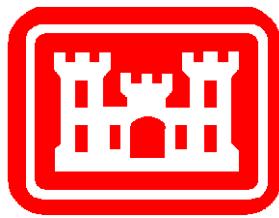


PUBLIC WORKS TECHNICAL BULLETIN 200-1-129
31 MARCH 2013

**DEMONSTRATION AND GUIDANCE OF
AUTOMATED RADIO TELEMETRY SYSTEMS
FOR MONITORING ANIMAL POPULATIONS**



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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
441 G Street NW
Washington, DC 20314-1000

CECW-CE

Public Works Technical Bulletin

31 March 2013

No. 200-1-129

Facilities Engineering
Environmental

DEMONSTRATION AND GUIDANCE OF AUTOMATED RADIO TELEMETRY
SYSTEMS FOR MONITORING ANIMAL POPULATIONS

1. Purpose

a. This PWTB provides guidance to natural resource managers on the potential benefits and/or limitations of using different types of automated radio telemetry tracking techniques (e.g., automated radio telemetry systems, satellite tracking, Global Positioning Systems, hand tracking) to monitor animal populations on military and non-military lands.

b. The purpose of this PWTB is not to recommend one technique or system over another, but to describe each system adequately so that readers are able to decide which, if any, of the systems/ techniques described address their individual research question(s) the best.

c. All PWTBs are available electronically at the National Institute of Building Sciences' Whole Building Design Guide webpage, which is accessible through this link:

http://www.wbdg.org/ccb/browse_cat.php?o=31&c=215

2. Applicability. This PWTB applies to Natural Resource Managers on US Army facilities in the Continental United States (CONUS) where wildlife species of concern reside.

3. References.

a. Army Regulation (AR) 200-1, "Environmental Protection and Enhancement," 13 December 2007.

4. Discussion.

a. AR 200-1 "implements federal, state, and local environmental laws and Department of Defense (DoD) policies for preserving, protecting, conserving, and restoring the quality of the environment." AR 200-1 also now incorporates former AR 200-3, which required installations to be good stewards of land resources.

b. The DoD needs defensible data to understand how various animal populations utilize military lands to address the question of potential military effects (e.g., training maneuvers and noise), while also maintaining its ability to train to standard. Conventional field techniques for monitoring animal movement patterns and behavior (e.g., hand-tracking of radio-tagged animals, direct observation) can be labor-intensive, typically provide only infrequent sampling regimes, are prohibitively expensive, or provide limited data. Thus, it is important that managers of federal lands have access to detailed life history data for threatened, endangered, and at-risk animal populations on their lands. Such data are needed to effectively manage and recover animal populations, while also providing the information necessary to mitigate for future changes in land management needs.

c. New technology/techniques are needed to monitor wildlife species by using improved data acquisition capability and cost effectiveness when compared with conventional techniques. It is important that different radio telemetry techniques (i.e., hand-tracking and automated radio telemetry systems) be evaluated and compared based on their reliability, precision, cost effectiveness, etc. during the monitoring of activity and locations of animals of concern on military lands.

d. Appendix A provides background information on the history of wildlife radio telemetry and describes the basic components that make up wildlife tracking systems.

e. Appendix B provides information about the study site, the different types of automated radio telemetry systems tested (i.e., Rapid Multi-Channel Goniometer [RMG] and Automated Recording Unit [ARU]), and identifies the testing procedures used.

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f. Appendix C details project results and conclusions.

g. Appendix D describes the benefits associated with using hand-tracking and automated radio telemetry tracking techniques.

h. Appendix E describes the limitations or caveats associated with using different automated and conventional telemetry tracking techniques.

i. Appendix F provides information on lessons learned and recommendations for utilizing automated radio telemetry systems.

j. Appendix G contains references used in the appendices and a list of abbreviations used in this PWT

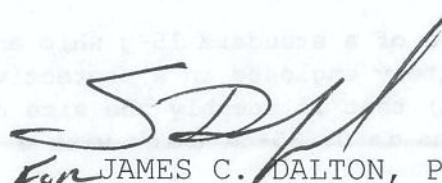
5. Points of Contact

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Appendix A

BACKGROUND

Radio telemetry is a powerful tool that has been used for more than 50 years to track animal populations (Le Munyan et al. 1959; Lord et al. 1962). This technology has provided invaluable life-history data for numerous animal species across many disciplines within the field of wildlife ecology (Kenwood 2001). Automated radio telemetry systems were developed soon after wildlife animal tagging began (Cochran et al. 1965), but have not been fully utilized until recently because of limitations of cost, availability of hardware, and computational power (e.g., Walde et al. 2003; McDaniel and McKelvey 2004; Borrowman et al. 2007).

Radio tracking systems are composed of three integral parts, a transmitting system, a receiving system, and a human interpreter. The transmitting system consists of a transmitter, a transmitting antenna, and a power supply (Figure A-1). Figure A-2 shows two examples of transmitter attachments on desert male and female tortoises. The receiving system is composed of receiver (Figure A-3), receiving antenna(s) (Figure A-4), power source, and recorder or human operator.



Figure A-1. An example of a standard 15-g whip antenna transmitter showing the transmitter and battery enclosed in a protective weatherproof casing (gray part) that is roughly the size of a quarter.
Antenna is 0.635-cm thick with a 22.86-cm long.

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Figure A-2. Transmitters (circled in white) are attached to desert tortoises (male in burrow, female just outside burrow) on Fort Irwin, CA. The position of the transmitter varies based on size and/or gender of the animal.



Figure A-3. An example of one of the radio telemetry receivers tested, which is part of the Automated Recording Unit (ARU) system.



Figure A-4. An example of the antenna array used with the ARU system. An array with six antennas is affixed on top of a tower and aligned every 60 degrees to fully cover the surrounding landscape.

Radio transmitters can vary substantially in weight, from 0.2-g units for small animals like arthropods, bats, reptiles, and small birds, to over 1-kg units for large terrestrial and marine mammals. Transmitters are designed to pulse roughly 40-60 times per minute, but this can be varied based on project requirements. The overall transmitter weight, configuration, battery life, pulse rate, and attachment mechanism depends on the animal being tagged and its weight, gender, and overall health condition. It is believed that transmitter weight should be <5% of the animal's body weight (Murray and Fuller 2000), though for some animal species the recommended threshold is <3%.

Radio transmitter battery life can vary substantially, from a few days for some glued-on units to years for collar type attachments, based on size and weight limitations for animal attachment purposes. Methods of transmitter attachment range from subdermal implants for snakes, collar attachments for mammals, harness/backpack/tail mount attachments for birds, to glue on units for reptiles (Figure A-1), etc. Transmitter weight for some transmitters monitored by near-Earth satellites has been reduced with the advent of solar-powered units a few years ago, but these units still weigh more than conventional radio transmitters and cannot run continuously without adequate exposure to sunlight. A 5.0-g solar version of transmitters for

reception by satellites is now commercially available at www.microwavetelemetry.com.

A number of different systems/techniques are available for tracking animal location and movement patterns, such as:

1. conventional hand-tracking;
2. automated radio tracking systems (e.g., Automated Recording Units [ARU] and Rapid Multi-Channel Goniometer [RMG] systems, which were both tested for this study);
3. satellite telemetry (transmitter-based); and
4. Global Positioning System (GPS receiver-based) satellite tracking (Kenwood 2001; Wilkelski et al. 2007).

Radio telemetry was the first technique to track animal location and movement patterns effectively (Lord et al. 1962), and is still the most commonly used technique for tracking animal populations due mainly to its low equipment costs and the availability of lightweight transmitters. High-powered transmitters and radio receivers used by other systems, such as satellite telemetry and GPS, are still heavier than conventional radio transmitters, reducing the number of animal species that can be tracked by these systems. It is estimated that upwards of 66.8% of all mammals and ~81% of all birds, for which body weight information is known, are not trackable because transmitter/receiver weights exceed the 5% threshold (Wilkelski et al. 2007). Radio telemetry and automated radio telemetry systems that use conventional transmitters are substantially less limited by transmitter weight.

Automated Radio Telemetry Systems

There are very few automated radio telemetry systems available that simultaneously monitor animal activity and location patterns. One of the first systems (ARU) was developed by Sparrows Systems of Fisher, Illinois, and is commercially available. A second-generation system (RMG) was recently developed by the University of Illinois through an ERDC-sponsored project, but is available only as a prototype. These systems differ in a number of ways as described below, but both automatically monitor an animal's direction from the receiving system, its movement patterns, and activity through information from radio signals emitted from standard radio transmitters that have been placed on animals. If multiple automated systems are used in concert, both the ARU and RMG are also able to provide detailed information on an animal's position through triangulation. Accuracy of a telemetry location is a function of the location of the animal relative to the receiver, the

location of the receiver, and the precision of the telemetry bearings (White and Garrott 1986, 1990). It is important to note that the error arcs that encompass the true bearing to an animal's position can show multiple possible locations for an animal (Figure A-5).

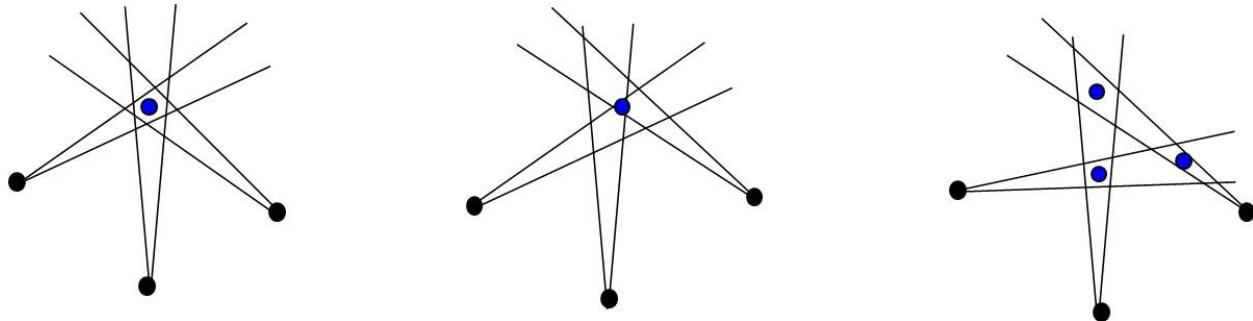


Figure A-5. Examples of the type of location error associated with radio telemetry bearings. Large error arcs can lead to multiple animal locations.
Adapted from Nams and Boutin 1991.

The basic approach of radio telemetry is to record and analyze the signal received from a radio transmitter mounted on a project animal. Because of the directional pattern of the transmitting antenna and because of variations in juxtaposition to its surroundings, any motion of the animal causes a change in the amplitude and polarization of the received signal; thus, a recording of the temporal variation of the received signal contains considerable information about the activity and location of the animal. Interpretation of these signals is amenable to automated analysis by computer algorithms.

Animal activity can be represented using a computer animated graphical user interface so individual activity patterns can be displayed. Activity data points can be represented as pixels on a user changeable graph (Figure A-6; Walde et al. 2003). It is important that the received signal from the transmitter is above the "noise floor" of the equipment and the surrounding noise environment so that the animal's activity signal can be clearly distinguished from the surrounding noise. When there is little to no activity by the animal the change in received signal is small and this is represented as a relatively flat line. When the animal is active there is a large amount of variability in the received signal and thus the plotted points appear scattered (Figure A-6). Data from multiple animals can be displayed on the same graph for visual comparison of animal activity over the

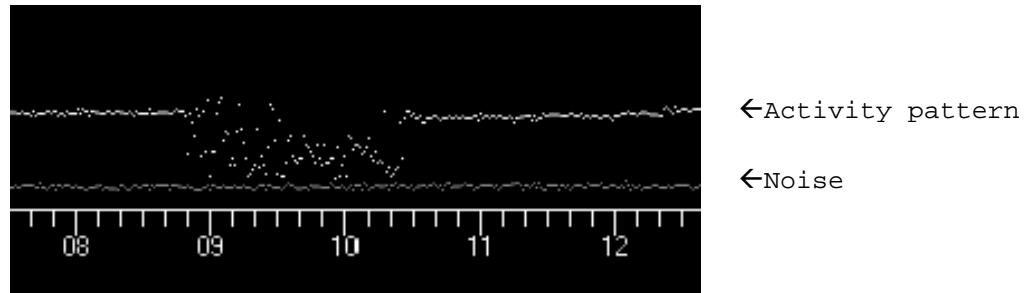


Figure A-6. Small sample of activity data is shown for a desert tortoise on Fort Irwin, CA (Walde et al. 2003). The gray line just above the time scale represents the background noise in the environment. The upper line white line represents the activity pattern of the tortoise, when the line is smooth the animal is inactive, when the pixels are scattered this represents activity of the animal. Based on this example, the tortoise was active from approximately 0850 to 1025.

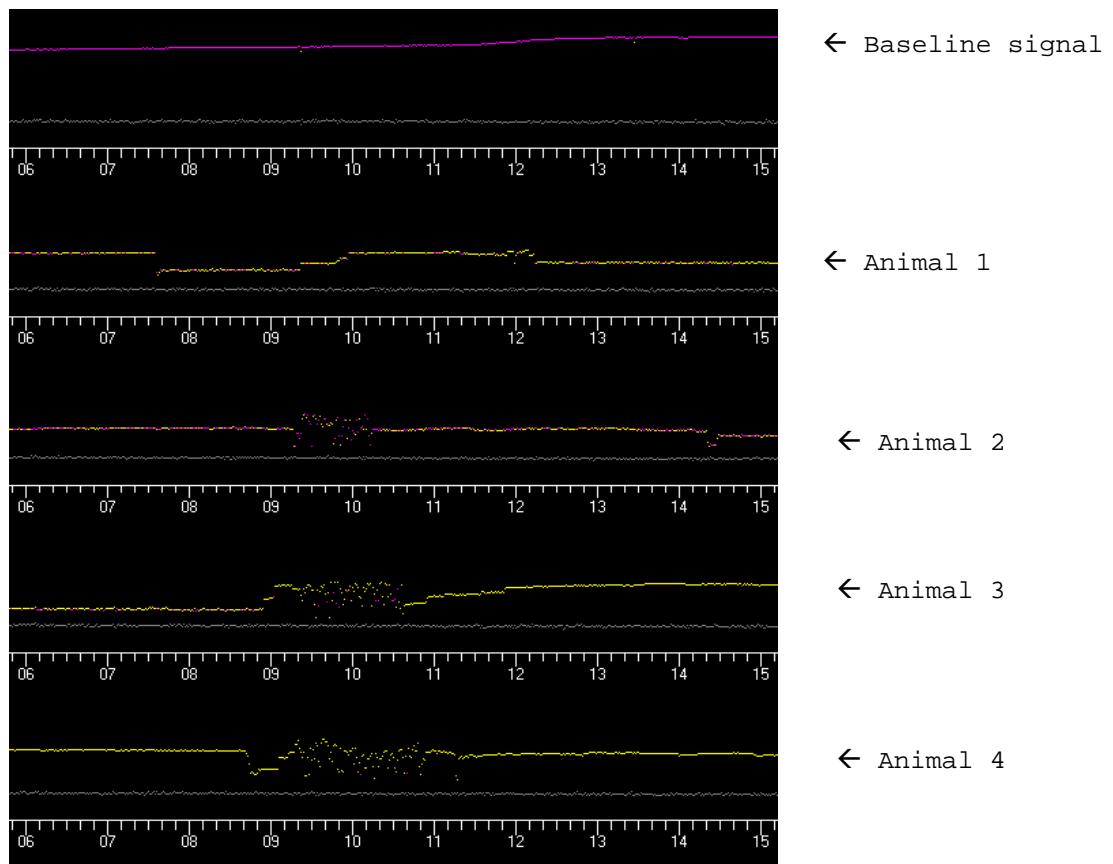


Figure A-7. Small sample of activity data for four tortoises and one stationary baseline transmitter placed on a wooden pole 1.5 m above the ground on Fort Irwin, CA (Walde et al. 2003). The line just above the time scale represents the background noise in the environment. The upper line represents the activity pattern of the animal, when the line is smooth the animal is inactive, when the pixels are scattered it means the animal is active.

same time period (Figure A-7). It is important to also record data from a stationary baseline transmitter within the same study area which is presumably under the same environmental conditions, to help distinguish true bouts of activity from erroneous data that can occur due to external sources (i.e., lightning storms). Baseline signals will transmit a steady flat pattern unless there is interference in the received signal. If there is any interference detected, the observer is then able to eliminate that portion of the data that was compromised from the dataset.

Multiple days of data for individual animals are also able to be displayed, which allows for trends in the activity patterns to emerge. Such "actograms" are helpful in understanding how animal activity can vary throughout the year, and can highlight important activity periods which may be difficult to identify using other techniques that do not collect as detailed an activity record for animals. A small sample of data is presented in Figure A-8 from a desert tortoise project on Fort Irwin, CA.

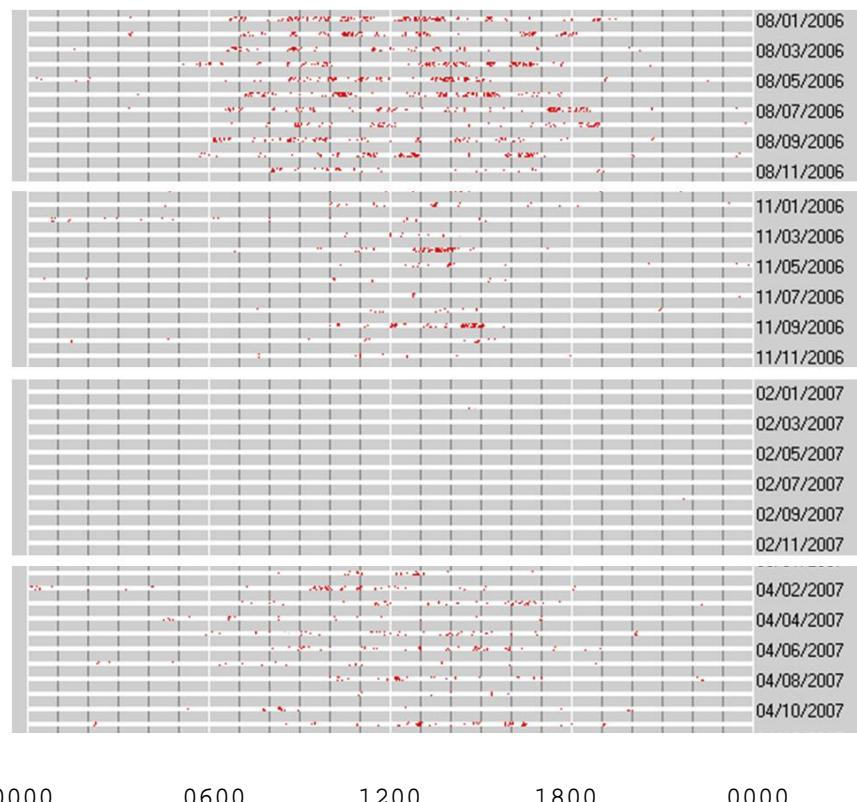


Figure A-8. An actogram illustrating the activity patterns of a desert tortoise during 4 different time periods throughout the year on Fort Irwin, CA (Walde et al. 2003). The white represents inactivity, while the red dots represent activity. The date is on the right margin and time along the bottom with noon at the center of the image.

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It is important that different radio telemetry systems/techniques be evaluated, demonstrated, and compared based on such factors as reliability, precision, and cost effectiveness for monitoring animal populations of concern on military lands. New technology/techniques are needed to monitor wildlife species through improved data acquisition capability and cost effectiveness compared with conventional techniques. The overall objective of this PWTB is to provide guidance on the use and effectiveness of automated radio telemetry systems for monitoring threatened, endangered, and at-risk species on military installations and Corps of Engineers facilities. The purpose of this report is not to recommend one technique or system over another, but to describe each system adequately so that readers are able to decide which, if any, of the systems/techniques described might best address their individual research goals.

Appendix B

STUDY AREA AND DATA COLLECTION METHODS

Study Area

This project was conducted on University of Illinois property at the Monticello Road Field Station in Champaign County, Illinois, from December 2010–March 2011. The site was an ideal test area due to its flat topography and lack of obstructions between the test transmitter (Figure B-1) and receiving towers (Figure B-2).



Figure B-1. A static position test is shown with the transmitter positioned at 45 degrees from vertical. The transmitter was ~389 m from the receiving towers seen in the background near the Monticello Road Field Station.

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Figure B-2. Monticello Road Field Station and two receiving towers (RMG tower on left and ARU tower on right) were used during testing; towers are approximately 10-m tall.

Methods

Automated Recording Unit

One Automated Recording Unit was used for testing purposes. This first generation automated radio tracking system is designed to track the locations, activity, and movement patterns of multiple radio-tagged animals semi-continuously, though location information can only be determined when 2 or more well spaced ARUs (preferably at least 3 units) are working in concert. Semi-continuous tracking is accomplished through an automated receiver that records radio signals from transmitters mounted on radio-tagged animals. The data are stored on memory modules that need to be periodically downloaded. The ARU utilizes multiple directional Yagi antennas pointed outward from a circle (Figure A-4 and Figure B-2). The receiver sequentially tunes between successive antennas and calculates a bearing once readings are received from all antennas. How quickly the receiver scans a frequency depends on the pulse rate of the transmitter (e.g.,

40-60 pulses per min), but typically it takes the receiver ~1.5-2 sec per antenna or ~9-12 sec for each animal frequency. The receiver must tune separately for each different transmitter frequency. Each animal transmits on a different frequency. The receivers record radio signals from animal transmitters as variations in signal amplitude.

Rapid Multi-Channel Goniometer

One Rapid Multi-Channel Goniometer was used for testing purposes. This second-generation automated radio tracking system is designed to track multiple animals like the ARU, but has incorporated some other components so it can simultaneously track multiple animals. Each RMG contains:

1. four dipole antennas (Figure B-2 and Figure B-3),
2. four software-defined, identical, very high-frequency receivers, and
3. a computer with a detection and direction-finding algorithm system.

This technology uses multiple receivers, coherent detection of the complex analytic signal, modern estimation algorithms, and modern software-defined receiver technology. Simple dipole antennas allow every antenna to receive each pulse and use all the information collected in the signal for bearing calculation. The RMG utilizes the mutual impedances of the four antennas



Figure B-3. This RMG antenna configuration was used during system testing at Monticello Road Field Station, Champaign, IL.

The use of a software-defined receiver increases the speed and flexibility of the RMG. Each receiver records a much larger band of frequencies at a time than conventional monitoring systems and can calculate the bearing instantly for each signal received in that band. Each antenna is connected to an independent receiver so signals are received simultaneously on every antenna as contrasted with the sequential tuning of the ARU system. By receiving multiple transmitted signals on every antenna at once, the speed of direction finding is increased by orders of magnitude. Both in-phase and quadrature signal components are used, increasing the information collected per pulse and thereby increasing the accuracy of the estimated bearing (Swenson et al. 2007).

Test Plan

Three different types of direction finding tests were conducted:

1. Driving test - vehicles were driven slowly (24-32 km/hr) along existing county roads that encircled the receiving site to test the performance of the ARU and RMG over different distances. Complete circuits around the field site were driven at distances of approximately 1.6, 3.2, and 4.8 km. Car top mounted antennas were used during the drive tests.
2. Walking tests - the transmitter was placed in a backpack in a vertically oriented position and was walked around the receiving towers at distances of 200 and 400 m from the receiving towers at a normal walking pace of approximately 3-4 km/hr in a counter-clockwise direction.
3. Static position tests - transmitters were placed with antennas in four different orientations (vertical; horizontal perpendicular; horizontal parallel; and at 45 degrees off both the horizontal and vertical plane), at different bearings (90, 135, 150, 180, 210, and 270 degrees) from the receiving towers, and over varying distances (400-1600 m) from receiving antenna towers.

Transmitters were attached at 1.5 m above ground to wooden poles driven into the ground for all static position tests. The test transmitter's frequency was 165.08 MHz and it pulsed every 0.2 seconds for approximately 15 milliseconds duration. All transmitters were run for a minimum of 1 min at all test locations. Transmitters were tested in different orientations to simulate different possible body positions by animals.

Appendix C

PROJECT RESULTS AND CONCLUSIONS

Results

Driving Tests

A vehicle outfitted with a transmitter was driven along county roads surrounding the Monticello Road Field Station to determine how well automated radio telemetry systems could detect transmitter signals across varying distances and signal strengths (Figure C-1). Both the ARU and RMG were able to detect transmitter signals from moving vehicles across a variety of distances, from a few meters to upwards of 5 km away from receiving towers (Figure C-2 and Figure C-3).

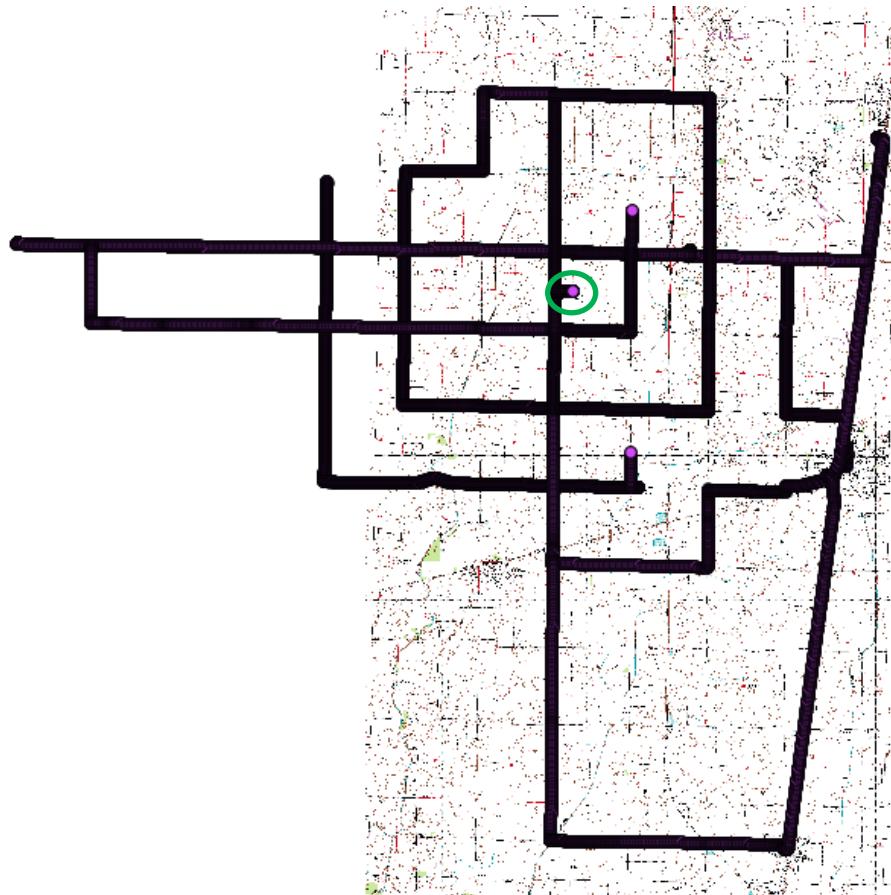


Figure C-1. Routes driven during driving tests on county roads surrounding the Monticello Road Field Station (circled in green) in Champaign County, IL.

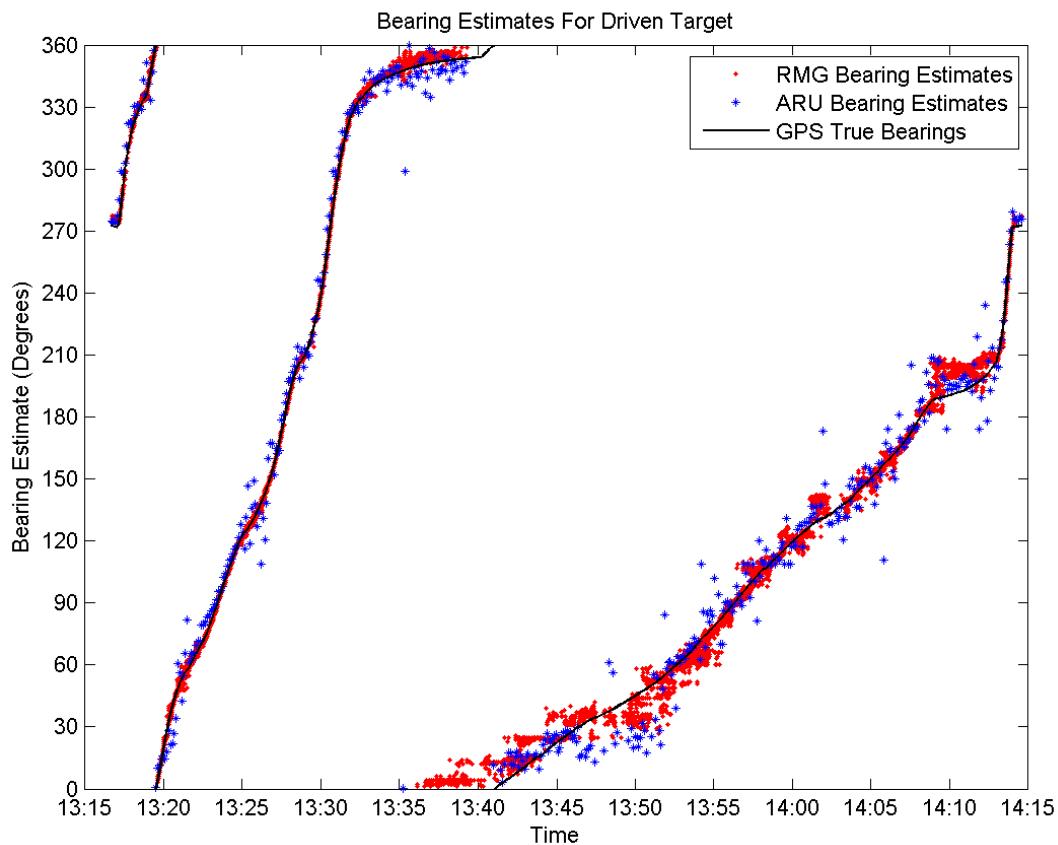


Figure C-2. Transmitter bearings from GPS locations and estimates obtained during a driving test near the Monticello Road Field Station, Champaign County, IL. Each red colored dot represents one pulse on which the RMG bearing estimate was based; each blue colored dot represents multiple pulses required by the ARU to estimate each bearing.

The RMG and ARU were more effective at detecting closer vehicles than farther vehicle distances according to how well their azimuths matched the true bearings from the GPS-determined routes (Figure C-2 and Figure C-3). Azimuth bearing estimates from the RMG, in particular, closely matched the true bearings at closer distances. Note that the RMG system collected substantially more data points over the same period of time compared with the ARU (Figure C-2). At farther distances (Figure C-3; i.e., timeframe of 13:35-14:13), bearing estimates from the ARU and RMG were similarly more variable around the true GPS bearings than the closer distance estimates (i.e., timeframe of 13:19-13:34; Figure C-2).

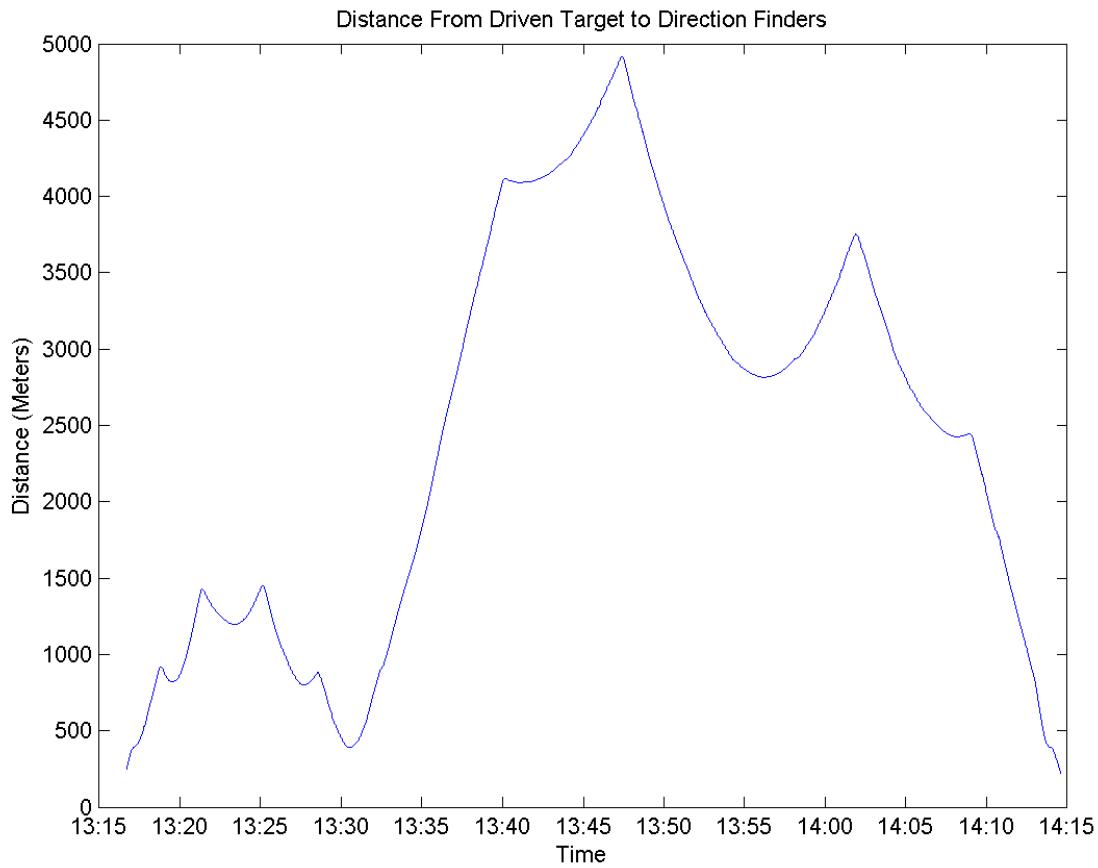


Figure C-3. Mobile transmitter distance from receiving tower systems are shown according to time of day (CST).

Walking Test

Field personnel walked in counter-clockwise circles around the Monticello Road Field Station at 200- and 400-m distances to determine how well automated tracking systems could track transmitter signals throughout the complete 360 degree detection area (Figure C-4) over closer distances. As was the case during the driving tests, the RMG recorded substantially more data points over the same period as the ARU (Figure C-5 and Figure C-6) during the 400-m walking test. Bearing estimates for the ARU and RMG accurately detected moving transmitters during walking tests. Both the ARU and RMG accurately detected transmitter signals throughout the 360-degree detection range and had similar levels of error compared with the true GPS bearings (Figure C-5 and Figure C-6).



Figure C-4. Walking paths taken to test ARU and RMG accuracy at 200- and 400-m distances are shown from receiving towers at the Monticello Road Field Station (shown with bright green dot surrounded by white circle), Champaign County, IL.

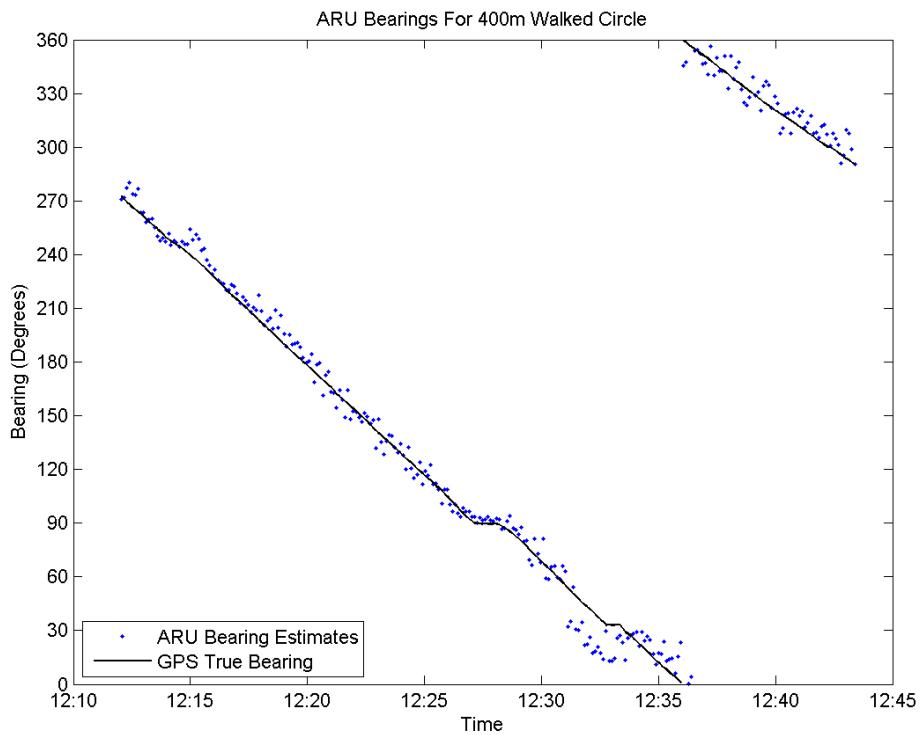


Figure C-5. Bearing estimates for the ARU versus true GPS bearings for the 400-m walking test, according to time.

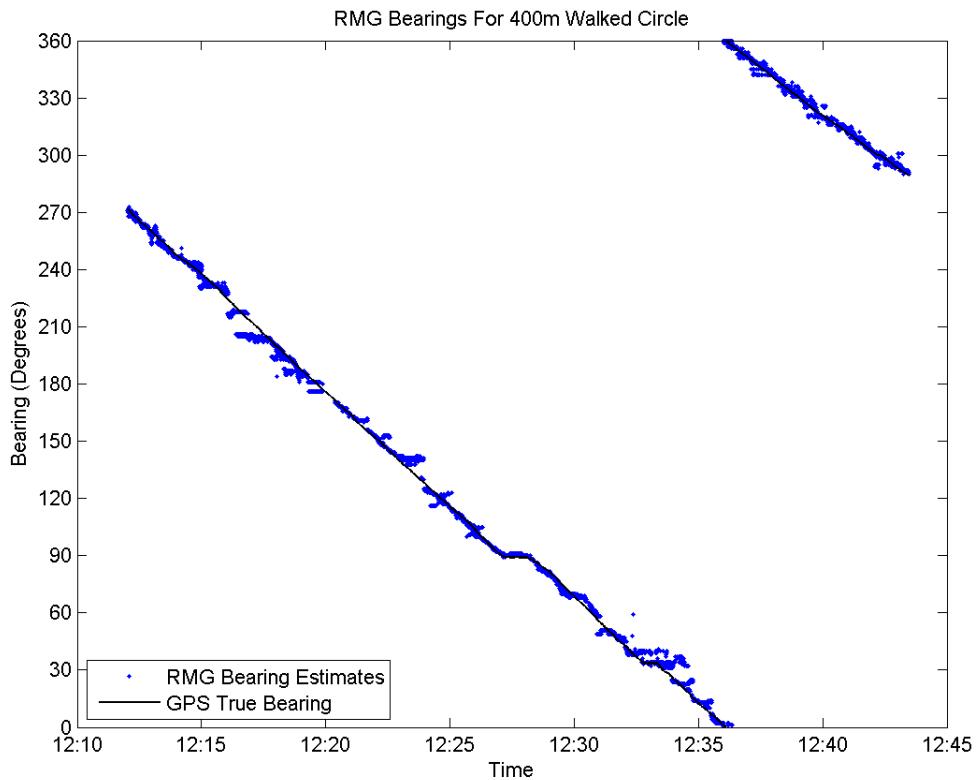


Figure C-6. Bearing estimates for the RMG versus true GPS bearings for 400-m walking test, according to time.

Static Position Tests

The ARU and RMG were tested during static position tests from a variety of distances using different transmitter orientations. Both the ARU and RMG accurately detected transmitter signals across the ~400-1600 m detection range for static position tests (Figure C-7 to Figure C-10). Bearing estimates from the ARU varied slightly (i.e., 1.05-1.90 degrees) from the true GPS bearings at ~400 m distances, while the RMG didn't vary, but was consistently off from the true GPS bearing by 0.9 degree (Figure C-8). A similar pattern was observed at the ~800 m static position test. The bearing estimate from the ARU varied from 1.0-3.0 degrees from the true GPS bearing, while the RMG was steadily off from the true bearing, but only by 1.2 degrees (Figure C-9). There was more variability in the bearing estimates for both the ARU and RMG at the ~1600-m station compared with closer tests. The ARU varied between 2.3-3.6 degrees, while the RMG varied 0.20-3.2 degrees from the true GPS

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Figure C-7. Locations of static transmitter test areas (green dots) are shown in proximity to the Monticello Road Field Station (circled in white), Champaign County, IL.

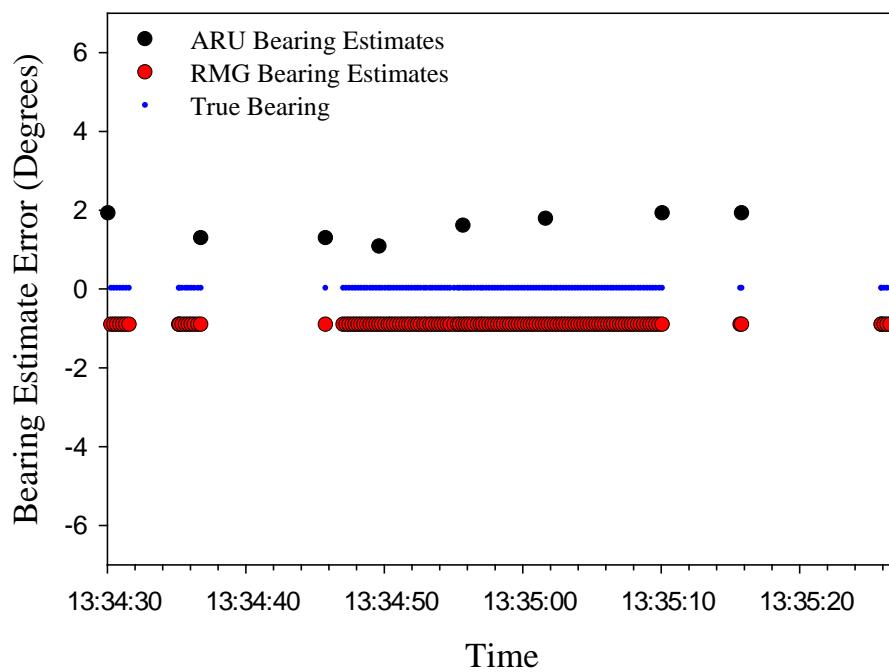


Figure C-8. Bearing estimate errors for ARU and RMG for static transmitter test (vertical on pole) ~396 m from receiving towers at the Monticello Road Field Station, Champaign County, IL, 2011.

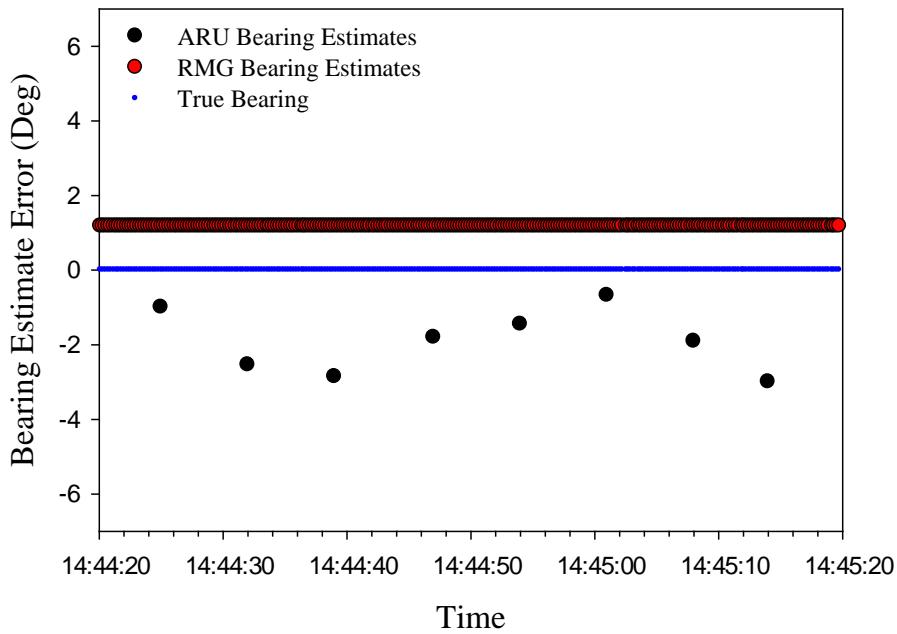


Figure C-9. Bearing estimate errors for ARU and RMG for static transmitter test (vertical on pole) ~803 m from receiving towers at Monticello Road Field Station, Champaign County, IL, 2011.

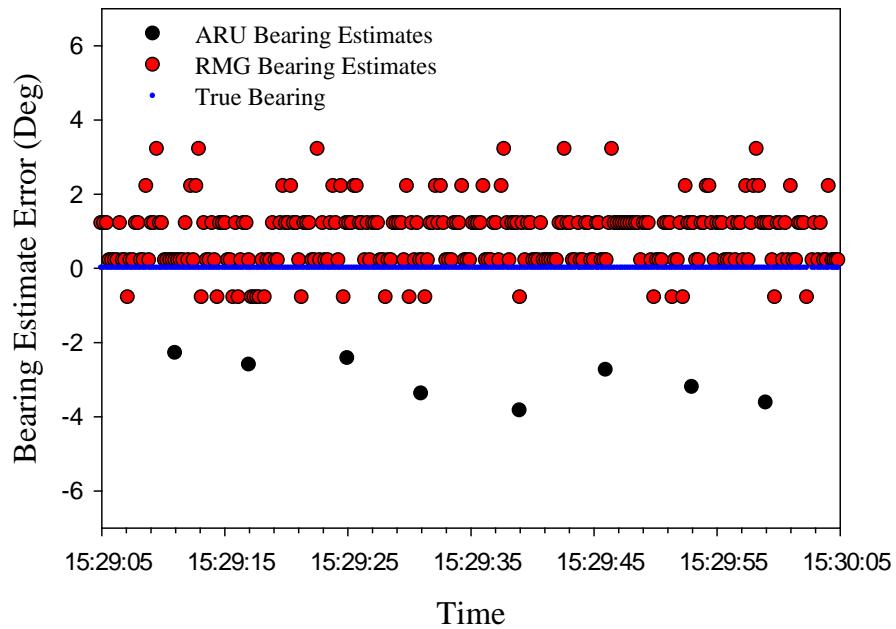


Figure C-10. Bearing estimate errors for ARU and RMG for static transmitter test (vertical on pole) ~1,596 m from receiving towers at Monticello Road Field Station, Champaign County, IL, 2011.

bearing (Figure C-10). The RMG results at the 1,600-m site were more variable than the ARU bearing estimates, but were closer to the true GPS bearings overall. As shown previously, the RMG consistently recorded substantially more data points than the ARU, regardless of testing regime.

System/Technique Comparisons

When considering which system/technique to use for animal tracking, it is important to consider cost. Table C-1 provides a gross scale hypothetical estimate on how much time, labor, and equipment costs it would take to continuously track 1 animal and a small population of 20 animals using hand-tracking methods compared with using the ARU or RMG. This gross-scale cost estimate assumes similar costs for all project costs other than labor and radio-tracking equipment costs. This cost estimate assumes three shifts of three personnel to hand-track animals 24 hr/day. Only one or two persons would be needed to automatically track animals once equipment was in place. Of course, it is unrealistic to track animal locations and activity patterns 24 hr/day without substantially influencing their behavior and losing track of animals during nocturnal hours, inclement weather, etc. For this exercise, however, it seems worthwhile to illustrate how unrealistic and expensive it would be to attempt to continuously hand track animals.

Table C-1. Gross scale cost comparison between Hand-Tracking, ARU, and RMG, based a theoretical example of continuously tracking a single animal and 20 animals for a year. Three automated telemetry systems of each type are included in this cost estimate.

Cost Input	Hand-Tracking 1 animal/ 20 animals	ARU 1 animal/ 20 animals	RMG 1 animal/ 20 animals
Number of Personnel	3/60	1/2	1/2
Labor hours	8.76K/175.2K	1.92K/3.84K	1.92K/3.84K
Labor and Tracking Equipment Costs	\$180.2K/\$3,540K	\$75K/\$115K	\$100K/\$140K

The two automated radio telemetry units tested during this project differ in a number of important ways (Table C-2). It is important for researchers to consider these variables when determining which system/technique is best suited for their specific project.

Table C-2. Comparison between conventional hand-tracking methods, currently available first-generation system (ARU), and new second-generation system prototype (RMG).

Monitoring Variables	Hand-Tracking	ARU	RMG
Observer effect	Variable, but can be substantial if distances too close	None/very limited	None/very limited
Direct observation	Yes	No	No
Impact of limited access (e.g., downrange of firing range)	Large effect	None/very limited	None/very limited
Impact on darkness/poor weather on tracking ability	Large effect	No effect	No effect
Number of simultaneous bearings recorded	1	1	Dozens
Freq. sensitivity range (simultaneous)	Very narrow	Narrow	Wide
Frequency tuning method	Manual	Sequential	Simultaneous
Time to record one azimuth	Up to a few minutes	~9-12 seconds	~1 second
Time to record multiple azimuths for multiple animals (e.g., 15)	Minutes to hours depending on distance between animals	3-5 minutes	1-2 seconds
Number of bearings per animal/day	Variable, ~1-12	Hundreds	Tens of thousands
Power consumption	Low	Low	High
Field testing to date	Extensive	Moderate	Low
Equipment cost/ Data reduction	Low	High	High
Equipment mobility	Very mobile	Limited mobility	Limited mobility

Conclusions

The purpose of this PWTB is not to recommend one technique or system over another, but to describe each technique/system adequately so that readers are able to decide which, if any, address their individual research question(s) the best. Each technique/system has its own benefits and limitations that need to be taken into account.

Small-scale, low-budget projects may best be served by using conventional hand-tracking techniques, due to low equipment costs, if adequate personnel are available to track the number of animals of interest. Hand tracking allows for very accurate location data through the ability to directly observe subject animals. As mentioned earlier, though, animal behavior can be substantially impacted by human presence, depending on the species of interest and the distance that an animal is tracked from. Not all hand tracking of animals needs to be done in close proximity to an animal's location, however. Teams of researchers can track multiple animals by sequentially monitoring different transmitter frequencies for short intervals and then moving on to other animals. Simultaneous tracking of multiple animal locations using hand tracking is possible, but requires large field teams, which can be expensive. If it is important to semi-continuously or continuously track the movement, activity, and location of an animal or group of animals, then automated telemetry systems provide a mechanism to do that which will not impact animal behavior, assuming correct attachment of the radio transmitter.

Based on the level of testing, both the ARU and RMG performed comparably well across all testing regimes. Where the RMG surpasses the ARU is in the number of data points collected over time and the ability to simultaneously track multiple animals. Bearing estimates for the RMG were also closer to the true bearings and were less variable than bearings for the ARU. These factors should allow the RMG to track larger animal populations and faster-moving animals more effectively and accurately than the ARU. Neither the ARU nor RMG are very mobile. This is an inherent limitation with stationary, automated tracking systems compared to hand tracking-, satellite-, or GPS-based systems. Multiple radio telemetry tracking systems can track multiple animals to provide animal location information if needed, but the error associated with the animal's true location will increase with increasing distance between the animal and the system receiver. It is important that receiving systems be placed in areas that provides the best long-term coverage of the animal population being monitored.

The power requirements of the RMG are a concern, and it is hoped that system engineers will be able to greatly reduce the amount of energy that this system requires to operate in remote field locations. Another related concern is the long-term functionality of the RMG compared with the ARU. The ARU has been field tested for many years under a variety of conditions (e.g., Walde et al. 2003; Kays et al. 2011). The RMG has not undergone

rigorous remote field testing. Regardless of the system being used, experience has shown the importance of having technically trained personnel for monitoring automated telemetry system operations (Kays et al. 2011).

A limitation of this project is that it only tested the automated telemetry systems under fairly ideal conditions (i.e., flat terrain, little or no vegetation, calm weather conditions, and low amounts of external noise interference). We acknowledge that forests environments and other habitats are difficult areas to deploy radio telemetry systems and can impact radio signal propagation. Based on discussions with the design engineers of the RMG system, we do not believe that vegetation will interfere with signal quality anymore than has been shown for the ARU (Kays et al. 2011), but additional testing needs to be done. Kays et al. (2011) extensively tested the effect of vegetation on signal transmission for the ARU (they termed their system that incorporated the ARU as "ARTS" for automated radio telemetry systems), in a tropical rainforest environment in Panama and within a temperate forest environment in Illinois, and concluded that vegetation only had a low-level impact, similar to their tests with hand tracking (Kays et al. 2011). It is important to note that Kays et al. (2011) used much taller towers, roughly 60 m tall, compared to the 10 m tall towers deployed in this study.

Another limitation is that we only recorded telemetry data from single ARU and RMG systems, and we did not record data from multiple systems simultaneously. We agree there needs to be detailed testing of multiple RMGs moving in concert to understand how topography and vegetation potentially influence signal propagation. The ARU has been field tested on multiple projects using multiple systems to determine detailed animal activity and location information (Walde et al. 2003; Kays et al. 2011). We did not have access to multiple RMG systems to compare multiple system tests between ARU and RMG systems. We acknowledge that more testing of the automated radio telemetry systems is needed to better understand how signal quality and signal acquisition is influenced by weather and terrain. We recommend that more real-world testing of automated radio telemetry systems be done. It is important that a variety of animals be field tested under varying field conditions and habitats/terrain, representing aerial and terrestrial species, under above-ground and below-ground periods of activity/inactivity.

Appendix D

BENEFITS OF TRACKING TECHNIQUES

Benefits of Rapid Multi-Channel Goniometers

The following is a list of some of the main benefits in using the RMG for tracking animal activity and location:

1. Little-to-no observer effect on animal behavior because animal activity and location information is recorded without human presence. The only time animal behavior could possibly be influenced is when personnel go in to check on equipment and download data files.
2. The RMG can be deployed for extended periods of time downrange of military training areas or remote field locations where access can be an issue.
3. The RMG is not limited by darkness or poor weather conditions in their ability to monitor animals.
4. The RMG is capable of recording tens of thousands of animal locations per day for multiple animals. Such large numbers of locations substantially improve the precision of animal location data when multiple systems are used in concert.
5. Based on the use of multiple receivers, RMGs are capable of recording dozens of simultaneous animal locations. This capability reduces location error and provides high-quality activity data, especially for fast-moving animals.
6. The RMG uses a simplified antenna array with only four antennas that are less expensive than Yagi antennas.
7. The RMG is able to use any commercially available radio transmitter. Other systems, such as satellite or GPS, are limited by which animals can be tracked because many animals cannot carry satellite or GPS transmitters due to weight restrictions.
8. The time to record one azimuth is ~1 sec. If multiple RMGs are used in concert, an animal's location can be triangulated using multiple azimuths simultaneously. The ability of the RMG to record simultaneous animal locations allows the RMG to record multiple azimuths from multiple animals in only 1-2 sec.
9. The RMG operates over a wide bandwidth using software-defined radio receivers. This enables simultaneous monitoring of all the frequency-diverse target transmitters, while effectively observing each transmitter in a narrow noise band.
10. The RMG uses both amplitude and phase for bearing calculations, which improves the overall accuracy of animal location data.

11. The RMG uses a modern bearing-estimation algorithm that outputs bearings of all animals simultaneously. The RMG also provides reliability estimates for each bearing.
12. The quality of RMG location and activity data is quite high due to both the very large quantity of data points being recorded and because data from all receivers is recorded simultaneously.
13. The location error associated with the RMG is greatly reduced compared with the ARU and hand-tracking at comparable distances due to the very large number of location estimates that are recorded.
14. Use of towers offers a more elevated and direct line of sight between the animal and the receiver. This improves the strength of the received signal and reduces the number of false readings (i.e., bounce).

Benefits of Automated Recording Unit

The following is a list of benefits from using the first-generation Automated Radio Telemetry Unit we tested:

1. As with the RMG, there is little-to-no observer effect on animal behavior because data are recorded without human presence. The only time animal behavior could realistically be influenced is when personnel go in to check on equipment and download data files.
2. The ARU can be deployed for extended periods of time in downrange or remote field locations where access can be an issue.
3. The ARU draws very low current and therefore require only low-amp/hour batteries and low-wattage solar panels for power, which reduces costs.
4. The ARU is not limited by darkness or poor weather conditions in their ability to monitor animals.
5. The ARU is capable of recording hundreds of animal locations per day over multiple animals when multiple systems are used.
6. The location error associated with this system is reduced compared with hand-tracking at comparable distances due to the relatively large number of location estimates that are recorded.
7. The ARU is able to use any commercially available radio transmitter. Other systems, such as satellite or GPS, are limited by which animals can be tracked because many animals cannot carry satellite or GPS transmitters due to weight restrictions.
8. The ARU has been extensively tested under a variety of field conditions and have been shown to be reliable.

9. Use of towers offers a more elevated and direct line of sight between the animal and the receiver. This improves the strength of the received signal and reduces the number of false readings (i.e., bounce).

Benefits of Using Hand-Tracking Techniques

The following is a list of the benefits in tracking animals using hand held receivers and Yagi antennas:

1. Hand-tracking techniques are not impacted by vegetation and terrain to the degree that fixed automated radio telemetry systems are. Researchers can move their position more readily to improve signal detection and actually physically locate animals to get very accurate location information.
2. The use of hand-tracking provides high quality animal location data. Researchers are able to directly locate animals and identify possible shelter locations, such as roosts, nests, burrows, dens, etc.
3. Allows researchers the ability to document and collect other types of life history data that is not possible without direct behavioral observation, such as social interactions, finding shelter locations, depredation events, etc.
4. Equipment costs for periodically hand-tracking a small number of animals are low and are substantially less than any other tracking systems/techniques.
5. Handheld receivers and Yagi antennas are able to use any commercially available radio transmitter. Other systems, such as satellite or GPS, are limited by which animals can be tracked because many animals cannot carry satellite or GPS receivers due to weight restrictions.

Appendix E

LIMITATIONS OR CAVEATS WITH USING TRACKING SYSTEMS

Rapid Multi-Channel Goniometers

The following are either limitations or issues to be aware of when using the RMG:

1. Because RMGs operate without human presence, direct observation of an animal's location or other detailed behavioral observations (e.g., social interactions, predator events, presence at burrows/shelters) is not possible. The RMG can of course be operated in concert with other techniques such as hand-tracking, which can allow for ground-truthing of automated data collection through direct observation. This direct observation can possibly influence animal behavior, however.
2. Start-up costs can be relatively expensive depending on the number of animals that need to be monitored and how wide ranging the animals of interest are, which in turn influences the number of systems that are needed and the amount of area that can be effectively covered by the receiving antenna towers.
3. Power requirements for the RMG are currently high. Systems require high amp/hour deep cycle batteries and large wattage solar panels to run remotely in the field.
4. The RMG has not been extensively field tested, so more testing would be necessary to prove that systems are able to effectively and reliably function for extended periods under a variety of field conditions.
5. The RMG is not very mobile. More mobile units can be used with shorter tower setups, but detection range would be impacted. Systems will need to be moved if animals leave the detection area.
6. Individual systems are able to record animal activity and the direction from the receiver to the animal's location. At least two, preferably three or more systems are needed to determine an animal's location remotely.

Automated Recording Units

The following are either limitations or issues to be aware of when using the first-generation ARU tested in this project:

1. As with the RMG, because the ARU operates without human presence, direct observation of an animal's location or other detailed behavioral observations (e.g., social interactions, predator events, presence at burrows/shelters) is not

possible. The ARU also operates in concert with other techniques such as hand tracking, which can allow for ground-truthing of automated data collection through direct observation. This direct observation can possibly influence animal behavior, however.

2. The receiver must tune separately for each different transmitter frequency, which reduces the number of bearings the system can collect for each transmitter. Retuning between different transmitters takes more time and requires complicated and expensive hardware in the receiver. It takes ~9-12 sec to get a fix on one animal's location (if using multiple systems in concert), or 2-3 min for 10 animal locations.
3. Each receiver can be tuned over only a fairly narrow frequency range (148-172 MHz).
4. The ARU can record a large number of animal locations per day compared with conventional hand-tracking techniques, but the number of locations still might be limited when monitoring fast-moving animals.
5. The ARU calculates bearing based on signal amplitude, which is effective and is the traditional method. However, the ARU cannot take advantage of newer estimation algorithms.
6. The ARU is not very mobile. More mobile units can be used with shorter tower setups, but detection range would be impacted.
7. The ARU is able to record animal activity and the direction from the receiver to the animal's location. At least two, preferably three or more systems are needed to determine an animal's location remotely.

Hand-Tracking Techniques

The following are either limitations or issues to be aware of when hand tracking animals:

1. The presence of an observer during animal tracking can have a substantial impact on animal behavior, depending on how close the observer is to the animal's position. Data collected using hand tracking may misrepresent the actual behavior that the animal was engaged in prior to any detection of the observer by the animal.
2. Variation in user experience and aptitude with telemetry equipment can greatly affect the amount of time necessary to locate an animal of interest, a fact which could influence an animal's behavior and subsequently increase the error associated with the true location of an animal.
3. Access issues to downrange areas or other remote areas on military installations can limit data collection.

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4. Periods of data collection are more limited by darkness and weather conditions than by the automated radio telemetry systems tested.
5. Hand tracking can be labor intensive and expensive when moderate-to-large populations of animals need to be tracked. One person can track multiple animals by sequentially monitoring multiple transmitter frequencies, but location error will likely increase due to increased time between tracking periods, especially for fast-moving animals. Multiple personnel can be used to track an individual animal, which will likely reduce location error, but this method can increase field costs and logistical considerations.

Appendix F

LESSONS LEARNED AND RECOMMENDATIONS

Lessons Learned

1. Automated radio telemetry systems become most cost effective when large populations of animals need to be tracked continuously/simultaneously over extended periods of time.
2. It is important when setting up receiving stations (receivers, towers, and antennas) that systems are calibrated often to make sure systems are providing accurate tracking information.
3. When attaching antennas to towers, it is helpful to line up one antenna boom in the N direction and to be consistent across all tower setups. This greatly expedites data reduction and analysis.
4. Polarization is an important issue that needs to be addressed when setting up receiving towers. Polarization describes the orientation of the electromagnetic field from an antenna. Antenna tines should be in a horizontal position to effectively track aerial and arboreal animals that are regularly above ground. Placing antenna tines in a vertical orientation most effectively tracks ground-based animals with transmitters.
5. It is important to understand that, while hand tracking may provide very accurate animal location information, human presence can substantially influence animal behavior and misrepresent animal location or behavior.
6. The accuracy and effective range of automated radio telemetry systems can vary depending on a number of external factors apart from the technology itself, namely:
 - a. species being tested;
 - b. pulse strength of the transmitter being monitored;
 - c. transmitting frequency spectra;
 - d. transmitting antenna configuration on the animal;
 - e. height of the receiving antennas;
 - f. position of the animal being tested relative to the location of the receiving antennas;
 - g. intervening vegetation/topography/structures,
 - h. soil composition;
 - i. weather conditions;
 - j. animal position [above or below ground or arboreal/aerial versus ground based];
 - k. transmitter height above ground
 - l. local radio noise; and
 - m. temperature/season/time of day.

All of these factors affect the external signal-to-noise ratio. All of the variables mentioned above will influence the actual effective range of telemetry systems to some degree, some variables more than others. Arboreal and aerial animals will have a longer effective range than ground-based animals due to more clear line of sight and lower ground interference.

7. The effective range of automated radio telemetry systems for ground-based animals is realistically on the order of hundreds of meters to kilometers, while signals from aerial species can range from kilometers to tens of kilometers depending on tower height and animal height above ground.

Recommendations

1. If project funding is limited and affordable field assistance is available, such as interns or students, hand tracking realistically provides the most cost-effective way to track individual animals or small animal populations on a periodic basis.
2. It is important that automated radio telemetry systems be more extensively field tested in complex environments where multipath issues more frequently occur and are more realistic for animal testing purposes. Multipath occurs when radio signals from transmitters take two or more paths due to obstructions or signal interference from objects in the environment (both natural and human made). Examples can include trees, rocks, topographic features (such as cliffs), and human structures such as power lines.
3. For the RMG to be effective for field use, engineers will have to reduce the energy draw substantially. Outfitting remote sites with large solar panels and deep-cycle batteries is not only expensive, but also can greatly limit data collection during times when solar availability is limited.
4. Radio transmitter placement should not impact an animal's ability to move, conduct daily activities, growth, or mating. Researchers sometimes do not take into account that the long antennas they leave trailing smaller animals can get lodged between rocks or vegetation.
5. It is important that size and weight of radio transmitters be strongly considered according to the subject animal species of interest.
6. It is important when placing transmitters on animals that their growth, mobility, and ability to mate are not impacted. It is also recommended that radio transmitters not exceed 3-5% of the animal's body weight.
7. When placing receiving towers on the landscape, it is important to take advantage of existing topographic features

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like hills, to enhance important line-of-sight between the receiver and the transmitter.

8. Receiving towers should be well spaced and equally distributed along the side or interior of the study area for the most complete coverage of the telemetry signals (see White 1985).

Appendix G

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Abbreviations

AR	Army Regulation
ARU	Automated Recording Unit
COE	Corps of Engineers
DoD	Department of Defense
GPS	Global Positioning System
HQUSACE	Headquarters, United States Army Corps of Engineers
MHz	megahertz
POC	point of contact
PWTB	Public Works Technical Bulletin
RMG	Rapid Multi-Channel Goniometer
RF	Radio Frequency

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