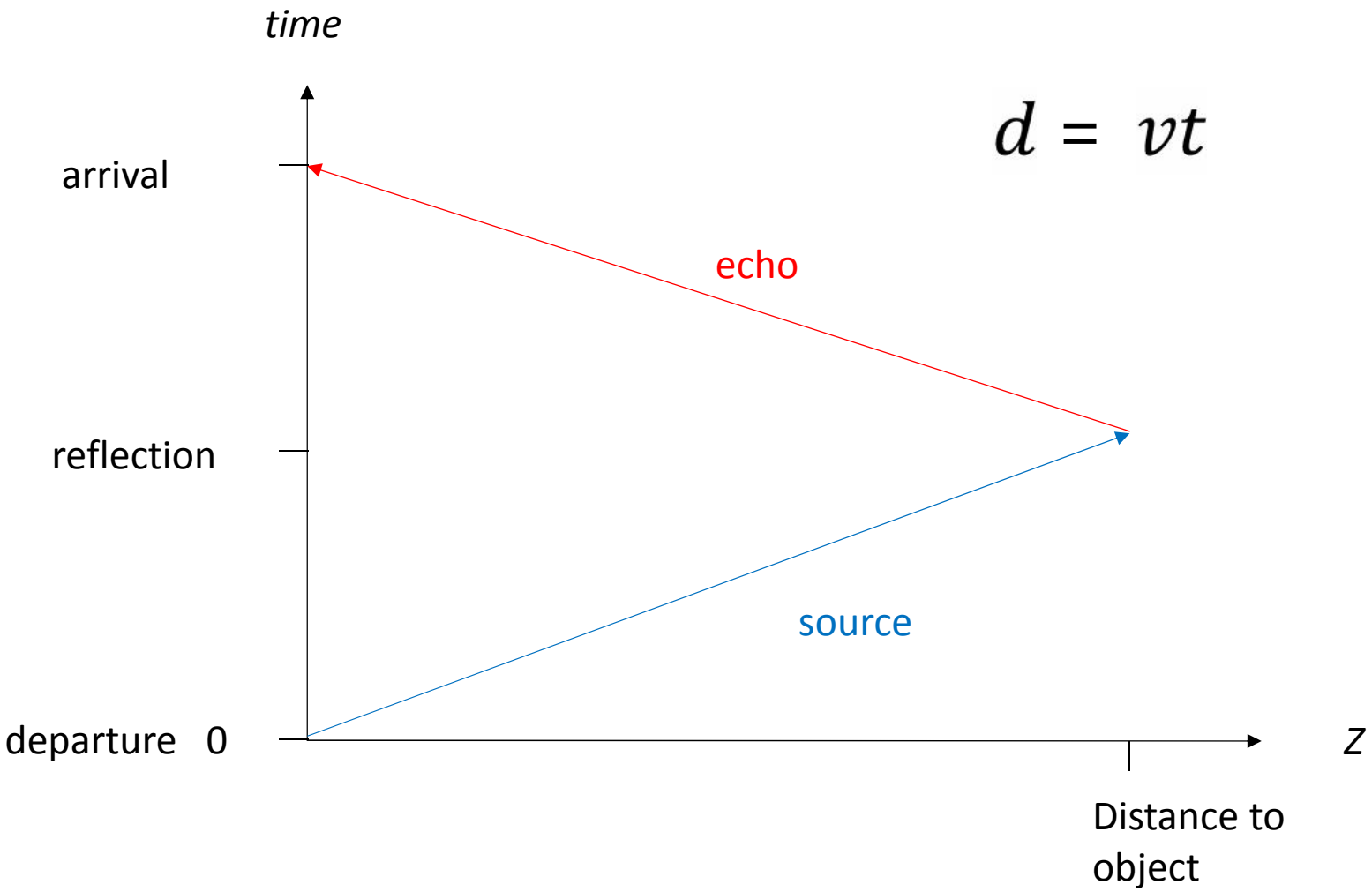
COMP 546

Lecture 23

Echolocation

Tues. April 10, 2018

Echos

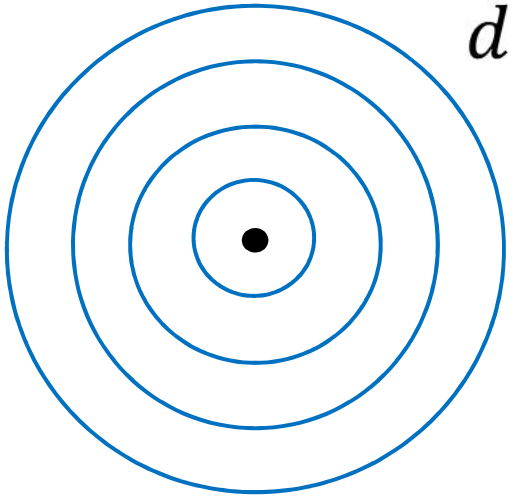


$$d = vt$$

Sounds travel distance is twice the distance to object.

Recall lecture 20.

$$d = v\,t$$

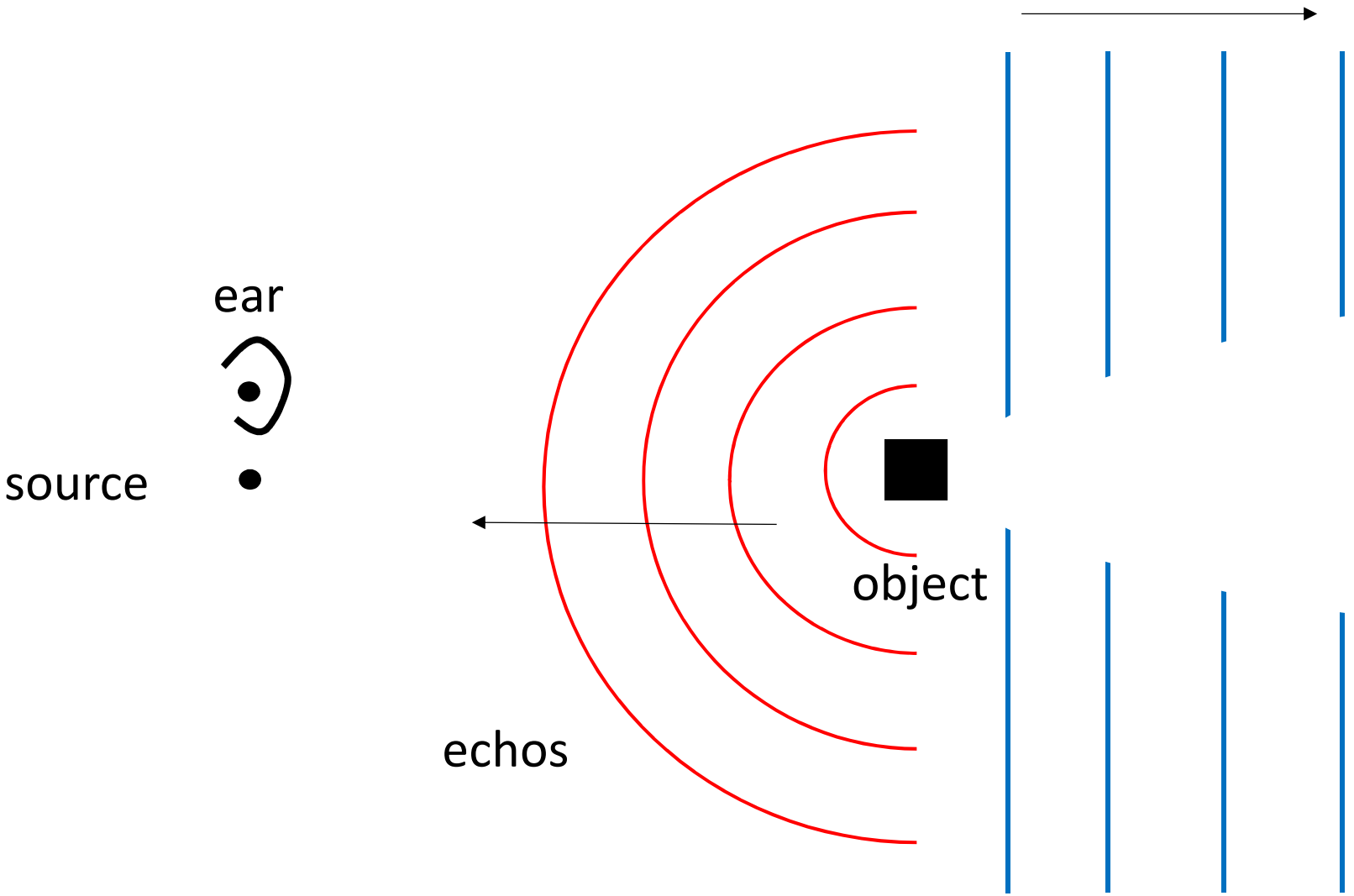


source

ear

$$I^2 \sim \frac{1}{d^2}$$

So, SPL $$I \sim \frac{1}{d}$$

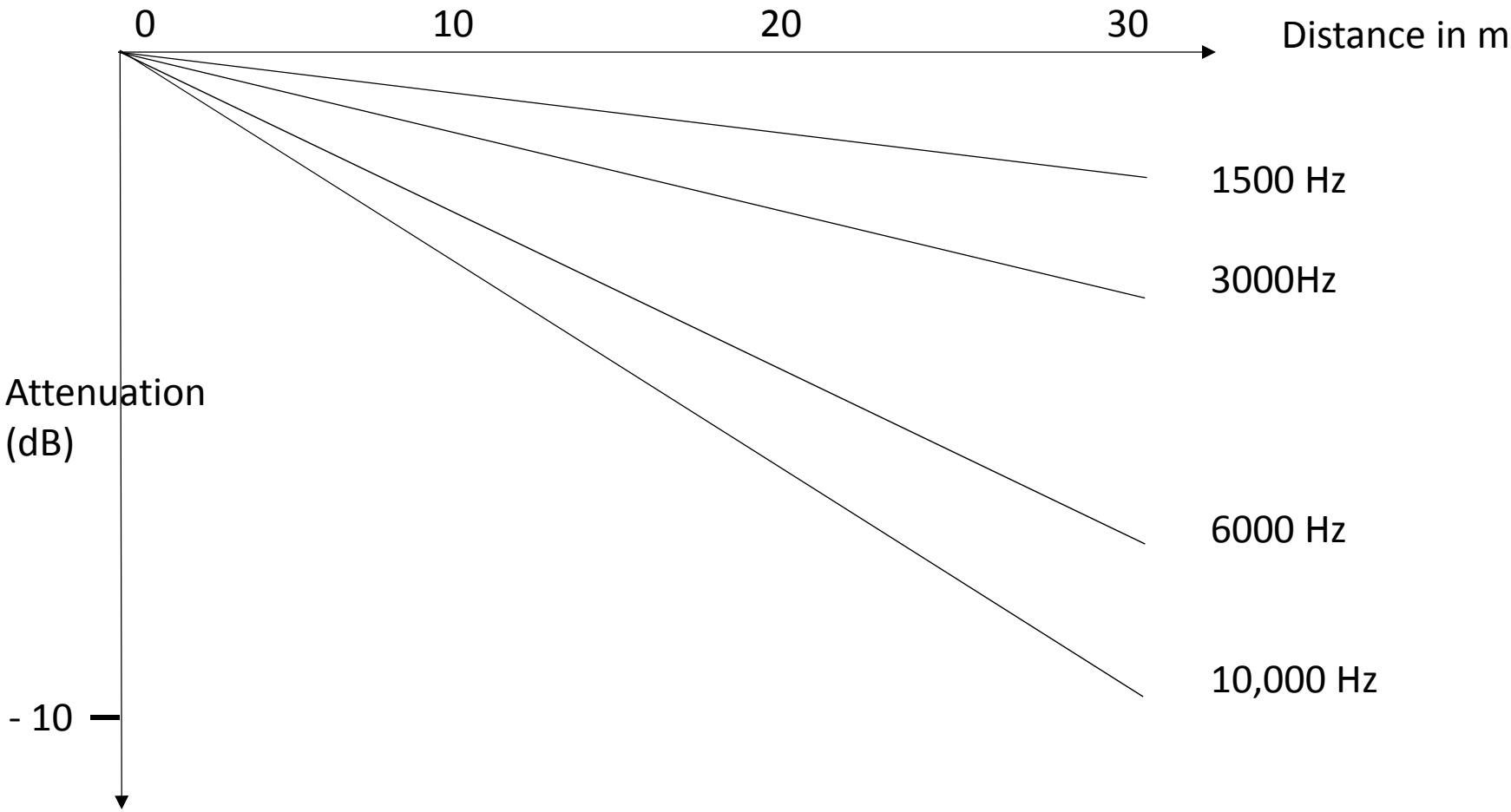


$$I^2 \sim \frac{c}{d^2} * \frac{1}{d^2}$$

So, SPL $$I \sim \frac{1}{d^2}$$

ASIDE: Sound absorption in air

(previous example ignored this)



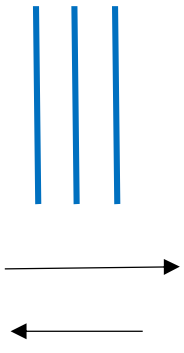
High frequency sounds are attenuated at a faster rate.

How do bats navigate and catch prey in the dark?

- Ancients: bats have sensitive eyes or skin ?
- Spallanzani showed bats use hearing (1700’s)
- Griffin measured bat ultrasound (1930's)

Sonar: Echos and Time Delays

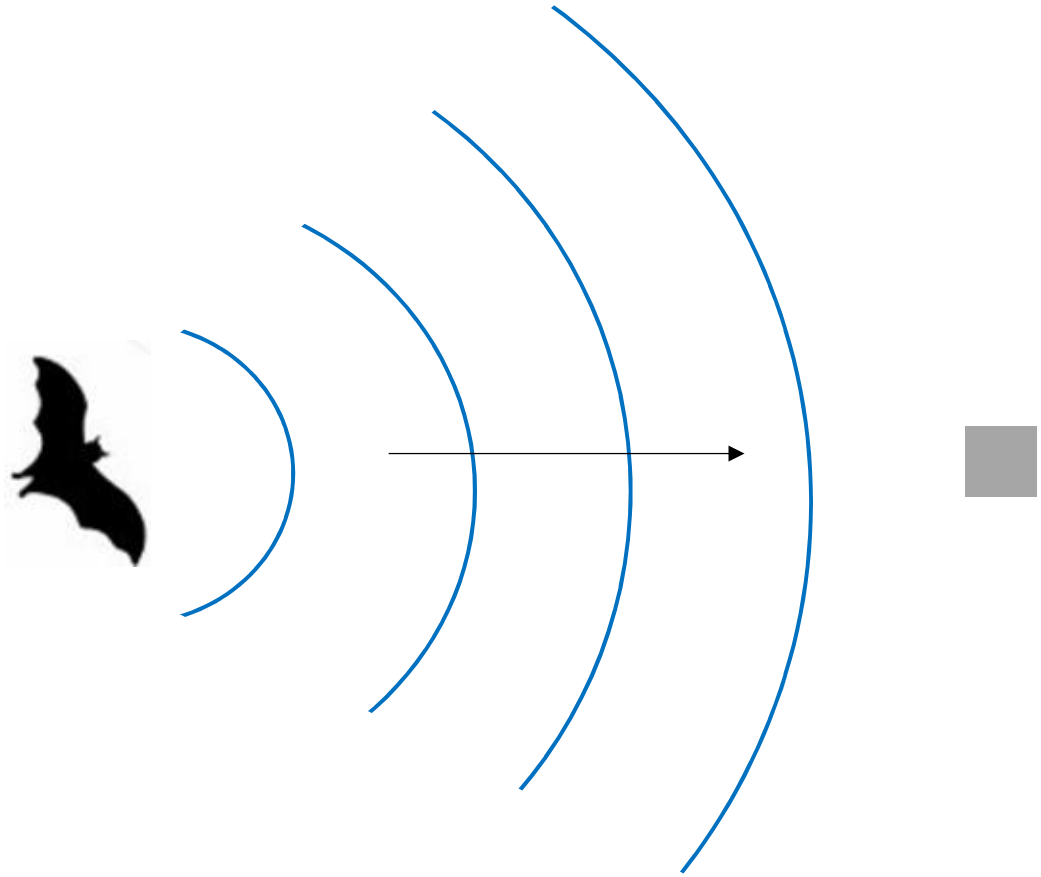
bat



object

$$t \sim \frac{2d}{v}$$

Measure t and estimate d.

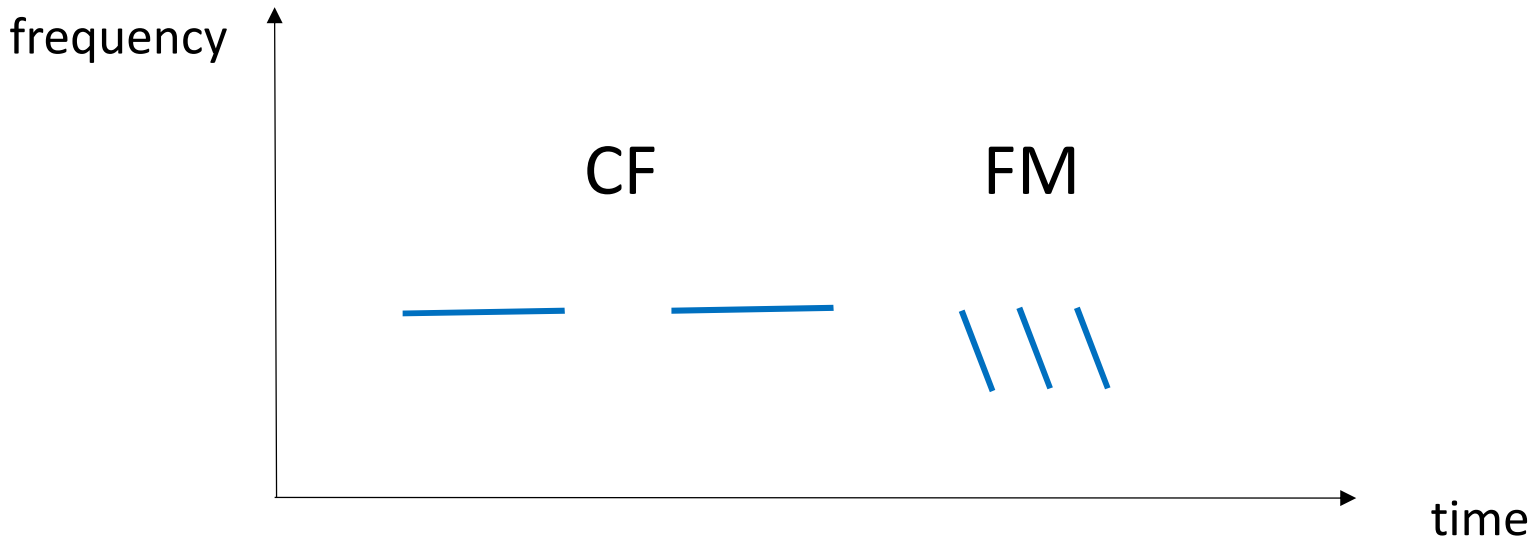


To get a louder echo, bat concentrates its cry over a small range of directions (~40 deg)
But still the emitted intensity falls off with distance squared.

Three Computational Problems

- Detection (tree branches, prey e.g. insects)
- Localization (distance and direction)
- Recognition

Two types of bat cries



CF - constant frequency

FM - frequency modulated.

(only the frequency with most energy is shown -- not harmonics)

Wavelength of ultrasound

- Humans are sensitive up to 22 kilohertz (kHz)

- Bats are sensitive up to 200 kHz

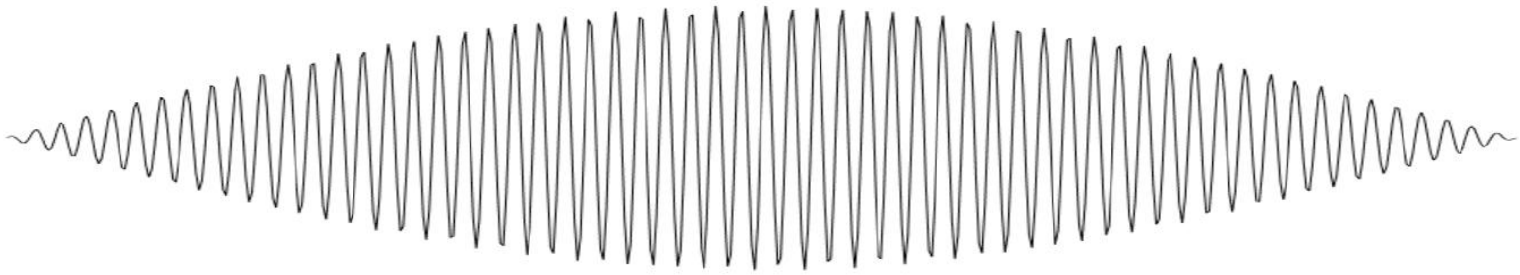
(34 kHz has wavelength of 1 cm
170 kHz has wavelength of 2 mm)

CF ("constant" frequency)

Suppose a CF cry is 10 ms duration. (Often *much* longer than that.)

"snapshot" length (meters) of cry in space ? (d = v t)

number of cycles ? (ω_0 cycles per second * duration)

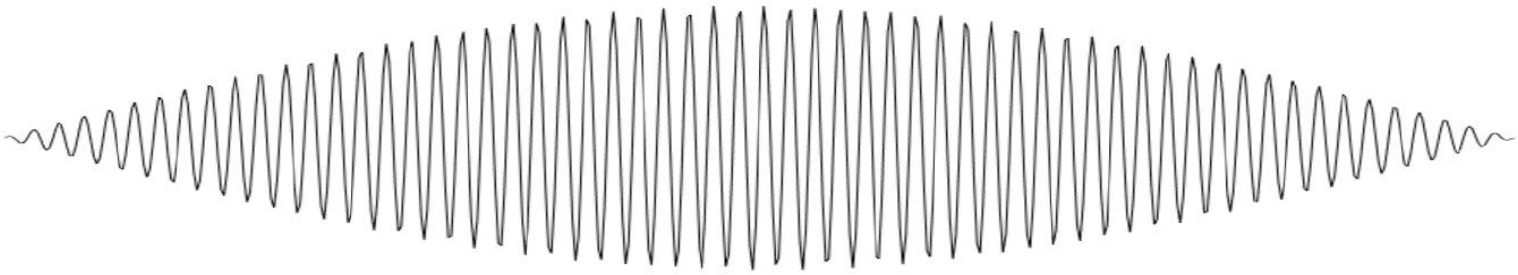


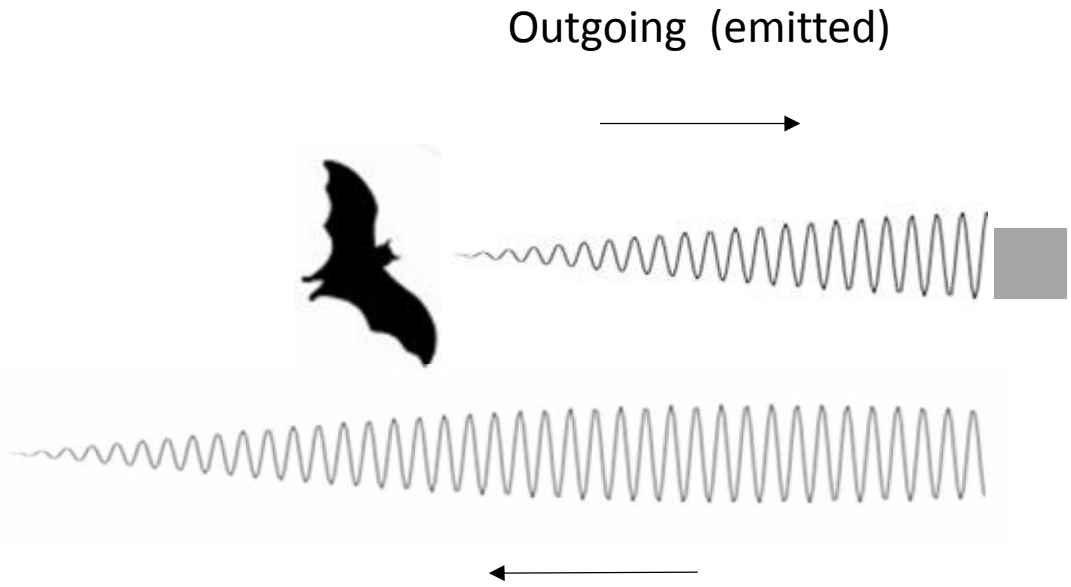
CF (“constant” frequency)

Suppose a CF cry is 10 ms duration. (Often *much* longer than that.)

“snapshot” length of cry in space : 343 m/s * .01 s = 3.4 m

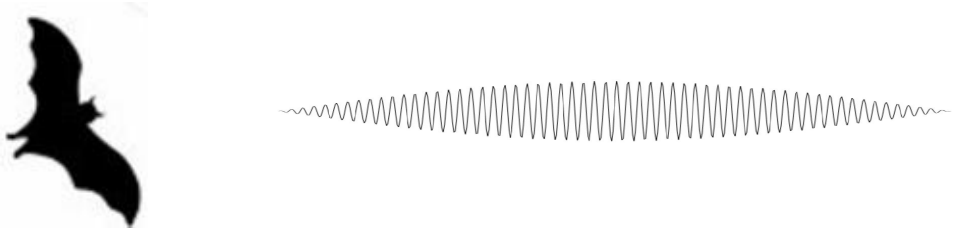
number of cycles ? If center frequency is ω_0 Hz, then we have ω_0*.01 cycles.





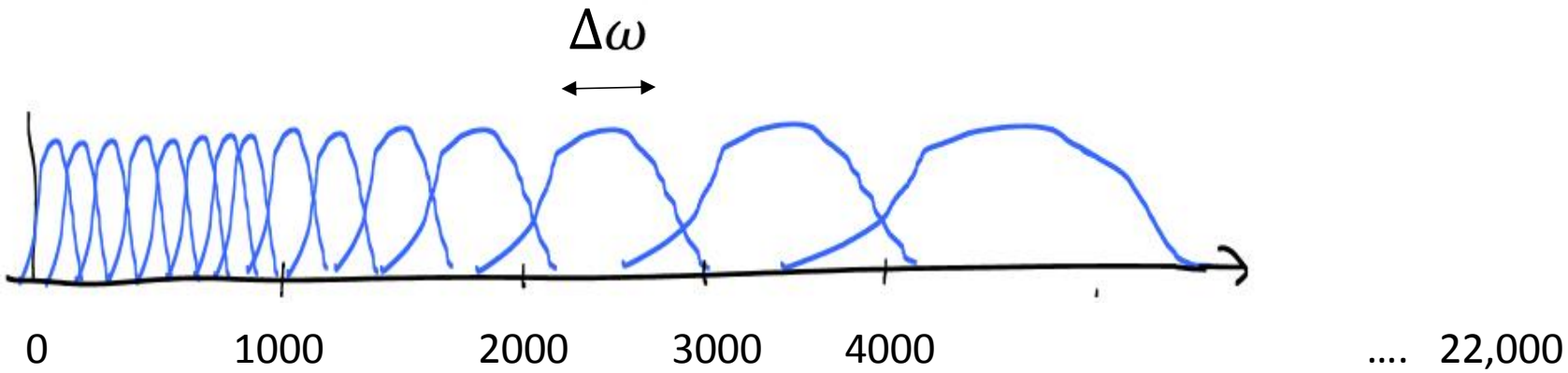
If the echolocated object is too close, then moth will start to receive CF echo before emitted cry is finished.

Outgoing (emitted)



Cry length (snapshot) should be less than twice the distance to object.

Recall: Human Auditory filters

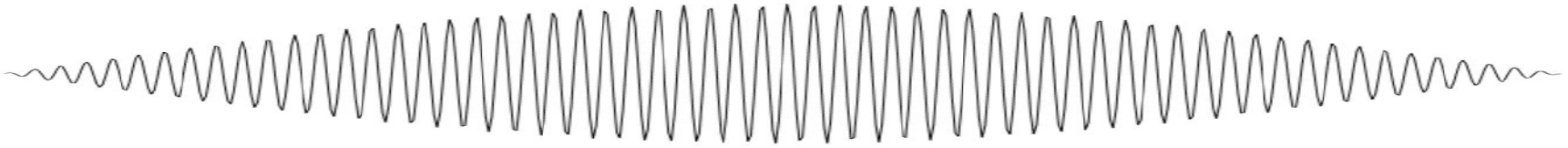


$\Delta\omega$ is ~100 Hz for center frequency up to 1000 Hz.

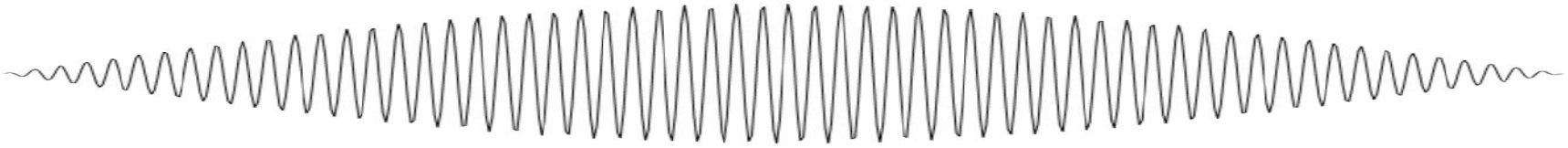
$\Delta\omega$ is ~ 1/3 octave from 1000 Hz up to 22, 000 Hz.

Bats also have bandpass auditory channels.
But they can hear up to over 100,000 Hz.

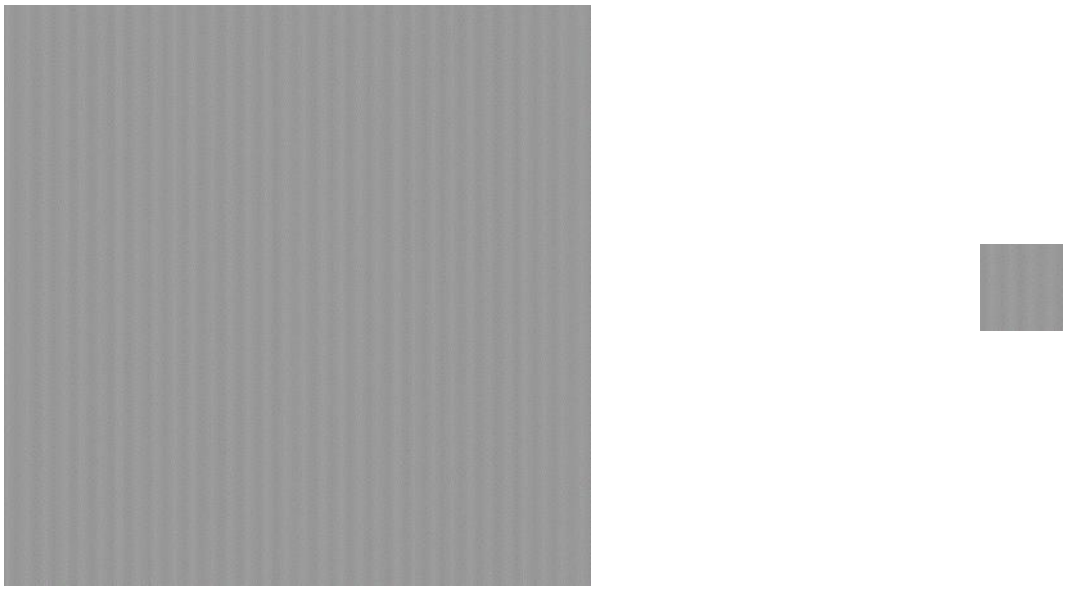
Main Advantage of CF: Lots of energy within one narrow auditory band makes the reflected echo easier to detect.



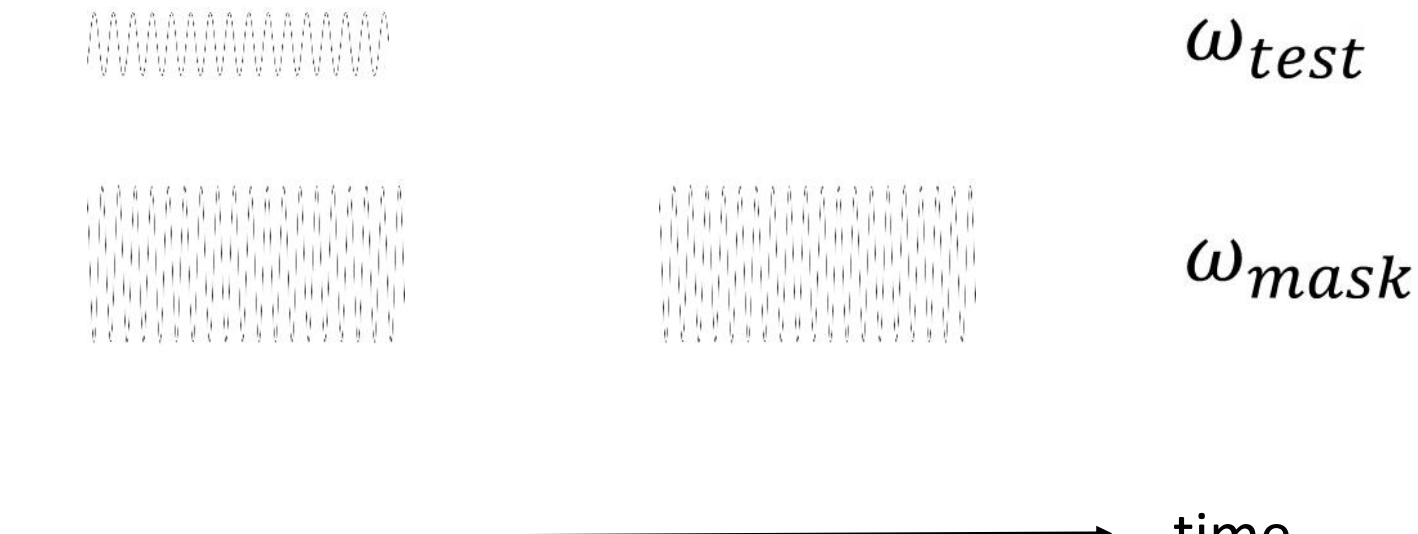
Main Advantage of CF: Lots of energy within one narrow auditory band makes the reflected echo easier to detect.



Analogy to vision: in presence of noise, you would have a better chance of seeing the sine pattern on left than on right.



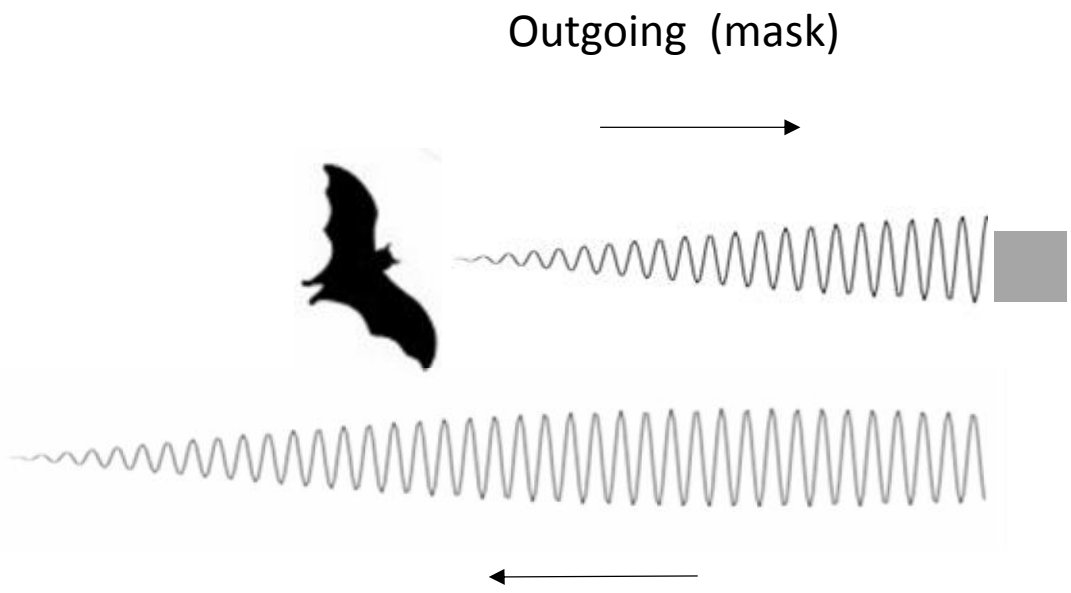
Recall: Masking Experiment



Task: Which interval contains the test tone?

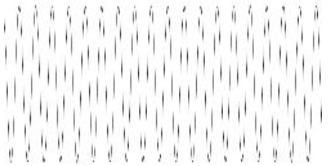
Simultaneous Masking

Outgoing cry overlaps echo.



Forward Masking

ω_{test}



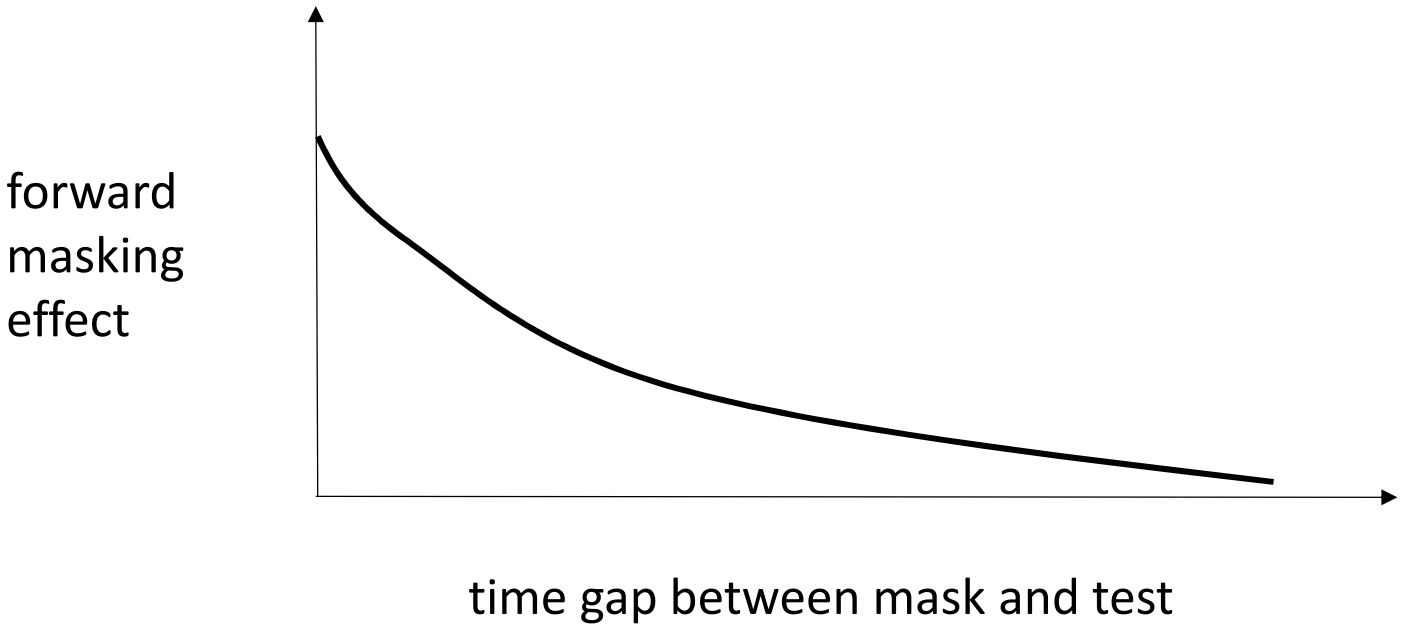
ω_{mask}

time

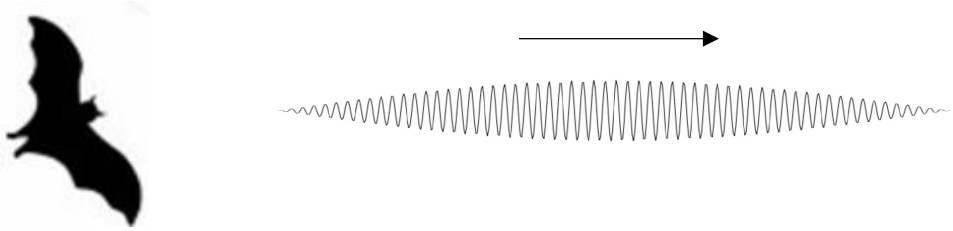
Interval 1 interval 2

Task: Can you hear the test tone ?

Forward Masking



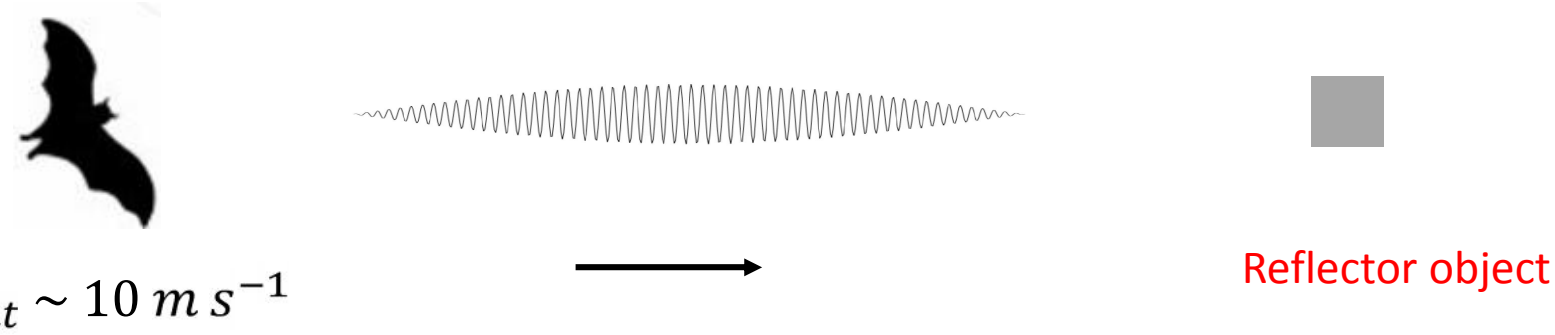
Because of masking, we would expect the cry to be finished long before echo is received.



But then … CF could only be used for distant objects, and echos are weak…. So it wouldn't work.

How to get around this problem?

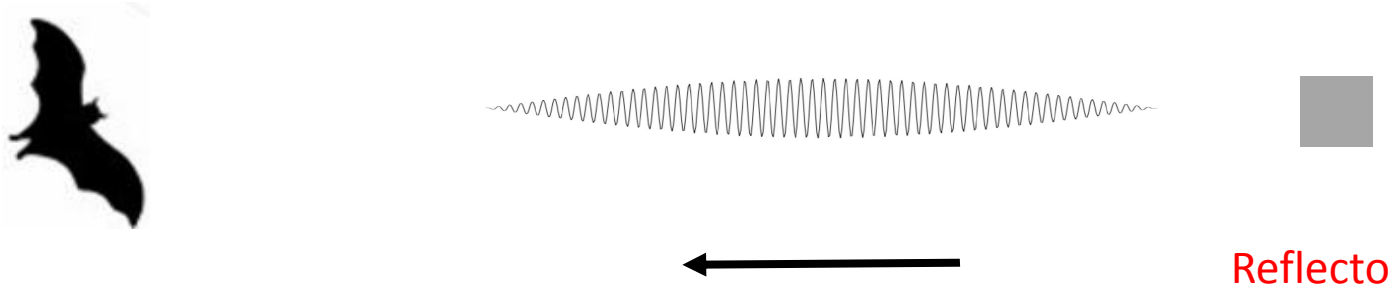
Avoiding masking using a Doppler shift (1)



As the bat emits its cry, it chases *each peak of the wave,* creating a higher frequency 'observed' at the reflector.

$$\omega_{observed\ by\ reflector} = \omega_{emit}\left(\frac{v_{sound}}{v_{sound} - v_{bat}}\right)$$

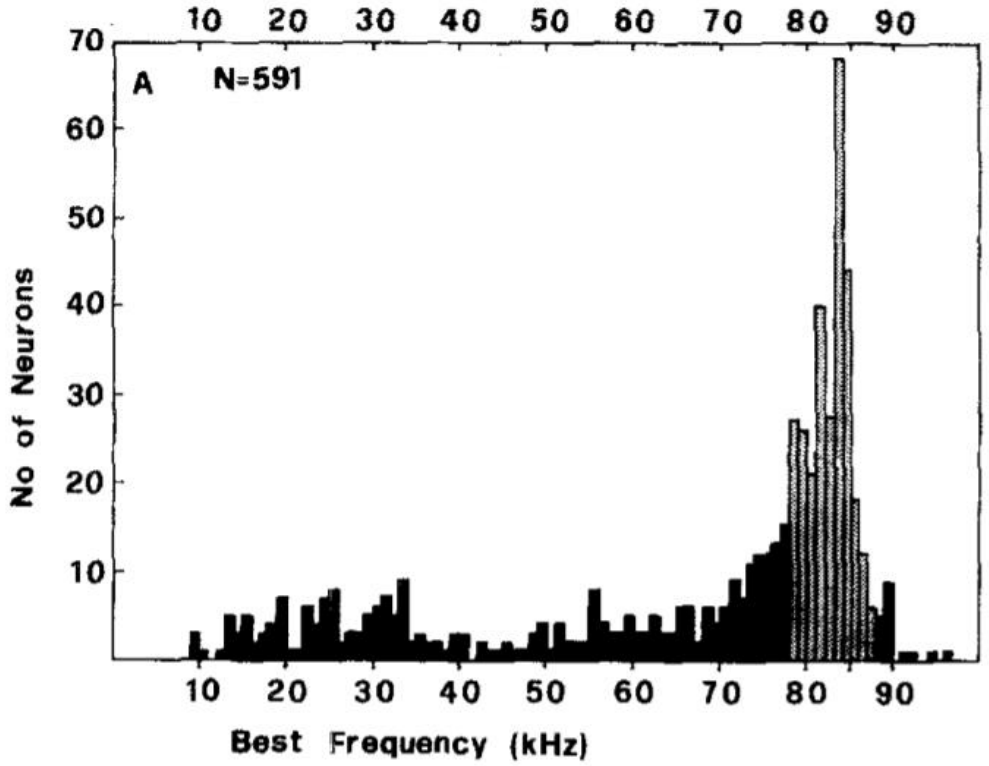
Avoiding masking using a Doppler shift (2)



As the bat flies towards the reflected echos, it *hears* a even higher frequency.

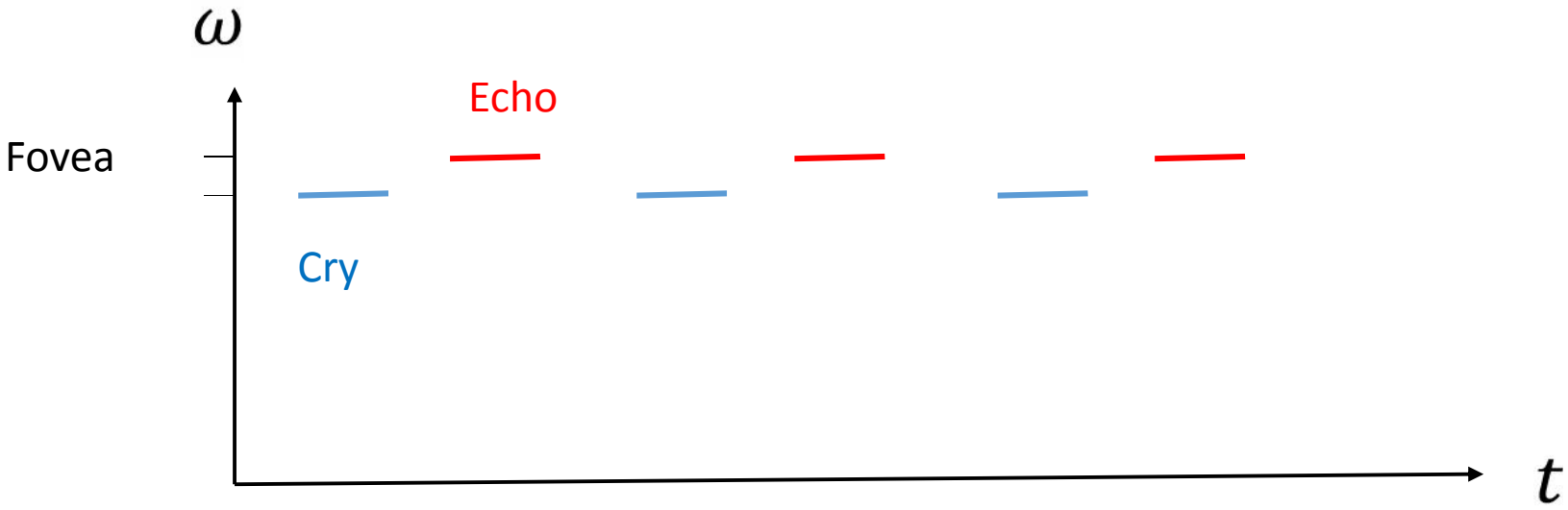
$$\omega_{observed\ by\ bat} = \omega_{emit}\left(\frac{v_{sound}}{v_{sound} - v_{bat}}\right)\left(\frac{v_{sound} + v_{bat}}{v_{sound}}\right)$$

Acoustic Fovea



(Neurons in brain region “inferior colliculus” of Horseshoe Bat)

Schuller & Pollak 1979



Fovea frequency is “hardwired”.

Bat emits at frequency *just below the fovea, so that the echo falls in the fovea.*

Three Computational Problems
(CF cries)

✓ Detection

X Localization

- Distance: delay between the cry and echo cannot be computed reliably since the envelope has a ramp.
- Direction: binaural cues (level and timing differences) are limited to one frequency band.

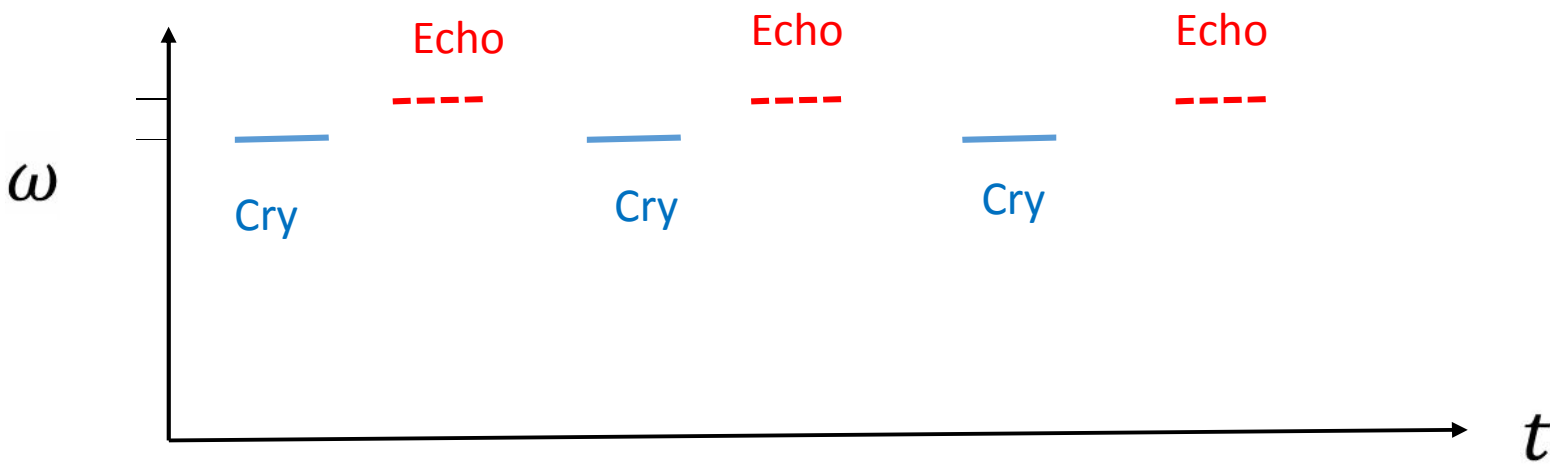
? Recognition

Recognition using CF

Moth wings beat at say 40 Hz (25 ms period)

Sound reflection only happens when moth wing is parallel to sound wave.

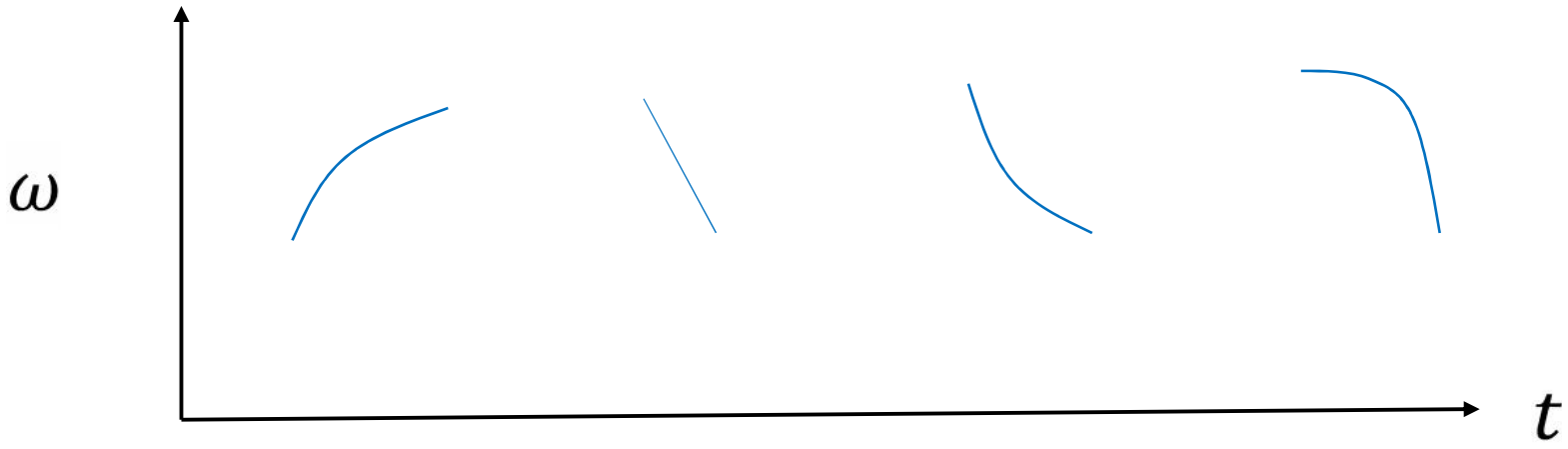
Use a cry of more than 100 ms.



Frequency modulated (FM) cry

$$I_{src}(t) = \sin(\ \omega(t)\ t\ )$$

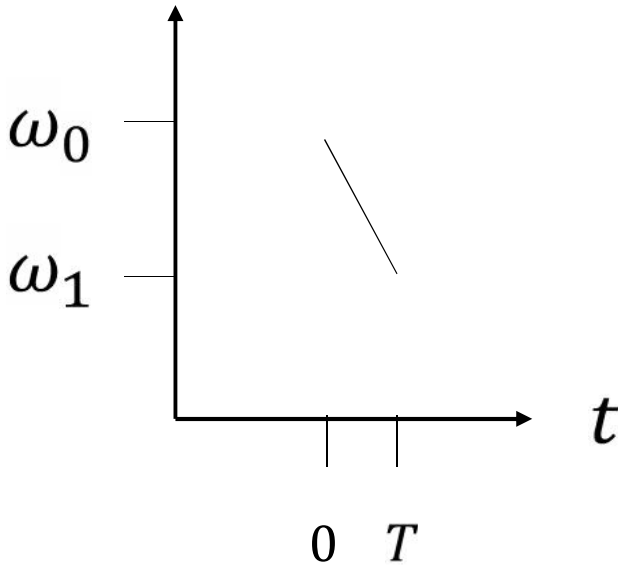
where $\omega(t)$ is a function of t

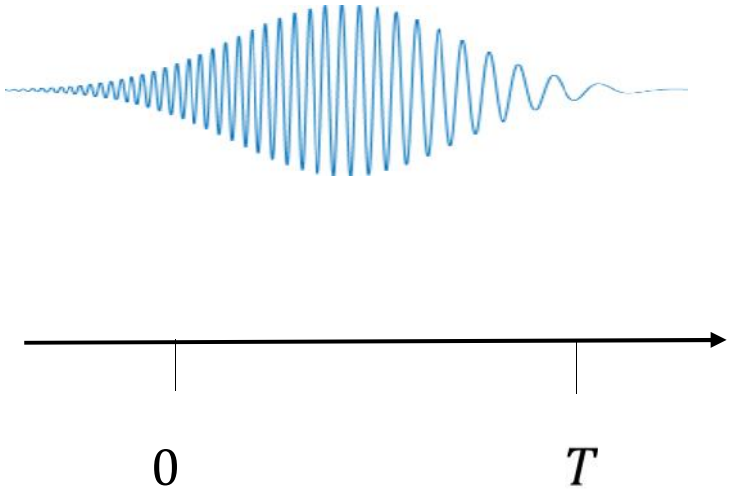


Example: linear chirp

$$I_{src}(t) = \sin(\ \omega(t)\, t\ )\ G(t)$$

where $\omega(t) = \omega_0 + \frac{\omega_1 - \omega_0}{2T}\ t$

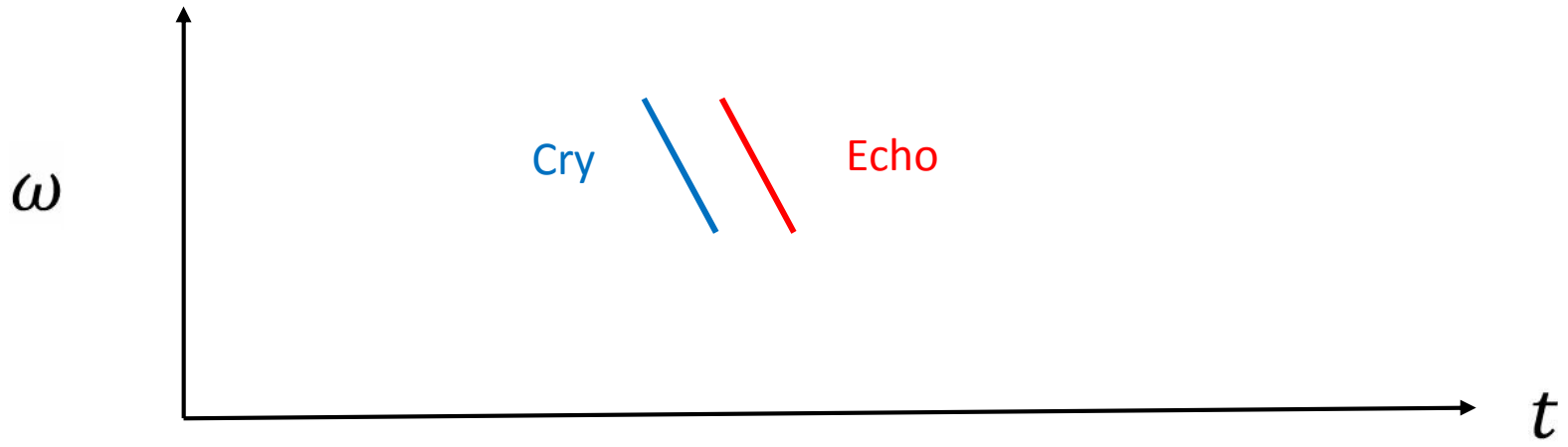




localization (distance and direction) using FM

delay

HRTF



Advantages of FM:

- echo is spread out over many bands
  ⇒ richer binaural HRTF cues

- duration within each band is short
  ⇒ precise timing, avoid masking

Disadvantages of FM:

- weaker signal in each band

Typical Bat Spectrogram

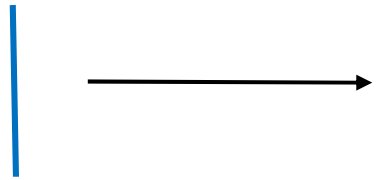
detection &
recognition
(moth wing beats)

localization &
recognition
(discussed next)

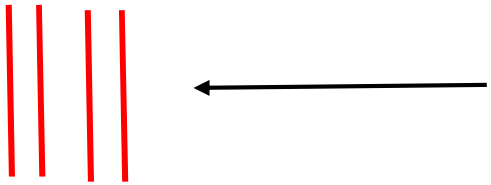
Recognition using an impulse cry

(model only – not physically possible for bat)

$\delta(t)$ impulse



$m(t)$ echo



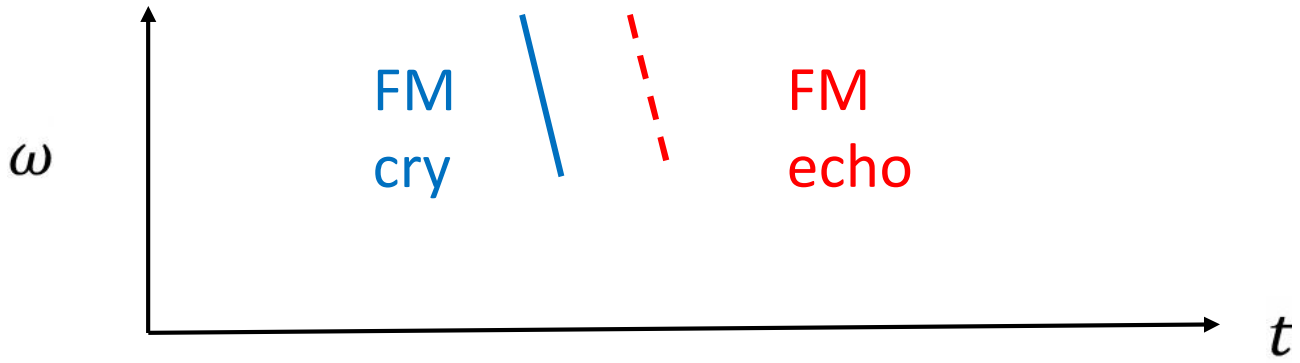
Recognition using an impulse cry

(model only: not physically possible for bat)

$\delta(t)$ Impulse

$m(t)$ echo

Recognition using an FM cry



The peaks and notches of the echo are a signature of the shape of the moth.

Why?

(Toy) Example

Suppose the *moth response function* consists of two echos, separated by τ *seconds*.

$$m(t) = a\,\delta(t) + b\,\delta(t - \tau)$$

$\delta(t)$ Impulse

$m(t)$ echo

(Toy) Example

Suppose the *moth response function* consists of two echos, separated by τ *seconds*.

$$m(t) = a\,\delta(t) + b\,\delta(t - \tau)$$

Then,

$$\hat{m}(\omega) = a + b\,e^{i\,2\pi\,\tau\,\omega}, \quad \text{where } \omega \text{ is cycles/sec}$$

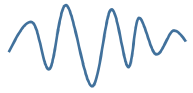
$$\omega = \frac{1}{\tau}, \frac{2}{\tau}, \frac{3}{\tau}, \ldots \qquad \text{constructive interference}$$

$$\omega = \frac{1}{2\tau}, \frac{3}{2\tau}, \frac{5}{2\tau}, \ldots \qquad \text{destructive interference}$$

I can do it too!

Cetacians (dolphins, whales, ..) don't use CF or FM.

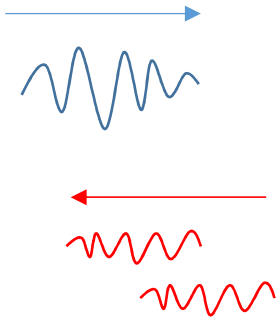
Instead they use "clicks" namely $\sim\frac{1}{2}$ octave Gabors with center frequency ω_0 of ~ 75 kHz.



$$v_{water} = 1500\ m\ s^{-1}$$

width of a fish!

$$\lambda = \frac{v}{\omega_0} = \frac{1500\ ms^{-1}}{75{,}000\ cyc\ s^{-1}} = .02\ m$$



Fish
(cross-
section)

Reflections off the front and back surfaces depend on fish shape and size.

For constructive interference, the width of fish must be half the peak wavelength.

fish width	interference
$\frac{v}{4\,\omega_0}$	destructive
$\frac{v}{2\,\omega_0}$	constructive
$\frac{3v}{4\,\omega_0}$	destructive

Human Echolocation

Can people echolocate? Yes, definitely. The blind use a cane to generate clicks and listen for echos.

Some blind people echolocate by making clicks with their mouth.

See Daniel Kish videos e.g.
https://www.youtube.com/watch?v=ob-P2a6Mrjs