Automotive Audio: System Engineering

by
Roger E. Shively

harman-motive, inc.
Martinsville, IN 46151 USA

AES Los Angeles Section
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Introduction

- Vehicle Listening Environment
  - Spectral
  - Spatial, Temporal
- Speaker Design, Placement
- Objective Measurements
- Subjective Evaluation
- System Integration

Vehicle Listening Environment

- **A small & noisy environment**
- **Many negative influences on the Spectral, Spatial, and Temporal attributes of a sound-field**

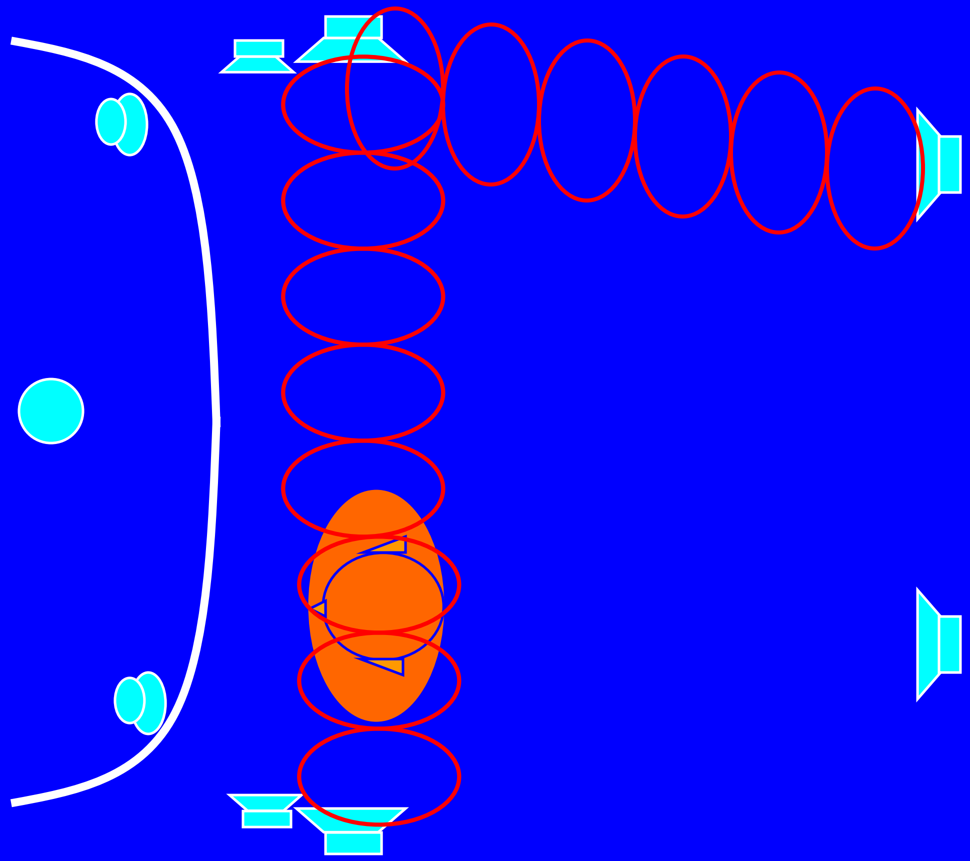
Spectral Characteristics

- Interior Volume
- Size and shape of surfaces
- Absorption characteristics
- Location of Speakers
  - relative to listener
  - relative to nearby surfaces

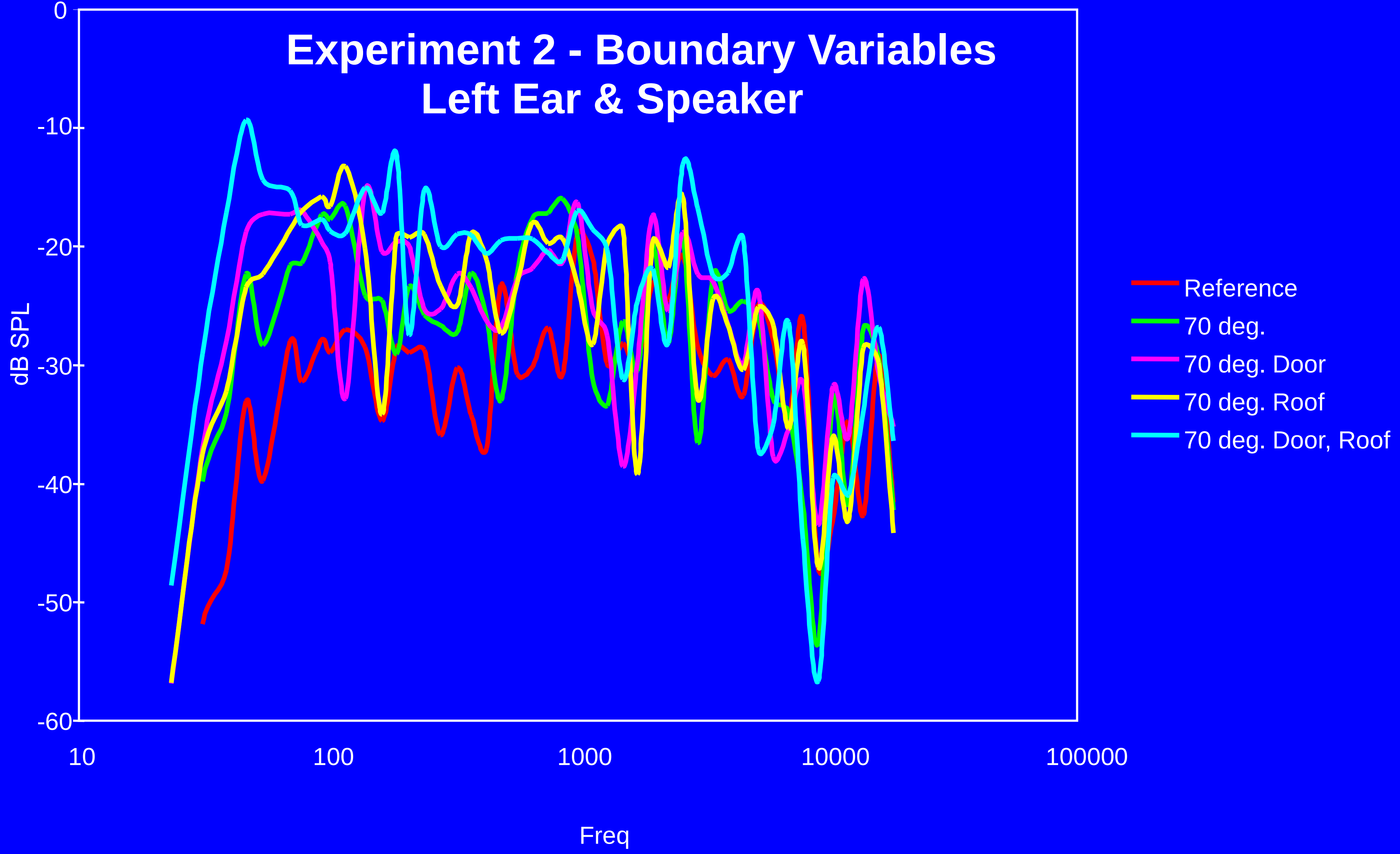
Spectral: Example

- **Average Mid-Size Car: 3.5 m^3**
- **Acoustic Modes**
  - **Uniform Coupled Modes 80 - 300 Hz (12dB)**
  - **Transverse Modes 120-150 Hz (12 dB)**
  - **Broadly Spaced Resonances 300-1k Hz (Q<3)**
  - **Trunk and Door (Spkr Encl) Resonances 150-500Hz**

Spectral: Example
Transverse and Longitudinal



Spectral: Example



Spectral: Example

- **Mechanical Resonances**
  - **Roof, trunk lid vibrations due to road motion or engine vibrations**
  - **300 to 1k Hz, Q>5, 4-6 dB SPL**
- **Boundary Reflections ⇒ Interference & Diffraction (>300-500)**
  - **Interference: Direct & Reflected waves**
  - **Diffraction: Spkr Mounting Holes, Grilles, Severe Off-Axis Conditions**

Spectral: Example

- **Road Noise**
  - **Tire, wind, and engine noise reduce dynamic range and mask low freqs.**
  - **Noise dominant below 500 Hz**
  - **Ave SPL > 80 dB, < 100 Hz, Velocities > 35 mph.**

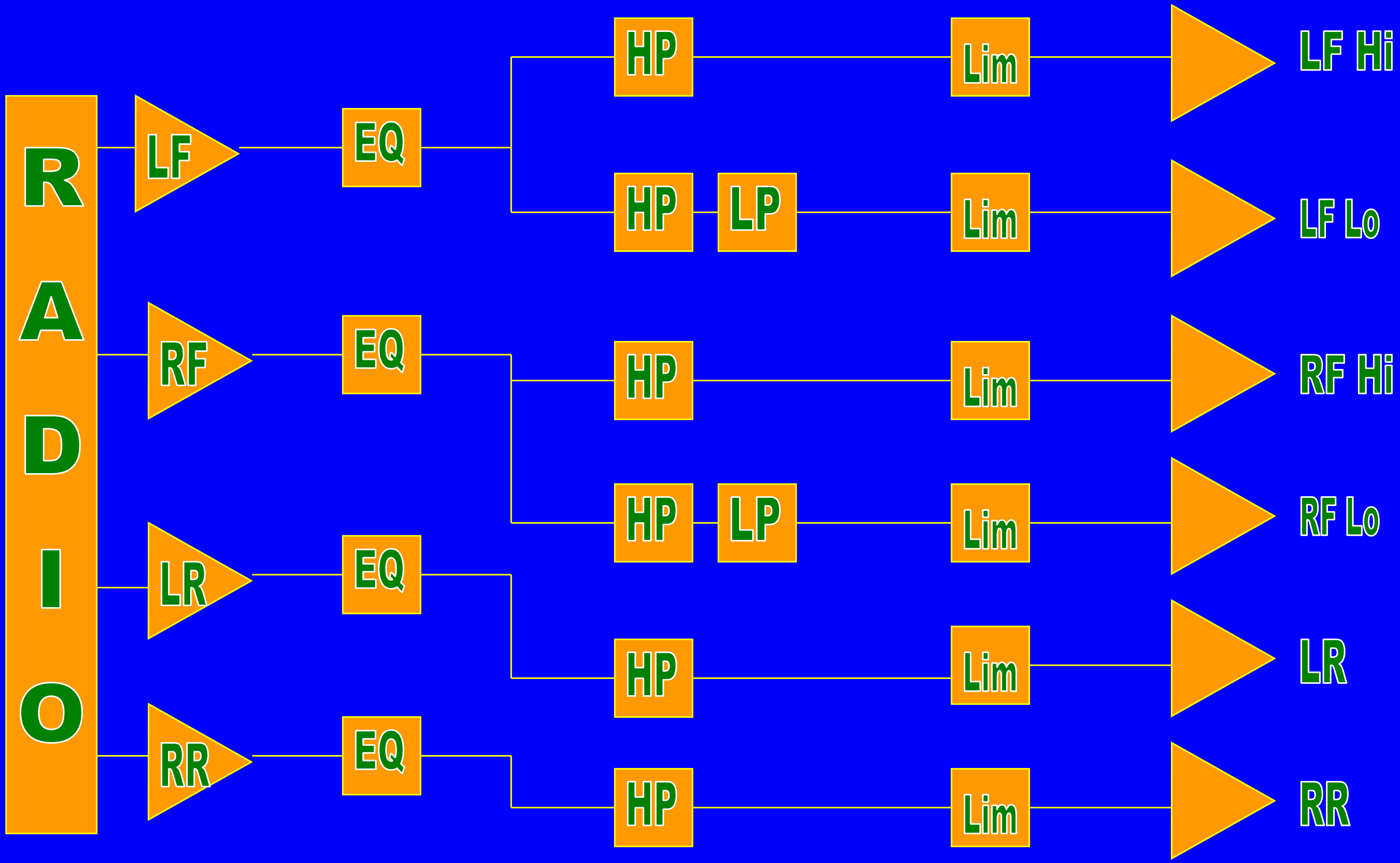
Spectral: Example

- **Control of Spectral Problems**
  - **Noise Masking: Dynamic Loudness**
  - **Mech Resonances:**
    - **Structural Rigidity**
    - **Acoustic Resonance Reduction (Yes & No)**
  - **Acoustical Resonances:**
    - **Equalization for most aberrations**
    - **Non-minimum Phase: No EQ**
    - **Peaks/Dips Q>5 = Audible Phase Shifts**
    - **EQ for Mech Vib: Less SPL, but poor damping**

(Spectral) ***Amplifier Design***

- Parametric EQ
  - Per quadrant at least, per channel best
- Split-Band HP and LP per channel
- Voltage Sensing Limiting
- Multi-channel &/or Bridged outputs

(Spectral) ***Amplifier Design***

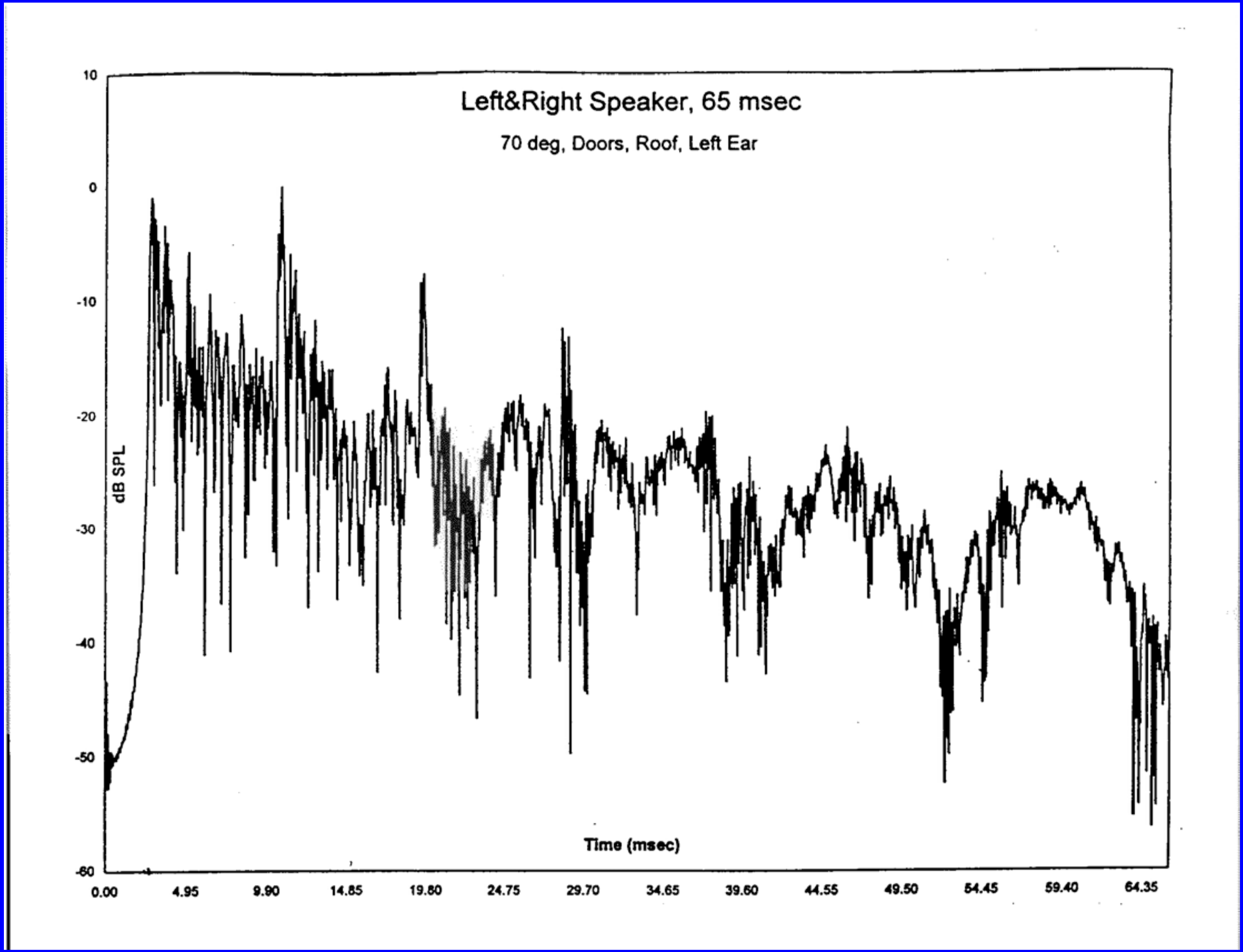


Spatial & Temporal Characteristics

- **No Reverberant Field**
- **Entirely Direct Energy & Early Reflections -- quickly absorbed or dissipated**
- **T_{60dB} = 30 to 50 msec.**
- **Dead Space**

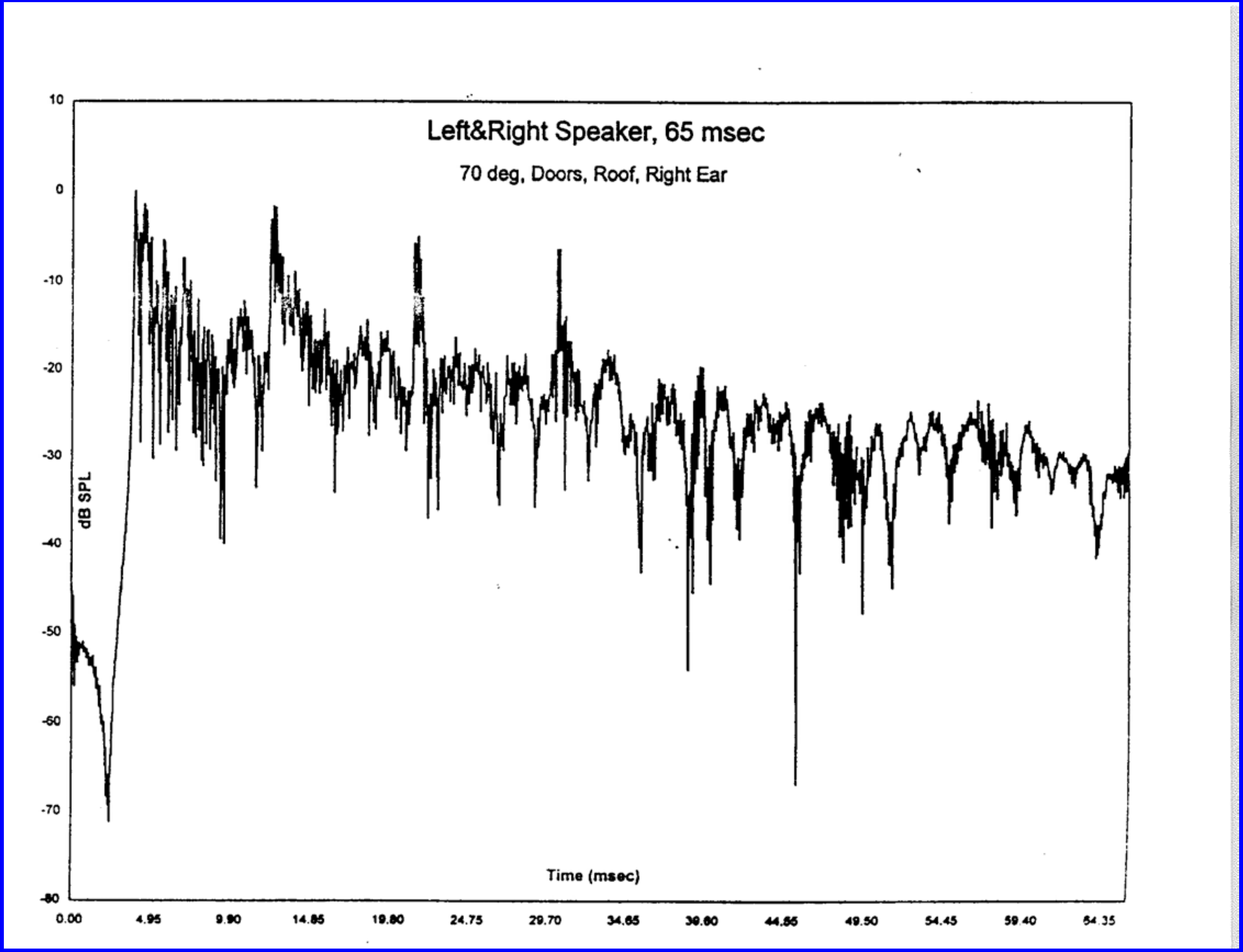
Spatial & Temporal Characteristics

Left & Right Speaker, Left Ear



Spatial & Temporal Characteristics

Left & Right Speaker, Right Ear

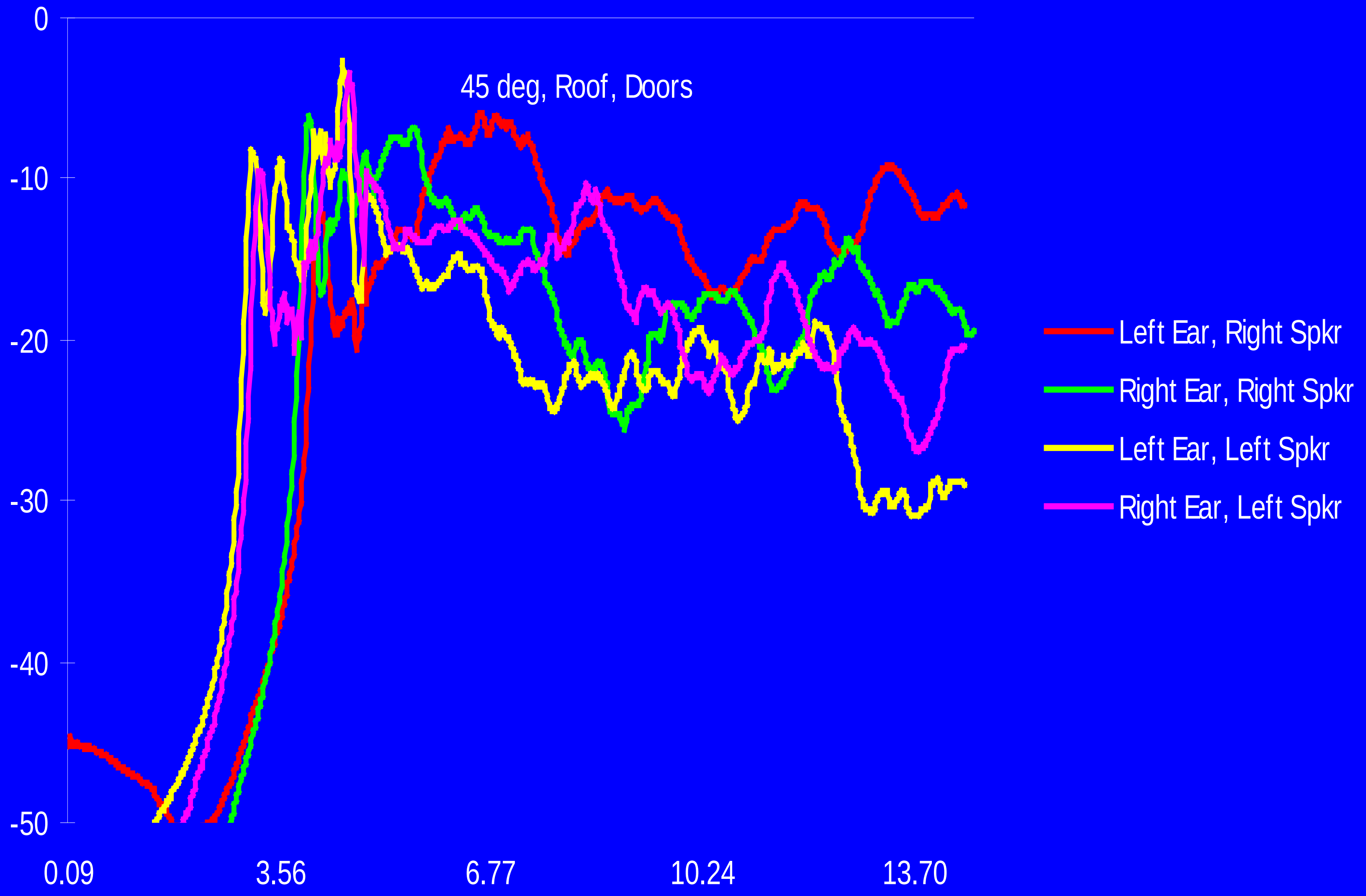


Spatial & Temporal Characteristics

- **Large # of early reflections $\Rightarrow$ Diffuse sound field, 90% of energy occurs within first 10 msec of direct wave arrival**
- **Listener experiences a diffuse and frontally incident sound field**

Spatial & Temporal Characteristics

Crosstalk



Spatial & Temporal: Driver's Seat Crosstalk

- **Right spkr to left ear: Arrives 1-2 ms later than Left spkr**
- **Ampl Right Spkr > Left Spkr**
- **Left Arrival decays naturally : Right Arrival window reflection 4-5 ms later, then decays.**
- **Right Arrival reflection Ampl = Right Arrival initial arrival**
- **Listener integrates subtle info ⇒ impression of stage width & breadth**

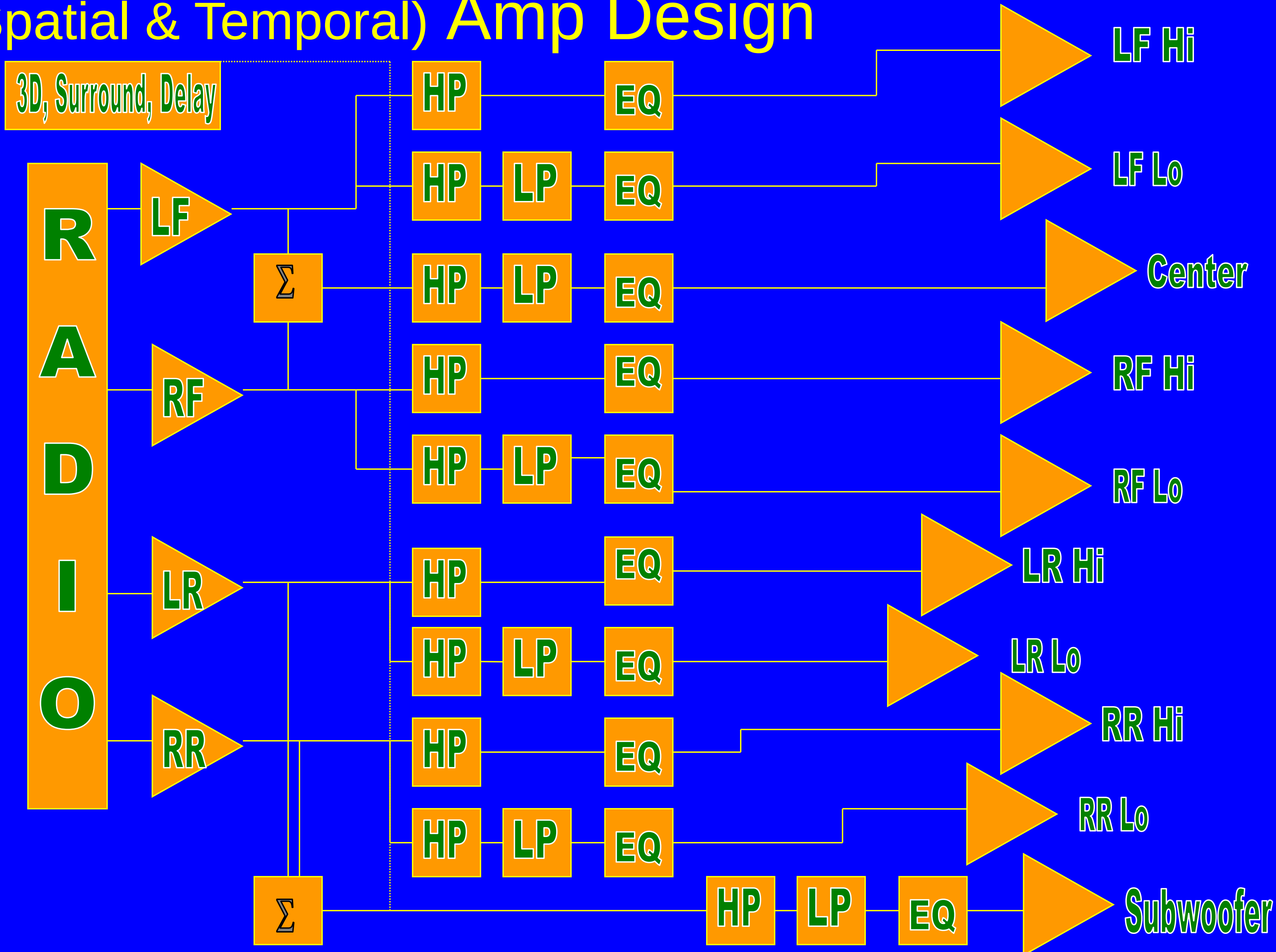
Spatial & Temporal

- **Control of Spatial & Temporal Problems w/ Practical DSP**
  - **Time corrections**
  - **3D algorithms**
  - **Surround Sound Processing**

(Spatial & Temporal) ***Amp Design***

- Multi-channel Parametric EQ
- Split-Band Filtering
- Limiting
- Time Delay, 3D Algorithms, Surround Sound

(Spatial & Temporal) Amp Design



(Spatial & Temporal) Amp Design

- Quality spectral and temporal electronic control can make up for some short-comings in speaker design limitations and location.

vice versa

- A good custom speaker design placed in the best possible location in a vehicle can make up for some short-comings in electronic capability.

Loudspeaker Design

- Speaker Characteristics:
  - Fo, DCR, Power Handling, Disspersion
- Generic speaker design, carryover designs are economic -- unless sound quality is compromised.

Loudspeaker Design

- A loudspeaker is designed to exploit its location in a vehicle:
  - Resonance matching to mounting location
  - Relative gain with respect to other speakers
  - Off-axis characteristics which best serve the overall freq. balance , stage, and image for everyone listening in the vehicle

Loudspeaker Placement

Loudspeaker Placement

- Loudspeakers are located to take advantage of their design and to reduce the amount of electronic control necessary to create the best spectral and spatial sound quality

Loudspeaker Placement:
Woofers and Subwoofers

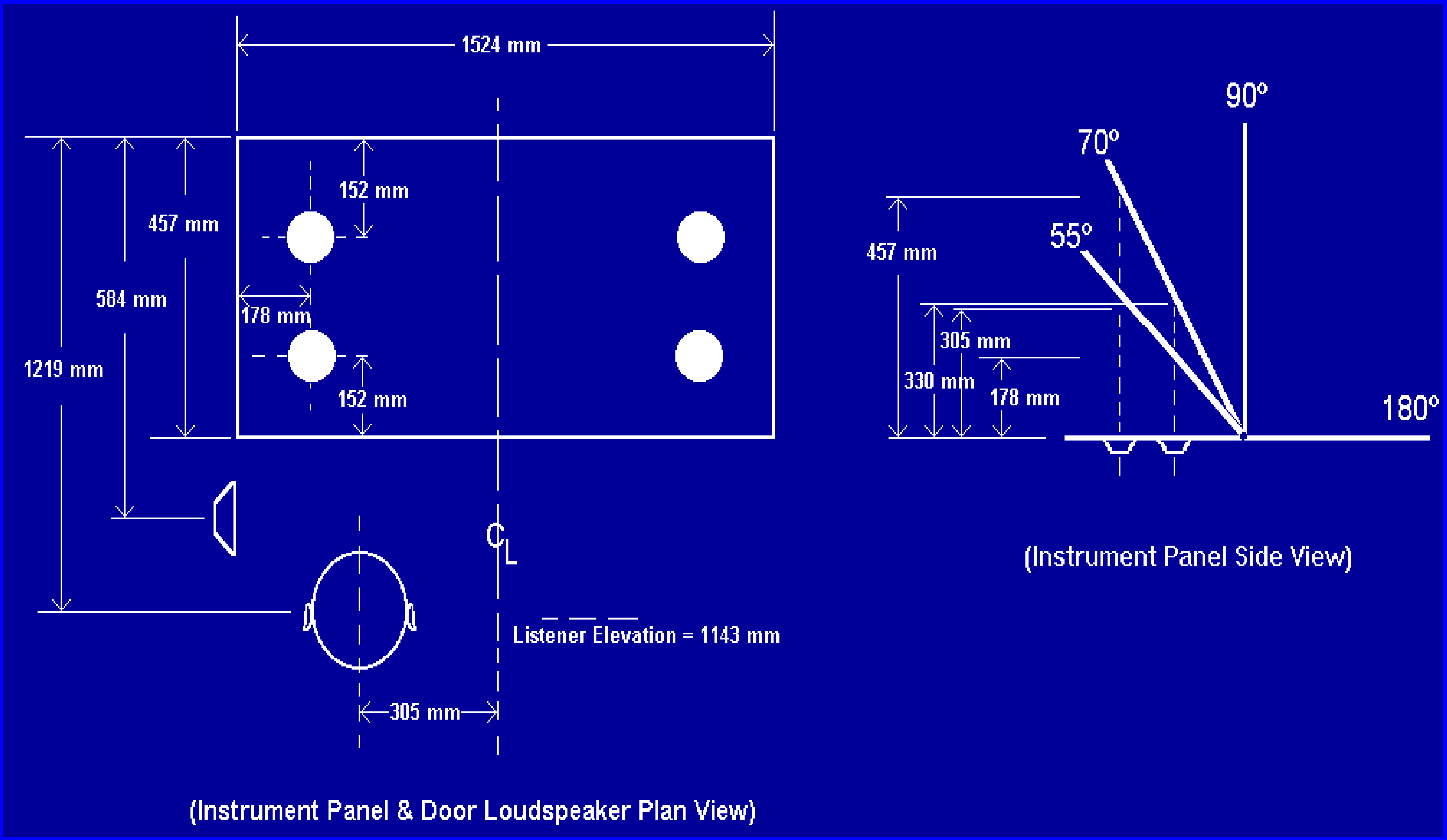
- Bass drivers are located so they can best couple with the structural and acoustical modes of a vehicle.
- Doors are used as vehicle integrated bass enclosures.

Loudspeaker Placement:

Midranges

- Placed at elevations above the knees, closer to ear level, raises stage and image. Not too distant from woofers for smooth transition between the bandwidths of the woofer and midrange
- Center speakers can be used for a complete, seamless stereo balance and multi-channel applications.

Loudspeaker Placement: Midranges



Loudspeaker Placement: Midranges

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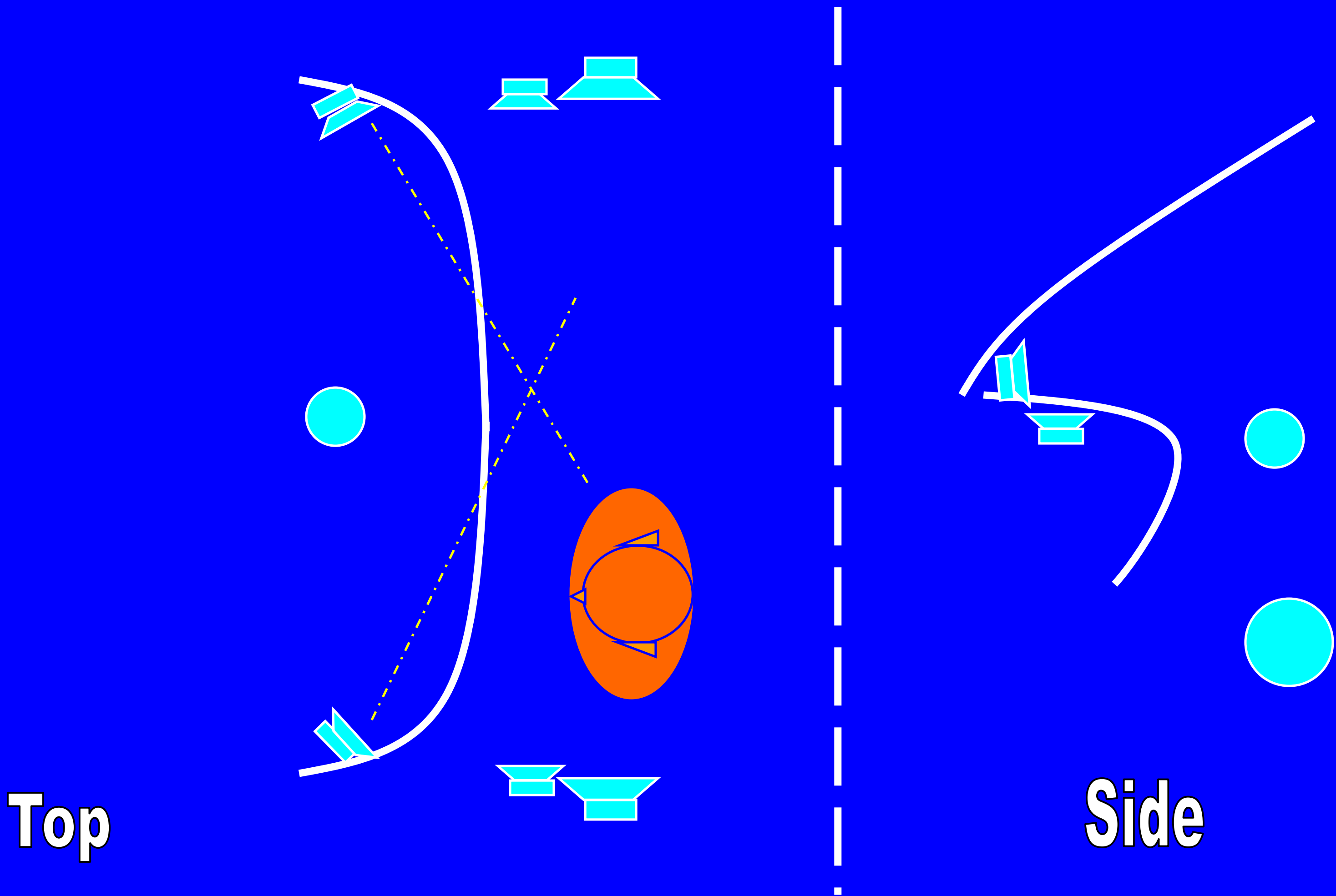
Loudspeaker Placement:
Tweeter and Upper Midranges

- Placed depending on the goal of the system:
  - Broad coverage or Close-coupling (i.e. , personalized) Soundfields
- Broad Coverage:
  - No direct aiming of drivers at the listening position
  - Drivers are cross-fired (aimed at opposing position)

Loudspeaker Placement: Tweeter and Upper Midranges



Loudspeaker Placement: Tweeter and Upper Midranges

- Close-coupling: Speakers placed as close to the listening position as possible, aimed directly at a single listening position
  - Headliner, headrest, etc. depending on electronic control ability to redirect or aim sound stage and image to normal listening position.

Loudspeaker Placement: Tweeter and Upper Midranges

Front and Rear Effects

- Placement of midrange and tweeters tempered by effects they have not only on the near seat positions, but on the effect they have on other seating positions.
- Better or worse, front seat speakers contribute to the rear seat sound, ***vice versa.***

Objective Measurements

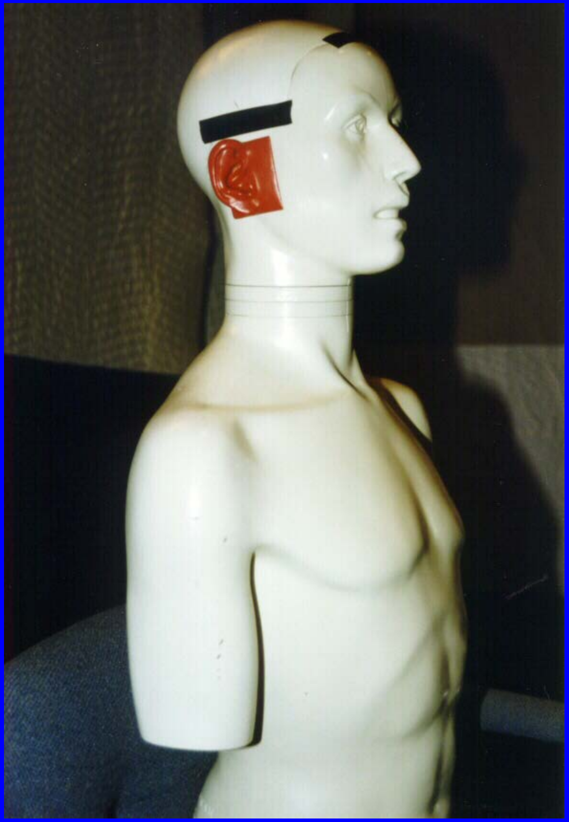
Objective Measurements:
Frequency Response & Total SPL

- CD Source & FM Transmission:
  - 6 mic array, 3rd Octave Pink Noise

Objective Measurements:
Frequency Response & Total SPL

- Binaural Analysis:

KEMAR dummy head



More Objective Measurements:

- Low Frequency Performance:
  - %THD w/ sinewave input: 1% Elec., 3% Acoustical
- Intermodulation Distortion: <5%
- Dynamic Capability:
  - SPL @ just clipping; 0dB, 1 Oct Corr Pink Noise, 4:1 crest factor

More Objective Measurements:

- Linearity (w/o Loudness):
  - MAX VOL Setting, -6dB, -10, -20, -30, -40, -50dB recorded levels pink noise
  - Max deviation in dB
- Dynamic Incoherence: Max deviation in dB
- Impulse responses: 85dBC

More Objective Measurements:

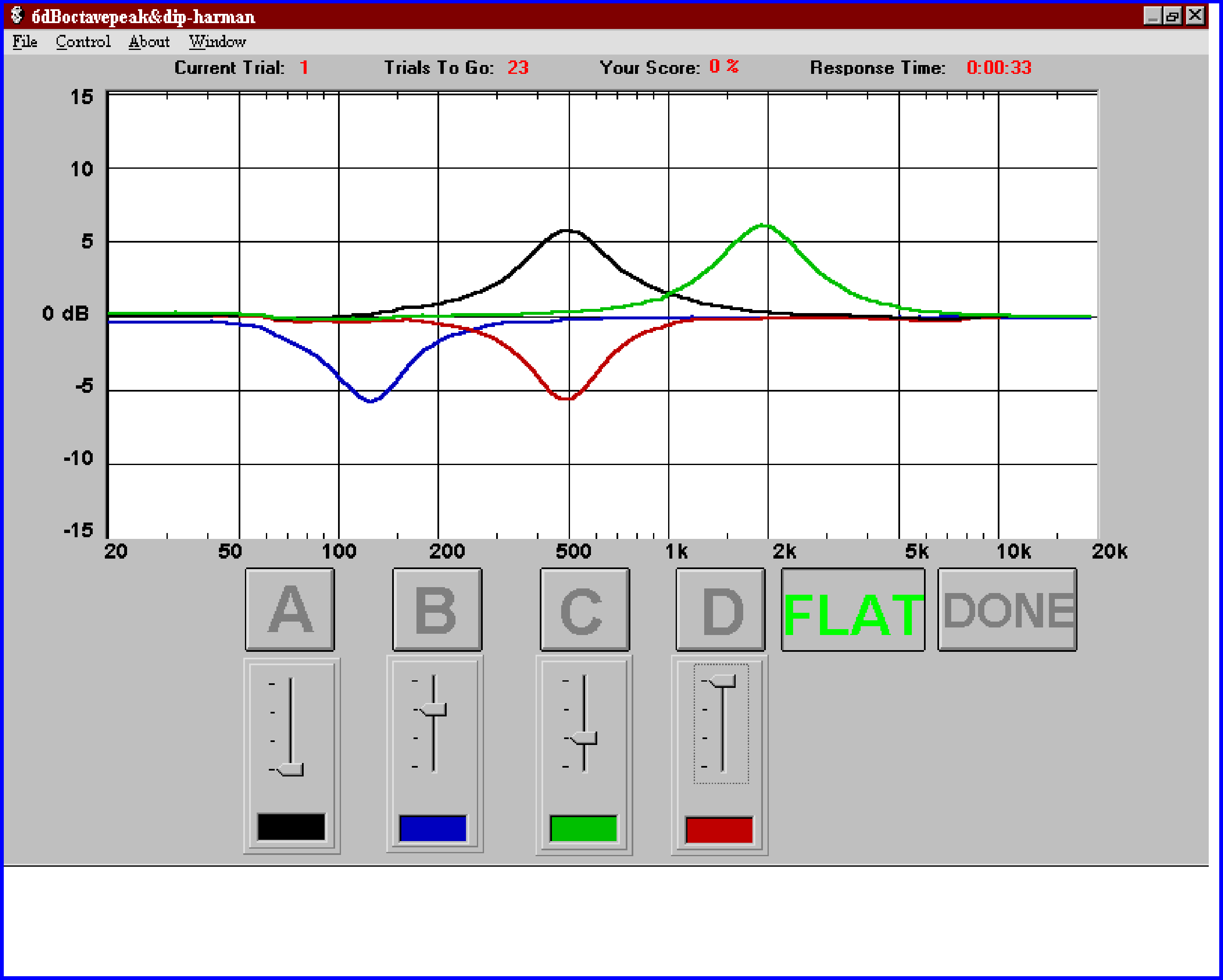
- Radio Frequency Response and Distortion
- Dynamic Measurements:
  - 0 mph Engine Noise, 10, 30, 50, 70 mph noise.

Vehicle Listening Test Methods

Vehicle Listening Test Methods

- More complex sound field than the typically controlled environment
- Valuable Listening Tests:
  - Repeatable, Statistically Significant, Quantitative Results
  - Useful to system designer, design team, and marketing team
- Careful training of listeners
- Simple, unbiased listening test method

Vehicle Listening Test Methods: *Listener Training*
EarTrain Software User Interface

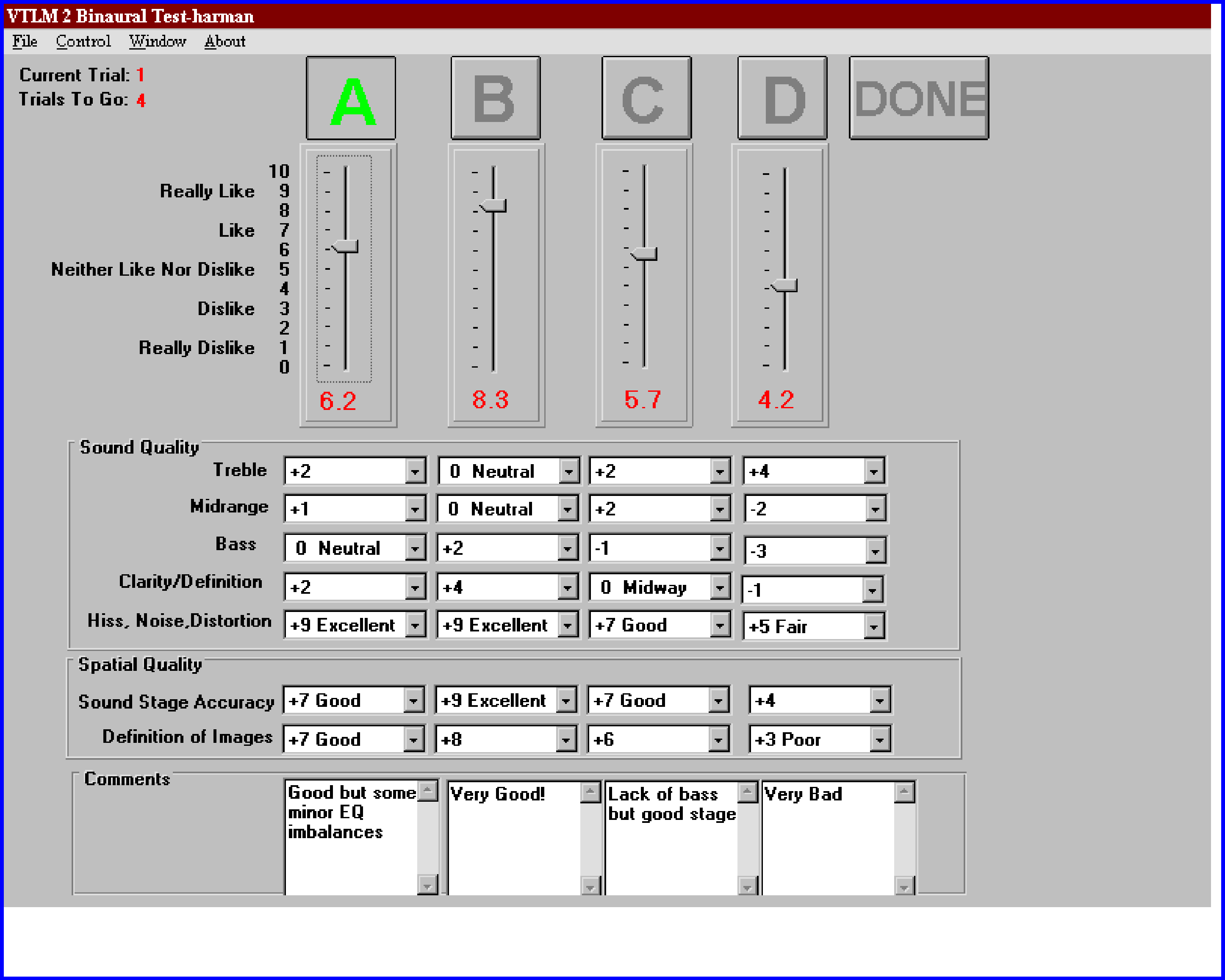


Vehicle Listening Test Methods: *Listener Training Using EarTrain*

- Self-administered PC program EarTrain: 24 trials, 4 EQs per screen & flat reference, feedback to user on score and correct answers, quantifiable results
- PC WAV files randomized, D/A converter, head phone amp, Etymotic ER4S headphones
- Broadband sources
- 6dB and 3dB peak & dip aberrations: .25 oct, 125, 500Hz, 2kHz, 8kHz
- 95% correct targets for 6dB and 3dB

Vehicle Listening Test Methods: *Listener Training*

PrefTest Software User Interface



Vehicle Listening Test Methods: *Listener Training Using PrefTest*

- Self-administered PC program PrefTest to test for proper use of resonance detection training and proper use of Preference scales
- Same software to be used in later listener experiments for comparative analysis.
- Same WAV files as EarTrain used, randomized.
- Overall Preference: 0 to 10, 0.1 point increments. 0.5 = slight, 1.0 = moderate, 2.0 = strong.
- Timbral balance of Treble, Midrange, Bass +/- 5, 1 point increment. 0 = neutral.
- Results evaluated using multivariate repeated-measures analysis of variance (ANOVA).
- Sessions repeated until consistent results.

Vehicle Listening Test Methods: *Listener Training*

EarTrain Acceptance Criteria

- **95% correct for experienced listeners**
- **85% correct for less experienced listeners (more time expected for training completion)**

Vehicle Listening Test Methods: *Listener Training*

Preference Criteria

- Group average 0.5 variance on 10 point scale
- Individual variance should be monitored against group mean and flat reference for compliance

Vehicle Listening Test Methods: *Listener Training*

Repeatability: # of Rounds Required

Listening Method	Rounds	Individual Variance	Comb. Variance
In-situ	5	0.5	0.5
Binarual	5	1.0	0.75
	7	0.75	0.5

Vehicle Listening Test Methods: *Listening Methods*

- In-situ Sighted
- Double-blind In-situ Benchmark
- Double-blind Binaural
- Double-blind Placebo In-situ

Vehicle Listening Test Methods: *Listening Methods*

- **In-situ Sighted**
  - Commonly used
  - Non-auditory biases: Price, Brand, Styling, Size.
- **Double-blind In-situ**
  - Static Listening
  - Rapid A/B Comparison Difficult + Limited Acoustic Memory
  - Randomization of Variables Difficult

Vehicle Listening Test Methods: *Listening Methods*

Double-Blind In-situ Benchmark

- Benchmark for single stimulus comparison of methods
- Interior Scented
- Seat, Console, Steering Wheel Covers
- Foot pedals covered
- Listener Blindfolded away from vehicle
- Headphones with pink noise
- Listener led to the vehicle

Vehicle Listening Test Methods: *Listening Methods*
Double-Blind In-situ Benchmark

Vehicle Listening Test Methods: *Listening Methods*
Double-Blind In-situ Benchmark

Vehicle Listening Test Methods: *Listening Methods* Double-Blind In-situ Benchmark

- Listeners use PrefTest run by administrator
- Administrator runs software beside listener or outside vehicle
- Radio controlled by administrator
  - Constant volume
  - Source selection, randomized by PrefTest
- Final test: Dynamic Response

Vehicle Listening Test Methods: *Listening Methods*
Double-Blind In-situ Benchmark

- Method is consistent,
- Repeatable with meaningful results,
- Capable of discerning subtle differences in a large set of very closely matched systems from same class,
- Needs rapid A/B and on-road evaluations.

Vehicle Listening Test Methods: *Listening Methods*

Double-Blind Binaural

- Rapid A/B/C/D comparisons
- Efficient and cost-effective
- Highly repeatable
- Excellent, systematic control of nuisance variables

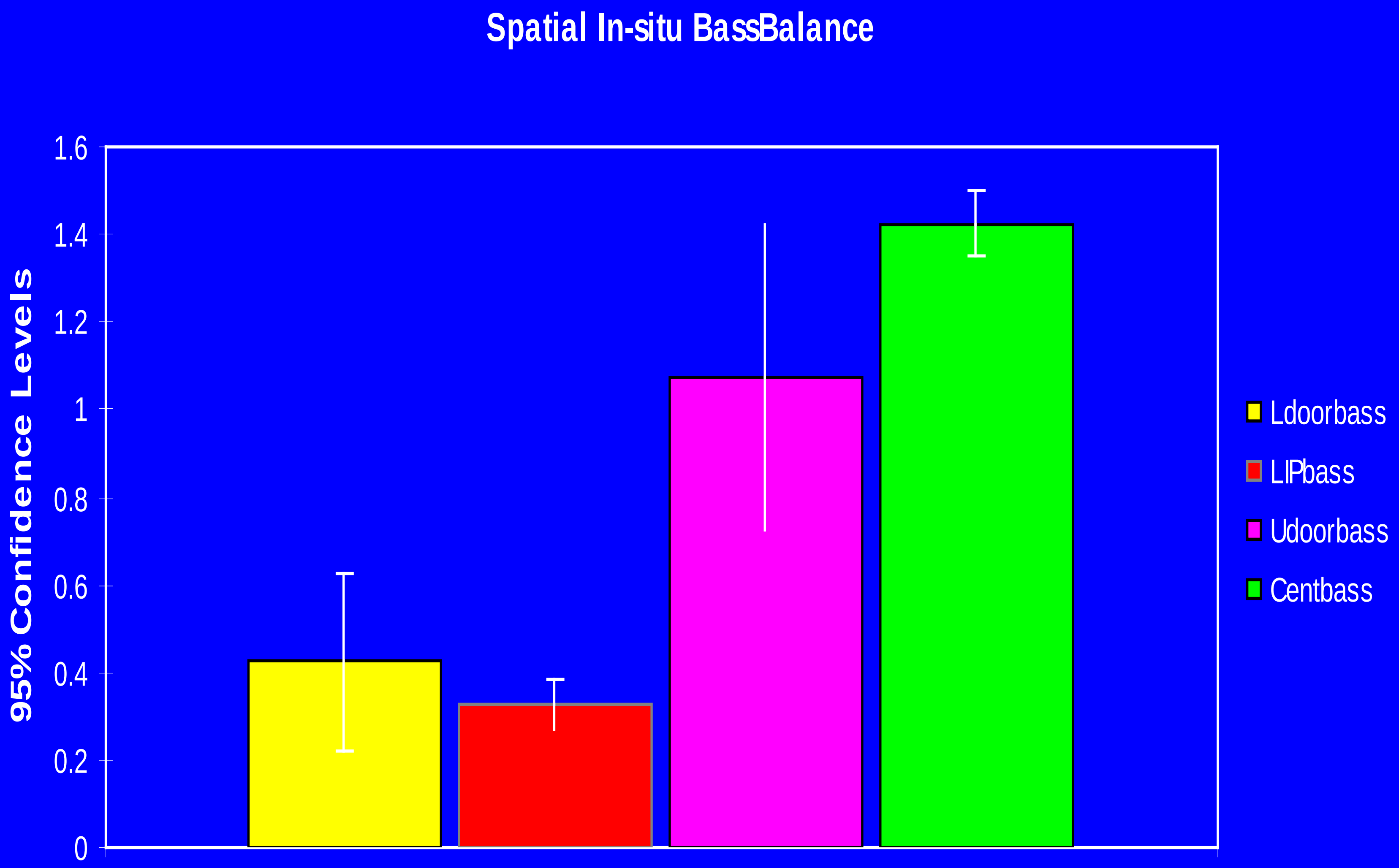
Vehicle Listening Test Methods: *Listening Methods*
Double-Blind Binaural

- Binaural recordings edited on PC as *.wav files
- Digital play back on PC w/ earphones
- PrefTest used to evaluate recordings
- Recordings possible under road conditions w/ varying volume settings
- Recordings synchronized and evaluated

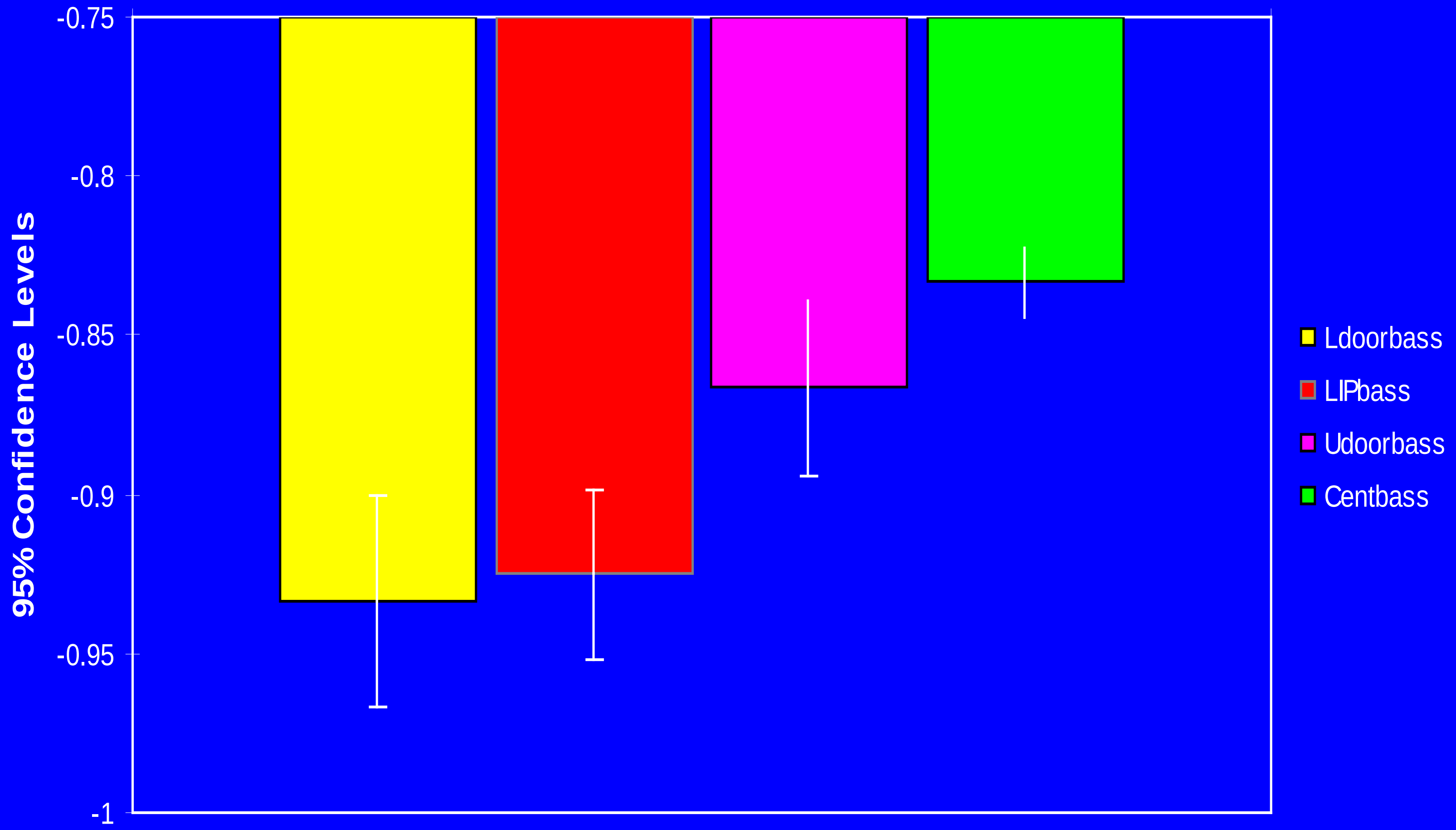
Vehicle Listening Test Methods: *Listening Methods*
Double-Blind Binaural

- Excellent results for spectral aspects
- Lack of bone conduction, effects absolute agreement : vs. Blind in-situ
- There is <u>relative</u> agreement . . . . . .

Vehicle Listening Test Methods: *Listening Methods*
Double-Blind Binaural vs. Blind In-situ
Bass Balance In-situ



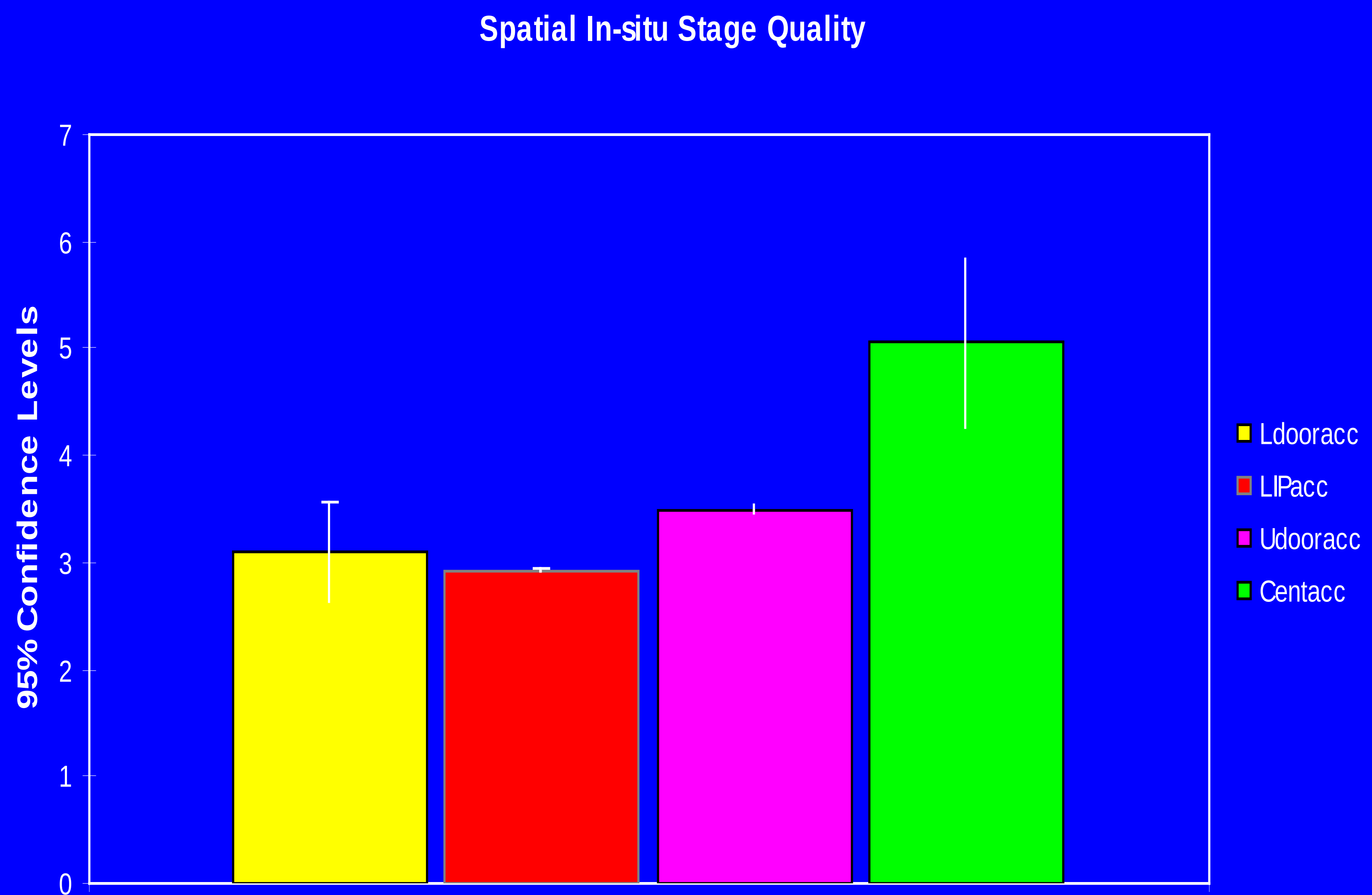
Vehicle Listening Test Methods: *Listening Methods*
Double-Blind Binaural vs. Blind In-situ
Bass Balance Binaural



Vehicle Listening Test Methods: *Listening Methods*
Double-Blind Binaural

- Spatial aspects using stationary binaural recordings less than accurate reproduction: Spatial confusion.
- Lack of head movement
- Pinna mismatches: dummy head/listener

Vehicle Listening Test Methods: *Listening Methods*
Double-Blind Binaural vs. Blind In-situ
Stage Quality In-situ

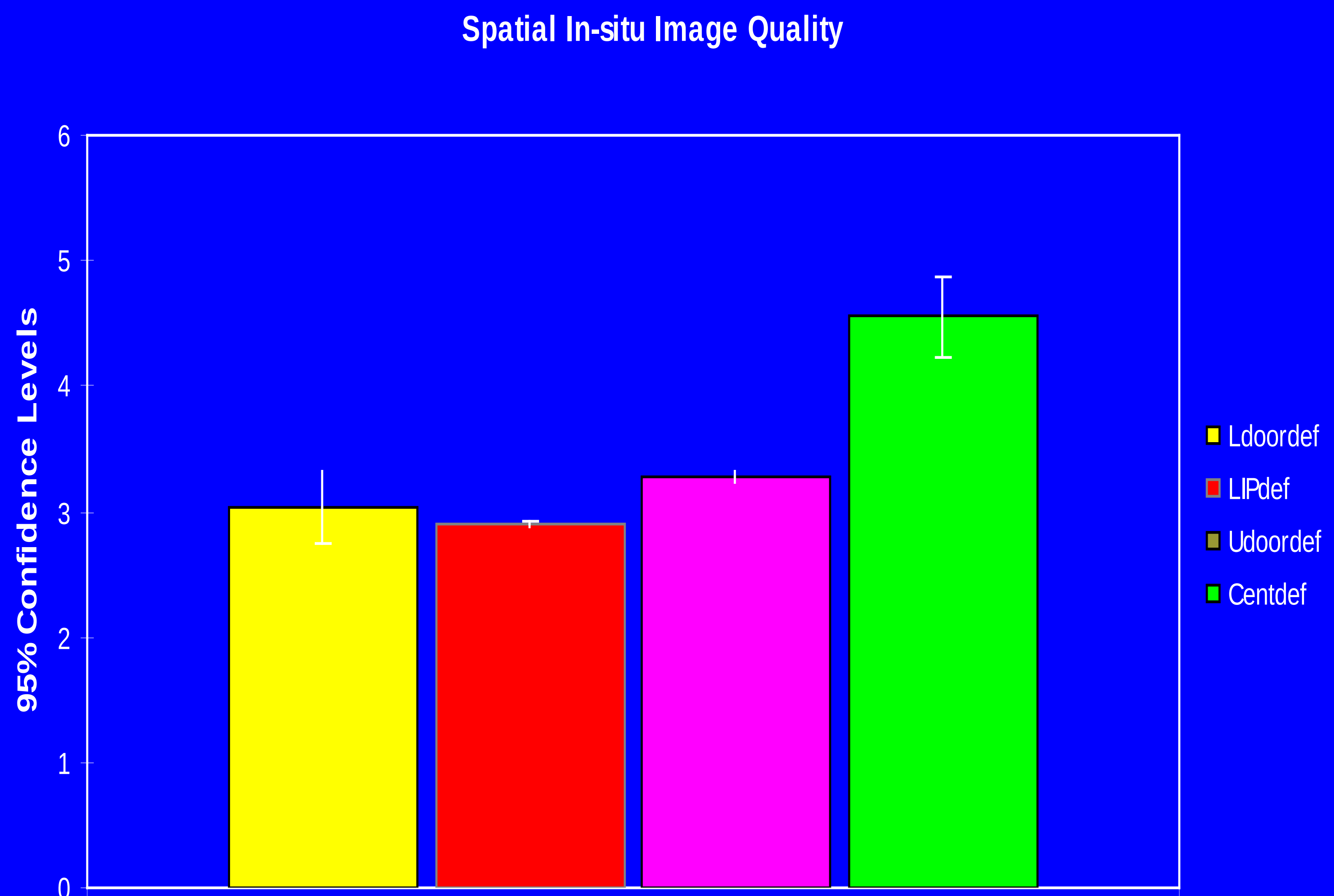


Vehicle Listening Test Methods: *Listening Methods*
Double-Blind Binaural vs. Blind In-situ
Stage Quality Binaural

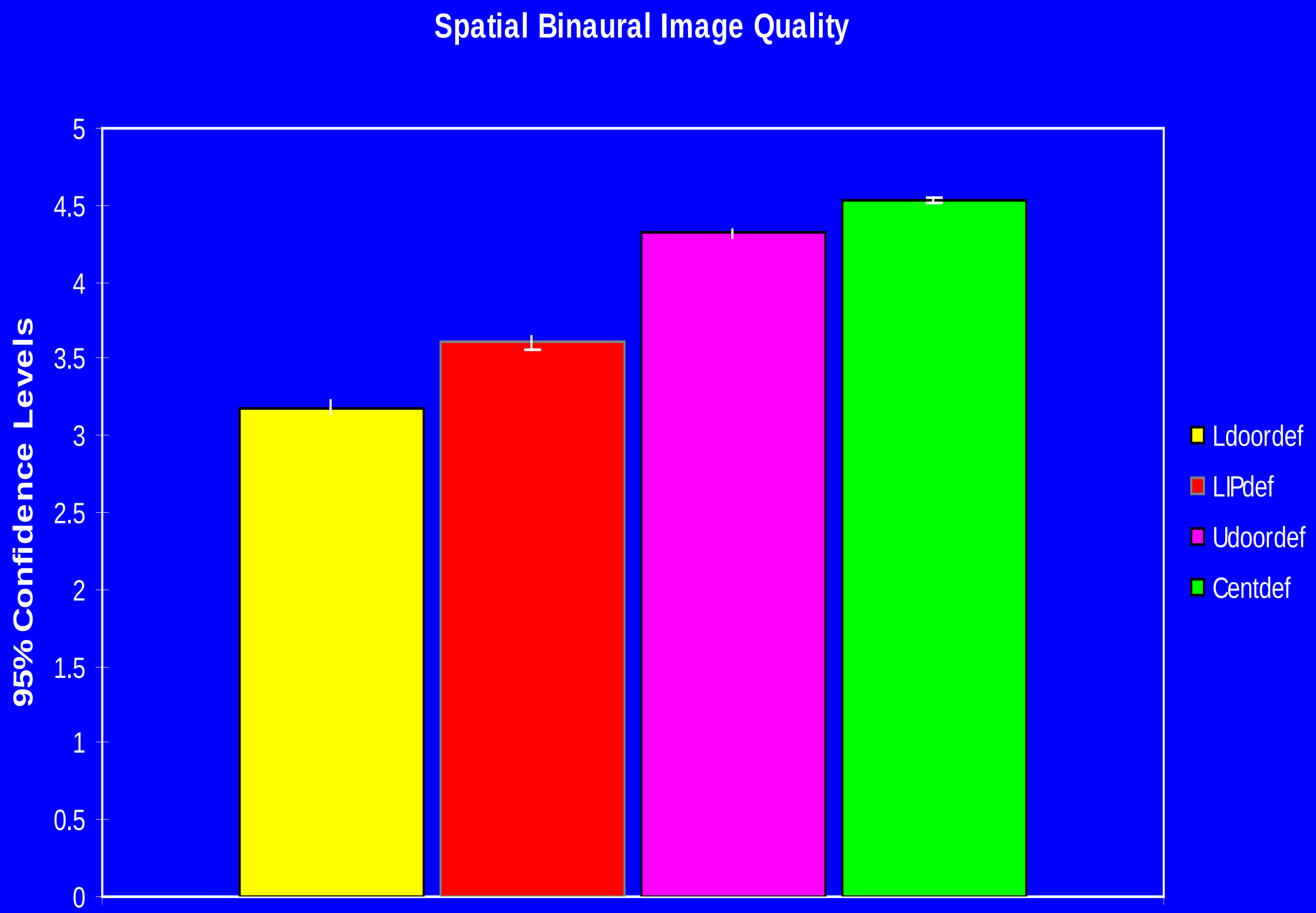
Vehicle Listening Test Methods: *Listening Methods*

Double-Blind Binaural vs. Blind In-situ

Image Quality In-situ



Vehicle Listening Test Methods: *Listening Methods*
Double-Blind Binaural vs. Blind In-situ
Image Quality Binaural



Vehicle Listening Test Methods: *Listening Methods*
Double-Blind Binaural

- **Potential for better Spatial Accuracy**
  - **Recordings using pinna similar to listeners**
  - **Recordings made related to head movement and synchronized to the listener’s head movement during playback**

Vehicle Listening Test Methods: *Listening Methods*

Double-Blind Placebo In-situ

- Pilot experiment:
  - Single Sound System
  - In-situ Blind vs. In-situ Placebo
  - Three EQ's: 1- Flat , 2 - w/aberration
  - Only data from flat is compared
  - Good agreement

Vehicle Listening Test Methods: *Listening Methods*
Double-Blind Placebo In-situ

- **Qualities of the Placebo Method:**
  - factors out non-acoustic opinions
  - in-situ w/o blindfold & on-road evaluations possible
- **Future considerations:**
  - Sonic aberrations made to source material on CD or cassette
  - Aberrations expanded beyond spectral: small time delays and phase shifts
- **Needed: rapid paired comparison.**

Summary

- Amp Design
- Speaker Design
- Speaker Placement
- Measurement & Evaluation
- System Integration

System Integration

- Audio for automobiles can include more than just AM/FM/Cassette/CD Stereo playback:
  – Audio for Video, On-Board PCs, Cellular Telephony, Navigation system, Satellite communications.