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A passive integrated transponder system for tracking animal movements

William I. Boarman, Michael L. Beigel, Glenn C. Goodlett, and Marc Sazaki

Abstract We describe an automated system that uses passive integrated transponder (PIT) tags to track movements of animals past specific locations. The system was designed to operate maintenance free for several months, be secure from vandalism and environmental damage, and record the identity, date, and time of passage of animals past a 2.4-m wide area. We used the system to monitor effectively the movements of 172 desert tortoises (*Gopherus agassizii*) through 2 storm drain culverts that pass beneath a state highway in the Mojave Desert, California. Four tortoises entered or passed through the culverts on 60 occasions. The system can be easily adapted to other species.

Key words desert tortoise, marking, movements, PIT tags, RF-ID, technology, Testudinidae, tracking

Knowledge of individual movements is fundamental to understanding behavioral ecology of species. We describe an automated system for tracking movements of individuals past specific locations, such as burrows, caves, and water holes. The system, developed primarily by AVID, Inc. and Beigel Technology Corp. (Norco, Calif.), used passive integrated transponder (PIT) tags. Passive integrated transponder tags are used to mark and identify individual animals (Camper and Dixon 1988, Prentice et al. 1990*a*). Passive integrated transponder tags have been used to census fish passing through specially equipped pipes (Prentice et al. 1990*b*). However, PIT technology has not been used widely to track movements of terrestrial animals. We refer to trade names to provide examples of equipment that works for our application. Use of trade names does not imply endorsement by the federal government.

Passive integrated transponder technology

Passive integrated transponder tags use radio frequency identification (RF-ID) technology (Ames 1990, Prentice et al. 1990*a*) and consist of 4 components: a microchip, an antenna, a chip-capacitor, and a housing, typically made of biocompatible glass. Glass tags are usually 2.1–3.85 mm in diameter and 11–32.5 mm in length. Tags also may be configured into a disk shape, typically 18 mm in diameter and 2 mm thick.

Passive integrated transponder tags lack an internal power source. They are energized on encountering

PIT tag (disk) on tortoise marginal.

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an electromagnetic (E-M) field emitted from a transceiver (reader) tuned to a specific frequency (usually 125, 134.2, or 400 KHz). The tag derives its power and timing signal from the reader's field. The tag's unique identity code (ID) is programmed into the microchip's nonvolatile memory. When energized, the PIT tag emits its ID by modulating the reader's E-M field. The reader detects and decodes the modulations and, thereby, reconstructs the tag's ID. To ensure accuracy, an error detection code is transmitted as part of the number sequence.

Most RF-ID readers used for animal studies are handheld units intended for manually scanning tagged animals. For unattended, fixed-point monitoring systems, the geometry of a reading coil must be appropriate to the application, the specific type of tag, velocity of the tag-bearing animal, and tag orientation and distance. The interaction between the reader's E-M field and the receiving-transmitting pattern of the tag coil determines the effective distance for a particular orientation of the tag to the fixed-point reader. The design challenge is to maximize the probability of reading tagged animals moving past the coil at random orientations and velocities. Each application requires consideration of animal morphology, method of locomotion, power consumption, and environmental characteristics.

Automated reading system (ARS) for desert tortoises

We used this system to study the effectiveness of a barrier fence for reducing mortality in the desert tortoise (*Gopherus agassizii*), a state- and federally listed threatened species, on highways in the western Mojave Desert, California (Boarman and Sazaki 1994). We predicted desert tortoises would use storm-drain culverts to cross beneath highways when barrier fences were erected to keep animals from crossing directly. We focused on movements through 2 1.6-m diameter x 66-m long, round, corrugated-metal culverts. Because we expected few tortoises to use the new culverts for the first several years of the project, we required a tracking system that would remain operational when unattended for long periods, require minimal maintenance, and have a low per capita cost over several years of the study. Because we were investigating tortoise movements past specific points, we could use a short-range detection system, such as PIT tags. However, we first had to overcome several automated reading system (ARS) design constraints to our application.

Power

The ARS units were in a relatively remote location and had to run maintenance free for ≥1 month. This required a renewable energy source that would function reliably during the approximately 8 months of the year (Mar–Oct) when tortoises were not hibernating. To accommodate cloudy periods of up to 7 days and seasonal changes in solar radiation, we chose a solar-rechargeable battery (Exide™ [Exide Corp., Bloomfield Hills, Mich.] 12 volt, vented, lead-acid, 18 amp-hr [Ah] at 10-hr rate). To enable recharging of the battery on a late autumn or early spring day with average sunlight, each ARS used either 4 0.5-amp photovoltaic (solar) panels (Edmund Scientific model 35,438 [Edmund Sci. Co., Barrington, N.J.]) or 1 2-amp unit (Siemens self-regulating model M-22 [Siemens Solar Industries, Camarillo, Calif.]). To reduce energy needs and because tortoises move slowly, we programmed the transceiver's duty cycle for 80 ms on and 100 ms off. We tested this duty cycle with captive tortoises, adjusting it to provide the minimum time and repetition interval required to read a tortoise passing the reading coil at maximum speed. Desert tortoises are largely diurnal; therefore, we also programmed the unit to turn on about 30 min before sunrise and off 30 min after sunset.

Length of reading coil

Entrances to the culverts were 1.6 m in diameter with a metal apron extending out to a length of 2.4 m and 2.4 m wide (Fig. 1). Because the reading coil had to be flush with the ground and the metal from the apron would alter the E-M field, thereby reducing the reading distance, we placed the reading coil at the distal edge of the apron. Thus, the reader had

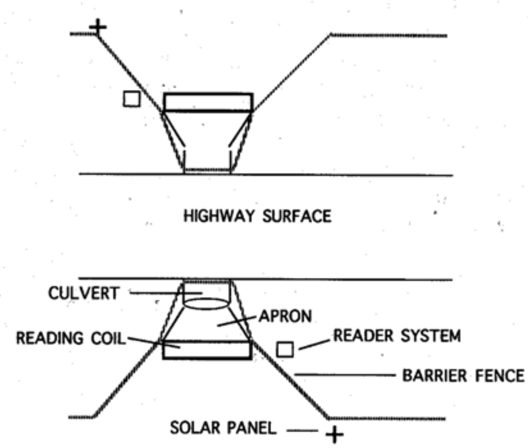

Fig. 1. Reading coils for detecting passage of desert tortoises bearing passive integrated transponder tags were placed at the distal ends of the aprons at each end of 2 storm drain culverts.

to cover an area 2.4-m wide. Because of short-distance limitations of the RF-ID technology, we designed the reading coil to cover the entire 2.4-m width.

Reading distance

A basic technological challenge was to ensure a PIT tag could be read from an optimal distance. An independent evaluation of commercially available PIT tags indicated the mean maximum reading distances for small PIT tags (10–14 mm) ranged from 26 (SD = 1) to 107 (SD = 4) mm using standard handheld readers (Anonymous 1991). To ensure that our largest tortoises would be detected when they crossed our reading coils, a reading distance of 75 mm over the entire 2.4-m length was required.

Also, reading distance was affected by the PIT tag's position relative to the reading coil's E-M field ($F = 48.48$; 1, 42 df; $P < 0.0001$; Table 1; see also Camper and Dixon 1988). Vertical placement (perpendicular to the axis of the coil) of the cylindrical tags and horizontal placement (parallel to the axis of the coil) of the disc tags, with respect to the ground, provided the best responses (for position x size interaction in 2-factor ANOVA: $F = 3.24$; 2, 42 df; $P = 0.049$; Table 1).

Burying the reading coil reduced reading distance because of absorption of the E-M field by minerals in the soil. To solve this problem we surrounded the reading coil with closed-cell foam. The reading coil dimensions were about 230 x 15 x 2.5 cm high. The surrounding structure was 240 x 46 x 13 cm.

Use of culverts

To determine travel direction and duration, 2 automated reading systems per culvert were deployed, 1 on each end (Fig. 1). The direction of motion was determined by comparing the calibrated time stamp of the reading at each culvert.

Security from environmental hazards

The electronic components of the ARS required special attention to prevent damage from environmental hazards. The primary hazards in the area were mild flash floods, high summer temperatures (often >40°C), and contamination by dirt and dust.

The reading coil housing was constructed like a surfboard, with coil and insulating foam covered by layers of fiberglass cloth and epoxy resin. A cavity was inlaid into the top of the structure to receive the reading coil. After placement of the reading coil, it was covered with an additional plate of fiberglass epoxy and sealed with silicone rubber to prevent water from leaking in.

The electronic equipment (reader board, battery, control panel, and datalogger) were enclosed in a locking, compression-molded, fiberglass box (Rose Enclosures Model 3040 [Rose Enclosures Sys., Inc., Frederick, Md.]) measuring 40 x 30 x 20 cm. To further protect the equipment from dirt when the box was opened for access, the box was placed in an irrigation-control box. The nested boxes were then placed in the ground, flush with the surface, to reduce damage from heat, theft, or vandalism (Fig. 2).

Security from human-caused hazards

The equipment was placed along a heavily traveled California State Highway (average daily traffic = 8,500 vehicles; Calif. Dep. of Trans. 1993), and our surveys of culverts for animal tracks revealed occasional use of culverts by people. Therefore, we had to protect all equipment from damage, vandalism, and theft. The surfboard technology used to make the reading coil housing provided sufficient strength. The top surface was finished with a fine coating of glue and desert soil taken from the location where the readers were installed. This camouflaged the unit and provided a rough surface, which kept a thin layer of loose soil on top of the structure.

To protect the reader and datalogger from theft and vandalism, we buried the system flush with the surface and covered the lid with 10–15 mm of loose soil (Fig. 2). Wires were buried out of sight and both boxes were locked.

The solar panels could not be hidden. The first one was placed on top of a steel fence

Table 1. Read distance of 3 types of passive integrated transponder (PIT) tags held horizontally and vertically with respect to the reader coil.

	Read distance (mm)					
	14-mm tag		18-mm cyl tag		18-mm disk tag	
Date of test	Hor	Vert	Hor	Vert	Hor	Vert
9 Apr 1994	15	98	30	150	180	140
10 Apr 1994	20	50	30	150	160	90
11 Apr 1994	15	50	50	140	190	150
12 Apr 1994	70	80	120	140	220	95
13 Apr 1994	40	75	105	115	190	90
15 Apr 1994	70	60	140	135	240	75
16 Apr 1994	50	70	100	130	220	160
17 Apr 1994	15	50	50	140	190	150
Mean	36.9	66.6	78.1	137.5	199.8	118.8
SE	8.55	6.15	15.23	4.01	9.15	12.13

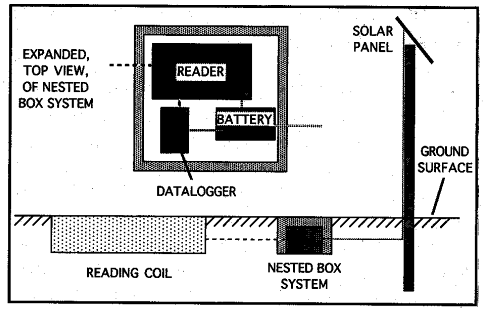

Fig. 2. Linkages between major components of the automated reading system used to detect and record identities of desert tortoises entering and exiting storm-drain culverts.

post (3 m high, 37 mm diam). It was stolen within 1 month. We placed the new ones on a 6.4-m high, 130-mm diameter, heavy gauge pole padlocked onto another pole that was sunk 1.5–2 m into concrete in the ground (Fig. 2). One such panel was stolen 9 months later. That one was replaced with an 8.4-m long pole of similar material sunk directly into concrete 2 m deep; no further losses have occurred.

Automated operation

Finally, the system had to require little maintenance and be able to operate unattended for several months. We used a Psion Organiser II (model LZ, [Psion Plc, Concord, Mass.]) datalogger with 3 ports: 1 for the reader, 1 to download data and upload instructions from a portable laptop computer, and 1 for a temperature probe, to be deployed later. The datalogger contained all instructions for automated operation (i.e., ON/OFF times, duty cycle, and other reader setup parameters). For each detection, the datalogger stored PIT tag number, time of day, date, and duration of time the tag was within the read zone of the coil. Multiple readings <30 seconds apart were treated as a single event. If a given tag was read more than once within 30 seconds, the reading "event timer" was reset and the duration was incremented for as long as the recurring reading took place. This prevented overloading of the datalogger's memory by repeated readings of the same tag and provided the "duration" for the animal at the reader.

A cable (0.75–1 m) connected the reading coil to the reader. The reader was linked to a datalogger and the battery. The battery was connected to the solar panel via a 2-conductor, 12-gauge, 30-m long wire enclosed in 12-mm diameter PVC conduit and buried 250 mm.

Application and discussion

We attached 14- x 2-mm cylindrical (AVID 2003), 18- x 3-mm cylindrical (AVID 2013), and 18- x 1-mm disk (AVID 2017) PIT tags (AVID Inc, Norco, Calif.) to the carapaces of 172 tortoises within approximately 3 km of 2 corrugated metal culverts 1.6-m diameter x 66-m long. Tag size depended on tortoise size. The 14- and 18-mm cylindrical tags were attached vertically to the pygal scutes of small tortoises and to the tenth or eleventh marginals of medium-sized tortoises, respectively. The 18-mm disk tags were attached horizontally to 1 of the marginal scutes of large tortoises. Devcon Five-Minute Epoxy® (ITW Devcon, Danvers, Pa.) was used to attach tags.

Installation of our system at 2 culverts was completed on 30 April 1995. Five tortoises (Nos. 24, 144, 192, 201, and 729) were recorded crossing readers on several occasions: No. 24, 27 times on 4 consecutive days in 1996; No. 144, 6 times on 2 days in 1995; No. 192, 9 times on 1 day in 1996; No. 201, 1 time in 1996; and No. 729, 29 times on 7 days in 1995, and 3 times on 2 days in 1996. Tracks, possibly of No. 729, based on timing and size of the tracks, were found crossing the same reader on 1 other day, but it was not detected by the reader. That animal, a large male (248-mm midline carapace length), had a 14-mm tag attached horizontally (the least effective combination of tag size and positions for effective detection distance). We saw no other tortoise tracks at the culverts while the readers were functioning.

The 1995 data from tortoise No. 729 exemplified the application of the ARS to assess use of culverts. Tortoise No. 729 was known to be on the south side of the highway on 15 August 1995. On 9 September 1995 it was recorded passing over the north reading coil of the first culvert at 1716 hours; the reader on the south side of the culvert had a blown fuse and was not working. The tortoise spent 25 minutes away from the reading coil, perhaps outside the culvert, then passed over it again, perhaps going into or through it for the night. The next morning it passed over the coil, probably exiting the culvert, at 0620 hours, and took 2 hours 57 minutes to arrive at the second culvert 460 m away. It took 7 hours 18 minutes to pass through to the south side of the 62.8-m long, 1.37-m diameter culvert. Nine minutes later it re-entered, spent the night inside, then exited the north end of the culvert at 0822 hours on 17 September 1995. After spending 1 night on the north side of the highway, it re-entered the first culvert at 1215 hours on 18 September 1995 and was next found south of the highway on 25 October 1995.

We made modifications to 4 new ARS units to improve performance. For example, 2 reading coils became wet when water leaked through a broken seal. In 4 new units deployed in spring 1996, we inserted the reading coil through the side of the housing, rather than the top. We also changed the type of seal and reduced its size. In the new units, we moved the reader module to a compartment inside the reading coil housing. This increased signal processing efficiency and reading distance by reducing noise signal pickup and reading coil detuning. Third, we replaced the vented lead acid batteries with sealed lead acid batteries (Panasonic® [Matsushita Electric Corp. of America, Secaucus, N.J.] No. LCL 12V20P 12 volt, 18 Ah at 10-hr rate). Finally, we found that reading distances vary by approximately 50% because reader tuning varies with temperature and perhaps moisture content of the soil. The new readers are self-tuning, which allows better tracking of environmental conditions without affecting reading distance.

The system is effective for monitoring movements of animals past specific points. It has been adapted for monitoring movements of Adelie penguins (*Pygoscelis adeliae*) in and out of a colony on Cape Bird, Antarctica (Peter Wilson, Landcare Res. New Zealand, pers. commun.). This system also measured the weight and direction of the penguins by incorporating an electronic scale and optoelectronic sensors into the reading fixture (see also Gendner et al. 1992). The ARS could be adapted for other applications, such as monitoring timing and use of snake hibernacula, timing and identity of visitors to nests of colonial nesting birds, and patterns of use of food or water sources. Other probes can be connected to correlate environmental and physiological parameters with specific behaviors, e.g., ambient temperature with burrow use. The initial cost of the reader ($1,250–$10,000) makes this unit a reasonable, cost-effective choice for studying large numbers of animals (i.e., >10), because, beyond the initial outlay for reading equipment, the cost per study animal is low ($5.00–$8.00 for PIT tags) compared to radiotransmitters or labor-intensive observation methods.

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Literature cited

AMES, R., editor. 1990. Perspectives on radio frequency identification (RF/ID): what is it, where is it going, should I be involved? Van Nostrand Reinhold, New York, New York.

ANONYMOUS. 1991. Final report on transponder system testing and product choice as a global standard for zoological specimens. Captive Breeding Species Group News 2:3–4.

BOARMAN, W. I., AND M. SAZAKI. 1994. Methods for measuring the effectiveness of tortoise-proof fences and culverts along Highway 58, California. Pages 284–291 *in* K. R. Beaman, editor. Proceedings of the 1987–1991 Desert Tortoise Council Symposium. Desert Tortoise Council, Palm Desert, California.

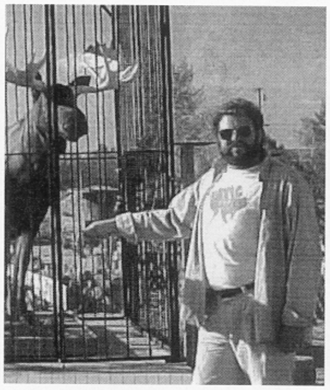
CALIFORNIA DEPARTMENT OF TRANSPORTATION. 1993. 1992 traffic volumes on the California state highway system. Department of Transportation, Division of Traffic Operations, Sacramento, California.

CAMPER, J. D., AND J. R. DIXON. 1988. Evaluation of a microchip marking system for amphibians and reptiles. Texas Parks and Wildlife Department Research Publication 7100-159.

GENDNER, J. P., J. GILES, E. CHALLET, V. VERDON, C. PLUMERE, X. REBOUD, Y. HANDRICH, AND Y. LE MAHO. 1992. Automatic weighing and identification of breeding king penguins. Pages 29–30 *in* I. G. Preide, and S. M. Swift, editors. Wildlife telemetry: remote monitoring and tracking of animals. Ellis Horwood, New York, New York.

PRENTICE, E. F., T. A. FLAGG, AND C. S. MCCLUTCHEON. 1990*a*. Feasibility of using implantable Passive Integrated Transponder (PIT) tags in salmonids. American Fisheries Society Symposium 7:317–322.

PRENTICE, E. F., T. A. FLAGG, C. S. MCCLUTCHEON, AND D. F. BRASTOW. 1990*b*. PIT-tag monitoring systems for hydroelectric dams and fish hatcheries. American Fisheries Society Symposium 7:323–334.



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