Envelopment and Small Room Acoustics

- David Griesinger

- Lexicon
- 3 Oak Park
- Bedford, MA 01730

- Copyright 9/21/00 by David Griesinger

Preview of results

- Loudness isn't everything!
- At least two additional perceptions:
  - Envelopment
  - Externalization

- Both require multiple drivers at LF
- Both are improved if the drivers are at the side of the listener
- Externalization better with a 90 degree shift

Loudness isn’t everything

- We all think we can perceive loudness.
  - (we know how to measure it.)
- BUT: rooms with identical loudness can sound quite different.
  - Small rooms have audible spatial properties.
  - These properties interact with the recording technique and loudspeaker placement.

Measurement and Modeling

- You don't understand anything
  - unless you can make a machine that measures what you perceive.
- A sound level meter measures loudness - (more or less)
- We need a machine that can measure our spatial perception of enclosed spaces.

OK - so build a machine!

- The method is clear - true envelopment is created by apparent motion of the reverberation from a syllabic source, created by flucutations in the ITD and the IID
- We have to detect the ITD and the IID the way the ear does
- Details of how the ear detects localization are not well known
  - and details are where it is at...

It’s all in your head

- To understand perception we must:
  - understand the physics of the sound detector
  - understand how the brain processes the detected stimulus
  - build a model that includes both.
- To understand rooms we must couple the room properties to the perception.
- Frequencies below 200Hz behave quite differently than higher frequencies

Interaural Time Delay (ITD)

- Interaural Cross Correlation a traditional measure
  - IACC cannot be easily calculated from the basilar membrane data
  - IACC combines Interaural Intensity Differences (IID) and ITD
  - Perceptual experiments show IID and ITD are separately perceived.

ITD and single reflections

- spatial properties of single lateral reflections depend on the delay
  - the delay dependency is different for cues based on ITD, IID, and IACC
- measured data show that below 200Hz ITD is the primary cue for spatial properties.
- Below 200Hz ITD is also the primary cue for localization.

Spatial perception and ITD

- A constant ITD (or ITD during a fast rise) is perceived as source azimuth.
- A rapidly varying or randomly varying ITD is perceived as a stationary source in the presence of envelopment.
- An absence of variation in the ITD in the presence of head motion results in in-the-head localization.

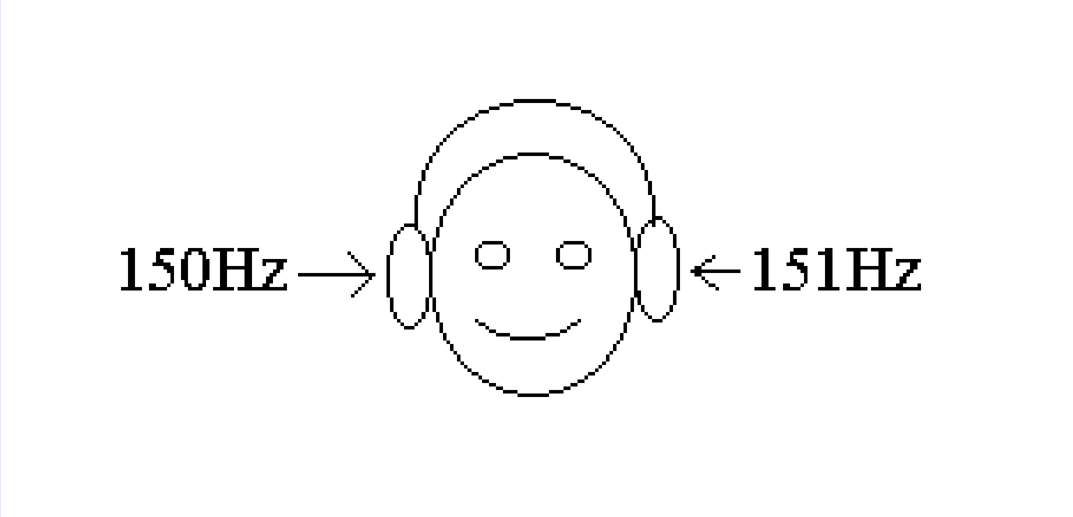
TWO spatial perceptions

- Envelopment
  - the perception that room sound - particularly reverberation - surrounds the listener.
  - most small rooms provide no envelopment of their own.
  - Envelopment must come from the recording
- Externalization
  - low frequencies are perceived as inside the head in many playback rooms.

How does the ear detect the ITD?

- ITD of sine waves seems easy to detect
  - but these are only weakly localized!!
- There are inherent ambiguities in the ITD of monochromatic signals
  - beyond a certain ITD the lead or lag of phase becomes ambiguous
- Steady tones are weakly localized
- Phase of steady signals is not detected above 500Hz.

Example - Sine waves with earphones



– We expect to hear a signal moving left and right at a one Hz rate
– actual perception is of a poorly localized sound moving ~+-30 degrees

Localization has several states

- 1. Sharply localized - (syllabic inputs with fast rise-times)
- 2. Poorly localized but moving (spacious)
- 3. Unlocalized - (surrounding but not enveloping)
  - it is possible that the perception I have called "continuous spatial impression" is related to the "Unlocalized" localization state.

And the localization depends strongly on the source

- plucked string bass produces strong localization and high envelopment
- Bowed (arco) string bass does not

- High source dependence makes the measurement of envelopment directly from an impulse response unlikely to be successful.

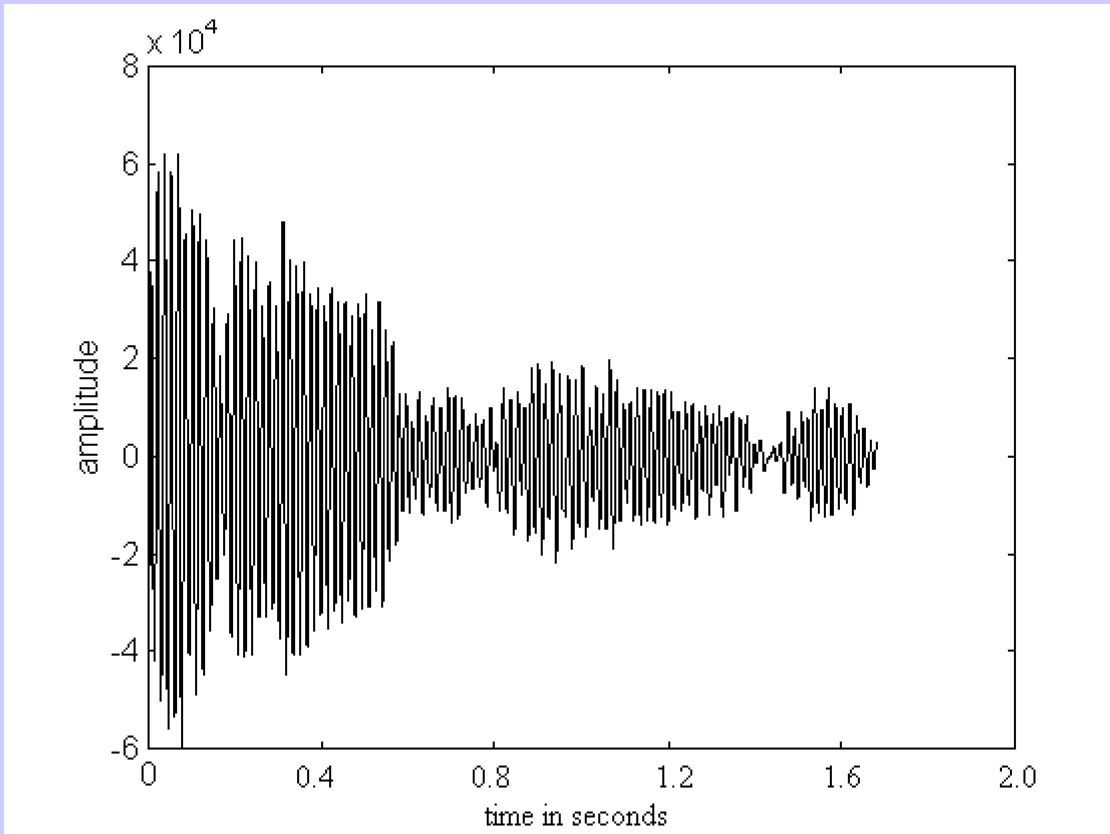
Human hearing detects the IDT during signal rise-times

- Most musical signals are NOISEY
- level and phase fluctuate rapidly
- The ear is always looking for ITD differences during the rising edge of signals
- IDTs during dips in the level (of either ear) are inhibited
- IDTs during steady tones are also inhibited

Some ideas for further experiments

- 1. How quickly does a signal have to rise to be strongly localized?
- 2. What is the difference between an unlocalized sound and a (syllabic) sound that is enveloping by virtue of high fluctuation in the ITD?

Example - decay in Boston



63 Hz stopped tone

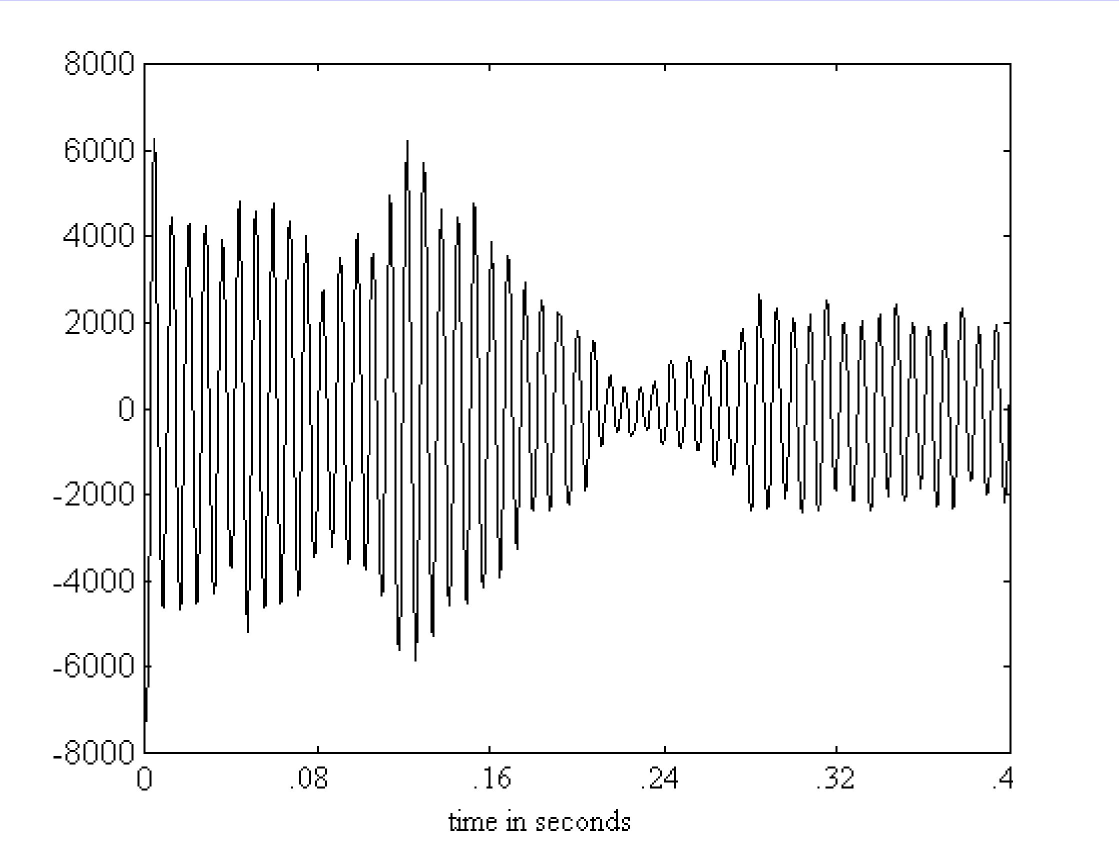
Envelopment

- envelopment is the Holy Grail of concert hall design
- when reproducing sound in small spaces envelopment is frequently absent
- sound mixing rooms with low reverberation times are often particularly poor
- In rooms where envelopment can be heard the strength of the perception depends on the recording technique.

How do we measure envelopment?

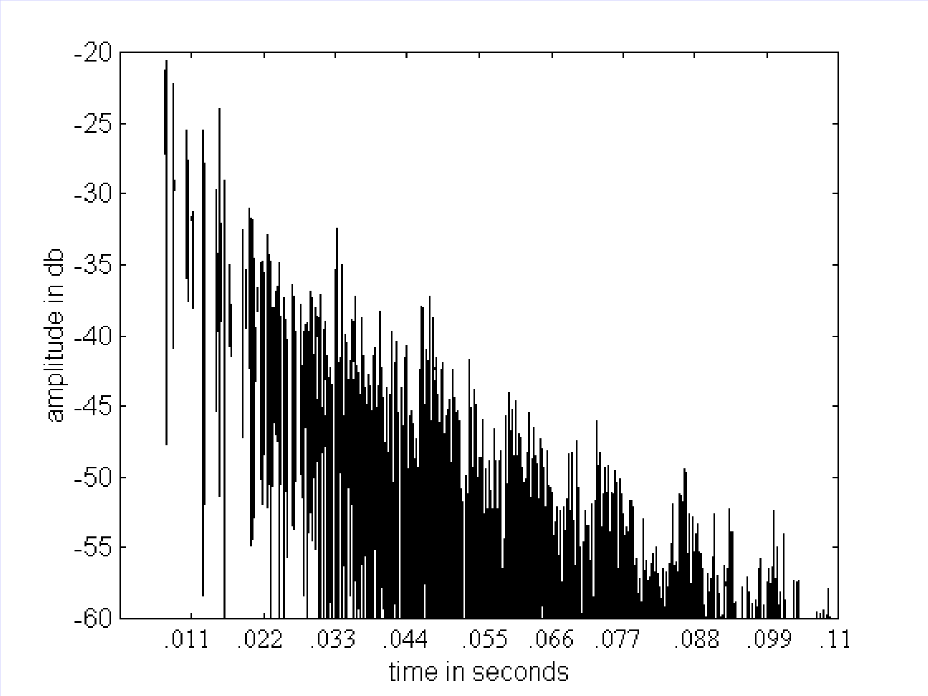
- ITD Fluctuation in the range of 2-20Hz is perceived as envelopment
- Fluctuations during the reverberant component of the signal stream are particularly important.
- Reflected sound causes ITD fluctuation
- The amount of fluctuation depends on the properties of the source music.

Reflected sound causes ITD fluctuation



- Large spaces can produce fluctuations even with narrow band signals.

The impulse response of a small room is short

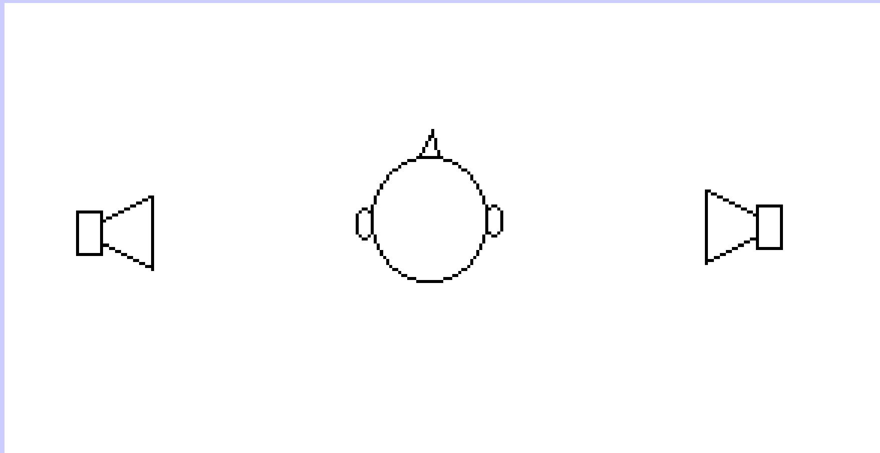


- 12’x15’x9’ room , RT ~0.2sec, TC ~ 30ms
- If the music signal varies slowly the room will always be steady-state

Small spaces - listening rooms

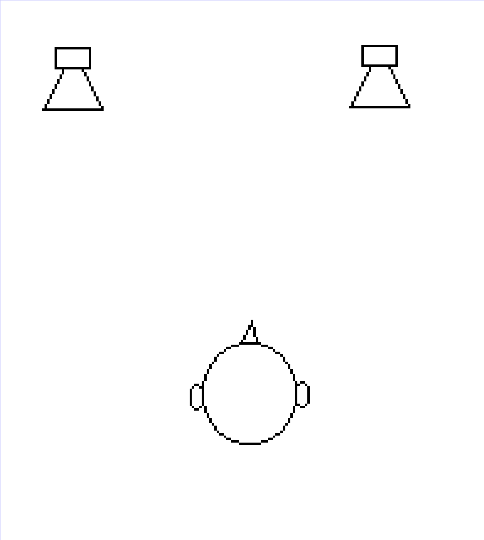
- Small spaces produce fluctuations in the 2-20Hz range ONLY if the sound source is broadband.
- For narrow band signals a fluctuating ITD can still be produced
  - IF the recording has fluctuating phase
  - AND there are multiple drivers.

Anechoic spaces



- envelopment can be created by reproducing sound from two decorrelated loudspeakers
- envelopment at LF is maximum when the loudspeakers are at the side
- a single loudspeaker gives no envelopment

Anechoic space - std stereo

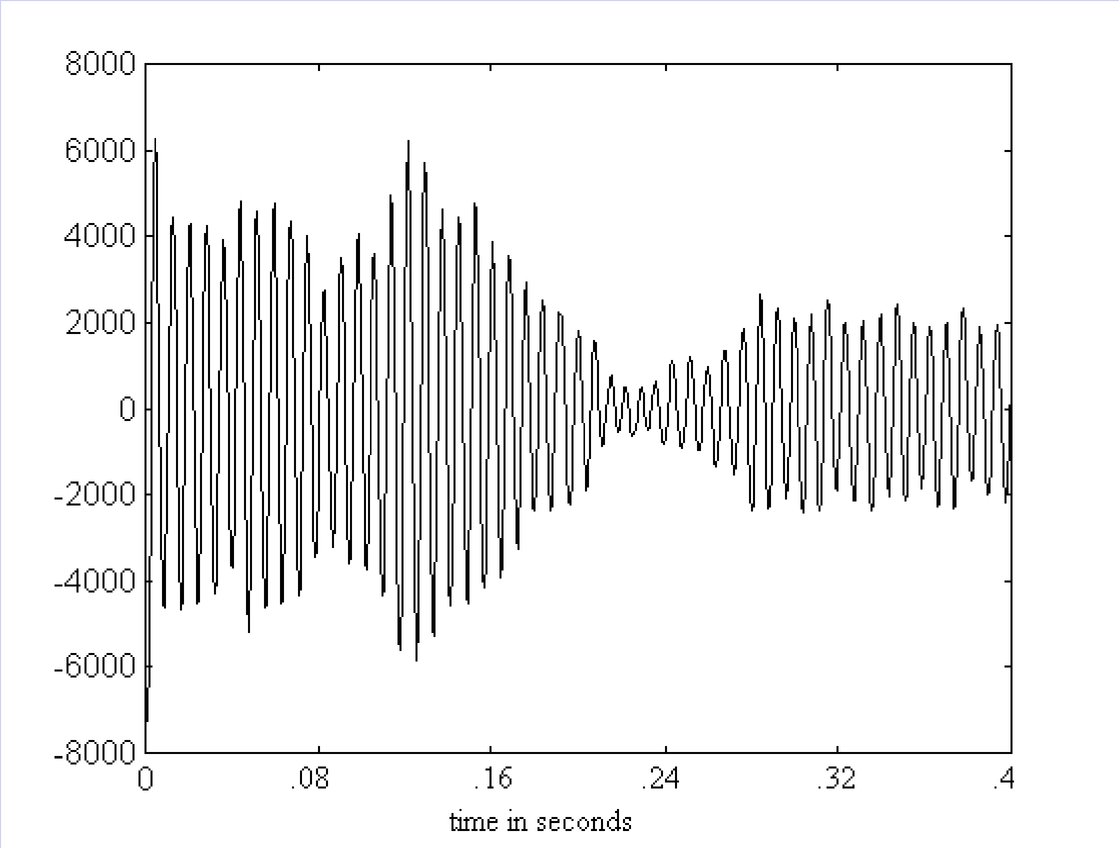


- Standard stereo gives little envelopment because the speakers are not lateral - even with decorrelated material.

Reflective spaces

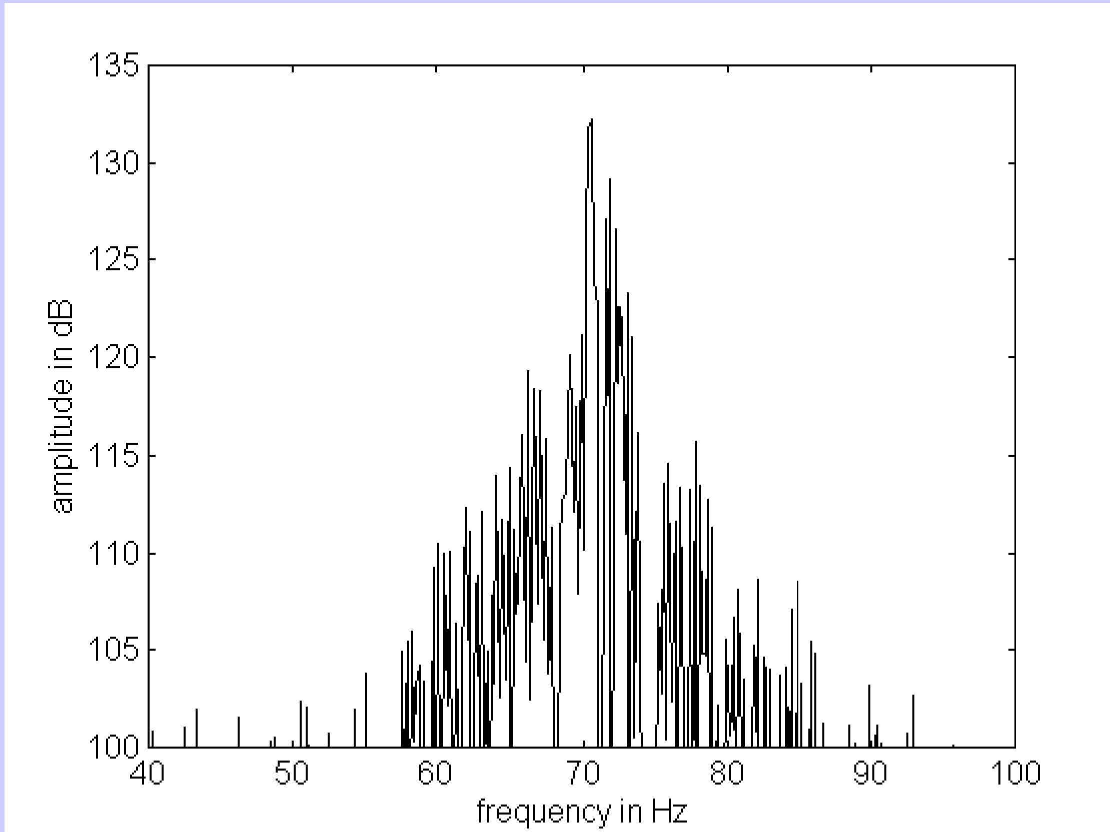
- can create envelopment directly ONLY
  - if the reverberation time constant is larger than the inverse bandwidth of the stimulus
  - or if there are multiple drivers reproducing material with fluctuating phase.

Recorded reverb has narrow bandwidth and slow variation



- A small room cannot produce a fluctuating ITD from a single driver.

Bandwidth of sound decay



Decay of a held sine tone in Boston Symphony

Note the bandwidth is 3Hz or less

A measure for Envelopment

- Must measure zero in an anechoic space
- Must measure low values when a single driver is used

- DG has not found a clever way of doing this directly from the impulse response or its Fourier transform!!

Brute force works for DFT

- To find the Diffuse Field Transfer Function (DFT) we model:
  - (or measure) the room, to find the binaural impulse response from multiple drivers
  - the musical signal - to convolve with the impulse response
  - the head-pinnae system, to calculate the ITD
  - calculate the fluctuation in the ITD
  - The average magnitude of the fluctuations is our measure

Image Model for Rooms

- Is valid at LF if all surfaces have identical absorption.
- This is almost never the case in listening rooms.
- The model works well enough anyway.

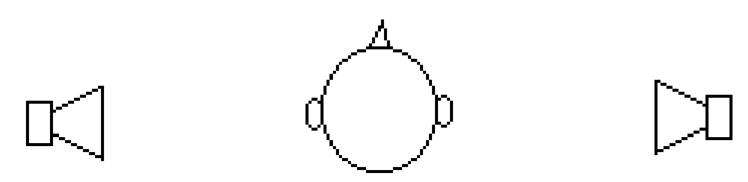
The Musical Signal

- We can use measured decays of musical notes in large spaces as test sources
  - must use an uncorrelated decay for each driver
- Narrow band noise (~3Hz bandwidth) appears to adequately model music
- Critical band noise models envelopment from broadband signals

The Head-Pinnae system

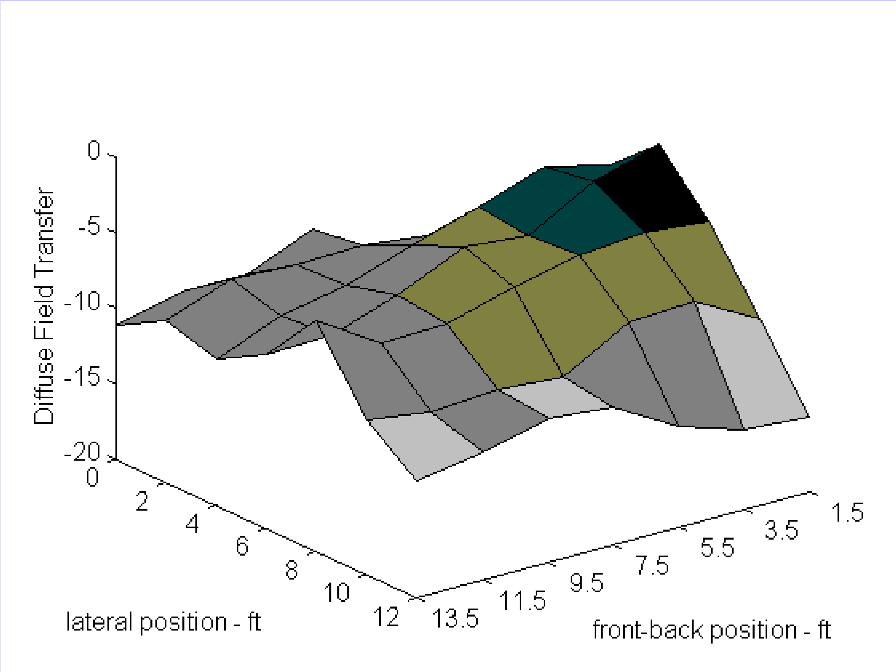
- We will model as two omnidirectional receivers separated by ~25cm
- Model is valid only below about 150Hz
- Such a model allows an enormous simplification of the problem
  - without losing qualitative accuracy

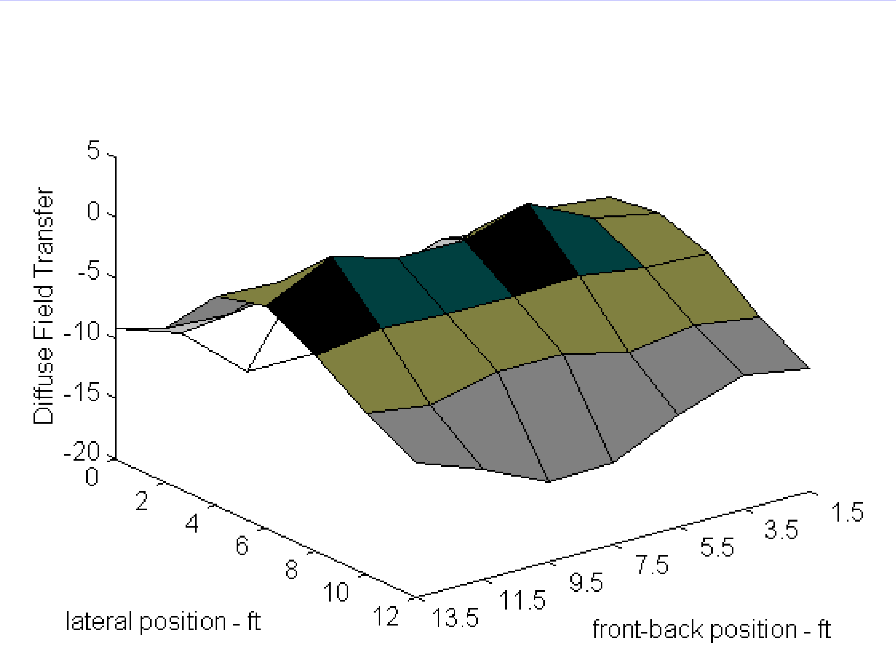
Calibration of the DFT



- The optimal angle for two uncorrelated loudspeakers can be tested
- limited listening tests reveal that below ~120Hz envelopment is optimal when the speakers are at the sides
- We can use this DFT value as a reference

Tests of the DFT



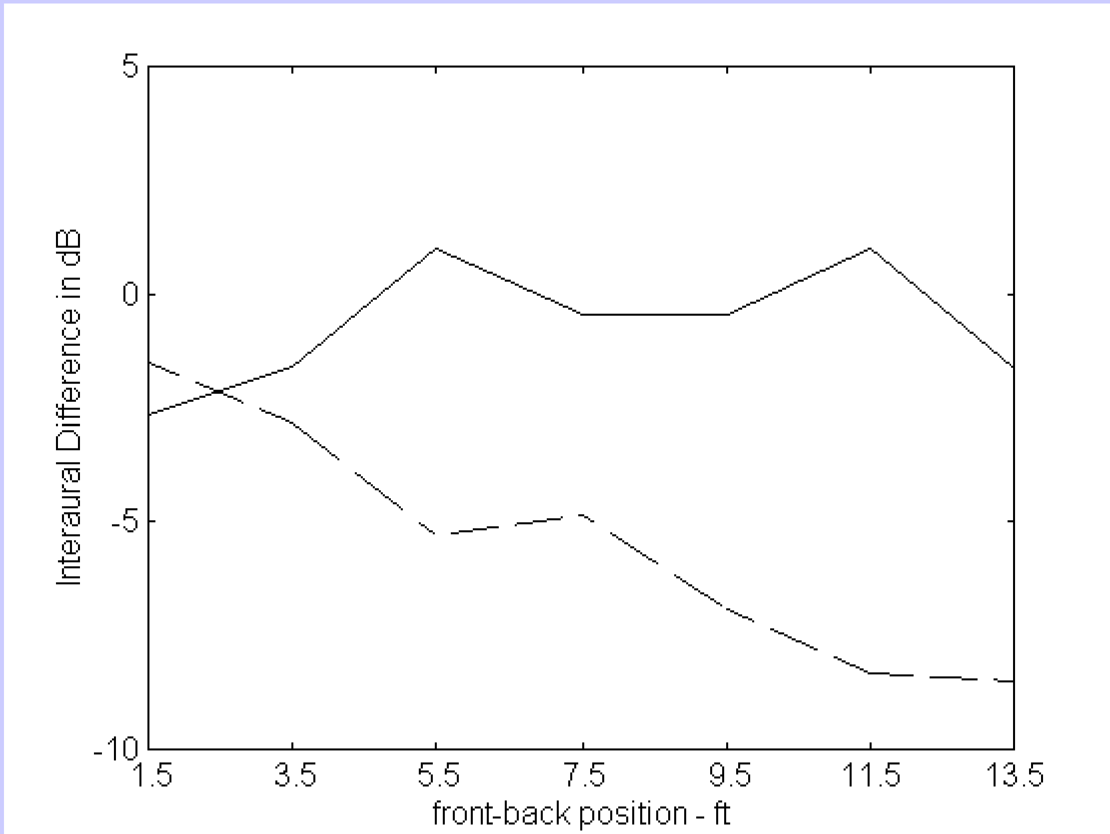


Drivers at the front

Drivers at the side

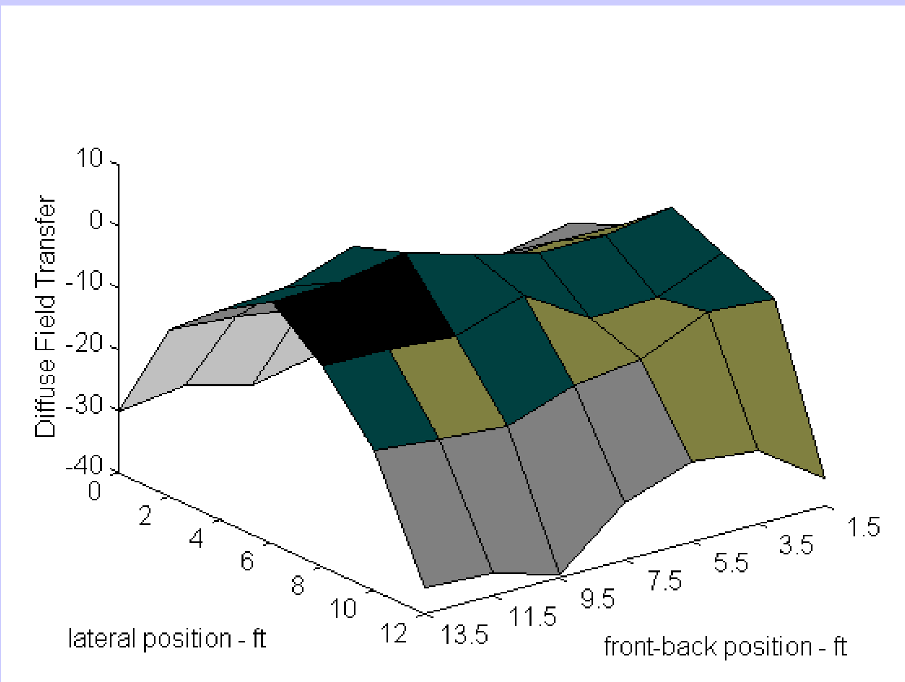
Anechoic Space

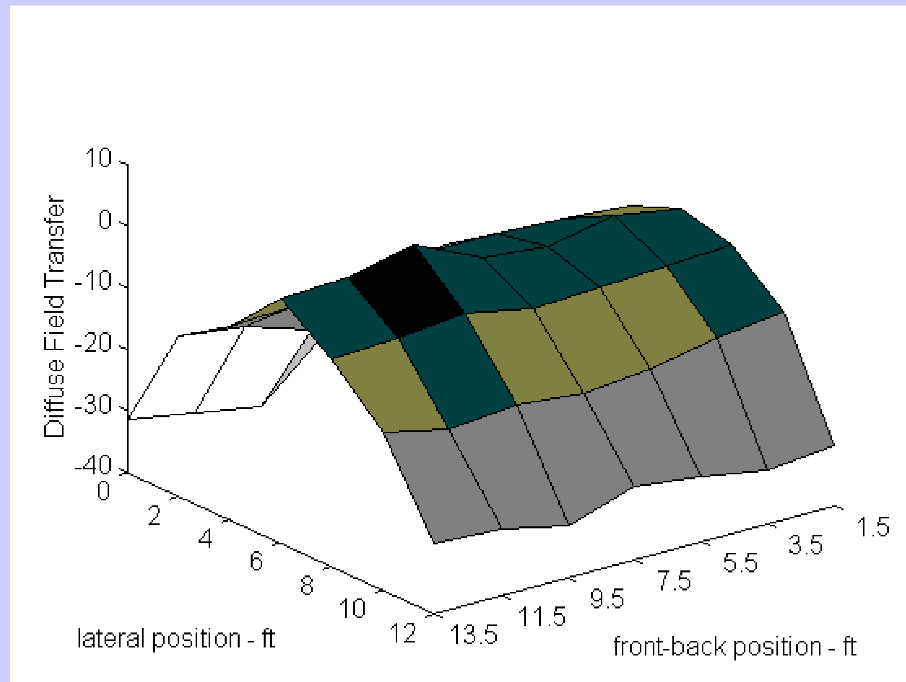
Anechoic DFT along the center line



____ = drivers at side;   - - - - = drivers in front

Octave Band Noise Sources in reflective space



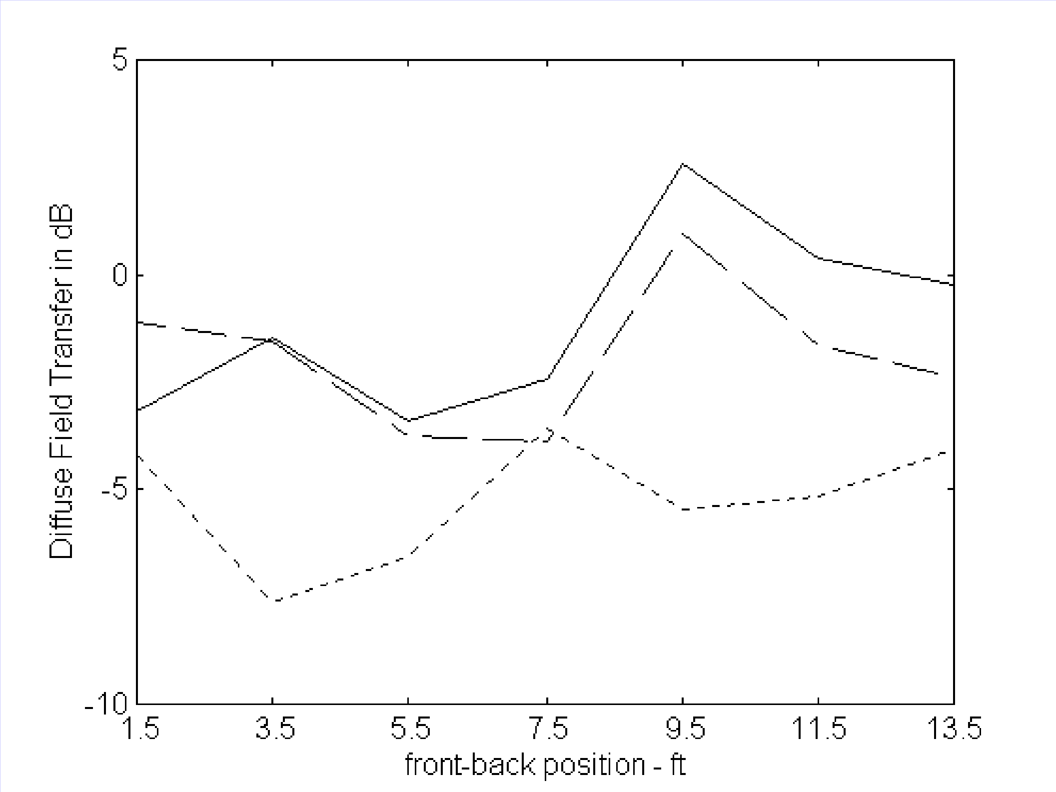


Single driver in corner

Two drivers in front, uncorrelated

12’x15’x9’ room, wall reflectivity 0.8

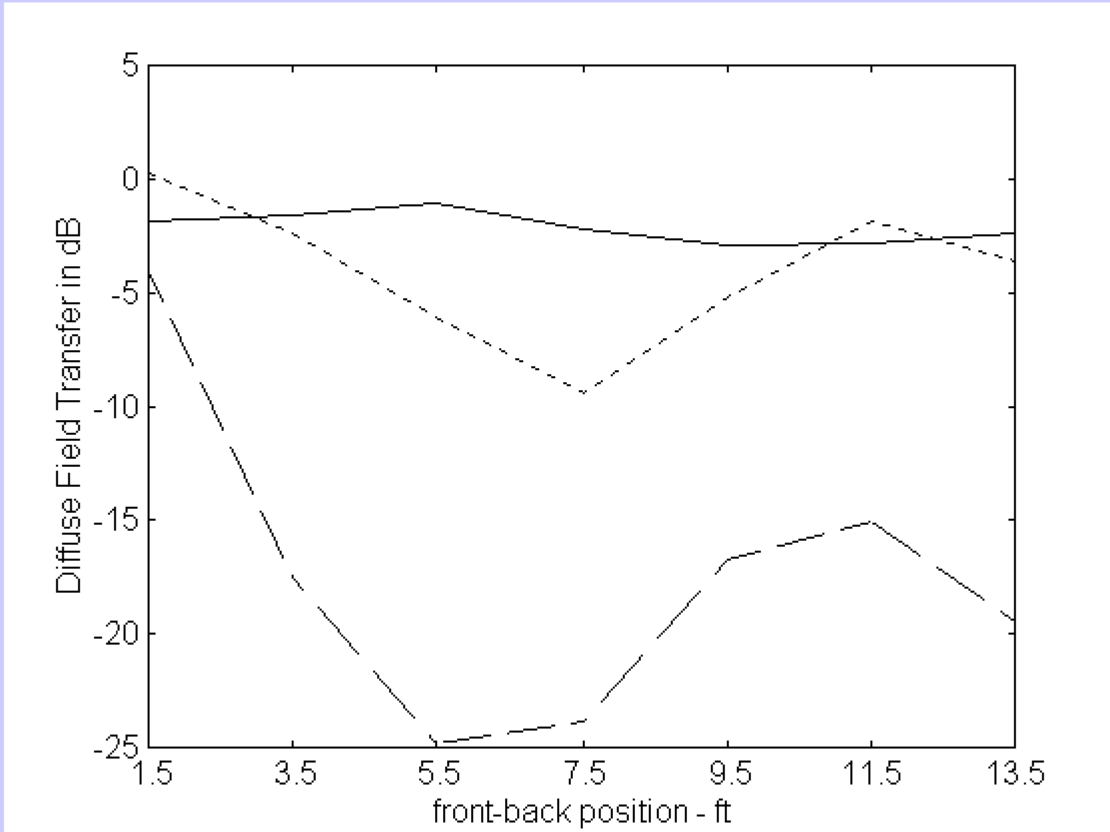
Octave Band DFT as a function of reflectivity



DFT along the center line; ___ = Two drivers, 0.8,

__ __ __ = Two drivers, 0.6, - - - - = One driver, 0.6

DFT with Music - 3Hz Bandwidth, reflectivity .8



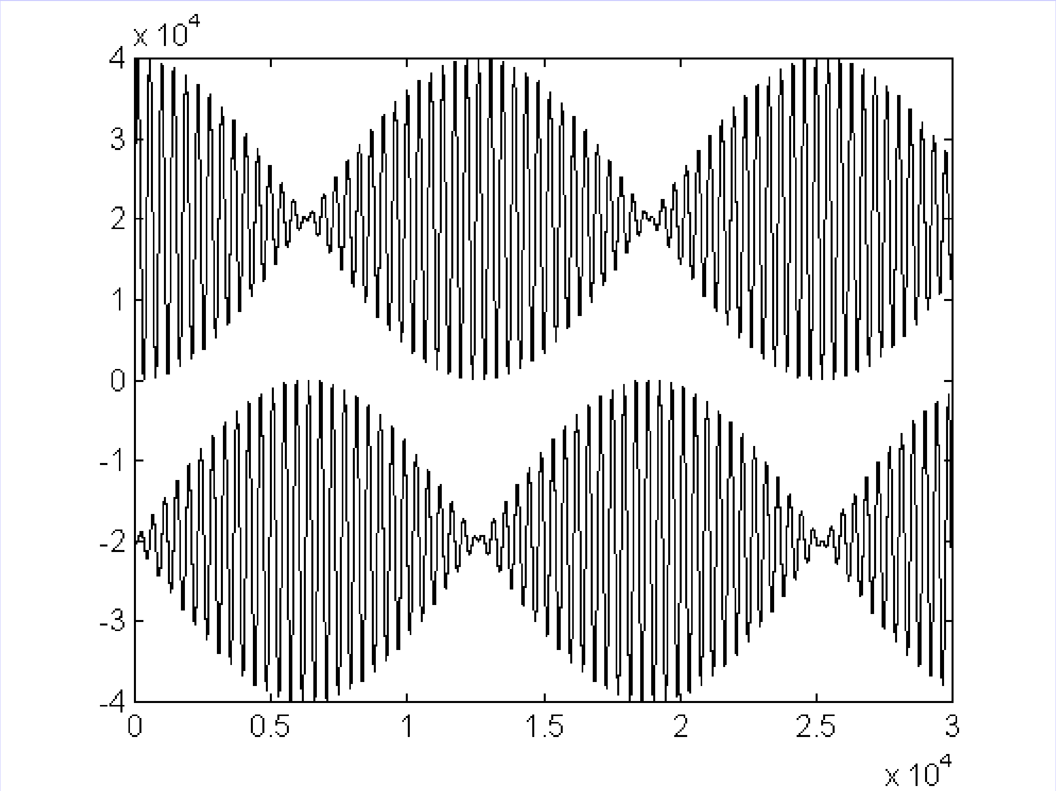
___ = Two drivers, at side, - - - = Two drivers, at front

__ __ __ = Single driver, at the front left

Conclusions on Envelopment at low frequencies

- Two + drivers are essential for music
- A single LF driver in the front does NOT create envelopment in a room with lateral reflectivity < 0.6
- LF drivers are better at the side.
- Recorded reverberation must be decorrelated

Demonstration of Low Frequency Envelopment

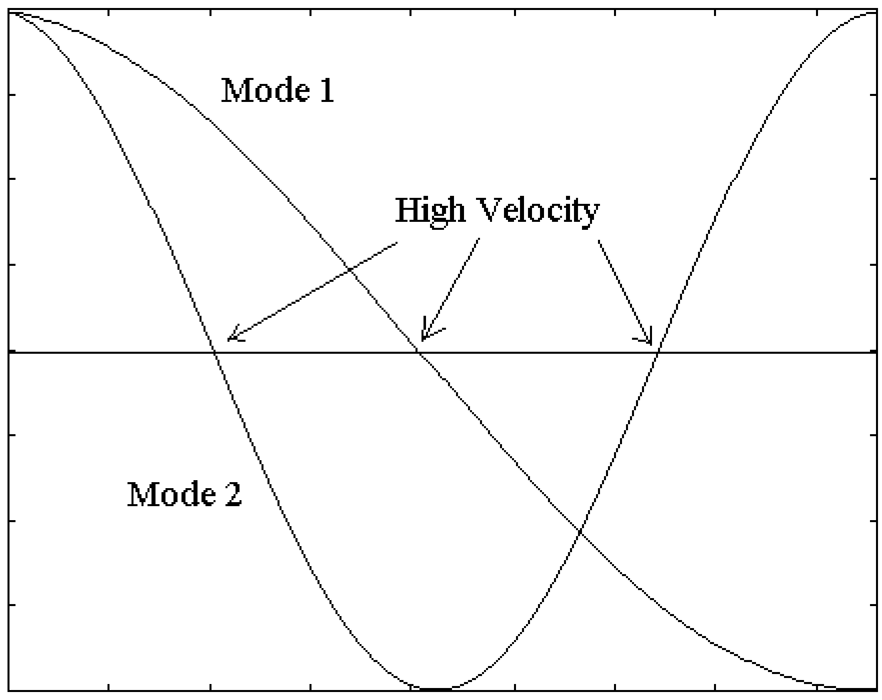


– we can design a beat frequency signal

And use it to test rooms

- envelopment is clearly audible whenever the listener is near a velocity maximum of a lateral mode
- envelopment is nearly inaudible when the listener is near a pressure maximum

Example



– A listener at a velocity maximum will hear high envelopment

Envelopment at High Frequencies

- Above 200Hz most music is no longer monochromatic
- Many (at least the best) playback rooms can be well damped
- Loudspeakers tend to be more directional
- Thus the reverberation radius can be larger than the source to listener distance

Above 200Hz room modes become less important

- Although a live room could produce substantial envelopment, rooms in common use do not.
- Above 1000Hz front/back differences begin to be noticeable.
- At 1500Hz just the front speakers can produce envelopment
- Between 200 and 500Hz the loudspeaker arrangement and the method of driving these loudspeakers become critical.

Measurement requires higher bandwidth

- 1/3 octave noise bands are useful

Success is elusive with a fixed listening position

- many experiments with a fixed measuring head did not yield results that agreed with subjective impressions.
- It is necessary to measure both lateral and front/back envelopment

2-5 and 2-7 Matrices

- Matrix systems are capable of greatly increasing both subjective and measured envelopment in most rooms
- However most matrix systems were developed to enlarge the sweet spot for dialog and sound effects, not to increase envelopment

A successful matrix increases envelopment by

- reproducing reverberation from the sides of the listener with maximum decorrelation
- reproducing low frequencies from the sides of the listener wherever possible
- reproducing enveloping sound effects - such as crowd noise or applause - with full separation to the sides and the rear of the listeners.

Not all matrix systems are the same

- Several 2-5 matrix systems are currently on the market
- These systems differ markedly in their subjective and measured envelopment
  - in general, image width and envelopment from the front speakers are reduced compared to two channel stereo
  - rear channels are not optimally decorrelated
- These differences are particularly noticeable in cars

Conclusions 1

- spatial properties of small rooms are determined by
  - the interaction between lateral and medial room modes
  - the bandwidth and syllabic properties of the source
  - the orientation of the listener

Conclusions 2

- small rooms develop their own sense of space if
  - the room time constant is greater than the inverse bandwidth of the source
  - the listener is not near a lateral velocity minimum for the source frequency
  - there are at least two drivers on opposite sides of the listener
  - the source material contains decorrelated reverberation

Conclusions 3

- most if not all the low frequency spatial properties of small rooms are measurable with a swept wobble tone, a binaural microphone, and a detector for interaural fluctuations
- A measurement system for higher frequency room properties is under development.
- (Keep checking the author's web page for updates)