Experiments in two-tone interference

Using zero-based encoding

An alternative look at combination tones and the critical band

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Time/Space Systems

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Functions of the experimental system:

- Variable frequency F2 runs in stepped scan increments.
  - Increments per scan can be selected for each test.
  - Frequencies of scan range and/or mask frequency are selectable.
- During F2 scan the sound of each increment heard in continous stream but may be interrupted for repetition to distinguish its timbre. (Here, timbre represents the composite of all subtones produced by the two-tone interference.)
  - At each interruption the listener may enter a label and record each point of changes in timbre. (As in the Roederer diagram.)
  - The sound of each increment can be presented sequentially or in randomized order to minimize listener bias.
- Results of each test scan are displayed in a plot of responses with labeled data presented for analysis.

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Two important experiments in two-tone interference:

- **Combination tones:** studied since the 18th century and still unexplained
- **Two-tone masking:** its "critical band" remains unexplained

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Combination tones

This experiment replicates the listener responses observed by R. Plomp and many others since 18th century violinist Tartini formally identified them.

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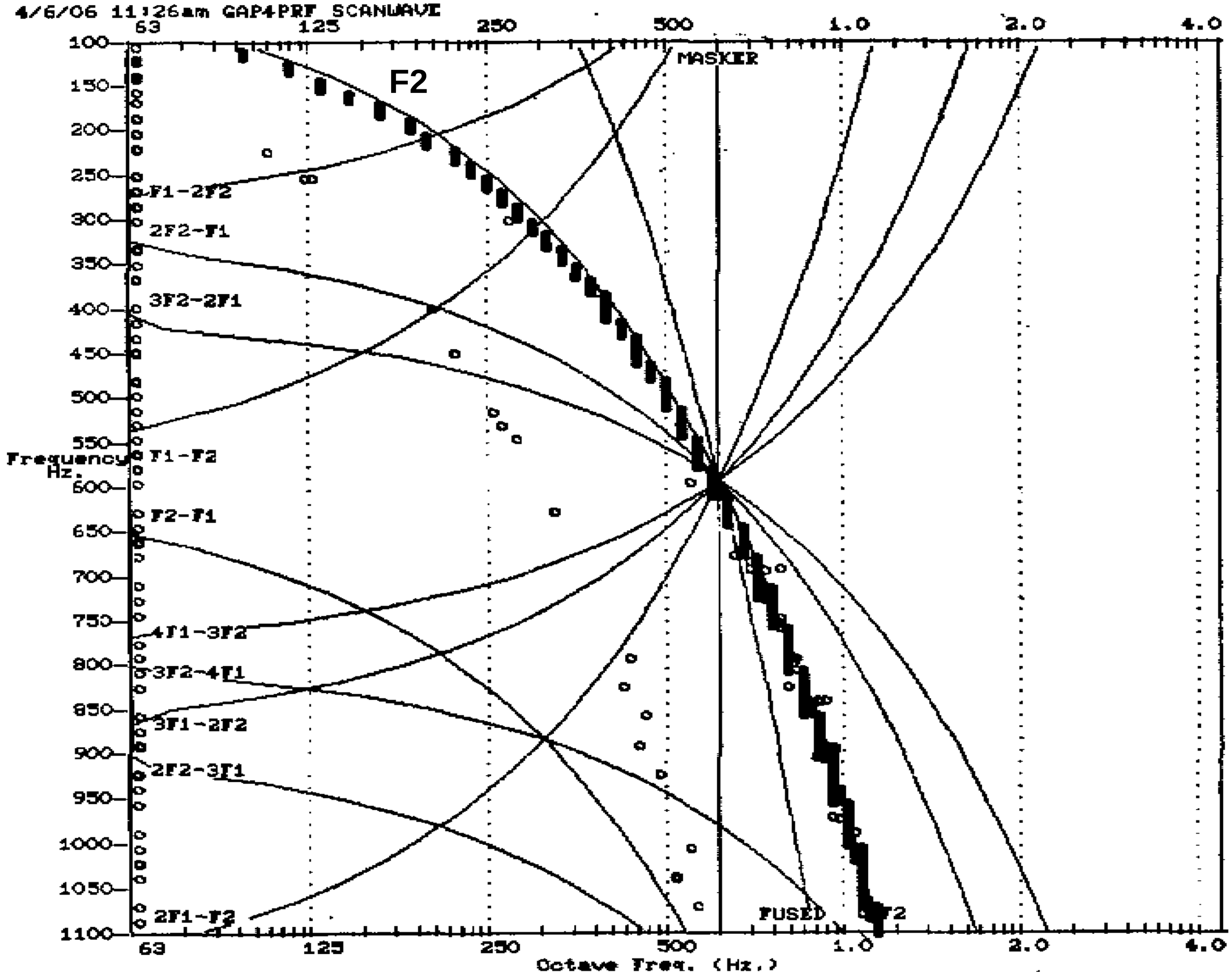

Figure 1: **For reference:** These are computed trajectories of "difference tones" which occur in two-tone experiments, used here to compare with the PSM's periodicity responses. They are designed to follow the variations in experimental parameters. To illustrate, a single sine wave is shown on the F2 trajectory scanning from 63 Hz to 1100 Hz. Note the stepped F2 variation.

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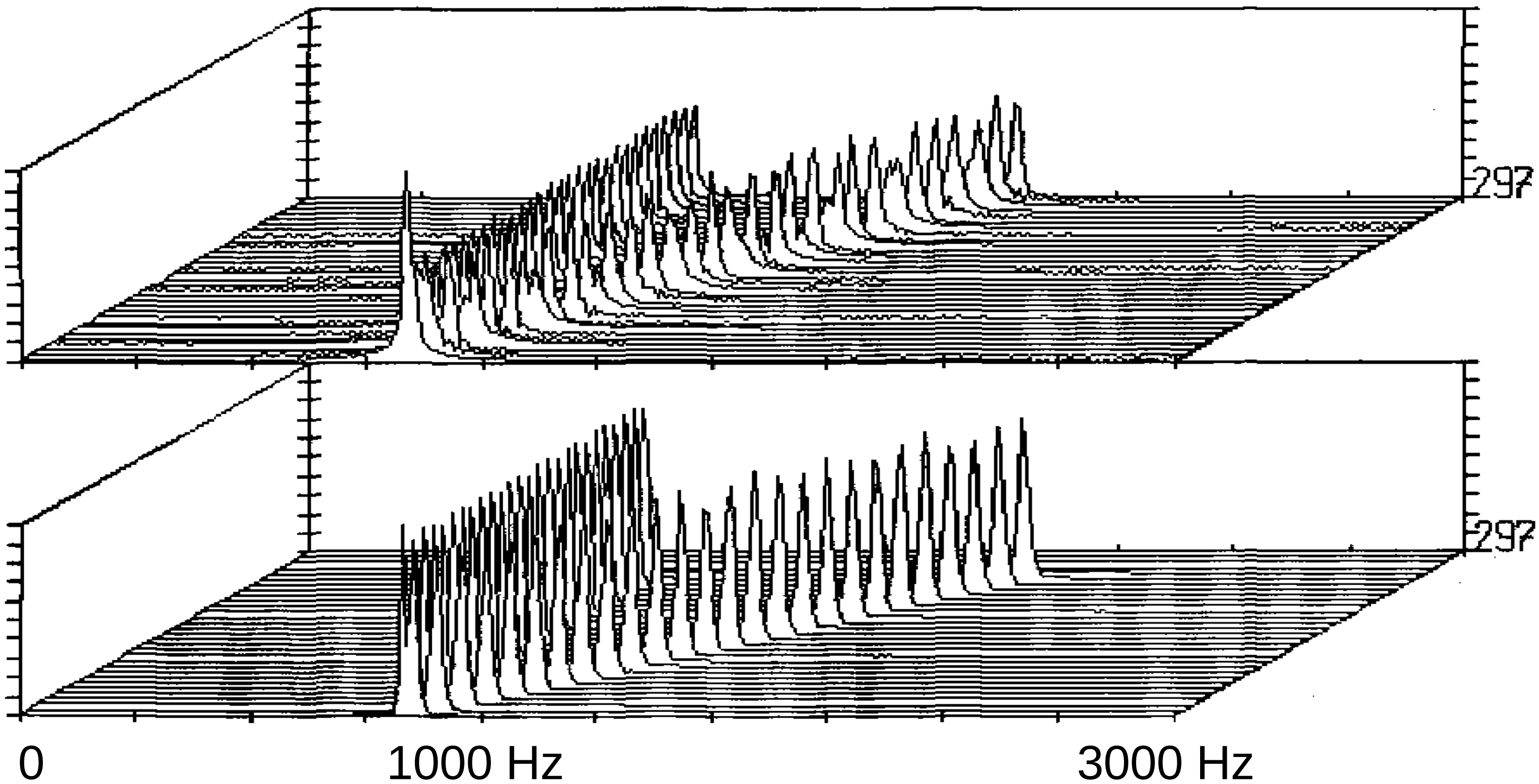

Figure 2: Spectral response of the *stepped* sine waves (upper) used in the combination tone experiments is compared with a pair of *streamed* sine waves. The stepped spectrum shows roughness but no significant harmonics that might cause auditory confusion with the subtones resulting from two-tone interference.

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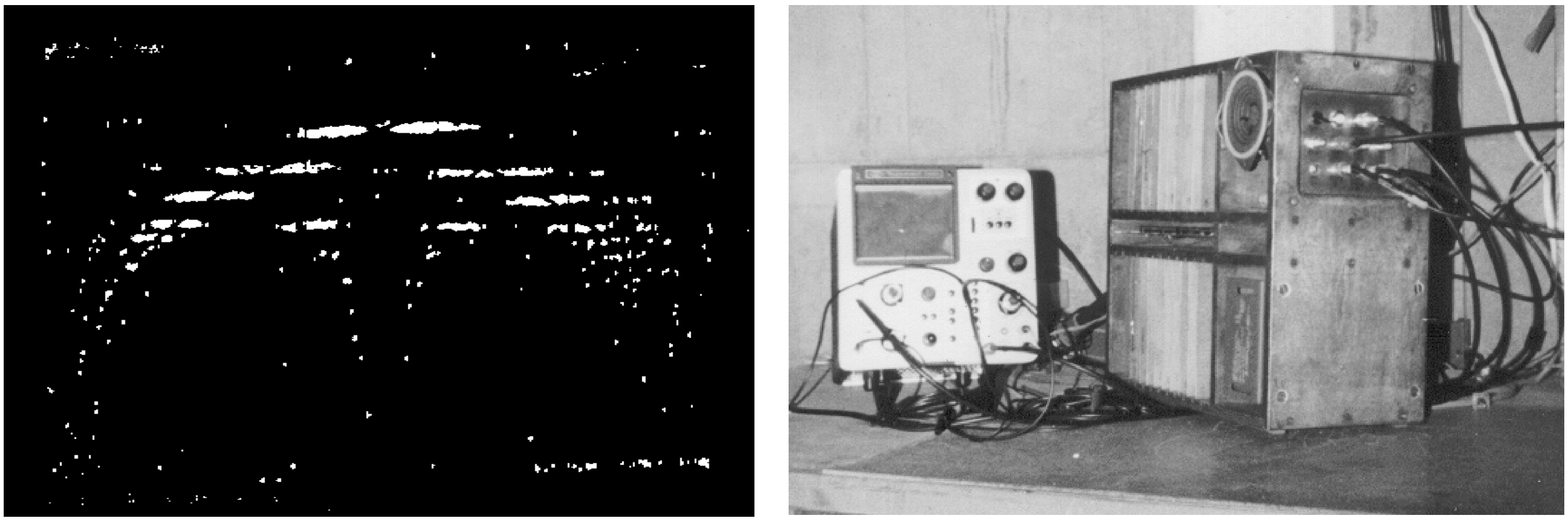

Figure 3: Photograph of combination tones taken from a hard-wired experimental periodicity sorting matrix that had 24 increments per octave instead of the 12 used in the present software PSM, and which *operated in real time*. Note fewer stray responses due to the better octave resolution and a higher sampling rate.

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Plomp's data in linear coordinates

Semi-logarithmic plot as produced by the PSM.

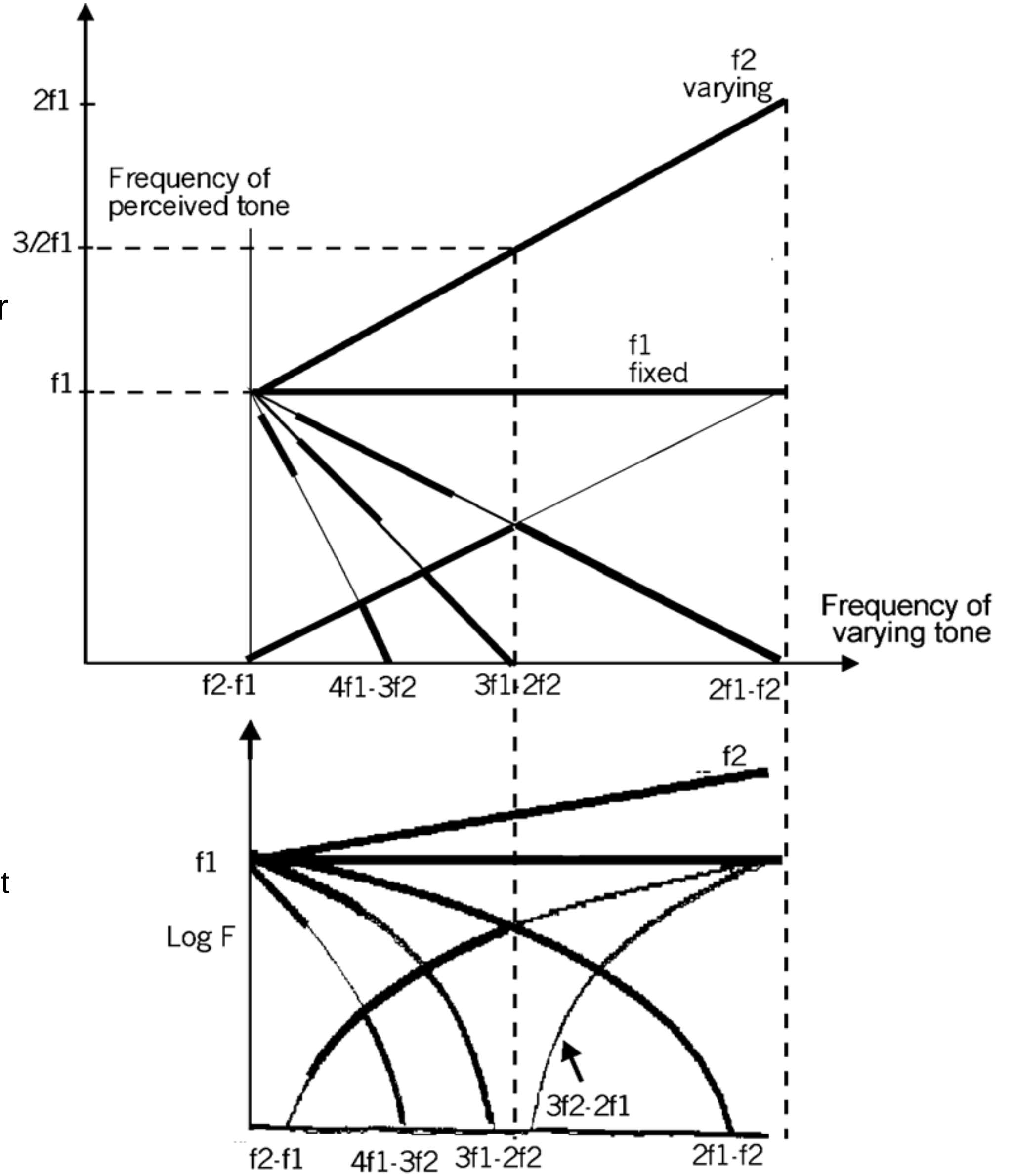

Figure 4: Summary diagram of Plomp's experiments on combination tones. Frequency range of semi-log data is 6 octaves vs. only about 1 or 2 in linear coordinates. Heavy lines indicate parts of range where listeners heard tones.

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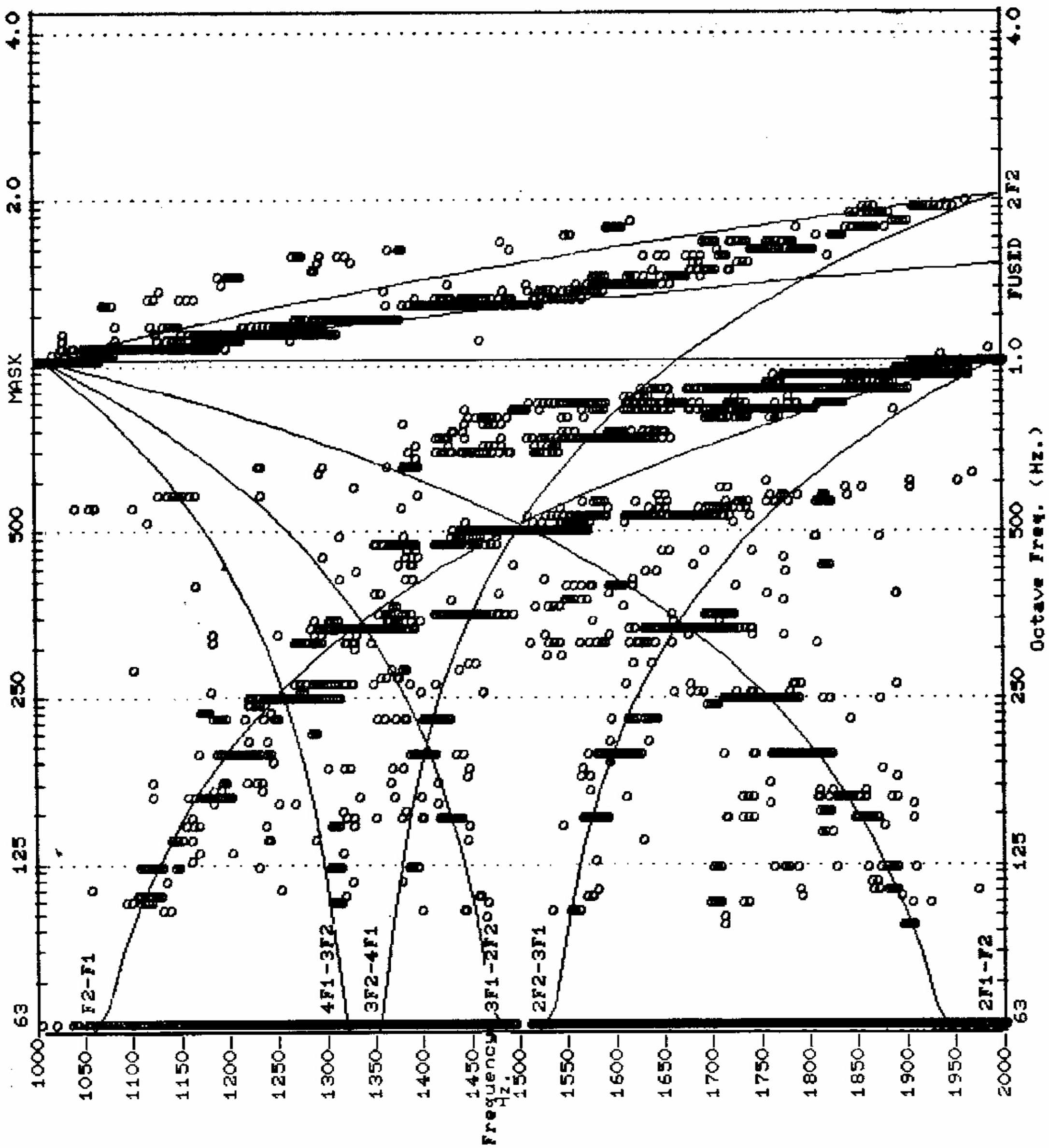

Figure 5: Subtones from waveform interference follow the computed combination tone trajectories. The clustered striations of subtones are caused by the inherent discontinuities of zero transitions, not by quantization effects in the PSM.

Critical Band Experiments

- The critical band and its associated phenomena are depicted in a chart taken from J. G. Roederer's book, *Introduction to the Physics and Psycho-physics of Music*.

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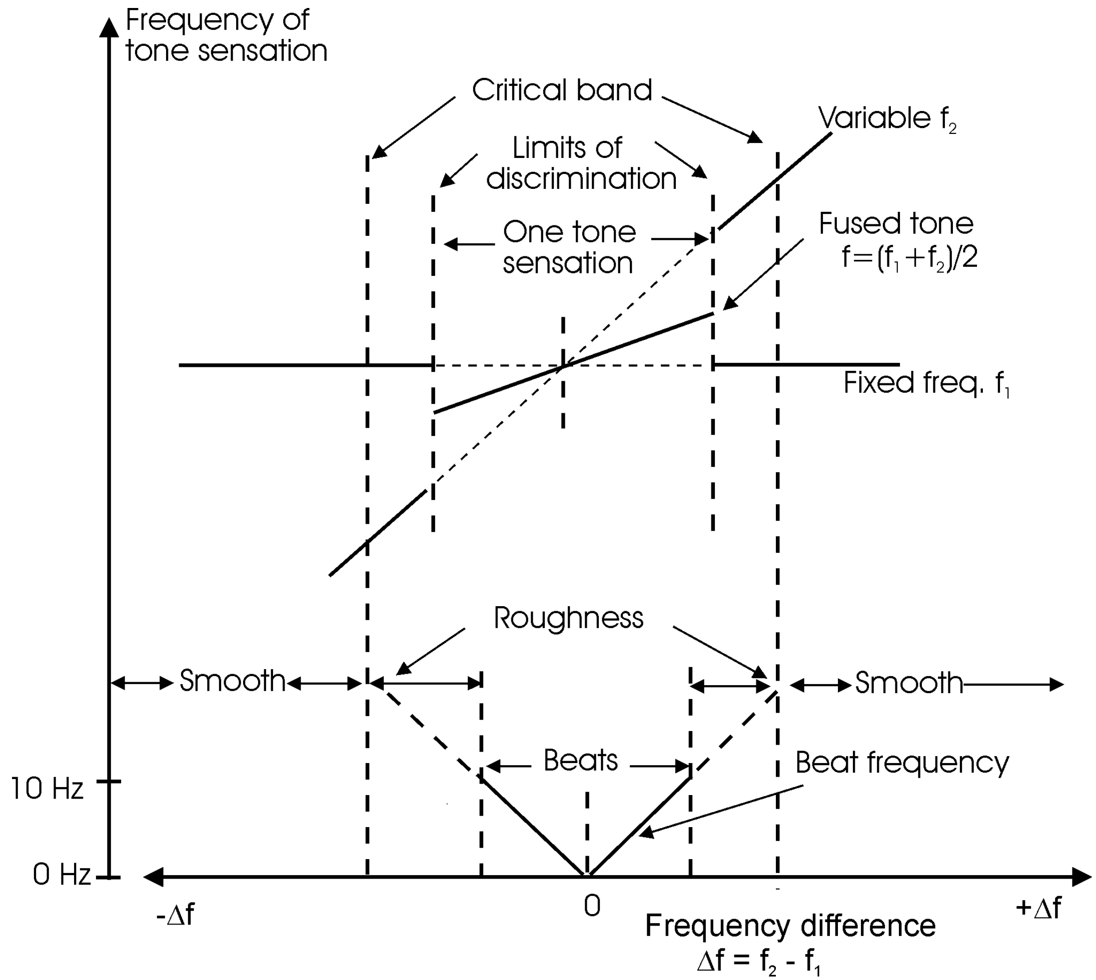

Figure 6: Summary of psychoacoustic responses on two-tone effects of critical band (after Roederer)

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Listener selects transitions in timbre and enters labels corresponding with PSM response changes.

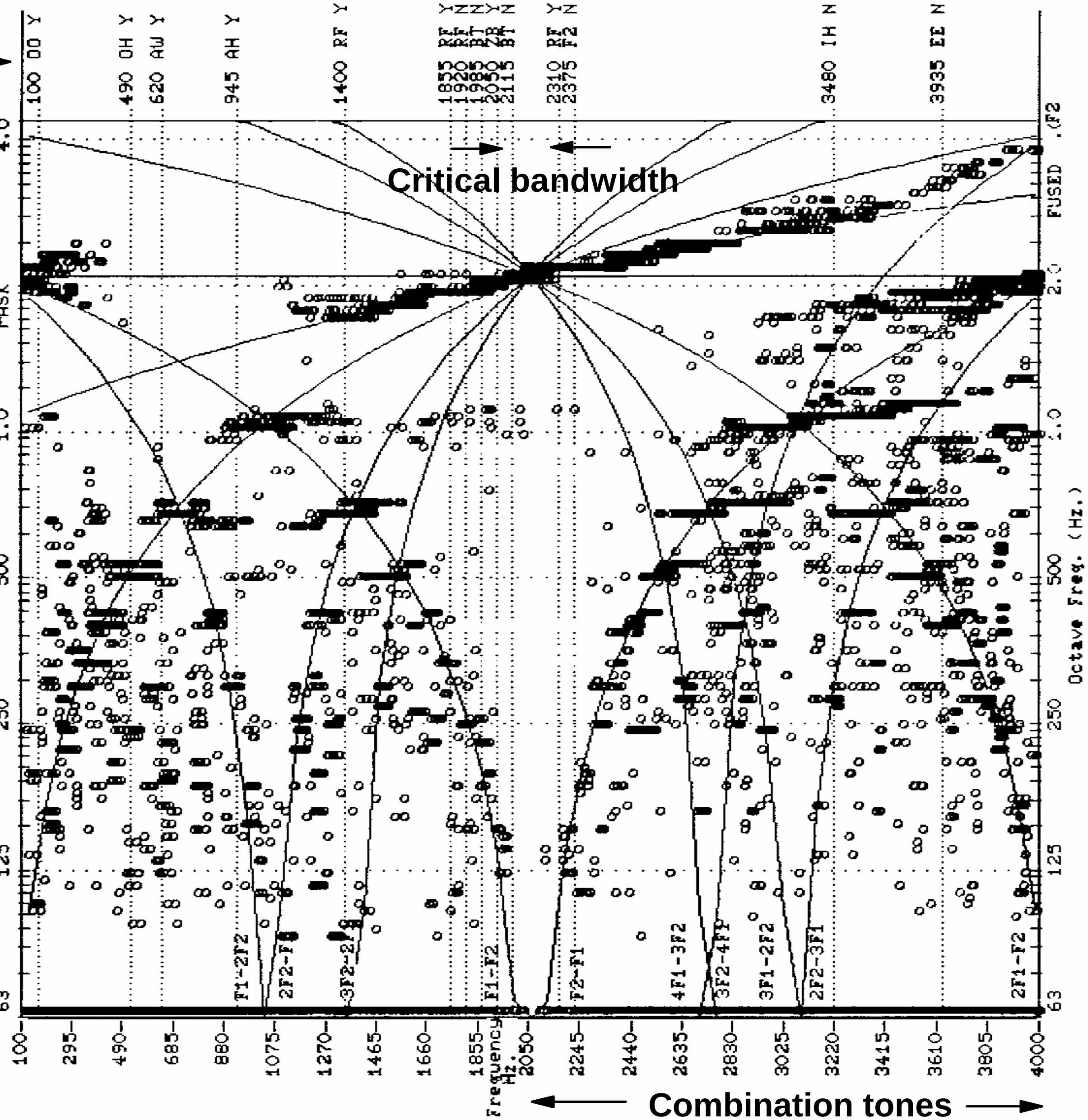

Figure 7: Subtone responses; variable frequency F2 scans from 100 Hz to 4000 Hz; mask frequency at 2050 Hz. The critical band surrounds the null. Notice that Plomp's combination tones are located in the high frequency side of the masker.

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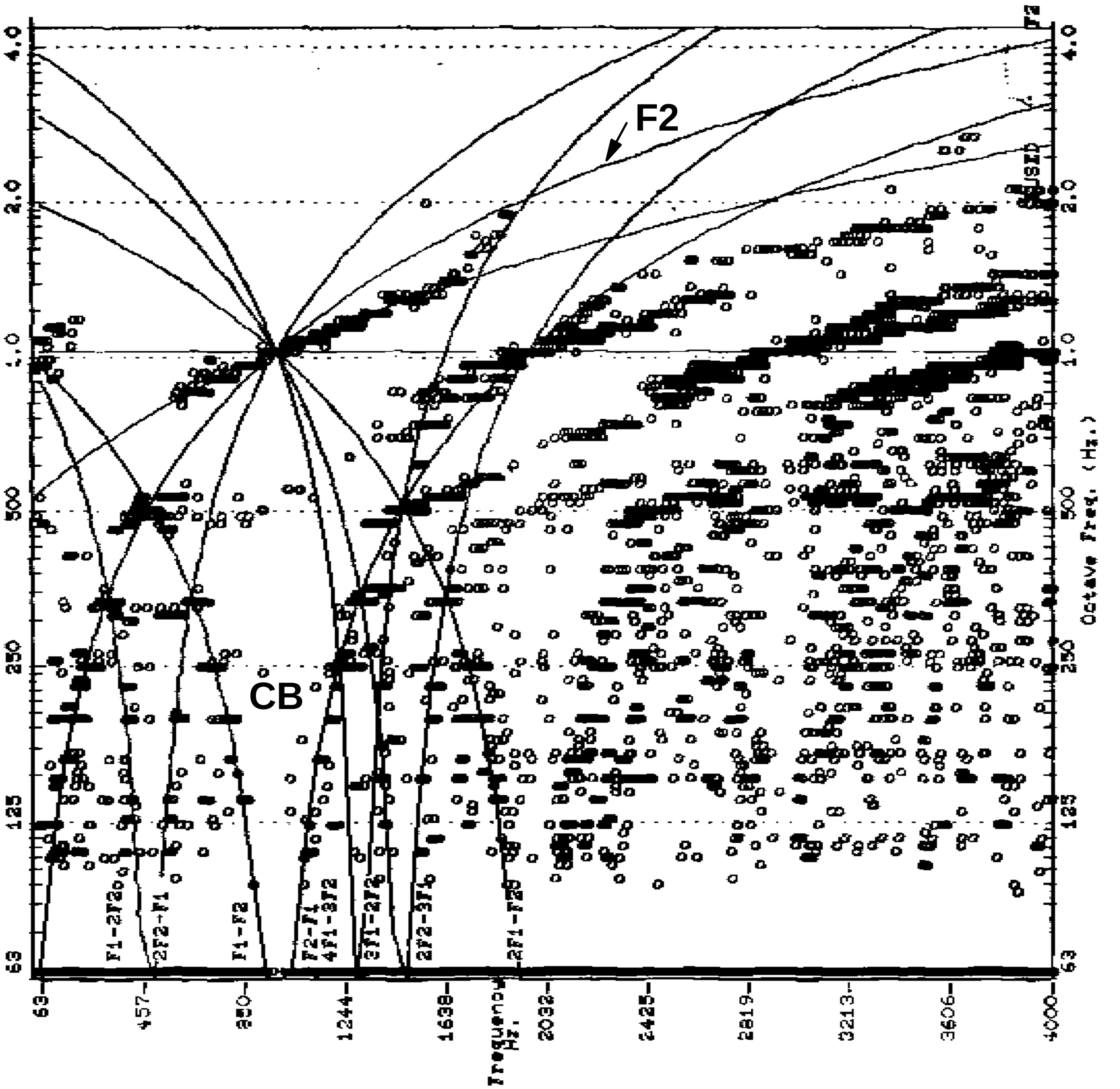

Figure 8: F2 scans from 63 Hz to 4000 Hz with mask frequency fixed at 1000 Hz. Note the smaller nulls following the CB response.

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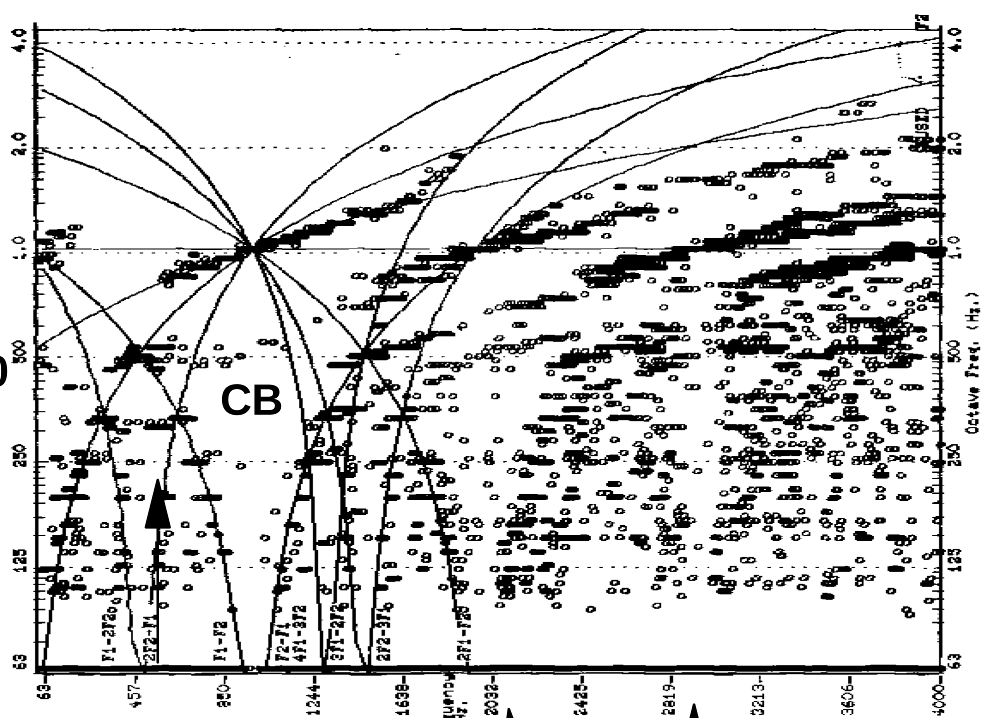
PSM response for mask at 1000 Hz. CB is at 1000 Hz. Nulls at 2000 Hz & 3000 Hz



Linear freq. scale

Listener responses in masking experiment by Wegel and Lane. Mask frequency 1200 Hz.

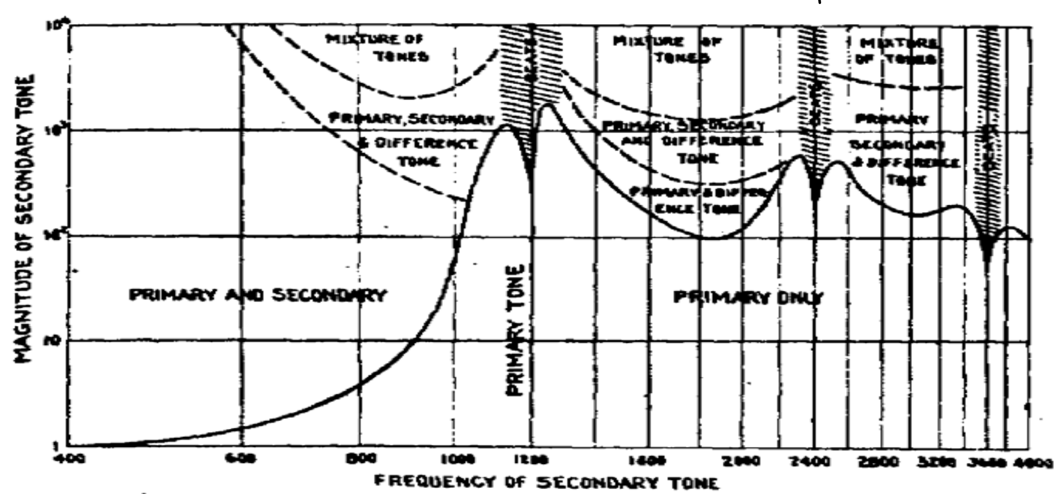


Fig. 5. Sensation caused by two pure tones.

Log freq. scale

Figure 9: Comparing null locations of Wegel & Lane with PSM periodicity response

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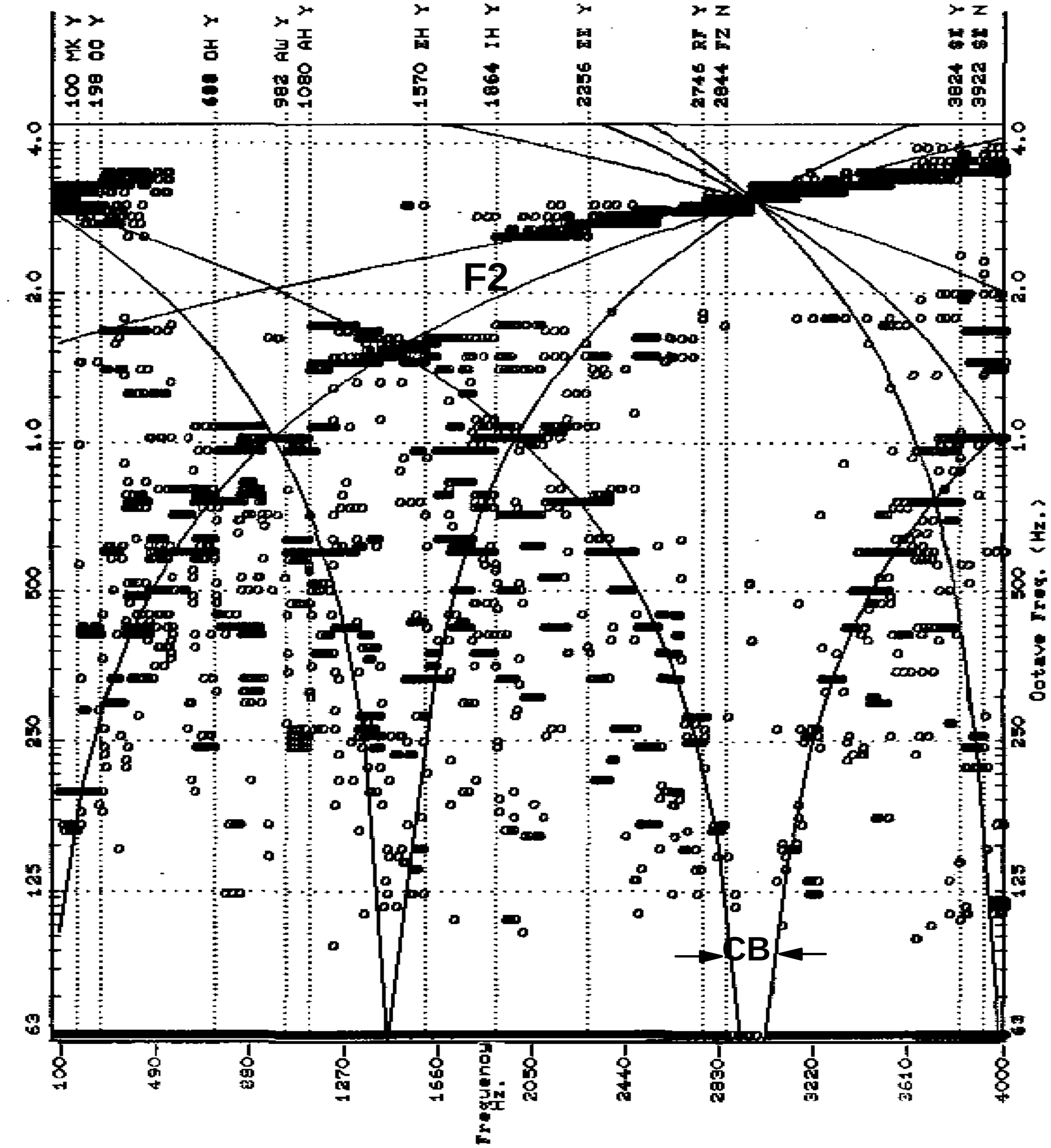

Figure 10: Masker at 3000 Hz, F2 scans 100 Hz to 4000 Hz. This test illustrates the octave equivalence of the PSM. Note the wider critical band at the higher mask frequency.

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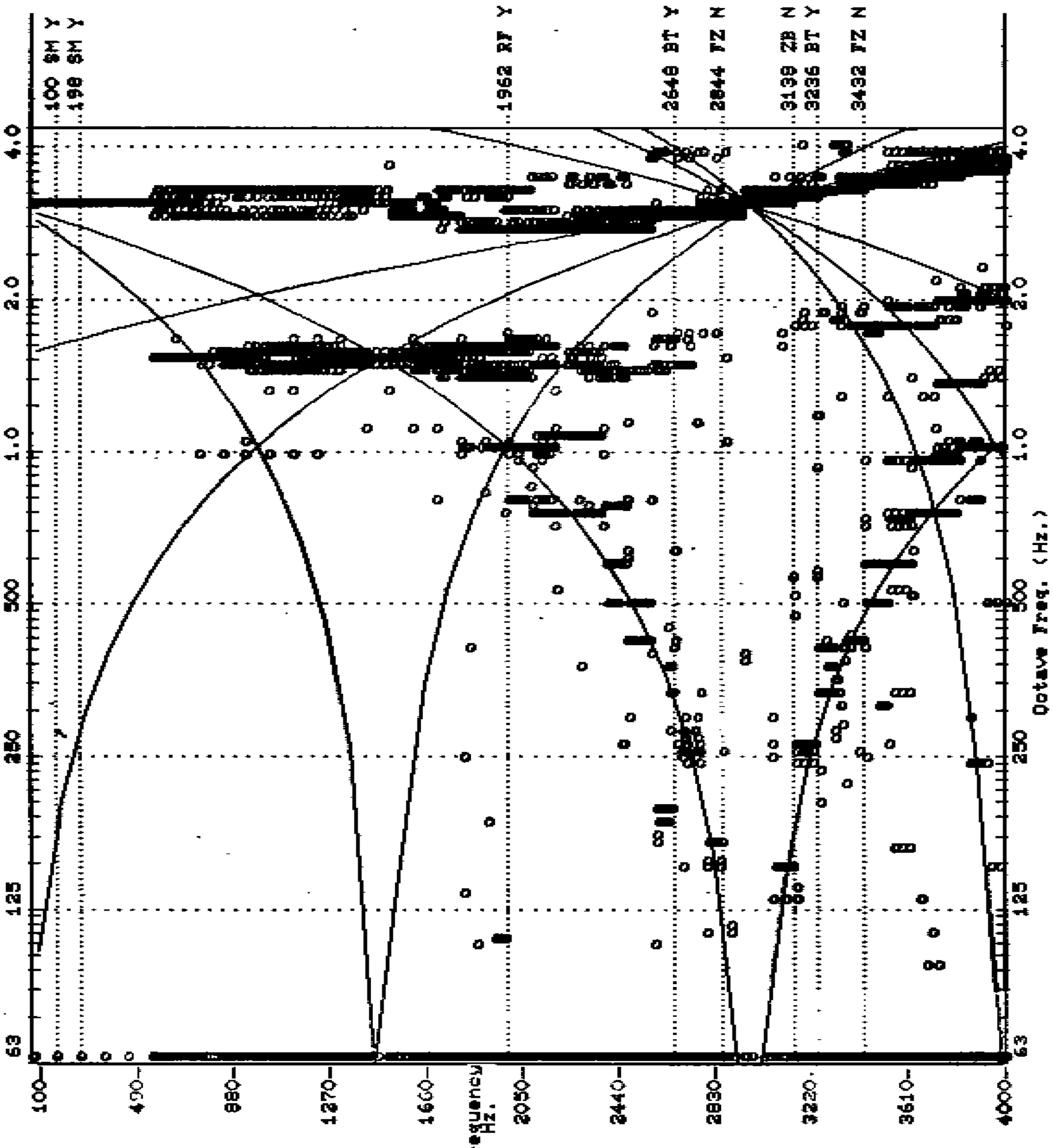

Figure 11: Repeat of mask at 3000 Hz with differentiated waveform. Differentiation emphasizes response of mask at lower frequencies and suppresses low frequency subtones. Listener response is similar.

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Summary and discussion

- The close match with predicted "difference tone" trajectories supports a zero-based auditory model.
- The critical band and combination tones are both caused by two-tone interference.
- The "filtering" effect of the critical band is caused by the mask's interference of its own zeros with the zeros of competing frequencies, not by electromechanical means, and also explains why bandwidth is always centered on the mask frequency. (There is no filter bank that is used conventionally to simulate critical band effects.)
- Zero-based encoding ultimately should include both real and complex zeros so as to identify and include the fine waveform structure.

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I can also show results and/or demonstrate:

- two-tone verification of missing fundamental and
- first and second effects of pitch shift (Schouten and de Boer's experiments)
- two-tone phase-shift masking of Terhardt and Fastl
- rippled noise experiment

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And I can show that WIV-based processing can:

- Separate and extract meaning from sound sources in real time:
  - monaurally, using shape recognition
  - binaurally, using direction of arrival
- Use accumulated knowledge, autonomously to decide which sound source needs attention at any instant.
- Compress and encrypt sounds and speech. WIVS are easy to shuffle around with random numbers.