



The On-Animal Tracking System (OATS): an affordable, wireless wildlife telemetry system

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ABSTRACT

Context. Wildlife tracking is often expensive and manufacturer delivery times sometimes delay critical research opportunities. Movement and activity data provide fundamental ecological information for developing conservation methods and management strategies. However, the aforementioned limitations of commercial animal tracking systems can prevent important research. **Aims.** To build an affordable and effective system for monitoring the movement and activity of captive and wild animals with a particular focus on mammals (weighing 3 kg and over) such as the Brush-tailed Rock-wallaby (*Petrogale penicillata*, hereafter 'BTRW'). **Methods.** A prototype hub-based animal tracking system was built for BTRW research. Data was uploaded from a collar to hub when an animal was within upload range via a wireless local area network and transmitted via a Message Queuing Telemetry Transport broker. This data package was subsequently uploaded via cellular networks to a cloud-based database and dashboard. **Key results.** The On-Animal Tracking System (OATS) prototype system was successfully tested in the field with nine BTRW for a period of up to 60 days and provided researchers with movement data for further analysis. **Conclusions.** OATS provides an affordable wildlife tracking system option with the design being publicly and freely available thereby, providing a tracking solution specifically designed for research. **Implications.** This system has set the foundation for other researchers to use and adapt the design to suit their research needs thereby, providing both a customisable and cost-effective method for carrying out movement and activity research. OATS has been deployed with BTRW (described in this manuscript) along with both wild canids and livestock.

Keywords: accelerometer, Brush-tailed Rock-wallaby, GNSS tracking, GPS tracking, internet-of-things, *Petrogale penicillata*, radio tags, radio telemetry.

Introduction

Telemetry systems are crucial for gaining ecological insights. Technological advances have expanded capabilities beyond what early pioneers imagined (Kenward 2000; White and Garrott 2012; Marrant *et al.* 2022), with modern collars remotely transmitting data (Bailey *et al.* 2018) and utilising time-release-drop-offs to eliminate the need for recapture. This improves animal welfare and provides researchers with real-time ecological insights. Furthermore, integrated sensors (e.g. accelerometers) can provide data on animal behaviour (Brown *et al.* 2013), while mortality sensors can detect when an animal is deceased (Cypher *et al.* 2014).

Despite these advances, commercial telemetry systems have significant limitations, primarily related to cost, availability, and customisable functionality (Matthews *et al.* 2013; Cypher *et al.* 2014; Hofman *et al.* 2019). These limitations have led us to develop and evaluate our own tracking system. Our goal was to create collars specifically designed for small-to-medium sized mammals (weighing 3 kg and over), and a larger, solar-powered device suitable for animals such as canids and livestock.

While other open-source solutions exist, they are typically limited to store-on-board devices (Foley and Sillero-Zubiri 2020; Wild *et al.* 2022) that require animal recapture for data download, systems designed to capture data from commercial collars via Very High

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Frequency (VHF) (Gottwald *et al.* 2019), or platforms using emitter-localisation techniques (Duda *et al.* 2018; Lu *et al.* 2021). The novelty of the On-Animal Tracking System (OATS) described in this paper presents an end-to-end, cost-effective, and research-ready solution. It is distinguished by its end-to-end data pipeline, cost-effective hardware, hybrid data transfer method, and lightweight multi-sensor collars. We describe the design and performance of OATS, offering a system that can be further refined by the open-source community to meet future research needs.

Materials and methods

Study site

Field testing was undertaken at two sites in New South Wales, Australia: (1) Oxley Wild Rivers National Park; and (2) Shannons Creek Escarpment. Both sites comprise of a volcanic rock outcrop (New England batholith) in steep terrain and vegetation is dominated by a dry sclerophyll eucalypt forest. At the first site New South Wales National Parks and Wildlife Service (NPWS) had a permanent live-feed camera monitoring the colony which was used alongside regular in-person health checks to visually check the animals for adverse behaviour or injuries.

System overview

The OATS consists of collar-based wearable electronics (hereafter ‘collars’), field-based data collection hub(s) (hereafter DataHub) and an optional cloud system for collating data from multiple hubs (Fig. 1). The cost of parts for this system was approximately AUD120 per collar and AUD1000 per DataHub with an ongoing cost of AUD10 per month (using a premium cellular service in Australia). The full design and deployment instructions are available on Github (refer to Data availability).

The collars (Fig. 2) included a low-power microprocessor (ESP32, Espressif Systems, China), Global Navigational Satellite System (GNSS) receiver (L86, Quectel, China), and accelerometer (ADXL343, Analog Devices, China) on a custom printed circuit board in a acrylonitrile styrene acrylate 3D-printed housing for an ergonomic, lightweight

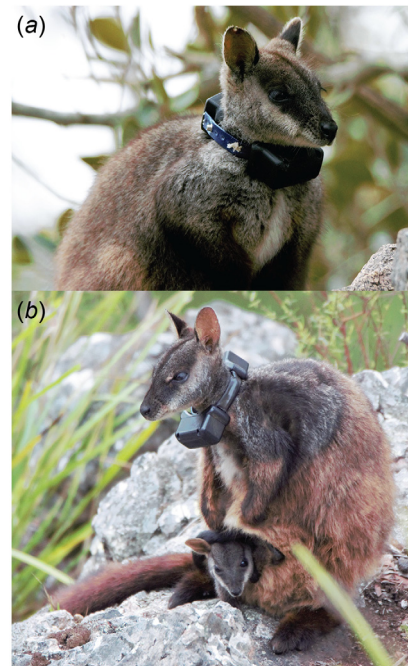


Fig. 2. The OATS collars on Brush-tailed Rock-wallabies at the Cave Colony site with (a) the breakaway release visible and (b) the other side of the collar visible on a female with a pouch young.

and fit-for-purpose collar mounted device. The functionality of the collars is shown in a state diagram (Fig. 3). The collars used in this study weighed 120 g, consumed less than 2.4 mAh with a 10-min data frequency allowing for the collars to last 60 days with a 3500 mAh primary lithium battery.

The DataHub (Fig. 4) was developed to receive data from the devices during field trials. The design consists of a single board computer (Raspberry Pi 3B+, Raspberry Pi Foundation, UK) with a cellular (4G) and wireless local area network (WLAN) modem (RUT240, Teltonika, Lithuania), and 6.5dBi Collinear 930 mm antenna (RFI Technology, Sydney, NSW, Australia) fitted to the top of the enclosure. A solar charge controller (SmartSolar MPPT 75/10, Victron, Netherlands) and a custom-made lithium 240 WH 18650 battery pack (Master Instruments, Australia) is used for power. The

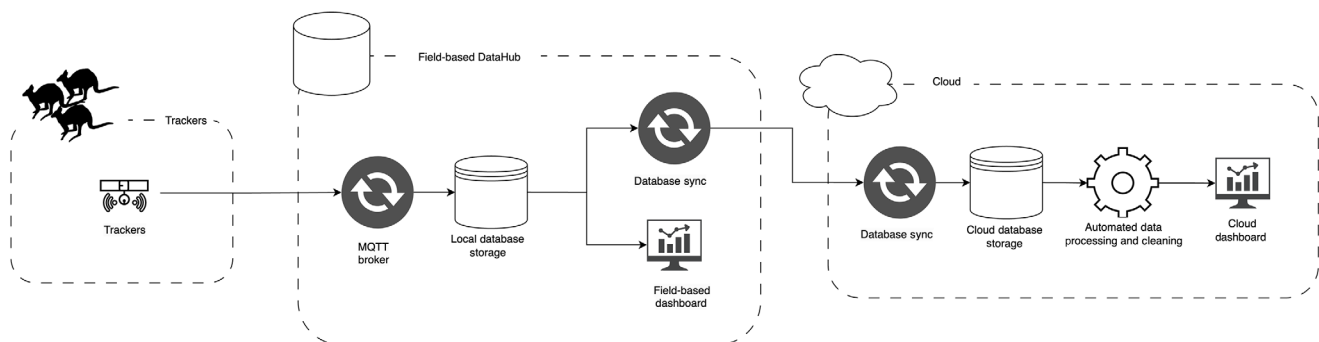


Fig. 1. A visual representation of the automated data pipeline of the OATS system.

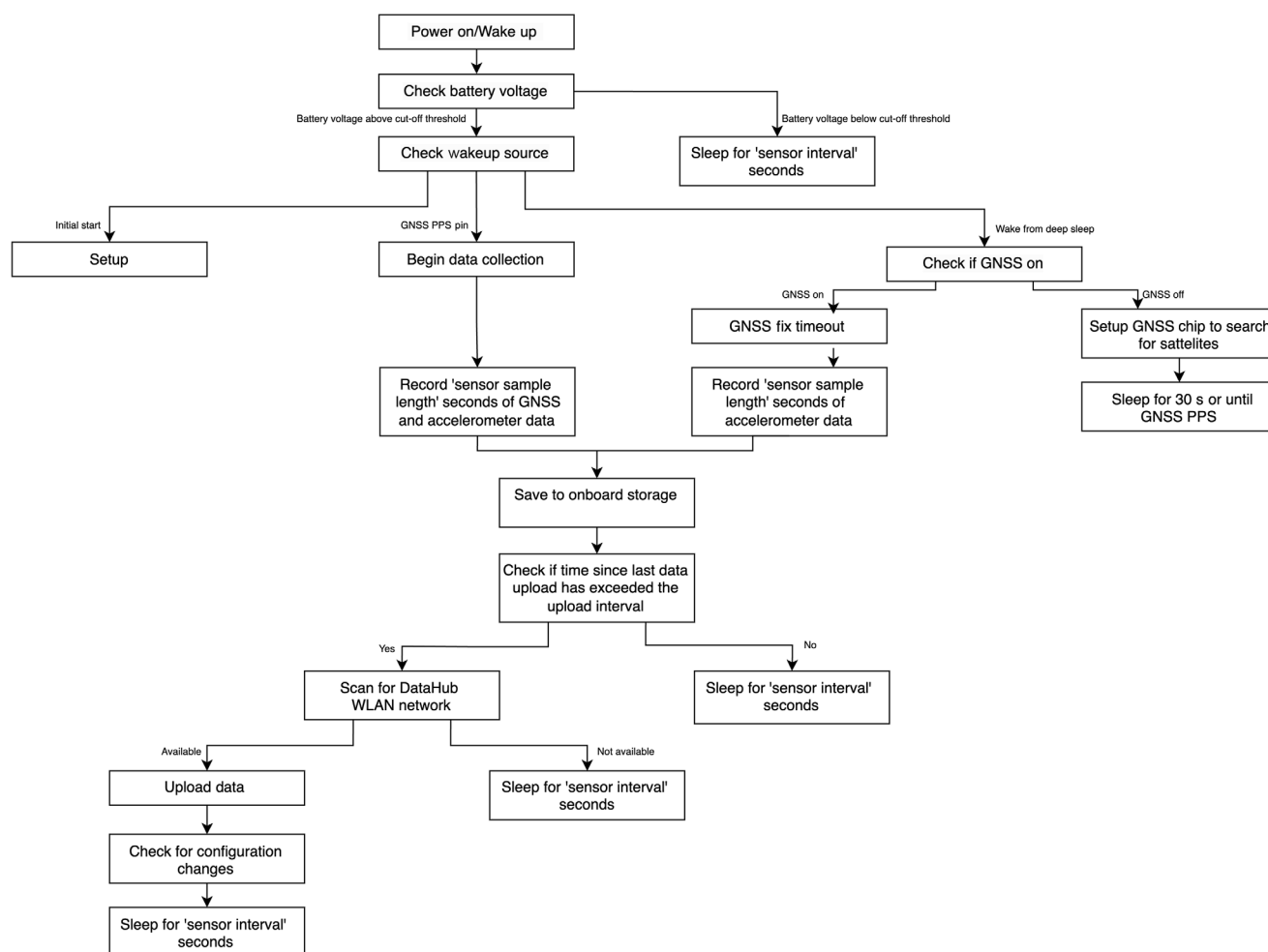


Fig. 3. The firmware state diagram for the OATS and DataHub.



Fig. 4. The DataHub setup in the field.

DataHub used a 19-V 50-W solar panel and bracket system (Master Instruments) for solar harvesting. The DataHub hosted a WLAN network and a Message Queuing Telemetry Transport (MQTT) broker to enable communication with the collars and Node-RED (developed by IBM, USA) for the data pipeline and user interface, which allows viewing data in the field and wirelessly changing settings such as data rates.

A cloud-based system was hosted on a virtual machine on the Nectar Research Cloud hosted by Intersect Australia. This virtual machine hosted the cloud-based PostgreSQL database and a custom RShiny app for visualising and downloading the data. When data was added from a DataHub, it was periodically processed to allow a ready to use dataset for download from the cloud interface. The raw data in JSON (JavaScript Object Notation) format is also available for download through the RShiny app.

Field test objectives

The field testing was undertaken with four objectives to: (1) test the fitting, ergonomics and robustness of the collar; (2) assess the reliability of data collection; (3) assess the GNSS accuracy and reliability; and (4) evaluate the reliability of

the telecommunication and power. Early iterations of this collar system were first tested and the design refined on domestic Sheep (*Ovis aries*) (Cafe et al. 2024) and captive Dingos (*Canis familiaris*) (O. Kimber, A. Dorph, C. Clemente, O. Wilson, G. Charlton, P. D. Meek, P. J. S. Fleming, G. Ballard, unpubl. data) to ensure the collars' reliability before deployment on free-living animals. Brush-tailed Rock-wallaby (*Petrogale penicillata*, hereafter 'BTRW') were trapped using Thomas traps (Meek et al. 2024a) at two colonies (Cave Colony and Shannon's Creek Escarpment) to fit collars to five female and four male BTRWs. A standard break-away release system was used (Povh et al. 2023) to ensure collars did not remain permanently on BTRW after the study. Each animal was released at the point of capture and observed at least monthly in person to ensure the welfare of the animals. The rate of data collection were 10-min data collection intervals and a 5-s settle time for GNSS (time between the first fix and recording of data) with an expected battery life of 60 days. It should be noted that while increasing the GNSS settle time would improve GNSS performance, it would also consume more battery power. This settle time is modifiable with over-the-air updates from the DataHub. An analysis of the percentage of data points recorded by the devices at the DataHub and cloud for both location and accelerometer data were compared with the expected data rate to analyse device and data syncing reliability.

The GNSS error was established using four stationary collars placed at a site within similar terrain to the field

sites for a period of 1-week. Collar error was calculated as both the modal and mean distance from the real location of each collar using a Garmin GPSMAP 64sx (typical accuracy within less than 3 m) allowing it to settle its location for greater than 1-h before reading the position and then averaged across all stationary collars and reported as mean $\pm$ s.e.

To demonstrate the utility of the system for ecological research, the resulting data were run through a standard activity area analysis pipeline built in R (R Core Team 2021) using the *adehabitatHR* package (Calenge 2006); see Meek et al. (2024b). Minimum convex polygons (95% MCP) and kernel density activity areas were produced in the early steps of this process to demonstrate the practical utility of the system (Fig. 5).

Application

While the distance between collar and DataHub for successful data upload has not been tested across a range of topographical conditions, within open-flat terrain with line-of-sight between the collar and Datahub, the upload distance exceeded 100 m. Based on the assumption of animal movement by experienced ecologists, the DataHubs were placed around the colonies to enable data capture.

Animal ethics

All field work involving BTRW was undertaken under authority ARA22-088 from the University of New England Animal Research Ethics Committee. Unpublished pilot field testing of using livestock (sheep; animal ethics approval

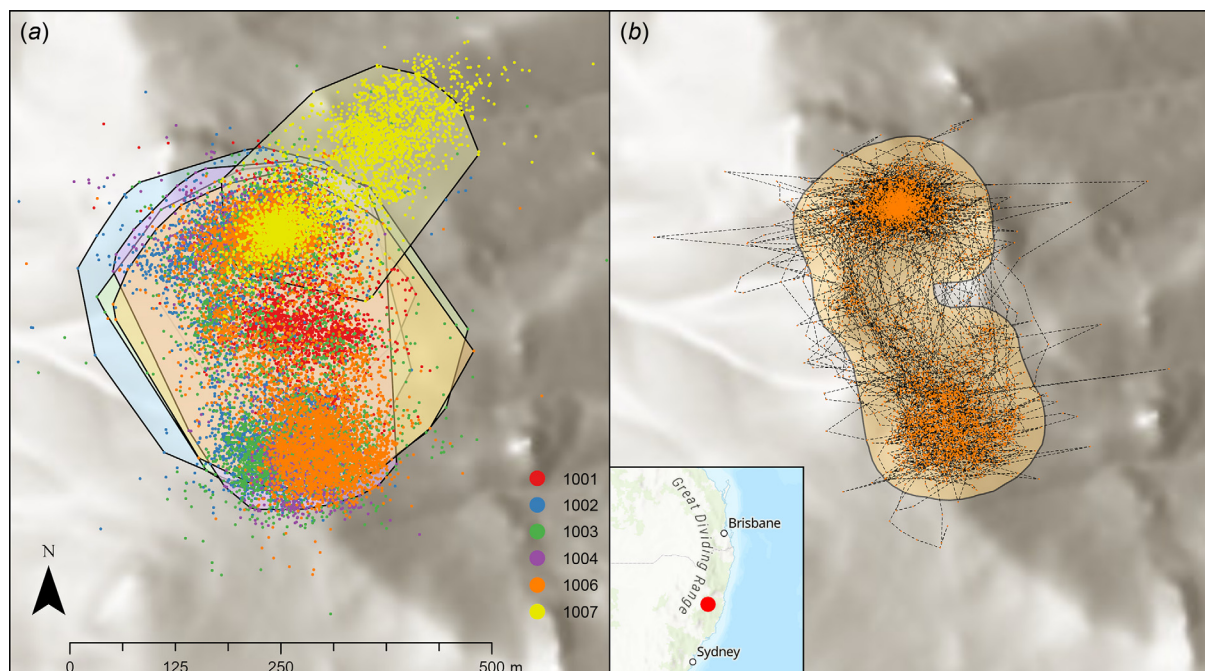


Fig. 5. (a) The 95% minimum convex polygons for six collared rock-wallabies from the Cave Colony overlaid with each animals' relocations coloured by individual, and (b) the relocations of OATS collar 1006, with ordered point-to-point connections and a polygon showing the kernel density activity area. Scale is preserved between (a) and (b); exact locality of the study site has been obscured to protect the colony location.

ARA21-068: University of New England Animal Research Authority) and captive animals (dingo; animal ethics approval ORA 22-25-6: Orange Animal Ethics Committee).

Results

Collaring

Six BTRW individuals (four females and two males) were collared at the first site and three BTRW individuals (one female and two males) were collared at the second site. The weight range of the nine collared animals ranged between 3.90 kg and 7.95 kg, meaning that the collar was between 1.51 and 3.01% of the animals weight. During field testing at the first site, observations on both the National Parks and Wildlife Service camera and from our camera traps did not show any adverse behaviour or injuries from the collars. At each health check, close observations were possible and assessments of photographs of each collared animal confirmed there were no adverse effects. One female BTRW with a pouch young recorded at trapping was reliably followed through the trial and was seen later with young-at-foot; meaning that this animal had successfully reared young while collared (Fig. 2).

Data frequency

Using the latest open-source design, $98.60 \pm 0.14\%$ of accelerometer and $95.26 \pm 0.76\%$ of location data points were successfully collected based on the expected 10-min data rate. Further, 100% of data points transferred to the DataHub from the collars were successfully synced to the cloud database.

GNSS accuracy and reliability

Stationary collars had a mean modal error across the four collars of 10.28 ± 0.78 m and a mean error of 28.75 ± 2.39 m; their distribution is in Fig. 6. During the analysis, the raw GNSS points were grouped around the 'real location' with no directional bias noted.

Discussion

OATS was specifically designed for species with high site fidelity, such as BTRW (Molyneux *et al.* 2011), enabling automated data uploads when animals return to a central refuge. The performance of the system, including data and location reliability, met or exceeded that of commercial collars previously used by the authors (P. D. Meek, unpubl. data). The

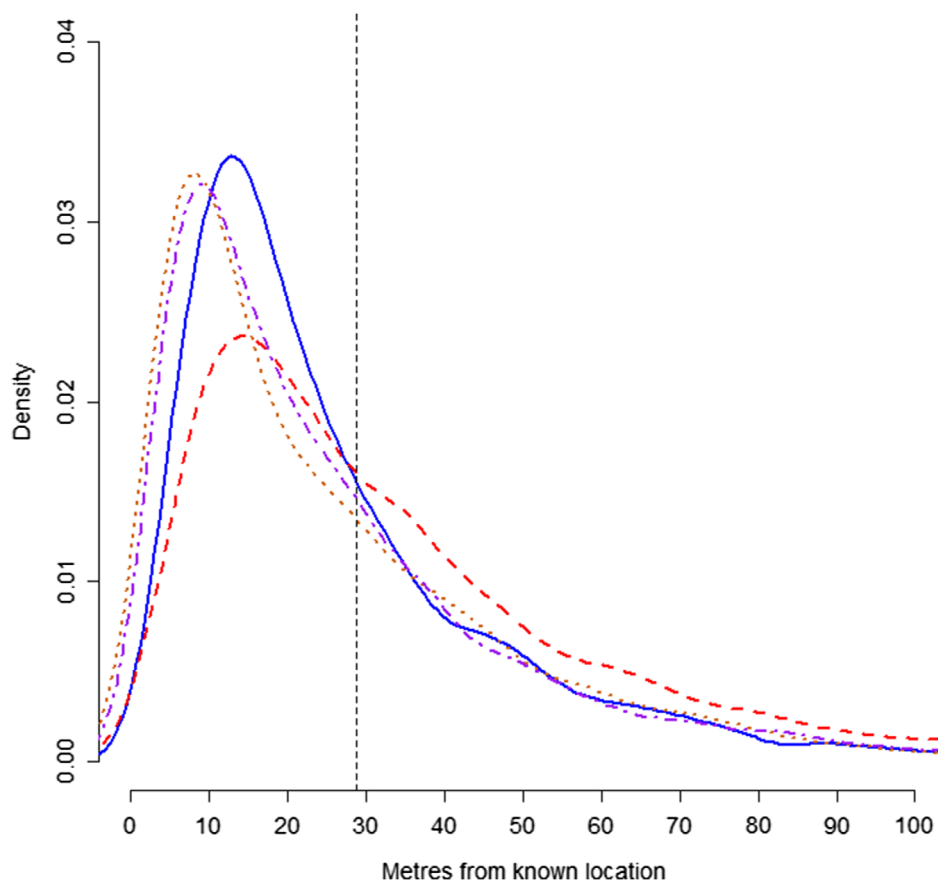


Fig. 6. Distribution of fixes (in metres) from the known location for each of the four stationary collars left at the Cave Colony site. Dashed vertical line shows mean of means. X-axis truncated to 100 m for clarity.

low power consumption (less than 2.4 mAh) facilitates a lightweight design suitable for mammals weighing 3 kg and over. Pilot testing suggests the system also has utility for tracking other mammals, such as canids or grazing livestock, that consistently return to a common location for refuge, food, or water resources.

This work advances previous open-source designs by providing a true end-to-end solution featuring a hybrid field-to-cloud data transfer method. Successful deployment requires placing DataHubs in locations that animals visit regularly. This strategy ensured roughly daily data uploads, and the collar's on-board storage successfully retained data even when an animal was not detected for several days. Overall, the OATS prototype was successful in collecting accurate GNSS location data for BTRW, and no adverse welfare effects were observed.

The location reliability seen with recent commercial collars used by the authors (Meek *et al.* 2024b; used with *C. familiaris*) was better than that reported in this study. However, this is relative to the settings used by the different devices. The authors hypothesise that the following could influence the reported GPS reliability; the geography of BTRW habitats being more challenging for GNSS receivers due to the steep rocky terrain, tendency for Kalman filters (an optimal, recursive algorithm that estimates the state of a linear system over time by combining noisy sensor measurements with a dynamic model) to accumulate positional drift when the unit is stationary (Frair *et al.* 2010; Gunner *et al.* 2022) and a low settle time to prioritise battery consumption. Testing to find the 'sweet spot' between increasing the settle time for GNSS reliability and battery life could improve this. Although the inclusion of accelerometer data was outside of the scope of this study, it could be used alongside the location data to identify animal behaviour, if an algorithm were to be trained from manual observations or be used for further tuning battery consumption by lowering the GNSS rate when the animal is stationary.

While the costs and savings described here are based on the cost-of-goods and labour time by an individual with specific expertise to manufacture the OATS collars, the cost for a 2-month trial with 20 collars would be ~AUD7060. This represents a ~70–85% saving compared to commercial options that have upfront and running costs of between ~AUD50,000 and ~AUD100,000. OATS is therefore, a highly cost-effective solution for studies of free-roaming animals that frequent central locations. Future developments could include; adding Very High Frequency beacons to locate dropped collars or a customised time-release-drop-offs triggered near a DataHub for easy collar retrieval.

Conclusion

This open-source design is novel due to the automatic data pipeline from collar/animal to the cloud, low ongoing costs

(i.e., a low data-only cellular plan per DataHub), the low power consumption (i.e., high fix rate for longer-term deployment) and the addition of an accelerometer to enable analysis of animal behaviour simultaneous with typical GNSS spatial variables. The results of the field testing and refinement process of the prototype have confirmed the OATS has application in movement studies of free-roaming animals that return to a common location for refuge, food, or water resources, including wildlife and extensive livestock. The authors invite and value other developers to suggest or contribute to the continued development of the system via GitHub to allow for ecology and animal science researchers to have access to affordable tracking technology to conduct impactful research.

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Data availability. The design files for the whole system are available via GitHub at <https://github.com/glencharlton/OnAnimalTrackingSystem>.

Declaration of use of AI. Artificial intelligence was used to augment human generated code development in this repository. All AI-generated code was manually reviewed and validated by the authors for technical accuracy and logical integrity.

Conflicts of interest. The author Paul Meek is an Associate Editor for *Pacific Conservation Biology* but was not involved in the peer review or decision-making process for this paper. The authors have no further conflicts of interest to declare.

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