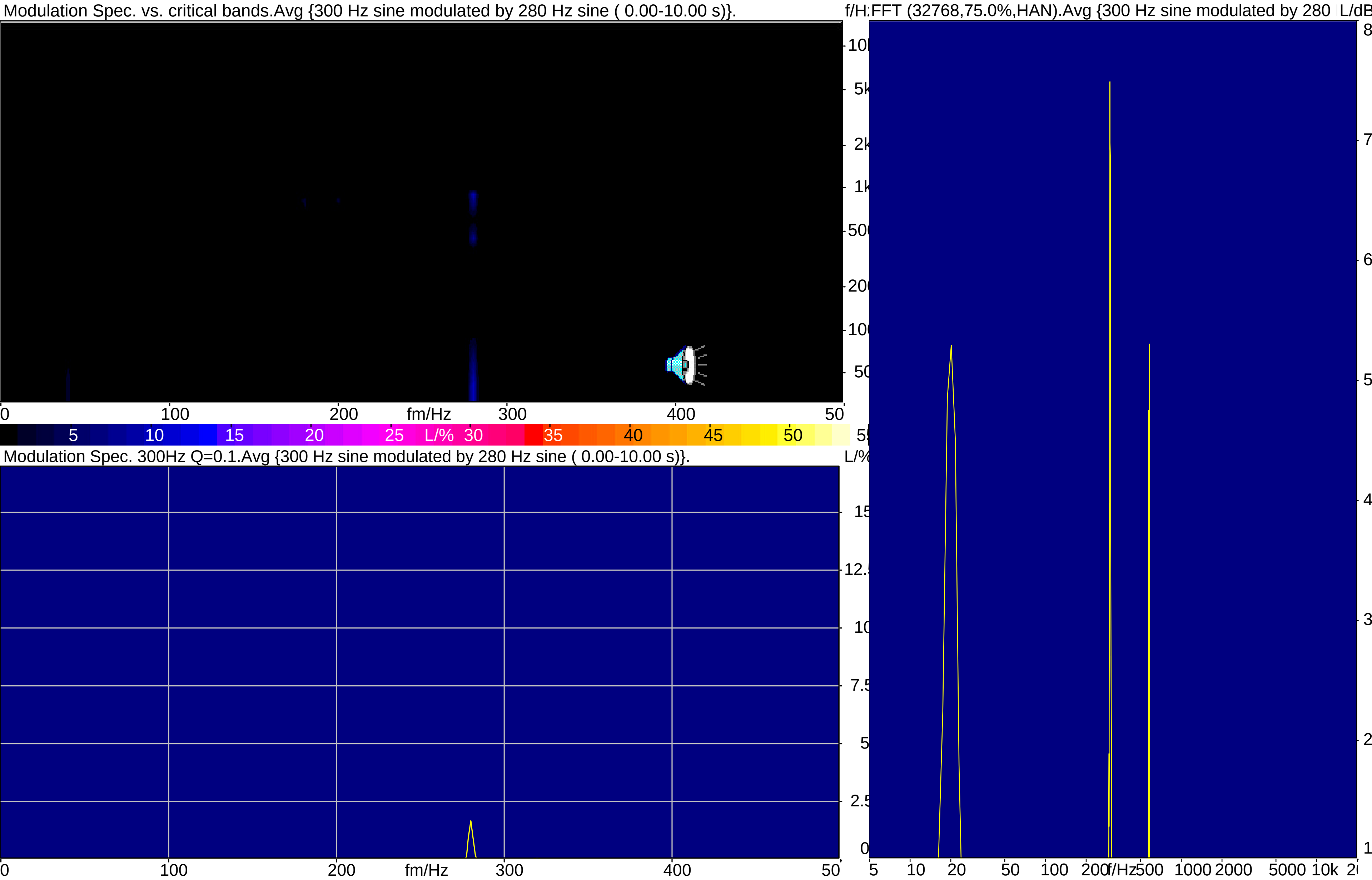
Same 300 Hz tone, modulated by 280 Hz sine tone of 75 dB SPL.
Note that the modulation strength drops as the rate increases.

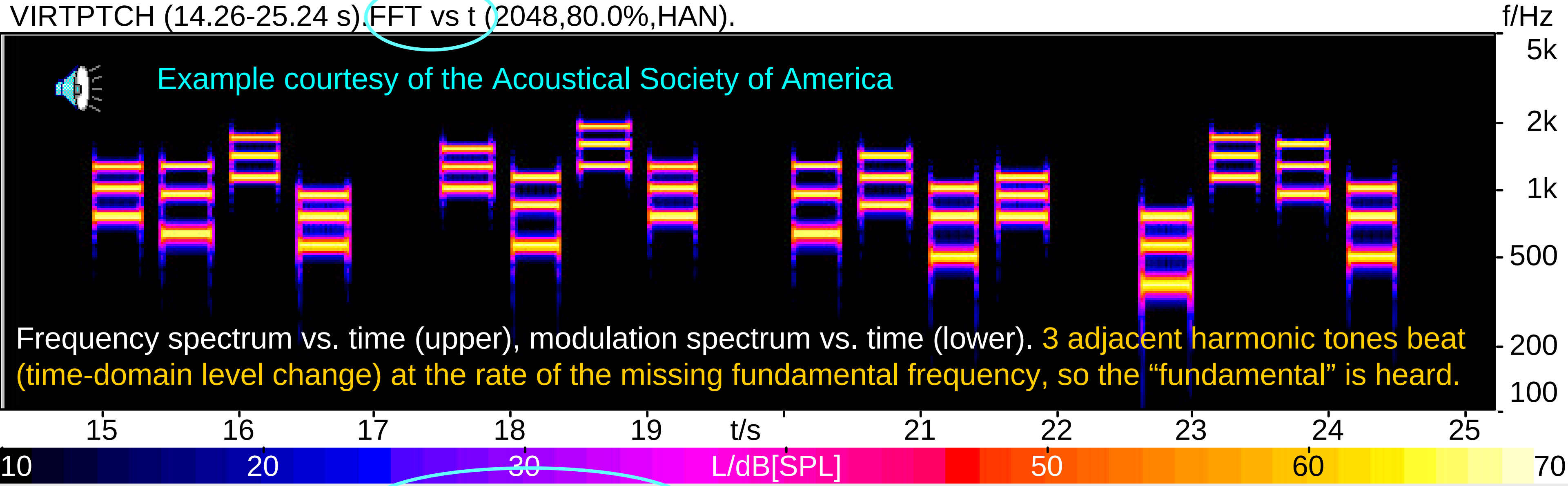


Modulation Spec. vs. critical bands.Avg {300 Hz sine modulated by 280 Hz sine (0.00-10.00 s)}.

f/H:FFT (32768,75.0%,HAN).Avg {300 Hz sine modulated by 280 L/dB

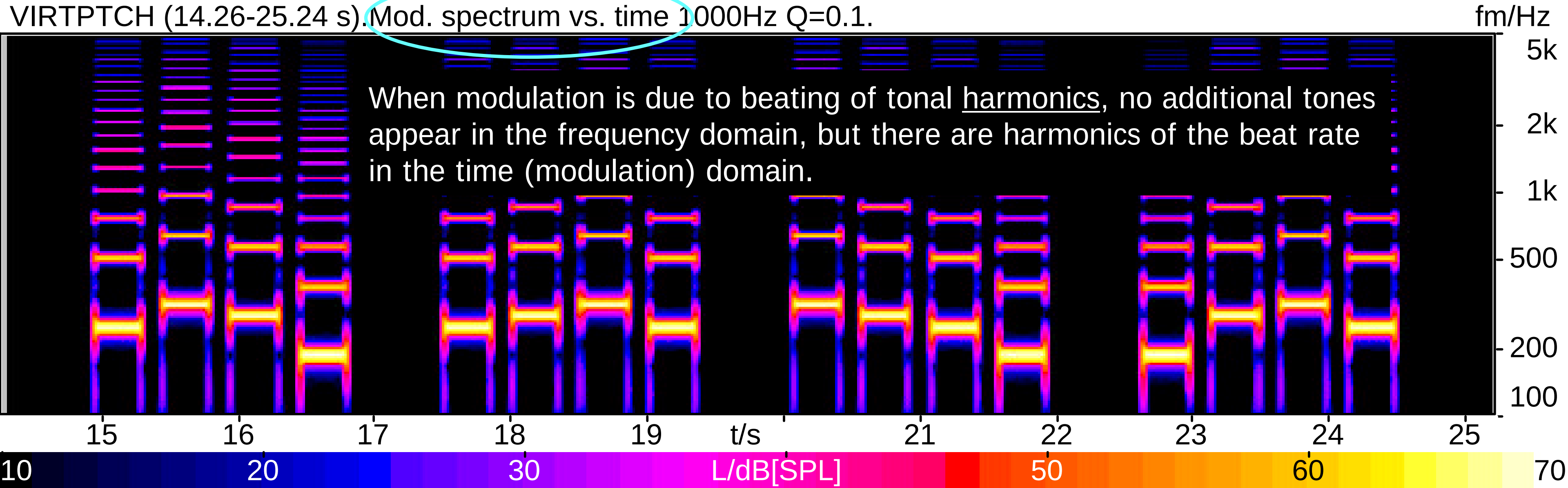
Modulation Spec. 300Hz Q=0.1.Avg {300 Hz sine modulated by 280 Hz sine (0.00-10.00 s)}.

A special case: Virtual pitch (hearing a pitch when frequency-domain content is absent at the "heard" frequency) is partly a function of modulation (the beats of the adjacent harmonics, too fast to be heard as time structure), and of the brain's recognizing that the harmonic frequencies present are related.



Example courtesy of the Acoustical Society of America

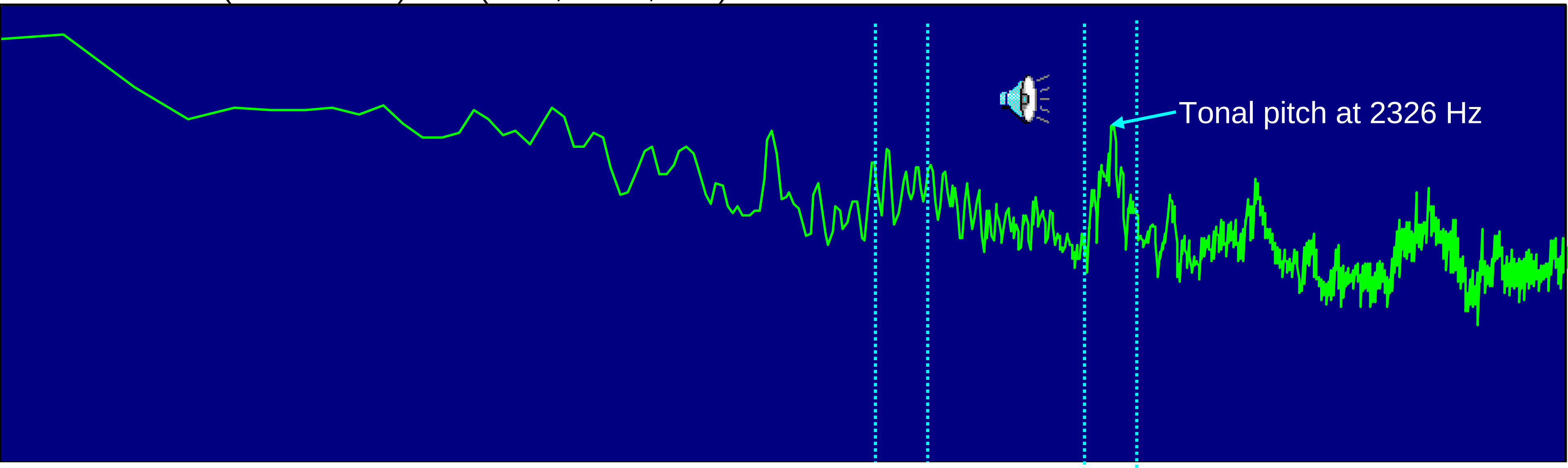
Frequency spectrum vs. time (upper), modulation spectrum vs. time (lower). 3 adjacent harmonic tones beat (time-domain level change) at the rate of the missing fundamental frequency, so the "fundamental" is heard.



When modulation is due to beating of tonal harmonics, no additional tones appear in the frequency domain, but there are harmonics of the beat rate in the time (modulation) domain.

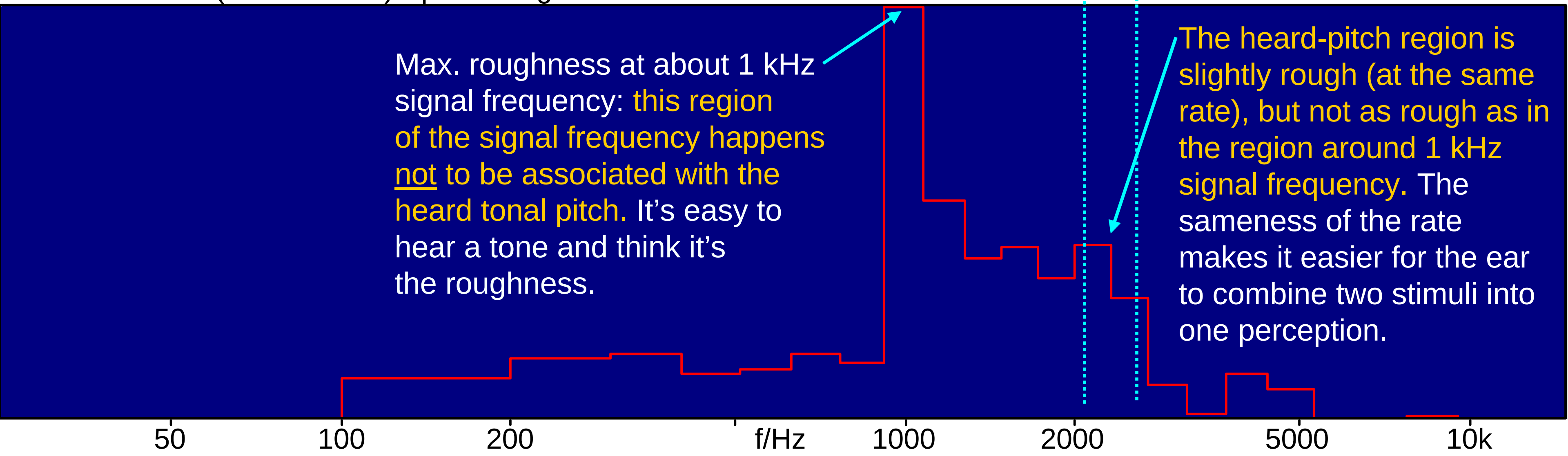
With rotating machinery, a tonal pitch and the region of maximum roughness (fast audible time structure, modulation) may be different, as here. Mixed stimuli can trick you. Practice listening <u>independently</u> to pitch and roughness.

SEAT 1 shorter (0.07- 0.94 s).FFT (4096,50.0%,HAN).



Tonal pitch at 2326 Hz

SEAT 1 shorter (0.07- 0.94 s).Spec. Roughness.

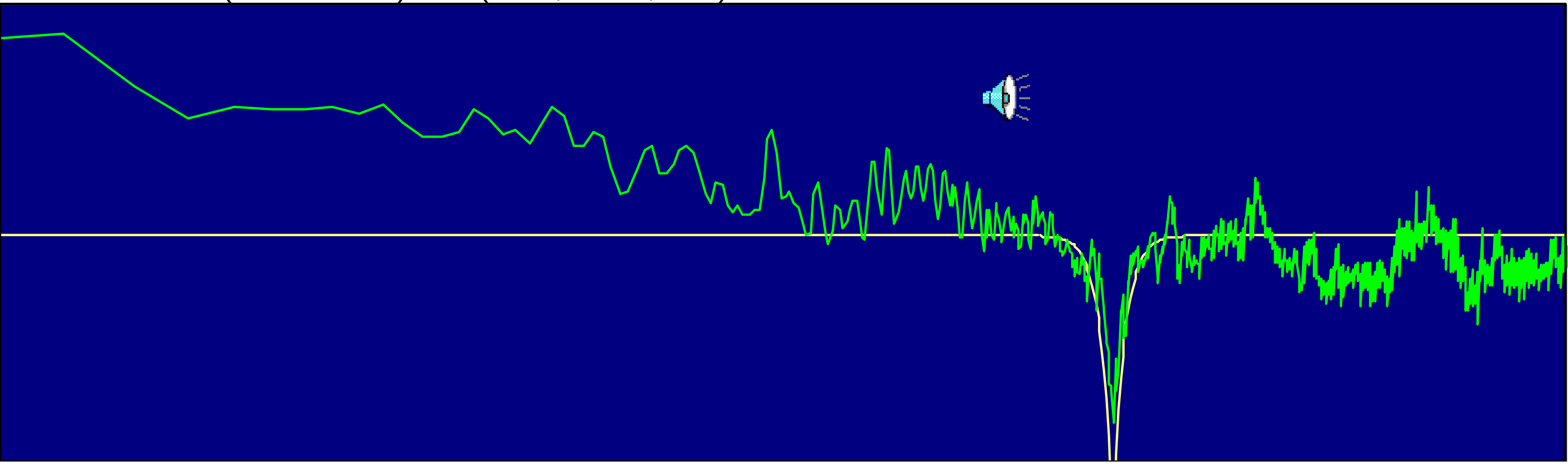


Max. roughness at about 1 kHz signal frequency: this region of the signal frequency happens <u>not</u> to be associated with the heard tonal pitch. It's easy to hear a tone and think it's the roughness.

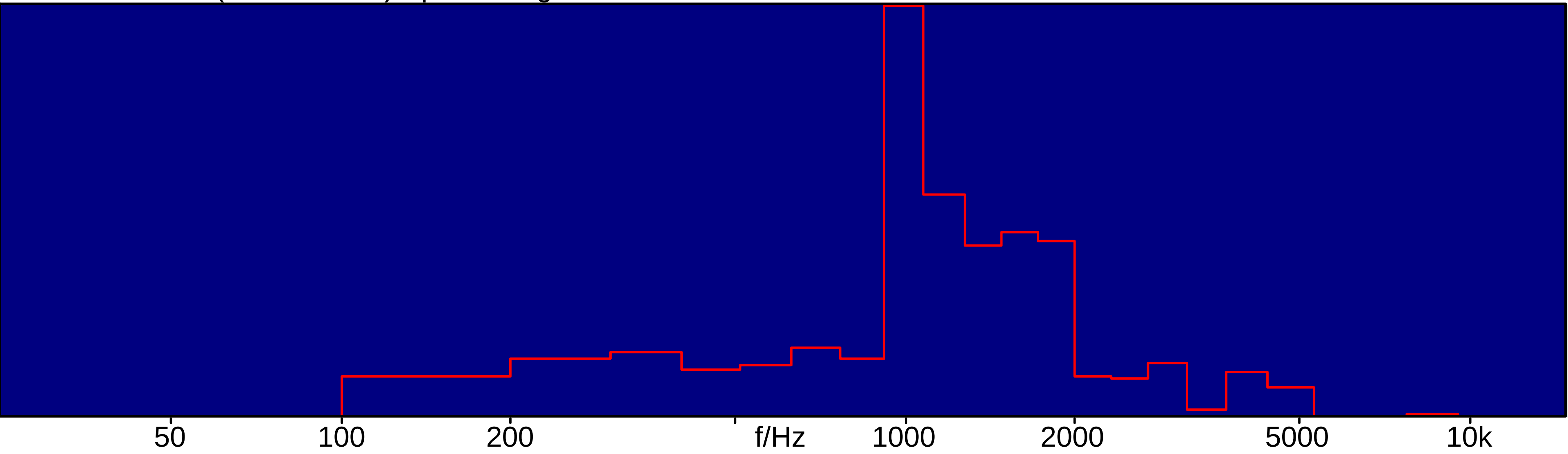
The heard-pitch region is slightly rough (at the same rate), but not as rough as in the region around 1 kHz signal frequency. The sameness of the rate makes it easier for the ear to combine two stimuli into one perception.

Filter out (only) the 2326 Hz tone:

SEAT 1 shorter (0.07- 0.94 s).FFT (4096,50.0%,HAN).

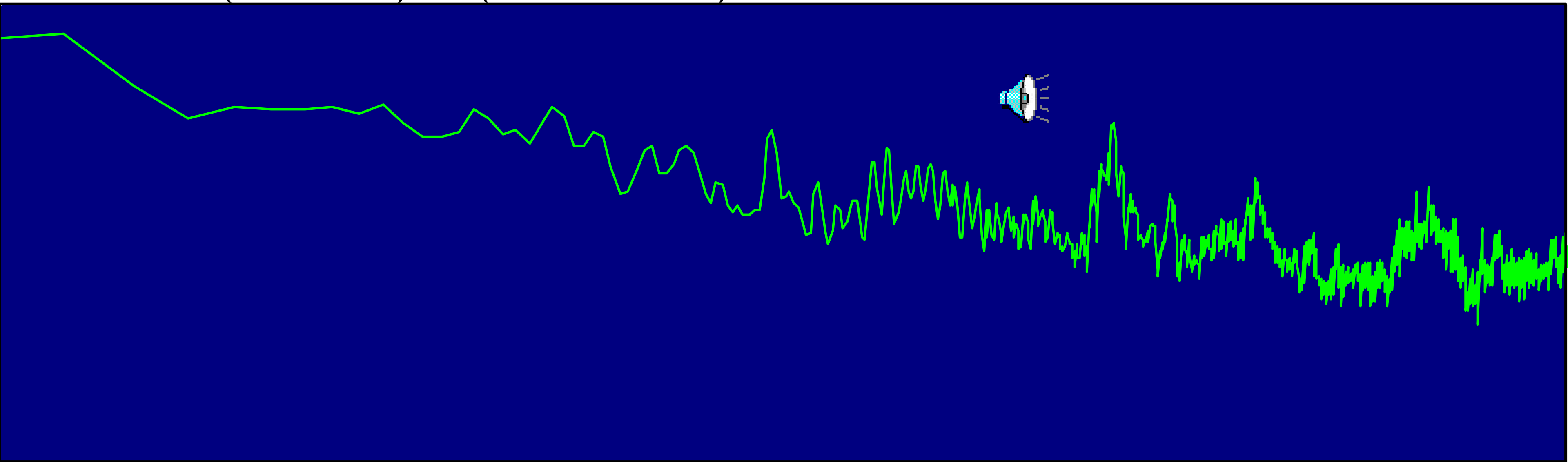


SEAT 1 shorter (0.07- 0.94 s).Spec. Roughness.

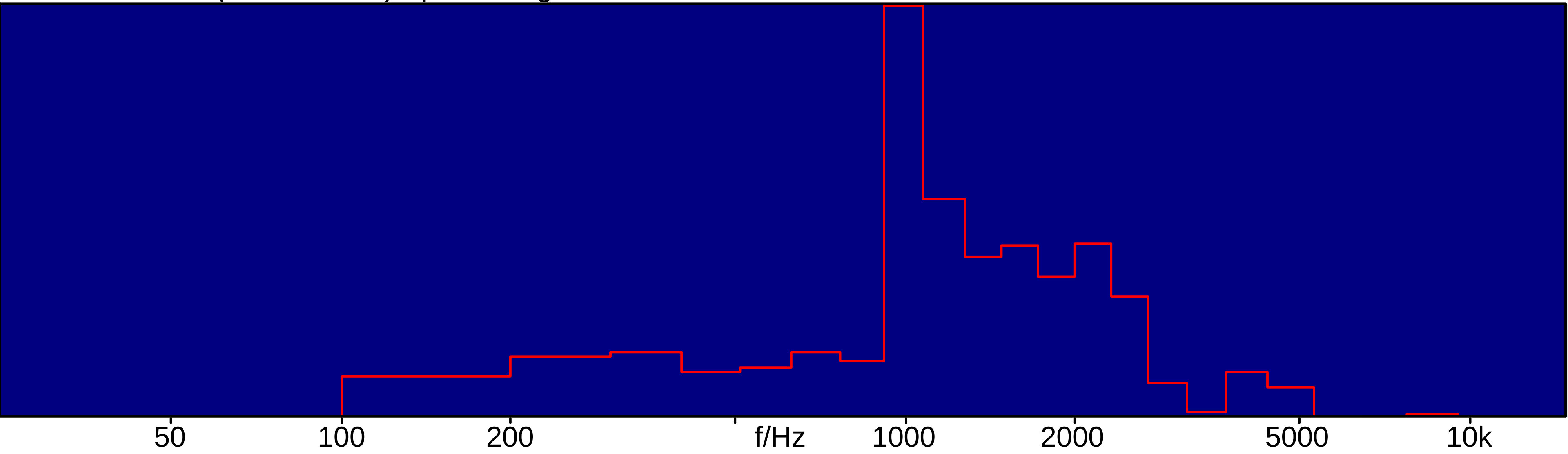


Back to the complete sound situation:

SEAT 1 shorter (0.07- 0.94 s).FFT (4096,50.0%,HAN).

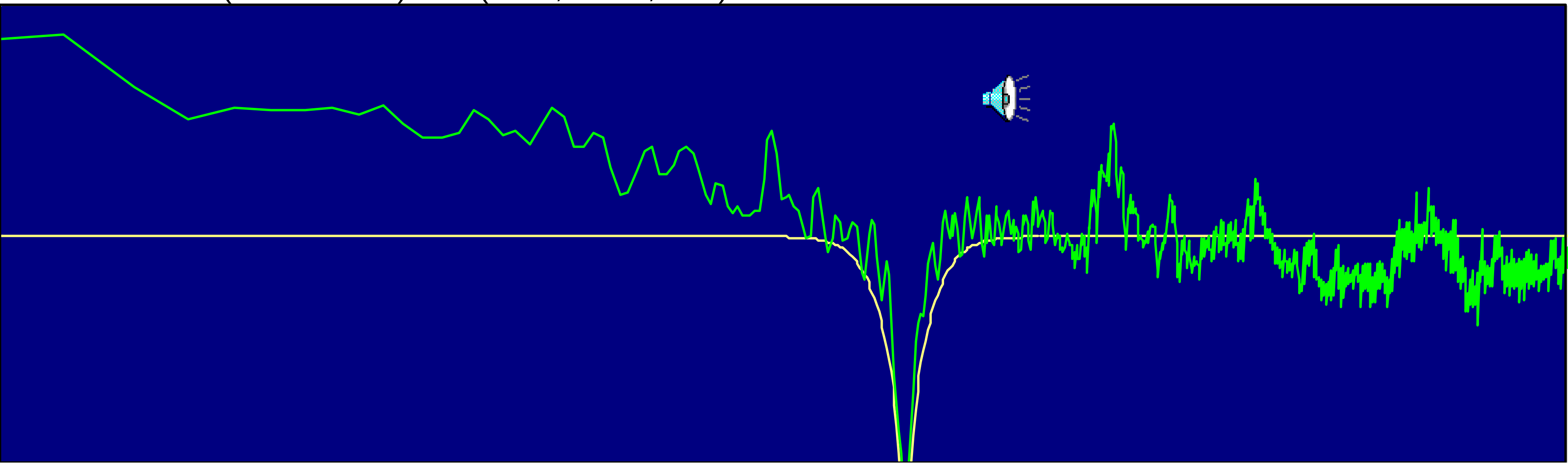


SEAT 1 shorter (0.07- 0.94 s).Spec. Roughness.

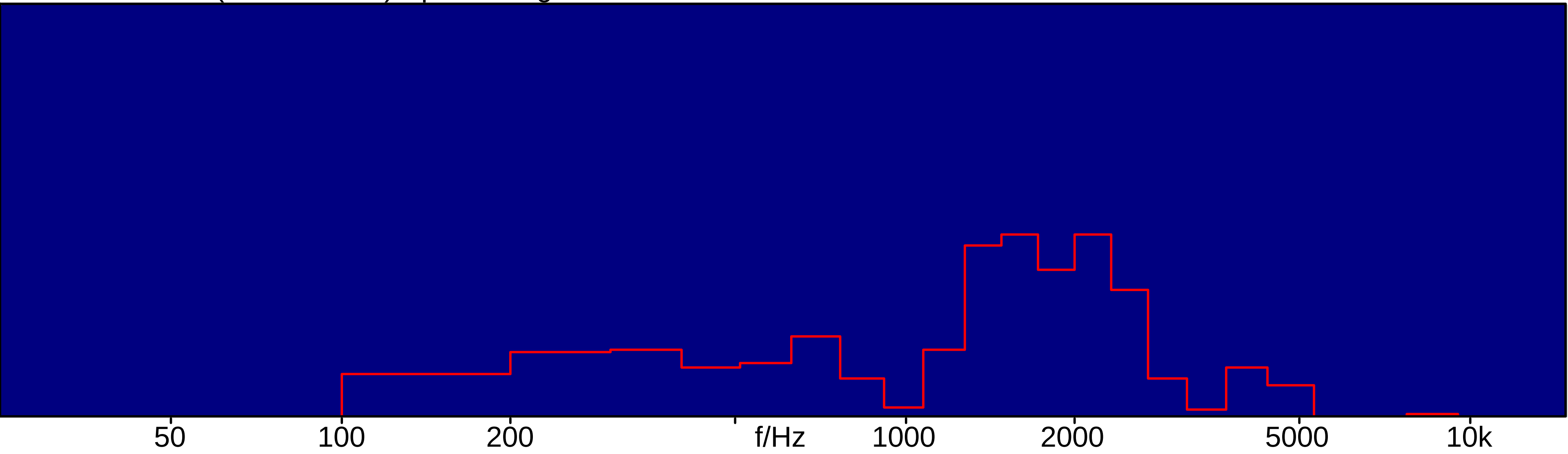


Filter out (only) the signal frequency region around 990 Hz where maximum roughness is measured:

SEAT 1 shorter (0.07- 0.94 s).FFT (4096,50.0%,HAN).

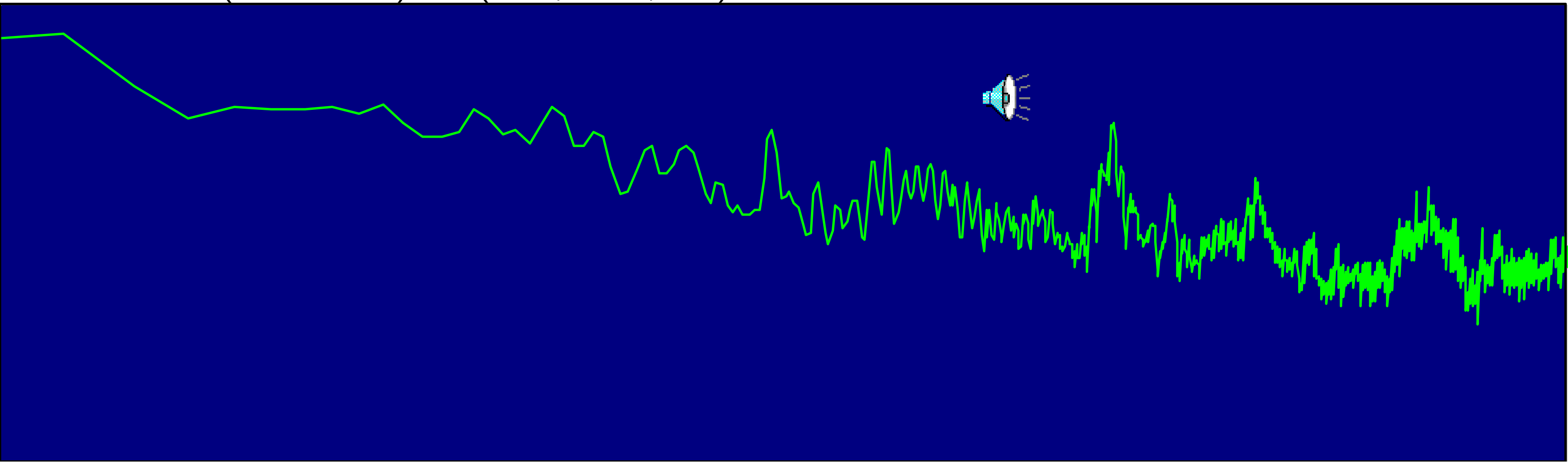


SEAT 1 shorter (0.07- 0.94 s).Spec. Roughness.

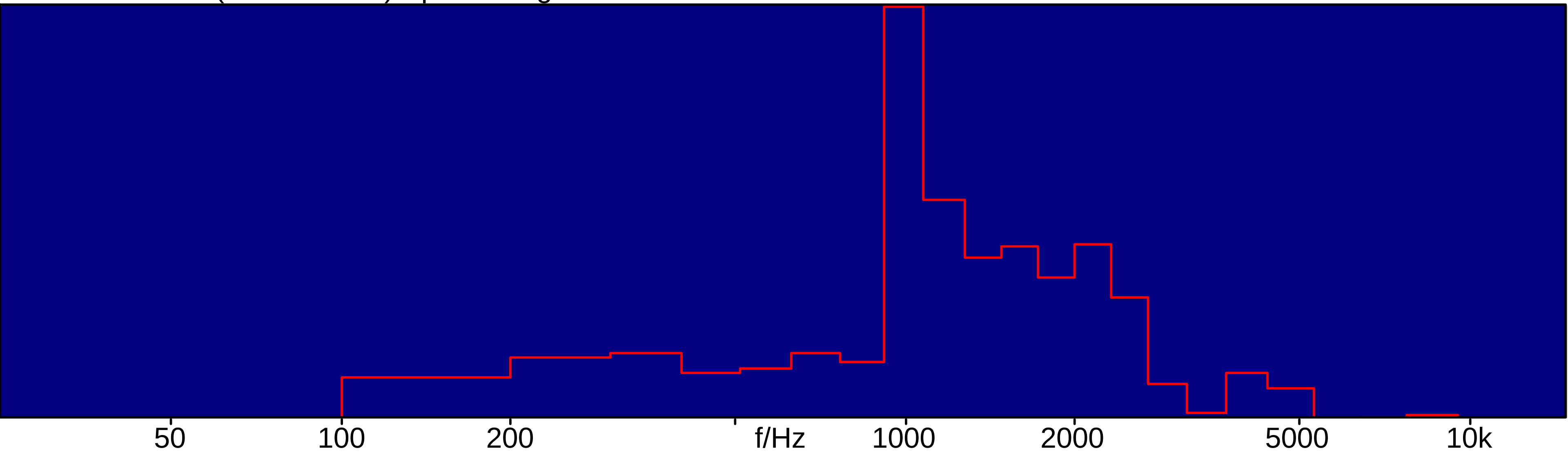


Back to the complete sound situation:

SEAT 1 shorter (0.07- 0.94 s).FFT (4096,50.0%,HAN).

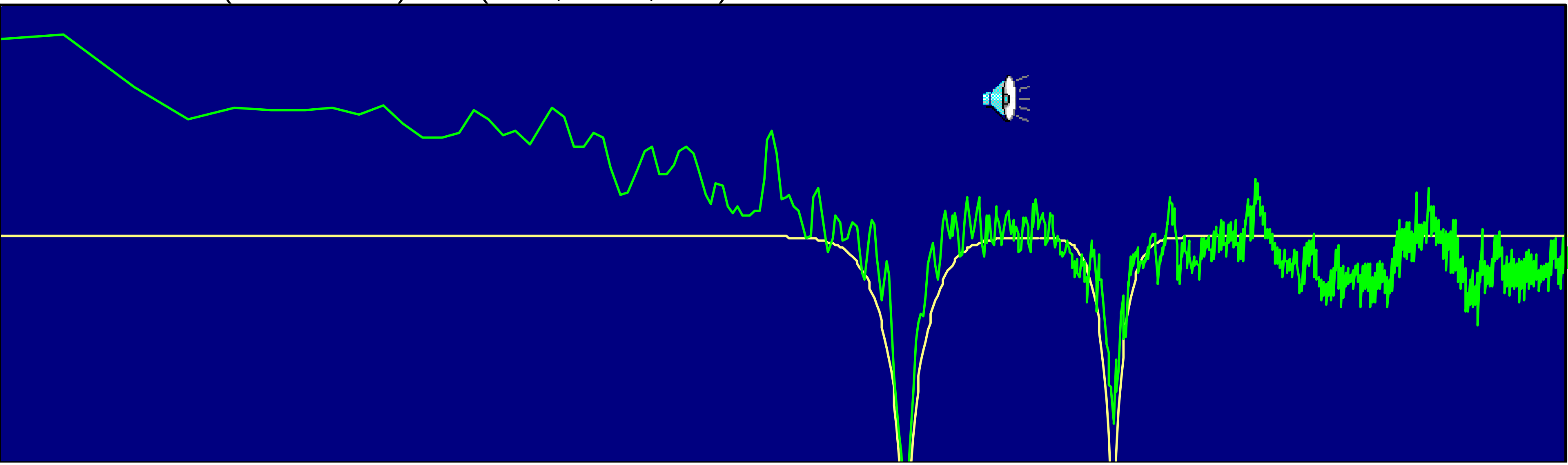


SEAT 1 shorter (0.07- 0.94 s).Spec. Roughness.

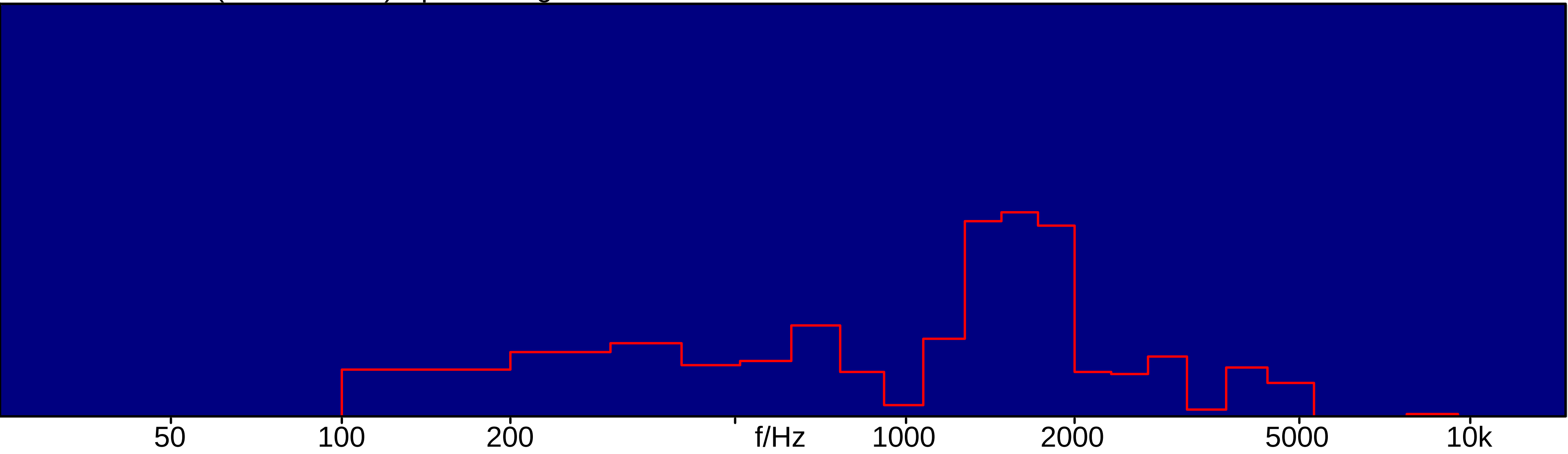


Tonal region and region of maximum roughness both filtered out:

SEAT 1 shorter (0.07- 0.94 s).FFT (4096,50.0%,HAN).

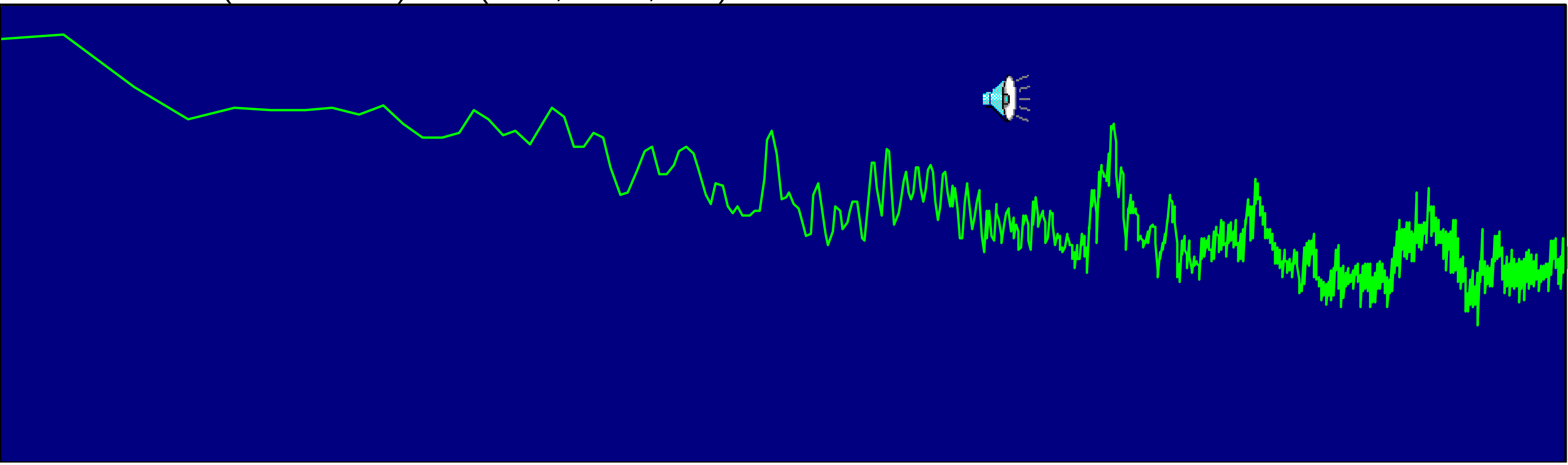


SEAT 1 shorter (0.07- 0.94 s).Spec. Roughness.

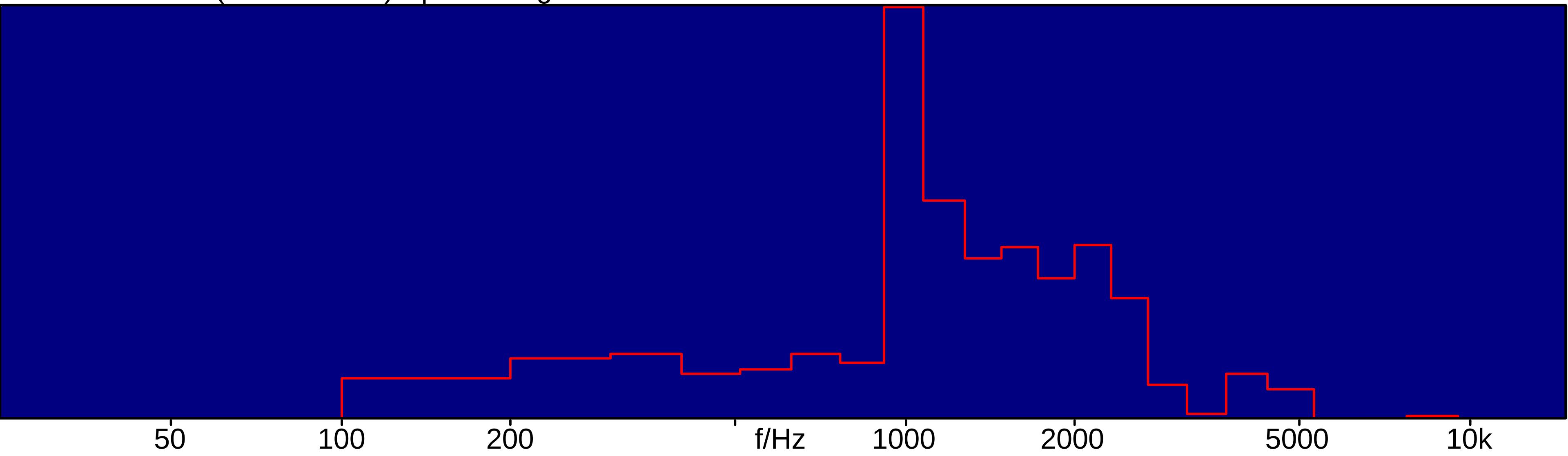


Back to the complete sound situation:

SEAT 1 shorter (0.07- 0.94 s).FFT (4096,50.0%,HAN).



SEAT 1 shorter (0.07- 0.94 s).Spec. Roughness.

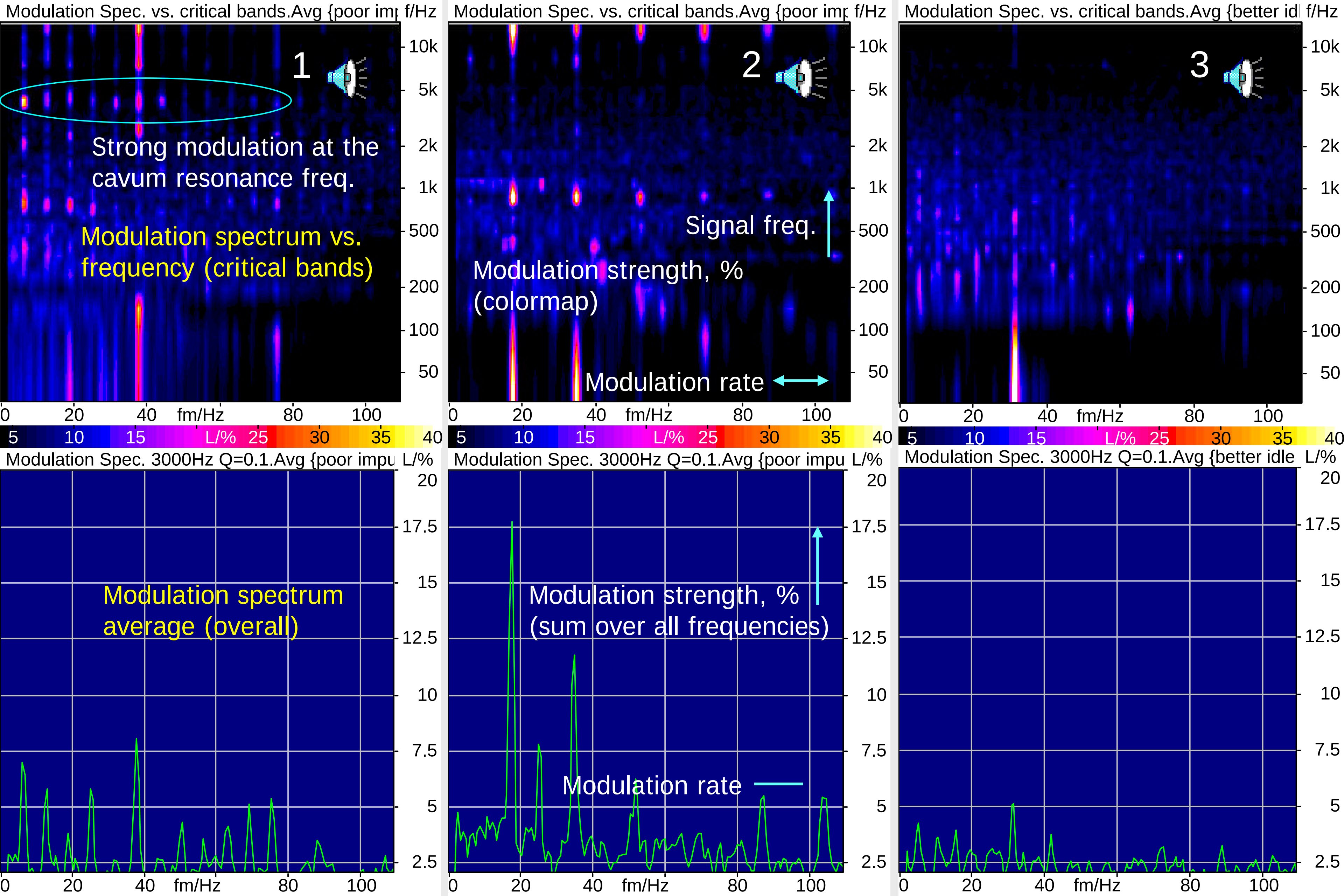


What kind of engine is this?

- Compression ignition?
- Spark ignition?

Answer: Spark ignition (it’s the left one), speaking an unfamiliar “language.”

The impulsiveness in 1 and 2 is due to fuel system operation.



Strong modulation at the cavum resonance freq.

Modulation spectrum vs. frequency (critical bands)

Signal freq.

Modulation strength, % (colormap)

Modulation rate

Modulation spectrum average (overall)

Modulation strength, % (sum over all frequencies)

Modulation rate

Non-Standard Metrics

Only stationary loudness has a standard (ISO532-B)

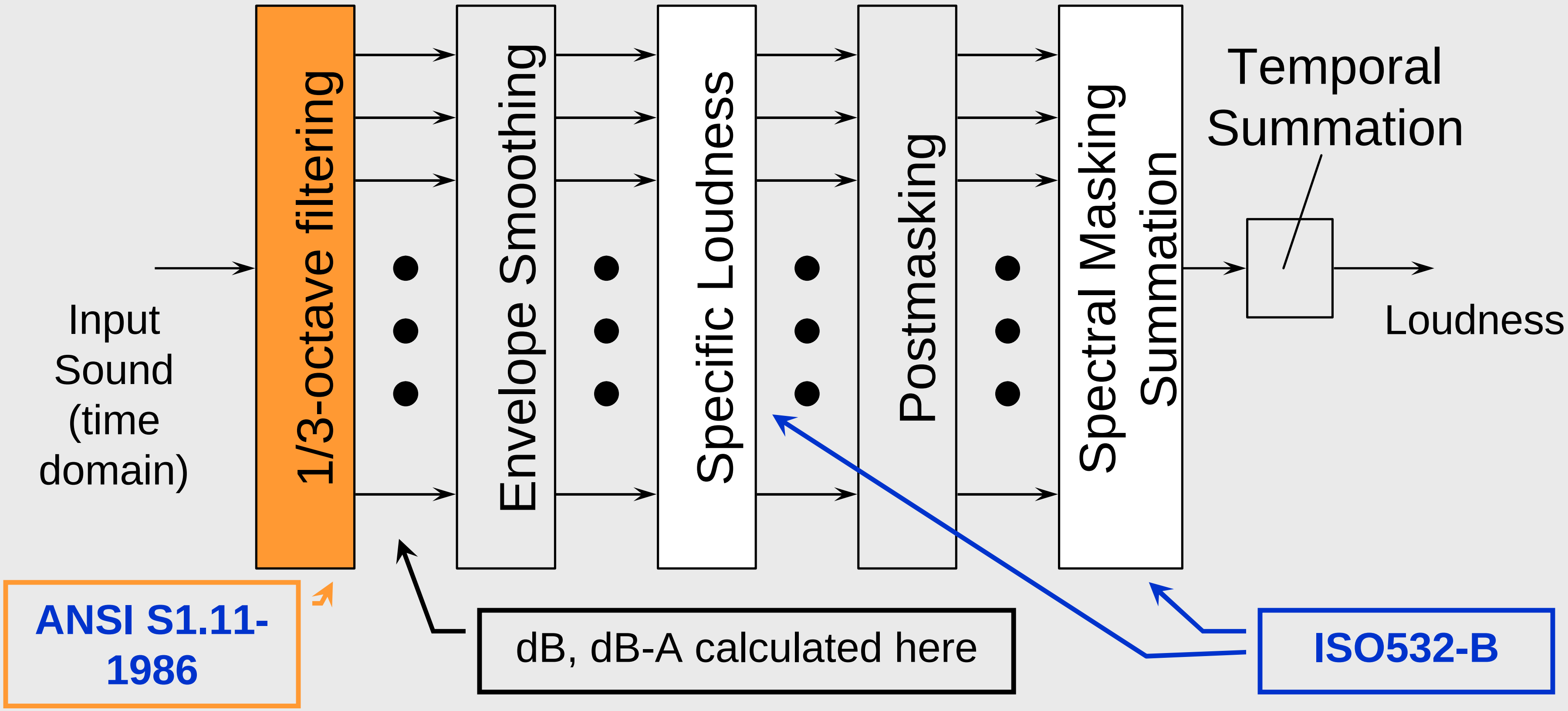
No standards for any other stationary or time-varying SQ metrics

- General agreement on signal flow for metric calculation, BUT...
- Implementation details (e.g., FFT vs. filtering, ...) can result in significantly different metric values for certain classes of sounds

Non-Standard Metric:
Time-Varying Loudness

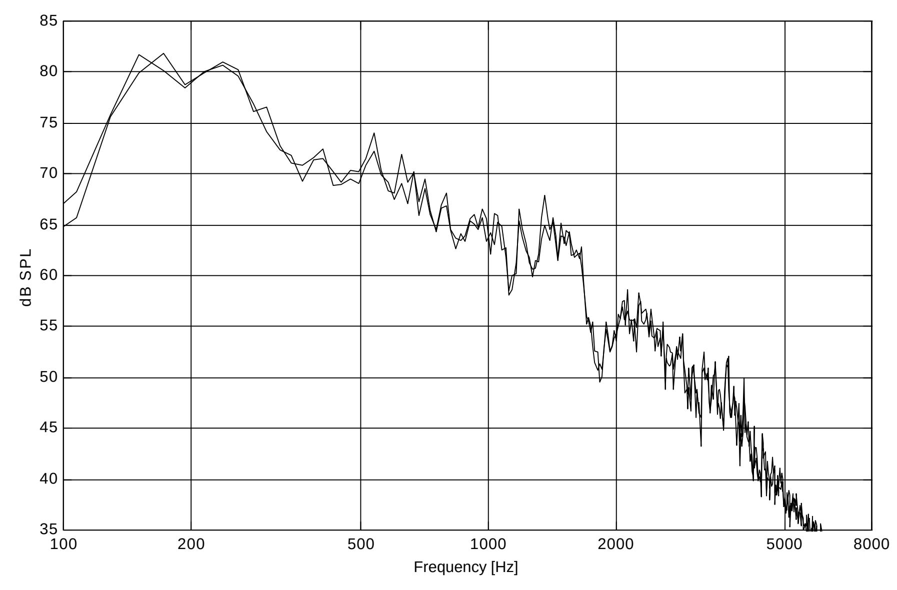
Based on Psychoacoustic research

- Specific Loudness and Spectral Masking are calculated according to ISO532B
- 1/3-octave magnitude response has ANSI standard (ANSI S1.11-1986)
  - No standard for phase response
- No other parts have a standard



Non-Standard Metric:
Time-Varying Loudness

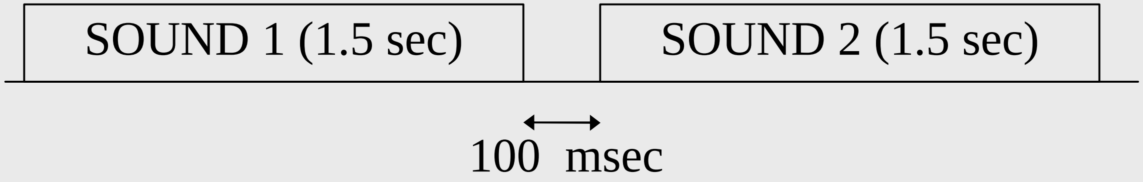
Why do we need time-varying loudness?



Same average spectrum

↓

Same ISO532B loudness

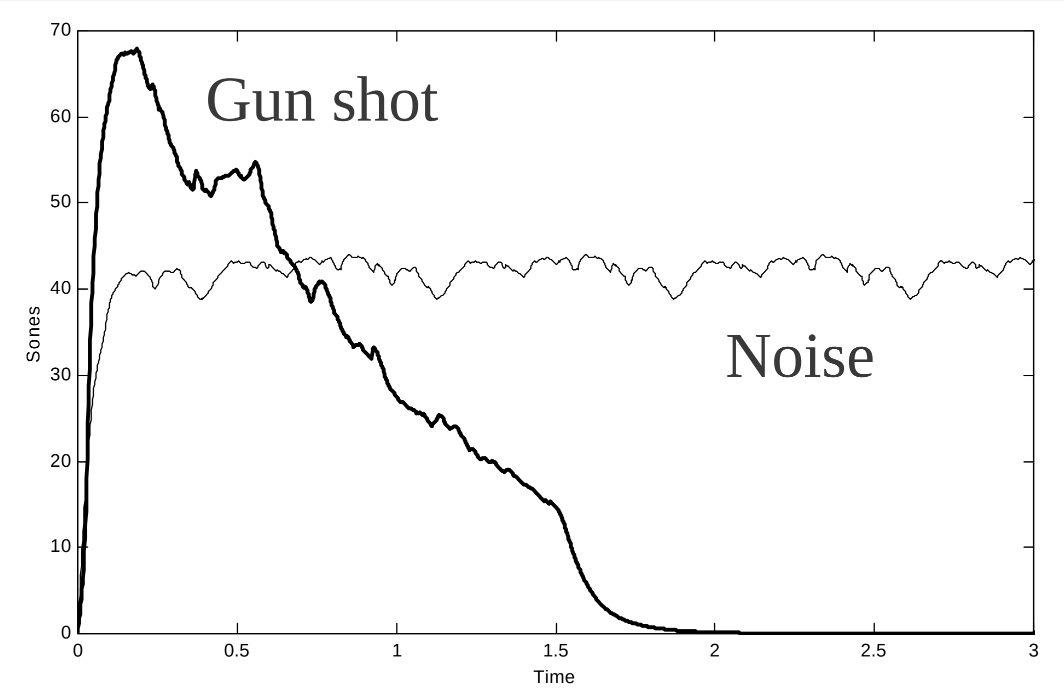

SOUND 1 (1.5 sec)

SOUND 2 (1.5 sec)

100 msec

Same perceived loudness??

Non-Standard Metric: Time-Varying Loudness



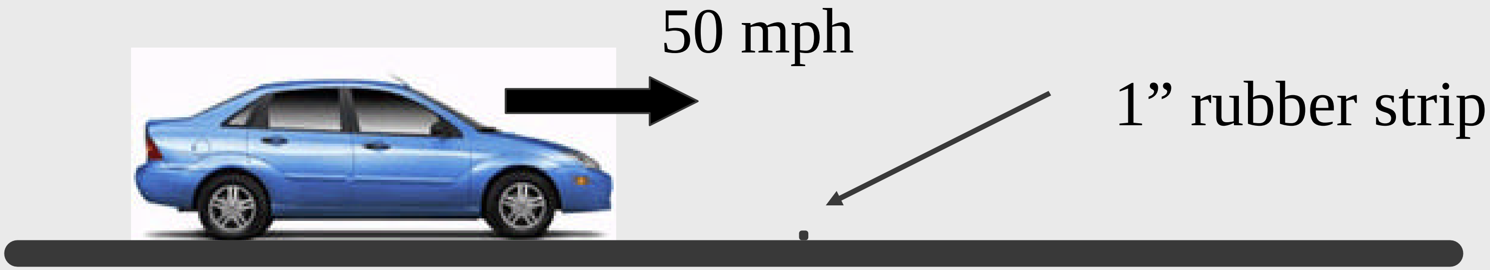
Non-stationary Sounds: perception generally correlates with peak loudness

Objective measures (statistics): N10 (90th percentile), MAX

Non-Standard Metric: Time-Varying Loudness

Example of differences in models

- Impact Harshness test
- Analyze same sound with 4 different systems
  - Look at relative and absolute differences



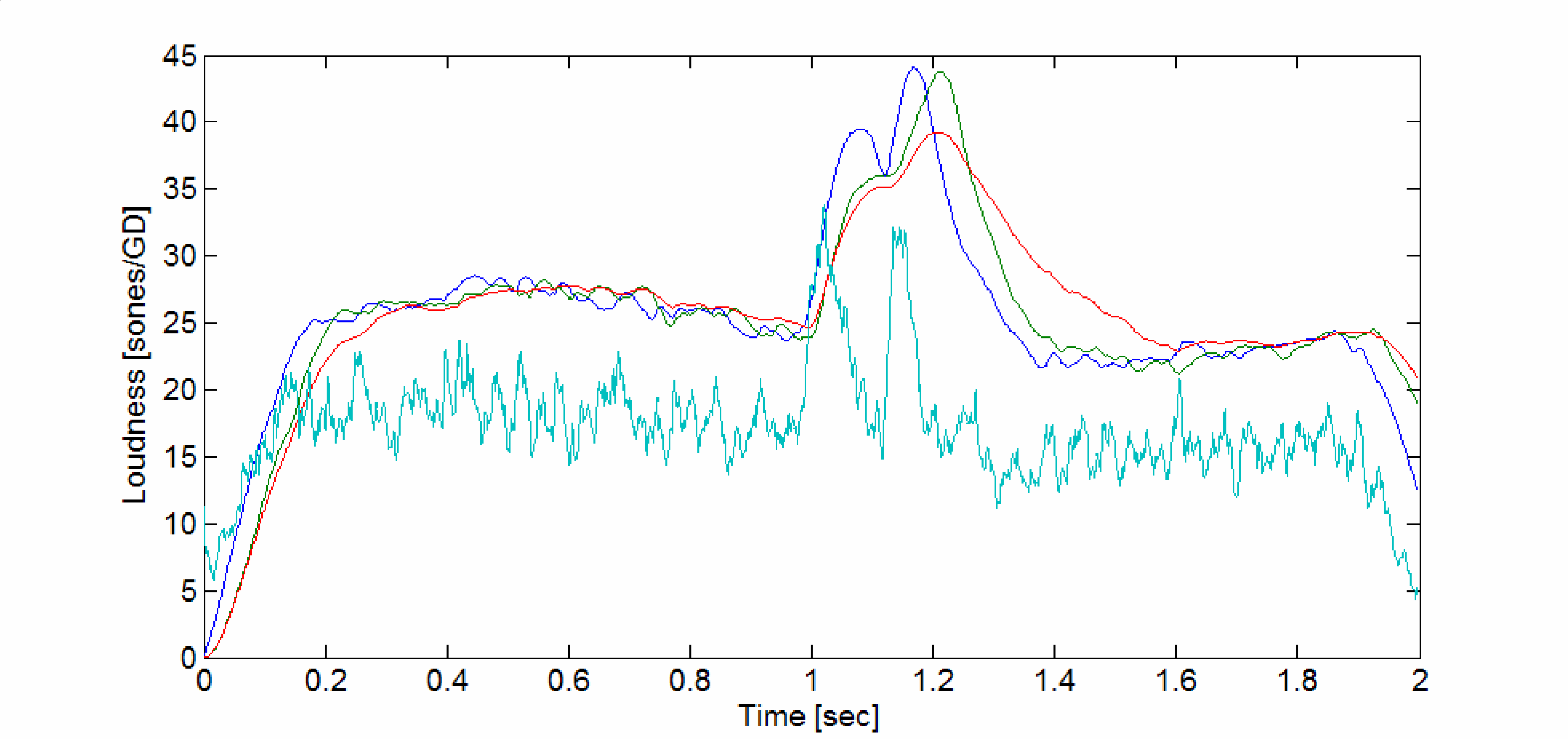
50 mph

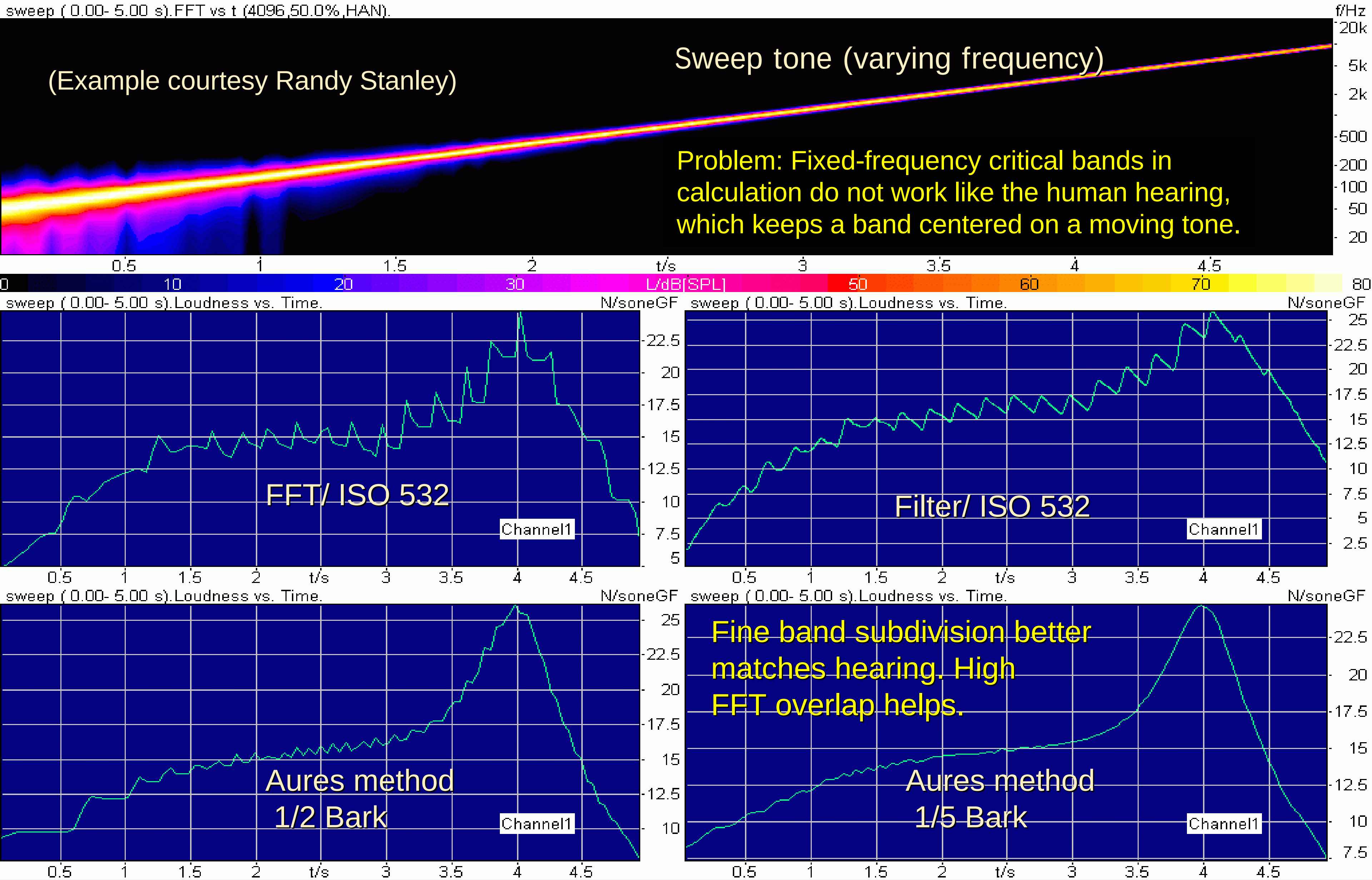
1” rubber strip

Non-Standard Metric:
Time-Varying Loudness

Comparison of loudness calculations

- 1 or 2 events??
- Which impact is louder? First or second?
- What is absolute loudness level of each impact?





Sweep tone (varying frequency)

(Example courtesy Randy Stanley)

Problem: Fixed-frequency critical bands in calculation do not work like the human hearing, which keeps a band centered on a moving tone.

Fine band subdivision better matches hearing. High FFT overlap helps.

Loudness vs. Time with different methods, responding to a varying-frequency tone of constant level. For sweep tones, the Aures method set to 1/5th critical band resolution works well.

Non-Standard Metrics

General solution is to have everyone use the same analysis system so that you’re comparing “apples-to-apples”

- Potential downsides are legacy issues, validity of historical database if change to different software, ...

Caveats & Observations In Using N10

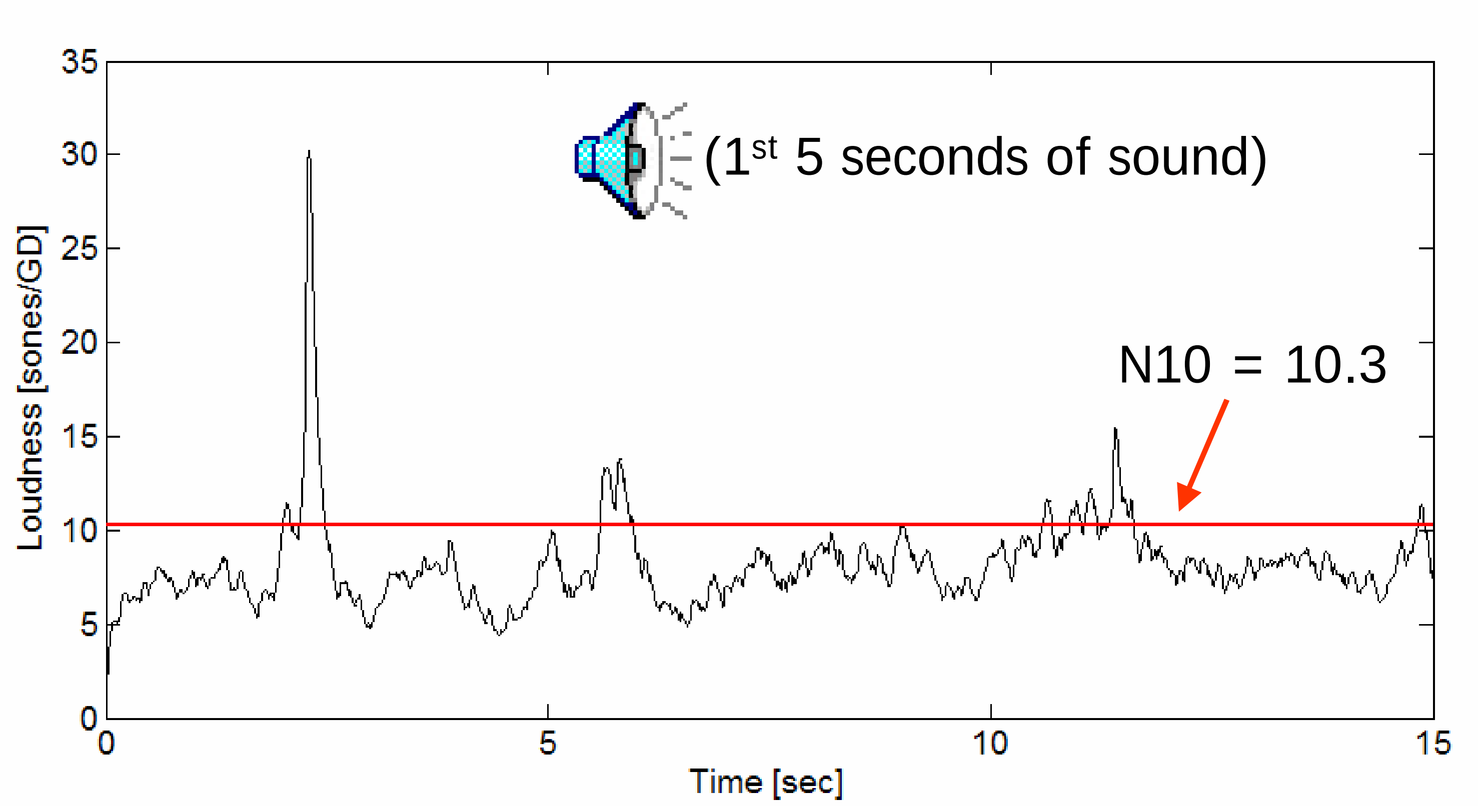
- N10 (90th percentile loudness) has been shown to agree with perceived loudness for *single* impactive events
    - Closures (e.g., doors, decklids, ...)
    - Switches
    - ...

- Care must be taken to apply N10 as a metric to sounds with multiple impacts...

Caveats & Observations In Using N10

Example: Squeak & Rattle testing on 4-poster

- Condition #1: Can miss very intermittent, but loud events



(1st 5 seconds of sound)

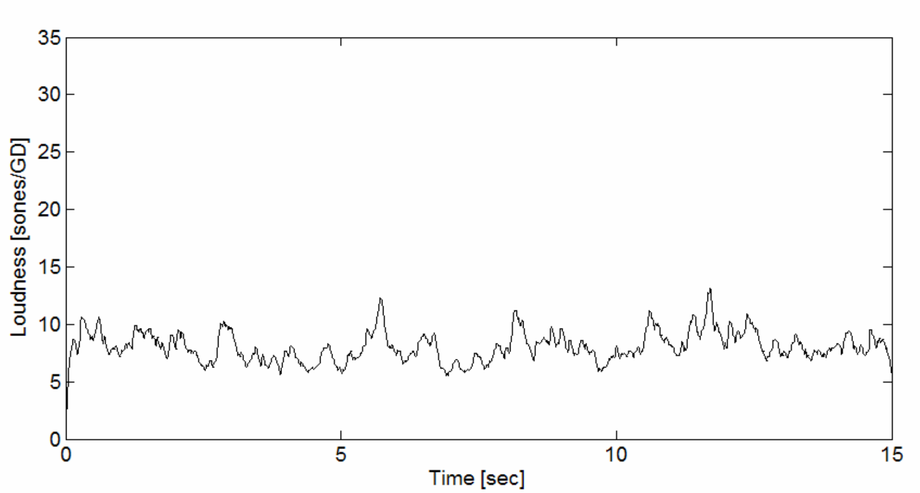
N10 = 10.3

Caveats & Observations In Using N10

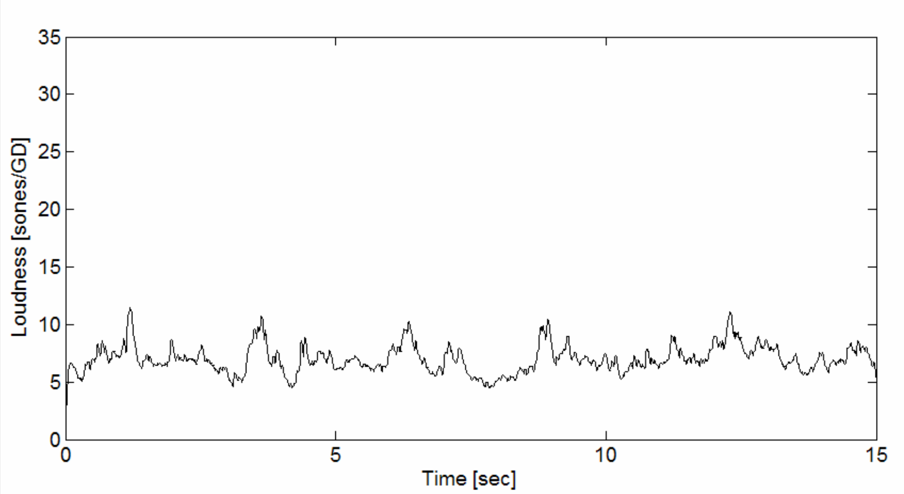
Condition #2: Miss persistent, but quiet events

- You don't always see what you hear, in the loudness trace

No S&R
(N10 = **9.8 sones**)



"Quiet Rattle"
(N10 = **8.5 sones**)



Subjective Evaluation

- Threshold
  - See 2003 SQ Workshop CD for Supra-threshold
- Example
- Levitt procedure
- Sound preparation
- Acquiring subjective data
- Analysis of subjective data
- Listening study demo

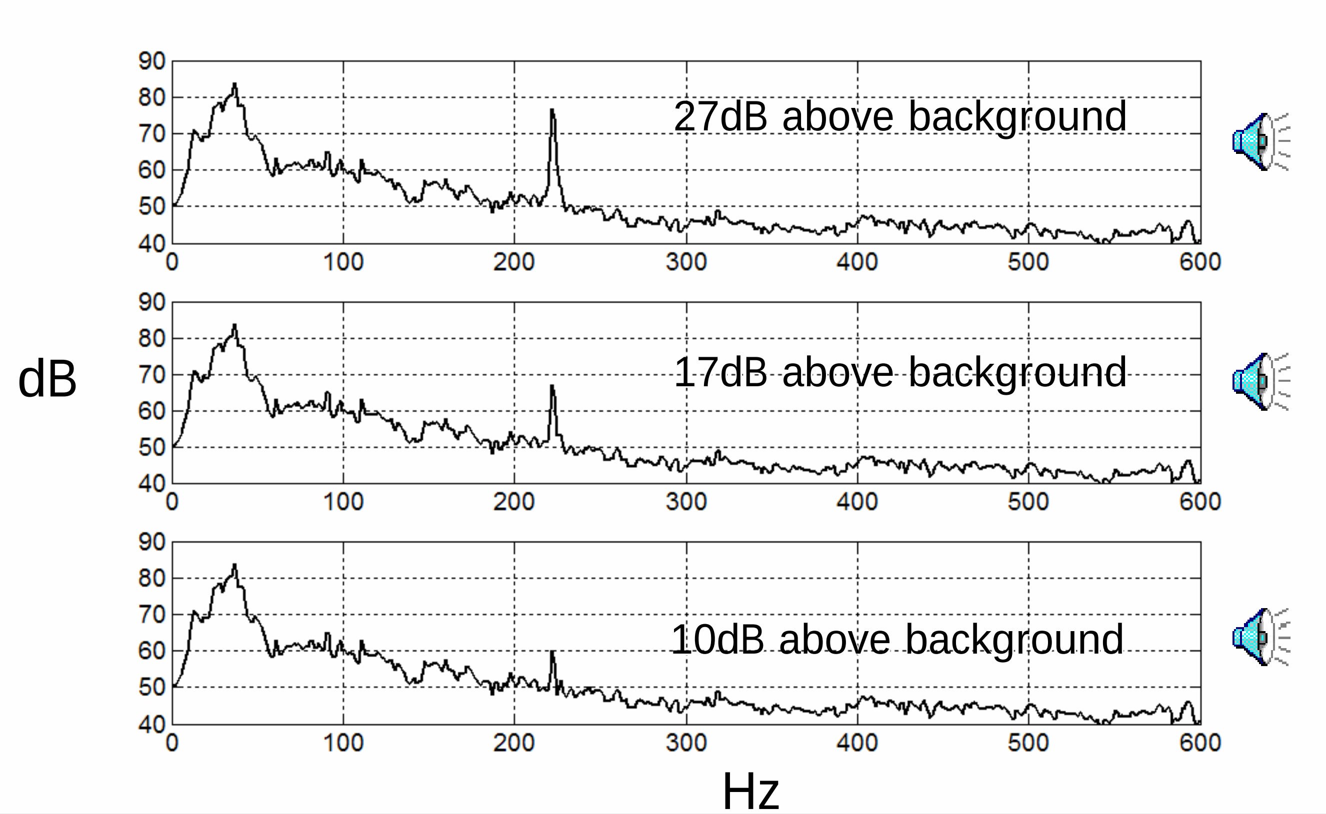
Reference:

H. Levitt, “Transformed Up-Down Methods in Psychoacoustics,”
J. Acoust. Soc. Am. (49) 2, pp. 467 477, 1971.

Example: Tonal Noise

At what point is tonal noise an issue?

- Can you hear it? (Detection Threshold)
- If yes, how bad is it? (Supra-threshold)



Threshold Methods

Classical

- Method of Adjustment
- Method of Limits
- Method of Constant Stimuli (Forced-choice)
- “Modern” Signal Detection Methods (Get probability of False Alarm, etc)
  - Yes-No
  - Two-Alternative Forced Choice (2AFC)

Adaptive

- Levitt
- Parameter Estimation by Sequential Testing (PEST)
- Maximum Likelihood Adaptive procedures

Biggest issues in selecting method

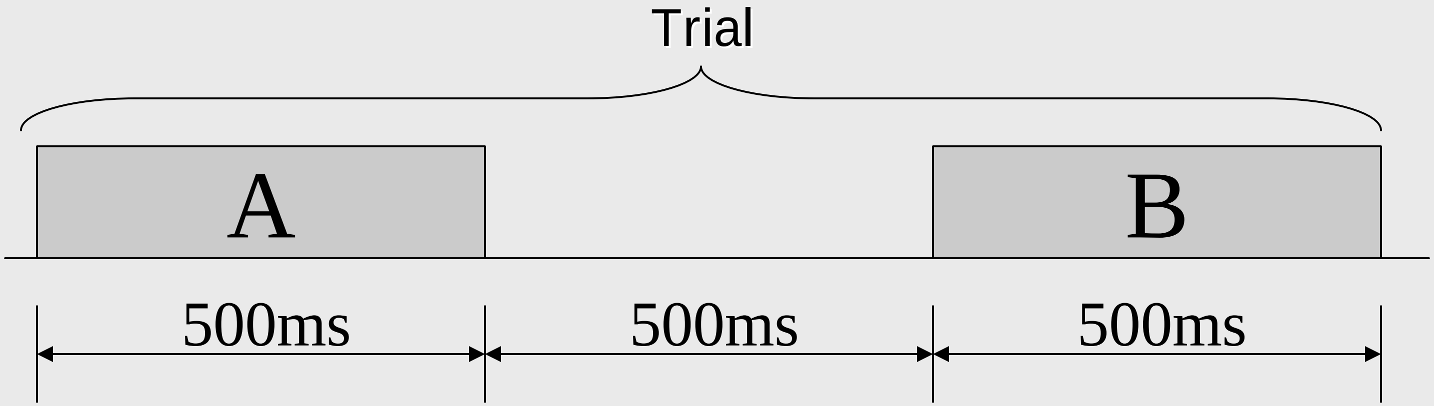
- Duration of test
- Variation in results

Levitt Procedure

Psychophysical procedure to estimate detection thresholds

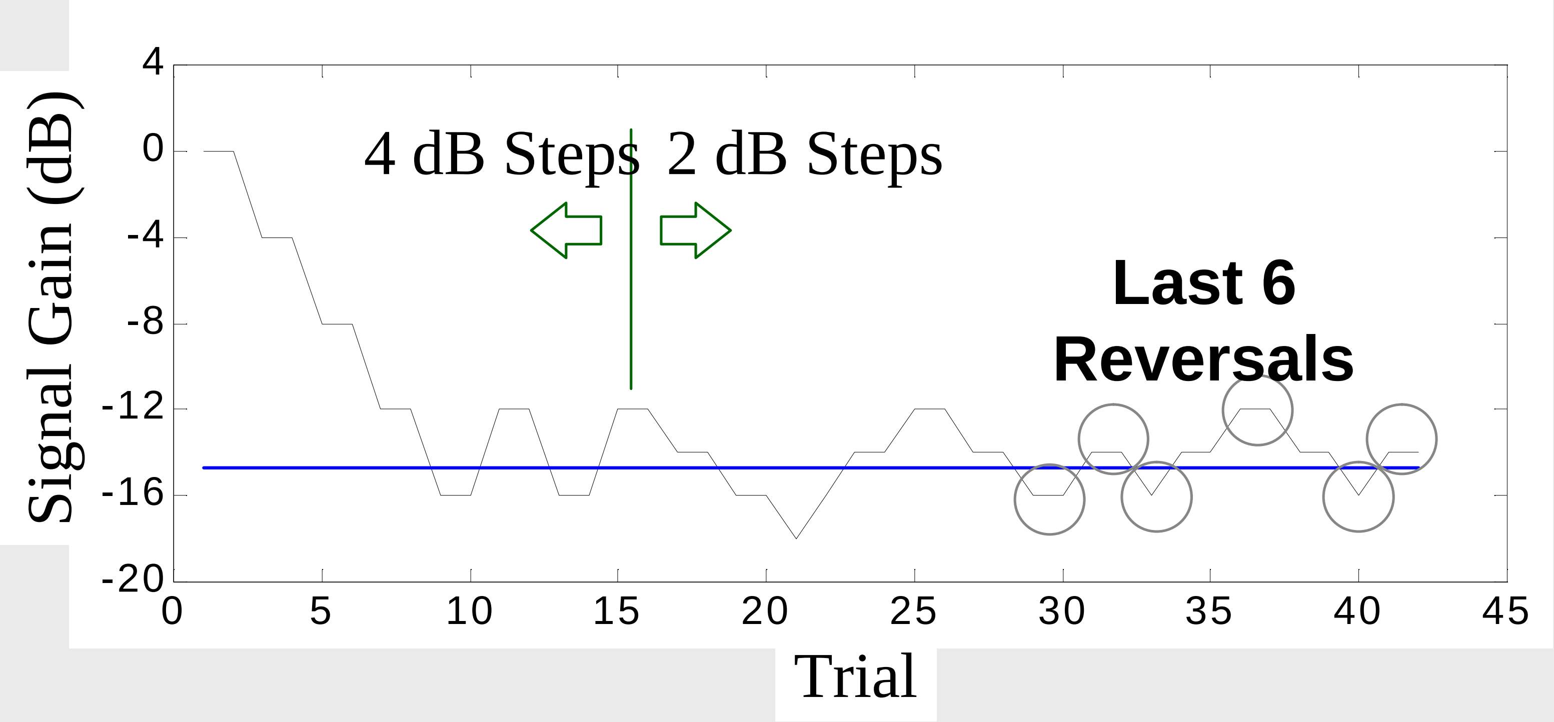
- Need “noise only” and “signal only” sounds
- Create two sounds:
  - Noise + a*(signal)   [where “a” can change]
  - Noise
- Listener selects which sound contains signal
- Use set of rules to determine whether “a” increases or decreases for the next trial

Levitt: 2-down, 1-up



- “Noise” and “Noise + a*(signal)” presented in random order for each trial
- Listener selects interval containing the signal in each trial
- Set of rules:
  - 2-down: If listener is correct for two consecutive trials, then decrease “a”
  - 1-up: If listener is incorrect, then increase “a”

2-down, 1-up Levitt Procedure: Determining Threshold



- Additional (suggested) rules:
  - Procedure is terminated after 12 reversals
  - Average last 6 reversals to get Threshold
  - Can have larger step size for “a” initially to get listener close to threshold

Levitt Procedure

Comments

- 3-down, 1-up is also popular, with 1-down, 1-up initially
  - 1-down, 1-up initially gets you near threshold faster
  - 3-down, 1-up later can give better estimate of threshold. Less chance of listener guessing correctly.

Sound Preparation

Sounds should be free of “distractions”

- Noise from vehicle instrumentation
- Unwanted squeaks, rattles from recording environment
- Talking/Breathing/Moving of person making the recording
- Other undesired characteristics that are not being investigated

Duration of sounds

- Long enough to capture the “event”

Apply onset/offset (fade in and out) to each sound to prevent “popping” on playback (25-50 msec is typical)

Acquiring Subjective Data

Demographics of listeners

- Gender, Age
- Vehicle Segment (e.g., luxury, truck, C-class)
- Expert vs. Non-expert Evaluators

Number of listeners

- ~30 works well
- Note: You can only run 1 person at a time, unlike paired-comparison, etc.

Listening environment

Description of test

Provide practice time, if needed

Provide feedback about correct/incorrect selection of signal

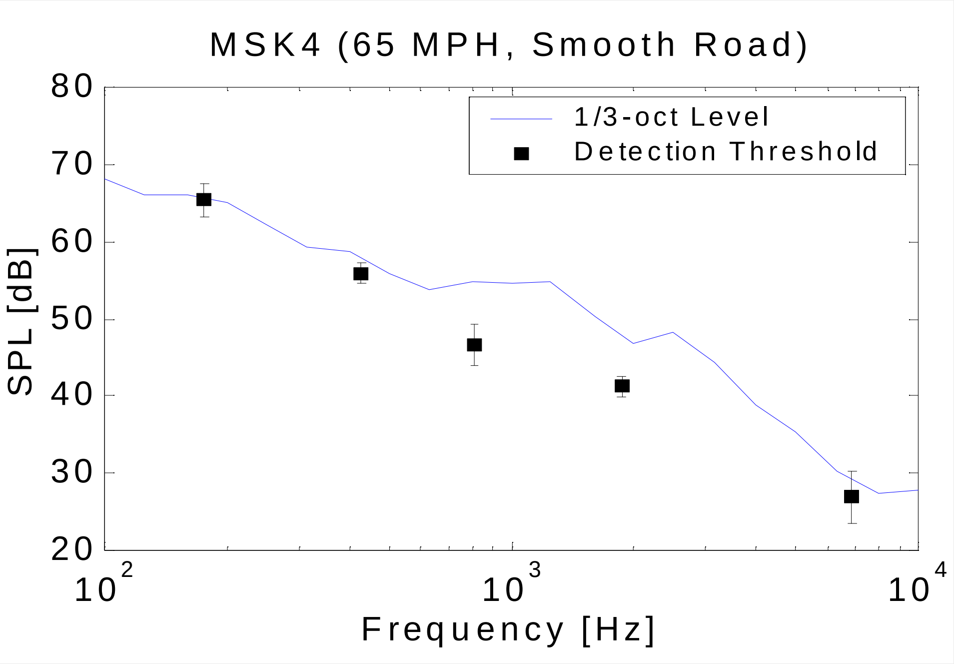
Analysis Of Subjective Data

Standard statistics for final thresholds

- Mean, standard deviation, confidence intervals, etc

Example

- Find out that 1/3-octave levels do not predict thresholds very well
  - Ear analyzes using Critical Bands
  - Spectral masking effects



Conclusion

Sound engineering has become very important.

Automotive products are becoming more refined.

Product differentiation is no longer just about “being quietest.”

Sound quality cannot be measured solely with conventional measurement technique.

Artificial Head, psychoacoustics, conventional metrics, modulation analysis, multi-channel analysis, all guided by listening and employing techniques like filtering, are helpful tools for sound engineering...

Listening studies provide the “voice of the customer” to validate subjective/objective correlation.

But:

For sound design we need the human factor, the expert to create a good sound.

Questions?

Contact Information

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Telephone: (248) 685-4163
e-mail: scott.a.lake@gm.com

Tools & Methods - References

Psychophysics and Psychoacoustics:

- *Psychophysics* - S. S. Stevens; ISBN: 0887386431
- *Psychoacoustics: Facts and Models* - Zwicker & Fastl; ISBN: 3540650636
- *Hearing* - Moore, B.C.J (Editor); ISBN: 0125056265
- *Spatial Hearing* - Blauert, J.; ISBN 0262024136
- Journals: *Acustica, Journal of ASA*
- CD: *Auditory Demonstrations*, available from Acoustical Society of America (ASA) website at: http://asa.aip.org/discs.html

Subjective Evaluation

- "Guidelines for Jury Evaluations Of Automotive Sounds" N. Otto, S. Amman, C. Eaton, S. Lake, *1999 SAE N&V Conf. 1999-01-1822*, Traverse City, MI
- *The Method of Paired Comparisons*, David, H. A.; ISBN: 0195206169

Tools & Methods - References

Signal Processing:

- *Digital Signal Processing* - Proakis and Manolakis; ISBN: 0133737624

Statistics for Subjective Evaluation:

- www.statsoft.com / Electronic Statistics Handbook
- Quantitative Applications in the Social Sciences: Sage Publications
  - *Magnitude Estimation, Factor Analysis, Multi-dimensional Scaling*, etc.
- *Introduction to Regression Analysis*: Montgomery and Peck, ISBN: 0471533874

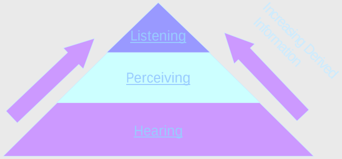
Of Related Interest:

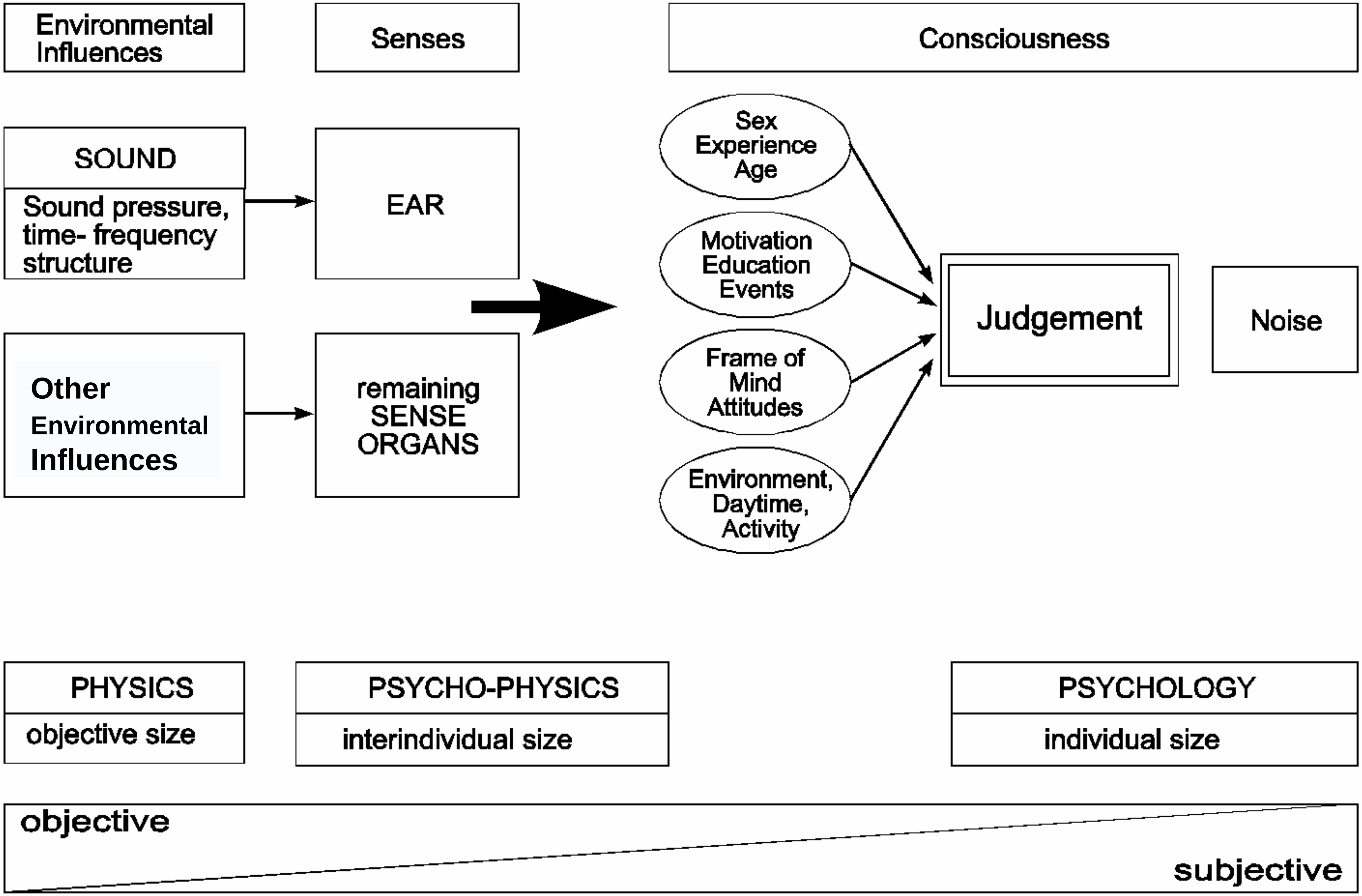
- *Music, the Brain & Ecstasy* – Jourdain, R.; ISBN: 038078209X

Listening - Definition

- Listening goes one step further than perception, introducing our expectations of the information as part of the processing of the information.

- Demonstration of two examples:
  - Famous Quotation
  - What are you hearing?





No <u>one</u> measure can
satisfy this continuum.