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Eavesdropping on Echolocation: Recording the Bat's Auditory Experience

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Abstract—**Insectivorous bats are able to locate and capture insects in complete darkness while flying at high speeds. They may consume hundreds of insects each night while avoiding obstacles in a complex environment. To investigate the processes associated with bat echolocation, we have developed instrumentation that allows us to record and visualize what a bat hears while flying through its natural environment. Recordings were made using a miniaturized radio telemetry system mounted directly on the back of the bat. This paper describes the design and testing of the components of this system, presents echolocation data collected from bats and discusses issues associated with the visualization and analysis of echoes recorded in a natural setting from the bat's point-of-view. It presents a new tool for visualizing a bat's experience by generating call sequence sonograms (CSSs) based on various signal parameters. CSSs based on time series amplitude, band-limited spectral magnitude and Q-factor are presented. This work demonstrates that CSSs based on Q-factor (computed by dividing a peak frequency estimate by a bandwidth estimate) provides a relatively clear representation of the objects producing echoes encountered by a bat during a continuous flight.**

I. Introduction

BAT echolocation is a fascinating process and continues to be an area of intense study and debate[1, 2]. Bats produce frequent, repetitive, short vocalizations in the ultrasonic frequency range while flying. Each vocalization is known as a "bat call" (also called a "pulse" or "chirp") and the particular characteristics of each call (or sequence of calls) are both species- and context- dependent[3, 4]. Immediately after each call, bats listen for echoes to detect and identify ensonified objects in the environment. The bat calls described in this paper are the frequency-modulated (FM) calls of the big brown bat (*Eptesicus fuscus*).

FM calls are frequency sweeps starting with fundamental frequencies as high as 80 kHz and sweeping down to as low as 15 kHz. High frequency harmonics approaching 200 kHz may also be present. The repetition rate of a call sequence depends on environmental context and often reflects the biological significance of the current target. The highest call repetition rates (90 to 150 calls/s) occur immediately before capture of an insect. Low repetition rates (8 to 15 calls/s) are used for scanning the environment. As targets of interest are detected and approached, the repetition rate increases and call duration and bandwidth decrease[5].

Traditionally, bat calls have been recorded using stationary ultrasonic microphones connected to ground-based instruments[6, 7]. Field recordings made using stationary ground-based microphones do not provide completely accurate representations of bat calls because they are unavoidably contaminated with environmental echoes and Doppler shifts[8]. Further, the high frequency end of a bat call is attenuated in ground-based recordings which makes measurement of call bandwidth unreliable[9].

This work had two primary goals: (1) obtain recordings of bat vocalizations in a natural setting and (2) examine the spaces between the calls to observe the echoes used by the bat to navigate and hunt. The first goal was accomplished by developing an FM radio transmitter, equipped with an ultrasonic microphone, small enough to be carried by adult big brown bats. We also developed techniques for testing in a natural setting that allow us to retrieve our transmitter and release the bat. To meet the second goal, we developed software to support the acquisition, visualization and analysis of the signals we recorded.

II. Instrumentation

A. The Wireless Ultrasound Microphone

We have developed a wireless microphone that is small and light enough for adult big brown bats to carry in flight (1.5 to 2.5 grams, 3 to 4 cm^2). It was determined that FM analog transmission was the most feasible way to quickly meet the size and weight criteria using off-the-shelf components. We used the smallest (60 mg) ultrasound transducer available for the microphone (SPM0404, Knowles Acoustics). The microphone output is connected directly to the input of a voltage-controlled oscillator (MAX260x integrated circuit, Maxim Semiconductor) that generates an FM radio signal. Power is provided by a small, rechargeable, lithium polymer (LiPo) battery (3.6 V, 10 mAh, PowerStream, Inc.) weighing approximately 300 mg. The antenna is a length of 28AWG magnet wire, ¼ wavelength long.

Using this scheme, we have built and tested transmitters that successfully broadcast at frequencies from 87 to 433

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MHz. These transmitters have produced stable, continuous broadcasts of up to 45 minutes on a single battery charge. The range of these low-power transmitters is limited to a maximum of 30 meters. Thus, our field tests employ a technique that tethers the bat to a zip line consisting of 25 meters of Teflon-insulated wire pulled taut and suspended between two poles approximately 2 meters above grade. During these tests, the zip line wire is also used as the reception antenna.

B. *The Receiver*

We have used both an inexpensive standard FM broadcast receiver and a more sophisticated wideband communications receiver. In both cases it was necessary to modify the receiver somewhat to obtain signals directly from the demodulators (before any audio filtering had occurred). The demodulated signals obtained from 10.7 MHz IF (intermediate frequency) stages generally demonstrate an adequate bandwidth (up to 100 kHz).

Although transmission in the commercial broadcast band was convenient and adequate for initial tests[8], interference from commercial stations was often problematic. Moving the transmission frequency up to a higher band (400 to 433 MHz) gave us quieter recordings and reduced the size of the antenna to the point where releasing an untethered bat with a transmitter for range-limited free-flight testing was possible.

C. *Data Acquisition*

All ultrasound signals were buffered using purpose-built analog filter/amplifiers before digitization. The signals were analog filtered (15 to160 kHz) to remove any low-frequency components and prevent aliasing. During field tests, the sampling rate for each channel was 500ksps. We routinely recorded two signals simultaneously; one from a ground-based microphone placed at the end of the zip line and one from the wireless microphone carried by the bat. Thus, during post-hoc analysis, we compare the onset of the two signals and the time difference was used to compute the bat's location along the zip line at the time of each vocalization.

Signals were digitized using a 16-bit digital-to-analog converter (USB-1616HS-2, Measurement Computing, Inc.) connected to a laptop computer and controlled by software developed in our laboratory. The system provided an external triggering mechanism that allowed us to synchronize concurrently recorded video with the ultrasound audio.

III. FIELD PROCEDURES

A. *Bat Preparation*

Bats were captured using mist nets. All captured bats were examined, weighed and banded. Bats weighing less than 16 grams were not tested. Healthy bats weighing 16 grams or more were equipped with a wireless microphone transmitter. The wireless microphone was attached to the back of the bat, between the scapulae, using surgical glue. This placed the microphone at the level of the neck and elevated to a position between the bat's ears. Adhesive tape was applied to the bottom of the transmitter circuit board before gluing to facilitate removal of the transmitter after testing. The tether was connected to the transmitter circuit board on one end and a nylon slip ring on the other. Fig. 1 shows a bat with a transmitter glued in place.

B. *Field Recording Setup*

The zip line was approximately 25 meters long with one end designated for release (the *start* end) and the other end designated for retrieval (the *stop* end). The zip line was suspended about 2 meters above grade and threaded through a nylon washer that could slide easily along the entire length of the zip line and served as a tether connection point. Two target objects were suspended 7 meters before *stop*, 2 meters to the left and right of the zip line and 2 meters above grade. Target objects were chosen for their unique ultrasound echo signature in hopes they would be investigated by the bats and produce recognizable echoes in the zip line recordings.

Infrared illuminators were situated at the *stop* end and pointed toward the *start* end to facilitate video recording in the dark. A high-definition infrared video camera was situated 19 meters beyond the *stop* end with the zoom adjusted to record a consistent view of the bat in flight across the entire length of the zip line. A ground-based microphone mounted on a tripod and connected to a filter/amplifier was also fixed at the *stop* end. A long cable was used to connect the ground-based microphone to the ground station.

A ground station was established about 2 meters beyond the *start* end. The ground station consisted of a laptop computer, data acquisition and triggering hardware, a modified radio receiver and a filter amplifier. As mentioned earlier, the zip line was used as the antenna for the radio receiver. The receiver's output was connected to a data acquisition input through a filter/amplifier. Thus, when triggered, software run on the ground station continuously acquired samples from both the ground-based microphone and wireless microphone carried by the bat at an aggregate rate of 1Msps. The samples from each run were stored in WAV format file on the laptop computer's hard drive.

Each traverse of the zip line produced a recording approximately 7 seconds in duration. Bats were retrieved and brought back to the *start* end for each subsequent test. Bats generally flew the length of the zip line between six and ten times before being released.

Recordings were examined in real time during traverses of the zip line so adjustments in gain or tuning could be made to improve recording quality. When the test was complete and the bat freed, the WAV files generated during the test could be examined in the field and events of interest could be noted.

C. *Data Visualization and Analysis*

1) *General*

Various tools were developed to examine the test data collected with the goals of (1) comparing calls recorded using the bat-based wireless microphone with those recorded from the ground; (2) identifying objects of significance by their echoes and (3) evaluating sources of noise to improve device performance and recording fidelity in future versions. All of our data was subject to both time series and spectral analysis. The time series was useful in identifying the shape of the call envelope and providing various standard call metrics such as amplitude, duration and interpulse interval (the reciprocal of repetition rate).

Spectral analysis was used to examine the full spectrum of calls and echoes, generate spectrograms and create call sequence sonograms for particular frequency bands. The spectrograms are used to compute additional standard call metrics such as quadratic parameters that describe how the fundamental frequency is modulated for each call.

2) Call Sequence Sonograms

The term "sonogram" is applied generally to describe images produced from sound recordings. There are various ways to obtain the data used to create sonograms using ultrasonic transducers. Sonograms are routinely used in industrial and medical settings to non-invasively visualize the internal structures of a physical body. We have developed a method for creating sonograms from bat-based recordings of bat call sequences (call sequence sonograms, CSS, Figs. 4-6). The bat calls provided energetic ultrasound pulses and recordings during the time between calls contain the echoes heard by the bat (if the bat is carrying an ultrasound microphone).

At the most basic level, each call in a sequence is used as an anchor to produce a single horizontal line in a CSS. From each call onset time, a predefined segment (35 ms along the X-axis in Fig. 4-6) of a bat-based recording is extracted and analyzed. Each time point relative to call onset, plotted along the X-axis, is an approximate echo-return time. A variety of metrics was computed for each call to modulate CSS intensity across each horizontal line. Each call was analyzed in sequence and used to build the CSS vertically from the bottom up. Thus, time relative to call onset is represented on the X-axis and time relative to the beginning of a zip line traverse is represented on the Y-axis. The X- and Y-axes of a CSS can also be interpreted as distances. The distance between a bat and an object creating an echo was estimated across the X-axis (0.172 m/ms). Similarly, the distance between the bat and the *stop* end of the zip line was estimated across the Y-axis (0.344 m/ms) for each call using the time delay to the call recorded by the ground-based microphone.

The time between calls was not uniform. Thus, horizontal lines were not evenly spaced and treating each time point as a rectangular pixel in an image distorts the Y-axis. To deal with this problem, each CSS was created using a filled contour plot where the contour lines are hidden.

The CSS produced were not as regular as sonograms produced in a medical or industrial setting using specialized equipment. This was because we had no control over orientation of a bat in flight or repetition rate of the call. In particular, there was uncertainty as to where the bat's call was being directed. Even with this uncertainty, the CSS was a valuable visualization tool that allowed us to see how a bat views its environment. We assumed that the bat behavior would reveal echoes of biological relevance. We knew this because the duration and interpulse interval both decrease significantly when a bat is approaching a target of interest. Thus, observing portions of each CSS where the call duration and interpulse interval decrease and correlating those regions with corresponding video recordings help us locate objects of interest.

We constructed CSS based on a number of metrics such as: time series amplitude, intensity in a particular frequency band, peak frequency and spectral bandwidth, to name a few. These may be useful in visualizing biologically relevant objects producing echoes in bat call sequences.

IV. RESULTS

A. Ground-based vs. Bat-based Recordings

Our recordings showed that individual bat calls observed using a bat-mounted wireless microphone were markedly different when compared with those observed from the ground even though the microphones were identical. The envelope of the call time series was distorted in the ground recording and the call spectrograms were different even though the call of origin was the same (Fig. 2). In particular, high frequencies at the beginning of the call were attenuated in the ground-based recording.

B. Echoes and Behavior

Bat-based recordings provided information about the echoes heard by a bat flying with the wireless microphone attached (Fig. 2). Echoes from substantial, nearby, objects were strong and were apparent in the time series representation. Spectrograms were an excellent tool for visualizing individual echoes when they overlapped. In Fig. 2, six separate strong echoes are visualized in the echo-enhanced spectrogram that are not apparent in the time series. Fig. 2 also shows a long-duration diffuse echo that was likely associated with debris on the ground.

Where a spectrogram is helpful for visualizing echoes for individual calls, a CSS is helpful for visualizing an entire call sequence. A CSS based on time-series amplitude and created from a zip line recording showed a bright region to the left representing the call followed by an echo-sparse dark region (representing empty space) and then a region of varying intensity representing the return of various environmental echoes to the source (Fig. 3). As the horizontal extent of the dark region gets smaller, the echoes indicate objects are being approached.

In this call sequence, the bat reduced the call duration and interpulse interval twice (around 5300 and 9000 ms on the vertical axis), indicating the bat had detected objects of biological relevance. Thus, there ought to have been echoes in these recordings indicating objects being approached shortly before these times. One way to obtain better definition in a CSS is to filter out all but the dominant frequencies represented in the call. In Fig. 5, a narrow band of frequencies is represented (44 to 49 kHz) and more echo detail is apparent in this CSS when compared with Fig. 3.

Another technique we developed for visualizing echoes is based on overall spectral parameters. Q-factor magnitude was used to generate the sonogram shown in Fig. 6. Here, a great deal of detail is revealed. Q-factor is obtained by first computing the spectrum for overlapping 256-point segments of the time series across each call/echo region. The parameters for a first-order Gaussian curve fit were calculated for each spectrum. The Gaussian fit provides parameters that represent amplitude, peak frequency and bandwidth across each 256-point segment. Q-factor is computed by dividing the number representing the peak frequency by the one representing the bandwidth. We have found that bat calls exhibit a relatively high Q-factor and the echoes share this property. The detail revealed in Fig. 6 demonstrates how Gaussian-based parameters and the Q-factor may provide enhanced visualization of echoes. Echoes preceding times of call shortening are more apparent here than in the other two CSS representations. Further, the echoes demonstrate a consistent approach pattern with latencies decreasing (echoes moving to the left) as the bat moves forward.

V. CONCLUSIONS

Insectivorous bats use echolocation to navigate the environment and hunt for small flying insects in darkness. If we are to obtain a good understanding of bat echolocation, we must capture and analyze the signals bats hear. The simplest way to learn what a bat hears is to equip a bat with a microphone so we can listen to the calls produced and the echoes that return as a bat flies through a natural setting. Thus, we developed a wireless ultrasound microphone small enough to be carried by a bat and techniques for using the instrumentation in a natural setting. We have developed software to acquire and analyze the recordings and a new visualization tool, the CSS, which has great potential for future echolocation studies.

We have shown that the CSS can provide a clear picture of objects that a bat encounters during a flight. However, a CSS can only be generated from a good quality bat-based recording. We intend to improve the quality of our recordings by reducing tether-based noise and ultimately increasing the range of our transmitter/receiver system to obtain tether-free bat-based recordings of substantial duration. Such abilities would facilitate powerful new insights into the hunting and social vocalizations of free-flying bats; subjects that have been poorly studied for lack of suitable instrumentation.

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FIGURES

Fig. 1. A bat equipped with a wireless ultrasound microphone and prepared to fly while tethered to a zip line.

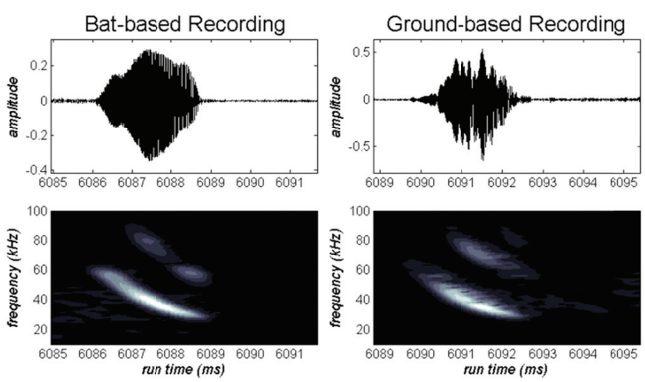

Fig. 2. A bat call recorded using the bat-based wireless ultrasound microphone (left column) and an identical ground-based microphone (right column). There are apparent differences in the envelope shape of the time series (top row). The spectrograms (bottom row) show that high frequencies produced at the beginning of the call (bottom, left) are attenuated in the ground-based recording (bottom, right).

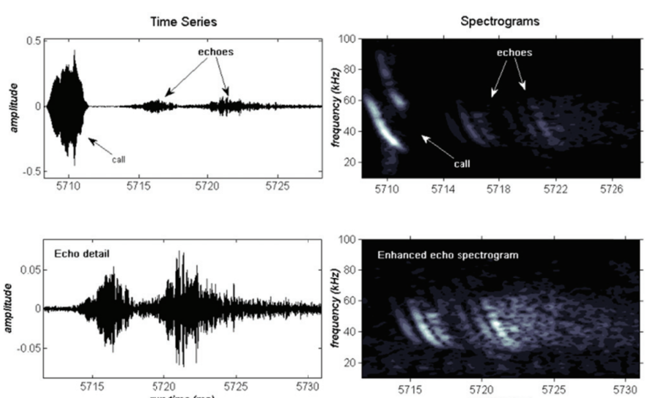

Fig 3. A bat-based wireless ultrasound microphone records the echoes a bat hears. The top row shows a recording that includes the call for reference. Isolating the echo portion of the recording in the top row reveals details of the echoes (bottom row). This recording shows the presence of multiple echoes. Strong echoes from substantial objects can be seen in the time series. Spectral methods are required to visualize multiple weak echoes. This call occurred as the bat approached the end of the zip line. The strong echoes are from instrumentation set up at the end of the zip line. The long-duration, diffuse, echo is most likely reflected from debris on the ground.

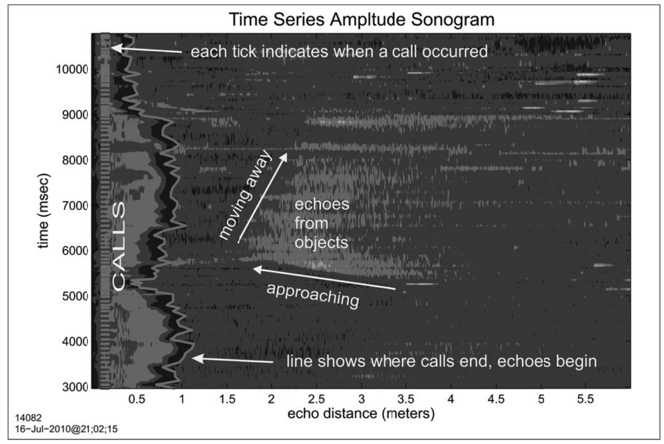

Fig 4. A sonogram based on signal amplitude representing a single traverse of the zip line. The recording was made using the bat-based wireless ultrasound microphone. There is a region of diffuse echo between 5400 and 8000 ms indicating an object (or objects) at various distances (1.7 to 3.5 m). Shortening of the call duration at 5300 and 9000 ms indicates an object is being approached but the echo from the object is difficult to resolve in this view. Ticks drawn on the left indicate the time of each individual call.

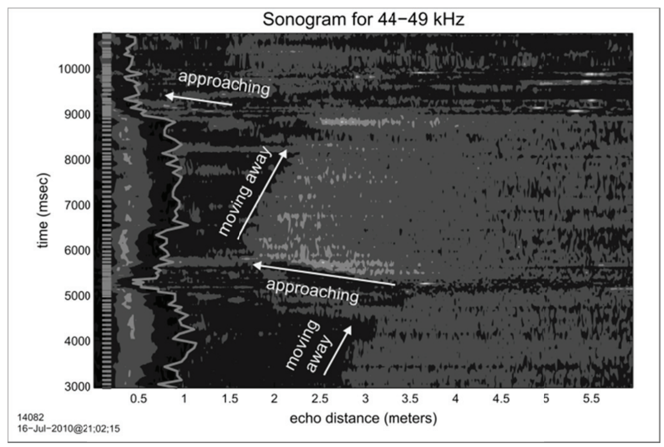

Fig 5. A sonogram based on a narrow frequency band (44-49 kHz). The call sequence used to generate this sonogram is the same as in Fig. 4. Note that more detail is apparent when the frequencies are restricted to a narrow band. Ticks drawn on the left indicate the time of each individual call.

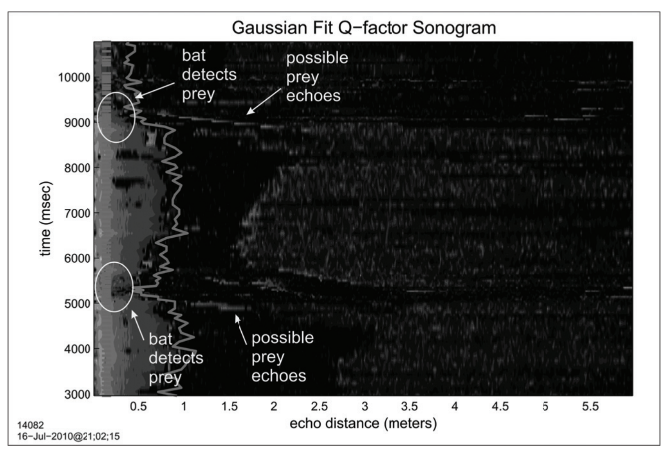

Fig. 6. A sonogram based on Q-factor (see text for details). The call sequence used to generate this sonogram is the same as in Fig. 4. Note that this figure clearly visualizes more echo detail than either Fig. 4 or Fig. 5. In particular, echoes preceding call shortening at 5300 and 9000 ms are apparent in this representation.