Journal of Mammalogy, 84(2):571–578, 2003

A NEW SYSTEM FOR AUTOMATIC RADIOTRACKING OF SMALL MAMMALS

THOMAS BRINER,* JEAN-PIERRE AIROLDI, FRITZ DELLSPERGER, SIMON EGGIMANN, AND WOLFGANG NENTWIG

Zoological Institute, University of Bern, Baltzerstrasse 6, 3012 Bern, Switzerland (TB, J-PA, WN)
Institute of Engineering and Architecture, University of Applied Sciences, Bern, Morgartenstrasse 2c, 3000 Bern 22, Switzerland (FD, SE)

We developed a radiotracking system for automatic and continuous data collection, which allows the radiotracking of several animals at the same time. Based on a system controller, 3 fixed antennas, and small-size radiotransmitters (<2 g, 14 by 12 by 4 mm), the system has the capacity to record several individuals continuously at intervals of <5 min. Antennas, positioned at fixed points in the field, forward the signals from tagged animals to the system controller, where data are collected. The coordinates of the individual's locations are calculated through triangulation on the basis of the angles of incidence from the transmitter signal to each antenna. Transmitters are individually identified by the chronological sequence of their signals. Field tests with *Microtus arvalis* show the utility of the new technique and possibilities for the system.

Key words: automatic system, continuous radiotracking, field test, *Microtus arvalis*

Many studies on small mammals use trapping protocols to gather data on animal movements. In trapping studies, it is possible to survey a large area inhabited by many animals, with a reasonable amount of labor. However, trapping yields only limited information on temporal and spatial distributions of animal movements and may in fact influence animal activity. Radiotracking technology has been widely available since the early 1960s as an alternative method for the study of animals' spatial distributions and activity patterns (Cochran and Lord 1963; Kenward 1987; Marshall and Kupa 1963). Radiotracking allows one to monitor animals that are not easy to survey visually because they have nocturnal habits or live in dense vegetation (Amlaner and Macdonald 1980). However, normally there is a trade-off between locating a few positions per day or per week of a larger group of radiotagged animals and following a single individual intensively for a short period of time.

The 1st studies using automated telemetric systems were carried out in the 1960s and 1970s. Cochran et al. (1965) described a system based on fixed rotating Yagi antennas on 70- and 100-feet towers. The system permits tracking of 52 individuals simultaneously, on different frequencies, with a maximum of 1,920 locations determined per day. Disadvantages of such a system are, however, the size and immobility of antenna towers and transmitter weight (32–300 g), which is suitable for large or medium-sized animals, such as rabbits, foxes, or deer, but not for small mammals. The system of Lemnell et al. (1983), which was the 1st to use 2-way communication transmitters based on a converted hyperbola navigation principle, also was at a disadvantage because of its need for tall receiving towers and heavy transmitters (800 g). Chute et al. (1974) proposed a method using

* Correspondent: thomas.briner@zos.unibe.ch

a grid of overhead wire antennas. A 30-m square was enclosed and straddled by the grid of wire antennas 1 m aboveground at intervals of 1.5 m. The intersection of grid wires nearest to a transmitter received the maximum signal strength. By ''scanning'' the wires in X and Y directions, the position of the tagged individuals could be assessed. The main advantage of this system is a high and constant resolution with a maximum deviation of 0.75 m from the true coordinates. On the other hand, the system is very restricted in its range; to survey an area of 30 by 30 m, it requires about 2 km of overhead wire. Furthermore, the system is not easily movable, and because it needs a manual readout, it is not practicable to follow more than 1 animal at a time.

To improve on conventional tracking systems, we developed a new system that allows one to track several animals at the same time, automatically and continuously. Our system is based on transmitters that both receive and emit signals. A trigger activates and synchronizes the transmitters, which then send a signal after a predefined time that is characteristic for each animal. Signals are received by fixed antennas.

Advantages of our system over previous automated systems are the combination of small transmitters that allow tracking of small mammals, the possibility of tracking several individuals almost simultaneously at intervals <5 min, and the ease with which the whole system can be moved to different places in the field. The range, accuracy, and weight are comparable with those of the commercially available portable devices. We present a detailed description of our system and the results of the 1st field tests of the system.

MATERIALS AND METHODS

Our system is based on interaction between a fixed station and a mobile object that is to be tracked. The fixed station consists of a system controller, a trigger antenna, and 3 fixed antennas and receivers (an antenna-and-receiver couple is referred to here as a ''tracker''). The system controller is the master of the system, which controls the connected components. The communication runs through a bus system using a pairwise twisted and screened data cable (cross section = 0.75 mm^2). The bus cable allows a maximum distance of 200 m between the system controller and the farthest component. The parameter measured is the angle of incidence from the transmitter signal to the tracker antennas. Each tracker yields a line of position (virtual line from the tracker to the transmitter), and the coordinates of the radiotransmitter's location are calculated from the points of intersection of the lines of position.

The radiotracking device has a modular setup with a computer station as master of the system, which controls the connected components. The system controller has 2 main functions: 1st, it sends the starting signal for each set of localizations to the trigger and the trackers and 2nd, it records and saves the data. The system controller is determined by software developed at the University of Applied Sciences, Bern, Switzerland. The software is written in C++ programming language, is based on Windows® (Microsoft Corporation, Redmond, Washington), and supports an automatic measuring procedure. Several dialog boxes allow configuration of the measurements. The most important parameters are the number of tagged animals (≤256), the number of antennas and receivers (≤4; usually 3), the number of localizations, and the time intervals between the sets of localizations. A set of localizations consists of locating all operating transmitters at a given time. The interval between 2 sets depends on the number of tagged animals. The shortest interval corresponds to the highest code number of a transmitter in use plus a 5-s safety margin before the next set of localizations to ensure that sets of localizations do not overlap. The code number is the time lag between activation of a transmitter and the signal it sends (e.g., transmitter #1 sends after 1 s, transmitter #2 sends after 2 s). When 10 animals are tagged, therefore, the shortest interval will be 15 s.

Radiotransmitters are normally in standby mode. A starting signal provided by the trigger synchronizes them by sending a signal at the beginning of each set of localizations. The trigger is a dipole antenna with vertical polarization, which operates at a frequency of 148.75 MHz, the same as for the transmitters. Its high-fre-

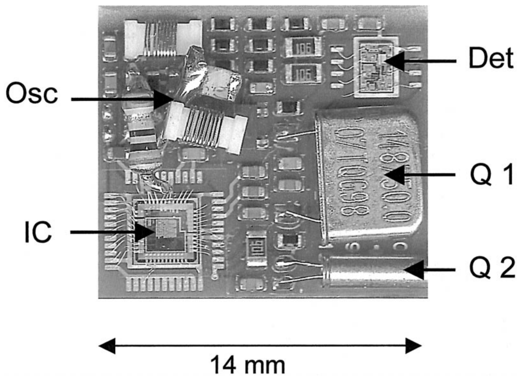

FIG. 1.—Design and layout of components of a transmitter. The detector receives the trigger signal and then activates the transmitter and timer. After a fixed, programmed time lag, the transmitter sends its signal, which then returns to standby mode. (Osc: oscillator for tuning antenna to maximal transmitting power, IC: integrated circuit containing timer and sender, Det: detector, Q 1: quartz for transmitting frequency, Q 2: quartz for timer.)

quency generator has an output of 10 W (+40 dB m).

Radiotransmitters were constructed so as to minimize their size and mass in order to reduce possible effects on the animal. Transmitters weigh 0.8 g, measure 14 by 12 by 4 mm, and are powered by a 3-V lithium battery weighing 0.7 g. A protective layer on the battery, a collar consisting of a nylon cable tie and the antenna, weigh an additional 0.3 g. Thus, the total mass is 1.8 g. The transmitter antenna is an external thread of nickel–titanium memory steel (0.1-mm diameter and 30 cm long). Memory steel is an optimal material for the antenna because it always tends to straighten. Thus, the antenna will be in a linear position whenever possible, avoiding the formation of knots or bends and giving the best signal.

The main components of the transmitter (Fig. 1) are the detector with an analog circuit (operation amplifier and comparator), which receives the trigger signal, a quartz crystal to generate the transmitting frequency, and the custom-designed integrated circuit, containing a timer, a high-frequency generator (output ≥ -10 dBm at 50 Ω), and amplifiers. The integrated circuit was developed at the University of Applied Sciences, Bern, Switzerland, and is based on bipolar complementary metal oxide semiconductor technology. The quiescent current of the transmitter is very low (<10 μA).

Functioning of the transmitters is based on 2-way communication similar to that described by Lemnell et al. (1983). A starting trigger impulse is recognized by the detector, which activates the transmitter and starts the timer. After a predefined time lag, the timer activates the HF-generator, which sends a signal for 0.5 s. The time lag between activation of the transmitter and sending of the signal is characteristic for each transmitter. Because we use multiple transmitters, all at the same frequency (148.75 MHz), this time lag is the code for individual identification of the transmitters and is permanently programmed for each transmitter. For example, a transmitter with the programmed number 5 will always send its signal 5 s after activation.

The tracker consists of an antenna and a corresponding receiver. To triangulate, 3 trackers are normally used. Tracking is done according to the Watson-Watt method (RDF Products. 2002. Basics of the Watson-Watt radio direction finding technique. http://www.rdfproducts.com/wn002_apl_01.pdf), which is based on nonrotating fixed antennas, contrary to the Yagi principle, where antennas have to be moved by the user and pointed toward the incoming signal. Watson-Watt systems use a direction-finding antenna with an array of spatially displaced aerials that produce characteristic voltages, unique for every received azimuth. For a direction-finding antenna, we used a 4-element Adcock antenna (with 2 orthogonal components of 1-m length), which is superior in performance to loop antennas often used in other systems. The Adcock antenna and a 1-channel Watson-Watt receiver were both constructed at the University of Applied Sciences, Bern, Switzerland. The receiver amplifies antenna signals and modulates them to get an amplitude-modulated signal. An additional rod at the antenna provides information about the strength of the incoming signal. The direction of the signal is evaluated using a Fourier transformation with window length of 50 ms. Through communication with the system controller, the receiver ‘‘knows’’ when a set of individual localizations starts, i.e., when the signals from the transmitters will arrive. As a signal comes from a transmitter, data are saved for 1 s and sent back to the system controller (1 s of data received every 50 ms correspond to 20 data

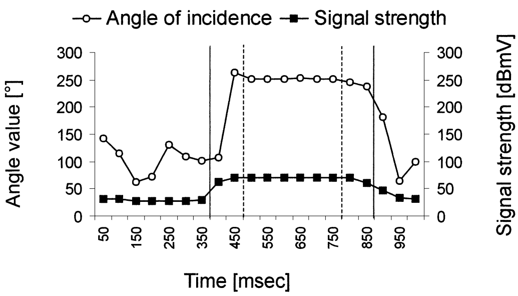

FIG. 2.—Data from a single transmission of 1-s duration sufficient for 1 location fix. Solid vertical lines enclose the 10 values with highest signal strengths received from the transmitter. Dashed vertical lines enclose the 6 angle values used for computing mean angle of incidence.

points; Fig. 2). Although a transmitter only sends for 0.5 s, data are collected over a period of 1 s because perfect synchronization between transmitters and tracker is technically difficult. The 10 angle values from the 0.5-s interval are distinguishable from background noise by the clearly higher signal strength. Data are saved in a Microsoft Access file and processed using Microsoft Excel (Microsoft Corporation).

Field tests of this system were performed by monitoring a population of the common vole, *Microtus arvalis*. Voles were captured using Longworth mammal traps with nest boxes (Penlon Ltd., Abingdon, United Kingdom). The transmitters were attached to voles under light anesthesia with Flurothane (Wyeth-Ayerst Laboratories, Philadelphia, Pennsylvania), with a nylon cable tied around their necks. After 2–5 min, the voles were released at the place of capture. Twenty-nine voles weighing 20–50 g were monitored for ≥24 h each at intervals of 1 min.

Data gathered by radiotracking included time of localization, vole identification numbers, and 20 data points of incoming signal direction and strength for each vole and for each antenna.

Data for each localization were reduced to a single angle of incidence for each vole and tracker. Ten data points with highest signal strengths were selected. From these, the first 2 and last 2 data points were eliminated because they were usually unstable (Fig. 2). A mean angle was calculated from the remaining 6 values. If signal strength from a transmitter was not clearly distinguishable from background noise, it was omitted. Signal strength depends on position and distance of the transmitter from the antenna. Maximal signal strength (y) was 1.45 dB μV and decreased exponentially with distance (x) from the antenna ($y = 1.45e^{-0.017x}$, $R^2 = 0.95$). Background noise varied between 0.5 and 1 dB μV. For our analyses, we chose an arbitrary critical value of 0.1 dB μV difference between the signal strength of the transmitters and the background. If the difference did not exceed this value, the record was omitted.

Variation in angle values (y) for a given localization is largely dependent on signal strength (x) of transmitters. The relationship is described by the exponential function $y = 703e^{-5.68x}$ ($R^2 = 0.79$). Angle of incidence was determined according to a coordinate system defined by reference transmitters placed in the field. Reference transmitters also helped to ensure that the alignment did not change unnoticed. Finally, coordinates of voles' locations were calculated by triangulation. Actually, we calculated the centroid of the triangle formed by the lines of position from each tracker to a given transmitter; this is needed because these lines rarely intersect at a single point. If directions of angles of incidence intersected at a very acute angle, the computed localization was not used because a minor deviation of the angle caused a great deviation of the calculated coordinates (White and Garrott 1990). The value for the limiting angle can be set at a researcher's preference. We omitted all calculations based on angles of ≤20°. As an additional criterion, we also calculated the perimeter of the triangle formed by angles of incidence. If the perimeter exceeded a critical value (set to an arbitrary value of 10 m in our case), data were also dropped. If 1 antenna failed to get a transmitter signal, a coordinate was calculated by intersecting the 2 remaining bearings as described by White and Garrott (1990).

RESULTS

The accuracy of localizations was estimated using 17 transmitters identical to transmitters attached to voles. These were placed at fixed positions in the field at distances 5–25 m from the antennas. At tracking intervals of 1 min, we received an average of 589 signals transmitter^{-1} day^{-1} (lower quartile = 341, upper quartile = 910). From these signals, an average of 366 coordinates were calculated (lower quartile

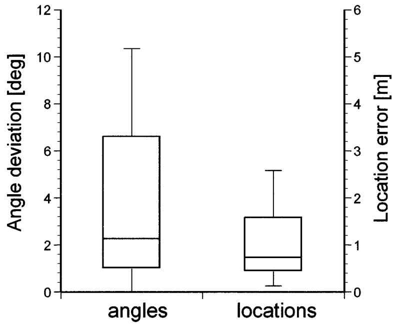

FIG. 3.—Accuracy of automatically computed location fixes for radiotransmitted signals. Deviations of computed angles of incidence from true (measured) angles of incidence (n = 51) for radiotransmitter signals were calculated for 17 transmitters placed at fixed positions relative to receiving antennas. Location errors (n = 17) describe deviation of triangulated location fix from the true location that results from these deviations of angle of incidence. Boxes represent the middle 50% of measurements, horizontal lines represent medians, and vertical lines represent ranges.

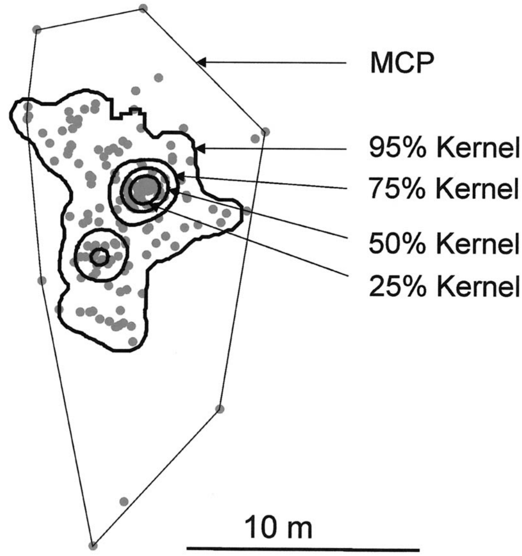

FIG. 4.—Estimated home range of a representative vole, *M. arvalis*, tracked for 24 h during field tests of a new automated radiotelemetry system. The minimum convex polygon (MCP) measure of home range (Mohr 1947) and distribution contours for home-range use as determined by kernel methods (Worton 1989) are illustrated.

= 213, upper quartile = 531). The median deviation of calculated angles from true angles was 2.27° (lower quartile = 1.35°, upper quartile = 5.35°). These deviations lead to miscalculation of transmitter coordinates by 0.13–2.58 m (median = 0.74 m; Fig. 3).

From a total of 170 data points collected during the 24-h period of tracking of a representative vole, we calculated a minimum convex polygon (Mohr 1947) home range of 157 m^2 (Fig. 4). Kernel methods (Worton 1989) were used to illustrate different home-range core areas as well (Fig. 4).

The median longevity of a transmitter battery was 44 h, and the number of received signals was not reduced on the 2nd day of tracking (Wilcoxon $Z = 0.21$, $P = 0.84$, $n = 21$), nor was the number of coordinates (Wilcoxon $Z = 0.37$, $P = 0.72$, $n = 21$).

Theoretically, our system should work also with animals belowground. In tests with transmitters manually buried to a depth of 20 cm, the strength of received signals was only slightly reduced compared with transmitters on the surface. However, inexplicably, transmitters attached to voles could not be detected in most cases when voles were belowground. The lack of signals from animals belowground prevents a complete continuous tracking of animals, but because much of the activity of *M. arvalis* occurs aboveground, at least that part of the activity can be followed continuously. Our data also provide information that can be used to analyze aboveground activity rhythms. Fig. 5 illustrates a clear polyphasic pattern of activity of one of our radiotagged voles that is similar to activity described for *M. arvalis* by Lehmann and Sommersberg (1980).

DISCUSSION

Field tests under natural conditions demonstrated the capability of our automated system for radiotelemetry using small and light transmitters. The capacity to locate

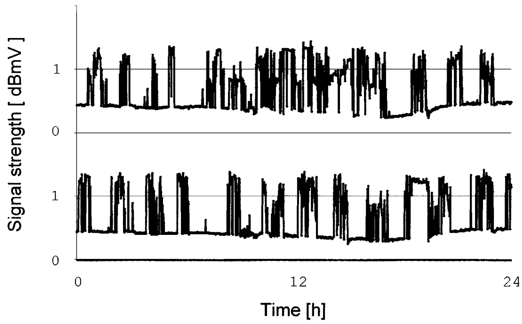

FIG. 5.—Signals from transmitters of 2 voles (*M. arvalis*) over 24 h, tracked at 1-min intervals, showing a clear polyphasic pattern of aboveground activity.

many small animals almost simultaneously over very short time intervals is a powerful tool for studies of movements, activity, and use of space. Although our transmitters contain an additional timer and function both as detector and sender, unlike commercial ones that only send a pulsed signal, their weight is <2 g.

Identification of transmitters by the chronological sequence of signals instead of by different frequencies for each animal has many advantages. With a single frequency, transmitters and receivers can be optimized for that frequency (i.e., to get the best signal). Additionally, it takes less time than sequentially stepping through a series of frequencies and angles. Battery lifetime (median = 44 h) was sufficient for about 3,000 emitted signals. At tracking intervals of 1 min, this amounts to 1–5 days, which does not allow long-term studies. But because the interval between 2 sets of localizations can be changed and batteries can be replaced, this may not be a major problem.

Telemetry bearings are only estimates and not exact locations of tracked animals (Springer 1979). Different factors can decrease the accuracy of these estimations, such as when an animal changes its location between 2 bearings or if the angle between readings is small (Kenward 1987). The 1st problem is eliminated with our system because bearings occur simultaneously. The 2nd problem is reduced by taking 3 bearings for triangulation.

Several indicators were used to test reliability of the measurements, of which the most important were signal strength and perimeter of the triangle formed by the lines of position. Because critical values of indicators can be chosen arbitrarily by the investigator, there will be a trade-off between number of acceptable data points used for analysis and reliability of those data. In a representative 24-h period of tracking a single vole at 1-min intervals using critical values that we presented earlier, we had to omit 39% of the data because signal strength was too weak. An additional 12% was omitted because the triangle formed by the lines of position exceeded the critical value (leaving out 170 points). The critical value that we selected for the perimeter of the position line triangle was 10 m. This means that the maximum area included by the triangle was 5.5 m^2. Thus, data that did not allow localization of a vole within a 5.5-m^2 area were discarded. Reducing the arbitrary critical limit for this perimeter, so that the included area is half as large, would result in an additional loss of 7% of the data points.

At difficult sites where signals may be biased by reflections, or if more than 3 antennas are used, it would be possible to calculate coordinates based on statistical models as described by White and Garrott (1990). In a planned redesign of radiotransmitters, emphasis will be on increasing strength of signals sent by transmitters. A stronger signal would provide improved range and better accuracy of localizations. The range of 30 m is sufficient to observe *M. arvalis* in a restricted habitat but would be too small for observing other species such as *Apodemus* with home ranges of up to 30,000 m^2 (Attuquayefio et al. 1986; Randolph 1977; Wolton 1985; Zubaid and Gorman 1993).

In summary, we developed a system that incorporates several existing radiotracking principles into a new and unique system.

Combination of a 2-way communication system (with transmitters able to receive and send) and Watson-Watt receivers allows tracking of more animals at a time and tracking over shorter time intervals than in any already existing system. Short sample intervals are especially desired in studies on movements and activity patterns, interaction between individuals, and intensity of range use. Our system allows tracking of several voles at intervals <1 min, providing abundant data for such studies. A further important improvement in our system is the miniaturization of the transmitter so that the automated system is applicable to many small-mammal studies, whereas former automated systems were more limited for use with large animals.

Given that our radiotracking system can generate so many data in such short periods, attention should be paid to concerns about autocorrelation when using the data for analyzing home ranges. Most statistical models involve the assumption of independence of data, which means that an animal's current position should not be influenced by its position during past observations. Often, data gathered by radiotelemetry fail to meet this assumption, especially when time intervals between successive observations are short, as they are with our system. Earlier studies assumed that lack of independence (autocorrelation) leads to a reduction in estimated movements and to an underestimation of home-range size (Swihart and Slade 1985). Swihart and Slade (1997) subsequently pointed out that sampling intervals resulting in autocorrelated data generally will not invalidate several common estimators and indexes of home-range size, provided that the time frame of the study is adequate and sample size is high. The time frame should therefore be longer than the time an animal requires to describe its home-range boundary. Otis and White (1999) give recommendations for calculating minimal sample size and for data-sampling designs so that autocorrelation should no longer be relevant. If one needs independent data, however, a review of methods used for testing independence in radiotelemetry data is given by Salvatori et al. (1999).

Acknowledgments

We thank A. Hamza, D. Holzer, E. Jutzi, P. Trifonov, and L. Wobmann for technical support. We are grateful to W. Z. Lidicker, Jr., B. Naef-Daenzer, and 2 anonymous referees, who made helpful comments on the manuscript. This project was supported by grants from the Swiss National Science Foundation (3100-049454.96) and Microswiss (CA-ZG-069).

Literature Cited

Amlaner, C. J., and D. W. Macdonald (eds.). 1980. A handbook of biotelemetry and radiotracking. Pergamon Press, Oxford, United Kingdom.

Attuquayefio, D., M. Gorman, and R. Wolton. 1986. Home range characteristics in the woodmouse *Apodemus sylvaticus*: habitat, sex and seasonal differences. Journal of Zoology (London) 210:45–53.

Chute, F. S., W. A. Fuller, P. R. J. Harding, and T. B. Herman. 1974. Radio tracking of small mammals using a grid of overhead wire antennas. Canadian Journal of Zoology 52:1481–1488.

Cochran, W. W., and R. D. Lord. 1963. A radio-tracking system for wild animals. Journal of Wildlife Management 27:9–24.

Cochran, W. W., D. W. Warner, J. R. Tester, and V. B. Kuechle. 1965. Automatic radio-tracking system for monitoring animal movements. BioScience 15:98–100.

Kenward, R. (ed.). 1987. Wildlife radio tagging. Academic Press, London, United Kingdom.

Lehmann, U., and C. W. Sommersberg. 1980. Activity patterns of a common vole, *Microtus arvalis*—automatic recording of behaviour in an enclosure. Oecologia 47:61–75.

Lemnell, P. A., G. Johnsson, H. Helmersson, O. Holmstrand, and L. Norling. 1983. An automatic radio-telemetry system for position determination and data acquisition. Pp. 76–93 in Proceedings of the Fourth International Conference on Wildlife Biotelemetry (D. G. Pincock, ed.). Applied Microelectronics Institute and Technical Universty of Nova Scotia, Halifax, Nova Scotia, Canada.

Marshall, W. H., and J. J. Kupa. 1963. Development of radio-telemetry techniques for ruffed grouse studies. Transactions of the North American Wildlife and Natural Resources Conference 28:443–456.

Mohr, C. O. 1947. Table of equivalent populations of North American small mammals. American Naturalist 37:223–249.

Otis, D. L., and G. C. White. 1999. Autocorrelation of location estimates and the analysis of radiotracking data. Journal of Wildlife Management 63:1039–1044.

Randolph, S. E. 1977. Changing spatial relationship in a population of *Apodemus sylvaticus* with the on-set of breeding. Journal of Animal Ecology 46:653–676.

SALVATORI, V., A. K. SKIDMORE, F. CORSI, AND F. VAN DER MEER. 1999. Estimating temporal independence of radio-telemetry data on animal activity. Journal of Theoretical Biology 198:567–574.

SPRINGER, J. T. 1979. Some sources of bias and sampling error in radio triangulation. Journal of Wildlife Management 43:926–935.

SWIHART, R. K., AND N. A. SLADE. 1985. Influence of sampling interval on estimates of home-range size. Journal of Wildlife Management 49:1019–1025.

SWIHART, R. K., AND N. A. SLADE. 1997. On testing for independence of animal movements. Journal of Agricultural, Biological, and Environmental Statistics 2:48–63.

WHITE, G. C., AND R. A. GARROTT. 1990. Analysis of wildlife radio-tracking data. Academic Press, San Diego, California.

WOLTON, R. J. 1985. The ranging and nesting behaviour of wood mice, *Apodemus sylvaticus* (Rodentia: Muridae), as revealed by radio-tracking. Journal of Zoology (London) 206:203–224.

WORTON, B. J. 1989. Kernel methods for estimating the utilization distribution in home-range studies. Ecology 70:164–168.

ZUBAID, A., AND M. L. GORMAN. 1993. The effect of supplementary feeding upon the size of the home ranges of woodmice *Apodemus sylvaticus* living on a system of maritime sand-dunes. Journal of Zoology (London) 231:233–237.

Submitted 2 April 2002. Accepted 10 September 2002.

Associate Editor was Ronald D. Gettinger.