WIRELESS MONITORING OF IN-FLIGHT BAT CALLS AND ECHOES FROM THE ECHOLOCATING FRUIT BAT *Rousettus aegyptiacus*

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1 INTRODUCTION

Bats have evolved to be one of the most successful life forms on the planet, accounting for more species than any other group of mammals except the rodents. Part of this success is certainly due to their unique use of sonar for navigation, orientation and predation, allowing them to exploit the nocturnal aerial niche. This ability of bats to perceive their environment in complete darkness was first documented by the Italian Abbé Lazaro Spallanzani [1] in the late 18th century. Spallanzani performed many experiments which indicated that bats require their sense of hearing, but not sight, to manoeuvre successfully, but he could not make sense of these findings. It was to be nearly 150 years before Donald Griffin and his colleagues would solve the puzzle by detecting the ultrasonic calls of bats as they flew, with Griffin coining the term *echolocation* [2].

Bats' perception of their environment comes from the echoes which they receive from their emitted calls. As such, these echoes are complex and composed of multiple frequency components. Yet given this complexity, bats are capable of successfully locating prey objects in poor signal-to-noise environments and have been documented to be capable of impressive feats of resolution. Many experiments have been conducted which indicate that bats are capable of resolving their environment to fractions of a wavelength of the shortest sonar signals they emit: for example, Mogdans *et al.,* 1988 [3] showed the greater horseshoe bat, *Rhinolophus ferrumequinum,* to be capable of avoiding wires less than 1mm in diameter, in comparison with the 4mm wavelength of their dominant 83kHz constant frequency (CF) call component. Similar findings are documented amongst other microchiropteran species [e.g. 4, 5].

The precision with which bats perceive their environment, coupled with their ability to work with poor signal to noise ratio, gives impetus to the study of their sonar systems; it is envisaged that greater understanding can lead to the improvement of ultrasonic sonar, ranging and imaging systems. The processing of echoes undoubtedly plays a vital role in obtaining such precision, however the signals themselves have been designed to suit the tasks which bats undertake. Indeed bats adapt these signals dynamically to the task in hand, especially during the phases of prey capture, illustrating that signal design is of importance to achieve any given objective. Thus, detailed study of the calls which bats emit, as well as those echoes which the bat receives and processes, will lead to greater understanding of the process. The work presented in this paper focuses on the development of a wireless sensor system which allows the detection of both the call emitted by an echolocating bat, as well as the echoes which return to the bat. This sensor is designed to be mounted on the bat whilst in flight hence avoiding the directionality and attenuation issues which occur when trying to record echolocation calls with a static microphone.

2 SENSOR DESIGN

Previous work with wireless ultrasonic sensors has been successful in recording the calls which bats make whilst echolocating in flight [6, 7]. Indeed, echoes from a wall of the flight chamber were even recorded [8]. However, the motivation for the current work was to develop a sensor capable of detecting both the emitted signal and the echoes which bats use in echolocation. One specific aim of this work was to detect echoes from smaller objects such as discs, spheres and wires which could be suspended in the flight room with captive bats. It is envisaged that this information would allow the entire process of echolocation to be more accurately examined. This is a significant challenge, in terms of design of a sensor small enough and light enough to be carried by a bat, which has a sufficient dynamic range to detect both emitted and reflected acoustic signals. This is demonstrated by the dynamic range with which bats are known to work. While emitted signals have been estimated as high as 133db peSPL in the wild [9], their hearing threshold is accepted as 0dB SPL (at their best frequency), as demonstrated in a number of studies using either evoked potential measurements within the ear [e.g. 10] or behavioural data [e.g. 11]. This represents an enormous dynamic range with which a sensor may be required to cope in order to study the emitted call, as well as all echoes audible to the bat.

The test subject for the wireless sensor was the fruit bat *Rousettus aegyptiacus*, a member of the only genus within the suborder megachiroptera which echolocates. The echolocation signals of this bat generally consist of pairs of "impulse-like" clicks produced with the tongue, and have been considered in the past to be rather basic in comparison to the coded signals produced by many microchiropterans. However, one study on *R. aegyptiacus* [12] indicates that its performance in wire avoidance tests is comparable to that of some microchiropterans, being capable of detecting wires of 1.3mm in diameter. This compares with its calls which have little energy above 50kHz, corresponding to a wavelength of 7mm. This species is also fairly large and robust, with a wingspan of up to 600mm and weighing up to 160g, which make it an ideal candidate for carrying a wireless sensor. The wireless sensors used in previous studies consisted of a microphone linked via a simple amplifier to a radio frequency oscillator of some description to provide the means by which to transmit wireless FM data. In this case, a simple amplifier would not suffice to provide the extended dynamic range required, and so the device is designed around a variable gain amplifier (VGA) which couples the microphone to the RF oscillator. This added complexity is made possible through use of a larger test subject, allowing a heavier payload to be deployed. A simplified schematic of the sensor is illustrated in Figure 1.

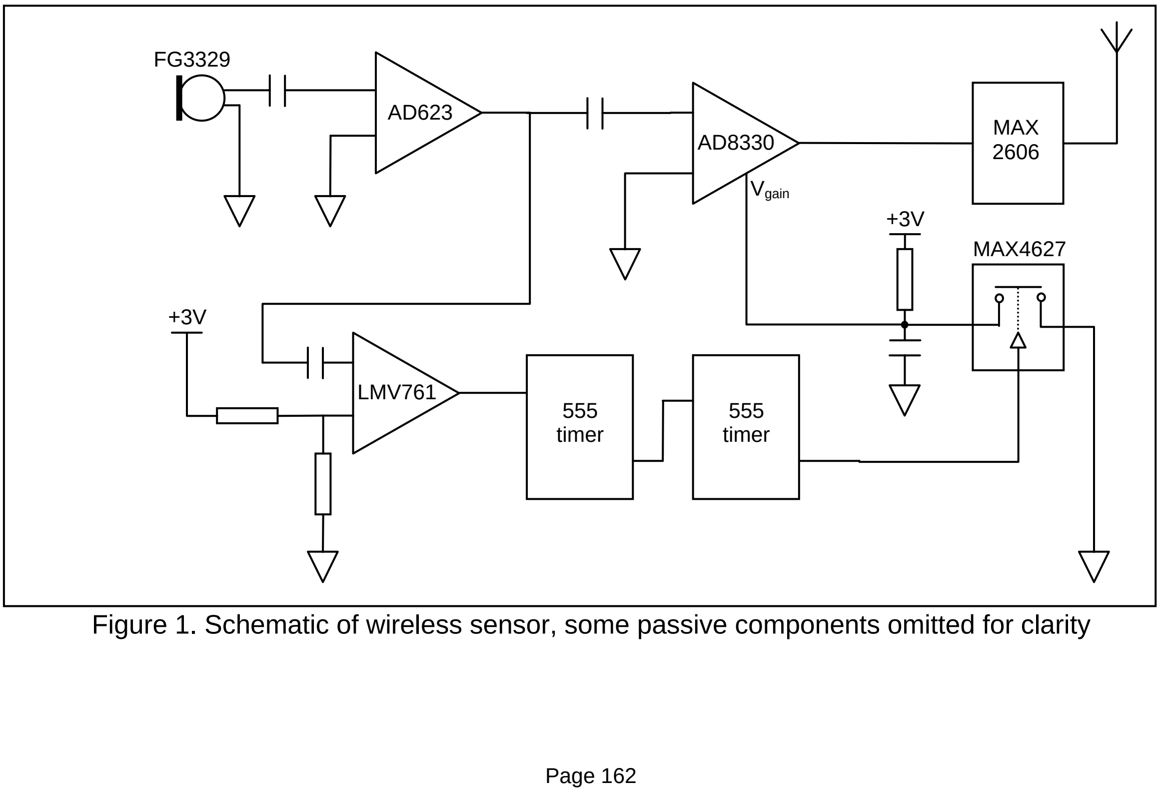


Figure 1. Schematic of wireless sensor, some passive components omitted for clarity

The microphone used is the Knowles FG3329 electret device, with initial amplification provided by a low-power instrumentation amplifier, Analog Devices' AD623. Further amplification is then provided by the AD8330, which can be used to provide variable gain via two gain-control pins. The timing circuit consisting of the LMV761 comparator, two LMC555 timers and a MAX4627 switch, is used to generate the gain control signal. When the bat emits an echolocation call, the comparator is triggered, which in turn triggers the first timer. This timer is set to produce a pulse which is of a similar duration to the expected echolocation call; in the case of *R. aegyptiacus*, this is approximately 200-300μs [12]. During this time period, the gain through the sensor is static so as to provide an accurate representation of the emitted signal. When this timer resets, the second timer is triggered, which opens the switch to allow the resistor-capacitor (RC) circuit to charge. It is this charging RC circuit which drives the gain-control pins on the VGA. When this timer resets, the system is restored to its default (low gain) state. Hence, with the emitted bat call as the reference point, the gain through the sensor begins to increase, providing a gain range of approximately 60dB. The output of the VGA is then coupled to a voltage-controlled oscillator (VCO) which produces a Frequency Modulated (FM) signal which is transmitted via a simple wire antenna. This FM signal is received on a standard FM tuner, with the demodulated signal accessed within the unit, prior to baseband filtering. Due to the use of a VGA the sensor consumes a relatively large current of approximately 30mA, requiring the use of a high-density battery technology. Three Nickel Metal Hydride (NiMH) cells were used which allowed the sensor to be active for 20 minutes before the battery was recharged, which was considered to be sufficient due to the nature of captive flight tests. The sensor has a mass of 6.8g, with 4.0g being attributable to the battery, and measures approximately 28mm×20mm.

3 SYSTEM TEST

The system was tested in two ways, firstly to calibrate its frequency response, and secondly to demonstrate its fidelity and dynamic gain performance. Its frequency response was calibrated using the substitution method: the output of a wideband electrostatic transducer was calculated across the frequency range of interest using a calibrated microphone (Bruel & Kjaer, Type 4138). The calibrated transducer was then used as the source to drive the wireless system, configured to have static gain. The measured frequency response was as shown in Figure 2. *R. aegyptiacus* has been documented [12] to produce calls with peak energy at approximately 19kHz, with little energy (-15dB) below 15kHz or above 45kHz; as such the frequency response is shown up to 80kHz, demonstrating suitability for use with the calls of *Rousettus*.

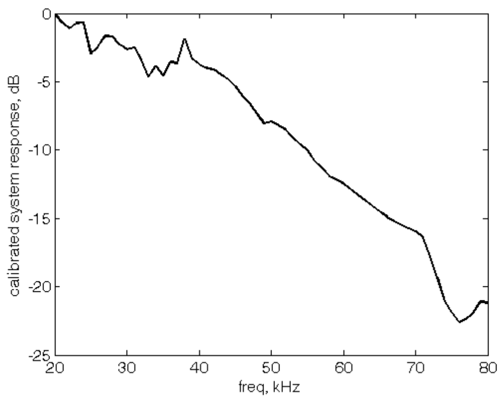
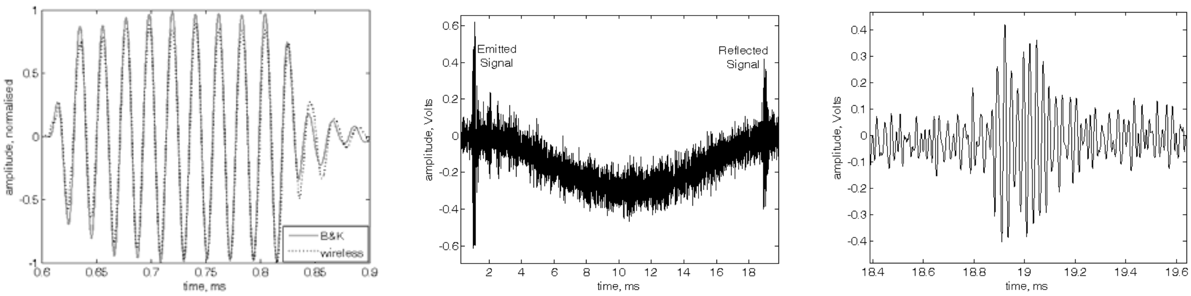


Figure 2. Frequency response of wireless sensor.

The system was further tested to demonstrate that it was capable of both accurate recording of an acoustic signal at the frequency of interest, and that its dynamic gain response operated effectively. Firstly, the system was exposed to a 50kHz acoustic toneburst of approximately 100dB SPL, with the system response being compared with that of the calibrated B&K microphone. The result of such a test is depicted in Figure 3(a) where it can be seen that the signal obtained from the wireless sensor correlates well with that of the calibrated microphone. Subsequently the wireless system was tested using Robat, a mechanical construction which is designed to propel a transducer along a linear track, allowing the effect of motion on bat echolocation calls to be studied experimentally. In this case, it allowed the sensor's performance and robustness to be evaluated while in motion. The tests consisted of "flying" a transmitting transducer and sensor at $5ms^{-1}$ towards a plane reflector, thus ensuring that emitted and reflected signals could be detected by the sensor. Given the dynamic nature of the work, no averaging can be used, and hence this situation is an excellent testbed for the intended use of the sensor. Again a tone burst, with peak SPL of approximately 100dB was used, and signals were captured as the moving sensor reached approximately 3m from the plane reflector. The resulting traces detected wirelessly from this test are illustrated in Figure 3, with the full trace in Figure 3(b) while an expanded version of the echo signal is depicted in Figure 3(c). It is estimated from static lab tests that the return echo is approximately 30dB reduced from the level of the emitted signal; the relative amplitudes of emitted and echo signals demonstrate successful operation of the variable gain. It should be noted that the "noisy" appearance of the trace is actually due to amplification of multiple return echoes from what was a cluttered environment. As such the "noise" is coherent and not due to poor noise performance of the wireless system. The low frequency signal evident in part (b) is due to the sound which Robat makes as it moves along its track. Further to this test, the dynamic gain and amplification was further adjusted to maximise the dynamic range of the system. Through lab measurement, the sensor was shown to have a dynamic range in excess of 80dB.



(a) (b) (c)

Figure 3. Testing of the wireless sensor system.
(a) Comparison of signals obtained from a calibrated microphone and the wireless system.
(b) Emitted and reflected signals obtained from Robat. (c) Expanded image of reflected signal

4 METHODS

Five *R. aegyptiacus* individuals loaned from Tropical World, Leeds were used to conduct the flight tests. The bats were maintained on a 12h light, 12h dark reversed photoperiod in a cage purpose built for their stay. They were provided with fruit and water throughout. Flights were conducted in a corridor measuring approximately 14m × 2.5m × 1.5m situated adjacent to the room housing the cage. The corridor was equipped with a mesh hung at one end to serve as an artificial roost, and had a 100mm diameter disc suspended half way along its length as an echolocation target. Two FM receiving antennas were placed along the length of the corridor to ensure that the sensor was close enough to one of them to ensure adequate signal strength at the tuner. This setup is shown in the photograph in Figure 4(a). Each bat made up to 16 flights in this environment, with a 3-second segment of the flight being recorded on high-speed video simultaneously with the acoustic data which was obtained from the FM tuner and digitised at a sample rate of 400kHz. The sensor was attached to the animal, as shown in Figure 4(b), using Velcro so that it was easy to remove without distressing the animal. The results presented here will concentrate on the acoustic data which was recorded.

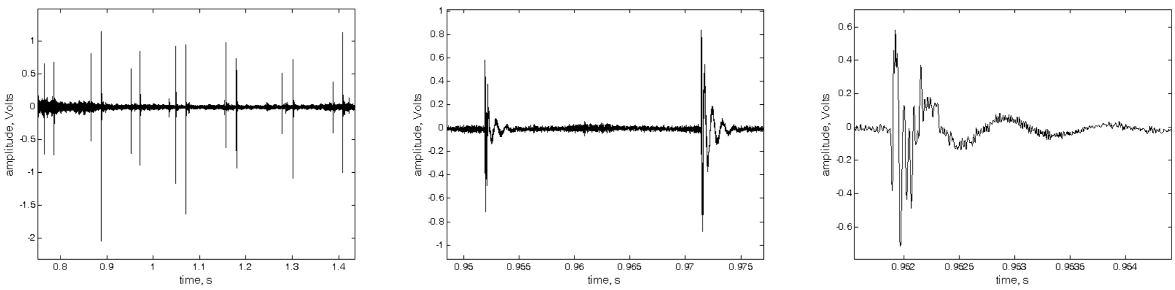
(a) (b)

Figure 4(a) The flight corridor, showing video camera, RF antennas and target.
(b) The wireless sensor mounted on *R. aegyptiacus*.

The sensor was used in two different modes, one with dynamic gain control, and one with static gain. The reason for this was that when gain control was employed, the signals obtained appeared to be noisier due to the huge increase in gain through the system. As with the testing described previously, this "noise" was simply the result of multiple echoes returning to the bat. In all, 58 flights and recordings were made by the five bats. Due to problems with environmental electrical noise, not all flights delivered usable recordings, but in all some 500-600 individual calls were recorded using the system.

5 IN-FLIGHT RECORDINGS OF ECHOLOCATION CALLS

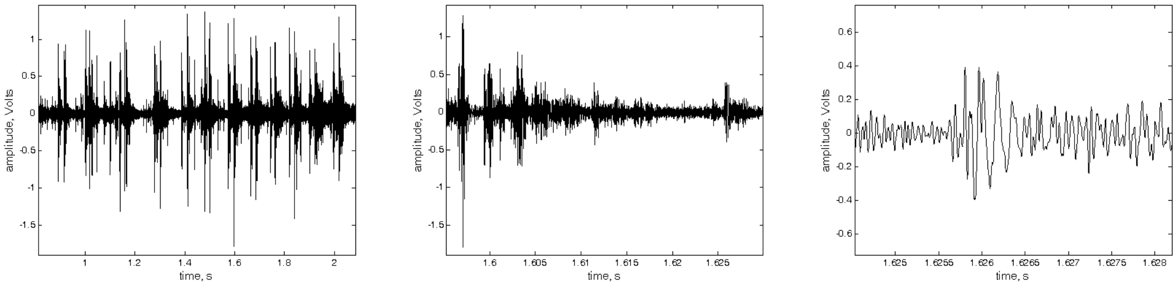
Using the sensor in its static-gain mode, produced clear representations of the emitted calls of *Rousettus* as depicted in Figure 5, where the typical "double-click" echolocation pattern can be discerned.



(a) (b) (c)

Figure 5. Echolocation signals captured using the wireless sensor mounted on a flying bat.
(a) Double-click pulse train. (b) Expanded double-click emission. (c) Expanded single-click

The sensor was also employed in its variable gain mode, in order to detect the echoes returning to the bat. Examples of the signals obtained are displayed in Figure 6.



(a) (b) (c)

Figure 6. Echolocation signals captured using the variable gain sensor.
(a) Train of emitted and reflected clicks. (b) Single click with echoes. (c) Expanded echo signal.

It can be seen by comparing part (a) of Figures 5 and 6 that the increased gain through the sensor generates far more acoustic information, resulting in a far busier trace. Examination of parts (b) and (c) of Figure 5 show that echoes returning to the bat up to 30ms after the emitted call are detectable, corresponding to a distance in excess of 5m to the target. This is only made possible by the use of variable gain.

6 DISCUSSION

The design of a sensor which is light enough to be mounted on *R. aegyptiacus* has been described, and its performance has been calibrated and demonstrated to be suitable for use with the sonar calls which this species uses. Furthermore, this sensor has been designed with dynamic gain control, which is triggered by the call of the bat, allowing return echoes to be successfully acquired from targets in excess of 5m distant from the echolocating bat. Such results will allow the echolocation system of bats to be more fully studied and understood.

The echoes which this system has recorded, give an insight into the signals which the bat must be capable of dealing with in order to navigate successfully using sonar. The expanded trace in Figure 6 (b) was selected for its relatively clean representation of the emitted and reflected signals, with echoes which are reasonably distinct from each other. Even so, this gives some indication as to the complexity of the task which faces the bat; it must be capable of decoding and understanding each individual echo in order to construct an accurate picture of its surroundings and any obstacles which lie in its path. The return echoes in a complex environment will certainly overlap and coincide, even from objects which lie in significantly different directions. Even given the relatively simple environment of the flight corridor used here, many of the traces recorded through use of the variable gain sensor generated extremely complex combinations of overlapping echoes, in effect looking like noise. This is the type of signal which the bat must cope with on a routine basis. Furthermore, echoes can clearly be detected in excess of 30ms after the emitted call, in comparison with the average time difference between the first and second click of a pair being approximately 21ms. Given this overlap, it is plain that there is the potential for ambiguity about the range of an object creating any reflection from the first click of a pair (for this reason, Figure 6 parts (b) and (c) relate to the second click of a pair). This is another hurdle which the bat must be able to overcome in forming an accurate image of its environment. It can be seen that even given a relatively simple echolocation signal and environment, the bat's task is by no means straightforward.

7 FURTHER WORK

Work is currently ongoing to analyse the data which this study has produced. The consistency of call structure amongst the five bats will be analysed, both in terms of time and spectral content. The high speed video will be used in conjunction with the acoustic data to investigate a number of aspects:

- The link between wingbeat cycle and sonar emission timing. This has been shown in microchiropterans which couple energy from muscles used in beating the wings into their laryngeal generation of calls [13]. Given the different way in which *Rousettus* generates its calls, this relationship is worthy of investigation.
- Any link between changes in inter-call interval and target approach. There are some instances of abrupt and significant changes in call timing in the acoustical data, which may be due to the approach towards an obstacle.
- Identification of echoes which originated from disc target. These echoes should be trackable through successive echolocation calls.

This study is part of an ongoing programme of work investigating bat echolocation. As part of this work, the intention is to conduct a similar study on echolocating British bats. This has obvious implications in terms of size and weight of the sensor, and so a lightweight sensor is currently being constructed. For this study to be wholly successful, the bandwidth of the sensor must also be extended in order to study the often rich harmonic content of FM and CF bat calls; a frequency range of up to 200kHz has been identified. Characterisation of the current system indicated that the response of the microphone is simply not capable of this, with significant attenuation of signals in excess of 120kHz. For this reason, a new wideband microphone is also being designed to extend the sensor's frequency range of operation.

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