Acoustics of Ship Collisions with Marine Animals

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USACE: WES
NAVFAC: LEGACY
FIND and FFWCC
USFWS PRT 761873 and PRT 795477

Marine Animals for Discussion

- Whales
- Manatees

- Both passive listeners dependent upon received acoustic signals
- Both face the challenges detecting approaching vessels near the surface and many times in relatively shallow water


LETS TALK OF WHLAES FIRST

While commonly identified and reported in coastal areas, collisions are not restricted to shipping lanes or shallow water. A common denominator is that they occur near the surface. Here prevailing acoustic conditions play a crucial role in the whales' ability to detect and locate approaching ship noise.

Psychological Factors: SHIP AVOIDANCE

- Sensory awareness:

  PARAMONT BEFORE ALL ELSE THERE MUST BE A STIMULUS TO BE PERCIEVED
- Auditory Masking and critical ratios (critical bands)
- Directional sensitivity, localization of ship noise
- Auditory scene analysis, associative learning, biological significance
- Habituation
- States of arousal and attending

Most ship strikes occur with ships >80 meters

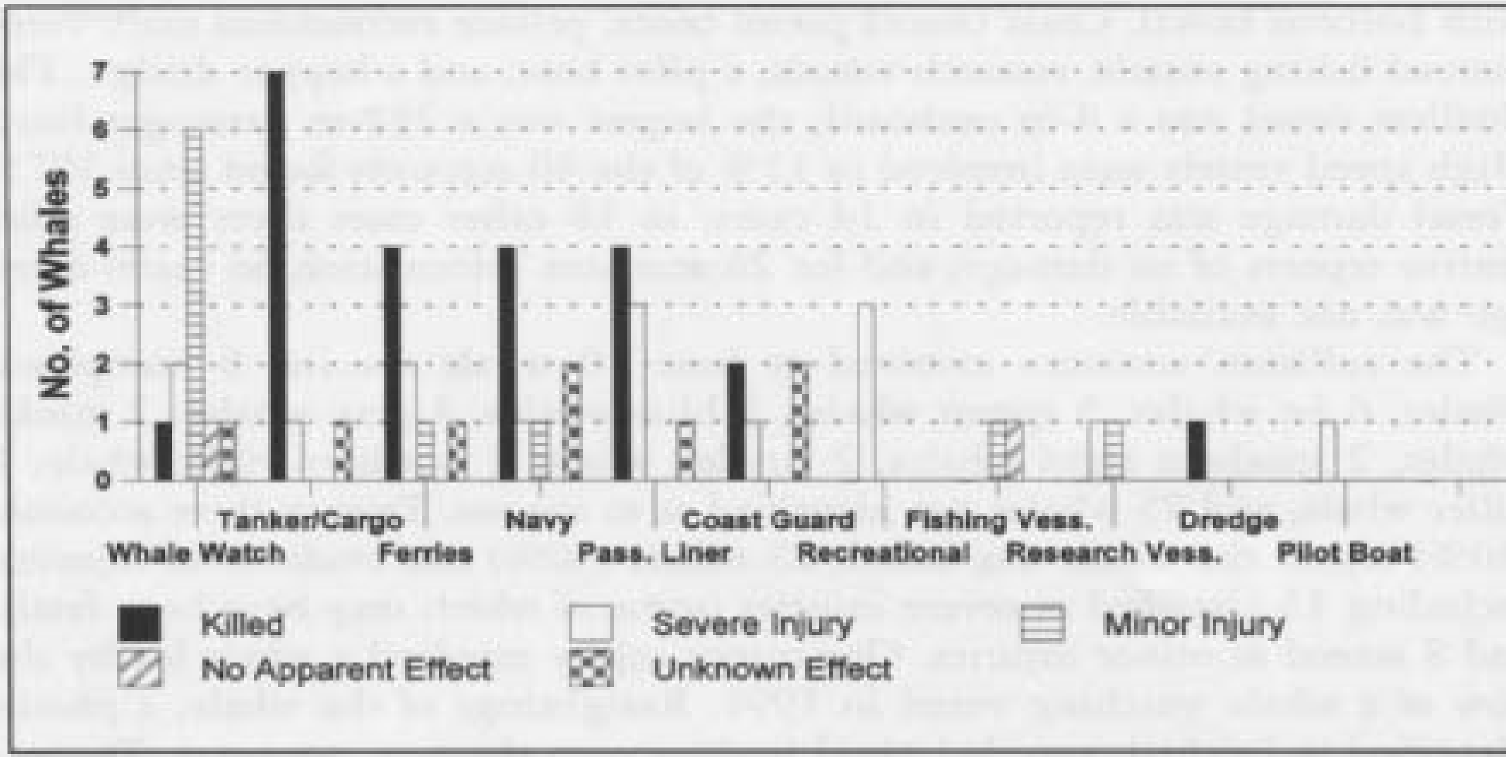


Figure 1. Number and fate of whales struck by different vessel types from collision accounts found in this study. Killed = observed carcass; Severe Injury = report of bleeding wounds or observation of blood in the water; Minor Injuries = visible non-bleeding wound or sign of distress with no report of blood; No Apparent Effect = resighted with no apparent wound or sign of distress and resumed pre-collision activity; Unknown = whale not resighted and no report of blood in the water.

Factors in Determination of Sound Pressure Levels near the Surface ahead of a Vessel

- Spherical Spreading from Propellers
- Lloyd Mirror Effect
- Acoustic Shadowing and Diffraction

Factors to Consider for Acoustical Solutions

- Spherical Propagation (prop to bow)
- Acoustical Shadows
- Lloyd Mirror Effect
- Time-to-Collision and Masking

Vessel Noise Sources

A vessel's propeller is the predominant noise source on it.

In nearly all cases, the acoustic center of a vessel from which sound radiates can be taken as the center of the propellers. Far-field should be calculated from the acoustic center which for ships is most often the geometric center of the propellers.

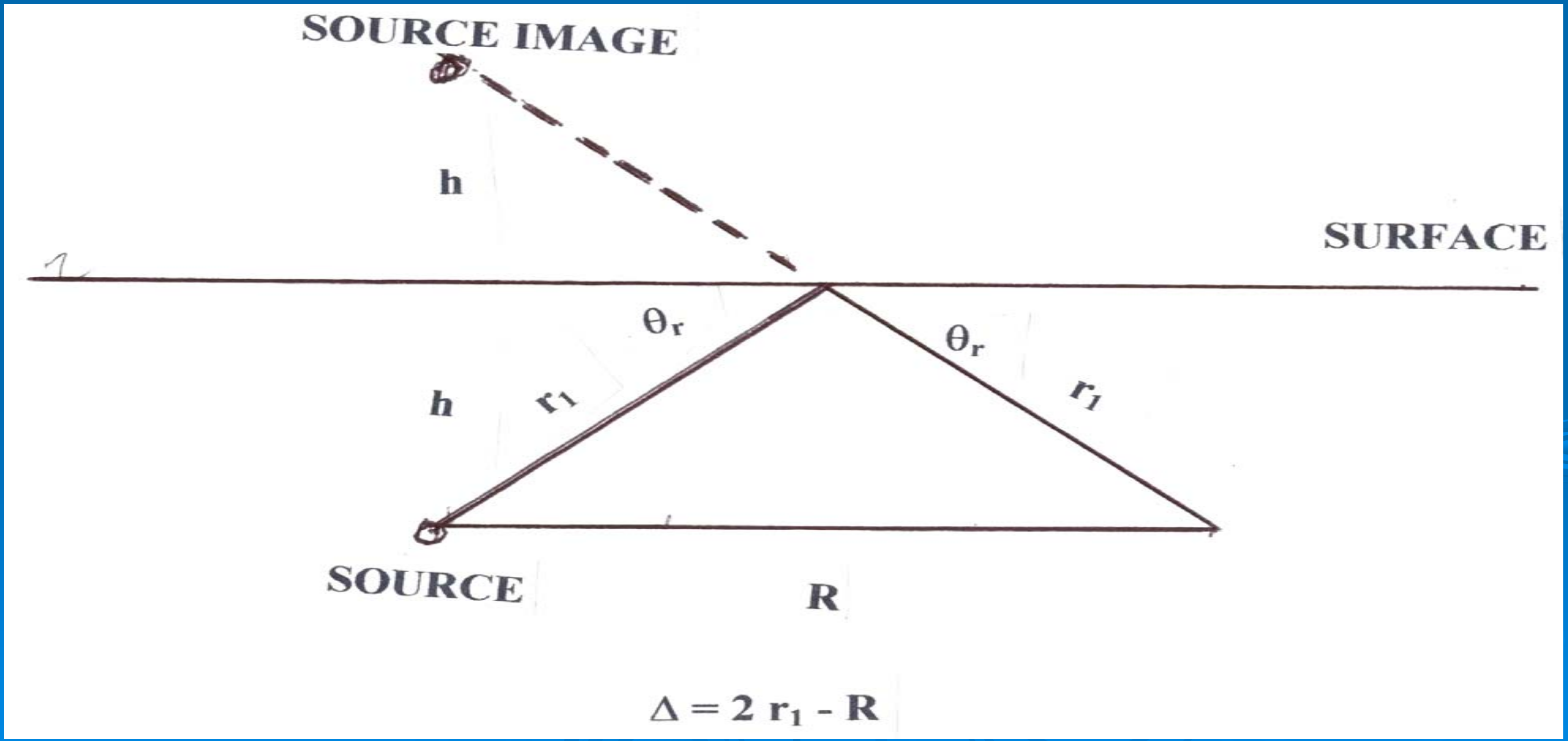
* Ross, Donald, Mechanics of Underwater Noise, Pergamon Press, New York (1976).

Propagation from stern

- When considering propagation from large ships, the acoustic center for the ship going at a few knots is the propeller. Spherical spreading from stern applies.
- What about hull borne sound?
  - Much of hull vibration energy is evanescent.
  - High frequency energy is attenuated by the hull.
  - Low frequency energy is subject to Lloyd Mirror/Pressure Release Boundary Effect.
  - Resulting sound is masked by ambient noise.

Lloyd Mirror Effect Geometry

This figure illustrates that the surface reflection can be viewed as the combination of a direct arrival ray and a reflected ray that is 180° out of phase with the direct arrival or as an imaginary image source located the same distance above the surface as the real source depth.

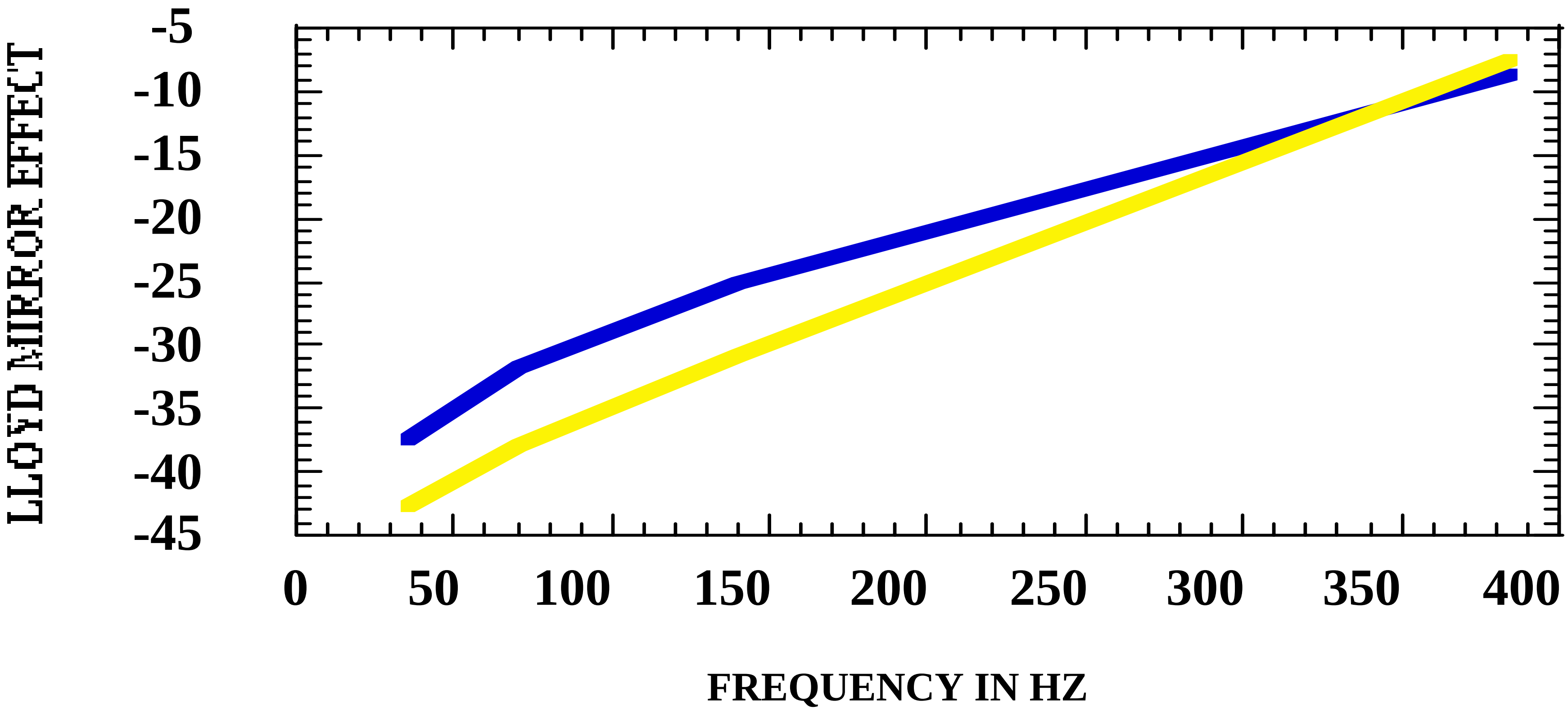


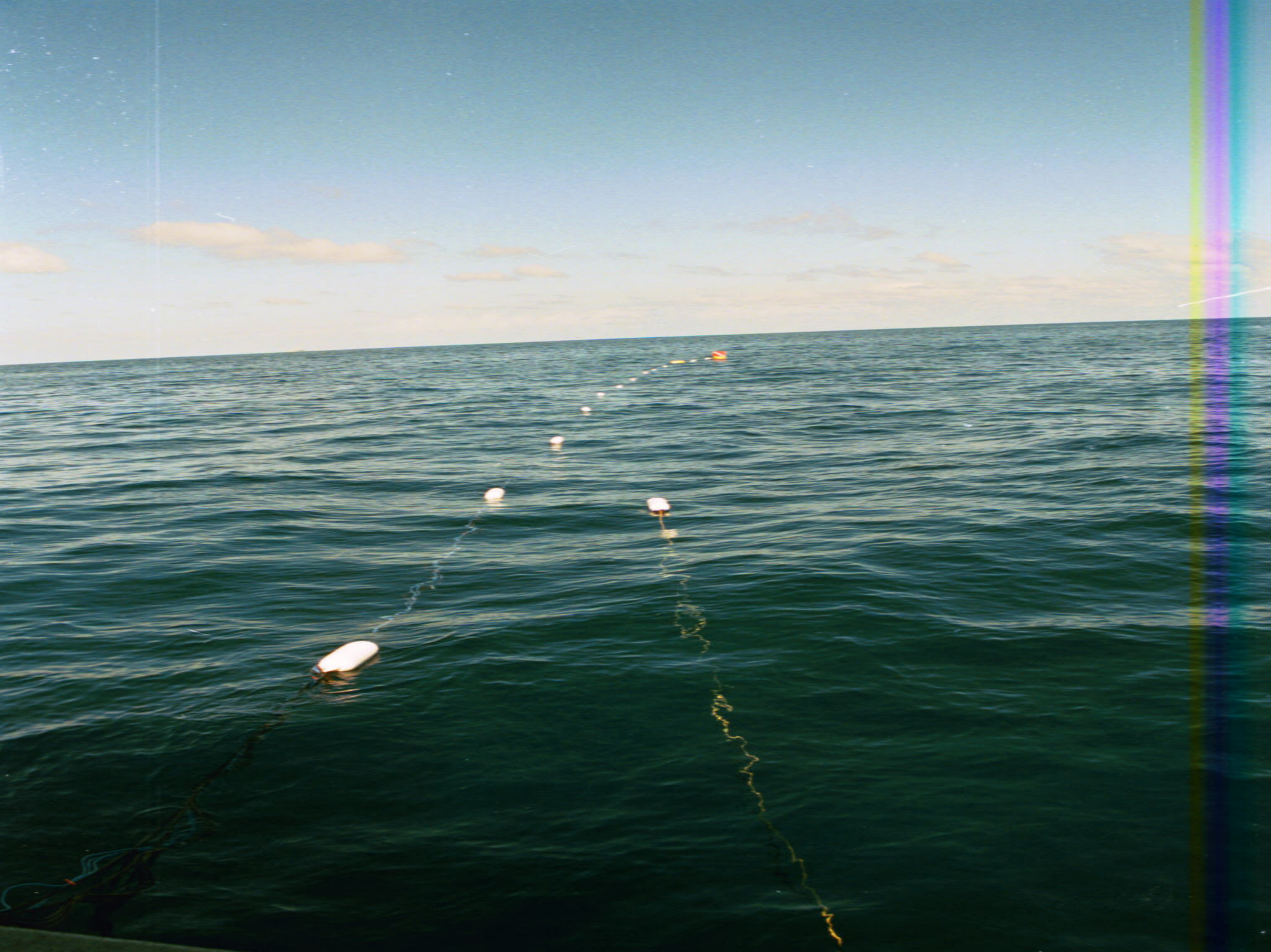
Loss from Lloyd Mirror Effect

Hydrophone at 3-m depth

Blue line – 100 meters

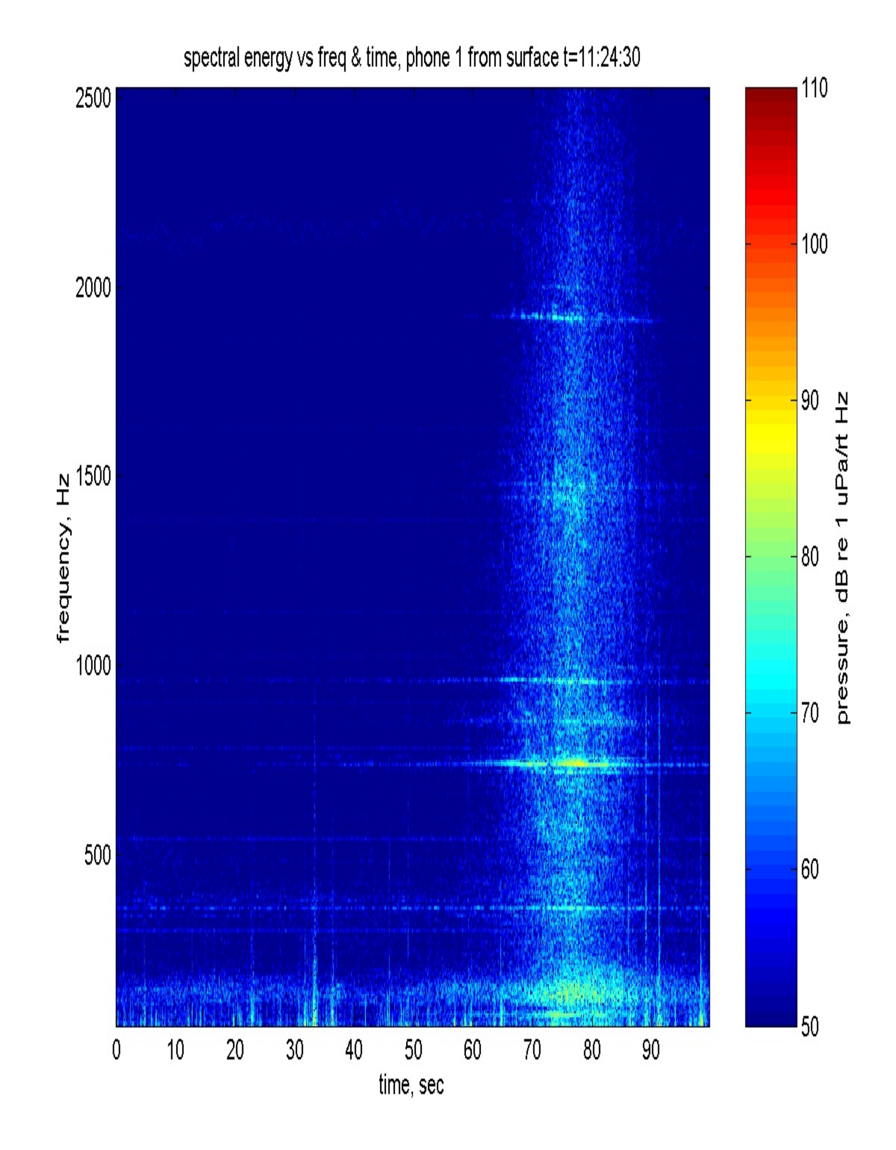
Yellow line – 200 meters

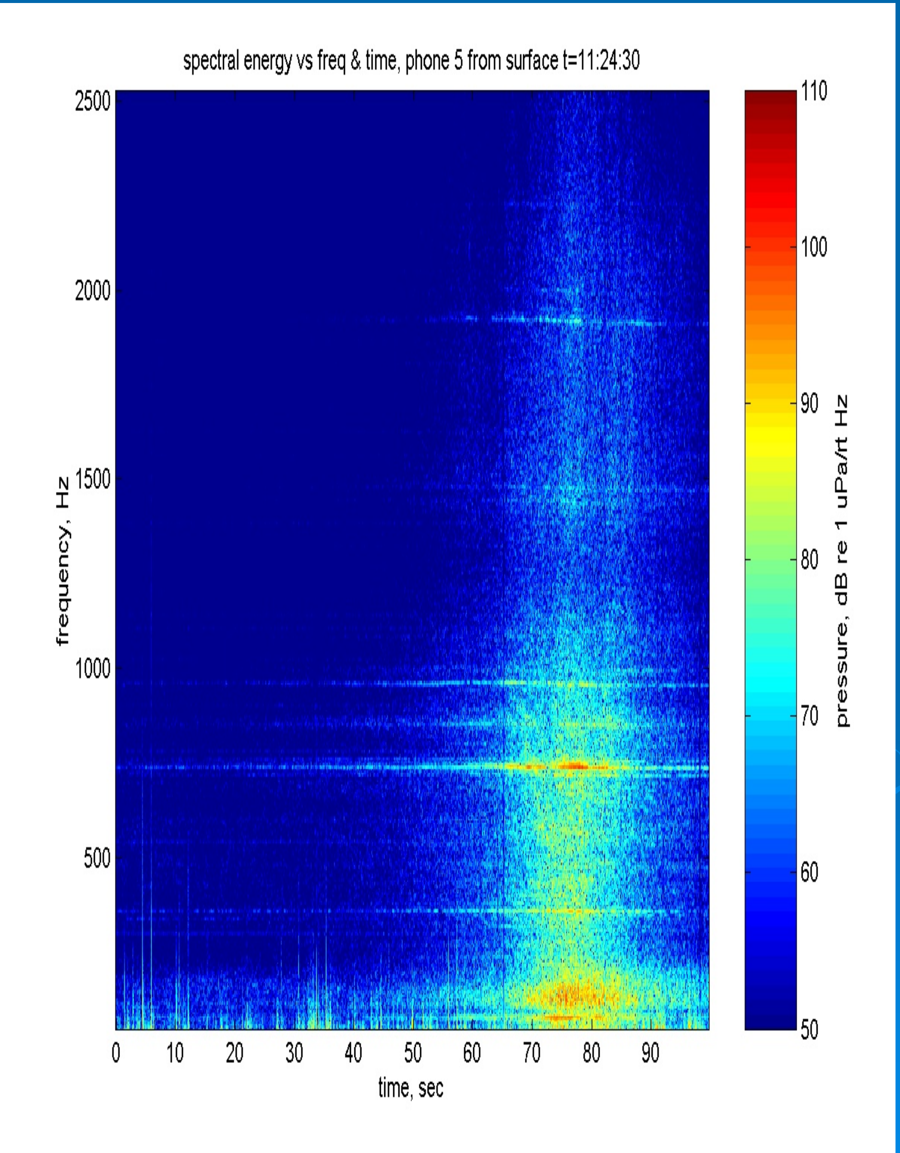




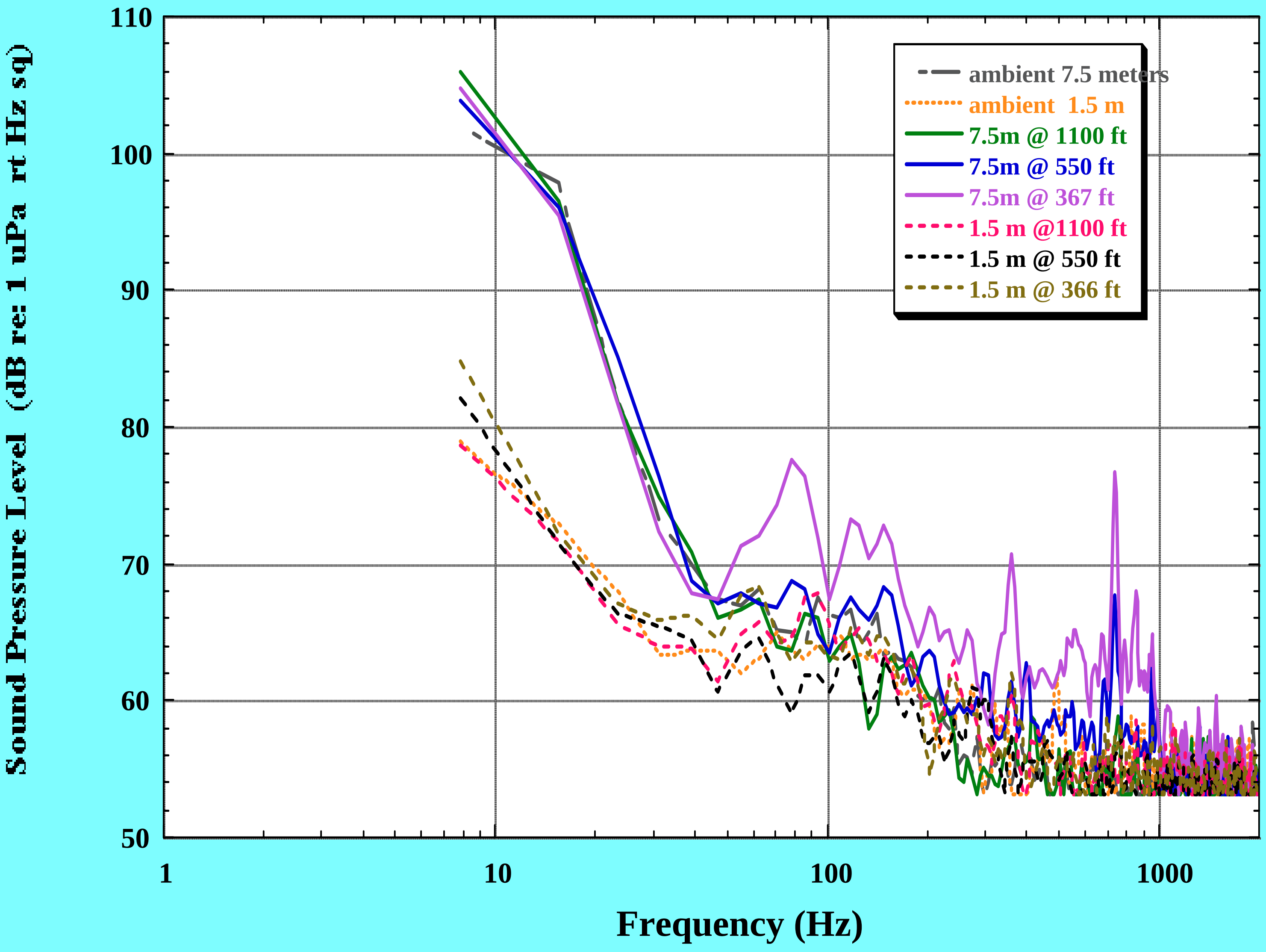

AUTEC
U.S. NAVY
RANGE ROVER

Spectral energy vs. frequency & time
1.5meters and 7.5 meters

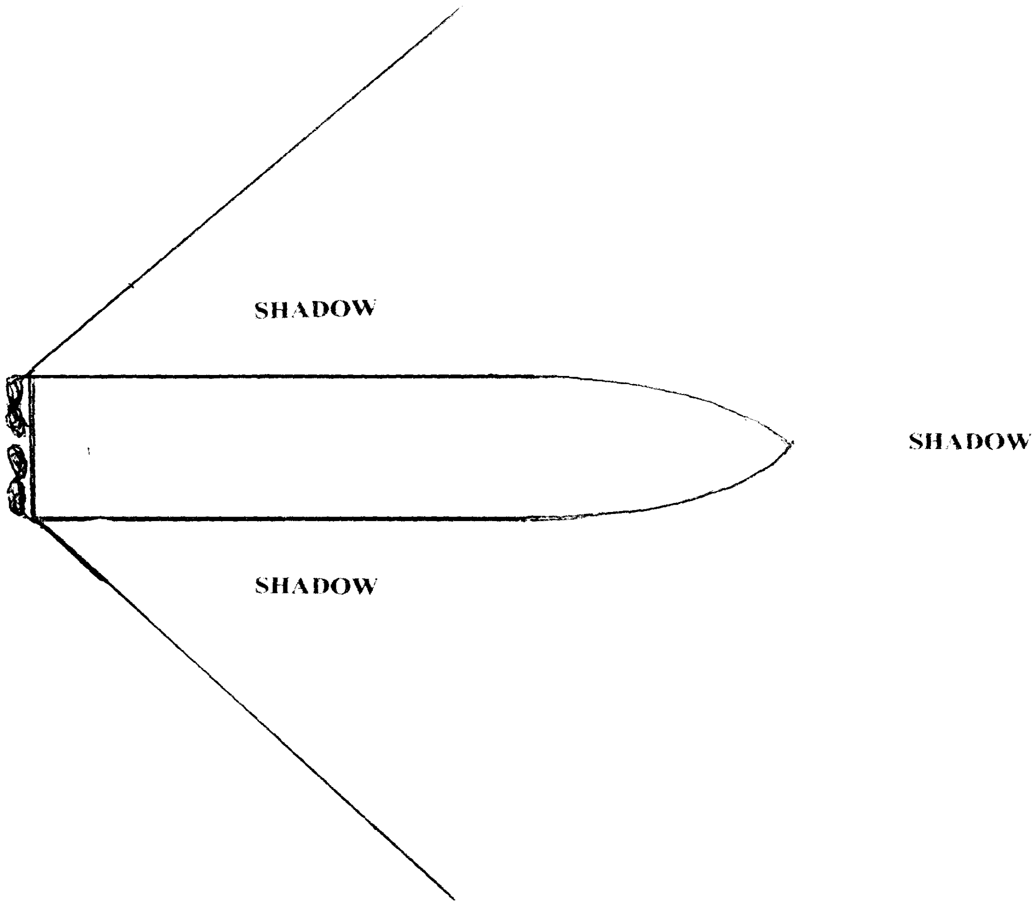




1.5 m and 7.5 m surface



Acoustic shadowing and diffraction

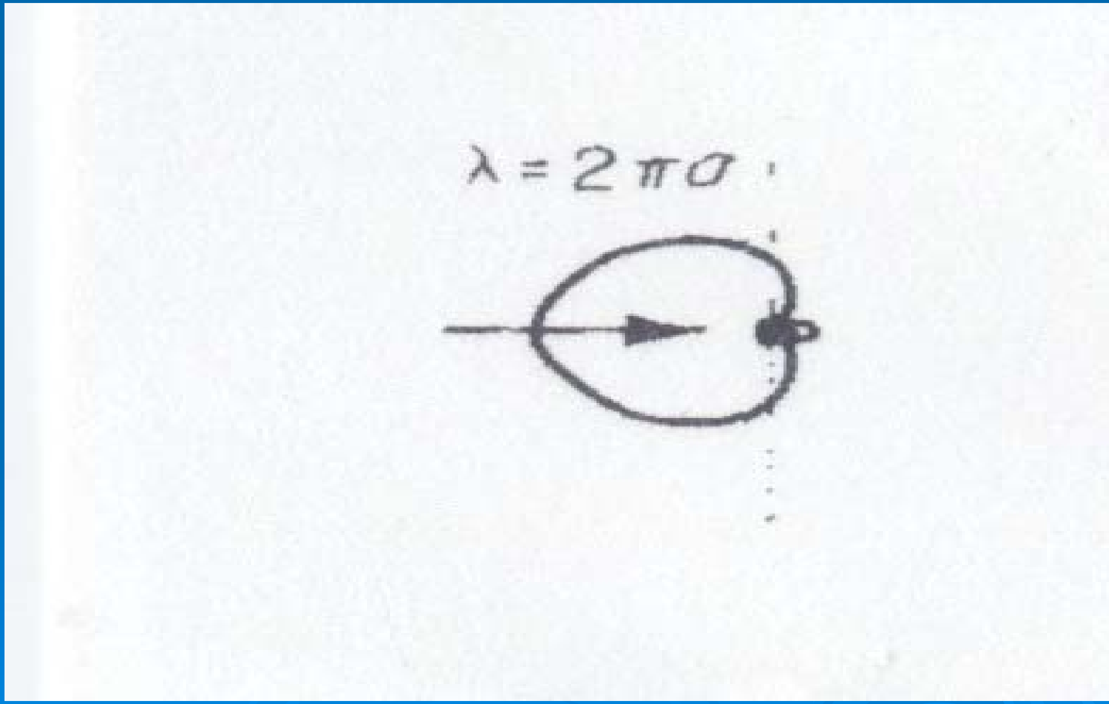


Diffraction illustration using sphere

Let 2a = w =beam of a ship

For w = 20 m, λ = 20π

Frequency = 24 Hz

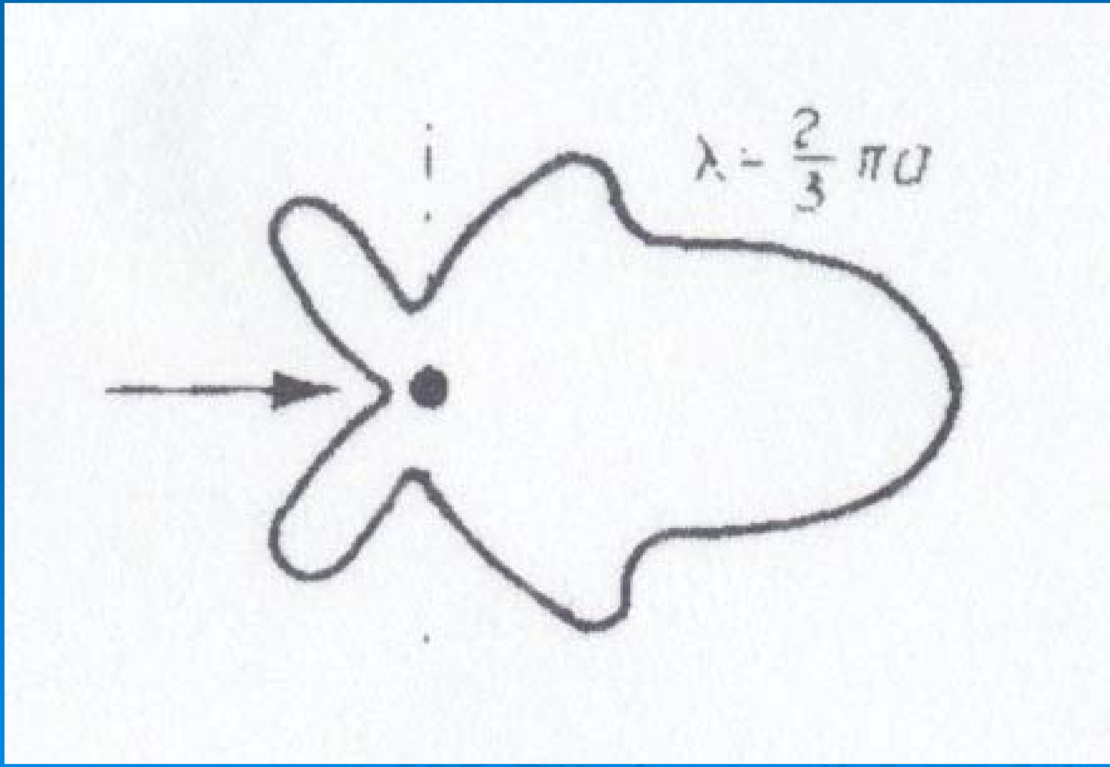


Diffraction illustration using sphere

Let 2a = w =beam of a ship

For w = 20 m, λ = 20π

Frequency = 8 Hz

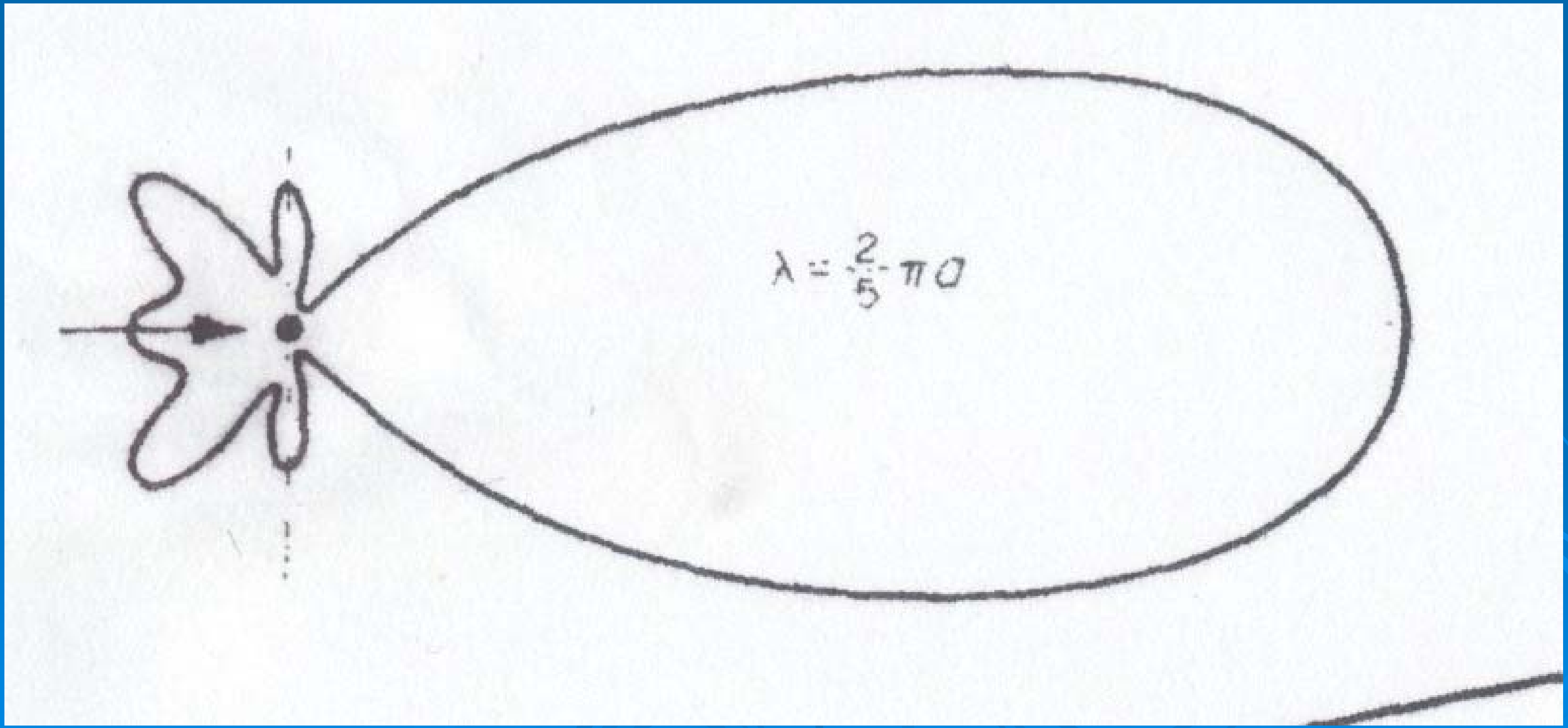


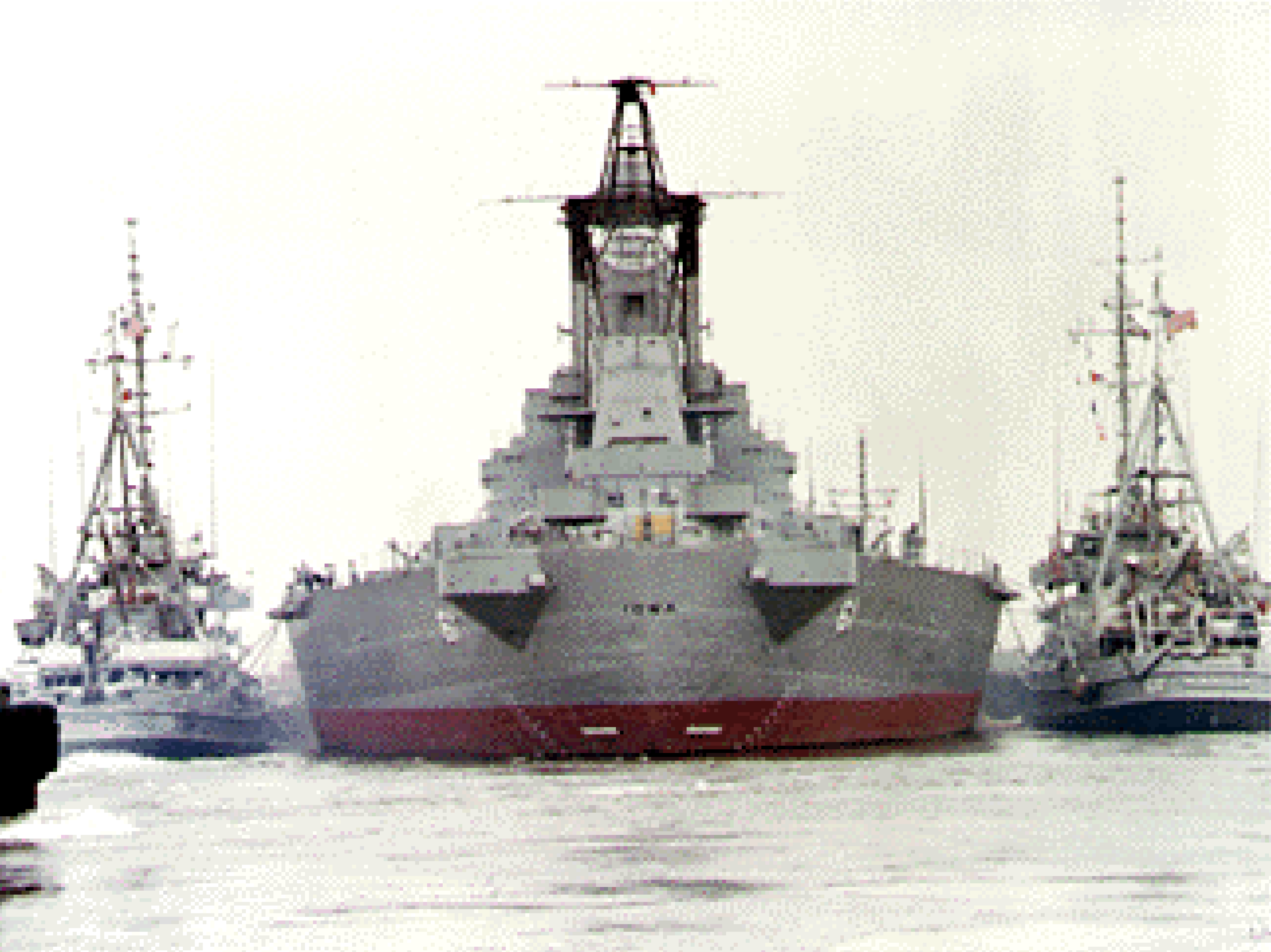
Diffraction illustration using sphere

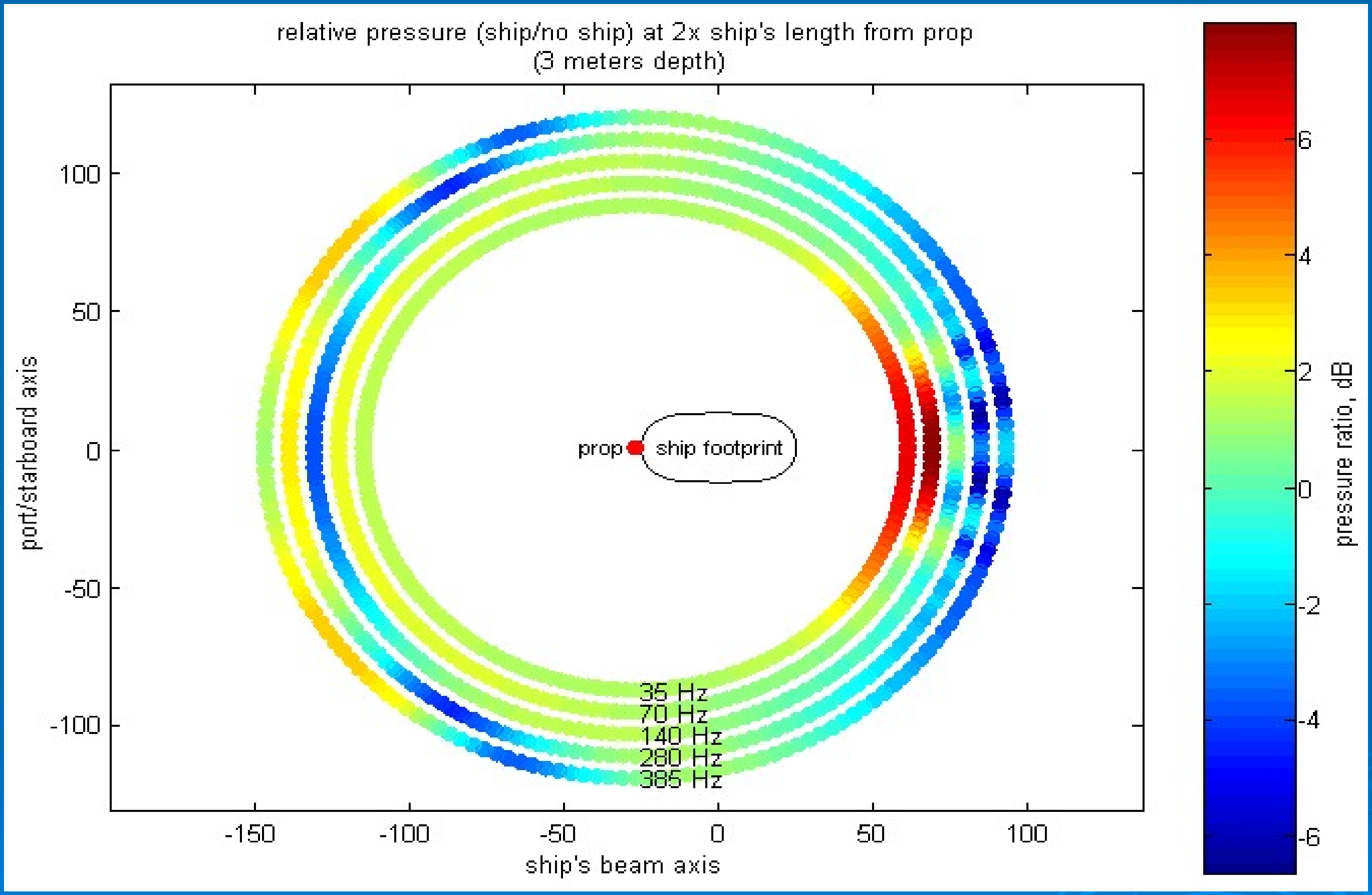
Let 2a = w =beam of a ship

For w = 20 m, λ = 20π

Frequency = 4.8 Hz





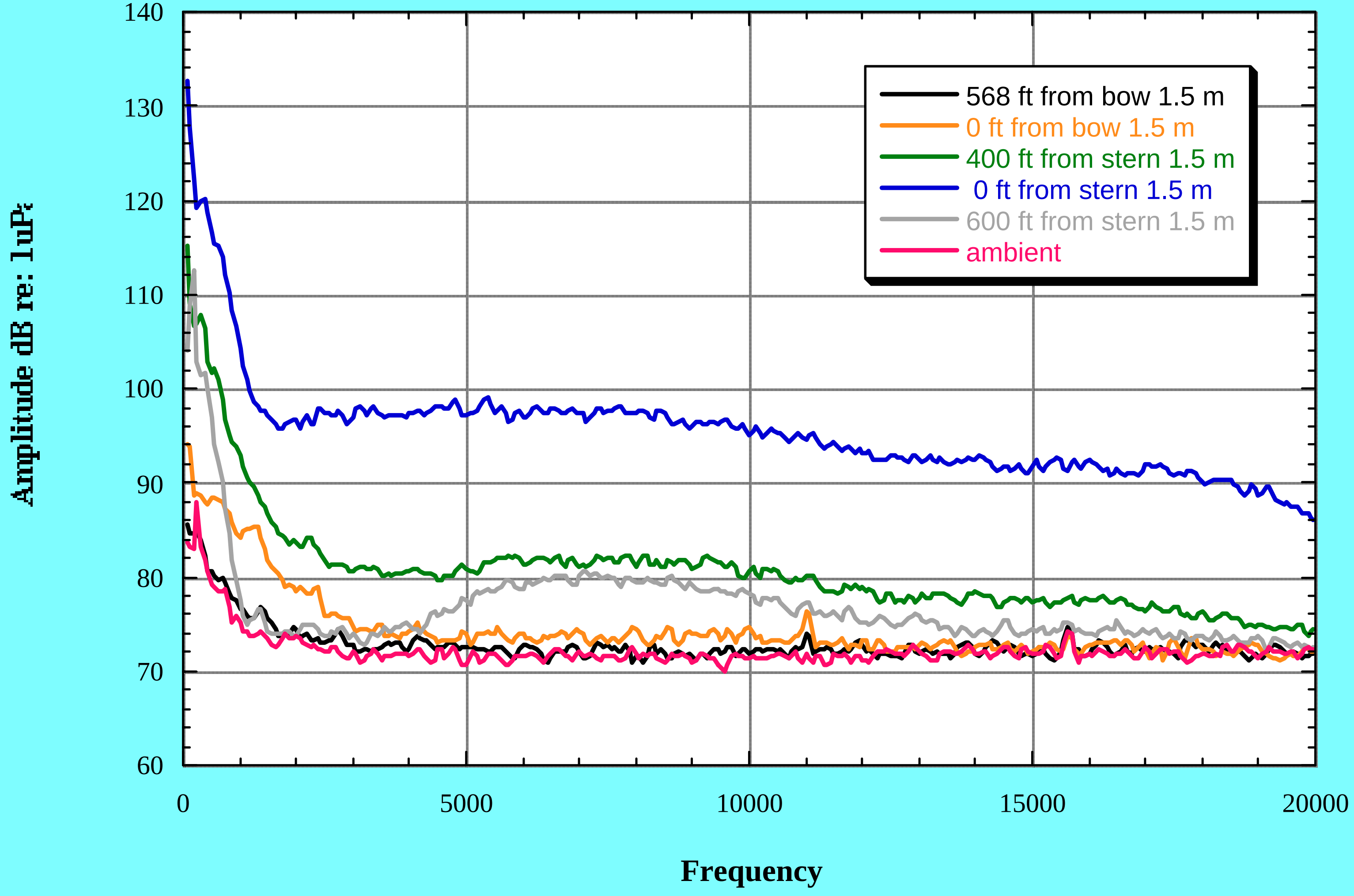


Pressure at 3 meters. Depth vs. horizontal angle for several frequencies. All distances are to scale. The ship is a blunted ellipsoid 50 meters long, 25 meters wide, and 12.5 meters deep (shown to scale). The prop is at half of the hull depth (6.25 meters) and 2 meters behind the stern end of the ship.

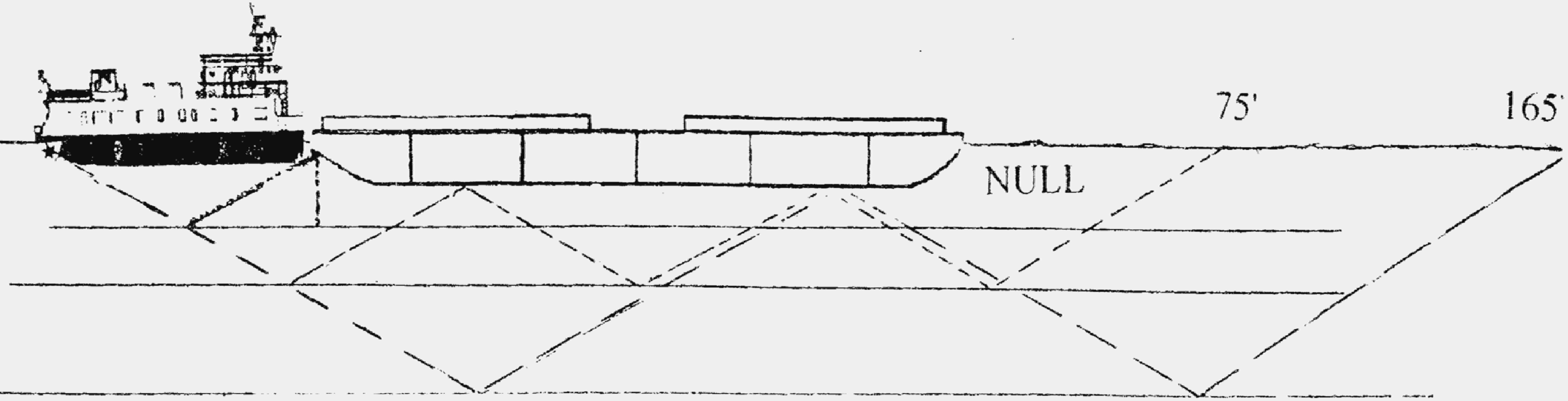
Disney Fantasy

855’ length, 103’ beam, 26’ draft, twin props variable pitch
12 KTS, surface recording depth 1.5 meters (distance 70’)

Acoustical shadowing
Disney Fantasy 12 KTS, 40’ depth, 73 degrees *F* isothermal

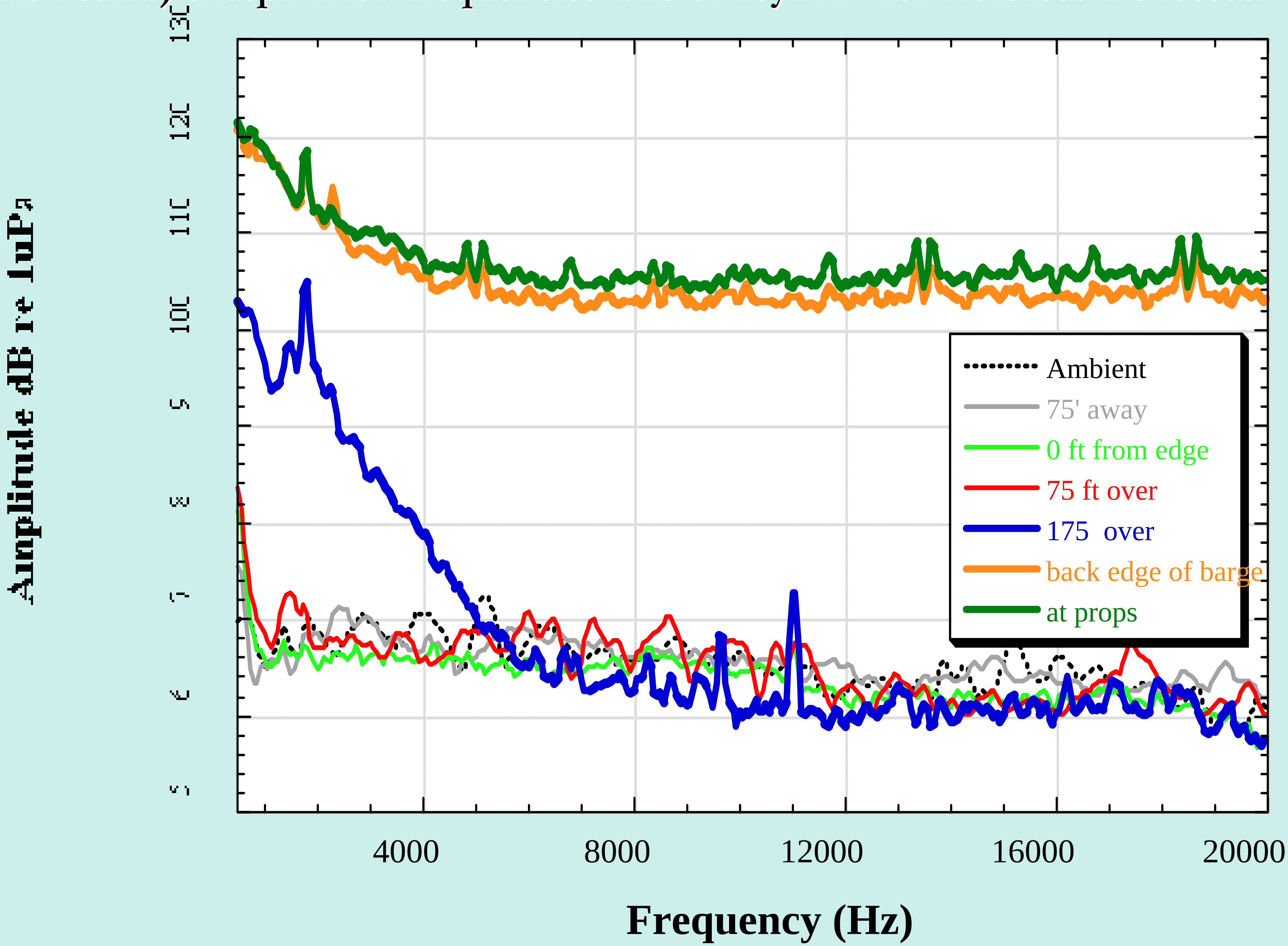


Manatee Challenges from Barge and Tug Acoustic Shadows 250'Barge 55' Beam & 60' Tug



Tilley Moran barge
4 KTS, full load, recording depth 2 meters

The spreading loss from the propellers to the bow of the barge is ~ 40 dB. If one subtracts 40 dB from the green or orange curves, one obtains levels near ambient black curve) except at low frequencies where Lloyd Mirror increases the losses.



Conclusions: Large Ships

- Spreading loss alone is sufficient to justify putting sound sources on the bow of large ships (>80-m long).
- The Lloyd Mirror Effect prevents very low frequency sounds that can diffract around ships from being heard near the surface
- Acoustic shadowing on ships with props above keel level alone is sufficient to justify putting sound sources on large ship bows.
- The confluence of the effects of spreading, shadowing and Lloyd Mirror make it very difficult for whales to hear large ships with props above keel level.

WHAT ABOUT MANATEES & BOATS ?

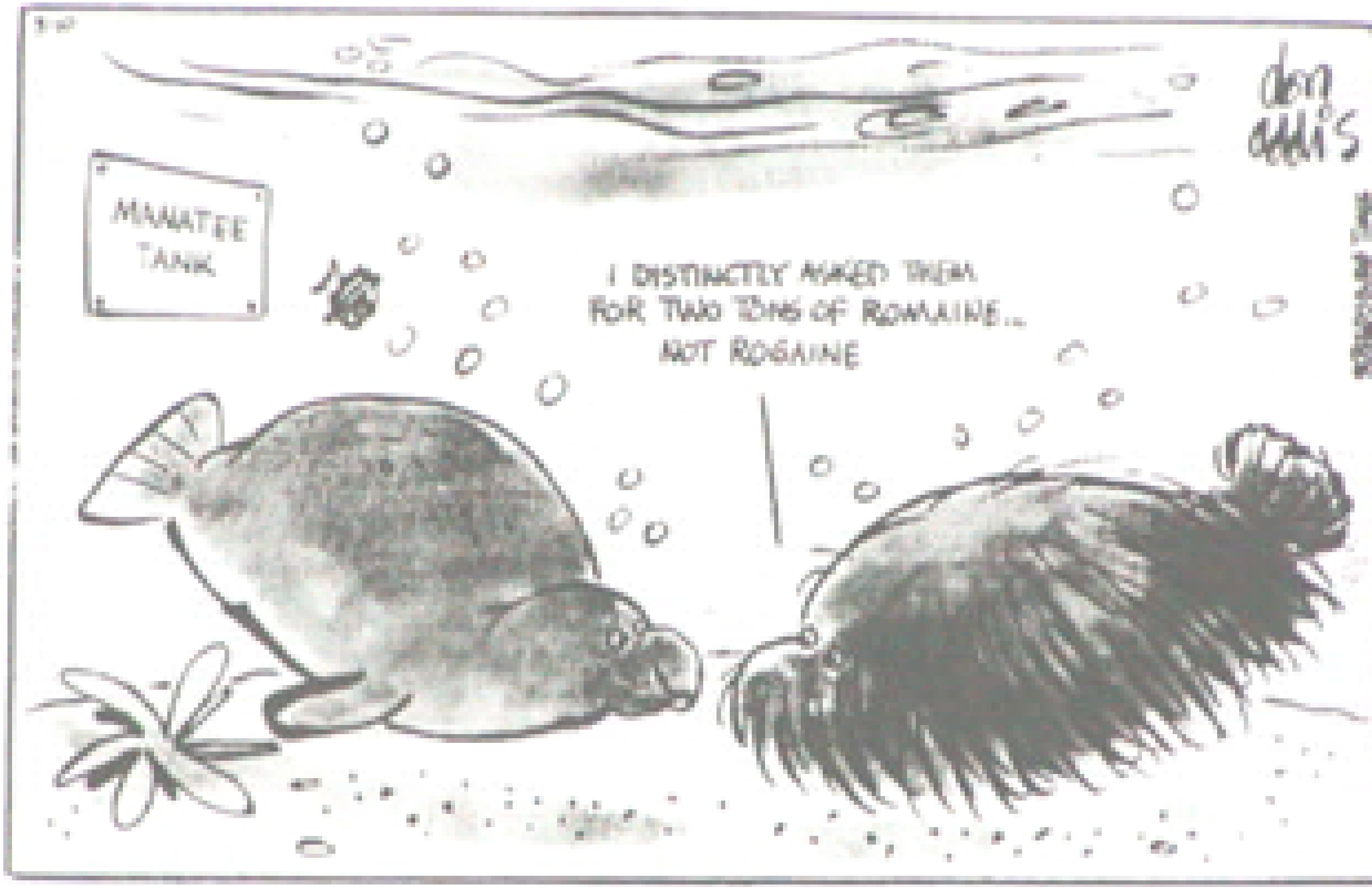
Basic Questions:

- Why Are Individual Manatees Hit Repeatedly by Boats?
- After They Have Been Hit Once, Twice, or Three Times Why Don't They Learn to Avoid Boats Better?
- Are Manatees Aware Danger Is Present?
- Can They Hear the Boat Approaching -- and if so -- from How Far Away and from Which Direction?

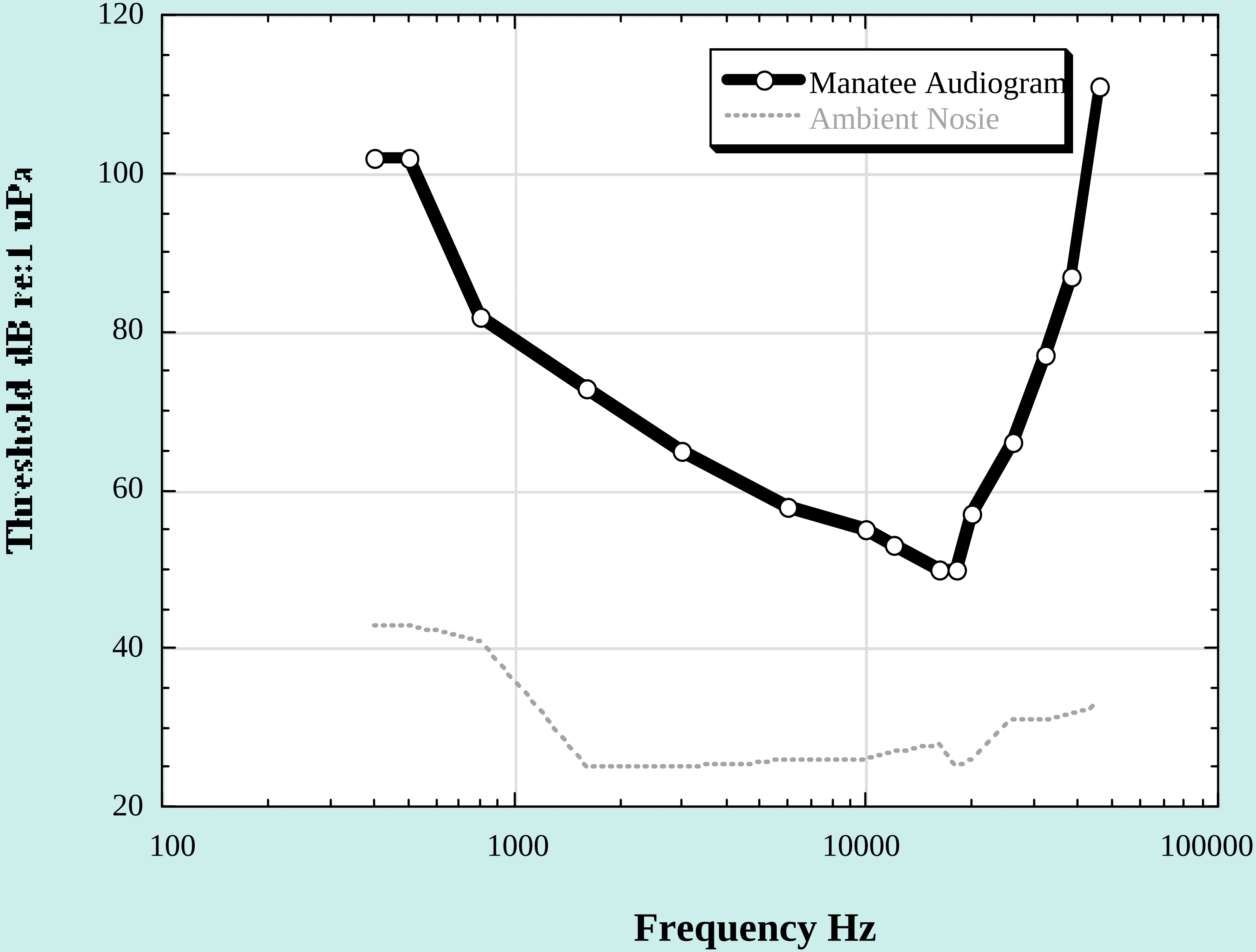
Research Questions:

- What Is the Overall Hearing Range and Capability of Manatees?
- What Frequencies and Amplitudes Can They Hear Best?
- How Is Their Hearing Affected by Background Noise?
- How Well Can They Localize Sounds Underwater?

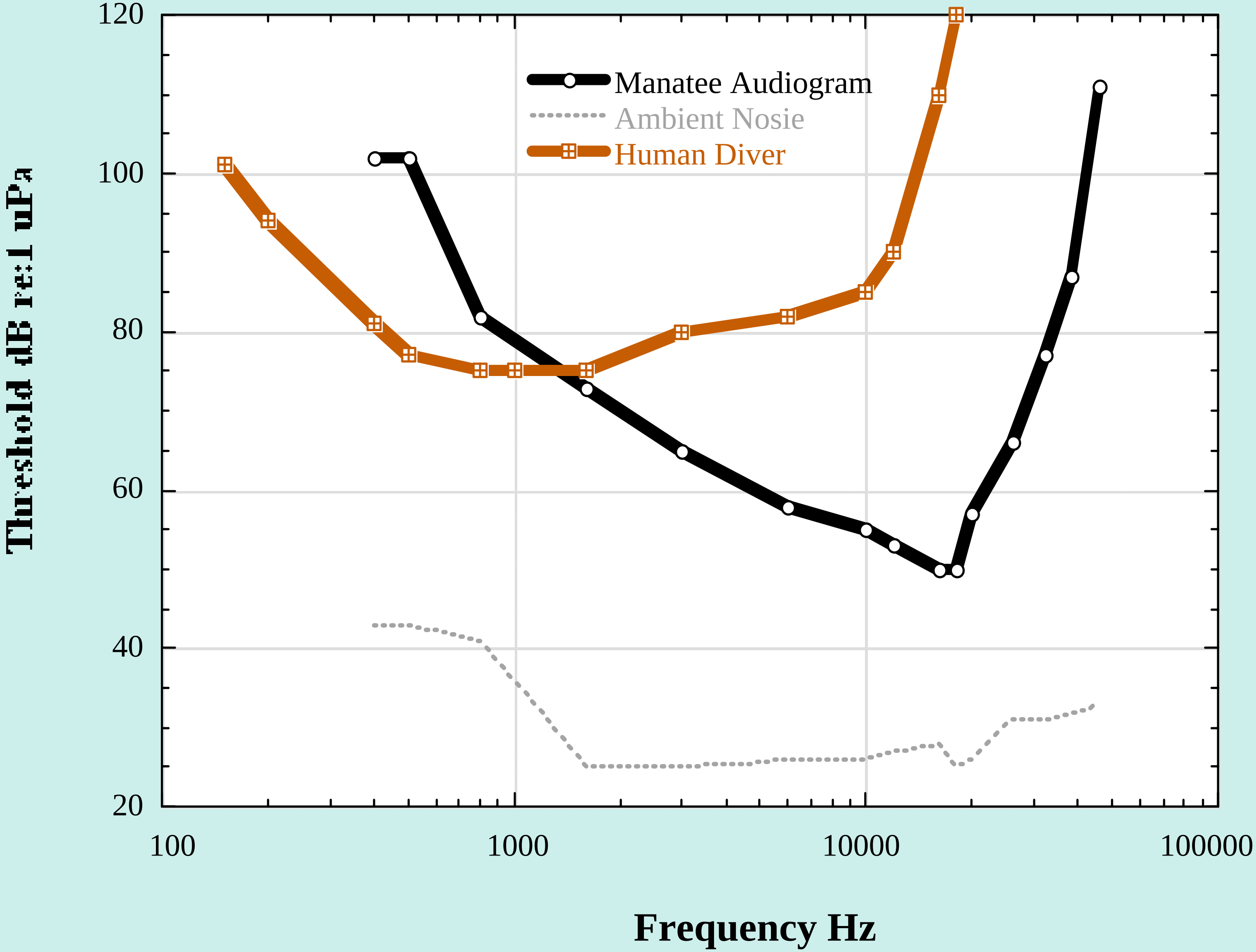
■ Don Addis


MANATEE
TANK
I DISTINCTLY ASKED THEM
FOR TWO TONS OF ROMAINE...
NOT ROGAINE
don addis

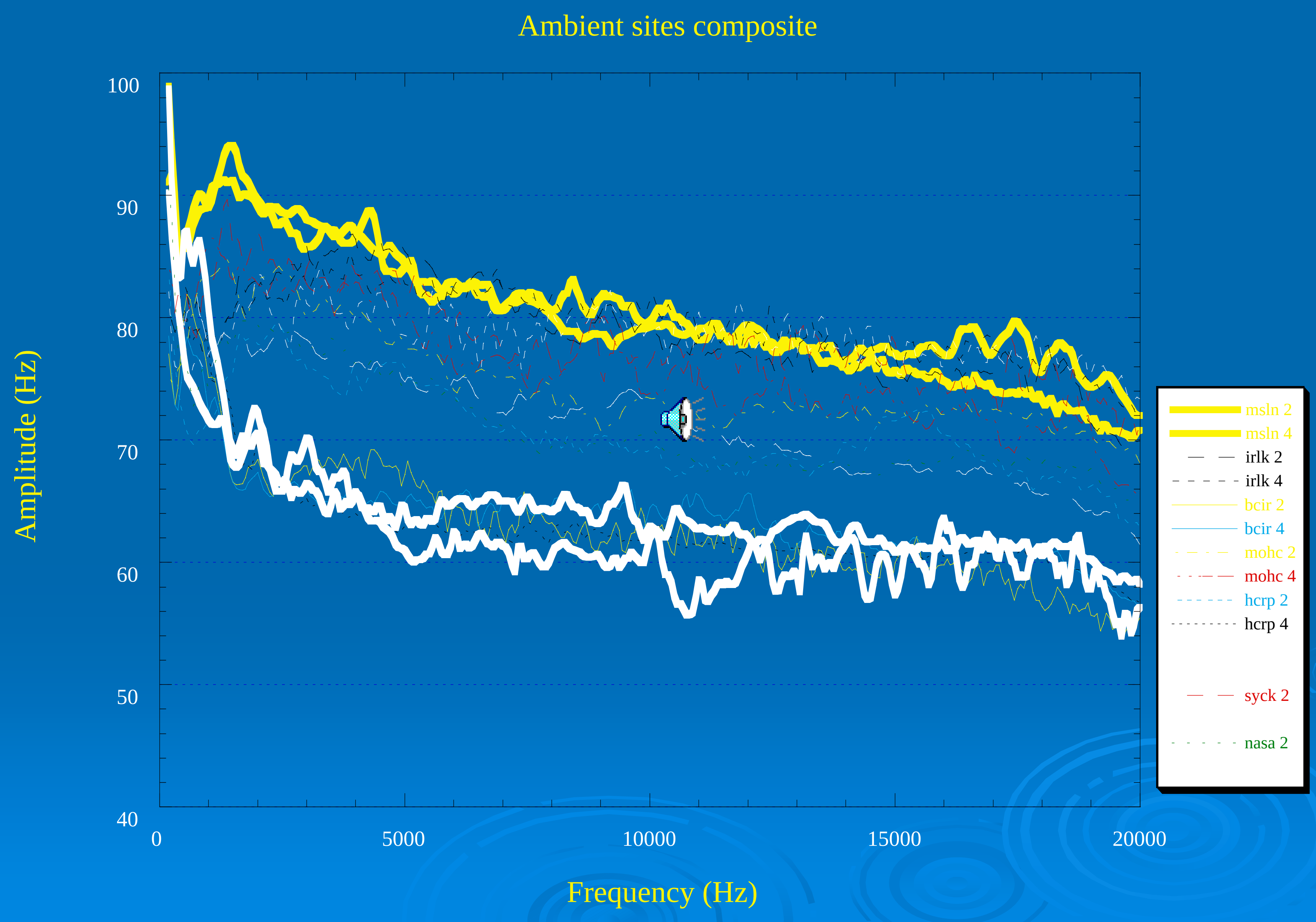

TO TEST A
MANATEE'S
HEARING



120
100
80
60
40
20
100
1000
10000
100000
Manatee Audiogram
Ambient Nosie
Threshold dB re:1 uPa
Frequency Hz

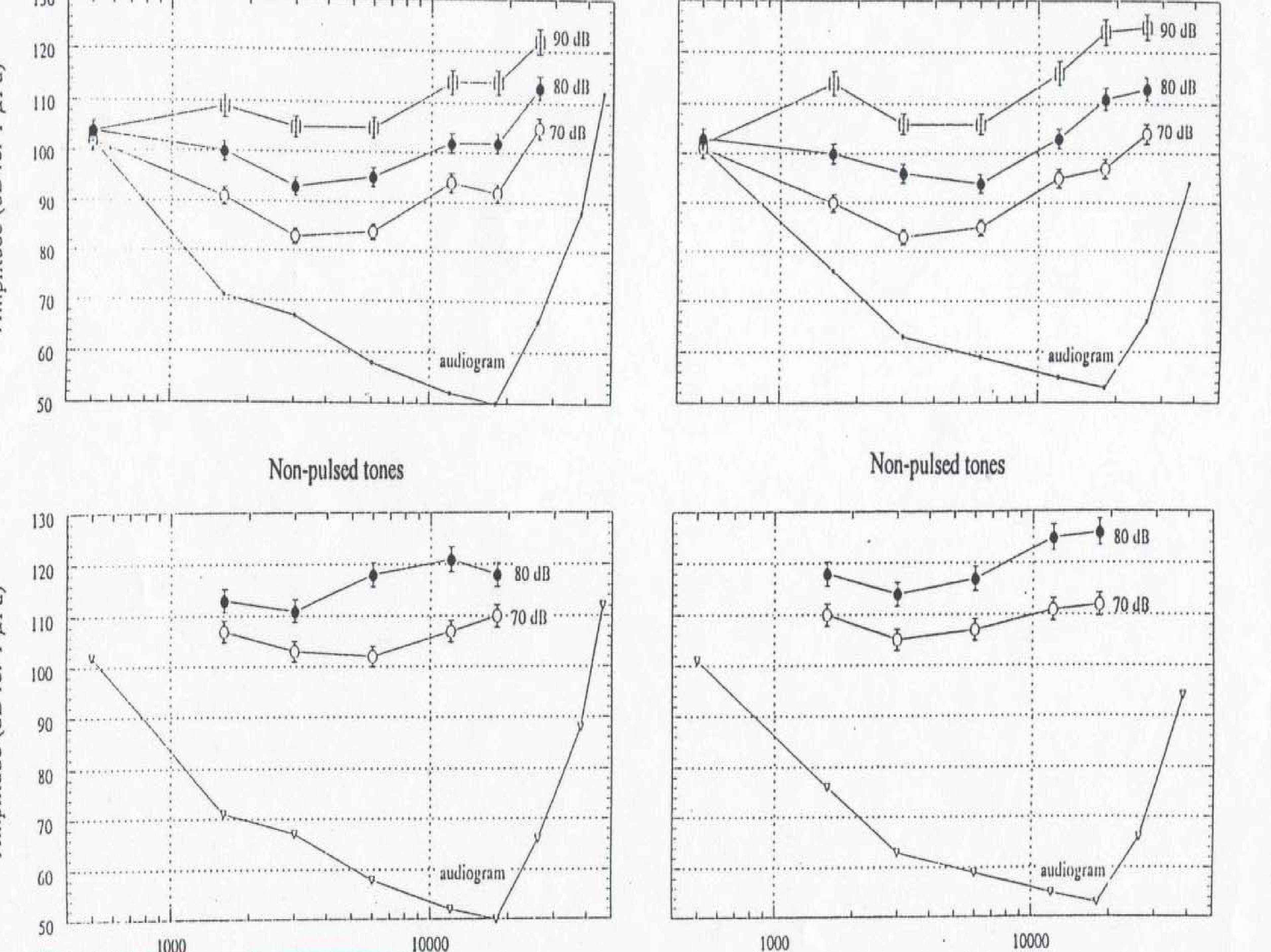


Threshold dB re:1 uPa
120
100
80
60
40
20
Manatee Audiogram
Ambient Nosie
Human Diver
100
1000
10000
100000
Frequency Hz


Ambient sites composite
Amplitude (Hz)
Frequency (Hz)
100
90
80
70
60
50
40
0
5000
10000
15000
20000
msln 2
msln 4
irlk 2
irlk 4
bcir 2
bcir 4
mohc 2
mohc 4
hcrp 2
hcrp 4
syck 2
nasa 2

Five Psychoacoustic Tests

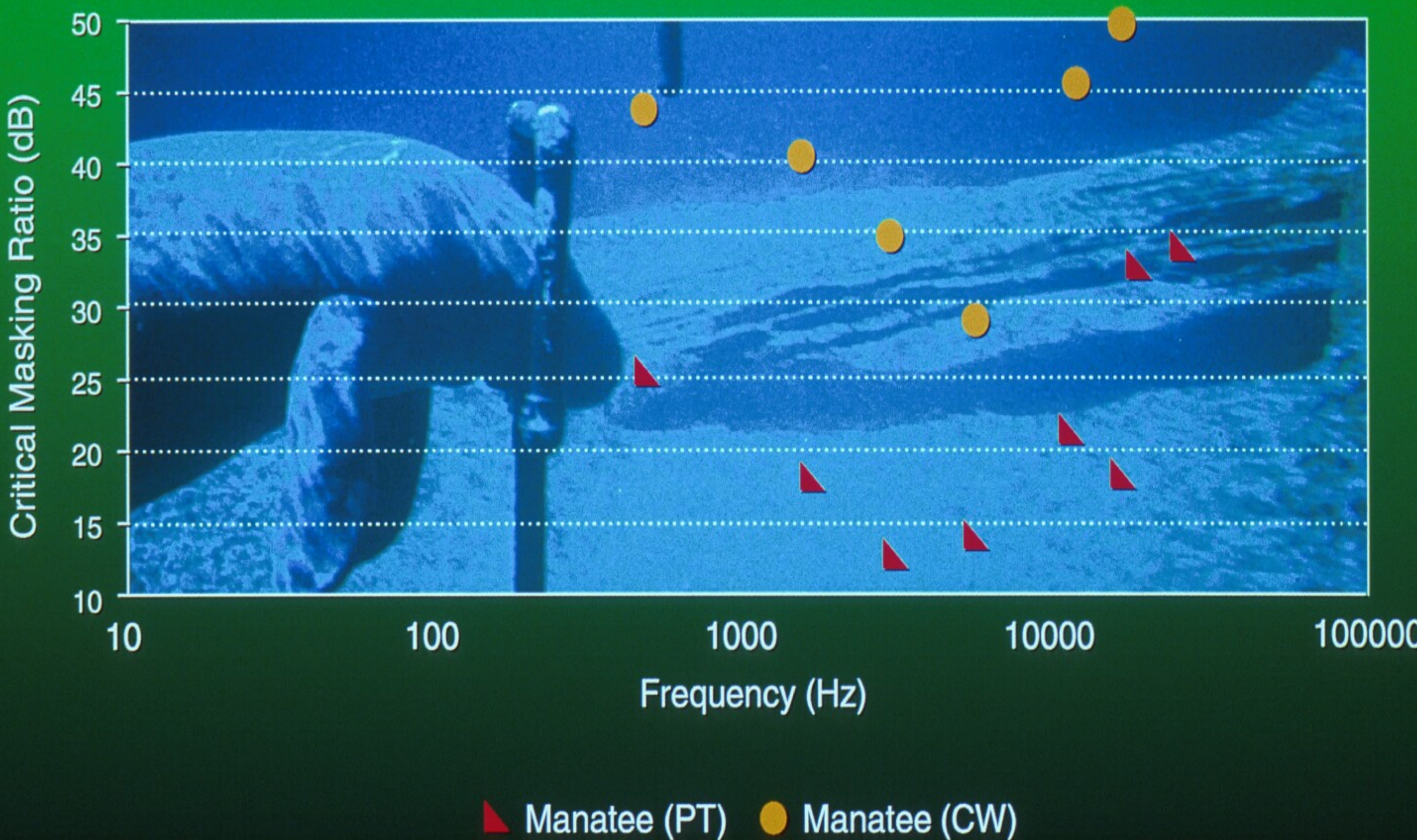
- Masked Thresholds: pulsed and continuous pure tones with 1/3 octave noise
- Masked Thresholds: pulse repetition, pure tones with broadband noise
- Masked Thresholds: complex FM tones with broadband noise
- Masked Thresholds: environmental sounds with broadband noise
- Directional Hearing: clicks with broadband noise



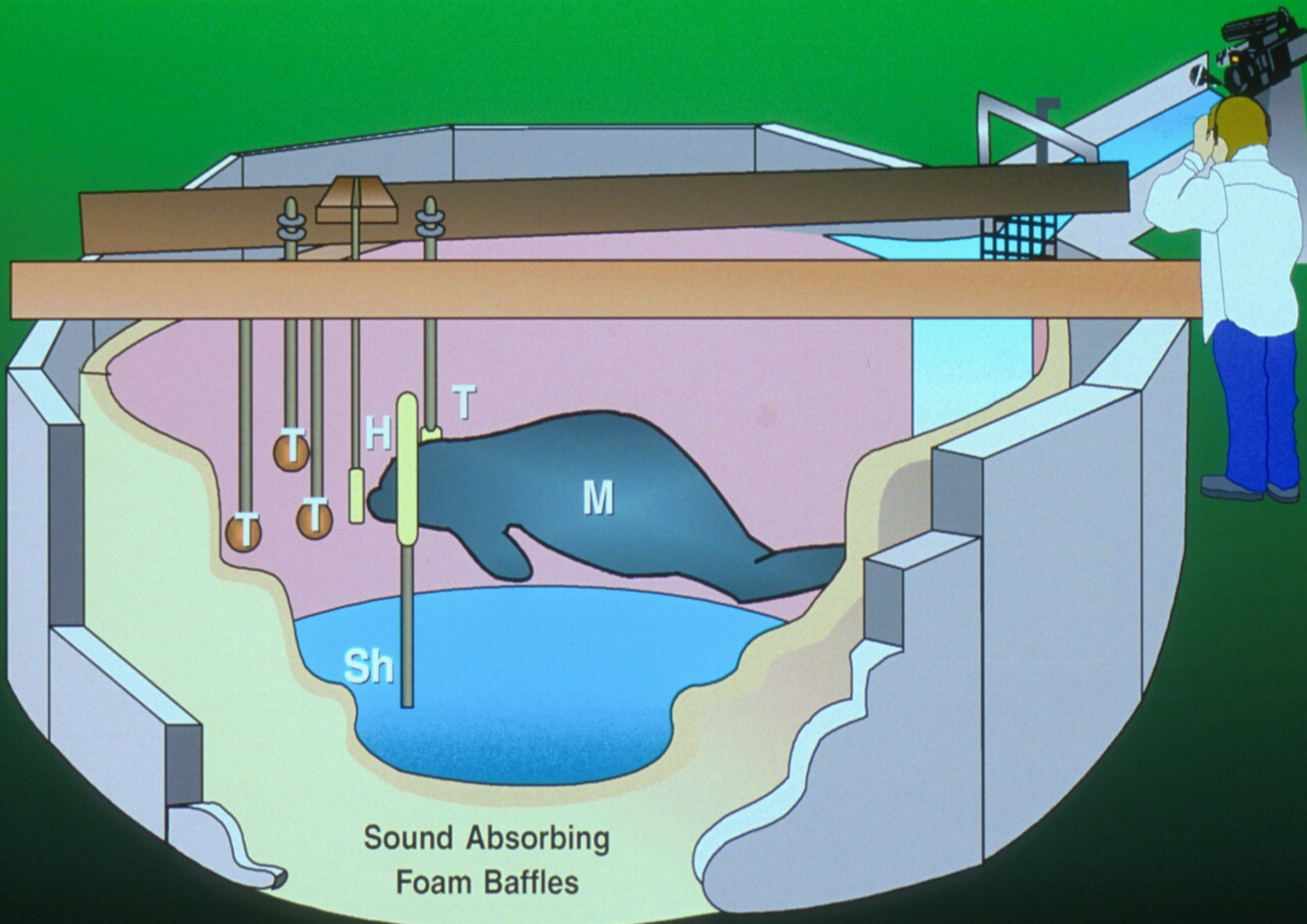
90 dB
80 dB
70 dB
audiogram
Non-pulsed tones
Non-pulsed tones
80 dB
70 dB
audiogram
130
120
110
100
90
80
70
60
50
1000
10000

Manatee Critical Masking Ratios

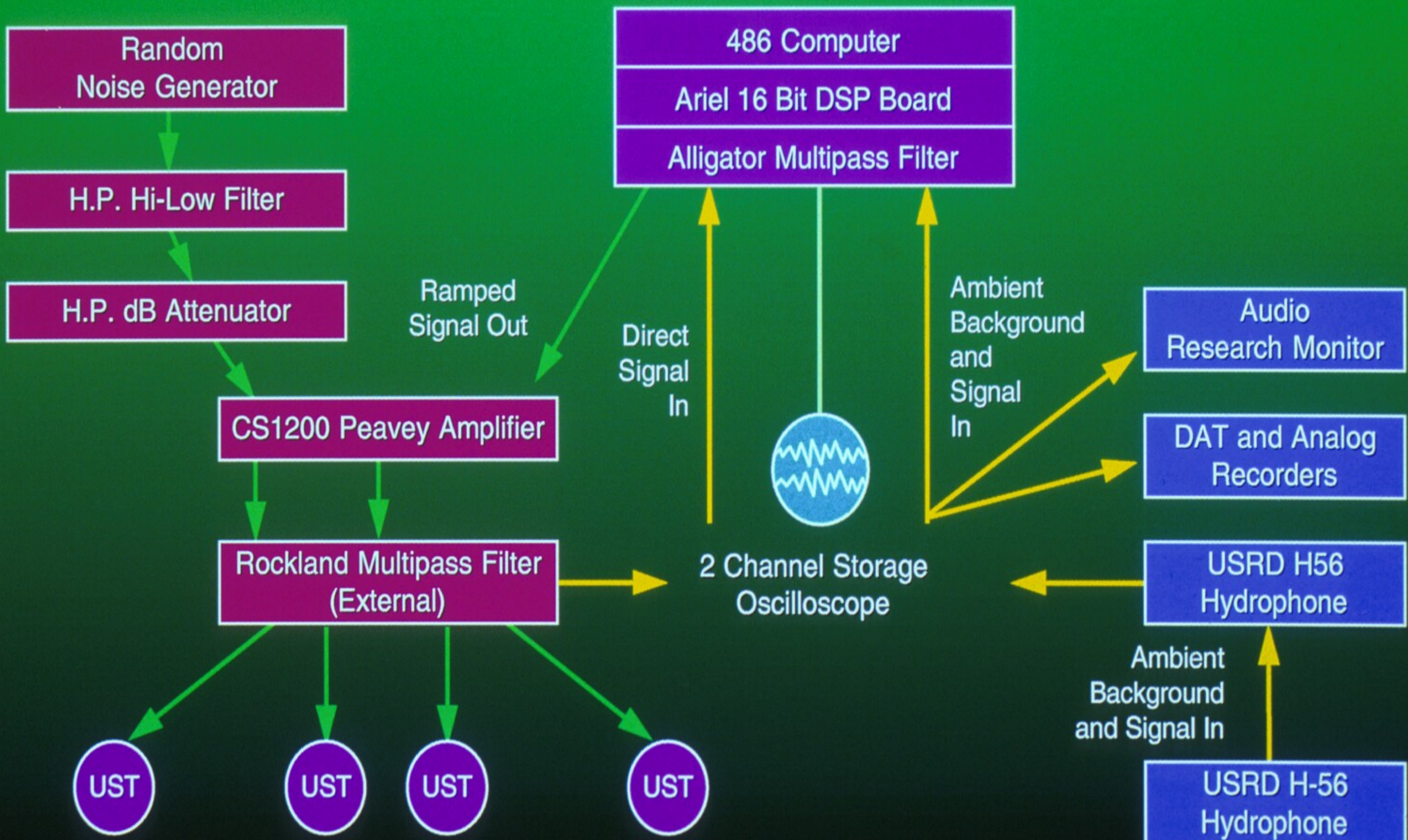
Pulsed and Continuous Wave Signals Against White Noise

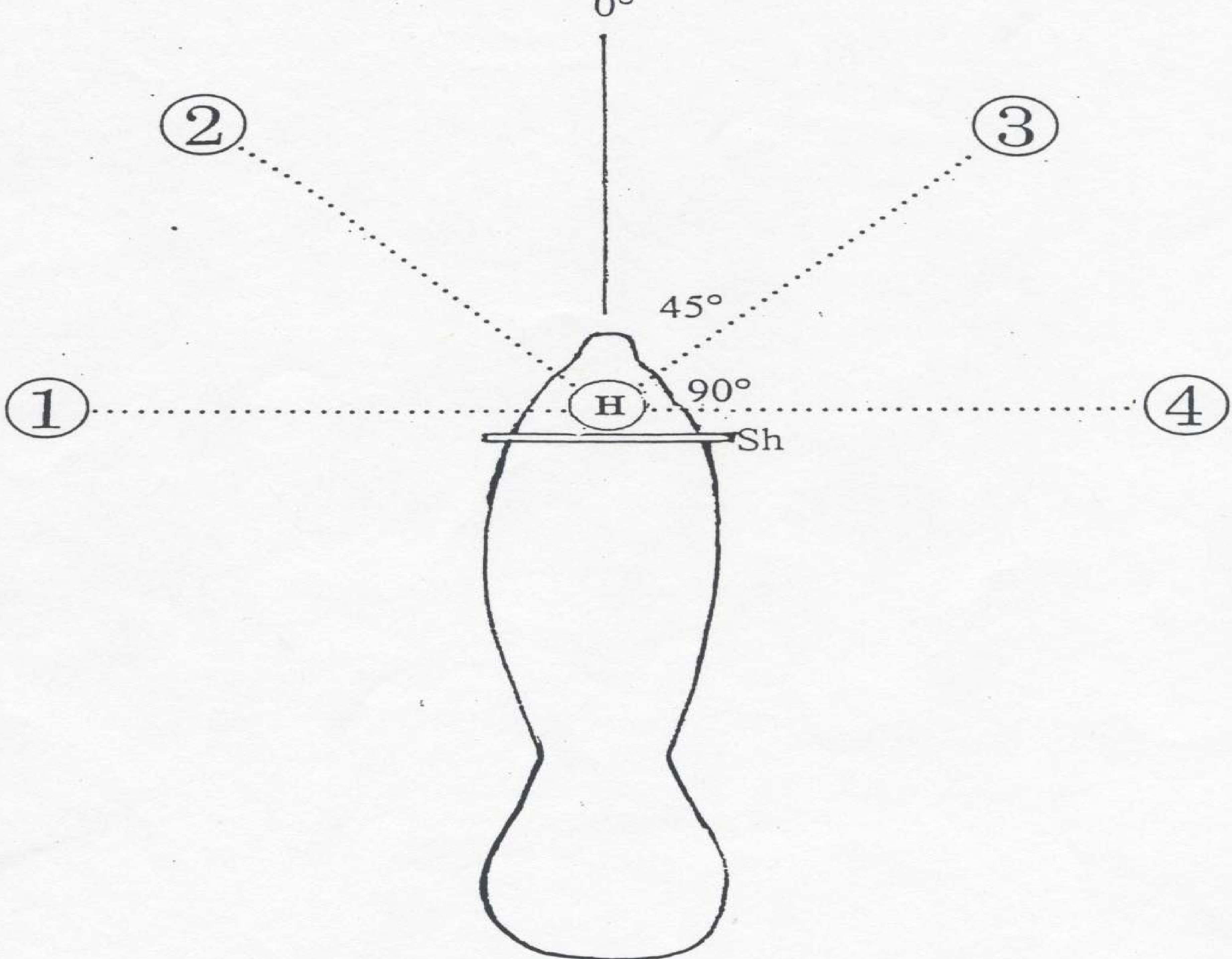


Directional Sensitivity



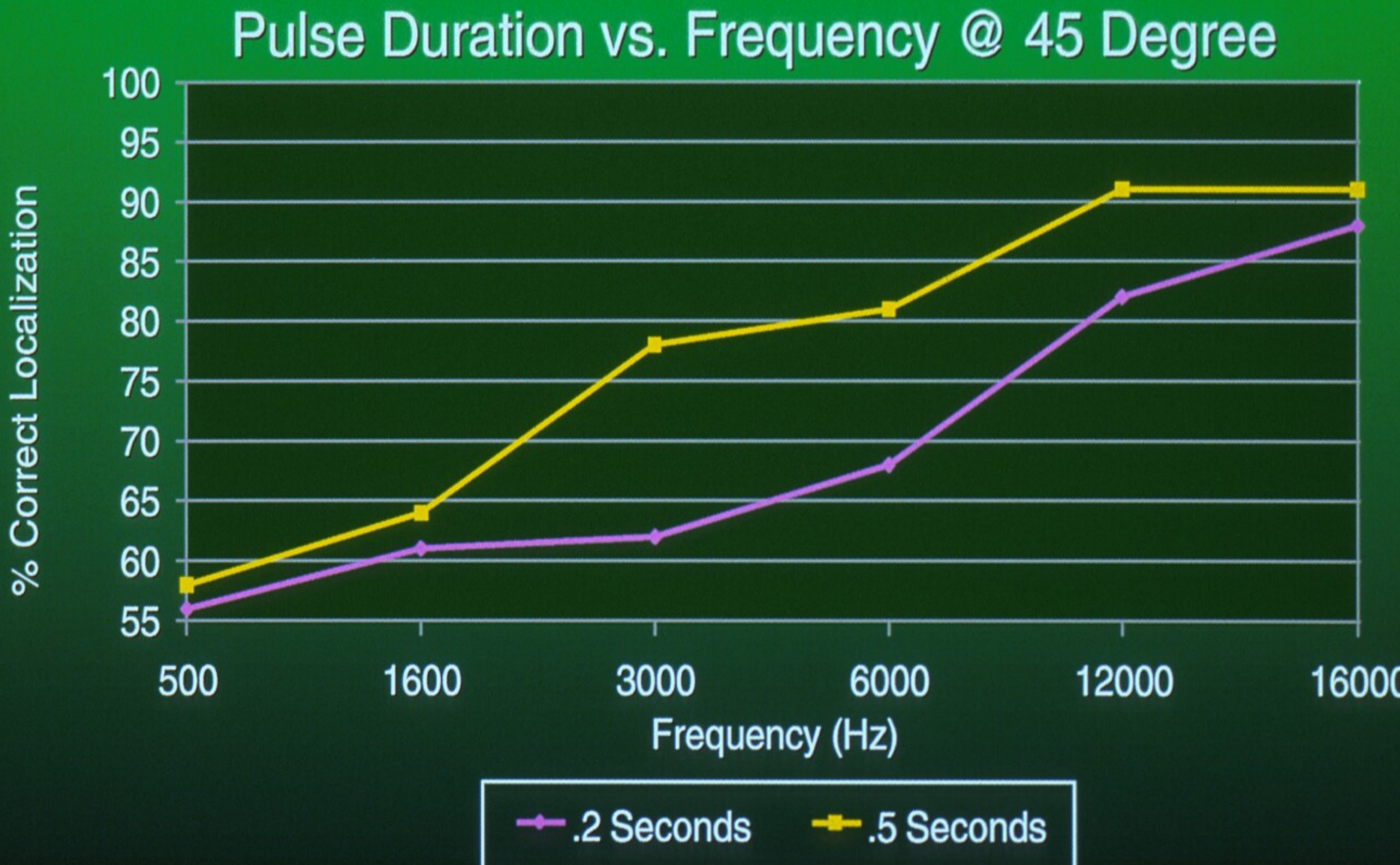
Flow Diagram of Signal Generation and Simultaneous Recording During Directional Sensitivity





0°
2
3
45°
90°
1
H
4
Sh

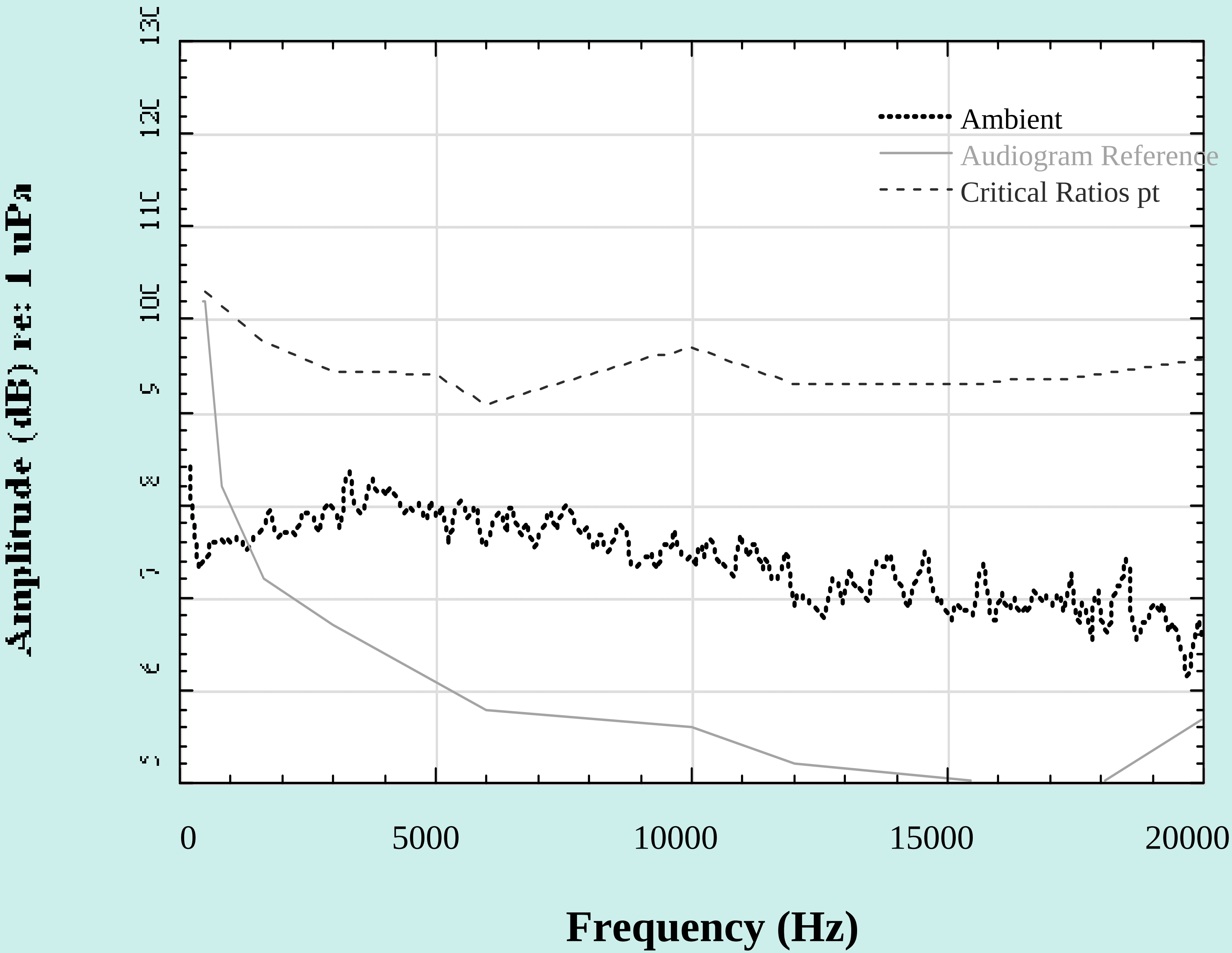
Directional Sensitivity



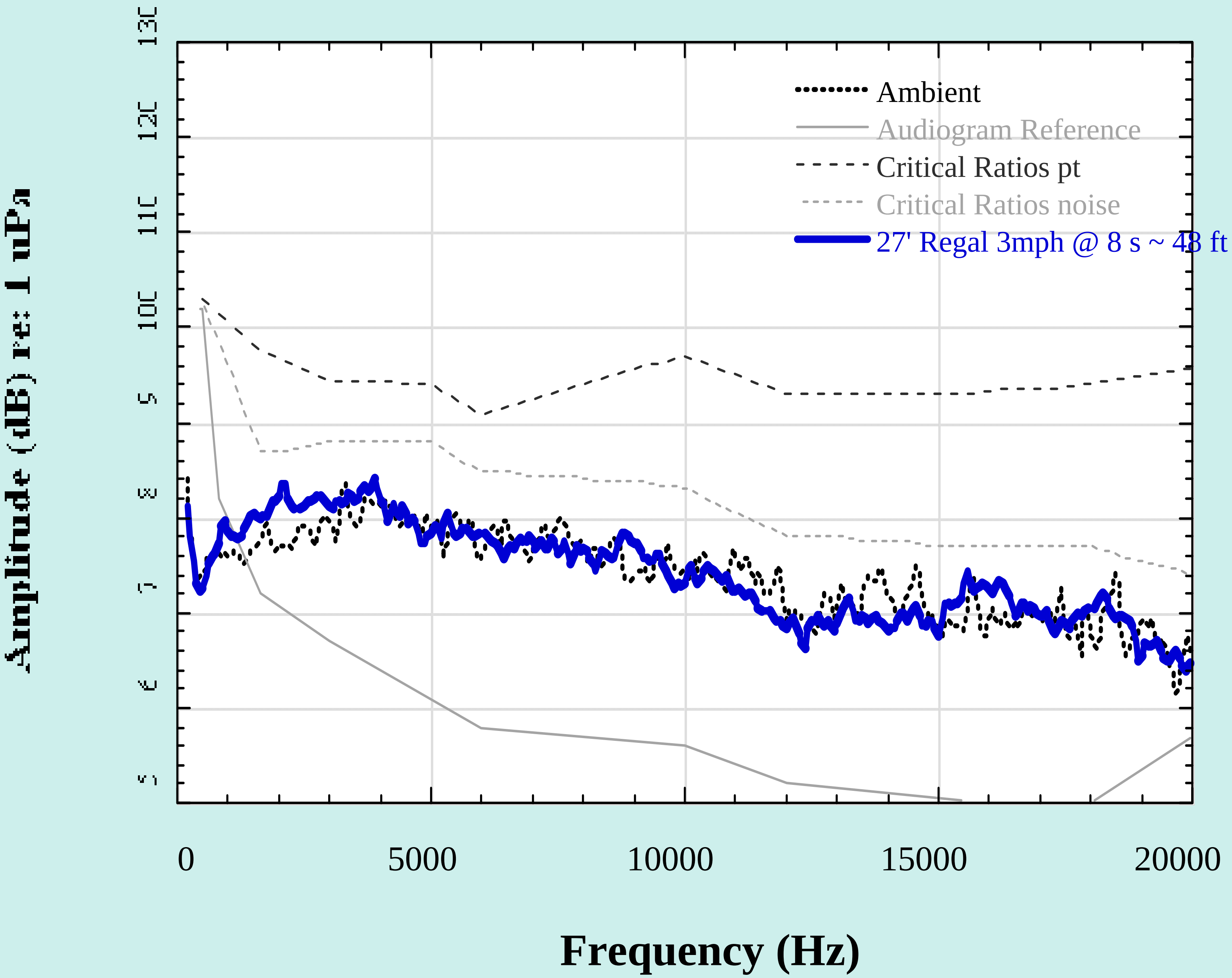
27' Regal 3.5 mph

27’ Regal 24 mph

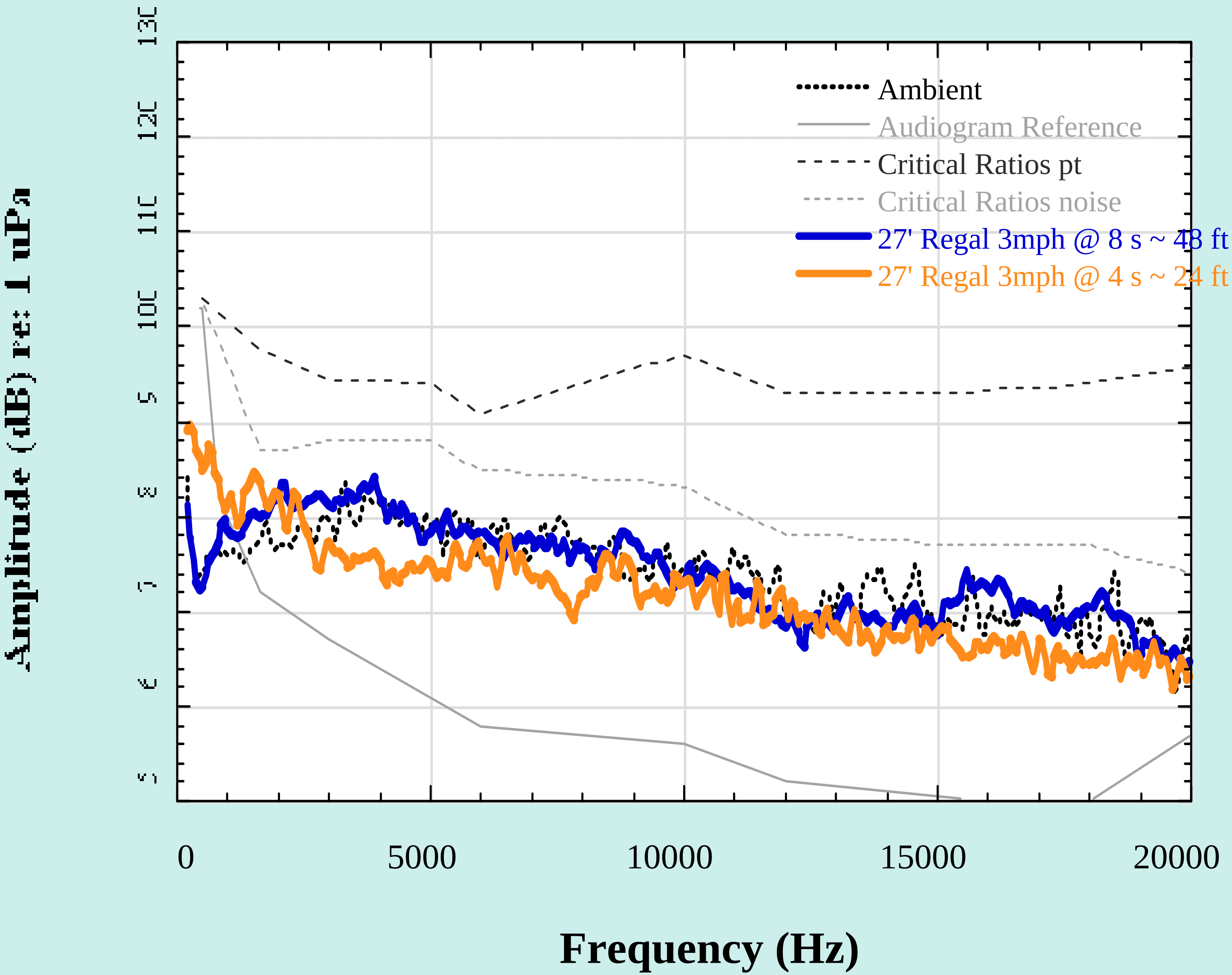
27 ft Regal series



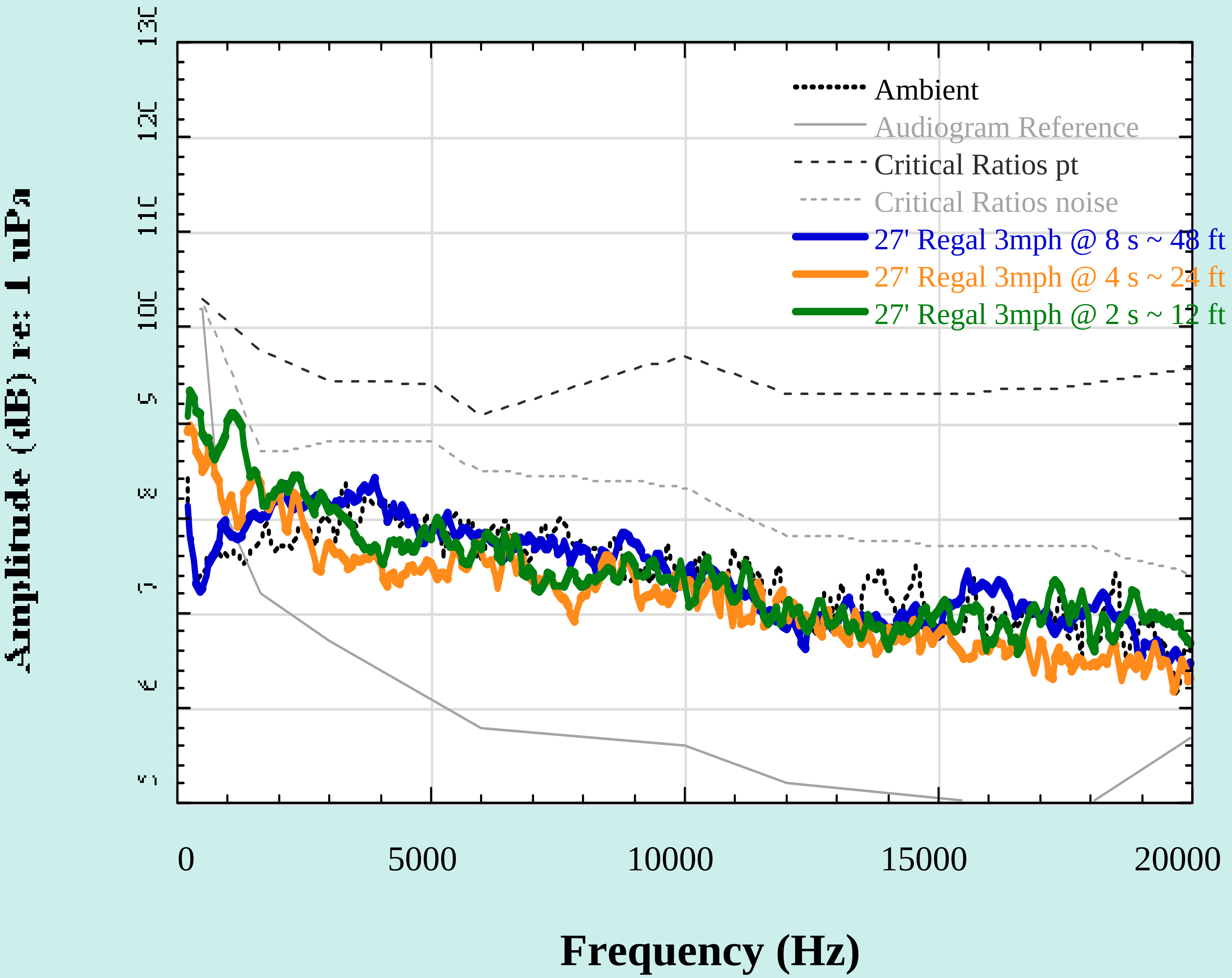
27 ft Regal series



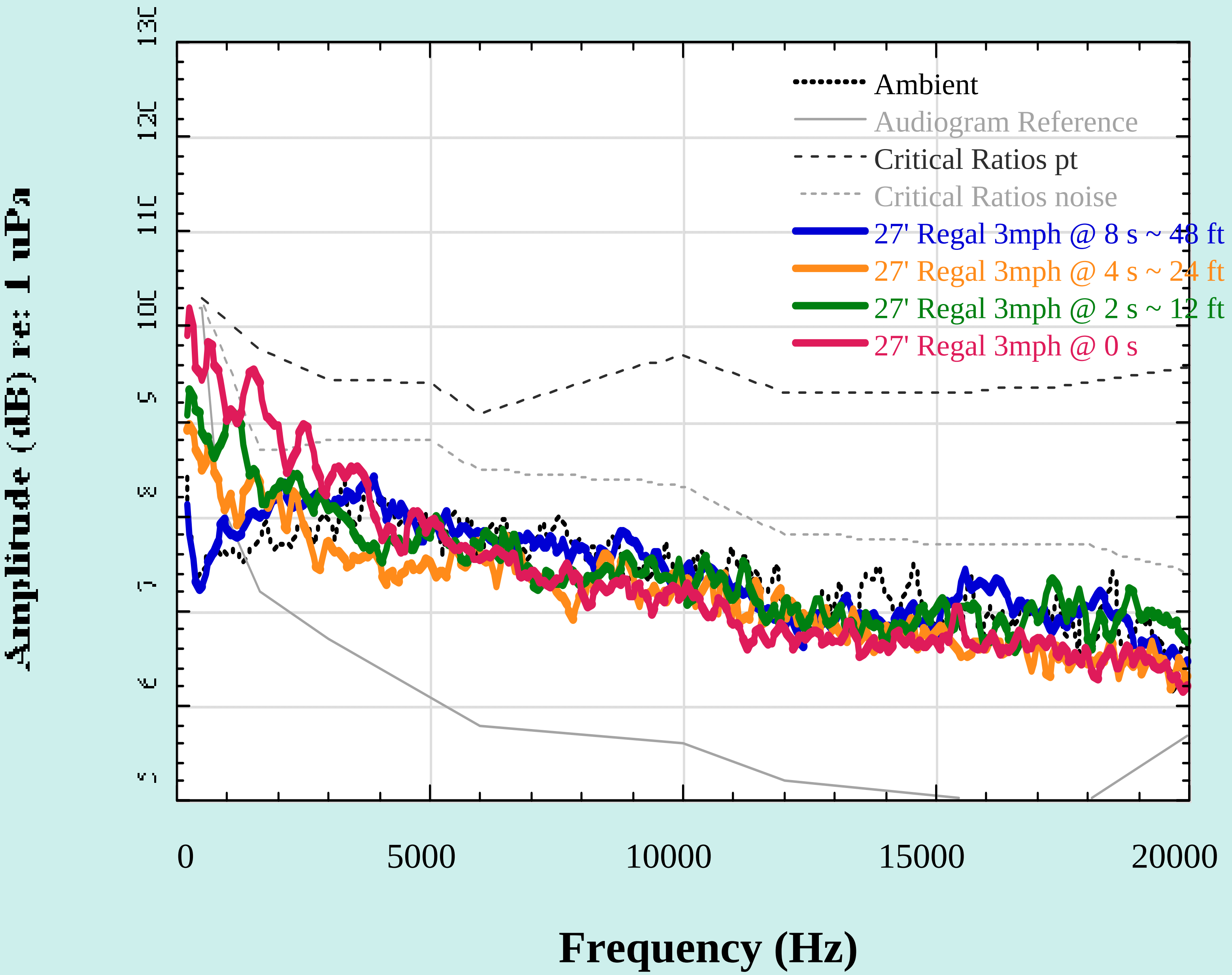
27 ft Regal series



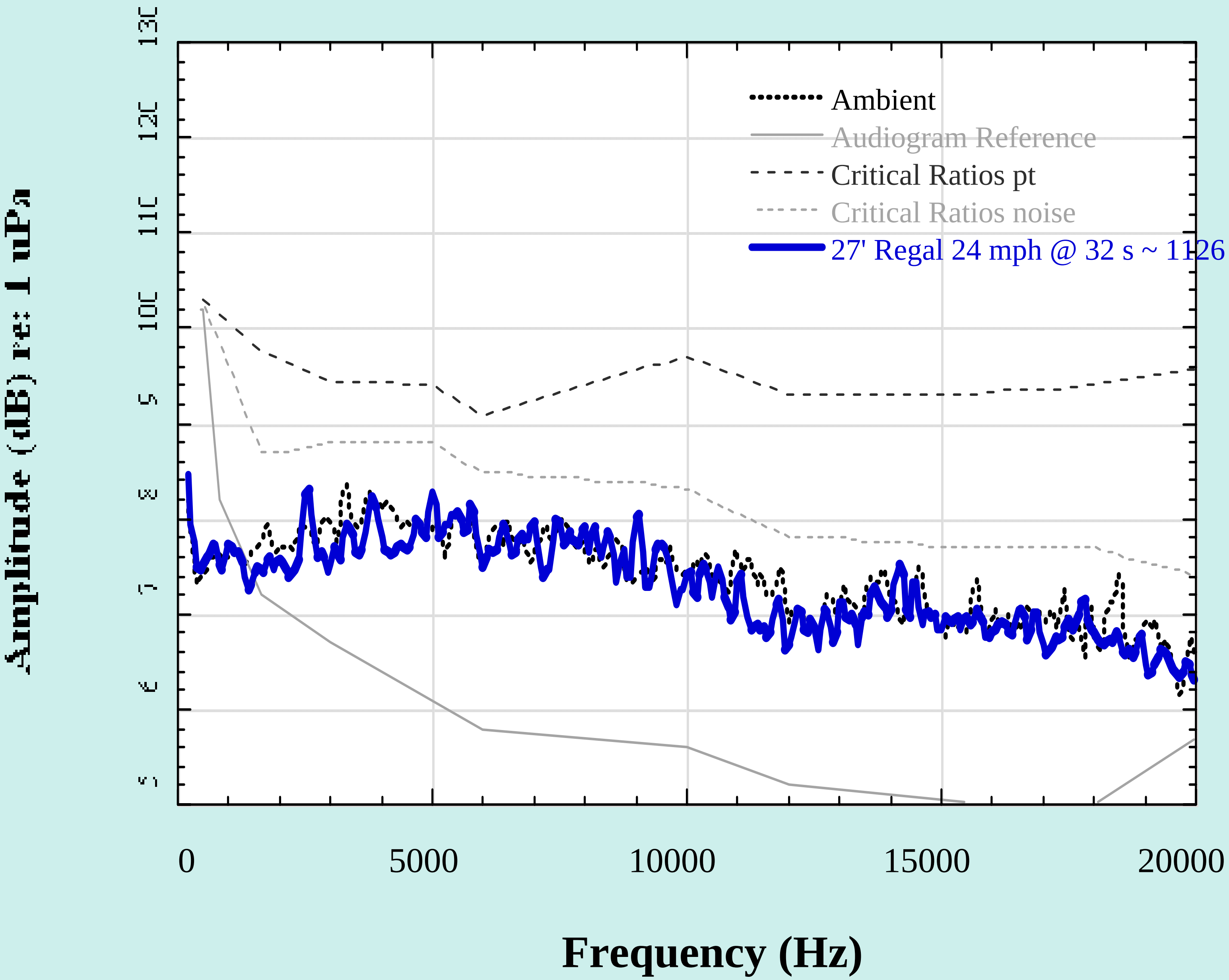
27 ft Regal series

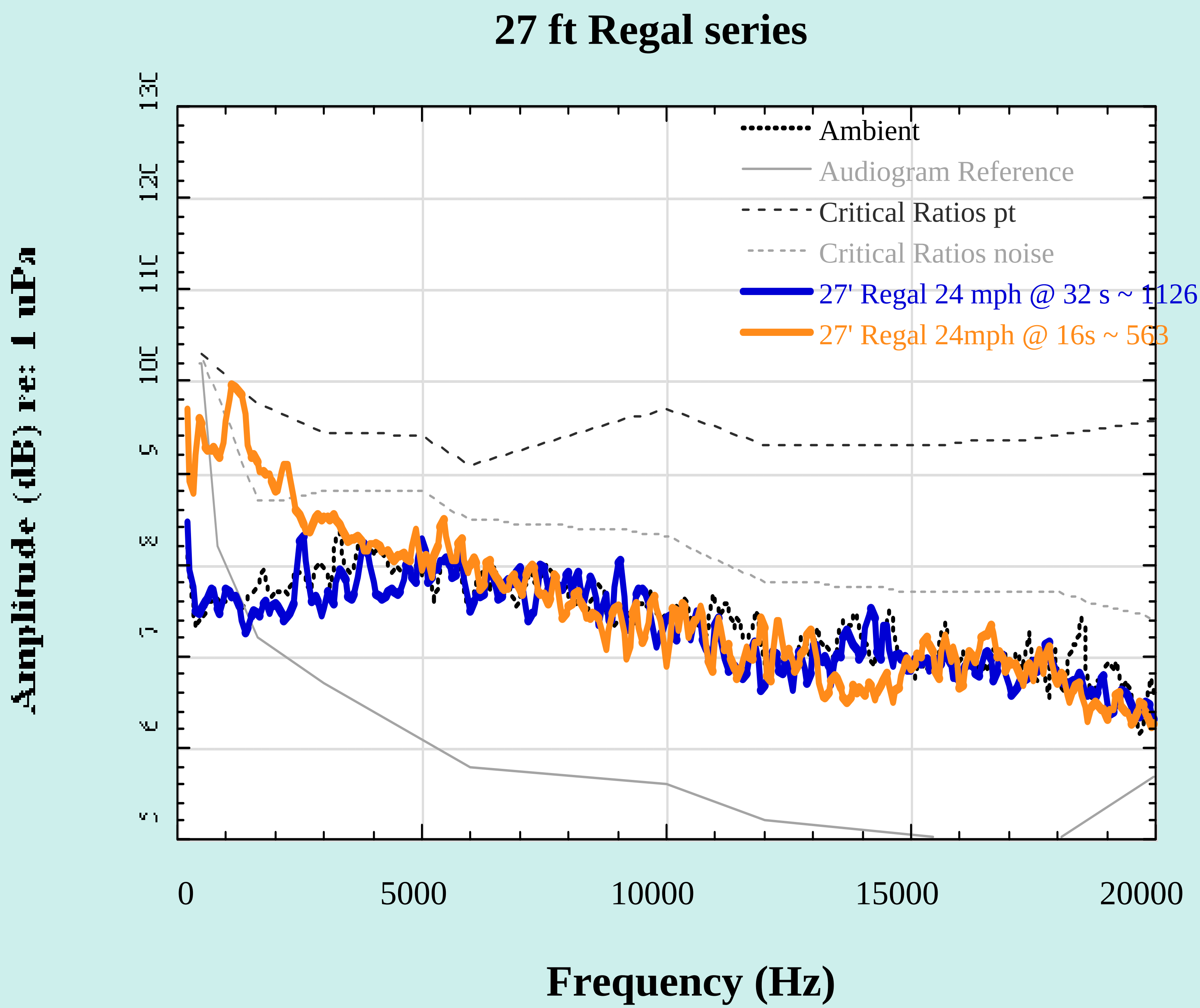


27 ft Regal series



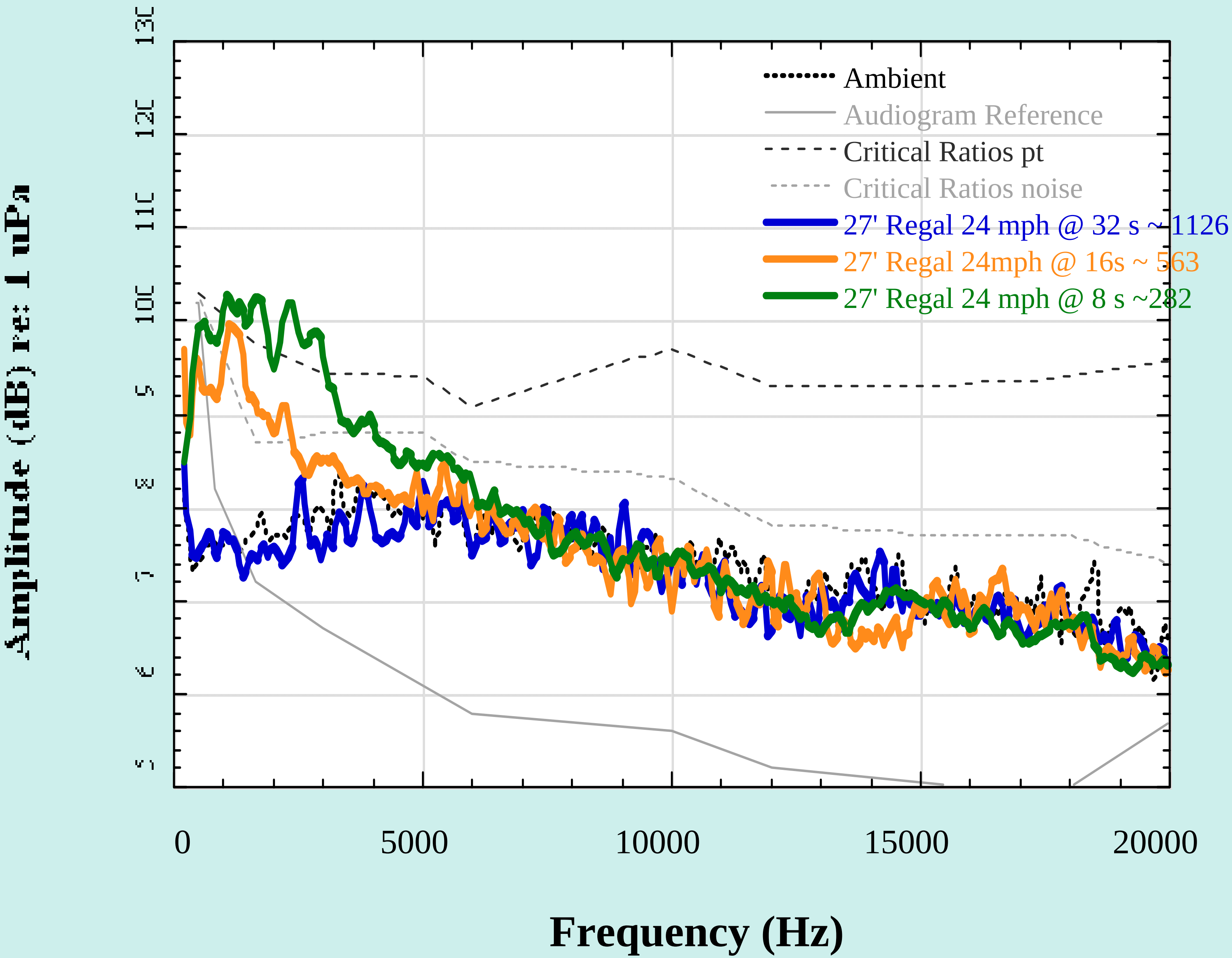
27 ft Regal series

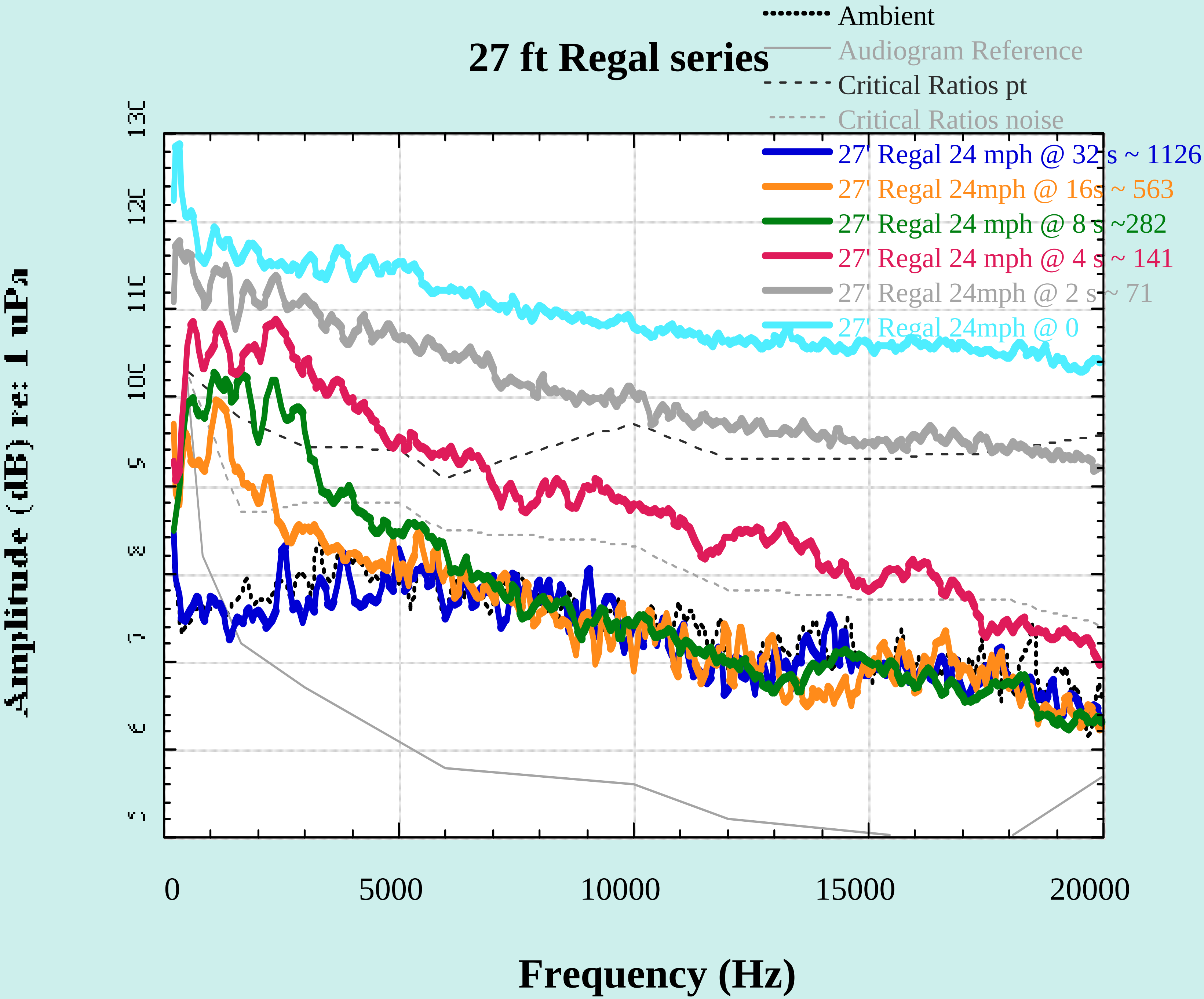




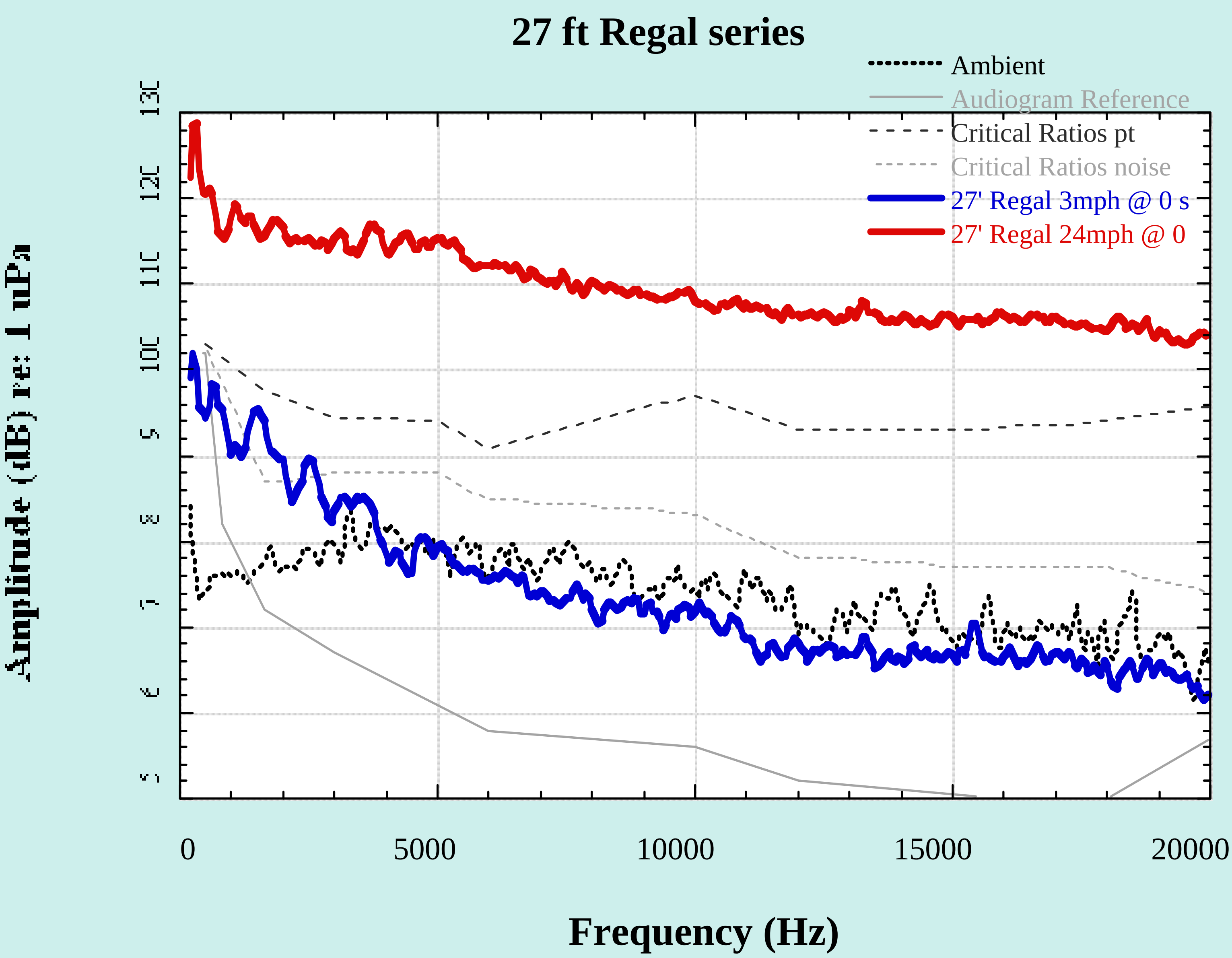
27 ft Regal series
Ambient
Audiogram Reference
Critical Ratios pt
Critical Ratios noise
27' Regal 24 mph @ 32 s ~ 1126
27' Regal 24mph @ 16s ~ 563
Amplitude (dB) re: 1 uPa
Frequency (Hz)
0
5000
10000
15000
20000

27 ft Regal series




27 ft Regal series
Ambient
Audiogram Reference
Critical Ratios pt
Critical Ratios noise
27' Regal 24 mph @ 32 s ~ 1126
27' Regal 24mph @ 16s ~ 563
27' Regal 24 mph @ 8 s ~282
27' Regal 24 mph @ 4 s ~ 141
27' Regal 24mph @ 2 s ~ 71
27' Regal 24mph @ 0
Amplitude (dB) re: 1 uPa
0
5000
10000
15000
20000
Frequency (Hz)

Comparison 3 mph vs 24 mph



Acoustic Consequences of Reducing Boat Speeds

- Lessens cavitation noise and overall acoustic energy
- Lowers the frequency content of the noise which reduces the audibility as well as directivity
- Increases the likelihood of acoustic masking by the prevailing ambient levels and the noise of distant boats and ships while increasing transect times and opportunities for collisions.

Critical Time-To-Collision

Detecting the approach

For whales and manatees to hear vessels, large or small, while underwater: The faster the vessel, the more time the animals have TO DETECT and possibly react and avoid the beam and draft.

As demonstrated and predicted by Lighthill's Theory of Aerodynamic Sound, vessel noise intensity depends on ship speed.

Time-To-Collision Theory

Hearing by all passive listening mammals

The continuity and momentum equations of fluid mechanics written for regions that include mass and force source terms

$$\frac{D\rho}{Dt} + \rho(\nabla \bullet v) = \frac{\partial \rho}{\partial t} + \frac{\partial(\rho v_i)}{\partial x_i} = q$$

$$\frac{DM}{Dt} = \int_V \left(\frac{D(\rho v_i)}{Dt} + \rho v_i \frac{\partial v_j}{\partial x_j}\right) dV$$

Lighthill's Theory of Aerodynamic Sound

$$\frac{D\rho}{Dt} + \rho(\nabla \bullet \vec{v}) = \frac{\partial \rho}{\partial t} + \frac{\partial(\rho v_i)}{\partial x_j} = q$$

Continuity equation in Lagrangian coordinants (co-moving derivatives)

$$\frac{DM}{Dt} = \int_V \left(\frac{D(\rho v_i)}{Dt} + \rho v_i \frac{\partial v_j}{\partial x_i}\right) dV = \int_V \left(\frac{\partial(\rho v_i)}{\partial t} + v_j \frac{\partial(\rho v_i)}{\partial v_j} + \rho v_i \frac{\partial v_j}{\partial x_j}\right) dV$$

Rate of change of momentum

$$\mathbf{I \sim U^5}$$

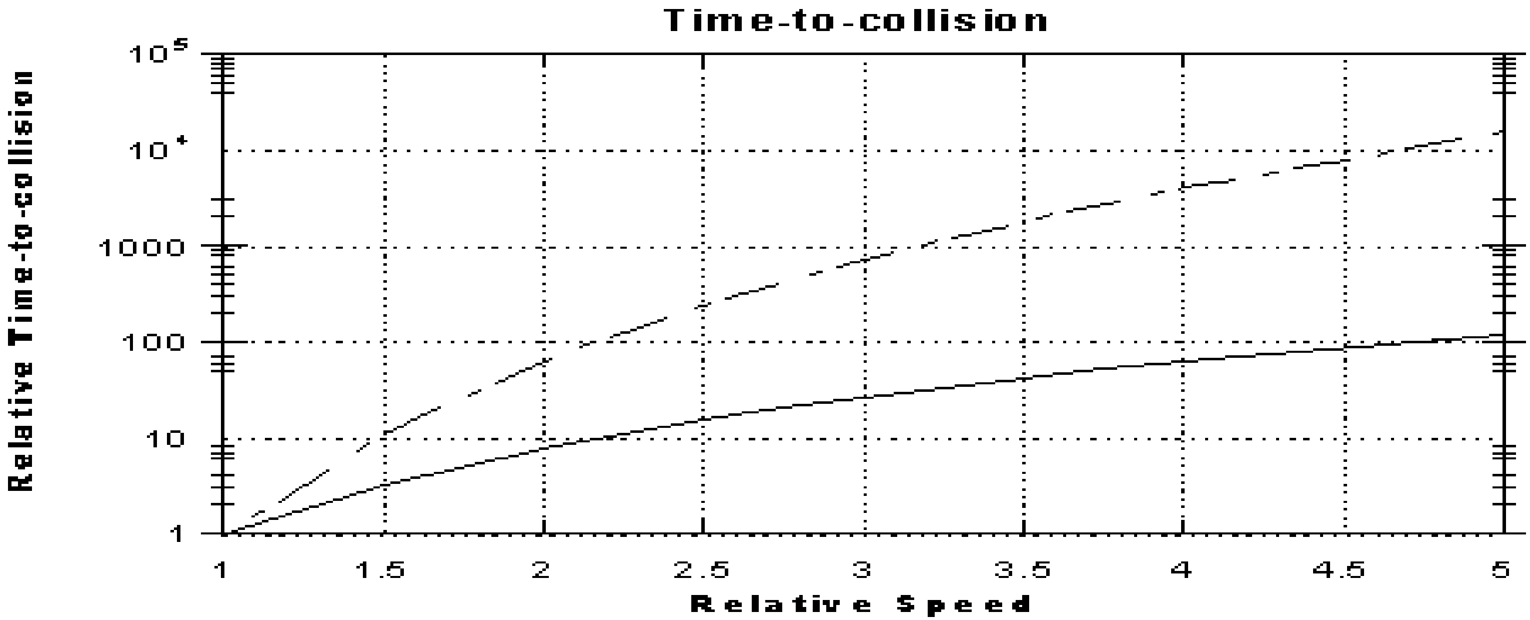
U is equal to the propeller tip velocity

$$\mathbf{V \sim U + \delta}$$

Time-To-Collision: Animal on hearing ship
Theory – Results

Relative time to collision for a vessel at prop tip speeds relative to the slow vessel. Solid line - spherical spreading

Dotted - cylindrical



Time-To-Collision Theory Discussion

Using a relative speed of 2 for a ship, one sees from the curves that time-to-collision for the faster ship is 8 to 35 times that of the slower one. The bad news is that the noise from the faster ship can mask the sounds of the slower ship out to 8 to 35 times the range of whale detection for the slower ship.

Closing Remarks On Whales

NFMS proposed mitigations for reducing North Atlantic right whale collisions call for:

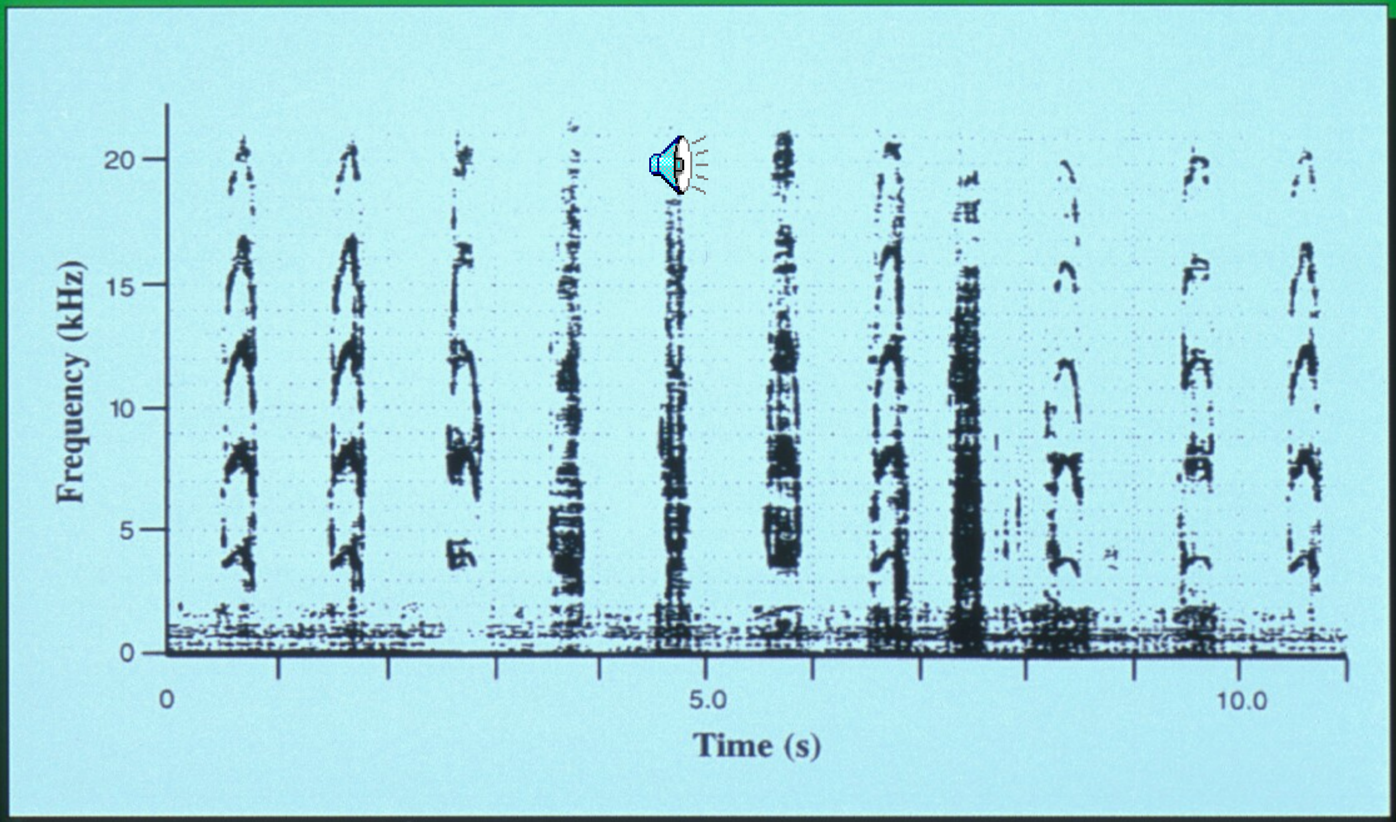
Reducing vessel speed
Rerouting shipping lanes
Increased aerial survaillnce

The blanket application of speed regulations can actually exacerbate the occurrence of ship strikes by reducing the audibility of approaching ships. The acoustic consequences must be mitigated.

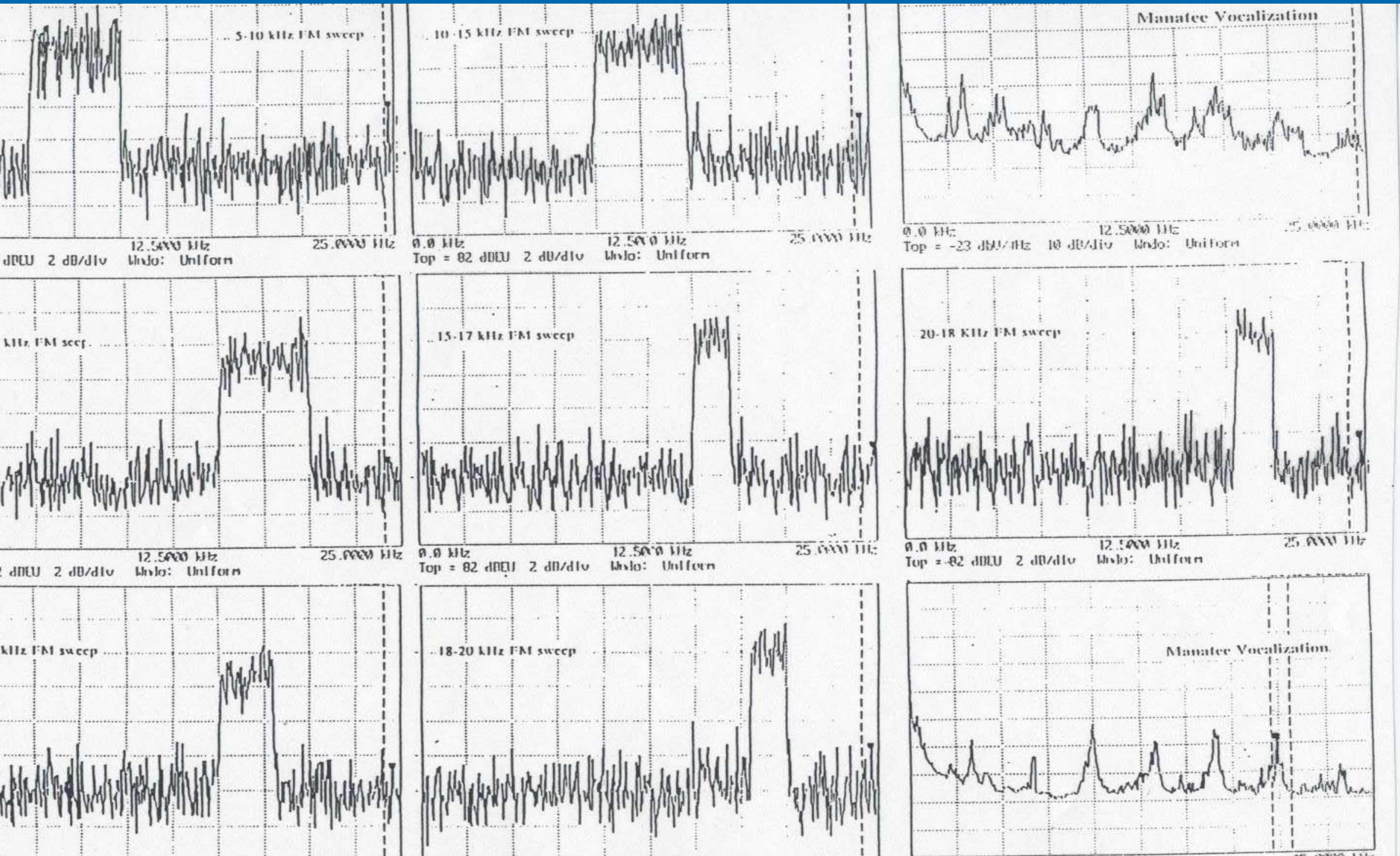
Adding directional noise sources using modulated ship noise projected from the bow could be employed to ensonify acoustic shadows and alert marine mammals directly ahead of ships.

An Acoustic Solution Designed for Manatees using Wavelet Analysis

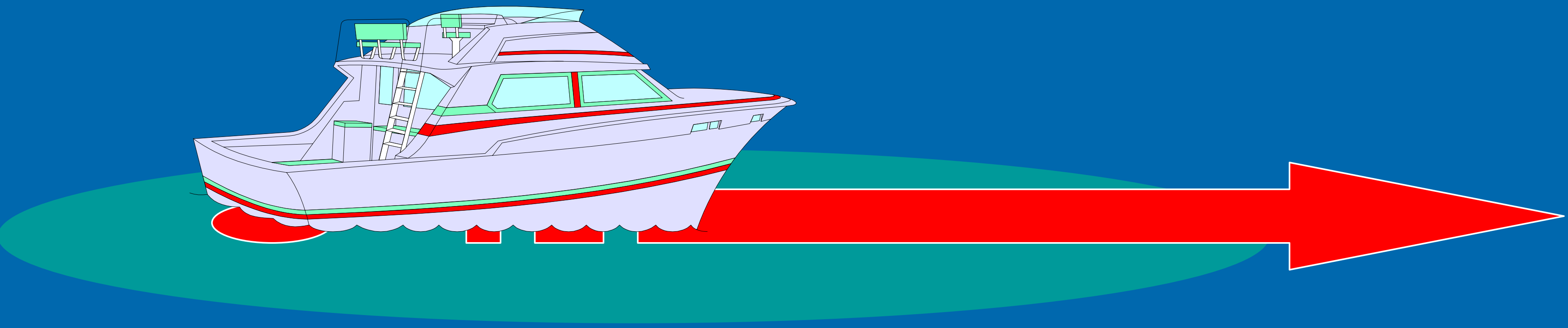
Manatee Vocalizations



Narrow band noise and manatee vocalizations



Manatee Warning Device



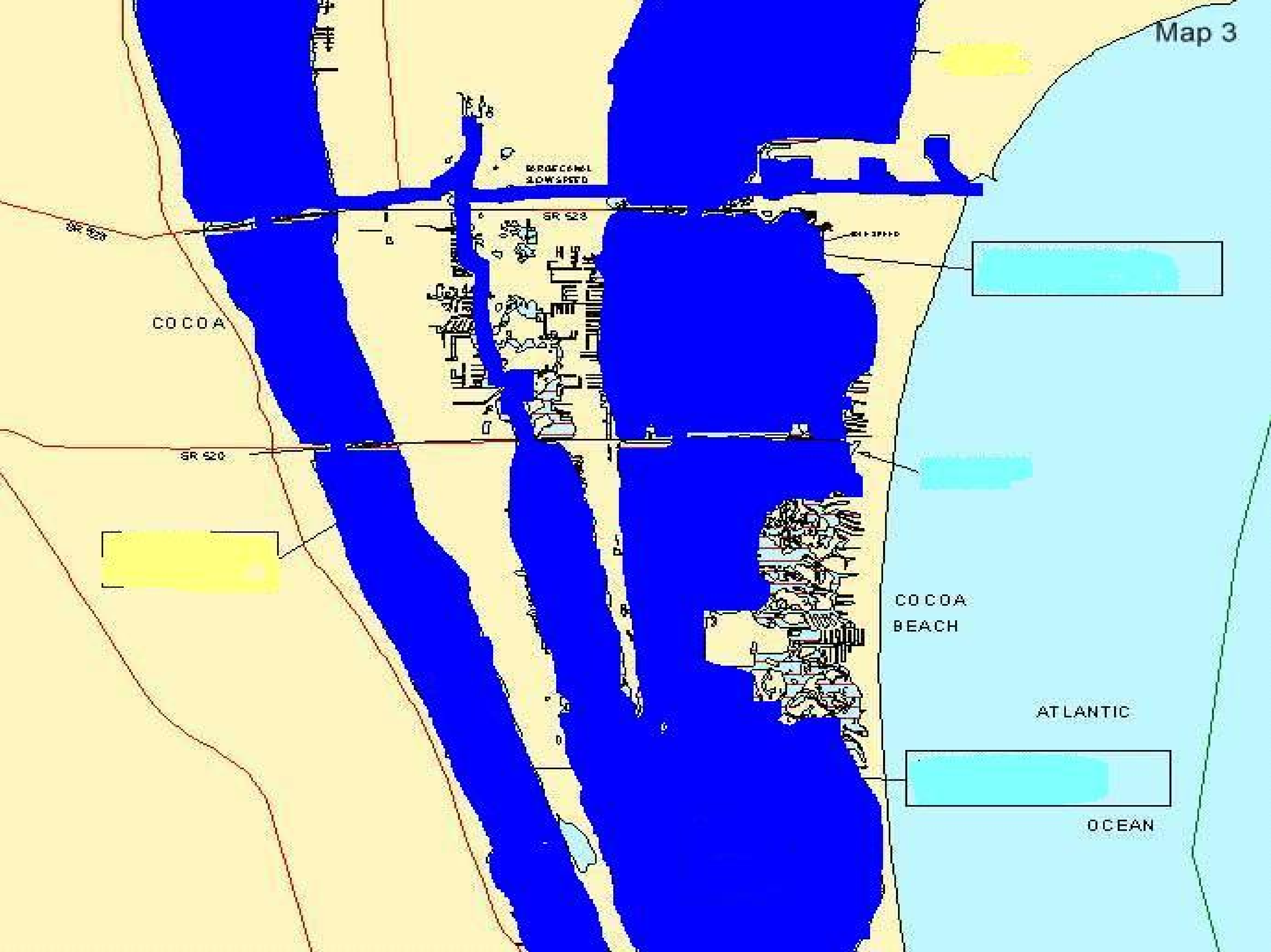
The manatee warning device is designed to project a low intensity, highly directional narrow band of sound in front of approaching boats. The selected signals exploit the manatees best hearing and localization abilities and are designed to enhance the manatees' sensory awareness of approaching boats and ships.

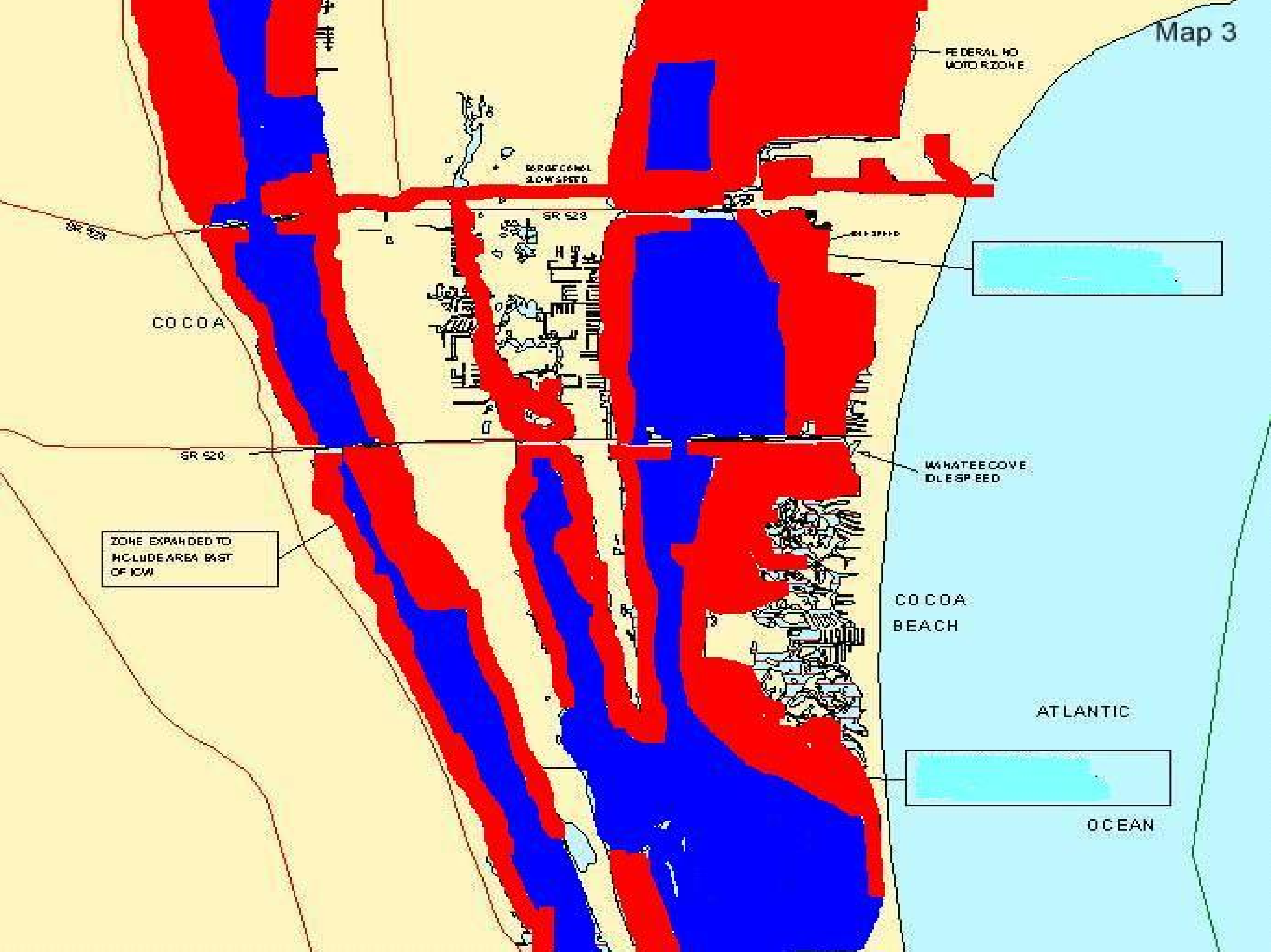
Warning Device

- Parametric projection technique enables a narrow beam with a small apertures, requires less power and little drag
- The sounds are low intensity modulated sweeps that exploit the manatees most sensitive and directional hearing capabilities
- The acoustic laws of directivity and absorption minimize the possibility of reinforcing and cumulative noise pollution concerns

Closing Remarks on Manatees

- The growing number of surviving manatees with multiple scars patterns is consistent with increased slow speed zones in turbid waters.
- While slow speed zones may reduce the chance of mortalities in turbid waters it does not mitigate the occurrence collisions that can still mortally injure individuals and reduce their fitness.
- Blanket speed restrictions without mitigating the associated acoustic consequences can exacerbate the risks of collisions through masking and increased transect times through populated areas.
- Acoustic shadows ahead of commercial vessels and barges may be responsible for many of these mortalities.
- An acoustic array designed to fill in these shadows could help alert manatees of an approaching ship or at the very least reduce the ambiguity of the quiet zone ahead of these vessels. Such a strategies may be helpful for whales that face similar challenges from ships near the surface


Map 3
SR 528
SR 528
COCOA
SR 520
COCOA
BEACH
ATLANTIC
OCEAN


Map 3
FEDERAL NO MOTOR ZONE
BARGE CANAL SLOW SPEED
SR 528
SR 528
COCOA
SR 520
SR 520
MANATEE COVE IDLE SPEED
ZONE EXPANDED TO INCLUDE AREA EAST OF ICW
COCOA BEACH
ATLANTIC
OCEAN


Map G

After all boating and fishing was finally banned in Florida, a few diehards went to Alaska where they could still fish. However, The Save the Orca Club by that time had learned how best to protect their marine mammals.