# Introduction to Loudspeakers and Enclosures

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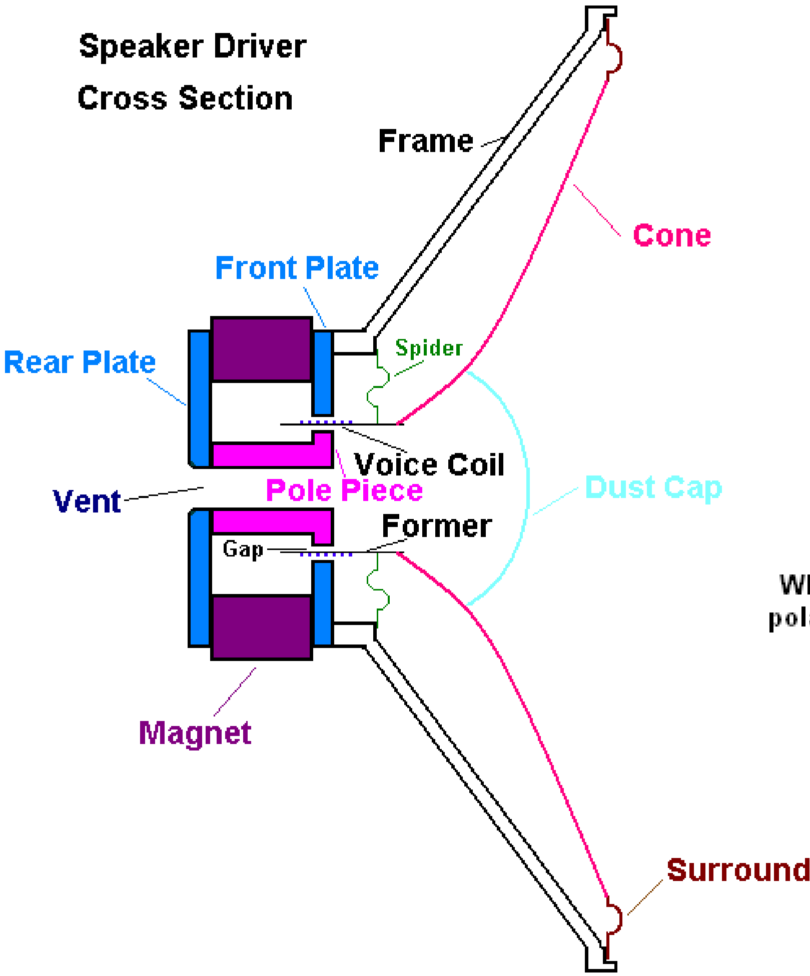
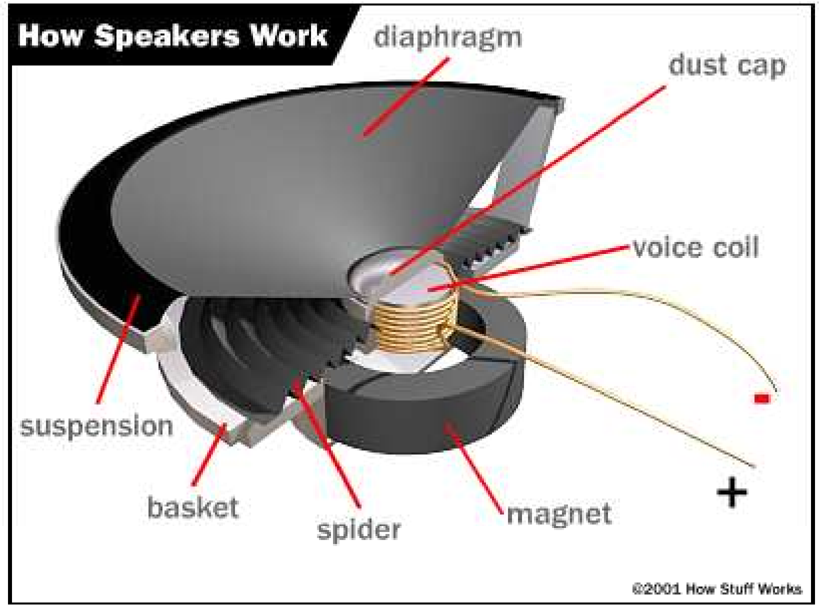
# Outline

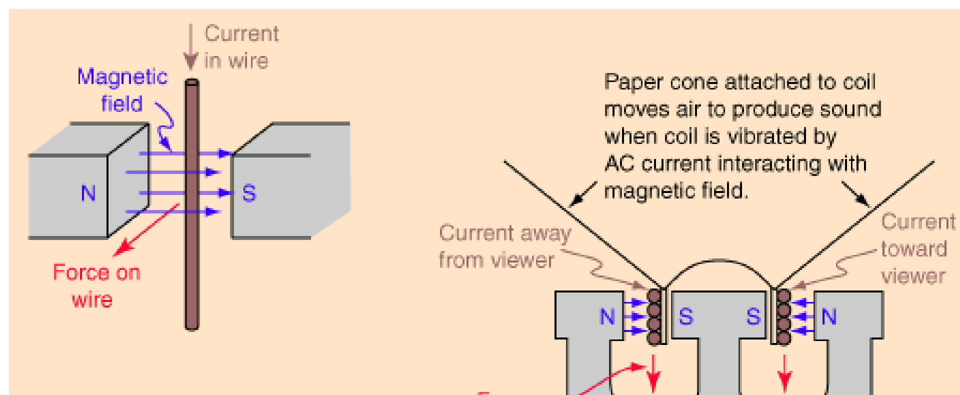
- **Background**
  - **How loudspeakers work**
  - **Waveforms**
  - **Wavelengths**
  - **Speed of sound**
  - **How sound propagates**
  - **Sound pressure level (dB)**
  - **Summation of audio signals**
  - **Phase wheel**
  - **Beamwidth**
  - **3D directivity “balloons”**

# How Loudspeakers Work



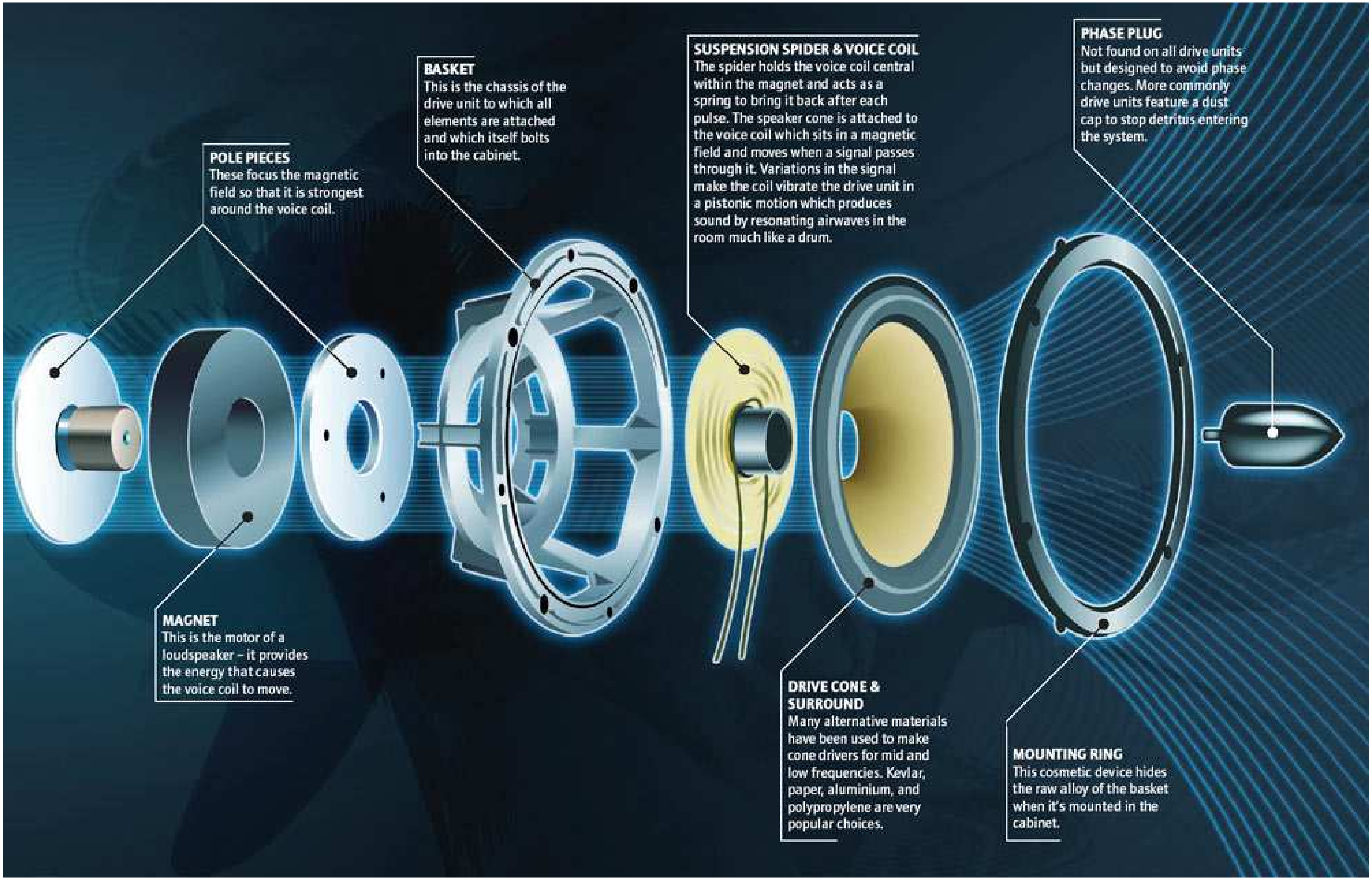




When the electrical current flowing through the voice coil changes direction, the coil's polar orientation reverses. This changes the magnetic forces between the voice coil and the permanent magnet, moving the coil and attached diaphragm back and forth.

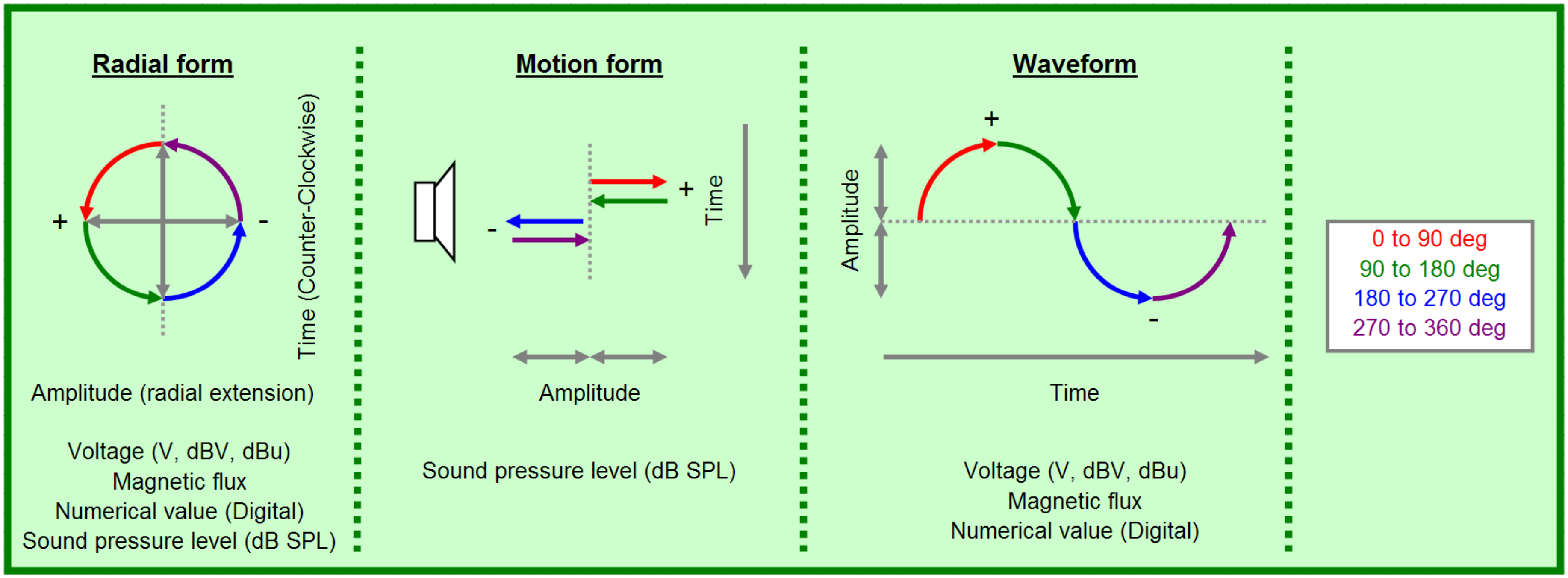



A current-carrying wire in a magnetic field experiences a magnetic force perpendicular to the wire.

# How Loudspeakers Are Made



# The Waveform



## Wavelength Reference Chart

| Frequency | Period | Wavelength (Room temp) | | Comparable size |
|---|---|---|---|---|
| (Hz) | (ms) | (m) | (ft) | |
| 20 | 50.00 | 17.24 | 56.56 | |
| 25 | 40.00 | 13.79 | 45.07 | Intermodal shipping container |
| 32 | 31.75 | 10.94 | 35.77 | |
| 40 | 25.00 | 8.62 | 28.17 | Band gear truck length |
| 50 | 20.00 | 6.90 | 22.54 | 1/2 size intermodal container |
| 63 | 15.87 | 5.47 | 17.89 | Gas guzzling SUV length |
| 80 | 12.50 | 4.31 | 14.09 | Full Size car length |
| 100 | 10.00 | 3.45 | 11.27 | Compact car length |
| 125 | 8.00 | 2.76 | 9.01 | Too wide for the truck |
| 160 | 6.25 | 2.15 | 7.04 | Shaquille O'Neal |
| 200 | 5.00 | 1.72 | 5.63 | Average height |
| 250 | 4.00 | 1.38 | 4.51 | Shoulder Height |
| 315 | 3.17 | 1.09 | 3.58 | |
| 400 | 2.50 | 0.86 | 2.82 | |
| 500 | 2.00 | 0.69 | 2.25 | Arm's length |
| 630 | 1.59 | 0.55 | 1.79 | |
| 800 | 1.25 | 0.43 | 1.41 | |
| 1,000 | 1.00 | 0.34 | 1.13 | Elbow to fist |
| 1,250 | 0.80 | 0.28 | 0.90 | Man's foot |
| 1,600 | 0.63 | 0.22 | 0.70 | Woman's foot |
| 2,000 | 0.50 | 0.17 | 0.56 | Eight fingers |
| 2,500 | 0.40 | 0.14 | 0.45 | |
| 3,150 | 0.32 | 0.11 | 0.36 | CD/DVD |
| 4,000 | 0.25 | 0.086 | 0.28 | Four fingers |
| 5,000 | 0.20 | 0.069 | 0.23 | |
| 6,300 | 0.16 | 0.055 | 0.18 | |
| 8,000 | 0.13 | 0.043 | 0.14 | Two fingers |
| 10,000 | 0.10 | 0.034 | 0.11 | |
| 12,500 | 0.08 | 0.028 | 0.09 | |
| 16,000 | 0.06 | 0.022 | 0.07 | One finger |
| 20,000 | 0.05 | 0.017 | 0.06 | |

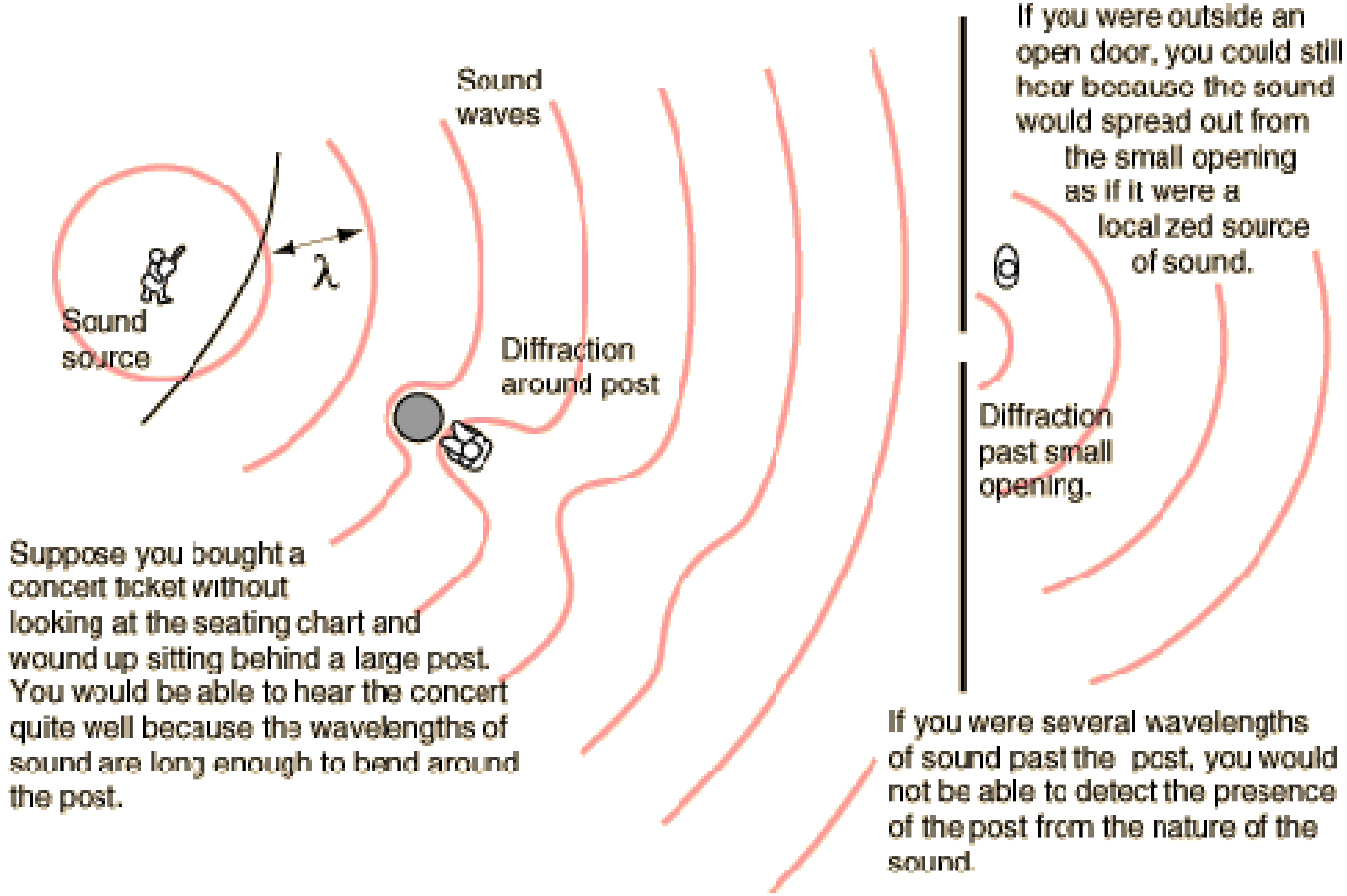
$$\lambda = C/F$$

C is speed of sound at ambient conditions

# Temperature Effects on Speed of Sound

| °C | C Speed of sound | Δ | ΔC | °F | C Speed of sound | Δ |
|---|---|---|---|---|---|---|
| Metric | | Temperature change | Speed of Sound Change | English | | Temperature change |
| Temperature Degrees (C) | Speed m/sec) | Degrees (C) | (%) | Temperature Degrees (F) | Speed (ft/sec) | Degrees (F) |
| 0.0 | 331.4 | -22.2 | 3.9% | 32 | 1087.2 | -40.0 |
| 1.1 | 332.1 | -21.1 | 3.7% | 34 | 1089.4 | -38.0 |
| 2.2 | 332.7 | -20.0 | 3.5% | 36 | 1091.6 | -36.0 |
| 3.3 | 333.4 | -18.9 | 3.3% | 38 | 1093.8 | -34.0 |
| 4.4 | 334.1 | -17.8 | 3.1% | 40 | 1096.0 | -32.0 |
| 5.6 | 334.8 | -16.7 | 2.9% | 42 | 1098.2 | -30.0 |
| 6.7 | 335.4 | -15.6 | 2.7% | 44 | 1100.4 | -28.0 |
| 7.8 | 336.1 | -14.4 | 2.5% | 46 | 1102.6 | -26.0 |
| 8.9 | 336.8 | -13.3 | 2.3% | 48 | 1104.8 | -24.0 |
| 10.0 | 337.5 | -12.2 | 2.2% | 50 | 1107.0 | -22.0 |
| 11.1 | 338.1 | -11.1 | 2.0% | 52 | 1109.2 | -20.0 |
| 12.2 | 338.8 | -10.0 | 1.8% | 54 | 1111.4 | -18.0 |
| 13.3 | 339.5 | -8.9 | 1.6% | 56 | 1113.6 | -16.0 |
| 14.4 | 340.2 | -7.8 | 1.4% | 58 | 1115.8 | -14.0 |
| 15.6 | 340.8 | -6.7 | 1.2% | 60 | 1118.0 | -12.0 |
| 16.7 | 341.5 | -5.6 | 1.0% | 62 | 1120.2 | -10.0 |
| 17.8 | 342.2 | -4.4 | 0.8% | 64 | 1122.4 | -8.0 |
| 18.9 | 342.9 | -3.3 | 0.6% | 66 | 1124.6 | -6.0 |
| 20.0 | 343.5 | -2.2 | 0.4% | 68 | 1126.8 | -4.0 |
| 21.1 | 344.2 | -1.1 | 0.2% | 70 | 1129.0 | -2.0 |
| 22.2 | 344.9 | 0.0 | 0.0% | 72 | 1131.2 | 0.0 |
| 23.3 | 345.6 | 1.1 | -0.2% | 74 | 1133.4 | 2.0 |
| 24.4 | 346.2 | 2.2 | -0.4% | 76 | 1135.6 | 4.0 |
| 25.6 | 346.9 | 3.3 | -0.6% | 78 | 1137.8 | 6.0 |
| 26.7 | 347.6 | 4.4 | -0.8% | 80 | 1140.0 | 8.0 |
| 27.8 | 348.3 | 5.6 | -1.0% | 82 | 1142.2 | 10.0 |
| 28.9 | 348.9 | 6.7 | -1.2% | 84 | 1144.4 | 12.0 |
| 30.0 | 349.6 | 7.8 | -1.4% | 86 | 1146.6 | 14.0 |
| 31.1 | 350.3 | 8.9 | -1.6% | 88 | 1148.8 | 16.0 |
| 32.2 | 351.0 | 10.0 | -1.8% | 90 | 1151.0 | 18.0 |
| 33.3 | 351.6 | 11.1 | -2.0% | 92 | 1153.2 | 20.0 |
| 34.4 | 352.3 | 12.2 | -2.2% | 94 | 1155.4 | 22.0 |
| 35.6 | 353.0 | 13.3 | -2.3% | 96 | 1157.6 | 24.0 |
| 36.7 | 353.7 | 14.4 | -2.5% | 98 | 1159.8 | 26.0 |
| 37.8 | 354.3 | 15.6 | -2.7% | 100 | 1162.0 | 28.0 |

# How Sound Propagates



# Acoustic Decibel (dB SPL)

- In acoustics, the ratios most commonly encountered are changes in pressure level, measured in dB-SPL:

**$\text{dB-SPL} = 20 \log_{10}(p/p_o)$ where $p_o = 20\ \mu N/m^2$**

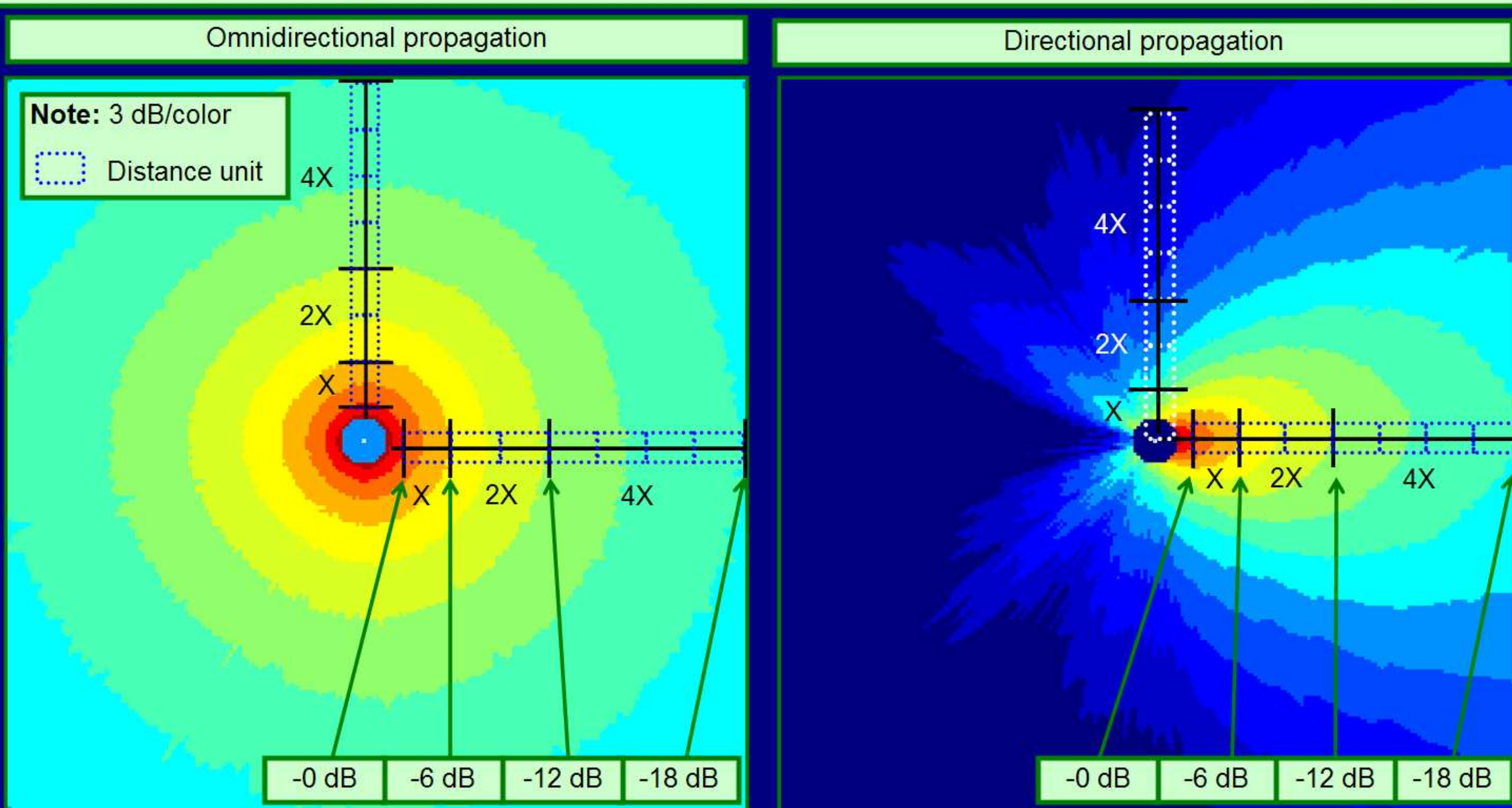
- As distance from a sound source doubles, the dB-SPL decreases 6 dB (this is called the inverse square law)
- Adding/subtracting dB levels:

**$\text{SPLa} \pm \text{SPLb} = 10 \log_{10} [\, 10^{\text{db-SPLa}/10} \pm 10^{\text{db-SPLb}/10}]$**

- Doubling acoustic power corresponds to a 3 dB increase in SPL
- Doubling perceived loudness corresponds to a 10 dB increase in SPL

# Acoustic Transmission: Inverse Square Law

6 dB loss per doubling distance is constant in free field omnidirectional and directional propagation




Relative level is equal in all directions over distance.
Doubling distance loss is equal in all directions.

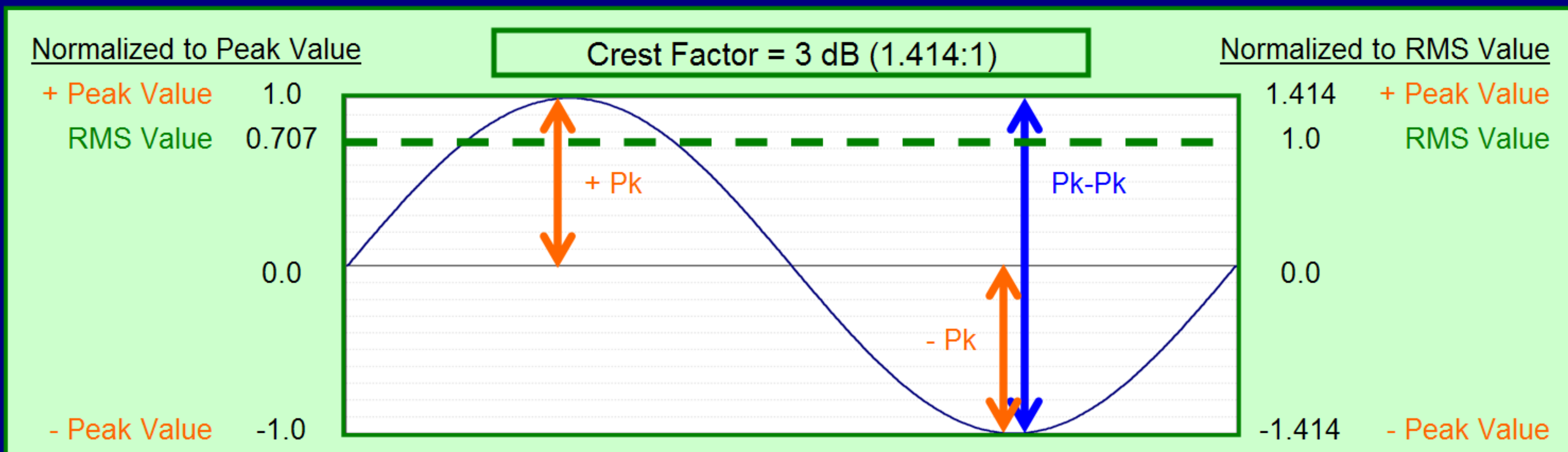
Relative level is not equal due to directional control.
Doubling distance loss is equal in all directions.

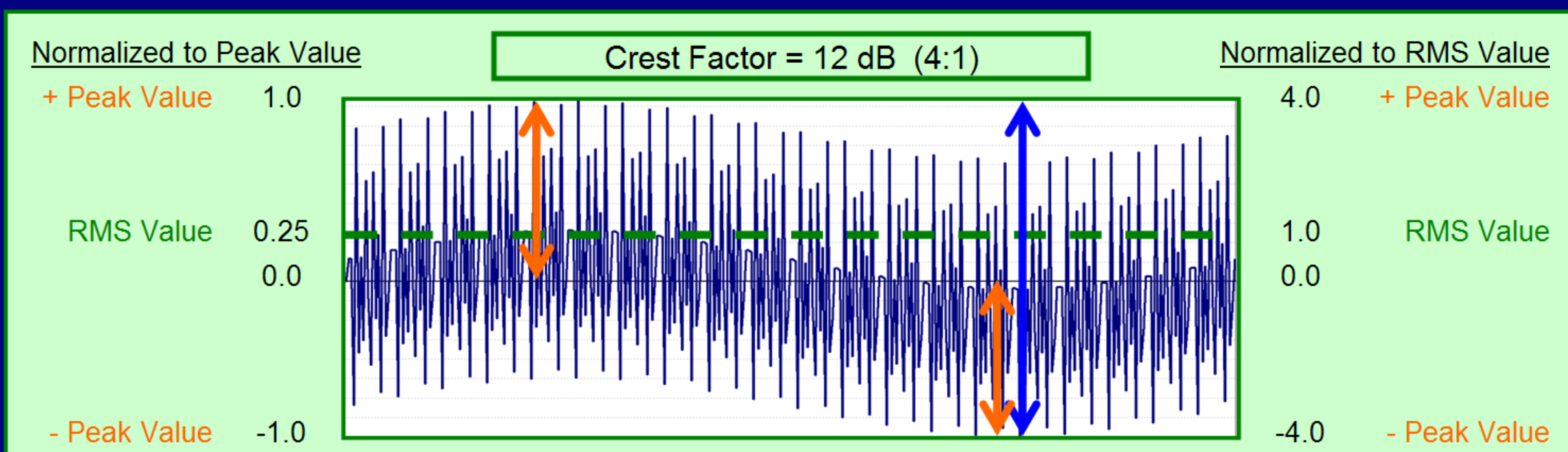
# Decibel Ratio Reference

| $20 \times \log(Level_1/Level_2)$ | | $10 \times \log(Power_1/Power_2)$ | |
|---|---|---|---|
| Pressure (SPL) | | | |
| Voltage (V) | | Power (P) | |
| Current (I) | | | |
| **Value (dB)** | **Ratio ($L_1/L_2$)** | **Value (dB)** | **Ratio ($P_1/P_2$)** |
| 0.0 | 1.00 | 0.0 | 1.00 |
| 1.0 | 1.12 | 0.5 | 1.12 |
| 2.0 | 1.26 | 1.0 | 1.26 |
| 3.0 | 1.41 | 1.5 | 1.41 |
| 4.0 | 1.59 | 2.0 | 1.59 |
| 5.0 | 1.78 | 2.5 | 1.78 |
| 6.0 | 2.00 | 3.0 | 2.00 |
| 7.0 | 2.24 | 3.5 | 2.24 |
| 8.0 | 2.51 | 4.0 | 2.51 |
| 9.0 | 2.82 | 4.5 | 2.82 |
| 10 | 3.16 | 5.0 | 3.16 |
| 12 | 4.00 | 6.0 | 4.00 |
| 14 | 5.00 | 7.0 | 5.00 |
| 15 | 5.63 | 7.5 | 5.66 |
| 18 | 8.00 | 9.0 | 8.00 |
| 20 | 10 | 10 | 10 |
| 26 | 20 | 13 | 20 |
| 32 | 40 | 16 | 40 |
| 38 | 80 | 19 | 80 |
| 40 | 100 | 20 | 100 |
| 60 | 1,000 | 30 | 1,000 |
| 80 | 10,000 | 40 | 10,000 |
| 100 | 100,000 | 50 | 100,000 |

# Crest Factor: Peak to RMS Ratio

The relationship of RMS, peak and peak to peak values to the audio waveform



# dB SPL Operating Levels

| Listening Level dB SPL | Listening Level dB SPL Pk | Ear Level Range | Comments | High Level Music | Medium Level Music | Low Level Music |
|---|---|---|---|---|---|---|
| 133.0 | 145.0 | | | | | |
| 130.0 | 142.0 | | Pain Threshold | | | |
| 127.0 | 139.0 | | | | | |
| 124.0 | 136.0 | | | | | |
| 121.0 | 133.0 | | Non-Linear region | | | |
| 118.0 | 130.0 | | | | | |
| 115.0 | 127.0 | | | | | |
| 112.0 | 124.0 | | | | | |
| 109.0 | 121.0 | | High Level Music | | | |
| 106.0 | 118.0 | | | | | |
| 103.0 | 115.0 | | | X | | |
| 100.0 | 112.0 | | | | | |
| 97.0 | 109.0 | | Medium Level Music | N | | |
| 94.0 | 106.0 | | | O | | |
| 91.0 | 103.0 | | | M | X | |
| 88.0 | 100.0 | | | I | | |
| 85.0 | 97.0 | | Low Level Music | N | N | |
| 82.0 | 94.0 | | | A | O | |
| 79.0 | 91.0 | | | L | M | X |
| 76.0 | 88.0 | | | | I | |
| 73.0 | 85.0 | | | | N | N |
| 70.0 | 82.0 | | | | A | O |
| 67.0 | 79.0 | | Speech at .5 meters | | L | M |
| 64.0 | 76.0 | | | | | I |
| 61.0 | 73.0 | | Speech at 1 meter | | | N |
| 58.0 | 70.0 | | Noisy HVAC | | | A |
| 55.0 | 67.0 | | Speech at 2 meters | | | L |
| 52.0 | 64.0 | | | | | |
| 49.0 | 61.0 | | Typical HVAC | | | |
| 46.0 | 58.0 | | | | | |
| 43.0 | 55.0 | | | | | |
| 40.0 | 52.0 | | Quiet Room | | | |
| 37.0 | 49.0 | | | | | |
| 34.0 | 46.0 | | VERY quiet room | N | | |
| 31.0 | 43.0 | | | O | | |
| 28.0 | 40.0 | | | I | | |
| 25.0 | 37.0 | | | S | | |
| 22.0 | 34.0 | | Recording Studio | E | N | |
| 19.0 | 31.0 | | | | O | |
| 16.0 | 28.0 | | | | I | |
| 13.0 | 25.0 | | Dream on! | | S | |
| 10.0 | 22.0 | | | | E | N |
| 7.0 | 19.0 | | | | | O |
| 4.0 | 16.0 | | Brownian motion | | | I |
| 1.0 | 13.0 | | Noise floor of air | | | S |
| -2.0 | 10.0 | N | and ear | | | E |
| -5.0 | 7.0 | O | | | | |
| -8.0 | 4.0 | I | | | | |
| -11.0 | 1.0 | S | | | | |
| | | E | | | | |

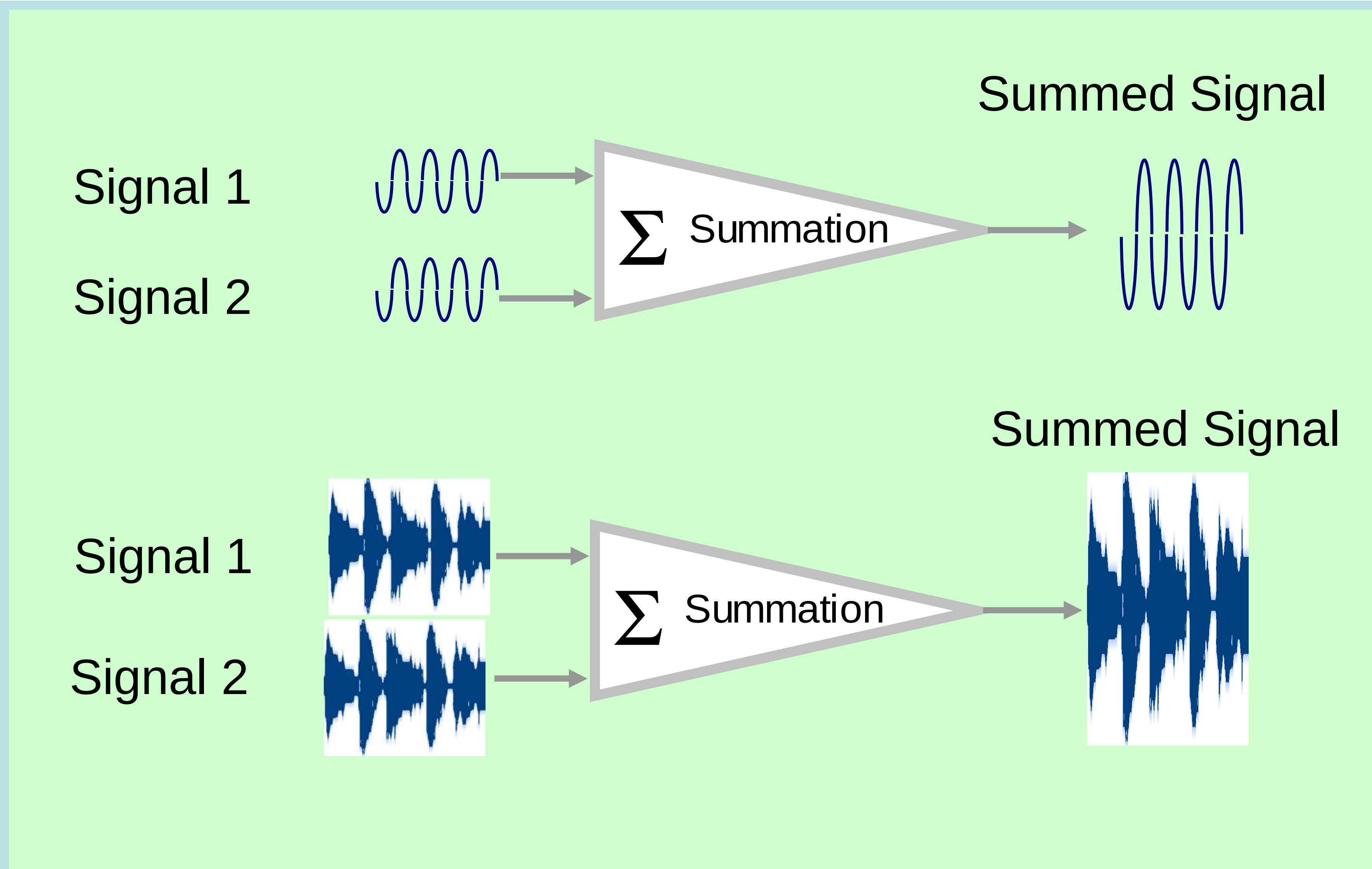
# Electrical Power Requirement

- When SPL goal at a given listening distance known, also need:
  - Sensitivity rating of loudspeaker (typically spec as 1m on-axis with input of 1 electrical watt)
  - Acoustic level change/attenuation between loudspeaker and farthest listening position
- Example: 90 dB program level at listening distance of 32 m outdoors
  - Loudspeaker sensitivity measured as 110 dB
  - Acoustic level change = 20 log (32) ≅ 30 dB
  - Add 10 dB for peak (program level) headroom
  - SPL required at source is 90 + 30 + 10 = 130 dB
  - Need 20 dB above 1 watt, or $10^{(20/10)}$ = 100 W

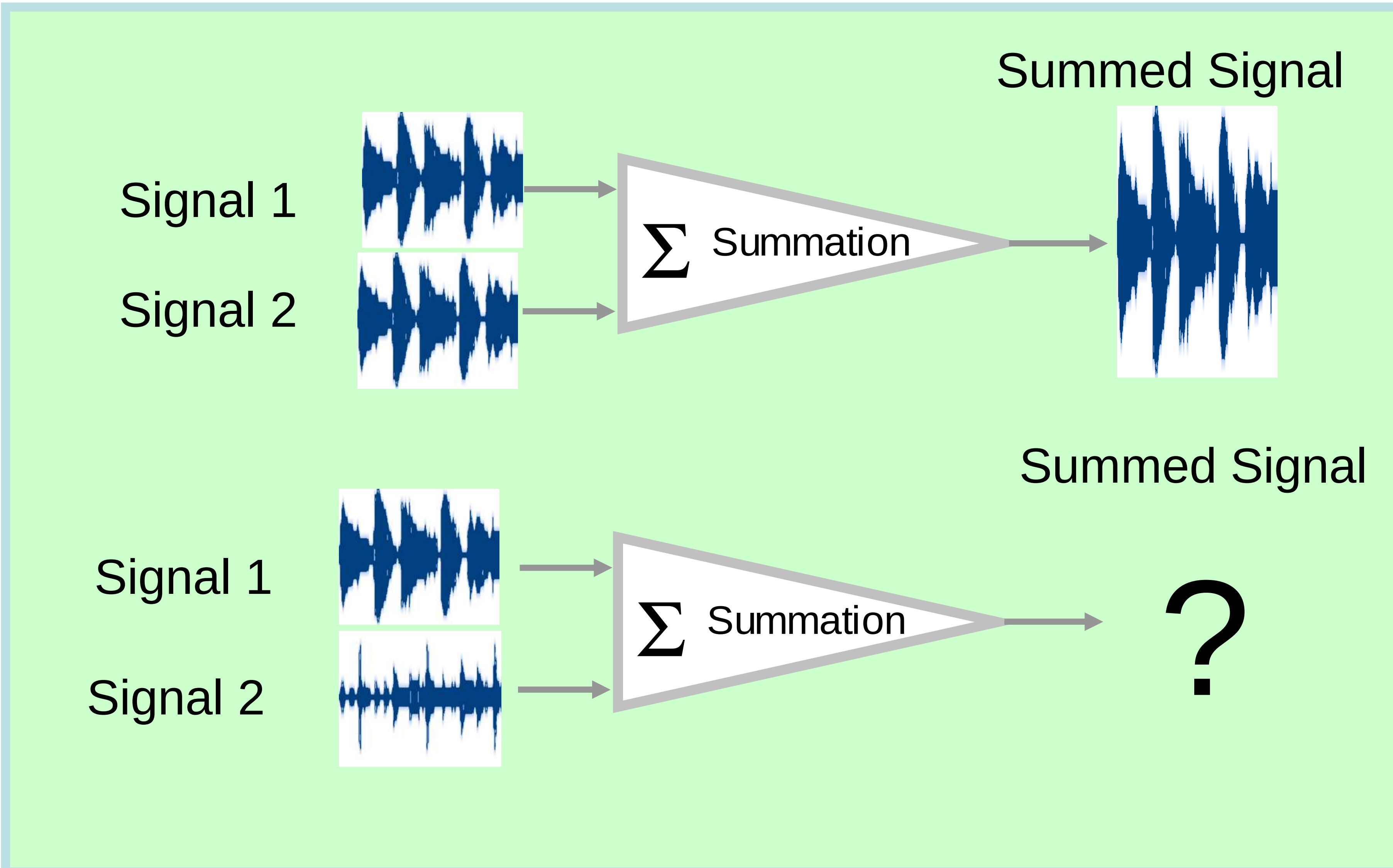
# Stable Summation Criteria

1. Must have matched origin
2. May contain unlimited multiple inputs
3. May arrive from different directions
4. Must have significant overlap duration

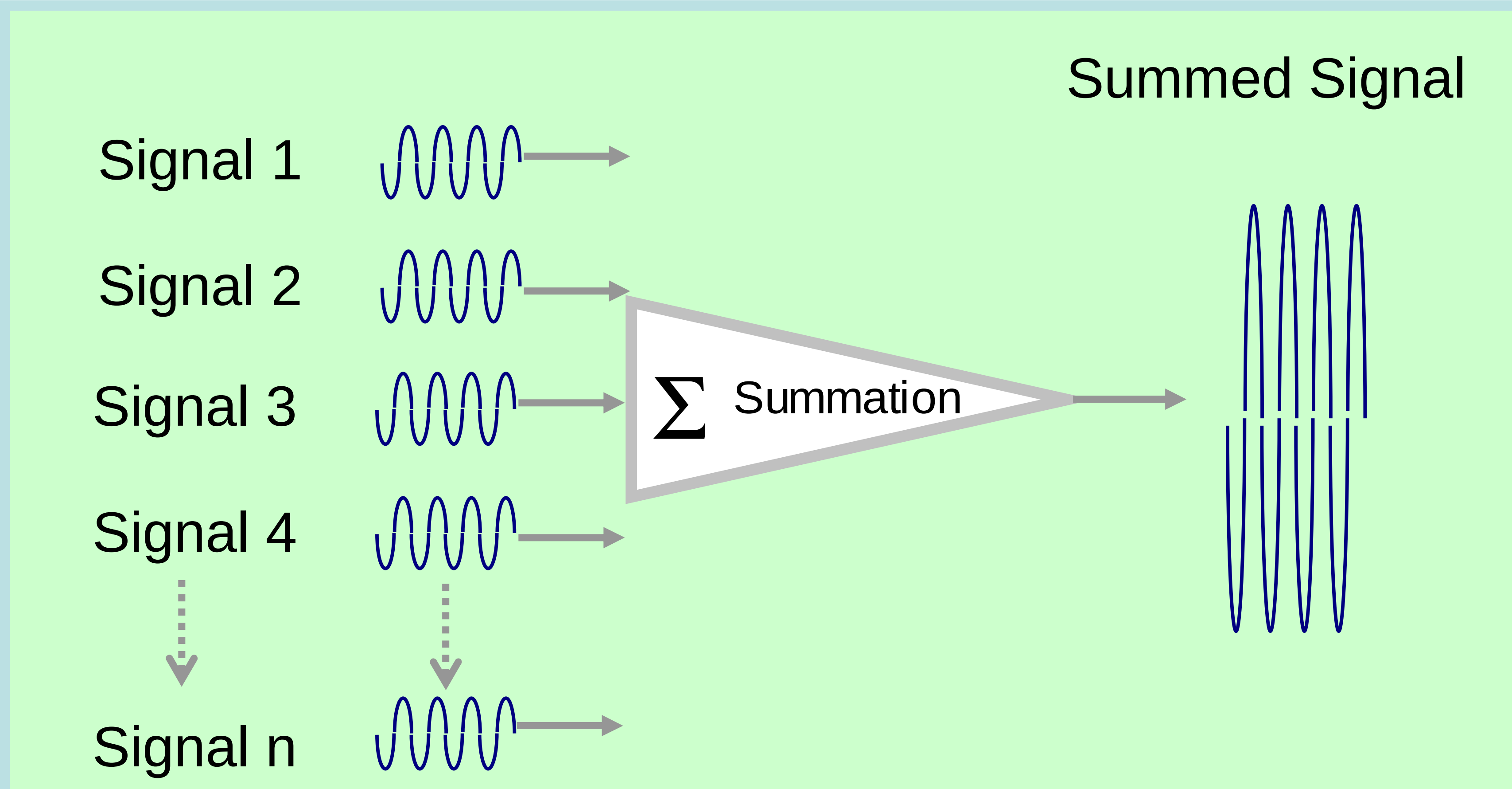
# Summation Criteria: Matched Origin



# Summation Criteria: Matched Origin

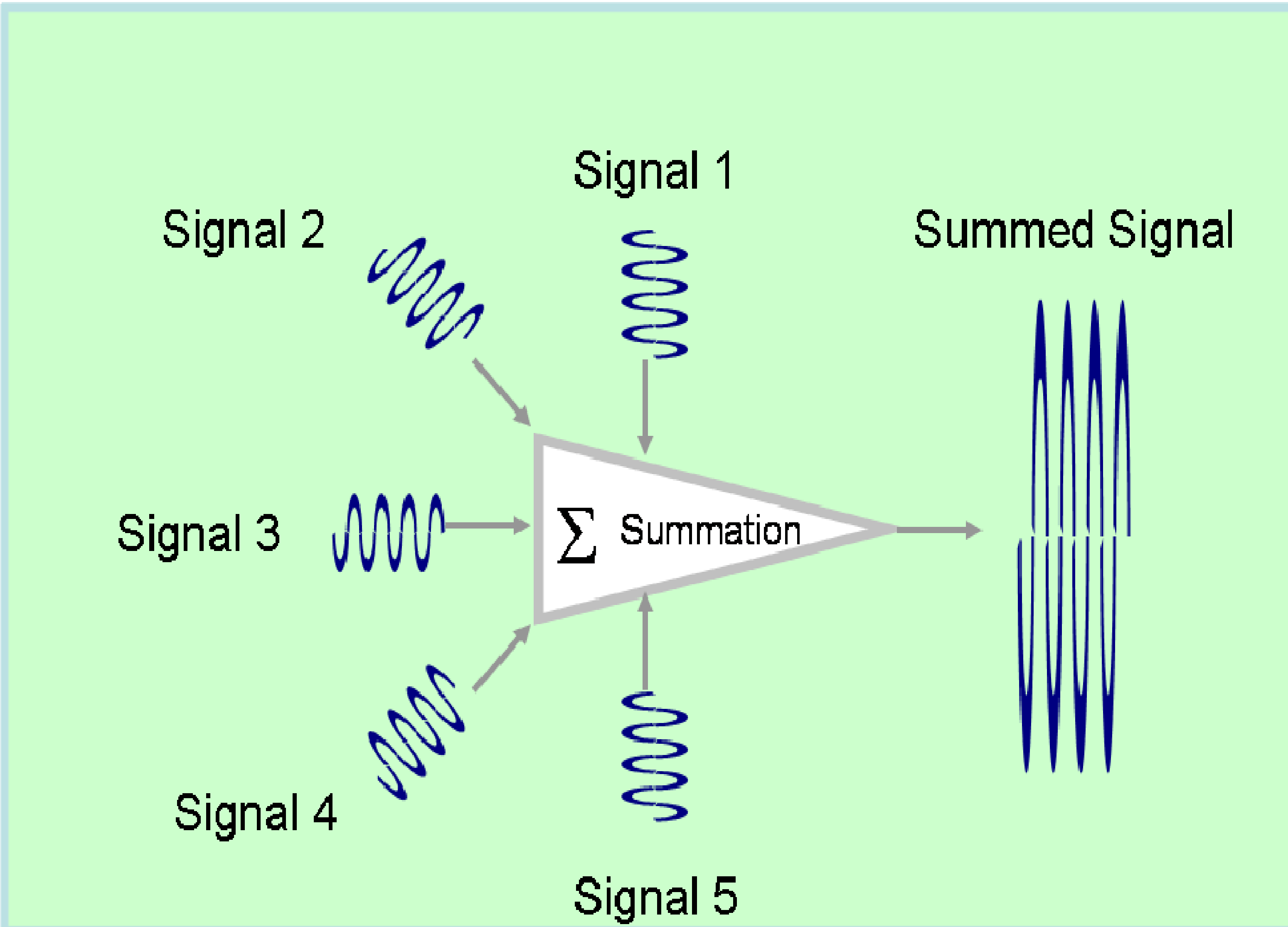


# Summation Criteria: Multiple Input Signals

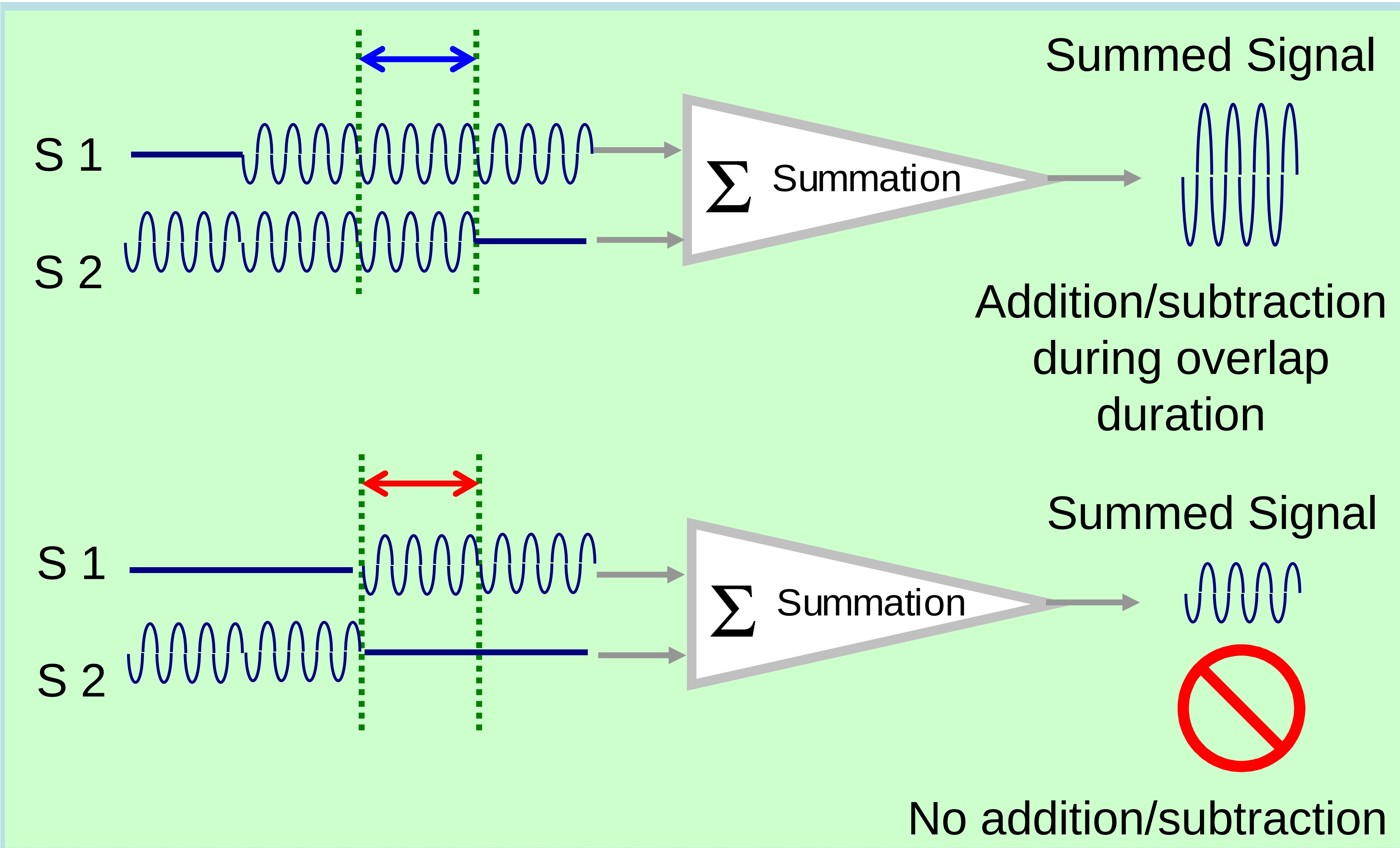



| Multiple Input Summation Level Reference | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **# of Inputs** | **2** | **3** | **4** | **5** | **6** | **8** | **10** | **12** | **16** | **20** | **24** | **32** |
| Level relative to single input | +6 dB | +10 dB | +12 dB | +14 dB | +17 dB | +18 dB | +20 dB | +22 dB | +24 dB | +26 dB | +28 dB | +30 dB |
| | Note: This is the **maximum** addition and will only occur when all inputs at matched level and phase | | | | | | | | | | | |

# Summation Criteria: Input Signal Direction



# Summation Criteria: Overlap Duration



# Adding dB-SPL

Two acoustic sources “a” and “b” of relative phase angles $\theta_a$ and $\theta_b$

$$\Sigma_{dB\text{-}SPLa+b} =$$

$$20 \log_{10} \left[ sqrt \{ (10^{dB\text{-}SPLa/20})^2 + (10^{dB\text{-}SPLb/20})^2 + 2(10^{dB\text{-}SPLa/20})(10^{dB\text{-}SPLb/20})(\cos(\theta_a - \theta_b)) \} \right]$$

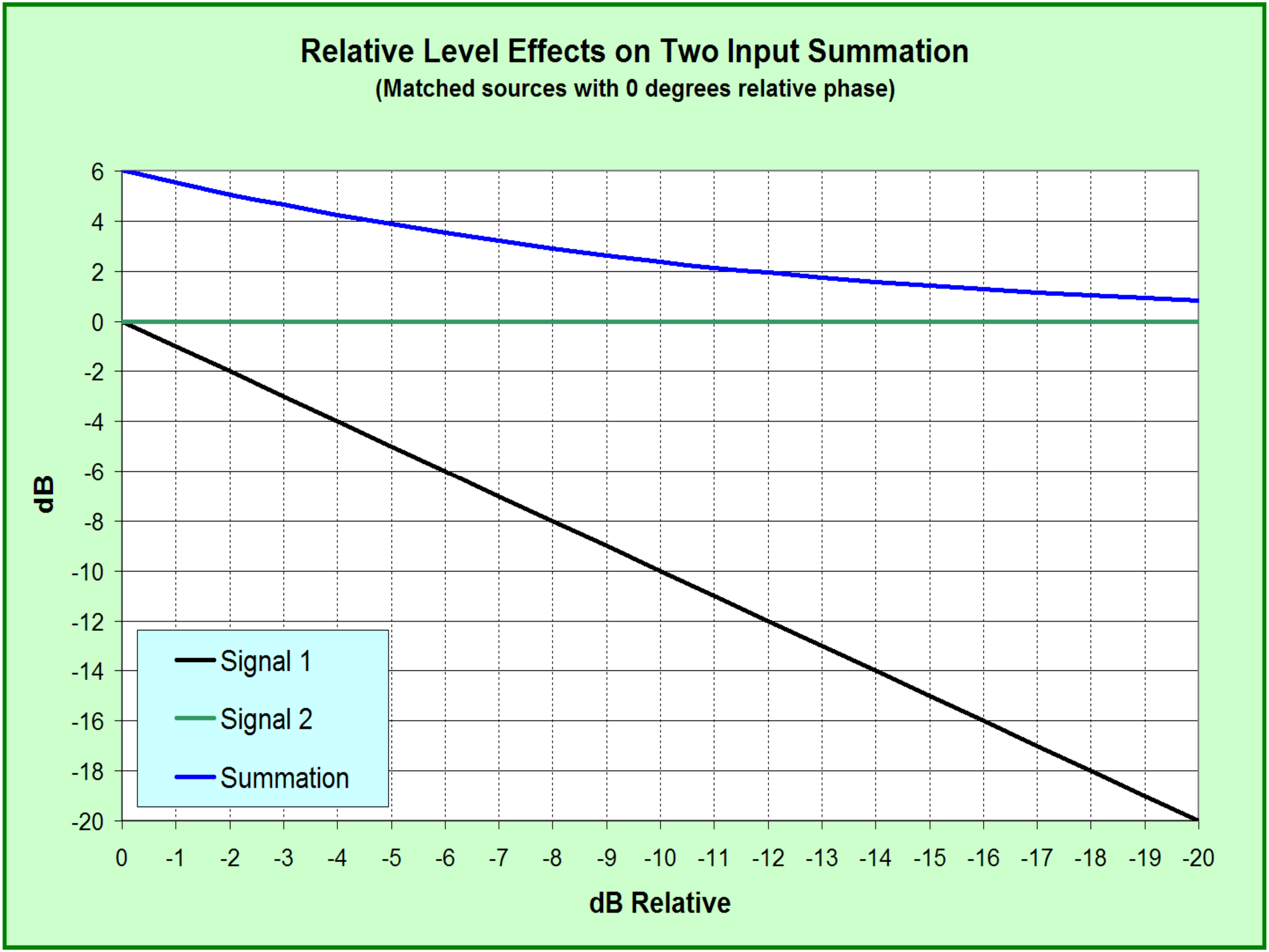
# Adding dB-SPL – "Simplifications"

If both sources are in phase and only the relative level varies (where source "a" is 0 dB, simplifies to:

$$\Sigma_{dB\text{-}SPLa+b} = 20 \log_{10} \left[1 + 10^{dB\text{-}SPLb/20}\right]$$

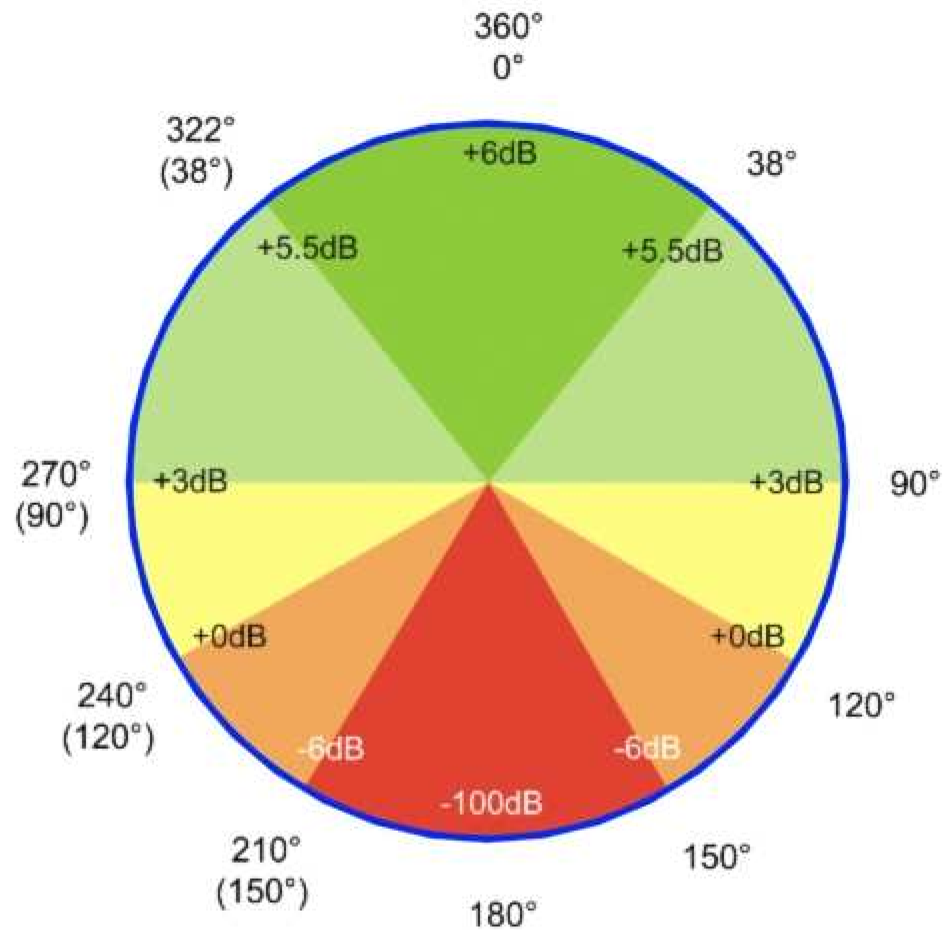
If both sources are at 0 dB and phase angle $\theta_a = 0$ (i.e., same level, only relative phase angle varies), simplifies to :

$$\Sigma_{dB\text{-}SPLa+b} = 20 \log_{10} \left[ \text{sqrt} \{ 2 + 2\cos(-\theta_b) \} \right]$$



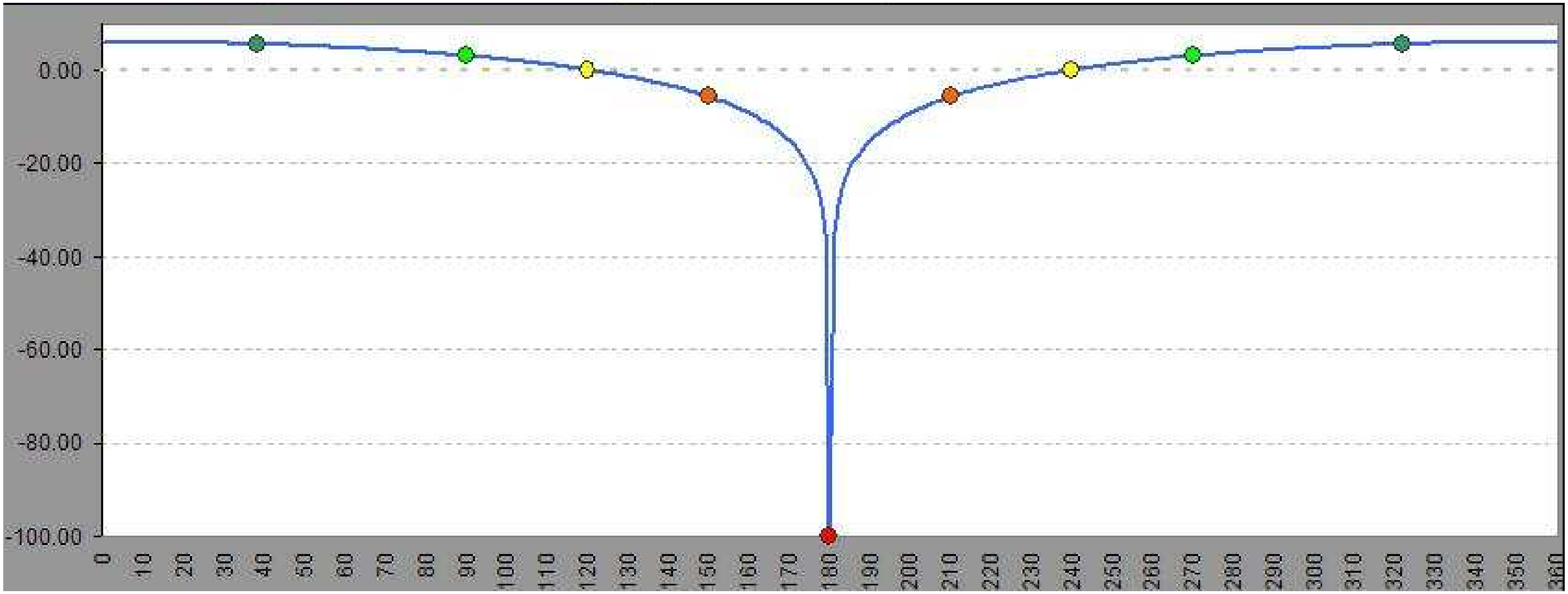
Relative Level Effects on Two Input Summation
(Matched sources with 0 degrees relative phase)
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
dB
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
dB Relative
Signal 1
Signal 2
Summation

# Acoustic Addition & Subtraction: The Phase Wheel




two identical signals summed at same level

# Acoustic Addition & Subtraction: Level vs. Phase




two identical signals summed at same level

# Factors Affecting Response at Summation Point

1. Level offset due to distance offset (inverse square law)
2. Level offset due to polar response (frequency dependent)
3. Phase offset due to path length difference

# Summation: Response Ripple

1. Time offsets shift all frequencies by the same amount of time
2. Time offsets shift all frequencies by a different amount of phase
3. Result of summation with time offset (of signals at same frequency) is response ripple

# Summation Zones Defined

- Coupling zone
  - Sources within ±1/3 wavelength (±120º)
  - Amount of addition ranges for 0 to 6 dB depending on phase/level offset
  - Ripple is ±3 dB
  - Most easily achieved at low frequencies due to large wavelengths

# Summation Zones Defined

- Cancellation zone
  - Effects only subtractive
  - Phase offset 150º to 180º
  - Ripple ±50 dB

# Summation Zones Defined

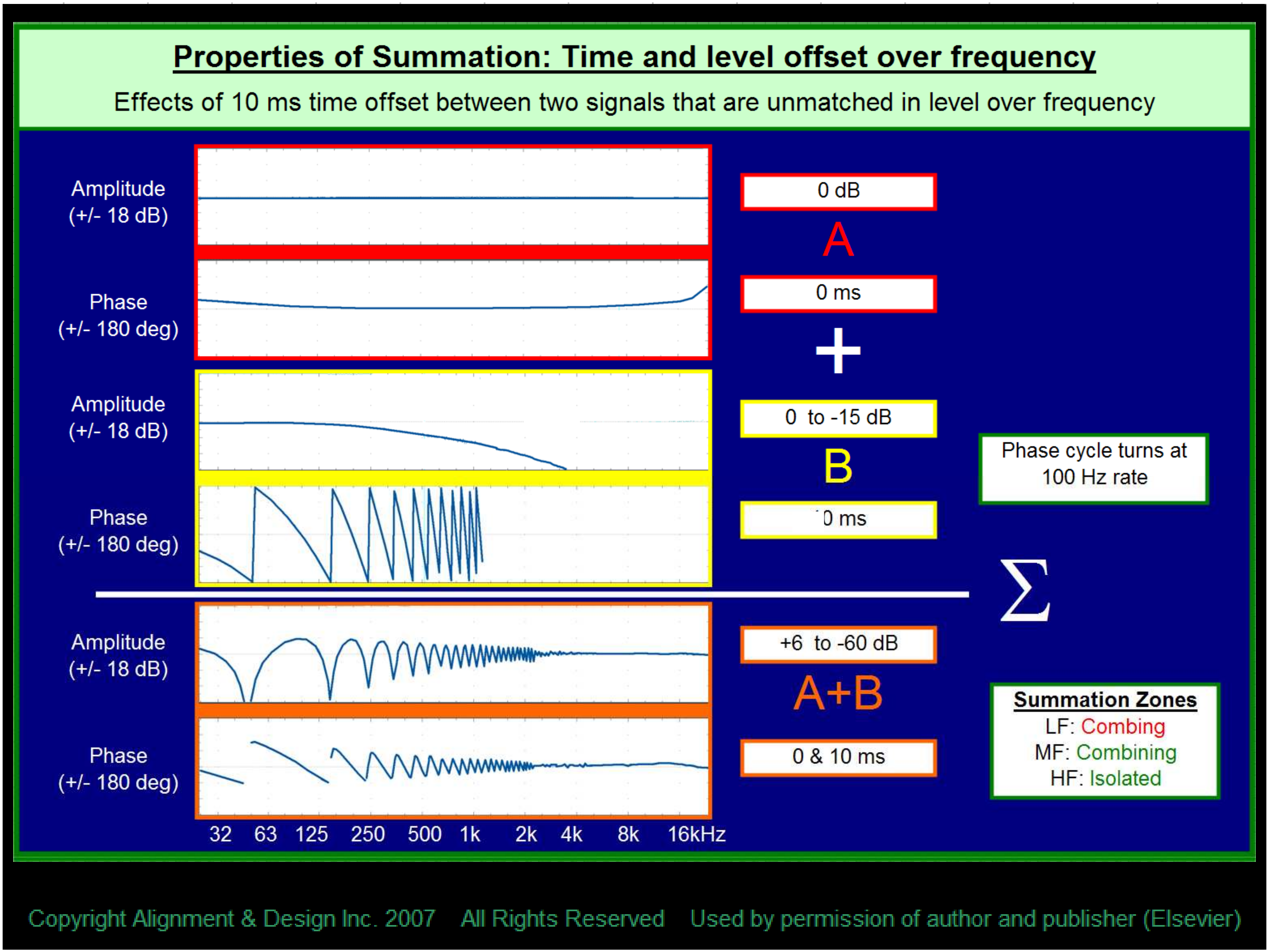
- Combing Zone
  - Phase offset reaches point where subtraction begins (> ±120º)
  - Less than 4 dB level difference
  - Characterized by addition at some frequencies and dips at others
  - Ripple ranges from ±6 dB to ±50 dB
  - To be avoided – highest form of variance over frequency

# Summation Zones Defined

- Combining Zone
  - Level offset ranges from 4 dB to 10 dB
  - Semi-isolated state relative to sources, which limits the magnitude of addition/cancellation
  - Ripple no more than ±6 dB

# Summation Zones Defined

- Isolation Zone
  - 10 dB or more of level offset
  - Relative interactions steadily reduced and eventually become negligible
  - At large level offset, relative phase has nominal effect
  - Ripple does not exceed 6 dB



Properties of Summation: Time and level offset over frequency
Effects of 10 ms time offset between two signals that are unmatched in level over frequency
Amplitude (+/- 18 dB)
Phase (+/- 180 deg)
Amplitude (+/- 18 dB)
Phase (+/- 180 deg)
Amplitude (+/- 18 dB)
Phase (+/- 180 deg)
0 dB
A
0 ms
+
0 to -15 dB
B
0 ms
Phase cycle turns at 100 Hz rate
Σ
+6 to -60 dB
A+B
0 & 10 ms
Summation Zones
LF: Combing
MF: Combining
HF: Isolated
32 63 125 250 500 1k 2k 4k 8k 16kHz
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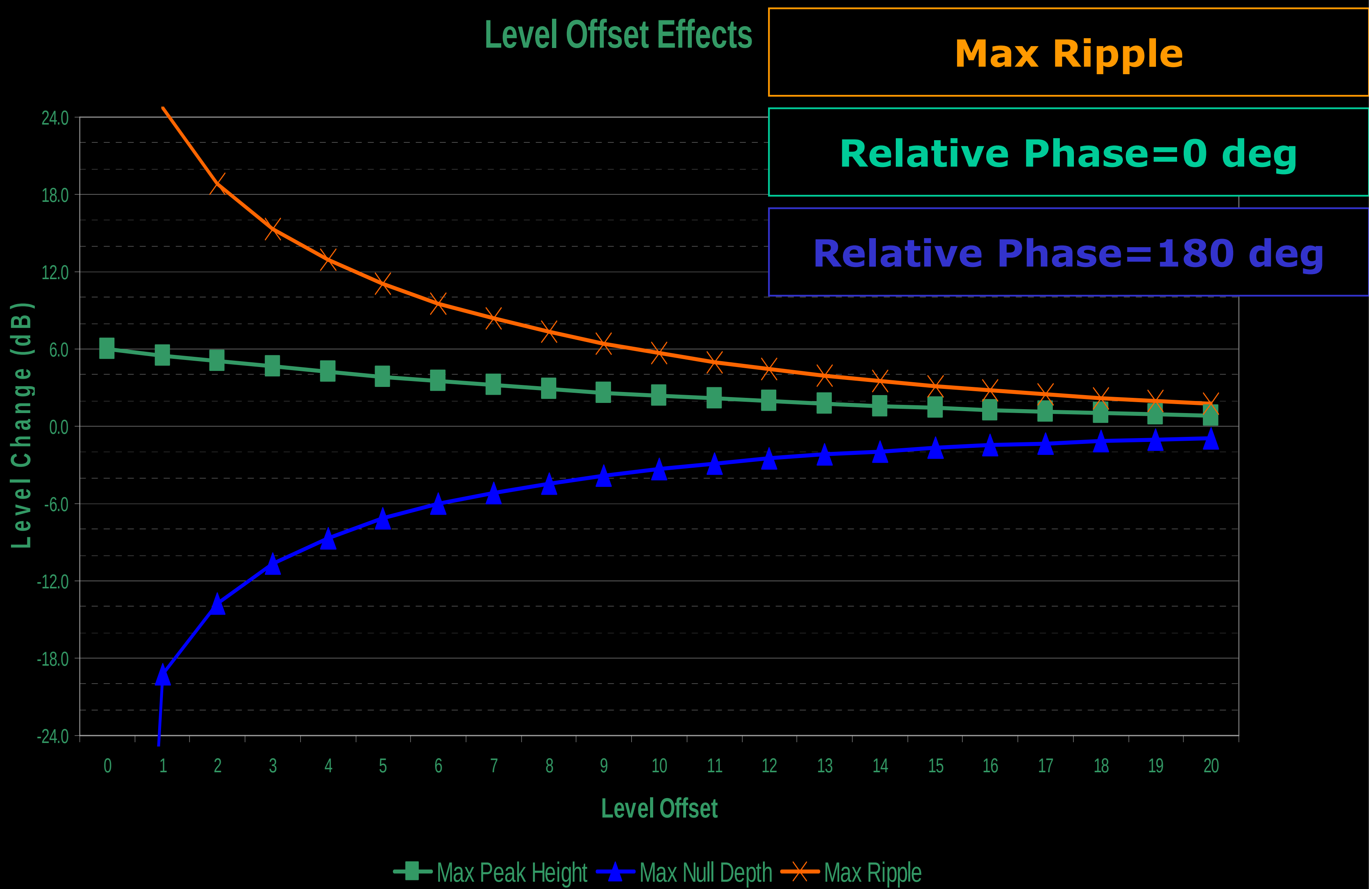
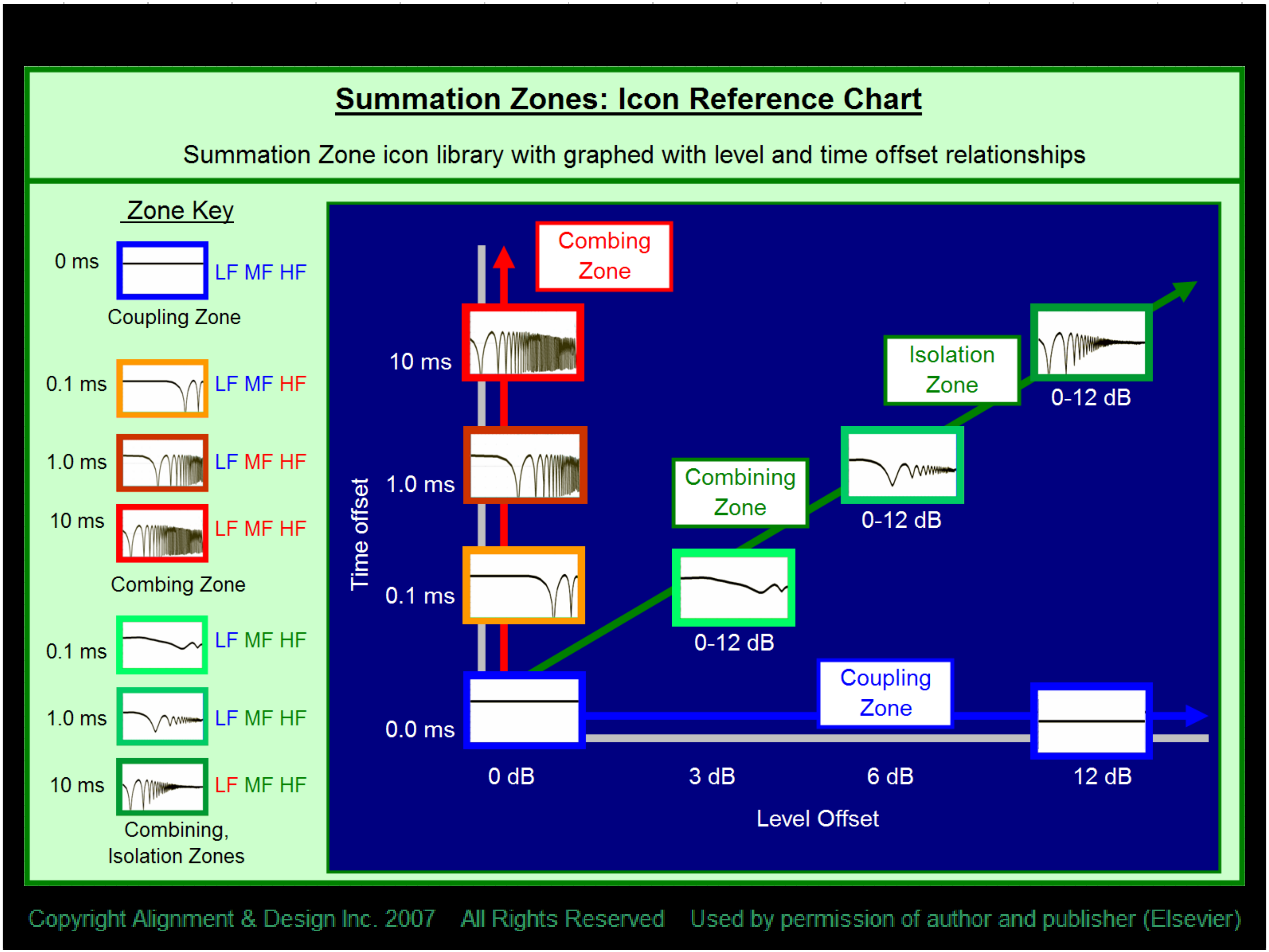
# Acoustic Addition and Subtraction: Level Offset Effects




Summation Zones: Icon Reference Chart
Summation Zone icon library with graphed with level and time offset relationships
Zone Key
0 ms
LF MF HF
Coupling Zone
0.1 ms
LF MF HF
1.0 ms
LF MF HF
10 ms
LF MF HF
Combing Zone
0.1 ms
LF MF HF
1.0 ms
LF MF HF
10 ms
LF MF HF
Combining,
Isolation Zones
Combing
Zone
Isolation
Zone
Combining
Zone
Coupling
Zone
10 ms
1.0 ms
0.1 ms
0.0 ms
Time offset
0-12 dB
0-12 dB
0-12 dB
0 dB
3 dB
6 dB
12 dB
Level Offset
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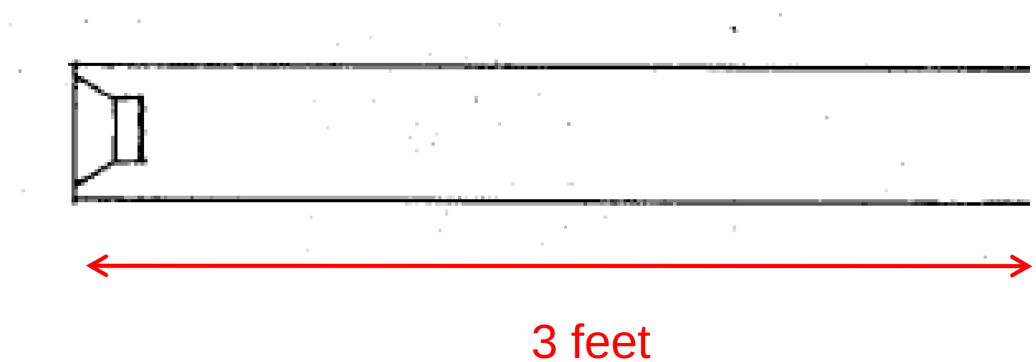
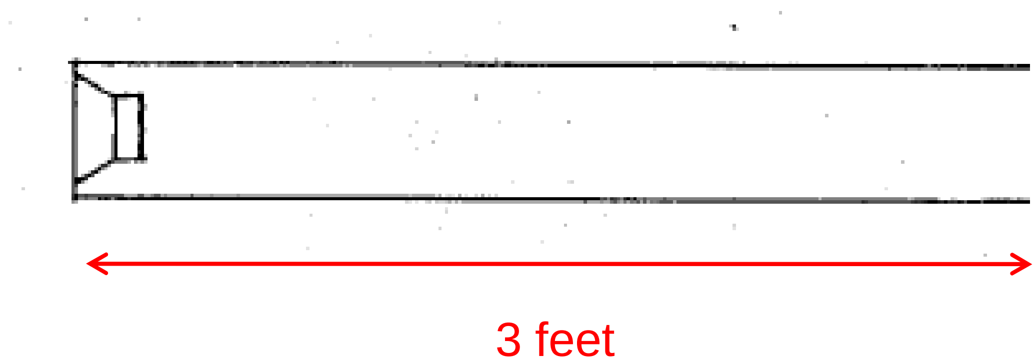
# Application

- loudspeaker mounted in a rigid (undamped) pipe 3 feet in length, open at one end, observed on-axis from “speaker end”



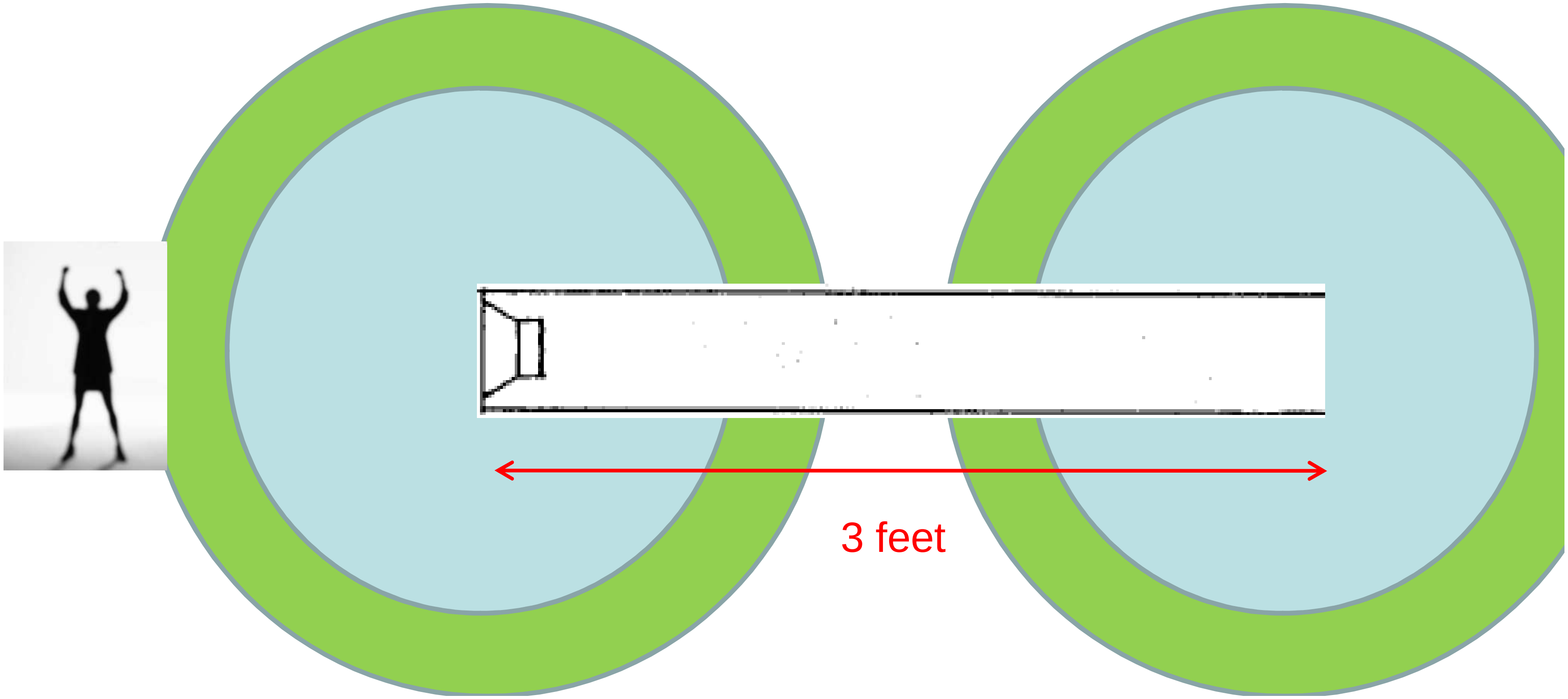
# Application

- how does sound propagate at low frequencies?



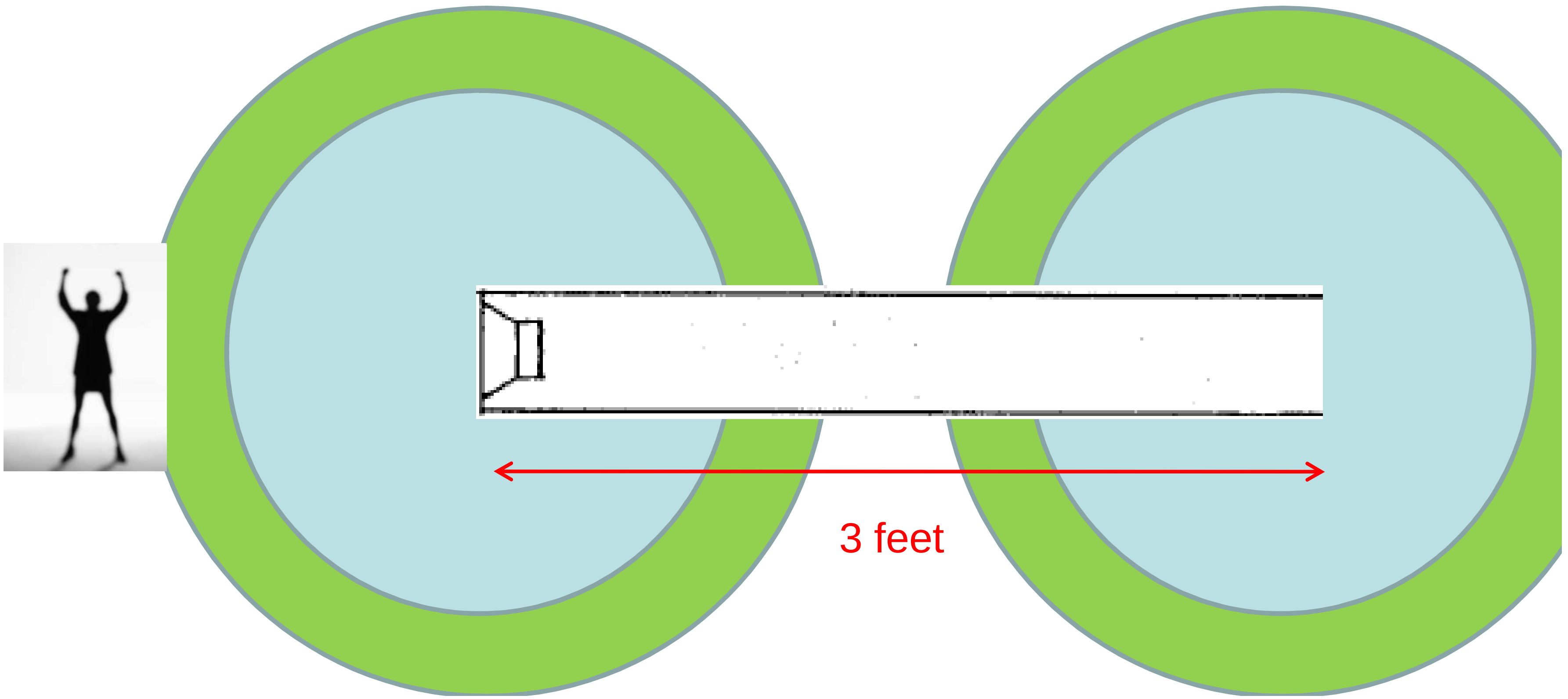
# Application

- how does sound propagate at low frequencies?



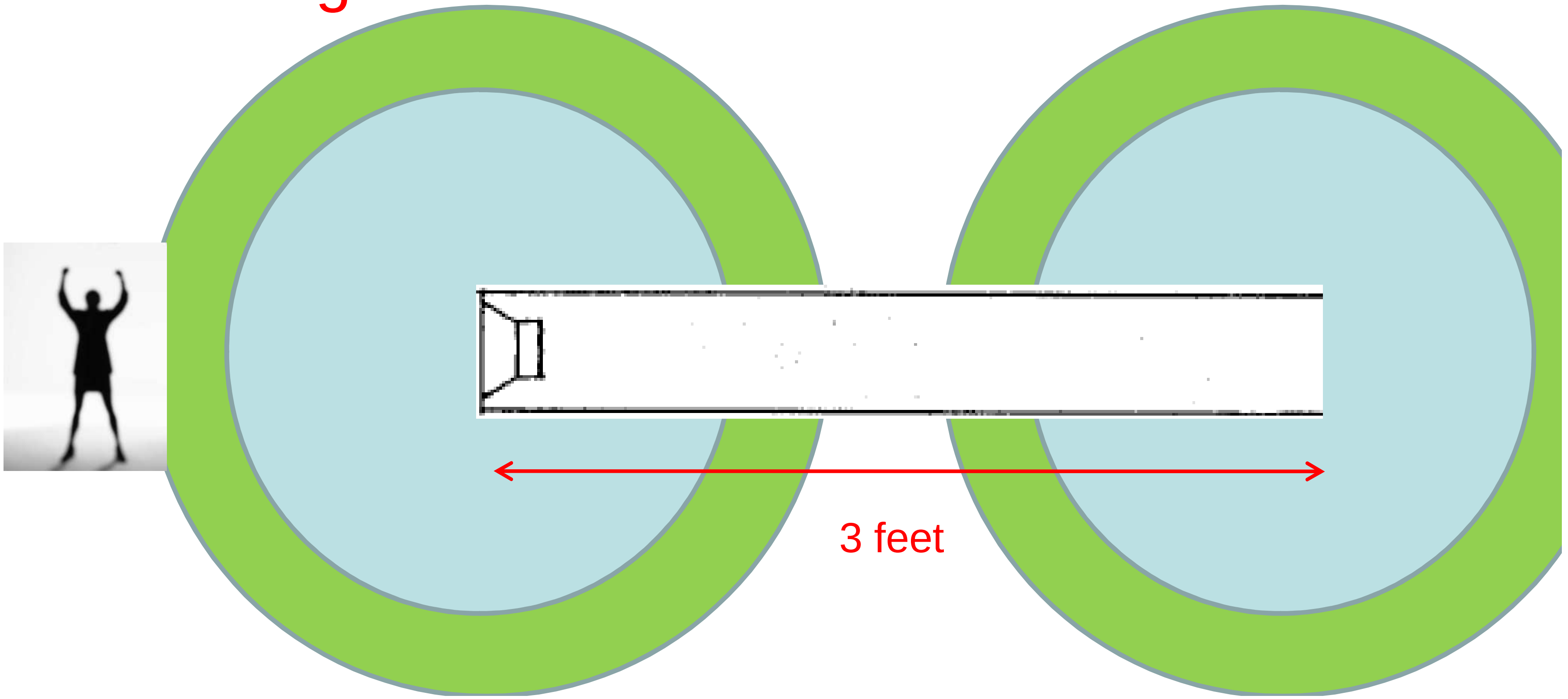
# Application

- if operated at 150 Hz, how much phase shift occurs as the wave traverses the pipe?



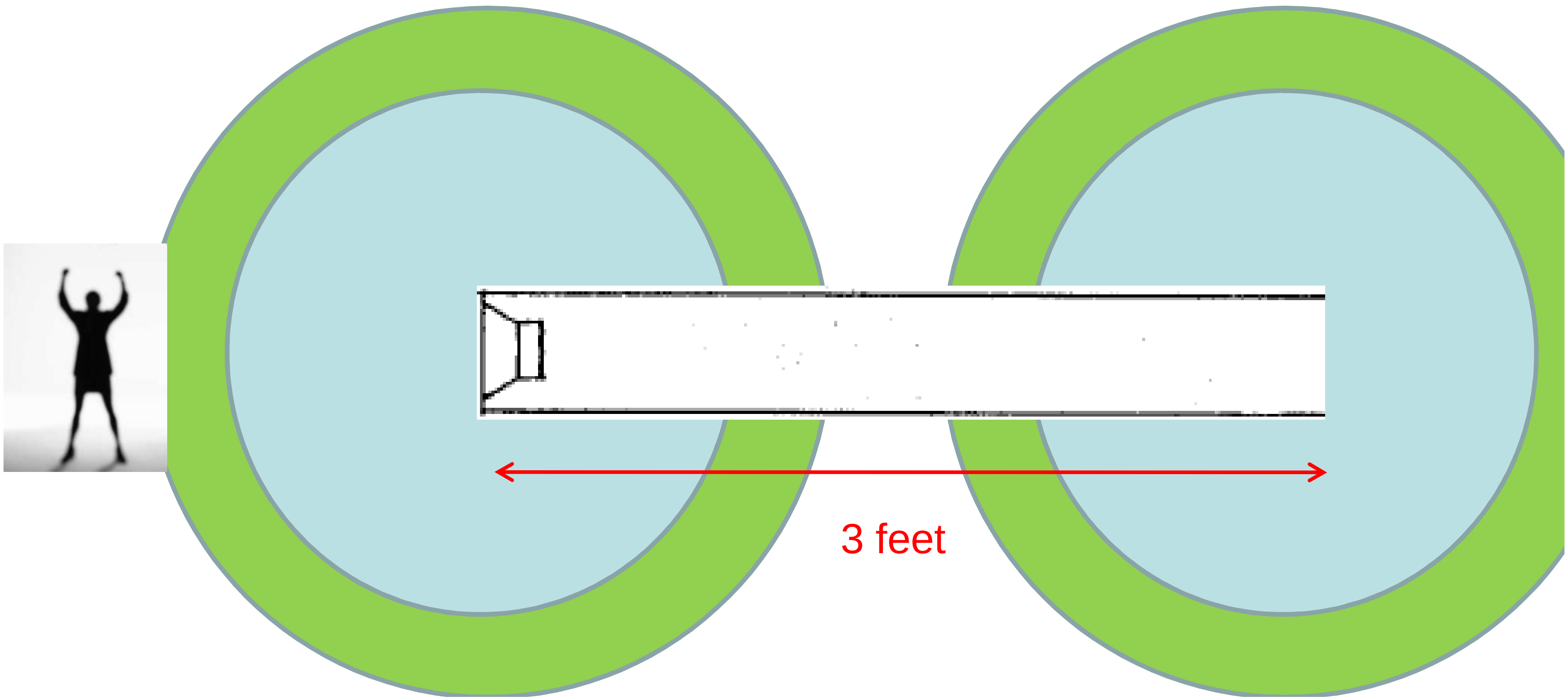
# Application

- if operated at 150 Hz, how much phase shift occurs as the wave traverses the pipe?
  wavelength = 7.53 feet; phase shift = (360x3)/7.53 = 143  degrees



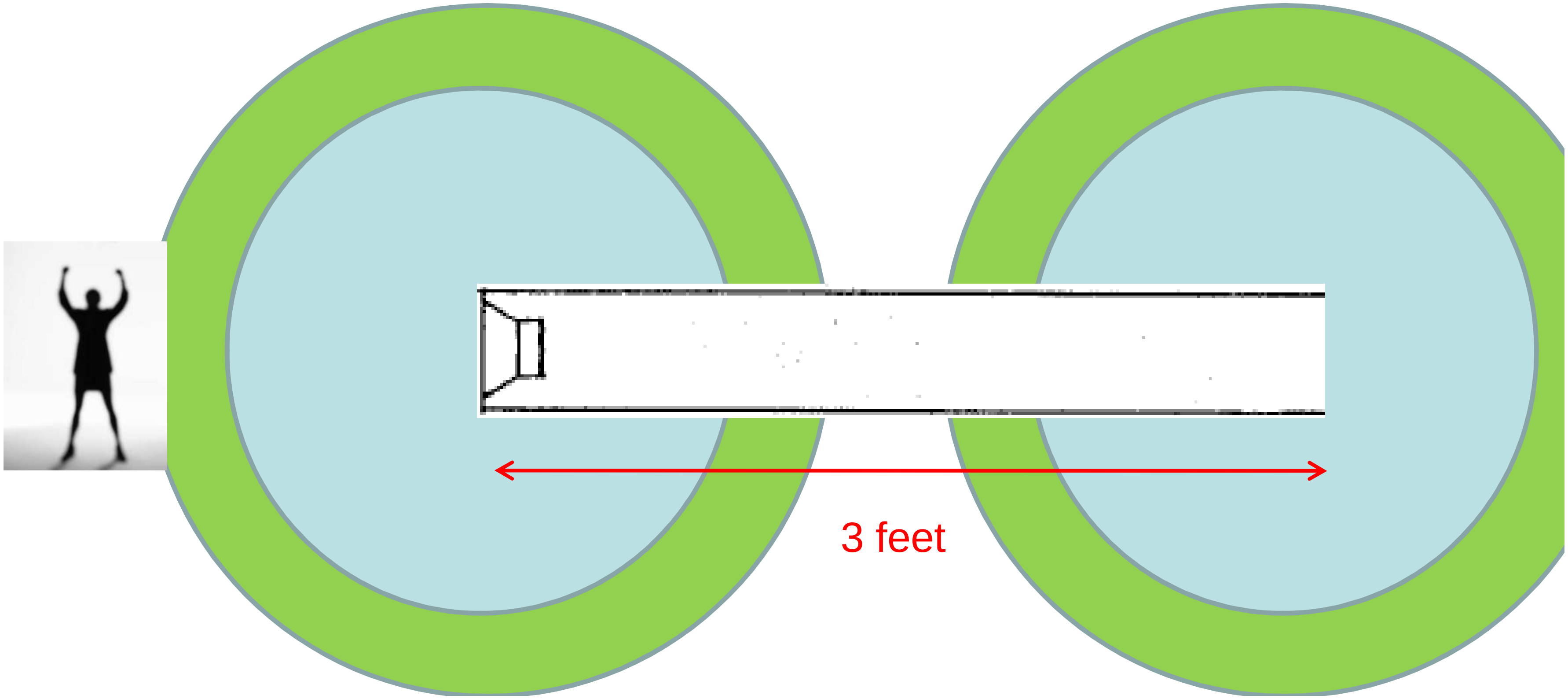
# Application

- what will be level of “combined” signal at observation point?



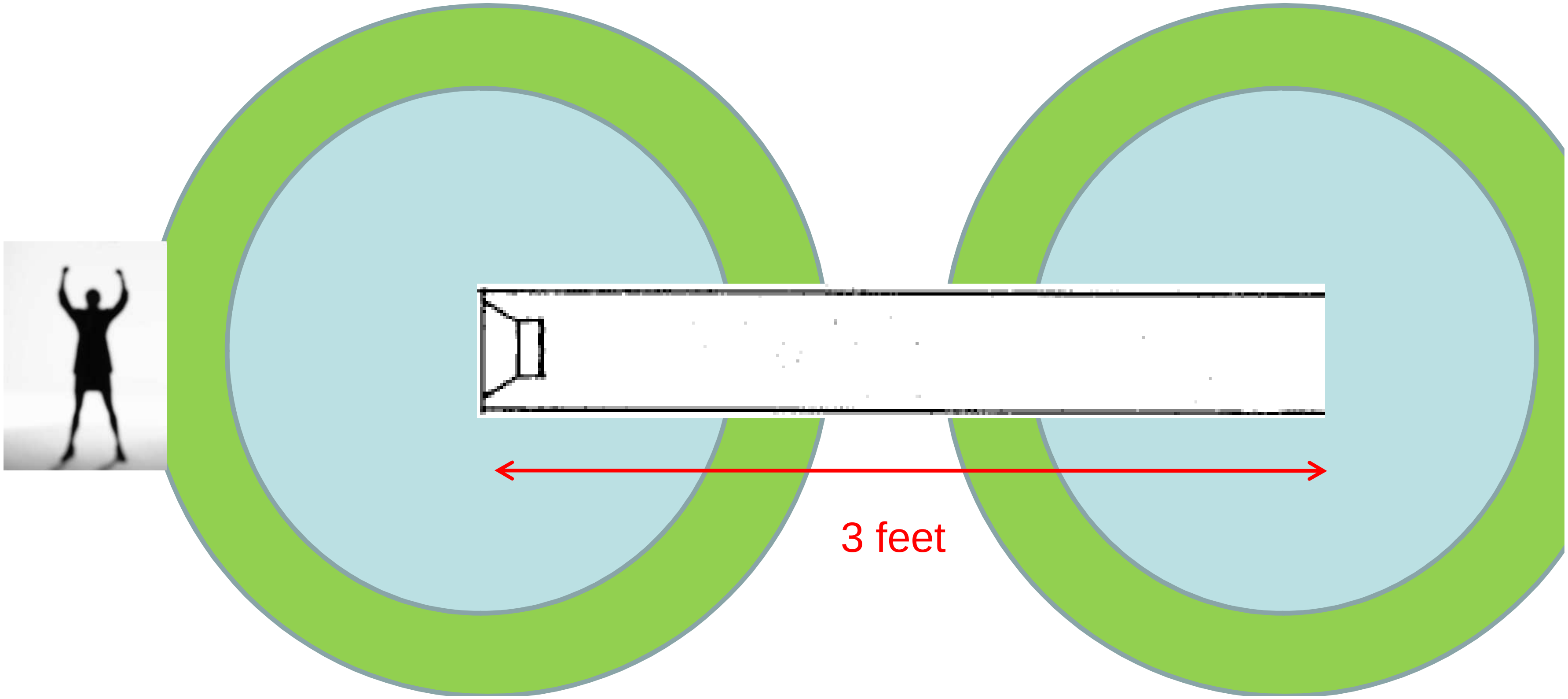
# Application

- what will be level of “combined” signal at observation point? total “round trip” phase shift = 180+143+143=466 degrees (106 degrees net); combined level will be 1.7 dB

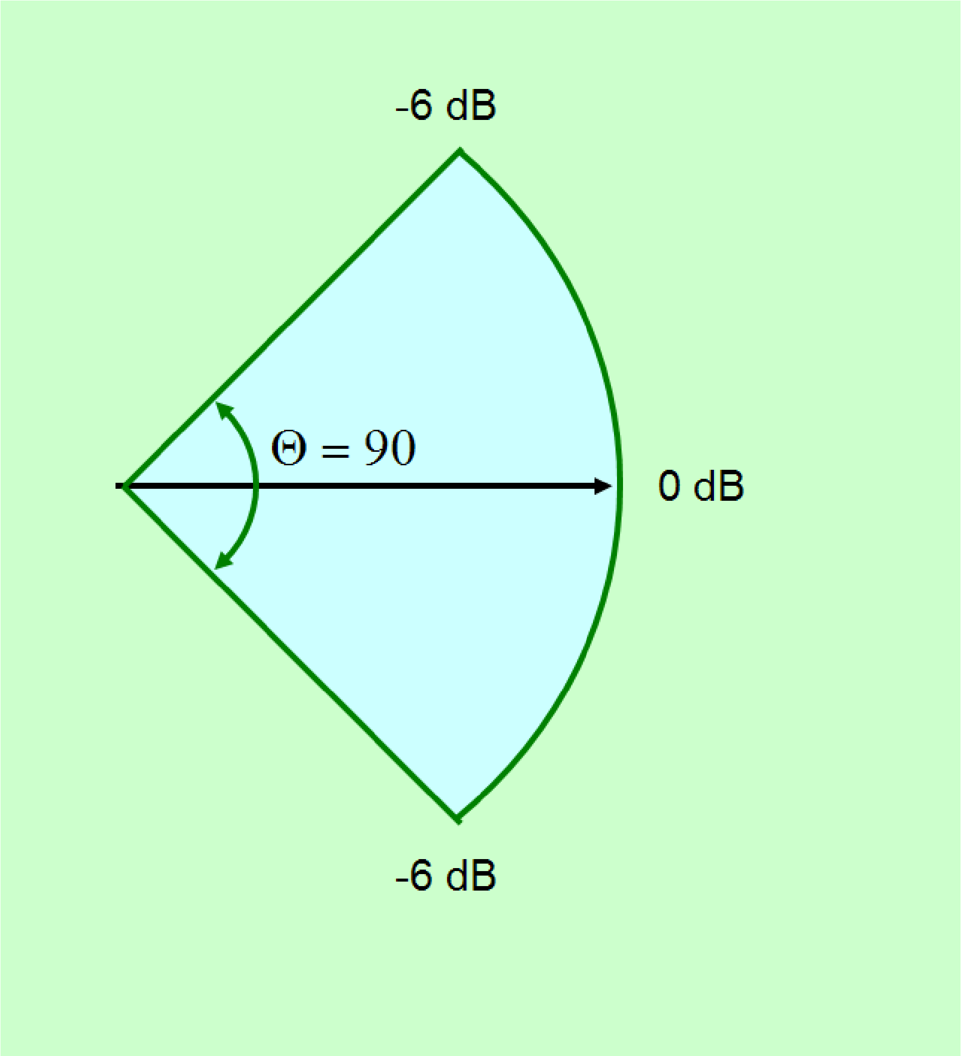


# Application

- if frequency changed to 100 Hz, what will be combined level? wavelength is 11.3 feet; phase shift traversing pipe 96 degrees; round trip phase shift is 371 degrees (nearly "in phase"); combined level is +5.95 dB



# Coverage / Beamwidth

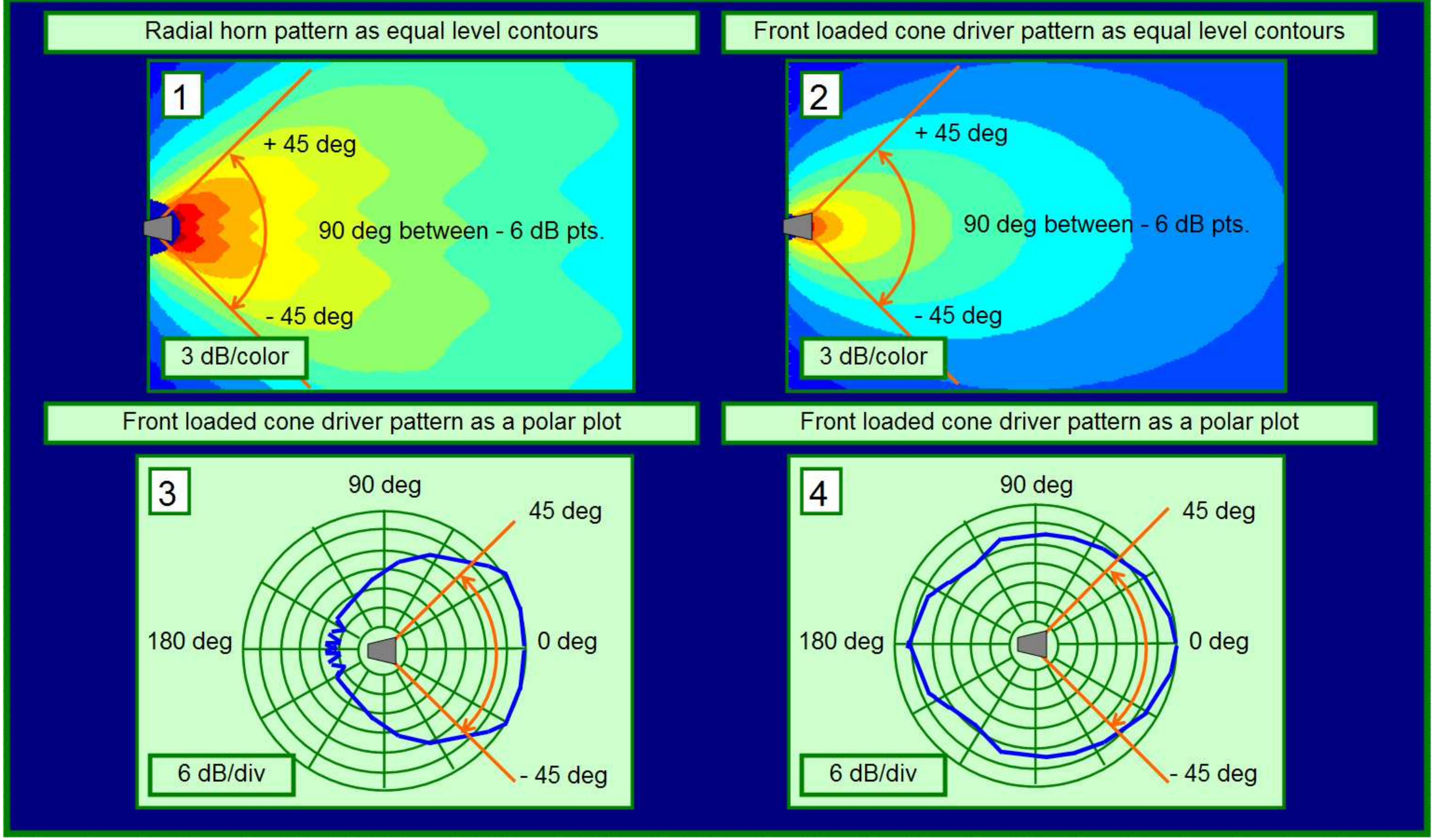


## Common Representations of Loudspeaker Coverage

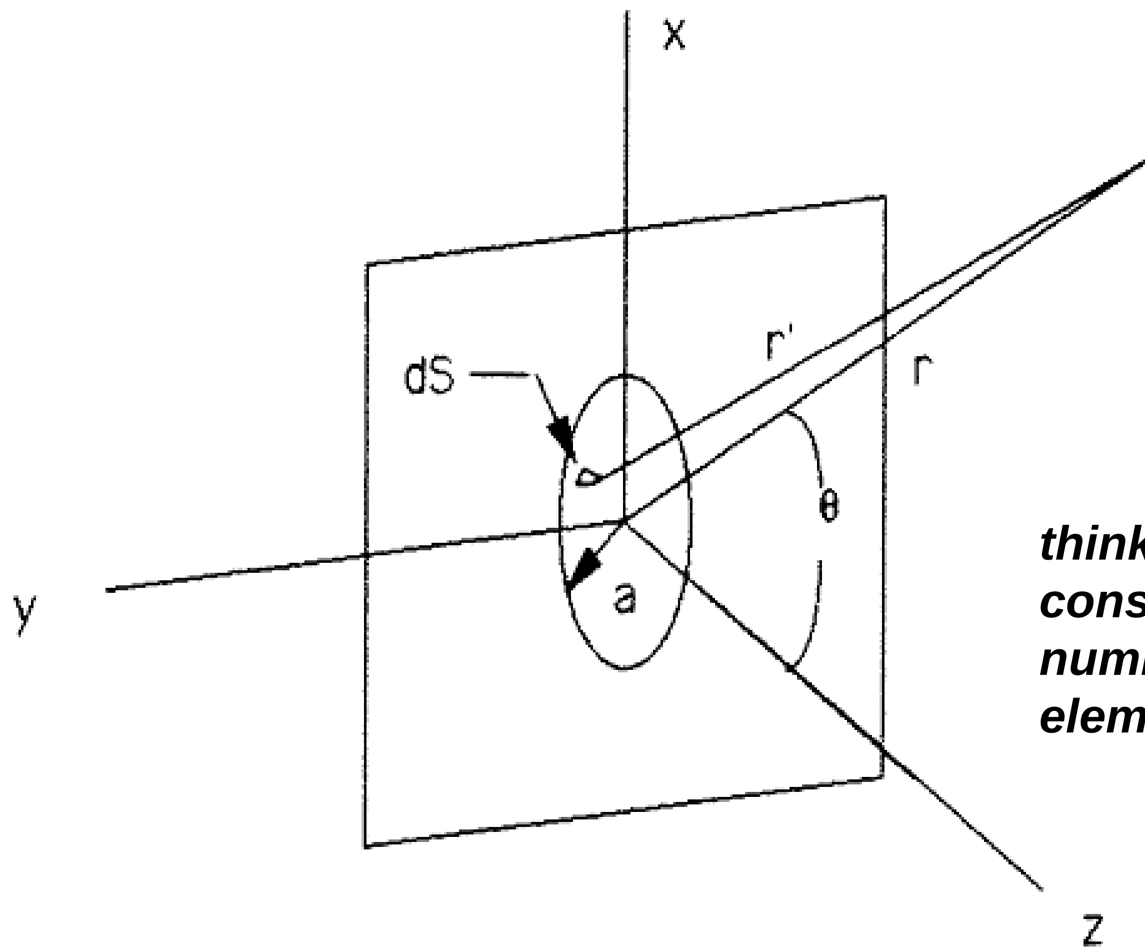
- Coverage angle $C_{<}$ (H / V) = 6 dB Beamwidth
- Polar pattern
- Equal level (isobaric) contours (“isobars”)
- Directivity factor (Q)
- Directivity index ($D_I$) = 10 log Q (also known as “front to back ratio”)
- Beamwidth vs. frequency
- 3D “balloons”

# Speaker Directivity: Coverage Pattern Renderings

Comparing protractor, equal level contour and polar plots for two different "90 degree" speakers



Example: Piston radiation into half-space (e.g., a cone-type loudspeaker mounted in an "infinite" baffle




***think of piston as consisting of a large number of very small elements of size $\Delta$S***

- integrating over the entire piston surface yields

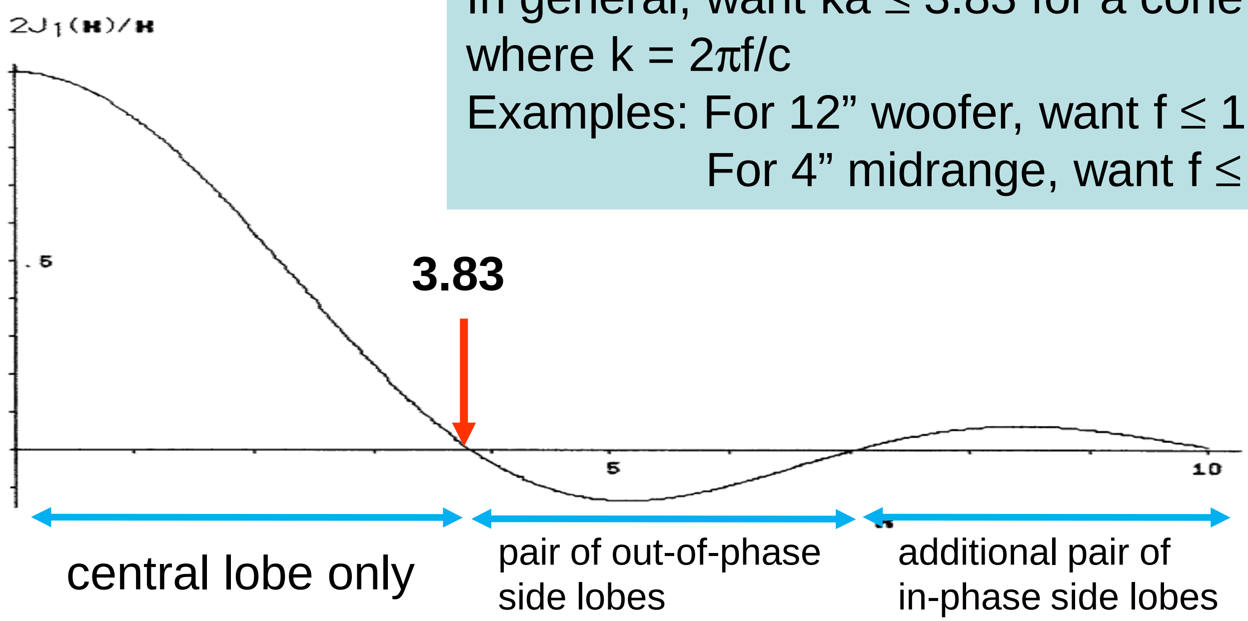
$$p(r,t,\theta) = -\frac{\rho_0 \omega u_m S}{2\pi r} \sin(\omega t - kr) \left[ \frac{2J_1(ka \sin\theta)}{ka \sin\theta} \right]$$

where S is the piston area $\pi a^2$ and $J_1$ is a Bessel function of first order

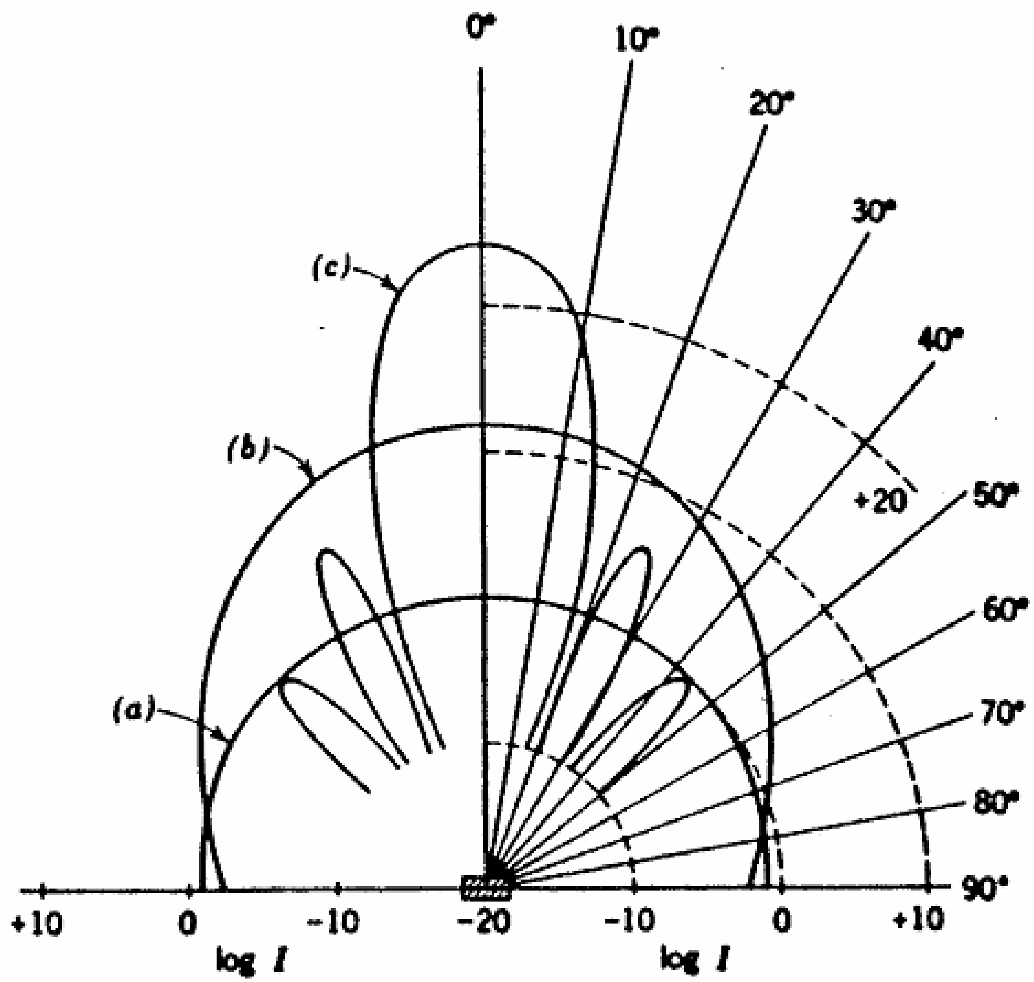
$$p(r,t,\theta) = -\frac{\rho_0 \omega u_m a^2}{2r} \sin(\omega t - kr) \left[ \frac{2J_1(ka \sin\theta)}{ka \sin\theta} \right]$$

- plot of $2 J_1(x)/x$

In general, want ka ≤ 3.83 for a cone radiator, where k = 2πf/c
Examples: For 12” woofer, want f ≤ 1378 Hz
For 4” midrange, want f ≤ 4134 Hz

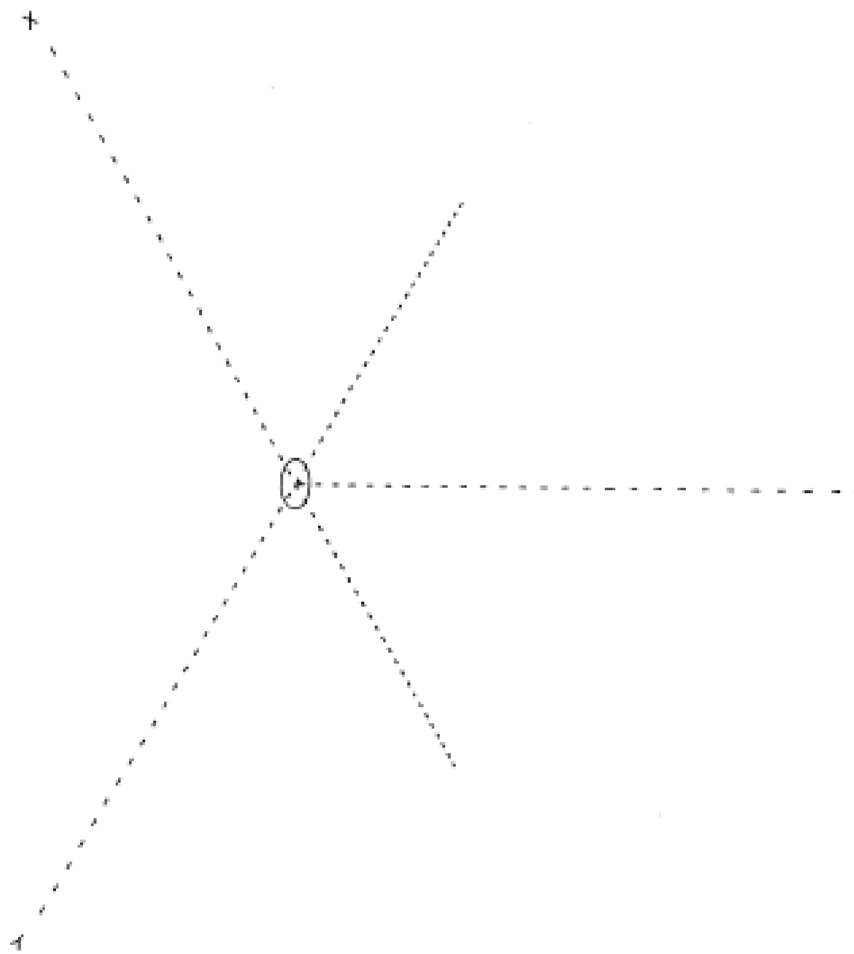


• directivity pattern of a flat piston for three different frequencies

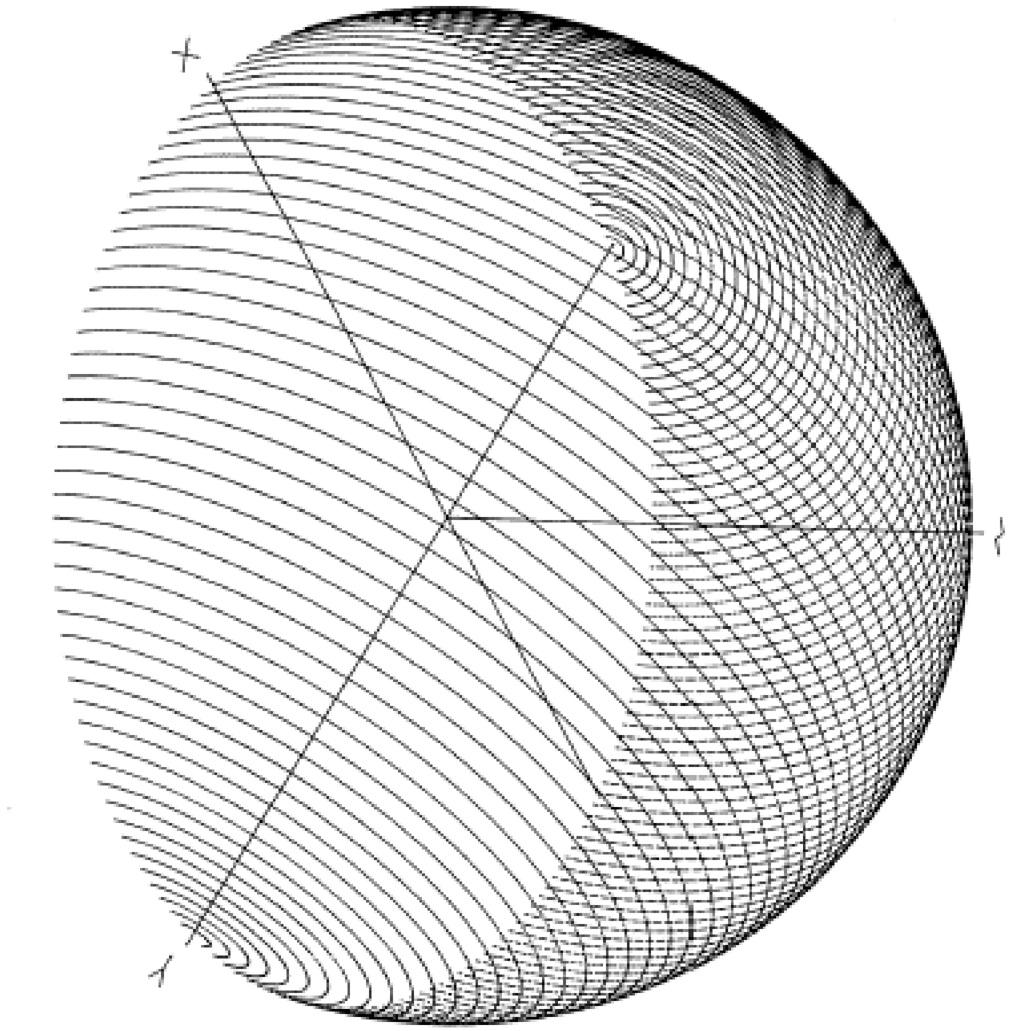



(a) λ=8a, (b) λ=2a, (c) λ=a/2

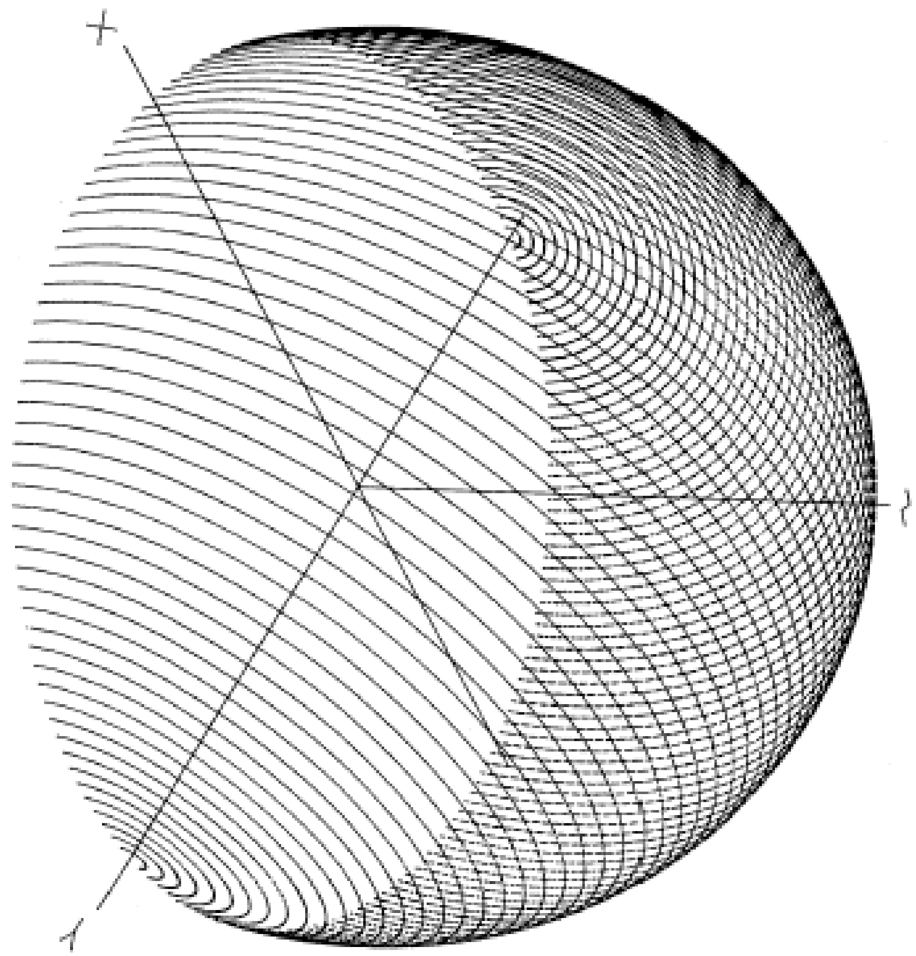
# Single 4-inch Loudspeaker



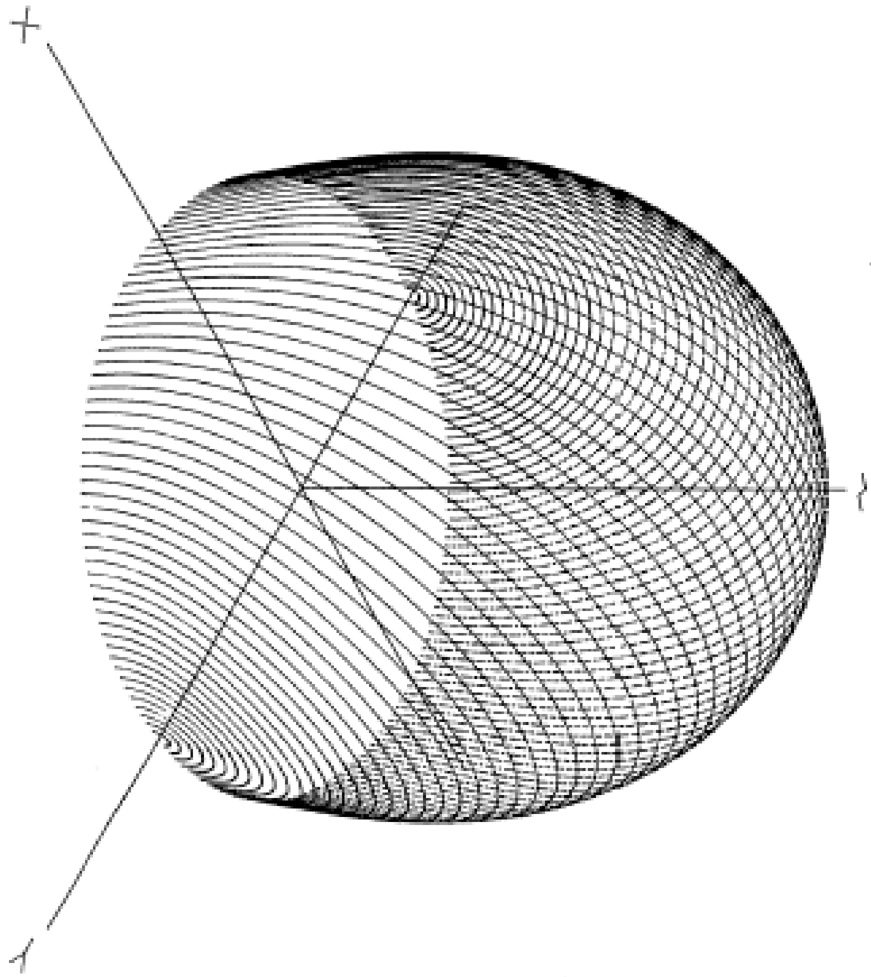
# Single 4-inch Loudspeaker @ 500 Hz



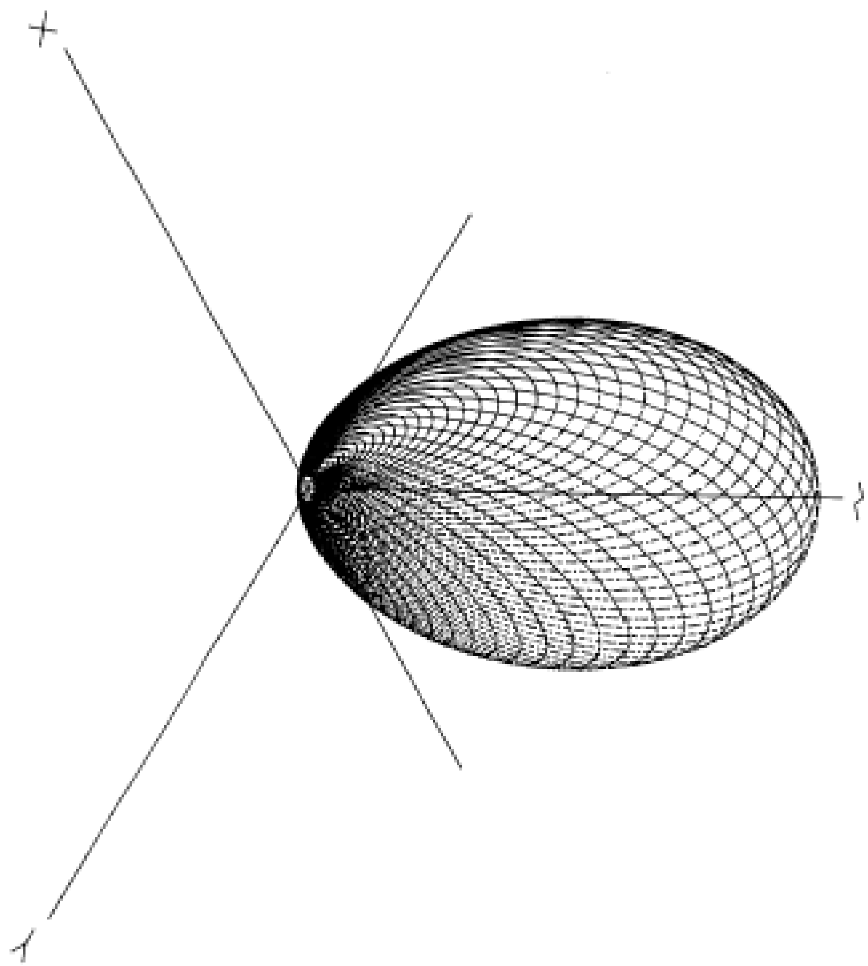
# Single 4-inch Loudspeaker @ 1000 Hz



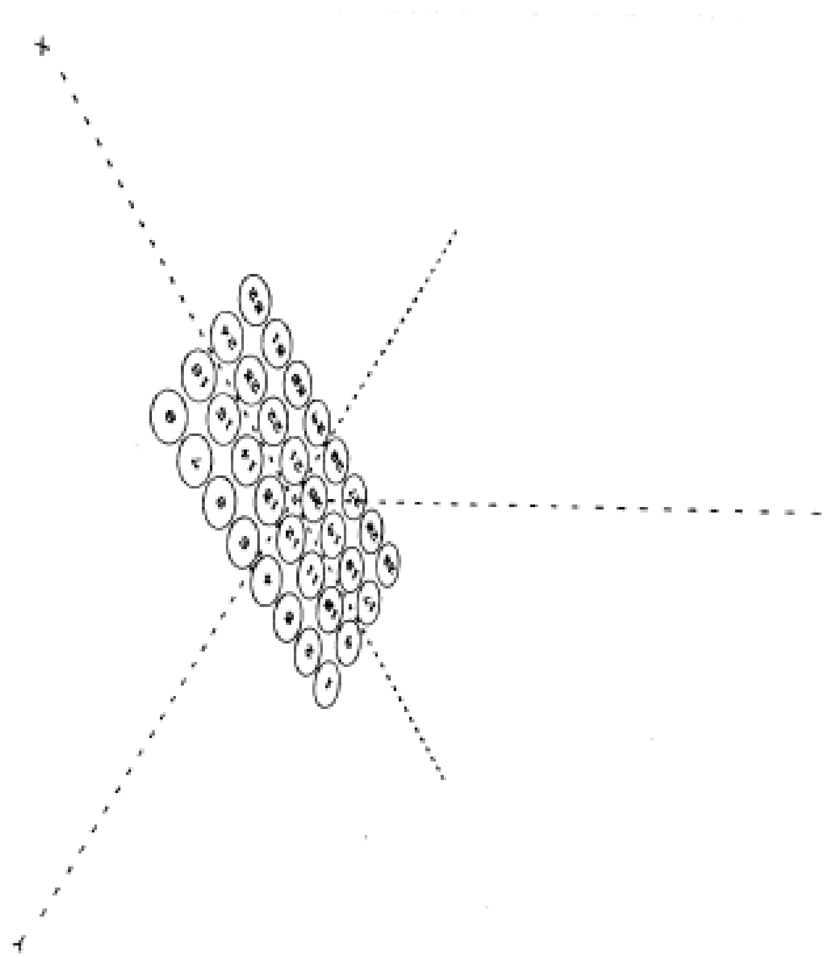
# Single 4-inch Loudspeaker @ 2000 Hz



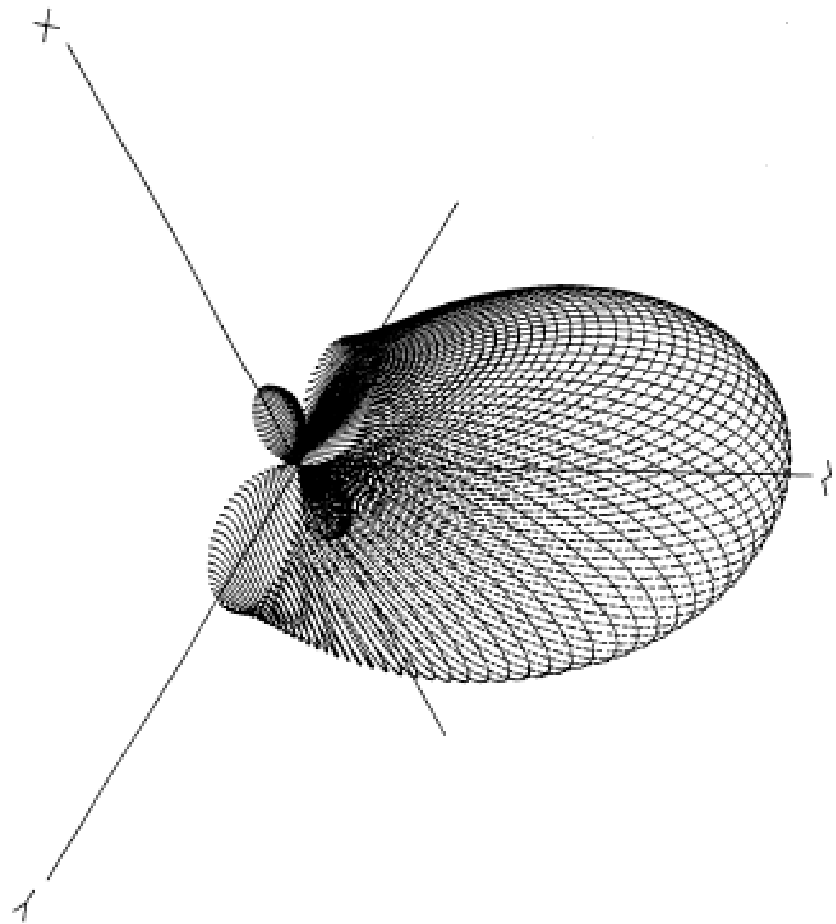
# Single 4-inch Loudspeaker @ 4000 Hz



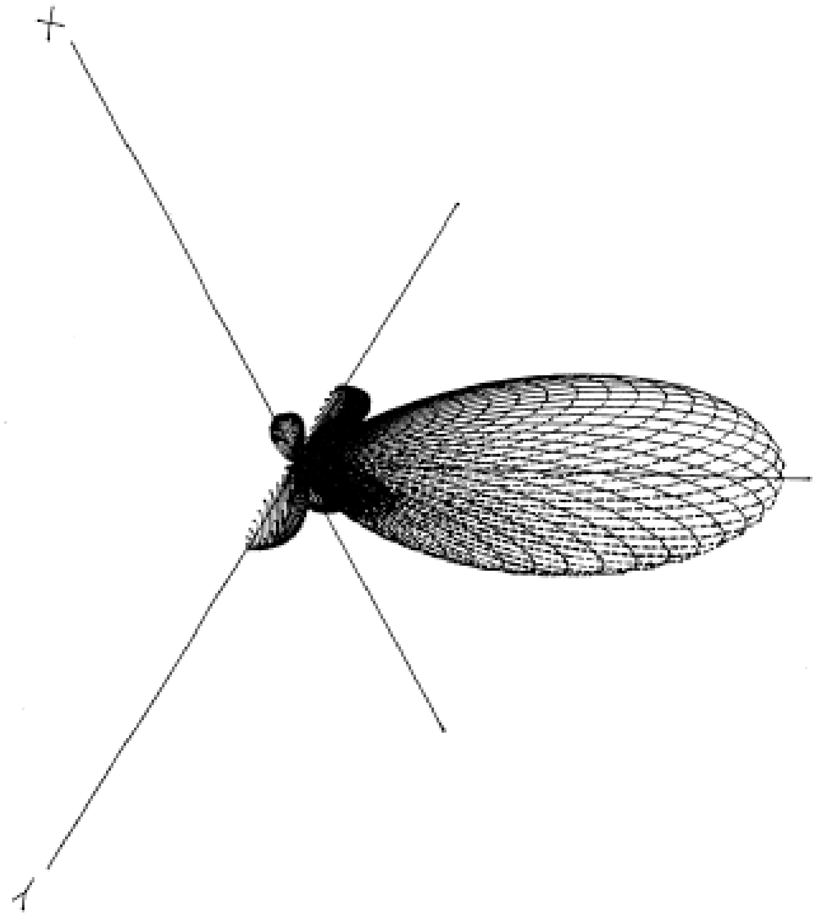
# 32-Element Array of 4-inch Drivers



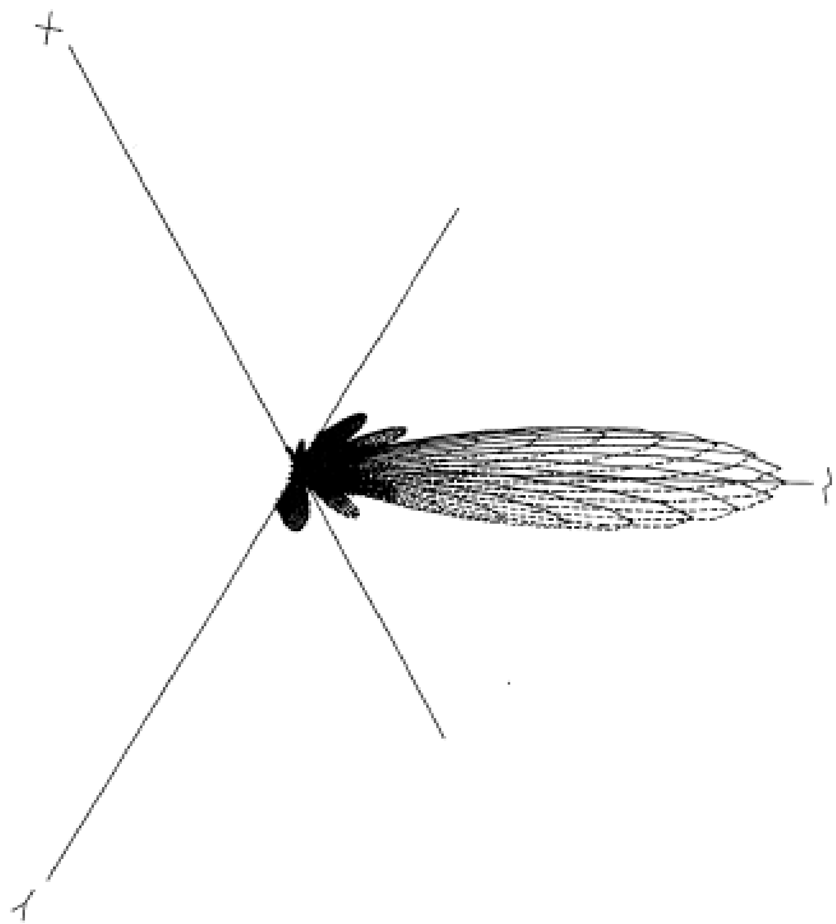
# 32-Element Array @ 500 Hz



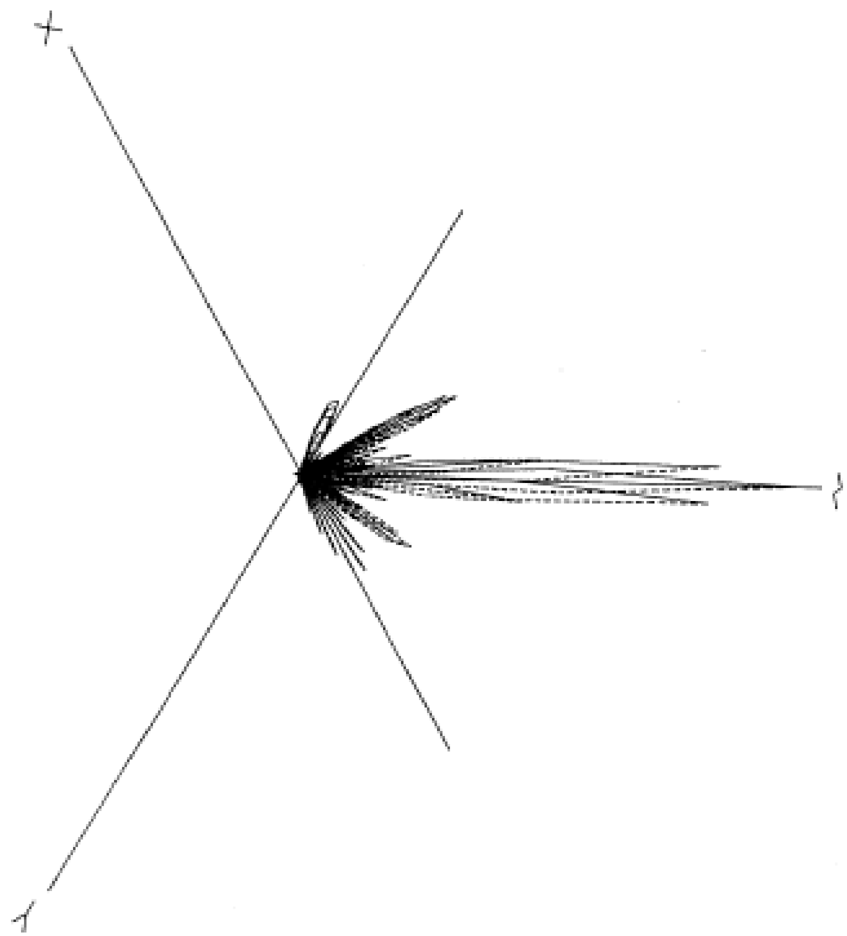
# 32-Element Array @ 1000 Hz



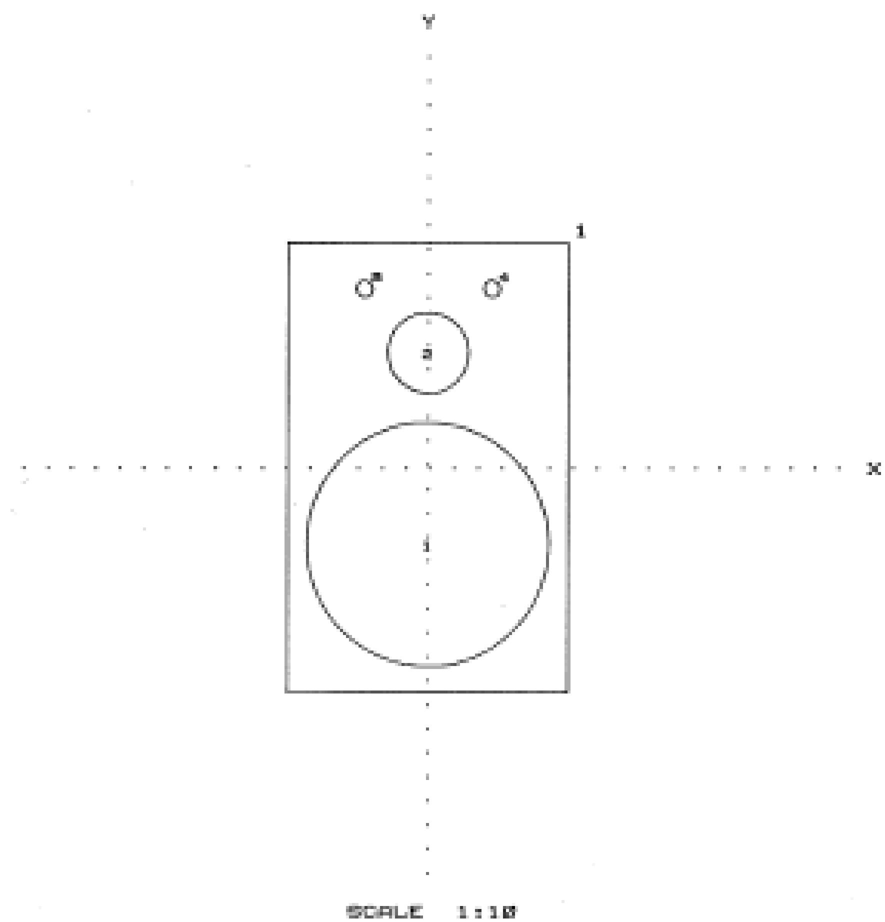
# 32-Element Array @ 2000 Hz



# 32-Element Array @ 4000 Hz



# “Home Stereo” Multi-way System



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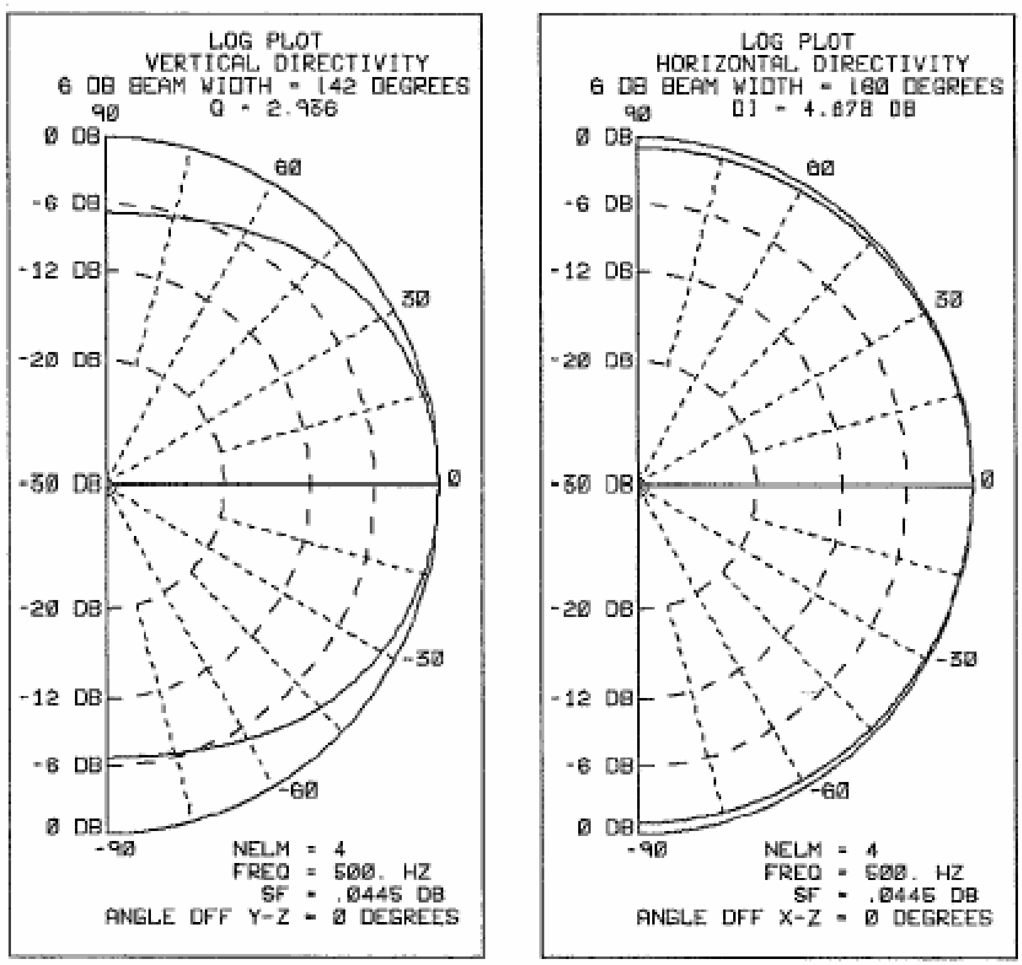

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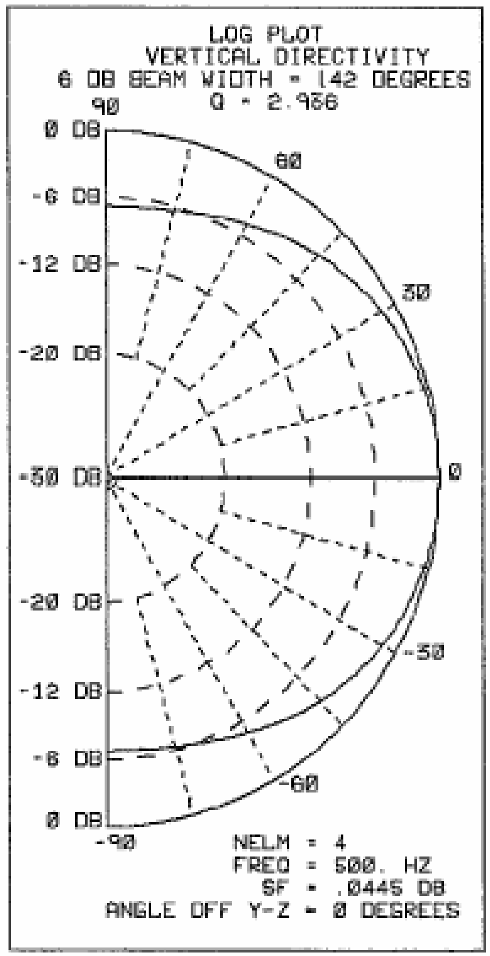


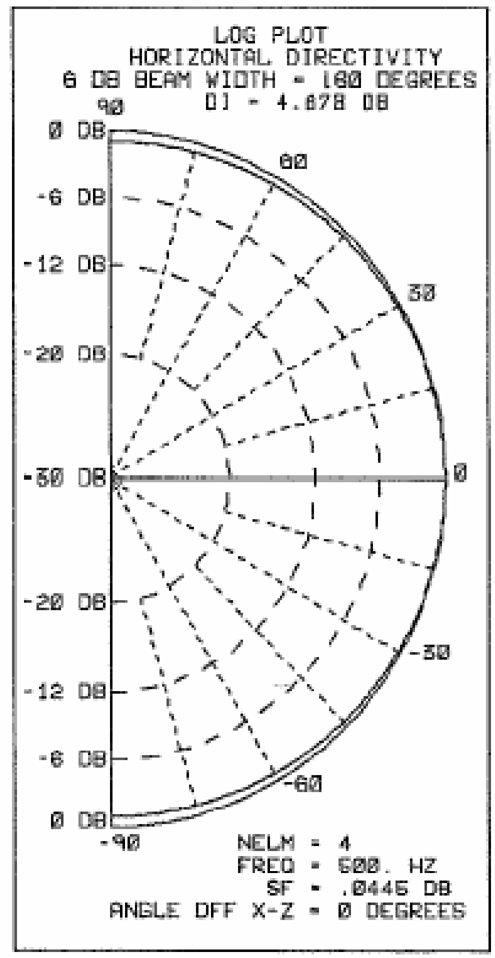

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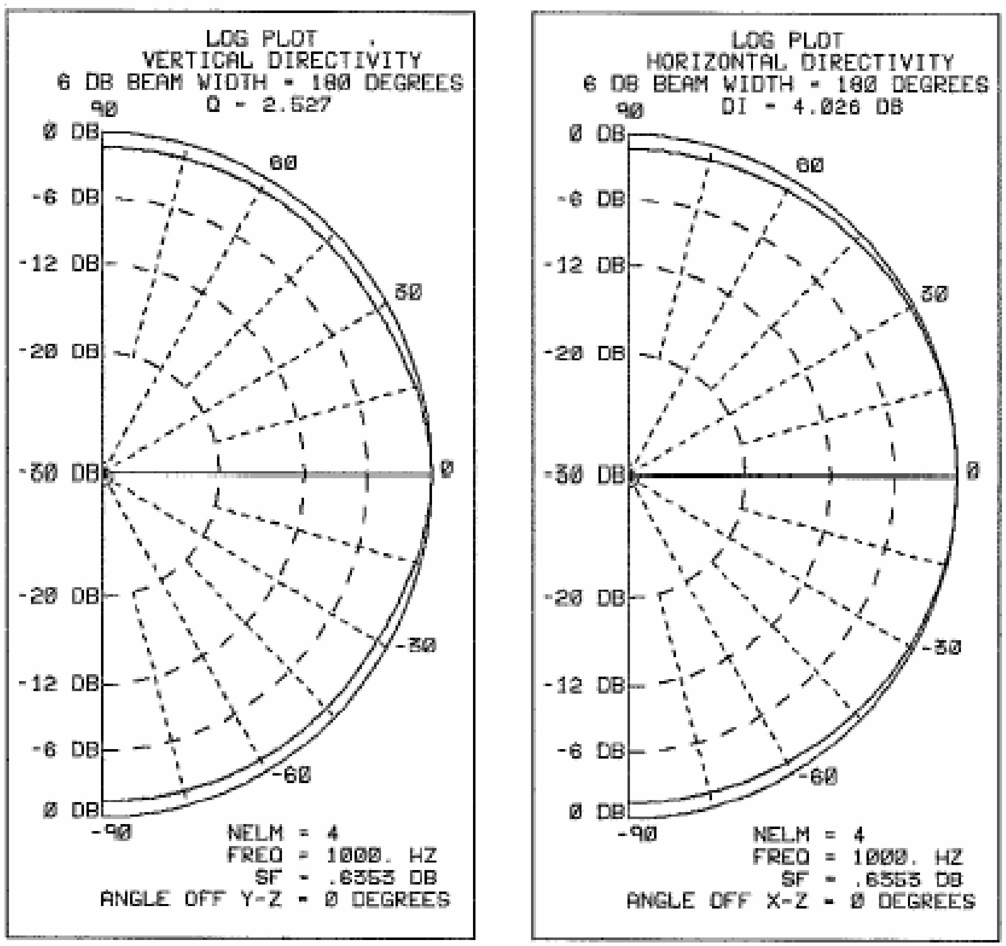

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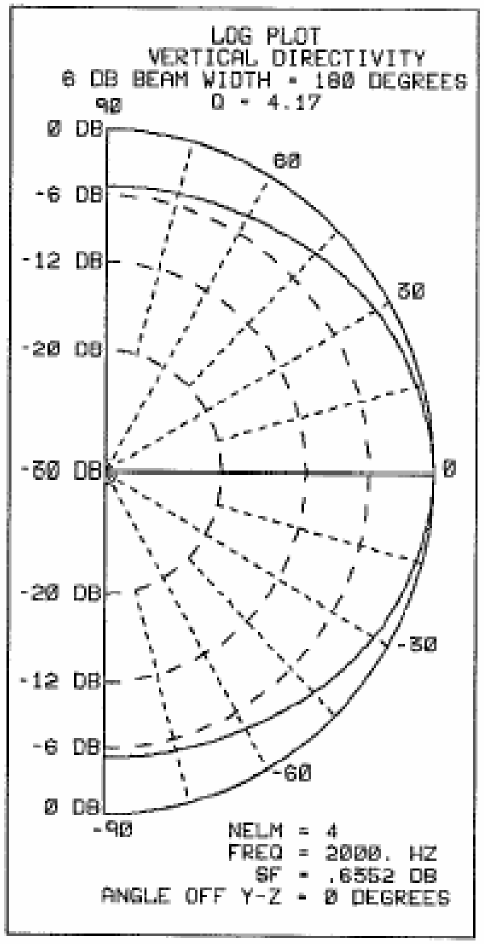


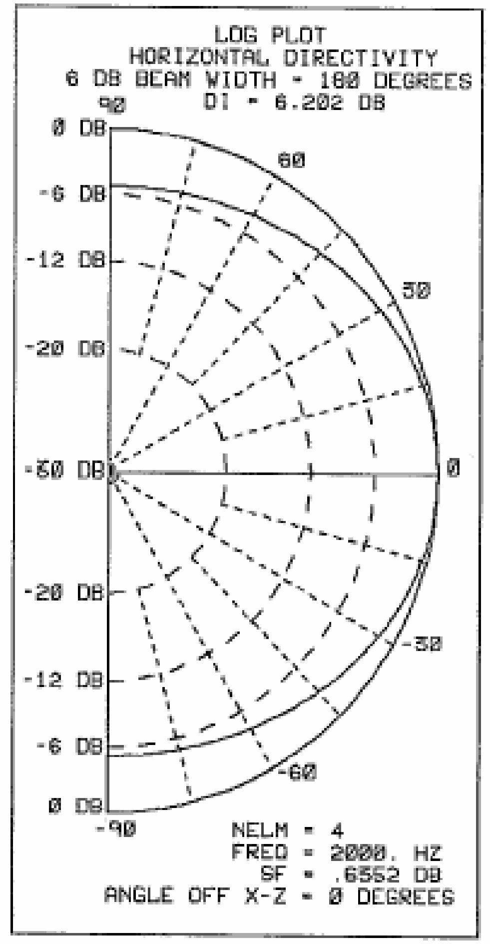

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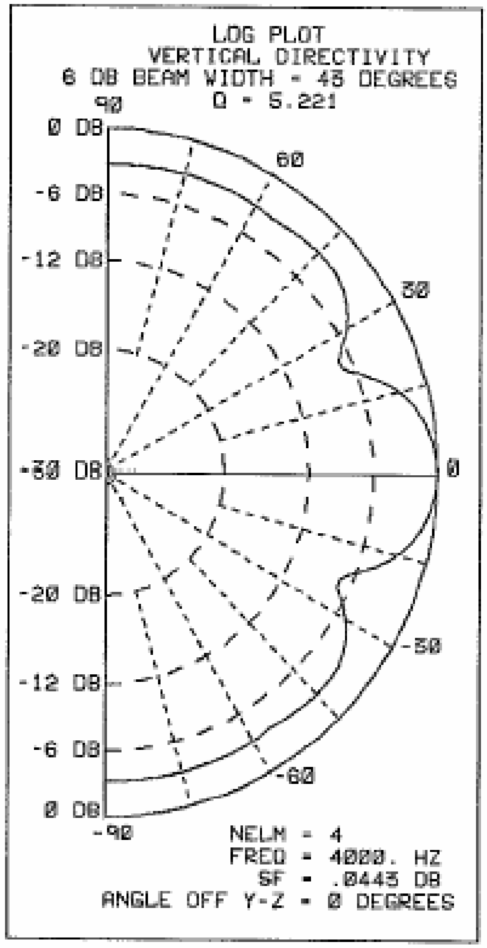


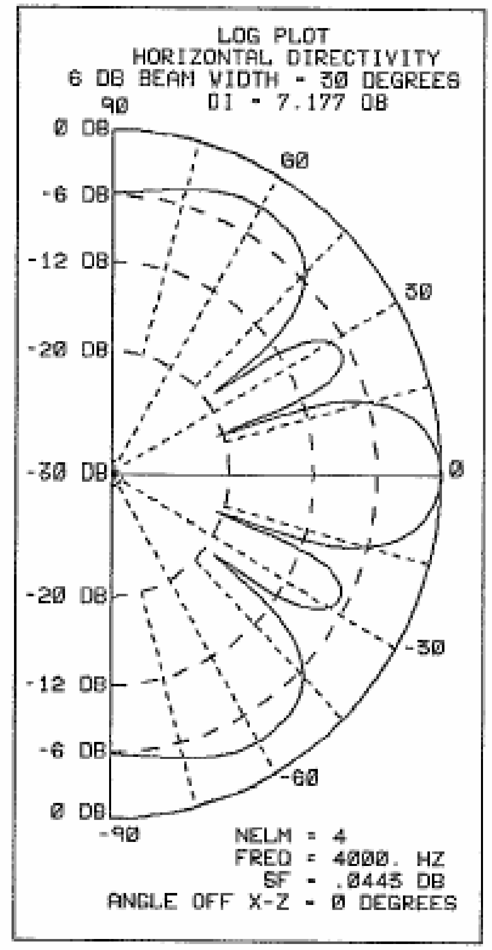

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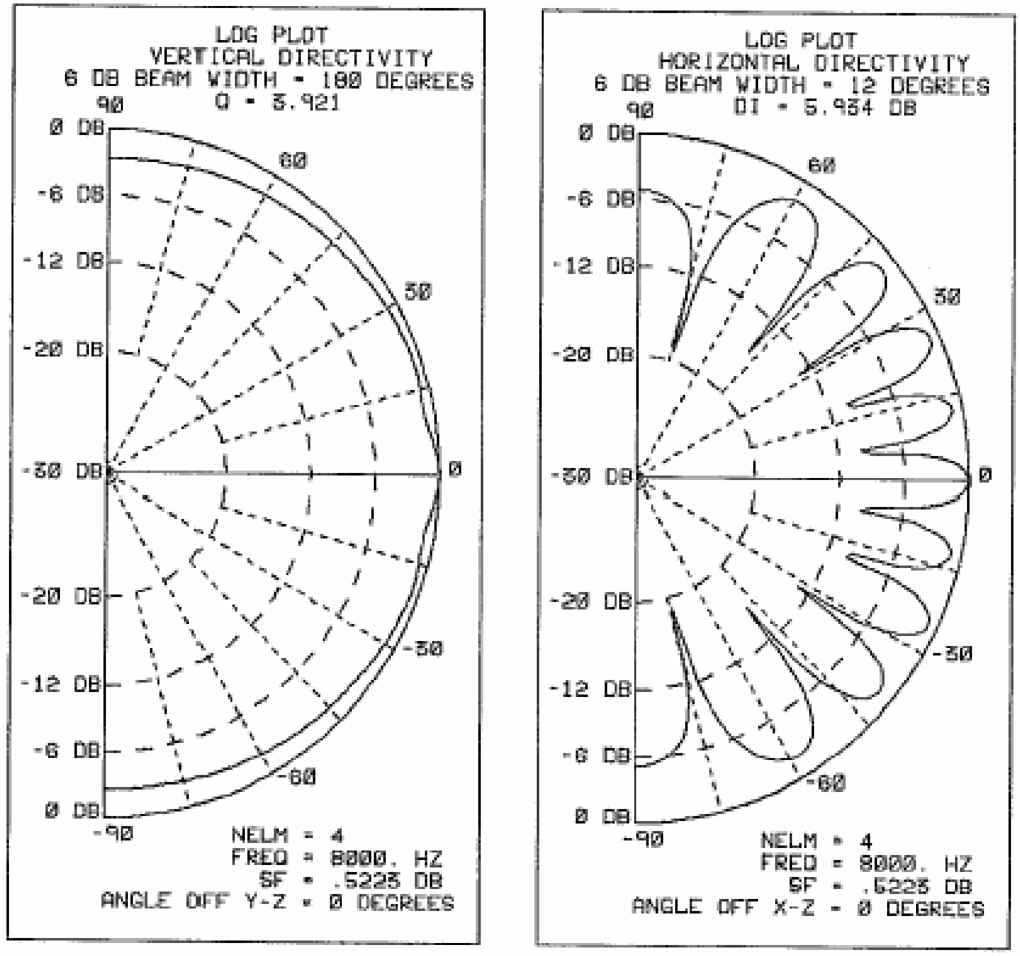
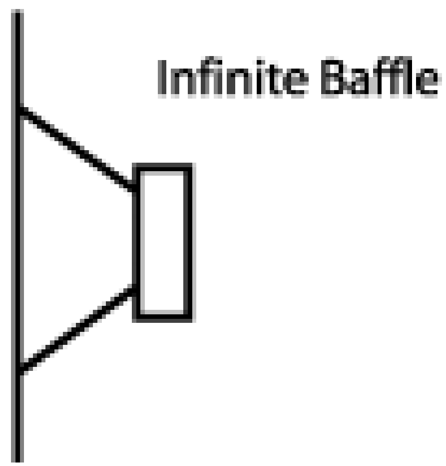
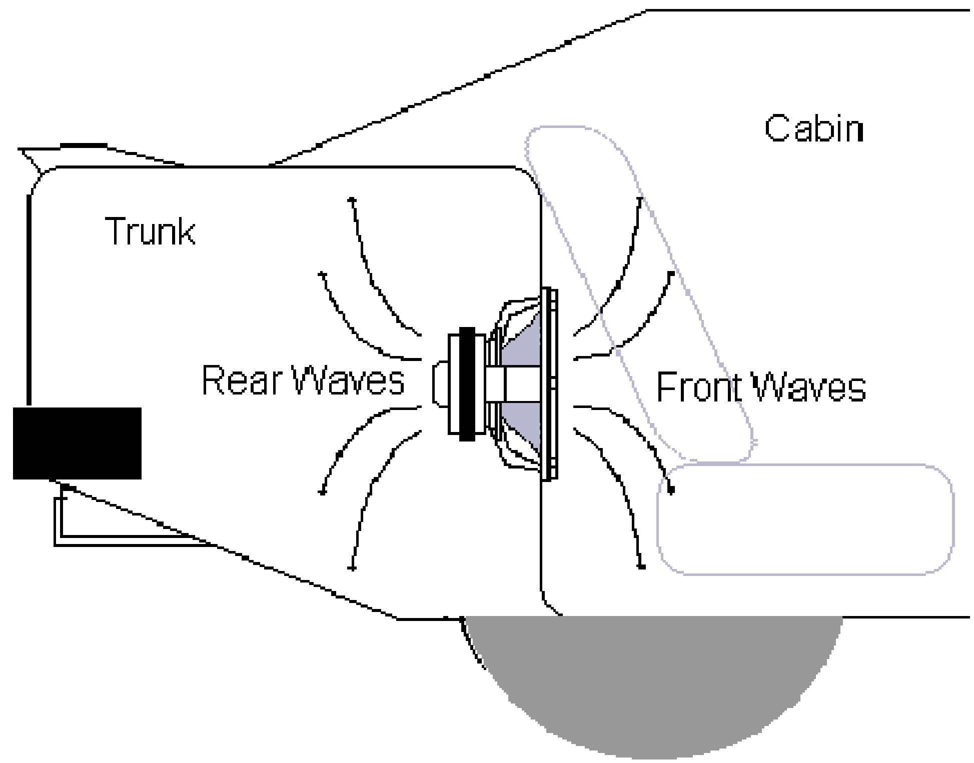


# Outline

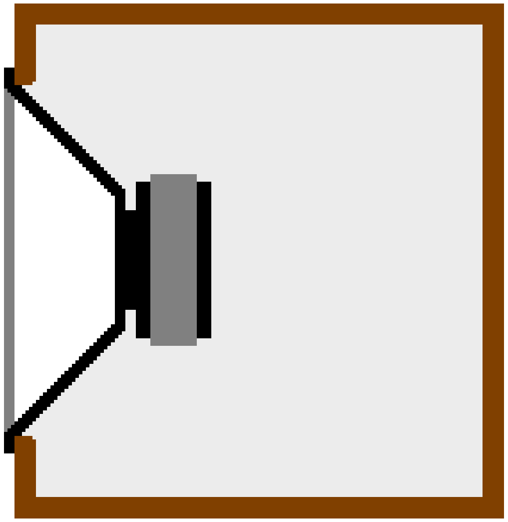
- **Overview of enclosure types**
  - **Infinite baffle**
  - **Sealed box**
  - **Bass reflex (vented/ported)**
  - **Passive radiator**
  - **Horn (front and rear loaded)**
  - **Transmission line (labyrinth)**
  - **Tapered tube (damped pipe/“waveguide”)**

# Infinite Baffle

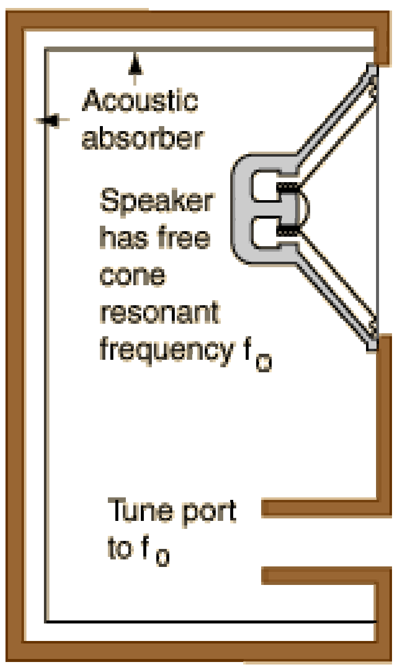


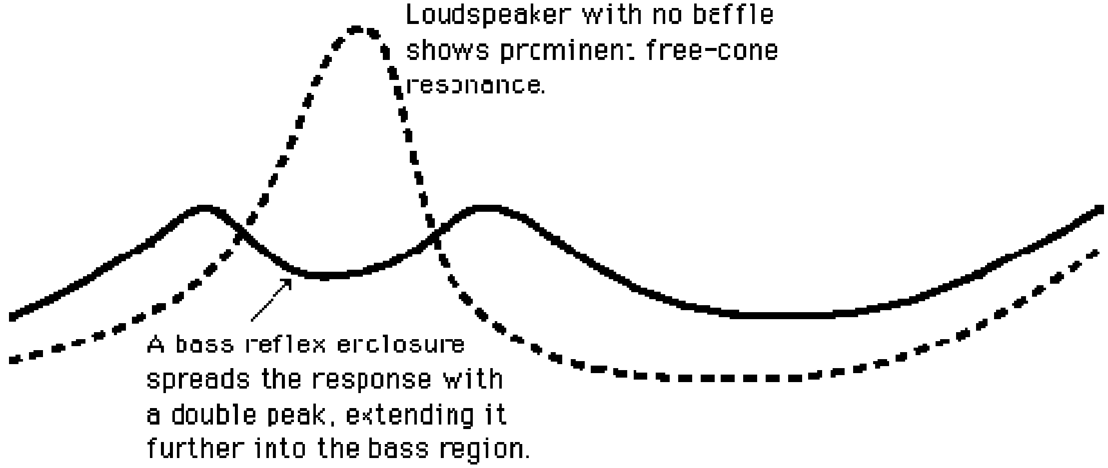



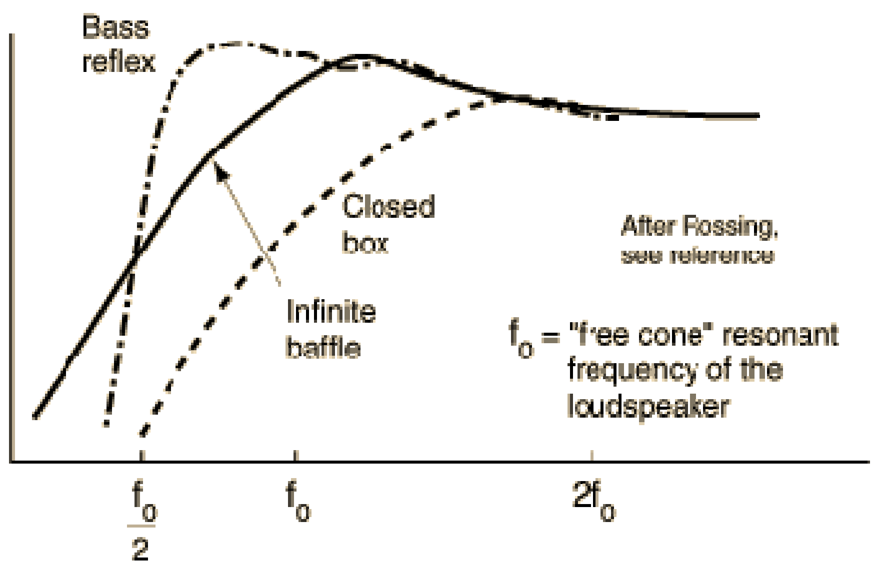
# Sealed Box



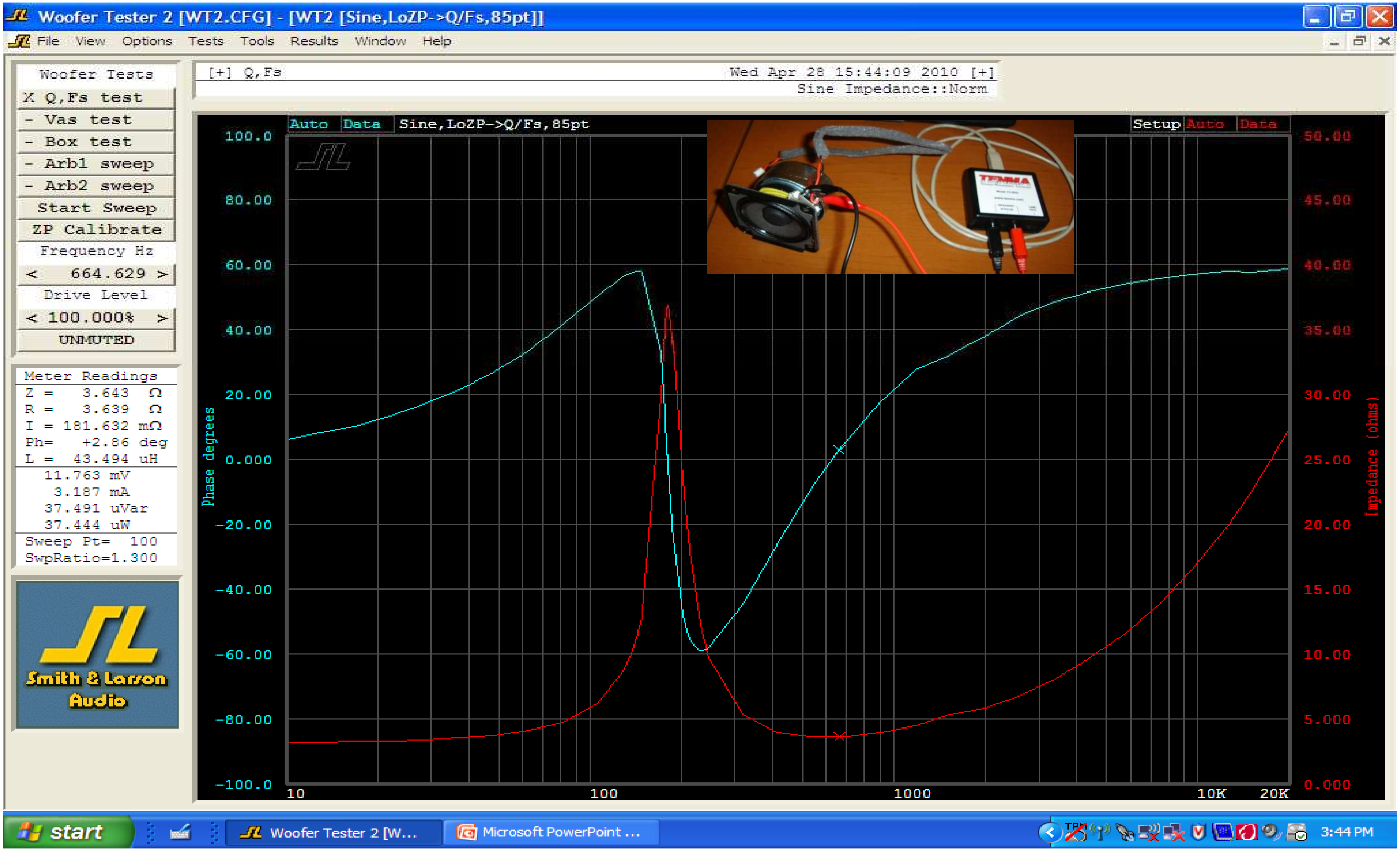
# Bass Reflex


Acoustic
absorber
Speaker
has free
cone
resonant
frequency $f_o$
Tune port
to $f_o$

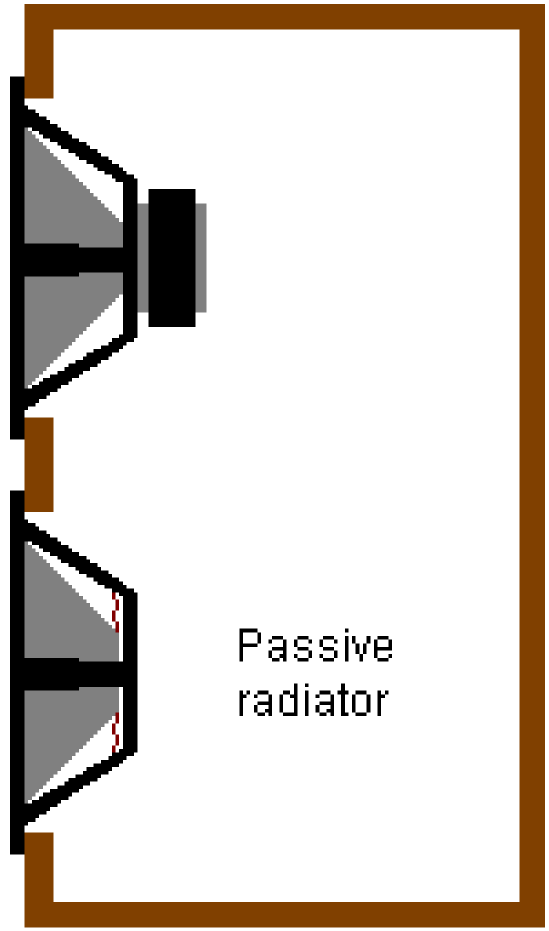

Loudspeaker with no baffle
shows prominent free-cone
resonance.
A bass reflex enclosure
spreads the response with
a double peak, extending it
further into the bass region.


Bass
reflex
Closed
box
Infinite
baffle
After Rossing,
see reference
$f_o$ = "free cone" resonant
frequency of the
loudspeaker
$\frac{f_o}{2}$
$f_o$
$2f_o$

# Measurement of Loudspeaker Free-Air Resonance

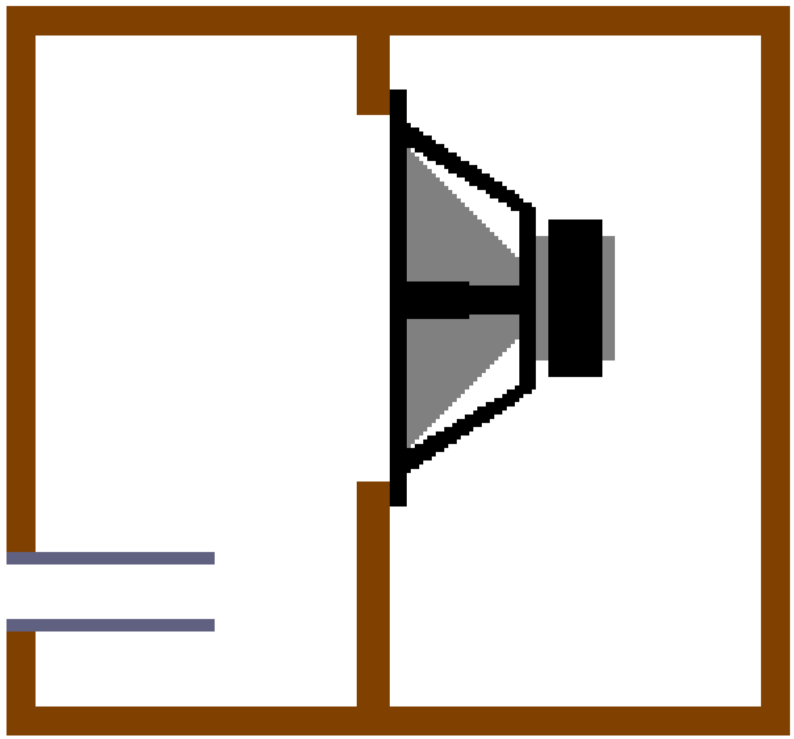


# Passive Radiator



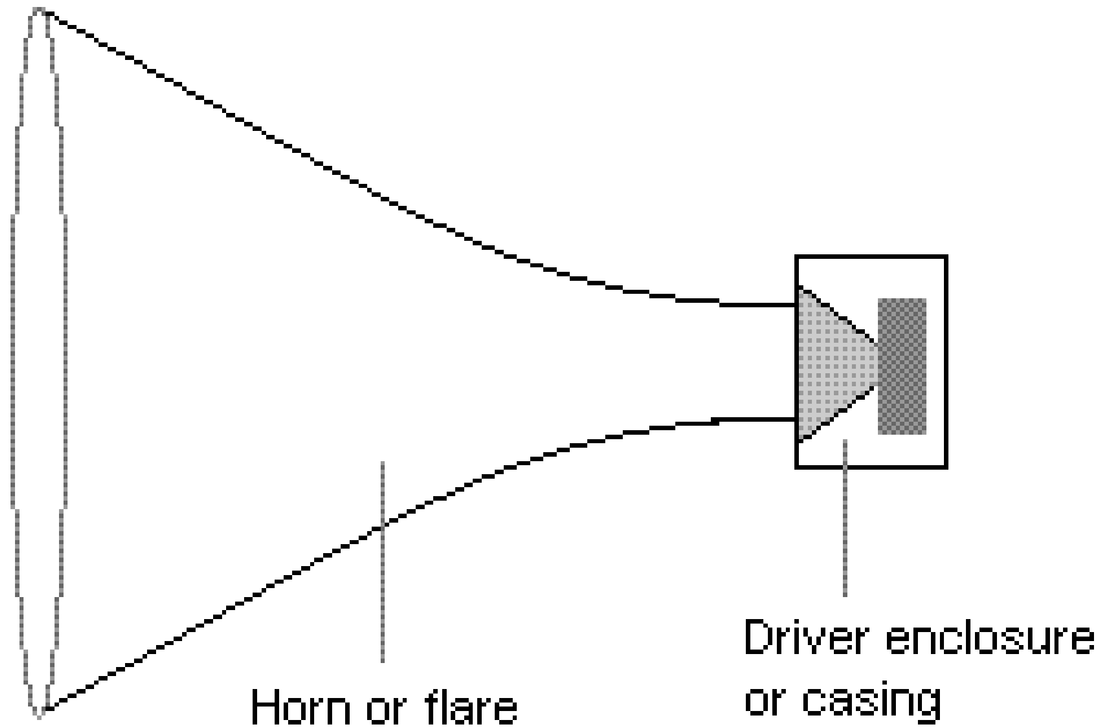

Comment: primarily applicable to subwoofer design

# Compound / Band-pass



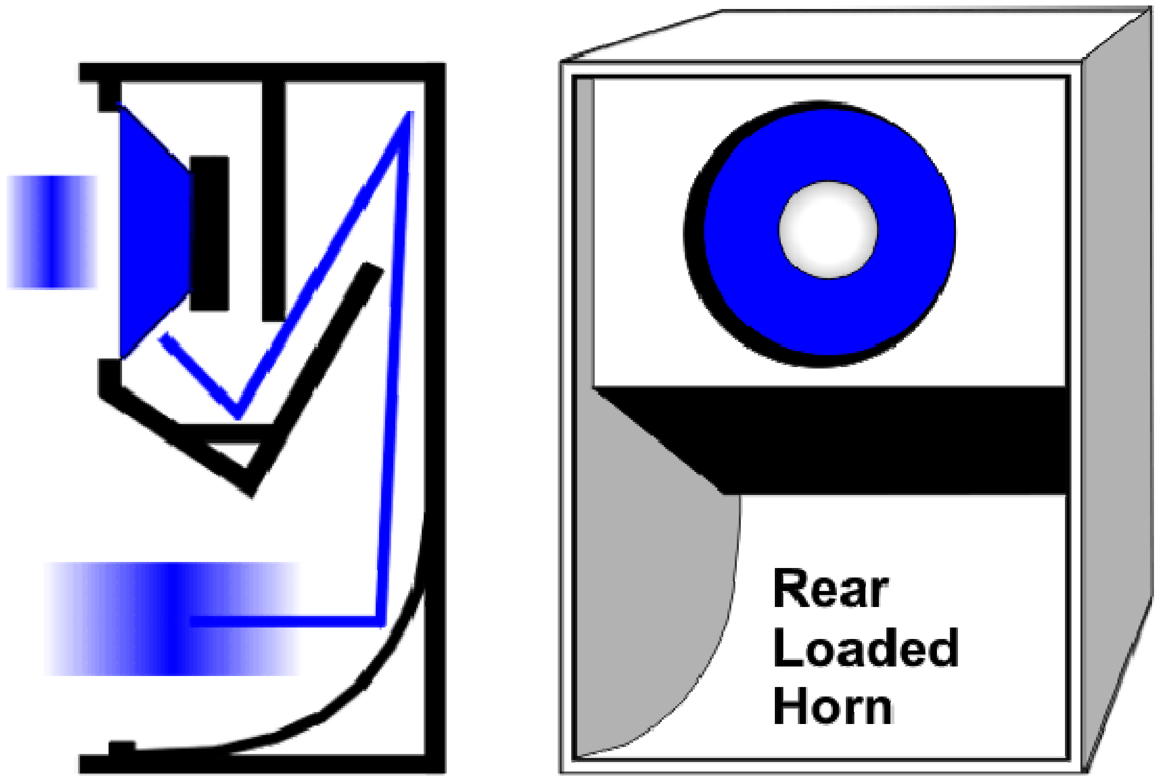
Comment: primarily applicable to subwoofer design

# Front-loaded Horn



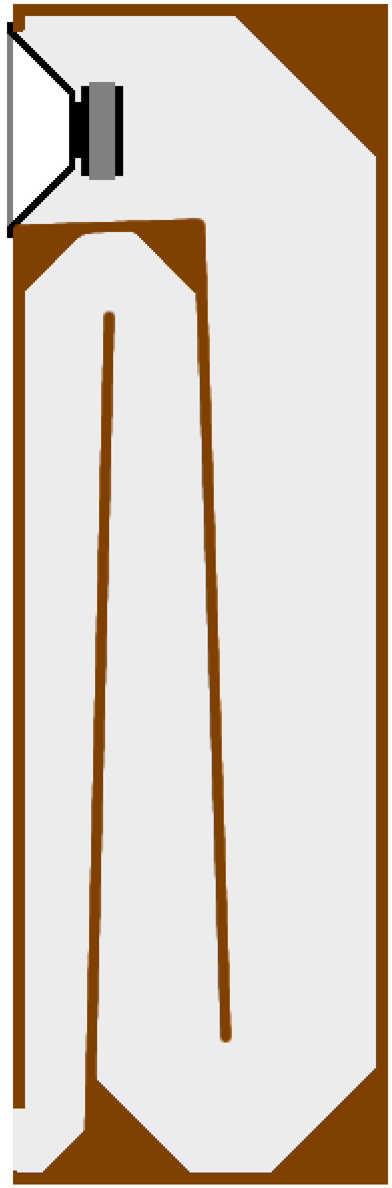

Comment: primarily applicable to mid/high frequencies

# Rear-loaded Horn




Comment: physically large!

# Transmission Line / Labyrinth



Length of transmission line has to be long enough to provide at least 90º of phase shift (1/4 of longest wavelength of interest)

Phase shift (degrees) =
360 x L / (C/F)
where L is effective length of labyrinth, C is speed of sound, and F is frequency of operation (note – add 180 due to rear radiation)

# Transmission Line / Labyrinth

- Transmission line – typically “heavily damped” (stuffed with acoustic material) to absorb energy from rear vibrating surface (or limit radiation from vent to low frequencies)
- Labyrinth – typically “lined” (with acoustic absorption material) but otherwise “substantially open” (radiation from vent limited to low frequencies)

# Damped Pipe

- Pipe driven at one end and open at the other will resonate at a frequency of $F_{res} = C / 4L$, where C is the speed of sound (1130 ft/sec at 72º F) and L is the effective length of the pipe ($F_{res}$ is called its "quarter-wavelength tuning" frequency)
- The effective (or "acoustic") length of the pipe may be longer than its physical length
- Use of tapering and/or acoustic absorption material can increase the effective length

# Damped Pipe / Tapered Tube

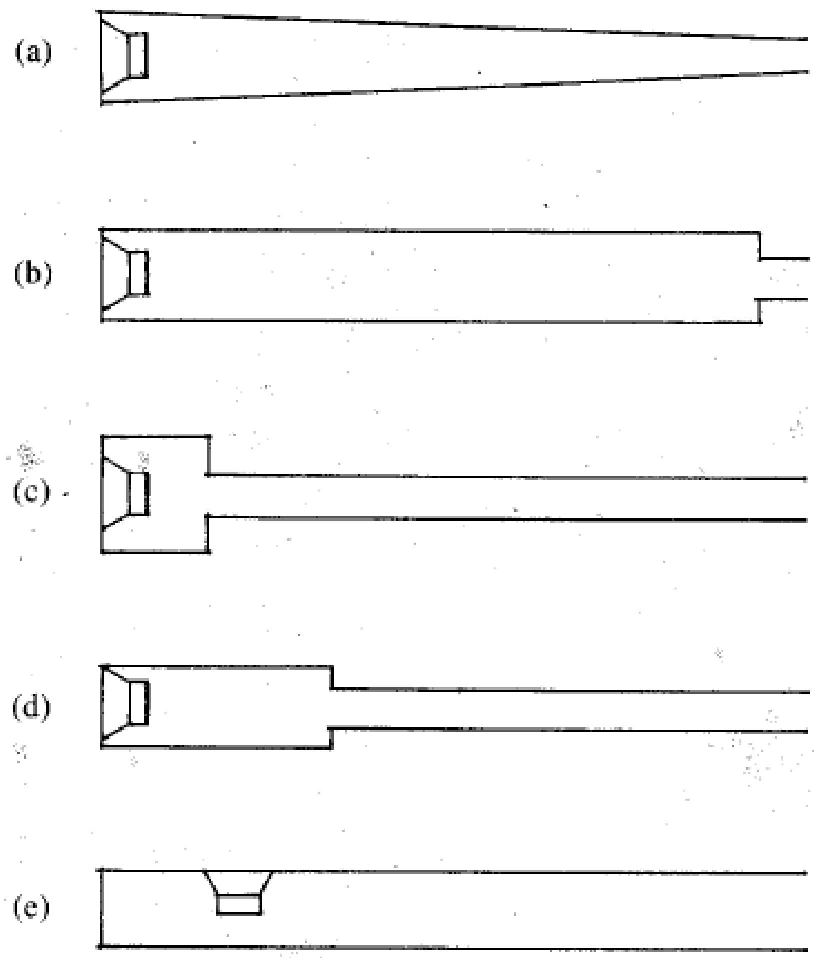



Fig. 9. Alternate pipe geometries. (a) Tapered. (b) Vented. (c) Chamber. (d) Stepped. (e) Offset loudspeaker.

Illustration from: G. L. Augspurger, "Loudspeakers on Damped Pipes," *J. Audio Eng. Soc.,* vol. 48, pp. 424-436 (2000 May).

# Bose AWR1 “Waveguide”

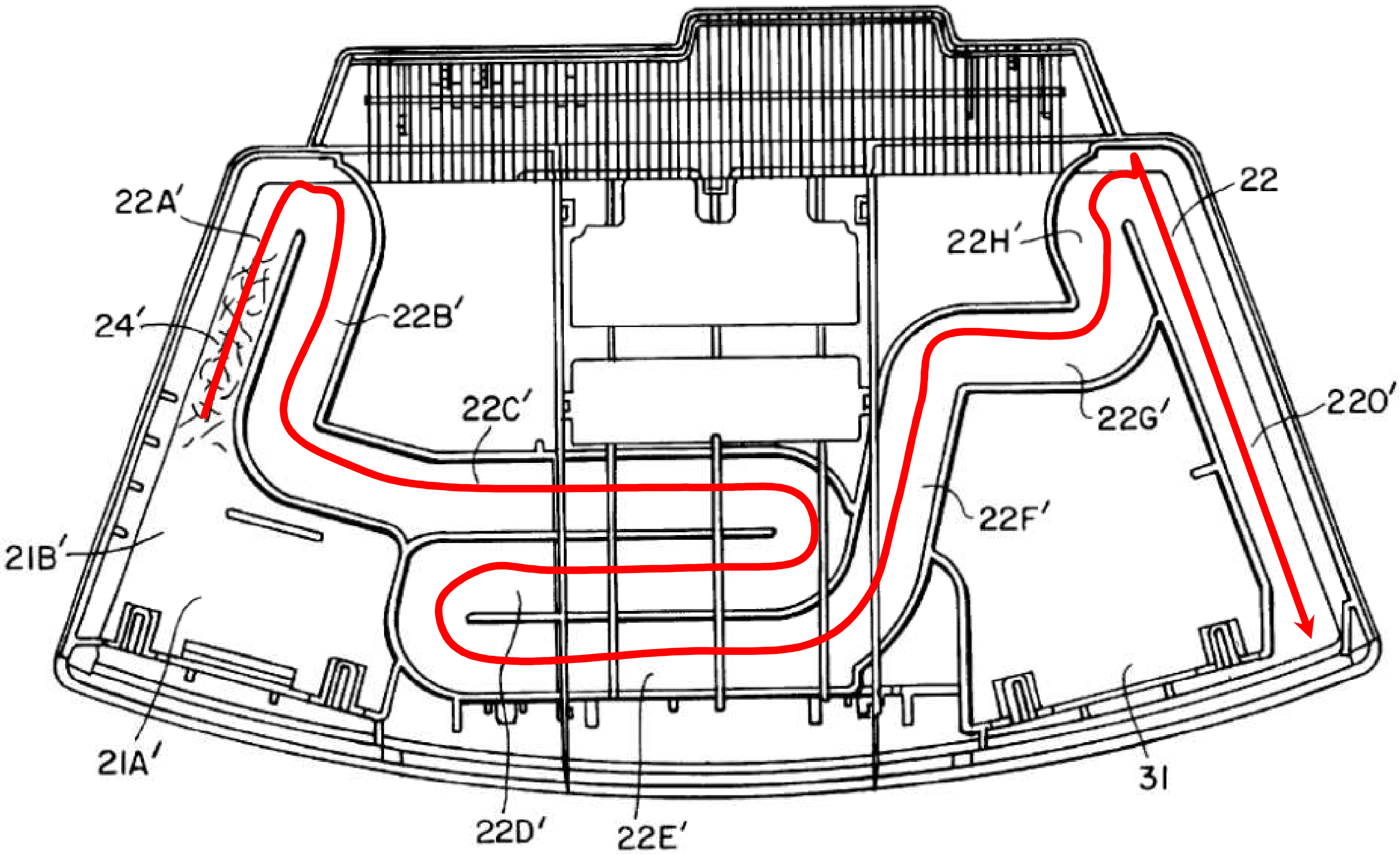



Illustration from: Fig. 4 of U.S. Patent 6,278,789

# Bose WRII “Waveguide”

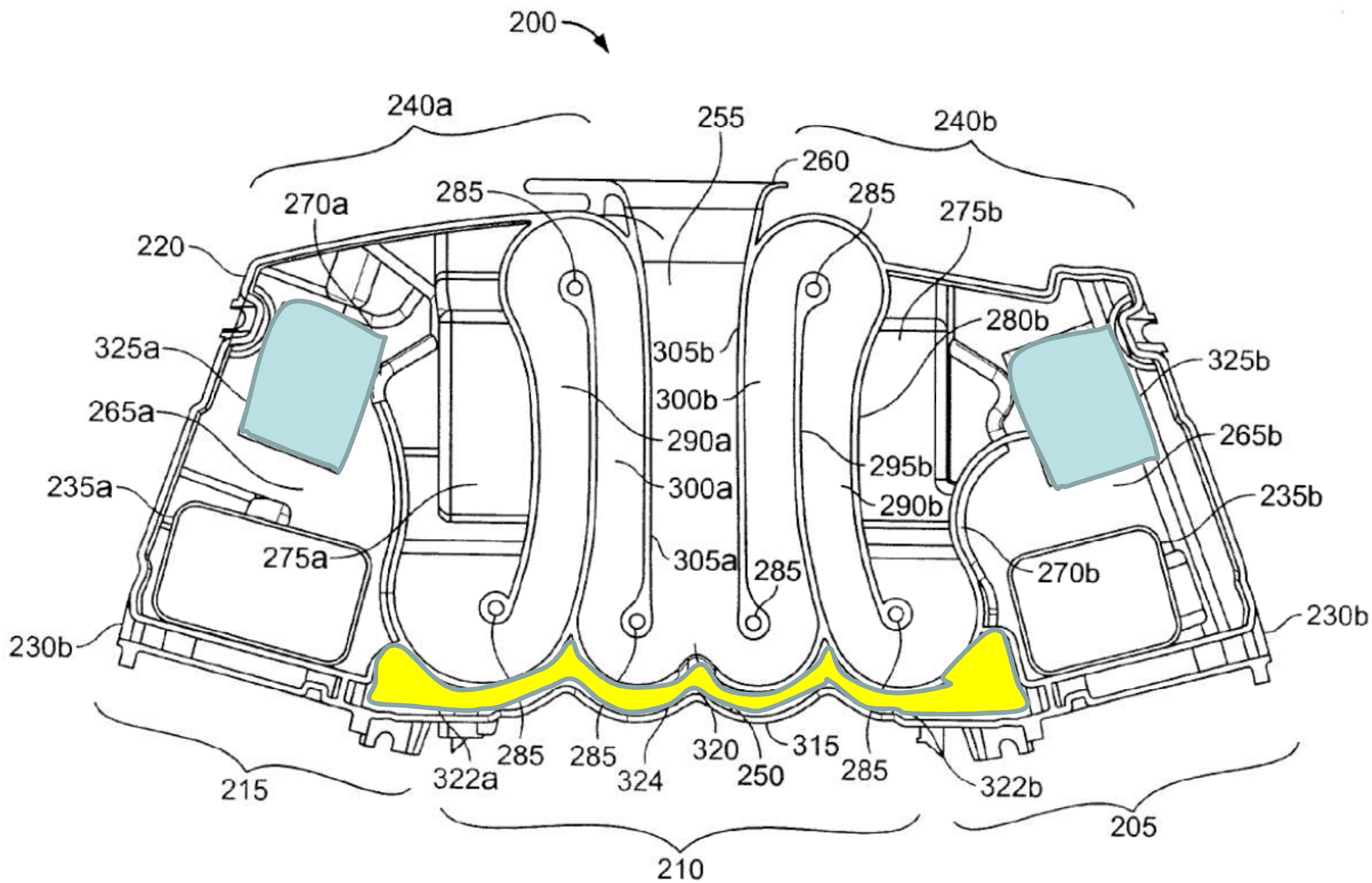



Illustration from: Fig. 6B of U.S. Patent 7,565,948

# Bose WRII “Waveguide”

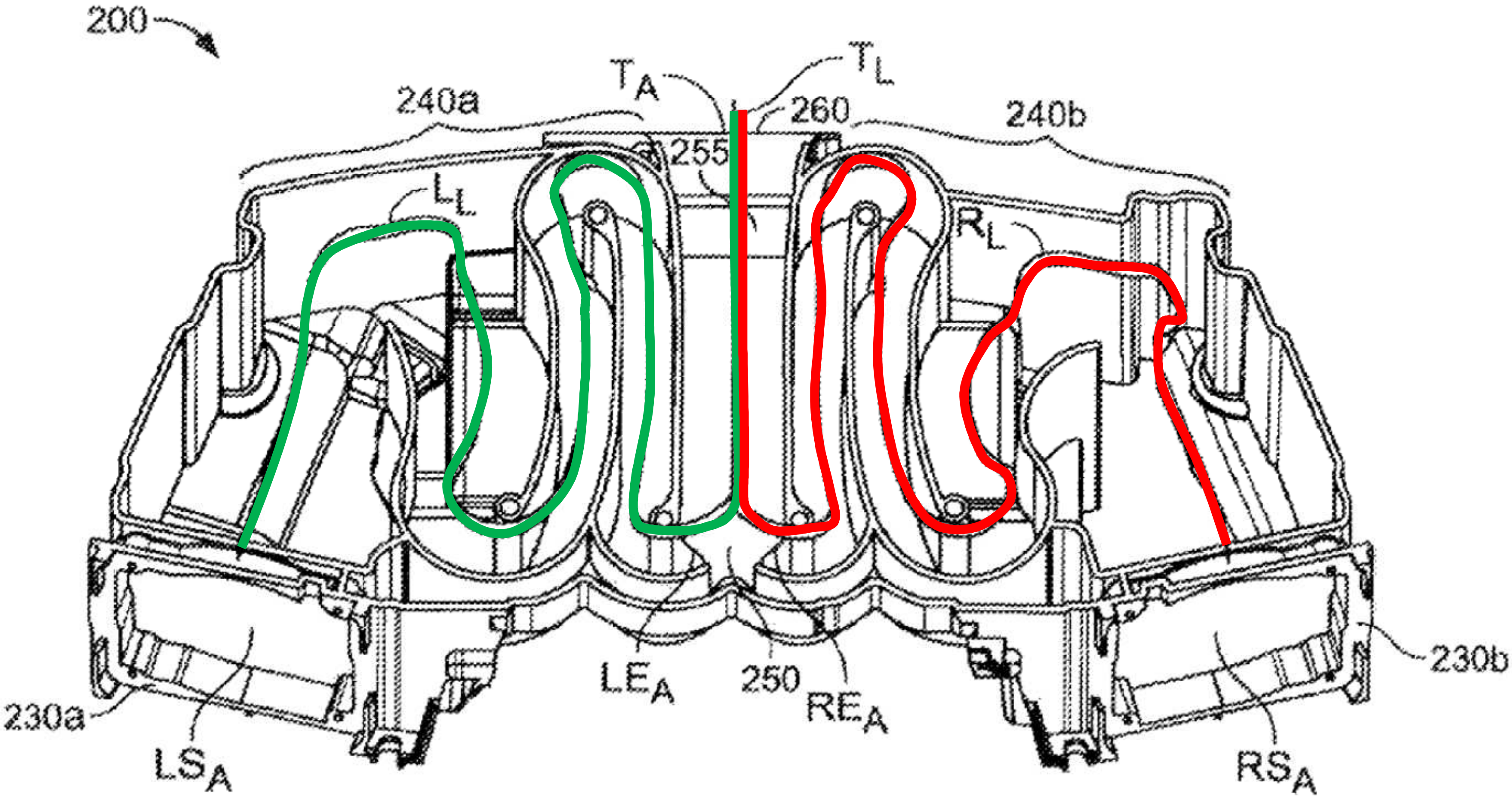



Illustration from: Fig. 9 of U.S. Patent 7,584,820

# Summary

- Viable enclosure types for project
  - sealed box
  - bass reflex / tuned port
  - transmission line / labyrinth
  - coupling chamber + (tapered) damped pipe
- Materials supplied
  - half sheet (4’x4’) of 3/4” MDF (cut per your specs)
  - acoustic lining/stuffing material
  - PVC pipe and couplers (per your specs)
  - glue (carpenter’s yellow, PVC cleaner/cement)

# References


- *Loudspeaker Design Cookbook, Vance Dickason (any edition)*
- U.S. Patent 3,523,589 “High Compliance Speaker and Enclosure Combination”
- U.S. Patent 4,655,315 “Speaker System”
- U.S. Patent 5,821,471 “Acoustic System”
- U.S. Patent 6,278,789 “Frequency Selective Acoustic Waveguide Damping”
- U.S. Patent 7,426,280 “Electroacoustic Waveguide Transducing”
- U.S. Patent 7,565,948 “Acoustic Waveguiding”
- M. J. King, “Construction and Measurement of a Simple Test Transmission Line,” accessed from http://www.quarter-wave.com
- G. L. Augspurger, “Loudspeakers on Damped Pipes,” *J. Audio Eng. Soc.*, vol. 48, pp. 424-436 (2000 May).
- L. J. S. Bradbury, “The Use of Fibrous Materials in Loudspeaker Enclosures,” *J. Audio Eng. Soc.,* vol. 24, pp. 162-170 (1976 April).