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# Success with GPS on Rosenberg's Monitor (*Varanus rosenbergi*) Using Modified Harness Design and Altered Monitoring Procedures

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*Abstract*.—**For herpetology to benefit fully from the current revolution in global positioning system (GPS) technology for wildlife, improved methods are required to attach GPS devices to reptiles for lengthy periods with minimal effect on their behavior or welfare. We developed a new harness design in stages during the course of a 5-y study on Rosenberg's Monitor (*Varanus rosenbergi*) by starting with a design used previously to attach radio transmitters and iteratively modifying the design based on observed deficiencies. The final design mounts the GPS on both sides of the tail, saddlebag style. This design has important animal welfare and research advantages over the dorsal attachments used in previous GPS studies on monitors. Side-of-tail placement was impossible when GPS were first used on a monitor (*Varanus*) species and has been made possible by the availability of improved wildlife GPS equipment. Our final design enabled us to ethically collect GPS data from the same individual monitors for long periods. The design has high potential for application to other lizard species. It was essential to frequently inspect harnesses and occasionally re-glue them due to unpredictable shedding of patches of scales in this species and its behavior of burrowing between rough granite rocks. To include females in the study, we required lighter GPS packs, and to inspect and reglue their harnesses, we needed field tactics that were more stealthy and more aggressive than for males.**

*Key Words.*—goanna; GPS attachment; GPS tracking; home range; lizard; movement; spatial ecology; Varanid

## Introduction

Wildlife GPS (Global Positioning System) receivers have transformed research on animal movements (Kays et al. 2015). A GPS-based paradigm shift (revolution?) is underway that is enabling researchers to study animal ecology, physiology, and behavior in ever-increasing detail (Williams et al. 2020; Wilson et al. 2020) based on a recognition that ecology is fundamentally spatial, with ecological processes occurring on heterogeneous landscapes (Cagnacci et al. 2010). Significant advances in GPS receiver technology were occurring at least annually until recently. As a result, GPS devices have been applied to progressively smaller species (Cagnacci et al. 2010; Tomkiewicz et al. 2010; Kays et al. 2015). An emerging understanding from GPS studies is that wide-ranging species move over areas that are orders of magnitude larger in scope than revealed by previous studies (Hebblewhite and Haydon 2010).

Simple neck collars enable GPS receivers to be fitted to many mammal species (e.g., Williams et al. 2014), and birds can be harnessed with lightweight solar-powered GPS (e.g., Kumar et al. 2020). Reptiles, however, have been under-represented in GPS studies due to challenges in safely attaching GPS equipment to them for extended periods and because of the small size of many species (Goldingay 2015). Improved methods to attach and retain GPS devices on reptiles are essential to answer important animal ecology questions, such as how energy budgets are managed and how behavioral decisions are influenced by the internal state of the animal, its physical environment, and the proximity of predators and conspecifics. These questions can be answered using GPS data with accompanying sensor data (Urbano et al. 2010; Williams et al. 2020). For monitor lizards, the GPS attachment method is critical to the success of tracking studies (Flesch et al. 2009).

We developed a new harness design suitable for attaching GPS devices to lizards during a 5-y study to characterize the home range and movements of Rosenberg's Monitor (*Varanus rosenbergi*) in part of the Australian Capital Territory (ACT). We altered the harness design in stages as we adapted to evidence of deficiencies. Together with modified field procedures, the final design enabled us to ethically collect GPS positions from the same individual animals for extended periods and to include the smallest adult monitors on the study site. This enabled us to include both sexes in our study after the third year. The final design and procedures resulted in substantial improvement to the quality and quantity of GPS data collected, mainly due to the increased time for which GPS equipment remained attached.

## Methods and Materials

***Study site***.—Our study site was the catchment of the Naas River downstream of the Boboyan Road crossing, within Namadgi National Park, Australian Capital Territory (Latitude -35.75, Longitude 149.08), an area of approximately 140 $km^2$. It is a forested valley trending south to north, with the Naas River descending from 1,100 m to 700 m elevation. The Booth Range and Clear Range form the catchment boundaries and vary from 1,200 m to 1,600 m elevation. The study area is characterized by steep slopes, in excess of 30 degrees in some areas, with much exposed rock and large boulders on the mid and upper slopes. We worked mainly along the 30 km Naas Valley Fire Trail, which parallels the Naas River down the middle of the site. We only occasionally visited the upper parts of the site. Monitors, however, were free to move anywhere, and our tracked animals occasionally took us outside the study site.

The rock that outcrops throughout the study site is Clear Range Granodiorite, which contains a high proportion of quartz (Abell 2008). When monitors moved beneath or between rocks and along burrows, quartz crystals rasped on the GPS packs, which resulted in some damage, including the breakage of several radio antennae. Hereafter the term GPS pack is used to refer to a GPS receiver and all associated electronic equipment (in our case a radio tracking beacon, a data transmission transceiver, and sensors for temperature and acceleration) as well as the harness used for attaching this equipment to the animal.

The vegetation has been comprehensively described (Baines et. al. 2013, https://actmapi-actgov.opendata.arcgis.com/datasets/ACTGOV::act-vegetation-map-2018/about). On most of the study site, the vegetation is open forest, most of which is dominated by Apple Box (*Eucalyptus bridgesiana*) and Broad-leaved Peppermint (*E. dives*). The river terraces are occupied by open woodland dominated by Yellow Box (*E. melliodora*). In the upstream third of the study site, open woodland is the main vegetation structure, comprised of Snow Gum (*E. pauciflora*) and Candlebark (*E. rubida*). Also in the upper valley are areas of river tussock grassland dominated by Snow Grass (*Poa labillardieri*) between patches of Black Sally (*E. stellulata*) and Snow Gum open woodland.

A bushfire burned through nearly all of the study site in February 2020 (near the end of the active season in 2019/20, hereafter Year 3). In most areas the fire intensity was severe. The bush fire defoliated the tree canopy and completely consumed many shrubs. It created large areas of bare ground. Massive sheet erosion occurred in a rainstorm that followed the fire, producing colluvial fans downslope, which filled gullies and in places, filled the river channel. Post-fire regrowth of grasses, forbs, and shrubs was so thick that by Year 5 it was difficult to see the ground surface, unlike pre-fire conditions. Austral Indigo (*Indigofera australis*) became the dominant shrub over large areas, where its stem density limited visibility and made quiet movement difficult (see below).

***Study species***.—Rosenberg's Monitor (Fig. 1) is smaller than any other monitor species previously studied using GPS. There have been six other GPS studies of monitor lizards: (1) on the Komodo Dragon (*V. komodoensis*; Ciofi et al. 2007); (2) on the Lace Monitor (*V. varius*; Flesch et al. 2009; Lei and Booth 2017); (3) on the Yellow-spotted Monitor (*V. panoptes*; Lei et al. 2017); (4) on the Perentie (*V. giganteus*; Cross et al. 2019); and (5) on the Asian Water Monitor *V. salvator*; Guerrero-Sanchez et al. 2022). Male Rosenberg's Monitors behaved differently to females. Males readily entered our cage traps and we often saw them basking in the open, especially on the Naas Valley Fire Trail. Females were hard to trap and basked under screening vegetation where we had greater difficulty seeing them or noosing them before they retreated into bolt holes (temporary refuges adopted in response to our approach) or burrows. Due to the density of ground layer vegetation in Year 5, females proved particularly elusive to catch that year.

Rosenberg's Monitors in our study site occupied three types of underground refuge. They occupied a winter burrow almost continuously for half the year. The other half of the year was the active season, October to

**Figure 1**. Rosenberg's Monitor (*Varanus rosenbergi*) excavating a nest chamber in a termitarium. (Photographed by Matthew Higgins).

March, during which they used any one of several night burrows daily. Bolt holes were the third type, which were distinguishable from burrows because monitors were unable to completely hide even when touched or when a flashlight was shone into the hole.

When we wanted to catch a particular monitor that was underground at the time, we were reluctant to dig into burrows but less concerned about bolt holes. If we started digging a bolt hole from the direction opposite the entrance, the monitor would usually emerge from the entrance, and we would capture it. We repaired most excavations, but in any case, alternative bolt holes appeared to be ubiquitous. Five burrows that we partly excavated were at least 3–7 m long and contained sharp bends and tight constrictions where stones of cobble to boulder size intruded. These burrows appeared to provide ample possibilities for a protruding GPS device, such as one attached dorsally, to prevent forward movement of the monitor while the device remained attached.

***Counteracting a sex bias*.—**All capture methods we tried produced more males than females. This appears to reflect greater boldness of males, mentioned above. Differences in boldness can reverse the relative susceptibility of lizards to different capture methods (Johnstone et al. 2021) but we did not find any capture method for Rosenberg's Monitors on our site that was not strongly male biased. In sandy soil on Kangaroo Island, Rosenberg's Monitors are readily caught in a way that is not sex biased, by following their tracks into burrows, which are typically only 0.75–1.0 m long and shallow (King and Green 1993; pers. obs.). These burrows can be excavated with little cost to either the researcher or the monitor; however, in our study site such tracking is not possible due to the hard, rocky soil. Also, burrows are significant constructions whose excavation could cost much time and energy for both researchers and monitors.

The bushfire at the end of Year 3 cleared the shrubby vegetation from large areas of the study site and enabled us to appreciate the extent to which termitaria of the Gluegun Termite (*Nasutitermes exitiosus*) were clustered at one end of the valley. Rosenberg's Monitors nest exclusively in these termitaria. By trapping more heavily in that area, and by trapping as early in the season as monitors began feeding, we began catching females.

***Prior consideration about GPS attachment options*.**—Telemetry devices for monitors and other squamates have previously been either of the following: implanted (e.g., for Merten's Water Monitor, *V. mertensii*, and the Mangrove Monitor, *V. indicus*: Smith and Griffiths 2009); harnessed with straps running around the limbs or body (e.g., for the Centralian and Common Blue-tongued Skinks, *Tiliqua multifasciata*, and *T. scincoides*; Price-Rees and Shine 2011); glued or taped directly to the scales (e.g., for the Perentie; Cross et al. 2019); or placed in a pouch that is glued to the scales (e.g., for the Lace Monitor; Flesch et al. 2009; Guarino 2002). Of these methods, the glued pouch appeared to have least disadvantages for our study species, as follows. Previous researchers have considered implantation to be unsuitable for GPS signal reception (e.g., Price-Rees and Shine 2011) although a protruding wire GPS antenna, similar to antennas on implanted Very High Frequency (VHF) radio transmitters, appears to have potential to overcome that problem to some degree (Quintin Kermeen, pers. comm.). The maximum size of an implanted device for our species, however, could not achieve the number of GPS fix attempts we required. Harnesses strapped around the body or limbs are liable to become entangled (Richmond 1998; Ussher 1999; Warner et al. 2006), which was a risk of particular concern regarding our burrow-dwelling species (see below). Direct gluing of devices as heavy as our GPS could apply considerable force to a small area of skin, especially if they were mounted on the side of the tail as we intended (see below), so the direct gluing method seemed likely to result in premature detachment of the GPS and would probably cause pain. Glued pouches provide a larger glued area for attachment than direct gluing and can conform well to the body shape of the lizard.

***Capture of monitors and attachment of GPS packs*.**—We captured monitors mainly using cage traps (90 × 30 × 30 cm; Sheffield Metal Fabrication, Perth, Western Australia, Australia) covered with shade cloth and baited with chicken that had been putrefied in moist conditions for two days. We set traps only during daytime in shaded locations 10–100 m from the fire trail and closed them 2–6 h later. If cold conditions developed unexpectedly, we closed traps early, otherwise normally docile animals were liable to damage themselves with extreme efforts to escape. We released the monitors where caught, generally on the same day, unless the air temperature was cooling rapidly in the late afternoon, when we released them on the following day. We captured tracked monitors when necessary, by noosing, by digging into a bolt hole, or by setting a cage trap outside a burrow.

On first capture, we implanted monitors with Passive Integrated Transponder (PIT) tags on the left flank anterior to the rear leg, fixed with tissue glue. Also, we photographed both sides of their head for future identification. We fitted monitors of suitable size (> 0.8 kg) with one of four models of GPS pack (Telemetry Solutions, Concord, California, USA). We used the largest of the four models that did not exceed 5% of body mass. In order of decreasing mass, including harness, the models were Q4000ER 17500 (82 g); Q4000ER 14250 (52 g); Nano Enhanced (48 g) or Nano (40 g). These GPS models all had sealed batteries; therefore, at the end of the active season, just before the monitors began occupying their winter burrows, we usually removed the GPS packs from the monitors and sent them to the manufacturer for battery replacement and renewal of radio antennas. If we expected to want the same animal again in the following season, we replaced the GPS pack with a small VHF radio transmitter mounted in a similar harness.

During the active season, we visited the site weekly to radio-track monitors and inspect them for shedding of scales in the vicinity of the GPS pack (except when the national park authority restricted access around the time of the bush fire in Year 3, and when flooding prevented access in Year 5). If a GPS pack appeared loose, we recaptured the monitor and re-glued the GPS pack; however, at times, packs were shed before we were able to re-glue them because the entire area of scales under the pack was shed at once, or inspections of some individuals were not frequent enough.

By responding to problems as they arose, we progressed through four harness designs (Fig. 2; Appendix). We began with a harness design used for attaching VHF radio transmitters or metabolic sensors to Gould's Monitor, the Lace Monitor, and our species (Green 1969; Thompson 1994; Guarino 2002). We retained four important features of this design throughout the study: (1) the equipment was positioned on the side of the tail just far enough behind the rear legs so as not to interfere significantly with movement; (2) a fabric tab extended forward along the dorsal surface above the pelvic girdle to increase the glued area; (3) the adhesive used to attach the GPS pack to the monitor was Selleys Kwik Grip Gel; and (4) potential wear points were coated with epoxy glue to increase abrasion resistance. We changed the design in four important ways: (1) we asked Telemetry Solutions to divide the equipment into two components with separate batteries and we placed one of them, the radio tracking beacon, on the opposite side of the tail to the GPS and other equipment (i.e., additional sensors and the transceiver used for downloading data); (2) we changed the fabric from denim to a lighter, stronger material used in the manufacture of backpacks; (3) we had nothing underneath the monitor; and (4) we developed a new double harness design with two parts (overlapping layers joined along the midline). What we called a glueing piece of fabric conformed exactly to the shape of the monitor and we sowed a pouch piece so as to hold the tracking equipment in two pouches. The double harness overcame the tendency in earlier designs for the shape of the pouches to lift the glued fabric away from the monitor. Finally, to maintain female monitors in the study for the duration of the active season, we changed our radio tracking and recapture protocol (Appendix).

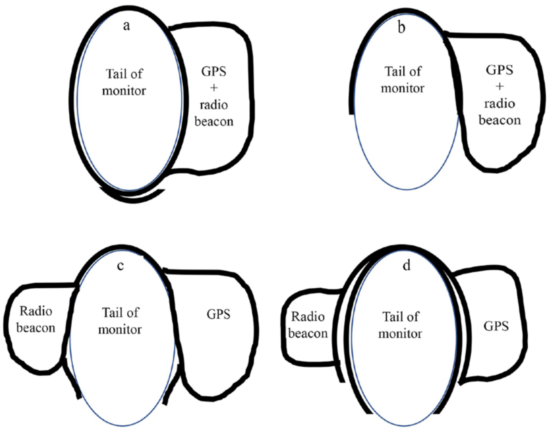


**Figure 2**. Cross-section view illustrating four GPS pack designs placed on Rosenberg's Monitor (*Varanus rosenbergi*) within Namadgi National Park, Australian Capital Territory, Australia. Designs a and b were used in Year 1. Design c was used in Years 2, 3 and 4. Design d was used in Year 5.

***Analysis***.—We categorized a GPS deployment as a failure if the tracking pack was shed in less than eight weeks (one third of an active season). We used the proportion of failed deployments in each field season as a performance measure and evaluated the change in performance over time using Linear Regression of square root-transformed proportions ($\alpha = 0.05$).

## Results

We captured 115 Rosenberg's Monitors (100 male, 15 female). Males had an average mass of 2.04 ± 0.05 (standard error) kg (n = 93) and an average snout-vent length (SVL) 50.0 ± 0.4 cm (n = 94). Females had an average mass of 1.10 ± 0.12 kg (n = 15) and average SVL of 42.0 ± 0.8 cm (n = 14). We made 59 attachments of GPS packs intended to collect movement data from a particular monitor for the remainder of an active season (Table 1). We replaced or re-glued, at least once, every GPS pack that remained attached to a monitor for the duration of an active season (half a year). Therefore, after Year 2, we came to regard re-gluing of GPS packs as a routine part of the study. We made 46 successful attachments. The annual proportion of failed attachments declined, but not significantly ($F_{1,3} = 5.55$, $P = 0.099$).

**Table 1**. Number and percentage of failed deployments by year of GPS packs placed on Rosenberg's Monitor (*Varanus rosenbergi*) within Namadgi National Park, Australian Capital Territory, Australia.

| | No. of deployments | No. of failures | Failure rate (%) |
|---|---|---|---|
| Year 1 | 3 | 1 | 33 |
| Year 2 | 14 | 6 | 43 |
| Year 3 | 15 | 2 | 13 |
| Year 4 | 17 | 4 | 24 |
| Year 5 | 10 | 0 | 0 |
| Overall | 59 | 13 | 22 |

In Years 4 and 5, we caught three times as many females proportionally as in Years 1–3 (15% of total captures compared to 5%), which enabled us to fit GPS packs to six females each year. Of the six attempted GPS pack deployments on females in Year 4, two failed and another was also shed prematurely, although after more than eight weeks. None lasted the full active season. Whereas we had managed to inspect all male GPS packs and had reglued them whenever necessary, in that year we had reglued none of the female GPS packs and there were some we never inspected. Too often, females had been inside bolt holes or night burrows by the time they were located in Year 4. In Year 5, when we used the new radio-tracking protocol and the fourth harness design, we re-glued all GPS packs at least once. For the first time, we experienced no failed deployments (Table 1). Only one GPS pack was shed before the end of season. This happened during a period of six weeks when high river flow prevented us from entering the study site.

We tracked 26 monitors for more than eight weeks, nine of them for two to four active seasons. We relocated the same individuals between field seasons, either by attaching VHF radio packs to them when their GPS packs were removed for the inactive season, by leaving the GPS pack in place all year, or by seeking them out at the commencement of the next active season. Thus, we refer to full deployment as the continual use of tracking packs (GPS packs in the active season and either VHF or GPS packs in the inactive season) on a particular individual monitor for one or more active seasons. We made 33 full deployments.

The mean mass of the 39 tracked monitors was 1.8 kg, which is close to the mean of the 115 monitors captured. We tracked them with GPS for a mean of 29.5 ± 4.52 weeks, excluding deployments categorized as having failed. The longest time that we tracked an individual continuously was 119 weeks (i.e., 2 y, 3 mo).

## Discussion

***Design criteria for GPS packs***.—For Year 2, we prepared a list of design and performance criteria for our GPS pack. The four most important elements were: (1) that the device would not protrude outside the cross-section silhouette of the monitor; (2) there would be no straps, or anything glued in front of either pair of legs; (3) it should mostly be possible for the monitor to pull free of the GPS pack, depending on how long since the animal had last shed its scales; and (4) the GPS packs would be colored to imitate the natural patterns of the monitor (Fig. 3). To determine home ranges and habitat use, we wanted GPS fixes to be attempted at least hourly from 0700 to 1900 daily for the entire active season (October to March). To minimize interference with natural behavior, we wanted to be able to download data at a distance without re-capturing the monitor. The VHF beacon was to operate for 2 y (well beyond the life of the GPS) and provide a signal strong enough for us to detect from several hundred meters distant when the device was inside a shallow burrow. These performance criteria had to be achieved without the equipment exceeding 5% of the mass of the lizard.

***Preferred position and design for GPS packs***.—Previous researchers attached GPS devices exclusively to the dorsal surface of monitors including for Komodo Dragons (Ciofi et al. 2007), Lace Monitors (Flesch et al. 2009; Lei and Booth 2017), Yellow-spotted Monitors (Lei et al. 2017), Perenties (Cross et al. 2019), and Asian Water Monitors (Guerrero-Sanchez et al. 2022). Researchers on other lizard species also commonly attach GPS devices to the dorsal surface, including ones of similar size to our species (e.g., Ariana-Sanchez 2022), medium size species (e.g., Leu et al. 2010; Price-Rees and Shine 2011), and smaller species, (e.g., Ryberg et al. 2019). In contrast, radio tracking transmitters and telemetry devices lighter than GPS, have long been mounted on the side of the tail (e.g., Green 1969; Weavers 1993; Thompson 1995; Guarino 2002), for monitors ranging from large size Komodo Dragons (Green et al. 1991) to small Spiny-tailed Monitors (*V. acanthurus*; Dryden et al. 1990). When the first GPS devices were used on monitors smaller than Komodo Dragons, such as the 240 g devices attached to Lace Monitors in 2008 by Flesch et al. (2009), their size meant that dorsal attachment was the only possible option. Later researchers had access to less massive devices but also placed them dorsally (Lei and Booth 2017; Lei et al. 2017; Cross et al. 2019; Guerrero-Sanchez et al. 2022). Our study has demonstrated that GPS equipment can be attached so that it does not protrude outside the cross-section silhouette of the monitor. This position has been made possible by the availability of lighter and smaller

**Figure 3**. Rosenberg's Monitors (*Varanus rosenbergi*) often rely on camouflage hence GPS packs (on tail) should be a similar color to the monitor, as seen here. (Photographed by Don Fletcher).

GPS devices (which are capable of collecting even greater volumes of data) and the potential to balance the weight across both sides of the tail, saddle pack style, as we did.

In our study, no monitor was killed or injured as a result of becoming trapped by its GPS pack. The burrows of Rosenberg's Monitor on our study site are several times longer and more complex in shape than the burrows used by either the Rosenberg's Monitors on Kangaroo Island (King and Green 1993; pers. obs.) or Perenties (King and Green 1993). Considering the number and dimensions of rocky bends and constrictions inside burrows that our monitors negotiate, our study appears to have provided a fair test of the ability of the design to allow the animals to undertake their normal behaviors and to minimize the risk of death due to entanglement. Many other Squamates pass through small spaces such as burrows, rock crevices, and hollow trees during their normal activities. Attachment of external devices to the side of the tail, near its base, appears to be a potentially advantageous option for such species.

Another consideration is streamlining the equipment for species that swim. Design criteria that we wrote to enable a monitor to pass through small holes and reduce its risk of entrapment are also relevant to swimming. Some Rosenberg's Monitors had home ranges that straddled the Naas River, which they frequently crossed. We saw one monitor swim through a white water rapid during a period of high river flow, where the design of GPS pack that enabled streamlined swimming performance may have helped it to avoid being dragged over a vertical drop. Both the division of the GPS tracking equipment into two parts mounted on opposite sides of the tail (introduced in Year Two) and the separation of the harness into a gluing part and a pouch part (introduced in Year Five), also appeared to be superior as soon as they were placed onto a monitor, and both seemed to result in more secure attachments.

***Shedding of glued GPS packs***.—Lizards shed glued GPS packs with their scales (Flesch et al. 2009; Price-Rees and Shine 2011) or by scraping them against rocks. Also, conspecifics may dislodge GPS packs (Cross et al. 2019). Price-Rees and Shine (2011) reported that even straps around the body did not prevent harnesses being shed with the scales and suggested that such losses should be regarded as inevitable. Shedding is somewhat predictable in many reptile species, enabling the GPS pack to be maintained on the same individuals (Price-Rees and Shine 2011); however, our Rosenberg's Monitors shed patches of scales throughout the active season unpredictably, like the Lace Monitors studied by Flesch et al. (2009) and Pascoe et al. (2019). Mostly we were unable to replace a detached GPS pack back on the same animal during the same season. Detachment of the GPS pack is a major advantage when it enables the animal to escape potentially fatal entanglement, but it is a significant setback at other times. That is because premature detachment can result in data being discarded at the analysis stage from the affected individuals, at least for that year. Having to disregard some of the instrumented animals due to insufficient data can substantially reduce the sample size of the study and is distressingly common. For example, Flesch et al. (2009) and Pascoe et al. (2019) discarded data from five of 14 Lace Monitors (36%) because their GPS packs detached in < 35 d and likewise, Guerrero-Sanchez et al. (2022) excluded six of 20 Asian Water Monitors (30%) from their study, due to having recorded insufficient locations for home range area to stabilize, which was defined as < 30 d or < 150 fixes.

Following premature detachment, researchers commonly transfer GPS packs to other individual animals, as we did, but data from the two animals can not readily be combined, and there is a risk that any singular events (events not repeated within a season) such as nesting behavior or breeding migrations, will be under- or over-represented by the study if the changeover occurs at around the timing of the event. Thus, it is strongly preferable, or arguably essential for some kinds of analysis (e.g., home range analysis), to reglue GPS packs at the point of shedding, and so maintain the flow of data from the same individuals. Our introduction in Year 5 of a specific radio tracking and capture protocol for the females (Appendix), was necessary to improve our performance in maintaining GPS packs on the same individual females for the full season.

***Duration of studies***.—Home range studies should last long enough to include all seasonal movements. The obvious answer is to track the same individuals for at least a year. No GPS studies have run as long, although four studies using radio transmitters on large monitors achieved this, or nearly so (for Mangrove Monitors and Merten's Water Monitors, 2 y using implanted radio transmitters; Smith and Griffiths 2009), for Rock Monitors, *V. albigularis*, 14 mo (Phillips 1995), and for Lace Monitors, 11 mo (Guarino 2002) and 9 mo (Weavers 1993). A benchmark of half a year (26 weeks) is often more appropriate because the activity of many monitor species occurs in one half of the year (Pianka 1994; Guarino 2002; Smith and Griffiths 2009) and GPS tracking may be harder to justify when the animals are almost immobile. Only two published GPS studies of monitors exceeded 20 weeks (Jessop et al. 2018; Guerrero-Sanchez et al. 2022), however, making our study the first GPS study of monitors to achieve the half-year benchmark.

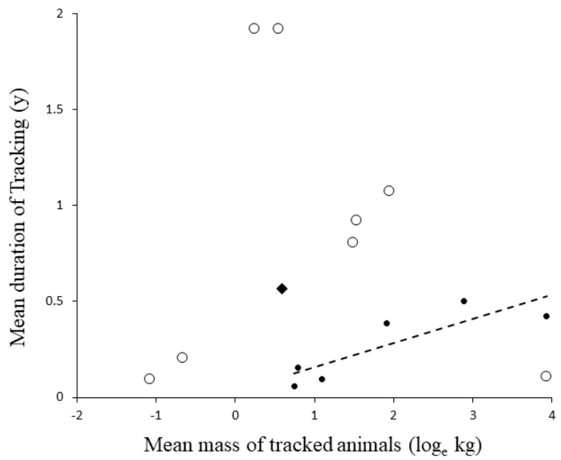


**Figure 4**. Relationship between mean body mass of monitors tracked in published studies (listed in text) and duration of tracking (years). Open circles = published radio tracking studies; filled circles and dashed regression = published GPS studies; diamond = this GPS study.

The mass and size of GPS equipment continue to constrain the application of GPS technology to monitors, including by limiting the length of studies, i.e., the relationship between log$_e$ body mass and study duration is significant ($r^2$ = 0.750, $F_{1,4}$ = 11.99, $P$ = 0.026). Because radio tracking studies use devices of lower mass, the relationship does not apply ($r^2$ = 0.005, $F_{1,6}$ = 0.030, $P$ = 0.807), which is the preferred situation (Fig. 4). In future, researchers are likely to track Varanids and other large lizards with GPS for longer periods, as has been achieved with radio tracking, and to track smaller species, so the relationship between animal size and GPS study duration should disappear. Our study is an example of progress in both ways, by tracking smaller animals and for longer duration (Fig. 4). The improvement is due to lighter GPS units, improved harness design, and regluing of harnesses (Appendix Figure).

Application of GPS to smaller species of lizards or for longer periods will progress faster if battery replacement or recharging is more widely adopted. Our sequential replacement of GPS devices on the female monitors enabled us to track them through the active season with sufficient fixes per day. Use of rechargeable batteries is an alternative that enabled Ryberg et al. (2019) to use GPS packs of 2.1 g to track 14 Reticulate Collared Lizards (*Crotaphytus reticulatus*) of mean mass of 61 g for 3 y, recording four GPS fixes per day by holding each lizard for a 4 h recharge every 12 d. All such methods depend on recapture of the tracked animals, however, which in our case took several years of field observations to achieve efficiently (Appendix).

***Future developments***.—Technological advances that reduce the size and weight of batteries in GPS devices, may in future lead to implantable GPS devices for monitors (either with sensitive GPS patch aerials that work from inside the body cavity, or with protruding wire antennae for GPS and radio). Implanted devices should raise little concern about animals passing through narrow spaces or streamlining of aquatic species. In the interim, development of improved ways to fit GPS packs to reptiles should be encouraged to enable more insights into aspects of movement behavior including foraging, territoriality, energy conservation and both intra- and inter-specific interactions.

Models of GPS equipment currently available are capable of recording data of a type that meets requirements for a wide range of ecological investigations, as well as home range analysis (see Williams et al. 2020 for examples). For example, our male-size GPS pack, weighing 82 g, was set to attempt a GPS fix every 30 min during daylight and to record temperature and acceleration every 15 min, for almost 6 mo. Reliable insights to the behavior and ecology of Squamates are possible whenever ways can be found to ethically maintain GPS accompanied by other sensors on these species.

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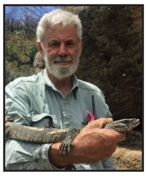

**Don B. Fletcher** received his Ph.D. in 2006 at the University of Canberra, Bruce, Canberra, Australian Capital Territory, for research on the population dynamics of Eastern Grey Kangaroos (*Macropus giganteus*), then worked as a Senior Ecologist for the Australian Capital Territory government on threatened species and pest species including the Eastern Bettong (*Bettongia gaimardi*), Eastern Quoll (*Dasyurus viverrens*), Little Eagle (*Heirateus morphnoides*), and Feral Pig (*Sus scrofa*). He was awarded the Australian Public Service Medal before retiring in 2016. He now leads a citizen science project researching Rosenberg's Goanna. (Photographed by Chloe Ives).

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## Appendix: Development of the Harness Design

***Pilot study and first two harness designs***.—In a pilot study in Year 1, we used two typical GPS devices that included batteries, a GPS, a radio tracking transmitter and a radio transceiver used for downloading data, all enclosed together in a matrix of epoxy cement. To attach each device to an adult male monitor, we made a harness similar to that used for attaching VHF radio transmitters or metabolic sensors to Gould's Monitor, the Lace Monitor, and our species (Green 1969; Thompson 1994; Guarino 2002). That is, we positioned the GPS device on one side of the tail in a denim pouch. To increase the glued area, a denim tab extended forward along the dorsal surface above the pelvic girdle. The adhesive was Selleys Kwik Grip Gel, as used by previous researchers (Green 1969; Thompson 1994, 1995; Guarino 2002; Flesch et al. 2009). We fastened the denim harness underneath the tail of the lizard with hook and loop tape (Fig. 2).

Both harnesses were abraded and torn by the granite and failed in three weeks. We found one still attached to the monitor by a few threads. We replaced it with a new harness. Therefore, that deployment was not classed as a failure according to the definition given below but only by a narrow margin. We transferred the other GPS to a new lizard after we failed to capture the original lizard for two weeks. We made replacement harnesses (Fig. 2) without hook and loop closures or anything passing underneath the monitor. We increased the abrasion resistance of the denim by applying epoxy glue thickly on potential wear points. After 11 weeks, at the end of the active season, we removed both of these GPS packs, each having required regluing at least once in that time.

***Saddlebag harness design***.—After Year 1, we asked the manufacturer to provide the GPS units in two parts. We positioned the VHF radio beacon and its battery on the side of the tail opposite the GPS and its battery (Fig. 2). The Ultra High Frequency (UHF) radio transceiver for downloading GPS data was included with the GPS unit, therefore there was a wire radio antenna on each side of the tail. On first attachment, the improvement was immediately obvious, with apparently less strain on the glue and the skin of the monitor due to the improved balance.

Also, we replaced the denim fabric with a stronger and lighter cotton-faced nylon fabric used for making backpacks, which had water-repellent and UV-resistant properties (fabric D41; Mont Adventure Equipment, Canberra, Australian Capital Territory). We used a triple stitch to reduce the potential for stitches to pull out. We placed the softer side of the fabric to the inside where it would be glued. We added fabric tabs to each equipment pouch to increase the glued area on the sides of the tail (Fig. 2). The total mass of the resulting Saddlebag GPS Pack was 82 g.

To adequately receive GPS signals, the GPS patch antenna that is hidden inside the epoxy coating must face upward. To maintain the skyward orientation for this antenna (i.e., to prevent rotation of the GPS unit within the cloth pouch), we fixed the wire antenna of the accompanying UHF radio in place using the pouch closure stitching and drops of epoxy glue. Initially, we angled the pouches so as to tilt the wire aerials higher from the ground.

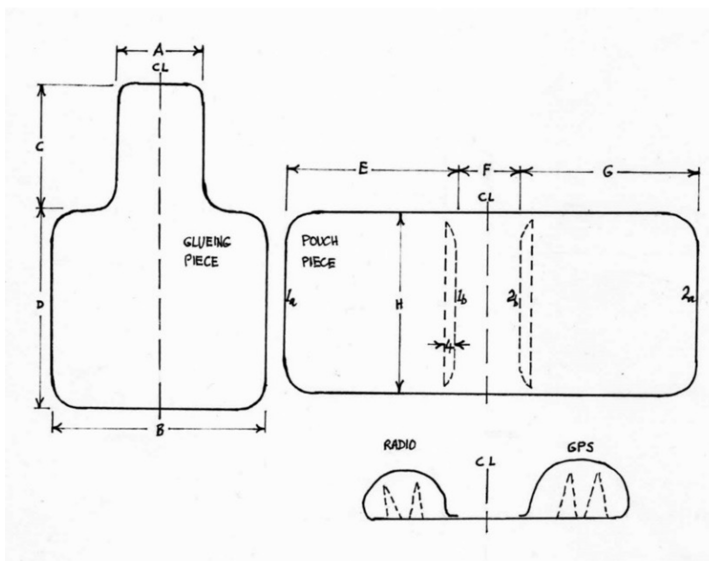
Immediately after we started using the third harness design (Fig. 2), the first few harnesses were quickly dislodged. Our measure of how well a shed harness had been glued was the proportion of glued area with scales attached. Thus, we diagnosed a fault in our gluing method as the problem, rather than the new harness. We learned to disregard the directions on the glue container to allow the glue to become tacky on both surfaces before joining them. It worked better to apply a thick layer of glue and bring the surfaces into contact immediately to be able to remove air bubbles as much as possible while the glue was still liquid. Thereafter, the third harness design served us adequately from Year 2 to Year 4.

In Year 3, we began catching females and so were able to fit GPS packs to four females heavier than 1.05 kg; however, all four GPS packs were quickly detached. On this occasion we diagnosed a flaw in the harness design. The tilted GPS and radio devices had resulted in the glued fabric being pulled away from the skin of monitor when the GPS packs were applied to the smaller tail radius of the females. We were unable to use this knowledge until the following year because we did not capture or see any more female monitors until then.

For Year 4, we altered the harnesses to hold the devices parallel with the tail, and we accepted that the VHF and UHF radio antennas would make greater contact with the ground. We did the same to the male GPS packs. The GPS tracking of males proved uneventful, however, despite fitting six females with GPS packs early in the active season, we still failed to obtain home range data covering the active season from all but one of them. The failure this time occurred because we only managed to inspect the harness and reglue it on one female, due to the greater wariness of females.

***Fourth harness design and changed field procedure***.—For Year 5 we made three changes. First, we developed a new double harness design (Fig. 2) that involved a separate piece of fabric for gluing, apart from the material used to make the pouches. We sewed the two pieces together along a central line above the vertebrae of the monitor. Our intention was that the entire area of the glued piece could conform exactly to the shape of the monitor, removing the tendency for the shape of the pouches to lift the glued fabric away from the monitor. The fourth harness design (Fig. 1) was markedly easier to make than its predecessors. Instructions for making it are given as a sewing pattern (Appendix Figure, Appendix Table).

Second, with additional funding, we obtained two GPS packs per female, so a second pack could be attached when the battery of the first pack was depleted. This enabled us to cover the entire active season while collecting 13 fixes per day. Third, we introduced a new radio tracking protocol that required us to be more stealthy and more aggressive to respond to the greater wariness and more cryptic behavior of female monitors. The new protocol required us to have two people to track the same female monitor simultaneously to more quickly determine its exact position in a vegetated area by cross bearings before it responded to our presence. If four weeks had elapsed since its harness was last inspected, we resolved to dig the monitor out of a bolt hole (temporary refuges adopted in response to our approach) if necessary to inspect its GPS pack.




**Appendix Figure**. Diagram of harness design for Rosenberg's Monitor (*Varanus rosenbergi*). Instructions: (1) Sew edge 1a to 1b and 2a to 2b; (2) Sew anterior ends of both pouches closed, placing tucks (dotted triangles) by eye so inner side of pouch sits flat; (3) Sew center line (CL) of pouch piece onto center line of gluing piece with four rows of triple stitch, reinforced at the anterior edge; (5) Insert telemetry equipment, marking the pouches where the magnet should be applied to switch the device on or off; (6) Sew the rear ends of the pouches closed, securing the wire aerials so as to prevent rotation of the devices inside the pouches. Paint the outside of the GPS pack to match the monitor. Apply epoxy glue to potential wear points. Dimensions given in Appendix Table.

**Appendix Table**. Dimensions (mm) of GPS pack designs shown in Appendix Figure.

| | Male | Female | Sub Adult |
|---|---|---|---|
| A | 44 | 38 | 32 |
| B | 120 | 100 | 80 |
| C | 80 | 68 | 60 |
| D | 114 | 94 | 70 |
| E | 94 | 90 | 80 |
| F | 36 | 26 | 18 |
| G | 100 | 98 | 86 |
| H | 100 | 82 | 66 |