Long-Distance Tracking of Birds

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GRIFFIN (ref. 1) phrased a need,

> It would obviously be helpful to know more about actual routes flown by individual migrating birds. If we had a number of accurate maps showing just where particular birds had flown on long migrations, we might be able to identify important factors influencing the timing and orientation of these flights.

and commented on a means,

> Glamorous press releases depict the tracing of barn swallows by radio receivers from North to South America, but in fact the limitations of this method are still severe. For the next few years radio telemetry of migrations seems likely to be limited to birds of the size of pigeons or larger.

Months later Graber (ref. 2) and Cochran, *et al.* (ref. 3) began following hylocichlid thrushes, a bird one tenth the size of a pigeon, on flights as long as 650 km (400 mi). Since that time some 11 000 km (7000 mi) of bird tracks have been recorded; some of these are shown in figure 1. However, for a migrant traveling several thousand or more km, a track of several hundred kilometers reveals little of a bird's orientation or navigation performance in terms of its goal and origin and less yet of its response or lack of response to the variety of stimuli that may come into play over such a long journey. Long-distance tracking is here considered as the following of an individual bird over a substantial portion, or ideally over all, of its migratory journey. This includes numerous flights interspersed with stop-overs along the way and involves weeks or even months of surveillance. This tracking has not yet been done, but the experience that has been gained and evolution of equipment and technique that has transpired since 1965 have made the following of birds for thousands of km a matter of desire and funding rather than a question of possibility. Some of the ingredients of long-distance tracking are discussed below. The purpose of this paper is to describe the radio-tracking technique and not to disucss the meaning of the conglomeration of bird tracks illustrated. The latter must include other data not shown and will be the subject of other papers.

BIAS

Perhaps the greatest single problem to be encountered in carrying out long-distance tracking is the problem of bias to the subject bird. It seems axiomatic that the use of telemetric devices on birds will affect their performance. This will be true whether attachment is by harness, implant, or adhesive, and no matter how small or light-weight the device is, or how comfortable it appears. Griffin (ref. 4) stated that

> Long-distance navigation shows some signs of being a pattern of behavior that is sensitive to even minor disturbing influences, and if it is to be studied effectively by telemetry, one must be sure that the radio tag is not distorting grossly the behavior pattern under study.

Further,

> The usefulness of radio telemetry will be much enhanced: that is, we will obtain more and better data from its use, the smaller the transmitter package (including batteries and antenna) relative to the marked animal. Ideally it should be not more disturbing than a bird band. It should be possible to attach the unit, release the bird within a few minutes, and have its behavior return to normal within a few hours.

What more can be said?

For a given species and study objective, a bias may be acceptable if it were known. Unfortunately quantitative evaluation of bias is difficult. Because telemetry affords numerous opportunities for visual observation of the subject, a qualitative estimate of behavioral bias can be obtained by comparing these observations with less frequent but similar observations of non-tagged birds of the same species. Or one may note obvious abnormalities such as inability to fly, or concentrated and sustained attention to removal of the transmitter. Also, progress or lack of progress in migration as compared with the species as a whole can function as an indicator; imagine having the only live Swainson's thrush in all of North America under observation in January!

There are numerous ways in which a transmitter may affect a subject bird. Weight of the transmitter and degradation of a bird's streamlining increase the energy required for flight. Shifts in a bird's center of gravity may cause even greater increases in energy requirements through alteration of the trim required for horizontal flight. Perhaps some species or individuals are of such a temperment that the mere presence of a foreign

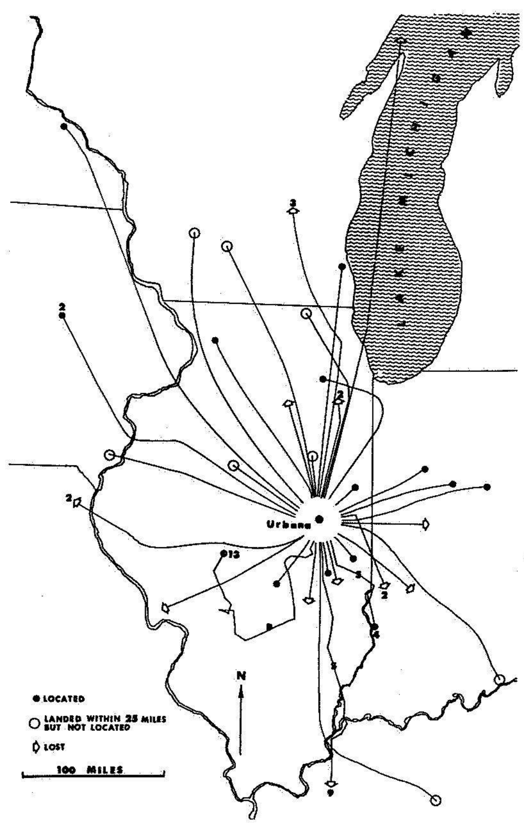


FIGURE 1. Summary of approximate flight tracks as determined by telemetry for the flights from Urbana, Illinois. All tracks within arc from east through south to southwest are fall flights; all others are spring flights. All flights are of hylocichlid thrushes except the two marked *S* (sharp-shinned hawk), and the one marked *P* (homing pigeon). Random nature of pigeon flight contrasts with migratory flights and suggests that many of the methods described in the text would not be useful for tracking this type of flight. Numbers at end of tracks are number of separate flights making up the track; no number indicates one flight.

object on their body affects their behavior in ways not related to physical factors.

For long-distance migration studies, the cumulative effects of these or other forms of bias must be considered. For birds observed for a few days or for one flight, the bias, as long as it is not severe, may not measurably affect performance. However, for studies involving long distances and weeks or months of observation, it is possible that the effects of a small impediment to a bird may accumulate until the bird becomes physically incapable of performing normally. The data given in table 1 for swans, geese, thrushes, and hawks indicate considerable hope for their long-term study, while for others such as the sandpiper and cowbird, it appears that such studies are impossible with present techniques.

ATTACHMENT

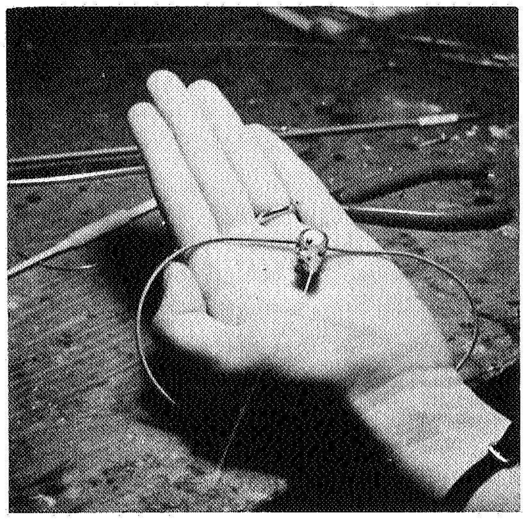
Numerous methods of transmitter attachment have been tried on a variety of species, and it appears that no one method is universally satisfactory. Adhesive only, single-wire harness only, and two-loop harness as well as thin-fabric and thin plastic sheets with wing holes were all tried on the hylocichlid thrushes. The adhesive did not last for more than a few days, and the single-wire harness fell off after 3 to 8 days. The double-loop harness and thin-sheet harnesses impeded flight. After several years of marginal results, a combination of adhesive (Eastman 910) and the single-wire harness was tried with immediate success. This attachment method usually outlasts the battery which has a 20- to 35-day life. One Swainson's thrush was observed for 2 weeks including two migratory flights lasting about 8 hours each; it was then recaptured and examined. It weighed 34 grams, 1 gram less than when initially captured, and showed no signs of abrasion or other ill effects. The adhesive and harness wire were still holding well.

The attachment is made as follows: Attached to the transmitter at its mid-point are two stranded, plastic-covered wires. The wire is very flexible. After having first affixed the transmitter with adhesive as described by Cochran et al. (ref. 3), the two wires are brought under and behind the wings and in front of the hips, worked into the feathers a little, and then tied with a square knot. Figure 2 shows some of the procedure.

EQUIPMENT

Principle transmitter variables are weight, battery life, and radiated power. Permissible weight has been touched on above; since it can not be too light, it should be as light as possible. The battery life required will depend on how long one desires to maintain contact with the subject without having to recapture it for transmitter replacement. Since frequent recapture and handling would certainly be an additional bias, the battery should last as long as possible. Although I might settle for a week, I am quite happy with the 20 to 35 days the most recent transmitters have been giving. Radiated power between 0.1 and 0.5 mW in the VHF or UHF frequency range will provide an operating range of more than 24 km (15 mi) to birds in flight. Several transmitters are shown in figure 3.

After having established that the smallest and lightest available components are used in construction and that the circuit used achieves near state-of-the-art energy conversion, further improvements in any one of the variables can be achieved only at the expense of one or both of the others. In engineering language, "trade-offs" must be made. Unfortunately many of the commercial and homemade units are not optimized with respect to



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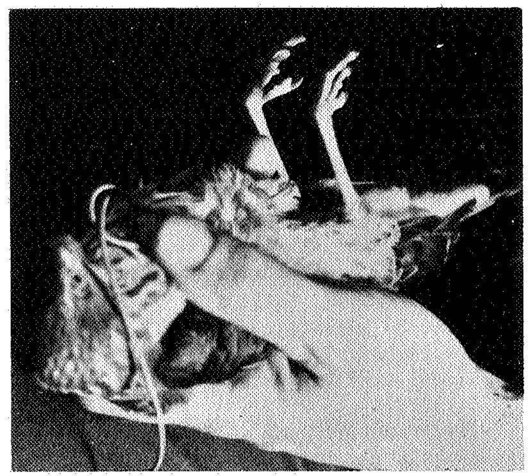

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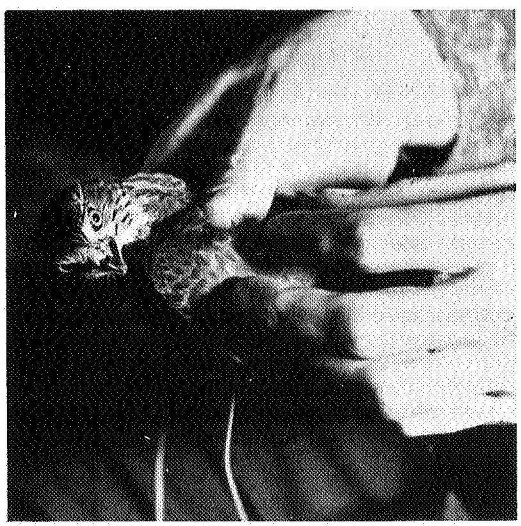

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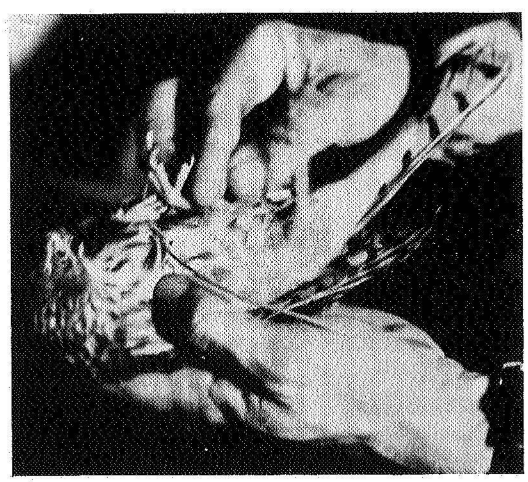

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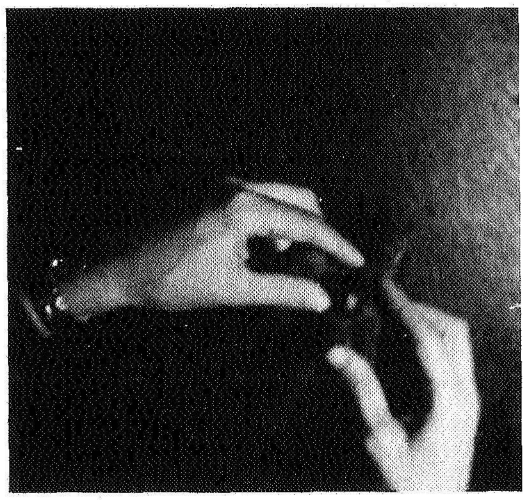

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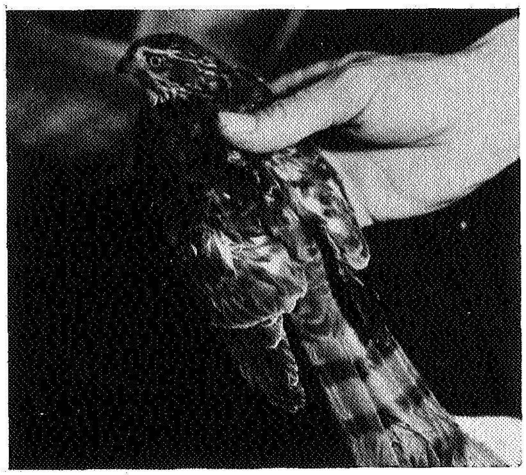


E

G

FIGURE 2. Installation on sharp-shinned hawk and hermit thrush: (A) transmitter—3.5g; (B) transmitter held to back while adhesive sets; harness wires have been run behind wings; (C) turned over, knot started; (D) knot almost completed; excess to be cut off; (E) ready to be released; (F) hermit thrush with 2.3g transmitter in place; and (G) ready for release.

TABLE 1.—*Summary of Various Bird Species Radio-Tagged by the Author*[a]

Species	Number observed	Approximate tag weight in % of body weight	Maximum flight distance observed	Maximum duration of observation in days for one individual	Estimate of annoyance	Types of attachment
Whistling swan (*Olor columbianus*)	25	1	1600	120	Occasional	*X*
Canada goose (*Branta canadensis*)	30	1	400	28	Occasional	*X*
Mallard (*Anus platyrhynchos*)	5	1.5	[b] 50	2	Occasional	L, *X*
Blue-winged teal (*Anus discors*)	2	3	[b] 25	5	Frequent	[c] W
Brown-headed cowbird (*Molothrus ater*)	1	8	[d] 2	3	Frequent	[e] WG
Gray-cheeked thrush (*Hylocichla minima*)	23	8	400	12	Seldom	[c] F, [f] G, [c] X, W, *WG*
Swainson's thrush (*Hylocichla ustulata*)	30	8	375	14	Seldom	[e] F, [f] G, [c] X, W, *WG*
Veery (*Hylocichla fuscescens*)	9	8	460	13	Seldom	[c] F, [f] G, [c] X, W, *WG*
Hermit thrush (*Hylocichla guttata*)	19	8	250	20	Seldom	[e] F, [f] G, [c] X, W, *WG*
Robin (*Turdas migratorius*)	5	4	[d] 5	5	Occasional	[e] F, G
Sharp-shinned hawk (*Accipiter striatus*)	3	3	250	15	Seldom	*WG*
Rose-breasted grosbeak (*Pheucticus ludovicianus*)	1	4	([g])	5	Seldom	*WG*
Yellow-shafted flicker (*Colaptes auratus*)	4	3	[d] 10	5	Frequent	[e] *W*, [f] *G*, [e] *WG*
Pectoral sandpiper (*Erolia melanotos*)	2	5	([h])	([h])	....	[h] WG
Homing pigeon (*Columbia livia*)	10	1.5	[b] 200	9	Occasional	L, *W*

[a] The next-to-last column gives a qualitative estimate of the frequency with which individuals pecked or pulled at the transmitter or harness. The estimate is based primarily on visual observation. The last column is type of harness tried; those *in italics* seemed satisfactory.
[b] Displaced birds; flights not migratory
[c] Birds could not fly well
[d] Local movements
[e] Transmitters known to have been removed by sustained efforts of the bird
[f] Transmitters usually fell off
[g] Departed on migratory flight but was not followed
[h] Could not fly with transmitters; transmitters removed
X 2-wire harness
L taped to leg
F fabric or plastic wing harness
W single wire harness
G Eastman 910 adhesive
WG wire plus adhesive

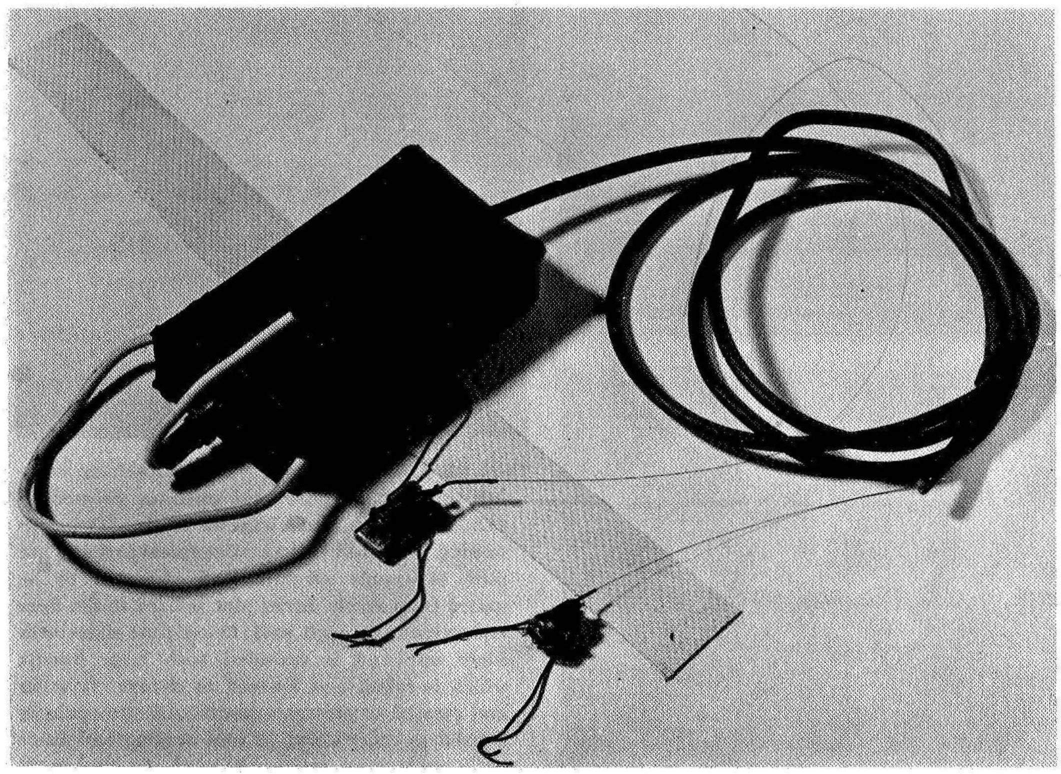
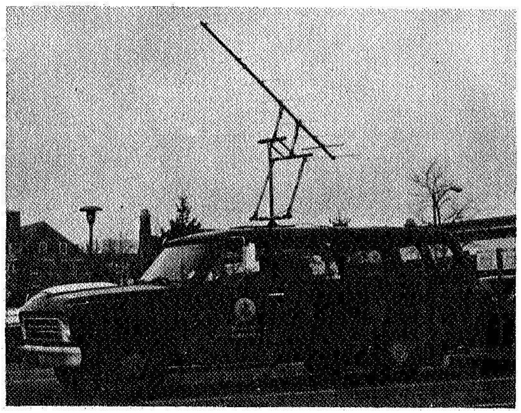


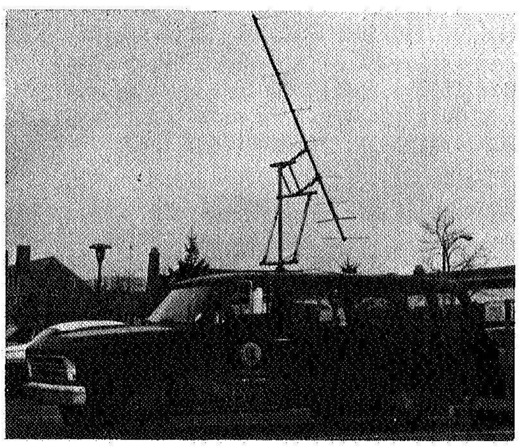
FIGURE 3. Three transmitters designed for birds. Left is 70g unit designed (but never used) for pigeons, which is similar to those described by Singer (ref. 5). Middle unit is of type used for most all work described in the text. Weight is between 2.2 and 2.4g; battery lasts for 25 to 35 days. An earlier version of this design is described by Cochran (ref. 6). To right is a 1.5g unit first used in 1970; except for weight it is similar to the 2.4g design. Both small transmitters were removed from thrushes after flights. Transmitters are shown 1/2 actual size.

either circuit or components and may miss the optimum by a factor of more than 10 if all three principle variables are considered simultaneously.

A receiver and receiving antenna are required. Sensitivity, frequency stability, reliability, portability, and a good ignition-noise silencer are probably the most important considerations in choosing a receiver. Six- or eight-element yagi type antennas are of convenient size for mounting atop a vehicle (fig. 4) and two- or three-element yagis are easily attached to the foot step or struts of small planes (fig. 5). Both provide sufficient gain and directivity to enable one to follow migrating birds. With a 16-element array mounted atop a 30.5-m tower, I have maintained signal contact with birds at distances up to 110 km (70 mi); but, of course, such installations are of little use because of their lack of portability.

Possession of suitable equipment is necessary but hardly sufficient to accomplish tracking of migrating birds over long distances. This is analagous to a fine sword not making a fine, or even tolerably poor, swordsman. It





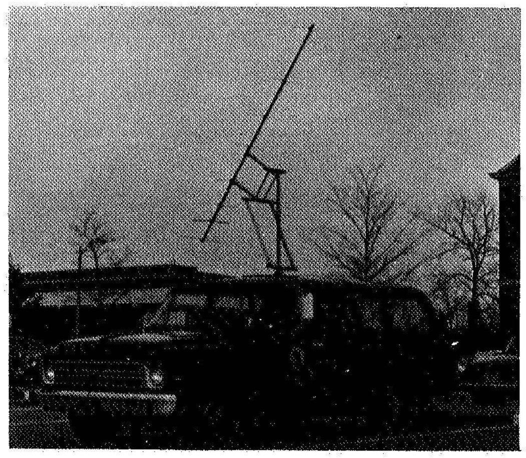


FIGURE 4. Several views of tracking vehicle showing the eight-element yagi antenna pointed at various azimuth and elevation angles. Two telescoping pipes and various mechanical linkages are used to enable azimuth and elevation to be varied from inside. Inner pipe is fixed to the floor and extends through roof. Outer pipe slides over inner one and is provided with large handle which is raised and lowered to change elevation and rotated to change azimuth. Azimuth pointer is fixed to inner sleeve of roof bearing and reads on a scale over operator's head. In horizontal position (elevation of 0°), clearance is 11 ft.

is surprising how few persons have the ability to rapidly read road maps, know their right from their left flawlessly, or relate right or left to map direction. One must also be able to scale distances and plot bearings on maps, to know how to add, subtract, multiply and divide, and to be able to read time from a clock. Lest one think I am trying to be funny, I might add that were it not too embarrassing to my colleagues and myself, I could take each of those functions mentioned above and describe how a bird was lost through human error in its performance. Repeatedly performing correctly for periods of up to 10 hr when one would normally be sleeping but instead is bouncing along a road or riding in a noisy airplane is not quite as easy as it might seem, and it is harder still unless one acquires the ability to perform almost without thinking. It is appropriate to mention here that birds can be followed by using a

TABLE 2.—*Typical Range (Miles) to 0.25- and 2.5-Milliwatt Transmitters on Birds as a Function of Altitude or Location of Both Bird and Observer*[a]

	Range (miles)			
	0.25-mw transmitter		2.5 mw-transmitter	
	Airplane at 3000 feet	Vehicle	Airplane at 3000 feet	Vehicle
On the ground in open, relatively flat terrain	4	0.5	....	1
On the ground in heavy woods	2	0.25	....	....
On a large body of water	18	....	35	6
A few feet off the ground in open, relatively flat terrain	6	1	....	4
A few feet off the ground in heavy woods	4	0.75	....	....
In a high tree in open, relatively flat terrain	20	8	45	20
Near the top of the canopy in extensive woods	10	3	20	5
Flying, 100 foot altitude	25	10	45	15
Flying, above 3000 feet	45	30	100	50

[a] In rolling terrain values may vary +20 percent to −90 percent from those given, depending on whether the transmitter is on a hill or in a valley. In mountainous terrain visual line-of-sight closely predicts transmitter range which will therefore be highly variable.

system, not just equipment, and that the system includes human operators with proficiency in these skills and knowledge of the techniques which are described below.

OPERATING RANGE

The maximum operating range to radio-tagged birds can vary by a factor of at least 100. Some of the ranges and conditions for which I have test information are given in table 2. These ranges are typical for signals radiated within 45° of a right angle to the transmitting antenna. Weak and fluctuating signals are radiated along or near the axis of the antenna. Since the antenna trails behind a bird in flight, it is a distinct disadvantage to fall behind in tracking. Fortunately the solid angle of weak or no signal is not large, giving range reductions of a factor of 5 or 10 for only about 10°. In fact, the null area is so small that when driving across a bird's track, either in front of or behind the bird, at a distance of 8–16 km (5–10 mi), the signal will be weak or undetectable for only a minute or less. Furthermore, the true bearings

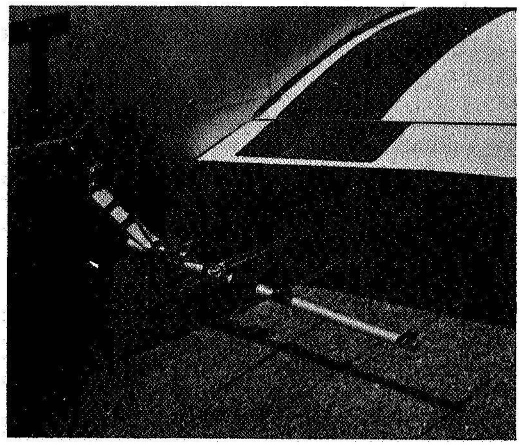


FIGURE 5. Two hose clamps hold three-element yagi to footstep of a Piper Arrow single-engine airplane. Coaxial lead is taped to footstep support and enters airplane through corner of luggage compartment door.

taken while crossing fore or aft of the bird will give its heading. Headings taken in this way have been typically within 10° of those calculated from bird track and concurrent winds-aloft information.

The reliable air-to-ground range of only 3 km (2 mi) to a transmitter in heavy woods dictates that a thorough search of a large area by airplane can be quite expensive.

ESTIMATING RANGE

The great influence of bird altitude and aspect on signal strength dictates that signal strength by itself is a very poor indicator of range. Still, with experience, it is possible to categorize range, with respect to the signal-to-noise ratio, as less than about 8 km (5 mi), 8 to 24 km (5 to 15 mi), or 24 to 48 or 64 km (15 to 30 or 40 mi). This may be supplemented by rate of change of bearing information. For example, if the vehicle speed is on the order of 0.8 km/minute (one half mile per minute) or more relative to bird speed and the vehicle is approximately paralleling the bird track, the bearing will change slowly if the bird is far, and rapidly if it is close.

TAKING A BEARING

Taking a bearing requires comparing the signal amplitude for various angular positions of the receiving antenna. With an eight-element yagi, signal amplitude begins to drop very sharply about 20° either side of the true direction so that achieving an accuracy of ±20° requires only one or two sweeps of the antenna. The limit is ±1 or 2° and this only from a stationary vehicle and after averaging the results of numerous sweeps of the antenna. Fluctuations caused by passing terrain limit accuracy obtained from a moving vehicle or to a low flying bird to ±4 or 5°. Since these are errors in bearings taken relative to the vehicle, the true bearing will include an additional error in measuring the vehicle's heading. When using accurate maps or when the vehicle can be aligned with the north star or a straight road, the added error need not be greater than 1 degree; but, when working with a magnetic compass or ordinary road maps in some areas, errors may be several degrees or even more if one is careless or in a hurry.

Bearings can be obtained from an airplane by observing the signal amplitude while circling. Because the directional pattern of a two- or three-element yagi is quite broad, and asymmetry of the airplane (for side searching antennas) causes distortion of this pattern, errors of 15 to 25° are typical.

ALTITUDE DETERMINATION

The ideal method for obtaining altitude information on birds carrying tracking transmitters is to telemeter the air pressure. If this were accomplished with a resistive transducer which modulated the transmitter pulse rate, then measurements of altitude could be made on a relatively continuous basis as long as the tracking vehicle was within signal range. The only equipment needed would be the second hand on a wristwatch. Unfortunately a barometric transducer has not been developed whose resistance changes at least 1 percent for every 2 percent change in absolute pressure and whose weight is a fraction of a gram. However, such devices may be quite feasible if the weight limitation were increased as appropriate for larger birds.

As has been discussed above, a crude estimate of range can be made on the basis of signal strength, if one assumes that the bird is high or low. Inversely, if the range is approximately known, then a crude estimate of altitude can be made. This was done regularly during the spring of 1966 but later, when the method described below was used as an independent check, I found that the accuracy was much worse than anticipated but still sufficient to categorize altitude as high, low, or landed. Of course, no sharp dividing line exists between the qualitative terms high and low. In practice the concept is valid if one accepts low as 30 m (100 ft) and high as 300 m (1000 ft) with the altitude range between as a transition zone. To restate: If the signal is weak and fluctuating at 16 km (10 mi) range the bird is low, and if strong and steady at this range the bird is high.

By providing means for orienting the receiving antenna in elevation angle from 0° (horizontal) to 90° (vertical), altitude may be obtained geometrically. There are numerous combinations of measurements of elevation angle, bearing, distance, and time which will yield altitude. If simultaneous observations are made from two places, the method is exact (although the measurements will not be). If all observations are made from a single tracking vehicle, there will always be at least one inherent assumption. I have tried most of the different combinations of measurements and have found only one to be fruitful in practice. This, illustrated in inserts A and B of figure 6, requires the measurement of elevation angle, the distance from the point of this measurement to a point under the bird's track, and information on the bird's track direction. It must also be assumed that the bird's track direction is reasonably constant during the relatively short period of time that the information is being obtained. This turns out to be a very reasonable assumption in practice, since the typical error in measuring the elevation angle affects the accuracy much more than uncertainty in the track.

Signal reflection from the ground causes very large errors in elevation angle measure-

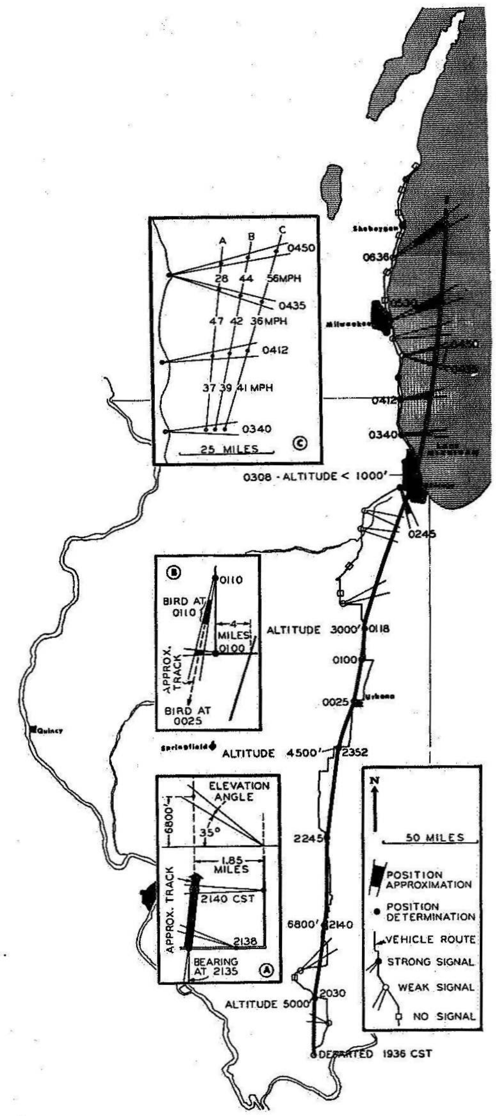


FIGURE 6. Flight of a veery, May 15, 1969. About one fourth of data gathered during flight is shown. Vehicle route diverged markedly from track after 2030 hours CST when we were lost and again shortly after 0118 hours CST to avoid passing through large towns and to take advantage of a four-lane highway. Inserts A and B show method used to determine altitude and position. Insert C shows how track over Lake Michigan was approximated (track B) by testing several tracks against the data.

ments below about 30°, and the method becomes very sensitive to errors in baseline measurement for elevation angles above about 60°. Also, cross-polarization makes the elevation angle difficult to measure when the tracking vehicle is in either of the two zones extending about 45° either side of the axis of the transmitting antenna. Therefore, it is desirable to be to the side of the bird and at a distance such that the elevation angle falls between 35° and 55°. To project where and when such conditions will occur relative to available primary roads and to be there at the right time is not as simple as it might appear in figure 6. The number of altitude determinations achieved in practice varies from about two per hour for a bird ground speed of 32 km/hr (20 mph) and numerous good roads to one or none in 6 hr for bird ground speeds above 64 km/hr (40 mph) and winding, less numerous, roads.

Although the method is valid regardless of the bird's altitude, difficulty in execution limits its use to altitudes above about 90 m. For example, a bird at an altitude of 30 m requires the positioning of the tracking vehicle about 30 m away for the period of 10 seconds or so that the bird is presenting a side aspect, then, in another 20 seconds or so moving the vehicle around 30 m to determine a cross-over position. That it usually takes some 15 seconds of rocking the antenna up and down to measure elevation angle is of itself sufficient to preclude such a feat, not to mention the difficulty in positioning the tracking vehicle. However, the rapid rate of change of signal strength and bearings as a bird moves in from a distance, passing within a few hundred meters, does at least dictate that the bird is very low. For altitudes between about 90 and 300 m, accuracy is quite poor (±30 percent) either because of the timing and positioning problems mentioned above or because a low elevation angle is involved as has been depicted in the insert in figure 9, page 53.

Determination of a bird's altitude by telemetry and while operating from an aircraft is accomplished by homing toward and past the bird at different altitudes. The homing run at which closest proximity to the bird is achieved is the one with an aircraft altitude that most closely matches that of the bird. Proximity is determined primarily by the rate of change in signal strength. When flying a path that passes within 75 m (250 ft) of a bird, the rate of change of distance is high; e.g., if the relative speed of approach is 60 m/sec (137 mph), starting at 900 m away, the range will halve to 450 m in 7.5 sec, to 225 m in another 4 sec, to 115 m in an additional 2 sec, and to closest point of approach in another 1.5 sec. Since halving distance increases the signal by a factor of 4, the signal increases very rapidly, especially during the last few seconds before closest approach. In practice, this is very obvious, almost terrifying as each successive beep dwarfs the preceding one giving one the impression of impending collision. If, however, the aircraft misses the bird by 225 m, the sequence starting at 900 m is to halve distance in about 8.2 sec and then to closest point of approach in the next 6.5 sec. This gives little more than a very noticeable increase in about 15 sec followed by a decreasing signal. Flying homing runs at altitude increments of 225 m seems to be a practical compromise between time consumed and accuracy, especially since there is no point in determining the bird's altitude more accurately than errors in winds-aloft measurements make meaningful. The method is of limited usefulness below about 150 m for flight safety reasons, especially at night. It is also unwise to use this method at night to determine the altitude of a large flock of whistling swans.

Because the method depends on proximity, large lateral errors in homing greatly reduce the rate of change of signal, even when flying at the same altitude as the bird. The side-looking yagi is neither accurate enough nor looking the right direction (ahead) for homing, but it is sufficient to establish the general direction from a considerable distance. For the last 2 km or so of approach, a different antenna system is needed. One simple system consists of two folded dipoles constructed from TV twin-lead and provided with coaxial cable baluns and equal-length coaxial cable leads. The two antennas are taped to the inside of the windows, one on each side, and placed as symmetrically as possible. A coaxial switch is used to switch the receiver back and forth between the left and right antennas. The procedure is to compare continually the signal amplitude obtained from each antenna and to maintain them nearly equal by instructing the pilot to alter the airplane heading. Because the axis of symmetry of an airplane is a vertical plane bisecting it fore-aft, and since the antennas are located off this plane of symmetry but equally so, the patterns of the antennas will be nonsymmetrically distorted and mirror image to each other. The asymmetry has been sufficient, in the several types of airplanes that I have used, to cause an easily detectable signal amplitude differential for deviations in the plane's heading of 5° from the true signal direction. Tests conducted on a transmitter in a tree gave consistent passes within a 60-m lateral error while flying at 90 m. Also, in using this method to follow a hawk migrating during the day, I found that about one-third of the closest passes resulted in a visual sighting of the bird within a few hundred meters.

The disadvantage of this method lies in the possibility that the observer will disturb the subject. This is especially pertinent during darkness when there is always the possibility that the airplane may force the bird to maneuver to avoid a real or imagined collision. Of the two dozen or so times I have used this method at night, there was only one passage close enough to have an observable result; the bird landed.

POSITION AND TRACK DETERMINATION

Positions are obtained by using various combinations of the measurements and estimates described above. A track is made up of a succession of positions. A position is an integral part of the geometric and proximity methods for altitude determination as described above.

A range estimate and bearing are sufficient to estimate position as for the numerous positional trapezoids of figures 6, 7, 8, and 9. Elapsed time coupled with track speed and direction measurements or estimates may also be used as with trapezoid *E F G H* of figure 9. A very accurate method requires maneuvering the tracking vehicle so that the bird will pass overhead. This is described and illustrated by Cochran et al. (ref. 3).

Another method requires two bearings spaced in time and from the same location, or several non-parallel bearings from different locations. These may be combined with approximate speed and track direction information to determine a best fit for the track segment or segments. Application of this method to position a bird over Lake Michigan is illustrated in insert C of figure 6 where track B is seen to be a better fit than A or C in regard to uniformity of ground speed.

ACCURACY

The accuracy of bearing measurements and range estimates under some of the variable conditions which occur has already been

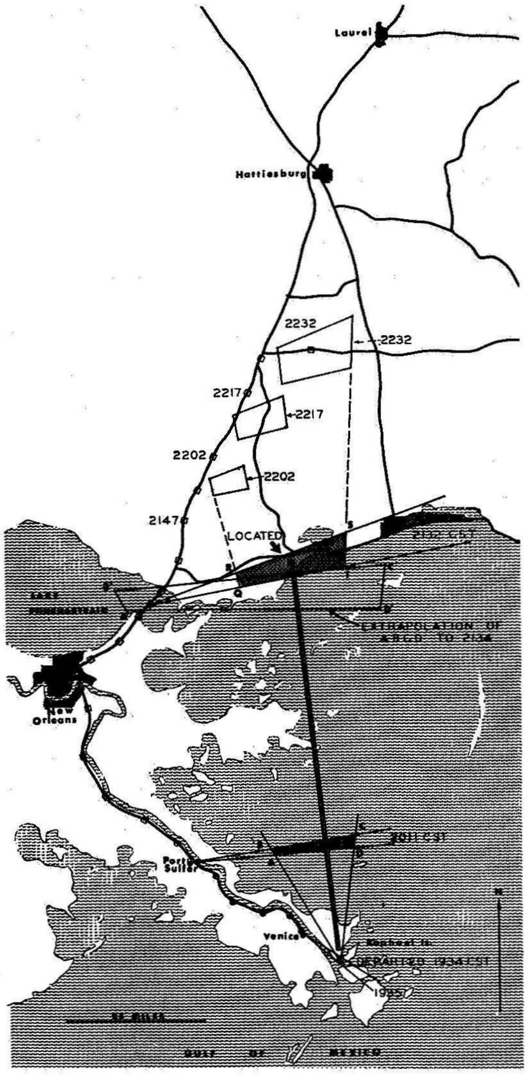


FIGURE 7. Flight of a veery from the Delta National Wildlife Refuge in May 1970. Key is same as in Figure 6.

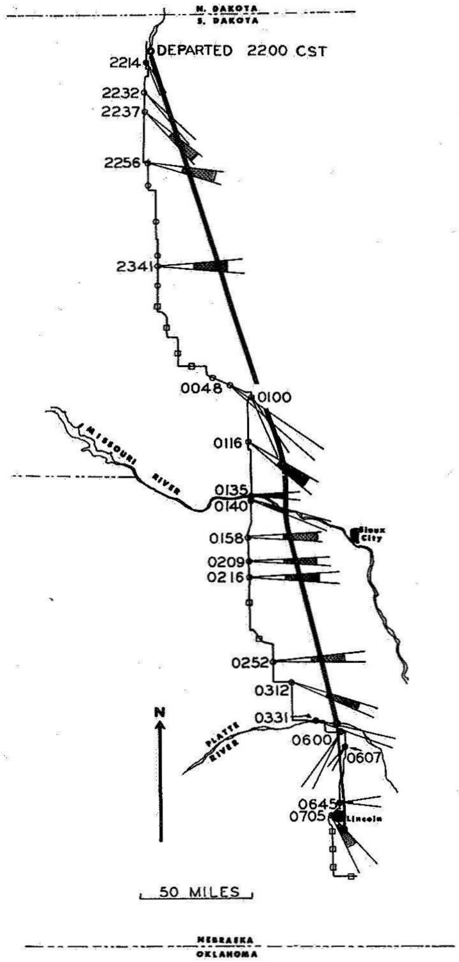


FIGURE 8. Flight of a radio-tagged goose (in a flock) in November 1967. Key is same as in Figure 6.

discussed. The word "estimate" has been substituted for measurement in discussing ranging by signal strength and fluctuation information since no numbered scale is used, but rather a judgment is made on the basis of past experience. Positioning, both altitudinal and map, involves calculations based on several measurements or estimates. The great variation in accuracy is evident from the difference between the positional approximations and determinations of figure 6.

From the standpoint of reporting results, especially where the results are used as arguments for or against a hypothesis, it is essential to discuss the accuracy of data to whatever extent such accuracy may affect the va-

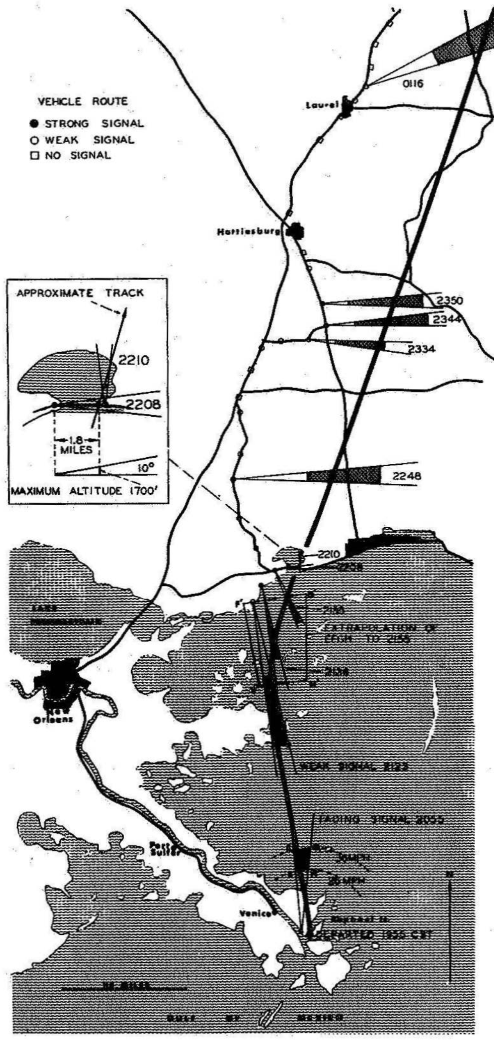


FIGURE 9 Flight of a gray-cheeked thrush in May 1970. Insert shows how position and altitude were determined at the bridge crossing the mouth of Bay St. Louis. No elevation angle was discernible indicating that it was less than 10°. The signal was not heard after 0116 hours CST and it was impossible to drive fast enough to be positioned on the extrapolated track further north. Key is same as in Figure 6.

lidity of the argument. In some cases positions are accurate enough that they may be plotted as points on a map with a scale of 12 or more km per cm without grossly misrepresenting their accuracy. Lines drawn between such points are inferred and must be regarded with caution. For example, four positions not lying on a straight line may be regarded in three ways. Three straight lines can be drawn between them showing a track change at the two middle points, two straight lines can be drawn showing a track change at their intersection, or a smooth curve drawn through them showing a gradual change in track. If a larger number of points is available and located such that they all fit a smooth curve but no three fit a straight line, then a smooth curve seems reasonable. If, however, they are located such that they fit two straight lines, then a track change at the intersection is probable although there is no way of knowing whether the change occurred in seconds or gradually over a longer period. Although the poorest position estimates determined by telemetry will plot as dots on a 30-cm (12-inch) globe, they must be represented as areas when a scale of about 12 km per cm is used. The greatest usefulness of position approximations is described below, but occasionally it is sufficient for an argument to be able to state that a bird was somewhere east of a given point at a particular time, etc.

The thick lines used in the figures to depict the tracks are shown only to clarify the technique and should be regarded accordingly. A careful examination of the relationships between the observations shown and the indicated tracks will be instructive in a way that cannot be fully described here.

TACTICS

Most of the methods and measurements required for obtaining a variety of flight information have been described above. A minimal objective in long-distance tracking is to locate the bird after each flight. Once a bird is airborne, the operational procedures observed in gathering flight information, interpreting this information and making decisions comprise tactics. Typical decisions to be made are which road to take from here, how fast to drive, when to take the time to get fuel, or make winds-aloft measurements, what area to search, whether to take a detour on a fast road and temporarily sacrifice contact or to proceed on a labyrinth of secondary roads in order to stay close, which bridge to take across a river, when to attempt an altitude determination, etc. For even a single flight, the possible combinations of decisions will number into the millions with thousands of these combinations potentially yielding success in regard to the minimal objective. Putting together a successful sequence of decisions that also maximizes the quantity of flight information gathered is more an art than a science. All information, including past experience with the particular bird or with the species, may need to be used in making decisions. Position estimates, although of limited usefulness as reportable data, are often the kind of information upon which better-than-random decisions are made. I have tracked many migrants without having to make other than the simplest decisions; however, these have been slow flights which happily coincided with good roads that enabled me to stay close. In tracking a bird over a long distance, the probability is low that such ideal conditions will prevail throughout.

STRATEGY

Because situations often arise where no tactical procedure can yield success, it is necessary to employ sound strategy to avoid these. To do this a careful overview of the situation is taken prior to the occurrence of a flight. When departure may occur, a variety of possible flight tracks, maximum probable speed of flight based on winds-aloft forecasts and bird capability, and whether some portion of the flight may occur over a large body of water or over mountainous terrain are considered in relation to road networks, average vehicle speed that might be confidently expected, proximity of an airport, and manpower available. These considerations result in decisions such as when to monitor and when to sleep, where to monitor from, whether to use an airplane or a vehicle, or both, etc. If funds were unlimited, one would always work with a comfortable redundancy of means; but such is not the usual case.

EXAMPLES

The number of examples available from 11 000 km (7000 mi) of bird tracking is almost endless so I shall pick from these only a few which will highlight some of the main tactical and strategic procedures.

One case of strategic error occurred when an early departure combined with a bit of tardiness resulted in the loss of a flight. Five days, including two night flights, brought a veery to a small woods about 6 km (4 mi) south of O'Hare International Airport northwest of Chicago. We drove to Chicago to monitor only on those days when the weather forecast indicated a chance for a flight. The relationship between weather and migration flights had been worked out from past flights and was highly predictable. The timing of departure in relation to sunset was also known from past flights but was not as predictable since flights had been initiated from 0.5 to 5 hr after sunset with most occurring from 1 to 3 hr after sunset. After 3 days, ideal weather conditions occurred. We arrived at the bird's location at sunset, took winds-aloft measurements and decided that an airplane would not be needed since the 32 km/hr (20 mph) southeast winds greatly reduced the likelihood that the veery would fly toward Lake Michigan. Because windspeed plus bird airspeed could combine to give up to 72 km/hr (45 mph) groundspeed we decided to monitor from about 32 km (20 mi) north in order to provide a head start and to avoid the weekend Chicago area traffic. But before we could move to a new location, the veery took off. During the first hour we traveled only 24 km (15 mi) and were trailing the bird in the weak-signal area off its tail. Even so, we managed to maintain intermittent contact for an additional 2 hr. Had we arrived sooner we would have been in a more favorable starting position when the bird took off, although the bird might well have outdistanced us anyway. In retrospect, I feel that the correct strategy would have been to employ an airplane due to the strength of the favorable wind and to the decreasing suitability of roads as one travels further north in Wisconsin.

A veery flight (fig. 7) illustrates what can be done with very little information. The drive from Venice to the Lake Ponchartrain bridge north of New Orleans was timed at 2 hr during the time of evening that a flight could be expected. Even with an 8–16 km/hr tail wind, a bird would not be expected to cover the 110 km (70 mi) from Raphael Island to the Mississippi Coast in less than 2 hours. At the time of departure, the signal was at first weak, but within a minute it had become fairly strong indicating that the bird had attained at least several hundred feet of altitude. When we reached Port Sulphur, the signal was getting weak so we stopped to obtain an accurate bearing and estimated the range to be between 24 and 48 km (15 and 30 mi). From these the positional estimate bounded by trapezoid *ABCD* was made. This was extrapolated to 2 hr after take-off (*A'B'C'D'*) to give an idea of where to expect the bird when we reached the coastal area. The signal was heard as we crossed the Lake Ponchartrain bridge but then abruptly disappeared indicating that the bird had landed, but I could not be certain of this because our loss of altitude coming down the north side of the bridge may have caused the signal loss. On the basis of the new bearing and range estimate, another positional trapezoid was made (*QRST*) and this extrapolated northward in segments selected to provide for their cumulative coverage as we drove north. Since the signal was not heard again, it was concluded that the bird had landed somewhere south of these segments but north of or within QRST. The bird was later located as shown. The most important tactical decision made during this flight resulted in our continuing the chase after I was fairly certain the bird had landed. If I had immediately begun a search of QRST and if the bird had continued its flight, I would never have found it, whereas having assured myself that the flight did not continue still left ample time, that night and the following day, for searching.

Another flight from Raphael Island was that of a gray-cheeked thrush (fig. 9). Previous experience with this species in Illinois had shown it to be a slightly faster flyer than the veery and to have a tendency to fly headings from 350° to 010° and to select nights for migration with strong southerly winds. These factors dictated a different strategy. One person stayed at the Delta Waterfowl Refuge a few miles from Raphael Island to monitor for departure and to obtain a departure direction with a portable receiver. Shortly after the bird took off, he telephoned this information to Waveland, Mississippi, where the tracking vehicle was stationed. This provided ample time to make winds-aloft measurements, and to decide whether to drive to an appropriate location to intercept the bird and plan a route, or, if the wind was very strong from the south, to pick up an airplane for which prior arrangements had been made. Had the track continued, even approximately, in the same direction after the bird reached land, the roads would have been quite adequate to follow the bird successfully. However, the inland winds aloft were stronger than and about 90° clockwise from the winds on the Gulf and caused the track to change to the east and the bird's ground speed to increase. These changes, coupled with poor roads to the northeast, enabled the bird to outdistance us and caused me to regret not having decided on using the airplane. I should point out here that I often tended to use the vehicle when, were it not for a very limited budget, I would have chosen an airplane.

The flight of a veery, illustrated in figure 6, is the longest flight recorded to date (about 740 km or 460 mi) and of the longest duration (at least 11 hr). This was completely unexpected on the basis of previous flights of this species. Therefore, the possibility for a flight over Lake Michigan was not even considered and no arrangements for an airplane were made. The increase in morning traffic, and our inability to remain awake caused us to lag behind so I have no idea whether the bird outdistanced us, fell in the lake, or flew out of range toward the east side of the lake. Because the vehicle route gave good coverage of the lake's west side for at least 80 km (50 mi) beyond the point where the signal was last heard and a thorough aerial search was made of the remaining 200 km (125 mi) of shore to the north, I am quite certain that the bird did not end up on the west shore.

The average ground speed of the bird was around 64 km/hr (40 mph) but excellent roads nearly paralleled the track over much of the flight; thus we were able to make numerous altitude measurements and occasionally afford the 10 min required to make winds-aloft measurements.

An interesting accessory was used to detect departure of the geese whose flight is shown in figure 8. A sensitive relay was connected to the receiver output and to the vehicle horn so that the horn blew whenever there was an increase in signal. If the threshold were properly set, the horn would blow only when the radio-tagged goose flew. The device proved effective for monitoring from distances up to 24 km (15 mi) from the geese. The goose departed on a migratory flight after about 2 weeks of our waiting and numerous false alarms due to local feeding flights. When the horn blew I was in bed and Mr. Kjos, the driver, was in the shower. Also, we had long since given up hurrying every time the horn blew. We got a very poor start on this flight. As can be seen in the figure, whenever we began to catch up in latitude we would be forced to go east and fall behind again. Nevertheless, we managed to maintain contact until the flock landed in the Platte River about 0334 hours CST. We placed the horn-alarm in operation and slept. At 0545 hours CST the alarm sounded and the chase was continued until the signal faded at 0705 hours CST. We proceeded as shown and, when no signal was heard along the extrapolated bird track, we back-tracked, conducting a search of the area of the position estimate of 0705 hours CST. The flock was located in a stubble field within an hour. Within another hour the transmitter failed, thereby thwarting the main objective which was to follow this bird to its wintering area in Oklahoma or Texas. Several points are of tactical interest. First, it was necessary to travel at top speed to keep up with the birds since they averaged over 95 km/hr (60 mph) groundspeed for most of the flight. Second, the only two accurate positions for the first leg of the flight were the departure and landing points; at all other times estimates of position had to be used in deciding our route. At 0048 hours CST I had decided to cross the Missouri River at Sioux City, but the bearing obtained at 0100 hours caused me to change my mind and cross at Yankton. Had the track continued in a straight line either choice would have been equally bad, but the birds altered their heading about 0116 hours CST from 190° to 240° and maintained the new heading until they crossed the river. Note that the track shown is the resultant of the bird's heading and airspeed combined with winds. This brought their path closer to our route and also slowed their ground speed to about 72 km/hr (45 mph), enabling us to catch up temporarily. This was luck of course, not tactical genius. Lastly, somewhat analogously to the procedure taken in the veery flight shown in figure 7, I projected the track after I was reasonably certain that the bird had landed (at 0705 hours CST) and proceeded to cover this projected track, going back to search for the landed bird only after I was certain that the flight had not continued.

This flight is a prime example of how, in terms of long-distance tracking, half a flight is little better than none at all. From copious banding records I was reasonably confident that the objective for these geese was one of several refuge areas straight south of their departure point at Sand Lake, South Dakota. Their heading during the portion of the flight ending near Lincoln was straight south or slightly west of south. Yet their track, due to the strong west-northwest wind, was taking them considerably east of this alleged goal. The next 480–640 km (300–400 mi) of flight and 1 or 2 weeks of observation would have given information about how and when they corrected for the drift or indeed if they were intent on a goal to the east of those I suspected. Anyone who has given considerable thought to the difficulties in defining and observing wind drift can appreciate the severe depression that this 500-km (370-mi) half-flight caused us.

LONG-DISTANCE TRACKING

The usefulness of the track data for a bird migrating over a long distance is not self-evident. The flight data that has been gathered to date have, as Griffin predicted, enabled us to identify important factors influencing the timing and orientation of these flights. It is ironic that, having reached the technological point where I am confident that a thrush could be followed from Canada to South America, I am not certain that the data would add enough to what has already been found to justify the expense. I would also like to add that should anyone wish to do so for the sake of generating a glamorous press release in his name, he ought to do it with his own money.

However, assuming that such a feat would provide useful data on gray-checked thrush migration, I will describe briefly the strategy required. Several transmitters with predicted battery endurance of 30 days would be required. Every 15 to 20 days the bird should be re-captured, examined, and have its transmitter replaced. Periods with unfavorable weather for migration should be utilized for recapture to minimize the disturbance to the bird's migration.

A vehicle equipped for tracking, taking winds-aloft measurements, and communicating with aircraft would be required. An airplane should be used for every flight; a twin-engine aircraft should be used when over-water flights or above cloud-cover operations are anticipated. An instrument-rated pilot must be available for flights in bad weather. For the trans-gulf flight a U.S. Navy destroyer would be ideal, but since this is out of the question, a multi-engine airplane would have to be used. Operating from a succession of nearest airport facilities, the airplane would be used to fly out to obtain a number of bird positions. The procedure would be repeated until the bird reached land.

The probability for success, barring a flight over Cuba, is very high. Of the 36 *Hylocichla* thrush flights I have traced with a vehicle, about half were completed to the landing point. Of the four thrushes followed with an airplane, two were located at the end of their flight. Thus, using only an airplane or vehicle for each flight, and assuming the percentages given above approximate probability, the probability of success for tracking a single bird for 10 flights would be one half to the tenth power or about .001. I feel that, had the techniques and equipment suggested above been used on all the birds I have followed, all would have been located after each flight. In fact, had only the expense for an aerial search for those birds lost been bearable, most would have been found. If the probability of success for each flight averages to 0.95 the chance for overall success for 10 flights is around 0.6. To have much of a chance for success in long-distance tracking, the technique must provide for a very high probability of success on each flight. This, coupled with the rapid accumulation of investment as the migration proceeds, dictates that a redundancy of means be employed. The situation is something like having to win 10 contests in a row; if the first is lost you can consider it practice, but if, after nine wins, the tenth is lost, it is a disaster.

ACKNOWLEDGMENTS

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DISCUSSION

WILLIAMS: How do you recapture radio-tagged birds?

COCHRAN: Different species may require different methods. Thrushes all seem to behave the same when they are stalked: they fly away. If a person moves slowly and does not create a great commotion the thrushes do not fly into the treetops but stay 10 or 20 m ahead and can occasionally be seen darting amidst the brush. They also travel in a circle, many times in fact, and it is only necessary to place one or two nets at places where they are seen to fly and to continue stalking until they complete the circle again—into a net. Stalking may be difficult in heavy underbrush with thorns, mud holes and so forth.

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