A GSM-based System for the Tracking of Birds

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***Abstract*—We present a prototype of a system for the tracking of animals, goods or people, by using only Global System for Mobile Communications (GSM) services. The system consists of two parts: a base device and at least one location device. The base device receives the Short Message Service (SMS) sent by the location devices and forwards the messages to an application that decodes and stores the location data in a database. The location device, the part actually attached to the animal, good or person being tracked, combines reduced size and weight with extended range. We present the energy consumption profiles and the computer applications developed to test the system and discuss the results of practical tests with wild and captive birds.**

Keywords–GSM-based location, location system, geolocation, tracking system, bird tracking

I. Introduction

Animal movement and migration has long fascinated man. Due to its scale, bird migration is one of the most striking. The number of birds involved is in the billions, the annual roundtrips of some bird species reach 70,000 km and some birds are known to perform non-stop flights of 10,000 km [1] [2]. Discoveries such as these are in part due to the use of tracking technology, which is of interest for multiple reasons. First, tracking is an important tool to better understand and protect the migrating species. Second, migrant animals are indicators of change. Human activity is having a global impact on the planet and migrant animals modify their behaviour due to human-caused changes and stressors. Birds, being the most mobile of all animals, are of particular interest in this regard. A better understanding of migration patterns also impacts climate change studies, energy generation, airstrike prevention, disease propagation, planning and urbanisation, agriculture, fisheries, and more.

Migration studies were once carried out by observation, but for more than one century they have relied on technological advances and breakthroughs. Bird ringing was one of those advances, and began with the efforts of a school master, Hans Christian C. Mortensen, in Denmark in 1899 [3]. A ring is a light metal band of appropriate size that carries a unique number, by means of which the bird can be identified, if and when recovered.

The relatively small probability of recapturing a ringed bird is a drawback that more recent technologies are helping to solve. One solution is to use electronic devices to send signals that are then picked up by radio receivers or satellites, enabling scientists to follow the movement of the tagged animals without having to recapture them. In fact, the receiver can be used to home in on the animal to get the device back.

Tracking an animal by radio involves two devices: a transmitter attached to the animal, to send out signals (data); and a receiver to pick up the signal (data). The transmitter can be placed around an animal's ankle, neck, wing, carapace, dorsal fin or it may even be surgically implanted. The advantages of implantation of subcutaneous radio transmitters are discussed in, e.g., [4].

Useful as they are, these devices are far more expensive than the low-tech, non-electronic tags. Also, their size and weight makes them useless for tracking some animals, including many birds species.

Receivers can also be placed in satellites or, more precisely, networks or groups of satellites (e.g., Argos). Satellite tracking ha been used to track caribou, sea turtles, whales, great white sharks, seals, elephants, bald eagles, ospreys and vultures [5]. For a review of traditional systems used in the tracking/location of birds, see [6]. In [7], a Global Positioning System (GPS) based tracking system was used in experiments of homing pigeons flying in flocks of up to 10 individuals. The GPS device, based on a commercially available product (u-blox AG, LEA-5H), is able to log 30,000 data points (latitude, longitude, altitude and time), measured 25×45 mm, and weighed 16 g. Upon recapture of the birds the log files are downloaded to a computer and processed. The GPS trackers used in [8] were also applied to study pigeons. The complete device measured $71 \times 41 \times 17$ mm, weighed 35 g. Hand-held, non-differentially corrected 12-channel GPS receivers capable of storing up to 1024 positions were used in central Norway to track hunters and their interactions with Willow Ptarmigan *Lagopus lagopus*, as reported in [9].

The system described in [10] weigths 12 g and includes a GPS receiver, micro-processor, 4 MB of memory for data storage, solar panel and battery. It has a tri-axial accelerometer to monitor behaviour and it is equipped with a radio transceiver for bidirectional communication with a ground-based antenna network, which enables data to be downloaded and new measurement schemes to be uploaded remotely. It enables the study of fine-scale movements (intervals of 3 s) to long-distance migratory movements (intervals of 20-30 min).

The system used in [11] to study the migratory strategy of herons uses DUCK III Ecotone GPS/GSM transmitters and a battery charged by a solar panel. The transmitters provided accurate information on geographical location every 3, 6, 12 or 24h. No data was provided concerning the device's weight besides the fact that "extra weight of the transmitters and Teflon harness varied from 3.4 to 3.9% of (herons') body mass".

A study concerning seasonal differences in migration patterns of soaring birds in relation to environmental conditions was presented in [12]. Here, 11 adult Booted Eagles were equipped with 22 g GPS-Argos satellite transmitters, and one individual with a GPS data-logger of the same weight. Transmitters were programmed to collect GPS locations on an hourly basis from 6:00 to 20:00 (GMT—Greenwich Mean Time) during migrations.

Other solutions can be considered [13]: data recovery using a VHF beacon data transmitter, radio modem technology, Argos DCLS, mobile communications (GSM/SMS, GSM/GPRS—General Packet Radio Services), LEO satellite telephone data services, Iridium satellites, globalstar satellites, or node-to-node networking. Note that some of these solutions have high power/energy consumption requirements.

The coordinates are the fundamental data in the tracking of birds (or other animals, persons, or goods). In the case of data loggers, they are saved in log files and then downloaded to a computer, upon recapture of the bird.

Light-based geolocation is an alternative when satellite-based systems cannot be used. Theoretically, a light sensor and a clock are sufficient to solve the geolocation problem, at only a fraction of the cost, size and weight of satellite-based systems. On the negative side, the errors increase near the equinoxes and the errors can be in the hundreds of km [14]. The template method [15] improves on this. Light-based geolocators are loggers and the data can be retrieved only if the bird is recaptured.

As far as we know, there is no bird tracking system that relies entirely in GSM technology. In this paper we show that it is possible to track birds in this way, taking advantage of GSM services. To this end we have developed a prototype that combines reduced size and weight with extended range, and that was tested on birds. Since the device is capable of transmitting its data, in the form of text messages, there is no need to recapture the bird.

The remaining of this paper is organized as follows. Section II is used to present the location system, which has two main components: the location device and the base station. Section III is used to explain how data can be viewed and interpreted. In Section IV we present the results achieved with the laboratorial tests. After that, some practical considerations are presented at Section V. The results of the tests carried on birds are presented in Section VI. The paper ends with the major conclusions, presented in Section VII.

II. THE LOCATION SYSTEM

The location system comprises two parts: the location device, attached to the animal (bird); and the base station, to receive the data from the location device.

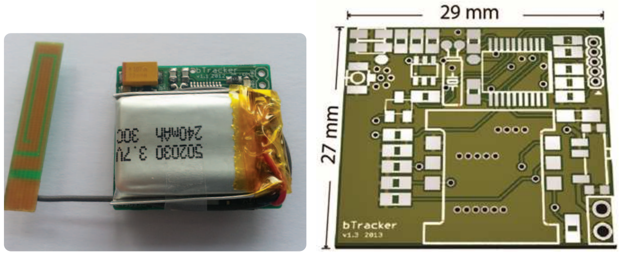

Figure 1. Left—Photo of the prototype with all components; in the PCB underside is just the modem. Right—Top view of the PCB; the lower view contains only the modem connections.

A. Location device

The prototype uses the following main components:

- **GSM modem**—Allows registration in the GSM cell/network in order to collect the necessary information (in this first phase is also used to send the data for later analysis). We have used a GL865-QUAD Telit modem with the following characteristics:
  - weight: 2.48 g;
  - dimensions: $24.4 \times 24.4 \times 2.7$ mm;
  - connectivity: Quad-band GSM / GPRS stack and Transmission Control Protocol/Internet Protocol (TCP/IP) supported.
- **Antenna**—Print Circuit Board (PCB) antenna with extension and U.FL connector.
- **Micro-controller (MCU)**—The MCU used (PIC24FV32KA301) was chosen considering the energy consumption, size and the presence of certain peripherals. Note, for example:
  - supply voltage: from 2.0 to 5.5 V;
  - Consumption in sleep mode: up to 2.2μA;
  - 2 UART units;
  - Real Time Clock (RTC).
- **Battery**—The LiPo (Lithium Polymer) technology was chosen due to its weight / capacity relation. As a starting point the battery capacity used was 200 mAh, with an approximate weight of 7 g.
- **Passive Components**—We have used surface-mount technology; surface-mount device, 0805 capacitors and resistors.

We developed a "first" (working) version of the device, which was debugged and improved, both in software and hardware. At the hardware level, the priority was to reduce the weight and dimensions. Figure 1 (left) shows the "second" version, referred to as "bTracker V1.1". To achieve this goal we produced a new design of the circuit with an array of different possible components that reduced the area by 36%, and at the same time reduced thickness from 1.5 mm to 0.5 mm. Some components have been removed or replaced in order to reduce the area and weight, while retaining all the features of the first version. This version weighs about 12 g, with all components and a battery of 180 mAh, and is distributed as follows:

- printed circuit—2 g;

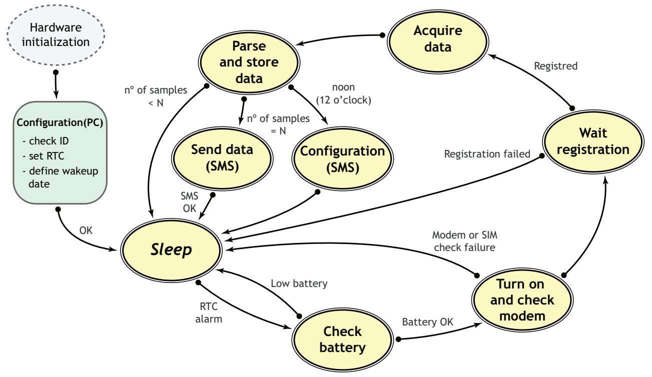

Figure 2. Location device system state diagram.

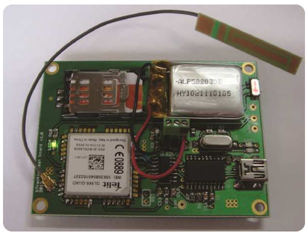

Figure 3. Photo of the "based device" to receive SMS data and subsequent visualization of the results on the map.

- GSM/GPRS modem—2.5 g;
- battery (180 mAh)—6 g (7 g for a battery of 200 mAh).

Figure 1 (right) shows the appearance and dimensions of the PCB.

At the software/firmware level, the second version represents an improvement in energy consumption, achieved through the reduction of downtime and the use of sleep mode during certain waiting times, leading to a slight reduction in the total energy consumption. We also reduced the clock frequency of the processor from 8Mhz to 2MHz; the consumption difference resulting from this change is presented in Section IV. Figure 2 presents a simplified state diagram of the location device. The complete schematics of the first and second versions of the device can be downloaded from www.mcabral.utad.pt/birds/.

B. Base device

The "base device" is used to receive the SMS sent by the location devices and to forward the messages to a (Java) application that decodes and stores the location data in a MySQL database. It was also used (as an interface card) to test the modem Telit GL865 and the AT commands. It allows commands to be sent directly from the PC to the modem via a terminal. In addition to the modem and SIM card, this base device contains a USB controller (MCP2200, Microchip), which is basically a TTL RS232 to USB converter. A battery, to ensure the 2 A current peaks that the modem used needs (recommended in the datasheet), and a charge controller (MCP73831, Microchip) for LiPo battery technology (charging via the USB port) were also incorporated.

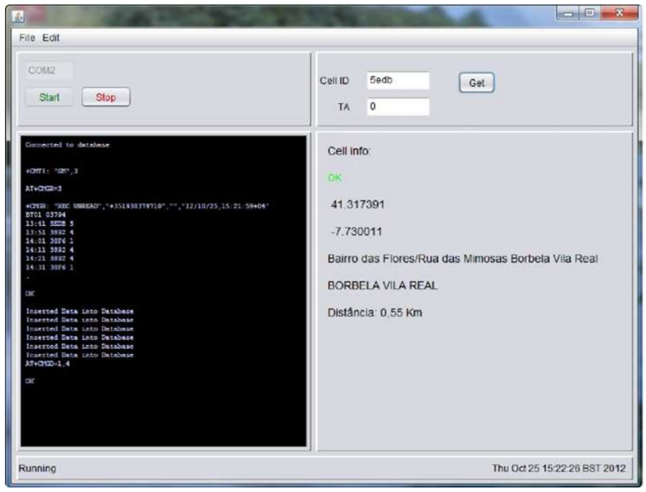

Figure 4. Graphical interface of the Java application responsible for receiving and storing data in the database.

Figure 3 shows a picture of the implemented "base device", in this case with a 200 mAh LiPo battery. The complete schematic can also be downloaded from www.mcabral.utad.pt/birds/.

At this point a brief description of the application management is in order to help understanding how the base station and location device work together. The application developed for data management performs several tasks. First, it must communicate with the modem via a (virtual) COM port in order to be able to receive SMS and send commands to the modem. After receiving the message, the application identifies the receiver device and sorts out the various fields of the received message. Next, the GSM network cell ID where the location device is linked is searched in the database and the corresponding geographical coordinates, as well as the address where the antenna is located, are retrieved from the database. It is also possible to perform a manual search of a cell ID and retrieve the corresponding data that are stored in a file (Excel). These data are then stored in a database for subsequent online viewing. Figure 4 shows a screenshot of the application.

III. DATA VISUALIZATION

This section explains how the data collected by the devices are presented to the end user.

A. SMS data format

The data collected are sent via SMS. The structure of the SMS is shown in Figure 5 (left).

The message header comprises a unique device identifier (4 characters), followed by the battery voltage in mV. After the header comes the data collected during the operation of the device. To minimise the message size, the date comes first (yy-mm-dd) followed by the complete set of readings on that date. Each line comprises time (hh:mm) followed by the GSM cell ID and Timing Advance. When there is a change in the data collection day a new date is inserted, as can be seen in Figure 5 (left).

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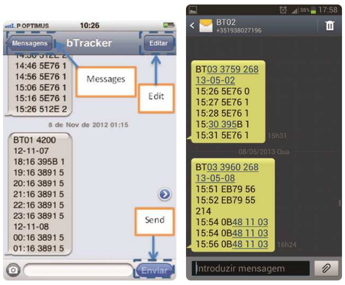

Figure 5. Format of data messages sent by the location device. Left—device identification (BT01), the battery voltage in mV (4200) followed by the date, time, GSM cell ID and Timing Advance (TA). Right—device is in roaming (bottom) and during normal operation (top).

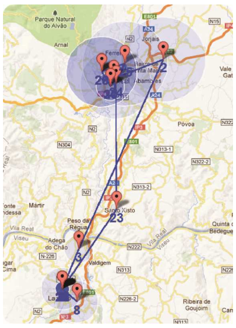

Figure 6. An example of data visualization on map. The bluish circles show the geographical location of the device.

B. *View on map*

All data received via SMS in the base station are interpreted and stored in the database and can be accessed over the web. The map showing the estimated device location is shown in Figure 6. The bluish circles show the geographical location of the device. As it can be seen, there are bigger circles and smaller circles, showing that the device was further or closer away from the antenna (cell ID). This "distance" is given by the Timing Advance value, and the central values of the circle correspond to the geographical coordinates of the cell ID (antenna).

IV. LABORATORIAL TESTS

The power consumption of the location device is a major concern since it determines the battery capacity, and the battery represents a large fraction of the device weight. We now present results of the energy consumption of the location device in different states and for different tasks. Note that the energy consumption of the base device is not a concern.

The operation of the location device can be divided into three essential states, representing different energy consumptions. All these states are linked by periods when consumption is very low (sleep state), and where a current consumption of less than 20μA was recorded.

A. *Device start-up*

The first state/task to consider is "start-up" where it is necessary to do some hardware checks and synchronization of the real time clock via the SMS service. Because this task involves sending and receiving SMS, it consumes a significant amount of energy. However this is done only once, and its influence on the device's autonomy is therefore reduced. This profile also includes the first acquisition of the cell ID where the device is connected to. Figure 7 shows the energy consumption profile (dashed green line) for this task.

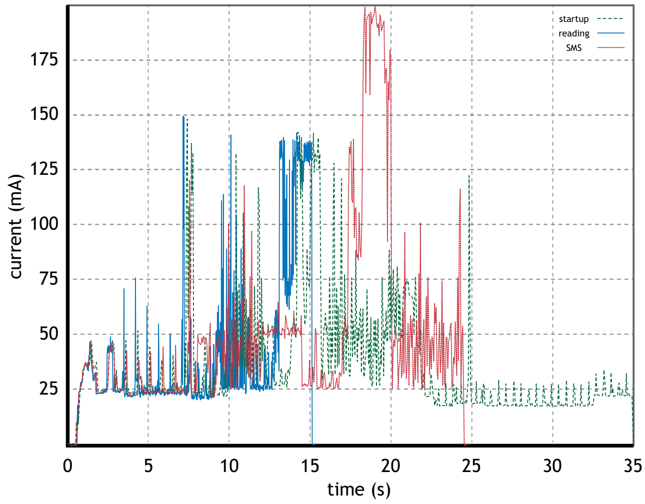

Figure 7. Energy consumption profiles for the three main states: dashed green—boot-up; blue—reading; dotted red—SMS.

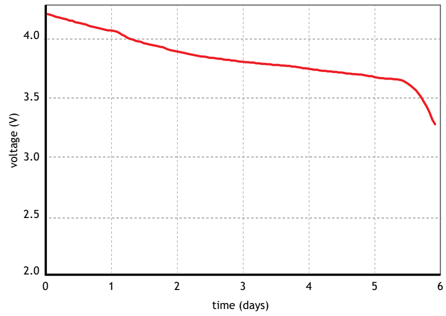

Figure 8. Discharge profile of the 200 mAh battery, for an interval of 10 minutes between acquisitions and every hour uploads (via SMS).

This state has the following characteristics:

- Average current consumption: 38.8 mA;
- Approximate duration: 36 s;
- Energy consumption: 1.45 mWh;
- Consumed energy fraction (200 mAh battery): 0.195%.

B. *GSM cell reading*

This state/task directly influences battery life, because it is repeated as a part of the normal operation cycle. The device leaves the state of sleep, does a series of checks, collects the cell information and returns to the state of sleep. The time that the modem needs to log into the network prevents the duration of this task from being shortened. Any change (gain or loss) on energy consumption in this task has a significant influence on the overall battery life and therefore on the frequency with which data can be acquired. Figure 7 shows the energy consumption profile (blue line) for this task.

This state has the following characteristics:

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- Average current consumption: 44.2 mA;
- Approximate duration: 15 s;
- Energy consumption: 0.75 mWh;
- Consumed energy fraction (200 mAh battery): 0.101%.

C. Sending SMS

The sending of data via SMS occurs immediately after the "cell reading" task. The extra consumption attributed to the SMS can be calculated as the difference to the previous profile:

- Average current consumption: 51.3 mA;
- Approximate duration: 24 s;
- Energy consumption: 1.38 mWh;
- Consumed energy fraction (200 mAh battery): 0.187%;
- Energy consumption (SMS only): 0.630 mWh;
- Consumed energy fraction (SMS only, 200 mAh battery): 0.085%.

Figure 7 shows the energy consumption profile (dotted red line) for this task.

D. Microcontroller consumption measurements

To obtain a good compromise between performance and power consumption we did a series of consumption measurements, involving only the microcontroller:

- Sleep: 20μA;
- 8 MHz: 4.9 mA;
- 4 MHz: 2.8 mA;
- 2 MHz: 1.8 mA;
- 1 MHz: 1.3 mA;
- 500 KHz: 1.0 mA.

The frequency of 2 MHz was selected because if allows a reduced consumption and an acceptable performance.

E. Battery life test

Knowing the energy consumption data it becomes possible to predict, for a given battery capacity, its expected life under various scenarios (depending on the acquisition and data sending frequencies). The quality of the network coverage imposes variations in the power consumption, adding to the difficulty of predicting operating life under real operating conditions. The data to estimate the battery life are:

- Energy consumed at startup: 1.445 mWh;
- Energy consumed by reading: 0.753 mWh;
- Energy consumed by reading SMS: 1.384 mWh;
- Energy consumed by SMS: 0.631 mWh;
- Battery capacity: 200 mAh;
- Battery rated voltage: 3.7V;
- Total energy in the battery: 740 MWh;
- Current consumption in Sleep: 0.02 mA;
- Energy consumption in sleep per day: 1.776 mWh.

For these data, and for intervals between acquisitions of 10 minutes and data uploads every hour (via SMS), we obtain the following:

- Number of acquisitions per day: 144;
- Number of submissions per day: 24;
- Total energy per day: 125.44 mWh;
- Battery: 200 mAh;
- Estimated Duration: 5 days and 20 hours.

The duration (5 days and 20 h) was tested in practice. Figure 8 shows a typical discharge curve for a LiPo battery technology. The test agrees with the predictions. In the last hours the battery condition was already critical, with a cell voltage below 3.5 V.

As another example, imagine that a reading is performed every hour and data is sent every 8 hours (3 times a day). Then,

- Number of acquisitions per day: 24;
- Number of submissions per day: 3;
- Total energy per day: 21.76 mWh;
- Battery: 200 mAh;
- Estimated Duration: 33 days and 23 hours.

V. Some practical considerations

After encapsulation, the devices are ready to be attached to the birds and cannot be easily turned on or off. To solve this problem we implemented a device configuration schema and a magnetic sensor that allows the device to be started immediately before deploying it.

During the assembly, it is possible to program the starting date and time at which the device starts gathering information. It is also possible to define an operating daily window, e.g., from 11:00 till 20:00. The interval between acquisitions is also configurable with a resolution of one minute. Thus, depending on the particular situation, the device can be switched on immediately after being encapsulated, or a date and time can be set.

A very important feature is the ability to change the operation of the device during its normal operation through a configuration message (SMS). The parameters that can be changed are:

- "Opening hours"—the daily window for location acquisitions;
- "Acquisition interval"—time between each acquisition (in case it is found that the acquisition time is not appropriate to the actual situation);
- "Progress in time"—allows advance in time; for example, with a 20 minute advance the device will sample at 10:20 instead of 10:00.

However, this approach presents the disadvantage of requiring a longer period of activity, so as to ensure that configuration messages are received. This is due to that during normal operation the time that the device is active is not sufficient to receive pending messages. It was then stipulated that every day at 12h00 the device remains active for 40 seconds, the time required to receive pending messages and proceed with the configuration, if this feature is to be used.

Because birds easily cross country borders, at the beginning of each message, immediately after the battery voltage, the country code was added. If the device is in roaming, at the

Figure 9. Left—Photo of devices ready to be used; "encapsulated" using two layers of thermo-contractile sleeve in opposite directions and in between a layer of silicone. Right—Test with cranes; placement of a tracking device.

end of each reading, after the TA field, the network code to which it is connected is also inserted. Only in this way we can determine the device's location across multiple countries. Figure 5 (right) shows the format of the messages when the device operates in roaming, compared to normal operation.

The device needs to be configured before being encapsulated and placed on the bird. To simplify this task, we have created a simple application that allows editing some important parameters.

The first step is to perform communication with the device so that it returns the parameters that are programmed by default. After that, the device internal clock can be set automatically, using the date and time settings of the PC. If necessary, the device's ID, the SIM number and the working schedule can be modified. Before leaving the configuration mode, a date and time for the device start-up must be set. After leaving the setup mode, the device stops responding to the application and enters the low-power mode (sleep), to return to the active state only at the scheduled time and date.

In order to adapt the device to the environmental conditions, it is necessary to prevent water and debris from interfering with the electrical circuitry without adding significantly to the final weight. We used thin thermo-contractile plastic film, adding two layers in opposite directions separated by a layer of silicone. Figure 9 (left) shows photos of devices ready to be attached to birds.

VI. Tests on birds

We performed three tests with birds in order to evaluate the devices' performance in real scenarios. Next, we will describe how they were made and the results obtained.

All birds were captured and handled by properly trained and authorised personnel. Two devices were prepared and placed in wild Mallards (*Anas platyrhynchos*) in February 2013. The devices failed soon after the start of the test, probably due to an encapsulation fault and the unforgiving nature of the environment (water). No useful information was collected and we decided to do an experiment with domestic birds, to see if the birds interacted with the device and how the device and the (meanwhile improved) harness and packaging behaved.

The second tests took place in March 2013. The results were positive. Both devices remained fully functional throughout the experiment and sent data as expected. Since the animals were confined to a limited space, there was no variation in position. The devices remained active for two weeks. After recovering them, we found that they were already showing some signs of water infiltration. This test was important to optimise the harnesses and the packaging.

TABLE I. Summary of the latest test data

Device	*Date of last SMS*	*Likely failure cause (Battery level)*
BT01	16-07-2013	Battery (3.4 V)
BT02	17-07-2013	credit of the SIM card (3.6 V)
BT03	05-07-2013	credit of the SIM card (3.8 V)
BT04	did not start	Water
BT05	06-07-2013	credit of the SIM card (3.8 V)

The third test began on June 17, 2013. Five devices were placed in Purple Herons *Ardea purpurea*, as seen in Figure 9 (right). Table I shows the date of the last received messages and the possible cause of device failure. As can be seen, one of the devices was damaged by water (possibly as a result of a packaging flaw), in another the battery voltage level suddenly dropped and in the remaining three cases the device did not fail until the budget available for the communications run out. The battery voltage level was still at a level that would have allowed the devices to work as intended. The herons did not leave the nest area during the test.

VII. Conclusion

We have presented a prototype of a tracking system that uses only GSM services. The location device transmits messages to a base device, which forwards all received SMS to an application that decodes and stores the location data in a database. The location device, which is the component attached to the bird being tracked, combines reduced size and weight with extended range.

We have presented the energy consumption profiles, the computer applications developed to test it, and the results obtained in practical tests with birds (wild and domestic). The results confirm that GSM-based solutions are entirely capable of tracking, for example, migratory birds.

The accuracy of the system proposed here can be increased using GSM-based triangulation methods, but it cannot match that of GPS-based tracking systems (which are often heavier and more expensive). Light-based geolocators are much smaller and lighter than the GSM-based system proposed, but are much less accurate. Also, as with any data loggers, the data that they collect can be used only if the bird is recovered. With GSM-based tracking, there is no such constraint.

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