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PERFORMANCE OF A NON-ROTATING DIRECTION-FINDER FOR AUTOMATIC RADIO TRACKING

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Abstract.—The expense of gathering location data on birds and other wildlife using traditional techniques often discourages observers from obtaining frequent samples. To automate the direction-finding (DF) task important in radiolocation, a prototype system based on a circular array of antennas with no moving parts is described. It can operate continuously and rapidly, recording bearings on multiple radio transmitters. Using fewer than 10 pulses of a radio transmitter, DF stations report bearings. Static DF accuracy in open country was comparable to reported accuracy of manual methods in various habitats; performance in worst-case, real-life tests with small transmitters on wild passerines in secondary growth was poorer. In static tests, habitat features near the transmitter proved to be important in measurements using "dither." Such low-maintenance devices have advantages, especially for continuous recordings, for simultaneous localization of many subjects, and when access to a site is difficult.

DESEMPEÑO DE UN LOCALIZADOR NO-ROTATIVO PARA RADIOTELEMETRÍA AUTOMÁTICA

Sinopsis.—El esfuerzo necesario para obtener datos sobre la localización de aves y otros tipos de vida silvestre utilizando métodos convencionales por lo general no estimula a obtener muestras frecuentes. Para automatizar la labor de encontrar la dirección (DF) mediante radiolocalización, se describe un sistema prototipo basado en un tipo de antena circular que no tiene partes movibles. El mismo puede operar rápida y continuamente, recogiendo información de múltiples radiotransmisores. Utilizando menos de 10 pulsos de un transmisor, la estación DF informa una coordenada. La exactitud del DF estático en campo abierto, resultó ser comparable a la exactitud de métodos manuales en varios tipos de hábitat. El desempeño del equipo, con paserinos pequeños en aéreas de crecimiento secundario, resultó menos eficiente. El equipo nuevo, además de necesitar poco mantenimiento, tiene ventajas sobre otros particularmente cuando se necesitan registros continuos para la localización simultanea de muchos individuos y cuando el acceso a una localidad es difícil.

Automated methods can reduce the labor of radio tracking and are especially appropriate when subjects' movements are sudden and unpredictable, when access to the study site is difficult or dangerous, when the presence of observers might disturb the subjects, or when the investigators need to monitor many individuals at the same time or observe throughout the diel period. We describe an automatic system for continuous and rapid direction-finding (DF) using multiple transmitters. With modifications it could be used for telemetry of other information. When rare events occur, such as when a transmitter ceases to be detectable, the nearly continuous data from the automatic system can differentiate between technical problems and biologically significant phenomena such as entering a nest hole or emigration from the study area. Even when radio transmitters are used merely to locate birds for subsequent visual observation, the system described here could be valuable in finding subjects efficiently.

Present automated and semi-automated systems for radio tracking are reviewed in Kenward (1987) and White and Garrott (1990) and have disadvantages. Depending on rotation rate, motor-driven rotating antennas (Cochran et al. 1965, Deat et al. 1980) trade accuracy of bearings for timeliness and synchrony of bearings and they require powerful, reliable rotation mechanisms, especially in windy conditions. Systems using the arrival time of a pulse at several distant antennas have no moving parts but, thus far, require relatively heavy transmitters (>40 g, Kenward 1987).

William W. Cochran earlier designed several non-rotating automatic tracking systems to detect California Condors (*Gymnogyps californianus*) in southern California and humans on a military base in the southeastern United States; in both cases results were mixed, partly due to rugged terrain. The system we tested was built by Cochran for recording departures of avian migrants in $\geq 10°$ intervals. We sought to measure the system's further potential by testing its static accuracy in flat, open country. In this situation, we hoped to approximate the physical and electronic limits of the system; therefore, compared with more complicated habitats, the tests may approximate the maximum attainable accuracy. Further tests on small passerines were performed to approximate worst-case field conditions with weak transmitters in dense secondary growth.

Methods

Description of the prototype system.—The automated DF stations estimate bearings to known transmitters at frequent intervals or on command and report their estimates to a central station, which issues commands, controls the flow of information, and displays and records data. A DF station is a tower with switching circuitry and an array of antennas on the top, a box containing a receiver and other electronics located near the base, and interconnecting wiring (Fig. 1). We tested two DF stations separately, each with an array of six, three-element yagi antennas and associated electronics mounted atop a tower (Fig. 1). Control lines switch on one of the six monolithic microwave integrated circuit amplifiers (+8 V on control line, 10 dB gain) and switch the rest off (0 V, −50 dB). Thus, the receiver can rapidly sample each of the yagi antennas, one at a time. Because each yagi is directionally sensitive (Johnson and Jasik 1984; Figs. 3–10), comparison of the strength of the signal among the antennas permits estimation of the direction of the transmitter.

The tower-mounted switching circuit has a filter (two-pole band-pass, 0.5 dB insertion loss) to prevent nearby commercial communication transmitters from overloading the input amplifiers. The receiver includes a noise blanker for reducing pulsed-noise interference. The DF stations can operate indefinitely on solar power and 12-V storage batteries. The yagis could be changed to either horizontal (H) or vertical (V) polarization (Cochran 1980) by climbing the tower.

Various algorithms could be devised to determine the direction of a pulsed signal arriving at a DF station. The prototype system employs a *synchronization phase* to establish timing parameters and a *DF phase* to

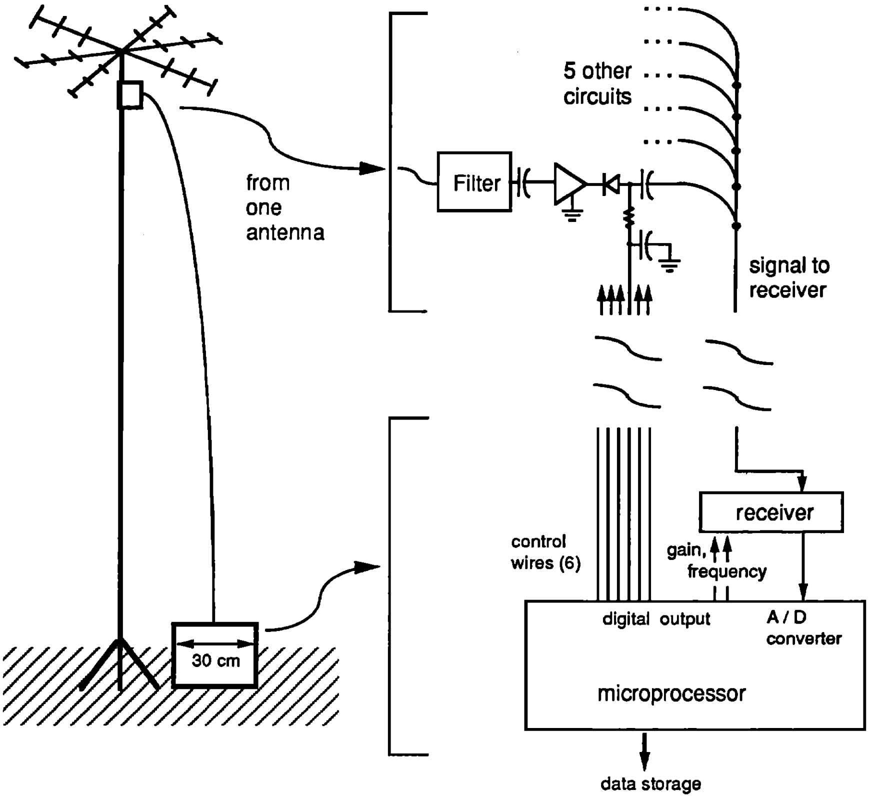

FIGURE 1. Sketch, not to scale, of a DF station (left) and its switching circuit and control box. The weather-tight enclosure located near the junction of the six yagi antennas at the top of the tower or mast houses the switching circuit and is connected via seven control wires and a shielded signal cable to another, larger weathertight enclosure, the control box, at the base. The specific microprocessor and data storage or communications device should be selected based partly upon availability of line power, telephone, and environmental control.

measure signal amplitude on the antennas in the array and estimate the bearing to the source. In the synchronization phase, a DF station records and examines a time series of receiver output to find incoming pulses and to estimate the current pulse repetition rate and pulse length. This is done under automatic gain control. The station then predicts when subsequent pulses will occur and schedules DF within such time windows. The algorithm is adaptive: sufficiently strong signals continually update the system's best guess of the current pulse repetition frequency (PRF), pulse length and best frequency for each transmitter, allowing for drift in these parameters due, for instance, to changes in a transmitter's temperature or aging of its battery.

The DF phase uses high-speed switching to compare different antennas in the circular array within a single pulse, eliminating pulse-to-pulse variability. With the typical 10–30 ms pulses used in radio tracking, signals from three or more tower-mounted antennas may be compared during one pulse. First, the DF station finds the two adjacent antennas receiving the strongest signal. The bearings of these two antennas bracket the estimated bearing of the source (in the prototype system, within a 60° sector). The DF station uses subsequent samples from these two antennas to optimize the receiver gain. Finally, it samples absolute receiver voltage to estimate the bearing. To remove the effect of pulse-to-pulse variation in signal strength, it estimates bearings using the ratio of the voltages from the same pulse on the two antennas, using a look-up table derived from an approximate gain function:

$$\mathrm{RATIO} = \{\sin(\mathrm{DEV})^{x} + \epsilon\} \,/\, \{\sin(\theta - \mathrm{DEV})^{x} + \epsilon\},$$

where DEV is the estimated angular distance in degrees between the transmitter and the antenna with the stronger signal, x is an empirically obtained power (~1.5 in the prototype), ϵ is an empirically obtained offset, and θ is the angular distance between the two antennas. Because the gain patterns differ for H and V, ratio functions were fitted by least-squares separately for H and V. Because all antennas were of identical design, fits for one pair of antennas were used for all pairs on each DF station.

The synchronization phase and the DF phase each generally require four to five pulses. Time required for DF decreases with high PRFs, long pulses, and strong signals.

For these tests, the prototype displayed numbers and stored them on computer disk for later analysis (SAS Institute 1990). In an operational system, other options for storage and display of data would be more useful. For instance, a real-time graphical display could be sent to a field base camp via modem.

Like most electronics, the prototype system was built of components and software that are now obsolete; some parts might now be preferably obtained from commercial vendors. Circuit diagrams, flow charts and software are available from the first author.

Procedures for calibrations and static tests.—We conducted calibrations and static tests with 302-MHz transmitters emitting 50-ms flat-topped pulses. We used an omnidirectional transmitting antenna because in initial tests a dipole transmitting antenna was found to give results sensitive to the orientation of the dipole. In addition, in an attempt to minimize possible reflected signals, we performed a calibration with a transmitter fitted with a small yagi antenna always pointed directly at the DF station tower. Distance tests were performed with three transmitters: an optimized transmitter with a flat-topped pulse and radiating −11 dBm when mounted on a plastic container filled with sugar solution to simulate the size and electrical characteristics of a stationary Ring-necked Pheasant (*Phasianus colchicus*) or Eastern Cottontail (*Sylvilagus floridanus*), a commercial-grade transmitter with a frequency-swept pulse and radiating −28 dBm when mounted in the same fashion, and a test transmitter radiating −9 dBm from a vertical (omnidirectional) half-wave antenna. Two DF stations were used for all tests: "G," tower height 34 m, distance from calibration transmitters 320 to 372 m; and "P," height 25 m, distance 606–749 m. Although transmitters and station G were almost entirely in open farmland during testing, station P was located in second-growth forest, and a few of the calibration transmitter locations used with DF station P were near wire stock fences.

The median measured angle was computed for each transmitter position and constituted the unit of analysis for summarization. (The signals from a particular position usually comprised several tightly clustered values and one or two outliers. For such data, the median is the preferred measure of central tendency.)

Static tests (stability, azimuthal accuracy, distance, and indirect scattering) had the goal of assessing the stability and accuracy of the non-rotating system per se, rather than when challenged by terrain, weather, etc. We therefore conducted such tests in open country on plowed fields or dirt roads just south of Urbana, Illinois, when vegetation was dormant (February through early April), avoiding times during and after rain. (Nevertheless, such terrain and conditions are in fact typical of much of the midwestern USA.) With compass, measuring wheel and tape, straight transects tangential to each tower were laid out to about 1-m accuracy and staked transmitter positions placed on the lines to 0.1-m precision.

We estimated medium-term stability in two, 4-h continuous sessions in which the system repeatedly located a 6.8-km distant flat-topped-pulse transmitter atop a 23-m tower.

For azimuthal tests, transmitters were advanced by measured intervals along transects tangential to the towers. In most tests two transmitters with different types of antennas were used simultaneously: (1) omnidirectional and (2) directional 3- or 4-element yagi kept pointed toward the antenna array on the DF stations. Tests were performed using H or V polarization of both transmitting and receiving antennas in separate tests on different days.

Distance tests assessed the ability of the system to detect and localize weak V polarization signals under controlled conditions. We measured signal strength and DF accuracy from the 34-m tower at 200-m intervals at a constant nominal bearing, out to the distance at which none of the transmitters could be detected by the system. We selected a bearing corresponding to the bisector of adjacent antennas because this angle generated the faintest expected maximum signal from the two antennas and therefore constituted a stringent test of detection range.

In practice, a transmitter does not act as a point source, but rather radiates a complex pattern consisting of direct propagation to the receiver plus indirect signals scattered ("reflected") off the substrate, vegetation, and other features (Cochran 1980: 518). To the extent that they are distributed asymmetrically, the indirect signals introduce error into the DF process. To assess indirect scattering, we repeated measurements at locations one to 1.5 m from the stake. We call such intentional introduction of small errors into the input data "dither," a term from the theory of servomechanisms. The effect of dither on static measurements was quantified for each position by dividing measured mean absolute change in angular position (introduced by moving the transmitter) by the mean angular SE of the mean, giving dither expressed in units of SEs. Such a change in position moves the transmitter substantially (≥ 1 wavelength) with regard to nearby scattering features but minimally ($<0.2°$) with regard to the DF stations. Results from dither positions around the nominal position were included in calculating medians.

Procedures and study area for trials on free-ranging passerines.—Using H polarization, we tracked transmitters mounted on female Brown-headed Cowbirds (*Molothrus ater*) that roosted and fed at distances of about 600–2000 m from the towers. We used typical small transmitters (1.6 to 1.7 g) that produced a signal that decreased in amplitude from approximately -22 to -31 dBm during each pulse. The actual position of the birds was determined by an observer using binoculars and a hand-held yagi antenna. The estimated XY position was computed by triangulation using the two towers, which were spaced 1320 m apart. Although most data were taken when birds were active during the day, night roosts were also located. The birds spent most of their time in dense leafy secondary growth (canopy <20 m), with occasional trips to feed in more open areas nearby. To identify sources of error in these data, we examined signal level, noise level, receiver tuning, time discrepancies between the field data and the tower system data, and, whenever available, general vegetation type and height of the birds in vegetation.

RESULTS FROM A PROTOTYPE SYSTEM

Calibrations and static performance tests.—Calibration curves of RATIO should be monotonic (lacking reversals in slope) with change in angular position, so that angles may be calculated unambiguously. RATIO measurements were better-behaved in this respect for H than for V (Fig. 2). When indirect scattering was reduced with a V directional yagi transmitting antenna, performance was improved, especially within-position variability. As expected from antenna theory, the slope of the ratio/bearing curve was greater for H than for V. Greatest departures from monotonicity typically occurred when the transmitter was nearly aligned with one antenna (discussed below) and in the region midway between the antennas (where sometimes one and sometimes the other antenna gave a stronger signal).

Several small anomalies appear in Figure 2: there are points to the left of Antenna 1, the slopes of the left and right halves of the curve are not always identical, and the trough aligns on a bearing somewhat less than the 30° nominal midpoint. These asymmetries arise from slight misadjustments in the mechanical alignment of some of the antennas by about 1° and in the electrical gain of the antenna-filter-amplifier system that made Antenna 2 about 0.5 dB (1.12 times) more sensitive in V polariza-

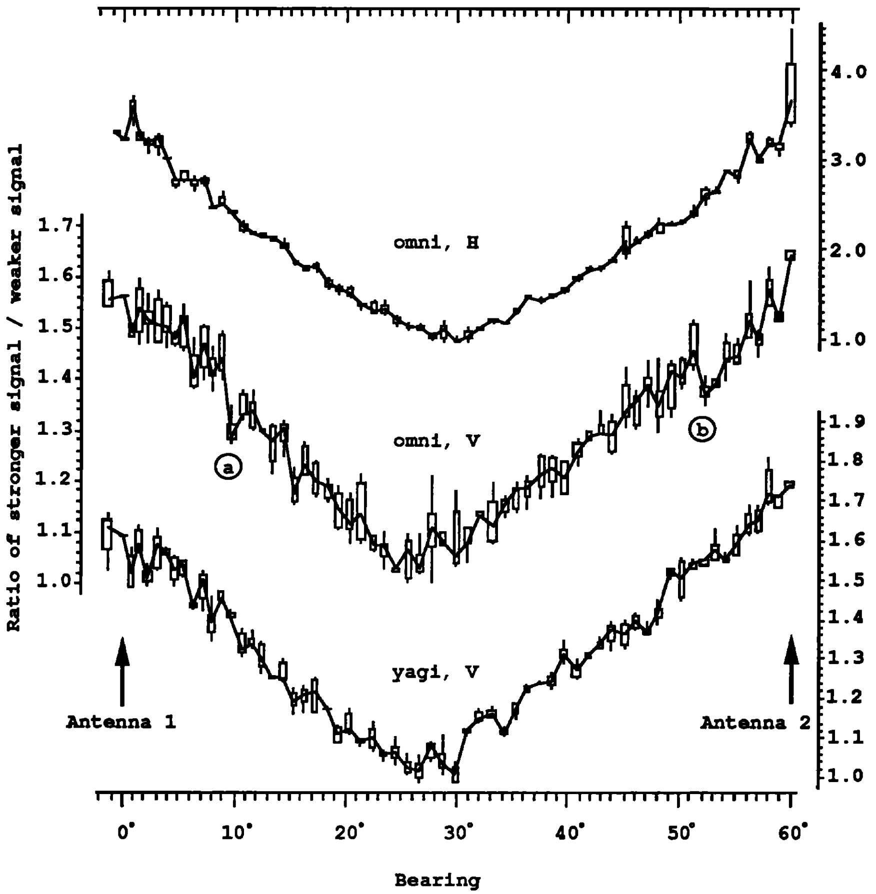

FIGURE 2. Ratios of signal strength used in calibrating Tower G. Equal signals are received by the two antennas at their nominal bisector, at 30°. In these Tukey plots, continuous lines connect median values of the RATIO of Antenna 1/Antenna 2 (left half) or Antenna 2/Antenna 1 (right half), boxes enclose the 2nd and 3rd quartiles, and vertical lines span the maximum and minimum value at each position. Top curve (note enlarged scale of ordinate): omnidirectional transmitting H antenna; middle curve: omnidirectional transmitting V antenna; bottom curve: three-element yagi V transmitting antenna. In the middle curve, the discontinuity at (a) occurred when the transmitter was moved radially 61 m to avoid nearby power lines; however, the discontinuity at (b) was unexplained, occurring when the transmitter was in a plowed field 50 m from the nearest object over 10-cm tall.

tion than Antenna 1. Further irregularities arose from accounted-for (e.g., point labelled "a") or unaccounted-for ("b") nonmonotonicity in the curves.

In stability tests on data from the 23-m tower, we discarded $n = 4$ outliers >8° from the mean. The standard deviations of the $n = 369$ and

TABLE 1. Errors[a] of stations direction-finding on stationary calibration transmitters and on free-ranging Brown-headed Cowbirds fitted with transmitters.

Polarization	DF station	Mean	SD	n
Calibration transmitters				
V	G	0.90°	2.5°	70
V	P	−2.60°	5.8°	85
H	G	0.44°	1.2°	66
H	P	−0.97°	1.9°	104
Cowbirds				
H	G	4.92°	6.7°	63
H	P	0.15°	7.5°	63

[a] Bias and precision as defined in White and Garrott (1990:82).

384 remaining measurements of angular position were 0.56° and 0.88° for the two towers, corresponding to ≤100 m at the 6.8-km distance of the transmitter. No pattern of variation of these small deviations with time was evident from time series plots of the bearings.

In azimuthal tests, DF was more accurate with H polarization than with V (Table 1), in accordance with the calibration curves (Fig. 2). Deviations of measured bearings from actual bearings followed an approximately normal distribution for all H (Shapiro-Wilk W statistic, $P \geq 0.14$), but not for all V ($P \leq 0.02$). Repeating measurements from a given position on a subsequent day gave medians falling within the range of bearings from earlier measurements. In preliminary tests, we found that other towers near a DF system tower and nearly its height introduced approximately 2° inaccuracies when transmitters lay in certain directions.

In distance tests, as expected, the test transmitter delivered the strongest signal and the non-optimized transmitter the weakest, with the optimized transmitter intermediate (n = 4 to 17 samples/transmitter/station). Nevertheless, all transmitters were detected out to the same maximum distance of 3.8 km from the 3-m tower. Signals from transect positions having evergreen vegetation and power lines nearby, such as that at 2 km, deviated in strength from nearby positions in open terrain. DF during range tests was unexpectedly accurate: over all distances right out to the 3.8-km maximum distance of detection, each of the transmitters was localized with little bias (the mode of each of the three transmitters differed from the nominal bearing by 1°), low variability (53% to 58% of observations in a ±0.25° sector), and no extreme outliers (total range 8.0°). Further distance tests with the receiving antennas at lower positions on the towers indicated that reducing the 34-m height of the receiving antenna to 17 m would diminish the range of detection to 3.2 km and that further lowering to 6.1 m would reduce the range to 2.2 km.

We dithered the position of the transmitter in seven tests. The immediate environment of the transmitter introduced variability into the DF process that averaged at least twice the intrinsic, pulse-to-pulse variability of the system (ratio of SEs = H: 4.6, 2.6, 4.3, 3.9; V: 1.9, 2.0, 2.6; n = H: 68, 12, 68, 98; V: 122, 120, 15).

Free-ranging passerine birds.—Data were obtained over two days on 1938 XY fixes, 63 of which were verified in the field by separate, manually-determined locations. As expected, birds spent much time in dense vegetation and signal levels from the tiny transmitters were frequently near or below noise levels, providing a worst case test of localization. Although usually only a short interval (median 5 s) elapsed between an observer report of a bird's position and the nearest-in-time tower report, this interval extended to a maximum of 330 s when the DF units detected the signals only intermittently. Weather varied from clear and calm to cloudy and windy.

Performance of the tower system localizing transmitters on Brown-headed Cowbirds during daytime foraging and other behavior was less accurate than the corresponding H results from calibration transmitters (Table 1). At typical distances of 0.7 to 0.9 km from the towers, which were separated in angle about 135°, the towers located birds 75 m (median value) from their observed positions. Much of this error (about 50 m) was angular bias away from the antenna with the stronger signal. The small transmitters' amplitude-modulated signal, which was far from optimum for best tower system performance, accounted for some but not most of the bias, which had not been observed with flat-pulse transmitters used in static tests.

The tower system permitted estimation of times of six movements of cowbirds to and from roosts to within about a minute. Nighttime roosts were in small trees in an open area about 3 km north of the closer tower and, for one bird one night, in a known but unanticipated roosting location in a treeless oat field. The automatic system could direction-find the weak signals only intermittently because of the distance to the roosts, almost 3 km for the more distant tower.

DISCUSSION

Accuracy of the automatic system is affected by errors in common with other methods and errors peculiar to non-rotating systems. Most of the kinds of errors described here are reviewed recently (Harris et al. 1990, Kenward 1987, White and Garrott 1990).

Errors in common with other methods.—Electrical noise, including noise from human sources (Cudak et al. 1991), is common to all applications of radio transmitters, but manual methods cope with noise differently from automatic methods. If noise prevents a human observer from hearing a signal, the observer can move around, retune the receiver, and otherwise attempt to hear the signal more clearly. With an automatic system one can add towers to multiply the directions and reduce maximum distances, continue to take bearings periodically for a long time until the noise diminishes, and, if data are critical, program the system to alert the researchers to deploy mobile receivers.

Rotational alignment and map location of the receiver are important to both manual and automatic methods but have to be established only when an automatic tower is installed, then checked periodically (e.g., with a telescope) if winds are a problem. In operational use, reference transmitters (Lee et al. 1985) will help ensure that alignment does not change unnoticed.

We tested static accuracy in flat, open country. In this situation, we hoped to approach the physical and electronic limits of the system rather than to find a "typical" habitat. Nevertheless, analysis of dither in the static tests indicated that features near the transmitter contributed about two to four times as much variability as the intrinsic variability in the measurement process, a new and unexpected result. This large apparent amount of indirect scattering was unexpected in an environment of dirt roads and plowed fields with no vegetation, fences, or other objects nearby. In retrospect, we presume that furrows, slight topographical gradients, >60-m distant wires and metal buildings, or other features acted as scatterers in this habitat. One or two such features may have dominated the electromagnetic environment. If this presumption is correct, conducting tests in an open but more complex, "natural" scattering environment might dilute the contribution of any one feature and thus give results that depend less on the exact location of the transmitter.

In any case, one can reduce certain DF errors resulting from the scattering environment near the transmitter by at least two techniques (W. W. Cochran, pers. comm.). A rapid series of bearings may be taken from a slowly moving bird, so that the bird's movements introduce dither for the investigator, or one may cancel local effects by taking bearings from multiple receiver positions widely spaced in angle. Whereas the former technique is ideally suited for the non-rotating automatic system described here, the latter method may be more efficient with portable, manual methods of radiolocation.

Movement error results when a bird changes position while the observer is also changing position for triangulation. An automatic system can be programmed to achieve nearly simultaneous bearings from >1 station, minimizing this problem. In observing the "actual" position of the cowbirds, the field worker noted some probable movement errors; these "errors" in ground-truth are included here as contributions to the reported error in the performance of the tower system, as are time lags between noted positions of the birds and tower system localizations.

Errors peculiar to non-rotating antennas.—Accuracy of construction of the antenna arrays is critical to their calibration. The measured median departure of individual yagis in the prototype system from exact 60° spacing was 0.3° and individual elements of the yagis were assembled to ±0.5 mm tolerance. Such low tolerances emphasize the importance of environmental influences on the long-term accuracy of "stationary" antennas, influences such as icing, wind motion of mast or tower, and birds perched on antennas.

Gain imbalances in the system, including the antennas, filters and amplifiers, will result in mis-calibration; the magnitude of their effect can be estimated directly from Figure 2. One can minimize errors in calibrating or in fitting the function of ratio $f(\theta)$ by periodic re-calibration and by using stationary transmitters at known locations. Calibration curves can be expected to change little from day to day on a working system, but perhaps would change on a longer time scale as antenna parts weather and values of electronic components drift. Our measurements on two towers are not sufficient to estimate how much, if any, loss in accuracy would result from calibrations being extrapolated to different antennas of the same design.

H polarization gives better localization than V, presumably because of electrical interactions among the individual V antennas. Consequently, one should, if possible, design transmitters with whip or loop antennas angled roughly H rather than V so that the receiving antennas may be oriented H. H also has advantages penetrating forest (Anderson and DeMoor 1971). Increasing the number of antennas/DF station and the number of elements/yagi would improve the performance of V.

Only the two antennas receiving the strongest signals were used for final estimation of bearings in this prototype system and the system was poorest at localizing a transmitter nearly aligned with one of these antennas (which we shall call antenna i), because the received signal from antenna i changed little with azimuth at the point of peak sensitivity. Performance should improve substantially if, in this region, the system were to use the ratio of the signals in nonadjacent antennas, $(i + 1)/(i - 1)$, rather than adjacent ones, $i/(i \pm 1)$.

Comparison with manual methods.—Even with an ideal automatic system, investigators will need hand-held or vehicle-mounted moving receivers to investigate problems, locate nest sites, etc. An automatic system should be regarded as a way to greatly reduce routine, repetitive mobile observations or to provide continuous or frequent coverage, not as a replacement for mobile work. The increased data rate permitted by this system is more flexible temporally but less flexible spatially than mobile methods. Automatic stations may be placed in locations that would be inconvenient or impossible for a person with a mobile receiver to reach regularly, however.

In the open location used for static testing, the system performed well in comparison with reported accuracies of other mobile and stationary systems, with mean errors 0.44°–2.6°. Lee et al. (1985) report SDs of 1.8°–5.3° by stationary towers in "diverse terrain" in Colorado. Mills and Knowlton (1989) tested human observers and found angular errors of 0.9° and 1.6° from 4-m towers located on "prominent hills" in Utah. Pace (1988) reports circular SDs of 2.6° and 5.7° from stationary systems in "very flat terrain" in Indiana. Pyke and O'Connor (1990) report mean errors of 0.5°–1.9°, using fixed transmitters to establish the positions of receiving antennas in "heathland". Further such studies are listed in White and Garrott (1990) and Priede (1992). Ideally the present study would have replicated the measurements of the automatic system with similar measurements made from the same vantage by hand-held or vehicle-mounted yagis. This replication was not done, partly because of good performance by the automatic system and partly because of physical constraints; the only location near the towers that was free of serious reflections from the towers and their guy wires lay at the top, where the automatic system's antennas were located.

Trials with cowbirds were nearly a worst-case test of the prototype system, with tiny, weak transmitters on quickly moving birds typically in dense vegetation. The towers, usually at distances of 0.7–0.9 km from the birds, were often unable to detect a strong enough signal to localize the transmitters; when they did so, one-pulse localization accuracy was about 2 ha (1 SD). Data from the towers could not be used to follow short tree-to-tree movements or identify the habitat used by the birds, but could be used to follow movements from roost to feeding areas to forest territories and would be excellent to direct a field worker with a portable receiver to find the birds quickly. Some or the majority of the error (namely the bias) in angular localization we observed should be reduced by using better-constructed transmitters. Averaging of many pulses from slow-moving subjects can be expected to increase the accuracy of localization. And an automatic system will have advantages where movements are difficult to predict and perhaps sudden, for instance in natal dispersal, migratory departure, and homing. Finally, we emphasize that stronger transmitters or more open habitat would reduce localization errors in a field situation, to a lower limit perhaps approximated by the static tests.

This system could detect signals about −133 dBm at the antenna input. To increase sensitivity, the synchronization phase algorithm to find pulses could be improved or more highly directional yagi antennas could be used, but the latter would necessitate more antennas in each array, increasing cost, wind resistance, and time needed to detect and localize signals. Ability of the automated system to attempt to localize a weak and fluctuating signal continually for a long period would partly compensate for a disadvantage in sensitivity.

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