# Observing the Invisible: Using Microphone Arrays to Study Bat Echolocation

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*Acoustic arrays have become an essential tool for investigating the behavior of echolocating animals in the field and the laboratory.*

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## Introduction

Sound is produced and sensed by nearly all animals. It provides a fundamental means of communication, detection and classification of predator and prey, localization of sound sources, and orientation relative to the environment. Most animals rely upon sound for survival, but a select few have developed a precise sense of hearing. Nocturnal birds such as the barn owl (Tyto alba) excel at passive localization of prey-generated sounds for capturing prey at night. A specialized group of mammals (e.g. bats and toothed whales, including dolphins) have evolved to use acoustics as their primary active sense in the absence of visual information. These echolocating mammals have developed an extreme acuity and agility with which their external world is precisely reconstructed from the stream of echoes received; however, the exact physical and neuronal mechanisms responsible for this precision are not well understood nor are they matched by any existing technological system.

The biosonar system of echolocating bats (Figure 1) and toothed whales represents the most advanced acoustic imaging solution known to exist. The sophistication of biosonar lies not in its complexity, but in the real-time performance that is achievable by a minimalistic set of hardware – a few acoustic baffles[1] and a compact network of neural circuitry.

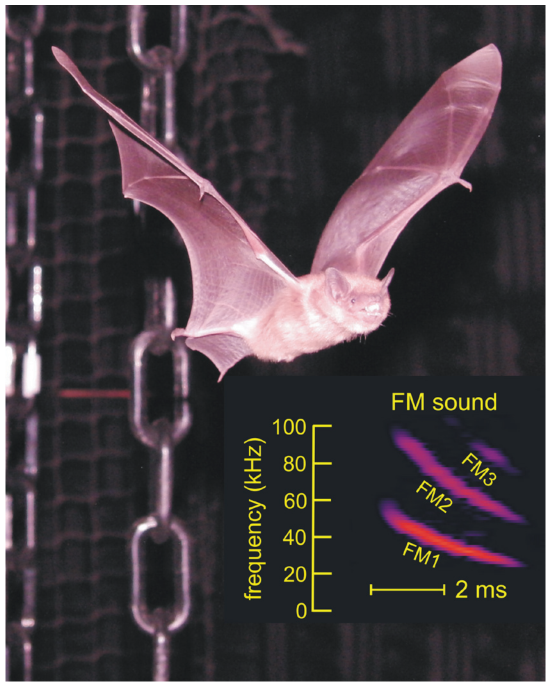


**Figure 1:** *Close-up view of big brown bat, Eptesicus fuscus, flying through an array of vertically hanging chains in tests of steering through cluttered surroundings. Inset shows spectrogram of FM biosonar sound with three down-sweeping harmonics. The signal's broad bandwidth provides for sharp registration of arrival-time at microphones, while the high frequencies largely preclude the occurrence of multipath reverberation—a major problem for underwater array measurements to locate cetaceans or in air for triangulation of lower-frequency animal sounds, such as birdcalls, in forests.*

[1] *e.g. nose, ears, mouth for bats*

Echolocation is a complex active sensory system in which animals forage and navigate in their environment primarily using emitted acoustic signals. By producing intense, ultrasonic signals and receiving their returning echoes, these animals can identify, discriminate, and track prey, often in highly cluttered environments. Bats and toothed whales are two distinctly different suborders of mammals that convergently evolved echolocation, and both have been intensely investigated to understand their mechanisms that may translate to man-made sonar and radar systems.

Bioacoustics researchers apply a variety of advanced tools to improve our understanding of animal echolocation. These tools range from mathematical signal processing algorithms to physical hardware and technology. This article focuses on the latter, which includes multi-sensor arrays. A primary objective when designing any measurement apparatus is to sense without affecting the phenomenon being sensed. This is especially important in acoustics, where strong reflections off the array itself can interfere with the free-field response being measured.

## Designing Specialized Microphone Arrays for Bioacoustics Research

Microphone arrays consist of two or more spatially separated sensors that convert acoustic pressure waves into a series of electrical signals. Common usage of microphone arrays in biosonar research might include monitoring biological activity in the field, tracking animals by estimating the source position of emitted sounds, measuring and visualizing the spatiotemporal directivity patterns, estimating head aim, and analyzing the time-frequency structure of bioacoustic waveforms.

Although the array sensing requirements are often unique, the specific solutions almost always consist of the same set of general hardware: sensing transducers, mechanical support and alignment, power and signal conditioning circuitry, digital converters and processors, and data storage. Invariably, there are numerous technical considerations to account for when defining the system requirements. The range of frequencies used by a particular animal species is a fundamental characteristic since it impacts the selection of all components in the signal chain from sensor to data storage. For example, many species of bats emit ultrasonic echolocation and communication signals that span the upper end of human hearing to the limitations imposed by acoustic absorption over several meters in air (20 – 200 kHz). Unfortunately, the majority of commercially available microphones, amplifiers, and converters are designed to work within the range of frequencies audible to humans (20 Hz – 20 kHz) such that selection of components with suitable ultrasonic performance can prove difficult.

Integrating video with acoustic data collection is essential in many experimental scenarios. Synchronized audio and video greatly facilitate the process of analyzing acoustic recordings, because a human can quickly filter out dead-time and focus on interesting events by scanning through a video track much more quickly than browsing multiple channels of audio data. Furthermore, if localization and tracking accuracy is needed beyond what the acoustic array can provide, a pair of overlapping video streams may be used to stereoscopically estimate the position of one or more objects in three dimensions. The major challenge here is that acoustic events are generally sparse and irregularly spaced in time; however, video tracking provides continuous discrete-time estimates. These disparate sets of data may be combined into an improved tracking algorithm using Kalman filtering or smoothing techniques.

## Algorithms for Acoustic Localization and Tracking with Arrays of Microphones

By far, the most common bioacoustic application of a microphone array is passive monitoring and tracking. In these scenarios, an array is used to estimate the position of one or more animals from the acoustic waveforms they produce. Fortunately, most signals emitted by echolocating bats have a stereotypical time-frequency signature. This allows researchers to both classify the species with high confidence and apply time-correlation techniques to filter out extraneous noise.

A variety of array signal processing algorithms are used for bioacoustics tracking problems. When real-time tracking is necessary, highly efficient algorithms such as frequency-domain beamforming from an array of closely spaced sensors are ideal. Frequency-domain methods require that the array have excellent phase agreement at every stage including mechanical alignment, matching transducer frequency response, and synchronous digital sampling. Furthermore, array elements must be spaced no greater than a half wavelength of the highest frequency to avoid grating lobes, or spatial aliasing.

Alternatively, when acoustic sensors can be deployed in advance at fixed known locations, tracking can be accomplished by time-domain beamforming with a distributed array. Time-domain beamforming has the advantage that grating lobes and other spatial aliasing effects are eliminated, because aliasing is an artifact of the processing rather than physical manifestations of the sound field. Within the context of a distributed array and time-domain processing, there are several options for array signal processing. The most straightforward is cross-correlation followed by time-difference-of-arrival (TDOA) (Brandstein et al., 1996; Gillette and Silverman 2008). Steered response power (SRP) and its variants (Silverman et al., 2005) are a bit more computationally expensive, but this class of algorithms can provide a one-step solution for localizing sound sources.

Although there are numerous beamforming algorithms to estimate sound source locations and produce acoustic images, the information used is largely the same – the relative time delay of a correlated signal arriving at multiple array sensor elements. Perhaps more important is the array bandwidth. Increased bandwidth translates to improved localization accuracy and resolution over a narrowband approach, because resolution in time is inversely proportional to signal bandwidth. For passive arrays, the bandwidth of the bioacoustic signal itself will determine the upper bound on array accuracy and resolution.

## Honey, I Shrunk the Technology

Recent developments in micro-electromechanical systems (MEMS) offer a low-cost solution to the acoustic measurement problem. MEMS devices are continuously improving through advancements in silicon integrated circuit manufacturing. Today, MEMS sensors are widely commercialized and have numerous benefits. Ultrasonic MEMS microphones, for example, have an effective aperture on the order of 1 mm or 0.04" (Figure 2). By comparison, precision condenser microphones have an aperture of 1/4" or 1/8". By reducing the acoustic aperture MEMS microphones offer a more omnidirectional response.

As a technology, MEMS does have limitations. All mechanical devices have resonances and stress related concerns; MEMS pressure sensing microphones are no exception. The acoustic sensitivity, dynamic range, and spectral noise floor of current devices does not yet match the specifications for any precision microphone devices; however, MEMS microphones are also 2 to 3 orders of magnitude lower in cost. MEMS vector sensors are also being developed for air and water. These sensors can be used to couple acoustic particle velocity measurements along with the traditional pressure-only measurements. Not only do vector sensors improve sound source location estimates, but also dense arrays of these sensors may be used to provide new insight into the near-field acoustics in close proximity to biosonar structures.

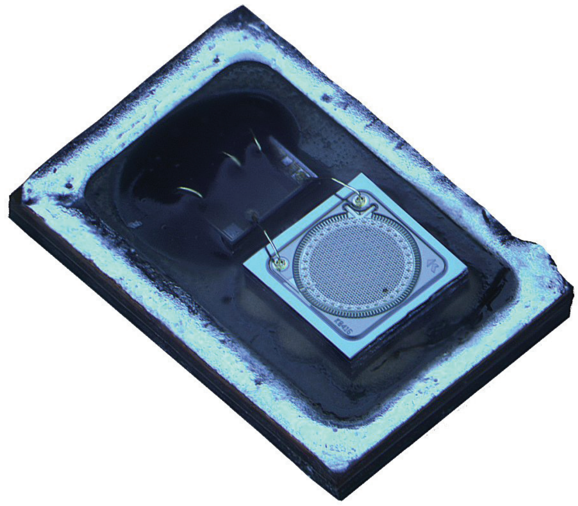

**Figure 2:** *A close-up photograph of a Knowles MEMS microphone sensor. The pressure-sensing surface is the approximately 1 mm diameter circle at the center of the MEMS substrate. Acoustic waves actuate the surface of the sensor and small changes in capacitance are translated into electrical signals that can be amplified and conditioned. Photograph is courtesy of Knowles Corporation.*

Until approximately a decade ago, large-scale acoustic measurement systems would be nearly impossible to construct without a substantial research budget. Aside from the large cost of pressure sensors and their associated electronics (i.e. preamplifiers, analog-to-digital converters, transceivers, memory storage), the collection of data across hundreds of sensor elements requires synchronized control of variable-gain amplifiers and analog-to-digital converter devices. This control can be performed in one of two basic ways: A very high-speed processor (such as a programmable digital signal processor) or custom parallel digital electronics. Hybrid solutions also exist in the form of graphical processing units (GPUs). The fully parallel solution is obviously more scalable to higher density measurements, but traditionally requires a significant investment in building specialized electronic circuit boards or application specific integrated circuits (ASIC) – both of which are expensive in development time and material cost. Commercial data acquisition systems that implement these solutions are abundant for applications requiring tens of channels recorded simultaneously, but not hundreds. Commercial systems that embrace the modular approach can be expanded to achieve the desired performance, but not without tradeoffs between cost and performance. Now that field programmable gate array (FPGA) technology has matured into a compact, highly integrated system-on-a-chip platform, the significant amount of time invested in building and debugging custom hardware solutions can be replaced by writing software-defined hardware. Reconfigurable FPGA devices are ideal as a rapid prototyping platform, because they take only seconds or minutes to download a new design configuration, all from the developer's keyboard. With the use of FPGAs, the ability to replicate numerous customized digital hardware blocks is trivial and concerns of repeatability and reliability are minimized.

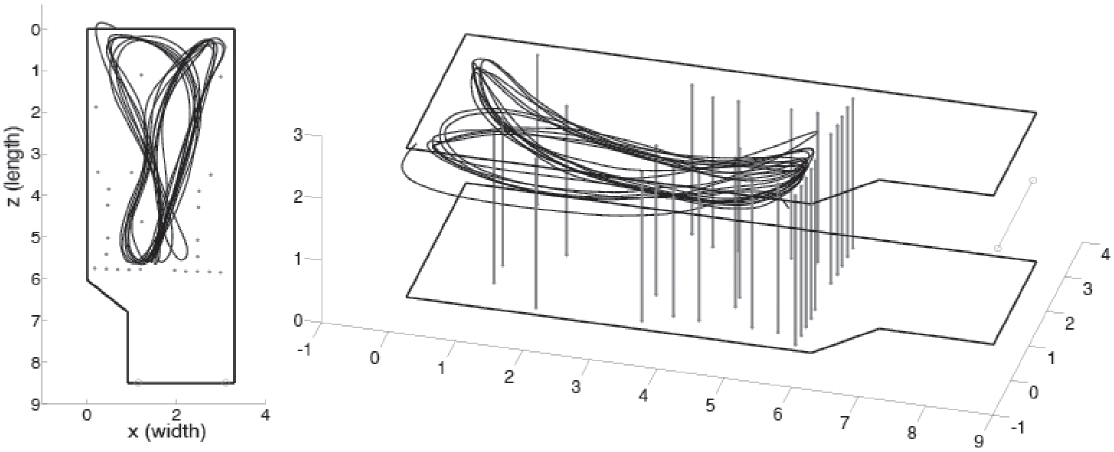


**Figure 3:** *Looping flight track of bat steering around the room with hanging chains. The bat is tracked from TDOA at 20 MEMS microphones distributed around the room. Left, plan view, right, diagonal view (Barchi, Knowles, and Simmons, 2013).*

## Microphone Arrays in Controlled Laboratory Environments

In a controlled laboratory environment, microphone arrays are ideal instruments for reconstructing the flight tracks of echolocating bats during an experiment. Due to the high pulse-rate of echolocation signals in flight, the animals' trajectories can be estimated fairly accurately by localizing each pulse and fitting spline curves to successive positions. Auxiliary uses of microphone arrays include simultaneously estimating behavioral parameters, such as head aim leading up to a prey capture, and acoustic parameters, such as the spatial directivity patterns (Ghose and Moss 2003; Matsuta et al., 2013; Surlykke et al., 2013).

In the Simmons' Lab at Brown University, echolocating big brown bats *(Eptesicus fuscus)* are tracked during flight experiments using a distributed array of 24 microphones that completely surround the 7.6 x 4.3 x 2.7 m semi-anechoic room environment. This species of bat emits high intensity (approx. 134 dB SPL re 20 µPa @ 1 m) broadband FM echolocation signals with a pulse repetition rate between 10 and 100 pulses per second during flight. Obstacles such as plastic chains or nets are configured in specific positions and densities to test various aspects of echolocation behavior (see video 1 at http://acousticstoday.org/?p=2413).

Custom microphone circuit boards are positioned around the room in a loosely uniform configuration and staggered between two vertical heights. This positioning provides a near field aperture that completely encloses the space and yields excellent coverage of the animal's directional sounds throughout the room. The microphones are commercially available ultrasonic MEMS pressure sensors (Knowles Acoustics, Ithaca, NY) that can be machine soldered to the surface of the printed circuit boards. A professional audio system (V4HD and pair of HD192, MOTU, Cambridge, MA) is used to integrate the audio stream sampled at 192 kHz and stereo thermal infrared video (Merlin and/or Photon 320, FLIR Systems, Boston, MA) running at 30 frames per second (see video 2 at http://acousticstoday.org/?p=2413). During experiments, a user controls the recording system through the MOTU and AudioDesk software and all data are recorded directly to a standard internal hard drive. All data are post-processed by using MATLAB (Mathworks, Natick, MA), since real-time tracking is not required. After detecting the sound sources with simple energy detection, echolocation signals received at each microphone must be paired across the entire array. Cross-correlation and TDOA estimation is implemented by a relatively simple algorithm (Gillette and Silverman, 2008).

Figure 3 shows an example flight track of E. fuscus during one experimental trial. The flight room recording system was jointly designed and constructed by Jonathan Barchi, Jeffrey Knowles, Jason Gaudette, and James Simmons, with a significant amount of assistance by many current and former members of the lab. To date, the flight room array has been used in studying the spatial memory and flight dynamics of big brown bats (Barchi et al., 2013), and is currently being used to understand acoustic and behavioral adaptations in varying degrees of dense clutter.

## Arrayzilla Lives!

Distributed arrays of microphones allow researchers to reconstruct the spatiotemporal directivity of bats' echolocation beams. This directivity is not only defined by azimuth and elevation, but also critically depends on frequency due to the broadband nature of these signals. These bioacoustic beam patterns are also time-dependent because, unlike man-made transducers, acoustic baffle structures such as the ears and mouth are constantly moving.

To visualize this multi-dimensional acoustic information with sufficient fidelity requires a very large number of sensors and supporting equipment to sample the space. Ideally, these detailed acoustic beam measurements would be made with high quality, precision calibrated microphones, which have a wide frequency response, low directivity, and excellent gain and phase matching. All of these characteristics are important for accurately measuring the broadband sound field relevant to animal echolocation, which spans over a decade of frequencies in many cases. Unfortunately, the expense of such high-quality equipment limits the number of elements in the array and therefore the angular coverage and spatial resolution that is achievable.

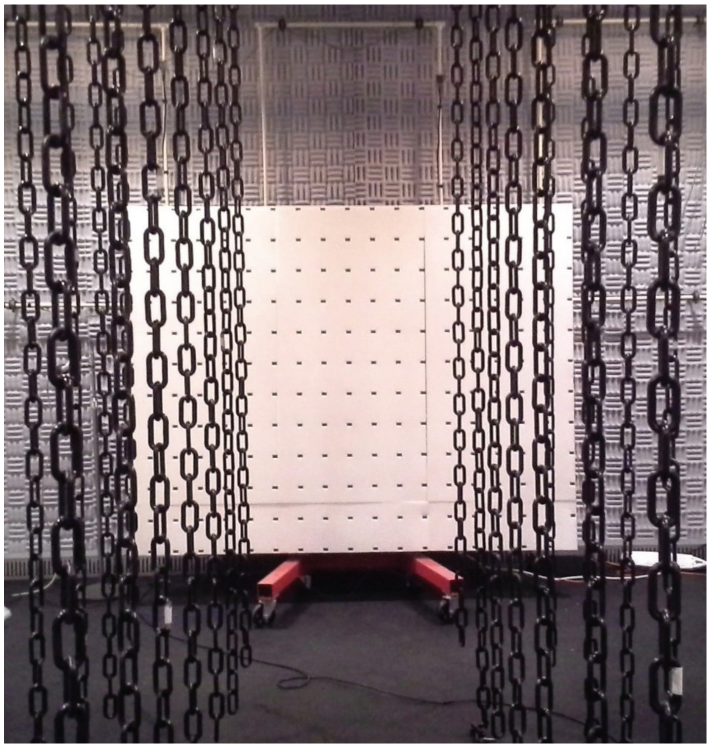

**Figure 4:** *Multiple-microphone "Arrayzilla" in-situ for visualizing broadcast beam patterns of bats flying through a corridor between rows of vertical chains.*

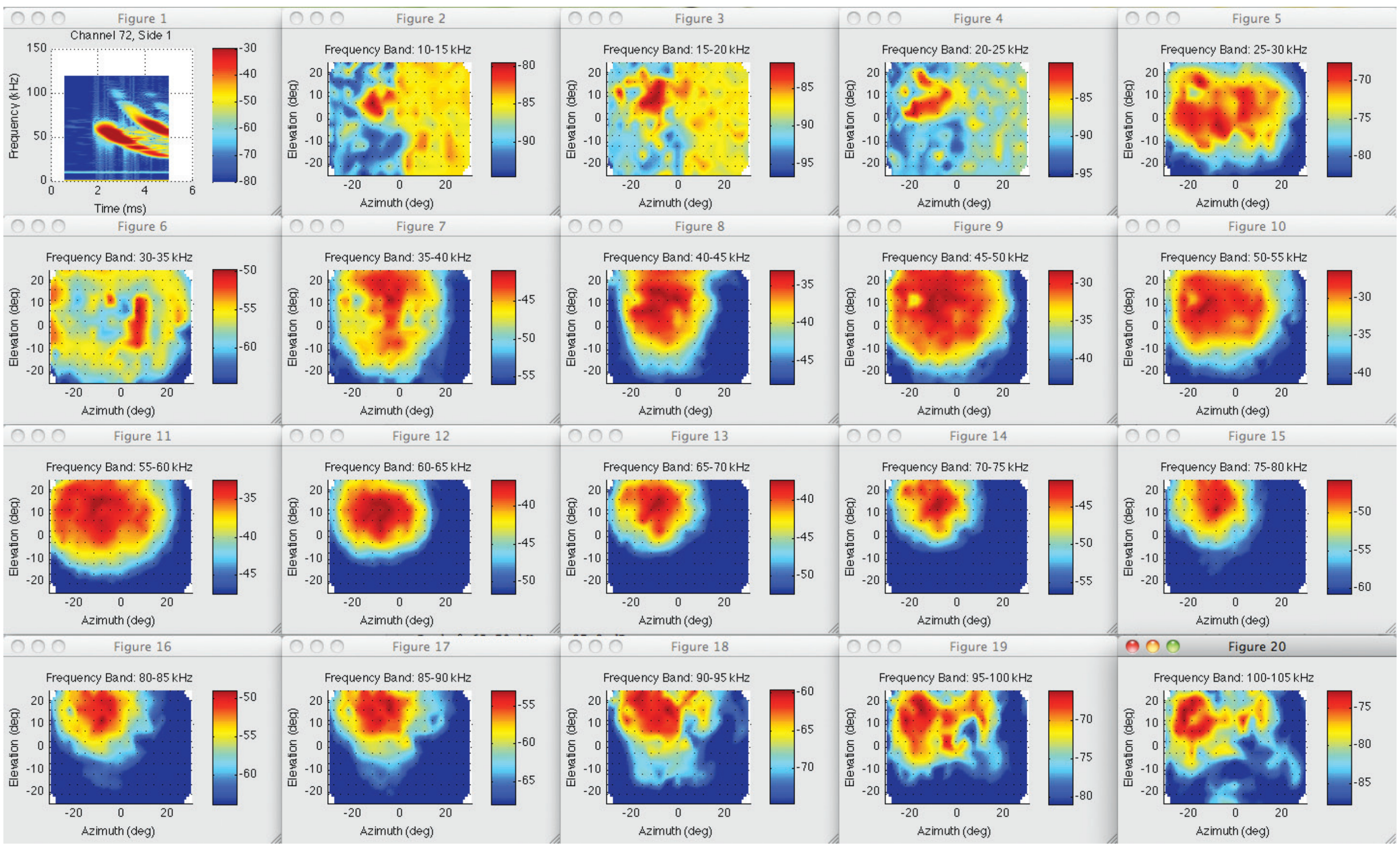


**Figure 5:** *Broadcast beam patterns (azimuth, elevation) for an FM biosonar sound (see Figure 1). Individual plots show a series of frequencies in 5-kHz bands from 10 to 105 kHz.*

Large-scale sensing requires that many concurrent requirements are met: Numerous spatially distributed sensors, sufficient bandwidth and synchronization of data acquisition equipment, adequate data transfer speed (both, throughput and latency), abundant storage, and automated software for rapid online or offline data analysis. Without meeting these requirements, researchers will spend less time searching for evidence of adaptive echolocation techniques and more time finding ways to compensate for the limitations imposed by their experimental design.

New and creative approaches to designing arrays with advanced technologies have enabled high-density acoustic sensing systems suitable for beam pattern measurements. Our lab has recently designed, built, and tested a large reconfigurable microphone array with up to 224 ultrasonic microphones along with supporting acoustic signal processing software (Gaudette et al., 2014). The broadband array has been used in a variety of experiments with bats from both, a stationary platform and in flight (see Figure 4). Due to its immense size and density, the array was affectionately named Arrayzilla (see video 3 at http://acousticstoday.org/?p=2413). This measurement array achieves unprecedented fidelity of bats' echolocation beams in the laboratory—a spatial sampling resolution between 3 and 6 degrees in azimuth and elevation. Figure 5 shows data from a single echolocation pulse during a stationary platform experiment with *E. fuscus*.

## Acoustic Measurements and Flight Tracking in the Field

Despite the large amounts of data that can be collected conveniently in a controlled laboratory environment, the behavior of bats in natural conditions still constitutes ultimate "ground truth" about the capabilities of biosonar. Laboratory studies can focus on aspects of echolocation behavior by creating conditions and measurement devices that emphasize one kind of response while minimizing variability, but there is no substitute for field observations of bats actually deploying their sonar. Field research involves bringing acoustic instrumentation into conditions beyond the reach of power connections, to situations where portability, battery power, and simplicity of operation are essential. The functional equivalent of the acoustic measuring equipment used in the laboratory must be transported to field sites where bats are known to fly in pursuit of prey, to engage in bat-to-bat chases, to fly in cluttered surroundings, or to aggregate in swarms. Prior scouting helps to locate study sites so that setting up apparatus is not wasted time. At a minimum, field recordings can be performed with a single microphone device, and, in fact, for half a century nearly everything we have learned about the behavior of bats in natural conditions has come from listening to their sonar sounds with "bat detectors" or recorded with only one microphone. The capability to process multiple-microphone recordings and exploit them as true arrays only became feasible when personal computers and the necessary applications programs became commonly available. The microphones in an array have to be located with respect to each other for processing the recordings to determine the direction of the sound sources. In a flight room, they can be mounted permanently on the walls around the room and their locations measured to provide 3D coordinates. In the field, it is often difficult to find corresponding features on which to anchor the array. One solution is to mount several microphones together on a frame, which can then be placed to face the area where bats are flying. To cover a larger area, several such frames can be arranged to surround the location. Then, the problem is to measure the distance and orientation between the frames. This method has been used especially effectively in studies of foraging by Japanese house bats (*Pipistrellus abramus*) in a well-defined feeding area (Fujioka et al., 2011; Hiryu et al., 2008). In many field sites, the location is irregular in shape, and there are trees, banks, or other features that constrain the placement of microphones. It then becomes necessary to position the microphones in a loosely defined grid and measure their positions as they happen. Figure 6 illustrates an array placed in a clearing in rain forest, next to a Mayan temple. The microphones are placed on poles of different heights to fill the clearing, and the locations of the microphones measured separately each time the array is emplaced. The processing algorithms have to take into account the grid formed by the microphones.

We have used a variety of microphone configurations to record bats in natural conditions (e.g., Eastman and Simmons, 2005). For example, using an array of 4 microphones in each of two towers, a design obtained from Japanese colleagues (Fujioka et al., 2011; Hiryu et al., 2008), we track big brown bats (*E. fuscus*) flying near each other at a foraging site. Figure 7 shows sample tracks for two bats flying past the two array towers at the same time. The method successfully follows each bat, in large part because the duty-cycle of the bats is low enough that their sounds do not coincide to obscure which bat is where. Besides just tracking the bats, which helps to locate capture maneuvers from the rapid burst of broadcasts accompanying interceptions, the characteristics of their sounds are available from the recordings. Figure 8 shows several acoustic parameters extracted from the two tracks. Big brown bats emit FM sounds with two harmonic sweeps (Figure 1). The first harmonic, FM1, at lower frequencies, is more broadly beamed and less susceptible to propagation losses due to atmospheric absorption. The plots show the starting frequency, the center frequency, and the ending frequency of the FM1 sweeps, plus the duration of FM1. These two bats differ in the frequencies of their recorded sounds, while the durations are about the same. However, due to the bats' movements relative to the microphones and to distances, only the ending frequency of the sweeps represents reliable data. From the distribution of ending frequencies, it is evident that these two bats differ in the span of frequencies in their broadcasts.

Several important findings have emerged from microphone array recordings in the field. The first use of a true array was to determine the elevation of foraging serotine bats *(Eptesicus serotinus)*

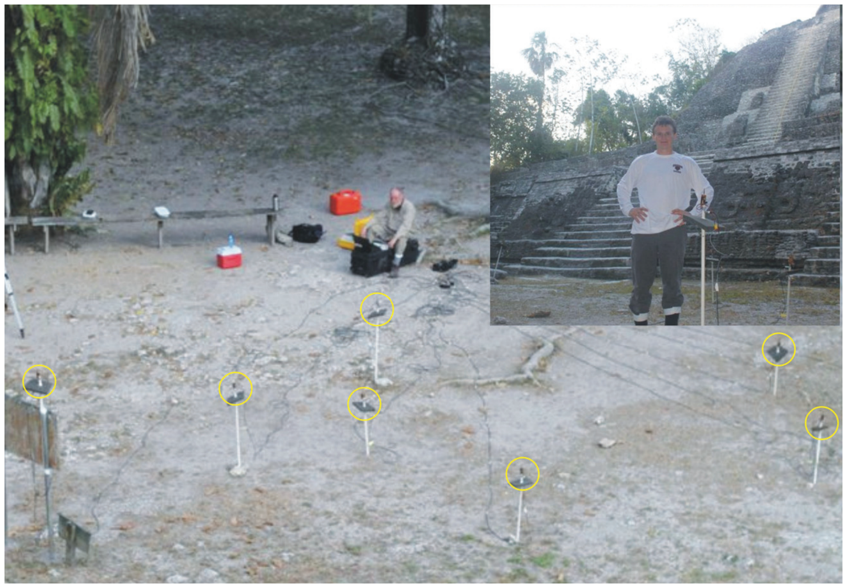

**Figure 6:** *Setting up an array of microphones (yellow circles) deployed as a tracking array in the field. Inset shows view back towards location of camera, and single microphone with Jeff Knowles. Field set-ups commonly have to conform to local topography, such as the Mayan temple, so there is no standard pre-configuration. Coordinates of each microphone are measured using a laser-equipped reflector-less total-station theodolite.*

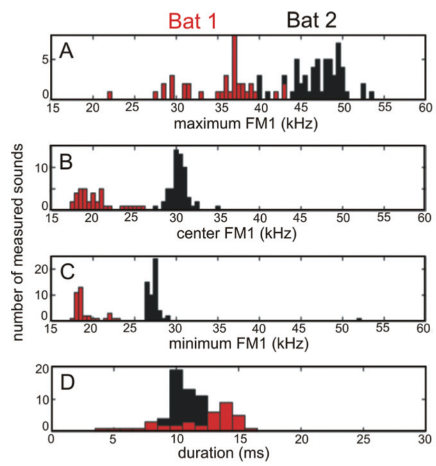


**Figure 8:** *Acoustic features extracted from sounds on the flight tracks plotted in Fig. 6. (A, initial FM1 frequency; B, center FM 1 frequency; C ending FM1 frequency; D, duration). These plots embody not only useful information but also potential pitfalls for using microphone arrays in the field, where the animals often are relatively far from the microphones. Bat 1 emitted biosonar sounds with lower frequencies in FM1 than Bat 2, but only the ending FM1 frequencies represent reliable frequency measurements. Data are limited to frequencies in FM1 (see Figure 1) to minimize artifacts related to broadcast beaming and distance for these rapidly moving bats. The bats' broadcast durations are similar.*

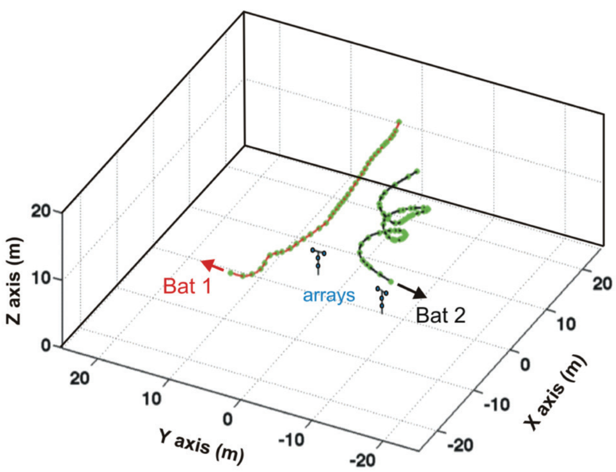


**Figure 7:** *Flight tracks of two big brown bats traced by TDOA measurements using two 4-microphone tower arrays of the Japanese design (Fujioka et al., 2011; Hiryu et al., 2008). The low duty-cycle of each bat makes it easy to separate their paths (data from Jeff Knowles).*

to correlate the characteristics of their biosonar sounds with flight altitude (Jensen and Miller, 1999). When flying higher than 8-10 m above the ground, their broadcasts were of constant duration, while bats flying lower changed the duration of their sounds correlated with height. The important finding was that the bats sense their distance from the ground and treat the size of the foraging space partly in terms of their altitude.

Another example of the utility of microphone arrays for tracking bats comes from a study of the adaptive changes bats make in their sounds depending on the distance to nearby objects (Holderied et al., 2006). The question is significant because bats may make adjustments to their broadcasts to sharpen their images for objects a particular distance—a potential "distance of focus." To assess this hypothesis, recordings were made with an array of 8 microphones to track individual whiskered bats *(Myotis mystacinus)* while they commuted along a row of vegetation to reach their feeding areas. The distance from the bats to the vegetation induced the bats to change their sounds in a manner consistent with the distance of focus.

One of the most extensive uses of microphone arrays to track bats in the field has been done by a Japanese group (Fujioka et al., 2011; Hiryu et al., 2008). They set up multiple frames of microphones to completely surround the foraging area used by Japanese house bats. Their array consisted of up to 32 microphones in clusters of two to four microphones mounted on frames deployed around the feeding area. The entire sequence of tracks and sound emissions was recorded across sequences of interceptions, revealing how the bats change their sounds and pace themselves during hunting.

## Conclusion

The implications of understanding the underlying mechanisms of biosonar are profound and far-reaching. Biosonar is not a theoretical development; it is a proven high-resolution acoustic imaging system that is functional and robust. The exceptional performance and adaptability by animal echolocators in the midst of dense clutter is what draws engineers and scientists to marvel at its simplicity.


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## Biosketches

*Dr. Jason E. Gaudette* is a research engineer at the Naval Undersea Warfare Center in Newport, RI. In May 2014 he received the Ph.D. in Biomedical Engineering from Brown University under the guidance of Dr. James Simmons. Jason received the Electrical Engineering degrees of M.S. from the University of Rhode Island in 2005 and B.S. from Worcester Polytechnic Institute in 2003. He has been an active member of the Acoustical Society of America since 2010. Jason's current research interests include acoustics, neural information processing, and reconfigurable computing for embedded applications.

*Dr. James A. Simmons* is a professor of Neuroscience at Brown University, in Providence, RI. He has been carrying out research on echolocating bats since 1965. He received the Ph.D. from Princeton University and previously has held faculty appointments at Washington University in St. Louis and the University of Oregon. In recent years, the Simmons Lab has collaborated with Prof. Hiroshi Riquimaroux and Dr. Shizuko Hiryu, at Doshisha University in Japan, to understand how bats form biosonar images of desired targets while preventing off-side clutter from interfering with these images but still allowing bats to steer through the off-side scene.

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