LIFE AQUATIC WARBLERS ON THE MOVE

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Set Up Telemetry Pilot
&
Tagging and Telemetry Pilot

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Abbreviations

AWOM	Aquatic Warbler on the Move
CTT	Cellular Tracking Technologies
FGN	Fundación Global Nature
ICTS	Singular Scientific and Technical Infrastructure
RSSI	Received Signal Strength Indicator
EBD	Doñana Biological Station

Executive summary

To better understand the spatial behaviour and ecological requirements of the Aquatic Warbler (*Acrocephalus paludicola*) and to assess the effectiveness of wetland restoration across its migratory and wintering ranges, a detailed analysis of habitat use and selection is essential. Emerging bird-tracking technologies enable such analyses by providing more precise information on spatial location and residence time within specific areas. Within the LIFE Aquatic Warblers On the Move (AWOM) project, we conducted a pilot study in which we deployed automated radio-telemetry receiving nodes and aerials to test this technology and assess its suitability for achieving the project's objectives. Given the interdependence of Milestones MS42 and MS43, these are reported together to avoid unnecessary duplication.

1. Introduction

Bio-logging tools have revolutionised ecological research, yielding fine-scale insights into animal biology, including migration strategies, spatial ecology, diel rhythms, and behavioural patterns (Kays et al. 2015; Bäckman et al. 2017; Tonra et al. 2019; Beltran et al. 2024; Yanco et al. 2024). Their application, however, has traditionally been confined to species large enough to carry relatively heavy tags, such as large birds and mammals. There is a widely accepted guideline that the mass of a tag should not exceed ~5% of a bird's body mass (Kenward 2000; MITECO 2015), although this threshold is only weakly supported by empirical evidence and largely reflects convention, commonly traced back to Brander and Cochran (1969). In any case, advances in miniaturisation and remote-detection technologies have broadened opportunities to track smaller species while optimising the trade-off between data resolution and quality and the minimisation of potential impacts on survival and animal welfare.

For instance, Cellular Tracking Technologies (CTT) (see Section 3) has developed GPS loggers weighing just 3 g and radio tags as light as 60 mg. Integrated with an innovative node-based receiver network, these radio tags can deliver near-GPS performance, providing the high-precision data needed to characterise fine-scale habitat use in organisms as small as butterflies. Owing to the small size of these high-resolution devices, and therefore their reduced potential adverse effects on tagged individuals, this technology represents a strong candidate for tracking the threatened Aquatic Warbler (*Acrocephalus paludicola*; 10–14 g) across stopover and wintering areas, thereby supporting the development of the coherent, comprehensive, and climate-resilient network of key sites envisioned in LIFE AWOM. Achieving this goal requires evaluating habitat extent and quality and the relative importance of staging and wintering locations. To that end, a complementary toolkit—encompassing habitat characterisation, assessments of food availability and migration monitoring—will be applied, with CTT technology supplying the fine-scale movement data needed to inform each component.

Within this framework, this document details the tagging and telemetry design for studying the migration of the Aquatic Warbler, as well as the pilot deployment of CTT technology at Laguna de Boada (Palencia; northern Spain) in August 2025.

2. Scheduling constraints and methodological adjustments

According to the original schedule, field trials were planned for spring 2025. However, between the planning stage and the scheduled start of the trials, new advances in radio-tracking technologies emerged. The smallest devices available during the planning phase ranged between 0.35 and 0.45 g, approaching the 5% body mass threshold (Kenward 2000). Shortly before the scheduled start of the field trials, the company CTT announced the launch of ultralight 0.2 g battery-powered radio tags that did not exceed 2% of the body mass of the smallest aquatic warblers. Despite these tags being available in spring 2025, the company announcement also included a solar-powered radio tag that, in addition to a battery, incorporates a solar panel. This design greatly extends the device's operational life, potentially enabling full annual-cycle tracking. Although the commercial release of these tags was repeatedly delayed, to take advantage of this major improvement we decided not to postpone the trials from spring to summer, but no later than August. While these new tags could not be incorporated into the Boada trials as they only recently became available, they substantially broaden the range of potential applications and will be rigorously evaluated before the first birds in the project are tagged.

Another factor contributing to the delays was the supplier's lead time of approximately three months, as CTT manufactures devices to order and does not hold stock. While the shift to August improved access to and movement within the lagoon (dry in summer) it also ruled out the pre-nuptial tagging of Aquatic Warblers (or closely related species) for trial purposes. Accordingly, we replaced field tagging of actual birds with drone-based trials. It is important to note that, even though drones do not replicate avian behaviour, they enabled controlled testing (e.g. maximum detection ranges) while reducing unnecessary disturbance to wildlife.

3. Automated radiotracking system: Cellular Tracking Technologies (CTT)

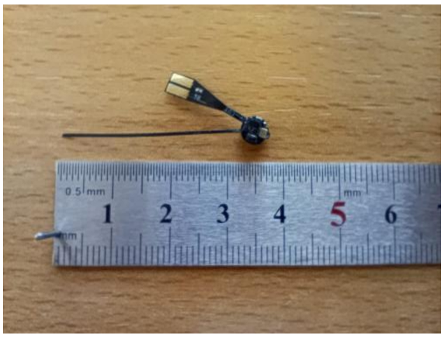
After an extensive review of the technologies available from companies in the sector, we selected CTT, as it is one of the very few (if not the only) companies that offer a node-based system enabling automated radio-tracking for fine-scale analysis of habitat use. In addition, CTT provides some of the lightest radio transmitters currently available (as little as 0.2 g), making them suitable for tagging species with such a small body mass (~10 g).

The installation of the complete automated radio-tracking system consists mainly of components supplied by CTT, but it must also be complemented with additional parts that need to be purchased separately and are not provided by the company. Below, we describe the different components used in the field trials.

3.1 CTT-Supplied system components

3.1.1. BlūBat tag

It is the smallest battery-powered, digitally coded radio tag of its kind, designed for nocturnal and light-sensitive species such as bats, nocturnal birds, small mammals and birds that may be exposed to potential shading effects from plumage or dense vegetation. It has been developed to ensure reliable detection, long-term operation, and seamless integration with CTT's BlūSeries infrastructure. The BlūBat includes a test pad that allows users to verify transmission and check battery voltage prior to deployment (Picture 1, Table1). When the tag (i.e. the pad section) comes into contact with a metal surface, it begins to transmit; transmission stops as soon as contact is broken, allowing the pad to function as a switcher. This feature enabled us to test tag detection by both receiver nodes and antennas without draining the tag battery solely for this purpose. To deploy the tag on a bird, the test pad simply needs to be cut to activate transmission, and a small drop of glue is applied to cover the cut. This device transmits at a frequency of 2.4 GHz, which can be detected either directly by the nodes or by the Sidekick (see below).



Picture 1. Photograph of the CTT BlūBat tag showing the test pad that must be cut before deployment on the bird to activate transmission. More details are provided at https://celltracktech.com/products/ctt-blubat?_pos=1&_sid=5c1e43853&_ss=r and the text below.

3.1.2. SensorStation (V. 3.0)

This is the central component of the tracking system, which receives all information (at 434 MHz) from the nodes or from the BlūSeries Receiver (see below), and from which the data collected by the installed node grid can be downloaded. The SensorStation is a self-contained Motus receiver fully compatible with SensorGnome software. It incorporates a Raspberry Pi Compute Module 3+ (16 GB storage), six USB ports supporting FunCube (V3), five LifeTag reception channels, onboard Wi-Fi, and optional connectivity via cellular networks or the Iridium satellite system (Picture 2, Table 1).. As open-source hardware, its design files are publicly available for download and modification.

The SensorStation can be used as a standalone unit (e.g. to detect presence–absence) or in combination with a node grid, enabling studies of fine-scale space use at strategic sites. In our case, as we use BlūBat tags transmitting at 2.4 GHz, it is necessary to install the BlūSeries Receiver (see below), which functions as a transformer that receives the signal from the 2.4-GHz tags and sends the data via cable to the SensorStation, allowing the latter to function as a node itself. The SensorStation must be equipped with an antenna to receive the information transmitted from the nodes. In the field trial, an omnidirectional antenna was used (see Section 3.3. for details). For specifications, see https://celltracktech.com/products/sensorstation-for-sensorgnome-version-3-1?_pos=1&_sid=5526aa43a&_ss=r

Picture 2. Photograph of the CTT SensorStation installed in Boada in August 2025. The system is powered by solar energy generated by the solar panels owned by FGN.

3.1.3. Nodes (V3)

The nodes are the devices distributed across the study area that allow us to: (1) estimate the intensity of space use (e.g. grid search analysis); (2) estimate bird positions (e.g. multilateration analysis); and (3) infer animal activity (e.g. foraging or roosting times, or mortality detection). The CTT Node 3.0 is bilingual, equipped with both a 434 MHz radio and a 2.4 GHz BlūReceiver radio, making it capable of detecting the full suite of CTT tags (Picture 3, Table 1). The nodes receive transmissions from the tags at 2.4 GHz and forward the information at 434 MHz, which is received by the antenna connected to the SensorStation. Each node pack consists of the following components:

- 1 node with its protective case.
- 2 omnidirectional antennas, one operating at 2.4 GHz and the other at 434 MHz.
- 1 solar panel serving as the power source for the node.
- 1 cable connecting the solar panel to the node.
- 1 mounting plate for attaching the solar panel to the node.

Picture 3. Pictures of the CTT Node V3. The system is powered by solar energy generated by a small solar panel attached to the node. Once assembled, it is only necessary to switch on the solar panel for the node to begin operating. More details: https://celltracktech.com/products/ctt-node%E2%84%A2-version-3-0-with-dual-radios-434mhz-and-2-4ghz?_pos=1&_sid=f7117fb6f&_ss=r&variant=50012198469792

3.1.4. BlūSeries Receiver

The BlūSeries Receiver for the SensorStation is a plug-in upgrade that enables the existing unit to detect the new BlūSeries tags, such as the ultralight BlūBat tag (0.2 g; 2.4 GHz). It allows the SensorStation to operate as an additional node within the installed node grid. This component consists of two subunits: the *remote* unit, which is mounted on the mast, and the *plug* unit, which occupies one of the USB ports on the SensorStation (Picture 4, Table 1). Up to four antennas can be connected, either directional or sectorial; the latter were used in the field trial conducted in Boada (Palencia) (see Section 3.3).

Picture 4. Picture of the basic components of the CTT BlūSeries Receiver. More information: https://celltracktech.com/collections/digital-radio-products/products/bluseries-receiver

3.1.5. CTT Sidekick and CTT mobile app

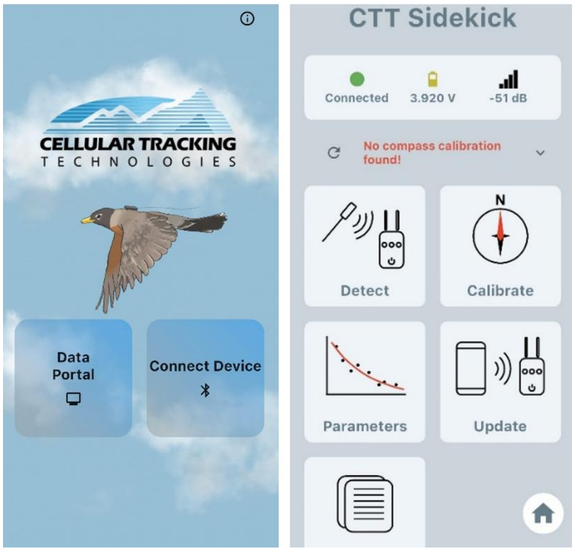
The CTT Sidekick is a handheld receiver that allows manual tracking of tags operating at both 2.4 GHz and 434 MHz (Picture 5, Table 1). It displays statistics such as Received Signal Strength Indicator (RSSI) versus time graphs and enables the calibration of nodes (see Section 8.2). It includes a free mobile application ("CTT mobile") available for both iOS and Android devices. The CTT Sidekick connects to mobile devices via Bluetooth and uses the device's built-in compass and GPS to determine the direction and position of detections. The application provides real-time information on signal strength (RSSI), frequency, and tag ID, allowing accurate localisation and verification of tag performance in the field. Data collected during manual tracking sessions can be exported in .csv format for subsequent analysis.

The package of CTT Sidekick includes the following items:

- CTT Sidekick
- 2.4GHz omni antenna
- 434MHz omni antenna
- USB charging cable
- SMA port covers (2)
- 2.4GHz yagi antenna (with handle and connecting cable)

Picture 5. Image of the CTT Sidekick with the 2.4 GHz omnidirectional antenna, the 434 MHz omnidirectional antenna, and a Yagi antenna (with handle and connecting cable). More details: https://celltracktech.com/collections/digital-radio-products/products/ctt-sidekick

To use the CTT Sidekick, one first needs to install the CTT Mobile app on an Android or iOS device. The smartphone is then paired with the Sidekick using the app. Once paired, the compass must be calibrated from the main menu of the application (Picture 6) to ensure accurate tag detection. CTT Mobile allows users to view the latest telemetry data from their CTT devices directly on a mobile device. In addition, the app can be used to assign device duty-cycle changes and to connect to Bluetooth-enabled CTT products such as the Sidekick and Node Version 3.



No compass calibration found!

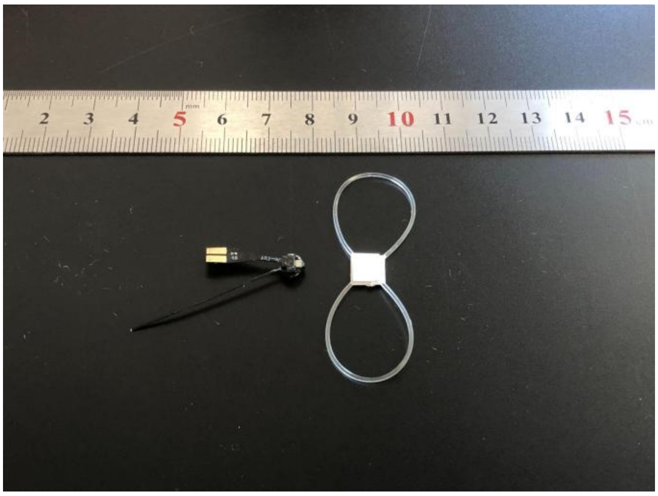
Picture 6. Screenshot of the main menu of the CTT Mobile app, showing the different options available.

3.2. Other necessary components

CTT provides us with the devices mentioned above, but some additional components are needed.

These include the antennas for the SensorStation and BlūSeries Receiver, as well as the mounting structures and power supply elements (e.g. solar panels, batteries, and cables). A list of the required materials is provided below.

- If a connection to the electrical grid is not available, an external **power source** is required **to supply energy to the SensorStation**. An important point to note is that the SensorStation operates at 12 V. This issue **should first be addressed** independently by each participating entity, as specific guidance can be provided depending on whether existing installations or power sources are available, or if new ones need to be installed.
- Internet modem with ethernet cable or wifi and VPN.
- A metal structure to place the SensorStation, BluSeries Receiver and antenna(s) (Table 2).
- 434 MHz antenna/s to allow the SensorStation to detect nodes (Table 2).
- Coax cable/s to connect the antenna/s to the SensorStation. The length will depend on where we deploy the SensorStation and the antenna/s. Be careful! If connecting directly to the board, each 434MHz radio has a **SMA Female** port, so our coaxial will require an **SMA Male** connector. If connecting to NEMA case (provided by CTT), the coaxial will need a **Type N Male connector.**
- 2,4 GHz antenna/s, connected to BluSeries Receiver, to allow the SensorStation to detect tags. In the Boada field trial, and following the recommendations of the engineers from ICTS, three sectorial antennas were used (see Table 2), although directional antennas may also be employed.
- Ethernet Cable to connect the BluSeries Receiver to the SensorStation (any length under 100 m). It is preferable to select a cable without end coverings, as these can make it difficult (or even impossible) to feed the cable through the glands and into the Receiver and Sensor Station.
- Node poles. The choice of material and size depends on the type of soil in the study area (see Table 2).
- Pelvic harness: constructed from elastic thread and two pieces of paper (Picture 7). The tag was attached to the harness with a drop of cyanoacrylate, and the leg-loop size was determined following Naef-Daenzer (2007). The paper piece should not exceed the size of the tag, in order to ensure that it remains as inconspicuous as possible.



Picture 7. Image of the tag and the type of harness that may be used for tagging. Note that the harness shown is larger than that used for the Aquatic Warbler and is provided for illustrative purposes only.

3.3. Budget and delivery times for the equipment

Tables 1 and 2 list all components of the automated tracking setup, indicating their approximate cost, whether they are supplied by CTT, and providing suggested purchase links for those that are not. Table 3 presents the newly released CTT products and their corresponding prices.

Table 1. List and prices of CTT components used in the Boada field trial.

	CTT components and options	Price/unit
SensorStation	SensorStation for SensorGnome Version 3.0	989 $
	Conectivity / Modem Type LTE	50 $
	Weatherproof NEMA case for SensorStation	110 $
	Power supply (12V 30W AC/DC) (if not already available)	25 $
	Antenna Bulkhead	10 $
	Cable Gland for BluSeries Receiver (see the “Additional Options” section on the CTT website)	10 $
Node	CTT Node versión 3.0 with dual frequency	300 $
	CTT SolarPack solar-rechargeable battery pack for CTT Node	75 $
BSR	BluSeries Receiver for SensorStation	200 $
Sidekick	CTT SideKick	650 $
	Handle and 2.4GHz yagi antena for SideKick	50 $
Radio transmitter	CTT BluBat radio transmitter	200 $
	4-corner suture / harness case for Radio Transmitters (optional)	25 $

Link to products: https://celltracktech.com/collections/digital-radio-products

Table 2. Prices of additional components required for the operational installation of the CTT setup. Some supplier links are provided for guidance purposes.

Other necessary components	Price/unit
Power source to supply energy to the SensorStation(1)	-
Fixed Base Turret 250mm to screw down (2) https://www.tdtprofesional.com/es/base-fija-de-torreta-250mm-para-atornillar-a-suelo.html	56.7 €
250mm Turret upper stretch 2,5m (2) https://www.tdtprofesional.com/es/torreta-250mm-tramo-intermedio-2-5m.html	213.5 €
RPR mast, 1.5m x 35mm ø x 1.5mm, snap on (2) https://www.tdtprofesional.com/es/mastil-de-1-5-m-carraqueado-35-mm-o-1-mm-de-espesor.html	13.9 €
DIAMOND X50N Dual band base antenna for SensorStation(3) https://pihernz.com/producto/antena-diamond-x50/	63.8 €
N male to PL male adapter (4) https://www.ondamania.com/b2c/producto/machonamachoplZ0915_1291/1/adaptador-macho-n-a-macho-pl	9.44 €
Coax cable Antenna-SensorStation (2m) https://cablematic.com/es/productos/cable-coaxial-hdf200-n-macho-a-n-hembra-2m-WE012/	19.42 €
MIMO WLAN 2,4 – 5,5 dual output antenna for BluSeries Receiver(3) https://www.sirioantenne.it/es/producto/wlan/smp-x-wlan-mimo	76.8 €
2,2m Pole (angle 40 with holes) for Node (5) https://www.cercados4caminos.com/productos-de-cercados/postes-vallado/%C3%A1ngulo/	6.60 €
Pelvic harness made of elastic thread and two strips of paper. https://www.leroymerlin.es/productos/cuerda-elastica-negra-25-metros-calidad-profesional-tecplast-9sw-cable-elastico-diametro-9-mm-83303175.html	46.99 € / 25m
Internet modem with ethernet cable or wifi and VPN (for remote connection).	-
Ethernet cable to connect the BlūSeries Receiver to the SensorStation	-

(1) To be decided by each member according to the existing infrastructure (if not already in place).

(2) Parts of the structure where to fix the SensorStation, the BluSeries Receiver and antennas.

(3) The model may be changed according to the needs of the study area.

(4) Adapter Antenna-coax cable. Depending on the type of connection of the selected antenna, an adapter may be required.

(4) Structure where to fix the nodes.

Table 3. Prices of newly released CTT devices and service plans.

New CTT components and options	Price/unit
CTT BluBird radio transmitter https://celltracktech.com/products/ctt-blubird-1?_pos=1&_sid=54372d3c0&_ss=r	250 $
Blu+ and Motus Registration Fee per tag https://celltracktech.com/products/motus-tag-registration-fee?_pos=6&_sid=0503485d9&_ss=r	25 $
Blu+ Data Plan per tag https://celltracktech.com/products/blu_plus_data_service?_pos=5&_sid=0503485d9&_ss=r	2$/month
4 antenna kit and mounting bracket (includes coax) https://celltracktech.com/products/bluseries-receiver?_pos=12&_sid=0503485d9&_ss=r&variant=52668649930912	225 $

As mentioned in Section 2 of this report, **CTT's delivery times are approximately three months**, as all devices are manufactured to order and no stock is kept. Therefore, it **is recommended to place orders well in advance of the system installation**. This lead time should be taken into account when planning fieldwork schedules and equipment deployment (requiring at least **2 full days of work for a team of 2 people**, see below).

4. System operation

To record fine-scale data on the space use of tagged birds, a grid of nodes must be deployed within the study area, ideally spaced at equal distances (but not necessarily) from one another, along with a SensorStation. If the SensorStation is intended to also function as a node, a BlūSeries Receiver must be installed. Once installed, when an Aquatic Warbler tagged with a radio transmitter (emits a 2.4 GHz signal) enters the study area, it will ideally be detected by several nodes simultaneously. This allows recording the time and signal strength (RSSI) at each node, information that will later be used to infer the bird's location or its residence time within the area and 'hence' its spatial behaviour.

Nodes that are sufficiently close to the bird to detect the transmitter's signal then transmit the information to the SensorStation at 434 MHz, where the data are stored for subsequent download. If a BlūSeries Receiver is present, the SensorStation will also detect the signals transmitted directly by the tags (2.4 GHz). It is important to note that without the BlūSeries Receiver, the SensorStation can only receive information transmitted at 434 MHz (i.e. from the nodes). Therefore, as explained above, to enable reception of the 2.4 GHz signals emitted by the tags, the BlūSeries Receiver must be included.

Consequently, **two types of antennas are required**: those that receive signals at 434 MHz (transmitted by the nodes) and installed on the SensorStation, and those that receive signals at 2.4 GHz (transmitted by the tags) and installed on the BlūSeries Receiver. The entire radio-tracking system does **not necessarily need to remain installed throughout the year**; the node poles and main station turret can be left in the field, while the electronic components can be deployed only during the months relevant to the project's objectives. This approach helps preserve the equipment and extend its operational lifespan.

5. Preliminary considerations before the field trial

Based on the experience gained during the Boada pilot trial and previous tests, we recommend taking into account the following considerations when installing the system, as these can help improve both its effectiveness and long-term preservation:

- **Verify shipment and delivery for potential damage:** it is recommended to check the condition of all materials as soon as they are received, since defects or damage have previously been detected in some components, possibly due to transport (Picture 8).
- **Vegetation height:** the height and density of the surrounding vegetation can influence signal transmission and reception. Antennas should be placed above the average canopy level whenever possible.

- **Livestock presence:** in areas with grazing livestock, protective structures should be used to prevent damage to poles, antennas, cables, and solar panels, as domestic animals often use these structures for rubbing.
- **Habitat structure:** in large homogeneous habitats (e.g. extensive water bodies), it may not be necessary to install nodes throughout the entire area. Strategic placement in key sectors may be sufficient (see section XX).
- **Wildlife interactions:** if local bird species frequently perch or nest on antennas or solar panels, deterrent measures may be considered to avoid interference or damage caused by bird droppings or nest building.
- **Solar panel orientation:** solar panels should be oriented southwards to maximise energy input.
- **Cable management:** all cables should be secured on the north-facing side of the poles, using UV-resistant cable ties to ensure durability (e.g. unex company).

Picture 8. Broken solar panel in one of the nodes delivered for installation in Boada (Palencia).

Following these guidelines will help ensure reliable system performance and reduce maintenance requirements.

6. Objectives of the pilot telemetry trial

The pilot telemetry trial aimed to evaluate the performance and applicability of the automated radio-tracking system under real field conditions prior to its large-scale deployment. Specifically, the objectives were to:

1. Familiarise the research team with the operation of the equipment and associated software.
2. Evaluate detection distances between tags, nodes, and the SensorStation under field conditions.
3. Design a spatial configuration of nodes adapted to a real case study (Boada, Palencia,

Spain).

4. Identify any technical or logistical issues that could affect future installations or data collection.
5. Develop technical guidelines to advise project partners on the installation of the system in their respective study areas.

7. Previous trials in Doñana National Park

Prior to installing the devices at the Boada wetland in Palencia for the pilot trial, preliminary activation and performance tests were conducted at the Doñana Biological Reserve. These tests were carried out with the support of expert staff from the Singular Scientific and Technical Infrastructure (ICTS-Doñana). During this preliminary phase, the various components of the system were assembled and powered on for the first time to verify proper operation and connectivity (Picture 9). Together with ICTS-Doñana engineers, we performed the initial pairing and configuration of the SensorStation, BlūSeries Receiver, and several nodes, ensuring that data transmission between devices operated correctly. These initial trials allowed the team to familiarise themselves with the equipment and software interface before deployment at the Boada site.

Before beginning data collection, the **Wi-Fi credentials were added to the SensorStation** to enable communication with the local network. To do this, the device was first connected to power by flipping the black switch located to the left of the LCD screen to the PWR ON position. Several lights begin flashing during boot-up, and after a few moments the LCD screen displays a menu that can be accessed using the four buttons to the right of the screen.

We need a properly formatted USB thumb drive (FAT-32 or MS-DOS formatting is currently supported). On the thumb drive, we created a folder named “wifi” (in lowercase). Inside this folder, we created a new file, set the Language Mode to *JSON*, and the End of Line Sequence to *LF* (Line Feed). In this file, we typed the following:

```
{
  "ssid":"name of wifi network",
  "psk":" password"
 }
```

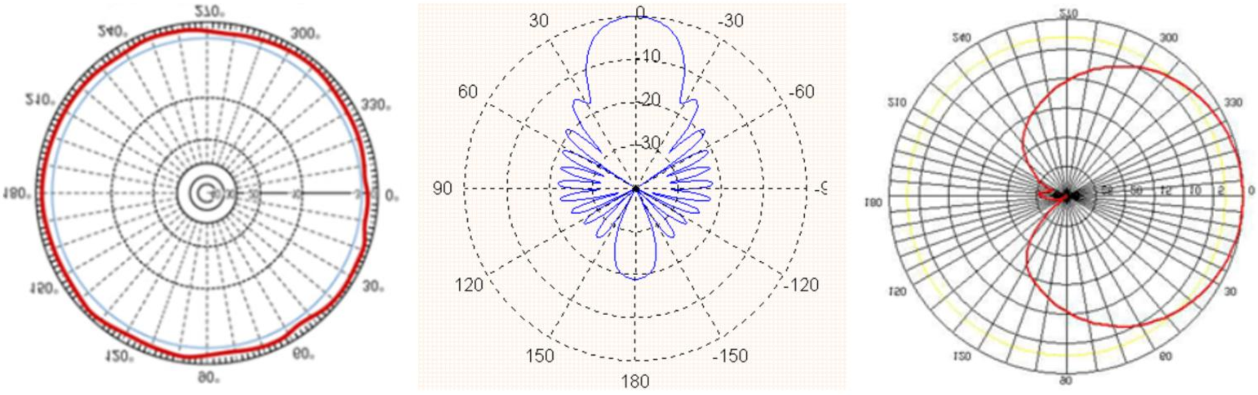
Once this is done, we inserted the USB thumb drive into one of the USB ports on the SensorStation and followed the steps below:

- Using the four buttons to the right of the LCD screen, navigate to Network > Wi-Fi > Mount USB and press the select button. A success message is displayed.
- Navigate to Network > Wi-Fi > Get Wi-Fi and press the select button again. Another success message is displayed.
- Next, navigate to Enable Wi-Fi.
- Finally, turn the SensorStation off and back on, then navigate to Network > IP Address and press the select button to verify connection to our local Wi-Fi network. A valid IP

address for the SensorStation is displayed.

Picture 9. Image of the tests conducted in Doñana, where the system was assembled and powered on for the first time.

Following the successful configuration and verification of device connectivity, we proceeded to determine the type and number of antennas required for the system. This decision took into account the need to collect data from two different frequencies — 434 MHz (used by the nodes to transmit information) and 2.4 GHz (used by the tags). The selection of antenna types depended on the size and layout of the study area. Three main types of antennas are available on the market: **omnidirectional, directional, and sectorial** (Picture 10). Omnidirectional antennas have a 360° detection angle but a more limited detection range; directional antennas offer a longer range but a narrower detection angle (5°–30°); and sectorial antennas represent an intermediate option (60°–120° detection angle). It is important to note that sectorial antennas are not available for 434 MHz.



Picture 10. Radiation diagrams of (a) an omnidirectional, (b) a directional, and (c) a sectorial antenna. Source:

https://www.comunicacionesinalambricashoy.com/wireless/que-son-las-antenas-omnidireccionales/2/ ; http://www.amsat.org.ar/REUNIONES/antenaslusac.html ; https://es.wikipedia.org/wiki/Archivo:Diagrama_sectorial.png)

Based on the recommendations of the ICTS-Doñana engineers, an omnidirectional 434 MHz antenna was selected for the detection of nodes by the SensorStation, along with three sectorial 2.4 GHz antennas for the detection of tags by the BlūSeries Receiver (and consequently by the SensorStation). Given the relatively small size of Boada Lagoon, this configuration adequately covered the study area and met the monitoring requirements. However, the choice of alternative antenna types remains open and should be adapted to the specific characteristics and needs of each installation site.

8. Field pilot trial in Boada (Palencia, Spain)

Initially, and following the recommendations of the Global Nature Foundation (FGN), the pilot trial was planned to be conducted at La Nava Lagoon (42° 04' 00" N, 04° 44' 57" W), as it is an emblematic wetland for the Aquatic Warbler in Spain. However, given the availability of existing power-supply infrastructure (solar panels, batteries, and Ethernet connection) owned by the Global Nature Foundation, and the limited extent of flooded areas, it was decided to carry out the trial at the nearby Boada Lagoon (41°58'55"N 4°51'42"W), another wetland used by the species during migration. In addition, the smaller area of Boada Lagoon (60 ha) facilitated the implementation of the field tests. The first step at Boada was the installation of the SensorStation, the BlūSeries Receiver, and several nodes. Once these devices were properly mounted and connected, detection-range tests were performed to evaluate system performance under field conditions.

8.1. Detection range tests

To ensure that the detection range of the tags covered the entire lagoon without losing spatial accuracy in the detection of marked individuals, a series of tests were conducted to determine the maximum detection range between the tags and the different receiving devices (BlūSeries Receiver, SensorStation, and Sidekick). This information served as the basis for designing the spatial distribution of the nodes across the lagoon.

8.1.1. Tag – Node distance

To determine the maximum detection distance of a tag by the nodes, one node was activated and connected to the CTT mobile application, while a tag was also activated using its test pad. Both devices were then placed at increasing distances and under different conditions: (1) the tag antenna oriented towards the node to simulate optimal detection, (2) the antenna oriented upwards towards the sky, and (3) the antenna oriented in the opposite direction to the node, representing the most challenging detection scenario. These tests were repeated for different node positions: (1) positioned at ground level, with and without vegetation between the devices, and (2) mounted 1.9 m above the ground on a metal “L”-shaped pole (“Pole-angle 40 with holes—for Node” in Section 3.3). This height optimized the balance between detection range and the visual impact on the landscape.

Tests assessing role of vegetation as an obstruction (Picture 11) were conducted in the area of the lagoon with the tallest and densest vegetation, consisting of a 150-m-wide strip of *Phragmites* sp. (~2.5 m tall). Using the mobile application, we were able to verify whether the tag was detected by the node under each of these conditions.

Picture 11. Temporary installation of one of the nodes to determine the detection range of the tags.

8.1.2. Tag – BlūSeries receiver

To test the detection range of the tag by the BlūSeries Receiver (with the SensorStation acting as an additional node), we used a quadcopter drone (Picture 12) to which the activated tag was attached using adhesive tape. The drone was then progressively moved away from the sectorial antennas (installed at a height of 2.3 m) of the BlūSeries Receiver and positioned at different heights and distances to assess detection performance under varying conditions.

Picture 12. Photographs of the quadcopter drone used for testing tag detection by the BlūSeries receiver.

8.1.3. Tag – Sidekick

The maximum distance at which the handheld tracking device (Sidekick) could detect the tags was measured using a vehicle, performing periodic detections at increasing distances. Once the tag was no longer detected, the final adjustment of the distance was made on foot. The tests were conducted under two different conditions: (1) with a direct line of sight between the tag and the antenna, and (2) with vegetation (>2 m high) obstructing the line of sight.

8.1.4. Node – SensorStation

Based on the estimated detection range for the tag–node, the node grid was designed (Section 8.1.5), and we verified that the most distant node was correctly detected by the SensorStation. It should be noted that the top of the 1.7-m SensorStation's omnidirectional antenna was positioned at a height of 4 m, while the nodes were placed 1.9 m above the ground (Section 8.1.1).

8.1.5. Field trial results

- **Tag – node distance:** The maximum reliable distance at which a node detected a tag with vegetation (~2.5 m high) in between was **150 m**, with the node positioned at the upper edge of the vegetation and the tag antenna oriented either towards the node or upwards. Based on these results, nodes could theoretically be placed up to 300 m apart to allow simultaneous detection of a tag under ideal conditions. However, environmental factors, such as weather and habitat structure, may reduce this distance. In addition, assuming that the tag antenna on a free-ranging bird is always oriented toward the nearest node is highly unrealistic. Therefore, a conservative approach was adopted, designing the node network with **nodes spaced 175 m apart** (Figure 1, Annex 1). This configuration increases the probability of simultaneous detection of a tag by multiple nodes, regardless of whether the tag antenna is oriented toward a node or in the opposite direction. With this layout, a total of 24 nodes, together with the SensorStation and BlūSeries Receiver, are required to cover the 60 ha of the entire lagoon and its immediate surroundings (Figure 1).

- **Tag – BlūSeries Receiver distance:** The detection distance between a tag and the BlūSeries Receiver reached approximately **700 m** (with the drone 10 m above the ground), a considerable range for such a lightweight transmitter. These initial measurements confirmed the suitability of the system for monitoring small passerine species such as the Aquatic Warbler. Moreover, the results provided a robust basis for optimising the spatial configuration of the network, ensuring reliable data collection under field conditions and validating the overall performance of the system prior to large-scale deployment.

- **Tag – Sidekick distance:** The maximum detection distance of the tag by the manual radio-tracking device (Sidekick) was 440 m when vegetation was present and **640 m** in open conditions. The latter value was similar to the distance recorded between the tag and the BlūSeries Receiver, demonstrating the system's outstanding reception capability.

- **<u>Node-SensorStation distance:</u>** The maximum distance at which the antenna detected the nodes was **700 m** (Figure 1). As detailed in section 3.3, the antenna selected for node detection by the SensorStation was a DIAMOND X50 dual-band base antenna, operating between 430 and 440 MHz and providing a gain of 4.5 dB for VHF and 7.2 dB for UHF, thereby considerably increasing its effective range. For larger sampling areas, the use of directional antennas to maximize detection range and an increased number of units would be advisable. The position of the SensorStation—and consequently of the antenna(s)—within the study area relative to the node grid must also be considered. In the case of the Boada Lagoon, the SensorStation was positioned near the centre of the site, where the power source was located, which made the use of an omnidirectional antenna (360° detection angle) appropriate. In other cases where these conditions are not met, specific guidance will be provided.

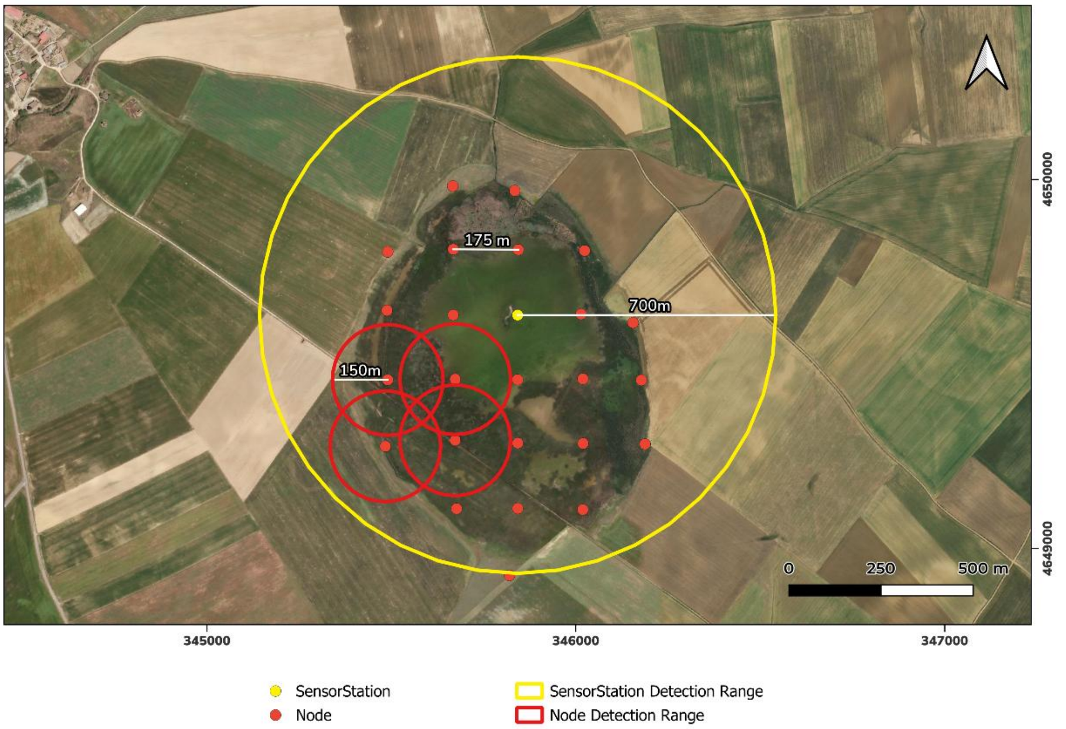


Figure 1. Map showing the node grid arrangement (24 nodes spaced 175 m apart) and the SensorStation at the Boada Lagoon (Palencia) in August 2025, indicating the detection ranges of both the nodes and the BlūSeries Receiver.

8.2. Node grid calibration

To estimate with the highest possible accuracy the locations or intensity of space use by tagged birds, it is necessary to calibrate the node grid. This process compensates for small variations in the GPS values of the nodes and prevents the generation of inaccurate received signal strength indicator (RSSI) values from the tags.

For this purpose, the use of the Sidekick device together with the CTT Mobile application is recommended. A transect should be carried out on foot across the node grid while carrying both the Sidekick and an activated tag (Picture 13a). During this calibration walk, it is important to verify that the Sidekick is detecting signals and recording the actual location of the tag. We recommend that this route cover all, or at least most, of the nodes' detection area (Picture 13b). Frequent stops should be made to ensure accurate tag positions recorded by the Sidekick and to maximise the number of nodes detecting each signal.

Picture 13. Walk-through calibration survey (a) carrying the Sidekick and an activated tag among the installed nodes (b).

Once the survey is completed, the CSV file generated by CTT Mobile should be downloaded. This file contains the tag's location for each signal emission (i.e. beep). In parallel, the detection data from all nodes should also be downloaded in order to match the beeps recorded in both datasets. The final objective is to obtain, for each mapped beep, both the distance and the received signal strength (RSSI) between the tag and any node that registered a detection. This information can then be plotted as a regression to verify that all nodes within the grid display consistent behaviour in terms of recorded signal strength relative to the actual tag-node distance, thereby confirming the overall calibration of the network (Figure 2).

If a Sidekick is not available, a similar calibration file can be created by walking across the node grid with an activated tag, stopping at chosen points to manually record the GPS coordinates and time. These data can then be compiled into a CSV file analogous to the Sidekick calibration file (see R Data Tools: https://cellular-tracking-technologies.github.io/)

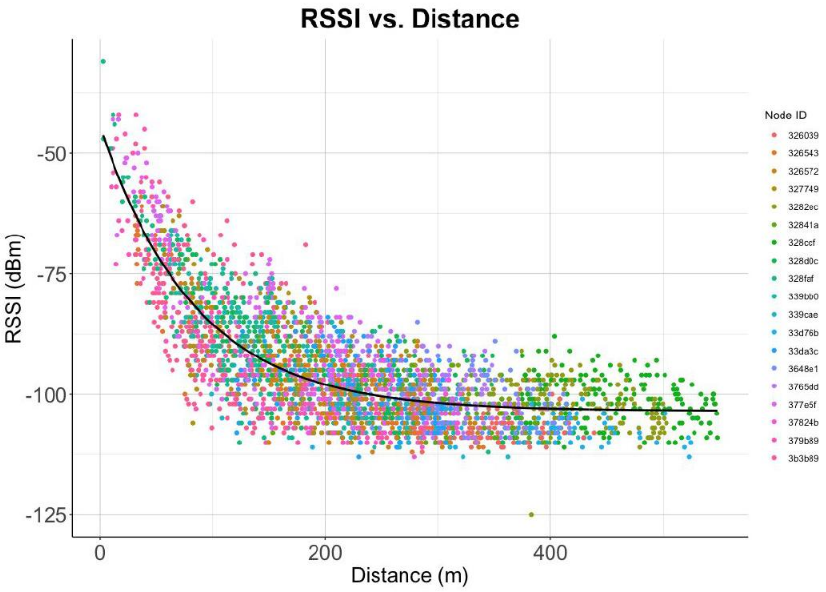


Figure 2. Relationship between the actual tag-node distance and the signal strength (RSSI) of each tag beep detected by the nodes.

9. Continuous improvements: new devices

During the course of the pilot trial, CTT released new devices, including an antenna designed to be coupled to the BlūSeries Receiver, consisting of four directional 2.4 GHz antennas, and the new hybrid transmitters known as *BlūBird*. These transmitters also weight 0.2 g and are equipped with a solar panel that powers the internal battery, thereby extending their operational life. Both devices could be tested in future studies to evaluate their performance.

In addition, CTT now offers a new service called *Blū+*, compatible with transmitters such as *BlūBat* and *BlūBird*, among others. This service enables the extension of detection capabilities beyond traditional receivers by integrating them into an IoT-based network connected to cellular systems. Work is ongoing to test all these innovations alongside previously tested components to ensure that the tracking system remains up-to-date.

10. Recommendations and operational considerations

- **Power supply and connectivity:**
  Electricity and internet access are already available at Boada Lagoon. Otherwise, it would be necessary to assess how to provide power to the system, taking into account location constraints and additional costs.
- **Node spacing and detection range:**
  To maximise the detection area covered by the nodes and ensure a cost-efficient setup, the spacing between them should not be based solely on the detection tests presented in this report. Local field tests should also be conducted, as variations may occur between sites due to differences in topography or habitat type.

- **Antenna configuration:**
  Given that the Boada Lagoon covers approximately 60 ha and that the power supply is located near its centre, an omnidirectional 434 MHz antenna enables the SensorStation to detect all nodes installed within the lagoon. In addition, three 2.4 GHz sector antennas were installed for tag detection by the BlūSeries Receiver, allowing the SensorStation to also function as a node and thereby increase the detection range. This configuration might need to be adjusted to the specific characteristics of each study site.
- **Antenna height and cable length:**
  The height at which the SensorStation and BlūSeries Receiver antennas are installed can influence reception capacity. In this trial, they were mounted at 4 and 2.3 m, respectively. It is recommended to adjust the antenna height according to the characteristics of the local landscape and the distances to and between nodes. Note that the antenna cable length should be consistent with the installation height.
- **Line-of-sight conditions:**
  A clear line of sight between the nodes and the receiving antenna(s) is recommended to ensure reliable detection by the SensorStation. Wherever possible, obstacles such as vegetation should be avoided by installing the nodes at a higher elevation, as this improves detection performance.
- **Environmental and maintenance considerations:**
  Mammals such as ungulates or livestock may use the poles supporting the nodes as rubbing posts. Similarly, nodes or other devices may be used by birds as perches, requiring occasional cleaning of the solar panels. For this reason, it is not necessary for the system to remain permanently installed and it can instead be deployed only during the relevant tracking periods (i.e. migration passages).
- **Procurement schedule:**
  When placing an order, bear in mind the company's estimated delivery time, which is approximately three months.
- **Installation time:**
  At least two full working days are required for a team of two people to complete the installation and setup of the system.
- **Technical support:**
  The Doñana Biological Station team (EBD-CSIC) involved in the AWOM project will provide technical assistance whenever required to address the specific needs of each study area where antennas are to be installed.

11. Supplementary information

Flashing your SensorStation's Compute Module:
https://cellular-tracking-technologies.github.io/ctt_documentation/flashingComputeModule.html

CTT User Guide Library:
https://cellular-tracking-technologies.github.io/ctt_documentation/

Installation Guide for the CTT SensorStation and CTT Nodes:
https://cellular-tracking-technologies.github.io/ctt_documentation/SensorStation-User-

Guide.html

CTT Node V3 User Guide:
https://cellular-tracking-technologies.github.io/ctt_documentation/CTT-Node-V3-User-Guide.html
CTT BlūSeries Receiver Guide:
https://cellular-tracking-technologies.github.io/ctt_documentation/CTT-BluSeries-Receiver.html

R Data Tools:
https://cellular-tracking-technologies.github.io/

12. References

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13. Annexes

Annex 1. Coordinates of the locations of the twenty-four nodes deployed during the field trial conducted at Boada Lagoon.

Device	WGS		UTM	
	Latitude	Longitude	Latitude	Longitude
SensorStation	41,983622	-4,860898	4.649.633	345.842
Node 1	41,986736	-4,863114	4.649.982	345.666
Node 2	41,986656	-4,861082	4.649.970	345.835
Node 3	41,985095	-4,865193	4.649.804	345.490
Node 4	41,985191	-4,863051	4.649.811	345.668
Node 5	41,985218	-4,860923	4.649.810	345.844
Node 6	41,985229	-4,858753	4.649.807	346.024
Node 7	41,983665	-4,865176	4.649.645	345.488
Node 8	41,983591	-4,863007	4.649.633	345.668
Node 9	41,983680	-4,858824	4.649.635	346.014
Node 10	41,983497	-4,857117	4.649.612	346.155
Node 11	41,981971	-4,865101	4.649.457	345.490
Node 12	41,982025	-4,862895	4.649.459	345.673
Node 13	41,982046	-4,860852	4.649.458	345.842
Node 14	41,982098	-4,858719	4.649.460	346.019
Node 15	41,982099	-4,856804	4.649.456	346.178
Node 16	41,980350	-4,865133	4.649.277	345.484
Node 17	41,980533	-4,862854	4.649.293	345.673
Node 18	41,980499	-4,860804	4.649.286	345.843
Node 19	41,980525	-4,858665	4.649.285	346.020
Node 20	41,980543	-4,856641	4.649.283	346.188
Node 21	41,978866	-4,862757	4.649.108	345.677
Node 22	41,978906	-4,860757	4.649.109	345.843
Node 23	41,978910	-4,858629	4.649.105	346.019
Node 24	41,977266	-4,860983	4.648.927	345.820