Echolocation in Bats

The Nature of Sound

Velocity: \( \frac{344 \text{ m/s}}{\text{wave energy per unit area}} \times \frac{t}{x} \)

Intensity: \( \propto \frac{P_0}{T} \)

Sound Pressure: \( \frac{P_0}{T} \) (cycles / s)

Frequency: \( \frac{f}{z} \)

Pitch: \( \frac{v}{c} \)

Bandwidth: \( \frac{f}{c} \)

Waveform: \( \frac{v}{c} \) > 20 kHz

The best signal for range accuracy = one with broad bandwidth (i.e. very short).

Range accuracy is determined by (the inverse of) signal bandwidth.

\[ \Delta R = \frac{c}{2\beta} \]

\[ \Delta R = \text{minimum discernible range difference (in cm)} \]

\[ \beta = \text{bandwidth (per second)} \]

\[ c = \text{speed of sound (cm / second)} \]

Echo delay: cue for target distance.

\[ R = \frac{c - t}{2} \]

C = speed of sound

T = time delay

R = target range

For short signals: \( T = \frac{1}{\beta} \), where \( T \) is the duration of the pulse.

\[ \Delta R = \frac{cT}{2} \]
Animals with Broadband Sounds

Dolphin echolocation clicks.
Short, broadbandwidth (includes ultrasound).

Dolphin clicks recorded at normal speed.

Dolphin Range Discrimination Performance

Training: discriminate between near and far objects using sound echoes only.

Results: accurate to 1-3 cm, at distances up to 7 m.

theory: \( R = \frac{1720 \text{ m/s} \times 40 \times 10^{-6} \text{s}}{2} \)

\[ \approx 3.4 \text{ cm} \]

Rousettus madagascariensis.
Rousettus sp.

Short sounds are weak

1) Total energy is proportional to duration of the call.
2) Geometric spreading:
   Outgoing: \( I \propto \frac{1}{r^2} \)
   Echo: \( I \propto \frac{1}{r^4} \)
3) Absorption of energy by atmosphere \( (\propto f^2) \)
4) Target size.
5) Off axis targets.
   \[ \therefore \] short signals will make very weak echoes.

How can bats generate louder sounds?
Distance Discrimination

JA Simmons. Work with *Eptesicus fuscus*
Bats trained to discriminate two targets from a distant perch, and to fly to closer one.

Results of Simmons 2-choice experiments

1) Target difference must be 2 cm or more for 75% correct discrimination.
2) When target distances differ by more than 2 cm, accuracy improves to 100%.
3) At threshold, echo delay is 60-70 microseconds.
4) Close match to the theoretical limit determined from radar theory.

Simmon’s Experiments (cont.)

3) Discrimination threshold is independent of target distance.
• Conclusion: bat must be using timing information to do distance discrimination.

“Optimal” Receiver

Radar and Sonar Theory: best estimate of echo delay is achieved when receiver “cross correlates” of entire echo with entire signal (not simply beginning), (i.e. delay the signal until it is most highly correlated with echo).

Eptesicus fuscus

Ultrasound slowed down 16 times

FM Sweep Improves Delay Estimation

FM Sweep from Eptesicus
cross correlation of echo with itself

Compare Cross Correlation for Two Bat Sounds

Bat’s head movements.
Trained to discriminate jittered from non-jittered target.

Jitter Experiment

Eptesicus performs as well as ACR predicts.
Resolves time differences of 2-5 µs.
Eptesicus chase, Terminal Buzz