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RESEARCH

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Assessment and validation of miniaturized technology for the remote tracking of critically endangered Galápagos pink land iguana (*Conolophus marthae*)

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Abstract

Background: Gathering ecological data for species of conservation concern inhabiting remote regions can be daunting and, sometimes, logistically infeasible. We built a custom-made GPS tracking device that allows to remotely and accurately collect animal position, environmental, and ecological data, including animal temperature and UVB radiation. We designed the device to track the critically endangered Galápagos pink land iguana, *Conolophus marthae*. Here we illustrate some technical solutions adopted to respond to challenges associated with such task and present some preliminary results from controlled trial experiments and field implementation.

Results: Our tests show that estimates of temperature and UVB radiation are affected by the design of our device, in particular by its casing. The introduced bias, though, is systematic and can be corrected using linear and quadratic regressions on collected values. Our data show that GPS accuracy loss, although introduced by vegetation and orientation of the devices when attached to the animals, is acceptable, leading to an average error gap of less than 15 m in more than 50% of the cases.

Conclusions: We address some technical challenges related to the design, construction, and operation of a custom-made GPS tracking device to collect data on animals in the wild. Systematic bias introduced by the technological implementation of the device exists. Understanding the nature of the bias is crucial to provide correction models. Although designed to track land iguanas, our device could be used in other circumstances and is particularly useful to track organisms inhabiting locations that are difficult to reach or for which classic telemetry approaches are unattainable.

Keywords: Conservation technology, Galápagos, GPS-tracking device, Land iguanas, Pink iguanas

Background

Species on the brink of extinction may need urgent actions that aim at preserving both habitat and population viability by, for example, protecting feeding areas, nesting grounds, and hatchlings. For this to occur, it is important to understand the intimate relationships between a species and its habitat.

In recent years, technological advancements greatly boosted wildlife in situ conservation (see [1]). The use of bio-logging and bio-telemetry has helped to uncover the use of unpredicted habitats [2], to investigate the social dynamics of reintroduced species [3], and to reveal unknown life history traits of threatened species [4]. In

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other words, technology can provide crucial information for the design of effective conservation strategies.

Challenging environmental constraints and/or strict ecological species requirements call for a continuous interaction between conservationists and engineers to produce sound technological solutions that best fit case studies, yet maintaining the potential for a wide spectrum of applications [5]. A compelling example in this regard is represented by the Galápagos pink land iguana, *Conolophus marthae*. This species, described in 2009, is listed as Critically Endangered in the IUCN Red List of Threatened Species [6, 7]. Despite its recent discovery, the pink iguana rapidly became a flagship and one of the most iconic species of the Galápagos archipelago [8]. Pink iguanas can only be found along the slopes and at the top of Wolf Volcano on Isabela Island, Galápagos (Ecuador). Threats include very small population size ($200 < N < 300$), extremely limited distribution (the area where the iguanas can be found is currently estimated at ca. 25 km^2), lack of recruitment (no hatchlings have been seen since 2005), and introduced predators such as cats and rats. In addition to this, pink iguanas are syntopic with *C. subcristatus*, another land iguana species endemic to the Galápagos archipelago, with a much wider distribution. Although the two species currently do not hybridize [9], they are likely to compete for resources and habitat.

Unfortunately, monitoring *C. marthae*, and the syntopic population of *C. subcristatus*, on Wolf Volcano is a very challenging task for logistical, biological, and environmental reasons. The location where these two species occur is one of the most remote in the Galápagos archipelago. Wolf Volcano is approximately 150 km far from the closest village. The remoteness of this site and the absence of any kind of facility and infrastructure make reaching the area very complex logistically and expensive. Field work longer than 2–3 weeks is, basically, unattainable. The volcano area is not covered by cellular network, which is available only in areas with human settlements on the islands. At present, communications from Wolf Volcano are possible only by ultra-high-frequency radio (UHF) and satellite connections.

To guide appropriate conservation actions for *Conolophus marthae*, such as a head-start program or animals' translocation, crucial information is needed to understand how this species uses its environment and interacts with *C. subcristatus*. Accurate measurements of position, temperature, humidity, solar radiation, and ultraviolet (UV) radiation are very important in this regard [8]. These parameters need to be estimated by sensors that, along with a GPS receiver, must be located in a small-sized device that can be harmlessly attached on iguanas for a long time. Iguanas shelter under bushes and recover in burrows where they also spend the night. For these reasons, an adequate protection of the device is also needed. In addition, a device must not jeopardize the survival of monitored individuals, alter their normal behavior, affect intra- and/or inter-specific social relationships or diminish regular access to resources. Thus, the combination of biological and environmental constraints calls for a device capable not only of collecting data and storing them, but also allowing remote data retrieval.

Here we present a new remote tracking device designed to monitor movements of elusive terrestrial animals inhabiting isolated and remote environments. We illustrate some technical solutions adopted to respond to challenges associated with such task. The device and its associated satellite-network infrastructure here described are currently being used in a long-term investigation aimed at the construction of species distribution models and habitat suitability maps for *C. marthae*.

Methods

Study system

Conolophus marthae is only found on the top of Wolf Volcano (WV, lat. 0.044432; long. − 91.352189), on Isabela Island [7]. Only one population of this species is currently known to exist and it is syntopic with the congeneric *C. subcristatus* (Fig. 1). The volcano reaches 1700 m above sea level and supports iguanas along the northwest slope from 600 m to the caldera. At lower to mid altitudes, the habitat is dominated by the lush endemic *Scalesia* forest. At higher altitudes, the environment shifts from forest to grassland with a general lack of trees and a variety of sedges and grasses. *Conolophus subcristatus* inhabits both the core area of *C. marthae* and surrounding areas. The two species could use the environment in different ways. For example, whereas the population of *C. subcristatus* on Wolf Volcano is known to actively use the internal area of the caldera for nesting and retreats (Gentile, personal communication), pink iguanas were never observed inside the caldera. This suggests that ecological requirements for the two species may be distinct. For researchers, reaching the caldera of Wolf Volcano is very difficult. In the absence of a helicopter, which may cost as much as $3000 US per hour, hiking is the only alternative option. This latter approach drastically limits the amount of equipment that can be transported because all the supplies, including water, food, gasoline, generator, batteries, and other field equipment, must be hand-carried.

It is clear that the use of remote tracking devices to uncover the relationship between the two species within their area of distribution, their habitat characteristics, and usage will allow to efficiently guide appropriate conservation actions for *C. marthae*. In fact, these devices

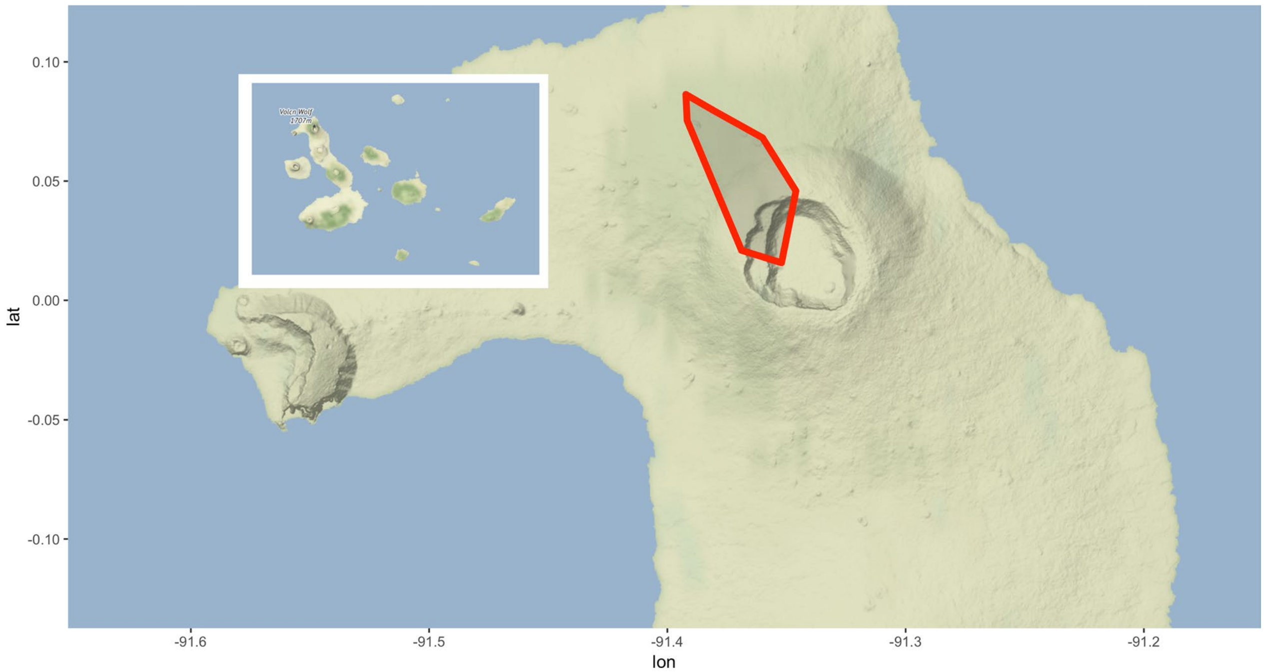

Fig. 1 Iguanas' distribution. Distribution of sympatric pink and yellow iguanas as observed during the field work conducted between 2012 and 2015. The red polygon, along the northern slopes of Wolf Volcano, encompasses the geographic area where all records of *C. marthae* and *C. subcristatus* were detected. Inset map shows the entire Galápagos archipelago with the relative position of Isabela Island and Wolf Volcano

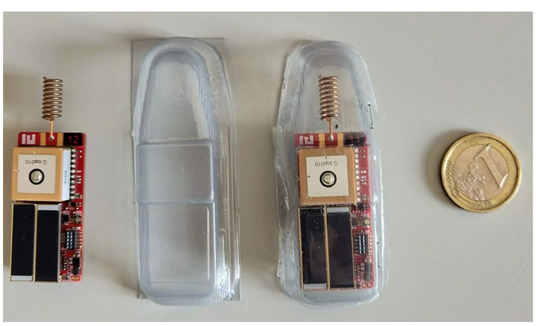

Fig. 2 WSN device. Shape and dimension of WSNs with and without the PVC casing. The 1 Euro coin in the pictures is used as scale reference

will provide crucial data while bypassing a number of logistical challenges.

Device and satellite gateway

Wireless sensor node

We developed a new "Wireless Sensor Node" (WSN) able to collect several environmental data. The architecture of the node has been described elsewhere [5, 10]. The device integrates solar panels and supercapacitors as key components to allow its continuous functioning (Fig. 2). Here we briefly report a list of the most relevant components of the device:

- a CC1310 wireless controller [11] with an ultra-low-power active RF and MCU electric consumption, and flexible low-power modes. This controller provides excellent battery life and allows long-range operation. It integrates a powerful 48-MHz Arm Cortex-M3 micro controller, a dedicated radio controller, and a ultra-low-power Cortex M0 sensor controller;
- an ADXL345 accelerometer [12];
- a digital HDC1008 humidity sensor with integrated temperature sensor [13]);
- a VEML6070 UV light sensor [14];
- a Global TOP PA6C GPS receiver based on MediaTek MT3329 chip-set and an integrated ceramic antenna. It is characterized by a larger receiver sensitivity (-165 dBm thanks to the TCXO Design) resulting in high position accuracy;
- a NOR flash memory storage with 1 GB capacity (serial number: MT25QL01GBBB8E12);
- the high-performance RF front-end module Skyworks SE2435L [15]. It operates in the 860-930 MHz frequency band that includes a power amplifier for transmission and a low-noise amplifier for reception.

All the functions are coordinated by the CC1310 controller implementing the node logic. The GPS receiver provides the position of the node; it communicates with the controller via a UART interface. Sensors deliver data to the controller by a I^2C interface. Finally, a SPI interface accesses the flash storage memory. The CC1310 integrates a wireless modem that directly generates and receives RF signals. To improve the node communication range, all the signals go through the Skyworks RF front-end module and a band-pass filter.

Satellite gateway

To transfer the information collected by the nodes to an internet server we built a satellite gateway relay station. The gateway has been designed to be energetically autonomous, have a good radio coverage range, and be mechanically resistant for deployment in the field. At the same time the gateway infrastructure must not represent a threat to local species and be easy to transport and assemble in situ.

Figure 3 shows the gateway station as it currently stands assembled on the top of WV. The bottom 40 cm of the metal poles are anchored to the ground with concrete, to ensure its stability. The stainless steel infrastructure holds a 102.87 × 67.8 cm solar panel with a maximum power of 100 W, a 12 dBi satellite antenna and an 8 dBi terrestrial antenna. A waterproof junction box (the grey box in Fig. 3) has been used to accommodate

- a low-power satellite transponder (connected to the satellite antenna);
- a voltage regulator and a 40 Ah deep-cycle AGM battery;
- a low-power computing device based on ARM11 processor (Raspberry Pi Zero);
- a receiver, connected with the terrestrial antenna, and controlled by the computer.

On the computer, we run a custom software that periodically scans the surroundings for WSNs and downloads the data collected from them. Then it uploads the data synchronously on our internet server through the satellite communication. Given that this real-time communication is not 100% reliable, a periodic script synchronizes the data from the server to the computer to prevent losses.

Casing and attachment procedure

To protect the devices against environmental impacts (scratches, bumps, breakages, and moisture), WSNs were encased in a custom-made PVC (Polycinyl chloride) package (Fig. 2). Besides offering efficient protection to the hardware and to provide an easy and safe attachment on animal skin, the packaging was designed to have minimum effect on sensors and on the energy-harvesting system. The case is transparent, furniture grade PVC, treated to be UV and impact resistant. This means that the box does not get brittle or brownish under prolonged sun exposure.

Fig. 3 Gateway relay station. The metal structure was assembled at the Galápagos National Park station to conduct final tests, prior to its deployment in the field

Special attention has been devoted to the attachment of the devices to the animal. A previous experiment showed that an attachment procedure using epoxy glue guarantees the device to stay attached on land iguanas for approximately 1 year (Gentile, personal communication). We are aware that shedding skin could in theory cause the earlier detachment of the device. However, we preferred to accept such a potential risk rather than increase the risk of harming iguanas using more invasive methods. In that first experiment, though, the PVC casing had not been designed yet. For this reason, in November 2018, we tested the attaching procedure one more time comparing epoxy and non-epoxy glues. Furthermore, during field work on WV conducted in September 2019 we also tested a combination of gluing and superficial, non permanent, suturing. The suturing was performed by a professional veterinary after properly disinfecting the skin and providing the animal with local anesthesia (lidocaine), according to a protocol approved by the Galápagos National Park Directorate (Fig. 4). Other methods based on fastened jackets were not considered as they proved unsafe to iguanas in long-term studies [16].

Data collection and testing

We measured the precision and the performance of the WSN sensors in the target environment. Our primary goals were to

1. test the sensors accuracy, in particular related to temperature, and the attenuation/error introduced by the PVC case;
2. test the effects of the vegetation on the precision of the sensed GPS position.

Among the sensors to be installed on the device, the thermometer is particularly challenging. One of the problems arising from using external thermometers is represented by the uncertainty of the measurement. More than one question must be answered: (i) what does a non-internal (but still incorporated in the device) thermometer exactly measure? (ii) Does temperature measured in such a way sufficiently correlate with animal's body temperature? (iii) Is there a measurement bias generated by the PVC casing? (iv) Is this bias systematic, so that it can be modelled and corrected? To answer these questions, we synchronously collected data from two identical digital thermometers Objecta mod.7264 (T1 and T2 hereafter) each of which equipped with two independent sensors: one inside the case (indoor: IND), and one external (outdoor: OUT) located at the end of a 1-mlong wire. We exposed the two thermometers to the same outdoor solar conditions. The external sensor of T1 (T1-OUT) was attached to the ground, whereas T2-OUT was kept permanently operating at approximately 5 cm from the ground. Two WSNs (WSN-1 and WSN-59) were placed next to T1 and T2. While WSN-1 was protected by the PCV case, WSN-59 was not. All devices were always exposed to the same external conditions while

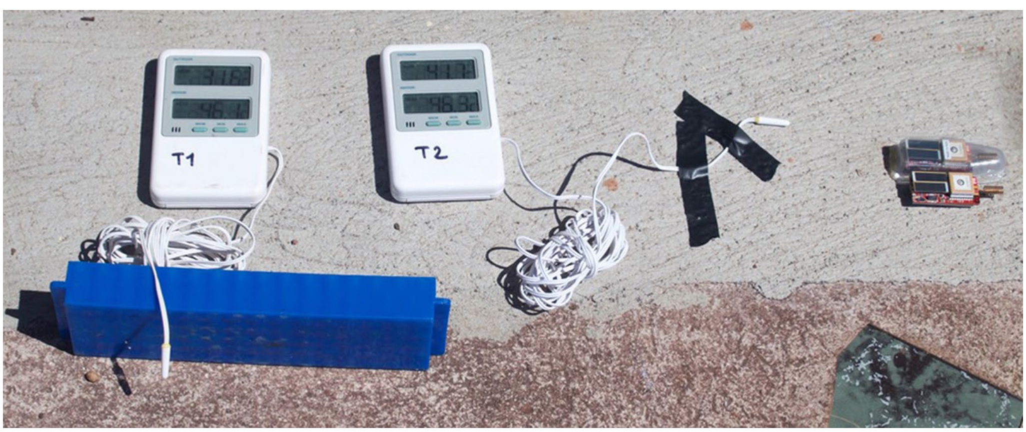

Fig. 4 Attaching experiments. The use of epoxy glue produced better results since it never completely crystallizes, conferring more elasticity and durability to the attached device. When paired with superficial suturing, epoxy glue ensures the device to stay in place

a Procedure without epoxy glue **b** Mixing the epoxy components **c** Procedure with epoxy glue and suturing.

Fig. 5 Experimental design. The external sensor of T1 (T1-OUT) was attached to the ground whereas T2-OUT was kept permanently operating at approximately 5 cm from the ground. The two WSNs (WSN-1, with PVC case, and WSN-59 w/o PVC case) were located close to the two thermometers operating (see Fig. 5). Data reading was synchronic and data collected were later used for statistical analysis.

To asses the impact of Galápagos vegetation on the GPS accuracy, we acquired 450 positions under sparse canopy cover in Puerto Ayora (Galápagos), and we compared these GPS fixes with those collected under an open sky condition in Rome, on the roof of our University.

We further wanted to gather information on the potential loss of GPS accuracy due to the attachment position of WSNs on the animals. As previously described, the devices are attached on the animals' tail and thus are naturally tilted. This inclination can cause a decrease in the location accuracy of the GPS fix. Since the real position of the animal is unknown, to evaluate this potential accuracy loss, we compared the HDoP statistics of the GPS fixes of WSNs attached to iguanas in the field on Wolf Vulcano, with data obtained during testing conditions in Rome and Puerto Ayora.

Results and discussion

Effects of plastic packaging on sensors: temperature (*T*)

Figures 6 and 7 show temperature trends over time as measured during the experiment described in "Methods" section. Table 1 shows square regression coefficients of each parabolic curve, along with their probability values. Quadratic regression equations for each dependent variable (*T* estimates provided by different sensors) are also reported.

Although a 3-h-long segment of data (10:30 a.m.–1:30 p.m.) is missing, because of lack of data from T1 and T2 thermometers, quadratic regressions provided very strong and statistically significant fit. Clearly, T1-IND and T2-IND and WSN-1 provided very similar temperature estimates (regression parables largely overlap). As expected, the T1-OUT and T2-OUT sensors returned very different values, with T2-OUT (taped onto the ground) providing estimates closer to those given by T1-IND, T2-IND, and WSN-1. T1-OUT provided much lower values. This is a very important outcome as it demonstrates that WSN-59 actually measures the temperature of the substrate where it is located. It is not affected by heat dispersion as T2-OUT and (particularly) T1-OUT are.

WSN-1 provided much higher temperature records. This was also expected, as these values testify for the "green house" effect caused by the PVC casing. However, the very high fit of the regression curves of all

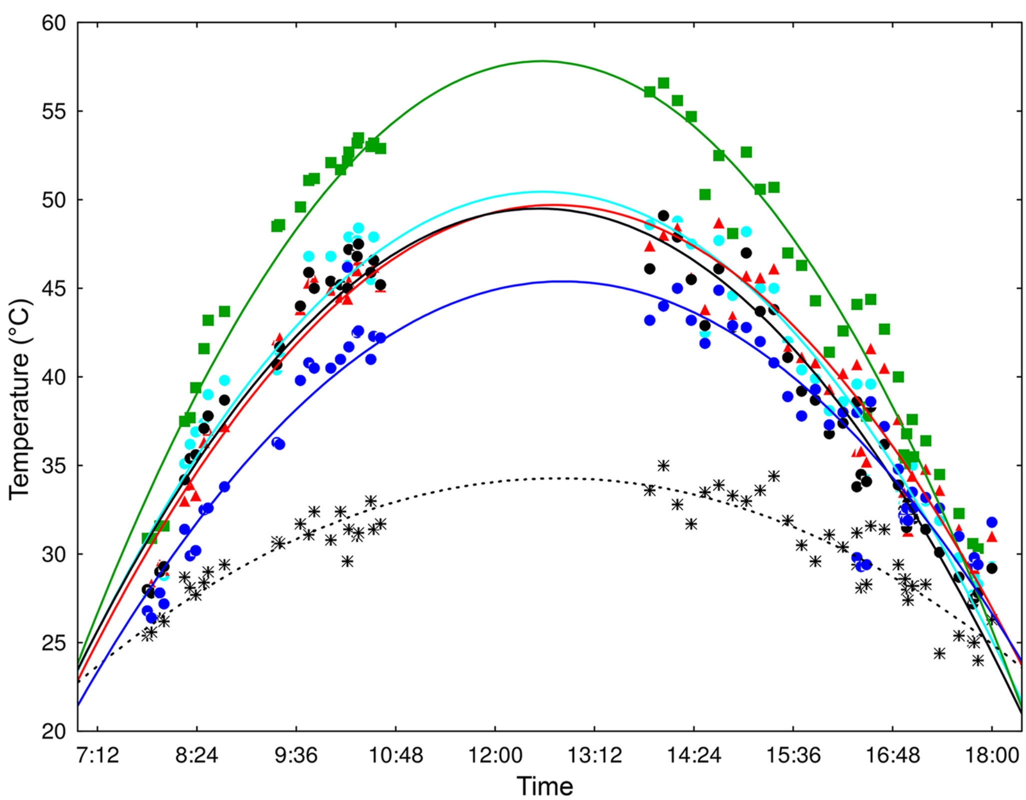

Fig. 6 Temperature trends (°C). Temperature was measured in full sun-light conditions. Green: WSN-1; cyan: T1-IND; black: T2-IND; red: WSN-59; blue: T2-OUT; dotted: T1-OUT

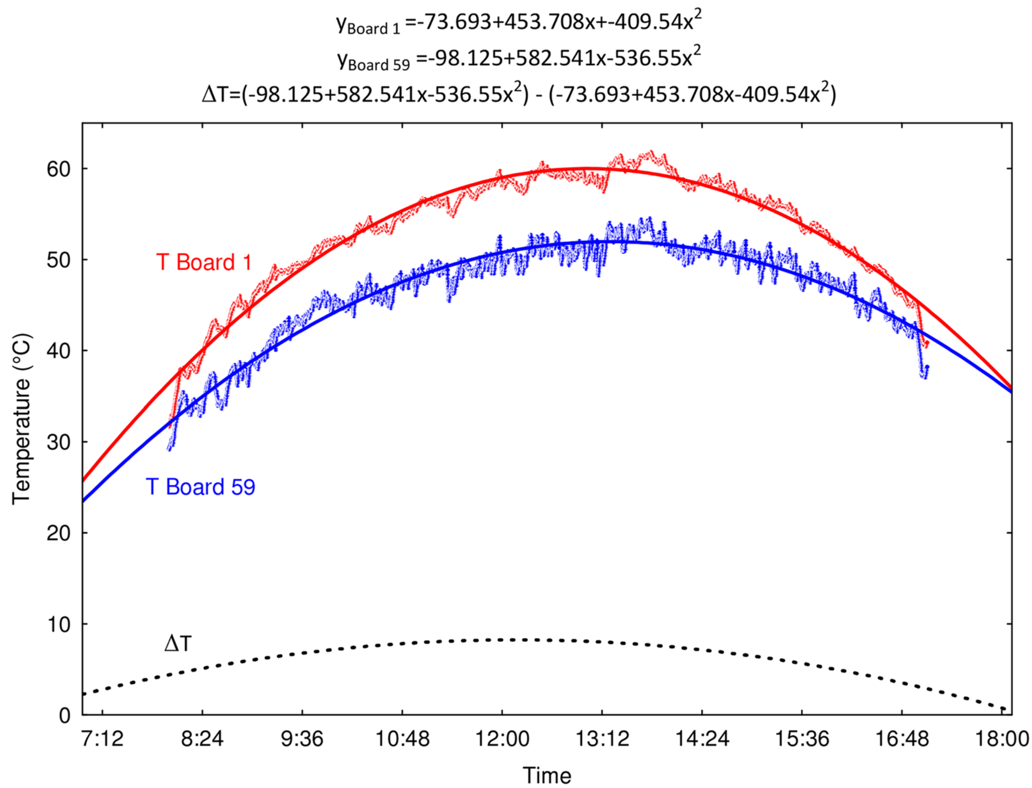

Fig. 7 Temperature trends (°C). Temperature was measured in almost full sun-light conditions. Red: WSN-1; blue: WSN-59; black dotted: ΔT

Table 1 Quadratic regression

Dependent variable	Quadratic regression equation	R^2	p
T1-IND	$y = -85.26 + 518.15 - 494.61x^2$	0.913	$\ll 0.001$
T1-OUT	$y = -21.40 + 209.32x - 196.74x^2$	0.845	$\ll 0.001$
T2-IND	$y = -82.15 + 504.34x - 483.01x^2$	0.932	$\ll 0.001$
T2-OUT	$y = -69.27 + 429.41x - 402.05x^2$	0.846	$\ll 0.001$
WSN-1	$y = -113.22 + 653.66x - 624.54x^2$	0.935	$\ll 0.001$
WSN-59	$y = -81.54 + 495.78x - 468.19x^2$	0.912	$\ll 0.001$

Square regression coefficient is estimated as SSR/SST, corrected for the mean. The dependent variable (y) is temperature as estimated by each different sensor. The independent variable (x) is time. Statistical significance (p) is shown in the last column

models allows the precise correction of the systematic bias introduced by the PVC case.

In fact, once that we confirmed that WSN-59 (w/o PVC) measures the temperature of the background where it is attached, it became necessary to correct for the bias introduced by the PVC casing. For this reason, we used 16, 372 temperature values collected synchronously by WSNs-1 and 59 every 2 s during a whole day under almost full sun-light condition. Data were fitted to a quadratic model. In an attempt to increase the amount of explained variance, a cubic polynomial equation ($y = a + bx + cx^2 + dx^3$) was also tested for regression. However, such equation was not used because the introduction of a fourth parameter in the model did not increase the coefficient of determination (R^2). Table 2 reports the quadratic and cubic equations for WSN-1 and 59, along with their R^2 and associated p value of regression parameters. The ΔT between WSN-1 and 59 was estimated from the quadratic regression equations (Fig. 7) as follows:

$$\Delta T = (-98.125 + 582.541x - 536.55^2) \\ - (-73.693 + 453.708x - 409.54^2)2.731 + 0.823x.$$

Consequently, a conversion of T estimates from devices in PVC case into the correct T reading that would be obtained without PVC casing can be obtained by the following equation:

$$T_{\text{converted}} = (-98.125 + 582.541x - 536.55^2) - \Delta T.$$

Clearly, ΔT increases with increasing T. Despite $T_{\text{converted}}$ estimated in this way being precisely defined, it is still formally dependent on time. We observed that the combined effects of stochasticity of weather conditions during which measurements were carried out, latency in the response of devices, and buffering generated by PVC casing caused only a negligible offset between parabolic curves of WSNs 1 and 59, which remain well centered on the same axis of symmetry. Thus, we could provide an estimate of ΔT independent of time by performing a quadratic regression between T values of WSNs 1 and 59. Given that ΔT quadratically increases with increasing T (Fig. 7), a quadratic regression seems more appropriate than a simple linear regression. However, a linear regression fits equally well the data and would provide very similar results (see Fig. 8). Thus, the equations in Fig. 7 can be used to convert T estimates from devices in PVC case into the correct T reading without PVC casing.

Effects of plastic packaging on sensors: UVB

The UVB radiation power measured with and without the enclosure is reported in Fig. 9 together with the related standard deviation. As we can see, the enclosure remarkably affects the sensed UV radiation (both UVB and UVI) although a strong correlation of the measurement suggests that measurement can be scaled and tuned. Because of a scattering effect introduced by the PVC casing, the measured level of UV radiation presents a remarkable error both in terms of mean and variance. As for the mean, a systematic error correction similar to the one previously described can be adopted. The variance instead can be reduced by averaging on multiple points. This is a viable solution since one UV sensing lasts about 50 ms.

Table 2 Quadratic (above), and cubic (below) regressions

Dependent variable	Regression equations	R^2	*p*
WSN-1	$y = -98.12 + 582.54x - 536.55^2$	0.973	≪ 0.001
	$y = -67.96 + 399.72x - 177.64x^2 - 228.70x^3$	0.974	≪ 0.001
WSN-59	$y = -73.69 + 453.70x - 409.54x^2$	0.950	≪ 0.001
	$y = -57.09 + 353.10x - 212.03x^2 - 125.85^3$	0.950	≪ 0.001

Square regression coefficient is estimated as SSR/SST, corrected for the mean. The dependent variable (*y*) is temperature as estimated by each different sensor. The independent variable (*x*) is time. Statistical significance (*p* val) is shown in the last column

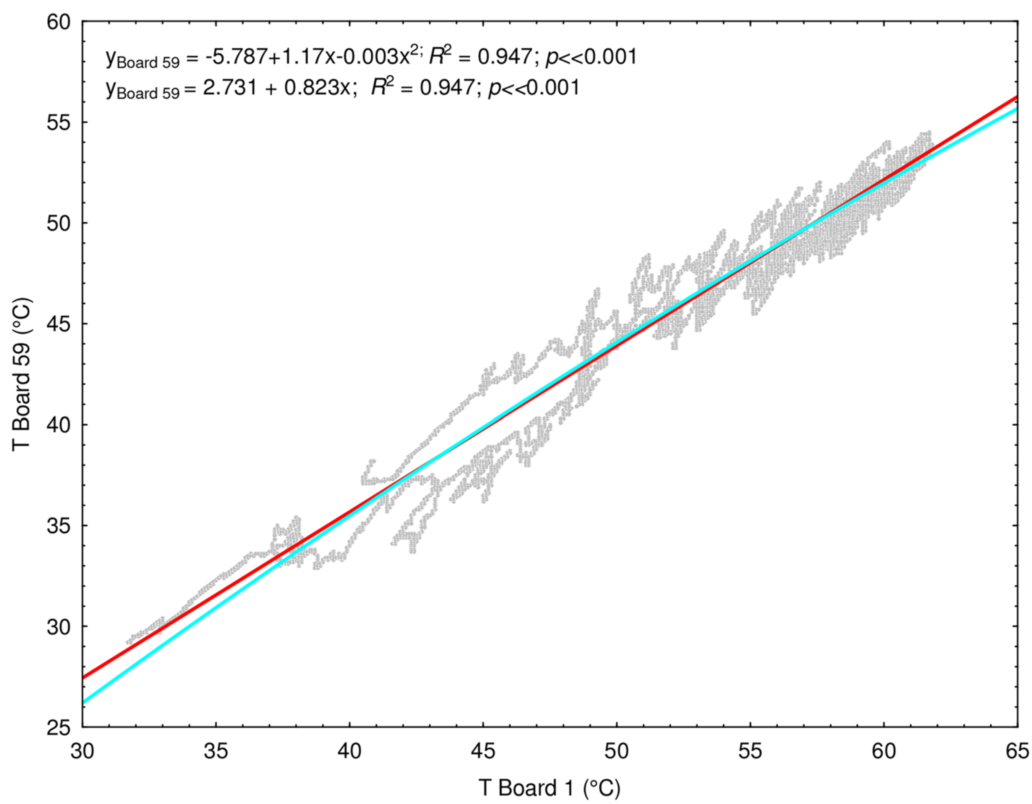

Fig. 8 Regressions. Quadratic (cyan) and linear (red) regression between 16,372 temperature values collected synchronously by WSNs 1 and 59 every 2 s during a whole day under almost full sun-light condition

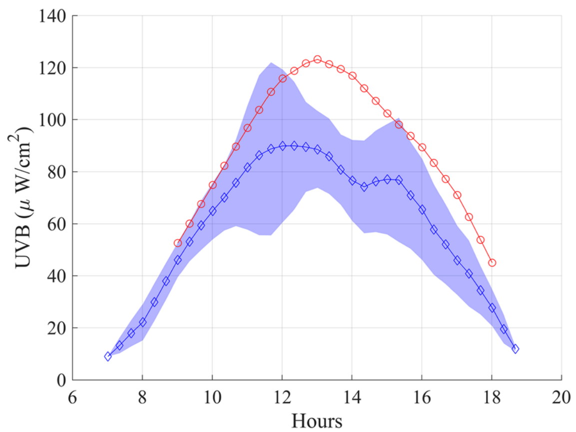

Fig. 9 UV radiation. With and without PVC enclosure. The red line is the UVB radiation sensed by a device without the enclosure, the blue line is with the enclosure and the area behind is the error (standard deviation)

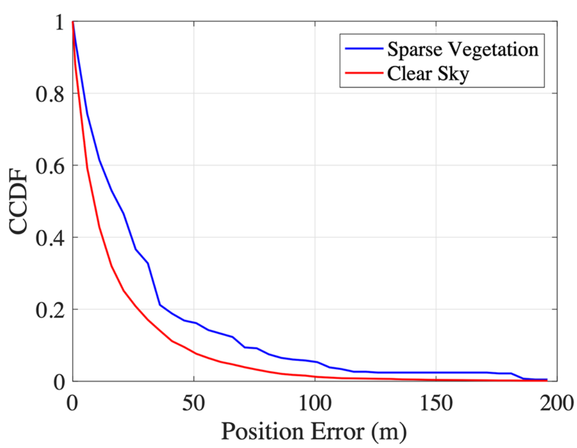

Fig. 10 Counter cumulative distribution function for GPS accuracy. Data collected in Rome (red line) and data collected in Puerto Ayora (blue line)

Effects of environment on GPS fixes accuracy

In Fig. 10, we compare the counter-cumulative distribution function (CCDF) of the error of GPS positions acquired in Rome (red line) and Puerto Ayora (blue line). As expected, it is possible to note that the vegetation introduces a decrease of achieved accuracy. This reduction is, however, acceptable, leading to an average error gap of less than 15 m over the 50% of the cases.

Evaluation of accuracy from WSN devices deployed in the field

In Fig. 11, we show the GPS fixes of a WSN device attached to a yellow iguana on Wolf Volcano. Due to the high value of these iguanas in the illegal pet trade, we prefer not to georeference the points in the map. Additionally, although the relative geographic distances between points are real, the characteristics of the landscape are not provided in the map. Green dots represent GPS fixes with HDoP values ≤ 1.4, while orange dots represent values $1.4 < \text{HDoP} \leq 2$, and red dots represent GPS fixes with HDoP values ≥ 2. We used a cut-off value of 1.4 based on the distribution of HDoP values compared between Wolf Volcano and Puerto Ayora (Fig. 12, top) and Wolf Volcano and Rome (Fig. 12, bottom). Despite being slightly greater than the median value of HDoP distributions (see later), such threshold well discriminates points grouped together from those more geographically dispersed, as shown in Fig. 11. For this reason, we conclude that geographic locations indicated by points with HDoP > 1.4 must be regarded as unreliable.

We further estimated and compared the medians of such distributions, after rejecting normality ($W_{\text{Shapiro–Wilk}} = 0.126$, 0.066, 0.119; $p \lll 0.001$, for Rome, Puerto Ayora, and Wolf Volcano, respectively). Medians resulted very similar (1.24 for Rome and Puerto Ayora and 1.26 in Wolf Volcano), yet statistically different ($H_{\text{Kruskal–Wallis}} = 15.72$; $p \ll 0.001$). When the Mann–Whitney test was applied (Table 3), Wolf Volcano was statistically different from Rome, whereas it was not from Puerto Ayora, although in this case, statistical significance was marginal.

These data indicate that despite a decrease in the quality of data received from Wolf Volcano, such an effect is not severe. In fact, it was almost negligible.

Conclusions

In conclusion, we illustrated some of the technical challenges related to the design, construction and operation of devices to track animals in the wild, with particular focus on iguanas. Problems related to the collection of data from sensors installed on the same device may be successfully tackled by comparing data collected under different environmental conditions. Systematic bias may exist, in some cases, they are idiosyncratic (collection of GPS positions), in other cases, they are introduced by the technological implementation of the device (in our case, temperature and UVB measurements). Understanding the nature of the bias is crucial to provide models for their effective correction.

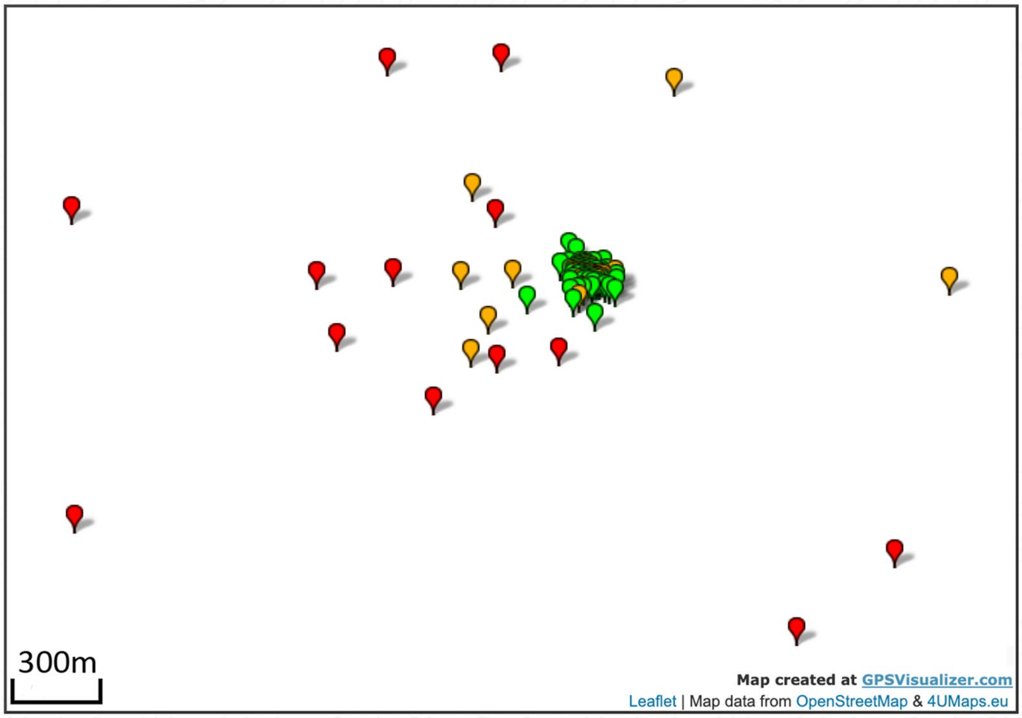

Fig. 11 GPS fixes of a yellow iguana. The above map shows data collected from a WSN device attached to a yellow iguana on Wolf Volcano. Green dots represent GPS fixes with HDoP values ≤ 1.4, while orange dots represent values 1.4 < HDoP ≤ 2, and red dots represent GPS fixes with HDoP values ≥ 2

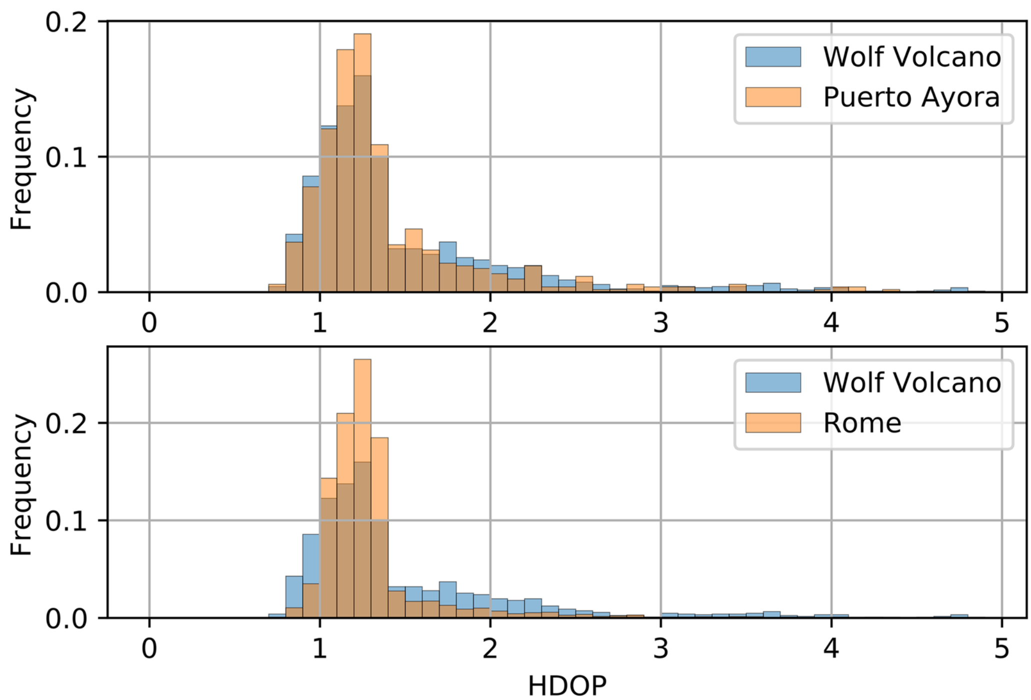

Fig. 12 HDoP value distribution comparison. Distribution of HDoP values compared between Wolf Volcano vs Puerto Ayora (top), and Wolf Volcano vs Rome (bottom)

Table 3 Mann–Whitney *U* statistic is below the diagonal

	Rome	Purto Ayora	Wolf volcano
Rome	–	0.474	⋘ 0.001
Purto Ayora	1165294	–	0.069
Wolf volcano	2599286.5	294801	–

Probability values (*p*), after Bonferroni correction, are above the diagonal

Abbreviations
CCDF: Counter-cumulative distribution function; GPS: Global positioning system; HDoP: Horizontal dilution of precision; PVC: Polyvinyl chloride; UVB: Ultraviolet light, type B; WSN: Wireless sensor node; WV: Wolf volcano.

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Authors' contributions
PL and LB, contributed with software design, data collection and analysis, and writing the manuscript. MDL contributed with software designing and devices' casing design. GC and GG contributed with experimental design, collection and analysis of data, and writing the manuscript. CV contributed with field work and data collection. GPG contributed with technical reviews and writing the manuscript. All authors read and approved the final manuscript.

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Not applicable.

Consent for publication
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Competing interests
The authors declare that they have no competing interests.

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