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Characterisation of a new lightweight LoRaWAN GPS bio-logger and deployment on griffon vultures *Gyps fulvus*

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Abstract

1. Information provided by tracking studies using remote telemetry is providing ecologists with invaluable new insights into animal behaviour and movement strategies. Here we describe a new type of GNSS (Global Navigation Satellite System) tracking device currently under development and nearing commercialisation, which transmits data via LoRaWAN (long range wide area network) gateways. These tags have the potential to be a low weight and power consumption solution for tracking the movement of animals at high resolution. 2. We characterise the position accuracy and data transmission range, including uplinks and downlinks, for the tracker using a series of ground-based field tests. Data transmission range was tested by visiting locations with line of sight to the LoRaWAN Gateway at distances up to 75 km and recording whether data transmission was completed successfully from each location. These tests were complemented by a trial deployment of six devices on griffon vultures *Gyps fulvus*. 3. These LoRa tags reliably provided accurate position estimates, particularly on more frequent acquisition cycles. At 1-min intervals the GNSS location bias was 4.71 m in the horizontal plane and 5 m in the vertical plane while precision, measured by standard deviation, was 3.9 m in horizontal space and 7.7 m in vertical space. Ground-based range tests confirmed data transmission from a maximum distance of 40.7 km. Initial results from a deployment on griffon vultures yielded useful information about flight speeds, altitude, and transmission range (up to 53.4 km). 4. With consistent GNSS position accuracy and the ability to transmit data over tens of kilometres, the LoRa tags demonstrated potential for monitoring animal movement over large areas. The small size and power needs of the device allow for flexibility in which combination of battery, solar panel, and housing they are paired with. The tags can be assembled in housing formats ranging in size from less than 5 g for deployment on Kestrel sized birds to 80 g for deployment on large birds such as vultures. The devices are particularly suitable for philopatric (site-faithful) species because LoRa gateways can be installed near breeding sites to maximise opportunities for data transmission. Our findings are informative for studies seeking to use LoRa for tracking birds and other animals using the miro-Nomad or a different type of GPS-LoRa logger.

Keywords GPS tracking, Biologging, LoRa, LoRaWAN, LPWAN, Animal movement

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Background

Advances in biologging technology are allowing ecologists to collect data about animal movements and behaviour at unprecedented high spatial and temporal resolution. GNSS (Global Navigation Satellite Systems), of which GPS (Global Positioning System) is one of four main systems alongside GLONASS, Galileo, and Beidou, provide positional information accurate to within a few metres [1, 37]. This level of detail allows researchers to remotely monitor the location and movement behaviour (speed, flight height, direction of movement, energy expenditure and dwell times). Alongside location information, some bio-loggers record data from accelerometers and other sensors which can be used to categorise behaviours (resting, feeding, flying or walking for example) and measure environmental variables such as temperature and air pressure [12, 38, 40, 53]. Many trackers are now able to combine information from these sensors to change the quantity of data recorded depending upon what the animal is doing for example recording a burst of GNSS/GPS or accelerometry data when a bird commences flapping or gliding during flight [58].

The data from tracking studies are providing new insights into animal movement and ecology [48, 67]. High-resolution tracking data can be paired with environmental variables such as climate, weather, season, terrain and landcover to help understand the drivers of animal movement. Using this approach, the flight paths and height above ground of Black Kites Milvus migrans were shown to be predicted by the strength of orographic uplift (caused by terrain diverting wind currents vertically) and thermal uplift (cause by the temperature differential between the ground and the atmosphere) [50]. Tracking data can also be used to assess the importance of human impacts such as disturbance, land use change and the availability of artificial food sources upon the movement behaviour of birds. For example, the availability of food at landfills is changing the movement and migratory behaviour of white storks Ciconia ciconia in Portugal [16]. Another application is to better understand conflicts between wildlife and human activities such as renewable energy development as demonstrated by Schaub et al. [52] who used high-resolution tracking behaviour to better understand the avoidance behaviour of Montagu's Harriers Circus pygargus around wind turbines in the Netherlands. These examples highlight how bird-mounted tracking devices can provide important information to inform conservation actions for birds and other animal species, however it is important to balance this with the potential impact on individual animals [4].

To date, the major factors which have limited the wider use of biologging technology have been the financial cost, size and weight of tracking devices [6, 23]. The purchase price of GPS tracking devices ranges from a few hundred to several thousand Euros. Alongside this, data costs associated with sending the data via mobile phone networks (GSM or GPRS) or satellite systems (Iridium) can cost hundreds of euros per year per device [6]. For animal welfare reasons, tags should not exceed 3–5% of the animal's weight [6, 47] and lower weights are recommended to make sure the devices do not negatively affect animal behaviour or fitness [25, 47]. To reduce energy requirements, tracking devices suitable for smaller species often rely on the physical recovery of the device from the tracked animal or, as is the case with devices which utilise UHF download of GNSS/GPS location data from within a few hundred metres of the animal [13, 38, 59]. The requirement to physically retrieve the tag or get close to the animal to receive the data can be labour intensive and losing data is a significant risk if the animal dies or the device falls off before retrieval [13, 44]. Transmitting data remotely, over long distances, is a better solution since it can provide near real time understanding of an animal's movements and reduces the risk of losing data [13, 46]. Most remote tracking systems capable of sending data over long distances do so via GSM (Global System for Mobile communications), ARGOS or Iridium satellites [38]. However, the financial cost associated with data transmission subscriptions needed for these methods (Additional file 1: Table S1) can place a constraint upon sample sizes and the high energy consumption biases tracking studies towards larger species because of the need for larger, heavier, batteries and solar panels [6, 46, 56]. Currently the lightest solar powered GPS-GSM bio-loggers for birds weigh over 6 g while others weigh over 8 g [19, 28] (Additional file 1: Table S1). New low-cost, light weight technologies with the capability to remotely record and send data at high frequencies are needed to help expand the use of satellite telemetry to a wider range of species and applications.

As highlighted by Mekki et al. [30], open source low-power wide area networks (LPWAN) offer a potential alternative solution to GSM for transmitting data from GPS/GNSS tags over long distances. LoRa (long range communications) is a type of unlicensed LPWAN (low-power wide area network system) communications protocol within the IOT (Internet of Things) architecture alongside Sigfox (now unsupported) and the proprietary NB-IoT. Under this architecture the devices, often referred to as Nodes, are connected to the internet by transmitting data to a LoRaWAN (long range wide area network) gateway which in turn forwards the data to a server via a GSM, WIFI or Ethernet internet connection. A data subscription is only needed for each gateway which can provide connectivity for hundreds of LoRa devices meaning the total annual data cost per tag can be reduced to almost zero [27, 30, 61]. The low energy consumption of LoRa, typically ~ 28 mA, with a maximum of ~ 118 mA during data transmission, compares favourably with more energy intensive methods of data transmission such as GSM, typically 240–360 mA but can exceed 1000 mA during data transmission [14, 42, 55]. This allows LoRa to efficiently send data over long distances, typically 3 km in cluttered environments and over 25 km with clear line of site [14, 30, 34, 55]. However, the low energy requirement does have a drawback in terms of the rate of data transmission. LoRa data payloads are limited to less than 243 bytes and the maximum data rate is 50 kbps (kilobits per second) which is roughly one-third of the speed of the 3G GSM transmission typically used by GPS-GSM tracking devices and approximately 1/2000th the speed of 4G (100 Mbps) [36].

Data transmission speed for LoRa also varies depending on the spreading factor (SF), which is effectively a measure of the duration of the transmission, usually referred to as a CHIRP (Compressed High-Intensity Radar Pulse), required to send a given unit of data [30]. LoRa uses six spreading factors SF7 to SF12 which are adaptively used depending on factors such as proximity to the LoRaWAN Gateway which affect the transmission duration. Higher spreading factors are used when more time and energy is required to send a packet of data whereas a lower spreading factor is used when less energy and time is required to send the data [30]. Within Europe where LoRa devices use the 868 MHz frequency band with a bandwidth of either 125 hHz or 250 kHz data transmission speeds range from 250bps (bits per second) at SF12 to a maximum of 11,000 bps at SF7 [20]. To put that in context a typical location or ACC (acceleration) payload sent by the Nomad tracker consisting of 160bits would take approximately 13 ms (milliseconds) to be sent at SF7 compared to approximately 640 ms at SF12. To ensure compliance with the LoRa fair usage policy [61] most LoRa devices use an adaptive data rate system to ensure the advised maximum airtime of 30 s per 24 h is not exceeded. As such, it is important when planning the deployment of LoRa devices to understand if the animals being studied are likely to spend a significant amount of time away from transmission range to a LoRaWAN Gateway and adjust data acquisition and transmission rates accordingly.

In this paper, we describe the characteristics of the miro-Nomad GPS tracker. This is a new type of logger developed in partnership between the University of East Anglia, Movetech and Miromico to provide a lower cost, lightweight, high-resolution tracking solution. The logger uses LoRa to transmit data stored on the device and has the capability to recording high accuracy, high frequency, location data alongside other measurements [8]. The device has been used extensively to monitor for landslides and other geohazards [8] and is now being applied to study the movement of birds and mammals. While it is important to contextualise the use of LoRa with the performance of other technologies, several other studies have already performed similar comparisons [14, 30, 57]. This study specifically aims to describe the characteristics of a new LoRa miniaturised device in terms of the GNSS position accuracy, data transmission range, and post-deployment performance to assess its viability for animal tracking studies and provide recommendations for using LoRa in the context of animal biotelemetry.

Methods

Description of the nomad GPS-Lorawan devices

The miro-Nomad GPS-LoRa logger equipped with a ZOE GNSS chip (Figs. 1, 2), referred to as "Nomad" hereafter, used in this study has been developed under a NERC Proof-of-concept project led by University of East Anglia in a collaborative project between Movetech Telemetry and Miromico [31, 64]. The Nomad PCB (printed circuit board) module measures 23 mm by 13 mm, weighs 0.9 g alone and less than 1.5 g when paired with wire LoRa and GNSS antennas (Fig. 2a, c). Where weight is less of a constraint, other types of antennae can be used, such as ceramic (Fig. 2a), to suit the study species' needs. The devices are capable of recording GNSS measurements up to every second (1 Hz) independently of the other sensors which include two accelerometers, a gyroscope, a magnetometer, a barometer, and thermometer. The 9-axis sensor can capture acceleration measurements at resolutions ranging from 10 to 200 Hz, and can be programmed alongside the gyroscope and magnetometer, with each sensor able to record data at the same or different rates. As with the location data, data from the 9-axis sensor is then processed and stored by the tag until it is in contact with a LoRaWAN Gateway for sufficient time for the data to be sent via LoRa. The device also measures battery voltage and temperature so battery health can be monitored and reprogrammed remotely as needed using the downlink function on LORIOT. Although the devices can protect the battery from being discharged, for configurations which use solar, a harvester is recommended to help regulate energy consumption and protect the battery from overcharging. A version of the Nomad PCB with built-in harvester is currently in development which will allow for smaller housings and additional weight savings during tag assembly.

Data are sent via a LoRa to a LoRaWAN Gateway (Figs. 1b, 3), which then forwards the data via the internet to an Internet of Things network server such as LORIOT [27] or The Things Network [62] which in turn can forward the data to a data repository such as Movebank or

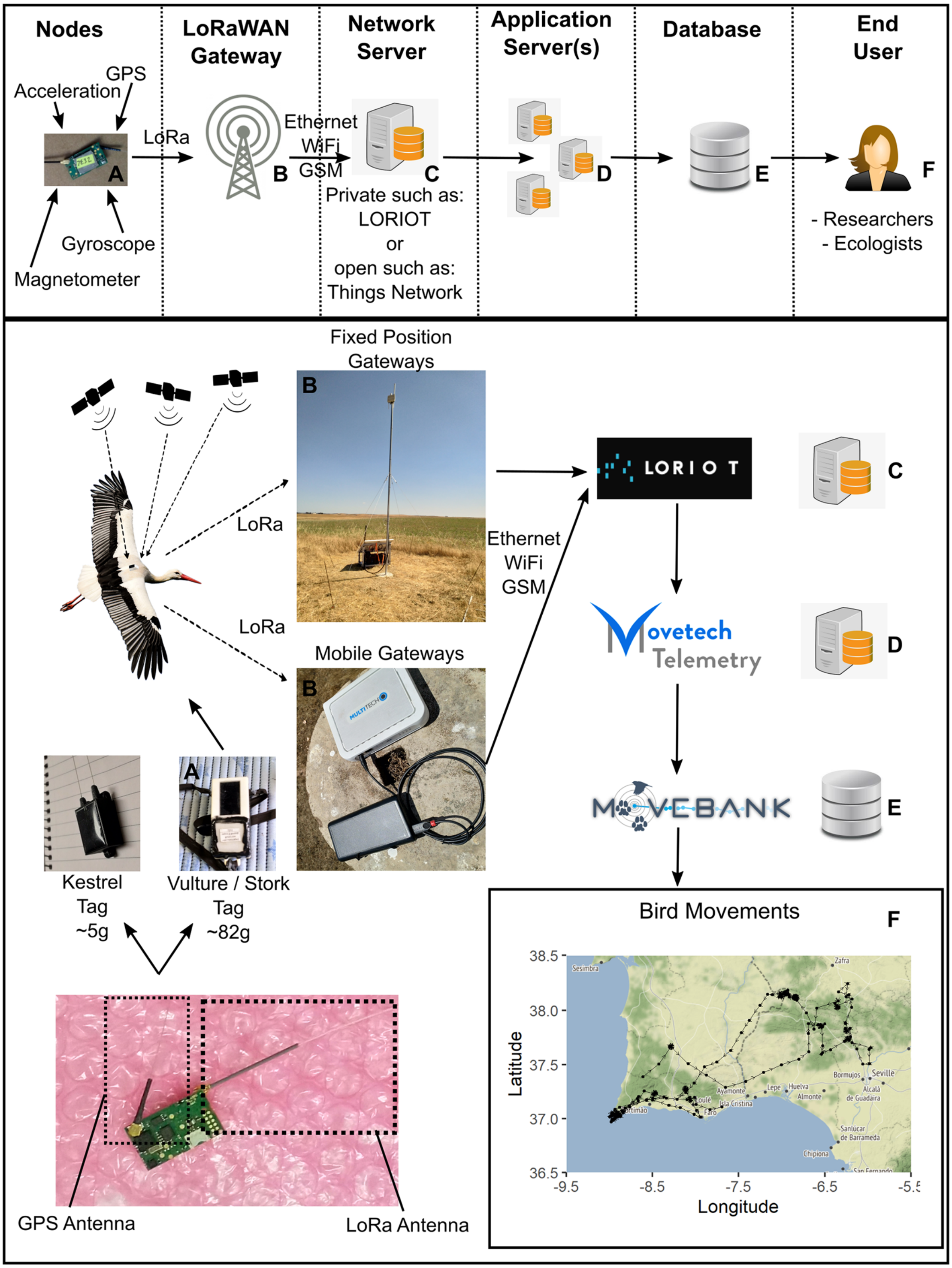

Fig. 1 HYPERLINK "sps:id::fig1||locator::gr1||MediaObject::0" An overview of the LoRa system. The data are sent via LoRa (**A**) to a gateway (**B**) which in turn forwards the data to a network server such as LORIOT or TTN (**C**) via an internet connection such as GSM, *WiFi* or Ethernet. The network server then forwards the data onto one or multiple application servers (**D**) which decode and store the data. From the application server, data can either directly downloaded or re-formatted and forwarded to a publicly accessible data base such as *Movebank* (**E**) where the data can be downloaded for analysis by multiple users (**F**). Fixed position gateways can be indoors, mounted to a building or standalone solar powered systems. Mobile gateways can be powered by a portable power bank and carried in a car, on foot or flown on a drone to maximise coverage. The lower panel highlights how these tags are used in practice to track animals

Fig. 2 **A** GPS-LoRa tag configured for vultures prior to assembly using a ceramic GNSS antenna, *molex* flexible LoRa antenna and a 1100 mah LiPo battery. During assembly the housing was re-enforced with potting epoxy. **B** The GPS-LoRa tag deployed on a vulture, photo taken immediately prior to the bird flying away. **C** The PCB which can be paired with different types of GNSS/GPS and *LoRA* antenna depending on weight requirements, with wire or flexible antennas it weighs 1.5 g. **D** GPS-LoRa tag configured for kestrels with a total weight of 4.5–5 g including housing, solar panel, antennae and 40 mah battery. **E** Tag deployed on a common kestrel *Falco tinniculus*. **F** 10 g GPS-LoRa tag configured with a solar harvester and 30 mah battery prior to assembly. **G** The 10 g GPS-LoRa tag used for the position accuracy tests

IoT Wonderland [21, 33] (Fig. 1). Where good coverage provided by gateways registered on the open TTN network is available, typically in urban centres [63], using a TTN server can be a low-cost option for deploying new LoRa devices. However, in southern Portugal and Spain, TTN coverage remains limited, as such we deployed gateways and GPS-LoRa devices registered on a private LORIOT server. LORIOT can provide greater control over the number of devices using the LoRaWAN Gateways deployed by the account holder along with

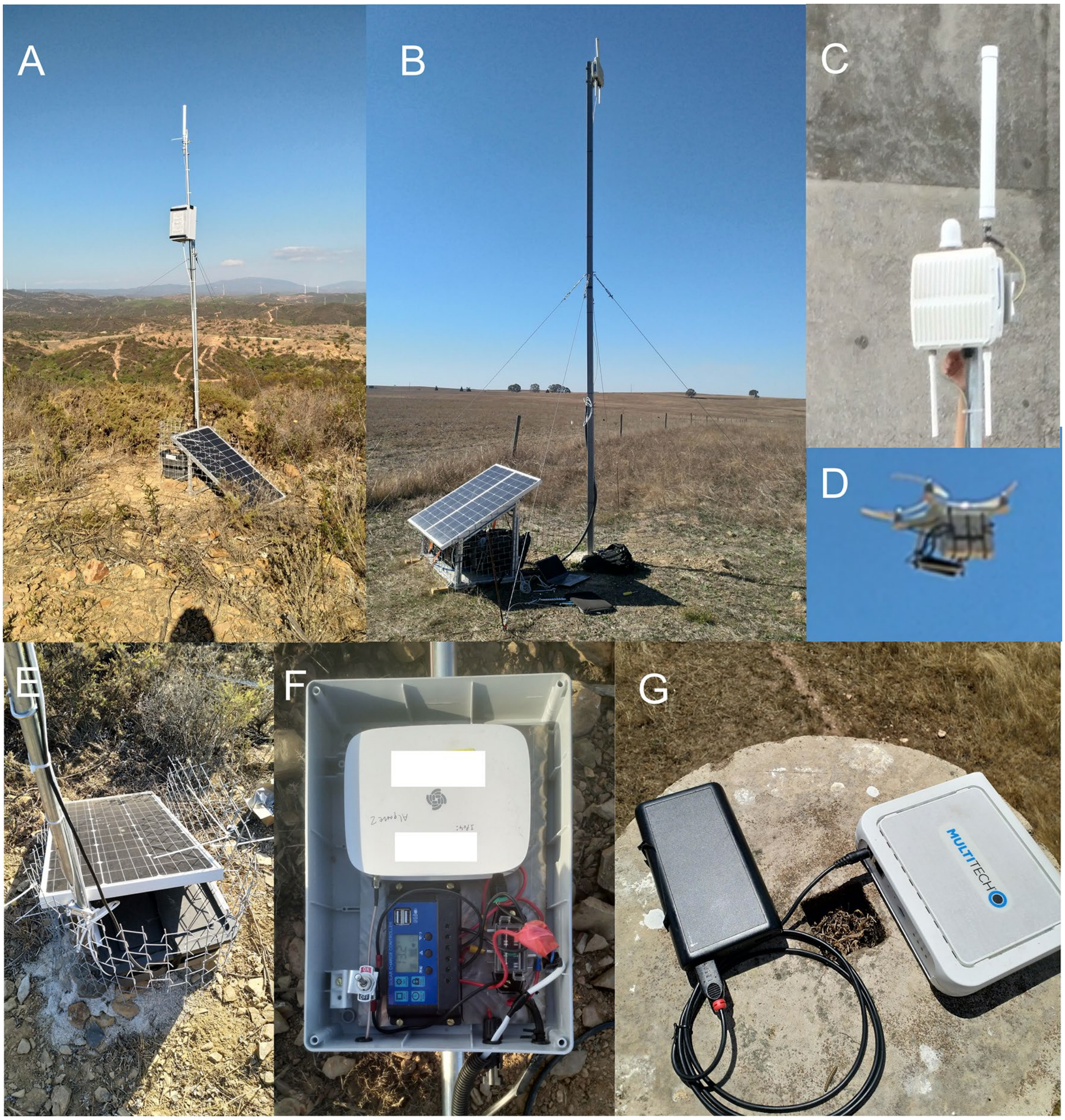

Fig. 3 Examples of *LoRaWAN* Gateway configurations. **A** Custom *LoRaWAN* Gateway solar system constructed by ruggedising a RAK 'indoor' *LoRaWAN* Gateway, total materials cost at the time (2021) was approximately £500. **B** LoRaWAN Gateway solar system with a 24v solar system and MultiTech IP67 gateway [34], total system cost approximately £2500. **C** Close up of the IP67 MultiTech *LoRaWAN* Gateway. **D** A proof of concept UAV (unmanned aerial vehicle) flight with the mobile gateway. **E** View of the solar and battery set up for the 12v system to supply the adapted RAK indoor gateway. **F** Inner workings of the ruggedised gateway solution put together using off the shelf components. **G** A mobile *LoRaWAN* Gateway powered by a USB power bank

scalability to allow for hundreds of gateways and nodes on one account along with technical support to help users integrate their devices with different platforms and data servers. The gateways used fall into two broad categories: fixed position 'Outdoor' gateways (Fig. 3a–e) and mobile gateways, sometimes referred to as 'indoor' or 'mobile' gateways (Fig. 3G). The cost of LoRaWAN Gateway systems range from less than 100 euros for a simple ethernet or WiFi connected 'indoor' LoRaWAN Gateway up to 2000–3000 euros for a fully autonomous, "off the shelf" solar powered outdoor gateway system with LTE (long-term evolution)/GSM connectivity.

The Nomad tracker software allows users to tailor the data collection to the research question depending on study species and battery size. GNSS position and acceleration can be recorded at regular intervals or to trigger recording of higher intensity data based on trigger parameters detected by one of the accelerometers. For example, when the force measured by the accelerometer exceeds a pre-programmed force threshold. This allows for live detection of collisions between birds and human infrastructure and more intensive sampling when the bird is moving. The tags used in the tests described in this study can store up to 60,000 data records in the onboard memory, newer versions can store up to 100,000 records. Each record represents a single data payload in containing either a welcome message, status message, location information (GNSS), acceleration data, magnetometer data or gyroscope data. Users have the option of deciding whether to transmit this data in chronological order or to receive the most recent data first by changing the data buffer mode.

The loggers can be set to send data in chronological order of when it was recorded or send the most recent data first. With a migratory bird it might be useful to ensure the most recent locations are sent first whenever the bird is in range of the gateway, whereas for a more sedentary species which is likely to remain within gateway range most of the time sending the data in chronological order may be preferable. When a device is in range of a gateway it will try to transmit on a user-specified duty cycle (usually one payload every 15–20 s or up to 180–220 payloads per hour). The device detects when it is in range of a gateway because an acknowledgement message is sent by the LoRaWAN Gateway once the data have been successfully forwarded to the server. The acknowledgement ensures that each message stored on the payload buffer on the device is only deleted from memory after it has been successfully forwarded to the server by the LoRaWAN Gateway. This confirmation feature also facilitates the remote programming of device settings and ensures data not received by a gateway, is not lost. If an acknowledgement message is not received, data are kept in the buffer and the device switches to a user-specified longer interval forced transmission duty cycle (usually 30–60 min) once the payload is sent and an acknowledgement is received the device restarts transmitting data more frequently according to the standard duty cycle.

Animals may move away from the range of existing gateways (or may be in landscapes with signal obstructions) and in these cases the data transmission alternates between TX and TXF cycles to save energy. The TX cycle is used when the tag is in contact with the gateway whereas the TXF cycle is used when out of gateway range to force the tag to attempt to contact a gateway at a user-specified interval. Weaker signals are associated with a high spreading factor and reduced data transmission speed. Meaning the acknowledgement from the gateway that a given payload has been successfully forwarded to the server is less likely to be received by the device within the required timeframe, designated as the RX1 (usually 1-s) or RX2 (usually 2-s) window (TTN 2021). Where confirmation is not received within the RX1 or RX2 windows the data are stored until contact with a gateway is re-established. Transmission speed decreases by a factor of two as spreading factor (SF) increases. SF also influences the data rate. This is because the devices have an adaptive data rate (ADR) feature to ensure compliance with the LoRa fair use policy [32, 61]. The NOMAD devices do this by measuring the spreading factor (SF). As with other LoRa devices, in practice this means that at a lower spreading factor the user-specified transmission cycle will be closely followed whereas when the device is further from the gateway or there's interference resulting in a high spreading factor the data rate may drop to just a few messages per hour to avoid breaching the fair use policy and conserve power [24].

Quantifying position accuracy

The devices use a uBlox ZOE-M8Q GNSS chip capable of communicating with GPS, Glonass, Navstar and Beidou satellites to determine the spatial co-ordinates and altitude of the tag. The accuracy of GNSS measurements was tested under different fix acquisition rates (1, 30 and 60 min) by leaving a tag in position on a geographical marker (Additional file 1: Fig. S1; Fig. 2g) with known co-ordinates (37.7481317, − 8.0403338), a clear view of the sky and altitude above sea level (222 cm) for sufficient time to acquire at least 300 locations (358 locations at 60-min intervals, 367 locations at 30-min intervals and 767 locations at 1-min intervals). The GNSS sampling interval was adjusted remotely via the downlink feature in LORIOT. Total device weight including housing, solar panel, harvester, epoxy and batter was 11 g. During the 60-min cycle test the tag was in sight of a mean of 11.7 ± 1.3 (standard deviation) GLONASS and 7.4 ± 1.5sd Galileo GNSS satellites, for the 30-min cycle this was 10.6 ± 1.7sd GLONASS and 7.9 ± 1.6sd Galileo satellites and for the 1-min cycle this was 12.9 ± 1.3sd GLONASS and 5.7 ± 1.4sd Galileo satellites. No Navstar or Beidou satellites were observed by the tag during the tests.

Accuracy for each location estimate was calculated by calculating the distance between the horizontal and vertical co-ordinates with the known location of the geographic marker. These horizontal distances were calculated using the Geosphere package in R version 4.0.5 [17]. Accuracy encompasses two components, bias and precision [65]. Bias was calculated as the mean location error relative to the true location to inform us about the magnitude of systematic over or underestimation of the true position resulting from the GNSS measurements and the standard deviation was used to quantify the precision, i.e. the random spread of the error relative to the true value [65]. A one-way ANOVA and post hoc Tukey's HSD significance test was used to determine whether there was a significant difference in accuracy between different GNSS acquisition cycles in terms of horizontal and vertical location estimation.

Quantifying LORA transmission range

The documented estimates of maximum transmission range of long-range wireless vary considerably in the available literature. Data transmission for a mobile gateway model (MultiTech Conduit MTCAP-LEU1-868-001A) can range from 17 km with clear line of sight and 2–3 km in more cluttered environments [34] but it has also referred to be up to 40 km with clear line of sight for LPWAN data transmission [30]. The world record for data transmission between a node and a LoRaWAN Gateway with LoRaWAN within the Earth's atmosphere of 766 km was set in 2019 using a weather balloon at high altitude [60]. The record highlights the potential of this technology to send data long distances however, this kind of transmission distance is not realistic under most usage scenarios.

The main focus of the range tests was on data transmission from a NOMAD node to a Multi-Tech IP67 outdoor gateway [7] located at co-ordinates 37.731°, − 8.029°, mounted on a mast 5.5 m above the ground (Fig. 3b). During the range tests gateways other than the target gateway were switched off. Four NOMAD devices with different antenna types (flexi, gold-plated wire, brass wire and silver-plated wire) were set to record and transmit GNSS locations and status messages at least every 15 min. Acceleration and other sensors were disabled. The devices were taken to locations of known distance away from the gateway ranging from < 1 km to ~ 70 km. Test locations were identified using viewshed analysis in QGIS [41] to determine locations with line of sight to the gateway. The viewshed analysis assumed that both device and gateway were at 5 m above ground level. To achieve this, the devices were placed in anti-static bags and suspended vertically with antennae pointing toward the sky from a frame elevated using a telescopic pole to a height of 5 m at all test locations (Fig. 4a). At each location, the data stream from the gateway was monitored using a web browser interface on a smartphone and the devices left in position until either all four devices had successfully transmitted data, or half an hour had elapsed to allow for transmissions on a 15-min TXF cycle. Transmission was deemed successful from a given location if at least one device was able to contact the gateway for sufficient time to allow for multiple data packets (status and/or location) to be sent. Transmissions consisting only of the initial 'welcome' message data packet used to confirm communication with the gateway was not classed as a successful transmission. The range test was also repeated at the locations in Fig. 4c with two Nomad™ devices using a portable Multitech™ Mobile Gateway (MTCAP2-L4E1-868-002A-POE) up to 17 km. All range tests were conducted under field conditions in Portugal during May and June of 2021 on calm, dry days with minimal cloud cover.

Case study with griffon vultures

In October of 2021, six devices were deployed on griffon vultures *Gyps fulvus* as a trial deployment to test the GNSS and accelerometer features of the loggers. Here we report on the location information acquired during this trial deployment and the data transmission performance. The GPS-LoRa Modules were assembled in a solar powered configuration including an integrated solar panel and harvester, 1100 mah lithium-polymer battery, ceramic "high gain" GNSS antenna using a Movetech flyway-50 housing (Figs. 1, 2, Additional file 1: A1: Fig. S2). Griffon vultures have powerful beaks, to increase tag durability the top half of the housing was re-enforced with several layers of potting epoxy prior to assembly and additional plastic was mounted on the exterior of the housing to help increase durability of the device. As such, the final device weight was 83 g, which equates to approximately 1% of the body mass of the tagged birds. The component cost for assembling the device was approximately £350 in 2020 although this does not account for the labour costs involved in tag assembly. The final price once commercialised will likely be similar to that of GSM tags with similar capabilities.

The devices were programmed to record a GPS/GNSS location every 30 min and one second burst of acceleration measurements at a frequency of 50 Hz whenever a force exceeding 3.2 g was detected with a view to detecting avoidance or collision events. The loggers were deployed in Southern Portugal under licence from CNF—Instituto da Conservação da Natureza e das Florestas, on the 23rd and 24th of October 2021 using a backpack style harness with a weak link consisting of

(See figure on next page.)

Fig. 4 **A** Pole used to elevate the NOMAD devices to 5 m at each location. **B** Ground-based range test locations for the fixed position LoRaWAN Gateway. **C** Ground-based range test locations for the mobile LoRaWAN Gateway. **D** The mobile gateway used. **E** The location in Portugal where the mobile gateway was tested. Hollow circles represent locations where data transmission from the devices to the gateway was not confirmed, filled circles represent locations where data transmission was confirmed. The orange areas represent areas with line of sight to the gateway at 5 m above ground, this was calculated in QGIS using the viewshed analysis tools and a 30 m digital surface model from [41]

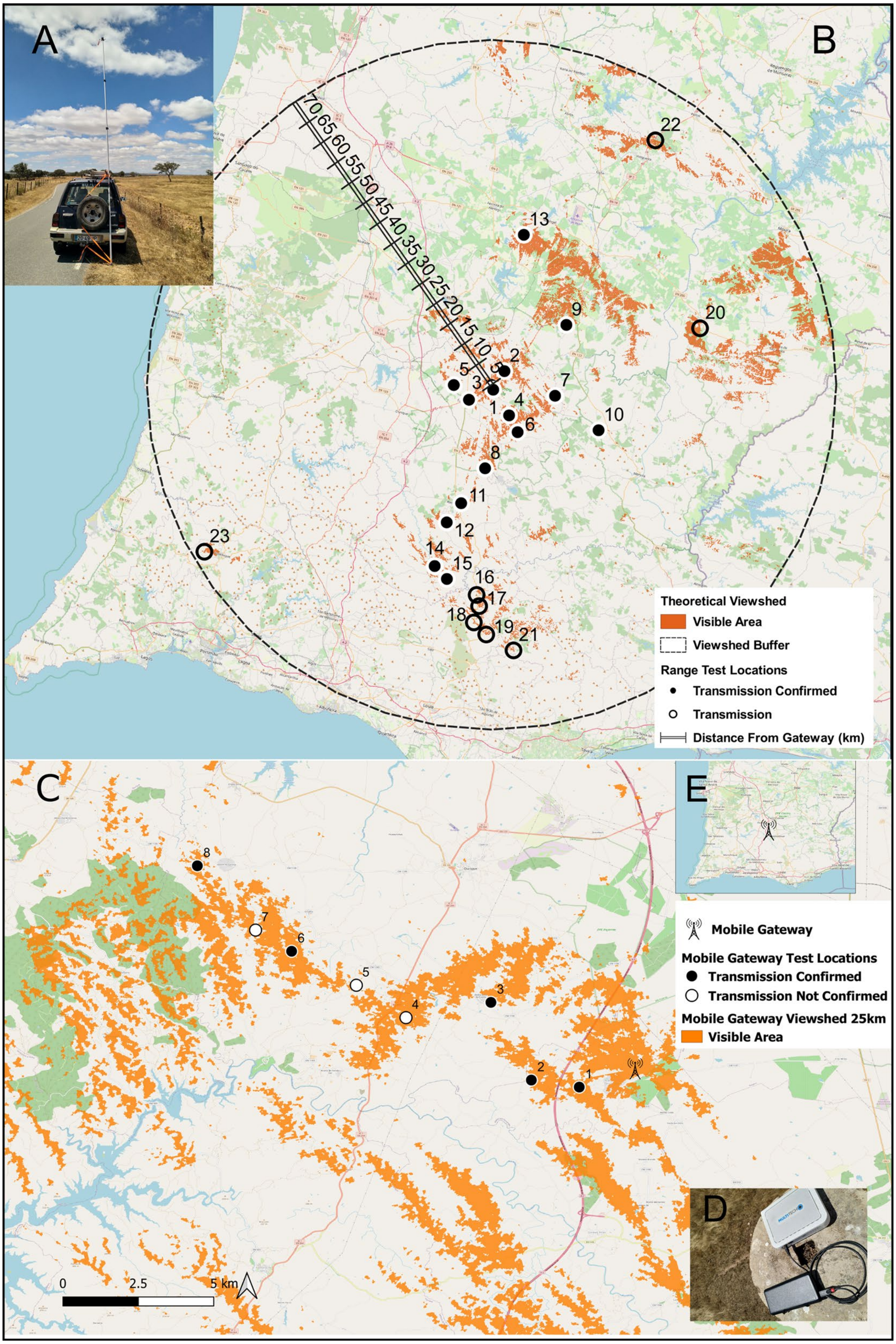

Fig. 4 (See legend on previous page.)

cotton thread which is used to sew on the back pack harness where the straps meet at the birds' sternum [3]. The cotton is intended to biodegrade over time to ensure the loggers fall off after a few years (typically 1–3 years) without harming the bird. Four of the tagged birds were caught and tagged near Bensafrim, north of Sagres in Southwest Portugal on the 23rd of October and the remaining two birds were rehabilitated birds. The rehabilitated birds were released near Mertola, in Southeast Portugal. To support the vulture tracking work, an additional three fixed position LoRaWAN gateways within important areas for bird migration in Southern Portugal and Spain (Fig. 6e) to complement the Multitech IP67 gateway deployed near Castro Verde in April of 2021. The three additional gateway systems used RAK Wisgate Edge Lite indoor gateways housed within a weatherproof IP56 rated plastic junction box and paired with a 3 dbi outdoor rated gateway (Fig. 3a, e, f). Each system was powered by a single 100 w solar panel and 60ah 12 v battery using a generic 30a solar charge controller. There are plans to deploy more gateways to cover the main migration route between Portugal and Tarifa. Data were processed in R version 4.0.5 [43] and maps were produced using the ggmap and patchwork packages [39, 66].

Here we report the initial results from tracking data received during the first two weeks after tag deployment allowing us to understand the performance of the tags under real world conditions including data transmission range and GNSS performance. Data transmission range was assessed using the pointDistance function in the raster package in R [18] to measure the distance between the nearest LoRaWAN Gateway and the GNSS location of the bird. Transmission success was coded as a binary variable with 0 representing locations where transmission was not possible and 1 representing locations where the GNSS position was successfully sent to a gateway within 1 min of the GNSS location being recorded. Transmission success was then modelled in a binomial generalised linear model (GLM) with a logit link to identify whether any factors aside from distance to the nearest gateway significantly influenced transmission success. The initial model included distance to the nearest LoRaWAN Gateway (km), height of the bird above ground (m), roughness of the terrain as measured by the terrain roughness index (TRI) [11, 45] and landcover associated with each GNSS location [10]. Landcover was investigated because features in the landscape such as buildings and trees may impact upon transmission, however including landcover in the model was found to introduce significant bias because the birds favoured certain habitats over others. As such it was not possible to meaningfully assess the impact of landcover and therefore it was not included in the final model. Co-linearity was checked using the ggpairs function [54], non-significant variables were sequentially eliminated from the model in a stepwise fashion until the most parsimonious model with the lowest AIC value was established. Model outputs were then plotted using the ggeffects function [29].

Results

Position accuracy from GNSS

Location bias relative to the true location in horizontal space (Fig. 5a; Table 1) ranged between 4.71 m for the 1-min cycle, 6.63 m for the half-hourly cycle and 8.44 m for the 60-min cycle. Significant differences between cycles were detected in terms of horizontal precision (Fig. 5a), ANOVA (F (2, 1486) = 19.62, $p < 0.01$). Location precision was highest in the 1-min cycle (3.88 m precision) and lowest the 60-min cycle (18 m precision) (2.79, $p \leq 0.01$, 95% C.I. = [1.68, 3.90]). Errors greater than 100 m only occurred on three occasions representing 0.2% of recorded locations and were associated with the hourly GNSS position cycle.

Location bias relative to the true position in vertical space (Fig. 5b; Table 1) ranged between 2 and 5 m for the three acquisition cycles used. Vertical precision was significantly different between GNSS acquisition cycles (Fig. 5b), ANOVA (F(2, 1486) = 12.72, $p < 0.01$), with the post hoc TUKEY-HSD test confirming the significant differences between the 60-min cycle (28 m precision) and the 1-min cycle (7 m precision) (− 3.44, $p < 0.01$, 95% C.I. = [− 5.37, − 1.52]) as well as the 30-min (15.3 m precision) and 1-min cycles (− 3.25, $p < 0.01$, 95% C.I. = [− 5.16, − 1.34]) but not the 60-min and 30-min cycles (− 0.19, $p = 0.98$, 95% C.I. = [− 2.43, 2.04]). These results indicate a slight overestimation of altitude relative to the true position across cycles with reduced position bias observed in the 30-min and 60-min cycles compared with the 1-min cycle. A small but significant reduction in both horizontal and vertical precision at lower frequency cycles (30-min and 60-min) was also detected which manifests in a greater spread of position estimates compared to the 1-min cycle (Fig. 5a, c; Table 1).

Data transmission range

Ground-based range tests in locations with theoretical line of sight to the "Castro Verde" gateway (Fig. 4) confirmed the ability of these tags to transmit data reliably at all locations at distances less than 40.7 km from the gateway (Fig. 4B). The successful transmission of a single data payload from over 62 km to the North of the LoRaWAN Gateway Mendro (Test location 22, Fig. 4B) suggests that the devices can send data over that distance. However, the latency may be too great for the tag to receive acknowledgement of the payload, or the gateway detects that the signal is weak and therefore fails to

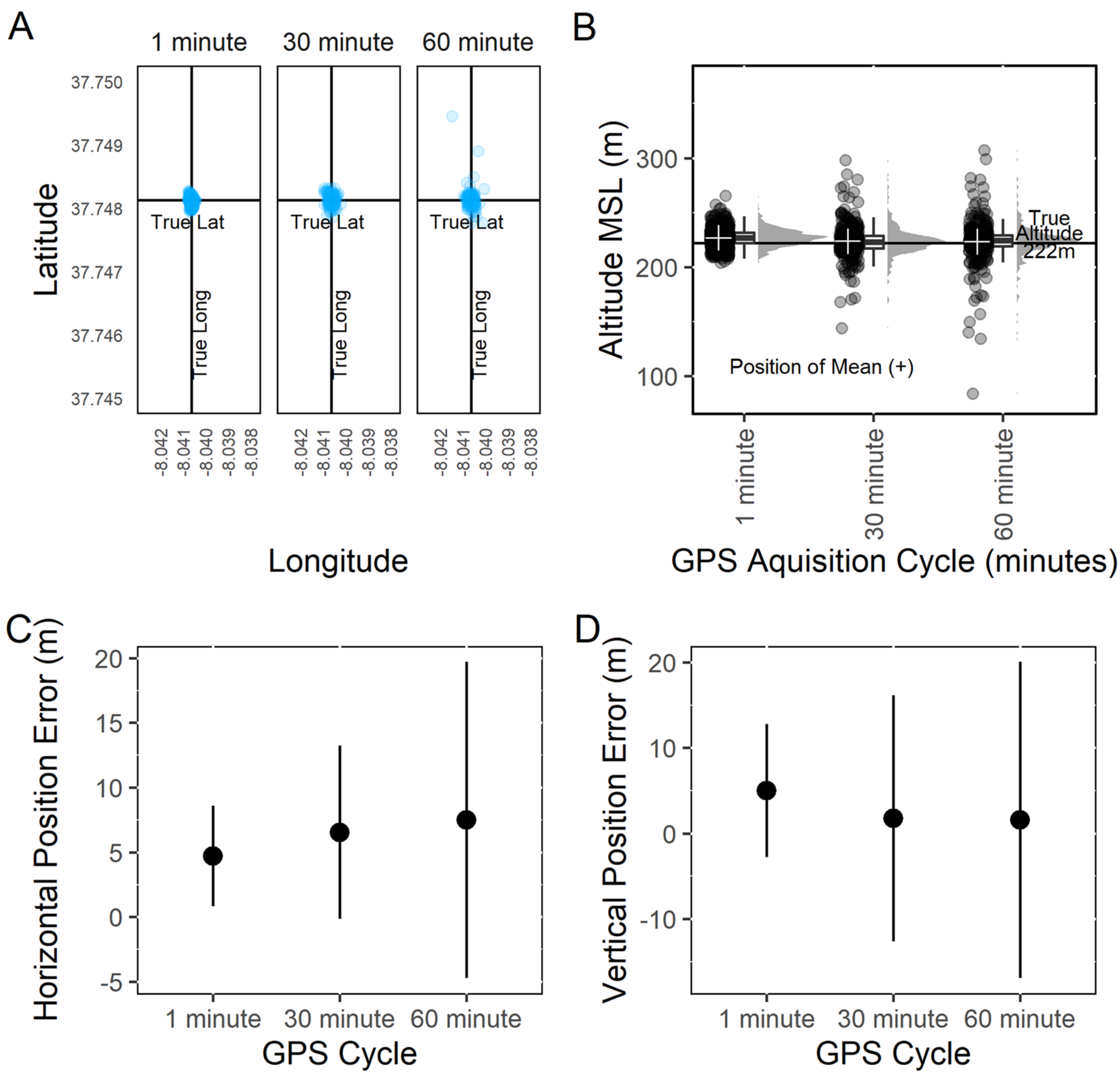

Fig. 5 **A** Distribution of horizontal GNSS/GPS locations relative to the true position under different GNSS acquisition cycles. The mean position in all instances is similar, however the precision of the altitude is best under a 1-min GPS acquisition cycle. **B** The distribution of position estimates relative to the true position in vertical space. **C** Horizontal position error under a 1-min, 30-min and 60-min acquisition cycle, error bars represent the standard deviation from the mean. **D** Vertical position error under a 1-min, 30-min and 60-min acquisition cycle, error bars represent the standard deviation from the mean

send the acknowledgement back to the device. Without an acknowledgement the tag will not send further data which is why this was not categorised as a successful transmission. The tags used during these tests had different types of wire antenna namely, flexible plastic-coated wire, brass wire, silver wire and gold-plated wire but it was not part of the objectives of this study to determine whether this affected transmission range, transmission success was confirmed for all antenna types. This is broadly in line with findings by another study which investigated transmission range and data transmission speed in low-power wireless networks which indicated a maximum transmission range of between 20 and 40 km [30]. Furthermore, we performed range tests using a LoRa device and a mobile gateway. These tests were performed in areas which did not have line of sight to the fixed position Castro Verde gateway and ranged from 2 to 17 km (Fig. 4c). These tests demonstrated successful data transmission at 17 km from the gateway which is in line with the manufacturer claiming a range of 800 m in cluttered environments, 15 km with line of sight [35]. The tests also highlighted how transmission can be impeded by terrain and vegetation because data transmission was

Table 1 GNSS/GPS position error (bias) and precision (standard deviation) in horizontal and vertical space for different transmission schedules from the ground-based test of position accuracy

Cycle	Total Locations	Horizontal Bias	Min Horizontal Error	Max Horizontal Error	Horizontal SD	Horizontal 2.5 Percentile	Horizontal 97.5 Percentile	Horizontal CI 95%	Vertical Bias	Min Vertical Error	Max Vertical Error	Vertical SD	Vertical 2.5 Percentile	Vertical 97.5 Percentile	Vertical CI 95%
1 min	767	4.71	0.35	21.9	3.88	0.53	15	14.4	5	− 18	43.1	7.77	− 10.4	21	20.5
30 min	367	6.63	0.35	39.5	6.91	0.53	27.5	27	2.03	− 78.3	102	15.3	− 26.4	36.4	35.9
60 min	358	8.44	0.35	224	18	0.35	34.7	34.3	2.99	− 138	349	27.4	− 40.2	42.8	42.4

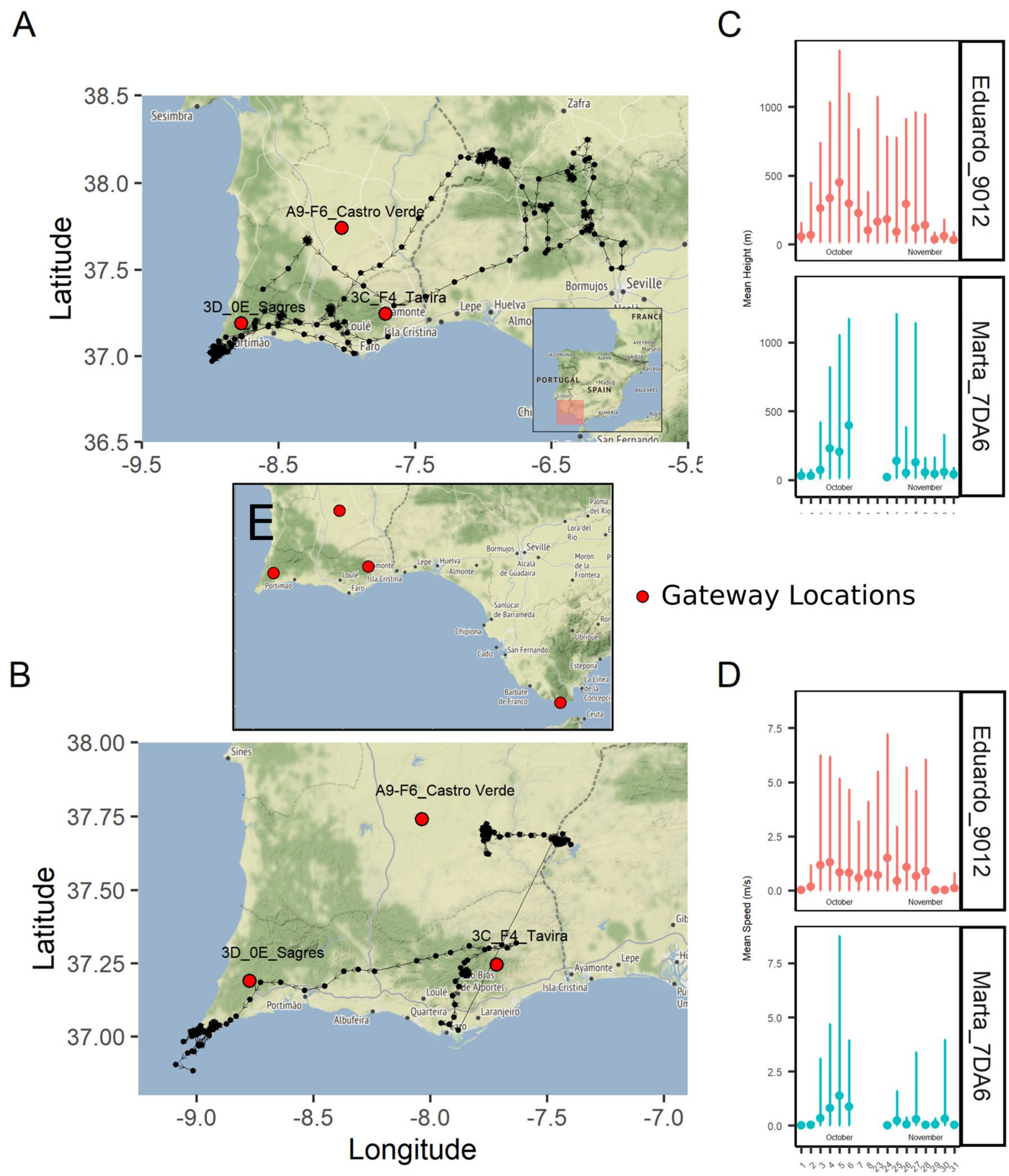

Fig. 6 **A** and **B** Show the movements of the two tracked vultures. All locations shown are in flight. **C** Mean height of the birds above ground and the 95% confidence interval. **D** Mean speed of the birds along with the 95% confidence interval and panel **E**: location of the four *LoRaWAN* Gateways deployed for this project

not successful at 7 km, 9 km and 14 km where there was higher tree cover.

Performance during deployment

Initial data from the deployed tags provided some useful insights into their performance; location data were obtained for two of the six birds which stayed within the vicinity of the LoRaWAN Gateways allowing full data download to occur, the other four tags provided accelerometer data only. This provided 2208 GNSS locations which allowed us to plot the post tagging movements along with daily height and speed for two of the six vultures (Fig. 6a). A daily summary of the movements is provided in Fig. 6 for each bird. Both birds exhibited a high daily variation in movement behaviour in terms of mean daily speed (0–2.65 m/s), height above ground (− 24.9–450.9 m) and total daily displacement of (0.06–209.3 km). The low average step-speed across both birds of 0.26 ± 0.52 SD m/s during this period suggests they may have spent a significant proportion of their flight time circling on thermals. The wild caught bird, 9012_Eduardo, flew to the Extremadura region of Spain near the Portuguese border prior to returning to the area around Sagres, southwest Portugal. The tag on this bird was last seen by a LoRaWAN Gateway on 08/11/2021 as it was travelling west to east along the southern coast of Portugal toward Spain. The rehabilitated bird, 7DA6_Marta, stayed close to the release site near Mertola, Portugal before heading to the Southwest point of Portugal (Fig. 6b). The final location received from this tag was over the Atlantic to the south of Lagos, Portugal at 15:40 on the 6th of November (36.88323, − 9.01409). This vulture lost altitude over the hour preceding the final GNSS record obtained (1474 m down to 583 m above sea level). Had the individual returned to the Algarve, one of the gateways would have picked up the signal from the tag suggesting that, most likely, this individual failed to return to land and likely drowned.

The devices of the other four individuals only sent acceleration but no location data. Despite this it was possible to follow the birds' movements by monitoring which gateways received data from them and when. Data were most recently received from two of the birds on 08/11/2021 and 07/11/2021 by the 3C_F4_Tarifa gateway near the southern tip of Spain suggesting that two birds attempted to migrate to Africa. This is a total minimum distance of approximately 480 km from where they were tagged in southwest Portugal. Two of the six tags deployed appear to have stopped sending data within 48 h after deployment and it is unclear whether this is because the birds moved out of range of the gateway or some other issue. In both cases, the payload buffer on the tag was clearly filled by acceleration recording being erroneously triggered numerous times suggesting an issue with the user defined accelerometer settings. We do not summarise acceleration data further as it is beyond the scope of this paper.

Locations within range of a gateway ($n = 300$, 13.2%) obtained at the time they were transmitted, ranged between 4.1–53.4 km from the nearest LoRaWAN Gateway, whereas locations which were recorded but not immediately transmitted ($n = 1908$) ranged from 9.3–106 km from a gateway (Table 2; Fig. 6). A binomial GLM confirmed distance from the nearest gateway in kilometres has a significant negative relationship with transmission success (− 0.135, DF = 2270, SE = 0.011, $p < 0.001$, $Z = 11.98$) and height above ground in metres was found to have a significant positive effect on transmission success (0.003, $DF = 2270$, SE = 0.0002, $p < 0.001$, $Z = 8.84$). A univariate model in which only height relative to ground was included as a predictor of transmission success was performed less well (AIC = 1357) compared to the model containing both distance and height (AIC = 1276). No significant difference was found between tags and there was no significant effect of terrain roughness detected by the model, this is likely because during flight the birds will generally be above any features on the ground which could obstruct line of sight to the gateway. Plotting the output of the binomial GLM using the ggeffects package [29] suggests the probability of successful transmission drops below 50% at approximately 15 km from the nearest gateway and that transmission range from these devices during deployment is limited to 53.4 km (Fig. 7).

Discussion

Our tests of tag performance revealed the GNSS position data provided by the miro-Nomad is sufficiently accurate for high-resolution animal tracking studies such as those seeking to evaluate the fine scale movement of birds in relation to weather, habitat and landscape factors [51]. Horizontal bias was < 9 m with precision < 18 m and vertical bias was < 5 m with precision of < 28 m (Fig. 5) on up to one hour location acquisition cycles. Accuracy was improved at higher frequency of GNSS position acquisition. LoRa is a promising technology for animal movement studies. Especially for colonial species that frequently return to the same locations and for smaller species because of the possibility to assemble devices

Table 2 Locations obtained within range of a gateway (Y) and their distance in kilometres to the nearest LoRaWAN Gateway and locations which were recorded by the device while out of gateway range (N) which were transmitted a posteriori

Bird ID	Gateway range	Count	Minimum distance (km)	Mean distance (km)	Max distance (km)	Standard deviation distance (km)	Percent
Eduardo_9012	N	283	14.8	81.8	106	32.4	94.6
Eduardo_9012	Y	16	8.6	29.6	50.2	9.21	5.4
Marta_7DA6	N	1625	9.3	34.5	54.2	13.9	85.1
Marta_7DA6	Y	284	4.1	21.5	53.4	6.99	14.9

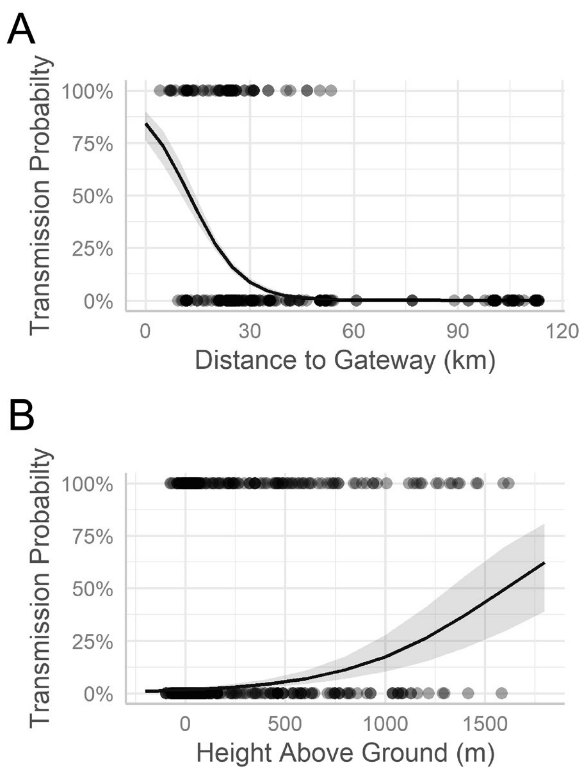

Fig. 7 Predicted relationship of the likelihood of successful data transmission with distance from a *LoRaWAN* Gateway (**A**) and height above ground (**B**) using the output from the GLM in Table 3. The model is derived from the vulture tracking data

Table 3 Summary of final binomial GLM derived from the vulture tracking data relating the probability of successful data transmission to the height above ground (*m*) and distance of the logger (km) from the gateway

(Intercept)	1.53***
	(0.26)
Minimum_Distance_to_Gateway_km	− 0.13***
	(0.01)
Height_Above_Ground	0.003***
	(0.0002)
AIC	1282.66
BIC	1299.85
Log likelihood	− 638.33
Deviance	1276.66
F	98.89
Num. obs	2270

weighing less than 5 g. Ground-based tests confirmed data transmission up to 40.7 km from the gateway and data from deployed tags indicate a maximum data transmission range of 53.4 km. This confirms that GPS-LoRa devices can perform similarly to devices using GSM while offering advantages in terms of reduced data costs and energy consumption. The ability to send data over tens of kilometres also offers a clear advantage over alternative lightweight GNSS loggers using shorter range transmission methods for data download to a basestation (e.g. UHF download or ZigBee). While these other devices perform similarly in terms of GNSS position accuracy, they generally require the animal to pass within a few hundred metres of a receiver in the case of UHF download or within a few kilometres (< 8 km) for download via Zigbee [5, 13, 46, 59]. Whereas GSM devices' need for larger batteries and solar panels places a constraint on tag weight, the smallest available GPS-GSM tags are currently over 6 g (Additional file 1: Table S1).

Position accuracy from GNSS

Under all GNSS position acquisition cycles tested, horizontal position bias was less than 9 m (4.71–8.44) relative to the true position of the tag with precision of 18 or less (± 2.88 – ± 18.0) as measured by the standard deviation from the mean (Fig. 5; Table 1). This is comparable with other, commercially available GPS/GNSS devices and bio-loggers [2, 13, 15]. The relationship between the GNSS position acquisition interval and accuracy indicates that where high position accuracy is a concern, a shorter interval between location acquisition can be adopted. The vertical position bias varied between + 2 and + 5 m relative to the true position. Across all cases these results suggest a slight bias towards over-estimating altitude relative to the true position of the tag in vertical space (Fig. 5d). Precision, as measured by the standard deviation from the mean (Table 1), was best for the 1-min acquisition cycle (± 7.77 m) compared with the 30-min (± 15.3 m) and 60-min (± 27.4 m) cycles (Fig. 5). The variation in accuracy between location acquisition cycles is likely due to the GNSS chip switching off or going to sleep between fixes whereas during the 1-min cycle, the GNSS remains switched on constantly meaning it can maintain contact with a larger number of GNSS satellites. This relationship between GNSS accuracy and sampling interval in the Nomad™ tags is comparable to that observed in other GNSS tags [13]. It is important to be aware of these errors when planning deployment of these tracking devices, particularly where height data are used to assess the behaviour of the animal relative to anthropogenic hazards such as planes, powerlines or wind turbines [22].

LoRa data transmission range

Our ground-based tests confirmed data transmission up to distances of 40.7 km (Fig. 4). While tags deployed on griffon vultures demonstrated data transmission up to approximately 53 km is possible (Fig. 7; Table 2). The probability of successful data transmission declines significantly in relation to distance from the gateway and proximity to the ground. This makes sense because at higher altitudes, the tags are more likely to have obstruction-free line of sight to a gateway caused by rough terrain. Our results suggest that placing gateways approximately every 30–60 km should provide sufficient coverage for tracking studies for birds, particularly when paired with the use of mobile gateways which may be temporarily deployed in the field at colonies, nest sites or known migratory stopover areas to complement the fixed position outdoor gateways.

Although we did not detect an effect of landcover or terrain roughness on the probability of successful data transmission in the vulture tracking data, this is likely because the birds tend to fly at heights where the presence of tree cover or large boulders is less influential. For mammals or species of bird which habitually fly very close to the ground, obstructions to line of sight are likely to be a more significant factor in inhibiting data transmission than was found for the griffon vultures. This effect of landcover was observed during the tests of data transmission to the mobile gateway (Fig. 4c) at location 7 which was on a high point on a track surrounded by a Eucalyptus plantation. Depending on how mobile the study species is, to facilitate studies of mammal movements, the viewshed would likely be more limited than for birds. As such gateways would need to be placed within ~ 5–10 km of each other to provide sufficient coverage of the study area. Alternative solutions such as regular drone flights or vehicle transects with a mobile gateway to download the data or deployment of gateways near den sites or known feeding areas could also help in areas where perfect coverage from static gateways is not possible to achieve.

Power consumption

It is difficult to assess power consumption in a standardized manner under field conditions because of daily variations in solar and temperature conditions and variations between batteries which make it difficult to fairly compare devices using different settings. There are other studies such as [14] which have compared the power consumption of different technologies such as GSM and LPWAN (LoRA, Sigfox, NB-IoT and others) under controlled laboratory conditions. As such, testing power consumption of the devices was not one of the core research questions of this research. What we can say based on the performance of the device used to assess GNSS accuracy is that even with a small 0.3 mah battery paired with a solar harvester (Fig. 2f–g), the device was able to recharge sufficiently during daylight hours to maintain continuous GNSS recording at the programmed schedules (1 min, 30 min and 60 min), with data sent up to every 15 s, over a period of 6 weeks in May and June when solar conditions in Portugal are usually optimal (Additional file 1: A1: Fig. S3). To inform potential future deployments of Nomad or other GPS-LoRa devices, a spreadsheet for estimating power consumption and battery longevity under different settings has been provided by the manufacturer in Additional file 2: A2.

Deployment performance

Preliminary results from the trial deployment of the Nomad tags on griffon vultures confirmed that tracking data can be obtained over large areas. This study demonstrated this technology can be used to successfully follow the birds' daily movements (Fig. 6), obtain information on the daily variability in flight speed, flight height relative to ground level and measure the daily displacement. This included the detection of a failed sea crossing attempt of one bird (Fig. 6b). However, to date, we have only successfully received post-deployment location data for two of the six birds tagged so we are not able to comment on the long-term performance of the tags deployed on vultures.

Acceleration data were obtained for the remaining four vultures. Although we do not know the route taken by 9DF1_Jethro (total of 2156 data payloads sent) and 6923_Carlos (2047 data payloads sent) between southwest Portugal and Tarifa, the minimum possible distance travelled is approximately 480 km. The data transmission pattern around the Tarifa gateways suggests that the birds were likely thermaling in vicinity of the gateway to gain altitude and then moved further away. Hence these birds likely attempted to cross the Strait of Gibraltar, but this has not been confirmed. The tags for FB45_Benoit and 7E32_Aldina most likely moved to areas out of transmission range. Issues related to animals moving beyond transmission range will ease as the number and density of LoRaWAN gateways continues to increase. The vulture 9012_Eduardo was not detected by the LoRaWAN Gateway in Tarifa, suggesting that it did not migrate to Africa. Provided the tag was still on the bird, had it migrated, data would have been received by the gateway in Tarifa.

The capability of the NOMAD tags to record high-resolution accelerometer data means they have the potential to record when birds collide with infrastructure such as wind turbines or if a bird is shot. To test this feature, the devices were programmed to trigger acceleration acquisition at 50 Hz when forces exceeding a 3.2 g threshold were detected. Using this feature, the GPS-LoRa tags have been successfully used to study movement of boulders where the accelerometer triggered events can be used to detect movement of objects in response to environmental factors (e.g. floods or heavy precipitation) [8]. This threshold was exceeded for 4 birds during transport and deployment of the loggers resulting in large quantities of acceleration measurements being collected prior to the release of the birds, so clearing the memory buffer prior to the birds' release is recommended. Further work is required to refine the appropriate settings to avoid the 9-axis sensor from being erroneously triggered and preventing location data from being sent.

As with other gateway or antenna reliant systems, an important consideration for the settings on these tags is how often the bird or other study species is likely to be in range of a gateway. This will inform the sampling regime and the number of gateways deployed to collect the data. Using the upper limit of flight speeds recorded during the trial deployment on griffon vultures as a guide (Fig. 6). A bird flying at 6 m/s (21.6 km/h) will pass through the area in range of a mobile gateway (17 km radius) in approximately 2833 s (47 min) allowing up to a maximum of approximately 188 payloads to be sent. This is assuming perfect coverage and no obstacles to transmission. For a more powerful fixed position gateway, depending on terrain, the potential transmission radius is up to 53 km meaning the bird could be in range for 17,666 s (4.9 h) allowing for up to approximately 1177 payloads to be sent depending on SF. These are theoretical values, in reality, a high SF when the device is further away from the gateway is likely to reduce the transmission rate to a few payloads per hour [62]. For the data from the two devices for which we have GNSS location data, the mean number of locations recorded per day from each bird was 55.7 (range 2–167). On days when the birds were in range of a gateway 184.5 (range 1–749) locations were transmitted per day. One potential future development which may assist with this is the implementation of delta compression which significantly reduces the size of individual payloads by "coding the difference between the actual acquired value and the previous acquired value" [49].

Conclusions

This is an exciting time in the field of movement ecology, a diverse range of technologies are available to monitor the movements and behaviours of animals [46]. The tags described in this paper can currently be deployed in form factors weighing from 5 g up to the 83 g format deployed on griffon vultures as part of this study. Prior to commercialisation, further development of the tags and housing designs is ongoing with a view to further reduce the minimum weight of the fully assembled tag. This includes plans for a large-scale trial deployment of the 5 g tag format with lesser kestrels and common kestrels in Portugal and the installation of additional LoRaWAN gateways.

Our tests of GNSS position accuracy, transmission range and deployment performance of the GPS-LoRa tags have demonstrated their potential as a viable alternative to other tracking technologies currently available. These results and the information provided in this paper will be informative for researchers seeking to use or develop tags which use LoRa to transmit data. The key advantage over tags which transmit via satellite or GSM is that LoRa uses less energy to send the data over long distances (tens of kilometres) [14]. This affords the ability to use smaller batteries and solar panels compared to GSM devices which in turn has the potential to help increase the range of species we can track in near real time. While data costs for GPS-LoRa tags can be almost zero when using open-source, publicly accessible, networks like TTN or when the cost of a paid for server such as LORIOT is spread across a large number of devices [27, 62].

One disadvantage is that away from urban areas, LoRa coverage provided by publicly accessible gateways is currently limited. This means that, researchers would likely need to instal their own gateway systems to provide coverage for the area of interest. As such, we would currently recommend the use of GPS-LoRa devices to monitor either resident or site-faithful species because gateways can be set up adjacent to breeding sites, along known migratory routes and near known foraging areas to download stored tracking data. This strategy would suit many long-distance migrants ranging from seabirds like Terns to colonial soaring migrants like storks. Provided optimal placement of the LoRa gateway to allow for data transmission at low spreading factors. Upon the bird's return to the breeding site, it could take as little as one day to download a month's worth of tracking data accumulated at a rate of one location every half an hour without breaching the LoRa fair use guidance. For determining optimal gateway placement, we would advise the use of Viewshed analysis tools commonly available in GIS software such as QGIS and Arcmap [9, 41]. As gateway coverage improves, there will be less need for researcher to invest in their own gateway systems to receive data and the range of species that can effectively be tracked will increase. That said, the flexibility of LoRa to deploy new LoRaWAN gateways relatively inexpensively to receive data in situations where a lack of GSM coverage would prevent data being received from being received from GSM devices. There are also plans to launch LoRaWAN gateways into space which would provide global coverage and the ability to receive tracking data in real time via LoRa from almost anywhere on Earth [26].

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40317-023-00329-y.

Additional file 1: **Table S1**: Data cost estimates for different types of GPS logger as stated by the relevant manufacturer or data provider. Tag weights are for the smallest solar powered tag produced by that manufacturer with the capability to send data via GSM or via satellite. **Table S2**: Detailed description of range test results between the LoRa-GPS devices and the IP67 gateway located at the LPN reserve to the north of Castro Verde (Gateway A9_f6_Castro_Verde). **Figure S1**: The device on test, Garmin GPS unit used for scale. **Figure S2**: Kestrel GPS-LoRA tags (which use the Nomad PCB) alongside three Movetech 50 GPS-GSM tags. **Figure S3**: Battery voltage reported by the Status payloads sent by the tag during the GPS Accuracy Tests performed between June and July of 2021 in Portugal. The line follows the moving average of battery voltage over time.

Additional file 2. An excel based tool provided by Mirimico for estimating the power consumption and battery life of the GPS-LoRa loggers under different settings.

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Author contributions

JGG is the principal author of the work; AMAF suggested the initial idea for the paper and provided advice throughout the analysis and writing stages of the work along with PWA, JPS and AS. All authors contributed critically to data collection, drafting the manuscript, gave final approval and consent for publication of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

All data and R-scripts used to produce this work are available for download from Figshare at: https://tinyurl.com/bdz4rehv. A parts list for assembling the gateway system at lower cost using a ruggedised indoor gateway is available here: https://tinyurl.com/diygatewaysystem

Declarations

Ethics approval and consent to participate

All fieldwork with vultures was performed under license from CNF—Instituto da Conservação da Natureza e das Florestas (the Portuguese Government agency responsible for wildlife and forests) and Ethics approval was granted by the ethics committee of the University of East Anglia.

Competing interests

AMAF, PA and JPS obtained proof of concept funding to co-develop this tracking device with Miromico as a Movetech project. The devices assembled for the vultures were developed for research purposes only and are not available commercially. Aside from this, all authors declare that they have no conflict of interest with the content of this work.

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