were considered opaque only when surface weather observers reported 10/10ths cover before and after the period of tracking, when RHI photographs (as shown in fig. 5) showed heavy cloud layers, and when satellite photographs indicated that the clouds extended over large areas. Figure 7 presents all available tracks under such conditions. These data clearly show the ability of birds to maintain course even over open ocean without reference to the stars. The birds in figure 7 could, however, probably see the lights on
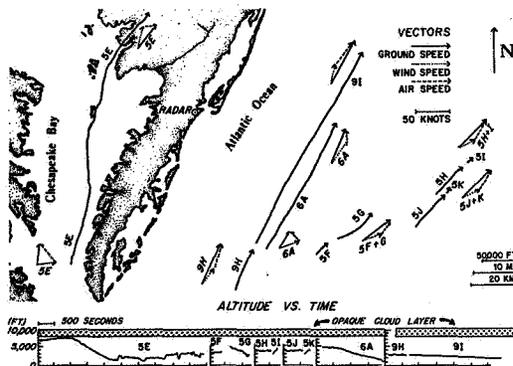
FIGURE 7. Tracks of birds flying under overcast,
SPANDAR radar, symbols as in figure 6. Altitude
of cloud layer shown by stippling on altitude
plots.

FIGURE 8. Tracks of birds flying between cloud
layers. Symbols as in figures 6 and 7.

land. Track 5E is interesting in that solid
overcast moved over Wallops Island about
one hour before we began that track. At the
beginning of track 5E, the bird was at 2100
to 2400 m near the cloud layer, and bucking
a strong crosswind. Shortly after we began
tracking, the bird descended rapidly (the
rapid changes in altitude during the later
part of the track may be due to anomalous
propagation of the radar beam), and success-
fully maintained course despite having to
change its compass heading more than 120°.
The changes in course near islands and
shorelines suggest the use of landmarks for
piloting. Target 6A also descended and ob-
tained more favorable winds without altering
its true course despite a change in heading of
about 60° (see vector diagrams in fig. 7).
Since this bird was almost 48 km (30 mi) at
sea, the use of landmarks is less likely than in
track 5E.

On April 2, 1969, heavy fog or low clouds
at about 180 m (600 ft) obscured the sky
during our period of tracking. The RHI
shown in figure 5 indicated a dense cloud
layer at about 4.6 km (15 000 ft). Surface
observations and satellite photographs before

and after our tracking indicated that this was
a totally opaque cloud layer. Thus, the birds
tracked on that night were probably flying
between layers of clouds without visual refer-
ence to either the sky or the earth. The tracks
of these birds are shown in figure 8 with the
exception of two very short tracks 7J and 7K.
Track 7C–D–E represents the only case of
birds flying with the wind that night; in all
other cases the birds flew at some angle to
the wind. The straightness of tracks 7I,
7C–D–E and 7F–G–H might be explained by
the birds' flying at some constant angle to the
wind, with the turn in track 7G being ex-
plained by a short downwind flight to avoid
turbulence. But 7A–B and 7L–M–N cannot
be explained in this way; these tracks clearly
do not maintain a constant angle to the
wind. Both the direction and speed of the
wind in track 7A–B changed considerably as
the target descended. The velocity of the bird
relative to the ground also changed during
the same period. The air velocity, however,
remained remarkably constant both in direc-
tion and speed. This may be even more
clearly seen in the case of 7L–M–N. The rele-
vant data for this track are given in table 2.
Thus, the tracks of these two birds may be
best explained by the bird's maintaining a

constant compass heading without reference to the sky or land and despite shifting winds. The curves in the tracks would be due to the changing direction of the wind, the birds perhaps being unaware of the changes in their actual track.

In the fall of 1969 we made simultaneous observations at Cape Cod (Massachusettes) and Bermuda in addition to those made at Wallops Island. Figure 9 is a PPI photograph made on October 14 at the Q-6 Bermuda radar. The outline of the Bermuda islands can be seen to the left of the center due to anomalous propagation and echoes from side-lobes of the radar beam. The figure shows a strong movement to the SSE—120 targets heading from 120° to 180°, six from 190° to 230°, and four from 010° to 060°. These birds were not simply following the wind; in fact the wind on that night was from the East (see tracks 1B and 1C, p. 124). It thus appears certain that large numbers of birds actively cross the open Atlantic Ocean in migrations from North America to South or Central America. In the future we hope to correlate observations at several radars along the Atlantic coast with observations at Bermuda and Antigua (W. I.) to learn more about this migration route. In October 1969 we were able to observe only three strong migrations over Bermuda. Observations at Cape Cod indicated large numbers of birds departing from the Cape to the SSE between 28 and 40 hours prior to the appearance of
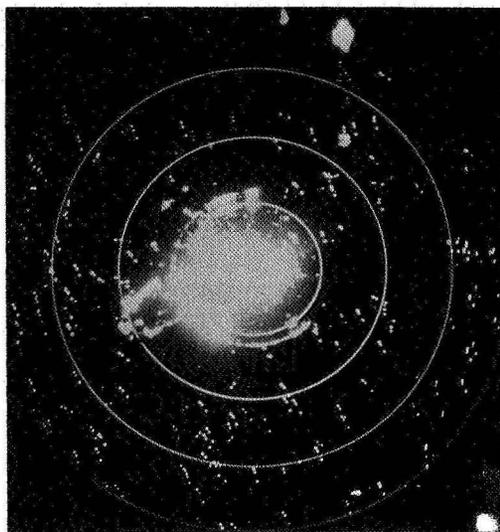
FIGURE 9. PPI photograph of birds migrating over Bermuda. FPQ-6 radar, October 14, 1969, 1745 GMT, 5-mile range marks, 1/2° elevation.

large numbers of birds over Bermuda islands.

Figures 10 and 11 present all the tracks longer than 10 km obtained from Bermuda of birds moving south. As with birds moving over Wallops Island, the x,y standard errors are about 1 percent of the track length, and the altitude standard errors are about 0.1 percent of the track length. All tracks taken at Bermuda were made under clear or only partially cloudy skies. The straightness of the tracks does not appear to be correlated with either compensation for wind drift (compare figs. 10 and 11) or with level flight. Fig-

TABLE 2.—*Vector Analysis of Track L-M-N*

Vector	Direction of vector for track			Change in vector during flight
	L	M	N	
Wind..................................	115°	140°	160°	45°
Track.................................	40°	20°	300°	100°
Heading of bird.......................	335°	340°	330°	10°
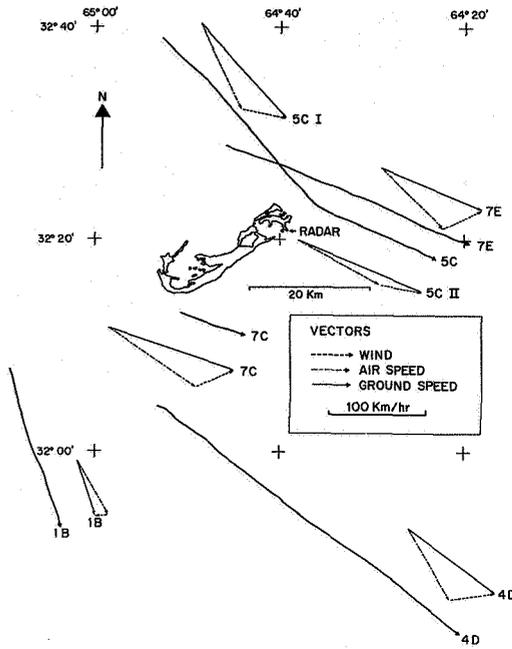
FIGURE 10. Tracks of birds migrating to the southeast across Bermuda. Symbols as in figure 6. Plots of altitude vs time not shown.

ure 12 shows the altitude plots for tracks 4C and 9E. Both birds were flying within 20° of the wind direction. Track 4C maintained altitude, and its x,y error was 917 m (3010 ft) or 4.1 percent of the track length. Bird number 9E, like other birds on day 9, produced a very irregular altitude plot (presumably due to turbulence behind a recently passed cold front), yet the birds on day 9 produced very straight tracks; the error for track 9E was only 177.4 m (582 ft) or 0.43 percent of the track length.

Figure 13 presents all the tracks longer than 10 km obtained at Bermuda that were not shown in figures 10 and 11. All these birds are moving eastward, but they are not being blown in that direction by the wind (see track 3A and 3B); they are actually flying a compass heading of between 100° and 120°. These courses even without wind drift would fail to intersect the South American continent. Thus, these birds appear to be actively moving to the east. Such movements are by no means uncommon; they were ob-
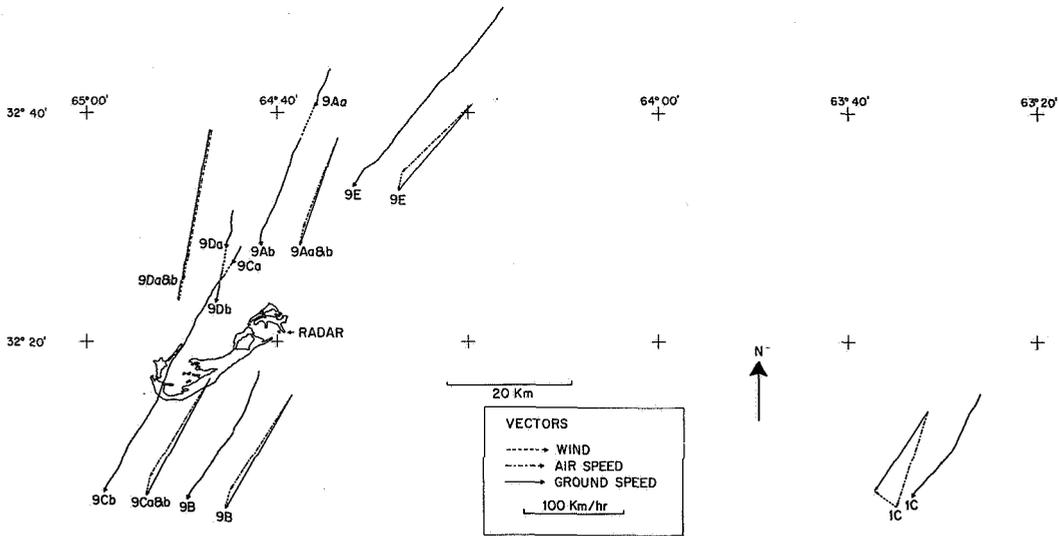
FIGURE 11. Tracks of birds migrating SSW across Bermuda. Symbols as in figure 6.
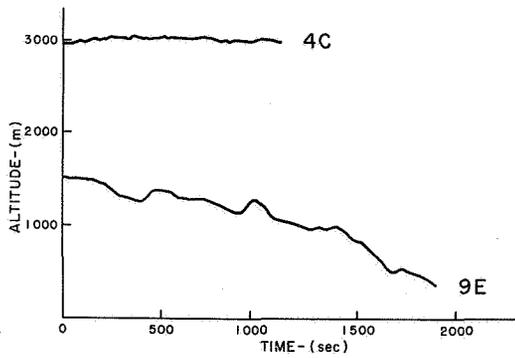
FIGURE 12. Plots of altitude vs time for two tracks of birds moving across Bermuda.

FIGURE 13. Tracks of birds moving east across Bermuda. Symbols as in figure 6.

served on 5 of the 9 days we were able to observe at Bermuda. At present these tracks, which might be continuations of tracks such as 23A and 28H in figure 6, represent a new facet of the study of bird migration: Is the navigational apparatus of these birds upset in some way or are they part of some new migration route either to Africa or, by an indirect route, to South America?

To date our principal findings are the ability of birds to maintain course under overcast skies and the movements of birds across Bermuda. If future data confirm our present results, it would appear that birds are able to maintain a compass heading by some means other than visual reference to the sky or Earth. It appears, however, that the birds cannot compensate for shifts in the wind without visual reference. Under these circumstances bird migration might be accomplished by maintaining a compass heading between checkpoints, either celestial or terrestrial. In this regard tracks such as 5C in figure 10, in which a target altered course as it passed near Bermuda, are most interesting.

In the future we hope to increase our knowledge of the radar targets in order to separate what we believe are distinct populations of migrating birds with different goals

and perhaps different navigational techniques. Also we would like to know whether we are dealing with single birds or flocks that might pool their information. The radar crossection of the target is often helpful in the latter instance. The largest targets we have followed (with a crossection of 0.1 m²) are certainly flocks while the smallest (with a crossection of 0.00001 m²) are probably single targets. Another valuable tool in this effort will be the analysis of radar signatures (see also Bruderer and Steidinger, this volume.) Figure 14 presents the records of the automatic gain control (AGC) voltage which is proportional to the amplitude of the radar echo. In the upper portion of the figure, one may see the effect of increasing the number of birds in a target. A single brant gives an AGC record with regular fluctuations at about three per second; the azimuth and ele-
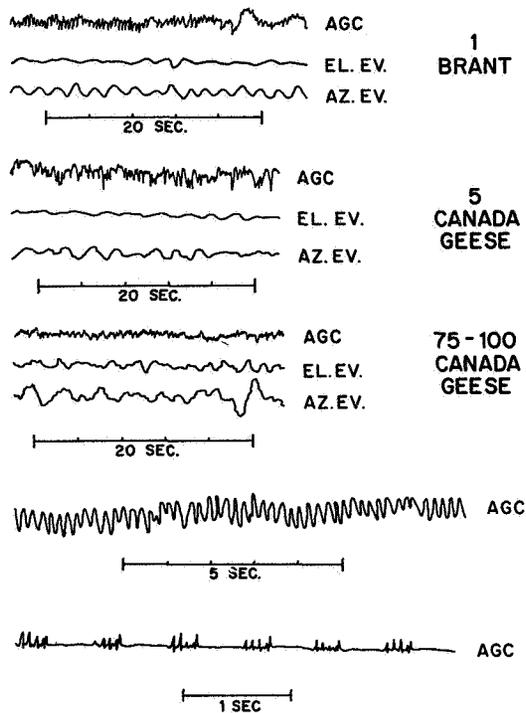
FIGURE 14. Radar signatures of migrating birds. AGC is output of automatic gain control, proportional to radar echo amplitude. EL. EV. is elevation error voltage, a function of vertical extent of the radar target. AZ. EV. is azimuth error voltage, a function of horizontal extent of the radar target. Upper part of the figure illustrates changes in radar signature with increasing numbers of birds in a target; lower part of figure presents two AGC records: the first presumably a waterfowl, the second probably a small passerine.

vation error voltages, also given in figure 14, are small and regular. A group of five Canadian geese no longer produces regular AGC changes, and the error voltages are irregular as the beam locks onto centers of density within the small flock. The record for 75 to 100 geese shows a great increase in irregularity in all parts of the records. (Absolute value of the AGC level should be disregarded here as it is a function not only of the target

crossection but of the range of the target.) Of particular interest are the very large error voltages; visual observation through a boresighted telescope revealed that this was due to the radar "walking" between different targets within the large flock. The lower section of the figure illustrates the way in which we hope to identify birds by their AGC records. Although neither of these records were identified visually, the upper record is strongly suggestive of the wingbeat pattern of small waterfowl (regular at about 5 cycles/sec) and the lower might well result from the undulating flight of small passerines (a rapid burst of wingbeats followed by a short glide with wings folded). By identifying more signatures, we eventually hope to at least divide our targets into general groups of birds.

We hope to gain insight into the sensory mechanisms involved in navigation by analyzing the errors of tracks under different visibility conditions. Figure 15 presents all the available standard errors plotted against track length. A major diffiuclty at present is that the error is apparently a function of track length; in other words the tracks do not simply oscillate around a straight path. It may be that the errors are of two sorts—a small one representing the ability to maintain course and a larger error (more than 1000 ft) resulting from corrections of position or navigation. At present it is at least clear that there is no obvious difference in track errors under clear, overcast, or partially cloudy skies.

ACKNOWLEDGMENTS
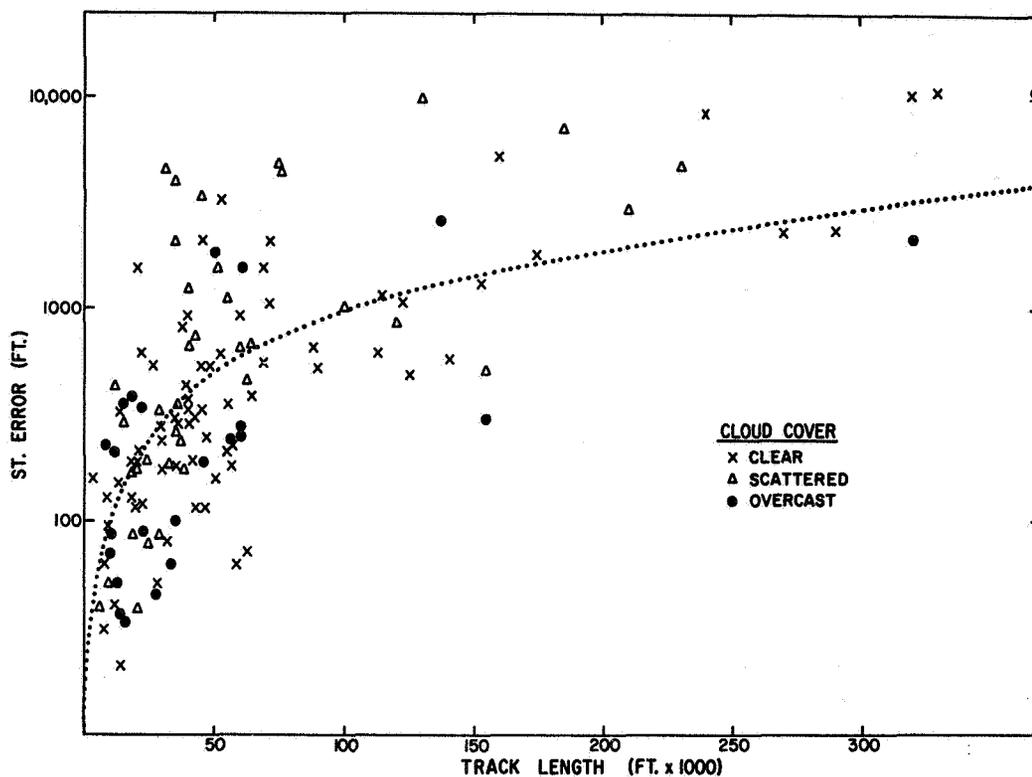
FIGURE 15. Plot of x-y standard error vs track length under three weather conditions as indicated. Dotted line gives level of 1 percent of track length.

phases of the work we were and are grateful for the help of both the radar and supervisory staff who have often gone far beyond the bounds of duty in helping us to understand and utilize the equipment.

The use of the radars and data analysis were generously donated by NASA. Funds for travel were provided by NSF grants GZ 259 and GB 13246 and Grant 508651F from the Research Foundation of the State University of New York.

DISCUSSION

WALCOTT: Did you see a greater number of birds on the upstream side of Bermuda and fewer on the downstream side, because of the birds coming in and landing?

WILLIAMS: Not for movements that went from north to south; in other words, the typical migra-

tion direction. But, on one or two days there was a difference—-it looked as though there were more targets coming in from the west than were going out to the east. In general, we did not see too many landing. The birds that were seen on the ground represent a miniscule fraction of what was flying overhead, plus the fact that large numbers of the tracks and the PPI particularly showed no funnelling into Bermuda.

SLADEN: Are you sure you are tracking birds and not bats, gulls or butterflies? And if so, are you certain you are following the birds going out to sea from the mainland? Might they not have been normally feeding?

WILLIAMS: The analysis of the radar cross section of the targets that we tracked indicated that none of the targets were insects since they would be too small. Furthermore, our radar has the greatest skin tracking capability of any radar that I know.

The SPANDAR was used for insect tracking at a range of 1.6 km. We didn't try to track anything that near; 4.8 km was the nearest.

We have a few target signatures analyzed, but very few. As for gulls and so on, most of the targets are terribly high including track 28 H, which is one of those going out. The two straight ones going out to the east were both about 3000 m (10 000 ft). At that time the PPI display indicated large numbers of birds going out in the evening in that direction. We tried once to analyze the question—Do they come back?—by staying up all night. We found that they continue going out to the east all night long. They didn't turn around and come back; they were high; they kept on; and we didn't see them coming back.

My experience is that gulls and other shore birds are apt to be low flyers when they go out over the ocean. Furthermore, we see them coming in from the east to Bermuda.

COCHRAN: Where did you get your wind information for Bermuda?

WILLIAMS: At Kindley Air Force Base just a few miles from the radar. The winds aloft, in our case, were taken within 48 km of the bird, within 2 hours, and within 150 m (500 ft) of the bird's altitude. We also used the radiosonde to check the cloud layer.

BRUDERER: Have you eliminated dc outputs in your echo signatures?

WILLIAMS: No. That is the raw AGC level.

BRUDERER: What about low frequencies? I did not see slow changes of the AGC level, which we are used to seeing in our own echo signatures.

WILLIAMS: The low frequency is primarily due to changes in aspect and changes in the range of the target. We compute cross-sections by knowing the range and the AGC level. The low frequency changes were observed for soaring birds with large aspect changes, but for constantly flapping birds the aspect changes were minimal, which strengthens our ideas about the heading.

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