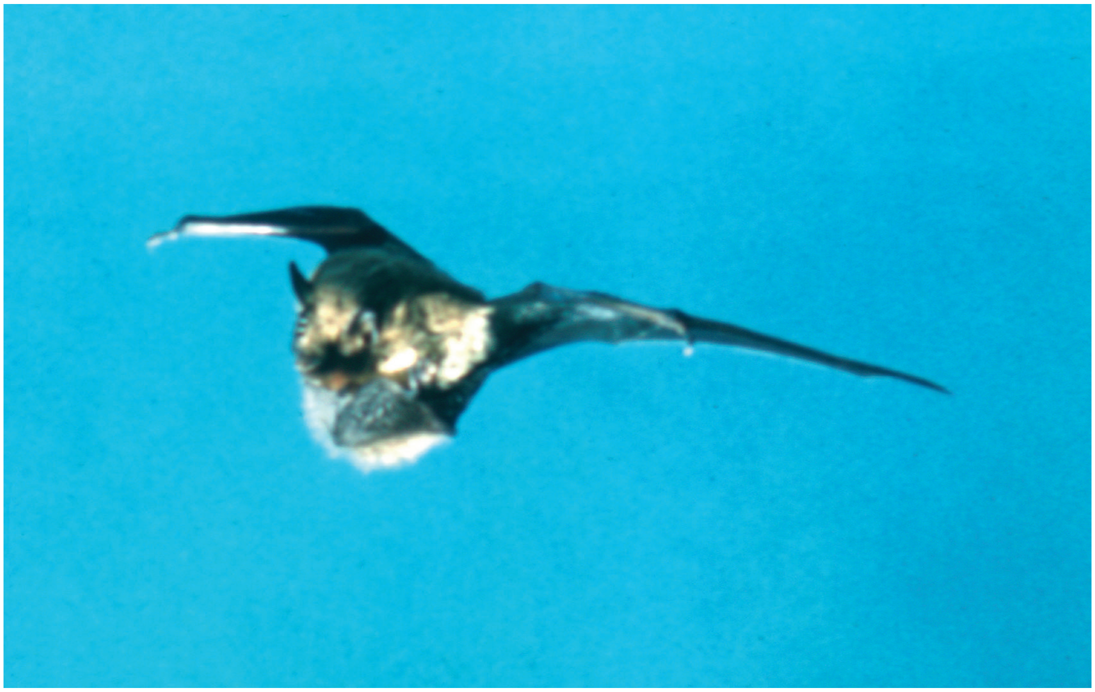

Myotis lucifugus homes in for the kill.

Evolutionary Radar—Sensing for Survival

Lincoln Laboratory investigators tracked down an intriguing sensor whose performance was postulated to be much better than that of our nation's 1960s-era radars.

Consider an airborne "radar-like" sensor that allows its platform to avoid obstacles, navigate, surveil and detect targets of interest, identify same, home in on the desirable targets, and finally close in for capture of the target. This impressive sensor appears to use a highly sophisticated transmitter waveform with linear frequency modulation (FM) of an *octave* bandwidth. (Linear FM was rare in the early 1960s radars.) Finally, throw in the most intriguing factor of all: this sensor seems to operate well in severe jamming or interference environments in which our classical information theory says it cannot possibly operate! What is wrong with us radar types who demand a signal-to-interference ratio of some 10 dB to operate?

The first explanation is that platforms like *Myotis lucifugus* (little brown bat) and *Plecotus auritus* (long-eared bat) have had 50 million years to perfect their sensor apparatus, and we radar engineers have only had 70 years or so. Secondly, the bats' seeming indifference to jamming was only suspected on the basis of relatively crude evidence from admittedly difficult experiments.

But the prospect that bats' ultrasonic transmitter, receiver, and brain-processor equipment might be remarkably superior to the radar techniques of the day was enough of an inducement for Lincoln Laboratory researchers to take a hard scientific look at Mr. Bat via a series of intriguing experiments in the early 1960s.

Bat Navigation Signals

In the 18th century, Italian and Swiss scientists had discovered that a bat's navigation did not require eyes but did require ears, but how the bat navigated remained a mystery. It was not until the 1920s that scientists postulated the bat was transmitting and receiving sounds above the frequency range of human hearing. Professor Donald Griffin, a zoologist from Cor-

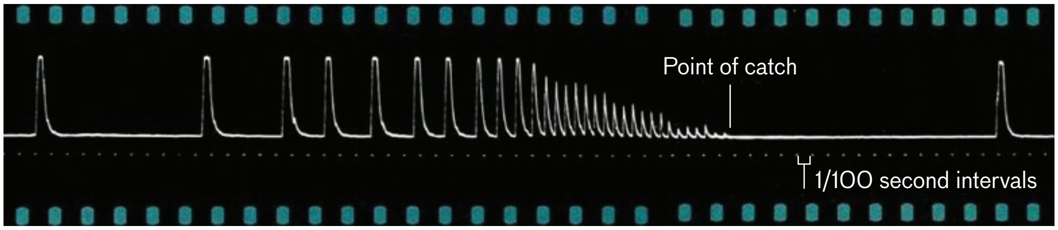

FIGURE 1. This filmstrip recording shows the envelope of bat pulses from surveillance to "catch."

nell and Harvard Universities, conducted many experiments with bat ultrasonic navigation, starting in the late 1930s [1]. He conducted a number of these at Harvard University in a laboratory facility in Cambridge, Massachusetts; this laboratory was the starting point for Lincoln Laboratory's investigation.

There are approximately 1000 species of bats, and each species tends to have its own ultrasonic signaling format. One bat species catches small fish that have ventured too close to the water's surface. Exactly how this bat detects the fish is unknown. Some bats, such as fruit bats (the largest species), do not emit ultrasonic signals but navigate with conventional vision enabled by well-developed eyes.

Any single bat will have a broad repertoire of signals, but an example will illustrate a typical signaling scenario. A bat emits pulsed signals of 3 ms typical length. The pulse is frequency modulated and sweeps downward in frequency from about 80 to 40 kHz. The pulse compression possible with these signals provides a range resolution of about 0.5 cm.

When the bat is cruising at night for insects, the pulse-repetition rate is typically 10 pulses per second in this search mode. As a target is detected and the bat homes in on it, the pulses get shorter (down to 0.3 msec), and the repetition rate increases to nearly 200 pulses per second just before the insect is captured. Figure 1 is a filmstrip recording of the pulse envelope as the bat maneuvers to the point of catch.

A bat is a prolific insect catcher, capturing many hundreds of insects per nighttime sortie. Some insects can detect the bat's signals (much like our radar warning receivers), and they take maneuvers to avoid capture. A favorite maneuver is a dive for the ground. So there is a significant countermeasure environment for the bat to master, but the insect countermeasures pale in comparison to intense interference signals from the bat's environment or from pesky MIT and Harvard researchers.

Bats and Jamming

A bat is born into a severe jamming and interference environment. Bats live in caves that can contain thousands of bats, each one navigating in the dark cave with similar ultrasonic signals in the same frequency band. Scientists are uncertain how the bats find their own weak return signals in this background of much stronger signals transmitted by bat neighbors. Researchers have speculated that a bat resists jamming by using the directionality of its well-developed ears. This conjecture makes one think of radar antenna adaptive array processing— a recent radar innovation. Scientists have also suggested a fair amount of discrimination of unwanted signals by the bat's brain processing, which may focus on the fine details of the bat's own signals.

Early experiments with jamming of a bat's signals in flight pointed to an unexpected level of resistance to intentional broadband noise interference. In fact, the bat seemed to defy the fundamental detection and estimation theory that a signal needs to be substantially stronger (a factor of 10 or so) than the competing noise to achieve reliable differentiation. Some experiments in the 1950s suggested that a bat could operate in noise fields that were 200 to 3000 times stronger than its own received signal! This apparent contradiction of our fundamental theory got the radar crowd excited enough to dig in and find out if Mr. Bat was that good and if we humans were truly that inept!

The Lincoln Laboratory Bat Program

The Lincoln Laboratory bat program was initiated in the early 1960s in collaboration with Prof. Griffin at Harvard University. The lead Laboratory researcher was Dr. J.J.G. McCue [2]. He was joined by Frederic Webster, a Harvard researcher, and David Cahlander, a young Lincoln Laboratory staff associate. Cahlander's PhD thesis at MIT was a

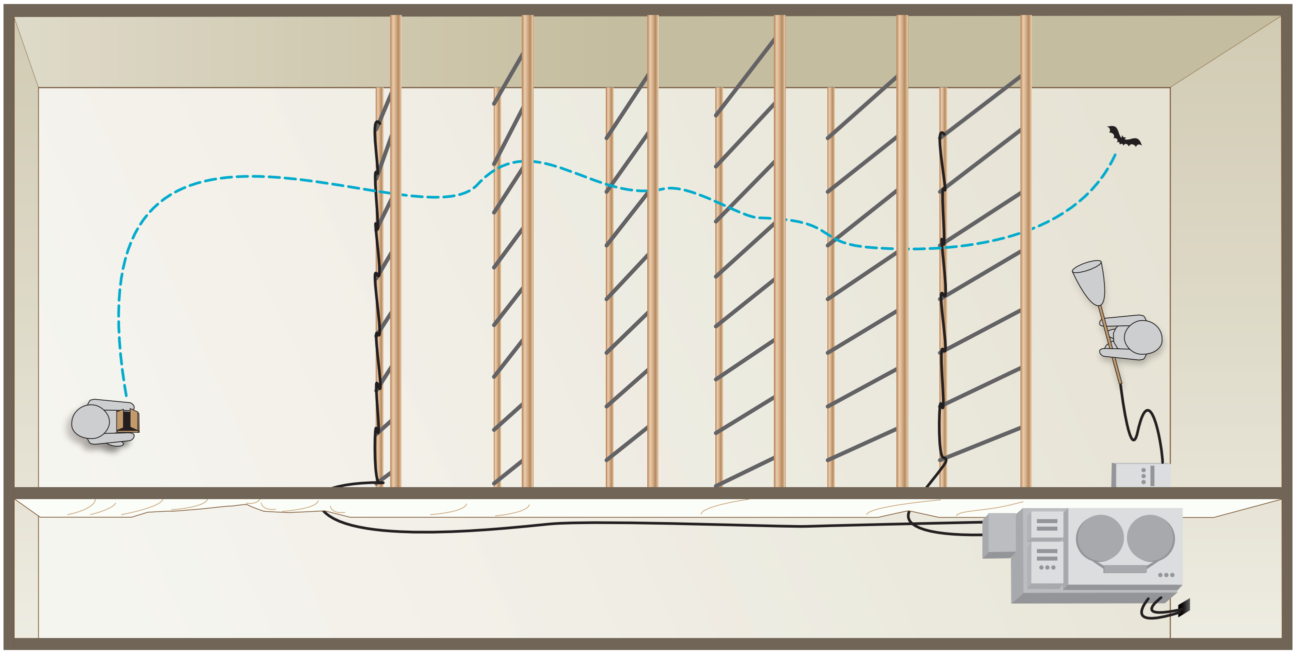

FIGURE 2. Illustration of the test chamber setup at Webster's laboratory in Cambridge, Massachusetts.

detailed quantitative look at bat signals, their range-Doppler ambiguity functions, and their expected performance in jamming noise [3].

The test environment used for Lincoln Laboratory's program was a fascinating example of scientists conducting very demanding experiments with a low budget and the seemingly primitive instrumentation of the early 1960s. Webster volunteered his personal laboratory, housed in a Quonset hut in his backyard next to Mount Auburn Cemetery in Cambridge. The hut was converted into a bat test chamber. This chamber—5 m long, 2 m wide, and 2.4 m high—was outfitted with five arrays of thin wires, each wire in an array spaced at twice a bat's wingspan (Figure 2). The wires were loosely connected at the base so that collision with a wire would not harm the bat. Arrays of about 50 ultrasonic loud speakers at each end of the room could broadcast jamming signals [4]. Ultrasonic microphones captured a bat's signals and the jamming noise.

Cahlander devised a "gun" to toss a mealworm in the air for a bat to detect and capture. High-speed flash photography was used to record the bat's flight. Figure 3 shows Cahlander on the floor level launching a mealworm while Webster captures the bat's flight with a high-speed camera.

Bats for the experiments were selected on their ability to (1) fly willingly and learn to catch mealworms in the air, and (2) avoid the obstacle wires. (Only 1 in 25 bats became adept at these skills.) The best of these skillful bats were used in the experimental trials—and were rewarded with catchy nicknames such as Macbeth. Individual experiments might consist of 100 to 700 flights, so the selected bats worked hard.

Without any jamming (quiet rooms), a bat could navigate through the fine wires rather effortlessly with an ability to miss the wires some 95 percent of the time. As the experimenters cranked up the broadband noise jamming, the bat's ability to miss the wires degraded slowly to 60 and then 40 percent. When the noise level became too high, the bat would simply refuse to fly.

The Key Question

The key question was, "At what signal-to-jamming-noise ratio did a bat have difficulty navigating?" This measurement was fraught with difficulties:

1. The experimenters had no direct measure of the bat's received signal intensity or even of its transmit intensity. They estimated the received signal intensity by calculating a backscattered signal off the vertical wires, using the bat's distance from the wire and

a presumed transmit signal level estimated from a handheld bat measurement.

2. The jamming noise field was far from uniform since the room's walls and the wire apparatus reflected signals.
3. The exact positions of the bat's ears were important because bats had been shown to use the directivity of their ears to combat interference. The orientation of the bat's head was also important but difficult to measure. The desired signal and the jamming signals generally came from different directions. As a bat approached the wire obstacle arrays, it was often observed flying unusual trajectories to presumably enhance a directive reduction of the noise. One estimate cited nearly 15 dB of noise reduction from this directivity.
4. The experimenters had to assume the nature of the bat's brain signal processor. They assumed it functioned as an ideal matched-filter receiver of classical communication theory, but a variety of evidence suggests the bat's brain processor is more complex than that.
5. There was the possibility that the bat might integrate several pulses. Also, in a jamming field, the bat was observed to increase the intensity of its transmitted signal.
6. Many instrumentation limits and difficulties made data collection inaccurate despite the experimenters' diligence to calibrate all instruments.

Some experiments in the 1950s suggested that a bat could operate in noise fields that were 200 to 3000 times stronger than its own received signal!

FIGURE 3. David Cahlander launches a mealworm for the circling bat. Frederic Webster runs the camera.

Best Estimate

The experimenters winnowed down the many error sources as best they could and settled on a conclusion that the bat was navigating well with the interference three times stronger than the expected signal (signal/noise = –5 dB). They then folded in the 15 dB noise-reduction estimate to account for the bat's ears' directivity. The final estimate then was that Mr. Bat was navigating well at a signal-to-noise ratio of +10 dB, which is in consonance with our information theory.

So, we humans are probably not so dumb, but we still must confess a certain awe at Mr. Bat and his sophisticated airborne sensor.

—BILL DELANEY

Bill Delaney is a veteran of 57 years at Lincoln Laboratory. He is currently the Director's Office Fellow and is a former Assistant Director. He professes no expertise in "bat radar" but became a close colleague of Dr. J.J.G. McCue years after his bat research. Bill is a fly fisherman who has inadvertently caught (and then released) bats on quiet nights on Lake Winnipesaukee when he is fishing a yummy looking bug-type fly on the lake surface

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3. D.A. Cahlander, "Echolocation with Wide-Band Waveforms: Bat Sonar Signals," submitted in partial fulfillment of the requirements for the PhD degree at the Massachusetts Institute of Technology, February, 1963.
4. D.R. Griffin, J.J.G. McCue, and A.D. Grinnell, "The Resistance of Bats to Jamming," MIT Lincoln Laboratory Technical Report No. 285, 23 October 1962.