Tones in HVAC Systems
(Update from 2006 Seminar, Quebec City)

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Outline

- Review Fundamentals
- Frequency Spectra
- Tone Characteristics
- Tone Detection Methods
- Masking & Critical Bands
- Tone Prominence
- Examples
- ISO 1996 (Part 2)

Characteristics of Noise

Random or Predictable

Level or Loudness

Frequency Content

Steady, Fluctuating, or Transient

Noise Level

$L_p = 20 \log_{10}[p/p_{ref}]$ (dB)

Threshold of Hearing = 0 dB

Threshold of Pain = 120 dB

Change in Noise Level

10 dB : Twice as Loud

5 dB : Clearly noticeable

3 dB : Just noticeable

1 dB : Undetectable

Acoustic Frequency

Full Range of Human Hearing

20 Hz to 20,000 Hz

20, 40, 80, 160, 320, 640, 1280, 2560, 5120, 10240, 20480 Hz

10 OCTAVES

Octave Bands

31 Hz : 22 Hz to 44 Hz

63 Hz : 44 Hz to 88 Hz

125 Hz : 88 Hz to 177 Hz

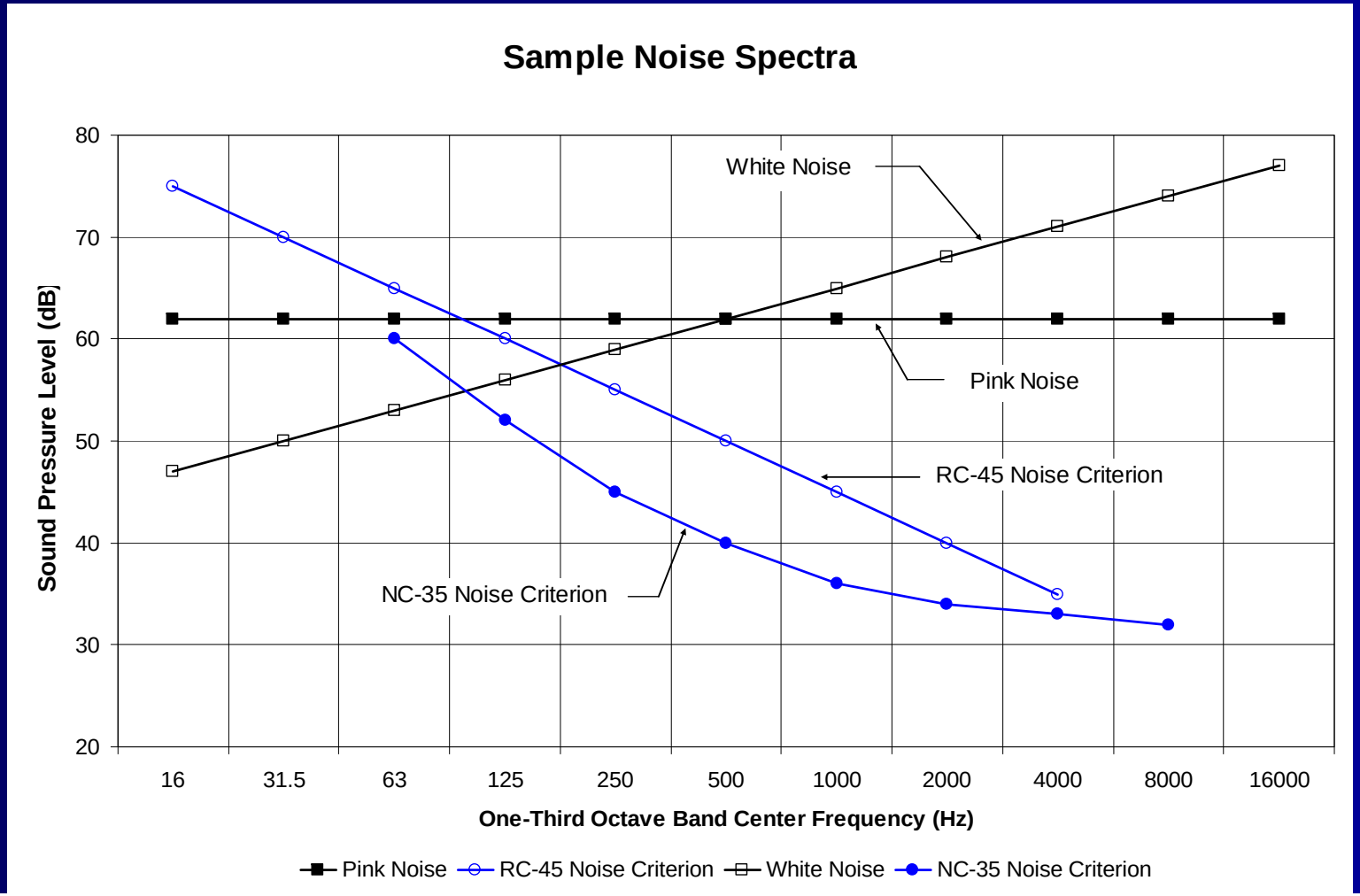
250 Hz : 177 Hz to 355 Hz

500 Hz : 355 Hz to 710 Hz

1,000 Hz : 710 Hz to 1420 Hz

(CPB = 70% of center frequency)

Octave Bands



1/3-Octave Bands

63 Hz Octave : 50 Hz, 63 Hz, 80 Hz

50 Hz : 44.7 Hz to 56.2 Hz

63 Hz : 56.2 Hz to 70.8 Hz

80 Hz : 70.8 Hz to 89.1 Hz

(CPB = 23% of center frequency)

Frequency Bandwidth

1/1-Octave (70%): 11 bands

1/3-Octave (23%): 33 bands

1/12th Octaves (5.9%): 132 bands

1/24th Octaves (2.9%): 264 bands

FFT (constant bandwidth): 400 lines

What is broadband noise?

- Random noise that contains a broad range of frequencies simultaneously
- Examples: waterfalls, freeways, electronic masking noise systems

Broadband Noise Characteristics

- Of all sounds, least likely to be detected by the human ear at low levels
- If source is constant, sound level will vary only slightly with time and space (inside a room or in free space)

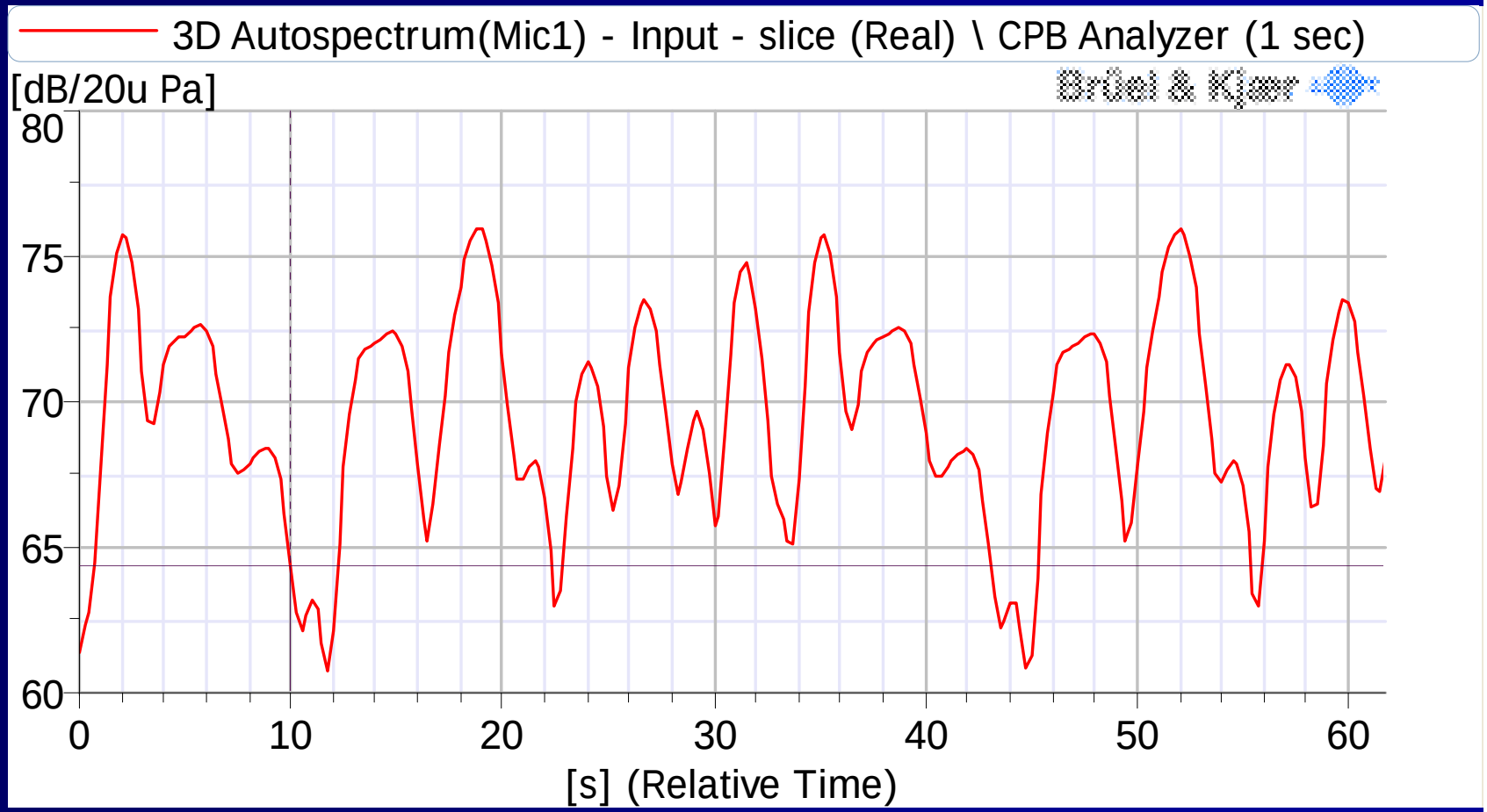
What is a tone?

- A tone is sound where all or most of the energy is concentrated at a single frequency
- Examples: musical instruments, sirens, whistles, etc.

Tone Characteristics

- Of all sounds, most likely to be detected by the human ear at low levels
- Can vary dramatically in level with location in a room, but not outside

Spatial variation of 180 Hz Steady Tone in Reverberation Chamber



Tones in noise

- Most mechanical noise sources generate tones and broadband noise simultaneously
- Tones may go unnoticed if masked by broadband noise

Tones in noise

- Tones usually cannot be detected with octave band analysis
- Tones can sometimes be detected with 1/3-octave band analysis
- Tones can always be detected with narrow band (FFT) analysis

Tone Evaluation Methods

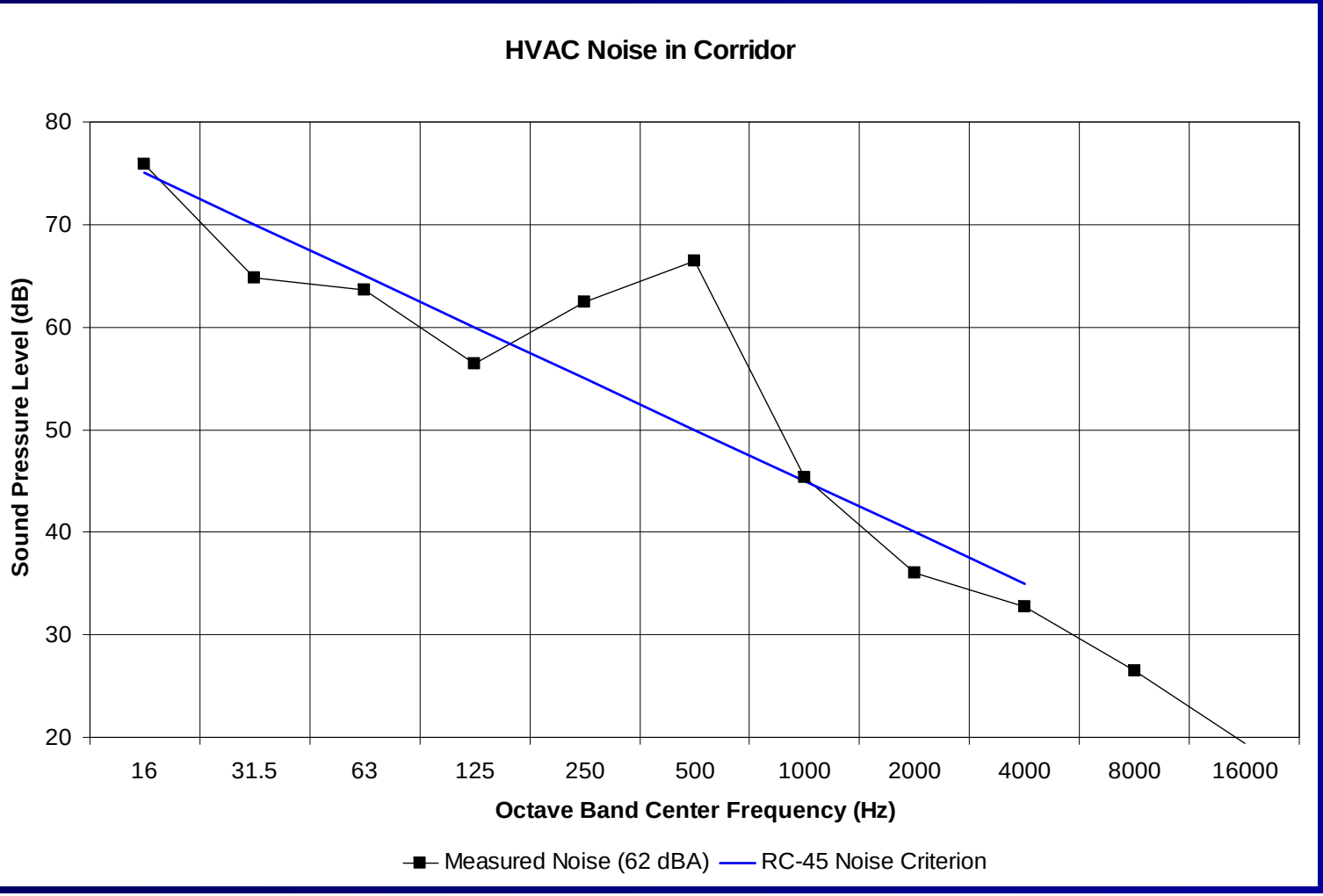
Audibility (subjective)

1/3-Octave Band Method

Tone to Noise Ratio

Prominence Ratio

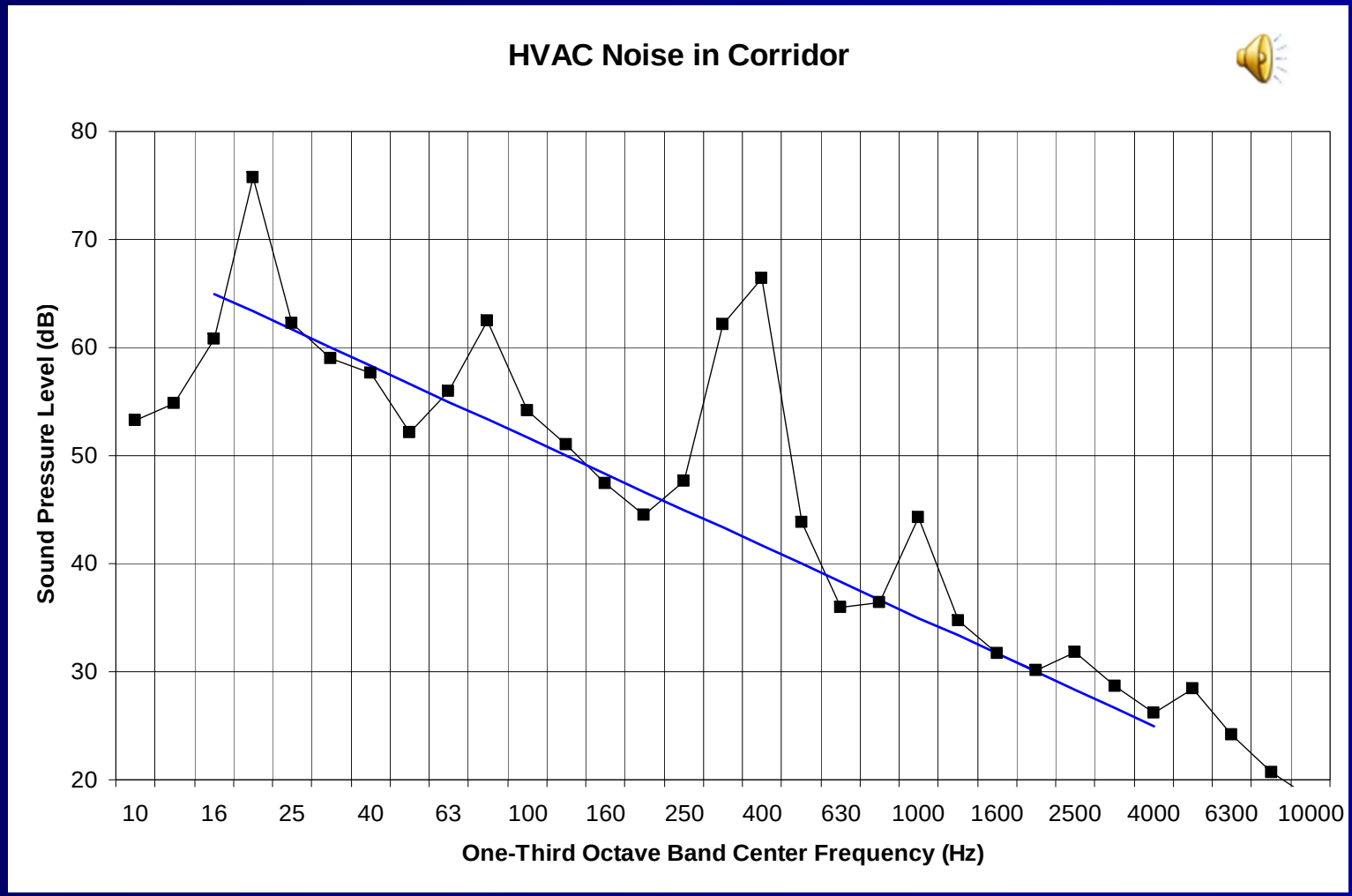
Octave Bands



1/3-Octave Band Method

1. Determine which band tone is located
2. Compare the level of the band with the tone with the arithmetic average of the two adjacent bands: Δ
3. Assume tone is present if :
   - Δ > 15 dB (f_{tone} < 125 Hz)
   - Δ > 8 dB (125 Hz < f_{tone} < 500 Hz)
   - Δ > 5 dB (f_{tone} > 500 Hz)

1/3-Octave Bands



1/3-Octave Method

- L_p (20 Hz) = 75.8
- Average of adjacent bands is 61.5 dB (60.8 + 62.2)/2
- 75.8 – 61.5 = 14.3
- 14.3 < 15 dB, Not a Prominent Tone (0.7 dB under)

Frequency (Hz)	Lp (dB)
16	60.8
20	75.8
25	62.2
31.5	59.0
40	57.6
50	52.2
63	56.0
80	62.5
100	54.2
125	51.0
160	47.4
200	44.5
250	47.7
315	62.2
400	66.4
500	43.8

1/3-Octave Method

- L_p (400 Hz) = 66.4
- Average of adjacent bands is 53.0 dB (43.8 + 62.2)/2
- 66.4 – 53.0 = 13.4
- 13.4 > 8 dB, Tone is **Prominent** (5.4 dB over criterion)

Frequency (Hz)	Lp (dB)
16	60.8
20	75.8
25	62.2
31.5	59.0
40	57.6
50	52.2
63	56.0
80	62.5
100	54.2
125	51.0
160	47.4
200	44.5
250	47.7
315	62.2
400	66.4
500	43.8

Sound Masking

Complete masking occurs when one sound overwhelms the original sound so that the original sound is no longer audible

A tone can be masked by broadband noise, if the broadband noise is loud enough

Only sound in the frequency region near the tone contributes to the masking effect

Critical Bandwidth

Concept originally proposed by Fletcher

He postulated that a pure tone is completely masked when the total power in the tone equals the total power of the broadband noise in the critical bandwidth centered on the tone frequency

Critical Bandwidth

$$\Delta f_{critical} = 25 + 75[1 + 1.4(f_0/1000)^2]^{0.69}$$

Critical Bandwidth

$BW_{critical}$ = 100 Hz (f < 500 Hz)

$BW_{critical}$ = 0.2f (f > 500 Hz)

note: 1/3-octave bandwidth is 23% f_{center}

Critical Bandwidth

More recently, Zwicker has found that Fletcher's assumption was wrong, and a tone is completely masked when the power in the tone is approximately:

½ the power of the masker (f < 500 Hz)

¼ the power of the masker (f > 500 Hz)

Tone to Noise Ratio
(ANSI S12.10, ISO 7779)

$$T/N = 10 \log_{10}(W_{tone}/W_{noise})$$

W_{tone} is the total power in the tone

W_{noise} is the total power of the noise surrounding the tone in the critical band (excluding the tone power)

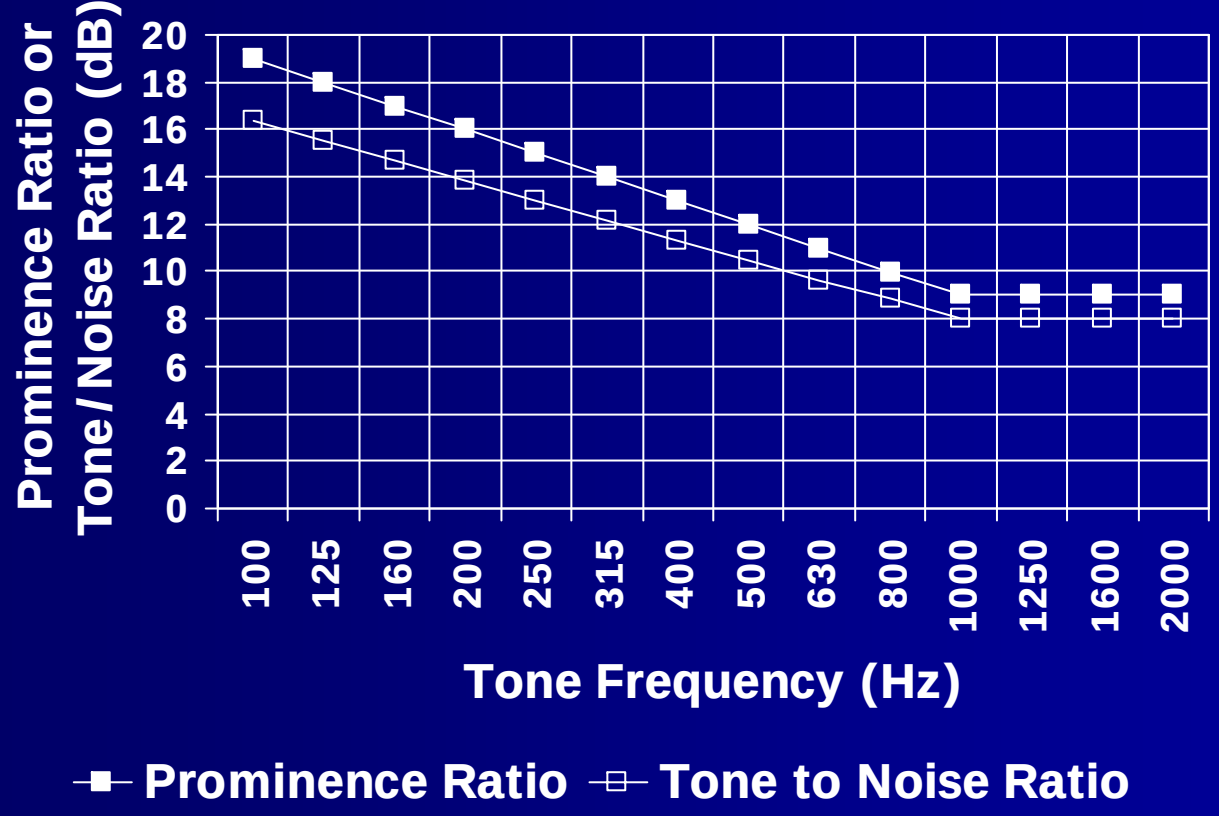
Prominence Ratio
(ANSI S12.10, ISO 7779)

$$PR = 10 \log (W_{toneband}/W_{noiseband})$$

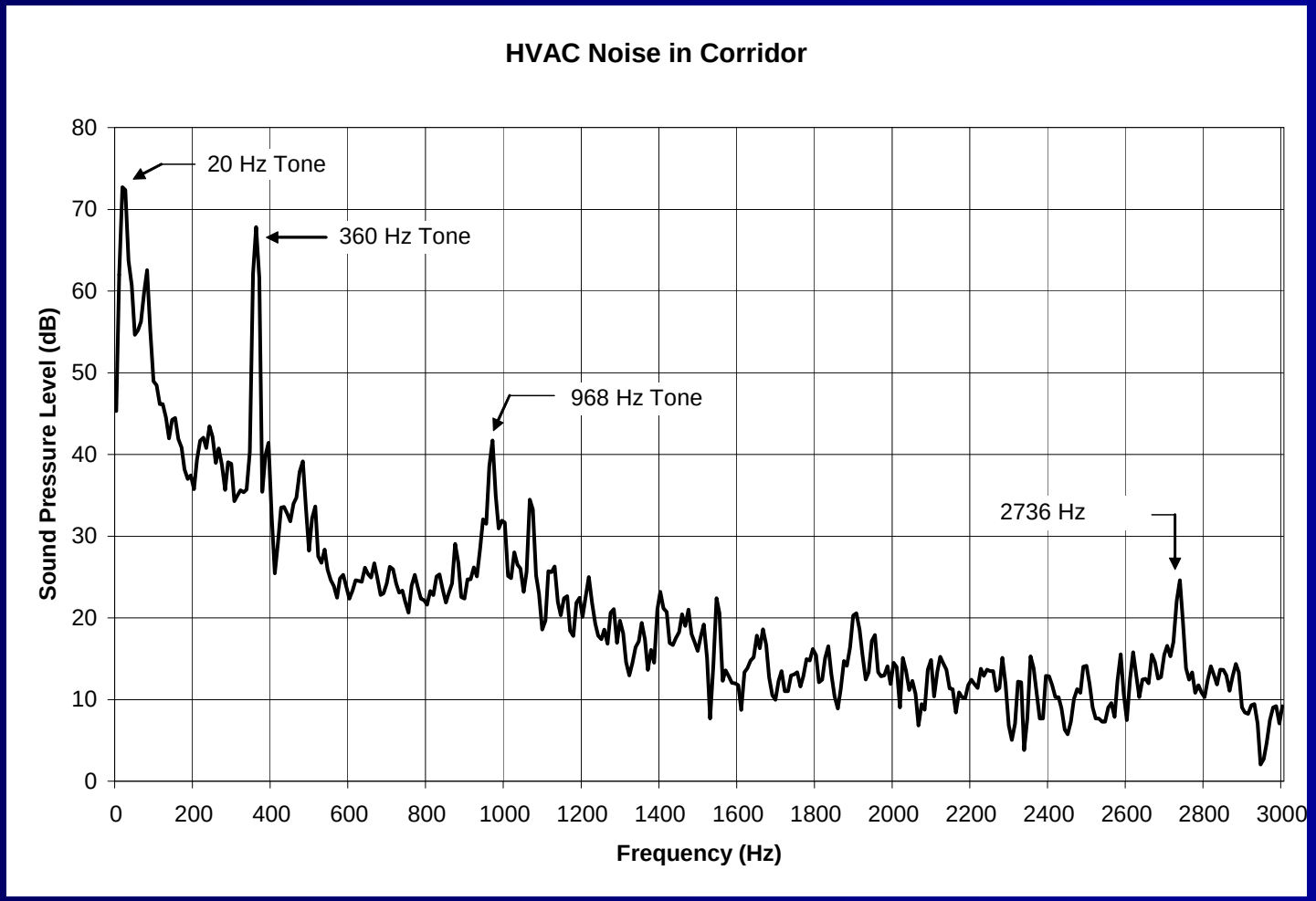
$W_{toneband}$ is the total power in the critical band centered on the tone

$W_{noiseband}$ is the average power in the 2 adjacent critical bands

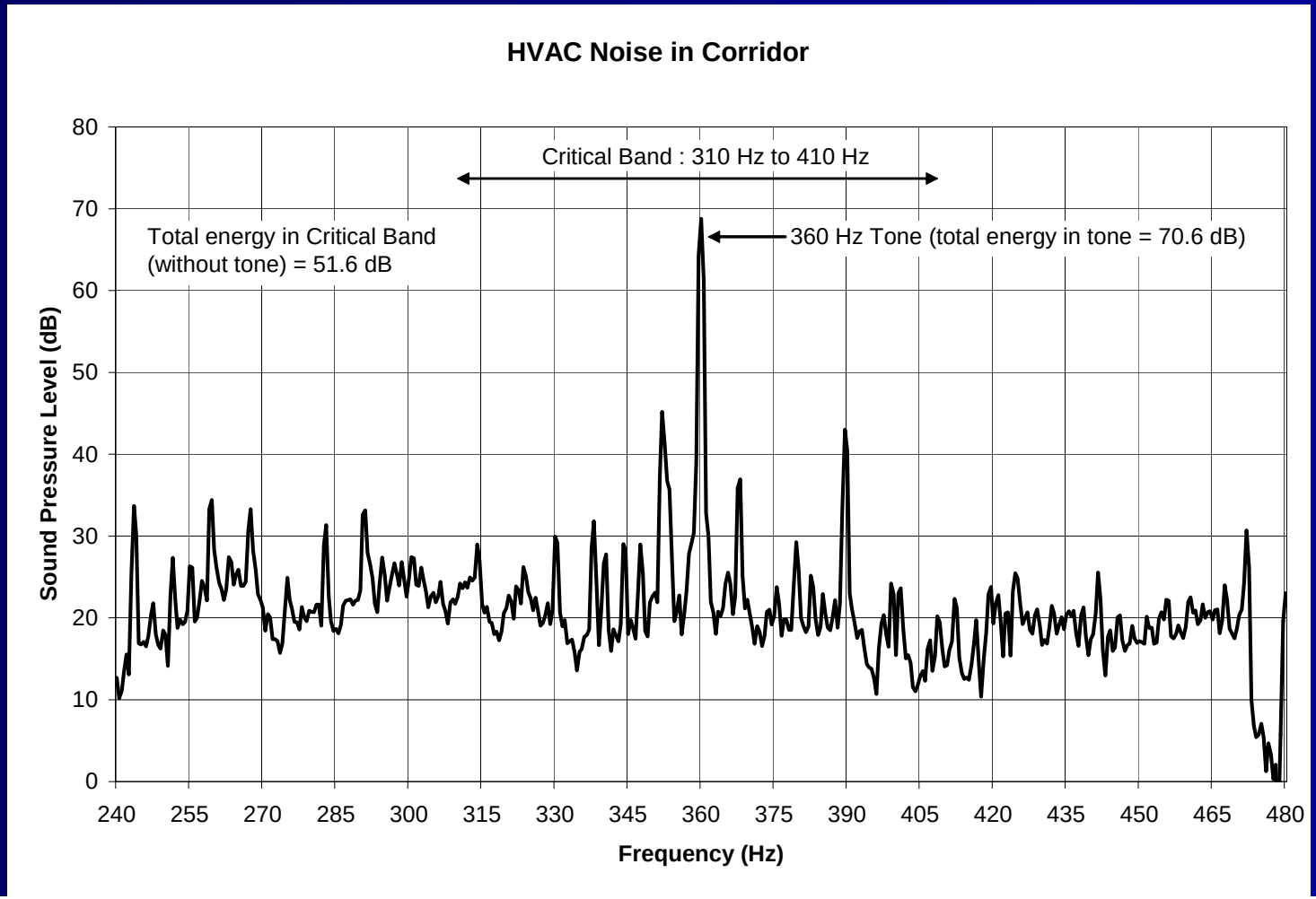
Prominent Tone
(ECMA-74)



Tone to Noise Ratio



Tone to Noise Ratio (360 Hz)



Tone to Noise Ratio (360 Hz)

- T/N Ratio = 70.6 – 51.6 = 19 dB
- 19 dB > 12 dB,
  360 Hz Tone is **Prominent**
  (7 dB over criterion)

Prominence Ratio (360 Hz)

Total energy in $CB_{360\ Hz}$ = 9182516

Total energy in $CB_{260\ Hz}$ = 138988

Total energy in $CB_{460\ Hz}$ = 35567

Average (260 Hz & 460 Hz) = 87278

Prominence Ratio (360 Hz)

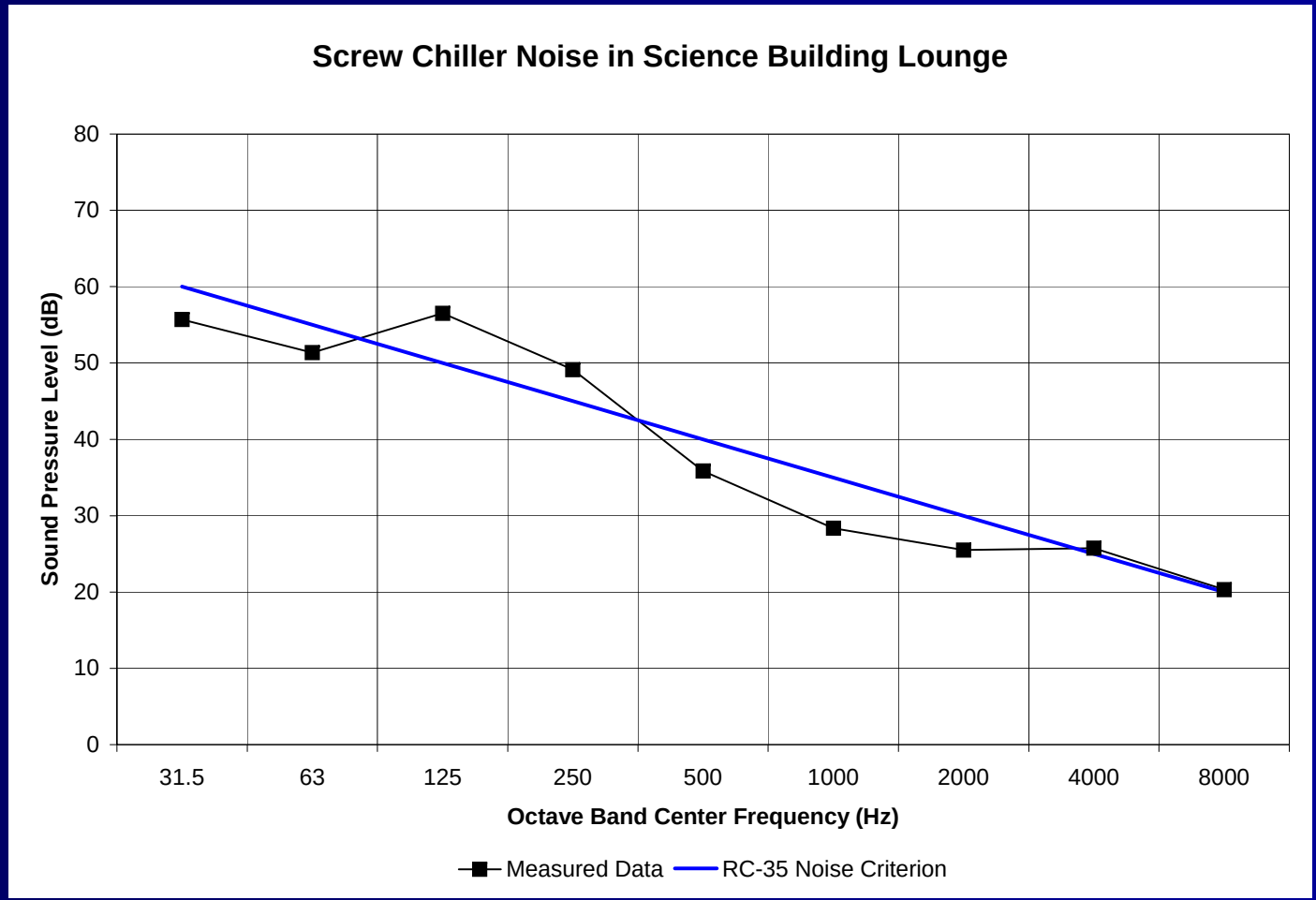
$PR = 10 \log_{10}(9182516/87278) = 20.2$

20.2 > 13.6 dB,

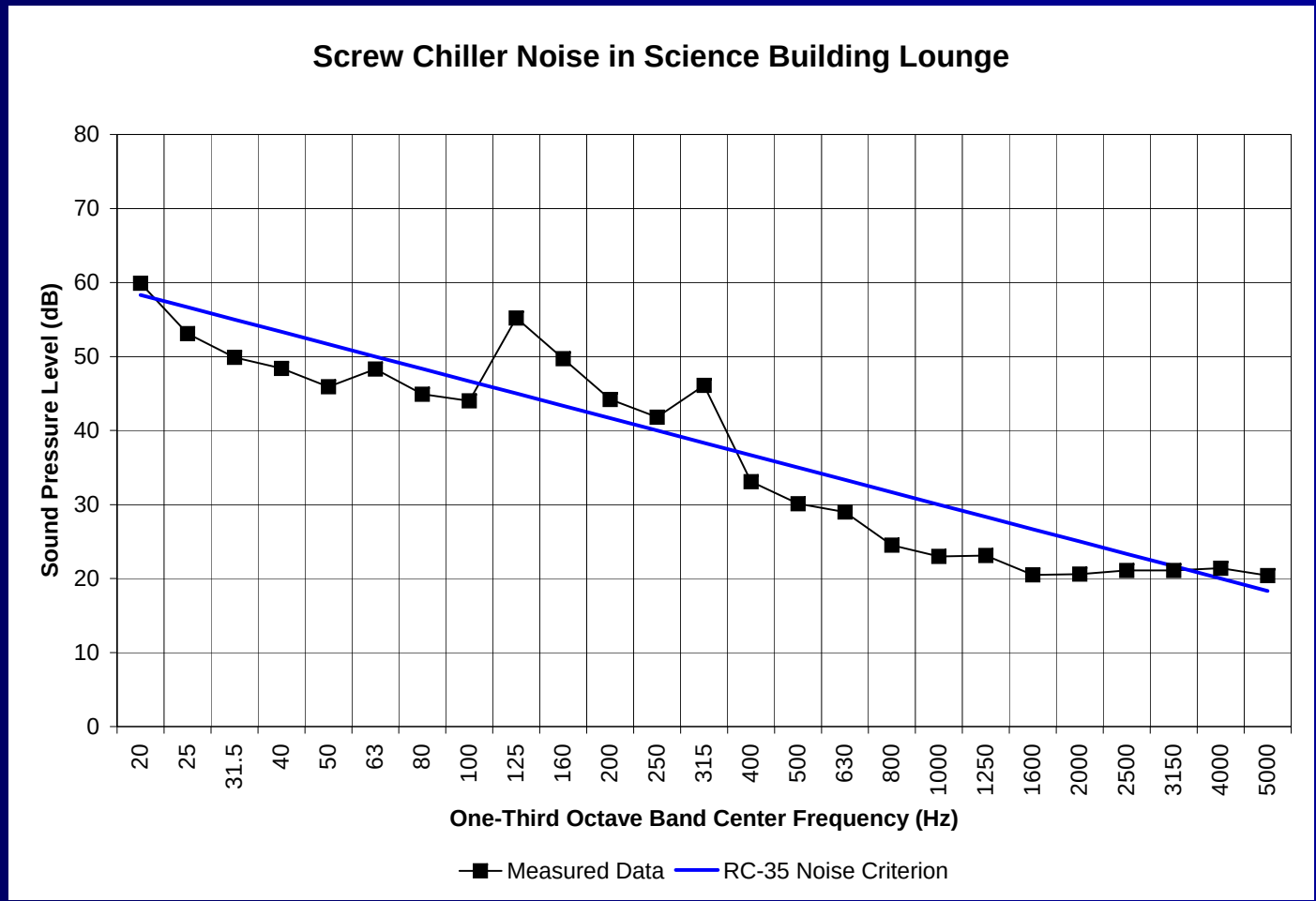
Tone is **Prominent**

(6.6 dB over criterion)

Screw Chiller Noise: 1/1-Octave



Screw Chiller Noise: 1/3-Octave



1/3-Octave Method

- L_p (125 Hz) = 55.2
- Average of adjacent bands is 46.8 dB (44.0 + 49.7)/2
- 55.2 – 46.8 = 8.4
- 8.4 < 15 dB, No Tone (6.6 dB under criterion)

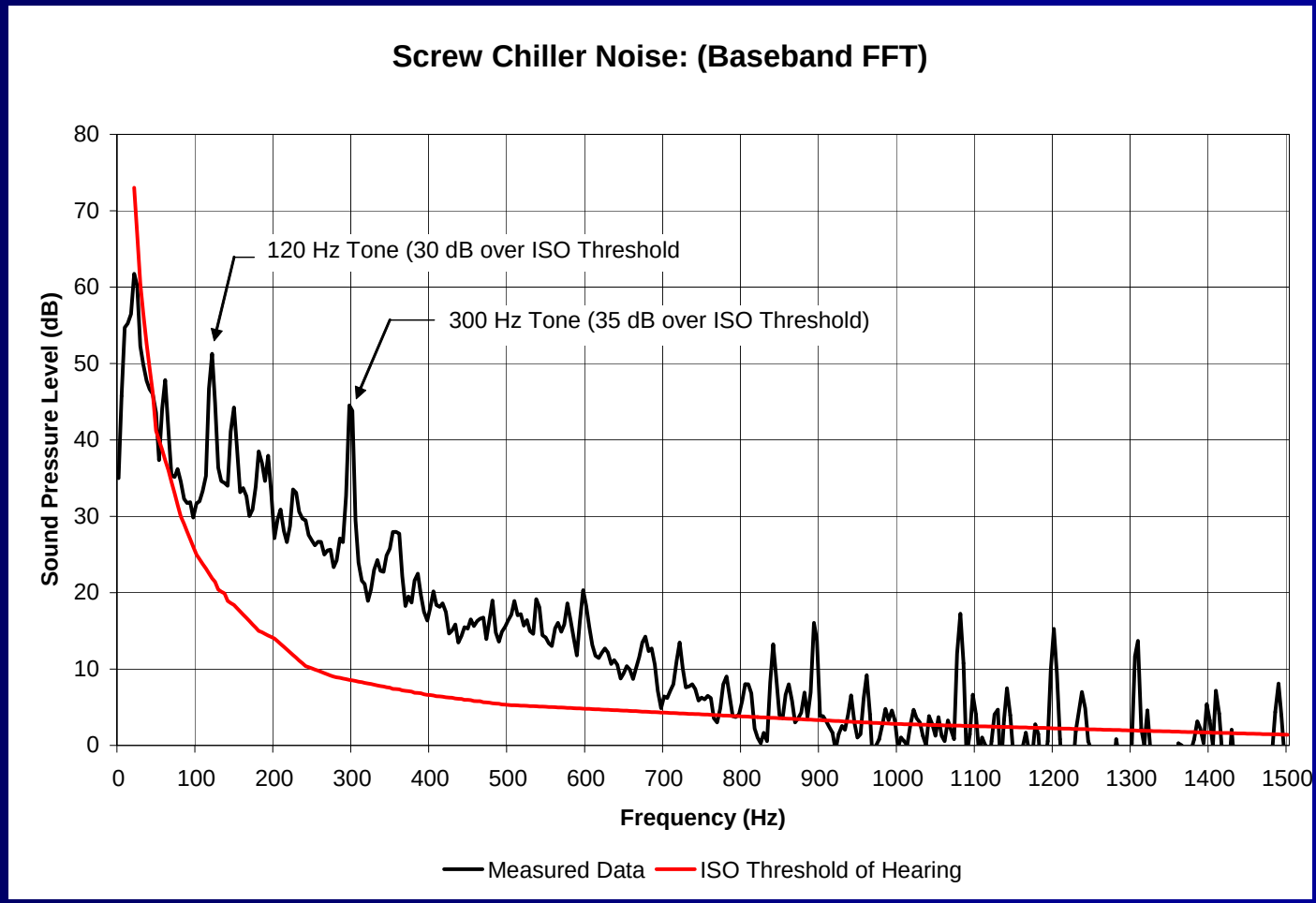
Frequency (Hz)	Lp (dB)
50	45.9
63	48.3
80	44.9
100	**44.0**
125	**55.2**
160	**49.7**
200	44.2
250	41.8
315	46.1
400	33.1
500	30.1

1/3-Octave Method

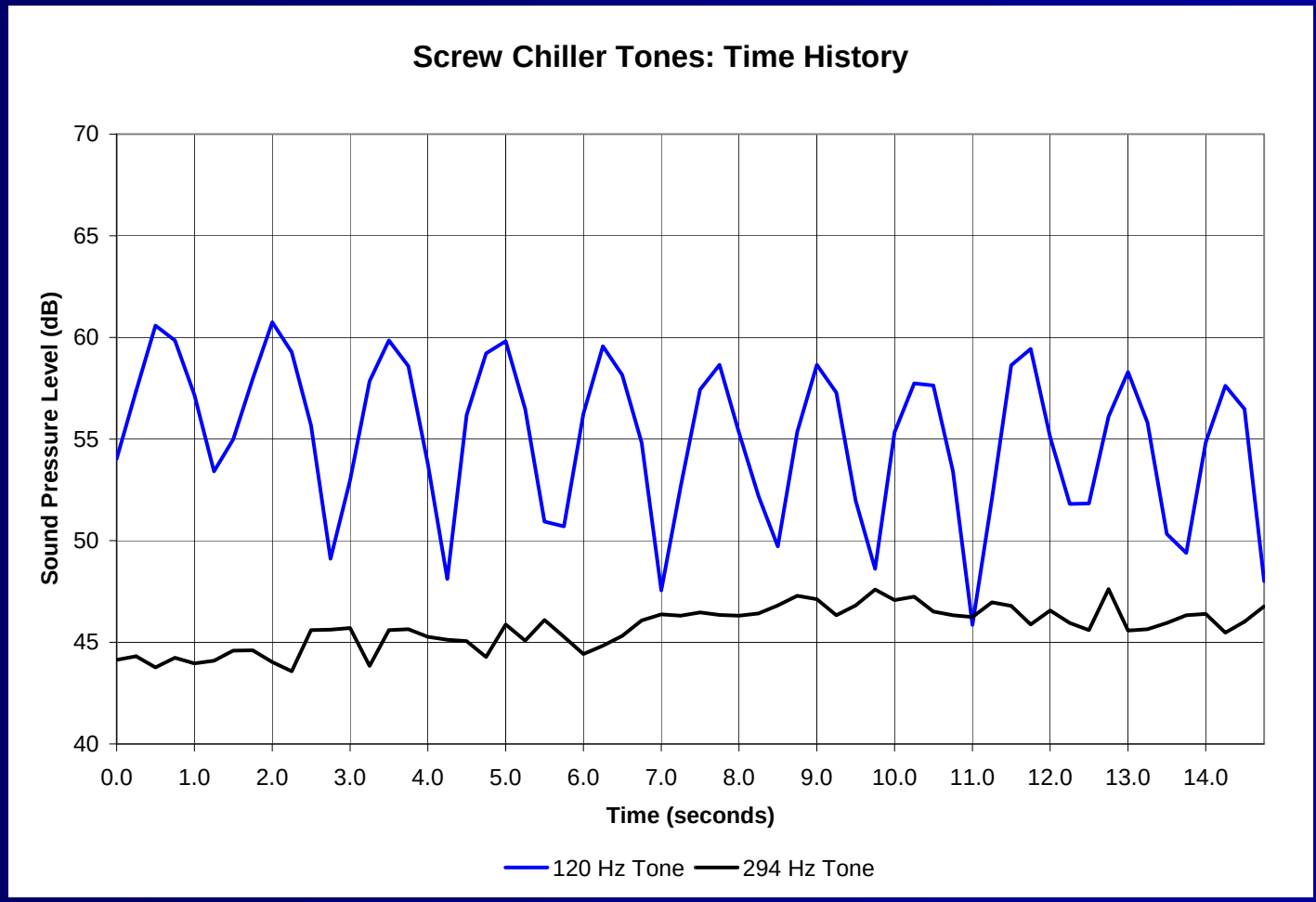
- L_p (315 Hz) = 46.1
- Average of adjacent bands is 37.5 dB (41.8 + 33.1)/2
- 46.1 – 37.5 = 8.6
- 8.6 > 8 dB, Tone (0.6 dB over criterion)

Frequency (Hz)	Lp (dB)
50	45.9
63	48.3
80	44.9
100	44
125	55.2
160	49.7
200	44.2
250	**41.8**
315	**46.1**
400	**33.1**
500	30.1

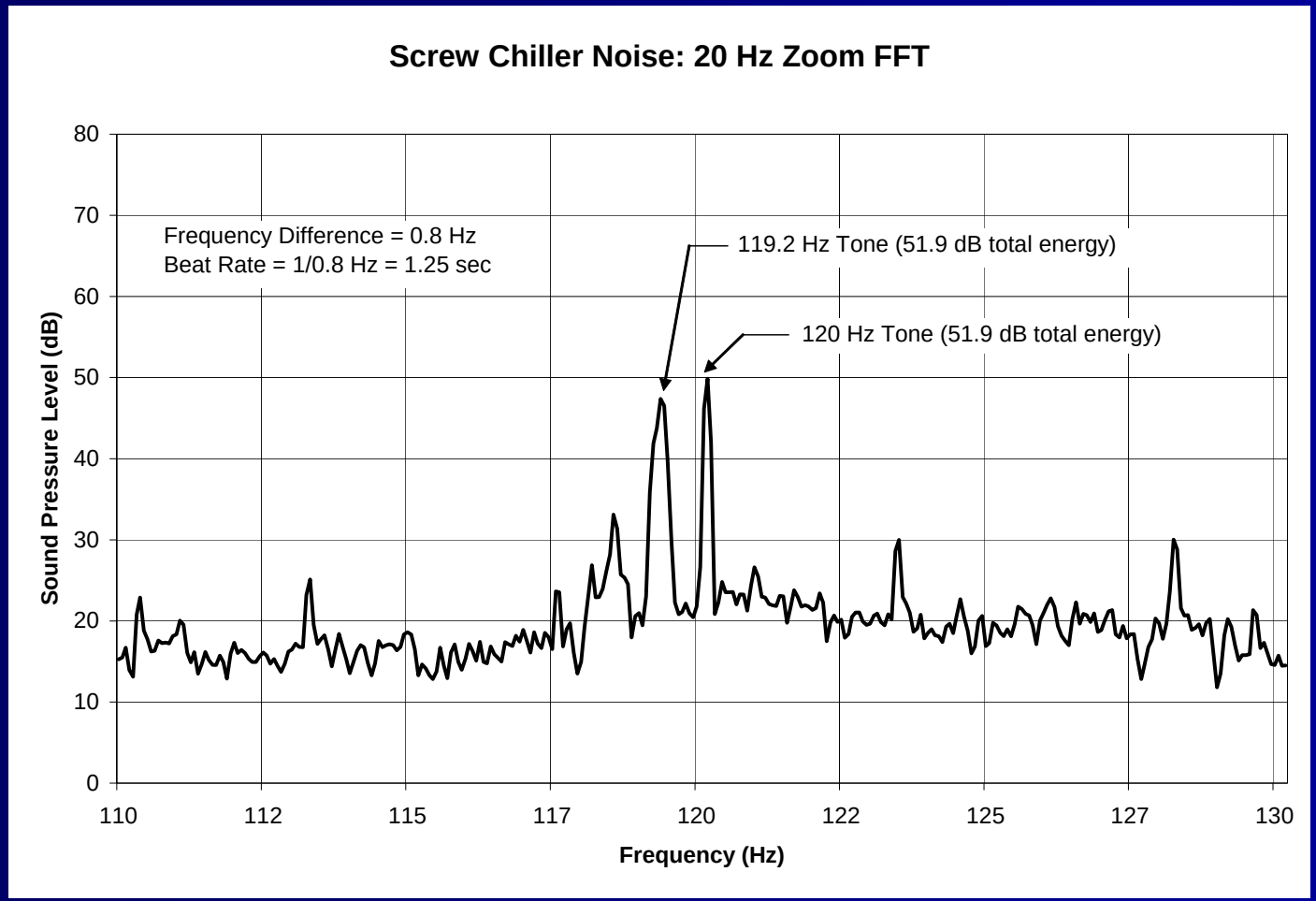
Screw Chiller Noise: FFT



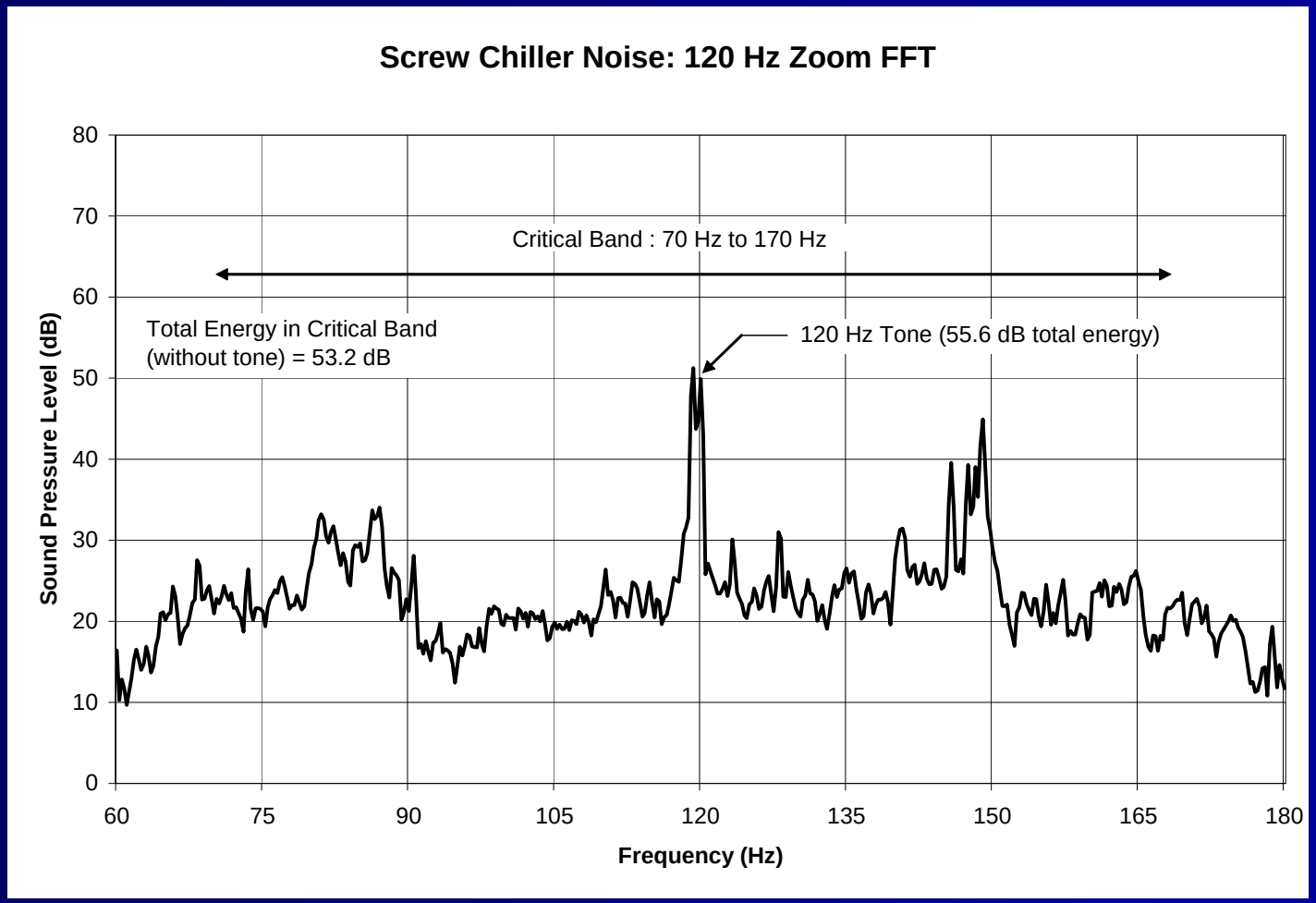
Screw Chiller Noise: FFT



Screw Chiller Noise: Beats



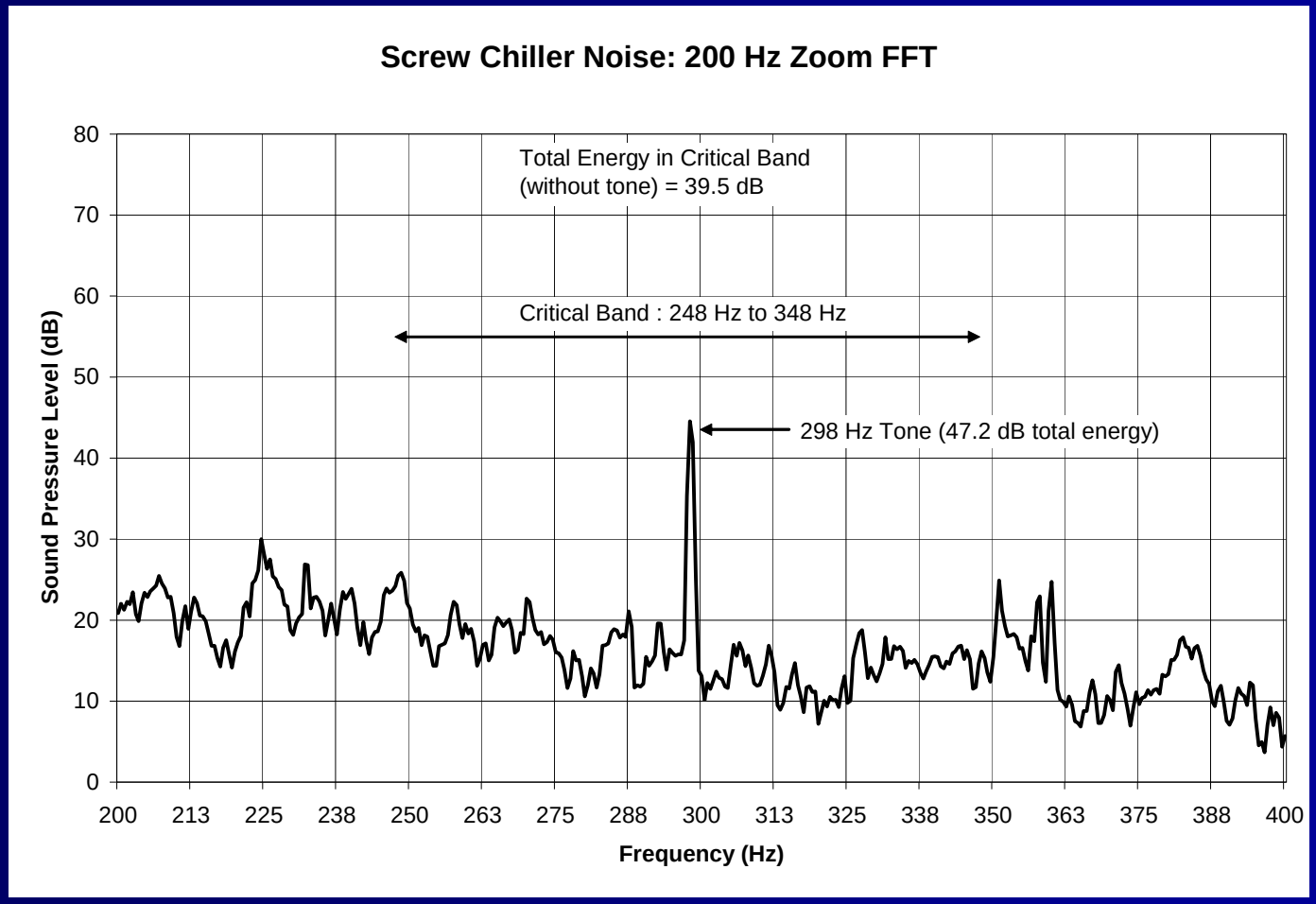
Screw Chiller: Zoom FFT



Tone to Noise Ratio (120 Hz)

- T/N Ratio = 53.3 – 49.7 = 3.6 dB
- 3.6 dB < 15.5 dB,
  120 Hz Tone is **not Prominent**
  (11.9 dB under criterion)

Screw Chiller: Zoom FFT



Tone to Noise Ratio (298 Hz)

- T/N Ratio = 47.2 – 39.5 = 7.7 dB
- 7.7 dB < 12 dB,
  298 Hz Tone is **not Prominent**
  (4.3 dB under criterion)

Prominence Ratio (298 Hz)

- Total energy in CB_{298} = 61406
- Total energy in CB_{198} = 81126
- Total energy in CB_{398} = 3775
- Average CB_{198} & CB_{298} = 42450

Prominence Ratio (298 Hz)

- PR = 10 log (61406/42450) = 1.6
- 1.6 dB < 14 dB
  298 Hz Tone is **not Prominent**
  (12.4 dB under criterion)

ISO 1996 (Part 2)

- Ignores prominence ratio
- Analysis based on tone to noise ratio using FFT (Annex C) or alternative 1/3-octave method (Annex D) is allowed, but not preferred)

ISO 1996 (Part 2)

- Defines tone audibility ΔL_{ta} (in dB) as:

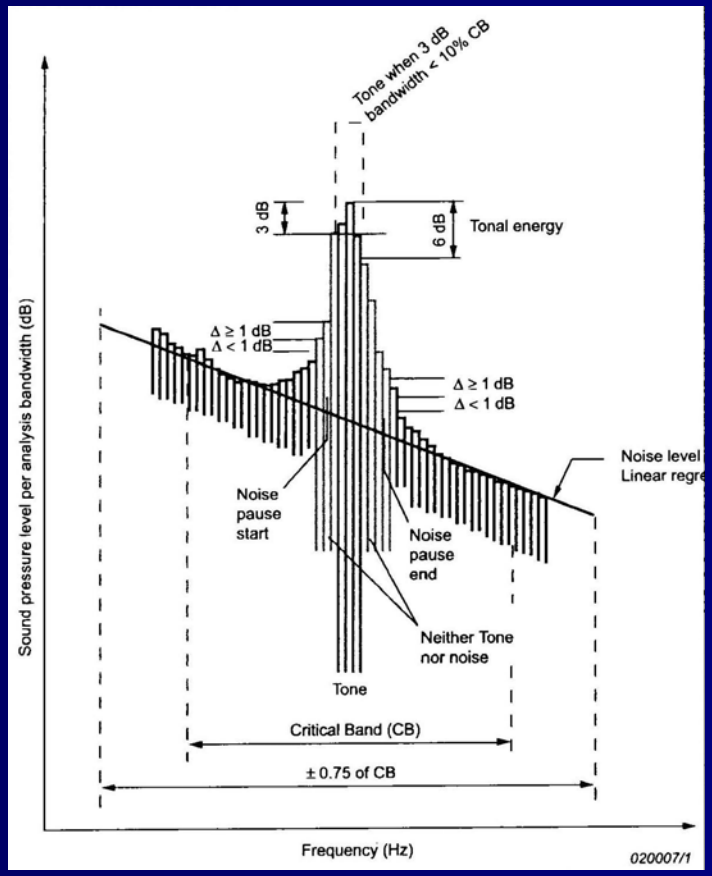
$$\Delta L_{ta} = L_{pt} - L_{pn}$$

where: L_{pt} is the power in the tone
and L_{pn} is the power in the noise in
the critical band centered on the tone

Instruments to measure tonality

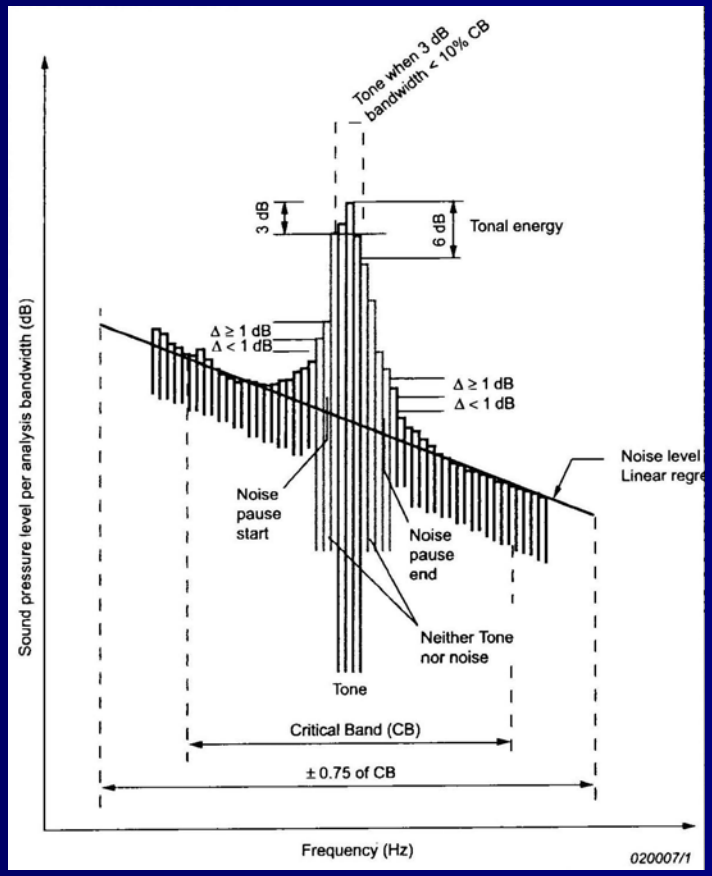
- B&K 2250/2270 has tone assessment option for both FFT and 1/3-octave analysis mode
- Tonality is based on ISO 1996-2:2007 (Annex C, Annex D)
- Standard setup is 6400 lines, 0-20 KHz with 5 Hz bandwidth (other options OK)

FFT Tone Detection Algorithm



- Detect peaks which represent a possible tone (i.e., noise pause)
- Tone exists when 3 dB bandwith < CB/10
- L_{pt} includes all energy within 6 dB of tone center frequency

FFT Tone Detection Algorithm



- L_{pn} is calculated from a linear regression of the spectrum within 0.75 CB of tone frequency
- $\Delta L_{ta} = L_{pt} - L_{pn}$

Tone Penalty (ISO 1996)

- ISO 1996 recommends adding a penalty, K_t, to the A-weighted sound pressure level to compensate for the presence of an audible tone. The penalty, K_t, is a function of the audibility ΔL_{ta} :

  If $\Delta L_{ta} < 4$ dB, $K_t = 0$ dB
  If $\Delta L_{ta} > 10$ dB, $K_t = 6$ dB
  Otherwise, $K_t = \Delta L_{ta} - 4$ dB

Summary

- Tones are more annoying than broadband noise
- Tones can be accurately measured with narrow band analyzers
- Tone detection algorithms are available, and standardized in ISO 1996-2 (2007)
- Tones should be incorporated into criteria